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Syndrill fracture detection: A potential tool for sweet spot evaluation in tight carbonate reservoirs of Proterozoic Vindhyan Basin, India

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Abstract

Proterozoic Rohtas Limestone reservoirs in the Son Valley sector of Vindhyan Basin, India are unconventional tight gas reservoirs. These rocks are micro-fractured with low matrix porosities, permeabilities and reservoir pressure. Understanding the stress regimes and designing of fracture oriented directional wells for suitable completion/stimulation is imperative to attain commercial production. The detection of fractures while drilling is precursor and critical for preparing the course of action to stimulate the wells. Deployment of advanced Coriolis flowmeter to detect subtle micro-losses associated with micro-fractures and evaluate mud flow rate with accuracy of 10 lit/min in all types of mud is necessitated. Coupling the analyses with mud gas, torque and other drilling indicators will assist in early recognition of the fractured intervals. Concurrently, the real time evaluation of statistical log parameter 'P' from LWD logs would also help identify the fractures. The two approaches could be synchronized to identify fractured and gas bearing intervals. Rock properties such as porosity and permeability can be modelled by analysis of advanced mud gas and mud flow detection results. The accurate monitoring while drilling of micro- losses and other parameters associated with fractures provides important data to characterize fractured reservoirs, to identify gas zones, and to support testing and stimulation decisions.

Introduction and Geological Background

In India, significant tight gas resource potential exists in Son Valley, Vindhyan Basin (Figure 1). The presence of high-quality thermogenic gas within Meso-Proterozoic Rohtas Limestone and immediately overlying Basal Kaimur Sandstone has been established at shallow depths (1 to 1.6 km) through concerted exploratory drilling. Although these tight gas plays are thick and regionally extensive, Rohtas Limestone with multiple gas bearing reservoirs, commercial exploitation of gas is challenging in view of low matrix porosities (2 to 4%) and extremely low permeabilities (0.01 to 0.5 mD). Gas flow potential is primarily dependent on secondary permeability generated by the presence of network of natural fractures that are dominantly sub-vertical. All the existing wells till date are vertical and thus, the intersection of fractures with vertical well bore are minimum, which might be detrimental to the gas flow rate.

Success in achieving commercial gas flow rates from this tight gas play lies in application of advanced technologies in formation evaluation, reservoir characterization, reservoir engineering, well designing and suitable completion / stimulation methods. Clear understanding of the existing fault and fracture network alignment, evaluation of the stress conditions in the reservoir and information generated from the drilled vertical wells and their stimulation results is essential to convert technical success into economic success. The fractures analyses from the vertical offset wells, shows multiple sets of fractures with different scales (Mukherjee et al., 2015). The most frequent are discontinuous micro-

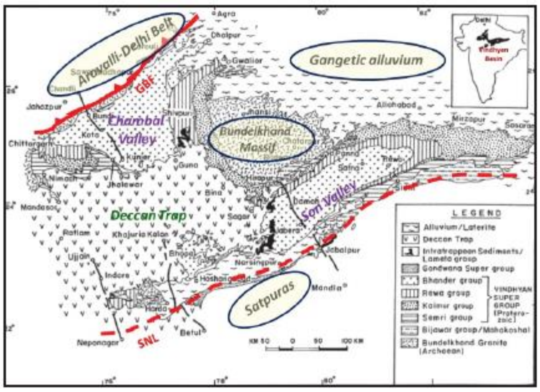

Figure 1. Geological sketch map of the Vindhyan Basin (Prasad and Rao, 2006)

fractures. In this regard, the critical questions are, how faults and fractures are distributed including their stress tensor and what are the factors controlling their distribution. The answers to these questions represent one of the main tasks in characterization of these reservoirs. Conventional solutions of fractures detection with geophysical methods do not give the required unique solution due to subsurface complexities. Most logging tools, developed to evaluate conventional reservoirs, often lose their sensitivity in ultra-low permeability, low-porosity reservoirs (Mukherjee et al, 2015). Due to the limitations of conventional logs, the zones of interest within Rohtas limestone sections are interpreted based on gas shows observed during drilling and fractures identified from XRMI logs. Hence, close monitoring of gas shows is critically important while drilling these tight reservoirs. Furthermore, conventional testing revealed the presence of sub-commercial gas and stimulation of vertical wells did not yield the desired results. Therefore, techniques need to be devised to evaluate these reservoirs particularly the fractures before it is damaged by drilling fluid to plan effective hydraulic fracturing. This paper addresses the detection of fractures while drilling for preparing the course of action to stimulate the wells to establish commerciality.

Real time fracture detection

We propose a two- pronged syndrill approach to decipher/locate the occurrence of fractures in the well. First the intensive mud logging approach using advanced Coriolis flow meter integrating with advanced mud logging parameters (time-logs) and secondly the real time log interpretation of standard LWD logs (Depth logs) using the statistical log parameter ‘P’ defined by Porter et al (1969). The two approaches done concurrently can be integrated for quality control and decipher the fractures and the gas bearing intervals. All mud logging and drilling parameters must be observed as time logs as against the LWD logs in the standard depth format.

Advanced flow monitoring system

The more direct instantaneous indication of the presence of an open fracture in a well comes from the mud flow variations. We are dealing with micro-fractures with low flow potential and hence sensitivity must be very high. The standard techniques to detect mud losses are: 1) Mud level monitoring in active mud pits with acoustic, floating sensor and 2) Measuring the flow out using a flow paddle sensor installed on the flow line. Both techniques are not suitable for the purpose of micro-fracture detection because they lack the required accuracy to identify the associated micro-losses. In the best scenario a 0.5 bbls mud loss can be identified by measuring the mud level in the total active mud system, when usually the micro-losses associated with the fracture is of the order of 10-30 lt/min. With reference to the flow paddle, it provides only a qualitative indication of mud flow variation without quantitative measurement of the flow out. It is not sensitive enough to identify subtle flow changes linked to the initial stages of an influx or to the minor fluid loss occurring when a formation fracture is encountered. A better accuracy and a quicker response to measure the flow out and to detect micro- losses have been achieved elsewhere using a high-resolution electromagnetic flowmeter.

An advanced system for mud flow measurement while drilling enables detection of fractures and intervals of high permeability within a tight, fractured low permeability reservoir via the identification and interpretation of mud micro- losses. The system is based on an electromagnetic flowmeter installed on the flow line which has a very high accuracy compared to the standard flow measurement system typically used in the field. The performance of the flowmeter is not affected by mud conditioning, and it is capable of measuring the flow rate with an accuracy up to 10 lt/min. The method enables us to identify natural open fractures through the detection of the micro-losses while drilling; whenever the bit intercepts an open fracture the mud invasion leads to mud micro-losses. Such losses are identified at the surface, in real-time, through accurate and continuous monitoring of the mud flow out. A Coriolis flowmeter can be mounted in the line between the active mud tank and the mud pumps to measure fluid pumped into the well. A second Coriolis flowmeter can be installed at the flow line to measure the fluid returning from the well.

Comparing the return flow out of the well to another Coriolis flowmeter on the suction side of the mud pump can provide an effective means to monitor formation micro losses. Formation losses can be monitored in real time by subtracting the flow rate out (Volume OUT) from the flow rate in (Volume IN (Figure 2). Any volume of fluid not returned to surface can be considered a formation loss. A portion of fluid is lost to spurt to build a filter cake; the rest is considered normal seepage loss and will contain some proportion of solids and liquid.

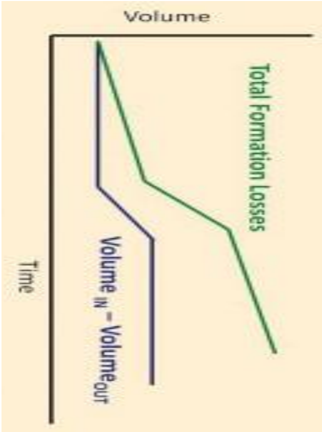

Figure 2: Flow rate formation losses trend in real time (Jason Norman 2011)

Interpretation of micro losses

The methodology consists of an integrated approach using delta flow time data (difference between Flow OUT and Flow IN) along with drilling data and gas data from mud logging. . We need to identify the natural open fractures, their typology, and to gather information using the micro-losses dynamic trend analysis versus time. The real-time analysis has to be carried out at the well by a specialist. The same analysis can be performed even from the office; however, the rig site is preferable for better quality control. The Delta Flow trend versus time is characteristic of the type of losses and consequently of the downhole fractures (Figure 3).

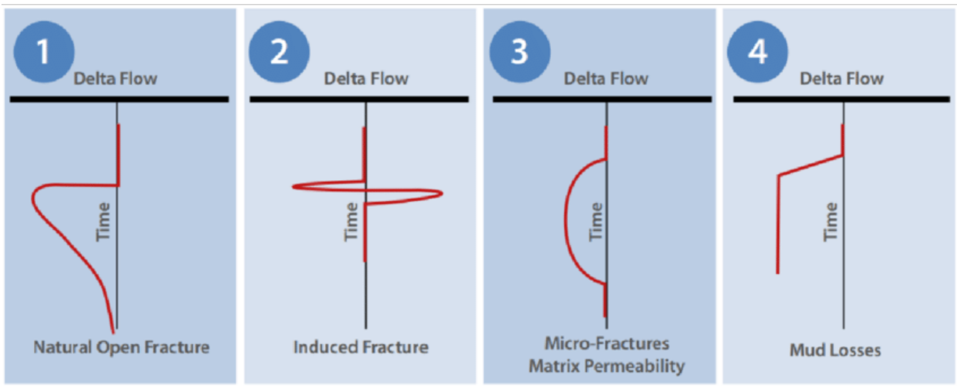

Figure 3, Delta Flow trend and Fractures/Permeability downhole events, from Beda and Carugo, 2001

1) In a natural open fracture, the mud invades the fracture, and a sudden decrease of Delta Flow is recorded in the surface by the electromagnetic Flow Out Sensor; the solid particles of the mud gradually plug the fracture and Delta Flow returns to the base line.

2) On the contrary, a mechanical fracture induced by the action of the bit shows a Delta flow decreasing when the fracture is generated, with an immediate recovery when the fluid invaded is given back.

3) The response of the Delta flow in the case of micro-fractures pattern or matrix permeability shows a gradual decrease due to the invasion of the mud into the pores or micro-fractures, and at the end of the permeable zone the Delta flow gradually increases.

4) In cavernous zones the mud losses occur suddenly at a high rate, with no return at the surface.

Interpretation of well bore ballooning

The occurrence of reversible mud losses and gains while drilling in naturally fractured formations is of primary concern. Coriolis flowmeters can also help to monitor ballooning. The phenomenon of ballooning is the slow loss of mud while drilling ahead, followed by a more rapid mud return after the pumps have been turned off (Figure 4). Borehole ballooning can complicate the already difficult practice of fingerprinting the changes in the return-flow profile, hence undermining the reliability of kick detection. The fluid progressively flows in and out of fractures as a consequence of three mechanisms: bulk volume deformation, fluid compressibility, and fracture-aperture variation (Silvio Baldino et al.2018)

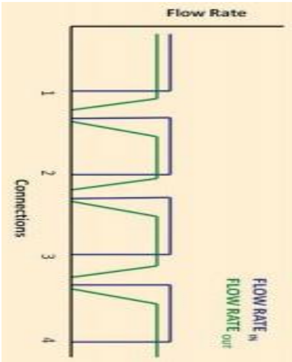

Figure 4 Typical signature of ballooning effects (Jason Norman 2011).

Intensive Advanced mud logging

Mud logs are fundamental industry standard formation evaluation tools that represent the first opportunity for evaluating the potential economic viability of a well. While drilling through a reservoir, a lot of valuable information can be obtained from mud logging to support formation evaluation. While the well is in a secure mode, an important aspect of well control includes fingerprinting, which simply means that once the shoe is drilled out, the well can be circulated at various rates while recording BHP and PWD data. The mud flow anomalies while drilling ahead can be validated with surface drilling parameters and gas indications.

The fracture detection capability can be enhanced by the analysis of drilling and hydraulic parameter variations recorded in real-time; their changes related to changes of the mechanical properties or the rock. Fractures on drilling are associated with increase in torque and gas indications. Some micro-fractures are partly or completely closed with secondary minerals or are visible only as planes of fluid inclusions, whereas other micro-fractures are open, have sharp sides, and lack secondary minerals. These can be observed on the cuttings and under the well site microscope.

Torque at the bit is a measure of the amount of energy needed to breakdown the rock. This energy is proportional to the torque and rotating speed. Rotating torque often increases due to the rock property contrast between the fractured and non-fractured rock, the increased porosity and fluid content of the formation, combined with a decrease in chip hold-down pressure, allow greater penetration of the rock by the drill bit. This leads to an increase in ROP and a greater friction (increased torque) between the bit and the rock. However, increasing torque is also caused by drilling deviated holes, out of gauge holes and bearing wear. The variations in torque must be analysed in conjunction with other observations.

The data acquired with the flow analysis are integrated with mud logging time data such as WOB, Torque, Standpipe Pressure and Pump Strokes. The integrated analysis can confirm that the flow rate variations are related to downhole formation losses and not to other causes (such as plugging of drill string, standpipe pressure variations). Companies rely on dedicated software routine and algorithms to synchronize the gas readings from depth allowing prompt identification of the gas peaks associated with the fracture in a time plot.

Gas while drilling

A decisive parameter to be monitored is the mud gas, since gas variations are often associated with the presence of open fractures in which hydrocarbons were circulating. Gas chromatographic analysis is also part of every gas while drilling campaign. Formation evaluation process uses the gas readings, as well, to identify any gas increase in correspondence to the open fractures and identification of permeable zones. The system and procedure are globally recognized as a valid solution for fractured reservoir detection. The advantage here is that the first response comes immediately on drilling without formation damage unlike the wireline logs. Mud gas also needs to be interpreted when ballooning takes place in some micro-fractures

Rock property prediction

The integration of the gas data along with the drilling parameters (ROP, Flow) can be valuable inputs for the qualitative prediction of rock properties such as porosity, permeability and identification of fractures while drilling.

1. Gas vs. drilling rate; Porosity indicator- C1/ROP, compare by establishing a base line.
2 Gas vs. flow indicator; Permeability indicator- C1/.ΔFlow (Flow IN- Flow OUT), In case of micro-fractures, micro- mud losses will gradually increase and then gradually decrease when mud plug the micro-fractures.
3. Both gas presence and flow data, where they support each other or even standalone at times are fracture indicators

Gas analysis must exclude other gas data resulting from swab gas, trip gas, connection gas, recycled gas, and background gas. Gas quality ratio (GQR) should be determined to ensure quality of the gas data by GQR= Total Gas ***/*** $(C1+2\times C2+3\times C3+4\times (nC4+iC4)+5\times (nC5+iC5))$
Good gas quality data will have a GQR between 0.8 and 1.2.

Statistical log parameter 'P'

Porter (1969) defined a parameter 'P' in terms of formation resistivity and porosity tool response. It is found that 'P' has a square root normal distribution for zones whose water saturation is 100%.whilst 'P' has a different and unidentified distribution for hydrocarbon bearing zones. Thus, the presence of hydrocarbon bearing zones can be detected by observation of the distribution of 'P'. A plot of P ½ versus cumulative frequency, thus, yields an approximate straight line. Hydrocarbon zones would deviate from this line (Figure 5). When this technique was extended to naturally fractured reservoirs (Aguilera, 1982), 'P' also had a square-root normal distribution for 100% water zones. The method does not require a priori knowledge of water resistivity, of the cementation exponent, or of the constants in the porosity-tool response equation, provided these quantities are constants for the zones considered.

When working with Sonic log 'P' is expressed as, $R_t\ (\Delta t - \Delta t_m)^m$ and with Density log it is $R_t\ (\rho_m - \rho_b)^m$
Both are equal to aRwBI where 'I' is the resistivity index, and B is $(\Delta t_f - \Delta t_m)$ and $(\rho_m - \rho_f)$ as the log used. The above is from the basic equation $R_t = a\varphi^{-m}R_wI$
It may be noticed that a, Rw, B and I occur on the same side of the equation and therefore 'P' should be constant for 100% water saturated zones if the resistivity, sonic and density measurements were true and the others constant. The LWD suite should suitably position the resistivity and porosity tools so that optimum coverage of the formations is obtained at the earliest.

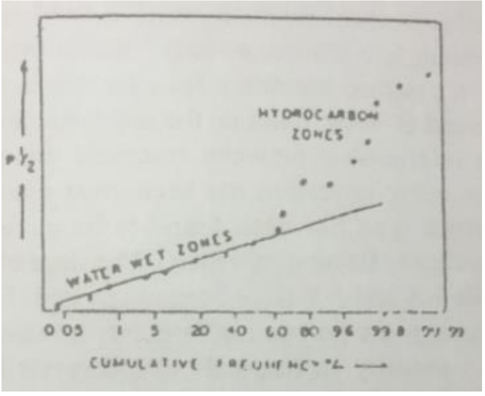

Figure 5: Idealized plot of P ½ vs. cumulative frequency (Porter et al, 1969)

Applicability.

The proposed approach to fracture detection while drilling is based on the concept of case based reasoning of similar situations elsewhere. Case-Based Reasoning (CBR) is the process of solving new problems based on the solutions of similar past problems (Figure 6). The vertical wells drill data must be revisited, and observations calibrated to establish surrogates or proxies for monitoring the wells to be drilled in future. Surrogates are substitutes or proxies for fracture observation (Laubach, 2003). For

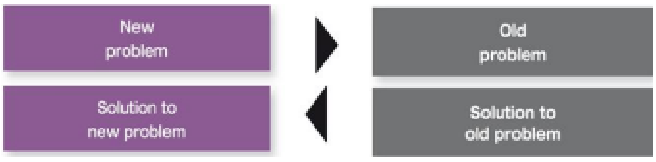

Figure 6: Case-Based Reasoning Model (Xuan Vandeberg Harris 2013)

large fractures, microstructure surrogates have previously been used to assess fracture strike (Laubach, 1997). The surrogates or proxies proposed here are the drilling and mud log observations that enable pinpoint depth intervals that are fractured/micro-fractured. This kind of data acquisition and analysis of the data obtained will enable the identification of fractures in carbonate reservoirs and reservoir sweet spots. We suggest the generation and utilization of such data in future wells and in conjunction with offset data from previous wells and existing literature, to decipher fractures.

Conclusions

Proper evaluation of fractures is key to exploration of these tight unconventional reservoirs. Cores and image logs are used for fracture characterization, but they do not provide real-time response. The patterns in the variations of mud flow, using an advanced Coriolis-type mud flowmeter could enable to identify open fractures. Combining this with real time P ½ evaluation will enable detect micro-fractures and gas bearing sweet spots. Rock properties such as porosity and permeability can be modelled by advanced mud flow and mud gas detection. We suggest the generation and utilization of such data in future wells and in conjunction with surrogates from offset data analyses to decipher micro-fractures to effectively plan the testing and stimulation of these tight reservoirs.

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