Structural Element Analysis, Faults, Fracture and Bedding by Integrating all Geological and Geophysical information, including EDDE, Image Log and Seismic

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Abstract

Understanding flow profile patterns in mature reservoirs is the foremost challenge to overcome when working on maximizing production in brown fields. To this effect, the new 3D Reservoir Mapping While Drilling (RMWD) capable of detecting water floods and reverse coning hundreds of feet away was combined with a high-resolution electrical image for structural and diagenetic feature analysis along seismic and more acquired data in a Lower Cretaceous reservoir onshore Abu Dhabi.

The 3D RMWD uses a modular Logging While Drilling (LWD) tool comprised of one transmitter and two receivers. The transmitter would fire Electro Magnetic (EM) wave signals in a large range of frequencies, collecting channels with 360 degrees sensitivity and with a depth of investigation nearing 400ft True Vertical Depth (TVD) in radius around the wellbore. Several longitudinal and transverse inversions are run revealing a resistivity map of the reservoir that can be tied to the seismic data. Field scale information is integrated with near microscopic borehole level data from the electric image and logs, to cement the understanding of reservoir dynamics.

The Ultra High-Resolution Image (UHRI) interpretation showed resistive and conductive fractures and ones with displacement. Textural and fracture aperture analysis gave insights into possible fluid flow patterns alongside the features' dip and azimuth. The displacement was confirmed by the RMWD where a visible shift close to 8ft TVD was calculated at the fault depth picked on the image. Reverse coning was observed on the RMWD inversions around the fault zone. Seismic data and field knowledge showed the possible sources of the water onset based on nearby well injectors combined with the direction of the larger fault plane connecting both. Water flooding was detected at distances ranging between 75 to 90 ft TVD from the borehole. Drilling polarities were extracted from the UHRI to combine bedding planes and faults into a true stratigraphic thickness output, which when integrated with reservoir scale RMWD interpretation leads to a

multi-structural scale analysis and a static geomodel update. A 3D volume was generated revealing the reverse coning dimensions and flooding directions relative to the well's azimuth. Higher water saturations were resolved for on one side of the wellbore compared to the other, offering a vital information into the dynamic reservoir model.

An understanding of the full reservoir fluid dynamics gave way to optimizing placement and completion of a single wellbore. Integrating information from reservoir to borehole scale, allowed the mapping of the reservoir layers, water flooding and reverse coning along with connecting fractures and overall image interpretation to the understanding of water flow patterns. Lower completion was re-designed to isolate high water saturation zones, and new wells will be planned based on the novel 3D field information.

Introduction

A mature carbonate reservoir in Onshore Abu Dhabi has been producing injected water unexpectedly. This water production is the result of water slumping or reverse coning which is a complex dynamic behavior occurring in an environment with numerous but specific reservoir conditions: high permeability streaks at the top units of the reservoir and low permeability at the base of the geological formation coupled with negative capillary pressure, peripheral water injection in both formations and change in reservoir pressure due to nearby well oil producers, vertical permeability heterogeneity and finally, presence of tectonic events. These pre-existing geological settings coupled with long term oil production and water injection, resulted in the fluid travelling horizontally to unknown extents above or within the reservoir itself. Therefore, to maximize the returns from brown fields, it becomes imperative to understand the flow patterns of the water movement and be able to map its occurrence around the horizontal wellbore, to optimize completion and extend the well production life. This paper is a case study whereby, seismic, ultra-high resolution electrical images and three-dimensional (3D) Reservoir Mapping While Drilling (RMWD) technologies were integrated to, not only map and identify, water front's positions and volumes, but also determine the dynamics driving their occurrences.

Job Planning and preparation:

The 6in horizontal section was planned in a subunit at the base of the reservoir where the oil saturation and potential production output is believed to be the most promising. Nearby offset wells, do show that some of the upper subunits are flooded (figure 1).

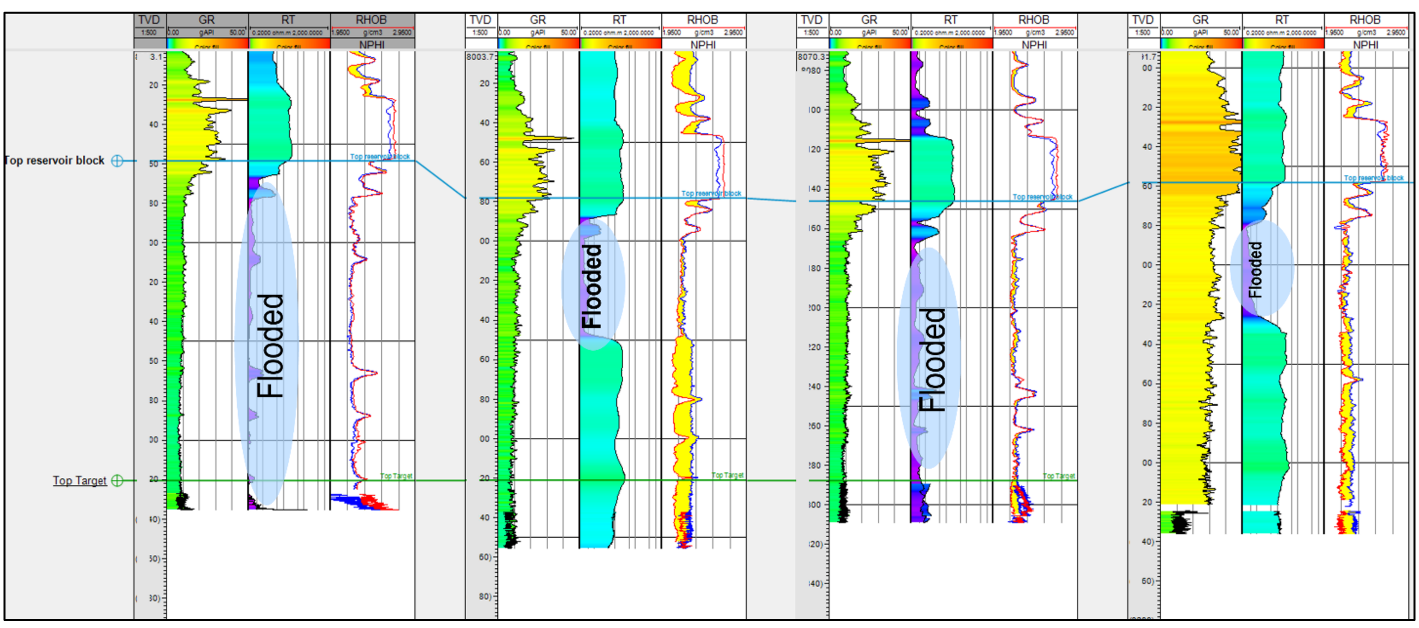

Figure 1: Horizontal offset wells, showing the flooded zone with a resistivity of 0.5 ohm.m and non-flooded zone with a resistivity of around 13 ohm.m.

There is currently not enough input to build a comprehensive database to properly simulate the size of the water flooding. One main variable that is mostly unknown, is the extent and connectiveness of the conductive fractures along with the dispersion of heterogeneities. The Ultra High Resolution Images (UHRI) has a vertical resolution of 0.4in and is based on a focused and calibrated laterolog measurement with azimuthal sensitivity. Acquiring this image while drilling will give the insights needed to understand the tectonic implications in means of fractures and displacement identification around the wellbore and its impact on the fluid movement. And to be able to identify the hydrocarbon from the water, the 3D RMWD was used. It is a modular Logging While Drilling (LWD) tool that uses one transmitter and two receiver's subs. A new transmitter hardware sends a powerful signal burst ensuring a deeper EM waves' traveling depth and longer transmitter – receiver spacing with less noise effect. 1D longitudinal and 2D transverse inversions are run to reveal a resistivity map of the reservoir that can be tied to the seismic data. A 3D volume is generated from this resistivity map extending over 100ft radius around the wellbore.

In order to optimize the Bottom Hole Assembly (BHA) and data to be transmitted in real time, a feasibility study was run in a flooded and non-flooded scenario. A geological cross section was created using the surfaces from the geomodel in the direction of the planned horizontal well and populated with the properties of the offset wells. The RMWD tool's response was then simulated taking into account both the geometry and petrophysical values. Results are shown in figures 2 & 3

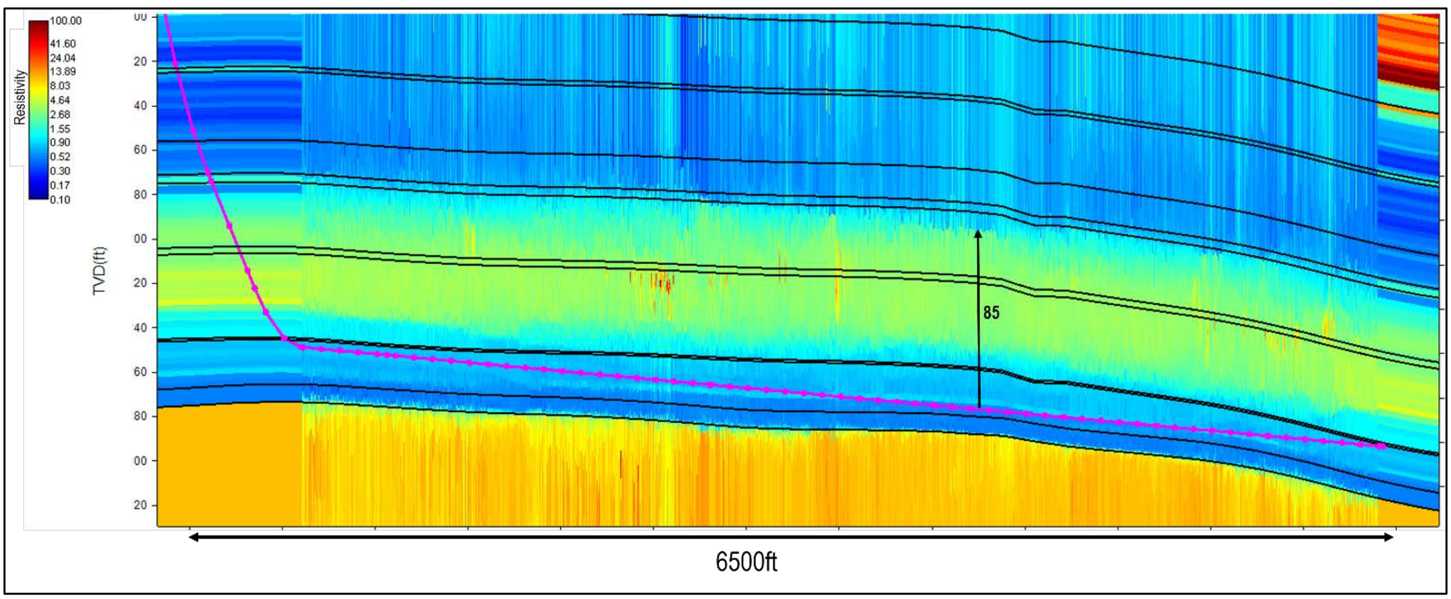

Figure 2: 1D longitudinal inversion results in a target with high water saturation and with flooding in the upper half units of the reservoir block.

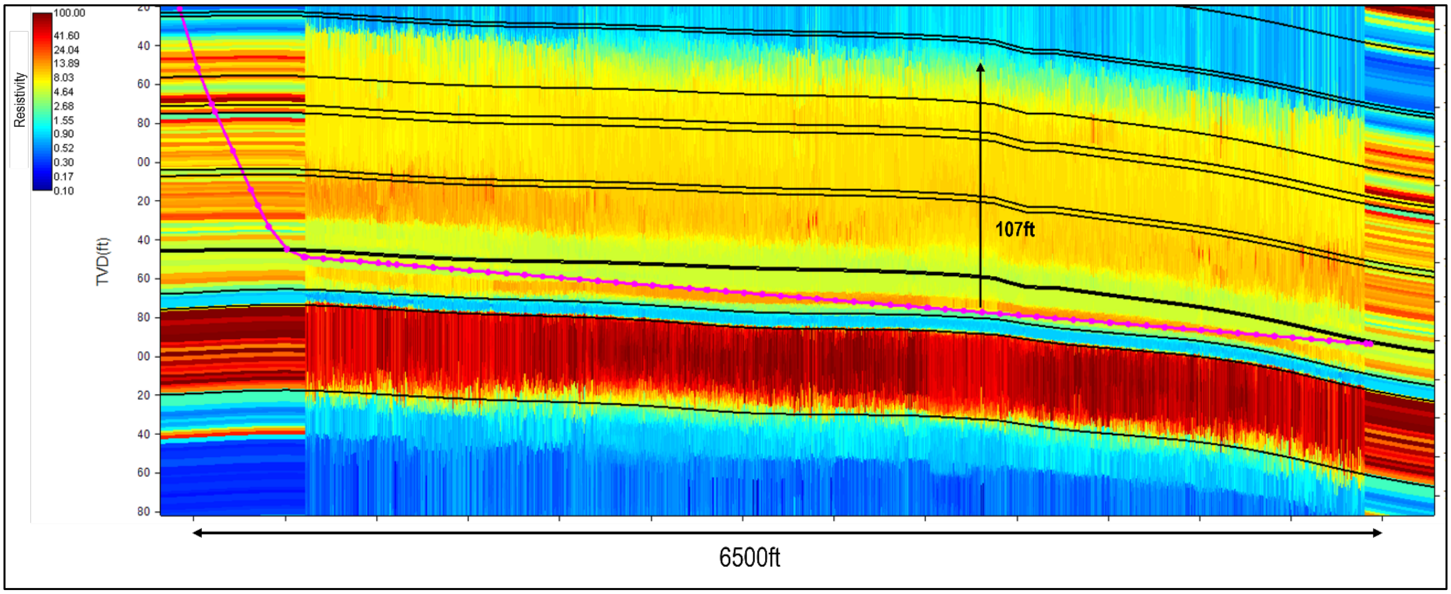

Figure 3: 1D longitudinal inversion results in a target with high oil saturation and with flooding in the upper reservoir units.

The feasibility study results gave confidence that flooding could be mapped with a Depth of Detection (DOD) larger than a 100ft TVD radius.

The final BHA to be run would comprise of a motorized Rotary Steerable System (RSS), one transmitter and two receivers, the propagation resistivity and the resistivity image tools along with the density neutron (figure 4). With this configuration, we were able to achieve a Transmitter-Receiver spacing of 119ft.

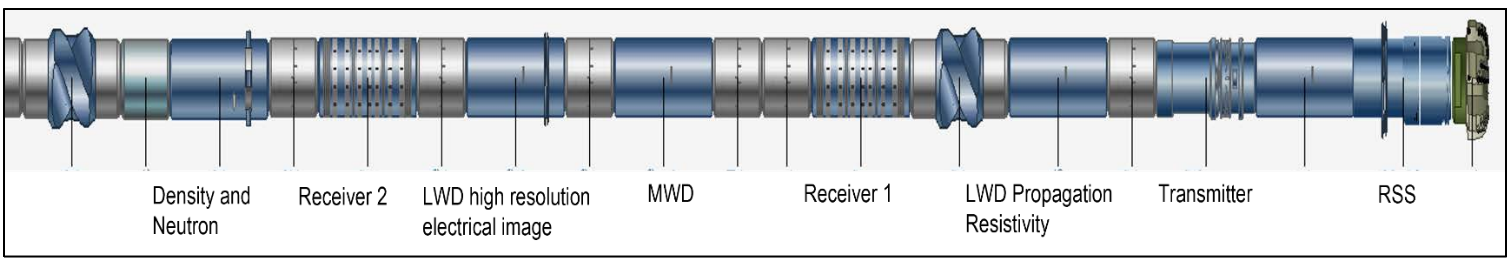

Figure 4: Final BHA used for the job execution

Execution and results:

A total of 5810ft MD were geosteered in a target zone with a thickness ranging between 8 and 13ft. The high-resolution electrical images were used to compute apparent dips in real time alongside the 1D longitudinal inversion from the RMWD. A 12 KHz frequency bandwidth was used for telemetry, so there was no need to control drilling speed to get good data updates. The final real time results are shown in figure 5.

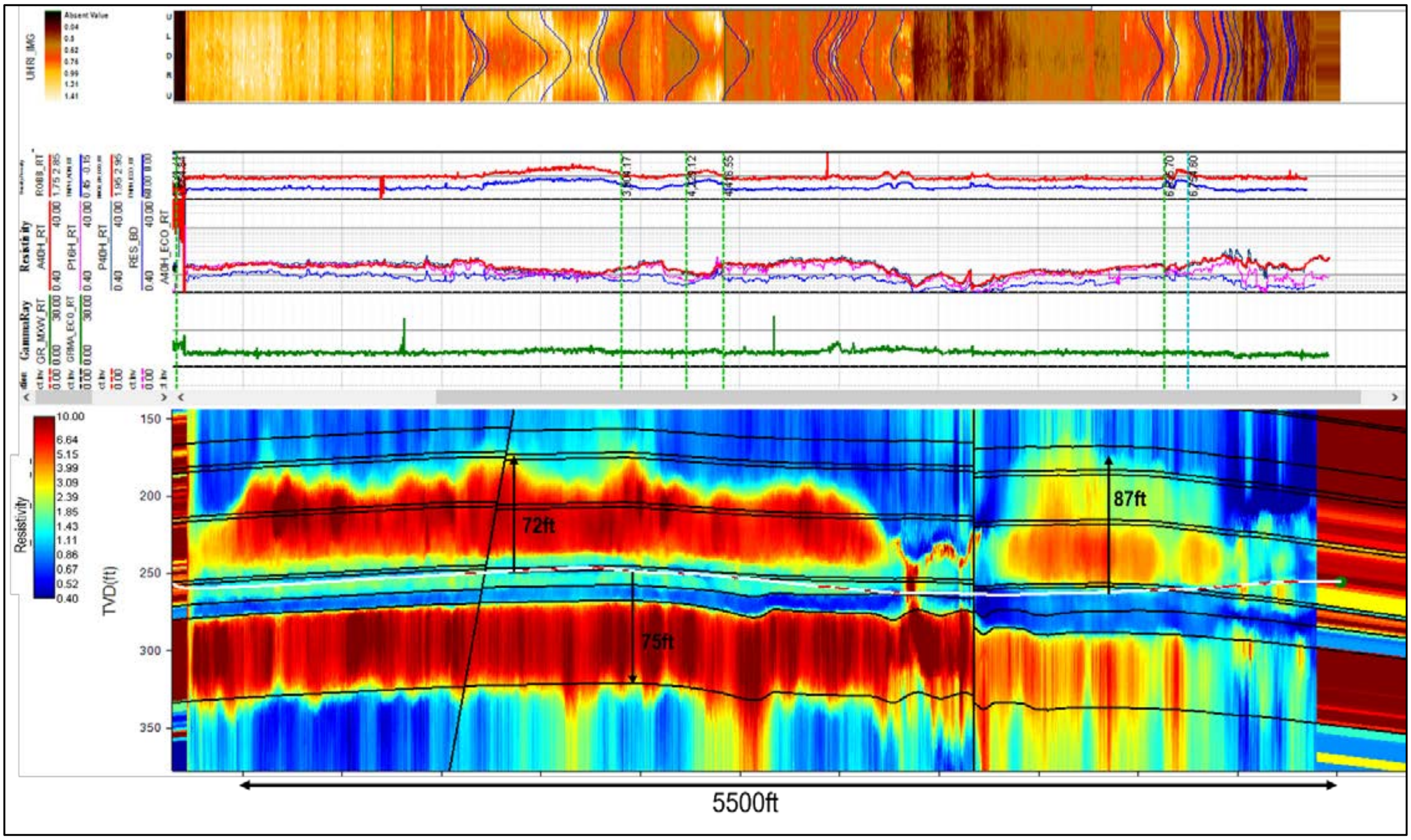

Figure 5: Real time cross-section showing the horizontal section well trajectory at TD in white. The real time high-resolution electrical image is on the top horizontal track with the density (red) and neutron (blue) in the track below followed by the resistivity and the GR tracks.

The sinusoids shown on the image track are the bedding dips picked and the corresponding apparent dips in the well drilled direction and are represented as the red dashes on the trajectory. The final model has been updated to match the computed bed boundaries' angles to horizontal. Two faults were picked from the image. The first one has no apparent displacement as confirmed by the 1D inversion. A displacement of 8ft TVD is observed on the RMWD inversion at the second fault's depth, which plane was identified and interpreted on the electrical image.

The 1D longitudinal inversion mapped multiple layers up to a distance exceeding 90ft TVD. The target layer was mapped alongside the 8ft TVD high conductive layer at the base of the reservoir block. Flooding was detected between 70 and 90ft TVD above the trajectory, in line with the tendency in the offset wells. A higher resistivity layer was mapped above the target layer, and the 40ft TVD thick dense limestone separating two reservoirs' blocks was solved for in a consistent and continuous manner. The RMWD 1D longitudinal inversion was also able to detect the top of the second reservoir block below the dense barrier. A clear change in the conductivity profile was observed after crossing the second fault, where the target zone's resistivity dropped, and decision was taken to drill in the upper units looking for better oil saturation zones. The most interesting feature found on the RMWD in real-time however, was the reverse coning detected in the 500ft interval preceding the fault depth. Advanced image interpretation, 2D transverse inversions and 3D volumes were performed to properly evaluate and understand this occurrence.

Post-drill processing and interpretation:

The high-resolution electrical image with 160 sectors from 8 buttons with 0.4 in diameter, was interpreted from the recorded mode data. The final results are shown in figure 6.

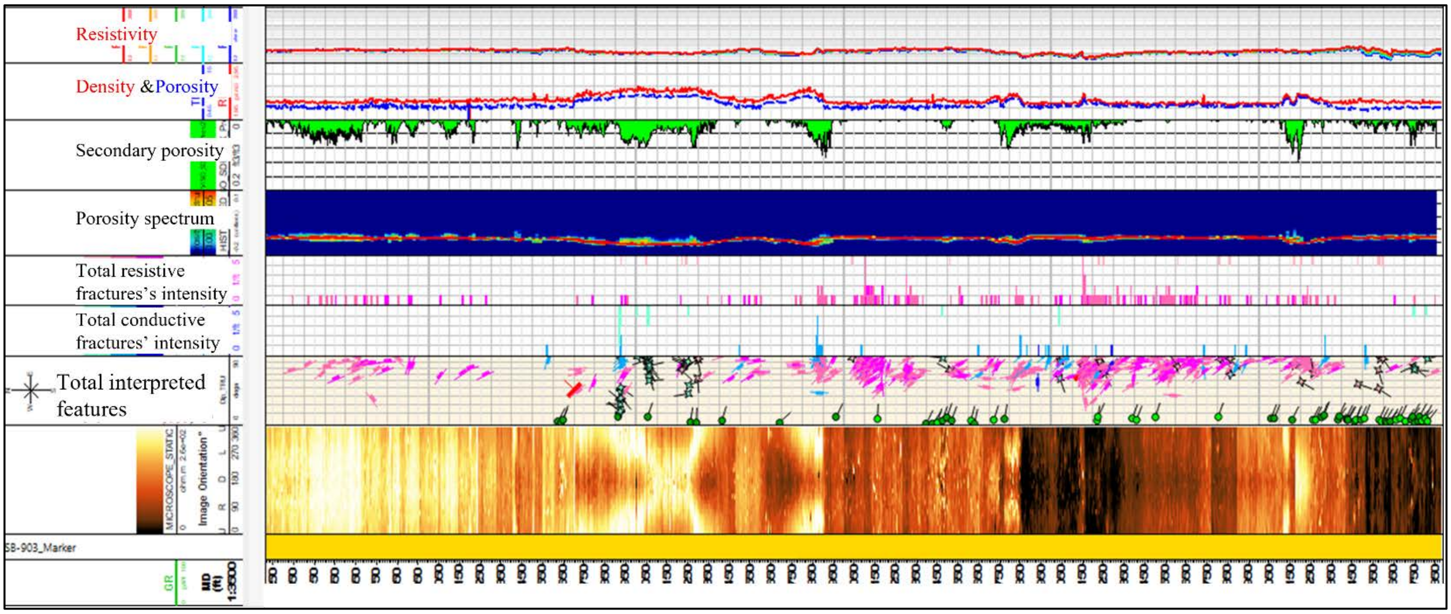

Figure 6: Final image interpretation showing the bed boundaries, conductive and resistive fractures, faults, and secondary porosity generated from the fractures. Depth scale: 1/3500ft.

Bed boundaries (beddings) were identified with a computed average structural dip of 4.7 / N116.1. A total 436 fractures were picked, either resistive or conductive, and classified as continuous, discontinuous, and segmented. These fractures have a general trend of NW-SE which is parallel to the regional fault trend and a mean true dip near vertical. The natural fracture layout and connectivity generally have a huge impact on fluid flow in hydrocarbon reservoirs. Characterizing the natural fractures (length, aperture, and volume) is therefore essential in order to provide an accurate estimation of the oil reserves and of the reservoir producibility. Borehole images acquired while-drilling, are very convenient to that purpose. Fracture attributes have been estimated for Continuous and Discontinuous Conductive Fractures which may be possibly open using the Luthi-Souhaité method, which is based on the evaluation of the excess current flowing through a fracture from the measuring button electrode.

Maximum fracture aperture computed is 0.7 mm and maximum fracture porosity of 0.1 % is noted. The final plot is shown in figure 7.

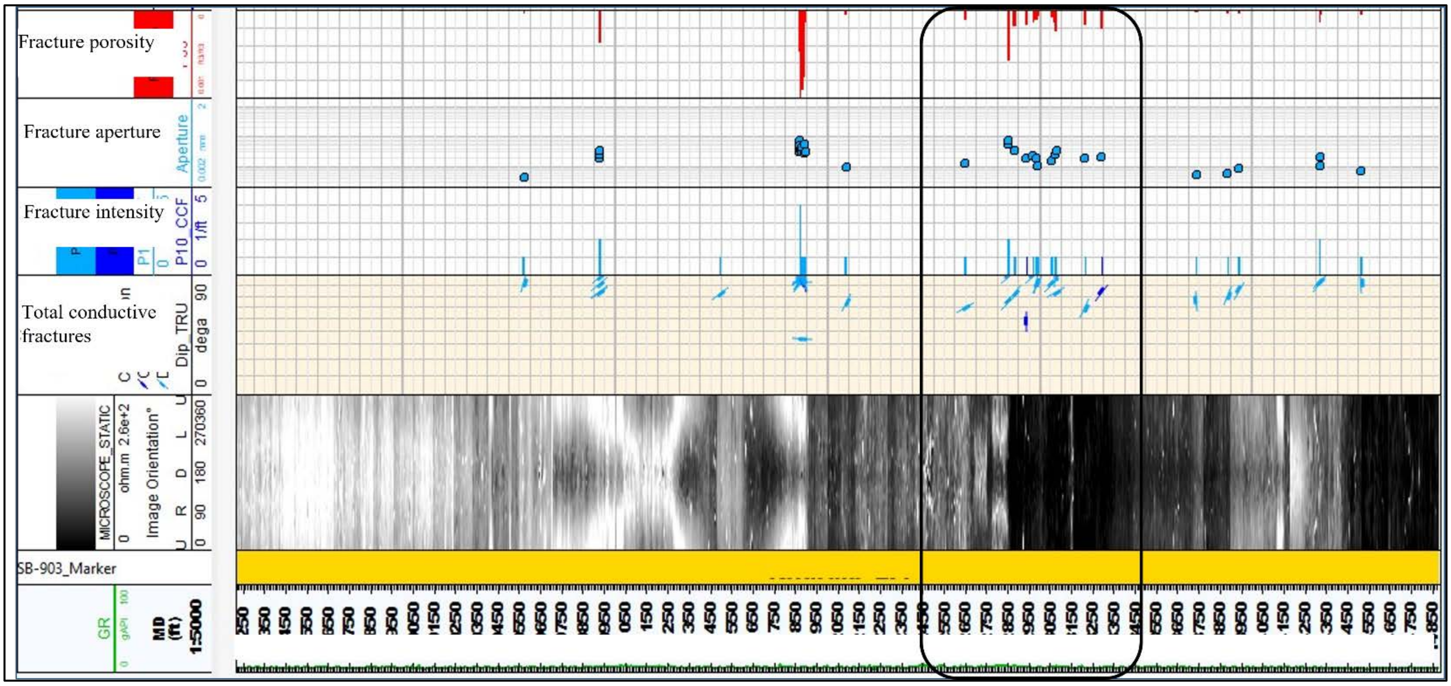

Figure 7: Final fracture aperture computation from the conductive fractures picked along the borehole. Note the conductive fractures' cluster in the highlighted interval. Depth scale: 1/5000ft.

These conductive fractures were plotted on the well trajectory cross-section alongside the 1D longitudinal inversion (figure 8). The first noted observation was that the reverse coning from the RMWD is mapped at the same depth interval of this fractures' cluster.

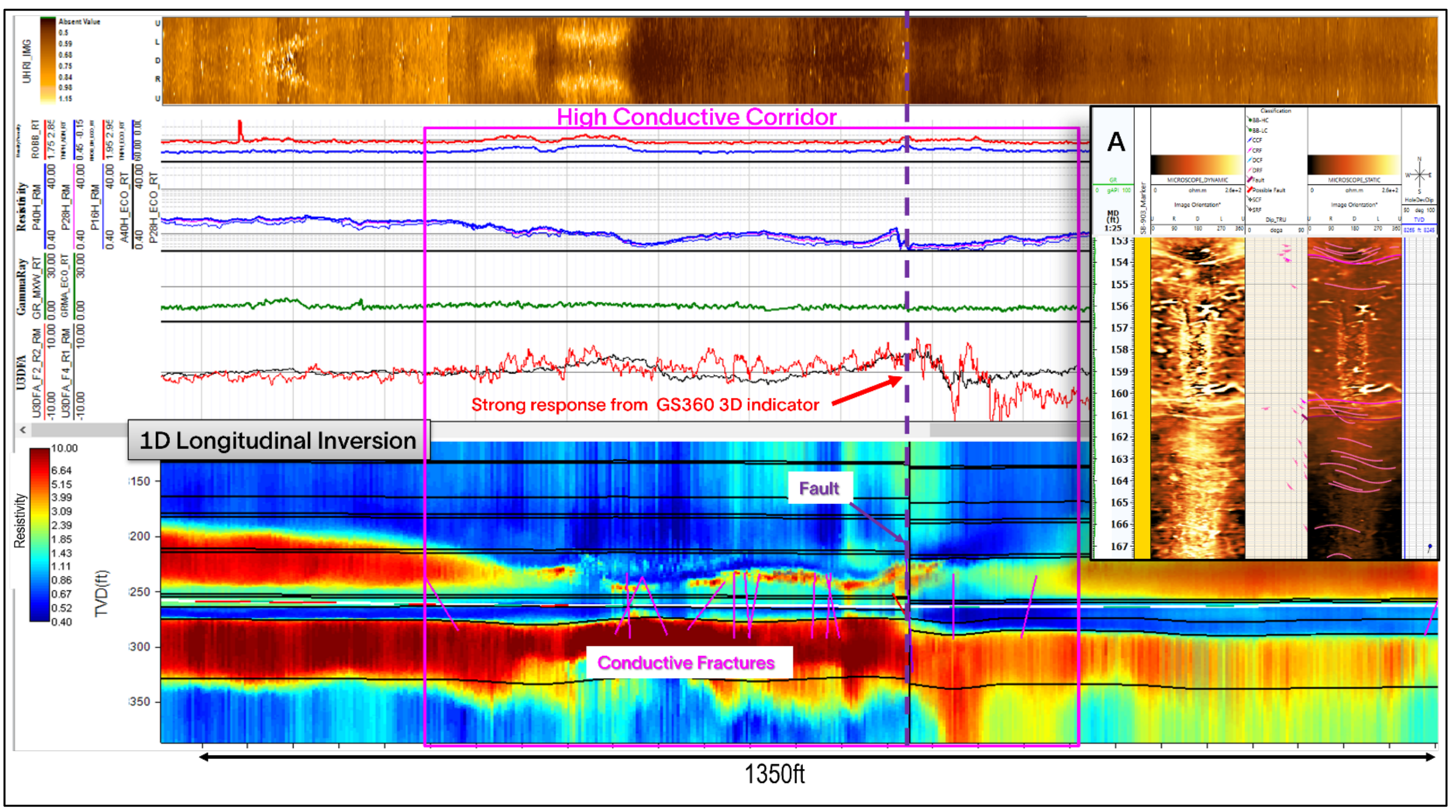

Figure 8: Conductive fractures plotted along the trajectory, correlating with the reverse coning from the RMWD 1D inversion. The fault with displacement is also shown. The electrical image is on the top track

followed by the density neutron track, resistivity and GR. The last track shows the three-dimensional channels from the RMWD LWD tool. **A:** The high conductive corridor's interval's corresponding fractures' interpretation on the high-resolution image. The dynamic image is shown on the left and the static on the right. Depth scale: 1/25ft.

Within the reverse coning's interval, the 3D channels are strongly reacting to the observed petrophysical and geological events, indicating that they are extending around the wellbore as well. To this purpose, the 2D transverse inversions and 3D volume were run to estimate the extent of the water slump laterally around the trajectory. The deep directional measurements have 3D sensitivity all around the wellbore, with a depth of investigation equal to the longest transmitter – receiver spacing. With no assumptions made on the formation properties, a Gauss-Newton inversion is run by discretizing the 2D transverse imaging plane using a non-uniform pixel distribution (Thiel & Omeragic, 2018). The lateral resistivity distribution solves for multiple layers and confirms the expected formation properties and thicknesses. The 2D transverse inversion has a depth of investigation of 125ft on each side of the well and is mapping the flooding above the trajectory and the thick dense barrier below. Figure 9 shows the initial transverse inversions results (to the left) and the resulting computed 3D resistivity volume (to the right). A general observation would be an overall tendency for the highest conductivity to be located on the right side of the well. At the reverse coning interval, the flooding appears to be spreading deeper than the limits of the transverse inversion. This indicates that an extensive water slumping has developed in this area, where conductive fractures and faults are present with a water movement in the NWW-SEE direction, which is similar to regional fault trend of NW-SE.

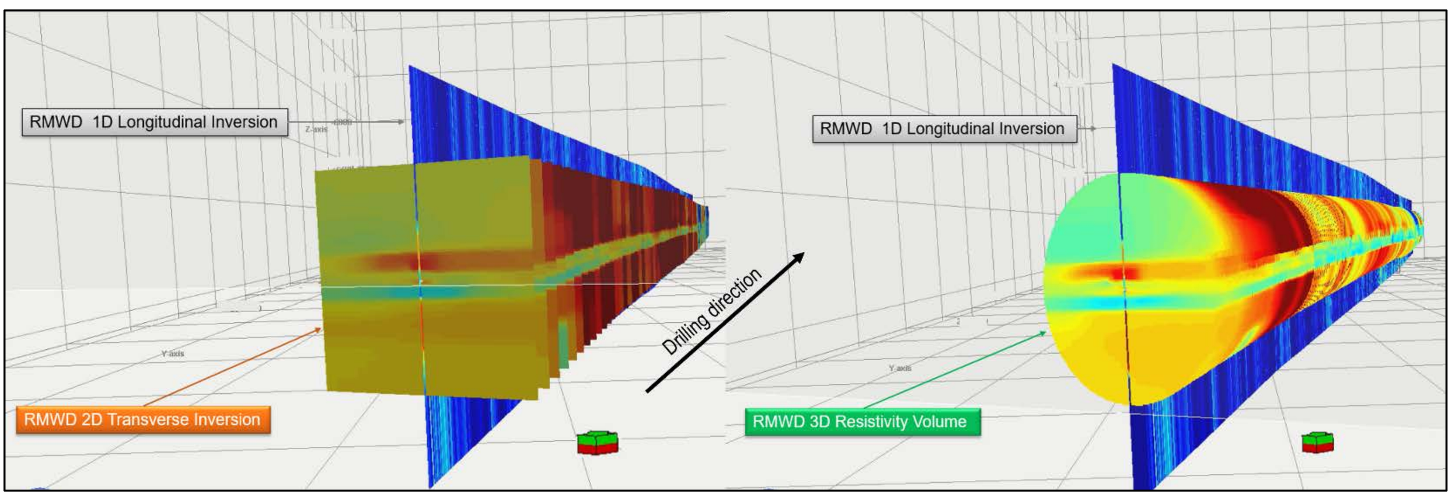

Figure 9: 2D transverse inversion slides to the left an 3D resistivity volume to the right.

A closer look was taken to the reverse coning volume as seen in figure 10. It extends 550ft MD longitudinally, and over 250ft laterally, beyond the tool's depth of detection. The transition zone before and after the water slump along the drilling direction is also mapped above the trajectory. Resistivity filtering with a cutoff of 0.8 ohm.m was applied to visualize the high-water content zone from the producible zone. The dense barrier is also seen at the bottom of the cylinder.

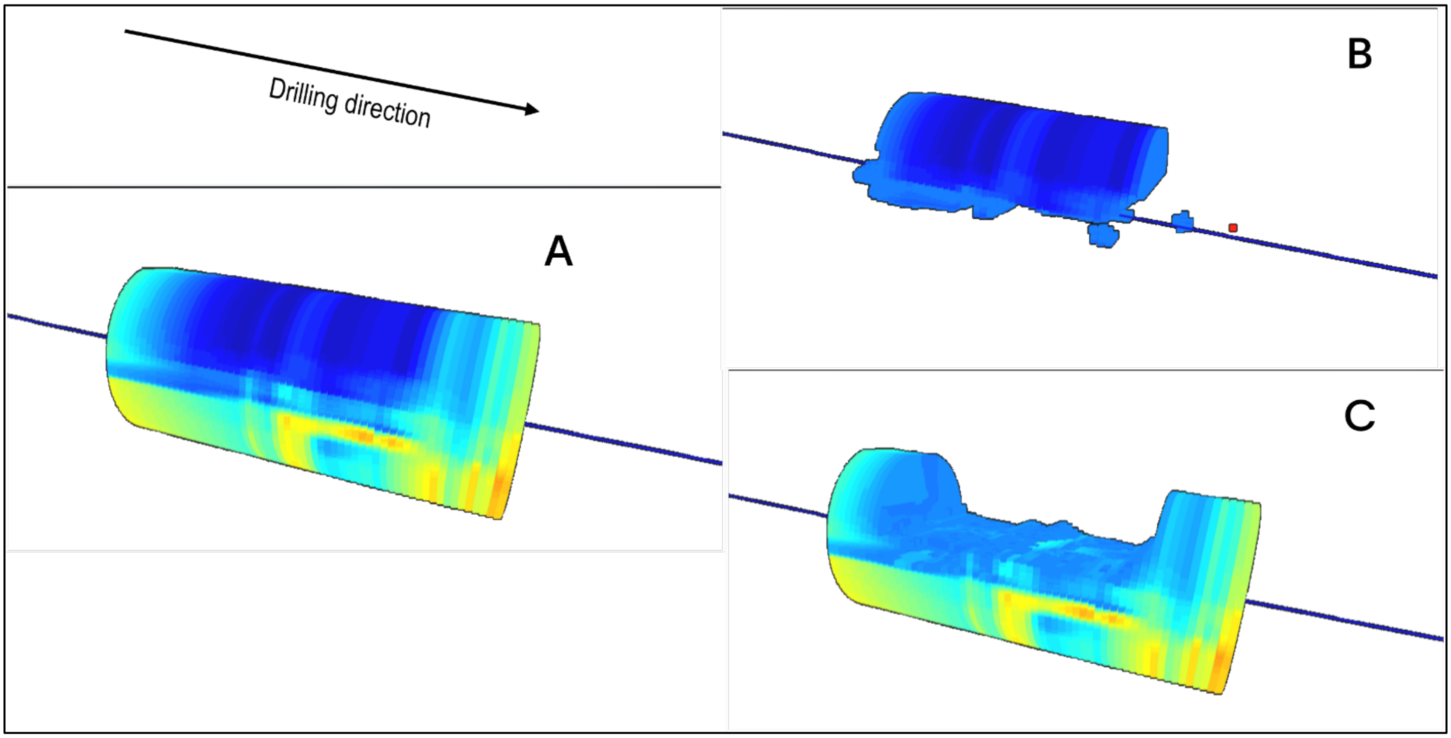

Figure 10: Visualization of the reverse coning. **A:** Full 3D volume cylinder. **B:** Filtering at 0.8 ohm.m. Only values with associated resistivities less than 0.8 ohm.m are displayed. **C:** Values with associated resistivities higher than 0.8ohm.m are displayed. The cone shape and volume can be analyzed and computed separately.

The water flood was identified and mapped. To better understand the dynamics behind this phenomenon, the results were integrated with the seismic cross-section and the picked fractures (figure 11). Since the faults encountered are sub-seismic, they are not visible on the slice, but the RMWD results are deep enough to be correlated with the seismic's interpreted surfaces and both show the same general dip trend. With the incorporation of the conductive fractures, the relationship between them and the conductivity profile becomes evident. Horizontal water movement can start flowing vertically through a fracture plane which acts like a conduit, creating different saturation profiles on each side of the tectonic break. In this particular case study, it is believed that the higher concentration of conductive fractures around the fault area has hastened the water flow from the top reservoir units, creating this reverse coning effect.

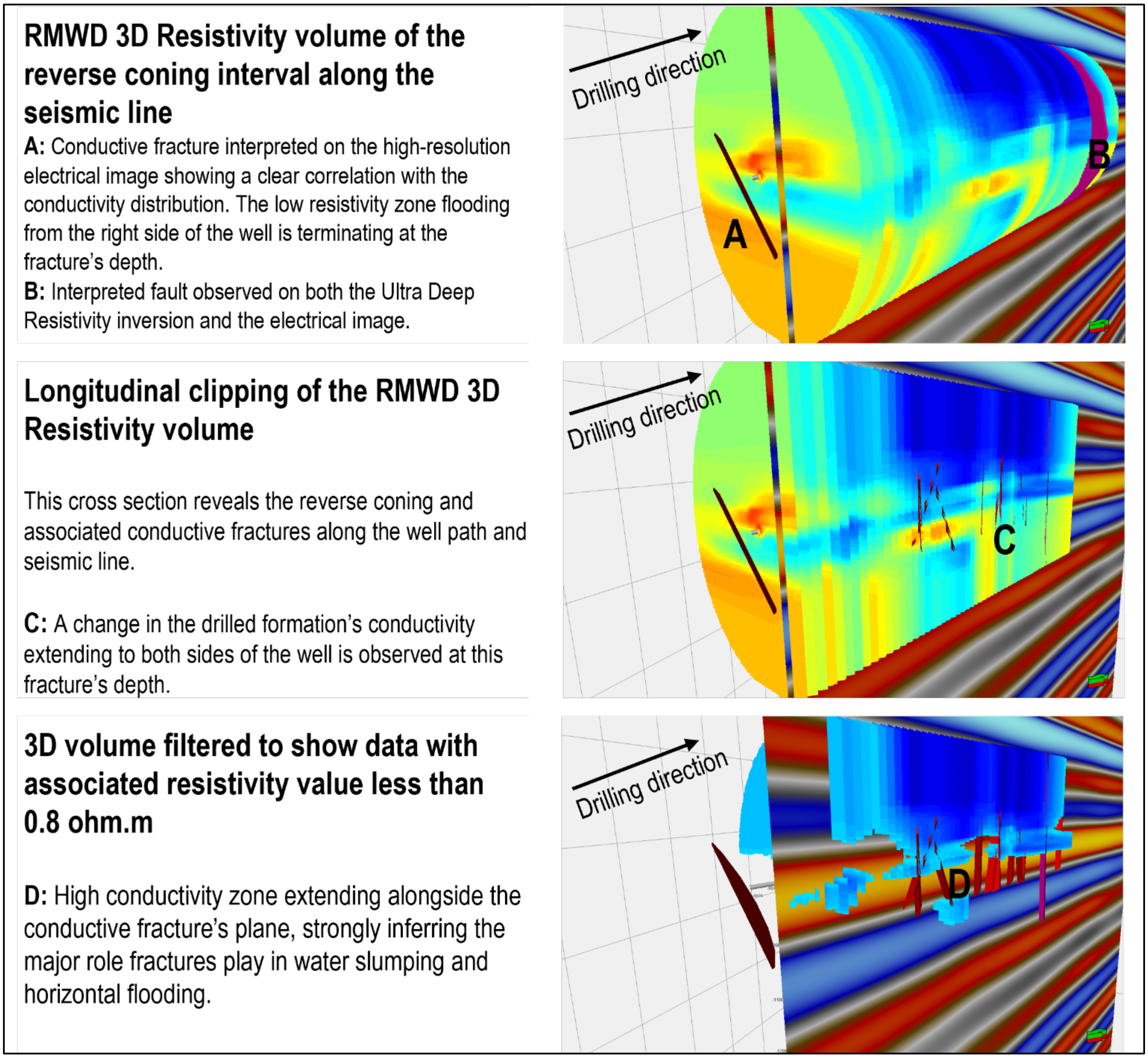

Figure 11: Integration of 3D Resistivity volume, seismic and fractures at the reverse coning interval

Conclusion

The conditions behind the onset of water fronts and water slumps are many, and their impact on the oil production is serious. To further optimize and extend the production from these mature reservoirs, using the right technology to gather a comprehensive set of information becomes key. The vertical and lateral extent of the water were mapped through the 3D Ultra Deep Resistivity technology on a reservoir level, they were then integrated with the fractures' interpretation from the high-resolution electrical image on a borehole level and correlated on a seismic scale. The completion was designed to blanket and isolate these never-before-seen zones. It prevented a planned side-track in the advent of early water production. As the knowledge of the water movement across the field expands, so will the future development plans and reservoir production simulations. It will enable a smarter and more cost-efficient planning for the upcoming wells to be drilled.

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