APPLICATIONS OF A MULTI-FREQUENCY DIELECTRIC MEASUREMENT IN THE CRETACEOUS CARBONATES OF THE MIDDLE EAST

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ABSTRACT

Resistivity-based methods have been the mainstay of saturation evaluation for decades. Although evaluation should be relatively straightforward in carbonates because of their usually simple mineralogy, the complexity and sharp variation of carbonate texture and wettability makes estimating the Archie’s cementation and saturation exponents challenging. Reliable determination of in-situ remaining oil saturation (ROS) by accounting for variation in the texture and pore water salinity is another challenge.

A new generation of dielectric multi-frequency measurements is being utilized to measure the flushed zone oil saturation relatively independent of pore fluid salinity, rock texture, and composition in a vertical resolution of core plug scale. In clean carbonates dispersion analysis of the dielectric multi-frequency data simultaneous with the petrophysical inversion permits rock texture analysis leading to the computation of Archie’s parameters in addition to accurate water-filled porosity.

This tool generates a rich set of data from the array transmitters and receivers measured in two axes of polarization. The abundant data from the tool with high vertical resolution help account for the well bore and invasion effects reliably, in addition to providing a robust quality check.

The tool was run initially in many fields in Abu Dhabi with Cretaceous carbonates as the target reservoir for varied applications like residual oil saturation, remaining oil saturation after a variable sweep, low-resistivity-pay evaluation, and the assessment of rock texture and wettability. The result of the interpretation is compared to other logging measurements and available core data.

INTRODUCTION

Dielectric logging was introduced more than three decades ago as a saturation evaluation measurement. The industry welcomed the opportunity to compute formation water volume relatively independent of salinity and free from resistivity models and the model parameters. The tool was considered as a bonanza for petrophysicists in saturation evaluation of reservoirs where resistivity-based methods present difficulties, as in fresh water formations. However, the service did not meet the expectations because of measurement limitation, modest accuracy, and insufficient quality control.

A new generation of dielectric measurement recently introduced in the industry (Hizem et al. 2008) overcomes many limitations associated with the traditional dielectric tools. The new tool operates at multiple frequencies and generates a rich set of data from the array sensors measured in two axes of polarization. The abundant data generated help to correct for the borehole environment reliably, in addition to affording robust quality check and error estimation. The dispersion analysis of the multi-frequency data allows the evaluation of the rock texture leading to the assessment of clays in shaly sands and the cementation and saturation exponents in carbonates.

The tool has proved its utility in many environments targeting diverse applications (Hizem et al. 2008). More benefits of the tool data are emerging as the tool gets deployed in more and more locations around the world. It has become a service of choice in heavy oil and fresh water environments (Mosse et al. 2009; Little et al. 2010) where dielectric measurement has obvious advantages in reservoir saturation estimation. In applications where accuracy of flushed zone saturations is needed as a premium this is a preferred service over other means of logging for saturation, like in remaining oil saturation (ROS) studies (Schmit et al. 2011; Serag El Din et al. 2011) or in the recently launched in-situ enhanced oil recovery (EOR) studies (Arora et al.) Previous works have
covered the tool principles (Hizem et al. 2008) and the interpretation methodology (Schmit et al. 2011) in detail. The current work focuses on presenting field examples.

This paper discusses the answers derived from the tool in the Cretaceous carbonates from one of the oil provinces of Middle East. In all, the results from four wells will be presented covering the applications of residual oil saturation (S_{or}) in a field swept by water flood, remaining oil saturations (ROS) in a variable sweep, assessment of S_{or} in a delineation well, carbonate texture and wettability, and vertical limits of oil in a low resistivity pay. An additional example demonstrating immovable hydrocarbons in a source rock will also be presented, although this was not a targeted application in the subject well. The results will be compared with those from other logging measurements and available core data. A short discussion on the target applications will precede the examples themselves.

APPLIED IN CARBONATES DISCUSSED IN THE EXAMPLES

Remaining Oil Saturation
Most of the oil we will discover is from the oil we have already found. With the shrinkage of new oil finds, producing fields are expected to cater to the incremental oil demand at least in the near and medium term. This has placed an increased focus on secondary and tertiary recovery techniques. To plan these recovery methods optimally, an accurate measure of the remaining hydrocarbon saturation is required to establish if there is sufficient quantity of hydrocarbons left in the reservoir to make the recovery process worthwhile. Determination of ROS is the starting point of EOR planning and execution.

First, we need to define remaining oil saturation and residual oil saturation. Remaining oil saturation (ROS) is the oil saturation at the current level of the flood irrespective of the flood process and may include moveable oil. 2. Residual oil saturation (S_{or}) is the ultimate reservoir saturation at the terminal stage of a displacement process; this oil is immobile. Typically the water base mud filtrate invasion displaces many pore volumes of formation fluids from the reservoir rock close to the well bore. Therefore, saturation measured from very shallow reading devices tend to be an approximation of S_{or} after an actual water flood (Neuman 1982), thus giving a fair idea of producibility even in unexploited reservoirs, but more so in a well drilled in an area already flushed by water flood.

Several engineered logging procedures are in vogue for the determination of ROS:

1. **Log-Inject-Log (LIL) technique using nuclear magnetic resonance (NMR) logging in open hole.** The NMR logging is carried out twice: first with normal water-base mud and after re-drill/reaming with a mud doped with a fast relaxing water soluble material, shifting the water signal on the NMR T2 distribution to the lower T2 values and facilitating the separation of oil and water volumes (Crowe et al. 1997; Horkowitz et al. 1997).

2. **LIL using pulsed neutron techniques in cased hole.** The water saturation derived from flushing the near zone using brines of two contrasting salinities (Kidwell et al. 1980) and deducing an S_{w} which is free from errors in the parameters and formation lithology. The saturation is derived from the sigma measured in the two passes and the salinity difference of the brine. The brine salinities are measured accurately at surface.

3. **MicroPilot**. In-situ core flooding experiment (Arora et al. 2010), literally a log-inject-log technique. Injection of the fluid achieved through the modified cased hole formation tester tool. Saturation before and after injection measured by varied logging sensors (including the dielectric tool) carried down in the same string.

The methods clearly involve additional operational time and cost, besides meticulous planning and execution of the tasks for success. Key to the methods compared to normal logging is enhancement of accuracy and diminishing the measurement and interpretation uncertainties.

Laboratory measurements on core samples is a more direct method of determining ROS, two of the common coring techniques for the purpose are

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* Mark of Schlumberger
1. *Sponge coring.* This involves the attempt to cut core before invasion and to measure rock fluids directly. An oil wet polyurethane film lines the inner core barrel to trap any fluids from escaping.

2. *Trapped liquid coring.* The core is eliminated in 3-ft sections and each is sealed to prevent liquid losses. These coring techniques entail detailed operational planning and core handling in addition to high operational cost and time. Besides, there is usually a long wait time before the laboratory results are available. Operators traditionally were willing to bear the cost to obtain this crucial reservoir parameter as accurately as possible.

The principal answer from the dielectric tool is water filled porosity at a shallow depth of investigation (from the borehole wall up to 4.0 in. in the formation) which is ideal for ROS measurement. The tool acquires the data in much simpler and faster way compared to the LIL techniques with enhanced accuracy (0.2 pu for the water-filled porosity). The vertical resolution of the tool approximates the core plug scale and this makes the comparison to core robust. Immediate availability of the result continuous with depth is an obvious advantage over the coring techniques.

**Carbonate Texture and Wettability**

Carbonates usually have a simple mineralogy, which makes the analysis of rock composition relatively straightforward. Correct mineralogy composition analysis results in representative formation porosity and improves the accuracy of the interpreted saturation, including the one from dielectric tools where the porosity is a necessary input in the saturation computation. However, because of its biologic origin, carbonate rock texture is in general complex and tends to exhibit lateral and vertical heterogeneity. From a saturation evaluation perspective, the textural heterogeneity potentially makes the Archie’s cementation exponent \(m\) quite variable within the same reservoir. Besides, the carbonates have a tendency to become oil wet after migration, making the Archie’s saturation exponent \(n\) variable, within the reservoir depending on the degree of wettability. Obviously, in reservoirs where these parameters are varying, saturation evaluation employing Archie methods is beset with considerable uncertainties. The common practice of keeping \(m\) and \(n\) fixed for a formation or improvising by zoning the parameter from sparse core data does not give the desired results.

Inversion of the tool data at multiple frequencies using a dispersive petrophysical model accounts for the textural variations in the computation of water-filled porosity. Besides, water space tortuosity which can be considered a combination of \(m\) and \(n\), is available as the output of inversion.

**Low-Resistivity Carbonate Pay Zones**

Some of the saline water formations in the area have oil saturations much above what would be obtained from a conventional resistivity-based interpretation. While tensor resistivity measurements have been successful in evaluating the low-resistivity pays in the shaly sand sequences, the heterogeneity and poor layer definition in carbonates make the success of this measurement limited. Alternate saturation evaluation methods to resistivity have been attempted for the reservoirs, and the measurements having a volumetric response to formation components are preferred. Akasura et al. (2001) attempted a pore partitioning technique from the NMR data to infer separate Archie’s constants for the micro, meso, and macro pores in carbonates and include them in the saturation computations to describe the low-resistivity behavior. The technique was thereafter extended by Petricola et al. (2002). Pulsed neutron capture measurement, either in cased hole (Asakura et al. 2001) performed after dissipation of invaded mud filtrate or by LWD tool measured with minimal invasion of mud filtrate (Griffith et al. 2006), tends to give much enhanced oil saturations compared to the resistivity methods. In the oil-base mud wells, the limit of moveable oil can be mapped by comparison of the LWD sigma data from while-drilling pass to that of repeat pass during tripping (Gyllensten et al. 2009).

As mentioned previously, the dielectric tool gives flushed zone saturation in very good vertical resolution. The remaining oil saturation derived from the tool precisely delineates the oil limits in low resistivity-pay zones and would be valuable in defining the hydrocarbon-to-water contact when it is problematic to deduce from other sources.

**EXAMPLES**
Well A: ROS in Zones Swept by Sea-water Flood

Well A was a sidetrack from an existing injector, drilled with the objective of assessing ROS after a sea-water flood. Trapped liquid coring and NMR LIL techniques were planned. After the first pass of NMR, the well was reamed using a doped mud system. This proved to be insufficient to properly re-invade the formation with the doped mud filtrate, and the NMR technique did not provide any trustworthy answer on this well.

The new dielectric tool was logged for the first time in offshore Abu Dhabi in this well. Although only one pass for the dielectric measurement was necessary to measure ROS, the dielectric tool was run twice in combination with the NMR. This showed that the repeatability of the measurement is excellent and the water volume measurement is not affected by the change in the mud.

Later on, the saturation measurements in the laboratory from 56 core plugs and 165 whole cores confirmed the quality and accuracy of the ROS measured by the tool. Comparison of the saturation results from the tool and Dean Stark saturations from the whole core samples is presented in Figure 1. The figure also shows that the Rxo measured by the micro resistivity tool and the constructed one from the dielectric measurements using a dispersive model match up well providing additional quality control.

Well B: ROS in Zones Variably Swept by Saline Floodwater

The subject well is one of the four study wells in a field-wide assessment of the ROS in a giant on-shore field (Serag El Din et al. 2011) under peripheral saline water injection. The significance of obtaining non-Archie saturation was evident in another well covered by the study, where the saturation evaluation was carried out solely from resistivity measurements. This well was an S-shaped side-track from an existing injector. The side-track hole was evaluated using the same Archie’s parameter as were used for the vertical hole. Oil was observed in the core from the side-track hole across the water leg interpreted in both the sidetrack hole and the equivalent zone in
the vertical hole (Figure 2). The wells needed to be re-evaluated using modified Archie’s parameters to match the core saturations.

Well B was a fresh hole drilled in an area of the field where the subject reservoir is partially swept by saline floodwater. The purpose of the well was to assess the residual oil saturation in fully swept intervals and to demarcate zones with producible oil for completion. NMR and resistivity data were acquired along with dielectric data. The tool was deployed for the first time in onshore Abu Dhabi in this well. Part of the target was cored by trapped liquid coring technology. The flushed zone saturations from the different logging techniques fall within a reasonable range (Figure 3). The residual oil saturation obtained from the core in fully swept zones is reading unrealistically low values, as low as 5%, across some intervals. The oil saturation derived from the core seems to be an underestimation; evaporation of fluids from the core is suspected (Serag el Din et al. 2011). Comparison of dielectric saturation with that obtained from the deep resistivity measurements demarcates zones of producible oil. The sample collected from the formation tester confirms the trend of moveable oil inferred from the logs.

Well C: ROS in an Assessment Well Showing the Effects of Carbonate Wettability

Well C was an assessment well in an unexploited reservoir. Accurate flushed-zone saturation was needed here to determine ROS and assess the recoverable reserves to help plan the facilities for field development. Micro-resistivity and NMR fluid stations were planned in the well, in addition to the dielectric survey for obtaining shallow zone saturations. The logged interval straddled an oil/water contact (OWC).

Figure 4 shows the results of the analysis of dielectric data on the well. The flushed-zone water salinity inverted from the dielectric data (Track -1) reads close to the mud filtrate salinity of 20 ppk. The conductivity and dielectric permittivity of the flushed zone, after borehole correction and radial processing of the tool array data are presented in Tracks 7, and 8 respectively, for the four different frequencies at which the tool operates. Water space tortuosity from the inversion of the multi-frequency data using a dispersive petrophysical model is presented as “mn” curve in Track 2. The thumbnails on the right give the fit of dispersion pattern in the model at two sample depths; at X955 ft in the water leg the dispersive curve is rather flat indicating a low value of mn, whereas at X825...
ft up in the oil leg the dispersive curve is rather steep indicating a higher tortuosity, thus a higher value of $mn$. Flushed-zone saturation from the dielectric dispersion inversion is presented in track 3. Excellent agreement is observed with the Sx0 derived from the NMR (Zielinsky et al., 2010) fluid surveys recorded at 12 station depths;

Figure 3: Saturation measurement from multiple logging techniques and core analysis in Well B. Flushed zone saturation from different logging techniques presented in tracks 2-4 fall within a reasonable range, although the match of is not perfect across the entire logged interval. Track 1 compares the Sx0 derived from the logging techniques to that derived from the core, the log and core saturations are expected to match in the fully swept intervals. However, the core derived oil saturations reading lower than that from the logging techniques. The core saturations read unrealistically low in certain sections, as low as 5%. Note that the core oil and water saturations complement to a value less than 100%, indicating possible fluid loss. Comparison of the far and near field saturations in Track 5 demarcates the zones of producible oil. The fluid samples collected by formation tester validate the producibility prediction from the logs.

exception occurs at X805 ft against a zone of lower porosity. The ROS for the field indicated by Sx0 is around 35%, a value higher than what is observed for the formation in other fields of the area. This is not surprising considering the reservoir oil is comparatively more viscous in this field. Note the higher residual oil in the flushed zone around the depth of X940 which is found to be a tar zone from the NMR depth log. The match of the Rxo measured by the micro-resistivity tool and the one reconstructed from the dielectric saturations using the $mn$ curve, presented in Track 4, serves as an additional quality check for the tool data and the results from the data inversion.

In the absence of information about Archie’s parameters, the exploratory wells of the field had been evaluated using the standard value of $m=2$ and $n=2$. The $mn$ curve reads a steady value of 1.72 in the water leg indicating an $m$ value of 1.72. Up in the oil leg the $mn$ curve is variable and reads higher up to a value of 2.5. The variation is interpreted to reflect the wettability alteration that has occurred in the oil zone, suggesting a higher saturation
exponent and consequent increase in $mn$.

Figure 4: Results of the dispersive analysis of the dielectric data in Well C. Track 1 gives the flushed-zone water salinity. Track 2 gives the $S_{xo}$ from the inversion of the dielectric data as a black curve and that from the 12 NMR stations as red dots. Also presented in the track is the $S_{xo}$ computed from the microresistivity data (blue) using $m=1.72$ and $n=2.0$. Track 5 gives the saturation result from the inversion as fluid volumes. The results of lithology and porosity analysis from the triple combo and NMR data that was input to the dielectric inversion is presented in Track 3. Track 4 shows $R_{xo}$ recorded by the resistivity tool (green) and that computed from the dielectric data (blue). Tracks 7 and 8 present the conductivity and permittivity computed for each of the four tool operational frequencies. The thumbnails on the right gives the dispersive patterns for one depth level each from the oil and water legs.

It must be mentioned here that conventional wisdom would have had the log analyst use a value of $m=1.72$ and $n$ as the standard value of 2. The computation would have given significantly (up to 20%) lower values for $S_{xo}$ as shown by the blue curve in Track 2, grossly underestimating the recovery factor for the reservoir. If, on the other hand, the analyst chooses to use $m = n = 1.72$, the difference would have been even more.

Well D: Vertical Limits of Oil in a Low Resistivity Low Contrast Pay

This sub-zone in Well D, drilled with saline water-base mud, has very little contrast of resistivity between oil- and water-bearing layers, with the deep resistivity reading 0.6 ohm-m in the oil leg at the top of the reservoir and 0.3 ohm-m in the water leg. The sub-zone had a long oil-to-water transition zone marking the determination of the OWC from the resistivity data a difficult task. The fluid volumes computed in the flushed zone from the dielectric data are displayed in the last track of Figure 5 and gives the depth limits of oil in the reservoir in good vertical clarity and thus fixes the OWC to be at X370 ft. From the resistivity data, the OWC would have been picked much shallower probably at X292 ft. The above cited example is not a striking one of low-resistivity pay from the area, but it serves to demonstrate the value of tool data for low-resistivity pay evaluation.
Because of the mismatch of resolution between porosity and the high-resolution dielectric measurement, the saturation computed at the thin inter zone tight layers tends to be erroneous. Please note that the high oil volumes computed at the tight layers (for example at X256 ft and X308 ft) is a result of this mismatch and therefore is incorrect.

**Figure 5:** The flushed-zone saturation results from the dielectric tool for Well D. Track 3 gives the array resistivity data. Track 4 displays the fluid volumes computed from the dielectric data.

**Well E: Immovable Hydrocarbon in a Source Rock**

The tool acquired data across a source rock in one of the subject wells drilled with water-base mud. The lithology and porosity analysis was carried out using the neutron-density porosity in a similar fashion as would be done for normal reservoirs. The dielectric data taking porosity input from the analysis computed very little water volume in the shallow zone, as would be expected from such a rock containing immovable kerogen in this layer. The situation here mimics the response in heavy oil where the tool is not only sensitive to flushed zone but also can assess the actual reservoir saturations as very little of the oil will be displaced by the mud filtrate.

**CONCLUSIONS**

1. The new dielectric tool provides an excellent means of determining ROS in carbonates, relatively independent of rock texture and flushed-zone water salinity in a more facile manner compared to existing logging and coring techniques.
2. The results from the tool were especially valuable when other core and log methods did not succeed.
3. ROS results from the tool at various scenarios are presented—reservoir fully swept by water flood, reservoir partially swept by water flood and an assessment well in a virgin reservoir.
4. Good agreement of ROS derived from dielectric data with Dean Stark saturations on quality core data and other logging measurements is observed.
5. The handicap of resistivity-based saturations when the Archie’s parameters are unknown and variable is illustrated; the value of dielectric data for saturation determination in this scenario is demonstrated.
6. Inferences on rock wettability were drawn from the textural answers from the dielectric data acquired across an interval straddling an OWC.
7. Vertical limits of oil could be determined across a gradational OWC in a low-resistivity low-contrast pay-zone.

ACKNOWLEDGEMENTS

Authors would like to thank the the ADNOC group of companies-Abu Dhabi Oil Company (ADOC), Abu Dhabi Company for Onshore Oil Operations (ADCO) and Zakum development Company (Zadco)-for permission to publish the work.

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Doug Boyd graduated with an HBSc degree in geology from Laurentian University in 1976. His 31 years of experience includes core description, convention and special core analyses, wireline operations, log interpretation, reservoir description, and log data management for three major wireline companies, two core analysis companies and two oil companies. A member of the APEGGA, CWLS, SPE, SPWLA and SCA, Doug has authored and co-authored 25 technical papers on various topics of log interpretation and data management. Presently he is working as a petrophysicist for Zakum Development Company, in the United Arab Emirates.

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