Using dielectric permittivity to evaluate Orinoco reserves

Previously masked by low resistivity and other well and formation conditions, producible heavy oil was identified using a new petrophysical measurement device designed to negotiate rugose borehole profiles.

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The vast heavy oil reserves of Venezuela’s Orinoco belt are not easy to characterize. While there is no mystery as to the reservoirs’ location and massive volumes of oil in place, the Orinoco oil fields can become quite complex as one steps out from producing blocks. Reservoirs become thinly bedded, creating low-resistivity pay situations, and water salinities vary from traditional saline to fresh, making it difficult to determine the volumes of producible hydrocarbons. Since Orinoco oil is of low API gravity, it is quite viscous, so a formation’s permeability to oil is typically very low compared to its permeability to water.

Other impediments that make accurate formation evaluation problematic in the Orinoco belt include thinly bedded shaly sands and rugose boreholes. These factors, combined with the heavy oil and variable water salinity issues, move most traditional logging technologies away from their optimum operating environments.

In this challenging environment for reservoir characterization, PDVSA has experienced positive results using a new petrophysical measurement device from Schlumberger as part of an extensive reappraisal of the Orinoco belt. The wireline tool uses multifrequency dielectric dispersion to deliver high-resolution measurements that accurately determine oil saturation irrespective of clay content, water salinity, oil viscosity and marginal borehole conditions. In one case study in an appraisal well, the device delivered accurate measurement results under well conditions that included poor interwell correlation, and confirmed the operator’s suspicion about the existence of low-contrast pay.

CHARACTERIZING HEAVY OIL PAY ZONES

The Orinoco belt has been under extensive study and development for many years. Historically, development depended on information from numerous vertical wells. Cross-correlation methods assumed that conditions between wells mimicked those observed in the wells themselves. Recently, however, field mapping revealed that the formations were diverse and transitioned from relatively homogeneous thick oil-rich beds to thinly bedded, discontinuous reservoirs. Sand quality varied all the way from fine talcum-like grains to coarse pebbles. Recently, an extensive reappraisal has been made that has benefited from use of the new dielectric measurement device.

The formation’s propensity to produce water was a major unknown that needed to be resolved. The difference in mobility between water and the Orinoco viscous crude was so significant that even low water saturation could result in high produced water fractions. Waters were fairly fresh for the most part, with salinities less than 2%, and since the holes were drilled using fresh mud, there was very little resistivity contrast. A wet formation could show a resistive spike due to the presence of hydrocarbons or, more likely, due to the presence of fresh water in a fine-grained matrix. Conversely, a pay zone could be interpreted as wet due to thinly bedded low-contrast sand/shale sequences. Poor borehole conditions further impaired the identification of potential pay zones.

Because of the heavy oil content, nuclear magnetic resonance (NMR) measurements were unable to characterize formation porosity, which adversely affected saturation determinations.

Although dielectric tools had been around for quite a long time, their use in the types of geological environments found in the Orinoco belt was not always successful. They were mandrel tools, limiting their use in rugose holes. Most operated using single frequencies and had single radial depths of investigation, preventing radial profiling and salinity estimates. They were insensitive to variations in rock texture, and thus were constrained to interpretations based on Archie’s law without any way to deal with changes in the cementation factor or the saturation exponent across various strata.

NEW PETROPHYSICAL MEASUREMENT

The new wireline petrophysical measurement device, called the Dielectric Scanner multifrequency dielectric dispersion tool, has an articulated borehole-compensated transmitter/sensor pad that can negotiate rugose hole profiles, Fig. 1. Located in the pad are two electromagnetic transmitters capable of broadcasting at four different frequencies ranging from 20 MHz to 1 GHz and at two axial orientations. Two arrays of four receivers bracket the transmitters and allow radial formation fluid profiling at four spacings. In some cases, vertical resolution of 1 in. can be achieved for evaluation of extremely thin formation laminations. The tool is able to perform in both water-based and oil-based mud systems.

A close look at the pad architecture reveals that each transmitter or receiver consists of orthogonally crossed dipole antennae; in addition, two electric dipoles are oriented perpendicular to the pad surface just outside the transmitters. These are used in propagation mode in
Reservoir Characterization

In conjunction with the transverse magnetic dipole transmitters. One measures the properties of the mud cake immediately in front of the pad.

Transmitter and receiver dipole orientation is longitudinal (parallel to the tool’s axis) or transverse (at right angles to the tool’s axis). The antenna array makes nine separate automatically calibrated borehole-compensated measurements. The measurements are symmetric and include both phase shift and attenuation. A complete measurement is defined as the amplitude ratio and phase shift measured at a specific receiver with respect to the signal from transmitter A versus the same properties measured with respect to the signal emitted from transmitter B.

A rich data set is generated because of the four frequencies emitted from the transmitters plus the four radial depths of investigation afforded by the combination of different transmitter/receiver spacings and transmission frequencies—the lower frequencies propagating deeper into the formation. Borehole compensation is achieved by the symmetric combination of the array measurements.

In the petrophysical world, four classic “zones about the borehole” have been recognized for decades—the mud cake, the flushed zone, the transition zone and the virgin formation, Fig. 2. One advantage of varying radial depths of investigation is the ability to develop a radial resistivity profile that can be related to fluid mobility. In heavy oil applications, depth of invasion is frequently shallow and the measurement easily reaches the virgin zone. As a result, the electromagnetic and geometric parameters can be related, allowing invasion profiles to be derived irrespective of fluid salinity (resistivity).

From Physics to Productivity

The scanner measures dielectric, or relative, permittivity, defined as the ease by which an electromagnetic field can permeate a given formation. The large contrast between water permittivity (50–80) and that of the matrix/hydrocarbon (2–10) is the basis of the dielectric water-filled porosity measurement, independent of water salinity. Signals from dielectric devices experience dispersion, which is defined as the variation of the dielectric measurement that accompanies changes in signal frequency. Since the multifrequency dielectric dispersion tool makes its measurements at four separate frequencies, the dispersion pattern can be characterized using a curve-fitting technique. In carbonates, the shape of dispersion is a function of two key factors—the cementation factor and the saturation exponent. These factors are unknowns in the famous Archie saturation relationship and, for more than half a century, have affected the accuracy of saturation determinations. Similarly, in shaly sand the dispersion measured is a function of the shale volume, or cation exchange capacity, which is a key input in shaly sand saturation equations.

With the ability to determine the textural parameters in both carbonates and shaly sands, hydrocarbon saturation can be determined accurately in a wide variety of scenarios that were previously problematic, such as carbonates, low-contrast clastics, and heavy oil reservoirs. The new tool design addressed each of these deficiencies.

With the rich data set available from the tool, interpreters are able to discriminate between Orinoco belt wet zones that look like potential pay zones and pay zones that appear to be wet. The implications of this are great. Many heavy oil plays are marginal at best, and operators do not want to miss any potential pays, nor do they want to waste money and effort trying to produce zones that will only make water. Among other parameters, economic valuations are based on net pay thickness. In laminar zones, the ability to accurately quantify beds as thin as 1 in. assures operators that they will not miss potentially productive zones previously masked by thin-bed effects.

Similarly, since the tool determines formation-water-filled porosity irrespective of water salinity, low-contrast pay zones can be detected and their production potential verified. Fresh water,
which can be present in shallow heavy oil reservoirs, will not give false readings indicative of potential pay.

**CONFIRMATION OF LOW-CONTRAST PAY**

In an appraisal well drilled in the Junin Block, in an area where there is relatively poor interwell correlation, a conventional logging program showed a 100-ft-thick reservoir between x,420 and x,505, Fig. 3. However, the operator suspected that some additional low-contrast pay existed.

An NMR log (Track 7) was run but was unable to detect an oil signal because of the high viscosity of hydrocarbons left in the pore space.

The caliper log (black curve in Track 1) confirmed that the borehole was extremely rugose. This undoubtedly affected many mandrel-type logging tools, but did not adversely affect the articulated pad-type dielectric tool.

Highlights of the new dielectric measurement tool results can be seen in Tracks 2 and 6. Considerable movable oil can be seen between x,558 ft and x,650 ft, as well as between x,685 ft and x,720 ft. The viability of these zones was confirmed by cores.

Subsequently, fluid samples were acquired using a dual-packer formation tester tool operated in a cased and perforated wellbore. The dual inflatable packer enabled the engineer to straddle the perforations at each zone to

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**Fig. 3.** Core analysis and formation fluid sampler results corroborated the presence of additional pay indicated by the dielectric measurements taken in a representative Orinoco belt heavy oil well.
be tested, in order to minimize sample contamination. First, a zone identified by the scanner tool as 100% water was tested, and 100% water was recovered. Then a sample taken at x,701.5 ft presented mostly oil with some water, but the sample at x,574 ft presented 100% oil, water free, as did the uppermost zone, which was tested at x,447 ft. The fluid sampling results inspired sufficient confidence in the dielectric measurements that a decision was made to use the new device alone for subsequent well evaluations.

Based on interpretation results, the operator added 150 ft of net pay to the well profile, all characterized as low resistivity. Importantly, the ability to acquire shallow and deep water saturation values that are independent of water salinity in these heavy oil conditions allowed assessment of oil mobility in spite of poor hole conditions.

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