Naturally Fractured Reservoir Stimulation Mechanism : A Case study in Vindhyan Basin

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Keywords

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Summary

The reservoir within Rohtas Limestone having ultra-low matrix porosity (in range of 0.14% to 4%) and very low air permeability (in the range of 0.01mD to 0.46 mD). Ultra low matrix porosity and permeability narrowed down the possibility of gas flow during drilling and well testing. The fluid flows in these reservoirs are due to presence of natural fractures only. The geomechanical characterization of these natural fractures reveals that only negligible numbers of natural fractures are Critically Stressed. The present study is based on the Critically Stressed Fracture (CSF) characterization and methodology for stimulation of non-CSF to CSF state within Proterozoic Rohtas limestone formation. A natural fracture is considered to be critically stressed fracture if the ratio of shear and normal stresses acting on the fracture surface exceeds the frictional strength of the reservoir rock.

Introduction

The Vindhyan basin is a Proterozoic intercontinental that developed in the central part of India. It occupies a large area in Central India and attains a huge thickness of more than 5 km. The rocks are metamorphosed and undisturbed to moderately disturbed with low angle dips. In fact, the Vindhyan Supergroup is the thickest Precambrian sedimentary succession of India and the duration of its deposition is one of the longest in the world.

The discovery of gas in well Nohta-B within the Rohtas Limestone did open up new vista to explore and establish the prospectively of Son Valley sector of Proterozoic Vindhyan Basin. Rohtas Limestone and Kaimur formations emerged as the primary exploration targets. As part of concerted exploratory effort; wells were drilled in the Nohta-Damoh-Jabera corridor of the PEL block during last few years. These wells have established the presence of gas within different units of Rohtas Limestone. Due to absence of primary porosity (and hence permeability), Fluid flow in Rohtas rocks is largely controlled by critically stressed fractures; therefore, critically stressed fracture analysis may enable to systematically identify producing fractures in the reservoirs.

Methodology

A 1-dimensional geomechanical model was built using well log, wellbore image, drilling data, rock strength testing on core. The geomechanical model characterizes in-situ stress and pore pressure. The borehole breakouts appeared on micro resistivity image logs were used to constrain the orientation and magnitude of maximum horizontal stress using poroelastic method. Present day maximum and minimum horizontal stress directions were determined, which is 110^0 with respect to North and same is cross validated with azimuth of fast shear wave from dipole sonic logs. 1-D geomechanical model of wells under study area infers strike-slip stress regime in Rohtas Limestone section.

Borehole image were used to characterize the natural fracture system in the reservoir. Effective normal and shear stress are calculated at each fracture plan. Stress normal to fracture plane and shear stress along fracture plane were estimated and plotted on Mohr-Coulomb diagrams, fractures surfaces with shear and normal stresses exceeding the frictional strength of the reservoir rock flagged in Red color are Critically Stressed Fractures. The critically stressed fractures (CSF) were identified at in-situ stress and in-situ pore pressure conditions. CSF analysis reveals negligible presence of Critically Stressed Fractures in in-situ stress and pore pressure conditions.

In next stage, Geomechanical simulation were carried out for the stimulation of natural fractures and critical pressure required for shear slip of pre-existing natural fractures was determined. Different scenarios were simulated by increasing injection pressure to determine critical injection pressure required for shear slip stimulation (conversion of CSF from non-CSF state) of natural fractures. By geomechanical simulation, it has been seen that shear slip of natural fractures starts at injection pressure of 1000-1200 psi above normal pore pressure. Increasing injection pressure to 2000 psi above normal pore pressure converts 30% of non-CSF to critically stressed state. These additional CSF's would contribute to increase yield in gas. Digram in Figure-1 represents brief methodology of the study.

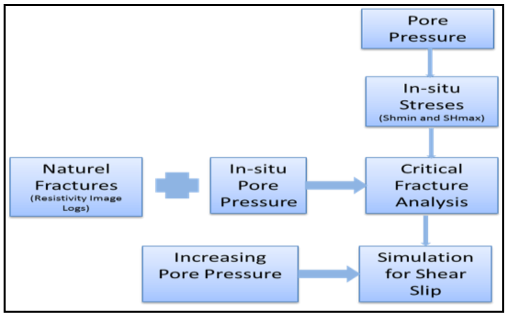


Figure 1: Diagram showing methodology for Geomechanical Simulation of Natural Fractures.

Natural Fractures

Micro-resistivity image data is used to identify natural fractures. Fractures were picked manually using standard Image processing software module. In Figure-2, GR, standard resistivity logs, neutron-density log, and dynamic image are given in track 1, 4, 5 and 6 respectively. Fracture dip and azimuth are presented in "DIP" track-7.

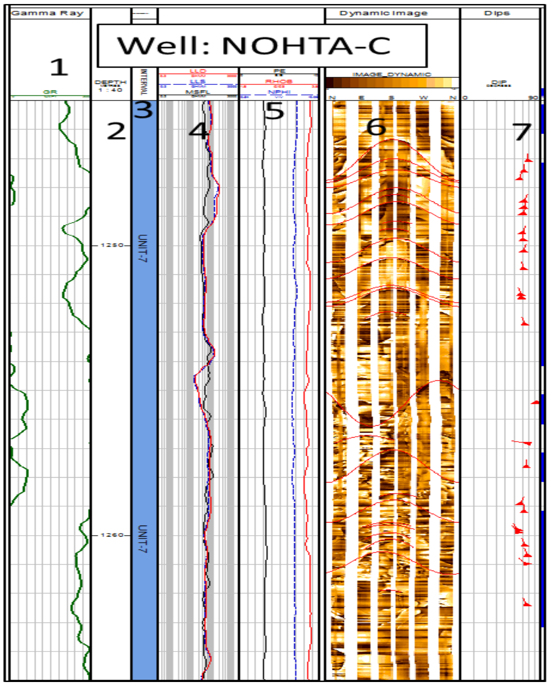


Figure 2: Resistivity image log showing natural fractures.

Rock Mechanical Data

Rock mechanical testing were carried out to determine UCS, Young's Modulus, PR, Tensile Strength and Frictional Coefficient on the conventional core recovered from Rohtas Limestone section of wells NOHTA-A, NOHTA-B and NOHTA-D. The dynamic elastic properties are generated using empirical equations and calibrated with lab determined static mechanical data to generate continuous static mechanical property curve.

Horizontal Stress Directions

The minimum and maximum horizontal stress direction is determined from failures observed on borehole wall i.e. the azimuth of borehole breakouts seen on micro-resistivity image logs are the azimuth of Shmin. As it is a known fact that orientation of SHmax is right angle to Shmin i.e. at $\pm 90^0$ to the azimuth of Shmin.

In-situ Pores Pressure and Stresses Magnitude

Rohtas Limestone formation rock is super mature; so the pore pressure is expected to be normal hydrostatic only. Based on mud weight data and drilling data, the pore pressure of the Rohtas Limestone taken normal hydrostatic.

Overburden pressure is the pressure or stress imposed on a rock surface by the weight of overlying formations. It is computed by integrating overlying rock mass; i.e. by integrating density of overlying formations. In surface sections where density logs were not available; density of 2.2 gm/cc is taken in absent section for computation of overburden stress.

The horizontal minimum and maximum stress magnitudes are computed using isotropic poroelastic horizontal strain model;

$$SHmax = \frac{POIS * (PRESS_{OB} - BIOT * PRESS_{FM})}{1 - POIS} + BIOT * PRESS_{FM} + \frac{YMOD * STRAIN_{MAX}}{1 - POIS^2} + \frac{POIS * YMOD * STRAIN_{MIN}}{1 - POIS^2}$$

$$Shmin = \frac{POIS * (PRESS_{OB} - BIOT * PRESS_{FM})}{1 - POIS} + BIOT * PRESS_{FM} + \frac{YMOD * STRAIN_{MIN}}{1 - POIS^2} + \frac{POIS * YMOD * STRAIN_{MAX}}{1 - POIS^2}$$

The value of Shmin and SHmax is obtained using iterative process by putting tectonic factor value “0” initially. In the next stage Shmin is calibrated by adjusting/increasing value of tectonic factor; in this process the value of tectonic factor is adjusted in such a way that Shmin curve passes through the LOT points.

Integration rock mechanical data, pore pressure and in-situ stresses, one dimensional geomechanical model is prepared. One dimensional geomechanical model of Rohtas Limestone section of well NOHTA-B is given in Figure 3.

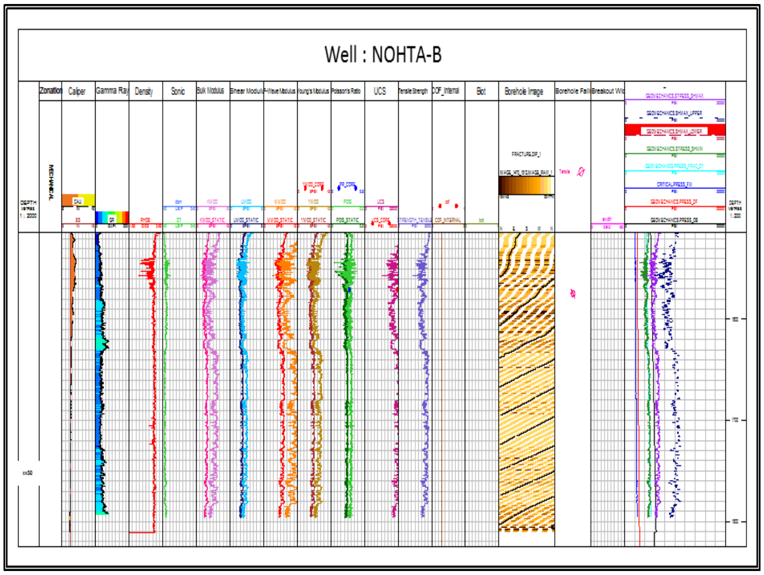


Figure 3: One dimensional geomechanical model in Rohtas Limestone section of well NOHTA-B

Shear Slip of Natural Fractures

Effective stresses are coupled with pores pressure of formation, as showe in Figure-4. Increasing pore pressure by injection of fluid in the fractures increases the pressure which, in turn, causes a reduction in the effective normal stress. Further reduction of effective normal stress due to injection may lead to shear slip on the fracture surfaces i.e in state of failure(CSF state). Sufficiently large shear displacement discontinuities initiates the wing cracks at angle approximately 70 degrees from the tip of the fracture. Wing cracks tend to reorient and propagate in the direction of maximum in-situ stress.

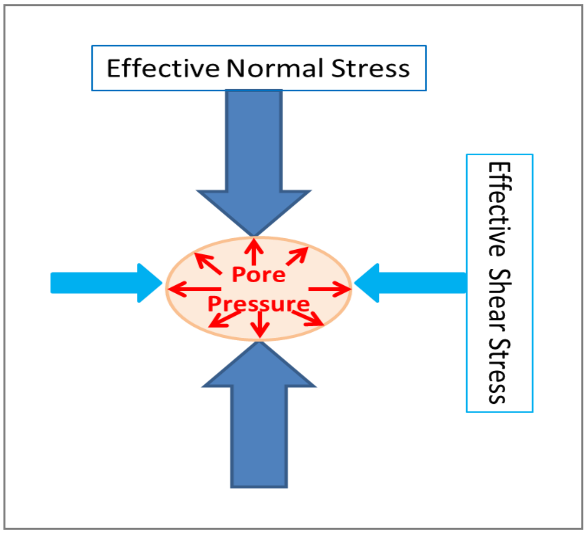


Figure 4: Effective stress coupling with pores pressure.

Results and Discussion

Critical Fracture Analysis is carried out at in-situ reservoir pressure condition for the wells NOHTA-A, B and C are given in Figure-5a, 5b and 5c respectively. Coefficient of sliding friction (failure line) is taken 0.76; considering friction angle determined from core study in NOHTA-A and NOHTA-D. The maximum friction angle in three core samples of wells was 37.5 degree. It is evident from the Figure-4a, 4b and 4c below that there is no critically stressed fracture present in-situ pressure condition in Rohtas section of wells NOHTA-A, NOHTA-B and NOHTA-C

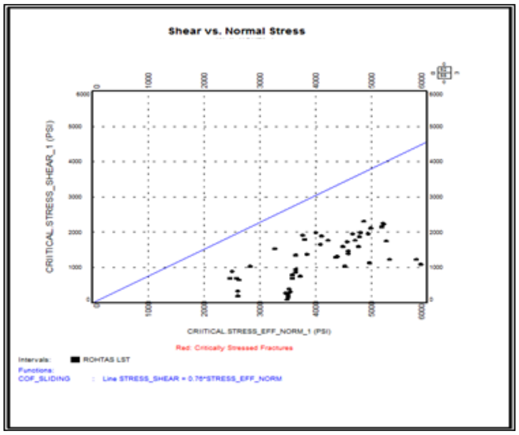


Figure 5a: CSF analysis at in-situ pore pressure condition in Rohtas section of NOHTA-A.

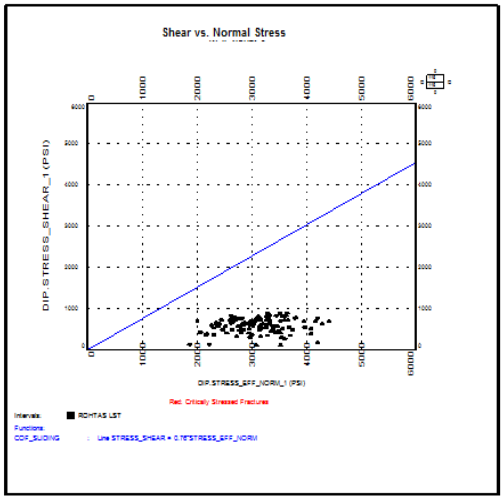


Figure 5b: CSF analysis at in-situ pore pressure condition in Rohtas section of NOHTA-B.

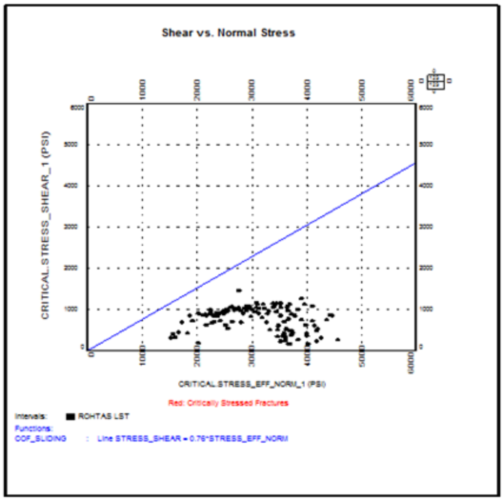
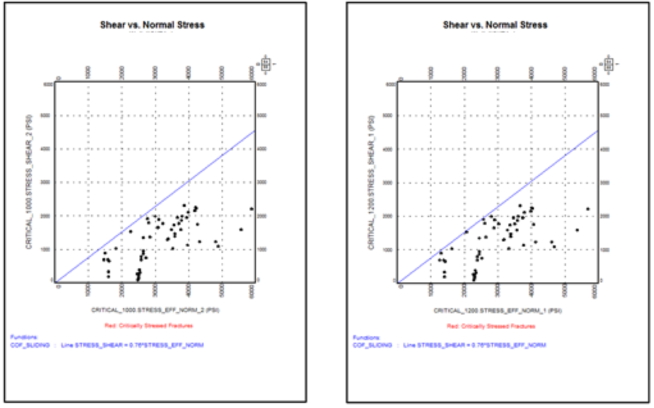


Figure 5c: CSF analysis at in-situ pore pressure condition in Rohtas section of NOHTA-C

Presence of non-CSF is cross validated with the production testing results in these wells, none of the wells among NOHTA-A, B and C had flow of gas during initial production testing(without any stimulation).

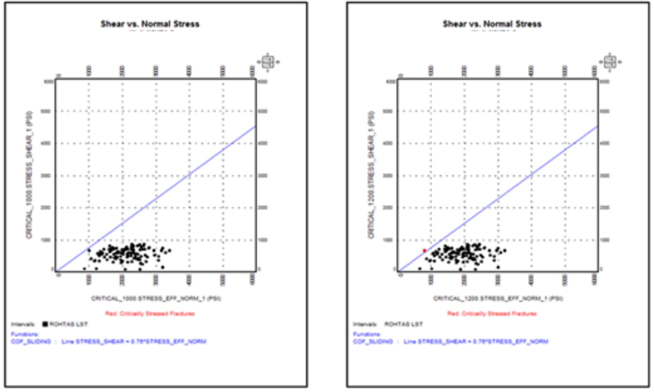
To see the stimulation effects on the natural fractures, repeated CSF analysis is carried out with injection pressure of 1000-1200 psi above normal pore pressure; it has been seen that non-CSF's started converting into shear slip mode (i.e. non-CSF are started converting to CSF) at injection pressure between 1000-1200 psi above normal pore pressure for Rohtas limestone section. CSF analysis at injection pressure of 1000 psi and 1200 psi are given in Figure-6a, 6b and 6c for the wells NOHTA-A, B and C respectively.



Injection Pressure of 1000 psi

Injection Pressure of 1200 psi

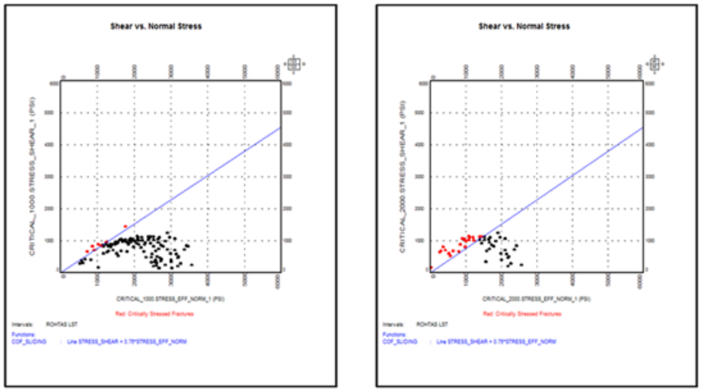
Figure 6a: Simulation for shear slip at different 1000 and 1200 psi injection pressure in NOHTA-A.



Injection Pressure of 1000 psi

Injection Pressure of 1200 psi

Figure 6b: Simulation for shear slip at different 1000 and 1200 psi injection pressure in NOHTA-B.



Injection Pressure of 1000 psi

Injection Pressure of 2000 psi

Figure 6c: Simulation for shear slip at different 1000 and 1200 psi injection pressure in NOHTA-C.

Finally CSF analysis is carried out with an injection pressure of 2000 psi above normal pore pressure given in Figure-7a and 7b for the wells NOHTA-A and NOHTA-B respectively; in this case around 30% of the natural fractures are going above the failure line. These fractures are in critical state i.e. these will be hydraulically active and will contribute to production.

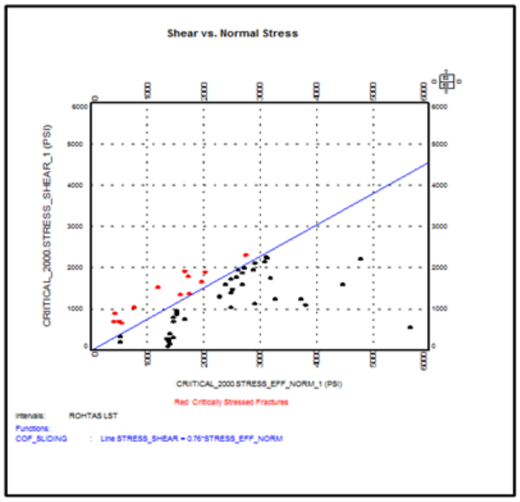


Figure 7a: Critical Fracture Analysis at injection pressure of 2000 psi well NOHTA-A.

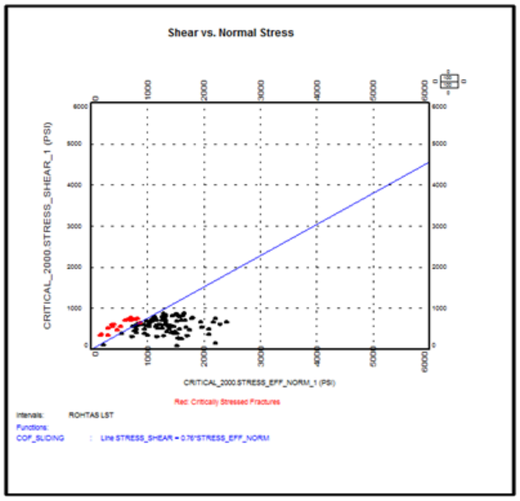


Figure 7b: Critical Fracture Analysis at injection pressure of 2000 psi well NOHTA-B.

Conclusions

- Rock testing analysis on the core recovered from Rohtas Limestone section indicate UCS of the rock from 90 Mpa to 169 Mpa (13,050 psi to 24,500 psi), conventional hydro-fracturing is a difficult task in this kind of reservoir rock. Alternative mechanism to create productive fracture rather than going for conventional hydro-fracturing may be making natural fractures to shear slip.
- Geomechanical model suggests strike slip stress regime within Rohtas Limestone section in Nohta area.
- Critical fracture analysis is carried out for all the wells using one dimensional geomechanical model and image logs; which reveal presence of non-critically stressed fractures.
- CSF analysis is carried out in stimulating reservoir pressure conditions; with stimulation pressure of 1000 psi to 1200 psi pressure above normal pore pressure, the non-CSF started converting to CSF state and after increasing stimulation pressure to 2000 psi around 30% of the naturel fractures are converted to critical state which actually contributes to fluid flow.

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