Resistivity Images for Horizontal Drilling – A Case Study

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Abstract

This work presents the results of the first two horizontal wells in deepwater offshore Brasil drilled with the aid of resistivity images for Petrobras.

The GeoVision Resistivity (GVR) tool is a laterolog type LWD tool, giving azimuthal gamma ray measurements as well as a resistivity measurements at the bit, three resistivity measurements of different depths of investigation each capable of providing 56 azimuthal segments of resistivity in real time. The images created in this way show the relative orientation of the formation beds being drilled. In combination with a rotary steerable tool and a mud-pulse telemetry system capable of high transmission rates, the well can be drilled and geosteered while continuously rotating using real time images of the wellbore throughout the length of the trajectory.

The use of this tool was critical to the success of the horizontal section of well C, with more than 1000 m of net pay for a total of 1082 m. drilled. This occurred in a zone where the dips calculated from this tool during drilling actually showed a structure dipping in the opposite direction to the surface seismic section.

In addition to the images, the resistivity curves and azimuthal gamma ray curves from the GVR tool were combined with log data from other LWD tools, the Azimuthal Density Neutron and Array Resistivity Compensated tools, which were run simultaneously with the GVR. These were used to interpret the presence of nearby beds, faults, fractures, concretions and other structures. Despite their importance, these fall outside the scope of the current work.

Introduction

Logging While Drilling (LWD) tools have been in existence for many years, however with the advent of an increasing number of horizontal wells being drilled worldwide, the development of imaging technologies for drilling has been key to reducing risk and establishing a new level of successful well placement. Images enable the relative position of the tool with respect to the formation to be determined while drilling in more intuitive manner, allowing timely and informed steering decisions to be made while drilling.

It is in this context that the GVR tool was used for the first time in Brasil with success in Wells B and C drilled by Petrobras

A Tool for Resistivity Imaging

The GeoVision Resistivity (GVR) tool is the most recent upgrade of the Resistivity at the Bit tool (RAB) which was first developed in 1996. It generates high-resolution images with 56 resistivity measurements per rotation, using a laterolog principle whereby current is focused directly into the formation.

Best results are achieved in water-based muds and resistive formations. Three images with different depths of investigation of 1", 3" and 5" are obtained from small button electrodes mounted towards the top of a 6-¼" collar. The data from these images are recorded in memory and are available for transmitting in real time to the surface. The button electrodes are focused perpendicular to the wellbore wall, in order to minimize shoulder bed effects. In addition to azimuthal resistivity readings (Bottom, Top, Right or Left), the button electrodes also provide averaged resistivity values.

The ring resistivity measurement comes from a ring shaped sensor half way along the tool and gives an average resistivity, which can be used in conjunction with the button resistivity measurements. The distance from the ring sensor to the button electrodes is 24 inches (Figure 1)

An additional resistivity measurement is available at the bit (RBIT), by focussing current in the drilling direction using the bit below the GVR tool as an electrode. The measurement point for this curve corresponds to the mid-point between the bit and the bottom of the tool. When a further tool is connected below the GVR tool, such as a near bit stabiliser this distance is less than 2 meters. Available processing techniques can be used to automatically convert these measurements into an environmentally corrected true formation resistivity (Rt), invaded zone resistivity (Rxo), measurements of the invasion profile around the borehole, and an estimate of the diameter of invasion (Di) as well a measurement of hole diameter.

The tool's azimuthal gamma ray sensor can be used in conjunction with the resistivity measurements to support the interpretation issues relating to the reservoir structure.

Limitations

The laterolog resistivity image tool referred to here is suitable for running in 8 ½" hole size when equiped with an 8 ¼" sleeve, in conductive muds, with optimum performance in resistive formations. Minimum rotation for optimum quality images is 30 rpm.

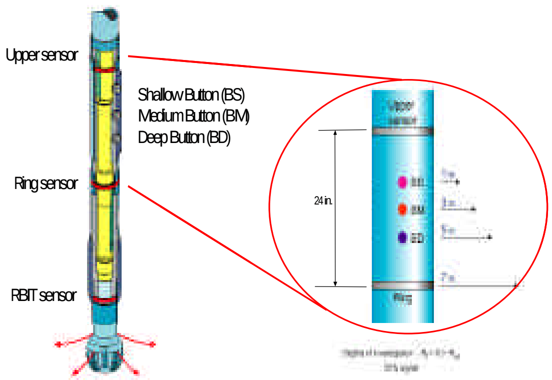

Figure 1 – Geometry of the GVR tool with depths of investigation of the button electrodes

Image Interpretation Techniques for Well Placement

The use and interpretation of resistivity images allows the orientation and dip of formation beds to be determined relative to the drilling direction (Figures 2 and 3). This provides information to help in timely drilling steering decisions.

Figure 3a shows the approach of the wellbore to an underlying shale bed, drilling *downdip*, while Figure 3b shows the approach of an overlying sand body, drilling *updip*. In Figure 3c the nearby shale is overlying the wellbore being drilled *updip* and in Figure 3d the underlying sand is being drilled *downdip*.

The images can also be used to identify fractures and other internal reservoir structures. Additional applications include time-lapse analysis, logging for drilling and the monitoring of hole conditions.

Results – Well B

Well B was sidetracked off Well A with the objective to drill 1100 m within the reservoir, passing through several flow units and evaluate the upper reservoir. The well was to be drilled geometrically based on the surface seismic section (Figure 4).

The 8 ½" section for Well B was started at 3298 m (9 5/8" casing shoe) and remained within the reservoir for 141 m. In order to confirm that the top of the reservoir had been reached and no further structure existed above, a further 219 m. was drilled in the shales from 3325 to 3644 m., with deviation up to 98^o.

Having planned the trajectory to be drilled geometrically the need for running the GVR tool was questioned. However, the actual information acquired during this well was vital to confirm the true structural dip as being opposite to that expected (see Figure 5). This important information was then key to planning the subsequent and successful sidetrack of Well C.

Results – Well C

Well C was drilled as a sidetrack from below the casing shoe of Well B, with an objective to stay within the sands of the reservoir, passing through several flow units, while maximising net pay, thereby optimising oil recovery.

With information from the image and log interpretation from Well B, where, contrary to the seismic section, dips up to 7^o (figure 5) towards the southwest were obtained, the geometric drilling plan for Well C was abandoned. The revised plan for Well C called for drilling the well using geological criteria (geosteering) with inputs from resistivity logs and images from the GVR tool in combination with the density-neutron (ADN) and GR, resistivity measurements (ARC)

The 8 ½" phase of Well C started at 3298 m. with a deviation of 89^o, maintained until 3425 m, when images help to confirm that the reservoir was being drilled *updip* (Figure 6), with a risk of exiting out through the top. The inclination of the well was therefore reduced in order to drill back down through the structure, reaching 80^o at 3581m (Figure 7), with the images eventually indicating drilling *downdip* again. From 3715 m. shale intervals were detected. This combined with the known presence of an underlying zone of heavy oil resulted in a change of well inclination to 90^o at 3880 m.

At 4200 m. with the well still at 90^o a reduction in porosity from the density-neutron logs was observed (Figure 8). A gradual increase was applied to the wellbore inclination with the intention of returning to the higher quality reservoir previously drilled. By the end of the well at 4380m a deviation of 93^o was reached, however without further improvement in reservoir quality.

Figure 9 shows a summary of the tool configuration used in both Wells B and C. It should be mentioned that the use of a rotary steerable tool (such as *Powerdrive*) was indispensable for the correct steering of the well while drilling and rotating continuously, without which the availability of images throughout the wells would not have been possible. High mud pulse data transmission rates from the tools downhole to the surface (12 bits per second) with the *PowerPulse* telemetry tool were fundamental in having the resistivity images available in real-time, while achieving high rates of penetration (up to 70 metres per hour).

Conclusions

The ability to determine the dip of the formation beds using the real time resistivity images obtained from the GVR tool, was fundamental to the ability to make timely decisions while drilling, and to the success of this project. The required contrast in formation log parameters (resistivity and gamma-ray) between the reservoir and the adjoining shale are essential factors.

Due to the apparent conflict in dip information obtained from the logs and that observed from the surface seismic section, it would not have been possible to achieve a net pay of over 1000 m. of reservoir without the use of this tool and these techniques.

The availability of resistive images in real time, with high data transmission rates, are only possible with the use of a rotary steerable tool and mud pulse data transmission tools with data transmission rate of up to12 bits/ second.

The use of the images produces, associated with other azimuthal curves (*Up* and *Down* resistivity and *Up* and *Down* Gamma Ray) was key to anticipating drilling navigation decisions without actually leaving the reservoir.

The use of resistivity images in horizontal exploration wells should be encouraged in the cases where the operation risks (drilling, completions etc) usually associated with this type of project, are also reduced.

Acknowledgements

We would like to thank PETROBRAS and SCHLUMBERGER for permission to publish this work.

Abbreviations

GVR = GeoVision Resistivity
RAB = Resistivity at the Bit tool
GR = Gamma Ray
ADN = Azimuthal Density Neutron
ARC = Array Resistivity Compensated
BHA = Bottom Hole Assembly
Rt = True Formation Resistivity
Rxo = Invaded Zone Resistivity
Di = Diameter of Invasion
Rpm = revolutions per minute

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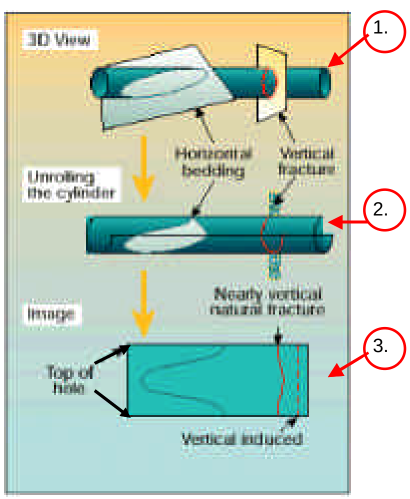

During drilling the button electrodes sample 56 resistivity measurement segments for each revolution. Each segment has an azimuthal coverage of 6.4º. The image acquired in this way defines a cylinder as drilling progresses.

The cylinder outlined in the above manner is cut along the top edge, parallel to the axis of the wellbore in the direction of drilling, and then unrolled

After unrolling the cylinder, the 2-dimensional image of the wellbore is displayed on a plane, with the top part of the well (T) along both sides of the cut and the bottom part of the wellbore (B) in the center of the plane. On this image a sub-horizontal bed defines a sinusoid and a vertical fracture a straight line cutting the 2D image across the plane from one side to the other.

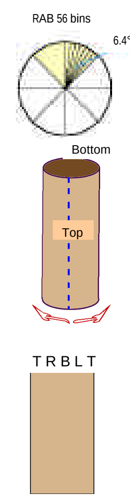

Figure 2 – How to interpret borehole images

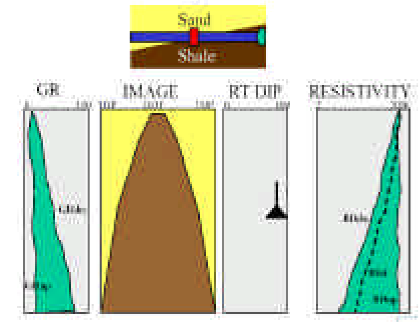

Figure 3a

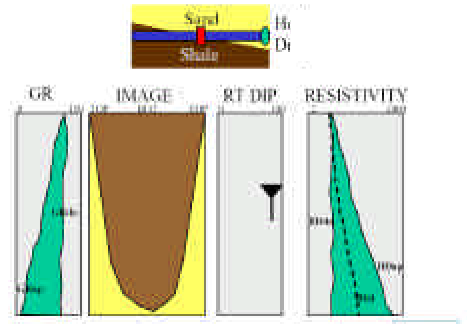

Figure 3b

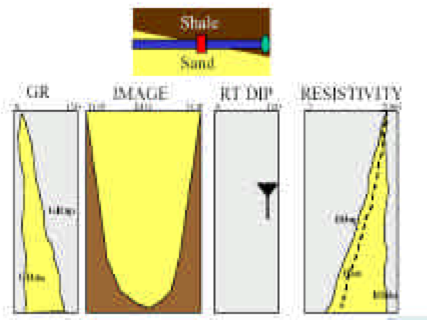

Figure 3c

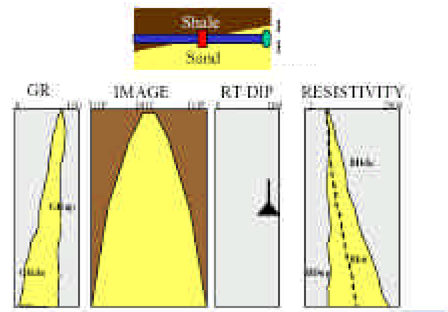

Figure 3d

Figure 3 – Summary of interpretation scenarios using resistivity images from the GVR tool.

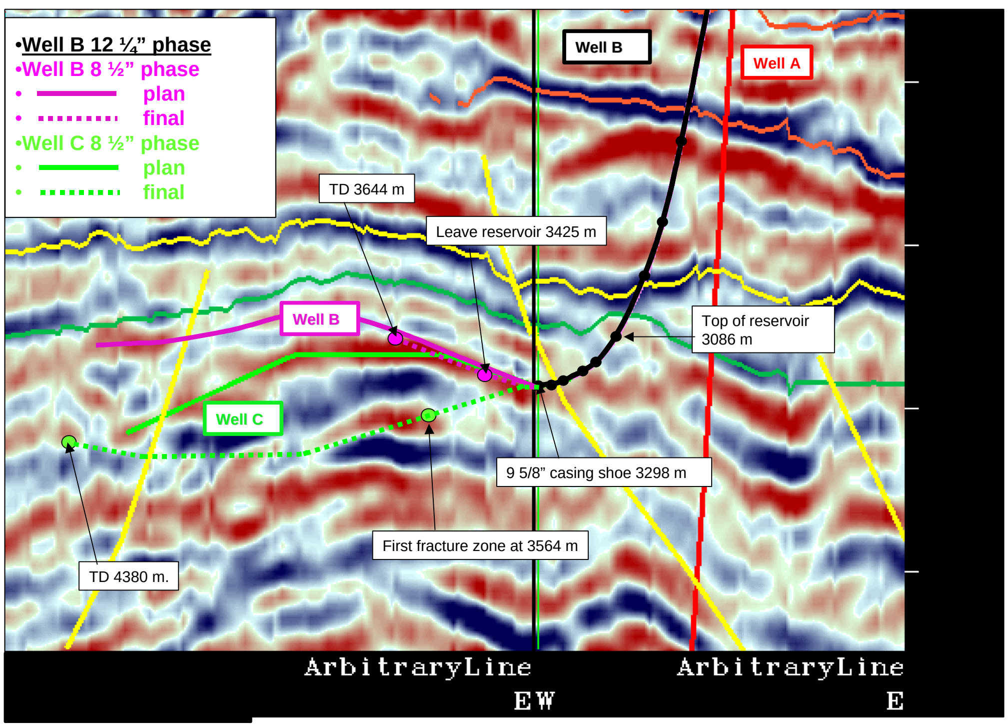

Figure 4 – Depth matched seismic section showing planned and executed well trajectories

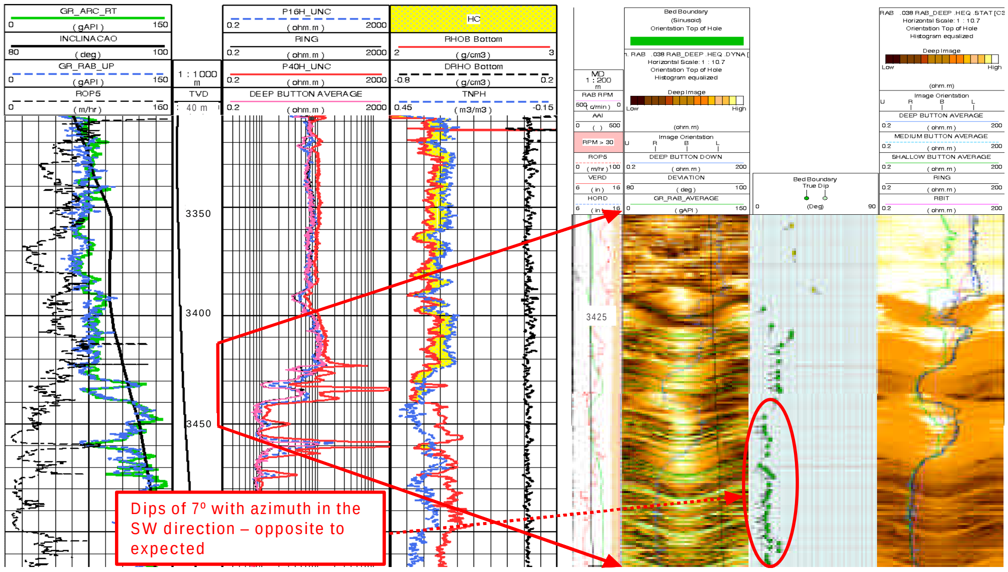

Figure 5 – Well B – Image log with computed dips opposite to the seismic section.

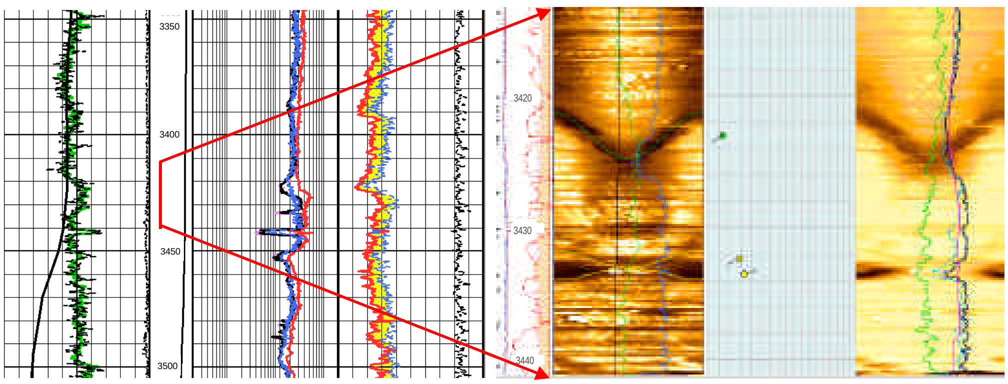

Figure 6 – Well B – Image log showing drilling *updip*

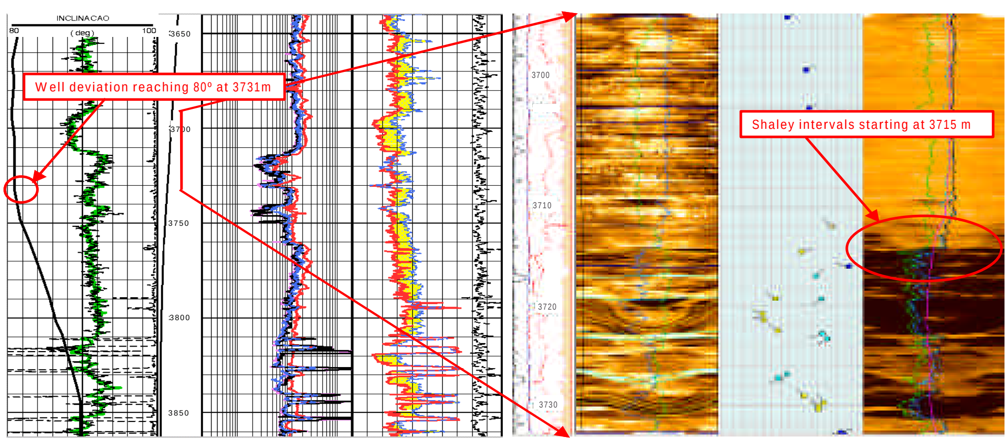

Figure 7 – Well C – Image log showing the well reaching 80^{o} and shaly intervals at 3715 m

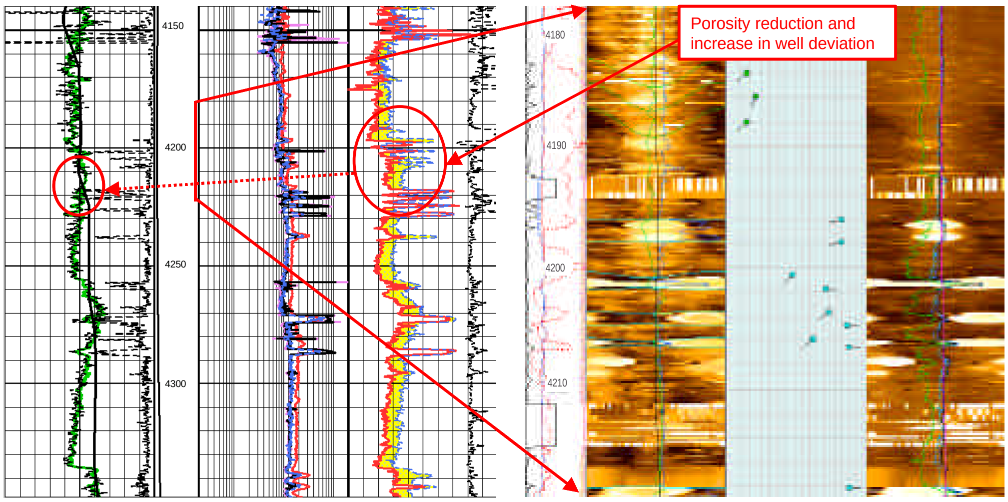

Figure 8 – Well C – Reduction in porosity and the decision to orient the well back updip at 4200 m.

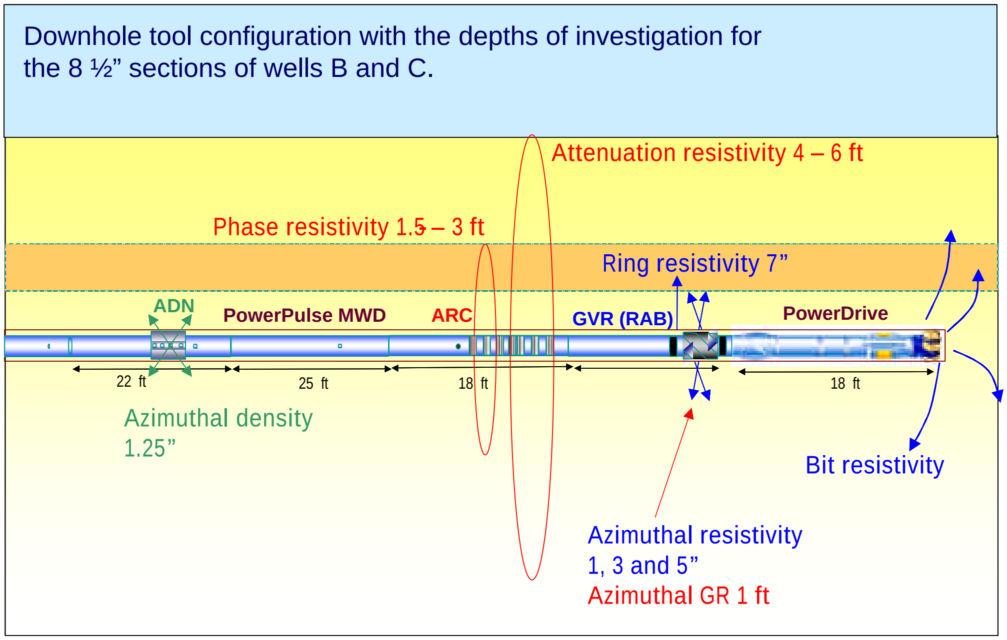

Figure 9 – Bottom Hole Tool Assembly for Wells B and C