FRACTURE, TEXTURE and SATURATION ANALYSIS FROM HIGH RESOLUTION LWD IMAGES AND RESISTIVITY

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ABSTRACT

In a large carbonate oilfield located in the United Arab Emirates horizontal drilling has been used to enhance well productivity, injectivity and to reduce water coning. A key to the development of this field is an improved understanding of reservoir characterization to better appreciate the production impact of faulting, fracturing and secondary porosity.

In lieu of these objectives a new logging-while-drilling (LWD) tool has been deployed to acquire high resolution borehole images and multiple-depth of investigation (MDOI) laterolog resistivities. The use of a LWD tool is particularly relevant to lateral wellbores drilled in relatively thin layered reservoirs as the interpretation and deployment of traditional wireline-conveyed measurements is complex.

Traditional resistivity measurements acquired in horizontal wells can be difficult to interpret due to combined shoulder-bed, anisotropy and proximity effects, and as a result can lead to unrealistic estimates of water saturation ($S_w$). LWD laterolog measurements are mostly affected by invasion and relatively unaffected by resistivity anisotropy and shoulder-bed effects. This has a distinct advantage in horizontal wells as the resistivity measurements are negligibly influenced by nearby lateral beds or proximity effects, and if acquired while drilling also have minimal invasion effects.

In this large carbonate oilfield the new LWD tool was used along with conventional triple combo propagation resistivity, neutron porosity, and formation density measurements. Accurate formation saturations in this previously problematic environment were computed, and images similar to those from wireline micro-imaging tools were acquired for structural, fracture, and porosity textural analysis.

LWD acquisition parameters to optimize image quality were also investigated; most notably drilling rate of penetration (ROP), tool rotation speed (RPM) and formation/mud resistivity contrast ($R_t/R_m$).

INTRODUCTION

Due to geometry of high angle wells, whereby the well is often near-parallel to geological bedding, traditional resistivity based Archie approaches to evaluate $S_w$ can have limitations as often high angle bed boundary artifacts are imposed on the measurement that are independent of the reservoir fluid saturation properties that we want to quantify.

Rock texture and fractures have an important influence in Middle Eastern carbonate reservoir production, borehole image logs have long proven invaluable for the evaluation of these reservoirs. Historically borehole image logs have been acquired with wireline (WL) but recent advances with LWD acquisition have made it possible to acquire high resolution borehole image logs while drilling. This is particularly significant for high angle and/or horizontal wells where WL log acquisition can be problematic.

LWD PROPAGATION AND LATEROLOG RESISTIVITIES

Resistivity is commonly used to compute reservoir water saturations via the application of the Archie equation. LWD resistivity measurements are based on the physical principles of either laterolog or electromagnetic propagation. Compared to wireline, LWD logs are normally acquired while drilling at a time when drilling fluid invasion is small, making it possible to derive resistivity of the undisturbed zone.
For the laterolog measurement, currents are injected into the formation and returned to electrodes. The voltage drop caused by the current flow through the formation is measured across multiple electrode pairs and is related to formation resistivity. Usually multiple curves with different depths of investigation (DOI) are presented. LWD laterolog DOI’s typically vary from 1 inch to 6 inches. Laterolog tools are better suited than propagation tools in conductive mud systems, relatively high formation resistivities and in intervals of conductive invasion. Laterolog measurements are essential for accurate resistivity evaluation in highly deviated or horizontal wells drilled in thin reservoirs where propagation resistivity polarization horns are evident (Griffiths, 2009), (Bonner et al, 1996), (Bonner et al, 1994a).

For LWD electromagnetic propagation resistivity measurements a transmitter coil emits an electromagnetic field which oscillates. Receiver coils are placed in the field and a voltage is induced in each receiver. The amplitude and phase shift of the induced field is compared between receivers and differences are related to formation resistivity. Usually there are multiple curves that represent different transmitter receiver spacings with different depths of investigation. For the same transmitter receiver pair the attenuation reads deeper than the phase-shift resistivity. It is less affected by invasion, but is more affected by the surrounding beds. The attenuation measurement has a poorer axial resolution and is less affected by anisotropy. Depths of investigation and axial resolution of both measurements vary with the average formation resistivity. Propagation tools work well in low conductivity borehole fluids, and high conductivity formations (Bonner et al, 1994b), (Clark et al, 1988).

When propagation tools pass through a dipping bed boundary with a significant resistivity contrast the resistivity log can have a high apparent resistivity called a ‘polarization horn’. Polarization horns are caused by charge build-ups along the bed boundary due to discontinuities in the electric field. Polarization horns are useful in well placement to identify bed boundaries but the resistivity value is not representative of the true formation resistivity. The size of the horn is a function of bed boundary resistivity contrast and the relative angle between the wellbore and formation. It can be significant for relative dip angles of more than 50 degrees. If the tool runs along a high resistivity contrast boundary, the polarization horn can be extended over a long distance. Figure 1 represents a graphical description of a polarization horn. Other factors to consider in high angle and/or lateral wells are resistivity anisotropy whereby the horizontal resistivity (R_h) is different to the vertical resistivity (R_v) (a concern in thinly laminated reservoirs), and the proximity effect. Proximity effect is due to the presence of nearby bed boundaries which have different resistivity properties than those near to the wellbore. Deep reading resistivity tools would see a mixture of the near wellbore and nearby bed boundary resistivities and therefore measure a value that is not representative of formation resistivities in the immediate vicinity of the wellbore. Shallow reading resistivity tools are minimally affected by proximity effects (Griffiths, 2009, (Farouk et al, 2012).

Figures 2 and 3 describe how bed boundary and proximity effects affect the LWD propagation resistivity but not the laterolog measurement. In high angle wells propagation resistivity measurements can be difficult to interpret and can result in unrealistic computations of \(S_w\). Shallow laterolog measurements due to their relatively shallow DOI are mostly influenced by invasion and less by anisotropy or shoulder bed effect. The use of laterolog measurements for formation evaluation in horizontal wells placed in thin reservoirs is advantageous and can result in more realistic \(S_w\) computations. More accurate estimates of \(S_w\) will result in more accurate reserve estimates and/or stock-tank oil initially in place (STOIP). In large oil fields, inaccuracies in \(S_w\) can result in large discrepancies in STOIP calculations (Farouk et al, 2012).

**HIGH RESOLUTION LWD RESISTIVITY IMAGING TOOL**

A high resolution laterolog LWD imaging tool was used to measure formation resistivities and to acquire high resolution borehole images. The tool is sensitive to resistivity/conductivity variations in the formation. Common causes of resistivity variations around the borehole are bed boundaries, cross-bedding, natural conductive and resistive fractures, drilling induced and/or enhanced fractures, faults, vugs and matrix textural changes.
As for any LWD imaging device, the tool needs to rotate to acquire azimuthal data (resistivity image). The mud should be conductive to allow current flow; hence oil based mud or highly resistive mud should be avoided.

**LATERAL WELL RESISTIVITY LOG EVALUATION**

Figure 4 shows the resistivity well logs for the studied lateral. The lateral was drilled through a carbonate oil bearing sequence. LWD propagation and laterolog tools were both included in the bottom-hole assembly (BHA) as were high resolution images. The bottom most track has the GR, density derived caliper and true vertical depth (TVD). The depth track in 1000’s of feet is contained in the second track from the bottom. The third track from the bottom has the laterolog toroidal resistivities. The fourth track contains the propagation phase shift resistivities, the fifth track the propagation attenuation resistivities and the sixth track has the azimuthally focused (up, down, left and right) deep laterolog resistivities. The seventh track has the high resolution dynamic image, the next track has the compensated neutron and formation density logs presented on a limestone matrix combatable scale. The last track shows the azimuthally focused (up, down, left and right) formation density logs.

Figure 4 shows that the laterolog toroidal resistivities are confined to a resistivity range of 0.5-1.0 ohm-m, while both the propagation phase and attenuation deep resistivities range from 0.5 to 4.0 ohm-m. The interval highlighted by the red rectangle shows a large discrepancy between the toroidal and both the propagation phase shift and attenuation resistivities. The resistivity image, and both the azimuthal laterolog resistivities and azimuthal formation density logs, show that this interval is one where the wellbore intersects different reservoir laminations with different petrophysical properties. The relatively high propagation resistivities are caused by their relatively deep DOI. A combination of the TVD, resistivity image, azimuthal laterolog and azimuthal formation density measurements indicate that the well trajectory is touching a denser layer at the top of the wellbore. The productive reservoir is the one with the lower density and lower resistivity.

The interval highlighted by the blue rectangle is also of interest. It shows various increases in the phase shift resistivities that are not supported by either the attenuation or laterolog resistivities. A review of the resistivity image indicates that various bed laminations are being crossed causing small polarization horns on the phase shift. The attenuation resistivities are also affected but to a much lesser degree so the affect is not readily apparent.

It is interesting to note that the bottom laterolog resistivity has a relatively constant range throughout the interval, between 0.5 and 1 ohm-m.

In thin carbonate reservoirs, without the benefit of azimuthal laterolog and density measurements, the risk of erroneous reservoir saturation and hence STOIIP property estimates can be significant.

**EVALUATION OF LWD RESISTIVITY IMAGES FOR FRACTURES AND TEXTURE**

Open fractures, in a clay free formation, have a conductive appearance on the images due to mud invasion into their aperture. Mineralized or sealed fractures appear resistive if the filling material of their apertures is dense and non-conductive like dense calcite or dolomite. While open fractures can significantly increase reservoir permeability and producibility, they can also hinder production by acting as a conduit for water coning and thus can cause an increase in water production. Hence, for reservoir management and well completion design, knowledge of fracture presence, density, aperture and orientation are important reservoir parameters.

Figure 5 shows fractures observed on high resolution LWD images. Being acquired in a horizontal well the borehole images are oriented to the top of hole (TOH), the middle of the image is oriented to hole bottom. The fracture events were automatically extracted from the image via a length and contrast filter. Track 1 shows the GR and caliper, and track 2 the depth index where each digit represents one foot of axial length; i.e. the difference between xx001 and xx002 is one foot of wellbore length. Track 3 has the laterolog toroidal resistivities and track 4 has the neutron porosity and formation density logs on a limestone compatible scale. Track 5 shows the high resolution dynamic borehole
image and track 6 contains the fractures automatically extracted (highlighted in pink) from the borehole image.

Figure 6 shows a highly fractured interval. Fractures on image logs usually occur as linear features with generally steep dips. In a horizontal well, as per this paper, fractures often appear as relatively flat sinusoids. Tracks 1, 2, 3, 4 and 5 of Figure 6 are the same as Figure 5. The digits on the depth index represent one foot of axial length; i.e. the difference between yy01 and yy02 is one foot of wellbore length. Track 6 shows the borehole image with the sinusoids from automatic fracture aperture analysis. The colour code scales the fracture aperture size from small (pink) to large (dark blue). Track 7 contains the fracture aperture size computation (Luthi and Souhaite, 1990) in microns.

Figure 7 shows a highly textured interval with connected vugs, isolated vugs, and resistive features. Conductive and resistive patch information can be used for core-to-log integration and to infer borehole scale heterogeneity for flow models. Tracks 1, 2, 3, 4 and 5 of Figure 7 are the same as Figure 6. The digits on the depth index represent ten feet of axial length; i.e. the difference between zz10 and zz20 is ten feet of wellbore length. From the dynamic image one can readily observe vugs that appear as dark conductive bands/patches/spots parallel or sub-parallel to bedding. Track 6 shows the borehole image with porosity distributions for various heterogeneity classes. The image distributes porosity to different pore types. The conductivity image is converted to a porosity image with a modified Archie equation (Newberry et al, 1996). Then the image porosity is associated with a heterogeneity type in the heterogeneity image. Porosity values for resistive heterogeneities, connected vugular porosity, unconnected vugular porosity and the remaining matrix porosity. One can clearly observe that this is a dual porosity system. Track 7 shows the image extracted porosity type contributions to total porosity. The colored shading indicates the contribution from each pore type.

HIGH RESOLUTION LWD RESISTIVITY IMAGE ACQUISITION

As for any LWD imaging device, the tool needs to rotate to acquire azimuthal data (resistivity image). The mud should be conductive to allow current flow; hence oil based mud or highly resistive mud should be avoided. LWD borehole image quality is also dependent on tool design and specifications, and the drilling environment.

Sampling distance refers to the distance in depth between subsequent measurements that constitute two lines on the final image. As a general statement decreasing the sampling distance increases image quality and resolution. As such drilling rate of penetration (ROP) and tool rotations per minute (RPM) can influence image quality.

When drilling a LWD tool rotates azimuthally around the wellbore and advances along the trajectory. As shown in Figure 8, the motion of a LWD electrode can be viewed as a spiral. With constant ROP, a higher RPM offers better borehole coverage as the spiral becomes compressed. Likewise, the spiral can also be compressed if ROP is lowered and RPM is kept constant.

As per most LWD measurements data is acquired vs time and then converted to depth via the driller’s time to depth curve. This approach gives reasonable results in many LWD scenarios but when high resolution data is being acquired small time to depth discrepancies between the surface and downhole systems due to varying mechanical conditions and temperature can result in inferior image quality. To counter this a downhole depth correction is applied to the high resolution image based on differences between overlapping sensors.

SUMMARY AND CONCLUSIONS

In high angle and/or horizontal wells placed in thin reservoirs propagation resistivity measurements can be difficult to interpret due to shoulder-bed/proximity, and/or anisotropy effects. Shallow laterolog measurements are mostly influenced by invasion, not so much by anisotropy, shoulder bed or proximity effects and so in high angle wells often better represent actual formation resistivity. Due to their relatively shallow depths of investigation laterolog LWD logs can show separation due to invasion. This is not considered an impediment to formation evaluation as borehole fluid invasion at the time of LWD acquisition is relatively
shallow. In high angle and/or horizontal wells LWD laterolog resistivity measurements should be considered the resistivity measurement of choice for formation evaluation.

Recent advances in LWD resistivity image acquisition are changing the approach to lateral well borehole geological interpretation. The advent of this technology at reduced cost and acquisition risk, and the additional geological information it brings has the potential to re-invigorate the approach to field planning and development, reservoir characterization and modeling, and well completion design.

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**Fig. 1** Graphical description of polarization horn. When electromagnetic propagation tools pass through a dipping bed boundary with significant resistivity contrasts the resistivity log can have a high apparent resistivity called a ‘polarization horn’. Polarization horns are caused by charge build-ups along the bed boundary due to discontinuities in the electric field (Griffiths, 2009).
Fig. 2 Bed boundary and proximity effects on LWD propagation resistivity measurements.

Fig. 3 Minimal bed boundary and proximity effects on LWD laterolog measurement.
Fig. 4 Lateral intersecting carbonate oil reservoir. The red rectangle highlights differences between, propagation phase shift and attenuation, and laterolog resistivities. The propagation resistivity reads higher than the average laterolog resistivity due to bed boundary proximity effects. Inspection of the resistivity borehole image, the azimuthal laterolog resistivities and the azimuthal formation density logs indicate the wellbore scratched a more resistive and denser layer above the wellbore. The interval highlighted by the blue rectangle shows increases in phase shift resistivities. The resistivity image shows that various bed laminations are being crossed causing small polarization horns on the phase shift. Attenuation resistivities are also affected but to a much lesser degree, hence the affect is not readily apparent.
Fig. 5 Fractures observed on high resolution LWD images. Fracture events were automatically extracted via a length and contrast filter. Track 6 shows the automatically extracted fractures, highlighted in pink.
Fig. 6 shows numerous conductive fractures on a compressed scale. Track 6 has the borehole image with the sinusoids from the automatic fracture aperture analysis. The colour code scales the size of the fracture apertures from small (pink) to large (dark blue). Track 7 contains the fracture aperture size computation in microns.
Fig. 7 shows a highly textured interval with connected vugs, isolated vugs, and resistive features. From the dynamic image one can readily observe vugs that appear as dark conductive spots. Track 6 shows the borehole image with porosity distributions for various heterogeneity classes. The image distributes porosity to different pore types. The conductivity image is converted to a porosity image with a modified Archie equation (Newberry et al, 1996). The image porosity is then associated with a heterogeneity type in the heterogeneity image. Porosity values for resistive heterogeneities, connected vugular porosity, unconnected vugular porosity and the remaining matrix porosity. One can clearly observe this is a dual porosity system. Track 7 shows the image extracted porosity type contributions to total porosity.

Fig. 8 Motion of a LWD electrode can be viewed as a spiral. The left side spiral represents a tool operating with a certain ROP and RPM. The tighter right side spiral represents an electrode path with the same RPM as the left side but now with a slower ROP. The electrode path represented by the right side spiral has better borehole coverage than the left side.