Utilizing High-Resolution LWD Images to Improve the Well Productivity by Maximizing Reservoir Contact and Optimizing Completion Design in Carbonate Reservoirs

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Abstract

Developing thin, fractured carbonate reservoirs is challenging due to the associated geological complexity. While these reservoirs seem attractive to target, they represent many challenges in terms of drilling, well placement and production, in addition to understanding the geological variation.

The main challenges attributed to the development phase are primarily drilling horizontal laterals steered in thin reservoirs and maximizing the reservoir contact; secondly, determining the zones with high concentrations of extended natural fractures that would affect the well productivity by driving the water and, hence requiring zonal isolation. Both challenges are addressed through utilizing a high-resolution, laterolog-resistivity imaging tool, which has multiple depths of investigation that are not affected by bed boundaries, unlike electromagnetic wave resistivity, and which enhances the petrophysical evaluation of such thin reservoirs. In addition, the uncompensated measurements facilitate better understanding of the variation in carbonate reservoirs.

An innovative workflow was implemented for achieving optimum reservoir contact by using the real-time image and at-bit resistivity. This enabled the geosteering engineer to make changes quickly to keep the well trajectory in the sweet spot. This paper provides examples of the integrated workflow from job planning to post-job analysis and interpretation of the high-resolution recorded image for reservoir characterization. This is used to identify the fracture framework and structural information, which helps with designing intelligent completion stages by isolating the undesired zones for maximizing well productivity.

Using new, innovative technology firmware in real time enabled the navigation engineer to place the well in the most prolific zone by making quick changes in the trajectory to avoid tight boundaries at the reservoir top or bottom.

EXTENDED ABSTRACT

Introduction & Challenges

Carbonates make up about 20% of the world's sedimentary rocks and contain 40% of all significant hydrocarbon plays. In the Middle East, the development of these reservoirs has grown dramatically and accounts for most oil production. Thin carbonate reservoirs have continued to be a popular target for drilling plans and play a significant role in oilfield development and performance. These reservoirs are primarily made up of highly permeable zones that are locally amplified by natural fractures and vugs (Wang et al. 2017), but the expansion of such reservoirs has become more challenging due to the heterogeneous characteristics of the formation (Al-Musharfi et al. 2010) in addition to other major challenges listed below:

Geosteering and Well Placement

Proper placement of lateral sections into the target zones is crucial for achieving the main objective of maximizing the reservoir contact to optimize the well production. This objective is very challenging to achieve, especially when drilling thin-bed reservoirs with variable dip, bounded between undesirable tight layers above and highly fractured water-bearing formations below, which risk water encroachment in the early stages of production

Drilling Challenges

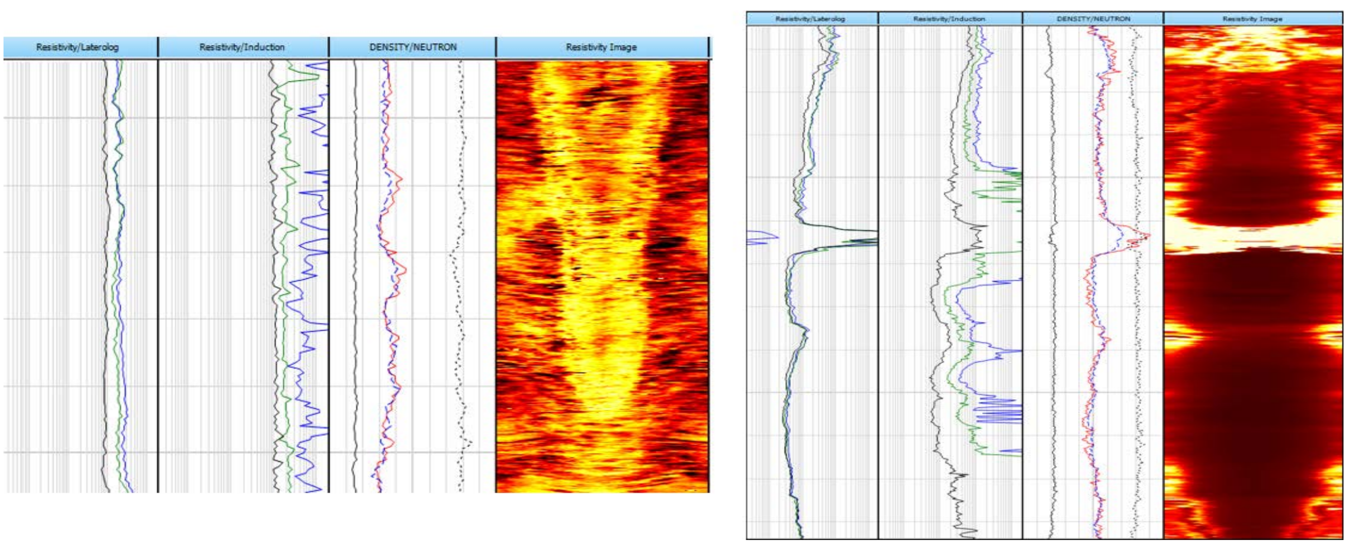
Avoid exiting the reservoir into the tight formation above is important to avoid the vibration issues that have a detrimental effect on drilling efficiency and downhole sensor failures that would influence the well delivery time. Additionally, it is essential to avoid exiting into the severely fractured zone below, since it frequently results in drilling fluid loss

Completion Design

One of the primary objectives is to prevent water flooding during the early phases of the well production by identifying open-fractured zones that lead to high water cuts. If these fractures have direct connectivity with the aquifer and total loss of mud circulation is brought, locating these zones from the image logs will help to optimize the smart well completion by isolating these intervals

Formation Evaluation

True formation resistivity is essential for reservoir evaluation. In thin reservoirs bounded by layers of different resistivity, the electromagnetic wave resistivity is generally affected by nearby boundaries, and a shallower measurement is needed, although even the shallow phase resistivity can be affected by these layers. In contrast, it has been observed that laterolog resistivity is more accurate in fractured formation than a conventional, wave-propagation resistivity (Fig. 1).



(Fig. 1) The log on the left demonstrates how the laterolog resistivity behaves in a more consistent and steady way than the induction resistivity that is highly affected by the high-resistivity boundary on the low side, as seen on the image. The log on the right shows the laterolog resistivity response while cutting across boundaries, giving a stronger resistivity response that better reflects the true formation resistivity, while induction resistivity is significantly affected by polarization effects that occur close to boundaries.

Integrated Workflow

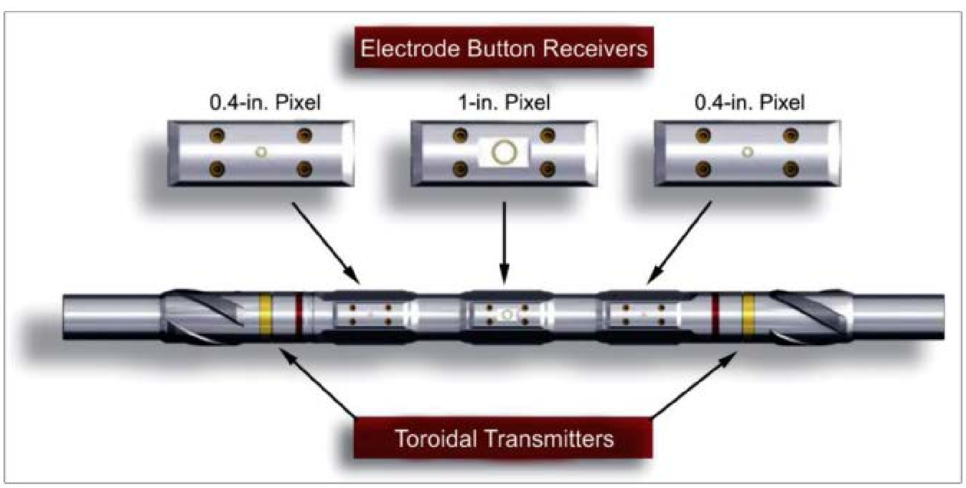
LWD Sensors and Data Acquisition

Conventional logging-while-drilling (LWD) tools are typically used for evaluation and geosteering in carbonate reservoirs. The bottomhole assembly (BHA) is generally designed to optimize the well placement and operational considerations addressing the reservoir challenges. The choice of density or resistivity imaging close to the bit depends on the pre-well model, with the challenge being to ensure the trajectory is maintained in the optimal position. The pre-well analysis and model is important to ensure the right assembly and BHA configuration is selected.

Density has typically been utilized as the main geosteering technology for most of the reservoirs and this is considered a lithology and porosity-based well-placement approach. In thin reservoirs though, the density may not be able to resolve the target zone, which could be better identified using a high-resolution resistivity imaging tool.

Resistivity imaging tools (Fig. 2) have the advantage of giving multiple measurements in real time, which are listed below:

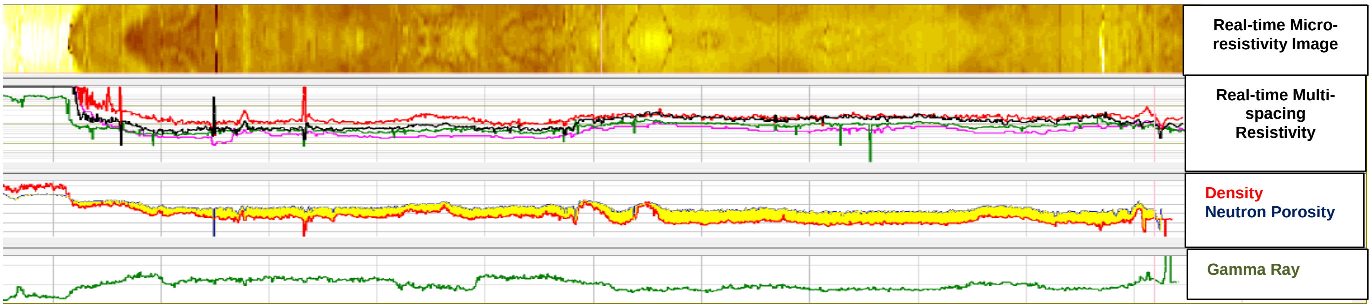
- At-bit resistivity – provides an early indication of fluid changes.
- Resistivity image – the micro-resistivity imaging tool has three receivers and two transmitters with different imaging resolutions (standard and high), with the lower transmitter and lower receiver usually being selected to provide the best resistivity image.
- Laterolog resistivity – provides a better measurement that EM-based technology that is not affected by nearby boundaries.



(Fig.2) Design of laterolog imaging tool with multiple spacings for laterolog resistivity Zeglache et al. 2016

Well-Placement Solution

There are different well-placement technologies available, depending on the challenge. In the past few years, proactive (deep or ultra-deep) resistivity measurements have been key technologies for optimizing well placement and avoiding reservoir exits. Yet, there are thin reservoirs (Fig. 3) that are beyond the resolution of deep and ultra-deep technologies and require a more focused measurement.

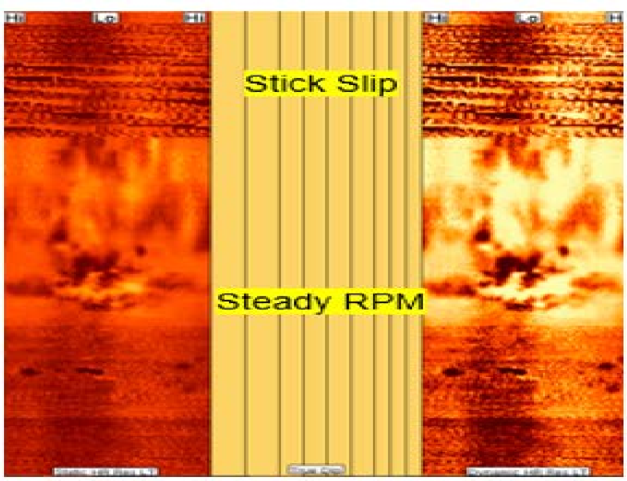


(Fig. 3) Integrating multiple logs with the real-time micro-resistivity image

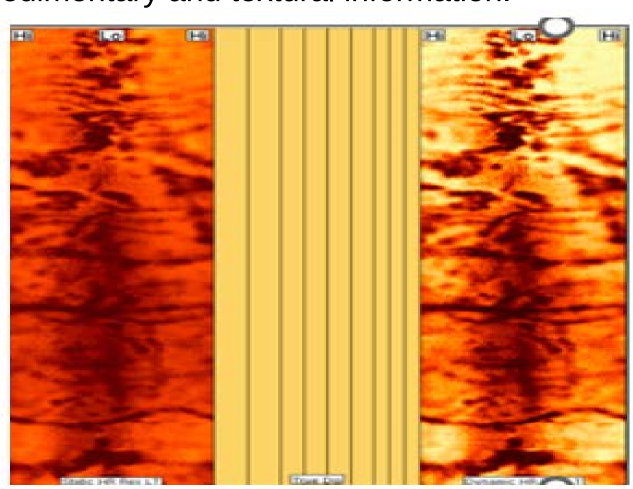
Fracture Identification and Interpretation

The image processing workflow starts with a generic QC process. Image QC for LWD tools starts with understanding the sensor performance and the impact of the drilling process on the image quality, due to axial motion and vibration. Stick-slip (Fig. 4) is one of the major factors that affects image quality, and it is critical to ensure there is a mitigation process in place.

There are two different images acquired by the laterolog tool, one having a higher resolution than the other. The standard-resolution image has a resolution of around 1 in., while the high-resolution image has a resolution of less than 0.5 in. The images can be presented using static or dynamic enhancement (Fig. 5). The static image is equalized using a histogram derived from the entire data set, and is generally useful for lithology and structural information. In contrast, the dynamic image is derived by equalizing the data using a histogram defined for each acquisition. Dynamic images are useful for sedimentary and textural information.



(Fig. 4) Stick-slip effect



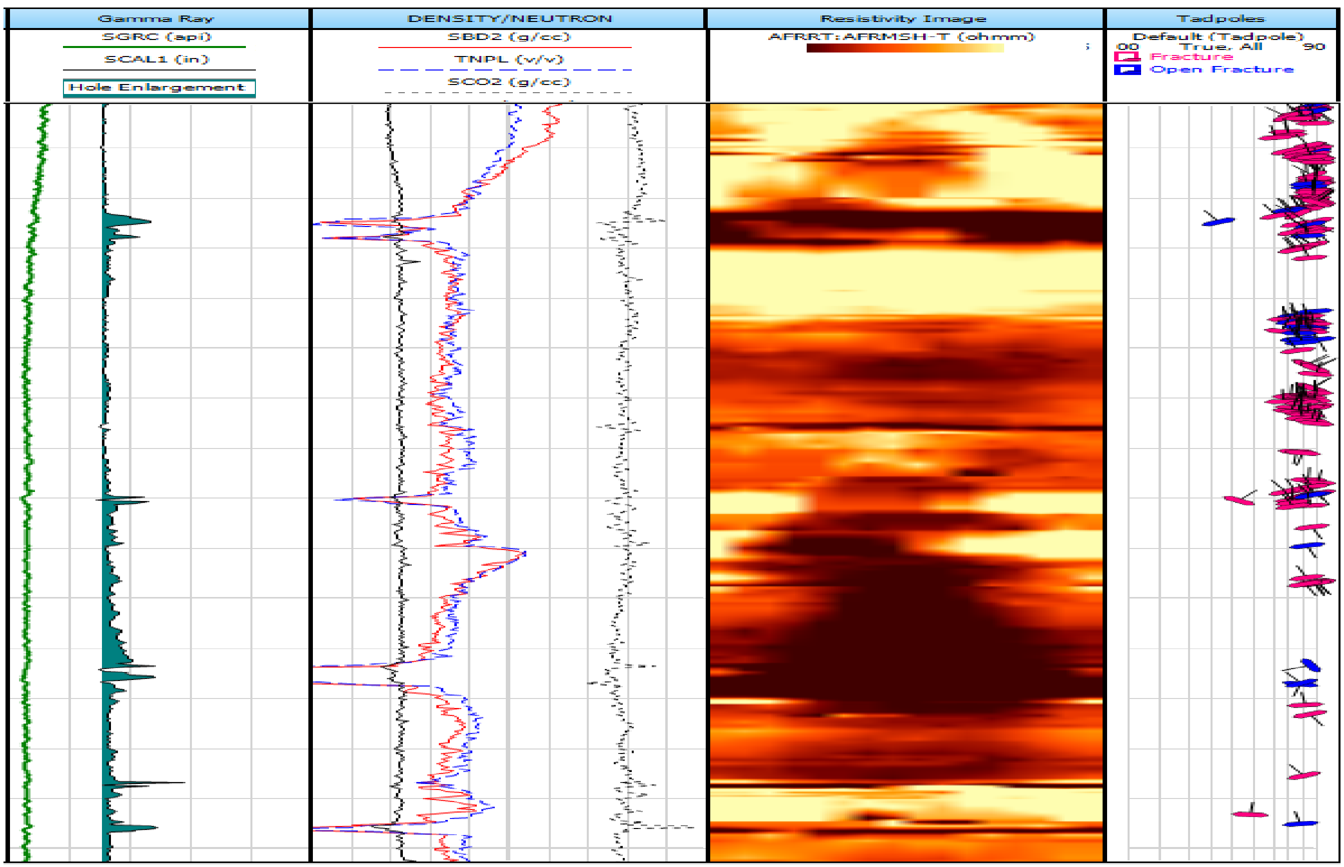
(Fig. 5) Static & dynamic images

Optimizing the Completion Design

Image interpretation is critical for optimizing the completion design, with the most important factor being identification of zones with open fractures that could impact the well productivity. Such zones can be analyzed for isolation based on the potential impact of open fractures on water encroachment due to their connectivity with the water-saturated zone below the well trajectory.

Examples:

Traditionally, conventional density images and other LWD measurements have been used to drill wells in similar environment. This has not been an efficient methodology for geosteering, production and drilling objectives because most of the real-time decisions were reactive. A new approach has been used integrating LWD tools utilized to acquire the measurements in real time with the micro-resistivity image and at-bit resistivity to place the trajectory in the high-porosity zone. Laterolog resistivity was utilized for proactive geosteering decisions by detecting the reservoir boundaries and dip changes, which were not detected by density tools, due to the enhanced resolution and at bit resistivity measurement. In addition, the high-resolution resistivity image was acquired in recorded mode, but even in real time, some of the major fractures and vugs were detected while drilling (Fig. 6).

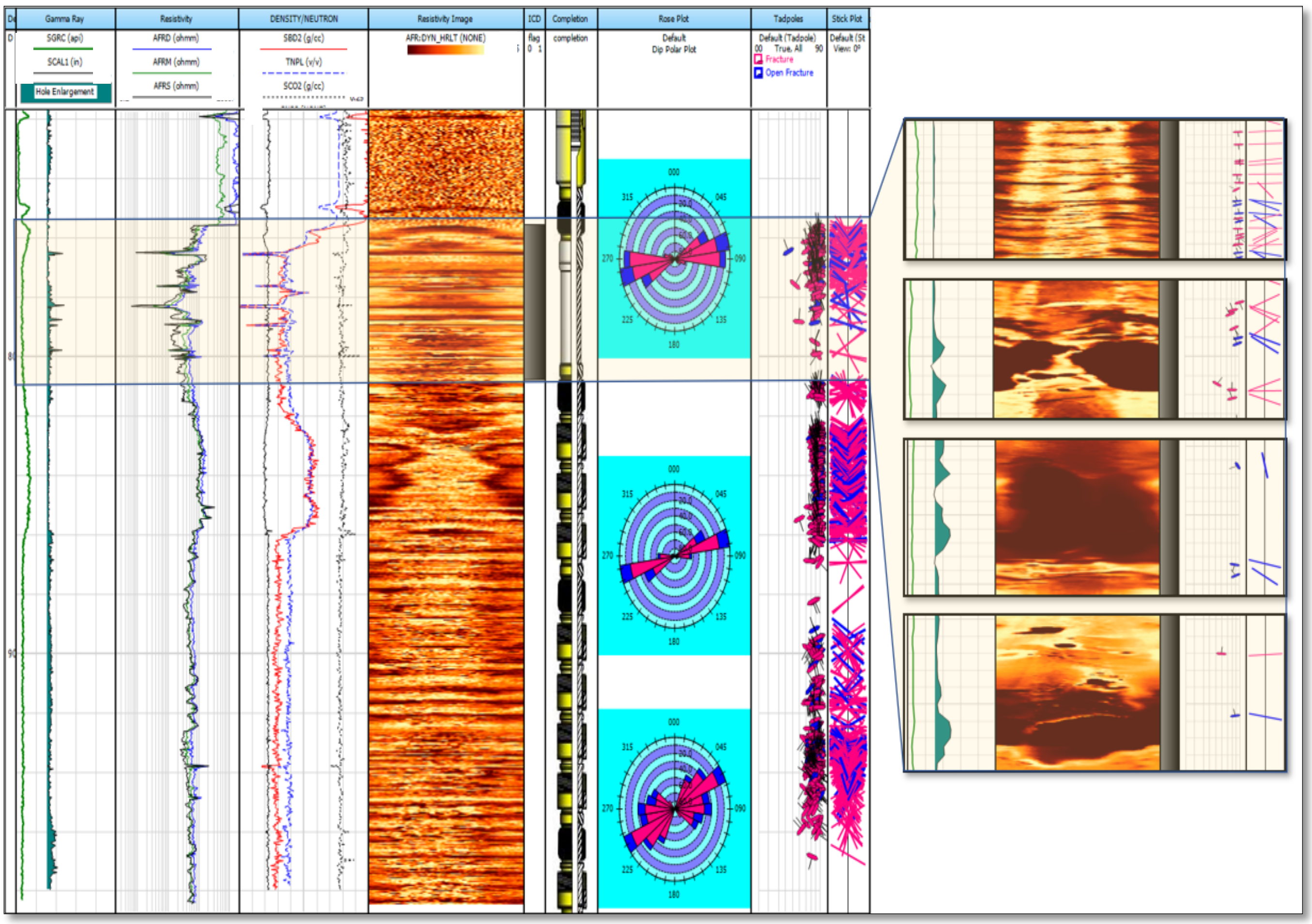


(Fig. 6) Resistivity image illustrating the fractured interval in real time while drilling, which appears with darker colors due to filling with mud fluids.

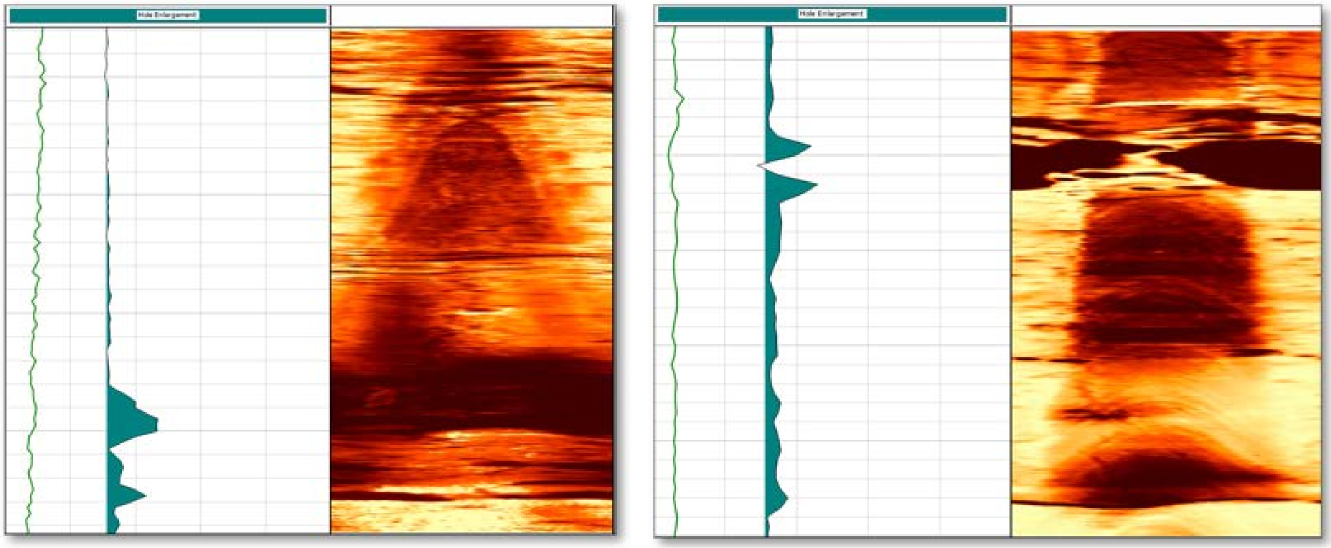
Applications of high-resolution laterolog resistivity in the below examples principally involve understanding the geological features in real time for decision making. This extends to the memory data, which is used to identify and evaluate the structural features, such as formation dip and fractures (Zhang et al. 2021), differentiating between open, closed and partial fractures, and determining fracture aperture, a key measurement for reservoir characterization. The below two examples from horizontal wells demonstrate the above-mentioned workflow for drilling in thin carbonate reservoirs.

Example #1

The well (Fig. 7) was drilled horizontally in a thin carbonate reservoir body subdivided into upper and lower lobes, separated by a tight, dolomitic limestone streak. The upper lobe was the original target zone, composed of limestone with high porosity and low density. However, it was found to be highly fractured and vuggy (Fig. 8), resulting in total mud losses. With support from the at-bit resistivity and the other high-quality LWD measurements, the decision was made to change the target layer to penetrate the lower tight dolomitic limestone streak by dropping the well inclination to 89°. Once the at-bit resistivity confirmed the penetration of the lower lobe the decision was to level the well to drill parallel to the structure until the end of the section, keeping the trajectory in the sublayer with high porosity and fewer fractures as indicated by the data.



(Fig. 7) Example#1 - The lower completion design displayed on the completion track was optimized based on image analysis by isolating the upper part, which had a high intensity of conductive fractures and where total mud losses were encountered.



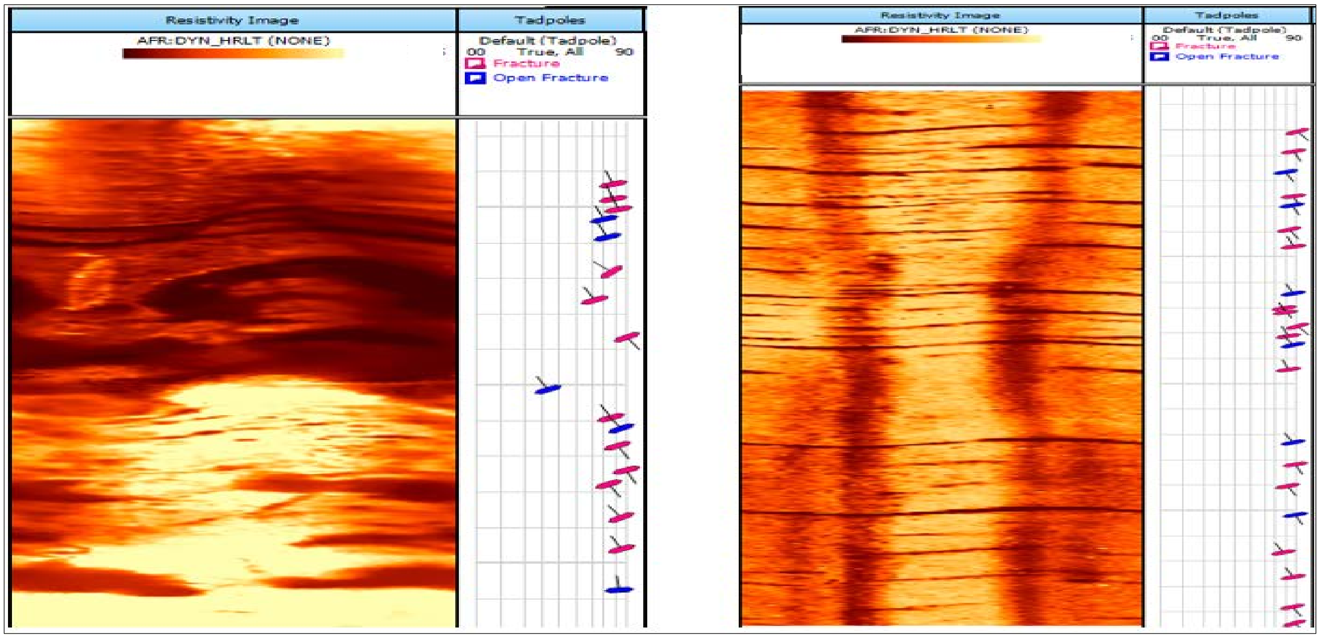
(Fig. 8) Highly fractured/vuggy zones seen on the high-resolution resistivity image.

Image Interpretation for Completion Optimization

High-resolution LWD electrical images were acquired with complete coverage of the borehole. The image was recorded with minimum borehole effect and stick-slip, resulting in high data quality that enabled identification of even small-scale structures and drilling-induced features.

The LWD image from Example #1, along with the caliper data and density-neutron responses, revealed two types of formation structure along the lateral section. First are natural fractures, which subdivided into open conductive fractures filled with mud fluid, and partially open fractures, which are not continuous on the image log (Fig. 9), trending NW-SE. Second, and most important, is to identify the open fractures associated with large connected vugs that cause total mud losses. These fractures, trending WSW-ENE, are connected to the aquifer and commonly cause water cut during production.

The high-resolution image revealed that most of the open fractures and vugs were observed in the upper part of the section, where total losses were encountered. However, it was also observed that the density of the partially open fractures was higher than that of the open fractures along the section. All these factors were taken into consideration when designing the smart completion, to isolate the upper part and prevent water cut by controlling the flow of fluids from these intervals.



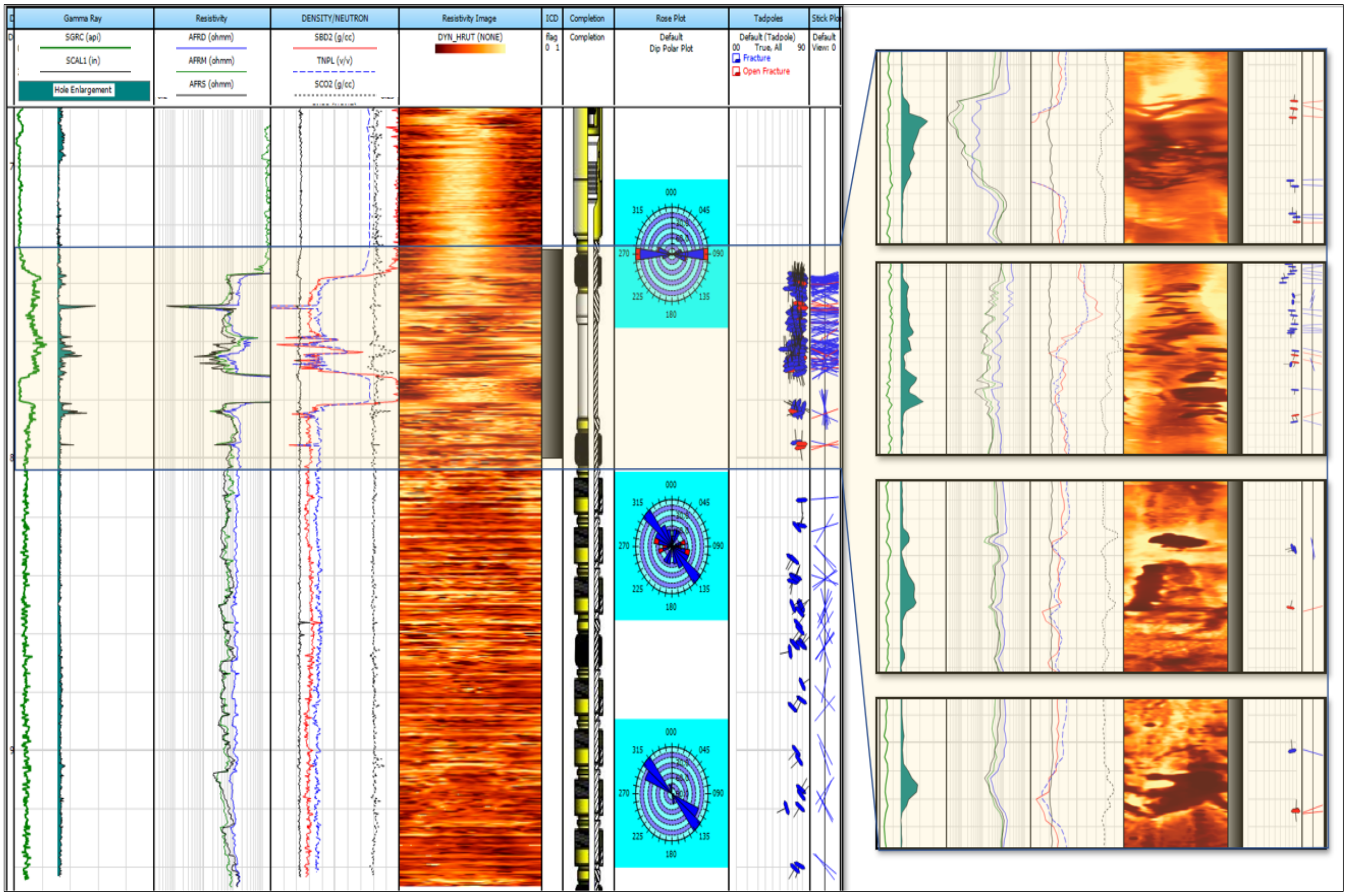
(Fig. 9) Open and partially open fractures identified from the image trending NW-SE.

Example #2

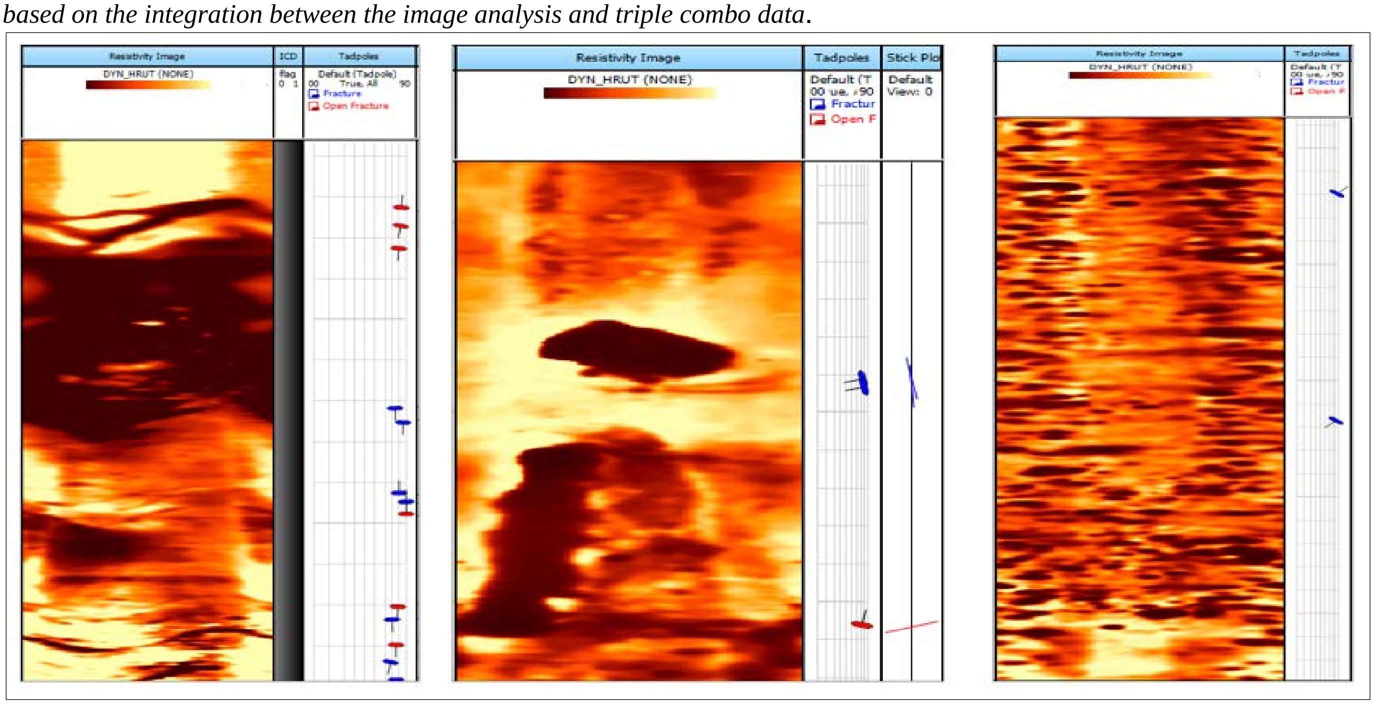
The well (Fig. 10) was drilled horizontally across a thin carbonate reservoir in the same area as Example #1 with similar challenges. Accordingly, the same workflow and technique was successfully applied for all the wells in this area, similar to the workflow utilized in example 1 , same workflow was followed by integrating LWD and imaging data for well placement and completion design optimization.

Image Analysis to Optimize Completion Design

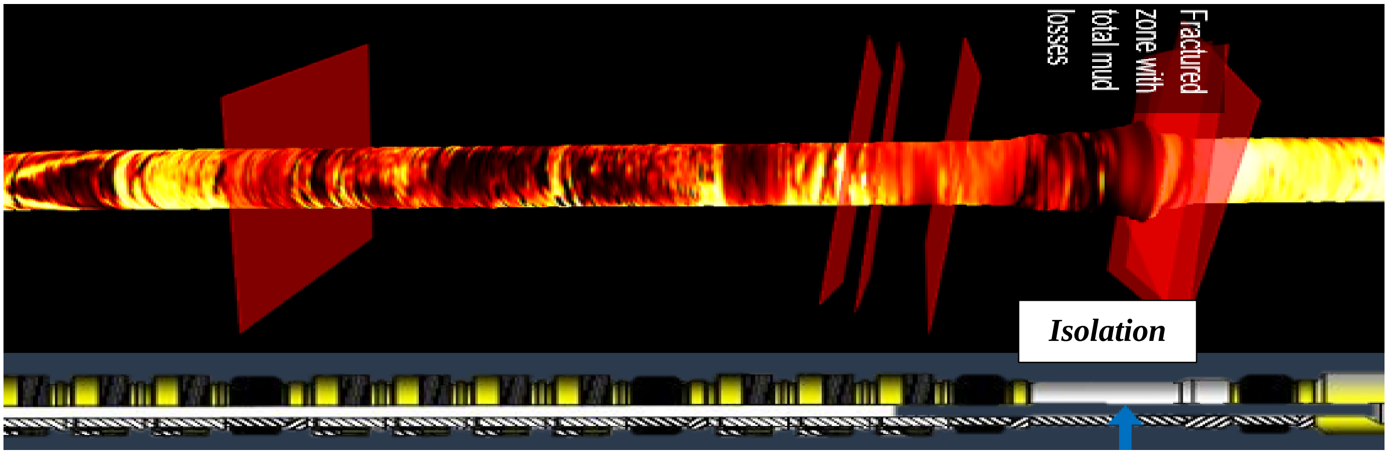
The image data (Fig. 11) showed several fractured intervals with vugs along the lateral section. Full image interpretation revealed that the highest concentration of fractures and vugs was observed in the upper part of the section, which was dominated by conductive fractures trending E-W. These features appear on the image with darker color indicating high conductivity as mud fluid replaces the hydrocarbon and flushes it away. Total mud losses were encountered reflecting that formation structures are well connected. All this analysis was taken in account to properly design and optimize the smart completion as seen in Fig. 12. The upper part was completely isolated by the lower completion to prevent water cut from the high-intensity fractures.



(Fig. 10) Example#2 - The lower completion design displayed on the completion track was optimized to isolate the upper part based on the integration between the image analysis and triple combo data.



(Fig. 11) Highly conductive fractures and vugs.



(Fig. 12) 3D image display combined with the lower completion design shows the upper part with highly fractured and vuggy zone was isolated.

Results & Conclusion

The traditional method of well placement and completion design for thin reservoirs has not been proven to be efficient. A new workflow has been introduced incorporating the micro-resistivity image with at-bit resistivity in real time to enhance understanding of the reservoir structure and improve dip evaluation in real time. This has provided optimized well-placement decisions by identifying formation boundaries in thin reservoir combined with the at-bit resistivity measurement. The high-resolution image was used for evaluating the fractures based on recorded data. The data processing and interpretation was used for optimizing the completion design by isolating potential water encroachment and connectivity of open fractures. The integrated workflow improved the reservoir exposure and minimized the reservoir exits. Where fractures are not avoidable, the fractures have been evaluated to provide a key input for completion design.

References

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