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Bed boundary mapping proves useful in a heavy oil environment

Deep azimuthal electromagnetic resistivity measurements were used to optimize the trajectory of wells drilled with a rotary steerable system.

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Primary (cold) production of heavy oil from the Faja Petrolífera del Orinoco (Orinoco oil belt) delivers very low recovery factors. Steam-assisted thermal production methods are increasingly being used in the region to enhance recovery. To optimize the heating efficiency of steam injection and the gravitational segregation of heavy oil, several of the steam-assisted techniques used in the region require precise positioning of horizontal wells close to the bottom of the reservoir sands. These sands are usually unconsolidated and highly heterogeneous, with lateral variations at subseismic scales. Many of the reservoirs are less than 20-ft thick.

Petróleos de Venezuela SA (PDVSA) has ambitious targets for improving oil recovery factors in the region. The company has been evaluating technologies to more accurately position wells and improve overall operational efficiency. PDVSA carried out a pilot project in a thin, unconsolidated package where a high drilling rate (up to 1,000 ft/hr) was expected.

The project deployed a rotary steerable system (RSS) combined with a deep azimuthal electromagnetic resistivity system. This enabled real-time bed boundary mapping, providing engineers with fit-for-purpose information with which to make geosteering decisions to optimally place wells within the pay zone. The new information was subsequently used to update and increase the accuracy of the geological model, benefitting future field development activity.

THE BARE HEAVY OIL FIELD

Bare Field is located in the Orinoco oil belt, one of the world's largest heavy oil accumulations, containing an estimated 1.3 trillion bbl of original oil in place, of which 300 billion bbl are considered recoverable. The belt extends for about 375 mi along the north side of the Orinoco River in the east of Venezuela, and is divided into four blocks: Boyaca, Junin, Ayacucho and Carabobo. Bare Field, with a surface area of about 1,560 sq mi, is in the Ayacucho Block, Fig.1.

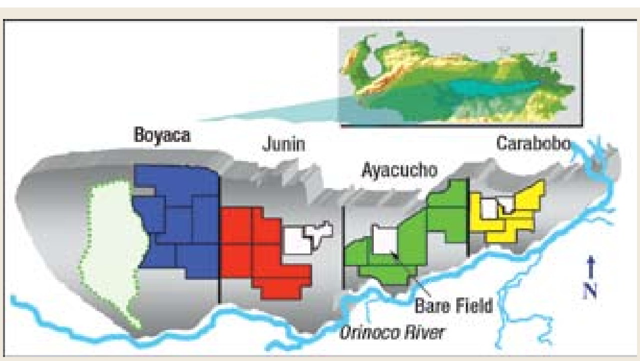

Fig. 1. Location of Bare Field, Orinoco oil belt, Venezuela.

Oil in the Orinoco belt is mostly contained in fluvial, nearshore marine and tidal sandstones of the Oficina Formation, deltaic sequences deposited during the Miocene and Pliocene epochs. Reservoirs range in depth from 500 to 4,600 ft, and they contain oil with gravities ranging 4–6°API. Viscosities range from 2,000 to 8,000 cP.

Because of its high viscosity, primary (cold) production of heavy oil from the Orinoco belt is typically expected to deliver recovery factors of just 3%. PDVSA has targets for much higher recovery factors, mostly to be achieved through steam-assisted thermal enhanced production methods.

The sandstones of the Oficina Formation exhibit considerable internal fluid-flow heterogeneity caused by juxtaposition of different facies and by shale barriers that reduce recovery efficiency. Between 30% and 40% of the oil in place in the deltaic sequence is in sand bodies less than 20-ft thick, representing an additional challenge to cost-effective exploitation.

The main reservoir of Bare Field is in the lower part of the Oficina Formation, and is composed of shale, siltstone, mudstone, coalbeds and sand bodies, interpreted as a product of a tide-dominated coastal plain setting. The main oil-bearing intervals are sands deposited as fluvial systems of braided plains, channels and channel-fill bars.

SIMULATION OF WELL PLACEMENT

A numerical simulation model using representative properties from Bare Field was developed to verify whether well location within the pay zone has a significant effect when applying the horizontal alternating steam drive (HASD) thermal recovery process.

The HASD process uses a set of parallel single horizontal wells acting alternatively as oil producers and steam injectors. The recovery mechanism is a combination of horizontal steamflooding between wells and cyclic steam stimulation of each of the wells in the pattern. Steam is continuously injected through one set of wells while a second set of wells is producing.

After a pre-defined period, which can last from days to months, the wells' roles are switched, with the injectors becoming producers and vice versa. The role-switching continues cyclically over the economic life of the production system. The process is designed to spread heat throughout the reservoir, decreasing oil viscosity and thus improving oil drainage.

The model simulated a five-well HASD pattern. Five different scenarios were considered, locating the five wells from near the bottom to near the top of the formation. Figure 2 shows the simulated temperature profile in the reservoir after 10 years of steam injection with wells near the bottom of the formation. The area colored in yellow represents the highest temperatures. The red line in Fig. 3 shows cumulative oil production plotted against distance from the bottom of the reservoir. This indicates that maximum production is achieved when wells are placed near the bottom of the reservoir.

Creating steam represents a significant operational cost, so cumulative steam oil ratio (CSOR) is an important parameter when evaluating the economics of a heavy oil project. The blue line in Fig. 3 shows that CSOR is lowest—meaning that the least steam will be required for a particular volume of oil production—when wells are placed near the bottom of the reservoir.

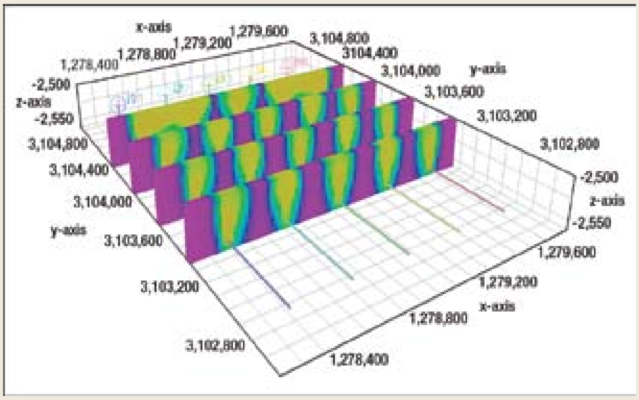

Fig. 2. Modeled temperature profile of a five-well HASD pattern after 10 years of steam injection.

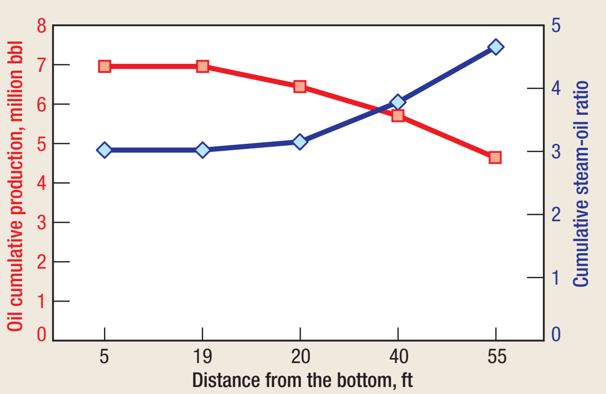

Fig. 3. Cumulative oil production (red) and steam-oil ratio (blue) plotted against distance from the bottom of the reservoir.

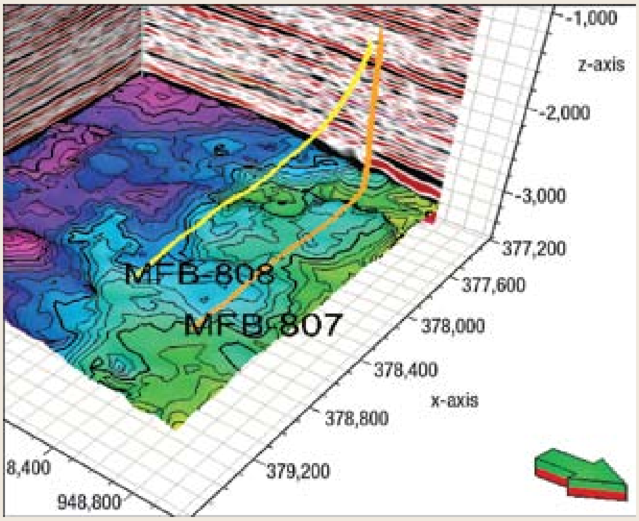

Fig. 4. Trajectories of the two candidate wells. The contoured horizon is a reflector below the TL sand.

OPTIMUM WELL PLACEMENT

PDVSA initiated a project to investigate whether new well placement technology could improve drilling and production efficiency in its unconsolidated heavy oil reservoirs in the Orinoco belt. Two candidate wells (Fig. 4) were identified in the central area of the Bare field in the TL sand, a 30-ft reservoir unit at 2,700-ft depth in the lower part of the Oficina Formation. Available log data indicated strong lateral variation in both sand thickness and petrophysical properties.

The project required the drilling of 3,000-ft horizontal sections for the two wells about 7 ft above the base of the reservoir. A key objective was that the wells should avoid sand exit, despite the expected subseismic geological variations, thereby avoiding the need for sidetracks.

In addition, it was decided that actual sand thickness should be measured along the trajectory. A point-the-bit powered RSS was selected to meet these objectives. The drillbit featured frontal jets to reduce washing out of the unconsolidated sand formation.

PROACTIVE GEOSTEERING

Many horizontal wells have been drilled in the Orinoco belt, usually using conventional well placement technologies such as log correlations, modeling and real-time image interpretations. The reactive nature of this conventional technology does not meet the requirements of advanced geosteering systems. A more proactive approach was required, based on real-time logging-while-drilling (LWD) measurements and software that would enable in-time drilling decisions.

The bottomhole assembly included a deep azimuthal electromagnetic resistivity LWD system—Schlumberger's proprietary PeriScope bed boundary mapper—deployed above the RSS to measure the distance to geologic boundaries in real time, allowing proactive geosteering through the reservoir. The tool was oriented azimuthally by the use of a magnetometer, and also provided annular pressure and azimuthal gamma ray (GR) measurements. The RSS provided a continuous inclination measurement about 14 ft behind the bit.

PRE-JOB MODELING

A multidisciplinary team was formed—comprised of a geologist, geophysicist, drilling and reservoir engineers, system engineers and well placement engineers—to plan the job details, which included specifying downhole tools, software, people and data transmission systems.

The team performed a feasibility study to quantify whether the sensitivity of the deep resistivity tool was compatible with the expected petrophysical properties of the reservoir. A 2D section along the proposed well trajectory was generated based on resistivity measurements from a nearby well and properties of the TL sand extracted from the 3D structural model, Fig. 5a.

Synthetic logs were also generated (Fig. 5b): GR, conventional resistivities and deep azimuthal electromagnetic resistivity raw data, which was used to predict distances to bed boundaries.

The deep azimuthal electromagnetic resistivity data is plotted on a symmetric scale. The tool is sensitive to nearby resistivity contrasts. When the readings are close to zero, the tool is away from any boundaries (areas marked "2" in Fig. 5b). If a more conductive bed is located above the trajectory, curves will deflect up proportionally to the resistivity contrast and distance ("1"). Conversely, if the more conductive bed is below, the curves will deflect downward ("3"). The modeling exercise indicated that the tool was able to accurately predict the base of the TL sand within a detection range of 7 ft, which met the requirements of the project.

LWD FIELD SOFTWARE

During the drilling operations, LWD data was transmitted in real time to the surface, where specialized software tools were utilized to present information that would enable proactive decisions to optimize the well positioning in the productive zone. A three-layer model inversion algorithm was used to obtain distance to bed boundaries, horizontal and vertical resistivity of the reservoir, and resistivities of the beds above and below the measurement points in the TL sand. The software provided bed boundary information through both azimuthal curves and inversion results.

Another software platform provided 3D interactive displays of the gamma ray images along the well trajectory and interpretations of formation dips. A seismic-to-simulation software application was also provided, allowing collaborative workflows and integration of operations between geophysicists, geologists and reservoir engineers.

RESULTS

The two wells, each with 3,000-ft horizontal displacement, were optimally positioned on the first attempt, so no sidetracks were required. The RSS, under the directional driller's command, responded to all geosteering requirements, delivering an in-gauge section with less tortuosity and smaller dogleg severities (below 5°/100 ft) compared with downhole motors.

Good geosteering operational performance, data signal level and sampling frequency were achieved at the same time as high rates of penetration (ROP), averaging more than 500 ft/hr and reaching up to 1,000 ft/hr. Net pay averaged 90%.

Figure 6 shows a representation of an interpreted structural model based on the distance to boundaries detected by the deep azimuthal electromagnetic resistivity tool in one of the wells. The boundaries on the 2D section are referenced to the executed well trajectory (red line) and color coded where darker colors represent lower resistivities.

Supporting this interpretation are the extracted relative dips, represented by blue lines on the curtain section (vertical section along the trajectory) extracted from the GR image interpretation on the top track. A shale section, accounting for about 10% of the total drilled interval, is indicated by the darker GR images on the top track coinciding with the region where the trajectory exits the sand interpretation.

The wells were drilled through sand bodies previously interpreted as being approximately horizontal along the well trajectory. After drilling 3,000 ft of horizontal section, variation in true vertical depth (TVD) was found to be about 20 ft, representing an average relative dip angle of less than 0.5°. However, dips relative to the well trajectory displayed larger (±2°) variations locally, providing a tortuous geometry that is only feasible to navigate using real-time bed boundary mapping technology.

GEOLOGICAL MODEL UPDATE

Information provided by the bed boundary mapper was used to update the geological model. Figure 7 shows the well trajectory (red) with a background picture of the inversion canvas. Superimposed are yellow and green sticks depicting the distances to boundaries and their inclinations. The distance to the boundaries results from the inversion of the readings. Every distance to boundary is associated with an orthogonal bed inclination for every trajectory point where the inversion is performed. This information is displayed as an angle toward one side of the well trajectory.

The new information enabled the creation of updated surfaces that better represented the reservoir boundaries. The new

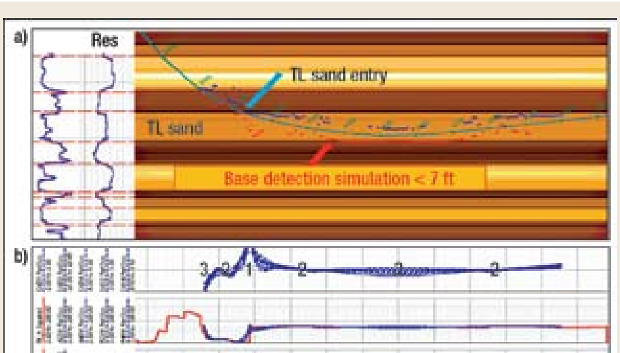

Fig. 5. a) The proposed well trajectory and b) synthetic logs: GR (bottom), conventional resistivities (middle) and deep azimuthal electromagnetic resistivity raw data (top).

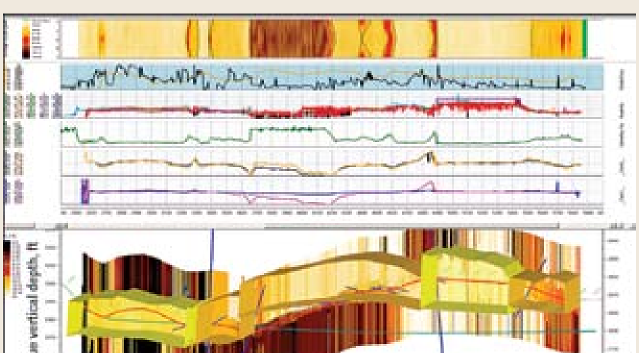

Fig. 6. Structural interpretation based on distance to boundaries detected by the LWD resistivity tool. The red line is the well trajectory.

model can be used to better forecast initial oil production, plan new wells in the area and study the application of enhanced oil recovery projects.

The surface seismic data was processed using impedance cubes that enhanced the identification of sedimentary patterns and reservoir conditions. Figure 8 presents a section along one of the wells in which the seismic attributes have been correlated with high-dip events extracted from the new LWD data. Although the seismic is not a geosteering tool, the seismic information can help on a larger scale to anticipate tendencies ahead of the drilling point in real time.

CONCLUSIONS

The RSS achieved high ROPs and delivered an in-gauge section with less tortuosity and smaller dogleg severities compared with downhole motors, and responded to all requested changes in well trajectory regardless of formation characteristics. The deep azimuthal electromagnetic resistivity tool provided real-time measurements to map formation boundaries.

The supporting software was able to acquire and invert the data in real time and present fit-for-purpose information that allowed engineers to make appropriate decisions to construct a horizontal trajectory compatible with the project objectives on the first attempt. The new information was used to update and improve the accuracy of the geological model, providing a better understanding of the reservoir.

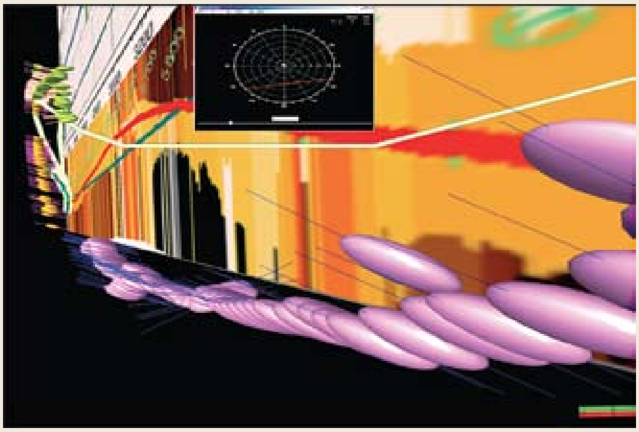

Fig. 7. Well trajectory (red) with updated surfaces based on the LWD resistivity measurements. Yellow and green sticks indicate measured distances and inclinations of the TL sand boundaries.

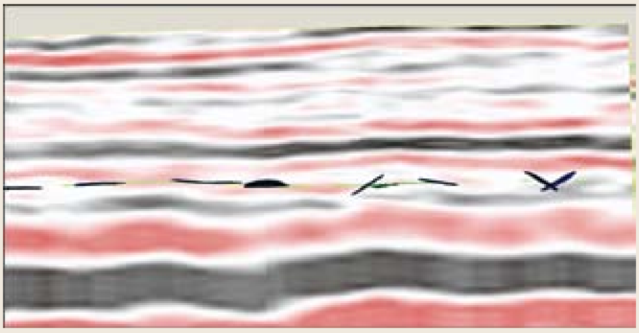

Fig. 8. A section along one of the well trajectories indicating a correlation between surface seismic attributes and high-angle dips; the well trajectory is extracted from the LWD data.

To achieve optimum cumulative production and steam-oil ratio, steam-assisted thermal enhanced recovery projects in the Orinoco belt require accurate positioning of horizontal wells close to the bottom of sand layers, which are often thin. The experience acquired during this job will be a reference for drilling future shallow horizontal wells at high ROPs, especially in heavy oil environments.

Real-time bed boundary mapping can improve overall field development costs by building wells in the optimum location at the first attempt, eliminating the need for appraisal wells and sidetracks. **WO**

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