ENVIRONMENTAL AND PETROPHYSICAL EFFECTS ON DENSITY AND NEUTRON POROSITY LOGS ACQUIRED IN HIGHLY DEVIATED WELLS

A. Mendoza, The University of Texas at Austin, C. Torres-Verdín, The University of Texas at Austin, and W. Preeg, Private Consultant (Retired Schlumberger).

ABSTRACT

Conventional interpretation methods of nuclear measurements for vertical wells can produce incorrect calculations of porosity in complex rock formations. The case of logs acquired in highly deviated wells relative to sand beds may yield inaccurate estimates of bed boundary depth and porosity.

We describe a systematic sensitivity analysis of petrophysical and environmental effects of neutron and density measurements acquired in highly deviated wells that penetrate sand-shale laminated sands. The study focuses primarily on the effects caused by the angle between the wellbore and formation layering. Raw nuclear tool responses are calculated with Monte Carlo simulations of generic source-sensor configurations via the code MCNP. Our objective is to quantify the effect of complicated formation conditions, such as thin laminations and high deviation angle of the wellbore with respect to the formation, on raw nuclear measurements. Moreover, we quantify the shift in vertical resolution with respect to angle of deviation.

Of special interest is the case of synthetic composite rock formations of sand–shale laminations for various formation thicknesses. Simulated neutron and density porosity logs for the case of highly deviated wells are compared against the logs simulated for the case of a vertical well penetrating the same formation. Our study also describes the effect, on the vertical resolution and bed boundary detection, of azimuthal tool position around the perimeter of the wellbore (azimuthal sensitivity).

Results from this study indicate that shoulder beds can have a significant impact on the nuclear response of thin layers penetrated by high-angle wells. Shifts in vertical resolution of 10 and 11 in. were observed in high-angle wells (70 and 85 degrees of deviation from the vertical) for a 30 in. sand bed bounded by shale beds for the case of density; similarly, shifts in vertical resolution of 14 and 16 in. were observed for the case of neutron measurements. In the case of a well deviated 70 degrees from the vertical, azimuthal effects on density measurements can originate biases on bed boundary detection up to 2.4 in., and up to 2.8 in. for neutron measurements. These results strongly suggest that improved interpretation methods are necessary to accurately estimate the porosity of laminated formations penetrated by high-angle wells.

INTRODUCTION

Existing neutron and density porosity tools were designed primarily for measurement acquisition in vertical wells; their calibration is performed in pits of uniform petrophysical properties. Complicated formation conditions such as thin laminations, shoulder beds, invasion, non-uniform salt concentration (Ellis et al., 1987), and formation geometry with respect to the wellbore (tool), can cause standard interpretation methods to yield incorrect calculations of porosity from raw neutron and density measurements. Factors affecting tool response in deviated wells near adjacent shale beds, or simply across sands with high variations of porosity, include the radial length of investigation, the vertical resolution, and the tool location around the perimeter of the wellbore (azimuthal sensitivity). Passey et al. (2005) reported biases in porosity calculations as high as 6 pu, over 50% uncertainty in water saturation, and significant ambiguity in bed thickness estimation. Such effects cannot be understood intuitively; it is necessary to quantify them with numerical modeling.

In this paper, we make use of previously introduced generic nuclear tool models referred to as the “Longhorn Nuclear Well Logging Tools” (LNLT) (Mendoza et al., 2005) to simulate neutron and density logs in vertical and deviated wells. We use the Monte Carlo method (MCNP) for the numerical simulation of neutron and density measurements. The simulations consider synthetic formations of sand-shale laminations...
penetrated by vertical wells, and by wells deviated 70 and 85 degrees from the vertical. Moreover, we assume homogeneous water-filled sand beds of 25 pu bounded by shale beds. Our objective is to assess the effects, on calculated density and porosity logs, of geometric factors between the wellbore and the formation, namely angle of deviation, using conventional processing techniques.

The vertical resolution of nuclear tools as well as their radial length of investigation play an important role on the processing of raw measurements to calculate final density and neutron porosity logs. Because the vertical resolution and radial length of investigation is different for each detector, the process of combining their individual responses has an important effect on the resolution of the estimated density and neutron porosity logs.

In vertical wells, several techniques have been used to process the near- and far-detector response to obtain the best vertical resolution for density and porosity logs acquired in laminated formations. The bed boundary detection capability of neutron and density logs in thin beds can be degraded beyond the intrinsic vertical resolution of the tool due to under sampling. This capability is improved by increased sampling and by calculating density with the near detector as the primary source of the measurements (Dodge, 1994). McCall et al. (1989) listed values of vertical resolution of density and neutron tools of 18 and 24 in., respectively. They also described the corresponding vertical resolutions for alpha-processed (1.2 in. sampled) measurements equal to 4 in. for density and 8 in. for neutron. Galford et al. (1986) introduced a processing method to amplify the vertical resolution of neutron porosity measurements by matching the resolution of the near- and far-detectors. This latter work was followed by Flaum et al. (1989), who introduced a similar technique to improve the vertical resolution of density logs. Their method consists of combining the response of the near-detector with the compensated density response. With the application of such a processing technique, Flaum et al. (1989) report a vertical resolution of less than 6 in.

In general, the above techniques have shown positive results in vertical wells. However, work on similar or new processing techniques applicable to highly deviated wells is in order.

**METHODOLOGY**

We simulated the raw neutron and density logs using the Monte Carlo method via the code MCNP (X-5 Monte Carlo Team, 2003). As illustrated in Figures 1 and 2, for both neutron and density tools, the radial length of investigation and vertical response are different and spatially complex for short- and long-spaced detectors.

![Fig. 1: Importance functions for the thermal neutron porosity tool. Colors describe the normalized formation sensitivity of the neutron tool response as a function of the distance from the bottom of the sonde (vertical resolution) and distance into the formation (radial length of investigation). The depth shift necessary to match the middle distance between the source and each detector is shown in the center of the figure.](image1)

![Fig. 2: Importance functions for the density tool. Colors describe normalized formation sensitivity of the density tool response as a function of the distance from the bottom of the sonde (vertical resolution) and distance into the formation (radial length of investigation). The depth shift necessary to match the middle distance between the source and each detector is shown in the center of the figure.](image2)
Ellis (2003) described density response maps for a hypothetical tool which exhibited highest sensitivity to the formation near the tool, in particular close to the source and detectors. Figure 1 shows the map of normalized importance for the thermal neutron porosity tool in a homogenous 25 pu water-filled sand. Similarly, Figure 2 shows the normalized importance map for the density tool. For each tool, the depth shift necessary to match the mid-point between the source and the near- and far-detectors is shown in the center of the figure. The functions are discretized in cylindrical cells. Each cell quantifies the normalized importance integrated over the azimuthal direction. In the case of the neutron tool, it can be observed that high sensitivity to the formation concentrates near the detectors. For the density tool, higher importance is observed near the source region.

Fig. 3: Comparative plot of importance functions for the thermal neutron porosity tool. Colors describe the normalized formation sensitivity of the neutron tool response as a function of the distance from the bottom of the sonde (vertical resolution) and distance into the formation (radial length of investigation). The top and bottom panels show importance maps for the near- and far-detectors, respectively.

Given that radial length of investigation plays an important role in deviated wells, Figure 3 compares this capability by way of normalized importance maps for the thermal neutron porosity tool in porous rocks of different petrophysical properties. We observe a longer radial length of investigation for the lower porosity formation (5 pu). Moreover, higher sensitivity concentrates near the detector at elevated values of hydrogen index (higher porosity formations). Similarly, as shown in the right-hand panels of Figure 3, for the case of equal-porosity formations, different fluid saturations would also have a measurable effect on the radial length of investigation of the thermal neutron tool. In the case of density measurements, the response capabilities remain nearly invariant to variations of petrophysical properties.

We estimate neutron porosity from the near- to far-detector ratio. Figure 4 shows the calibration curves for the thermal neutron porosity tool for the case of a homogeneous water-filled sandstone formation. Relative particle counts were calculated to an average relative error of approximately 1% for each detector after running 1 million particle histories with MCNP.

Fig. 4: Calibration curves for the thermal neutron porosity tool in water-filled sandstone. The top-left panel shows the log-log plot of the detectors’ count-rate and the top-right panel shows the count rate of each detector per sandstone porosity. The bottom panel shows the near to far detector-count ratio as a function of sandstone porosity units.

Density measurements for each detector as well as the density correction, \( \Delta \rho \), are calculated using the “spine
and rib” plot shown in Figure 5 following the procedure described by Bigelow (1995). The formation bulk density (compensated density), $\rho_b$, is then calculated by

$$\rho_b = \rho_{LS} + \Delta \rho,$$  

where $\rho_{LS}$ is the density estimated from the far-detector response.

Formation bulk density is calculated after depth-matching the near- and far-detectors as described in Figures 1 and 2. We also calculate the formation bulk density resulting from the “enhanced vertical resolution,” $\rho_{enh}$, using the procedure described by Flaum et al. (1989), i.e.

$$\rho_{enh} = \rho_b + (\rho_{near} - \bar{\rho}_{near}),$$  

where $\rho_{near}$ is the near-detector density and $\bar{\rho}_{near}$ is the near-detector density averaged to match the resolution of the far-detector density.

We assumed a synthetic rock formation consisting of a 30 in. homogeneous water-filled sandstone of 25 pu bounded by shale (illite) beds to simulate neutron and density logs. Calculated neutron and density logs in a vertical well are compared to logs simulated in wells penetrating the same formation at angles of deviation of 70 and 85 degrees. This procedure is repeated for the case of a formation consisting of 16 in. sand-shale beds of the same petrophysical properties as in the previous case. Also, simulated logs for a vertical well are compared to the logs for wells deviated 70 and 85 degrees from the vertical. In all cases, neutron and density measurements were simulated with a 1.2 in. sampling rate. Additionally, to illustrate fluid effects on density and neutron porosity logs, we show simulations for the case of a 30 in. sand bed fully saturated with gas (CH₄), bounded by a shale. Measurements in the gas-saturated sand bed are simulated in a well deviated 70 degrees from the vertical, and compared to logs simulated in a vertical well penetrating the same formation.

For the cases described above, the tool position against the borehole wall is assumed at the bottom of the wellbore. However, we assess the effect of azimuthal tool position by comparing the case of a 70-degree deviated well for the maximum change in tool rotation of 180 degrees. In all cases, the assumed borehole fluid was a fresh water-base mud with the same properties as formation water. To improve statistical accuracy in the calculations, we used superimposed importance grids consisting of 1600 cells for neutron simulations, and 3920 cells for density simulations, in a three-dimensional (3D) cylindrical coordinate frame.

**SIMULATION RESULTS**

Figure 6 shows a comparative plot of the simulated neutron porosity logs for the single 25 pu water-filled sand bed, for a vertical well and for wells deviated 70 and 85 degrees from the vertical. The plots describe the neutron porosity calculated using the mid-point depth-matching procedure described in Figure 1 and the neutron porosity calculated from raw measurements (no depth shift). Using this processing technique, we observe a better vertical resolution in the log for the vertical well. However, the tracks in the center- and right-hand panels of Figure 6 show less influence from depth matching at high wellbore angles with respect to the formation described in vertical depth. It can be observed that the vertical resolution of the neutron tool is adequate to calculate the true porosity for the 30 in. sand bed. Nevertheless, there are clear shoulder-bed effects in the shale-sand and sand-shale transitions. Similar effects can be observed in the 16 in. laminated...
case shown in Figure 7. Again, for the case of a highly-deviated well we note a decrease of sensitivity of the calculated neutron porosity to depth-matching of the far-detector response. Shoulder-bed effects are clear for both cases. However, as in the single-bed case, an apparent increase in resolution is observed in the deviated well case due to the longer exposure of the tool to the sand bed. The logs also show non-symmetrical shale-sand and sand-shale transitions.

Figures 8, 9, and 10 show the simulated density logs for the case of a vertical well and wells deviated at 70 and 85 degrees. The track on the left-hand panel shows the near-detector density, the depth-matched far-detector density, and the compensated formation bulk density. In the center panel we show the density correction, $\Delta \rho$.

The simulation of every sample point in depth for the neutron logs resulted in average relative errors of 1.1% and 0.9% for the near- and far-detectors, respectively, after running 1 million particle histories with MCNP.

The above results are shown versus vertical depth. There is a degradation of the vertical resolution if the comparisons are made along the direction of the borehole as a logging tool would acquire the measurements.

The simulation of every sample point in depth for the neutron logs resulted in average relative errors of 1.1% and 0.9% for the near- and far-detectors, respectively, after running 1 million particle histories with MCNP.
between the near- and far-detectors across bed boundaries, whereas the near response shows the best estimate of density. The log of $\rho_{\text{enh}}$ differs from the compensated density by sharpening the boundaries across beds in the three well cases. Figures 11 and 12 show the simulated density logs for the 16 in. sand-shale laminated formation. As in the neutron porosity case, we observe a degraded effect when depth matching the far density at high angles of wellbore deviation. Moreover, an apparent higher resolution, attributed to the longer exposure of the tool to the sand beds, is observed in vertical depth for the case of a deviated well.

The simulation of every sample point in depth for the density logs, after running 10 million particle histories, ith MCNP resulted in average relative errors of 1.4% and 1% for the far and near detectors, respectively.

![Fig. 8: Simulated density log for a 30-inch, 25 pu sandstone bed, bounded by shale beds in a vertical well. The panel on the left shows the near-detector density in blue, the depth-matched far-detector density in red, and the compensated density in green. The density correction is plotted in the center track, and the panel on the right shows the near-detector density in blue, the averaged density (resolution-matched) in magenta, and the resulting “enhanced” density in green. The black line describes the actual density of the formation.](image1)

![Fig. 9: Simulated density log for a 30-inch, 25 pu sandstone, bounded by shale beds in a well deviated 70 degrees from the vertical. The left panel shows the near-detector density in blue, the depth-matched far-detector density in red, and the compensated density in green. The density correction is plotted in the center panel, and the right panel shows the near-detector density in blue, the averaged density (resolution-matched) in magenta, and the resulting “enhanced” density in green. The black line describes the actual density of the formation.](image2)
Fig. 10: Simulated density log for a 30-inch, 25 pu sandstone, bounded by shale beds in a well deviated 85 degrees from the vertical. The left-hand panel shows the near-detector density in blue, the depth-matched far detector density in red, and the compensated density in green. The density correction is shown in the center panel, and the right-hand panel shows the near detector density in blue, the averaged (resolution-matched) density in magenta, and the resulting “enhanced” density in green. The black line describes the actual density of the formation.

Fig. 11: Density logs simulated in a sand-shale sequence penetrated by a vertical well. The left-hand panel shows the near-detector density in blue, the depth-matched far-detector density in red, and the compensated density in green. The density correction is shown in the center panel, and the right-hand panel shows the near-detector density in blue, the averaged (resolution-matched) density in magenta, and the resulting “enhanced” density in green. The formation consists of 16-inch, 25 pu water-filled sand beds, bounded by 16-inch shale beds. The black line describes the actual density of the formation.
DISCUSSION AND INTERPRETATION

As shown in Figures 1, 2 and 3 for both neutron and density tools, the radial length of investigation and vertical resolution are different and complex for short- and long-spaced detectors. Various techniques have been used to process the near- and far-detector measurements acquired in vertical wells to obtain the most accurate porosity and vertical response. In truly horizontal wells, beds can be detected away from the borehole at different distances depending on the detector’s radial length of investigation. In high-angle wells, the assessment of bed boundary and bed thickness is non-trivial.

In highly deviated wells, the vertical resolution of the detectors is enhanced when the results are compared in vertical depth and the amount of change in vertical resolution is a function of the angle of deviation. Also, the change in vertical resolution will be different between the near- and far-spaced detectors since they exhibit different radial lengths of investigation. The above results are shown with respect to vertical depth. There is a degradation of the vertical resolution if the comparisons are made along the direction of the borehole as a logging tool would acquire the measurements.

When simulation results are transformed into vertical depth, the response to bed boundaries becomes much sharper at large values of deviation angle because (a) the distance along the borehole is much longer than the vertical depth and (b) the tool resolution is determined by the distance along the borehole. Figures 13 and 14 show results from this exercise.

To concisely describe a case of combined fluid and formation geometrical effects on density and neutron porosity measurements, Figure 15 shows the effect of gas in a 30 in. gas-saturated sand bed penetrated by a...
well deviated 70 degrees from the vertical. These results are compared to logs simulated in a vertical well. For density measurements, we observe similar effects on bed boundary transitions and vertical resolution as in the case of a water-saturated sand. In this case, the sharpening of sand-shale and shale-sand transitions as well as the apparent increase in vertical resolution of the far-detector is more pronounced due to the higher density contrast between the gas-saturated sand and the bounding shale beds. Neutron porosity logs exhibit significant gas-effect in both the vertical and 70-degree deviated wells. However, in the case of the deviated well we observe more accurate bed boundary transitions.

![Fig. 14: Comparative plot of the raw and depth-matched single-detector neutron porosity logs describing shifts in vertical resolution corresponding to a vertical well and wells deviated 70 and 85 degrees from the vertical. The top panels show the raw far-detector neutron porosity in red, and the near-detector neutron porosity in blue. The bottom panels show depth-shifted far-detector neutron porosity in red and near-detector neutron porosity in blue.](image)

![Fig. 15: Comparative plot of simulated neutron and density logs for the case of a gas-saturated sand. The top panels show the single-detector density logs and the bottom panels show the simulated neutron porosity. All the logs correspond to the case of a well deviated 70 degrees from the vertical, penetrating a 30 in. gas-saturated sand bounded by shale beds.](image)

Given that we assumed a single tool position around the perimeter of the wellbore (bottom face) for all the simulations presented above, it is important to quantify the effect of azimuthal tool position on the symmetry of the logs acquired across bed boundaries for the case of deviated wells. Figure 16 shows the symmetrical variations of logs simulated across bed boundaries between the cases of tool location against the bottom face of the wellbore, and against the top face (rotated 180 degrees from the bottom). We observe a shift in the detection of bed boundaries of approximately 2.8 in. for the neutron porosity log and 2.4 in. for the density log. Moreover, these results exhibit an approximate shift of 0.8 in. in the far-detector density response. Despite the geometrical shifts in bed boundary detection because of azimuthal tool location, the vertical resolution of the near- and far-detectors for both neutron and density tools remains approximately constant.
Fig. 16: Comparative plot of simulated neutron and density logs for azimuthal tool locations of 0 and 180 degrees from the bottom face of the borehole. The top panels show the single-detector density logs and the bottom panels show the simulated neutron porosity. All the logs correspond to the case of a well deviated 70 degrees from the vertical, penetrating a 30 in. water-saturated sand bounded by shale beds.

SUMMARY AND CONCLUSIONS

Individual detector responses for neutron and density measurements are spatially complex. Each of these responses exhibits different vertical resolutions and radial lengths of investigation. Accounting for such properties of nuclear measurements is essential for estimating actual formation porosity. In the case of highly deviated wells, optimum combination of multi-detector responses is a more complicated process than in the case of vertical wells. Several techniques have been used to enhance the vertical resolution of neutron and density logs in laminated formations penetrated by vertical wells. However, these techniques have not been proven successful in deviated wells. In our study, we quantified the effect of high-angle wells penetrating sand-shale laminated formations on neutron porosity and density logs via numerical modeling.

Results from our study show that, for the case of a 30 in. water-saturated sand bounded by shale beds, depth-matching the far-detector response improves the detection of bed boundaries with the neutron tool. However, shoulder-bed effects bias the calculated porosity by approximately 2.5 pu through most of the sand bed thickness. Nevertheless, the resolution of the measurement was high enough to sense the true porosity (25 pu) of the sand bed. For the case of 16 in. sand-shale laminations, both neutron and density measurements exhibited sharper bed boundary transitions as well as reduced shoulder-bed effects in a well deviated 70 degrees from the vertical when transformed into vertical depth.

At high angles of deviation, the response of both neutron and density measurements was sharper than for the case of a vertical well, and we observed an apparent enhancement in vertical resolution. These effects are attributed to the much longer distance along the borehole of the response compared to the case of a vertical well.

Because of their sensitivity to hydrogen index, neutron porosity measurements are substantially more affected than density measurements by the combined effects of gas saturation and geometrical factors between the wellbore and laminated formations.

Rotation of the tool around the borehole caused a geometrical shift in bed boundary detection from simulated neutron and density logs. However, the vertical resolution remained approximately constant for both neutron and density measurements.

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ABOUT THE AUTHORS

Alberto Mendoza is a Graduate Research Assistant and a PhD student in the Department of Petroleum and Geosystems Engineering at The University of Texas at Austin. He received both Bachelor of Science and Master of Science degrees in Petroleum Engineering from The University of Texas at Austin in 2002 and 2005, respectively. From 2002 to 2003 he worked for Schlumberger as a field engineer in well testing. In the summer of 2005 he was an intern at Schlumberger-Doll Research. He was granted a 2003-2004 scholarship by the SPWLA. His research interests include petrophysics, log analysis, inverse problems, and well testing.

Carlos Torres-Verdin received a PhD degree in Engineering Geoscience from the University of California, Berkeley, in 1991. During 1991–1997 he held the position of Research Scientist with Schlumberger-Doll Research. From 1997–1999, he was Reservoir Specialist and Technology Champion with YPF (Buenos Aires, Argentina). Since 1999, he has been with the Department of Petroleum and Geosystems Engineering of The University of Texas at Austin, where he currently holds the position of Associate Professor. He conducts research on borehole geophysics, formation evaluation, and integrated reservoir characterization. Torres-Verdin has served as Guest Editor for Radio Science, and is currently a member of the Editorial Board of the Journal of Electromagnetic Waves and Applications, and an associate editor for Petrophysics (SPWLA) and the SPE Journal.

William Preeg received a PhD degree in Nuclear Science and Engineering from Columbia University in 1970. From 1980 to 2002, he held various positions with Schlumberger including Director of Research at Schlumberger-Doll Research (SDR), Vice-president of Engineering in Houston as well as Manager of the Nuclear Department at SDR. Prior to 1980, he worked for Los Alamos Scientific Laboratory, Aerojet Nuclear Systems Company, and the Atomic Energy Commission, largely in the area of nuclear radiation transport. He has also served on advisory committees at University of Texas, Texas A&M, Colorado School of Mines, and Georgia Tech.