Enhanced Oil Recovery with Horizontal Waterflooding, Osage County, Oklahoma

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Abstract

This paper provides details of a project to test horizontal waterflooding as a means of improved oil recovery in Osage County, OK. Supported by a grant from the Department of Energy (DOE), an independent operator, Grand Resources, Inc., has developed a process for selecting and developing candidate reservoirs for horizontal waterflooding. Reservoir screening is the first step in the process and then rock mechanics are used to predict wellbore stability for determining the most efficient completion method. Geologic and reservoir parameters are considered when selecting the radius of curvature for the horizontal well to be drilled and the air/foam drilling fluids to be utilized to avoid formation damage. The final step is to run a comprehensive set of logs through the curve and out into the reservoir allowing for petrophysical evaluation.

To accomplish an economically successful project, given the basic assumption of an existing field infrastructure having an adequate water supply well available, the following three goals must be met: 1) demonstrate that horizontal waterflooding is technically and economically feasible for recovering additional oil in shallow low permeability reservoirs; 2) demonstrate that open hole completions are a viable technique based on wellbore stability considerations; 3) demonstrate that short radius rotary steerable technology can drill horizontal wells at low cost and without reservoir damage.

Introduction

It is solidly established that significant amounts of oil are still trapped in the producing formations when wells in waterflooded fields are abandoned due to high water-oil ratio (WOR) causing production to be uneconomical. Many techniques have been developed with a goal of economically recovering this bypassed oil. This paper discusses the technique of using parallel horizontal water injection and production wells as a method of enhanced oil recovery

Background

Historical Waterflooding in Osage County

The Bartlesville reservoir in northeastern Oklahoma has been one of the most prolific oil producing formations in the United States. Ye[1] reports that 1.5 billion barrels of oil have been produced from the Bartlesville formation through the 1960s. The Bartlesville formation remains an important producing horizon even though it is considered to be in a mature stage of depletion. In spite of the large cumulative production from the Bartlesville, the recovery efficiency has been low, usually less than 20% of the original oil in place (OOIP). Recovery during primary production operations is low due to: (1) a solution gas-drive mechanism, which results in rapid pressure depletion and (2) low initial reservoir pressure which is a consequence of the shallow depth. The remaining 80% of the OOIP has attracted many secondary and tertiary recovery techniques to be attempted.

Secondary recovery operations are often not effective or economic due to shallow depth, existence of natural fractures and low permeability. The Bartlesville sandstone across Osage County ranges in depth from 1,000' to 3,000' is known to be naturally fractured[2] and typically has permeability values less than 50 millidarcies (md). In an attempt to improve the economics of Bartlesville waterfloods, operators frequently inject water above the fracture-parting pressure to achieve better injectivity. The result is often unfavorable since the water tends to channel through the fractures bypassing much of the remaining oil in the matrix. Development of small patterns with closer well spacing can lead to improved recovery, however, the economics are impacted negatively because of the number of wells required.

Recent Horizontal Waterflooding Reported

This process was first presented by Taber[3] and has been successfully demonstrated in several field projects, including those reported by several authors [4,5,6,7]. Most of the prior applications have focused on the use of horizontal wells in the deeper reservoirs (greater than 4,500') where horizontal wells can save money by replacing the need for multiple vertical wells. While horizontal waterflooding has been successfully demonstrated in various deeper formations, the application of horizontal injection and producing wells in shallow, low permeability reservoirs is an area of opportunity for horizontal well technology. Kelkar[8], in a DOE supported project,

attempted to use a horizontal injection well to overcome the injectivity limitations of the Red Fork (geologic equivalent of the Bartlesville) formation in a pilot area of the Glenn Pool Field, south of Tulsa. Unfortunately, the horizontal well was not completed due to mechanical difficulties.

Horizontal wells can be very expensive due to drilling techniques that typically increase completion costs. The use of mud as the drilling fluid is a serious problem in all wells; especially those wells drilled in low permeability and low-pressure reservoirs[9]. To remediate drilling mud invasion into the formation, expensive completion techniques are required to remove mud filtrate damage from the near-wellbore region and establish contact with the reservoir's natural permeability. These completion techniques can also destabilize the wellbore, requiring a liner to be set further increasing well costs.

In a review of the current applications of horizontal wells in 2003, Joshi[10] found most domestic horizontal wells were drilled in low permeability fractured carbonate reservoirs. In the same article, several fields are listed where horizontal wells have been used for waterflooding purposes. The key issues in correct application of horizontal well technology pivots around achieving desired productivity/injectivity of the project wells and the cost associated with drilling the horizontal wells without damaging the depleted, low pressure reservoirs.

Horizontal Waterflooding Project
Selecting Pilot Field Test in Osage County
Horizontal waterflooding as applied in this project consists of one horizontal injection well and two adjacent parallel horizontal producing wells that straddle the injection well. The basic concept is that large volumes of water can be injected at pressures below the fracture parting pressure of the reservoir. The horizontal producing wells in turn can capture the oil that has been mobilized. By contrast, conventional waterflooding is often not effective in shallow, low permeability reservoirs, typical of the Bartlesville sandstone, because of the inability to establish adequate injectivity below the fracture parting pressure. The fracture parting pressure is often exceeded resulting in channeling the injection water and the bypassing of reserves.

The project is attempting to demonstrate the economic impact of horizontal waterflooding in an area adjacent to a pre-existing vertical waterflood. The infrastructure of the existing field operations is assumed to be adequate to handle the increased injection volumes and produced water volumes with only minor expenditures for equipment upgrades.

Initially, the project team concentrated on the collection of data for a pilot in the Woolaroc Field (the location of this field is shown in Figure 1). Reservoir description studies were conducted to identify a suitable un-flooded area within the field for the pilot test area. A vertical well was drilled in the pilot area to collect additional data including well logs and cores. The plan was to plug back after the data collection and then drill a horizontal lateral into the reservoir. The core collected during this process indicated that the reservoir was relatively uniform in properties and contained a significant amount of oil, however, the permeability was unexpectedly low. Simulation studies using core permeability values

indicated that horizontal waterflooding would improve performance over conventional waterflooding, but not to a sufficient degree to be economically successful.

A suitable test site was identified in the nearby Wolco Field also shown in Figure 1. The Wolco field is adjacent to the North Avant Field, an abandoned 1980s waterflood. The Wolco Field was re-drilled in the 1980s, but not subjected to waterflood activities. In the pilot test area, there are three existing wells in the quarter section; Wolco #1A, #2A, and #3A. There is a shut-in water supply well in the adjacent quarter section to the southwest available for use in the horizontal waterflood pilot.

Simulation studies were conducted to confirm the suitability of the Wolco site and also to determine the optimum placement of wells. The Bartlesville sandstone at this site has a thickness of around 85', porosity in the range of 16-20% and estimated permeability in the range of 30-100 md. Based on simulation studies, the horizontal injection well should be drilled 20' from the bottom of the sand and the two producing wells will be drilled 20' from the top of the sand.

Figure 2 shows the results of a simulation performed in the pilot area. This simulation indicated that high injection and producing rates can be maintained during the life of the project. The oil is recovered quickly which will be highly beneficial in achieving an economic operation. The WOR increases which must be considered in the design and upgrade of surface production facilities.

Figure 3 is a structure map of the pilot test area, showing the location of the pre-existing wells and the three pilot area wells drilled parallel to the suspected prevailing fracture orientation within the field. Alignment with the expected fracture orientation was planned as a precaution in the event that open fractures are encountered. In such a case, good sweep efficiency can still be maintained while injecting water to displace oil toward the adjacent horizontal producing wells.

Figure 4 is a cross section X-X' drawn through the pre-existing wells showing the top and bottom of the Bartlesville formation with an upward dip of 1.5 degrees to the northeast.
Drilling Technique
Cost effective drilling operations are the cornerstone of this horizontal waterflooding program. Open hole completions provide the least expensive method of completing the wells into the Bartlesville sandstone. Rock mechanic studies indicate that the matrix of this Pennsylvanian formation has the strength and competency allowing for openhole completions.

The directional drilling is accomplished by using the proven rotary drilling system developed and licensed by Amoco (now BP). Simply put, this system consists of basically two drilling assemblies: a curve drilling assembly (CDA) and the lateral drilling assembly. The CDA drills a very predicable curve of a designed turning radius based on tool configuration. These wells were drilled with the CDA configured to drill a 70' radius curve. (The well path goes from vertical to horizontal following a curve scribed by a 70' radius.) Thus by drilling 110' measured depth, the inclination increased from zero (vertical) to 90° (horizontal).

The CDA is removed from the well and the lateral drilling assembly is run in to drill the desired horizontal section of the

well. To explain the details of this short radius, underbalanced drilling technique, the field operations for the Wolco #4A will be reviewed. The location of this well is shown on Figure 3.

The vertical portion of this well was drilled to a total depth of 1,628'. Open-hole logs (gamma-ray, induction and a sonic based borehole televiewer) were run to confirm geology and to identify fracture existence and orientation. No fractures were identified during this logging run.

The 5 ½" production casing was run to 1,627' and cement was circulated to the surface. The CDA was picked up and run into the well. A gyroscopic surveying tool was utilized to orient the CDA. The 70' radius curve was drilled per the well plan from 1,635' to 1,733' (measured depth). The curve maintained the desired direction and ended as planned, which allowed the lateral section to be drilled parallel to a slightly up dip formation. The curve was drilled using water as the circulating medium.

The lateral section was drilled underbalanced circulating with air/foam in an effort to minimize formation damage in the low pressured reservoir. Two different lateral drilling assemblies were used for drilling the horizontal section of the well. A modified air hammer bottom hole assembly was first run in the well, but a correction run was necessary as the air hammer assembly was dropping angle too quickly. After the correction run, a packed hole rotary drilling system was used, with frequent surveys taken to check for proper wellbore direction and inclination. The packed bottom hole assembly held the desired inclination angle and direction. Wolco #4A was drilled to a measured depth of 2,732'.

A directional plot of Wolco #4A can be found as Figure 5. This figure presents the well plan and the actual wellbore path based on survey results. The drilling of Wolco #4A followed the plan regarding direction, inclination and total length drilled.

Logging Short Radius Wells

Grand Resources has developed a method to log horizontal wells through short radius curves by deploying logging tools via sucker rods. The gamma ray, density, induction and borehole televiewer logs were run to determine fluid saturations, identify fractures and confirm geology through the horizontal section of Wolco #4A.

Logs were run into the horizontal section of the wellbore approximately 500'. After logging 500' of lateral section, friction and the flexibility of the sucker rods prevented the logs from going any further into the lateral. To overcome the distance limitation of the sucker-rod conveyed logging technique, work is currently progressing on adapting a commercially available down hole wireline tractor to pull the logs out into the lateral section through the short 70' radius curves.

The borehole televiewer log was run from 1,626' to 2,248'. This log is designed to detect and interpret fracture existence and orientation. The log encountered very few fractures in the wellbore. The density log was run through the lateral from 1,732' – 2,245' and porosity values averaged 16%. The induction log was run through the curve and 550' into the lateral portion of the well. Resistivity values in the top section of the Bartlesville (1,650' – 1,700' measured depth) were approximately 5 ohms. Resistivity values along the length of the lateral (1,732' – 2,270') averaged 2 ohms. Low resistivity values were expected in this wellbore due to its position near the bottom of the reservoir.

Project Economics

Three Bartlesville Sandstone horizontal wells were drilled in the Wolco Field in the following sequence: Wolco #4A; #6A; and #5A. A continuous improvement process of well planning, drilling and post well review is an effective method applying lessons learned from each well drilled. This technique resulted in each successive well being drilled more efficiently and more cost effectively than the last. The first well drilled, Wolco #4A, cost $257,000. The second well drilled, Wolco #6A, cost $214,000, and the third well drilled, Wolco #5A, cost $202,000. Today's cost to drill and complete a typical vertical well in the Bartlesville in the Wolco Field is estimated at $98,000.

Simulation results, coupled with an economic evaluation indicate a horizontal waterflood on 23 acre spacing would generate $2.9 million cumulative revenue over 6 years of operation, compared to $1.4 million cumulative revenue over 30 years of operation for a five-spot vertical waterflood. Present values (PV10) for horizontal and vertical five-spot waterfloods in the Wolco Field are $2.3 and $0.4 million respectively. Horizontal waterflooding responds more quickly to water injection, resulting in significant amounts of incremental oil produced early in the project. This early horizontal waterflood response yields more attractive investment opportunities as compared to vertical waterflood projects.

Production Results

Initial conditions prior to producing from or injecting into the horizontal wells were determined by taking fluid levels with an acoustic fluid level device in both idle wells and the new wells. The pressure in the pilot area averages 126 psi.

A water supply well (Wolco WS #1) has been completed with a submersible pump capable of moving 2,000 bwpd from the Arbuckle formation which is approximately 500' below the Bartlesville. The injection water is transferred directly into the injection well via the submersible pump.

Pumping units have been installed on the two producing wells. The tank battery is capable handling the produced fluids and disposing of produced water in a disposal well, Wolco #1A, on the north end of the pilot area.

The producing wells are completed with insert pumps in the 2 $^7/_8$" tubing set in the 5 ½" casing in the vertical section of the well. This places the pump inlet 90' above the horizontal section of the well. The producing wells began pumping in early January 2004.

The injection well, Wolco #4A, was completed with a packer in the 5 ½" casing in the vertical section of the well with 2 $^7/_8$" duo-lined (internally coated) tubing to combat the mildly corrosive nature of the injection water. Water injection began on December 30, 2003. The submersible pump in the water supply well is providing the necessary pressure to move the 2,000 bwpd being injected into Wolco #4A at zero surface pressure. This provides an initial injectivity substantially greater than the historical injectivity of former injection wells adjacent and to the south of the Wolco pilot area.

Between the time injection was begun and this paper was submitted for publication only ten days had elapsed, not sufficient time for a response to the injected water. Hence, there is no horizontal waterflood production data to report at this date. The results of the first four months of the horizontal waterflooding will be reported at the conference.

Conclusions

1. The originally proposed site in the Woolaroc Field proved to be unsuitable for a horizontal waterflood project because of the unexpectedly low permeability obtained from the Bartlesville core.

2. A nearby site in the Wolco Field appears to be much more suitable for the demonstration of this technology because of a thicker sand section and improved permeability.

3. Simulation studies for thicker sand sections indicate that optimum performance can be achieved by placing horizontal injection wells near the bottom of the formation while placing horizontal producing wells near the top of the formation. Good vertical permeability is required.

4. Reservoir modeling is critical in evaluating the suitability of a proposed area for a demonstration test.

5. The demonstration project has indicated that short radius horizontal wells can be drilled with air/foam economically.

6. Logging through 70' radius curves was successfully achieved.

Acknowledgements

References

1. Ye, Liangmiao and Kerr, Dennis: "Sequence Stratigraphy of the Middle Pennsylvanian Bartlesville Sandstone, Northeastern Oklahoma: A Case of an Underfilled Incised Valley", *AAPG Bulletin*, Vol. 84, No. 8, August 2000, pp 1185-1204.

2. Guo, Genliang and Carroll, Herbert B.: "A New Methodology for Oil and Gas Exploration Using Remote Sensing Data and Surface Fracture Analysis", Performed Under DOE Contract Number DE-AC22-94PC91008, February 1999.

3. Taber, J. J.; Seright, R. S.: "Horizontal Injection and Production Wells for EOR or Waterflooding", SPE 23952, presented at the 1992 SPE Permian Basin Oil and Gas Recovery Conference, Midland, Texas, March 18-20, 1992.

4. Huang, W. S.; Kaetzer, T. R.; Bowlin, K. R.: "Case History of a Horizontal Well Waterflood Project-New Hope Shallow Unit, Texas-An Update", Paper HWC94-08, presented at the Canadian SPE/CIM/CANMET International Conference on Recent Advances in Horizontal Well Applications, Calgary, Alberta, Canada, March 20-23, 1994.

5. Hall, S. D.: "Multilaterals Convert 5-Spot Line Drive Waterflood in SE Utah", SPE 48869, presented at the 1998 SPE International Conference and Exhibition in China, Beijing, China, November 2-6, 1998.

6. Lach, J. R.: "Captain Field Reservoir Development Planning and Horizontal Well Performance", OTC 8508, 1997 Offshore Technology Conference, Houston, Texas, May 5-6, 1997.

7. Collier, F.B.; Pickett, S.L.; Sharma, A.K.; Stewart, T.L.: "Horizontal Wells Optimize Waterflood", Petroleum Engineer International, November 1995, pp. 24-28.

8. Kelkar, M.C.; Liner, C.; Kerr, D.: "Integrated Approach Towards the Application of Horizontal Wells to Improve Waterflooding Performance", Final Report, DOE/BC/14951-16, October 1999.

9. Joshi, S.: "Horizontal Well Technology", PennWell Publishing Company, 1991.

10. Joshi, S.: "Cost/Benefit of Horizontal Wells", SPE 83621, presented at SPE Western Region/AAPG Pacific Section Joint Meeting May 19-24, 2003.

Metric conversion Factors

bbl	x	1.589 873	E – 01	= m^3
ft	x	3.048*	E – 01	= m
inch	x	2.54*	E + 00	= cm
lbf	x	4.448 222	E + 00	= N
md	x	9.869 233	E – 04	= m^2
psi	x	6.894 757	E + 00	= kPa

Nomenclature

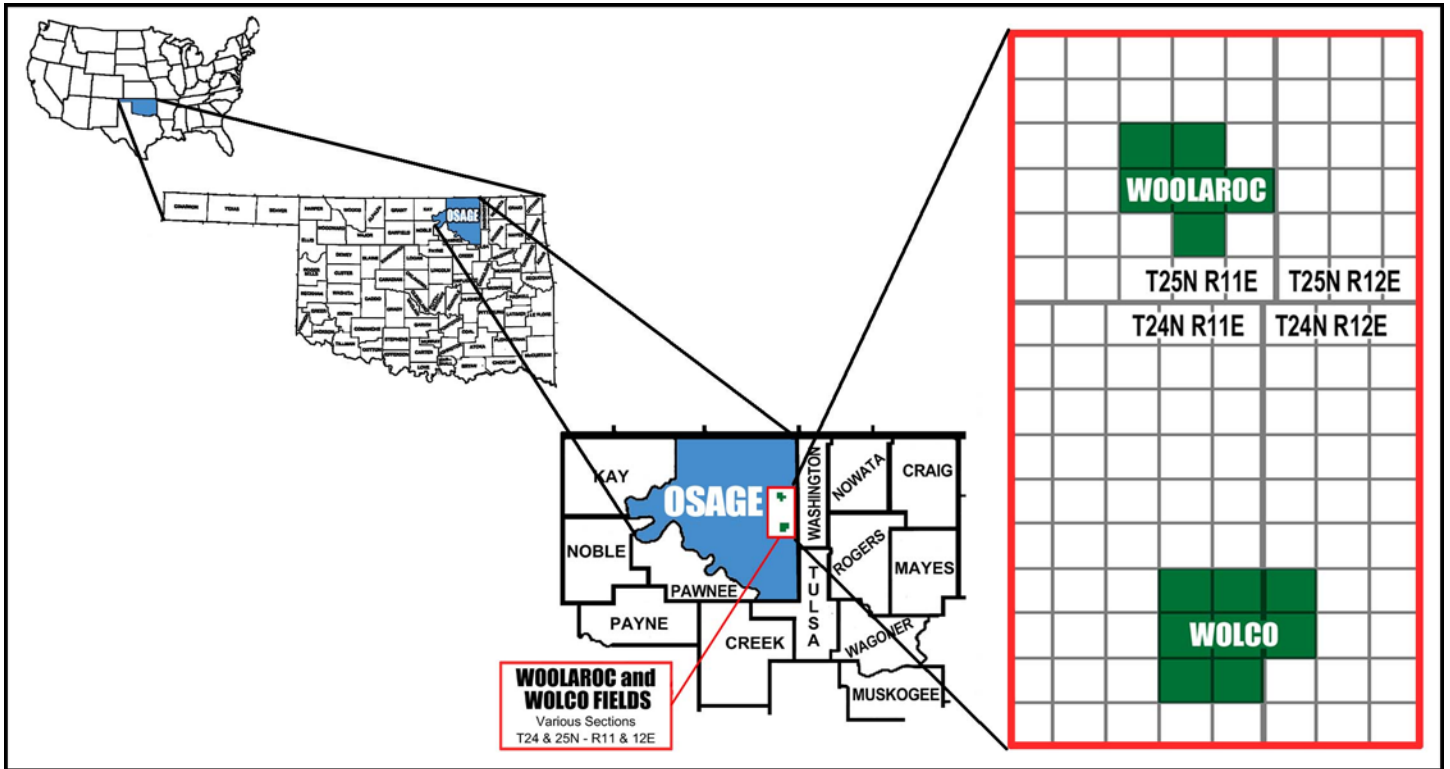|		
bbls	=	5.61 cubic feet
md	=	millidarcy
OOIP	=	original oil in place
WOR	=	water oil ratio

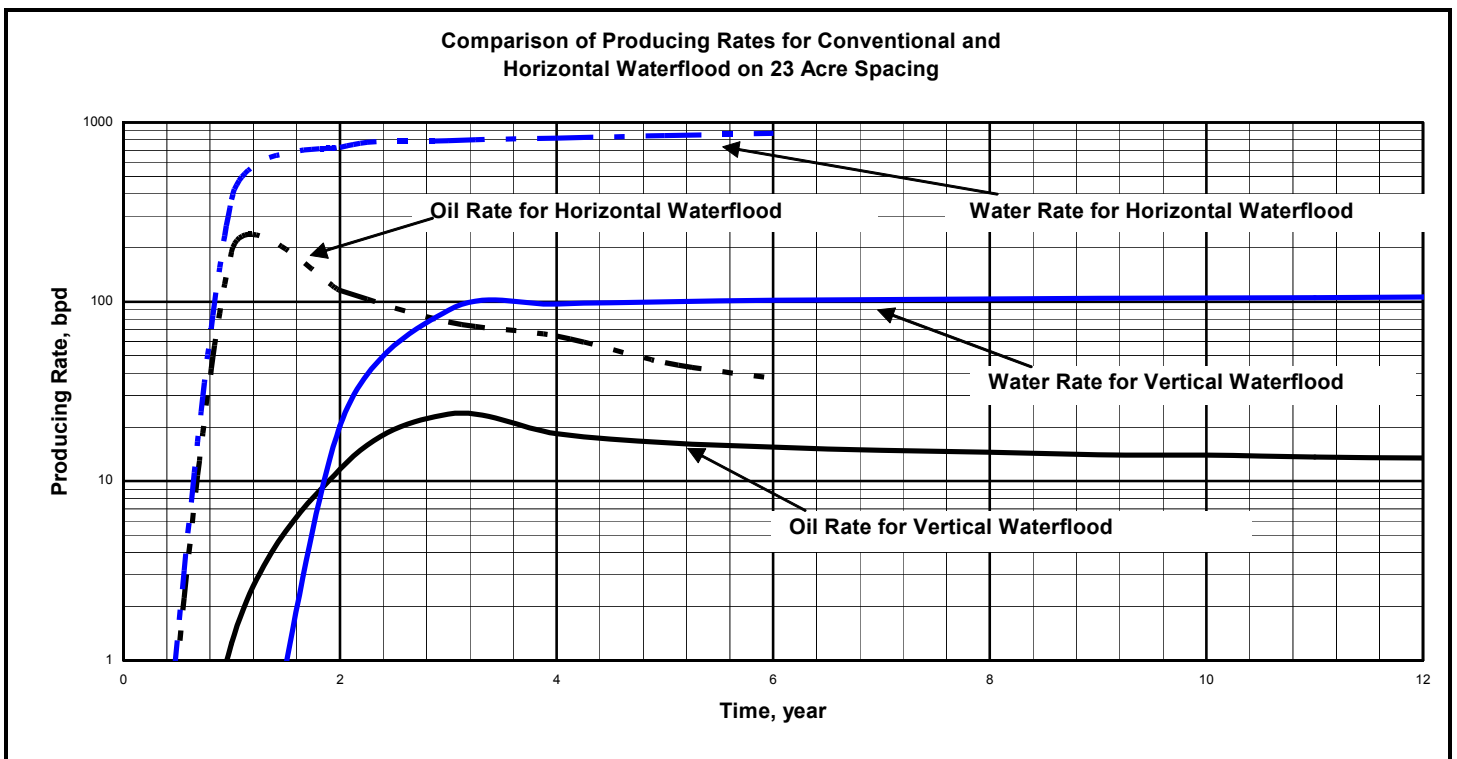**Figure 1   Location of Horizontal Waterflood Pilot Test Area**

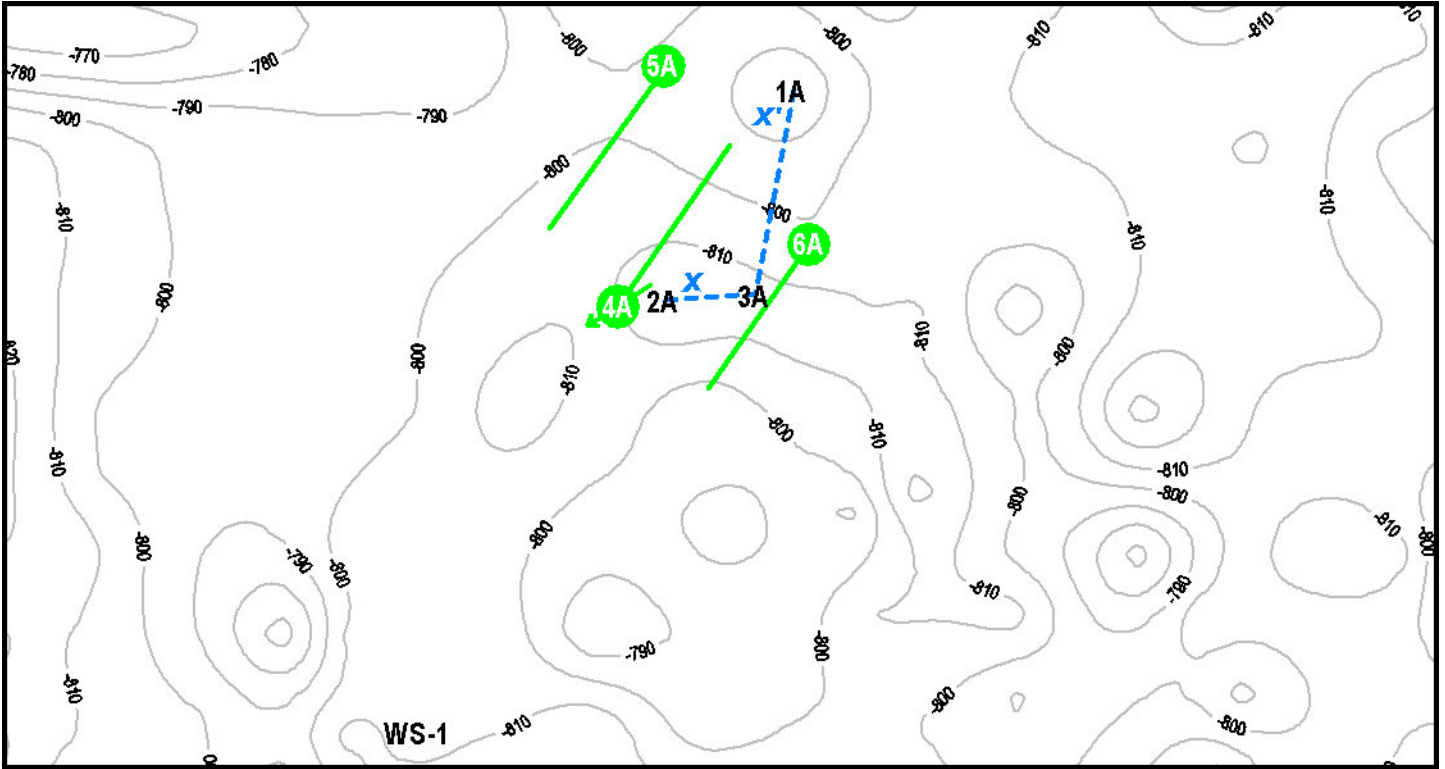**Figure 2   Comparison of Simulation Results for Vertical and Horizontal Waterfloods**

Figure 3   Structure Map of Bartlesville Sandstone in Pilot Test Area   **Scale 1 inch = 1000 feet**
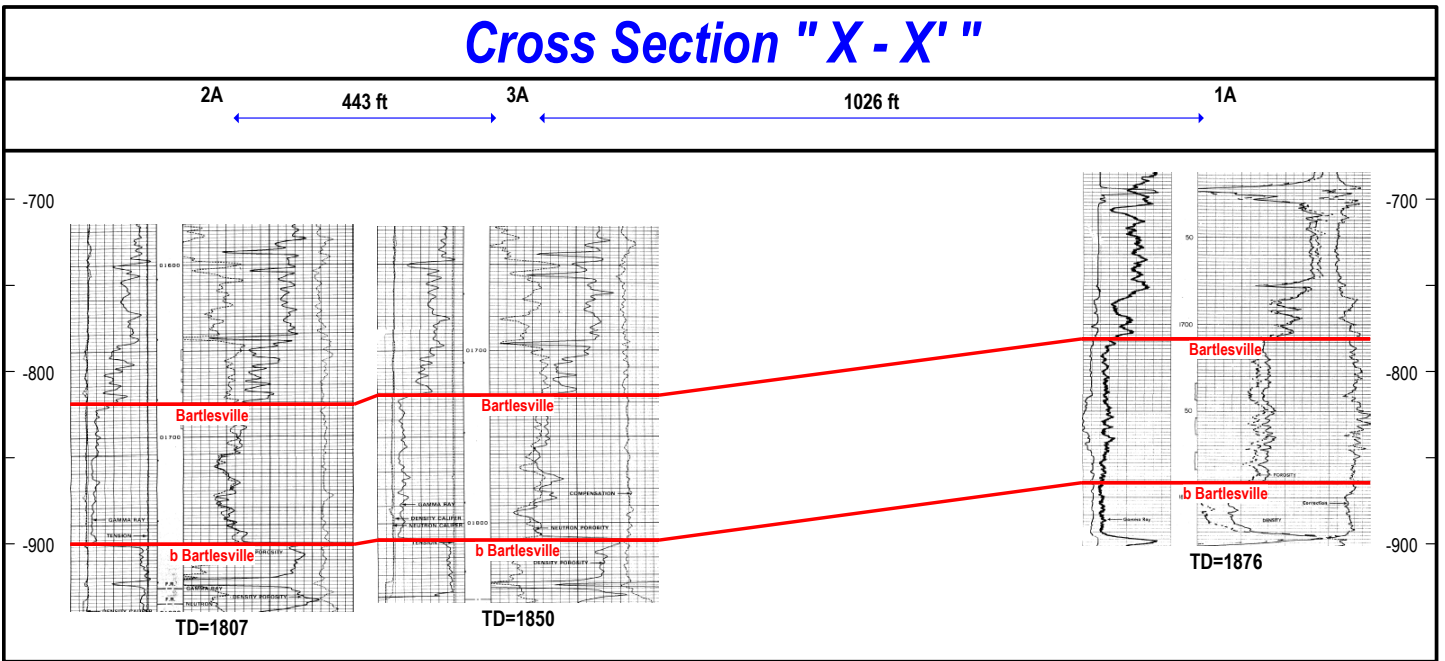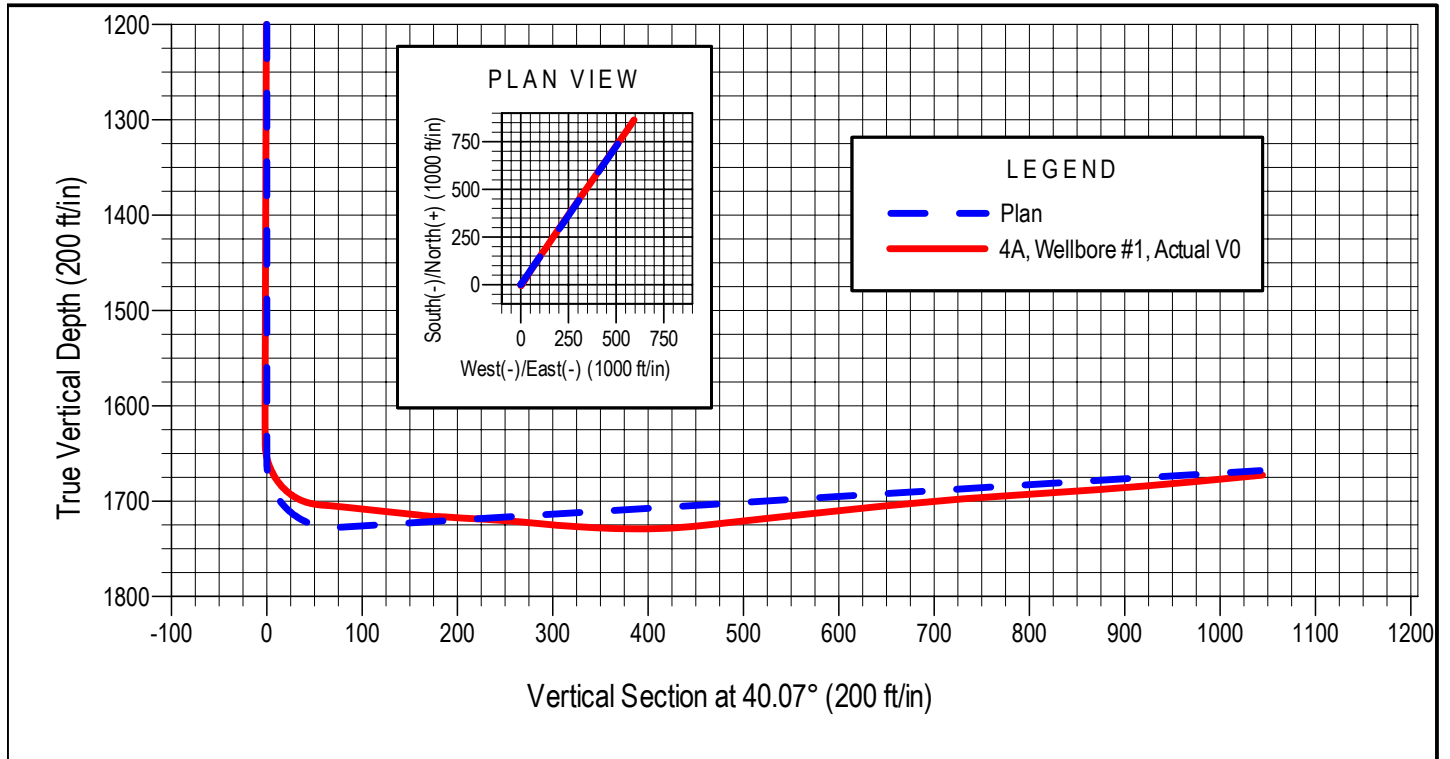

Figure 4   Cross Section of Bartlesville Sandstone in Pilot Test Area

Figure 5   Directional Plots for Wolco #4A