EARLY DETERMINATION OF FORMATION STRUCTURE IN HORIZONTAL WELLS USING THE LATEROLOG-WHILE-DRILLING TOOL: AN AID TO OPTIMIZING WELL PLACEMENT

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ABSTRACT

The Laterolog-While-Drilling tool has enjoyed considerable success for at least the last decade in solving formation evaluation problems, determining true formation resistivity, analyzing invasion, and enhancing well placement through azimuthal curves and real time images.

Development of marginal fields means more complex reservoirs with uncertain geological structures such as formation pinch outs, highly faulted and compartmentalized reservoirs, and heterogeneity in the form of channels cutting strike to a horizontal wellbore. These often abrupt geological features can be a great challenge in well placement.

High angle faults sometimes cut perpendicular or near perpendicular to horizontal wellbores. A unique response is typically observed in Laterolog-While-Drilling bit and button resistivity curves. The bit resistivity curve being an electrode device is dominated by the more resistive parts of the borehole/formation environment. However if the tool is about to penetrate a conductive bed, the current leaving the bit will find the easiest path and will be affected by the conductive bed ahead of the bit thereby showing sensitivity to exiting the reservoir (into surrounding conductive rock). The shape of the decrease in the bit resistivity has been observed to vary depending on the geological scenario immediately ahead of the bit that will cause the wellbore to exit the reservoir. The analysis of the bit resistivity curve behavior can bring an early qualitative indication of geological structure change which can lead to an earlier steering decision. The button resistivity curves whose position is further back from the bit resistivity, helps confirm the way in which the borehole approached the aforementioned structure feature.

The bit resistivity curve in horizontal wells often gives a unique insight into high-angle, sub-seismic features because its current path is axial to the borehole and into the formation ahead of the bit, at least initially. This information, together with latest generation technology such as azimuthal deep electromagnetic resistivity, can help us maximize the wellbore position inside the reservoir and optimize production and ultimately hydrocarbon recovery.

INTRODUCTION

LWD (logging-while-drilling) measurements have been used for a number of years to optimize the position of a horizontal well inside the reservoir. Real-time images are routinely employed in geosteering, indicating how the borehole trajectory is positioned relative to the reservoir structure, whether BHA is drilling up or down section. (Rasmus, 1999)

In recent years the development of directional electromagnetic measurements (such as the Periscope*) has brought enhancement to horizontal well placement. This technology has deep, directional electromagnetic (EM) measurements through the use of tilted and transverse current-loop antennas (Li et al, 2005). Boundaries up to 15ft from the borehole can be detected, enabling the proactive geosteering of difficult reservoirs such as those with thin, dipping and curving formations (Omeragic et al, 2005).

Current laterolog-while-drilling technology (such as the GeoVision* – GVR tool) provides fullbore resistivity images in real time from the three button resistivities and can therefore infer formation structural dip while drilling. Although the tool has azimuthal resistivities, they do not have the deep volume of investigation of those of the azimuthal EM measurements.

Figure 1 shows a schematic of the laterolog LWD tool. Three button resistivities (shallow, medium and deep) are focused and azimuthal, with measurements in different quadrants around the borehole. The ring resistivity is a focused non-azimuthal measurement and the bit resistivity is a non-focused non-azimuthal measurement. (Rosthal et al., 1995), (Bonner et al., 1994). Therefore, there are up to a total of fourteen distinct laterolog resistivity measurements available in real time. The volume of investigation of these measurements follows the same trend as those of other laterolog tools – that is the investigation increases with an increase in the ratio between R_t and R_{xo}, and therefore for quantitative

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resistivity measurements, the LWD laterolog tool should be run in water based mud. Where the contrast between apparent and mud resistivity is large the bit and ring resistivities have a range up to 200,000 ohmm.
The bit resistivity uses the BHA below the tool as an electrode, with the current path traveling out of the bit and into the formation. The resolution and volume of investigation of this measurement is therefore dependent upon the length of this electrode as well as the R_{xo} to R_t contrast. The current path leaves the bit into the formation and returns to the body of the tool from where it is detected by an antenna, with the resulting resistivity partially indicative of the resistivity of the formation ahead of the bit

An important difference between the LWD laterolog and the azimuthal EM is the special sensitivity of the bit resistivity compared with that of the azimuthal EM curves; the bit resistivity has sensitivity to the area of formation axial to the borehole and immediately ahead of the bit (when the bit is about to leave the reservoir) whereas the directional EM responses are more sensitive to a deeper volume that is lateral to the borehole. A combination of these two measurements provides more accurate characterization and much better reservoir understanding and could in theory provide a scenario that comes close to exploring a 3D volume completely surrounding the lower part of the BHA.

The motivation for this paper came with the realization that on a number of wells the behavior of the real time bit resistivity curve appeared to be sensitive to formation events that were occurring ahead of the bit. Since the bit resistivity is an electrode device, the current leaving the bit will find the easiest path and will be at least partially affected by a conductive bed ahead of the bit. Therefore it has a certain degree of sensitivity to exiting as opposed to entering the reservoir. The examples in this paper show that in horizontal wells the behavior of the bit resistivity can vary depending on whether the wellbore is crossing a high angle fault or channel strike to the wellbore compared with if the wellbore is crossing a low angle bed boundary dipping in the same direction as the wellbore azimuth..

APPARENT DIP DEFINITION

The apparent dip made between a wellbore and a geological feature such as a bed boundary can be calculated from a borehole image and is given by the following equation:

$$DIP_{app} = \arctan\left(\frac{Dip\_Height}{Penetration}\right)$$

DIP_{app} = Apparent dip between borehole and geological feature)
Dip_Height = Peak to peak amplitude of sinusoid on the image
Penetration = Diameter of investigation of the measurement

When a vertical well crosses a horizontal plane, by definition the apparent dip, DIP_{app} is zero. The image would show a horizontal line with Dip_Height equal to zero. This is analogous to a horizontal wellbore crossing a vertical fault normal to the fault plane. When a high angle well crosses horizontal beds, we have high amplitude sinusoids and apparent dip is large.

The true structural dip of a geological feature can then be computed from the apparent dip knowing the wellbore deviation and azimuth.

LWD LATEROLOG FIELD CASE EXAMPLES

Horizontal Well Crossing Flat Bed Boundaries

Numerous cases have been documented showing the behavior of laterolog curves crossing low structural dip bed boundaries in horizontal wells (Rasmus, 1999).

Figure 2 shows a field example of a horizontal wellbore crossing a bed with negligible structural dip. The bit resistivity senses the presence of the conductive bed at point A, while the deep button down (blue curve) decreases at the same time that the deep button up curve remains high (point B) indicating a conductive bed immediately above the wellbore and a decision should be made to steer down to stay in the pay zone. The 2MHz propagation resistivity phase curves show possible presence of electrical anisotropy in this interval (track 3) which would suggest vertical heterogeneity in the volume sensed by the tool. Since the resolution of the bit resistivity is less than the button resistivities, it is sensitive to both the conductive bed immediately above the wellbore and the reservoir bed itself. Its response is a slow and gradual decrease as the wellbore becomes sub-parallel to the beds and enters non-reservoir rock.

Horizontal Well Crossing High Angle Faults

In theory, a horizontal well crossing a vertical feature such as a vertical fault normal to the fault plane (and where there is a contrast in resistivity before and after the fault) should produce similar results to a vertical well crossing a horizontal bed boundary (with the same contrast in resistivity) assuming there is no anisotropy or invasion.

Figure 3 shows an example of a horizontal well crossing a high angle vertical feature at point B. The bit resistivity curve detects this feature at a depth 5.8 meters behind the bit (point A) and thereafter has shows a dramatic decrease. This decrease is sharp and 'concave' shaped compared to the corresponding behavior in figure 2 which shows more gradual and 'convex' behavior. Interpretation of the image at point B indicates the fault is inclined 68° to the horizontal plane (track 7). The bit resistivity at point A occurs when the bit is just about to cross the fault since the current path of the bit resistivity leaves the bit and initially travels axially into the formation (with respect to the borehole) before making its return to the body of the tool and therefore sensing formation above and below the lower part of the BHA. Since the button up and down resistivities are not superimposed, the apparent dip between the fault and the borehole is non-zero. The presence of a polarization horn on the 2MHz phase shifts suggests the relative dip is relatively high. Track 8 confirms an apparent dip of 76°.

Horizontal Well Crossing Channel Lenses

When a horizontal well crosses channel lenses, the bit resistivity curve in theory would have a similar response to when the well crosses a high angle fault if the apparent dip between the borehole and the channel is the same as the apparent dip between borehole and the fault. Usually the apparent dip between a channel and the borehole will be lower than the apparent dip between a borehole and a 'conventional bed boundary'.

Figure 4 is an example of a well crossing a channel. The bit resistivity senses the presence of this channel 6 meters before it is detected by other measurements (the button resistivities and resistivity image) at point B. This feature has true structural dip of around 15°, which is relatively low and could indicate that we are crossing the basal part of the channel. Furthermore the azimuthal button resistivities indicate that the wellbore enters this feature up-dip and exits this feature down-dip over a period of 5 meters. Another indication of this feature not having a very high structural dip is the presence of polarization horns which occur when apparent dip (between borehole and feature) exceeds around 50 or 60°: Analysis of the image shows an apparent dip of 82° (track 8, fig 4).

Figure 5 is an example of a horizontal well crossing a high angle feature. The true structural dip of this feature is 45° and has been identified as an abandoned channel. Since the button up and down resistivities are not superimposed, the wellbore is not cutting this feature with zero apparent dip; the apparent dip calculated from the image is indeed 55°. The GVR button curves confirm that the channel is entered up dip.

ANALYSIS AND INTERPRETATION

These examples together with numerous others suggest that the behavior of bit resistivity curve is a function of the following variables:

$R_{BIT} = f\,(R_{res}, R_c, DIP_{app}, x, y)$

Where:

R_{BIT} = Bit Resistivity

R_{res} = Resistivity of reservoir rock

R_c = Resistivity contrast between the reservoir rock and non-reservoir rock

DIP_{app} = Apparent dip (between wellbore and geological feature)

x = Sensitivity of RBIT to formations above and below the bed in which the borehole is located

y = Sensitivity of RBIT to formations ahead of the bit (other than the reservoir and non-reservoir rock)

If both the reservoir and non-reservoir rock are thick enough, we can neglect the effect of variable x on R_{BIT}. In cases where we have consistency in resistivity properties moving laterally in the horizontal plane, we can neglect the effect of variable y.

Modeling of bit resistivity curves under different scenario of bed resistivity contrasts was performed. Figure 6 shows a magnification of figure 3. The blue curve represents the modeled bit resistivity curve and is equivalent to assuming zero apparent dip. It is observed that a zero apparent dip scenario assumed by the blue curve (ie a horizontal well crossing a vertical fault) would cause the bit resistivity curve to drop more sharply than a scenario where apparent dip is 76° (ie the bit resistivity shown in this example). This illustrates the sensitivity of the bit resistivity curve to apparent dip between the geological feature and the wellbore. However, the response is primarily sensitive to the resistivity of the reservoir bed and that of the non-reservoir bed.

Figure 7 is a graphic of bit resistivity behaviors from a variety of horizontal wells. The different solid colored lines represent examples of bit resistivity crossing from zones of high resistivity (ie reservoir rock) to zones of lower resistivity (non reservoir rock). The dashed lines represent 1st derivatives of the solid lines. The different behaviors (especially in the inflexion points of the bit resistivity curve) correspond to different scenarios of reservoir rock resistivity, contrasts in reservoir to non-reservoir resistivity and the different structure interfaces between reservoir and non-reservoir rock.

Table 1 shows the interpretation of this data. Data analyzed and presented in the columns are **apparent dip** (between the borehole and the geological boundary between the reservoir and non-reservoir rock), **resistivity** (bit resistivity in reservoir rock), **ratio** (ratio of resistivity in reservoir rock to resistivity in non-reservoir rock), **d(res)** (1st derivative of bit resistivity), **d^2(res)** (2nd derivative of bit resistivity). The 1st derivative values in the table are taken as the apex points on the dashed lines in the plot of figure 7 (ie where the curve reaches a local minima), and the 2nd derivative represents the difference in gradients on either side of the inflexion points of the bit resistivity curve. In each case the relative dip was calculated from the GVR image.

A linear regression was performed on all the data from table 1 apart from well H in order to predict the apparent dip of the structure for a given combination of variables **(resistivity, d(res), d^2(res), ratio).** The results are summarized in figure 8. The resulting equation predicts apparent dip for given 'resistivity', d(res), d^2(res), 'ratio'. When this equation was applied to the parameters from well H, the calculated apparent dip was 75.8°. This compares well with the correct apparent dip of 72° documented in table 1. The same exercise was performed for all wells in table 1 except for well E. The equation that resulted in this case was able to closely predict the apparent dip of well E (prediction was 67.98° compared with correct apparent dip of 68°). Clearly, an algorithm of this kind should be used with caution because it is based on data from only 7 wells. Furthermore we do not have any wells whose apparent dip is less than 55°. Finally the possibility of using a non-linear regression has not been explored.

Nevertheless the results show that the manner in which the bit resistivity curve changes immediately around the inflexion point can provide us some information about the apparent dip of the wellbore / geological interface. A simple examination of table 1 and figure 7 shows that examples B and G have similar values of 'resistivity' and 'ratio'. However the behaviour of their curves are quite different, yielding different d(res) and d^2(res). The cause is a different apparent dip (76° of example G compared with 87° for example B). Similar observations are found for examples F and H: F shows more concave behaviour in bit resistivity compared with H. The apparent dips of F and H are 55° and 72° respectively.

In some cases it was observed that the bit resistivity was sensitive to formations ahead of it and variable y is no longer negligible. This observation is seen in figure 4 where the bit resistivity does not decrease to the baseline shale values shown by the deep button curves. This is due to the influence of the approaching reservoir rock ahead of the bit. When this example (C) is removed from the linear regression a better fit is observed in the data. When applying data from this example to this resulting equation, the relative dip was calculated to be 89°. This is compared with a (correct) apparent dip calculated from the image of 82°. The affect of lateral heterogeneity in this way increases the effect of variable y on the bit resistivity and causes greater uncertainty in the estimation of DIP_{app}

In horizontal wells, the effect of electrical anisotropy causes both bit and button resistivities to read higher than R_h. This will render variable x non-negligible. In our study we have assumed that variable x is negligible. In practice this is not always the case. Electrical anisotropy in horizontal wells causes a separation in GVR curves in a manner similar to invasion and therefore it could in practice be difficult to account for this.

It should be noted that none of the horizontal well examples shown in this paper had very low apparent dips. Very low apparent dips would bring higher magnitude d(res) and d^2(res). This occurs in cases where the dip azimuth of a high angle fault is oriented in a similar direction to the wellbore azimuth. Likewise for a lower angle structure (such as a bed or canal), a low relative dip would occur when the bed's dip azimuth is oriented perpendicular or sub-perpendicular to the wellbore azimuth, and the wellbore approaches this bed laterally rather than from above or below.

PRAGMATIC APPROACH IN WELL PLACEMENT

Estimation of apparent dip from the real time bit resistivity curve is in itself a 3D problem and requires modeling that can be complex and time consuming. However we have shown that knowledge of certain parameters while drilling can help us estimate the apparent dip of the structural feature immediately ahead of the bit reasonably well. Since we know the wellbore orientation and deviation, we can calculate the true structural dip of the geological feature.

In practice, the value of the bit resistivity RBIT in the reservoir rock can be used as input for the variable **resistivity**. An understanding of the low resistivity formations within and surrounding the reservoir rock can help us estimate the resistivity of the non-reservoir rock, and a reasonable estimation of **ratio** is possible. Variables **d(res)** and **d^2(res)** can be calculated from the bit resistivity just after the inflexion point.

An early estimation of formation structural dip can help us make an early steering decision to maximize wellbore position inside reservoir rock. A good geological model and an understanding of reservoir structure is an essential complement to the methodology described in this paper.

In most tectonically relaxed basins, faults are likely to be high angle, oriented greater than 50° or 60° from the horizontal plane. Therefore if our estimated structural dip is lower than this value, the feature is probably not a fault. Macro faults are often discernable on seismic. Using the methodology in this paper this feature can be detected at the earliest possible moment and allow us to steer accordingly to maximize position inside the reservoir. Likewise, where a macro channel strike to the wellbore is identified on the seismic, an early decision can be made to minimize the amount of footage drilled in the non-reservoir channel.

Where both of these features are sub-seismic in scale, the scenario brings greater challenges. In the case of high angle features (faults), it becomes necessary to understand the stress patterns and structural dipping trends within the reservoir to predict if the fault is normal or reverse. In the case of channels whose dip azimuth is perpendicular to the wellbore azimuth, knowledge of channel geometries in the field is desirable to predict whether the wellbore is crossing the channel in its upper or lower part.

Three field examples documented show how the methodology in this paper was used to make an earlier steering decision. The first is outlined in figure 4. The early detection of a channel with low structural dip allowed an early decision to steer down. Since the wellbore penetrated this channel in its basal part, the footage drilled in non-reservoir rock was minimized with this early decision. In the second example, before drilling it was acknowledged that the well would cross a normal fault as detected in the seismic trace. First indications of reaching this fault were detected from the behaviour in the bit resistivity curve (figure 3). Calculations showed that the feature had a higher true structural dip than would be expected for a canal. In real time it was possible to infer the presence of a high angle fault and a very early decision was made to steer down and re-enter the reservoir thereafter. This maximized the overall footage drilled in the reservoir. The third example is shown in figure 5. The shale channel in this example was identified on the seismic before the horizontal well was drilled. The behavior of the real time bit resistivity curve shown around point A helped to predict that the wellbore was just about to cross into this channel and allowed an earlier than usual steering decision to be made in order to minimize the footage drilled in this channel.

CONCLUSIONS

The bit resistivity of the laterolog while drilling tool is a relatively deep, non-focused measurement whose resolution is related to the length of the BHA below the tool. When the tool is in a reservoir bed and about to cross a geological interface (that separates the reservoir from non-reservoir rock), the bit resistivity curve has a unique behavior that depends on the absolute resistivity of the initial reservoir bed, the contrast in the resistivity between both beds, the apparent dip between the borehole and the geological interface, the presence of laminae or thin beds immediately above or below the bed and the presence of resistivity heterogeneity (a variation of resistivity ahead of the bit). Modeling this 3D problem is both complex and time consuming.

We have found that the bit resistivity shows strong sensitivity to resistivities of the reservoir and non-reservoir beds, and some sensitivity to the value of apparent dip between wellbore and a geological feature that is about to be crossed by the bit. In cases where we have negligible resistivity heterogeneity (ahead of the bit) and without presence of laminae or thin beds immediately above or below the reservoir bed, a reasonable estimation of apparent dip has been made assuming the resistivity of the reservoir and non-reservoir rock can be estimated together with a calculation of first and second derivatives of bit resistivity around the point of inflexion (where the initial decrease is observed).

The laterolog-while-drilling tool (GeoVision) together with azimuthal deep electromagnetic resistivity (PeriScope) provides a powerful combination in solving the 3D formation puzzle surrounding the wellbore, enabling better definition of structures including faults and nearby bed boundaries. The synergy between these two can help maximize well position inside the reservoir rock, enhancing well productivity.

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Example	Apparent Dip	Resistivity	Ratio	d(res)	d^2(res)
A	88	x3	1.9	-2.11	-2.45
B	87	x6	8.6	-6.00	-2.01
C	82	xx0	6.6	-65.00	-2.89
D	85	x0	3.5	-40.00	-4.68
E	68	x2.5	2.5	-6.29	-12.27
F	55	x0	4.4	-22.70	-9.96
G	76	x3	7.0	-43.00	-9.88
H	72	x0	4.0	-9.30	-4.30

Table 1: Relationship between apparent dip (between geological interface and wellbore), and various electrical parameters associated to the bit resistivity. 'Ratio' is the ratio between reservoir and non-reservoir rock resistivities. 'd(res)' and 'd^2(res)' are the first and second derivatives of the bit resistivity curves. 'Resistivity' is the bit resistivity in the reservoir rock

FIGURES

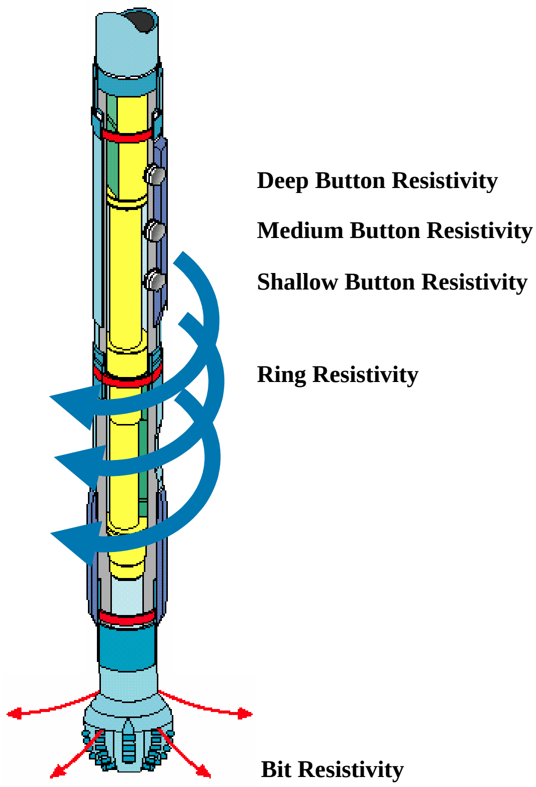


Figure 1: Schematic of GeoVision Laterolog-While-Drilling Resistivity Tool: button resistivity measurements are focused and azimuthal, the ring resistivity measurement is focused and non-azimuthal and the bit resistivity is non-focused non-azimuthal

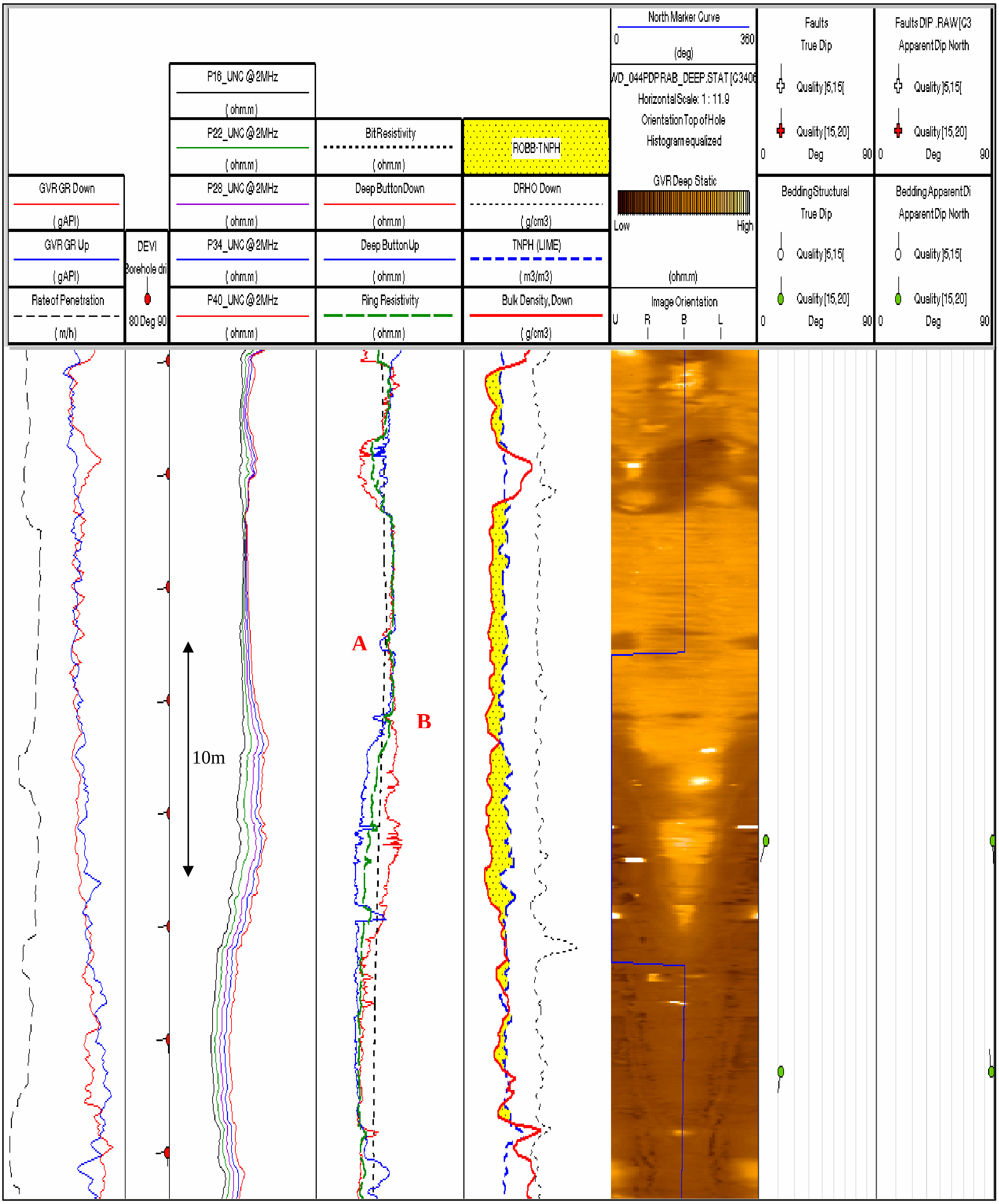


Figure 2: Near horizontal wellbore crossing a bed with negligible structural dip. The bit resistivity detects the presence of a conductive bed with a point of inflexion at A. At point B the deep button up resistivity decreases while the deep button up remains high indicating the conductive bed is located above the wellbore

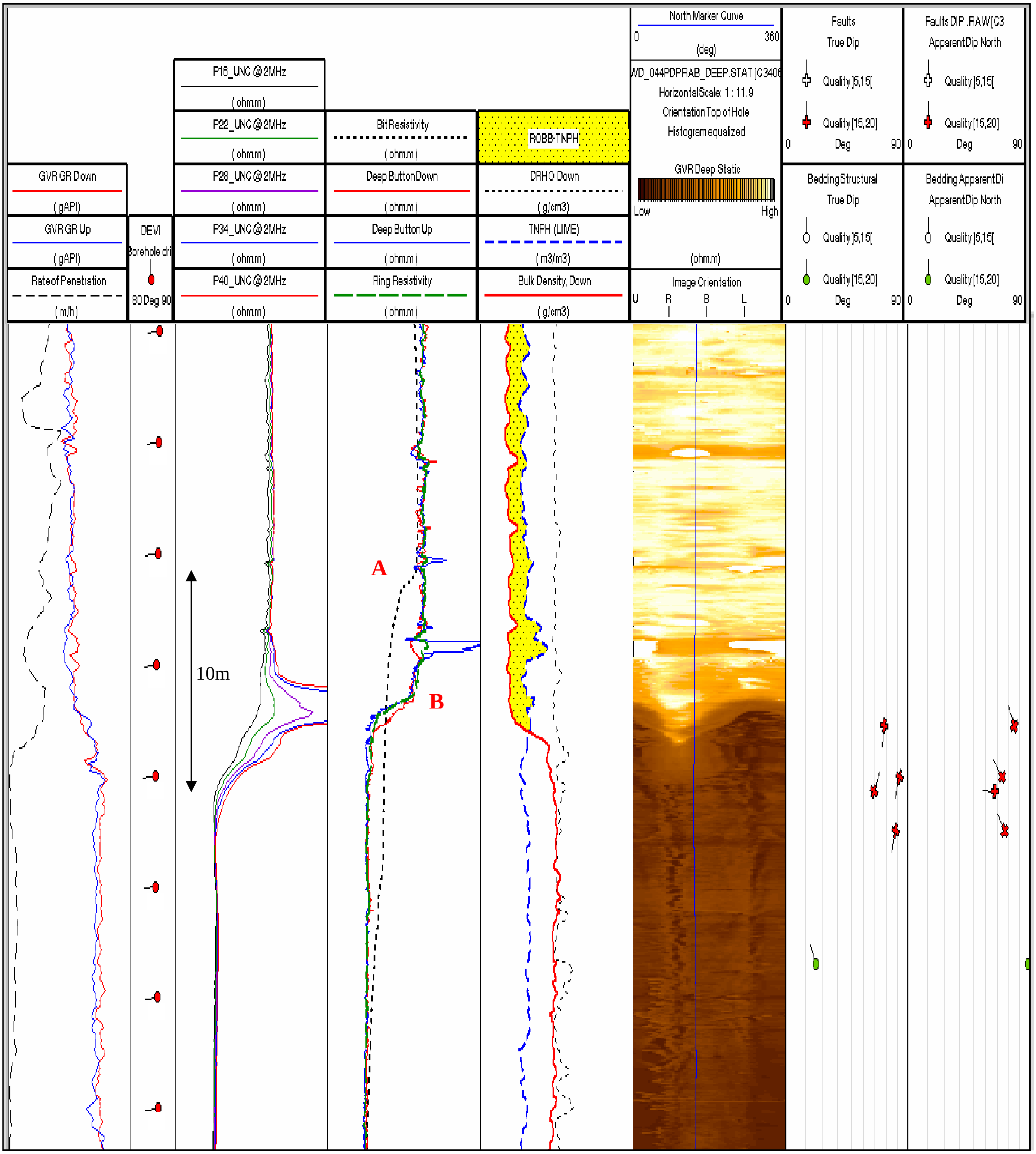


Figure 3: Near horizontal wellbore crossing a sub-vertical fault. At point A the bit resistivity detects the point at which the bit is just about to cross this fault. The bit is located 5.8 meters below point A. Track 7 shows that the true dip of this fault is 68°. At point B the up and down button resistivities are not superimposed indicating that the relative dip between the fault and the borehole is non-zero. The presence of a polarization horn on the 2MHz phase shift resistivity suggests that the apparent dip between the fault and the borehole is relatively high. Track 8 confirms a relative dip of 76°.

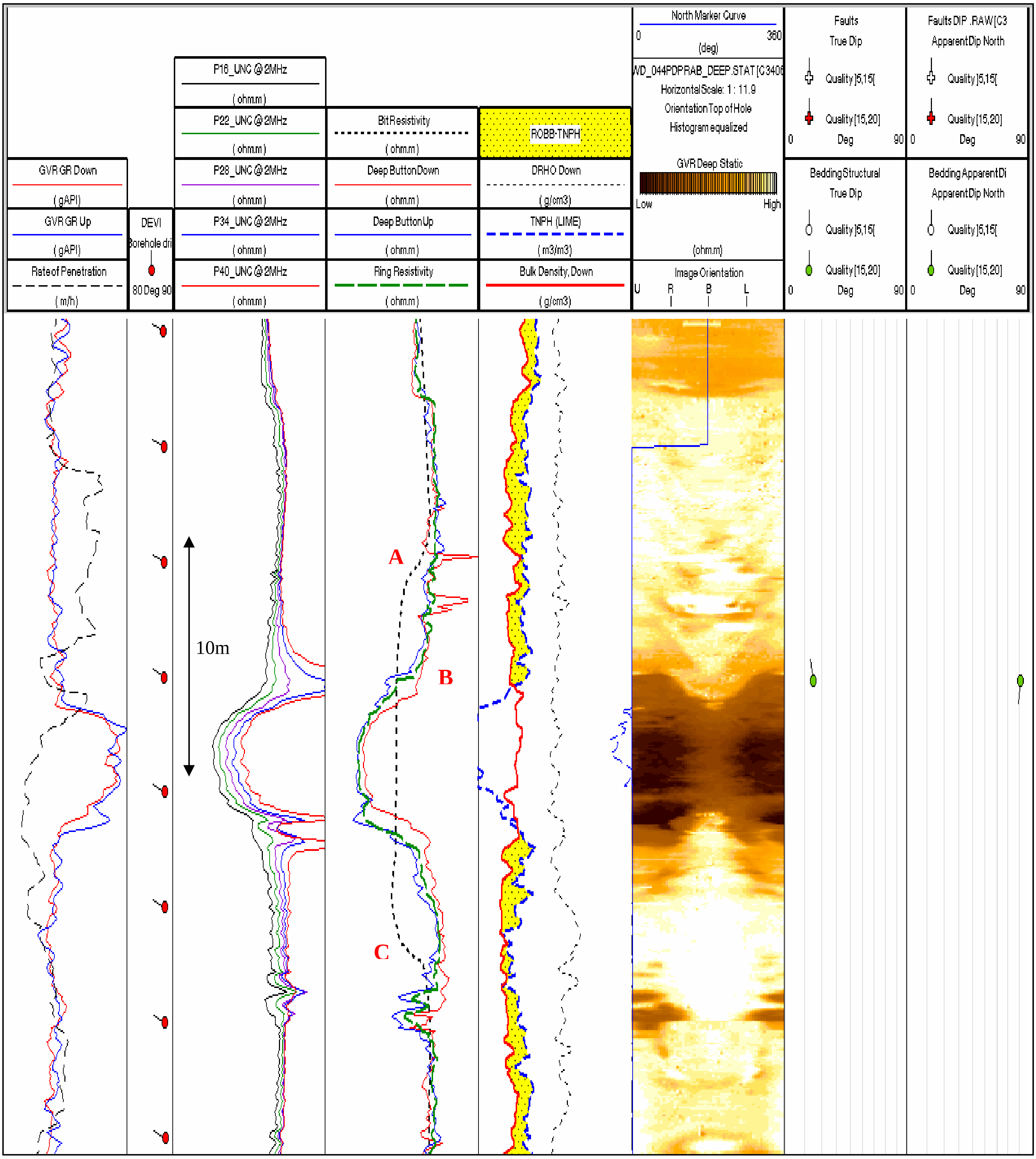


Figure 4: Near horizontal well crossing a channel lens. The true structural dip of the feature is 15° and it is almost strike to the wellbore. The wellbore crosses the feature at high relative dip (82°) and this is consistent with the occurrence of a polarization horn (track 3). The bit resistivity curve (track 4) is sensitive to a conductive bed ahead of the bit since it begins to decrease at point A.

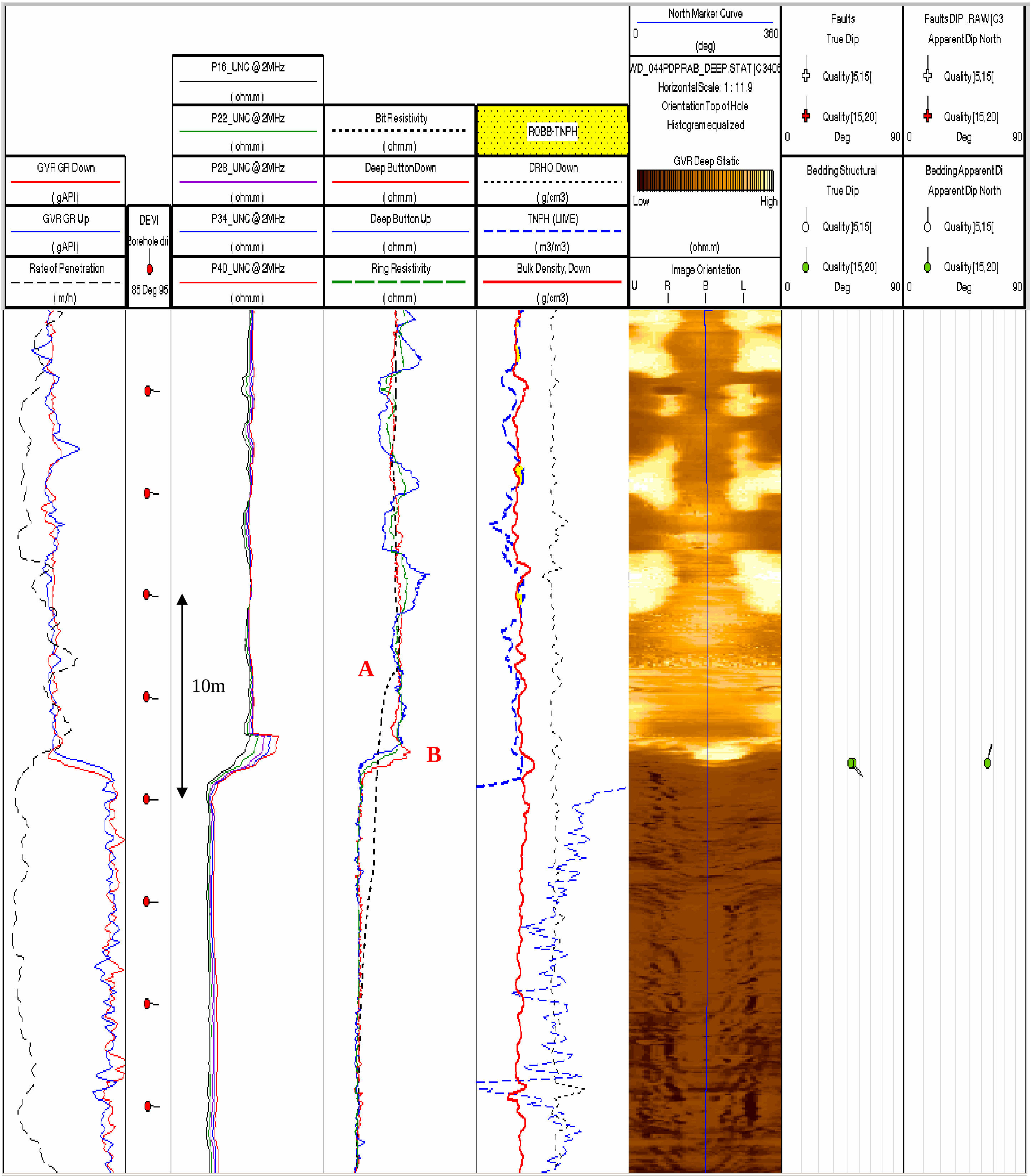


Figure 5: Near horizontal wellbore crossing a shale channel whose true dip is 45° oriented south east. The bit resistivity first detects this channel at point A with a characteristic 'concave' behaviour. The button resistivity curves at point B confirm that the feature does not have zero apparent dip with the wellbore and that we are drilling up-dip

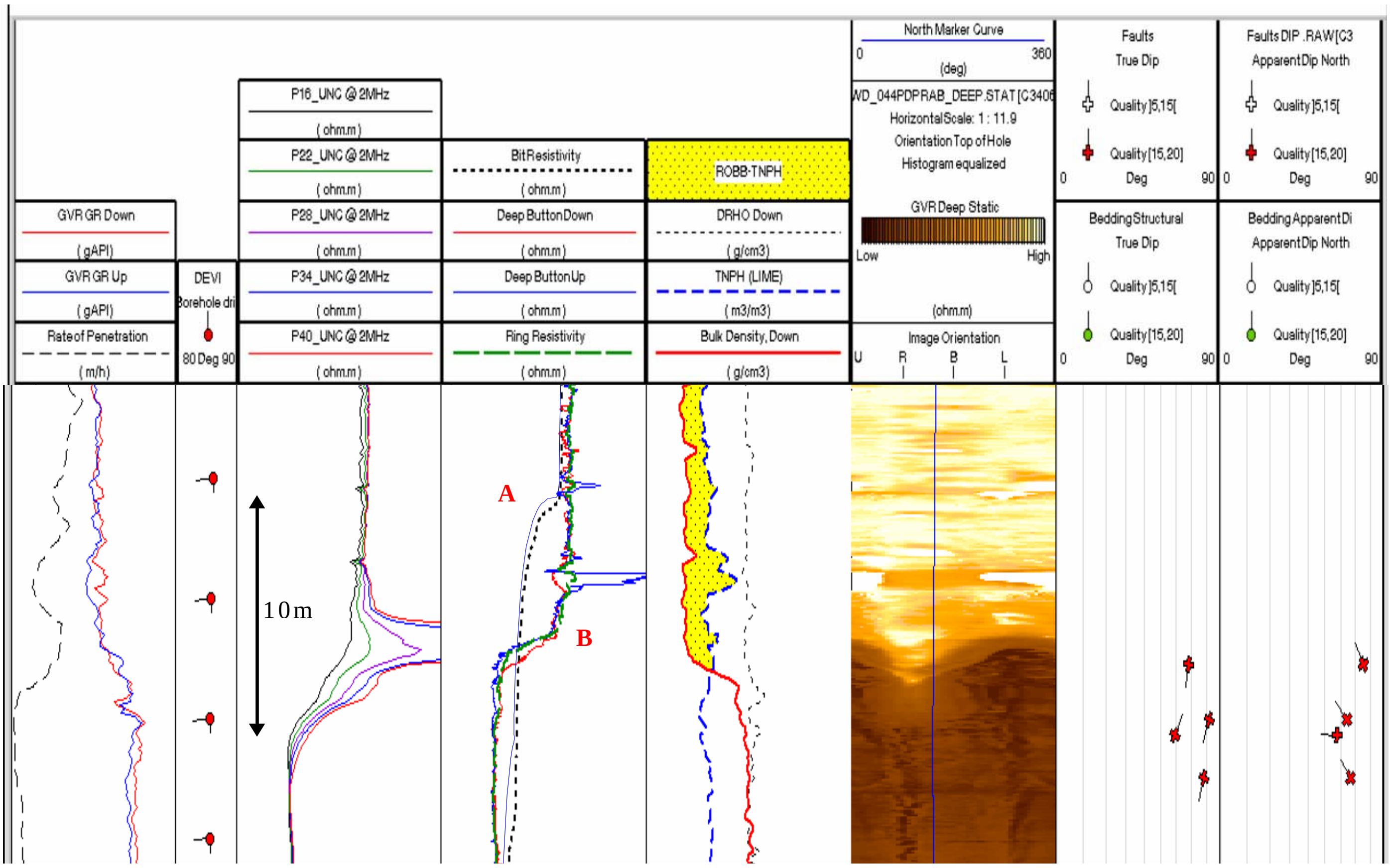


Figure 6: Magnification of figure 3: modeled bit resistivity curve (blue curve) superimposed on field bit resistivity curve (dotted curve). Blue curve modeled for bed resistivity contrast assuming no dip

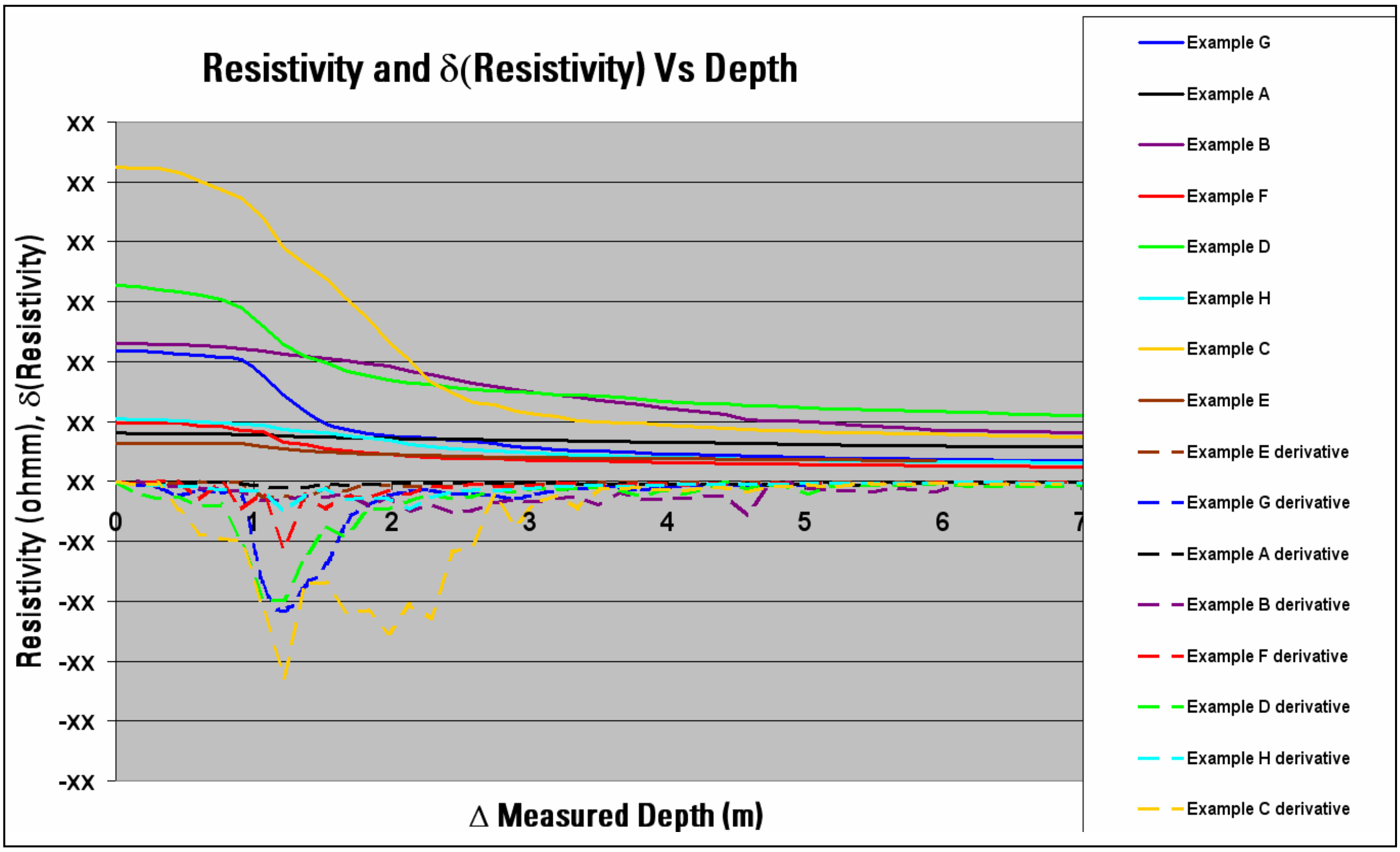
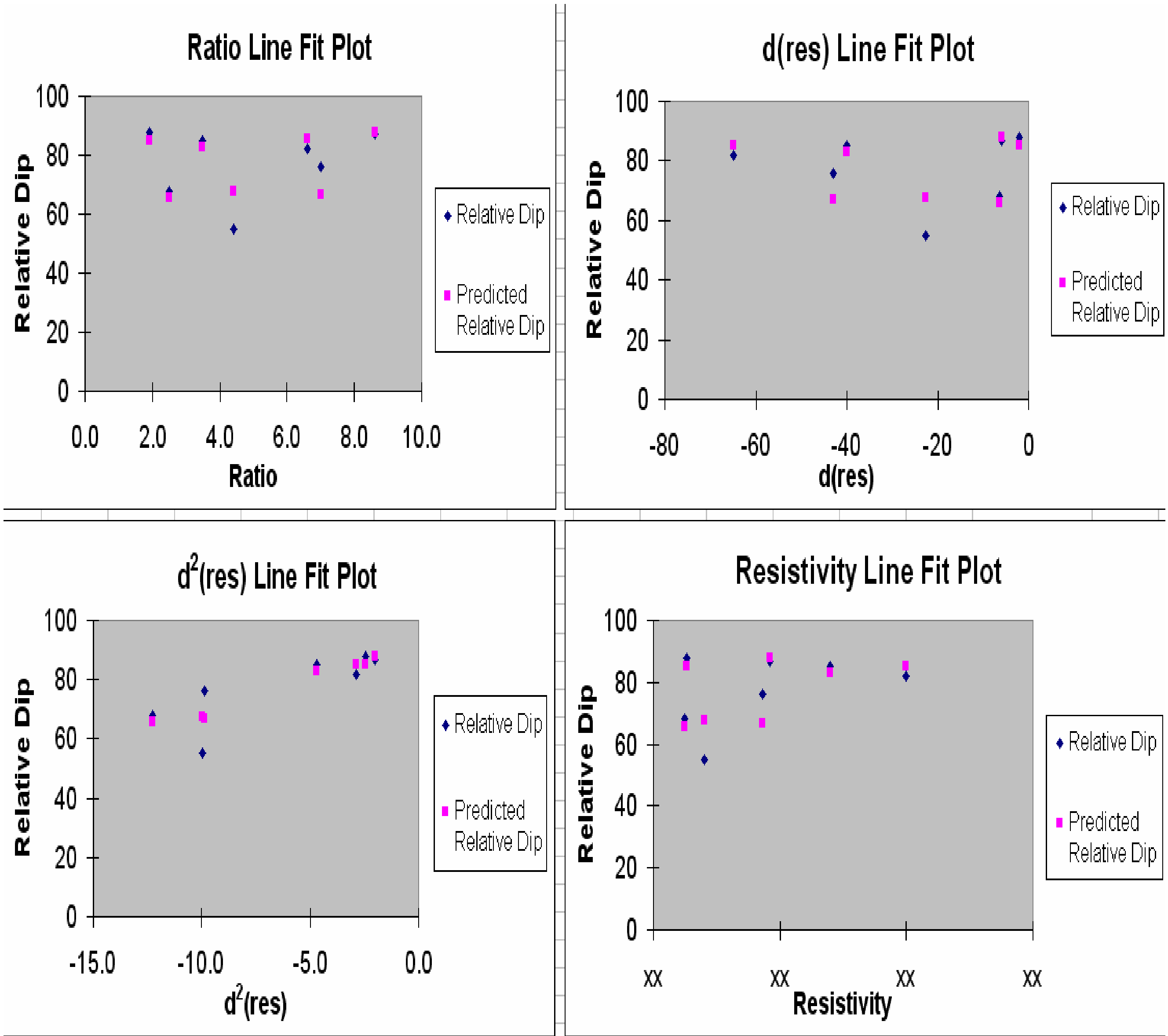


Figure 7: Graphic of bit resistivity (solid coloured lines) versus Δ measured depth for 8 different examples. The dashed coloured lines represent the delta bit resistivity versus Δ measured depth



$$DIP_{app} = a + b.d^2(res) + c.d(res) + d.res + e.ratio$$

a = 88.626 b = 1.854 c = 0.178 d = 0.163 e = -0.420

Regression Statistics	
Multiple R	0.829607
R Square	0.688248
Adjusted R Square	0.064744
Standard Error	11.68154
Observations	7

Figure 8: Results of linear regression performed on all data in table 1 except well H. The multiple R fit of 0.83 shows reasonable correlation. The formula shown here is a universal equation used to relate the apparent dip (DIP_{app}) to a number of variables: d^2(res) is the 2nd derivative of the bit resistivity curve, d(res) is the first derivative of the bit resistivity curve, 'ratio' is the ratio of resistivity in reservoir and non-reservoir rock, 'resistivity' is the bit resistivity in the reservoir rock. The coefficients of the equation (a,b,c,d,e) are calculated using a linear regression. When this equation was applied to the parameters in well H the resulting apparent dip calculated was 75.8°. This compares well with an actual apparent dip of 72° of well H.