An Integrated Approach to Stress Regime Characterization: Insights from a Fractured Carbonate Reservoir in the Bikaner-Nagaur basin, Rajasthan, India.

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Insitu horizontal stresses, borehole breakouts, induced fractures, anisotropy.

Summary

The Earth's subsurface rarely stays in a lithostatic stress condition with stresses equal in all directions. The equilibrium of the stress state is generally disturbed by movement of tectonic plates, leading to the formation of a regional stress system, partially or completely overprinted by localized stresses associated with faults, folding, volcanism and so forth. Stress can create pathways for fluids to migrate and accumulate, making certain areas more likely to contain these resources. The direction of stress explains the nature of the forces acting on rocks and how these forces lead to deformation. In order to determine the stress magnitude and directions in a field, an integrated study of image log, acoustic log and core data plays a vital role. Wells are usually planned along the minimum horizontal stress direction to optimize wellbore stability. In our area of study, the presence of intense fractures and borehole breakouts observed in the Upper Carbonate formation help in analyzing the orientation of maximum and minimum horizontal stresses which is crucial for well planning, well completion, and reservoir development. Information on the present day stress regime help in the assessment of risk of borehole damage deciding on the optimal orientation of horizontal wells, enhance hydraulic fracture placement and overall reservoir productivity.

Introduction

The Bikaner-Nagaur basin located in Rajasthan, India (Figure 1) represents a complex heavy oil reservoir characterized by fractured carbonate formations and a consistent stress regime. In the selected wells, the direction of drilling induced fractures and borehole breakouts was examined by using high resolution borehole imaging tool and acoustic tool. This study presents an integrated approach to reservoir characterization and in-situ stress regime analysis by leveraging image logs, acoustic data and core data from selected wells to not only gain a better understanding of the fractures and breakouts in the field, but also assist in planning the optimal locations for future wells.

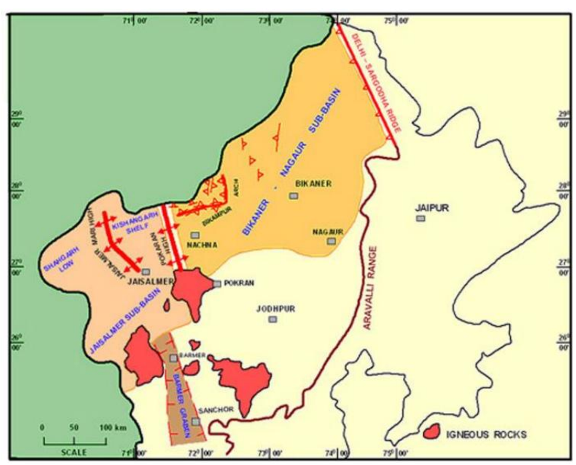


Figure 1: Basin map

Our area of study is located in the Bikaner-Nagaur basin, a south-eastern extension of Pakistan's Punjab Basin in the western India. This study is aimed at the resistivity image processing of the field wells for the study and integration through image logs. A total of ten wells of a field of Bikaner-Nagaur basin are taken for the study, mentioned in Table 1. The geological setting of the selected interval includes the Marwar supergroup of Neoproterozoic era, mainly the Upper Carbonate formation and a few meters of the Nagaur Formation. This study mainly focuses on the Upper Carbonate formation.

WELL	BIT SIZE (inch)
XX#1	8.5”
XX#2	12.25”
XX#3	12.25”
XX#4	12.25”
XX#5	12.25”
XX#6	12.25”
XX#7	12.25”
XX#8	12.25”
XX#9	8.5”
XX#10	12.25”

Table 1: Showing well names with the bit sizes

Methodology

This study involves a series of steps, foremost starting with the image data processing and fracture mapping of each and every well. A correlation of acquired information is done with core data and acoustic data to further validate the stress regime analysis.

Image data processing

To start with the image data processing, all the measurements were made considering magnetic north (N) as the reference. To convert magnetic N to true north direction, a magnetic declination value of 0.89 was used. The raw pad data is often found loaded with noise in the form of spurious signatures in different pads due to irregular tool motion. To remove this noise, data is subjected to speed correction at the time of acquiring data. Button equalization works by attempting to correct the response of each button so it matches a global response of all buttons taken together. Image-based speed correction uses a correlation algorithm to minimize the offsets. The pad data are then Re-projected to well-bore center using caliper data. The static and dynamic images are finally constructed to compare and enhance the image resolution, which are subsequently used for dip computation and further studies of dips computed for beds and fractures. Static images are good for an overview and relatively large-scale comparison in different sequences, while a dynamic image gives a more detailed characterization in finer scale within similar facies.

Fracture Identification and Mapping

Fractures were predominantly observed in the upper section of the Upper Carbonate Formation. In the selected field, the wells are observed to have good amount of natural fractures, in different directions (Figure 2) throughout the processed interval mainly concentrated on the upper part of the formation.

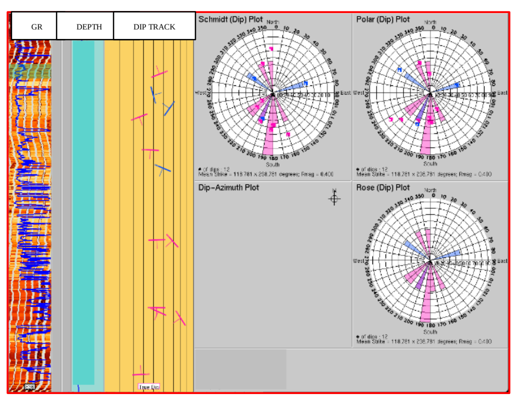


Figure 2: Dip statistics graph showing the direction of fractures at particular intervals for XX#2

The fractures are classified into open (conductive) and closed (resistive) fractures using borehole image logs. Figure 3 below shows an interval of a well with a dense network of interconnected fractures.

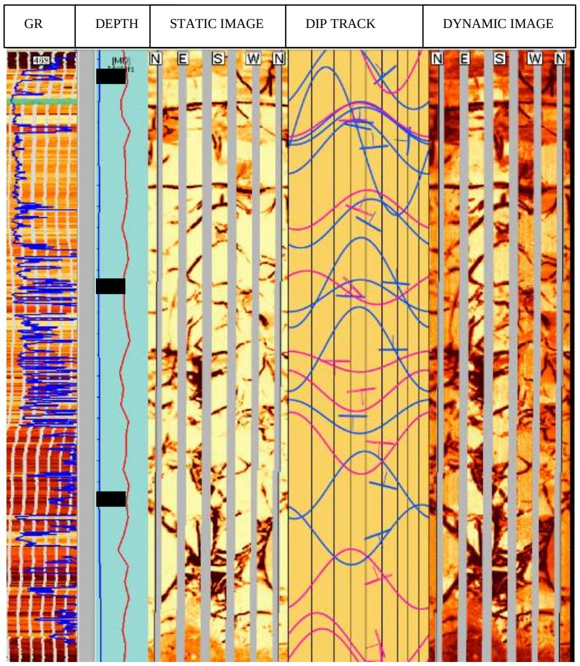


Figure 3: Borehole image showing an intensely fractured zone in the upper carbonate interval having open (blue) and partially open fractures (pink).

Core Correlation with image data

To confirm the presence of the picked fractures from the image log, it was correlated with the available core data. The fractures from the resistivity image log were found to perfectly match with the core data at all depths seen in Figure 4. Through this correlation, the values of the fracture apertures were also validated.

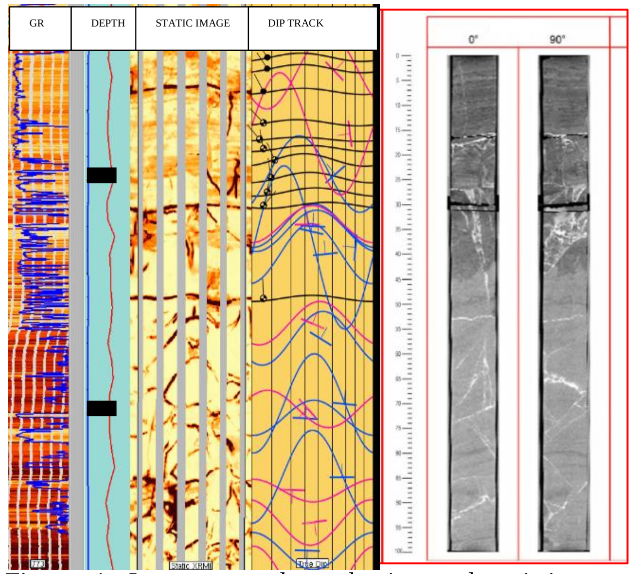
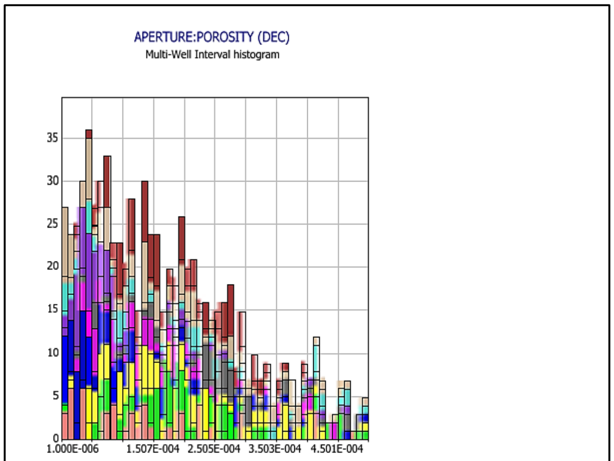


Figure 4: Interconnected conductive and resistive fractures seen in both images.

Fracture Aperture and Secondary Porosity

Fracture aperture is the width of the opening between the walls of a fracture, and it's a crucial factor in understanding how fluids flow through fractured rocks. Aperture size directly impacts rock mass permeability, which is essential for various geological applications, including oil and gas production, geothermal energy, and underground storage of waste.

Apertures for the wells is calculated and were found to be in the range of 0.1 mm – 0.9816 mm. The value of the aperture directly corresponds to the conductive pathway through the fractures.
Fracture porosity and permeability can be obtained by combining the fracture aperture and fracture frequency.



Curve	Well	Min	Max	Mean	Std Dev	Mode	P10	P50	P90
APERTURE:POROSITY	XX#1	7.0E-6	0.0005	0.0002	0.0001		1.868E-5	0.0001	0.0003
APERTURE:POROSITY	XX#2	7.25E-6	0.0005	0.0002	0.0001		0.0001	0.0002	0.0004
APERTURE:POROSITY	XX#3	1.805E-5	0.0005	0.0002	0.0001		0.0001	0.0002	0.0004
APERTURE:POROSITY	XX#4	1.25E-6	0.0005	0.0001	0.0001		1.3843E-5	0.0001	0.0003
APERTURE:POROSITY	XX#8	1.06E-5	0.0004	0.0002	0.0001		4.176E-5	0.0001	0.0004
APERTURE:POROSITY	XX#6	2.4E-5	0.0005	0.0002	0.0001		0.0001	0.0002	0.0004
APERTURE:POROSITY	XX#7	3.9E-6	0.0005	0.0001	0.0001		2.278E-5	0.0001	0.0002
APERTURE:POROSITY	XX#9	2.5E-6	0.0005	0.0002	0.0001		1.897E-5	0.0002	0.0004
APERTURE:POROSITY	XX#10	3.33E-6	0.0005	0.0002	0.0001	5.99E-6	1.794E-5	0.0002	0.0004
APERTURE:POROSITY	XX#5	2.97E-5	0.0004	0.0002	0.0001	0.0001	0.0001	0.0002	0.0003
All Zones		1.25E-6	0.0005	0.0002	0.0001	4.591E-5	3.216E-5	0.0001	0.0004

Figure 5: Multi-well histogram showing the variation in the value of the calculated porosity

Dr. Zoltan Barlai Model, a post-processing method for calculation of Porosity was used in this study which is calculated based on the idea that a greater open fracture corresponds to better electrical conductivity. The minimum size that a fracture can appear on a log because of the pixel density of the image, electrode spacing on the tool, and erosion of the wellbore adjacent to the fracture. Figure 5 shows a combined histogram of all wells representing porosity values in each well. Since our fracture dips are hand-picked, fracture frequency is more accurate and hence fracture porosity.

Borehole breakout analysis

In wellbore, there is always a hoop stress and a radial stress (Figure 6) which causes drilling induced fracture and borehole breakouts. Borehole breakouts are compressive failures that occur in the walls of boreholes, typically appearing as two parallel fractures aligned with the direction of minimum horizontal stress. These breakouts are caused due to the hoop stress that causes shear failure in the borehole. By uncovering the direction of borehole breakouts from the image logs, we can locate the direction of in-situ stresses.

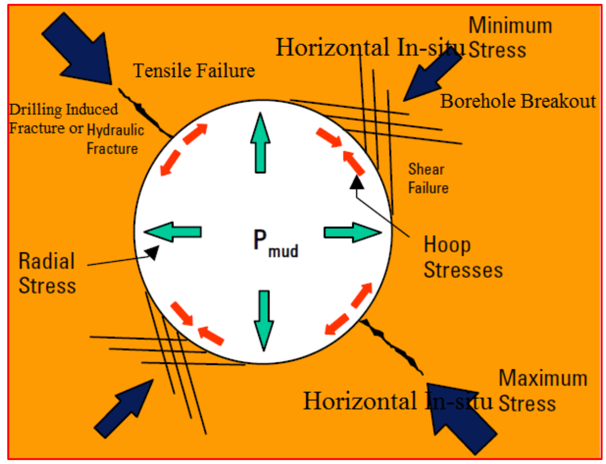


Figure 6: Pictures of the radial stress, tensile failure, drilling induced fracture (Hydraulic fracture), maximum horizontal stress, hoop stress, shear failure, borehole breakout and minimum horizontal stress.

When the mud weight is too low, the maximum hoop stress becomes much higher than the radial stress. Consequently, a shear failure of rocks exposed to the borehole takes place; this appears as borehole elongation on the orthogonal calipers and as long dark regions on the images that are 180 degrees apart. Many wells in this field were found to have borehole breakouts namely: XX#1, XX#3, XX#4, XX#5, XX#6, XX#8, XX#9 and XX#10.

Conversely, when the mud weight is too high, the radial stress increases and the hoop stress decreases; consequently, the rock around the borehole comes under tension and fails in tension. The fractures thus created are called drilling induced fractures, which appear as fractures seen in the images oriented at 180 degrees from each other (Figure-7).

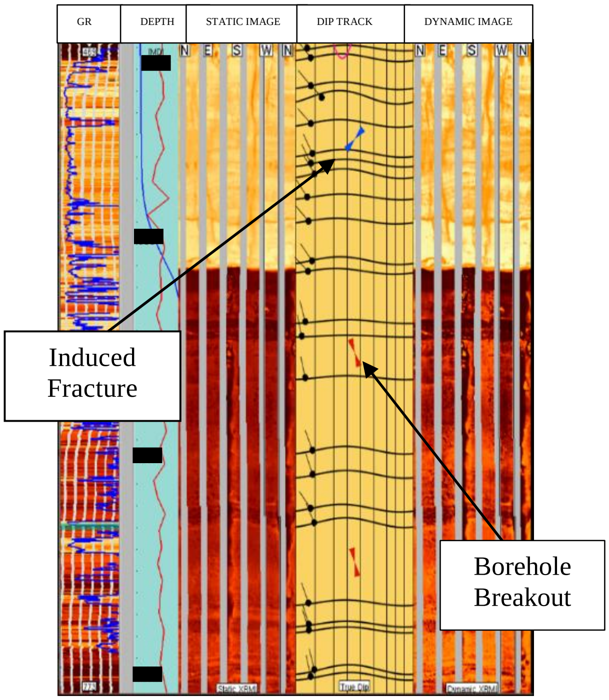


Figure 7: Image with Induced Fracture (blue) showing maximum in-situ horizontal stress direction is towards NE-SW along with Borehole Breakout (red) at 90 degrees in NW-SE direction which is the minimum in situ stress direction

Mud loss encounters

Mud losses have been observed in a few wells in the interval 600m to 800m. In the well XX#3, mud loss is observed in the depth 615 m -625 m due to drilling induced fractures. For other wells like XX#5 and XX#9 the presence of natural fractures is the main cause of mud loss in this interval.

Confirmation through anisotropy analysis

In Nature, there are two types of rocks: one, isotropic rock which exhibits any individual property same in all directions, and two, anisotropic rock exhibiting any individual property different in different directions. Anisotropy is addressed very effectively through acoustic devices having dipole sources and less effectively with monopole sources Fracture(s) in formations is the principal cause for anisotropy and fracture occurs in maximum stress direction. Shear wave in anisotropic medium (exhibiting fracture) splits and moves in two different velocities.

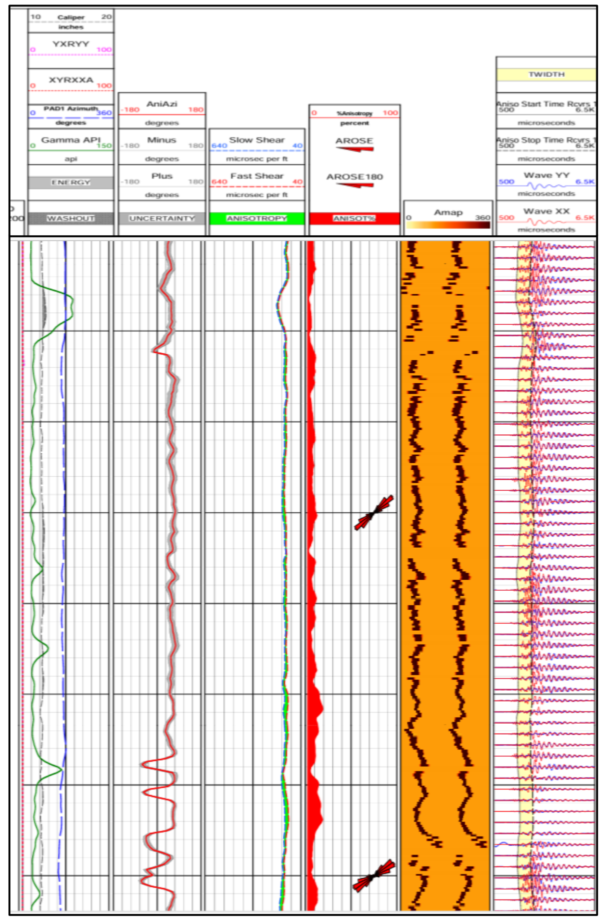


Figure 8: Maximum In-situ horizontal stress direction is towards NE-SW in XX#8 further confirmed by sonic data

Anisotropy analysis was done in all the wells. Taking example of well XX#8, the waveform shows feeble energy in both X and Y dipole in processed section at places in which anisotropy analysis and fast shear azimuth calculation is subjective. The anisotropy orientation map in which dark black part shows anisotropy and its direction. The map shows patches in the processed interval which tells that probable localized maximum stress direction is NE-SW in

Figure 8. This stress direction acts as a confirmation to the one computed from the resistivity image.

Application and Implications of the study

- The information of the insitu horizontal stresses is crucial for the wellbore trajectory design to lower the danger of wellbore breakouts or tensile fracture.
- The selection of suitable casing grades and setting depths in casing and liner design depend on an understanding of these stresses.
- Because fractures tend to propagate perpendicular to the direction of least horizontal stress, this orientation is crucial in hydraulic fracturing design. This information enables increased stimulated reservoir volume, optimal fracture stage location, and maximum contact between the fractures and the reservoir.
- Fracture aperture is a key parameter that helps engineers understand and optimize fluid flow, plan completions, design stimulation treatments, and forecast production in fractured reservoirs.
- Finally, in fracture containment and optimization, particularly in multi-stage hydraulic fracturing, recognizing the stress contrast between layers aids in fracture height control and ensures effective stage isolation, which is critical for managing the fracture network and optimizing reservoir drainage.

Conclusion

In-situ stress characterization using image and acoustic log analysis is critical for well design and reservoir optimization. The Upper Carbonate section for all the wells is found to be intensely fractured. The fractures are observed to have different strike directions. Borehole breakouts and anisotropy analysis reveal a dominant stress regime in the study area, with horizontal stress orientations of NW-SE minimum and NE-SW maximum. Fracture apertures for the wells were found to be in the range of 0.1 mm – 0.9816mm. Porosity calculated from these apertures in the Upper Carbonate section using the Dr. Zoltan Barlai Model is found to be in the range 0.0012% to 0.2500%.

These findings have direct implications for wellbore stability, fracture efficiency, and overall production strategy. Using integrated geophysical data, this study emphasizes on the importance of understanding subsurface stress regimes in maximizing hydrocarbon recovery while minimizing drilling and completion risks.

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