Geosteering Horizontal Wells using Resistivity Anisotropy obtained in an Offset Vertical Well.

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Abstract

Traditional resistivity logging instruments, when logged in vertical wells through horizontal beds, evaluate the horizontal resistivity (Rh) of the formation. The response of the laterolog tool in the same environment, however, is also sensitive to the vertical resistivity component (Rv). Used alone, neither tool is able to resolve the thin beds or evaluate resistivity anisotropy. However, with computer inversion software, data from both tools can be combined to quantify zones of resistivity anisotropy, as well as accounting for various environmental effects such us invasion and shoulder beds improving bed boundary definition.

This paper proposes a new approach, combining NMR logs data with the above technique, in order to obtain improved geological and petrophysical models, using field data. The models, with more accurately parameterized vertical, horizontal, true and invaded zone resistivity values (Rv, Rh, Rt, Rxo), as well thin bed boundary definition, are coherent across a range of reservoir formation types, and are then applied to help drill more precisely (and evaluate more accurately), a horizontal well in the same formation.

Introduction

The decade of the 90’s was marked by a great change of focus towards the exploration and development of deep-water oil fields. This development, previously mostly based on directional or inclined wells, now included more horizontal wells. New and modified techniques for drilling and evaluating these wells were required, particularly in the areas of traditional geological accompaniment and log interpretation. Investments in new logging and software technologies were key to facilitating the successful planning, drilling and evaluation of these wells, in environments where thin beds and laminated reservoirs were increasingly significant.

The technique proposed here was developed for the drilling of development wells in a deepwater turbidite environment, where the degree of electrical anisotropy is clearly related to the quality of the interlaminated oil reservoir. Here the optimal placement of horizontal producer wells is essential in order to ensure the successful exploitation of the field’s hydrocarbon reserves.

Turbidites and other thinly bedded environments are often described as “low resistivity pay”. This highly anisotropic environment is made up of layers of fine-grained sands and silt interbedded within the hydrocarbon bearing sand reservoir. As a result the resistivity log response in these zones is reduced, giving the idea of poor reservoir quality, even though the sands are full of hydrocarbon.

The quantification of both horizontal and vertical resistivity (Rh and Rv) from a vertical pilot well is therefore key to this process, since these parameters are used in all phases of the well placement strategy; when planning the horizontal well location, when drilling and geosteering the horizontal well using LWD logs, as well as in the post drilling validation phase.

General Summary

Typical field development in this area, involves drilling two nearby wells. The degree of lateral variation in reservoir lithology and quality, associated with the turbiditic environment, means that certain facies are not continuous over large areas. This requires that a pilot well be drilled adjacent to each planned horizontal well in order to confirm the reservoir depth, thickness and quality in that zone. Logs run in the pilot well define the expected local formation parameters and target horizons, which are then used to ensure the optimum placement of the horizontal section. Due to the long extent of the horizontal section, differences in the facies encountered in the vertical pilot well can be observed along the horizontal section.

The vertical pilot well is drilled first through the anticipated target reservoir, with water based mud and a bitsize of 8.5”. The wireline formation evaluation logging suite in this well includes both high resolution laterolog and induction tools (AIT* and HRLA*) in combination, as well as a nuclear magnetic resonance (NMR) tool. The NMR data is initially used to highlight zones of invasion within the thinly bedded reservoir.

Next, the AIT-HRLA resistivity data is processed in order to determine the Rv and Rh components. These parameters are then used as the principal criteria for chosing the target bed in the planning the trajectory of the horizontal producer well, and in developing a layered earth model, to be used for geosteering the section.[1]

From a location slightly offset laterally from the vertical well, the high angle producer well is then drilled towards the location of the vertical well, and landed in the the target zone identified from the anisotropy processing, and cased.

The horizontal 8 ½” section is then drilled and the well geosteered within the targer zone using LWD 2 MHz resistivity measurements (ARC*) in real time.

Vertical well

In the vertical pilot well a 18 m. thick hydrocarbon-bearing clastic turbidite reservoir was identified. Analysis of cores taken in this well, shows the reservoir can be divided vertically into 3 sections (A, B, and C) of differing lithological facies, each associated with distinct petrophysical parameters.

The lower, or basal section is made up of massive lobes of fine turbidite sandstones, with measured AIT resistivity values of 7 ~ 8 ohm.m. Zone C in figure 01. The middle section, has facies composed of finer laminations of fine to very fine sandstones. Zone B in figure 01. The upper section is made up of intercalations of shales and marls Zone A in figure 01. Fine sandstone and silts are also present in these overbank sediments. The middle and upper section of the core interval showed layers thinner than 1 inch, which correspond with the lowest AIT resistivity of 4 Ohm.m observed from the logs.

The zone of “low resistivity pay” consisting of the thin beds in the upper and middle cored zones has good petrophysical characteristics and substantial resistivity anisotropy. It is the reservoir zone in which the horizontal well will be placed.

Response of AIT and HRLA and ARC tools in an anisotropic environment.

Rv is defined as the vertical resistivity measured in a direction perpendicular to the bedding planes, while Rh is parallel to the bedding.

In a vertical well with horizontal layers, HRLA High Resolution Laterolog Tool has been shown to be sensitive to the vertical resistivity component (Rv) due to the current flow lines turning parallel to the tool axis, and perpendicular to the bedding planes. Although the deepest HRLA curve RLA5 has considerable sensitivity to anisotropy, the shallow curves are the most affected, leading to curve separation.[2]

The response of the wireline induction tool (AIT) in the same environment, however, is practically insensitive to the vertical resistivity component, Rv, reading close to Rh, up to significant relative angles of deviation.

The response of the LWD 2MHz resistivity tool (ARC) tool, which is traditionally used to geosteer horizontal wells, is similar to the AIT, since both are induction tools. It has little sensitivity to Rv at low angles of deviation. However, above about 45 degrees relative inclination the sensitivity to anisotropy increases. For a given transmitter-receiver spacing the deep reading attenuation curve begins to read less than the corresponding phase curve, as the angle of relative inclination of the well to beds of an oil bearing anisotropic medium increases.

This fundamental behaviour of the 2MHz resitivity tool is well documented, and is employed as the basis for geosteering wells using forward modeling techniques.[3, 4, 5, 6]

Inversion Processing and Formation Modeling

Inversion modeling software provides powerful tools to help solve questions of tool response in complex formation environments. Inversion processing allows formation parameters, such as borehole, shoulder or nearby beds and invasion effects, in addition to Rv and Rh, to be infered from the resistivity log data.[7]The formation model is first defined as a series of parallel beds each with specific parameters. The model parameters are adjusted until the modeled log response is matched by the actual log curves, at which point the model parameter set is considered to be a good approximation to the actual formation parameters. The estimation of the selected parameters is performed using an inversion scheme. The best measure of the degree of matching is obtained by minimizing a cost, or penalty function.

After several interactions, the coherency between the modeled results and the original data tends to increase. Once the coherency has stabilised the inversion process will output final inverted values for Rv, Rh, Rxo, Di.
The final coherency can be also used as quality control indicator. Lower values mean more coherent results.
In practice, models of varying complexity are required in order to offer robust solutions over a range of possible environments. The presence of invasion, for example, will cause resistivity curve separation in the response of both HRLA and AIT tools, confusing the anisotropy response.

Obtaining Rv and Rh using AIT-HRLA

In the non-homogeneous reservoir zone being modeled here, the wireline logs (AIT-HRLA) were acquired some time after the well was drilled, so invasion parameters needed to be considered in the inversion model in order to determine the Rh and Rv resistivity components more robustly.

The first step in building the model consists of defining the position of the bed boundaries. The HRLA curve RLA5 from the vertical well was used for this purpose, utilizing the inflexion point of the curve to detect the maximum number of bed boundaries.[8]

In a second step a "first guess" is made for the initial formation parameters: R_t, R_{xo} and d_i, based on the intial AIT/HRLA data. However, the HRLA response in the vertical well is affected both by anisotropy and invasion, so the HRLA curves alone contain insufficient information to robustly invert for both Rh, Rv and the invasion parameters. Additional information is needed to solve for this model.

In the same environment, the AIT tool alone has almost no sensitivity to Rv, reading close to Rh. Therefore, assuming an isotropic invaded rock model, curve separation of the AIT can be attributed to the invasion process, and the AIT log can be inverted to solve for both Rh and invasion .

Rv still remains to be determined. It is obtained from a further comparison between the modeled HRLA response in the isotropic invaded rock model and the original HRLA log response. The differences seen here can be interpreted as being principally due to the anisotropy effect. Having previously determined Rh, Rv can now be inverted and solved for.

Invasion and Model selection and Results

Selecting the appropriate model for a formation in a complex environment is essential if the most accurate representation of the formation and borehole environment is to be determined.

Two types of models were selected to perform the inversion for invasion and anisotropy, over the zone of interest from the vertical well.

1D: Sequence of horizontal non-invaded layers perpendicular to the borehole.[9]

2D: Sequence of horizontal invaded layers perpendicular to the borehole.

As the difference between these models is the presence of invasion, some independent indicator of its presence is needed in order to correctly select the appropriate model. Magnetic Resonance logging provides a simple and reliable method to evaluate fluid and pore size distribution within the measurement zone of the tool.[10]

The position in the T2 (Transverse Relaxation Time) distribution where the signal from a particular fluid appears depends on the relative position of the fluid and the rock surface, and offers a quantitative measure of permeability. Short T2's arise from fluids coming into close contact with the rock surface, usually as result of small pore space. Irreducible water, heavy oil and clay bound water are examples of fluids giving early T2 times. At the other extreme, fluids in larger pores, which do not come into contact with the rock surface will give a longer T2 time signal. The introduction of a T2 cutoff is desirable in order to separate irreducible or clay bound water from free or producible fluids.

For sandstones the empirical T2 cut off to distinguish free fluid and bound fluid is 33 ms, as used for the CMR data from the vertical well. The T2's of heavy oil and bound water are lower than the limit, while the T2's for free water and light oil is higher.

For a rock to be invaded, the fluids present need to be free to move meaning that the NMR response in a formation, in combination with the T2 cut off can be used to highlight invaded zones and select the appropriate model.

In the case where the rocks are without free fluid (CMR-FF curve close to zero) and are not invaded, the 1D model was used. At 50 m depth, for example, all the fluid T2 signal is located below the T2 cut off. This corresponds to bound fluid associated with clays and therefore no invasion. The 1D model is applied over these depths. The presence of fluid signal above the T2 cut off at 33 ms (Red line on Track 4) is indicative of invasion, and the 2D model was selected for this interval.

The selection of the most appropriate model for inversion provides the interpreter with improved answers since it increases the coherency of the results as well as decreasing the processing time (1D inversion has less variables to solve than the 2D inversion model). The CMR shows where there is reservoir even in thinly laminated bedding, improves inversion model definition as well as saturation determination.[11]

Results – Anisotropy Inversion

Figure 01 shows the results of Anisotropy Inversion over the reservoir section of the vertical offset well. Raw acquisition data and interpreted facies are presented on Tracks 2 and 3. The results from inversion processing are plotted on tracks 4 and 5. The presence of anisotropy is showed by the difference between Rtv and Rth, which was detected almost throughout the whole reservoir interval. Note that Rth tends to increase towards the bottom of the reservoir while Rtv remains constant. This behaviour indicates a decrease in the anisotropy ratio (Rv/Rh), and can be correlated with facies of massive sandstones (Facies C) from the cores.

Track 6 shows that the coherency of the inversion results is excellent. Low values of reconstruction errors across the interval indicate a minimal difference between the synthetic reconstructed curves from inversion results and raw data. Poor results of inversion due to the presence of washouts are observed at depths 08 m and 26 m.

In track 7 the choice of 1D/2D inversion models is shown. This criterion is based on the amount of free fluid from Magnetic Resonance, which is plotted on Track 8.

Horizontal well Placement and Drilling

The optimised invasion-corrected formation parameters (Rh, Rv, Di, Rxo) obtained by inversion of the log data from the vertical well are used to choose a target interval corresponding to a depth of 15 – 25 m. for the horizontal well to be drilled into.These same parameters are then used as criteria for real time steering decisions during the drilling of the horizontal phase using real time data principally from the LWD 2Mhz tool (ARC*).

Given the sensitivity of the response of the ARC tool to anisotropy in high angle well environments, an accurate and representative evaluation of the Rv and Rh values is paramount in establishing a successful formation model for the horizontal well.

Horizontal Well Modeling

Post job validation of the techniques proposed was carried out using INFORM* (Integrated Forward Modeling) software to create a geological model based on the petrophysical properties of the offset well, including Rh and Rv resistivity curves obtained from the AIT-HRLA anisotropy processing previously discussed.

This allowed the synthetic log response in the horizontal well to be compared to the actual log response of the LWD ARC* tool resistivity and GR measurements in order to validate the Rv and Rh resistivity components used to build the model.

Additional sources of information, such as dipmeter and surface seismic data were considered in order to assure the model consistency.

Results - Log Simulation vs Real LWD curves:

The close relative position of the horizontal and vertical wells in this work and their respective reservoir properties prvide an excellent basis for result comparison.

The main interval of interest corresponds to approximately the first 270 m of the 8 ½" section of the horizontal well section. It starts at the 9 5/8"casing shoe with inclinations ranging from 83.4° to 89.7°. The modeled interval was chosen to correspondent to the zone where the maximum effect of anisotropy is detected by the AIT-HRLA inversion processing and due its proximity to the offset well, where the maximum probability of continuity of the petrophysical properties occurs.GR: The top panel of Figure 2 presents a very good correlation between the synthetic synthetic GR from the INFORM* modeling with the actual GR data acquired in the horizontal well. This validates both the GR parameters chosen for the model and the bed boundary segmentation from the offset vertical well data, when applied along the horizontal trajectory. Resistivity: The simulated resistivity curves present good correlation with the real ARC data acquired on the field, as presented in the top resistivity panel in Figure 6. A very good correspondence in terms of curve separation and magnitude of the resistivity readings is observed in the modeled interval. The variable anisotropy solution shows is robust even across the zone of reduced anisotropy towards the base of the reservoir.

The synthetic resistivity curves from the INFORM modeling also confirm the expected anisotropy response for a highly deviated well drilled in a thin laminated environment, where Rv > Rh. The shallow resistivity curves (P34H) reads higher than the deep resistivity (A34H) and a clear separation between these measurements can be noted throughout most of the interval. The phase shift curves present minimum values around 6 ohm.m and maximum values around 30 ohm.m, while attenuation curves present minimum and maximum values around 4 ohm.m and 10 ohm.m respectively in the interval up to 270 m. from the casing shoe.

The log curve separation of the ARC thoughout the zone appears to be well reflected in the modeled based on anisotropy from the AIT-HRLA. Excellent coherence is seen in the zone of maximum anisotropy where the greatest separation of the ARC phase-attentuation occurs, within the first 100m. or so of the 9 5/8" casing shoe.

For comparison, the ARC curves were also modeled for 2 more traditional cases, where a variable anisotropy was not considered. Both these cases are also displayed in the lower 2 resistivity panels in Figure 6. The first model is based on the deep induction curve (AT90) from the AIT too alone, and the second is based on the deep laterolog curve (RLA5) from the HRLA tool alone. In both models Rh = Rv was assumed.

The modeled ARC curves based on the AIT-only model (Rh=Rv=AT90) show some phase-attenuation separation but the actual resistiviy values are lower, and the logs remain quite unresponsive along the trajectory, especially in the high angle zone just below the casing shoe.

The modeled ARC curves based on the HRLA-only (Rh=Rv=RLA5) model show significantly reduced phase-attenuation separation and much lower resistiviy values when compared to the AIT-HRLA modeled results. The slight character seen in the modeled attenuation curves (A34H and A22H) in some places arises because the RLA5 curve response, which was used for the model here, is actually sensitive to the real Rv in the offset well.
Both of these examples demonstrate the difficulty in properly understanding 2Mhz log response and evaluating the reservoir with these measurements if anisotropy is present but not correctly evaluated or considered.

Beyond about 270 m. from the casing shoe the actual log resistivity values increase markedly and the phase-attenuation curve separation decreases. This departure from the modeled logs is interpreted as occurring because of a lateral variation and facies change along the trajectory, which were not predicted in the formation model based on the offset well data. The reduced resistivity curve separation in this zone suggests a local decrease in reservoir anisotropy accompanying this facies change, which, as previously mentioned, is not unexpected away from the pilot well. Further analysis of this is beyond the current scope of this paper.

Conclusions

The curves modeled on the ARC tool, based on the inverted Rv, Rh from the AIT-HRLA data from the vertical well, match well with results from the actual ARC logs in the horizontal well, especially in the zone closest to the offset well, where the petrophysical and sedimentalogical characteristics could be expected to be most similar.

The results validate the AIT-HRLA inversion processing for resistivity anisotropy evaluation based on data from the offset well, and suggests the benefits of geosteering horizontal wells based on inverted Rv and Rh obtained from the vertical well.

Magnetic Resonance logs in the offset well are useful in understanding the reservoir pore properties and highlighting the correct choice of 1D or 2D inversion models. This improves the coherency and robustness of the final inversion, increasing the accuracy of the final values, while reducing the processing time.

A comparison with logs modeled with no anisotropy highlights the importance of correct model choice, the power of the combined NMR–anisotropy technique and the need for accurately parametrised Rv and Rh for successful geosteering of horizontal wells using 2Mhz tools.

The petrophysical application of Rv and Rh obtained using these techniques leads to an improved calculation of reservoir saturation in thin beds, resulting in increased net pay.

The quality of a geological model in thinly bedded and low resistivity pay environments can be clearly improved when variable anisotropy is considered. This leads to improved log matching in the landing and initial horizontal phases, which is key to the success of these wells.

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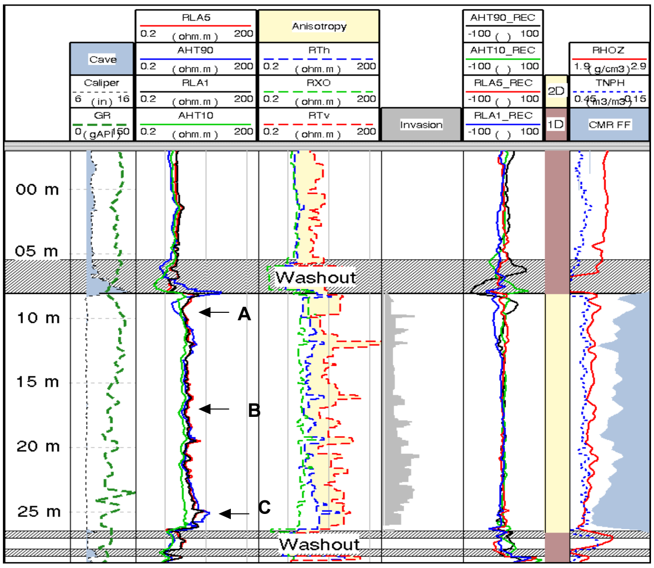

Figure 01: Results of Anisotropy Inversion over the reservoir section of the vertical offset well. Associated facies, are indicated.

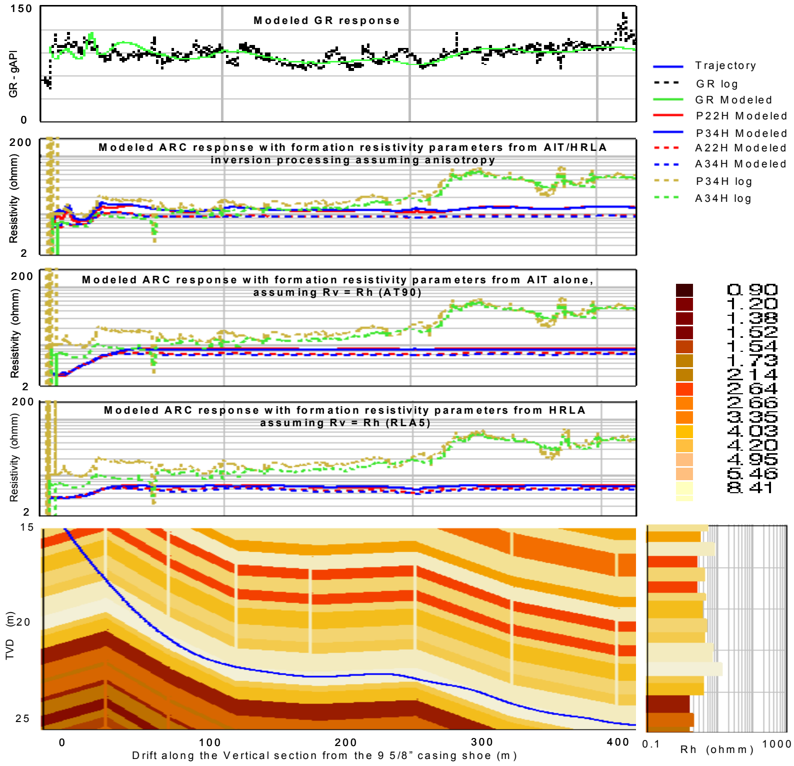

Figure 02. Horizontal well trajectory through INFORM layered earth model showing bed boundaries, and Rh property and ARC log response for 3 model types. The top resistivity panel shows the results using the model based on variable anisotropy from the AIT-HRLA inversion. The bottom 2 resistivity panels show the results where no anisotropy is considered in the model.