What is Rt? Logging-While-Drilling and Wireline Resistivity Measurements Spotlighted: An Offshore Case Study in Abu Dhabi*

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Abstract

Recent technology improvements in Logging-While-Drilling (LWD) electromagnetic wave propagation resistivity devices have provided dramatic improvements in well-placement applications. Azimuthal, deep-sensing measurements, coupled with other sensor measurements and significant software enhancements, have facilitated enhanced geosteering capabilities, which not only help maximize reservoir exposure, but also provide real-time updates of the local reservoir model. However, LWD propagation resistivity measurements in highly deviated and horizontal holes can also present challenges to the analyst in answering fundamental questions in relation to formation evaluation. Typically, it is not only problematic to correlate LWD resistivities to offset vertical and/or pilot resistivity data, but it is also difficult to deduce true resistivity (Rt) and the flushed zone resistivity (Rxo), particularly in thin beds, from the numerous multi-frequency and multi-spacing measurements available.

This article presents a case study from a thinly bedded offshore carbonate reservoir in Abu Dhabi. Two horizontal drains were drilled using LWD tools for the purposes of geosteering and formation evaluation. The available offset well data were from near-vertical wells, which were logged using wireline tools. The LWD propagation and laterolog resistivity measurements are compared to the offset wireline induction and laterolog resistivity measurements. Comparisons are also made between LWD propagation and laterolog resistivities acquired while drilling and while wiping after drilling. Differences between the various measurements are explored to identify the most appropriate choice of measurement in various circumstances. In light of the results, recommendations are made for data selection in future wells, with the intention of optimizing data acquisition practices for both well-placement and petrophysical evaluation.

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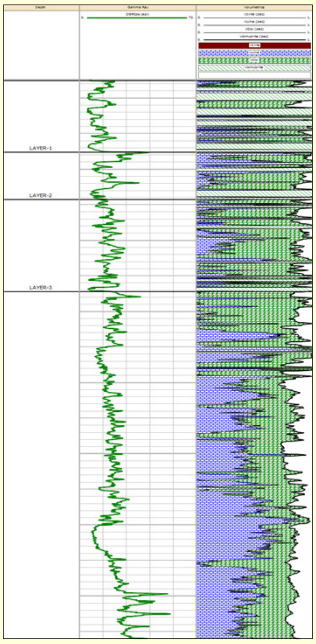

Fig. A The 3 main structural layers of the reservoir is Kimmeredgian age of Upper Jurassic sequence, consisting of limestone, dolomite and anhydrite lithologies deposited under regressive cycles of various sedimentation environments. This giant offshore field was discovered in 1958, production began in 1962 and down-flank water injection was initiated in 1973 followed by crestal gas injection in 1994.

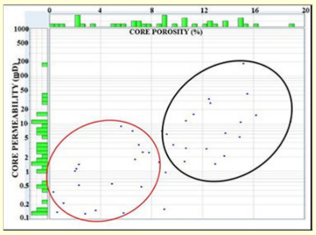

Fig. B Conventional Core Analysis Porosity-Permeability Cross-plot. To compensate for the limited vertical thickness and low petrophysical properties of the undeveloped layers in Reservoir-A, compared to other layers that have been producing for years, ambitious development plans include excessive drilling of horizontal and high- angle wells into the undeveloped layers, which have a porosity of up to 9% and permeability ranges between 1-10mD as highlighted in the red envelope above.

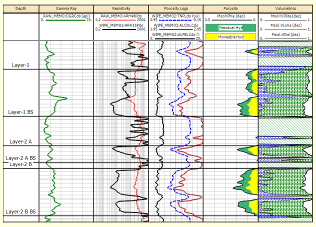

Fig. C Petrophysical evaluation of undeveloped reservoir layers to assess hydrocarbons-in-place and aid in the planning of a development drilling program with optimized well-placement, data acquisition and costs.

A hydrocarbon saturation assessment of these undeveloped carbonate layers is very critical. The "Archie" saturation computation model, $(Sw)^n = \frac{a}{\emptyset^m} * \frac{Rw}{Rt}$ is applied with *a, m, n* and *Rw* measurements determined from core measurements at reservoir conditions for each layer. After calibrating the computed porosity with core porosity for cored wells across the field, the remaining element is to compute an accurate value of the *Rt*.

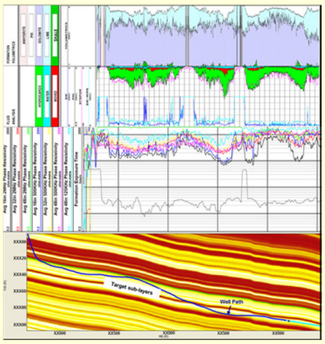

Fig. G After evaluating the original pilot and mother holes, the first lateral, Drain 1 in Layer 2, was drilled. The well was geosteered using the ADR™ and StrataSteer® 3D (SS3D) steering software. It is apparent that the ADR™ resistivity values are closer to the pilot hole wireline laterolog than the induction log, as the inclination in this hole section is approximately 87° to 89°.

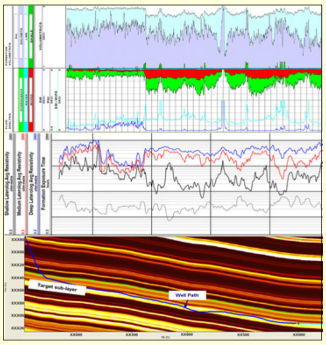

Fig. H In drain 2 in layer 1, the azimuthal focused resistivity (AFR™) and SS3D software were used to place the well. AFR™ is clearly much closer to the wireline induction log from the original deviated pilot hole. The inclination in this drain is 88 to 90°. AFR™ shows good promise in these thin beds for well placement as well as for determining Rt for formation evaluation.

Needless to say, invasion and adjacent bed effects needs to be considered for Rt determination. However, in horizontal wells, deep readings that have a much greater diameter of investigation are somewhat disadvantageous for formation evaluation purposes. Much shallower measurements, such as AFR™, can be used as long as the deep laterolog is not affected by invasion. It is also advantageous to be close to Rh in horizontal holes because of the robustness of Archie-based Sw algorithms.

The Rxo result is an interesting comparison. Although the invasion effects are evident in the wipe runs for both the ADR™ and AFR™, there seems to be more control over Rxo with the AFR™. For Drain 1, the shallow phase 16-in. resistivity (RH16P) from drilling was used as Rt, and the same RH16P was used as Rxo from the wipe run. For Drain 2, the AFR™ deep was used for Rt, and the AFR™ shallow from the wipe run was used as Rxo. Therefore, combining the ADR™ and AFR™ in both the drilling and wipe mode proved beneficial for obtaining Rt and Rxo.

- Determining true resistivity Rt, in horizontal or highly deviated wells is challenging because of anisotropy and adjacent bed boundaries effects. In vertical and low angle wells, wireline induction and LWD propagation tools with coaxial antenna structure tend to have no sensitivity to anisotropy and read the horizontal resistivity Rh. On the other hand, wireline laterolog and LWD toroidal resistivity tools have sensitivity to formation anisotropy in both dipping and non-dipping formations. Sensitivity to Rv increases with a higher dipping angle but at a much slower rate than with traditional induction and wave propagation resistivity tools.
- In horizontal wells, deep reading resistivity tools with deep depth of investigation is somewhat disadvantageous for determining true resistivity, Rt, because of adjacent bed effects. The shallower measurement from the tool can be used as long as is not affected by invasion.
- Anisotropy inversion is used in calculating horizontal resistivity, Rh, and vertical resistivity, Rv; and the calculated Rh was found to yield more representative formation evaluation results, particularly fluid saturations. Comparison against existing offset field data and production history showed reasonable water saturations and was consistent with nearby wells.
- Inversion has therefore enabled considerable improvement in formation evaluation and accurate water and hydrocarbon saturations in this type of multilayer formation with porous units separated by stylolitic sub-dense shoulder beds.

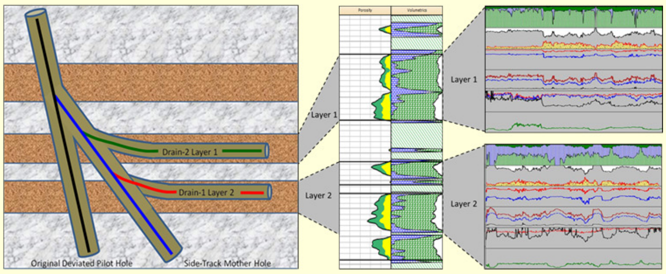

Fig. D The original Pilot Hole, shown as a black line in the above left schematic was drilled at a 47° inclination. To determine the resistivity profile of the well, the well was logged with both wireline induction and laterolog resistivity tools. After evaluating the pilot hole, another Side-Track Mother Hole was drilled at a 63° inclination. LWD tools were used in the evaluation of the Side-Track Hole. Azimuthal Deep Resistivity (ADR™) and Gamma Ray data were acquired in real-time, and another wipe run was performed with Azimuthal Deep Resistivity, Gamma, Azimuthal Litho-Density (ALD™) and Compensated Neutron (CTN™)sensors, which are shown as a blue line in the left schematic. After evaluation, two horizontal drain wells were drilled. Drain-1 was drilled in Layer-2 as shown as green line, and Drain-2 was drilled in Layer-1 as shown as a red line. The petrophysical interpretation of the original deviated pilot hole and both for layer-1 and layer-2 are illustrated in the right side of the schematic.

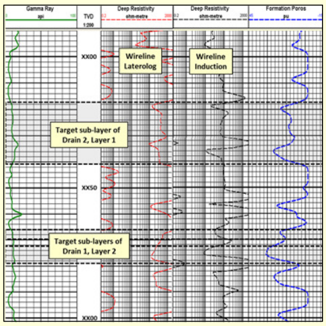

Fig. E The original deviated pilot hole wireline laterolog and induction resistivity logs at a 47° inclination represented in True Vertical Depth (TVD) scale, together with target the sublayers for Drain-1, Layer-2 and Drain-2, Layer-1. The gamma ray log is displayed on Track 1. The wireline resistivity laterolog is displayed in red on Track 2, and the induction log is displayed in Track 3. Both resistivity tools show good resistivity readings across the target sublayers. However, it is evident that the laterolog tool reads significantly higher than the induction tool. This is probably an indication that the zone is highly anisotropic.

In low relative angles and in the presence of anisotropy, laterolog tools read higher than induction tools; whereas in a low relative angles, whereas the induction tools tend to read closer to the horizontal resistivity (Rh).

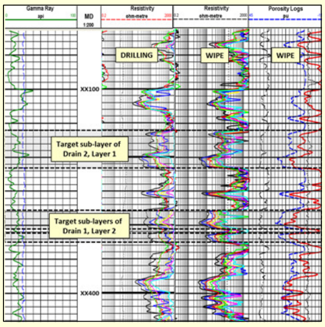

Fig. F The sidetrack mother hole was drilled at a 63° inclination. LWD tools were used in the evaluation of the sidetrack. Above figure displays the LWD logs obtained in drilling and wiping mode. The gamma ray log is displayed in Track 1. The ADR™ log obtained in drilling mode is displayed in Track 2, and the ADR™ obtained during wiping mode is displayed in Track 3. ALD™ and CTN™ logs are displayed in Track 4. Note that:

- The drilling mode resistivity reads higher than the wiping mode across the target zones which could be indicative of conductive invasion.
- The separation between the phase resistivities in the drilling mode may also indicate presence of anisotropy.
- ADR™ reads somewhat higher than wireline induction in the original pilot hole due to increased inclination increased of 63° in the presence of anisotropy.

Wireline and LWD resistivity measurements have demonstrated success in providing resistivity measurement in many reservoirs around the world. However, the resistivity measurement is often problematic in complex heterogeneous and anisotropic reservoirs. Anisotropic formations often exist in a series of laminated sediments that are characterized by multiple thin layers, each with a different resistivity property. These anisotropy effects produce a horizontal resistivity (Rh) with a lower resistivity value in a direction parallel to the formation plane, and a vertical resistivity (Rv) with a greater resistivity value in the direction perpendicular to the formation plane. The measurement of resistivity using traditional logging tools varies with the wellbore inclination.

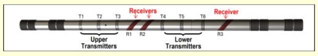

Fig. I Non-azimuthal sensors are not capable of measuring and resolving anisotropy for an accurate horizontal, Rh, and vertical resistivity, Rv calculation. Azimuthal resistivity sensors feature a set of tilted receiver coils with multiple transmitters to provide multiple depth-of-investigation measurements capable of providing anisotropy and dip angle calculation. As the sensor rotates in the borehole, resistivity measurements are acquired in 32 azimuthal sectors around the borehole. For any given spacing, these readings are displayed as resistivity logs that include the traditional resistivity measurement.

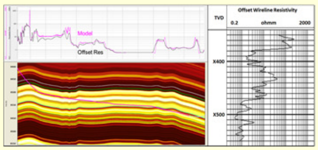

Fig. K Model response of the 48 inch spacing at 2MHz compared with an offset log.

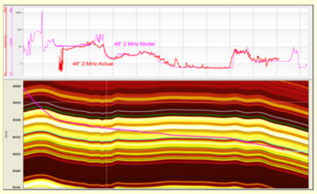

Fig. L Actual response of the 48 inch spacing at 2MHz compared with Model log.

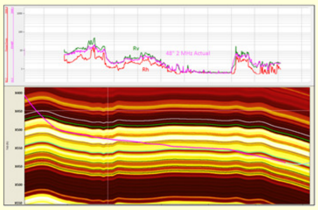

Fig. M Anisotropy calculation compared with actual resistivity of the 48 inch spacing

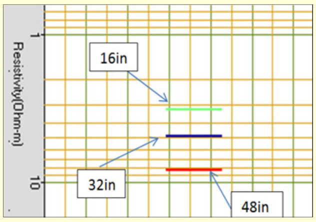

Fig. J The response of the 16, 32, 48 inch spacing 500KHz in anisotropic formation.

The inversion algorithm that determine the horizontal, Rh, the vertical resistivity, Rv and the dip angle is based on matching computed data with the field data. The inversion result is obtained by minimizing a cost function including the sum of data misfit and the sum of constraints of the formation models.

Based on a sensitivity analysis of tool response the cost function is set as:

$$S = \left\|\overline{R}\right\|^2 + \left\|\overline{e}\right\|^2 + M^{-1}\left\|\overline{\overline{\alpha}}^T \overline{H}\right\|$$

where,

R_i is the sum of misfit: $R_i = f_i(R_i^{\log} - R_i^{com})$.

$R_i^{\log}$ is the field log measurement,

R_i^{com} is the log from forward modeling.,

e_i is the regulation part,

M is the weighting function of constraints,

$\overline{\overline{\alpha}}$ is the weighting matrix, and

$\overline{H}$ is the constraint function.

The method of the steepest-descent can be used to invert true formation parameters. However, the steepest-descent undergoes a slow convergence after the first few iterations. To overcome this problem, we use the Levenberg-Marquardt Method.

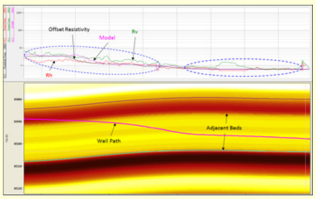

Fig. N Shoulder bed effect on Rh and Rv inversion

IMPROVED FORMATION EVALUATION WITH INVERSION TECHNIQUES USING LOGGING WHILE DRILLING AZIMUTHAL DEEP RESISTIVITY SENSOR – A CASE STUDY
Abdullah Al-Ameri, Indrajit Bandyopadhyay, Asma Hassan Balbaheeth, ADCO; Michael Bittar, Ahmet Aki, Ramy Essam Halliburton
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