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GLOBAL LNG REPORT

DEVELOPING THE WOODFORD SHALE
Improving shale gas production through accurate well placement

Integrating LWD technology for post-drilling assessment enhanced horizontal well planning, placement and completion.

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Shale gas reservoirs typically exhibit high levels of heterogeneity. They are usually produced with horizontal wells, steered using simple gamma-ray (GR) measurements correlated with vertical pilot wells in an attempt to achieve maximum reservoir exposure. Detailed examination has revealed that steering results for horizontal wells using averaged GR correlation techniques and subsequent structural modeling yield non-unique solutions. This article presents a case study in the Woodford Shale where the conventional process results in at least three different plausible well placement results. Incorporating an azimuthal density image into well placement analysis provides a single unique answer. The article also reviews measurements that indicate that well placement variation can have a large impact on stage-to-stage production.

INTRODUCTION

Most shale plays exhibit high natural gamma-ray activity, so GR logs are typically run in the vertical or offset evaluation wells to help delineate the reservoirs. These data are commonly used for correlation with GR measurement while drilling (MWD) when placing the horizontal production wells. These wells are typically steered within the defined target window using a non-azimuthal, averaged GR measurement. While GR measurements can be effective for correlations in vertical and high-angle wells, using this measurement alone for structural modeling can potentially provide non-unique solutions in a horizontal well environment. Inconsistent and inaccurate reservoir interpretations are likely to result in variable production rates, between hydraulic fracturing stages and also from well to well.

Resistivity measurements complement GR data, providing extra information for correlation. Further improvements in the accuracy of the modeled structure can be provided through estimates of dip along the well trajectory based on azimuthal images from real-time logging-while-drilling (LWD) density measurements. A validated structural model enables a higher level of confidence in real-time steering decisions. An accurate structural model is also an effective tool to aid completion designs, correlate formation properties, refine target delineation and provide a foundation for evaluating production logs and hydraulic fracture monitoring observations.

When sufficient measurements are made for formation evaluation, drilling and production results can be better understood and applied to enhance target selection, followed by accurate well placement within the selected target structure. This level of well placement accuracy will deliver consistent production results and provide a common platform for evaluating completion practices.
WELL PLAN

LWD technology has been used to augment MWD information for the placement and post-drilling assessment of horizontal wells to produce gas from the Woodford Shale in Oklahoma. The subject reservoir is about 190 ft in vertical thickness, Fig. 1. Baseline gamma-ray levels within the reservoir range 350–400 gAPI (API gamma ray units), with prominent markers peaking at 700 gAPI or more, while the overlying and underlying formations baseline at 150 gAPI and 30 gAPI, respectively. Data from vertical offset wells indicate that the high-GR markers consistently extend laterally through the subject field. Resistivity in this reservoir is around 200 Ω-m, with significant changes only at the boundaries, where resistivity drops to 20 Ω-m at the top and 40 Ω-m at the base.

The subject well for this case study was planned to be landed and positioned close to the centerline of the gross reservoir interval. This was to be achieved by geosteering along the high-GR marker annotated “centerline” in Fig. 1. This is a common target for landing horizontal wells in this reservoir. The seismic interpretation (Fig. 2) indicated that the planned lateral would follow a syncline into a short incline to encounter a second syncline prior to an opposing incline in the toe section. The plan for completing the well was to geometrically divide the 4,500-ft lateral production interval into nine stages, spaced 500 ft apart, for fracing, which was anticipated to propagate effectively above and below the centerline.

REAL-TIME GEOSTEERING

The well was drilled and landed as planned from the seismic interpretation. A single-curve, average GR measurement was the primary means of correlation to geosteer the well trajectory along the centerline. The model predicted by these real-time measurements placed the total length of the lateral section close to the target centerline throughout the 4,500-ft production interval.

Resistivity, density and porosity MWD data were available on three sections of the lateral. Standard non-azimuthal representation of these measurements can be effective in some reservoirs, depending on their rock properties. However, in this case, these non-azimuthal measurements provided very little steering information or contrast across prominent GR changes observed along the lateral.

By contrast, LWD images (Fig. 3) provided significant details that had potential to add value for real-time geosteering. Shallow-depth-of-investigation (DOI) photoelectric factor images provided near-wellbore details. Deep-DOI gamma ray provided azimuthal images at lower resolution. High-resolution density images showed details of thin beds, clearly defined boundaries and geological features. These images were not employed when drilling this particular well; however, they were used effectively in the post-well analysis.

COMPLETION AND PRODUCTION LOGGING

The well was completed in nine stages spaced 500 ft apart with four perforation clusters per stage. Perforation cluster spacing was 110 ft, with cluster length of 2 ft at six shots per foot (spf). The stimulation design was similar for each stage and consisted of 12,000 bbl of slickwater with 200,000 lb of 30/50 sand pumped at 80 bbl/min.

A production log was run after completion to determine the production contribution of each individual stage. Figure 4 shows production log results overlaid on the well trajectory, with red lines representing the percentage contribution from each perforation cluster. Each square indicates a perforation cluster grouped by different colors to represent individual stages. The block across Stages 1 and 2 represents a total combined production from all perforations across the area indicated, because the production log could not be run all the way to TD.
For shale gas development, it is often assumed that, as long as the lateral is placed within the target reservoir, fracturing will provide total reservoir connectivity. The production log results in this well challenge that line of reasoning; they indicate that, although equivalent stimulation designs were pumped at each stage, not all stages contribute equally.

Possible explanations for this variation include lateral heterogeneity; lack of isolation during hydraulic fracture stimulation; the presence of faults; the presence (or lack) of natural fractures; and poor stimulation execution. The MWD gamma-ray data indicated that this well was placed close to the centerline; however, the variation in production rates suggested that either the model was in error or other factors were impacting performance.

**POST-WELL ASSESSMENT**

The real-time geosteering results were remodeled using proprietary software.

**Single-curve, averaged gamma-ray MWD.** When using only the gamma-ray MWD data, as used while drilling, it was possible to make several different plausible structural models. The two interpretations shown in Fig. 5 illustrate the problem. Both of these models are different from model built during real-time geosteering. Both were modeled with reference to the same offset vertical well using the same horizontal data set to tie in their correlations to the boundary at the top of the target reservoir. The upper boundary is a field-wide marker, where an obvious increase in gamma ray occurs.

The top model indicates that the well enters the structure as initially interpreted, crosses the centerline at the syncline and builds back up through it. Well trajectory is then maintained above the centerline, deviating further from the centerline as it approaches the toe of the lateral. In the lower model, the well crosses the centerline at the same depth, but remains below the centerline throughout the lateral. The measured GR data correlates well with expected values in the real-time geosteering model and both of the recreated models, indicating at least three non-unique solutions to the position of the well trajectory for this structure. Additional measurements were clearly required to verify which, if any, of these models represents the correct interpretation of the well trajectory in the structure.

**Integrating azimuthal image data.** Although LWD images were available in real time while drilling, and could have been used while drilling, they were only applied during the post-well assessment. In real time, only the averaged GR measurement was used for correlation and structural modeling. The interpreted formation dip was used to confirm the correct structural model. The LWD images were imported into proprietary software to enable image interpretation and structural dip picking. Structural dips picked from images were displayed in 3D along the borehole for evaluation of their structural consistency prior to exporting them to the geosteering modeling software.

Figure 6 shows the same two models as in Fig. 5, annotated with interpreted formation dip represented by a short green line along the well’s trajectory and placed at the calculated dip angle. In the two locations circled in black, dips in the upper model differ significantly from expectations, indicating that the model is inaccurate. On the other hand, dips in the lower model conform to those expected, providing a multipoint calibration for the structural model and helping to validate its accuracy.

**Adding production log data.** Figure 7 shows the validated model overlaid with the production logging results. The low performance of Stage 4—just 2.8% of the well’s production—can be attributed to its being 80 ft below the centerline. Stage 9, completed in the sub-layers above the centerline, also showed poor production contribution. Stages close to the centerline illustrated higher and fairly consistent production. Good performance from Stage 7 (19% of the well’s production) might indicate a sweet spot for this area several sub-layers
layers beneath it. Additional information—such as mineralogy, effective porosity and geomechanical properties—and further analyses are needed to qualify production variations between the stages. While position within the reservoir seems to impact productivity, it should not be discounted that other reservoir or completion factors could play a role in poor production. The acquisition of additional data, such as advanced LWD measurements and microseismic monitoring, would be helpful in providing answers to deliver a more accurate structural interpretation.

**CONCLUSIONS**

Structural correlations based on real-time gamma-ray MWD enabled geosteering to position the lateral trajectory of this well within the 190-ft reservoir interval. However, interpretations for specific well positioning within the structure offered limited insight to the actual production potential and ensuing reservoir interpretation. Differing independent models using the same data set illustrated the capacity for non-unique structural solutions when using only gamma ray. Additional measurements, such as resistivity and density images, can be used to remove incoherent interpretations, refine the structural model and improve its accuracy. A multipoint calibration along the lateral well trajectory for a unique solution can then be obtained. This solution can be incorporated into future steering decisions to improve optimization across many wells. Incorporating further measurements, such as production logging data, illustrates the value provided from an accurate model where an in-depth understanding of production profiles can be used to redefine vertical targets for the lateral, its size and the importance of accurate well placement.

Having high confidence in the structural model promotes accurate steering decisions. This mitigates out-of-zone drilling that may lead to expensive and unnecessary sidetracks or poor producing intervals. During real-time drilling operations, azimuthal images can help steer horizontal wells for precise well placement within narrow target windows. Target windows less than 10 ft have been effectively steered within various shale plays using density images.

Providing an accurate account of the well’s position in the structure promotes the confidence to precisely tie in all measurements, such as LWD, wireline, frac monitoring and production logging, to the interpreted structure. The ability to perform this task with confidence offers several benefits in shale reservoirs. Geosteering to stay within defined sweet spots such as lower-stress zones can lead to more efficient and cost-effective hydraulic fracturing completions. In addition, these zones have been observed to deliver high rates of penetration, allowing a specifically tailored bottomhole assembly with a more aggressive bit that can reduce drilling time and cost. Accurate interpretation and modeling enable a more detailed understanding of a shale reservoir that can help improve target selection, increase initial production and ultimately optimize field development.

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