APPLICATION OF A NEW ARRAY DIELECTRIC TOOL TO THE CHARACTERIZATION
OF ORINOCO BELT HEAVY OIL RESERVOIRS

Eric Decoster¹, Olivier Faivre² y Rómulo Carmona³

¹Schlumberger, Faja Regional Technology Center, Torre BVC, Piso PH, Av. Intercomunal Andrés Bello, Sector Las Garzas, Barcelona, Venezuela, decoster@caracas.oilfield.slb.com
²Schlumberger, Etudes et Productions Schlumberger, 1, rue Henri Becquerel, 92142 Clamart Cedex, France, ofaivre@clamart.oilfield.slb.com
³Petróleos de Venezuela S.A., Intevep, Urb Santa Rosa, Sector El Tambor, Los Teques, Edo Miranda, Venezuela, carmonari@pdvsacom

Abstract

The Magna Reserva Project aims at the certification of an estimated 236 billion barrels of reserves found in 27 blocks of the Orinoco Belt, covering a surface area of 18,220 km². The project contemplates volumetric quantification of oil in place and mapping of the type and quality of crude oil to optimize recovery.

Preliminary log and core results show that, as the drilling of stratigraphic wells progresses away from blocks already in production, reservoir conditions become increasingly complex. Thinly bedded reservoirs and lower resistivity pay zones have been encountered. Fresh water, varying water salinities, biodegraded oil, tar and oil reservoirs that are not irreducible saturation have all been seen.

In an environment where oil can be 10,000 times more viscous than water, it is indispensable to predict zones of potential water production. Previous experience in the Orinoco belt has shown that resistivity and water cut are not directly linked and that medium resistivity layers can produce either oil or water.

For these reasons, PDVSA elected to participate in the field test of a new Array Dielectric device that represents a radical departure from earlier tools of the 1970's and 1980's. It is a pad-mounted tool consisting of two transmitters one inch apart and eight symmetrically located receivers transmitting simultaneously in longitudinal and transversal mode. Each transducer consists of two co-located magnetic dipoles, highly isolated and perpendicular to each other. Two electric dipoles measure the dielectric properties of the mudcake. The symmetric design allows full borehole correction and compensation for pad tilt. The tools measures dielectric properties at three frequencies between 100 MHz and 1 GHz.

By inverting the array data, the effect of the mudcake can be quantified and accounted for, giving the tool a depth of investigation that penetrates from 1 inch to 4 inches into the formation. As the heavy oil sandstone formations found in the Orinoco Belt rarely experience an invasion greater than two to three inches, the measurement spans the entire range from...
invaded to virgin zone, in spite of the inherent shallow penetration of dielectric measurements.

Using a suitable invasion model, the data can be inverted to give water-filled porosity and water salinity at 1 inch and 4 inches into the formation, with a vertical resolution of 1 inch. This allows quantification of oil in place at a previously unattainable vertical resolution, independently of water salinity, resolving the thin bed analysis and low water salinity problems simultaneously. Comparison of water saturations at 4 and 1 inch into the formation confirms that a heavy oil bearing sand is at irreducible water saturation or not, an essential information when steam injection projects are planned.

Knowledge of formation water salinity can be obtained even in layers that contain hydrocarbons, giving precious reservoir information regarding the significant water movements that have occurred in the vast area under study.

Results obtained on several wells logged with the tool in recent months in the Junin and Carabobo blocks are presented and discussed.

INTRODUCTION

Development of the original Orinoco Belt projects relied heavily on vertical wells used for stratigraphic correlation (Carmona et al., 2001). However, the need for detailed reservoir description grew as field mapping revealed a complex depositional setting where thick, homogeneous reservoirs could rapidly transform into thin and discontinuous layers. Core analysis confirmed that these stratigraphic variations were accompanied by significant changes in reservoir sand quality, from massive, homogeneous pebbly sandstones to fine sand-silt layered sequences.

In parallel, early water production quickly convinced reservoir engineers that in such a viscous oil environment it was indispensable to identify zones of potential water production. Unfortunately, the absolute values of resistivity measured over a reservoir proved to be an unreliable indicator, since layers of similar resistivity could correspond to finer grained producible sandstone reservoirs or to flushed layers containing a significant amount of residual oil, with water as the movable phase.

To make resistivity analysis more complex, all wells are drilled with relatively fresh drilling mud, rarely exceeding 5 kppm in salinity. This provides very little resistivity contrast between formation water, usually less than 20 kppm and mud filtrate at a bottom hole temperature of less than 130 deg F. Consequently, an analysis of invasion based on multiple resistivity logs of different depth of investigation is often difficult.

Early on, these logging conditions were recognized as suitable for dielectric propagation measurements. At high frequencies, electromagnetic measurements are increasingly sensitive to the dielectric properties of the formation, so that it becomes possible to measure not only the conductivity but also the dielectric permittivity of the formation. Since water has a far higher permittivity than rock matrix, oil or gas, such a measurement is sensitive to the amount of water in the rock and can differentiate it from oil or gas, irrespective of the water salinity.

Although several devices operating in the range of tens of MHz to Ghz were built in the 1980's (Cheruvier et al., 1986, Huchital et al., 1981), most failed to gain acceptance, largely because their interpretation was complex, often adversely affected by borehole and invasion effects and the effects of rock texture. Nonetheless, when a new device measuring permittivity and conductivity at several frequencies was ready for field test, PDVSA recognized the interest of the measurement in the conditions of the Orinoco belt and actively participated in the field test process.
TOOL DESCRIPTION

The tool is pad mounted. The pad itself is of a new design articulated with two degrees of freedom in order to ensure good contact with the borehole (Figure 1). The sensors consist of two transmitters and eight receivers placed symmetrically above and below the transmitters (Figure 2). Each transducer is made of two well isolated magnetic dipoles perpendicular to each other. When aligned coaxially the dipoles provide longitudinal propagation. When oriented in the perpendicular plane, they are coplanar and provide the lateral propagation mode. A pair of electric dipoles is also used in propagation mode to give a very shallow depth of investigation, and in reflection mode to measure the properties of the mudcake in front of the pad. The tool measures dielectric propagation at three frequencies between 100 Mhz and 1 Ghz.

The symmetry of the design allows for borehole correction and compensation for pad tilt. The multiple frequencies and depths of investigation provide a rich data set allowing to separate mudcake dielectric properties from formation properties, with a depth of investigation reaching four inches into the formation.

MUD FILTRATE INVASION IN THE ORINOCO BELT

A very important characteristic of mud filtrate invasion in the Orinoco belt is that it is normally shallow, not to exceed a couple of inches. A simple but effective proof of this phenomenon can be obtained by looking at the response of an NMR tool with multiple depths of investigation (De Pavia et al., 2003), as it investigates progressively deeper into the formation. The log presented in Figure 3 has been acquired by an NMR tool investigating the formation at three distinct depths of investigation, ranging from 1.5 to 2.7 to 4 inches into the formation. The acquisition was designed to extract T1, T2 and diffusion, in order to separate the volumes of water and oil based on their NMR properties (Freedman et al., 2001). The processing, known as MR4D, was optimized for the heavy oil conditions found in the Orinoco Belt (Heaton et al., 2007).

In this example, the amount of free water present in the formation is seen to decrease gradually as we investigate deeper into the reservoir, to become negligible when we reach 4 in. into the borehole wall. Therefore, all the reservoirs shown above can be considered to be at irreducible water saturation. While this can be an obvious conclusion in the case of the main reservoir sand, where resistivity exceeds a 100 ohm.m, it is certainly not so in the case of the upper sand body, at less than 30 ohm.m.
This simple observation implies that in the heavy oils of the Orinoco Belt, the new dielectric tool with a depth of investigation of four inches is actually a deep reading tool, in spite of the inherently shallow propagation of high frequency electromagnetic waves.

An accurate description of the mud filtrate invasion pattern, over the first few inches, is obtained through the inversion of the multiple receiver spacings, according to the schematic design shown in Figure 4.

Applying such an inversion model allows us to compute not only the volume of water measured by the tool at 1 inch and 4 inches into the formation, but also to determine the salinity of the water present in the formation, at these two depths of investigation. By the same token, the dielectric tool allows us to recalculate a low frequency resistivity at 1 inch and 4 inches into the formation, that can in turn be
compared to conventional deep and shallow resistivities, as a quality control. An example of the results obtained is given in Figure 5, over the same interval of Figure 3 previously studied with an NMR tool of multiple depths of investigation.

Figure 5. Dielectric Log, Carabobo.

Track 1 represents the salinities of the formation water and mud filtrate, along with the spontaneous potential. The deviation of the spontaneous potential confirms that the formation water is fresher than the mud filtrate. It also confirms a slight salinity change between the upper and lower reservoir sections. Track 2 provides a lithological column for reference, while the depth track also displays the depth of
invasion into the formation. Track four provides a comparison between micro-resistivity and shallow resistivity from the dielectric tool, along with deep laterolog and deep resistivity from the dielectric tool. Track five gives deep and shallow saturation from the dielectric tool, while track six presents a volumetric comparison. The upper sandstone reservoir, at x040 shows clear displacement of oil by water. In a heavy oil environment like this one, this observation also confirms the fact that this reservoir is at irreducible water saturation, in spite of its low resistivity.

This example shows that in a heavy oil environment where invasion is invariably shallow, the successful implementation of dielectric technology has the potential to change entirely the Petrophysicist's approach. Instead of having to infer formation water salinity from a hypothetical water zone, to later on estimate a water saturation from the application of a saturation relationship, the analyst using a deep reading dielectrical log knows the actual water saturation both in the flushed and the virgin zone, and its salinity, as long as invasion remains shallow.

APPLICATION TO THE CHARACTERIZATION OF THE JUNIN BLOCK

Area Map

The Junin block is one of the Orinoco belts blocks currently being characterized by the Magna Reserva team. As part of this effort, several dielectric logs were acquired during the first half of 2008 and we will describe the corresponding results. For ease of reference, a map of the Junin field, showing the position of the wells described in the following paragraphs is shown in Figure 6.

Well A

We will begin with the data acquired on Well A, located in the northern part of Junin and shown in Figure 7.
In this figure, the depth track contains the diameter of invasion shown by the dielectric tool. Track 2 shows a correlation gamma ray and the spontaneous potential. Track 3 summarizes the laterolog resistivities. Track 4 provides the available information on formation water and mud filtrate resistivities. Track 5 provides the water salinities derived from the dielectric data while track 6 compares formation porosity derived from a density-neutron analysis to water filled porosity, both shallow and deep, as measured by the dielectric tool. Track 7 shows a conventional petrophysical analysis, using the Rw estimated from the deep dielectric measurement.

Evidently, this well is located entirely in the water leg. The deep water filled porosity from the dielectric tool agrees well with the total formation porosity. Only traces of oil are to be seen, including some attic oil below a major shale layer. The point of interest in this example lies with the water salinities.
The dielectric tool confirms that the formation water is fresher than the mud filtrate, as indicated by the spontaneous potential. Differences between water salinities are small, and the formation water salinity is less than 5 kppm. In the water resistivity track, we have also displayed the conventional Rwa curve, assuming an m of 1.65, along with the Rw calculated from the Sp, and using as an input the shallow water resistivity determined by the dielectric tool. It is interesting to notice that the Rw determined by the dielectric tool agrees well with both with the conventional Rwa and the Rw from Sp. This indicates

Figure 8. Well B, water zone and oil zone
that in this particular well, invasion is not very deep, and the dielectric tool still reads deep enough into the formation to give a reasonable estimate of $R_w$. Thus we can conclude that in this part of the field, the formation water is sufficiently fresh to have clean water zones reaching 10 ohm.m and this with no trace of residual oil.

**Well B**

To continue, we will examine well B, shown in Figure 8, and located to the south-west of well A. The presentation is identical to the one used in the previous figure.

As in well A, the lower section of well B is entirely water bearing. This time however, invasion in the water zone is deeper, and the $R_w$ estimated by the dielectric tool is more closely reflecting the $R_{mf}$ than a true $R_w$. The separation between deep and shallow water salinity is reduced, in keeping with a deeper mud filtrate invasion. Relying this time on the $R_w$ from Sp and the conventional $R_{wa}$, we find that the formation water resistivity in the water leg is identical to the one estimated in well A.

Nonetheless, when we move to the oil bearing zone, we see that the formation water salinity is this time slightly higher than 5 kppm, and also higher than the mud filtrate salinity. This is in agreement with the normal Sp profile that is observed over the oil bearing section, indicating that the formation water is more saline than the mud filtrate. The estimate of $R_w$ from Sp also agrees well with the $R_w$ from the dielectric tool.

More importantly perhaps, the dielectric volumetric analysis shows that very significant volumes of oil can exist at resistivities in the range of 30 ohm.m and that this oil can be displaced, which implies that the reservoir is at irreducible water saturation.

We interpret the apparent invasion seen in the interval x500 to x520 as due to the hole rugosity. Based on the large number of NMR logs recorded in Junin, we associate this event to the presence of very viscous and probably degraded oil, which in our experience is almost invariably associated to poor hole conditions.

**Well C**

Well C shown in Figure 9 takes us even further south. At first glance, the long resistivity section at 10 ohm.m that is seen in the lower half of Figure 9 suggests that we are once again looking at a clean water zone similar to the water zones observed in the previous two wells. Yet the simple volumetric analysis provided by the dielectric tool shows us that this is not the case: a significant amount of residual oil is present this time in the lower part of the column.

This well constitutes a very serious challenge for a pad tool, due to the very rugose nature of the hole. If the deep water filled porosity measurement of the dielectric tool always remains reliable, it is however difficult to obtain as good a measurement in the shallow investigation zone, at around one inch into the formation. Nonetheless, we can deduct from the available information that there is very little contrast between mud filtrate and formation water salinity, with a change towards saltier formation water at x610 ft. Even below that depth, formation water is slightly saltier than in wells A or B, which explains why, at a constant 10 ohm.m we now have coexistence of water and residual oil, instead of water alone.

Above x610 ft, oil is the movable phase, and the reservoir is at irreducible water saturation, in spite of the low resistivity readings, as low as 30 ohm.m.
Well D is located almost due east from well C, and provides a very interesting comparison point, as can be seen from Figure 10.

Figure 9. Well C, transition from residual to live oil.
Close examination of this well, located several kilometers away from well C, reveals a similar pattern of transition from residual oil to movable oil, with a change in formation water salinity occurring at the oil water contact. When referred to TVDSS, the two oil water contacts are at the same depth, even though they are quite a distance away.
Well E

Located south of wells C and D, well E is shown below. This well raises a simple question: in view of the low resistivities, ranging from 10 to 30 ohm.m and seen below x510 ft, where the well enters the cretaceous, can this section not only contain oil but even more importantly still be at irreducible water saturation?

![Figure 11. Well E, oil bearing reservoir.](image)

The answer lies once again in the formation water salinity, which is this time much higher than the salinity of the mud filtrate used to drill the well. This result is obtained by the dielectric tool, and supported by the positive deflection of the Spontaneous Potential. The Rw from SP, driven by the shallow mud filtrate salinity measured by the dielectric tool is in good agreement with the formation water resistivity given by the dielectric tool at 4 inches into the formation.

A comprehensive program of water sampling with a wireline formation tester was attempted on wells D and E to verify the complex salinity distribution inferred from dielectric measurements. Unfortunately, the results were inconclusive, for two reasons. The first one is that sampling in these unconsolidated...
formations proved to be far more difficult than anticipated based on past experience in the Orinoco belt, with frequent and rapid plugging of the filters of the formation tester during the fluid pumpout phase destined to reach a representative formation fluid. Sidewall cores confirmed that these sandstone reservoirs were unusually fine grained. Secondly, as the pumpout phase had to be kept to a minimum, cleanup was insufficient, and Stiff diagrams on the few successful samples confirmed a high degree of contamination by the mud filtrate, in spite of the attempts to obtain a representative formation fluid sample.

**Well F**

A nuclear magnetic resonance log with multiple depths of investigation would have provided an elegant verification of the result obtained on well E. However this log is not available. It is
nonetheless available on well F, some distance east of well E and further south, and logged before the arrival of the new dielectric tool in Venezuela. The cretaceous formation in well F is less developed than in well E, but exhibits the same drastic reduction in resistivity seen in well E below x490 ft.

The volume of free water seen by the NMR tool at 4 inches into the formation is uniformly very small, irrespective of the absolute value of resistivity. We therefore believe that it corresponds to mud filtrate invading the formation. This is corroborated by the D-T1 map (Cao Minhet al., 2003, Heaton et al., 2007) in Figure 13 showing the progression of the fluid distribution from 1.5 to 4 inches into the formation.

Figure 13. MR4D maps, lower interval, Well F.

Well G

In order to complete this review of the various conditions encountered in the Junin block, and the interpretation challenge that it represents, we will show one last well, the southernmost one, well G in Figure 14.

With resistivities reaching several hundred ohm.m, Well G is clearly in the oil leg. The hole is also very rugose and washed out in several places. In such conditions, obtaining a reliable measure of the formation dielectric properties at one inch into the formation often proves to be an impossible challenge. Nonetheless, the measurement at 4 inches into the formation confirms the indications given by the resistivity and is largely unaffected by borehole rugosity. The deep reading NMR shows a considerable porosity deficit from the more rugose parts of the hole, which suggests a correlation between the presence of tar layers and hole conditions. Such occurrences have been witnessed on core in other parts of the Junin block.
Cross section through wells C, D E and G

To better convey the importance of clearly understanding the exact location in each well at which water ceases to be moveable and oil becomes the moveable phase downhole, we have prepared a SW-NE cross-section (see map of Figure 6) that covers a distance of more than 25 kms from end to end. Clearly, even a small error in the location of the transition from moveable water to moveable oil will have a tremendous impact on the total amount of recoverable oil in place.
CONCLUSIONS

A sector of the Junin block in the Orinoco belt was successfully interpreted, in spite of significant variations in formation water salinity. We believe that a significant influx of fresh water in a north-south direction has partially flushed the reservoirs. Consequently, stand-alone interpretation of resistivity logs becomes delicate, since similar resistivities can be associated to water alone, to a mixture of residual oil and water, and to oil at irreducible water saturation.

These conclusions are primarily based on the analysis of the data provided by a new dielectric tool that is capable of measuring the volume of water present in the formation as far as four inches into the borehole wall. As invasion in the Orinoco wells is invariably shallow, this depth of investigation is normally sufficient to reach the virgin zone.

In addition to a water filled volume, the tool also provides a measurement of water salinity, both in the invaded and the virgin zone. This measurement, especially when compared to a traditional Sp measurement, sheds additional light on the salinity of the formation water, impacting the estimates of oil in place.

Dielectric logging in the present case has played a major role in bringing Magna Reserva’s attention to the presence of significant amounts of oil in the cretaceous sands of the Junin block, previously neglected due to the very low resistivities encountered. Work is currently under way to further assess the potential of these reserves.

BIBLIOGRAPHY


Carmona, R., Decoster,E. “Assessing Production Potential of Heavy Oil Reservoirs From the Orinoco Belt with NMR Logs,” Transactions of the 42nd SPWLA Annual Logging Symposium, paper ZZ, Houston, TX, June 17-20, 2001.


