



Integrated Workflow for Reducing Uncertainties in Petrophysical Characterization and Fluid Identification of Fractured Basement - A Case Study from Cauvery Basin, Southern Onshore Field - India.

Authors: Sameer M[#], MV Phaneendra, Manju Xavier

Oil & Natural Gas Corporation Ltd. India.

Email: sameer_m@ongc.co.in

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Abstract

Attention towards exploration and development of fractured basement reservoirs has been on the rise as it holds great potential as a promising unconventional play. Conventional petrophysical assessing methods are often unfit for basement reservoirs because of the intricate nature of basement which leads to uncertainty in formation evaluation. In such reservoirs, mainly secondary porosity system exists (fractures/faults) which are dominantly due to tectonic activity and scaling from macro to micro levels, being the most significant and often the only component contributing to the production.

In this paper, authors propose a methodical workflow to address the non-Archie behavior of fractured granitic basement. Results derived from new-generation wireline logs along with basic logs were used for the petrophysical characterization and fluid identification in fractured granitic basement. Conductive fractures were differentiated from healed/closed fractures in the basement using borehole resistivity image data. Openness and extension of fractures away from the borehole were confirmed from low frequency Stoneley wave reflectivity analysis. Potentially fractured intervals were prioritized on the basis of fracture dip & azimuth, fracture aperture, Stoneley wave reflectivity index, borehole profile, and hydrocarbon shows during drilling. Two fractured zones were finalized for testing where conventional logs, image data and Stoneley reflectivity index results indicates that fractures are more likely to contribute to production. In-situ fluid identification (oil and water) was carried out with Dual packer formation testing and sampling tool against these fractured zones. Subsequently water producing fractured intervals were accurately identified in the basement section and isolated. Those water producing fractures were correlated with other nearby wells and LKO (Lowest Known Oil) limit was revised for the study area.

Subsequent wells drilled within the same structure, with revised target depths based on the newly established LKO, led to oil production from the basement without any water. The prodigious success of this comprehensive work flow for the petrophysical evaluation and fluid characterization in basement, can be further implemented in such unconventional reservoirs.

Introduction

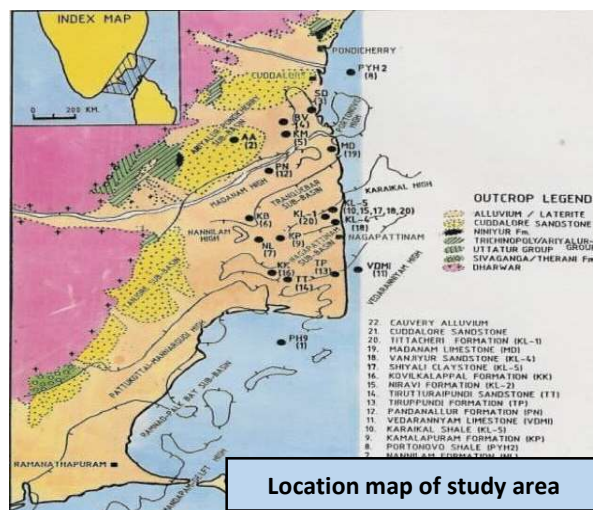
In worldwide, as the exploration focus moved to unconventional areas, attention to explore and develop fractured basement reservoirs has been augmented intensely. Fractured basement holds great promise as potential hydrocarbon reservoir in different parts of the world. However, routine formation evaluation methods are ill-suited for basement reservoirs because of heterogeneity, which leads to uncertainty in understanding basement. Basement mineralogy, identification and differentiation of open fractures from healed fractures, fracture aperture, extension (openness) of fractures and identification of potential zones are crucial in characterization of fractured basement. In naturally fractured basement reservoirs, identification of the oil/ water zones from conventional logs are quite challenging as the fluids are present within the fractures and not in the primary pore spaces as in the case of conventional reservoirs. Due to these complexities, basement requires new definitions and derivations other than conventional sedimentary reservoirs.

In the study area, fractured granitic basement belonging to the Precambrian age is the main hydrocarbon pay. So far, 13 wells were drilled with basement play as prospect. Prior field studies and nearby well performances show that early water break through from the basement and arresting water production are main challenges especially, in slotted (perforated) casing completion.

Regional Geology

Cauvery basin is part of the peri-cratonic rift system on the southern edge of Indian sub-continent. The basin encompasses an area of 45000 sq.km that includes both on land and offshore. Cauvery basin was evolved as a result of rift-drift phenomenon of Indian plate from Gondwana land during Late Jurassic - Early Cretaceous with taphrogenic fragmentation of Archean basement which has resulted in the development of faults and divided the basin into horsts and grabens/half-grabens. Configuration of Cauvery Basin is ideally suited for charging of the basement highs, having a series of elongated basement high put together on both sides by thick columns of sedimentary strata with proven source rock potential. A series of NE-SW, ENE-WSW trending faults are responsible for dividing the basin into half grabens with intervening ridges.

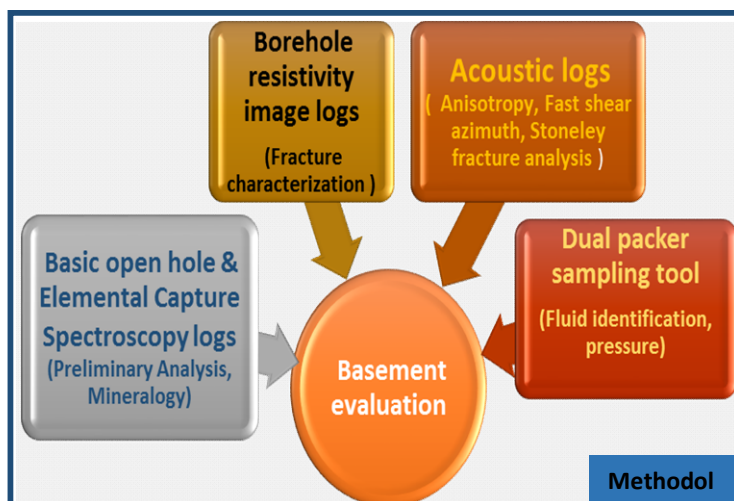
The presence of hydrocarbon in basement was established in Cauvery basin in early nineties. The study area, Pundi field in Cauvery basin, is a classic example of fractured granitic basement which is producing oil & gas in considerably good rates. The Pundi structure has two culminations, viz., eastern culmination, which produces oil and gas from the pre-cambrian Granitic basement and western culmination which mainly produces oil from the cretaceous sediments.



Methodology

All the conventional interpretation procedures are generally for sedimentary rocks and these methods won't fit well for the basement since the hydrocarbon accumulation and migration in basement is mainly through secondary porosity system (fractures, faults etc.). Productivity potential for each fracture can vary significantly due to pore structure heterogeneity. Lithological compositional variation and mineralogical make up of basement, identification and differentiation of fractures, determination of fracture attributes (dip, azimuth, apertures, density etc), openness and extension of fractures away from borehole, fluid conductivity and potentiality of fractured zones are essential in the basement evaluation. In addition to basic open hole logs, following advanced logs were used to frame up the work flow to address the petrophysical uncertainty in the basement.

Basic open hole logs: Gamma ray, Resistivity, Porosity, PEF logs were used as fundamental inputs for initial analysis. Abundance of radioactive minerals (thorium, potassium etc) can be established with spectral gamma ray logs. Separation of deep and shallow resistivity curves were used qualitatively to indicate the presence of fractures. However, solo dependency of conventional logs for the basement evaluation is inadequate since those measurements are bound to bring lots of other limitations.



Elemental capture spectroscopy:

Lithological compositional variations is another uncertainty in the basement evaluation. In the basement intervals, abrupt variation in log response are often seen mainly in density, PEF, neutron and gamma ray logs. Elemental capture spectroscopy logs are vital in evaluating mineralogical assemblage of the rocks. It gives a robust

measurement of dry weight elemental composition, mineralogy, possible rock type (mafic or felsic) and textural variation of the basement.

Borehole resistivity image: Fracture network study is an integral part of the basement formation evaluation as secondary porosity plays dominant role in producibility of the fracture basement formation. Borehole resistivity imaging tool provides high resolution resistivity images, which enable detailed assessment of the fractures around the borehole. It assist in identification of natural fractures, classification of fracture types (open fractures, resistive fractures, solution enhanced fractures, drilling induced fractures), fracture interconnectedness and fracture attributes (dip & azimuth, fracture apertures etc). Solution enhanced conductive fracture observed on image log can be potentially a large open fracture. However, exception has been also seen in the basement where such fractures may be filled partially/fully with clay or other conductive minerals and they still look as conductive fracture on image data.

Cross dipole acoustic logs: Advanced sonic measurements such as shear wave attenuations, shear wave anisotropy and Stoneley reflectivity analysis are used commonly in formation evaluation of unconventional reservoirs. Stoneley wave reflectivity analysis are sensitive to the presence of open fractures in the basement and distinguish between productive fractures and filled fractures. Fracture indicators from the Stoneley wave measurements are affected by bad borehole condition, so it is difficult to differentiate the highly fractured zones from washout area. With the combination of resistivity image data, openness and extension of fractures away from the borehole can be confirmed from Stoneley reflectivity analysis.

Dual packer sampling tool: Fluid characterization/identification in the basement is quite challenging as traditional evaluation methods will not work properly. In fractured reservoirs, dual packer module of wireline fluid sampling tool has preferred in place of standard single probe module. With the standard single probe sampling, it will be difficult task to place the sampling probe against the individual fracture in fractured reservoir. The straddle packer module, also called the dual packer, has two packer elements that are inflated to isolate a minimum borehole interval of about 1 m [3.3 ft]. The entire one meter borehole wall is open to the formation, so the fluid flow area is much larger than with conventional probes. It has improved pressure measurements and fluid sampling especially in fractured and low permeability formation. This tool delivers mainly reservoir pressure, in-situ fluid identification, PVT quality fluid samples, down hole GOR etc.

A comprehensive workflow is attempted to address complex architecture of fractured basement and fluid characterization based on borehole resistivity image data, advanced acoustic measurements, elemental capture spectroscopy logs and dual packer sampling tool.

Case study

To illustrate the proposed workflow, a typical basement well (Well-A) was selected. The well-A was drilled as inclined (~25° deviation) with an objective to produce oil from the Precambrian granitic basement. Around ~190 m basement was drilled in this well and hydrocarbon shows were reported in the top part of basement. The well was drilled with water based mud system. Drilling cuttings analysis shows lithology is weathered basement, very hard, crystalline, sharp and angular fragments, presence of Quartz, feldspar and mafic minerals and altered feldspar were observed.

A standard set of logs were recorded as shown in Figure-1 against the basement. Density-neutron, Spectral gamma, PEF logs were used to roughly indicate variation in lithological composition of basement. Higher gamma ray observed is due to higher thorium content which may be attributed to felsic nature of the rock. Density-neutron log shows several abrupt variations in lithology which are common in such areas. Resistivity values varies from 10 - 100+ Ω .m and compressional sonic travel time (DTC) is in the range of 50 - 80 μ s/ft. Density log shows high value in the range of 2.8-3.0 g/cm³ mainly in the intervals X308 - X321.5 m, X366-X375m & X326-X335 m.

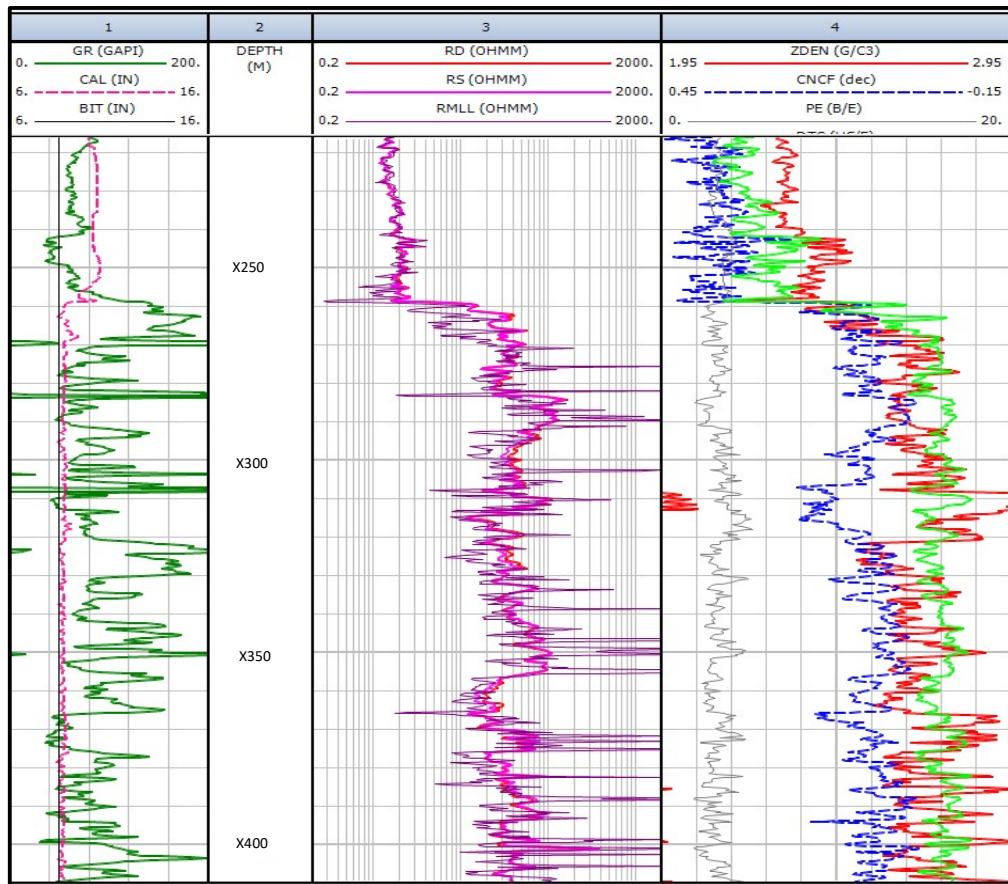


Figure - 1: Log motifs against basement section. Track -1: Gamma ray, caliper log shown. Gamma ray shows higher values at places due to thorium rich minerals. Track-2: resistivity log shows low at places indicates presence of conductive minerals. Track-3: Density-Neutron log shows abrupt variation in lithology in the basement section.

In the offset well, elemental capture spectroscopy log was recorded to understand the mineralogy. All over the section, it looks like weathered basement with felsic in nature at the top and becoming to mafic in nature towards the bottom. Presence of albite, anorthite (Plagioclase), K-Feldspars, with small concentration of biotite, calcite, amphibole & muscovite were also confirmed. Potassium & Thorium decreases towards bottom which is indicating the mafic nature towards bottom. A few conventional core cut in the study area confirmed biotite gneissic texture.

Borehole resistivity image data in the basement section confirms the presence of series of conductive sub vertical fractures, resistive fractures at places and gneissic bands. Naturally occurred conductive fractures were identified throughout the basement. These fractures were having dip angle 20- 70° with NE-SW strike direction dominantly. On the basis of image data, mainly seven zones were identified as potentially fractured intervals having good open fracture density and better fracture apertures.

Cross dipole sonic log was recorded in the basement. The Stoneley wave is particularly sensitive to the fractures intersecting or proximal to the borehole. The Stoneley reflectivity index shows that up- and down going Stoneley wave reflectivity can indicate the position and strength of reflectors. Stoneley reflectivity index was thus analyzed to determine openness of fractures against the fractured zone identified from resistivity image data. With combination of results derived image data and cross dipole Stoneley wave analysis, presence of open conductive fractures were observed in the basement mainly in the intervals X287-X295m, X302-X307m, X314-X321m, X340-X358m, X386-X394m, X402-X409 and X426-X436m.

In order to establish the fluid content, dual packer formation testing and sampling tool was lowered to test the potential fractured zones. In dual packer sampling job, the judicious selection of zones and its prioritized testing are essential since packer rubber assembly withstands only for a few inflation and each packer setting is time taking procedure. Therefore, a selection criteria was adopted for prioritizing the zones to be tested, in which fracture height, fracture aperture, opened/closed fractures, Stoneley wave reflectivity against the fractures, borehole profile, and hydrocarbon shows during drilling were the main selection parameters. Fracture amplitude is also considered (<1 m) in order to avoid any seal lost while sampling.

Testing Results

Out of seven fracture zones identified, two were finalized in which conventional logs, image data and Stoneley reflectivity index results indicated that those fractures are more likely to contribute to production. Accordingly testing has been done using wireline dual packer formation tester tool in the basement. Log motifs and image data against both zones are given in Figure-3. The zone wise details are given below.

Zone - 1: X387.7 - X388.7 m.

This zone is having good open fractures, fracture density, high Stoneley reflectivity index and in-gauge borehole. In order to identify the fluid, dual packer is inflated and tested the zone - 1. Downhole optical absorbance plot shows dominant presence of formation water along with minimum mud filtrate contamination in the zone - 1. Based on this testing result, it was confirmed that fractured zones below zone-1 are water bearing.

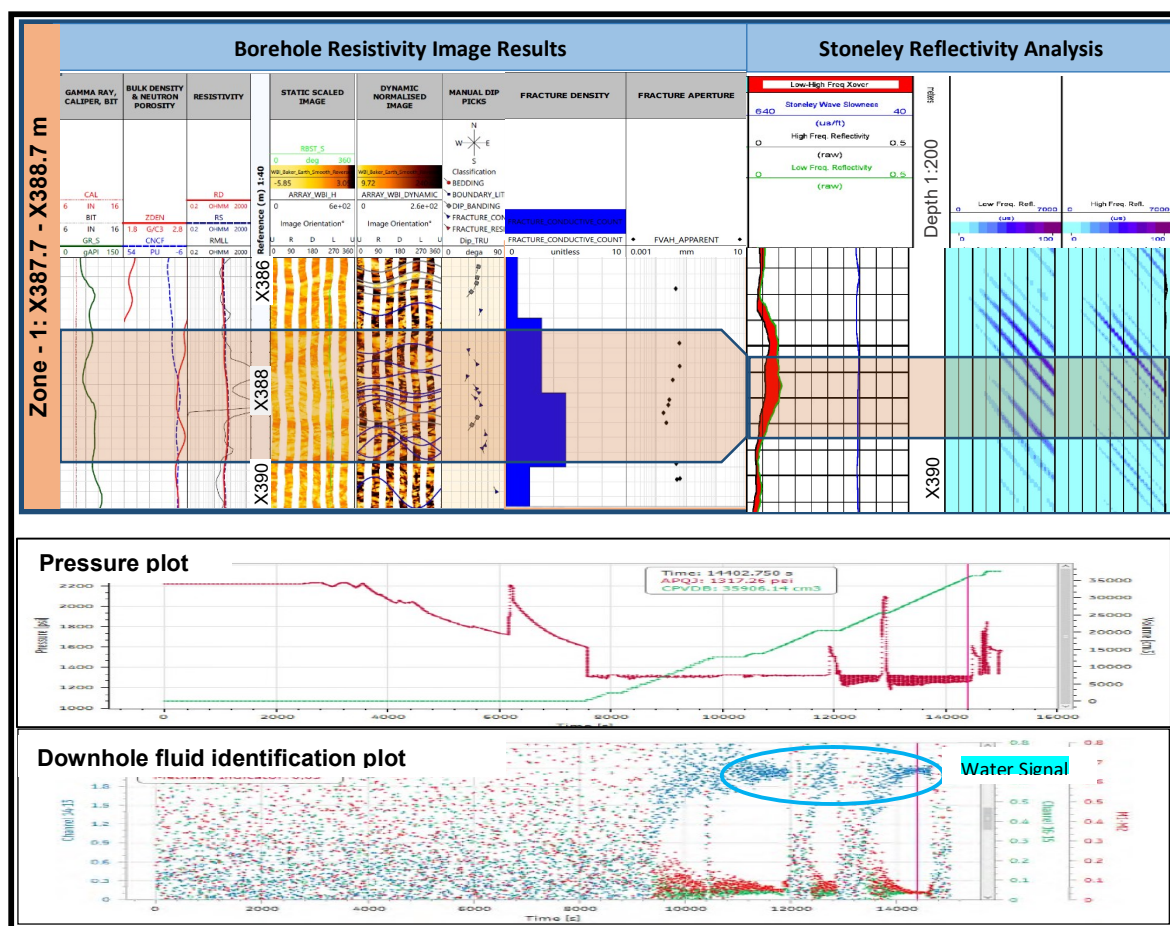


Figure - 3: The Zone - 1 shows presence conductive fractures and Stoneley reflectivity index shows openness of fractures. Pump out diagram and Optical absorbance plot against the Zone -1 also given. Optical absorbance plot shows a prominent presence of water.

Zone - 2: X353.6 - X354.6 m

This was another zone identified for testing which is having series of sub-vertical open fractures. Caliper log shows in gauge borehole. Zone-2 is having low Stoneley reflectivity compared to zone - 1 which may be due to low fracture aperture values. Hydrocarbon shows were reported in this interval. On dual packer testing, this zone flowed oil with fast build up.

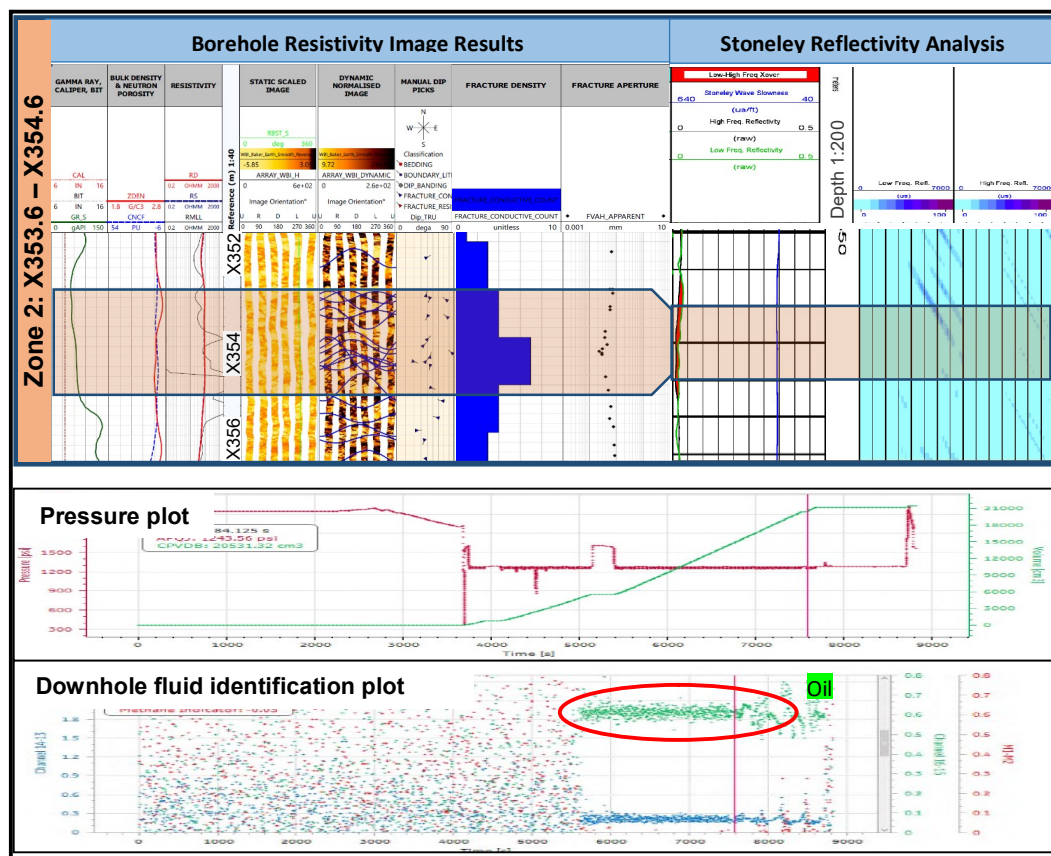


Figure - 4: The Zone - 2 also shows presence conductive fractures and Stoneley reflectivity index shows openness of fractures. With dual packer testing, oil sample was collected from Zone-2.

Based on the fluid identification done in these two zones of basement section, water producing fractures were isolated from X373 m to bottom with cement plug. Further, well - A was completed with slotted casing in the interval X373 - X359 m and flowed oil @ 32m³/day through 8 mm bean without any water cut.

New well Plan revisal and production results

Based on the results from workflow in the study well-A, fracture zone below X373 m is found to be water producing zone. These water producing fractured zones were correlated with offset wells in the study area. Accordingly, in the studied area, Lowest Known Oil (LKO) limit was reviewed and re-determined. Another well-B was already planned to be drilled in the same structure with the fractured basement as objective. At the initial stage of planning, well-B target depth was X400 m. However, target depth of the well-B has been further revised and reduced by 10 m in TVDSS. The well-B has been drilled with revised target depth and encountered 164 m fractured basement. Full set of open hole logs, image data, and cross dipole sonic logs were recorded. From the image data, fracture attributes were determined. Major fracture strike direction is found to be dominantly in NE-SW direction which is in agreement with Well-A. Well-B has been completed with slotted casing, leading to oil production from the basement without any water.



Conclusion

Since basement is unconventional reservoir, conventional measurements are inadequate for fruitful formation evaluation. Detailed integration of results from various measurements are inevitable in such unconventional reservoirs. Well testing results and production profile of studied well shows the mentioned workflow suits well for addressing petrophysical uncertainty and fluid identification in the fractured basement. The prodigious success of this comprehensive work flow for the petrophysical evaluation and fluid characterization in the basement, can be further implemented in such unconventional areas.

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