Geosteering Improves Bakken Results

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DENVER—Developing tight oil and gas-bearing formations often requires a dense pattern of wells with long lateral sections. To produce such fields economically, producing sections of wells must be positioned accurately within the targeted intervals, while drilling costs are kept to a minimum.

A cost-effective solution has been developed that includes predrill modeling of logging-while-drilling measurements along the trajectory of a planned well to compare with real-time LWD data. This provides the ability to support geosteering to and within the target formation. This geosteering technique has been utilized to develop Bakken Shale oil assets. The wells have been navigated to land consistently in the reservoir, and have successfully maintained position within the primary target zone for more than 90 percent of the lateral sections.

North Plains Energy LLC (NPE) is a Denver-based company focused on acquiring, developing and enhancing oil and gas assets within the continental United States. NPE operates acreage in part of the Williston Basin on the west flank of the Nessan Anticline. A 2008 U.S. Geological Survey assessment of the undiscovered resources in the Upper Devonian-Lower Mississippian Bakken formation of the Williston Basin Province in Montana and North Dakota estimated mean undiscovered volumes of 3.65 billion barrels of oil, 1.85 trillion cubic feet of associated natural gas, and 148 million barrels of natural gas liquids.

NPE is drilling and developing two blocks, aggregating approximately 50,000 net acres in the heart of the Bakken Shale in Divide, Williams, Dunn and McKenzie counties, N.D. (Figure 1). Led by a highly experienced, technologically focused management team, the company prides itself on customizing its drilling and completion methods to the unique geological and geophysical characteristics of its core project blocks.

Drilling History
Since early in 2010, Ensign Rigs Nos. 89 and 118 have been working for NPE in Divide, Williams and McKenzie counties. Wells are being drilled to target zones located between 9,000 and 11,000 feet true vertical depth. The horizontal producing sections of the wells average 8,000 feet of lateral, which is cased, perforated and fractured in multiple stages. The two primary intervals targeted within the oil reservoir are a clean dolomite member of the Three Forks formation and a 15-foot zone below a tight limestone within the Bakken Middle Member.

Initially, the horizontal production wells required drilling a vertical pilot hole that was sidetracked, deviated from vertical to build the curve, then drilled laterally within the producing zone. Wireline logs and cores were run in the initial pilot hole to determine the landing point for the sidetrack and to evaluate the optimal interval within the reservoir to target.

There was limited regional structural control in planning the laterals. The initial well required a sidetrack because it inadvertently drilled into the Upper Bakken Shale. NPE decided that a single geosteered well trajectory would be more cost effective, and the resulting smoother well profile should reduce the risk of losing the bottomhole assembly. It also would make the completion less problematic. In addition, using LWD tools in the region would provide valuable experience and knowledge about the subsurface geology of the target formations while drilling.

Geosteering Partnership
Prior to geological steering methods, the success of a directional drilling operation depended largely on steering the well through a target reservoir with an assumed position fixed in geometric space. However, a success in geometric terms
could be a failure in economic terms if the assumed and actual geometric locations of the reservoir differed.

Effective well placement in horizontal drilling requires that geological changes be detected quickly, and that the well plan be adjusted in a timely fashion. With this challenge in mind, a dependable geological steering partnership was developed between NPE and PathFinder, a Schlumberger company, for providing directional drilling and MWD/LWD services, supported by the company’s PayZone Steering™ services at the well site. The real-time forward modeling software assists in geologically steering deviated well trajectories by combining petrophysical data from LWD logs run in offset wells, the geological earth model, and the directional well plan to create a model of the formations being drilled.

During the early stages of the project, service company staff, working in close consultation with the operator’s technical team, focused on learning the geologic setting in the area. Effective communications among the team allowed it to assemble local earth models based on available seismic data, structural information, and information from selected offset wells. Wireline and LWD data from offset wells were utilized to calculate the expected LWD response of formations into which horizontal wells were to be drilled. LWD data types typically modeled included gamma ray, resistivity, density-neutron (imaging), and sonic measurements.

The objective of geological steering depends on the section of the well. In the build section, where the deviation increases from the kickoff point until the well enters the reservoir, the goal is to steer the well so that it enters the reservoir at a desired inclination and direction. In the lateral section, the goal is to position the well’s path to optimize well bore exposure to the reservoir.

These goals have been achieved consistently through interpreting real-time LWD measurements, gamma ray in the build section, and gamma ray combined with resistivity in the lateral section. These LWD measurements were selected by evaluating the log response characteristics within and adjacent to selected target zones of the Bakken Middle Member and Three Forks formations.

**LWD Resistivity**

Electromagnetic wave propagation resistivity tools delivered the standard deep-sensing LWD array wave resistivity measurements. Because these measurements were similar to wireline resistivity measurements, the LWD logs were correlated with similar wireline logs to locate important geological features. Because the wave propagation measurements were well characterized, the LWD log response was predictable under most conditions observed.

The LWD resistivity tools have multiple transmitter-receiver spacings and multiple frequencies. The resistivity measurement from each spacing and frequency responds differently to a resistivity interface located away from the well bore. Since the nature of the resistivity interface is known from the offset well logs, multiple resistivities can be leveraged to obtain a profile to help maintain the well’s position within the target interval at a distance from the interface.

During drilling, an experienced geosteering field engineer compared the measured LWD responses with the modeled synthetic responses to determine the position of the well’s path within the geological sequence. The engineer also referenced all other relevant information, such as cuttings sample observations from the mud logging geologist, to support the geosteering interpretation.

The resulting geologic interpretation, which incorporated observed differences between expected and measured LWD responses, combined with additional drilling-related data, was communicated to NPE to allow the drilling and geology team to make time-critical decisions efficiently about adhering to or modifying the well plan.

The team was able to adjust the drilling plan as the horizontal well was drilled, using actual well bore trajectory data and LWD logging measurements. In consultation with NPE, the team incorporated interpretations to reconcile the local geologic model with real-time data, allowing the well bore position to be maintained within the target zone.

**Refining Results**

Real-time LWD data acquired from within the zone of interest not only were correlated with the synthetic model, but also were back-correlated with previous measured data from the same well as the trajectory moved upstructure or downstructure within the target formation. All decisions regarding changes to the well...
FIGURE 3

Geologic Interpretation Displaying the Well Bore Position Within the Three Forks Formation Target Interval

FIGURE 4

Correlation Displaying Character Difference Between Top and Base of Three Forks Target Formation

trajectory considered BHA capabilities, the original directional well plan, and completion requirements in consultation with NPE. Continuous control of the well bore trajectory delivered reduced tortuosity and dogleg severity, leading to quicker well bore completion and production.

LWD data and forward modeling interpretation results were delivered at the well site and remotely, using secure Web-based applications. This enabled real-time collaboration from directional drillers, geologists, and other experts in multiple locations. A final post-well analysis depicts log evaluations and further refinement of the local model to obtain the best fit, resulting in a close-modeled approximation of the actual measured formation properties.

The enhanced model was incorporated into the plan for the next well, delivering an increasingly refined result. Observations of the results are compiled and documented for use as a future frame of reference to further optimize drilling procedures.

Directional drilling, measurement- and logging-while-drilling (M/LWD), and forward-modeling steering services, combined with the extensive experience of the NPE drilling team, have enabled consistent positioning of the horizontal wells in zone. Success in this geological well positioning partnership has been achieved through close teamwork and timely communications, while continually building on the knowledge gained from each well to accumulate an ever-increasing understanding of subsurface conditions and the optimal drilling parameters required to effectively and efficiently conclude the geologic interpretation.

Geosteering Support

Since July 2010, the PZS service has been used to support geosteering new production wells on NPE’s acreage in Divide, Williams and McKenzie counties. The software has provided a platform for interpreting log response to characterize key horizons in each well, typically focusing on either the Middle Member or Three Forks and their adjacent formations.

The service has leveraged and utilized the diverse experience of all members of a multidisciplinary team, including NPE drilling engineers and geologists, the rig crew, mud logger, well site geologist, directional drillers, M/LWD geological steering field engineers, expert log analysts,
and off-site geosteering operations personnel. A communication workflow was established that has met the challenges of delivering efficient decision protocols while involving all members of this diverse team.

Between August 2010 and August 2011, the PZS service was used to consult on 17 wells on NPE’s acreage. In these wells, approximately 130,000 feet of lateral section were drilled after entering the primary target zone(s), and 120,000 feet (92 percent) of those lateral sections were positioned within the primary target zone(s).

**Holland No. 9-19H**

The Holland No. 9-19H well, drilled during January-February 2011, is typical of wells drilled for NPE leveraging the forward-modeling geosteering technology. Prior to drilling, local geological models were constructed based on log data from five offset wells, including one of the pilot wells drilled early in the project, plus information from the Federal Land Bank of St. Paul. The geological objective of the new well was to land and maintain position within the dolomite section of the Three Forks formation.

The regional structural map of the Upper Bakken Shale top horizon predicted the target zone would have an upward apparent dip of 0.6 degrees in the direction proposed for the lateral. The drilling team was made aware of the initial drilling plan and possible alternate scenarios, along with their inherent uncertainties. Figure 2 displays the prewell geologic model with the anticipated logging response along the proposed well path.

After drilling vertically to 8,300 feet total depth, the PZS service was initiated to complement geological and mud logging information for picking the kickoff point. Building the curve started at 9,280 feet, using a 2.5-degree bend, PathFinder G2 mud motor, an 8¾-inch PDC bit, and 6¾-inch gamma ray logging and directional tools. The real-time geosteering technology was managed by an experienced field engineer on site. Prewell modeling, remote support during operations, and post-well analysis were performed in Lafayette, La.

Formation changes were logged and observed differences to the original model were used to compute adjustments to revise the landing point. At an angle close to horizontal, the well successfully entered the target zone at 9,805 feet TVD (10,096 feet TD) to reach the 9,808-foot TVD revised landing point, 2.5 feet below the top of the target clean dolomite within the Three Forks formation. This compares with a planned landing point based on the initial model at 9,815 feet TVD (seven feet deeper).

Seven-inch casing was set to 10,202 feet, then the lateral producing section was drilled using a 6-inch PDC bit, 1.5-degree adjustable steerable G2 mud motor, slim (4¾ inches) advanced wave propagation resistivity and gamma ray logging tool, and an MWD positive pulse telemetry system. While drilling the lateral, the geosteering field engineer used real-time gamma ray, resistivity, and directional data, combined with geological information from mud logging, to advise NPE on steering the well within the planned objective, following the dip of the formation (Figure 3). The inclination of the lateral ranged between 89 and 93 degrees, reacting to the regional dip changes. Accurate well positioning was achieved by characterizing

**FIGURE 5A**

Real-Time Structural Interpretation Conducted at the Well Site (Middle Bakken Formation)

**FIGURE 5B**

Correlation Displaying LWD Measurements Character As Utilized for Geosteering Decisions
measured gamma ray and resistivity response differences between the top and the base of the Three Forks formation target interval.

At the top of the target interval, the resistivity is higher with more separation, in combination with slightly lower gamma ray measurements at the top versus the base (Figure 4). Well total depth was achieved at 17,739 feet MD, 9,725 feet TVD. Of the 7,643 feet of lateral footage drilled, 7,214 feet (94.4 percent) of the wellbore was positioned within the target interval.

**Lessons Learned**

The LWD log responses observed for the wells targeting the Bakken Middle Member were characterized in a similar fashion as the Three Forks wells. The 15-foot thick target interval below the tight limestone maintains consistent, nondescript gamma ray and resistivity characteristics below the limestone, continuing down to the lower Bakken Shale.

The lack of character through the lower half of the Middle Member formation presents a challenging interpretation. Therefore, the cleaner gamma ray and slightly higher resistivity of the limestone directly above the target interval are utilized as benchmarks to solidify the geosteering interpretation.

The resistivity measurements begin to separate and increase according to their respective diameters of investigation as the wellbore approaches the contrast in resistivity between the target interval and tight limestone ceiling. Maintaining wellbore inclination near to formation dip allows the wellbore position to be confirmed without drilling into the limestone (Figures 5A and 5B).

Utilizing LWD measurements to actively geosteer in real time is a cost-effective way to support high-volume/high-

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