Research article

Technical difficulties of logging while drilling in carbonate reservoirs and the countermeasures: A case study from the Sichuan Basin

Zhang Shudong

Logging Company, CNPC Chuanqing Drilling Engineering Co., Ltd., Chongqing 400021, China

Received 30 June 2015; accepted 8 December 2015

Available online 24 May 2016

Abstract

In the Sichuan Basin, carbonate reservoirs are characterized by deep burial depth and strong heterogeneity, so it is difficult to conduct structure steering, pore space reservoir tracking and trajectory control in the process of geosteering logging while drilling. In this paper, a series of corresponding techniques for structure, reservoir and formation tracking were proposed after analysis was conducted on multiple series of carbonate strata in terms of their geologic and logging response characteristics. And investigation was performed on the adaptabilities of the following logging technologies to geosteering while drilling, including gamma ray imaging while drilling, resistivity imaging while drilling, density imaging while drilling, gamma ray logging while drilling, resistivity logging while drilling, neutron logging while drilling and density logging while drilling. After while drilling information was thoroughly analyzed, the logging suites for four common types of complicated reservoirs (thin layered reservoirs, thick massive reservoirs, denuded karst reservoirs and shale gas reservoirs) were optimized, and five logging combinations suitable for different formations and reservoirs were proposed, including gamma ray logging + porosity + resistivity imaging, gamma ray logging + resistivity imaging, gamma ray logging + porosity + resistivity logging, gamma ray imaging + resistivity logging, and gamma ray logging. Field application indicates that it is of great reference and application value to use this method for the first time to summarize logging while drilling combinations for different types of carbonate reservoirs.

© 2016 Sichuan Petroleum Administration. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Keywords: Sichuan Basin; Carbonate rock; Reservoir; Logging while drilling; Geosteering; Technical difficulty; Fine geologic modeling; Logging suite optimization

In recent years, logging while drilling (LWD) and geosteering drilling have been conducted in many horizontal wells penetrating carbonate reservoirs in those gentle structures in central and southern Sichuan Basin and steeply dipping structures in eastern Sichuan Basin. The series of strata involved range from the deep Sinian Dengying Fm, Cambrian Longwangmiao and Qiongzhusi Fms, Silurian Longmaxi Fm, and Carboniferous Huanglong Fm to the middle and shallow Permian Changer.

* Supported by “Well logging-based shale gas evaluation”, a sub-project of National Science and Technology Major Project (No. 2011ZX05018-003) and “Interpretation and supporting system development for electromagnetic wave imaging and well logging while drilling”, a China National Petroleum Corporation Science and Technology Major Project (No. 2013E-3809).

E-mail address: zhangsd-007@163.com.

Peer review under responsibility of Sichuan Petroleum Administration.
reservoir with complicated pore structure. Some reservoirs being drilled may suddenly disappear. The well path may also be lost in a thick reservoir or a set of reservoirs. (3) It is difficult to control the wellbore track during drilling due to the large distance (generally larger than 12 m) between the measuring point and the bit, which makes it hard to adjust the bit in time, especially for the drilling of thin reservoirs or strong heterogeneous structures.

The above challenges essentially originate from geologic complexity and variability. In order to meet these challenges, it is necessary to understand the geologic conditions and then select optimum logging suite and utilize applicable methods including geologic modeling and LWD. This paper discusses these technical solutions to geosteering issues in different blocks with different series of strata and reservoirs in the Sichuan Basin.

1. Carbonate reservoir features and precise geologic modeling

In fractured carbonate reservoirs with low porosity and low permeability in the Sichuan Basin, the heterogeneity of pore space, pore size and reservoir is dominated by sedimentary facies, karstification and structure. A horizontal well may penetrate as many reservoirs as possible through geosteering drilling with effective guiding strategies, LWD with optimum logging suite, and precise geologic modeling.

In view of different reservoir features in the Sichuan Basin, whether a geologic model is applicable depends on its geologic and logging responses, LWD methods, risks of real-time geosteering, etc.

A geologic model built to characterize complicated structures should be modified again and again in accordance with the drilling data available. A facies model should be built for the series of strata dominated by sedimentary facies that would be delineated jointly with well data and seismic data. If there are large lateral variations of reservoir features, it is necessary to construct a detailed reservoir model with logging, seismic and geologic information. A karst model is needed for reservoirs with dissolved pores and caverns. An additional fluid model is necessary for the well with complex gas-water contacts or a horizontal section close to the gas-water contact. The final drilling parameters and diagrams would be formulated after wellbore track optimization based on the geosteering model.

2. LWD techniques

2.1. Methods

LWD tools now in service in Sichuan and Chongqing are provided by Schlumberger, Halliburton, Baker Hughes and Weatherford for natural gamma logging, gamma imaging, compensated neutron logging, density logging, density imaging, EWR/lateral resistivity, and resistivity imaging.

2.2. LWD-based geosteering techniques

LWD data would be used to improve the interpretation of formation, reservoir, fluid and structure and locate real-time positions of wellbore track, gas-water contact and structure being drilled so as to further optimize the geologic model to guide the orientation of well drilling [5–8].

Carbonate reservoirs in the Sichuan Basin are dominated by structure, karstification, sedimentary facies and formation; accordingly structure tracing, reservoir tracing and formation tracing would be discussed in the following parts.

2.2.1. Structure tracing (structure steering)

Reservoir extension is confined by complicated structures (e.g. folds and faults), so it is necessary to accomplish structure interpretation and tracing before reservoir tracing.

Imaging-while-drilling data and conventional logging data could be used jointly to interpret structural parameters, delineate tectonic forms and predict tectonic variations. Imaging-while-drilling involving gamma imaging, density imaging and resistivity imaging would be used to estimate well path (down cutting or up cutting), interpret structure, and calculate stratigraphic dip and the included angle between the well path and the bed. These interpretations would then be integrated with the well path and stratigraphic correlation to restore the structure.

Conventional LWD data involving gamma, resistivity, compensated neutron, density, etc. may also be used to interpret structure. Whether the bed is in updip or downdip direction could be judged by vertical thickness. The stratigraphic dip variations could be estimated through stratigraphic modeling and bed relocating [9–12].

2.2.2. Reservoir tracing (reservoir steering)

Reservoir extension is dominated by reservoir features and their lateral variations instead of structures.

First, pores, cavities and reservoirs would be identified through porosity logs (neutron and density logs), resistivity imaging, resistivity log, gas logging and drilling time. Reservoirs would then be predicted based on seismic attributes. Finally the wellbore track would be located in the stratigraphic model to trace the reservoirs [13–15].

2.2.3. Formation tracing (formation steering)

Formation tracing is equal to reservoir tracing if both of them demonstrate consistent extensions. For example, self-sourced shale gas and coalbed methane reservoirs or reservoirs closely related to some lithologies (e.g. proximal thin reservoirs of the Da’anzhai Member) could be tracked with this method.

Build an appropriate stratigraphic model and key-bed model and select LWD information sensitive to stratigraphic variations for stratigraphic identification. Trace key beds and locate the well path. Perform structural interpretation for the adjustment of the well path and reservoir tracing.

2.3. LWD feasibility

Applicable logging techniques should be utilized for carbonate formations and reservoirs with various geologic features and logging responses (Table 1).
2.3.1. Gamma imaging while drilling

This method may be applied to the section with large vertical lithologic changes, e.g. Longmaxi and Qiongzhusi shale gas reservoirs, to make distinct logging responses.

2.3.2. Resistivity imaging while drilling

In terms of its high resolution and capability of bedding imaging, this method may be applied to the thin interbeds and thin beds with moderate resistivity (less than or equal to 2000 $\Omega\cdot$m), abundant bedding planes and large lithologic changes, e.g. Longmaxi Fm, Lei 1 (L1) Member, Jia 2 (J2) Member, and Da’anzhai Member (Fig. 1). Fig. 1 shows the down-cutting formation of the well path on an image of lateral resistivity imaging while drilling.

2.3.3. Density imaging while drilling

The application of this method is still in doubt because its low resolution makes it hard to differentiate among various lithologies with similar densities.

2.3.4. Gamma logging while drilling

Gamma log is closely related to shale content and would be used in the interpretation of formation, reservoir and sedimentary environment. This method is universally applicable, especially for the series of strata with considerable shale content variations.

Table 1
Optimized logging suites for separate series of strata in the Sichuan Basin.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Formation</th>
<th>Geologic model</th>
<th>Feasibility</th>
<th>Strategy</th>
<th>Optimal LWD</th>
<th>Cost-effective LWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin-layered reservoir</td>
<td>L$_1^1$ submember</td>
<td>Stratigraphic model</td>
<td>★★★★★</td>
<td>Structure steering</td>
<td>Portfolio 1</td>
<td>Portfolio 3 or 2</td>
</tr>
<tr>
<td></td>
<td>J$_2^1$ submember</td>
<td>Structural model</td>
<td>★★★</td>
<td>Gamma imaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Da’anzhai Member</td>
<td>Reservoir model ★</td>
<td></td>
<td>Resistivity ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluid model ★</td>
<td></td>
<td>Resistivity imaging ★★★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neutron ★</td>
<td></td>
<td>Density ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density imaging ★</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thick-layered reservoir</td>
<td>Longwangmiao Fm.</td>
<td>Reservoir model ★★★☆</td>
<td></td>
<td>Structure steering</td>
<td>Portfolio 1</td>
<td>Portfolio 3 or 2</td>
</tr>
<tr>
<td></td>
<td>Feixianguan Fm.</td>
<td>Sedimentary facies model ★★★</td>
<td></td>
<td>Gamma imaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Changxing Fm.</td>
<td>Structural model ★</td>
<td></td>
<td>Resistivity ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluid model ★</td>
<td></td>
<td>Resistivity imaging ★★★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neutron ★</td>
<td></td>
<td>Density ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density imaging ★</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathering karstic reservoir</td>
<td>Dengying Fm. L$_4$ Member</td>
<td>Reservoir model ★★★★★</td>
<td></td>
<td>Structure steering</td>
<td>Portfolio 1</td>
<td>Portfolio 3 or 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Karst model ★★★★★</td>
<td></td>
<td>Gamma imaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedimentary facies model ★★★</td>
<td></td>
<td>Resistivity ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structural model ★</td>
<td></td>
<td>Resistivity imaging ★★★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluid model ★</td>
<td></td>
<td>Neutron ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stratigraphic model ★</td>
<td></td>
<td>Density ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density imaging ★</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathering karstic reservoir</td>
<td>Carboniferous</td>
<td>Stratigraphic model ★★★★★</td>
<td></td>
<td>Structure steering</td>
<td>Portfolio 1</td>
<td>Portfolio 3 or 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reservoir model ★★★★★</td>
<td></td>
<td>Gamma imaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structural model ★★★</td>
<td></td>
<td>Resistivity ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reservoir model ★</td>
<td></td>
<td>Resistivity imaging ★★★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluid model ★</td>
<td></td>
<td>Neutron ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stratigraphic model ★</td>
<td></td>
<td>Density ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density imaging ★</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale gas reservoir</td>
<td>Longmaxi Fm.</td>
<td>Stratigraphic model ★★★★★</td>
<td></td>
<td>Structure steering</td>
<td>Portfolio 1</td>
<td>Portfolio 3 or 2</td>
</tr>
<tr>
<td></td>
<td>Qiongzhusi Fm.</td>
<td>Structural model ★★★</td>
<td></td>
<td>Gamma imaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reservoir model ★</td>
<td></td>
<td>Resistivity ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resistivity imaging ★★★</td>
<td></td>
<td>Neutron ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluid model ★</td>
<td></td>
<td>Density ★</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density imaging ★</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The significance or value increases with the number of stars ★.
2.3.5. Resistivity logging while drilling

This method is mainly used to identify reservoirs and differentiate among gas, oil and water. Resistivity and gamma logs would usually be used together to identify gas zones or sections with different electrical properties. This method is universally applicable to all series of strata.

2.3.6. Neutron logging while drilling

Compensated neutron log is mainly used to estimate reservoir porosity. It would also be used jointly with gamma, resistivity and density logs to interpret lithology and formation. Neutron log has played an important role in carbonate reservoir tracing and Longmaxi shale gas reservoir tracing with good results. This method is universally applicable to all series of strata.

2.3.7. Density logging while drilling

Density log is often used together with neutron or resistivity log to interpret reservoir and lithology and estimate shale gas reservoir quality. This method is universally applicable to all series of strata.

3. LWD suite optimization

3.1. Reservoir classification

Carbonate reservoirs may be classified into four categories, i.e. thin-layered reservoir, thick massive reservoir, weathering karstic reservoir and shale gas reservoir, in accordance with geologic features and applicable LWD techniques.

3.1.1. Thin-layered reservoir

This kind of reservoir, several meters thick, occurs within the formation of several to tens of meters thick with distinct lithologies and electrical properties. Many marker beds with distinct electrical properties could be used for geosteering. The risks come from small reservoir thickness and deformed lithologic association caused by tectonic compression, which makes it difficult to control the well path. So it is necessary to trace single layers with sufficient confidence. Resistivity or gamma imaging could be used to diagnose whether the well path penetrates the reservoir or not; gamma, resistivity and porosity (e.g. neutron) logs would be integrated for lithology identification and reservoir tracing. It is also suggested to use the LWD tool with small interval between the measuring point and the bit.

3.1.2. Thick massive reservoir

This kind of reservoir (several to tens of meters thick) with simple lithologies may occur within carbonate formations (tens to hundreds of meters thick) of reef and beach facies in a high-energy environment and exhibits thick massive sedimentary texture (short of bedding). Electrical properties are shown as low gamma with small undulation, high neutron, low density and medium to high resistivity. The risks in geosteering come from small variations of electrical properties and ambiguous marker beds. The solution is to use porosity logs (neutron, density or acoustic time) and resistivity log (lateral resistivity or EWR) in reservoir tracing; gamma log could only be used as a reference. Reservoir tracing may be better accomplished with geologic and seismic data in view of the controlling effect of sedimentary facies and karstification.

3.1.3. Weathering karstic reservoir

In view of variable residual thickness resulting from weathering and denudation at the top and karstification-dominated heterogeneous reservoirs, geosteering risks may be caused by poor correlation of formation and reservoir electrical properties in vertical and lateral directions; it is hard to select marker beds in formation and reservoir tracing. The solution is reservoir modeling with multi-well and seismic data based on the study of karstification and sedimentary facies. Such portfolio as gamma + compensated neutron + density + resistivity imaging should be employed.

3.1.4. Shale gas reservoir

Longmaxi and Qionghousi gas-bearing formations could be consistently correlated on lithological and electrical logs and high-grade shale gas intervals exhibit distinct lithological and electrical features, but it is difficult to differentiate among rhythmically deposited alternate layers and distinguish the horizons and sequences (geologic time) penetrated by the well path. The target may be lost if an improper marker bed is selected. The solution is to choose a guiding chamber and determine some specific positions at the well path which may facilitate the identification of formation. Such portfolio as gamma/gamma imaging and resistivity imaging, and additional neutron and density logging or geochemical well logging if possible, should be employed.

3.2. Logging suite optimization

3.2.1. LWD portfolios

Some LWD portfolios are designed here, i.e. portfolio 1 of gamma + porosity + resistivity imaging, portfolio 2 of gamma + resistivity imaging, portfolio 3 of gamma + porosity + resistivity, portfolio 4 of gamma imaging + resistivity, and portfolio 5 of gamma. Porosity log may be generated with all of or one of the three logs, i.e. compensated neutron, acoustic time and density.

3.2.2. Logging suite optimization

Logging suite optimization for an area or a well should be based on the geologic model, tectonic complexity, reservoir properties, LWD feasibility, geosteering feasibility and engineering to ensure a successful operation and reduce risks and costs. Table 1 shows a tentative scheme of logging suites as per statistical data for some wells in operation in Sichuan oil and gas fields.

4. Case study

The target stratum in Well TDXX is the Carboniferous System. Geosteering risks may be caused by the uncertainties of structure interpretation and lateral reservoir variation. It is suggested to combine structure tracing with formation tracing.
and use FEWD system developed by Halliburton to measure azimuthal gamma, EWR, neutron and density imaging as well as borehole deviation and azimuth, etc.

4.1. Pre-drilling modeling

4.1.1. Stratigraphic modeling

The target stratum is divided into 6 single layers as per log curves of a neighboring well close to the target well (Fig. 2). No. 1 layer of 3.8 m thick is composed of limestones with low gamma and high resistivity. No. 2 layer of 7.2 m thick is composed of dolomitic limestones with high gamma and high resistivity. No. 3 layer of 11.6 m thick is composed of dolostones with low gamma and low resistivity. No. 4 layer of 2.4 m thick is composed of limy dolostones with high gamma and high resistivity. No. 5 layer of 7.9 m thick is composed of dolostones; the upper part features low gamma and the lower part features high gamma and low resistivity. No. 6 layer of 5 m thick is composed of limestones with increasing gamma and resistivity. No. 3 and No. 5 layers are the targets of well drilling, No. 2 and No. 6 limestone layers are two marker beds for warning, and No. 4 layer is the marker bed for geosteering.

4.1.2. Structural modeling

As per 3D seismic data (Fig. 3), apparent dip angle changes from 2.8° at Carboniferous top to 6.5°, 8.5° and 11° at the positions 100, 200 and 280 m apart from the top, respectively. The angle of 11° basically remains unchanged after that. A pre-drilling geologic model was built in accordance with seismic reflections and neighboring well data (in Fig. 4, black dashed lines denote the top and bottom boundaries of the
Carboniferous system in the pre-drilling model) and then used to design the wellbore track (blue dashed line in Fig. 4).

4.2. Structure tracing

In the process of geosteering, structure tracing and reservoir tracing for 2 targets had been performed based on the structure model and stratigraphic model. The structure model had been modified four times. As per logging interpretation, 89.2% of good reservoirs have been drilled across the horizontal section of 700 m.

4.3. Structural modeling after drilling finished

A revised structure model (plotted in red in Fig. 4) was built with logging and log data after well drilling. Actual dip angle at the position 300 m apart from Carboniferous top is similar to the prediction. The dip angle slowly increases from 6.3° to 8.5° at the interval 300—530 m apart from Carboniferous top and then decreases to 2.4° at the interval 530—630 m apart from the top and finally quickly increases to 11° at the interval from the position 630 m apart from the top to the bottom hole. The large discrepancies between the pre-drilling model and post-drilling model (Fig. 4) demonstrate tectonic complexities and the significance of geosteering while drilling.

5. Conclusions

(1) Geosteering drilling of carbonate reservoirs is challenging due to the complexities of carbonate rocks. The solutions are detailed geologic modeling and LWD suite optimization.

(2) In view of reservoir features and LWD feasibility, 5 LWD portfolios are designed for 4 types of carbonate reservoirs to improve drilling operation and ensure that more reservoirs would be penetrated.

References


