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3d Resistivity Modeling to Formulate Inverted LWD squared logs – Solution for High Angle Wells Formation Evaluation

Abstract:

LWD measurements are predominantly recorded in high angle and horizontal (HaHz) wells. In such wells, the LWD tools crosses the bed boundaries at very high apparent dips. LWD induction propagation resistivity measurements read perpendicular to the tool axis. Hence, during logging while drilling a high angle well through layered formation, resistivity measurements will read more or less perpendicular to the formation layers. In this scenario depending on the layer thickness and measurement depth of investigation, these measurements may be affected by nearby beds / shoulder beds. Effect on measurement will also be dependent on shoulder bed properties/resistivity. The deeper the depth of investigation of the measurement, the more the challenge, as it will be an average of multiple layers. Resistivity, being a very deep measurement, with usual depth of investigation of approx. 1-4 ft, suffers majorly with this effect, along with other geometrical effects like polarization horns and anisotropy.

Resistivity being a major input in formation evaluation workflows, traditionally LWD or wireline logs acquired in high angle wells were considered unsuitable for formation evaluation due to the above-mentioned reasons. It is usually assumed that the measurements respond to the layer which was logged, which is usually true in vertical wells.

A new methodology has been developed to derived layer properties i.e. resistivity and other measurements in the form of square log. These square logs would be the actual properties of the layer cutting by the tool while drilling and logging. These square logs can be used confidentially for quantitative reserve estimation.

Through case study, this paper will demonstrate how an inversion (Mohammad et al., SPWLA 2015) which uses the bed boundaries and apparent dips, was utilized to resolve for these multi-layer geometric effects, by generating square logs for Rv and Rh for each layer. This made it possible to do accurate petrophysical evaluation using the LWD logs in this high angle well. This will also highlight the difference between water saturation estimation output by using two different inputs (measured and inverted resistivity).

Introduction:

Formation evaluation has always remained challenging in HaHz wells (Passey et al., 2005). This has forced many operators to use the logs from vertical wells and propagating them onto the horizontal wells, for petrophysical evaluation. The horizontal well logs are usually used for qualitative purposes of reservoir estimation and for well geosteering. This makes heaps of data acquired in horizontal wells unutilised, which if quantitatively incorporated in the formation evaluation workflow, will yield much more precise reservoir estimation results, than when using the vertical well logs only.

Recently, ONGC utilized LWD tools in a high angle well with inclination of about 60 deg. The resistivity values in the thinly bedded reservoir were different than what were expected from vertical well and core results. The variation of resistivity from phase shift measurements were from 47 ohm.m till 91 ohm.m at a given depth in the reservoir (Figure 2). These measurements were affected by various geometrical affects and it was not possible to choose a resistivity for quantitative reserve estimation, which would represent the true horizontal resistivity for that layer. Results from a very simple 1d model were incorrect, with Rh and Rv reading 11 ohm.m and 180 ohm.m respectively (Figure 2). Hence a 3d modeling was utilized. Not only does this give the correct Rv and Rh, it also generates squared logs for the measurement, which will be more accurate than conventional logs as the averaging of measurement at the boundary is avoided.

The 3d modeling methodology involves using log response to determine the bed boundaries. LWD density borehole image log was then utilized to pick the formation dips. Utilizing the bed boundaries and bed dips, near wellbore layered earth model is constructed. Knowing the tool response and the layered model, initial estimate of formation vertical and horizontal resistivity for each layer is constructed. A forward modeling is done with these initial estimates and a compare update iterative approach is followed until a good match with formation resistivity is obtained. The resulting layer properties, which have been derived from the measured logs by correcting for formation geometry around the well will be the true representation of each layer. In this paper, we will focus on correcting the resistivity by using an inversion built on Schlumberger's Techlog software, to output vertical and horizontal resistivity of individual layers as thin as 2 inches thick.

1d Resistivity Modelling:

A simple 1D model usually works in vertical wells. This model assumes a piston type invasion with a 2-layer step profile, for flushed zone and for invaded zone (Figure 1). It computes borehole compensated and borehole corrected resistivity logs and performs single-effect model 1D inversion processing on the LWD propagation resistivity data. It can perform invasion, anisotropy, dielectric and borehole processing inversions. It does not account for formation bedding or dips.

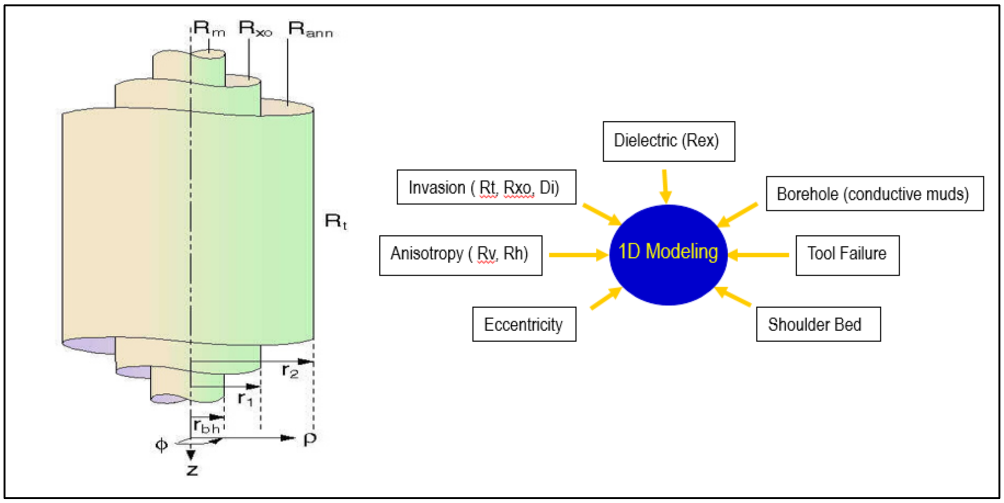

Figure 1: Representation of a simplistic 1d model

Figure 2 shows a zoomed reservoir section of the well Kida-1. It can be seen that the reservoir is thinly layered. All the phase resistivities are separated, ranging from 47 ohm.m to 91 ohm.m, which is majorly due to bed boundary effect, or in other words, due to multiple layers being averaged in the measurement. The time after bit for LWD tool measurements is less than 2 hours in this case, hence invasion effect is negligible. The results from 1D resistivity modeling (Figure 2) gives Rv of ~180 ohm.m and Rh of ~11 ohm.m, which are far off than the expected results. Comparison of saturation (derived using dual water equation and a=1, m=2, n=2 parameters) using P40H (assumed to be virgin formation resistivity reading deeper in the formation) and Rh from 1d resistivity modeling logs is also shown. Neither of these are correct as P40H from conventional logs is affected due to bed boundary effect and Rh from 1d modeling is very low and incorrect. Due to this reason, a more sophisticated approach which incorporates bedding and dip effect was needed.

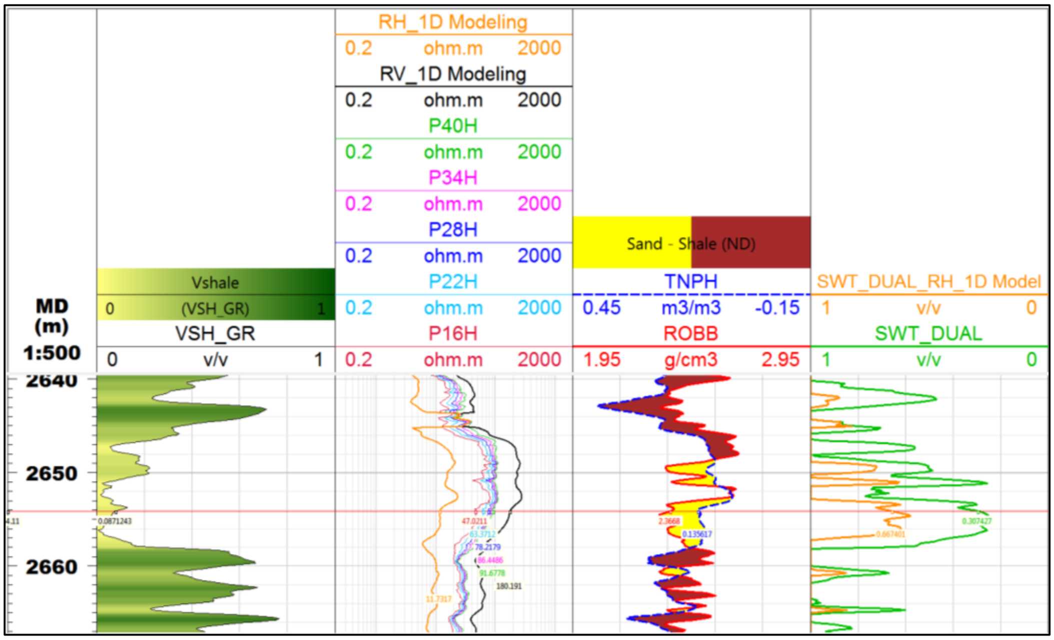

Figure 2: Resistivity and saturation using P40H (assumed to be virgin formation resistivity reading deeper in the formation) and Rh from 1d resistivity modeling. VSH_GR= Volume of shale, RH_1D Modeling= Horizontal resistivity from 1d modeling, RV_1D Modeling= Vertical resistivity from 1d modeling, P16H/P22H/P28H/P34H/P40H= Phase shift resistivities, TNPH=Thermal Neutron Porosity, ROBB=Bottom Quadrant Density, SWT_DUAL_RH_1D Model= Water saturation using Rh from 1d resistivity modeling, SWT_DUAL= Water saturation using P40H.

3d Resistivity Modelling:

In this method, high-resolution density images, acquired by logging while-drilling (LWD) tools while rotating, are analyzed to define the boundary position and dip (figure 3). A local layer model (LLM) is automatically constructed using these dips and boundaries (Figure 4). The log measurement is then utilized to provide an initial estimate of the layer properties. After the LLM is created and incorporated with formation properties, forward modeling is used to generate the analogous tool measurement. After finetuning, once a reasonable match is obtained between the original logs and forward modeled logs (Figure 5), the squared logs represent true layer properties.

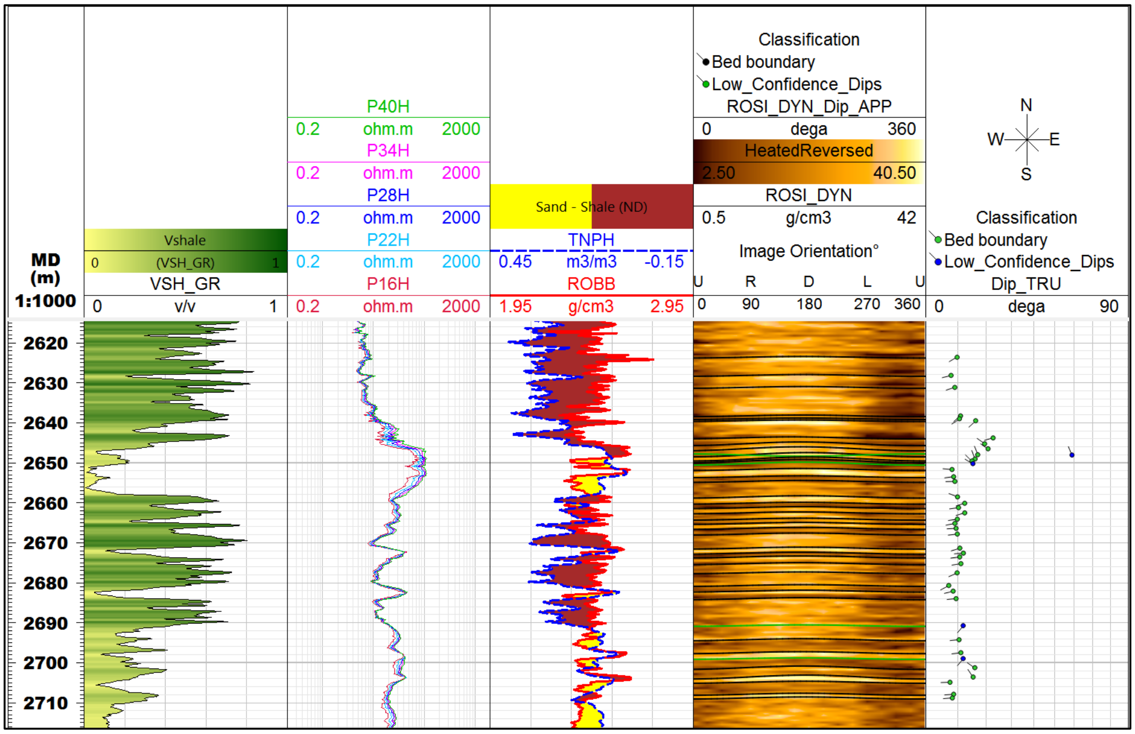

Figure 3: Bed boundaries and dips picked using LWD density image. VSH_GR= Volume of shale, P16H/P22H/P28H/P34H/P40H= Phase shift resistivities, TNPH=Thermal Neutron Porosity, ROBB=Bottom Quadrant Density, ROSI_DYN= Dynamic density image.

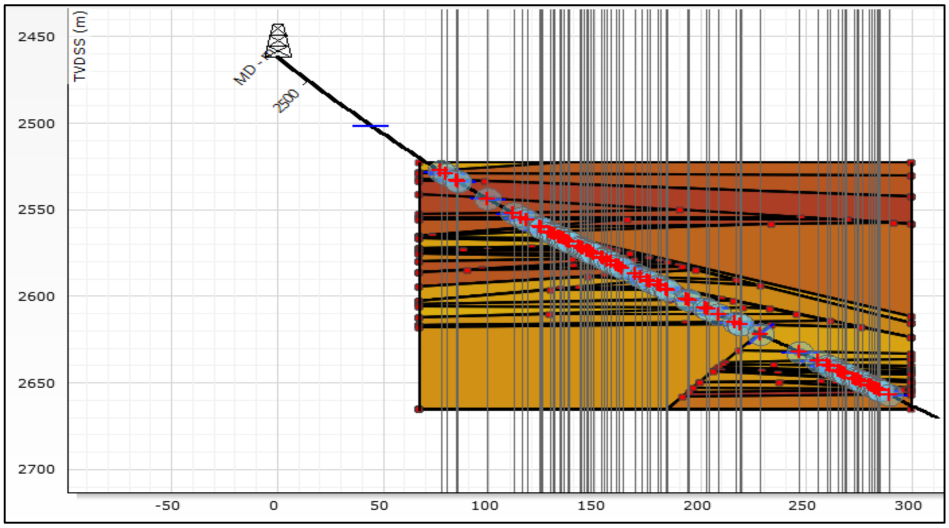

Figure 4 Local Layer Model (LLM) constructed utilizing the bed boundaries and dips

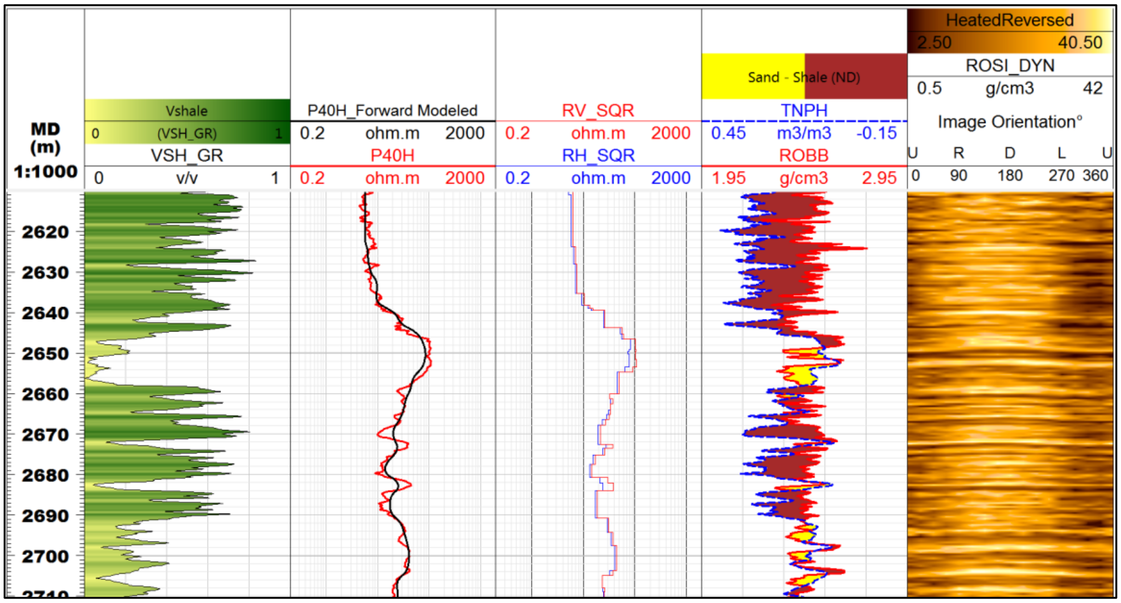

Figure 5: Forward modeled log matches the original log- comparison for P40H shown. VSH_GR= Volume of shale, P40H_Forward Modeled= Forward modeled log from 3d modeling using the squared logs, RV_SQR= Layered squared log for vertical resistivity, RH_SQR= Layered squared log for horizontal resistivity, TNPH=Thermal Neutron Porosity, ROBB=Bottom Quadrant Density, ROSI_DYN= Dynamic density image.

The resultant squared log for Rv and Rh represent the true formation layer properties (Figure 6). It can be seen that there is difference of upto ~50 ohm.m between Rv and Rh in the reservoir section. This has significant impact on the water saturation (Sw) calculation. Comparison of Sw using P40H, using Rh from 3d modeling and using Rh from 1D modeling can be seen in Figure 6.

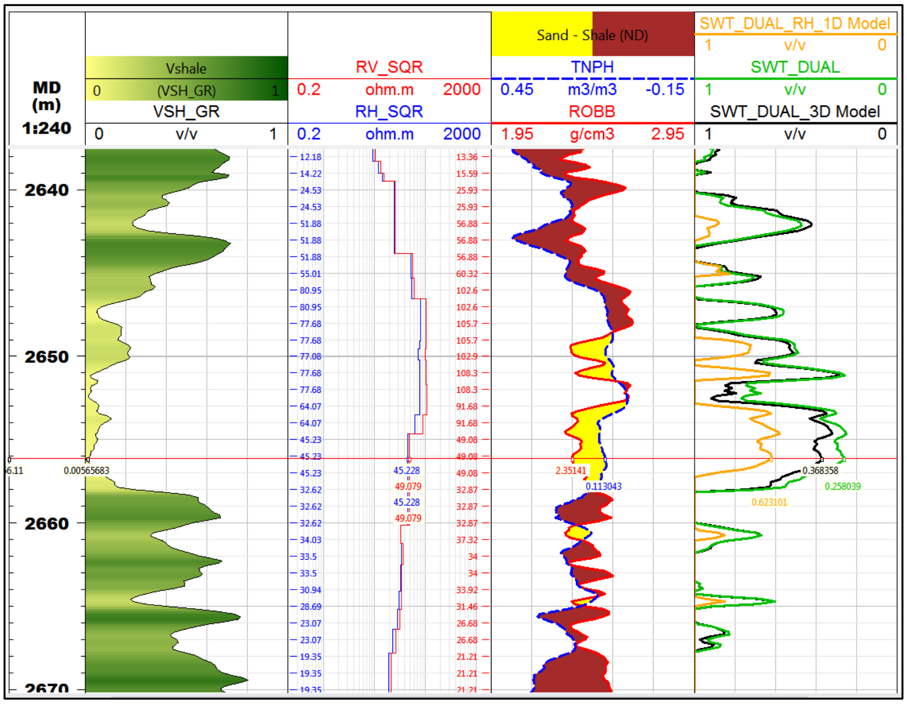

Figure 6: Squared logs of Rv and Rh from 3d resistivity modeling and comparison of Sw using P40H, RH from 1d modeling and Rh from 3d modeling. VSH_GR= Volume of shale, RV_SQR= Layered squared log for vertical resistivity, RH_SQR= Layered squared log for horizontal resistivity, TNPH=Thermal Neutron Porosity, ROBB=Bottom Quadrant Density, SWT_DUAL_RH_1D Model= Water saturation using Rh from 1d resistivity modeling, SWT_DUAL= Water saturation using P40H. SWT_DUAL_RH_1D Model= Water saturation using Rh from 1d resistivity modeling, SWT_DUAL_3D Model= Water saturation using Rh from 3d resistivity modeling.

Conclusion:

3D resistivity modeling helps to resolve for the individual layered resistivity in a high angle well. This allows to use the resistivity data in this high angle well, which otherwise was affected by bed boundary effect, and could not be used for formation evaluation. The forward model log from the squared logs, which were obtained using 2d inversion, matched very well against the original resistivity logs. This proved the preciseness of the layered squared logs that were generated and used for petrophysical analysis. It also further corroborates the accuracy of the dips that were picked. The results from 1d inversion were far off to be used for any practical analysis. Correct water saturation is determined by using Rh from 3d resistivity modeling.

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