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Looking into the Reservoir: Performance Evaluation of Fractured Long Horizontal Wells Using of Borehole Imaging Logs

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Abstract

Field G is a highly fractured and faulty field, this paper is seeking about the necessity to keep running Image logs in new oil wells and how the interpretation of the results would lead the team to completing wells optimally and to design our well completion properly to prevent high initial water cut. Learnings are summarized from 40+ image logs ran in this field over the last few years. A cross field G seismic interpretation confirmed on lapping reservoirs and 3 major fault trends with different transmissibility. Also, sseismic and sub seismic Faults and fractures are confirmed from BHI with a NE-SW strike of field G and can be possibly related to production behavior of some wells. In 2015, field G Water Encroachment Study was conducted to identify the cause of high initial water cut of producers. It proposed that detecting fractures early via under-balanced drilling, Borehole Imaging Tools (BHI) and sealing the conduits with production packers would help reduce initial water-cuts. BHI tools are open hole tools that measure either electrical conductivity of the borehole wall or the sonic travel time and amplitude. Micro-conductivity or amplitude and travel time measurements generate an image that shows bedding, fractures, and many other fine-scale features. Since 2015, all new wells implemented Fullbore Formation Micro Imager on Tough Logging Condition (FMI on TLC).

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1. Introduction

1.1 Image logging

Image logs are resistivity or acoustic devices that measure certain physical properties of the rock at or near the well that can be displayed as images of the wellbore, which can then be interpreted on a computer. Typically, rock properties are controlled by factors such as variations in composition, diagenesis, grain size, grain orientation, pore fluid variations, etc. Image logs can provide detailed picture of the wellbore that represent the geological and petro physical properties of the section being logged.

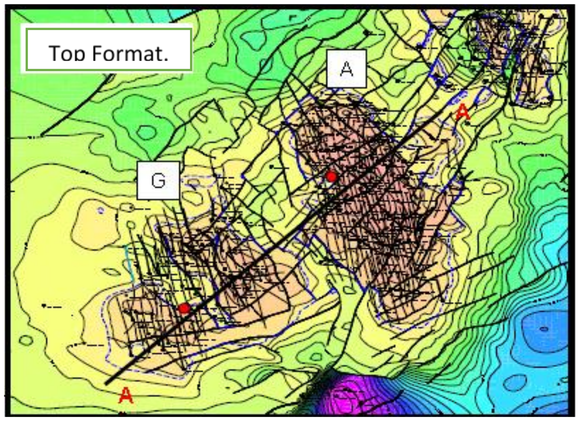


Figure 1: Filed G location showcasing major geological features picked up from seismic surveys, implying the presence of smaller fracture features that can affect the production

The current generation of tools available in the open market records an array of micro resistivity measurements from 192 sensors on eight pads mounted on four orthogonally placed caliper arms. The spacing and position of the pads provides 80% coverage of an eight-inch diameter hole and a resolution of 5 mm. Other oil field wireline service companies have since developed similar high-resolution electrical borehole imaging tools. The tool usually yields a continuous, high-resolution electrical image of a borehole (color-coded for resistivity values), and therefore complements whole cores cut in the same well. This becomes particularly useful in identifying and mapping out smaller fractures or any formation characteristics, hence, supporting the optimization efforts to complete the well in question for maximum success of hydrocarbon production.

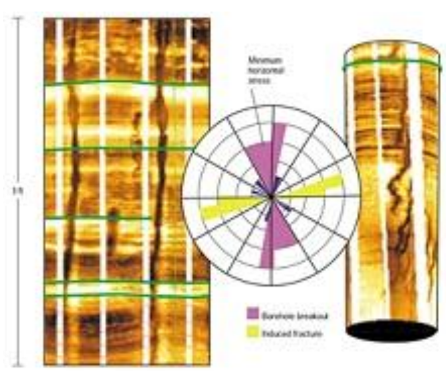


Figure 2: an image log can be utilized to model and create a cylindrical overview of the wellbore, image courtesy of Schlumberger.

The objective of this summary is to study the existence of fracture in field G and how it distributed and what dominate the flow behavior. Normally fracture can be assessed from field data such: cores, seismic, losses while drilling, BHI and dynamic data ‘PLT’. Whereas the main challenges were: a)Lack of production allocation data (PLT, etc.) to define the water source, b)Well test quality/frequency creates uncertainty around well performance, and c)Vendor interpretation bias of BHI data

1.2 Fractures Analysis

The team worked in available field data such as BHI, Logs, Cores, Tracer, any reports of losses while drilling and follow up results from well test and rod speed data, all lead to following results

1. Understanding the geomechanics conditions of fracture forming in field G area. An elementary rule of mechanical stratigraphy in siliciclastic rocks:
    - **Low ϕ (<15%)** High Cohesion: elementary deformation by opening mode-fracturing (joints, veins, "fractures") [1].
    - **High ϕ (>15-20 %)** Low Cohesion: elementary deformation by cataclasys (deformation bands, shear bands, compaction bands).

Rocks respond to stress in the brittle regime by forming extension fractures and shear fractures (slip surfaces). Such fractures are sharp and mechanically weak discontinuities, and thus prone to reactivation during renewed stress build-up. At least this is how non-porous and low-porosity rocks respond. In highly porous rocks and sediments, brittle deformation is expressed by related, although different deformation structures referred to as deformation bands.

The difference between brittle fracturing of nonporous and porous rocks lies in the fact that porous rocks have a pore volume that can be utilized during grain reorganization. The pore space allows for effective rolling and sliding of grains. Even if grains are crushed, grain fragments can be organized into nearby pore space. The kinematic freedom associated with pore space allows the special class of structures called deformation bands to form.

Figure 3: Cataclastic deformation band in porous Sandstone (left) and Sets of Cataclastic deformation bands in Sandstone (Right)

Most of these deformed bands interpreted as fractures in BHI whereas should not be a fracture, also these bands support contribution of water. Historically no reported losses while drilling field G, which proved that fractures should not be widely existent.

2. BHI tool limitation and interpretation influence our understanding, so by looking back on well-by-well basis of all wells drilled with FMI and got zonal isolation. The team tried to filter FMI features, so they kept only the high confident feature from FMI data and review well by well zonal isolation against Fracture (Gross rate, Water cut, oil rate. Finally, they conclude that most interpretations were optimistic as interpretation possibilities are limited by the experience and some of FMI raw data was not in good quality however got interpreted by vendor.

1.3 Importance of Fractures

For any petroleum engineer, identifying and understanding fractures presence or behavior is a crucial part in understanding any type of reservoir, this is due to the fact that fractures not only act as a secondary porosity/permeability provider, but as well as conduits for early water cut development and production, hence, it deserves the attention it commands to be looked after. The literature is abundant in articles and research papers on fracture behavior and analysis, we recommend the reader to review those specific materials to gain a broader understanding prior diving into a highly specialized area that we is being discussed in this paper.[3][6][7][8]

Any division in a geologic formation, such as a joint or a fault that divides the rock into two or more pieces is referred to as a fracture. In some cases, a fracture will result in a deep fissure or crevice in the rock. Stresses that exceed the rock's strength usually induce fractures, leading the rock to lose cohesiveness along its weakest plane. Fluid movement, such as water or hydrocarbons, can be facilitated by fractures. Because they may have both large permeability and fracture porosity, highly fractured rocks can produce good aquifers or hydrocarbon reserves.

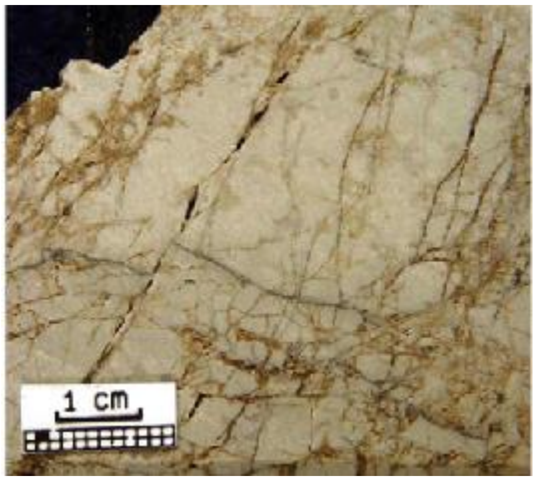


Figure 4: Core from reservoir interval in key well. Open fractures and oil stains are clearly discernible.

2. Image Logging Processing

In this part we will explore what is usually required for an image log to be processed and made useful, and will explore few of the terminologies utilized, BHI (Bottom Hole Imaging) can be classified into two main classes: LWD and WL. LWD BHI is mainly WBM and the WL tools also divided into OBM and WBM[4].

Our focus will be in FMI (Formation Micro Imaging) Processing. FMI consists of 4 arms and each arm consists of pad and flap and there are 12 sensors in each pad and other 12 sensors in the flap with an angle to the sensors in the pad to increase the coverage area as much as they can.

Data needed for the processing:

1. Image Data
2. Orientation Curves
3. Calipers
4. Accelerometer Data

FMI Processing steps:

<u>Step1:</u> Importing FMI raw data from recall choose the dils format and (Export External files in a single output tar files .tar).

Go to Processing then Image Processing Wizard
Collect all the data in one data set and change the GR curves to GR and the calipers to C1 and C2 and correcting all the references unit to M
We can use the first input curve from the processing to check the quality of FMI data (i.e. to see that all the pad and flap reads correctly and there is no missing curves)
Step 2: Inclinometry QC
We have to change the Declination, Inclination and the Magnetic Field using that websites (we enter the latitude, Longitude and date logged as inputs for this sites to get our requirement)
Step3: Speed Correction:
We have to change the sticking detection threshold to 0.01.
Step4: Array Processing:
We have to change the window size harmonization to 0.9.
Step5: create static image
We have to change the orientation to North in vertical wells and Top of hole in horizontal wells.
Step6: Create Dynamic Image:
The window size is 1m and again we change the orientation according to the well types.
The difference between Static and dynamic image:
In a static image, there is a fixed color coding for the whole entire FMI and we use it normally to find the facies such sand, shale, silt. etc. And we calibrate it with the resistivity logs.
Dynamic Image we divide the color coding per meter from the more resistive to the more conductive to know the features such as fractures, faults... etc.
Normalization:
Distribute the energy equally between the pads and the flaps.
Acceleromator:
See the tool and the cable tension as this varies overall.

3. The Approach to gathering required data

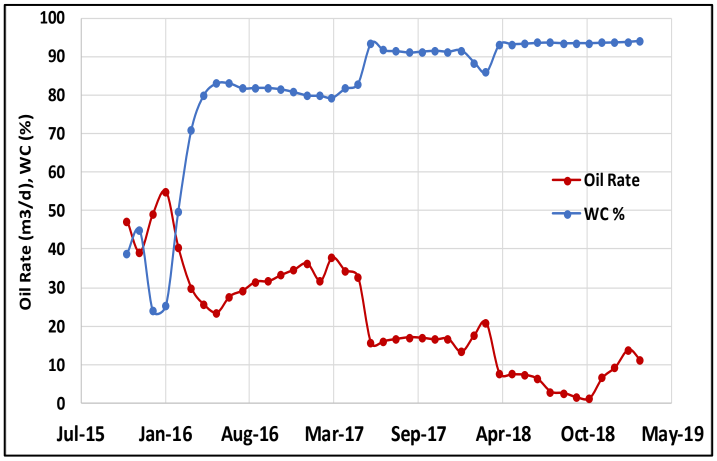
As a new well is drilled through target section to TD, here are some points to consider before completing the well:

1. Reservoir data logs for reservoir section interpreted and shared with team
2. If net sand >150m, need to acquire image logs and wait for interpretation else cancel
3. Combine Image log interpretation with RDL, to identify open fractures and fault[5].
4. Perform Completion meeting, to identify intervals that will contribute water production and then segment them by packers and blank pipes. The well get then segmented using packers. It should be also catered for later segmentations and send completion proposal to rig team.

4. Results and Discussion

Over last 5 years, image logs led very well to the presence of fractures and faults, and their eventual isolation for field G wells, resulting in delaying initial high water cut that had been seen in lots of wells. Below we will explore some of those wells and highlight the key observations.

- Well X-1/2015
- 6 CCF observed in this well and all of them are associated with relatively lower porosity rocks.
- All of these features are closed by packers & blank pipes during well completion.
- Closing the fractures is helping to control the initial WC
- The initial WC is between 28%-40%-18%



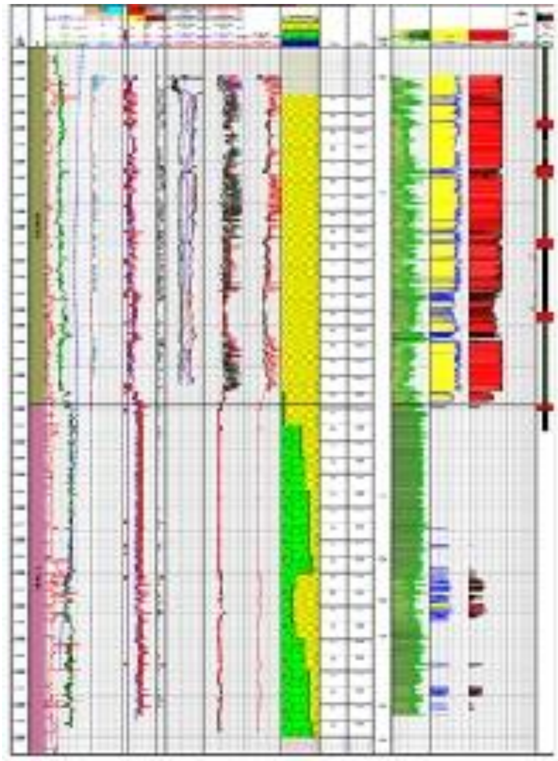
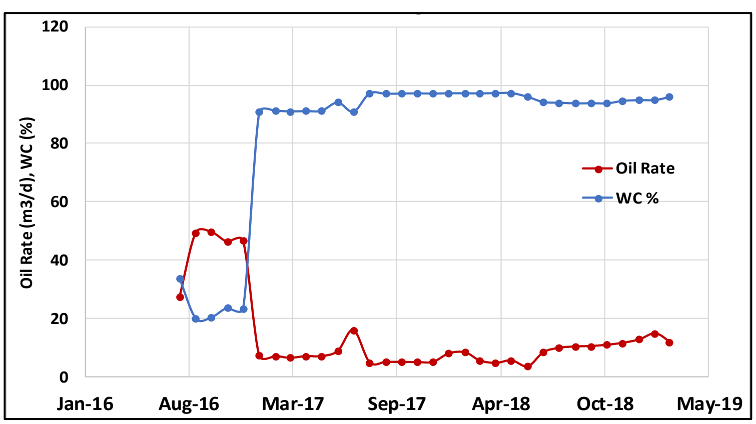


Figure 5: Production Plot and interpreted open hole log for well X-1/2015

- Well X-2/2016
- 1 possible fault, 19 CCF
- Some of these features were not closed.
- Initial WC (32%) from wellhead sample.
- First test in Jan 2017 showing 88% WC (after 4 months)
- Good gross rate (max ~ 315 m3/d)
- Latest test In March 2019 → WC~96.5%



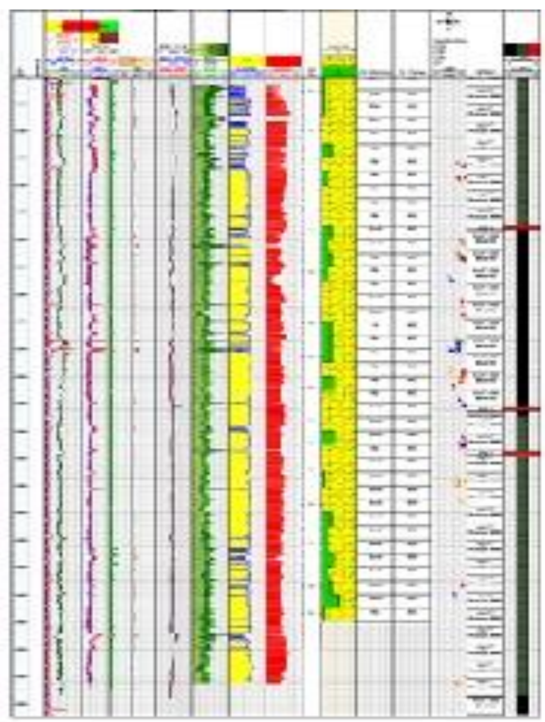
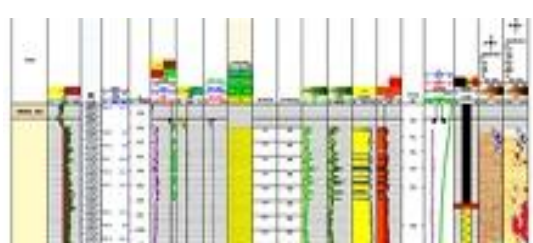


Figure 6: Production Plot and interpreted open hole log for well X-2/2016

- Well X-3/2017
- 2 possible fault, 13 CCF.
- Some of these features were not



closed while completing the well.
- Initial WC (50%) by metered test at the open-up. 2nd test 7 months later showing 55% WC
- WC jumped from 55% to ~82% after 11 months

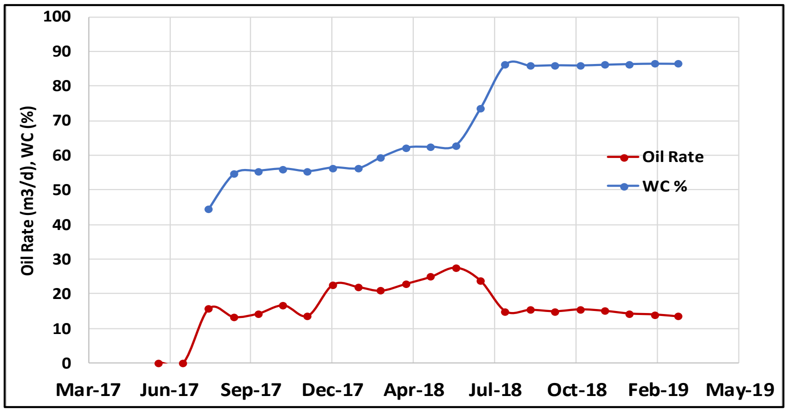
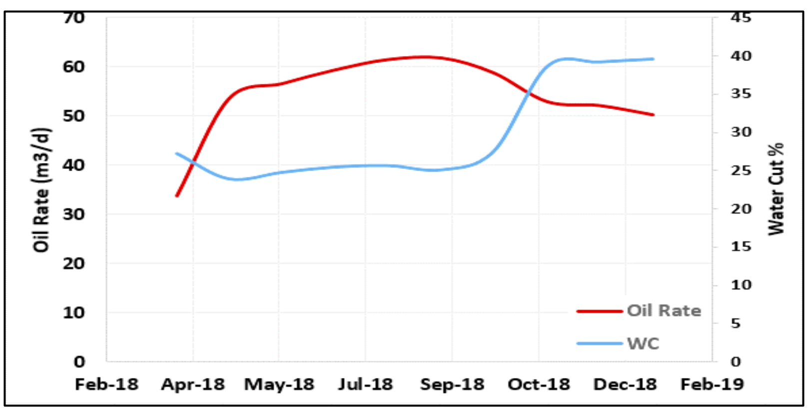


Figure 7: Production Plot and interpreted open hole log for well X-3/2017

- Well X-4/2018
- Vendor fracture picking is optimistic
- Production behavior showing matrix flow
- Initial WC (~19% 2 days after o/up). No metered test performed. Second test 1 month later after o/u showed ~ WC 19% (same).1 year from o/u, metered test showed WC 69%
- Gross rate-initial- ~ 65 m3/d
- pump speed increased from 80 RPM to 100 RPM, not resulting in WC increase



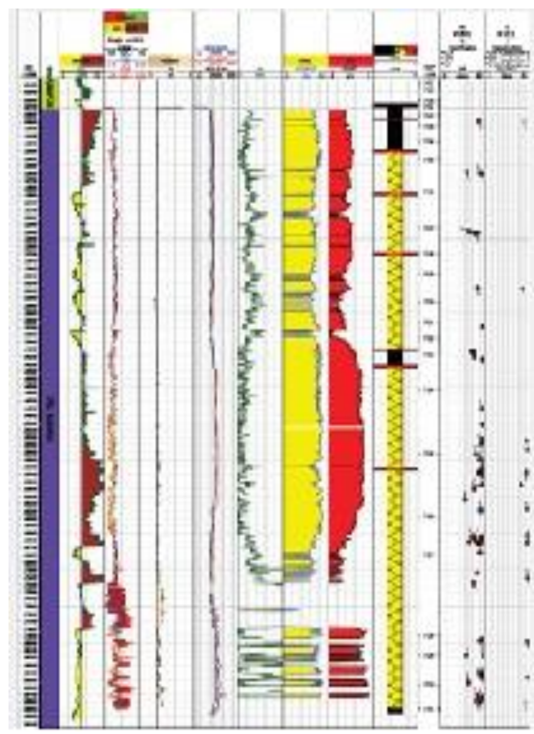


Figure 8: Production Plot and interpreted open hole log for well X-4/2018

5. Additional insight: A comparison of 2 tools

In this part we'll talk briefly about 2 different tools and measurement techniques and some high-level variations between them for the reader's references, those two tools in questions will be the FMI tool and the AFR tool. Running AFR constrains the drilling speed since the Rate of Penetration (ROP) has to be less than 25 m/h and the tool is in at least 50 Revolutions per Minute (RPM). Due to these constraints and knowing the high speed and many intervals logged while sliding historically in field G wells, the team decided to log the AFR while only pulling out of Hole (POOH) after reaching the Total Depth (TD). To maximize the AFR image quality, the AFR logging speed was too low that is around two stands per hour, 25 m/h and 60 RPM. Moreover, the AFR image cannot be interpreted using the Real Time (RT) data due to very poor image quality and therefore the data needs to be retrieved as Memory data before the interpretation[2]. The rig was idle waiting for the tally from the team that depends on the AFR interpretation. In the FMI run, the interpretation is done and the tally is shared before the tool reaches the surface. This results in almost the same time consumption for both tools in well X-13. To extend the FMI and AFR comparison, Well X-11 (FMI) is used since it has almost the same OH length (530m) as well X-13 (AFR). Even at long OH wells, there is no improvement in time saving since both tools consumed almost

One and a half day. Cost wise, FMI is slightly higher at long well and cheaper at the short well, ultimately, it all comes to quality and resolution of the AFR and FMI images.

Well X-13 AFR Quality discussion

This well is a typical well in field G SE flank, RDL shown below. The quality of the AFR image in Well X-13 is moderate. The features are hard to be detected and carry high uncertainty. This might be due to wash-out's across the well where the average caliper reading is 6.5" while the bit size is 6.125" as shown on the open hole interpreted log below. The gaps in the caliper log is because the curve is calculated from the density tool while rotating. Once the tool is in sliding mode, the caliper log cannot be calculated that results to gaps. Figure 9 shows the poor quality of the AFR and the high uncertainty in picking the features. There are only very few features which are interpreted with high confidence which are at the interval where the caliper shows good hole, it is very clear where the image quality drops as the caliper shows higher washed-out intervals. This results in fewer interpreted features at such intervals with high uncertainty for the picked ones. The explanation of this finding is that AFR is a rotating tool, which has no direct contact with the formation unlike the FMI. Therefore, the image is dark at the formation where less contact to the wellbore wall and no features can be identified, it is not recommended to run the AFR tool if there is a high chance of having washed-out intervals.

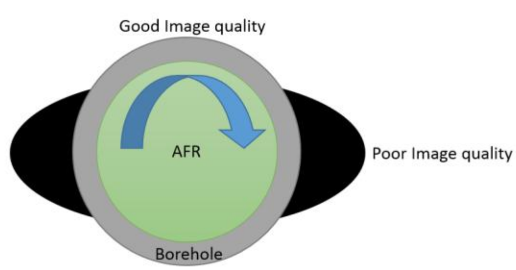


Figure 9: *Effect of Formation Washout on the AFR tool*

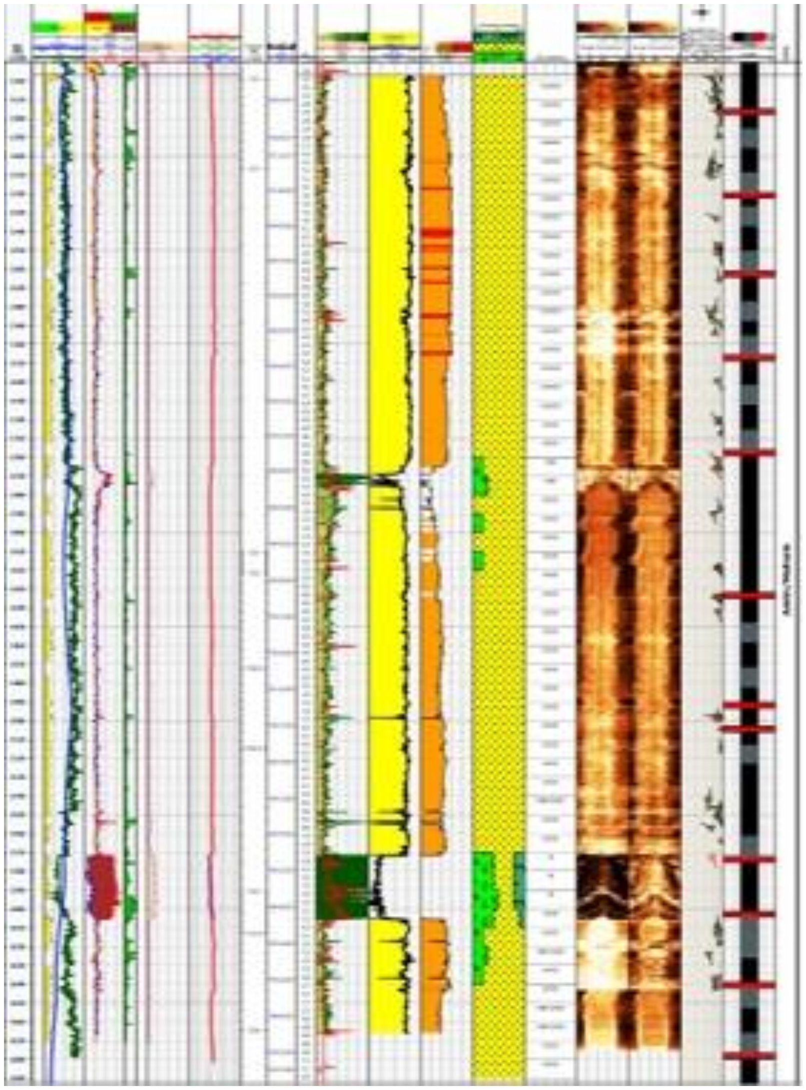


Figure 10: Interpreted open hole log for well X-13 as basis for comparison between two measurement tools and techniques

AFR can provide acceptable image quality in the ideal environment where the ROP and RPM are within the tool running range and only large features need identification. AFR can be utilized by acquiring the data while drilling instead of while POOH. This is applicable in low ROP and high RPM (no sliding) wells. AFR is only a good replacement for FMI on TLC at the very big features identification and high risk wells where the TLC logging is impossible. The statistics show there is no improvement in neither cost nor time for this environment where the ROP is high and RPM is low. However, if the logging interval is more than 400m, the AFR cost will be slightly lower than FMI on TLC and if the team accepts to identify the big features only, AFR can be utilized.

The team can utilize the cost of FMI on TLC by logging maximum 300m that is the minimum logging interval charge. The FMI is superior due to its higher vertical resolution and direct contact with the formation. Moreover, FMI on TLC gives the option of contingency based on the triple combo results. Hence, due to no improvements in all aspects using AFR instead of FMI, the team continue running FMI on TLC.

6. Conclusions

- Fractures identification through image logging is a very critical step required in any field where this type of features might be expected
- Isolating conductive features results in reduced early high water cut in said well
- Being in a 3D environment around the wellbore, sometimes it is not 100% effective to isolate those conductive features to delay early water cut development, as it has been seen that water will encroach eventually towards the wellbore
- The economics for running a relatively expensive imaging tool can be justified by the accelerated oil volume that will be produced early on from delaying the water cut encroachment
- Generally speaking, Multiple tools are available commercially in the market and they are all functioning to a certain desired technical extent and can yield usable results to be utilized for decision making. However, the real difference lies in the requirements for that specific well and field in terms of operability and the subsurface team support and capabilities, as well as the type of service contract in place between the operator and the provider. Some of those tools are Schlumberger's BHI and FMI tools, and StrataXaminer tool from Halliburton.
- The authors believe that the practices followed in this work are worth replicating and sharing to the wider community, for the significant value it has proven to present to the business, where integrating multi-disciplinary information to optimize wells and field development.

Conflict of Interest: The authors declare that they have no conflict of interest.

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