Silurian "Clinton" Sandstone Reservoir Characterization for Evaluation of CO_2-EOR Potential in the East Canton Oil Field, Ohio

Ronald A. Riley[1] (ron.riley@dnr.state.oh.us)
John Wicks[2] (jlwicksx@embarqmail.com)
Christopher J. Perry[1] (chris.perry@dnr.state.oh.us)

[1]Ohio Department of Natural Resources
Division of Geological Survey, Columbus, OH 43229-6693

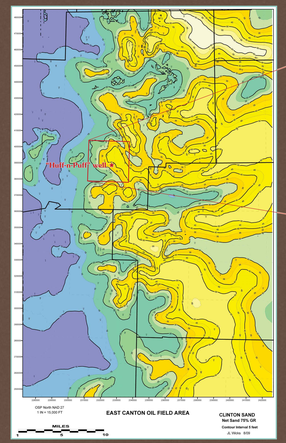
[2]J L Wicks Exploration, Wooster, OH 44691

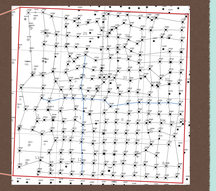
ABSTRACT

The Ohio Division of Geological Survey conducted a detailed reservoir characterization of the Silurian "Clinton" sandstone in the East Canton oil field to evaluate the potential for CO_2-EOR (enhanced oil recovery). This investigation, in cooperation with private industry, included an 80 ton CO_2 cyclic test ("huff n puff") in Stark County. The East Canton oil field has produced approximately 95 million barrels of oil through primary recovery since 1947 from approximately 3,100 wells within 175,000 acres. With an estimated 1.5 billion barrels of original oil-in-place, there remains significant "stranded" oil in this nearly depleted but economically promising oil field. There have been no secondary recovery efforts in this mature field because of the tight, heterogeneous nature of this reservoir.

Regional stratigraphic cross sections were generated across and surrounding the East Canton oil field and correlated to full-diameter cores and published reports to establish the regional "Clinton" sequence stratigraphy and depositional setting. The stratigraphic framework developed by these cross sections established regionally consistent formation/interval boundaries that were used for construction of regional structure and isopach maps. Detailed reservoir maps of up to five sandstone units and surrounding impermeable shale units within the "Clinton" interval were mapped and related to production in a 16 square mile area around the CO_2 cyclic test. The geologic model was used as input into a reservoir simulation to estimate behavior of reservoir fluids from CO_2 injection.

Heterogeneity in the "Clinton" sandstone is largely controlled by deposition and geometry of tidal/fluvial-dominated deltaic deposits. Regionally, the "Clinton" interval has an average gross thickness of 110 feet, and net sandstone thickness ranges from less than 10 feet in the offshore marine environment and interchannel areas to over 60 feet in the thicker, tidal/fluvial channel sands. Detailed mapping of these depositional units and fracture systems is necessary to better understand reservoir compartmentalization, fluid flow, unswept oil and for planning any future EOR development.

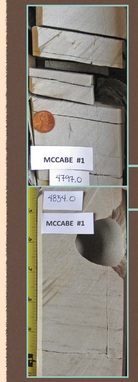


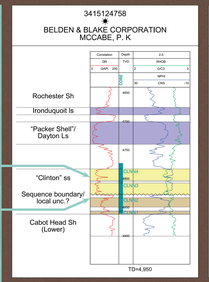


Location map of the area of interest showing all the "Clinton" penetrations and the cross section lines. Also shown is the CO_2 cyclic test ("Huff-n-Puff").

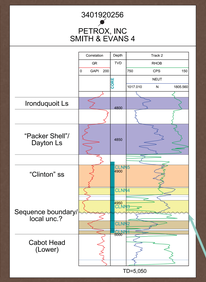
Regional net sandstone map of the "Clinton" interval based on a gamma ray curve cutoff of 75%. Also shown are the 16-section area of interest and the "Huff-n-Puff" test.

CORRELATION OF WIRELINE LOGS TO CORE

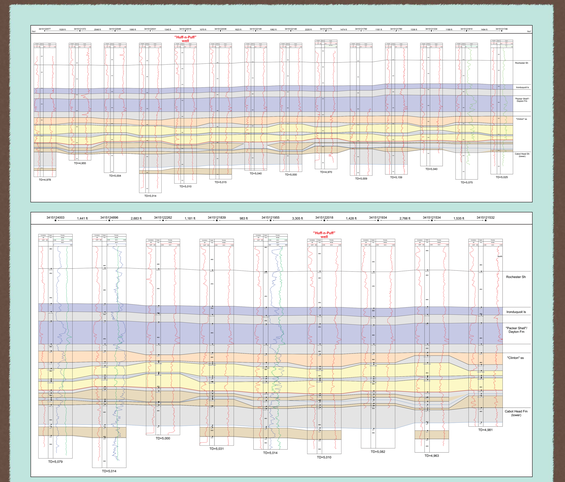




Wireline log of the McCabe #1 cored well showing the formation/unit boundaries of the "Clinton," overlying, and underlying intervals. The oriented core photos (left) illustrate fractures in the "Clinton" interval, which are important for production in this tight reservoir.

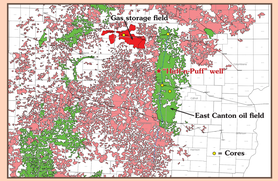


Wireline log of the Smith and Evans #4 cored well showing the formation/unit boundaries of the "Clinton," overlying, and underlying intervals. The core photograph (right) shows the sharp boundary at the base of the "Clinton" reservoir unit 3 and the underlying shale unit. This sharp contact (S3 of Ryder, 2004) is thought to represent a sequence boundary or a local unconformity.

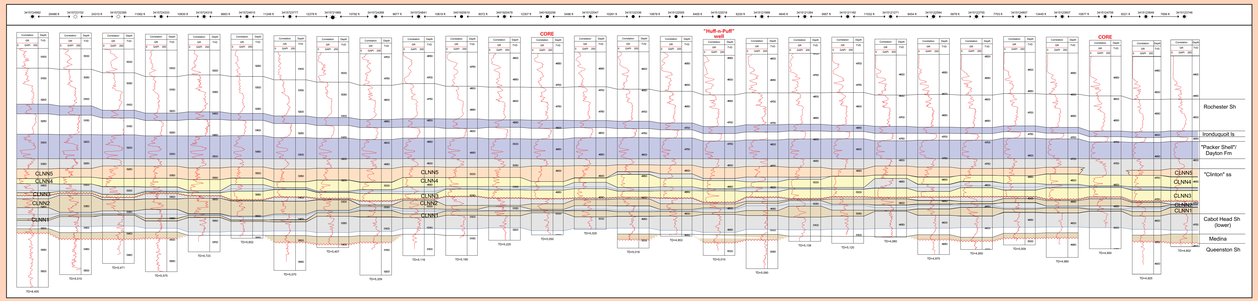


Detailed stratigraphic cross sections trending east–west (upper figure) and north–south (lower figure) through the area of interest (see blue line in the map at left). These sections illustrate the heterogeneity of the "Clinton" interval and the five sandstone units that were correlated and mapped. Datum is the base of the "Packer Shell"/ Dayton Formation.

REGIONAL CORRELATIONS TO ESTABLISH THE STRATIGRAPHIC FRAMEWORK

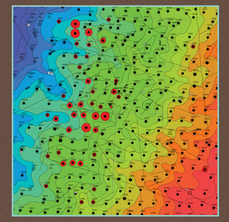


Map of northeast Ohio showing all of the "Clinton" oil and gas fields, "Clinton" cores, and the regional cross section lines.

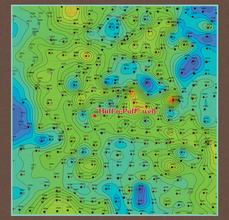


Regional stratigraphic cross section trending north–south (see blue line in the map at left) through the East Canton oil field illustrating the "Clinton" interval and the five individual sandstone units. Datum is the base of the "Packer Shell"/Dayton Formation.

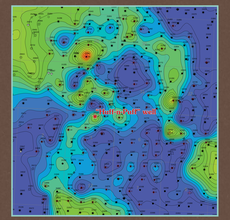
RESERVOIR CHARACTERISTICS AND MAPPING OF THE "CLINTON" SANDSTONE



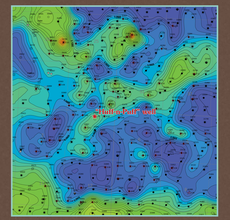
Structure map on the base of the "Packer Shell"/ Dayton Formation with interpreted lineaments from structure contours, LiDAR, and DEM. Also shown is a bubble map of cumulative production (red circles).



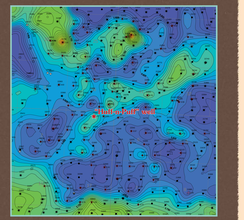
Gross sandstone map of the "Clinton" unit 3 using a RHOB cutoff of 2.55 gm/cc.



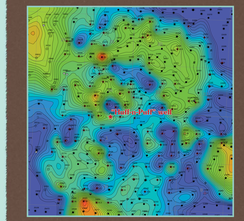
Net sandstone map of the "Clinton" unit 3 using a RHOB cutoff of 2.55 gm/cc.



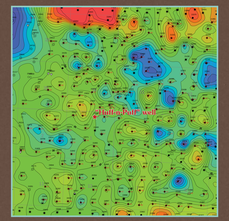
Average porosity map of the "Clinton" unit 3 using a RHOB cutoff of 2.55 gm/cc.



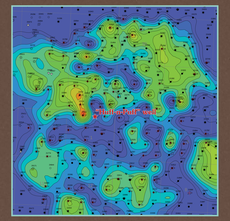
Calculated permeability map of the "Clinton" 3 unit using core to log correlations.



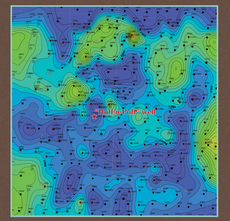
Net sandstone map of the entire "Clinton" interval using a RHOB cutoff of 2.55 gm/cc.



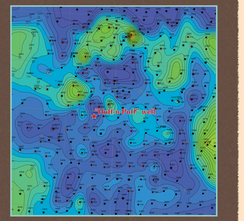
Gross sandstone map of the "Clinton" unit 4 using a RHOB cutoff of 2.55 gm/cc.



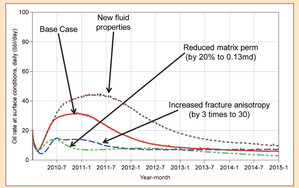
Net sandstone map of the "Clinton" unit 4 using a RHOB cutoff of 2.55 gm/cc.



Average porosity map of the "Clinton" unit 4 using a RHOB cutoff of 2.55 gm/cc.



Calculated permeability map of the "Clinton" 4 unit using core to log correlations.



Forecast of oil production rate for the East Canton oil field pilot area central producer for the five-year simulation period showing the Base Case and three sensitivity study cases. Modified from Fekete Associates, Inc. (2009).

SOME OUTPUT FROM SENSITIVITY TESTS
(reservoir parameters and pilot design were varied)

- Rock and fluid properties have a significant effect on oil production. In particular, for the rock, lower matrix permeability or a larger fracture anisotropy ratio could lead to a significant increase or reduction in oil production rate.
- Lowest oil production is realized from the pilot area when matrix permeability is reduced to 20 percent of the Base Case (0.13 md compared to 0.65md).
- Significant reduction in forecasted production occurs when the permeability anisotropy ratio in the fractures is increased from the Base Case of 10 up to 30. If a value of 30 is used, greater preferential movement of CO2 occurs along the fractures, and consequently less oil is displaced towards the central producer.
- If reservoir fluid properties differ from assumed, oil production could be significantly higher.
- Shutting in offset producing wells did not improve capture of displaced oil by the central producer.
- Shutting in the water injectors did not reduce oil production significantly. The potential for creating a water shield should be further evaluated.

Silurian "Clinton" Sandstone Reservoir Characterization for Evaluation of CO_2-EOR Potential in the East Canton Oil Field, Ohio

Ronald A. Riley[1] (ron.riley@dnr.state.oh.us)
John Wicks[2] (jlwicksx@embarqmail.com)
Christopher J. Perry[1] (chris.perry@dnr.state.oh.us)

[1]Ohio Department of Natural Resources
Division of Geological Survey, Columbus, OH 43229-6693

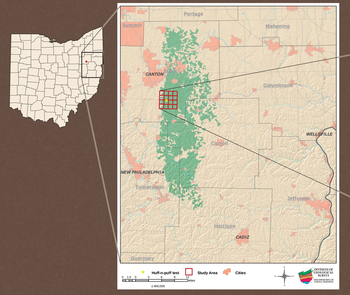
[2]J L Wicks Exploration, Wooster, OH 44691

CO_2 CYCLIC TEST ("HUFF-N-PUFF") FOR ASSESSMENT OF ENHANCED OIL RECOVERY AND SEQUESTRATION POTENTIAL IN THE EAST CANTON OIL FIELD

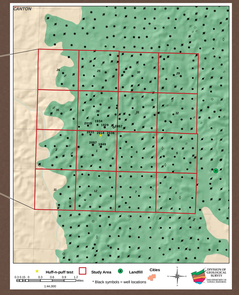
The Ohio River Clean Fuels, LLC (ORCF), Range Resources Corp., Ohio Division of Geological Survey (ODGS), and U.S. Department of Energy conducted a CO_2 cyclic test (also called "huff n' puff") operation on the Sickafoose-Morris Unit #1 well (API #3415122018) in the west-central portion of the East Canton Oil Field. This is the first documented CO_2 "huff n' puff" in the field, although three successful natural gas "huff n' puff" tests were conducted in the early 1980'and 1990's by Belden and Blake Corp.. The CO_2 cyclic operation was designed to test key formation and oil properties for response to CO_2 injection to allow further analyses on the potential of the ECOF for enhanced oil recovery by CO_2 injection and flooding.

At the Sickafoose-Morris Unit #1 well, 81 tons of CO_2 were injected over a 20-hour period on August 19 and 20, 2008, after which the well was shut-in for 32 days before reactivating production. The CO_2 cyclic process involves the injection of CO_2 into a single wellbore (the 'huff'), followed by a "soak" period during which time the CO_2 contacts matrix oil. It then diffuses into the oil adding solution gas drive to the system upon returning the well to production status (the "puff"). In a successful test, CO_2 moves into solution in the oil, swells the oil in the pore space, reducing its viscosity and decreasing interfacial tensions of the oil with the rock. This allows freer movement of the oil by enhancing the reservoir's relative permeability to water and gas. These immiscible effects of CO_2 on the oil, as addressed herein, are critically important to the success of a CO_2 flood. The second key parameter is "sweep efficiency" which allows contact of CO_2 with significant volumes of oil within the reservoir. The permeability of the reservoir to CO_2 in both the fractures and matrix is very important to this "sweep" and a cyclic test can be helpful by determining if fractures or channels within the formation exist to such a degree as to "short circuit" pairs of wells. A successful cyclic test can be defined as one demonstrating confinement of the CO_2 to the area drained by the subject well and not moving beyond that area through fractures or other high permeability zones. It should be noted, however, that more evidence than just a successful cyclic CO_2 project is required to effectively estimate sweep efficiency and a successful CO_2 flood.

To determine whether the volume of CO_2 injected into the Sickafoose-Morris well was confined to the area around the wellbore, gas samples from the Clinton sandstone interval of the eight wells surrounding the injection well were analyzed for composition. Casing pressures were also monitored with readings taken from these observation wells during the gas sampling. Well spacing in this area of the field is 40 acres (~1,320 feet between wells). These "offsetting" wells were tested prior to the injection, immediately following the injection, on a regular basis for two weeks after the CO_2 injection, and five days prior to putting the well back in production. While not entirely conclusive, the absence of elevated CO_2 above normal background values, lack of observed pressure anomalies in the surrounding wells, and absence of enhanced production in offset wells suggest the CO_2 remained near the test well. Post-soak period CO_2 composition and longevity within the gas samples in the subject well are also evidence of containment.



Map showing location of East Canton oil field and Sickafoose-Morris #1 well (permit number 2018). Proposed detailed-study area is outlined in red.



Map showing location of the Sickafoose-Morris #1 well (permit number 2018) and surrounding wells. Observation wells that were tested for gas analyses are labeled with permit numbers.

SITE OPERATIONS

Photograph of the Sickafoose-Morris #1 well huff-n-puff equipment and site layout.

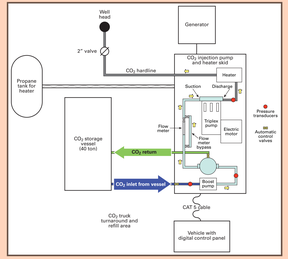
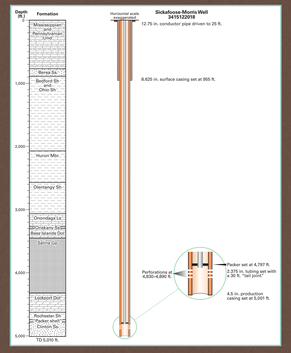


Diagram illustrating the Sickafoose-Morris #1 well huff-n-puff equipment and site layout.

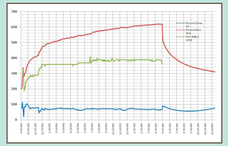


Sickafoose-Morris #1 well completion diagram with perforations and test set-up.

SUMMARY OF PRODUCTION AND CLINTON RESERVOIR CHARACTERISTICS

Completion Date	1969
Initial Production	115 BOPD
Cumulative Production	60,000 BO
Gross Sandstone	110 ft
Net Sandstone	52 ft (> 6 %)
Porosity Range	4–14 %
Completion technique	F/W 5,100 bbl water + 75,000 lb sd proppant + 100 scf of N

CO_2 INJECTION RATE

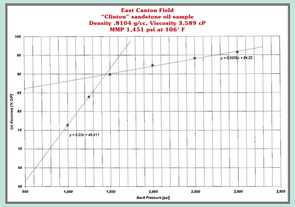


Graph of the Sickafoose-Morris #1 well CO_2 injection operation process temperature, pressure, and flow rate versus time, conducted on August 19 and 20, 2008.

Pressure (psi)	Effective Injection Radius (ft)	CO2 Volume Subsurface (cf)
1300	34	5986
700	68	24236
300	114	67425

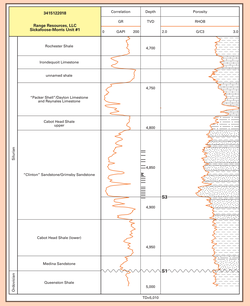
Estimated radius and volume of CO_2 within the formation through the range of pressures encountered by the cyclic test (Holtz, 2008).

MMP ANALYSIS

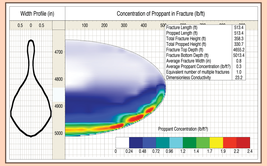


Minimum miscibility pressure (MMP) from oil sample of the #2 Thouvenin-Hall Unit (API NO 3415122019) from the "Clinton" sandstone in the East Canton oil field in Stark County, Ohio.

CO_2 CYCLIC TEST WELL



Sickafoose-Morris #1 wireline well log and lithology. Stratigraphic nomenclature is from the ODNR Division of Geological Survey (2004) and Ryder (2004).

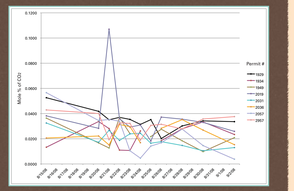


Halliburton model of the Sickafoose-Morris #1 hydrofracture produced in 1969. Stage profile for the Sickafoose-Morris #1 well in the East Canton oil field in Stark County, Ohio; "Clinton" sandstone—single stage water frac from 4,830 to 4,890 ft; 18 holes. Model created on November 25, 2008.

GAS AND OIL SAMPLING IN OFFSET WELLS

Photograph Sickafoose-Morris #1 (permit number 2018) oil sample taken on January 5, 2009. The high pressure hose connected to the tubing valve was purged and filled with oil prior to attaching it to the sample cylinder. The sample cylinder was filled with water that was slowly drained out the bottom of the vessel until it was fully displaced with oil.

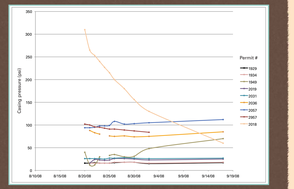
Photograph of gas sample collection at the Adelman #1 well (permit number 1929). The bullplug is screwed into the 2-inch outlet from the casing valve, which reduces to ¼ inch for attachment of the hose leading to the sample container. Pressure is read off the gauge near the sample cylinder valve.



Mole percentages of CO_2 measured in the wells offset to the Sickafoose-Morris #1 well prior to the CO_2 injection and during the "soak" period.

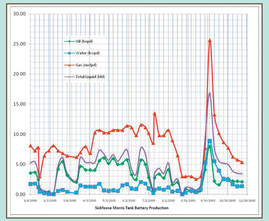
Close-up photograph of the sample container used for sampling of gas. It is 13-inches long with a 2.5-inch diameter. The cylinder is rated to 1,800 psi. There are inlet/outlet valves at each end. Caps are placed over the valve nipples after the sample is taken as a precaution to prevent leakage.

Photograph of oil sample cylinders filled under pressure at the Thouvenin-Hall #2 well (permit number 2019). These samples are in a crate ready to ship to SCAL, Inc. for testing of minimum miscibility pressure (MMP).

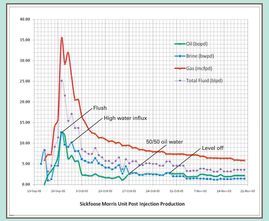


Casing pressures from the observation wells. The measurements for permit number 1949 were also taken off of the tubing on several occasions because of operational problems, which resulted in some variation of pressure readings.

PRODUCTION ANALYSIS



Sickafoose tank battery production from July 11, 2008, to September 19, 2008.



Graph of the Sickafoose-Morris #1 well production for the 60-day period following the CO_2 injection and 32-day "soak" period.

Date	Sickafoose Morris 2018		Sickafoose 2036		Brenner 2057		PER DAY TOTAL		5 WEEK AVERAGE	
	Gas (mcf)	Fluid (bbl)	Gas (mcf)	Fluid (bbl)	Gas (mcf)	Fluid (bbl)	Gas (mcf)	Fluid (bbl)	Gas (mcf)	Fluid (bbl)
7/18/08	3	1.42	3	1.42	3	1.46	9	4.3		
7/25/08	3	1.14	3	1.14	3	1.17	9	3.45		
8/1/08	4	1.72	4	1.72	4	1.77	12	5.21		
8/7/08	3	0.67	3	0.67	3	0.69	9	2.03		
8/15/08	3	0.86	3	0.86	3	0.88	6	2.6	9	3.52
8/22/08	shutin	shutin	shutin	shutin	shutin	shutin	shutin	shutin		
8/27/08	shutin	shutin	1.5	0.39	1.5	0.4	3	0.79		
9/5/08	shutin	shutin	1.5	0.67	1.5	0.67	3	1.34		
9/12/08	shutin	shutin	1.5	0.35	1.5	0.35	3	0.7		
9/19/08	shutin	shutin	1.5	0.71	1.5	0.72	3	1.43	3	1.07
Estimated Sickafoose-Morris average daily production prior to test									6.00	2.45
Estimate by fluid type: at est 2% water cut:									1.84	bopd
									0.61	bwpd
									6.00	mcfpd

*Production split equally among the 3 wells

2008 production from the Sickafoose tank battery commingling production from the Sickafoose-Morris #1 (permit number 2018), Sickafoose #1 (permit number 2036) and the Brenner #1 (permit number 2057) wells. The Sickafoose-Morris #1 was shut in after August 15, 2008, and turned on September 22, 2008. The Sickafoose #1 and Brenner #1 wells were shut in after September 22, 2008.

RESULTS OF CO_2 CYCLIC TEST ("HUFF-N-PUFF")

- Clearly demonstrated the capacity of the "Clinton" sandstone in East Canton oil field to accept significant volumes of injected CO_2. Approximately 81 tons (1.39 MMCFG) of CO_2 were injected into the test well during a 20-hour period.
- CO_2 was injected at a maximum surface injection pressure of 617 psi (1,300 psi bottom-hole pressure), which is below MMP of 1,450 psi. Results demonstrate that even under immiscible conditions CO_2 diffuses into the oil in the pore space, enhancing oil mobility. Injection of larger volumes of CO_2 at or above MMP is clearly feasible; moving to a pilot flood phase is appropriate and higher efficiency recoveries are anticipated.
- After the test well was returned to production, it produced 174 bbl of oil during a 60-day period (September 22 to November 21, 2008). This is an estimated 58% increase in oil production over pre-injection estimates.
- Majority of the injected CO_2 entered the matrix porosity where it diffused into the oil. Evidence includes: (A) the volume of injected CO_2 greatly exceeded capacity of the hydro-frac, (B) gradual injection and pressure rate build-up during the test, (C) the gradual flashout of the CO_2, and (D) a large amount of CO_2 off-gassed from wellhead oil samples 3½ months after injection.
- Multiple lines of evidence indicated the injected CO_2 did not channel off but stayed within matrix porosity near the test well: (A) absence of CO_2 found in gas samples from offset wells, (B) the persistent but gradual decrease of CO_2 in fluid samples taken from the injection well after production was restarted, and (C) a standard calculation of radius of influence. Holtz (2008) calculated the radius of influence to be approximately 68 ft.
- Most of the CO_2 was probably pushed into and then diffused within the higher permeability "Clinton" sandstone zones that communicate with the hydrofrac system near the borehole.