Geological controls on mechanical stratigraphy and its impact on multiscale fracturing of unconventional carbonate reservoir: Rohtas Limestone Formation, Proterozoic Vindhyan Basin, India

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Keywords

Mechanical stratigraphy, Strata bound fractures

Summary

Presence of thermogenic gas within unconventional tight carbonate reservoirs of Rohtas Limestone Formation has been established over a large area in Son Valley sector of Proterozoic Vindhyan Basin through a number of recent exploratory wells. Flow of gas from these unconventional tight carbonate reservoirs is primarily dependant on the presence of open / partially open natural fracture systems. The present paper brings out the results of genetic characterization of the fractured carbonate reservoirs through integrated analysis of outcrop lineaments, seismic attributes, image logs of drilled wells, depositional facies and geomechanical properties. Formation of multi scale natural fracture systems within different units of Rohtas Formation are controlled by tectonic forces as well as facies association. Maximum horizontal compressive stress direction is inferred to be ENE-WSW (80-87.5^0) to E-W (92.5-97^0) and minimum horizontal stress direction is N-S to NNW-SSE (350^0 to 07^0). Three distinct Mechanical Units (MU) have been identified within the stratified sequence of Rohtas Formation defined by geomechanical properties of different litho-facies. MU-1 and 2 within Upper Rohtas unit exhibit typical brittle rock fracture characteristics. MU-3 within Middle Rohtas unit depict fracturing under the influence of depositional composition and diagenetic changes within contrasting facies association, which impart distinct geomechanical properties to this unit. Four distinct fracture permeability systems, namely Fractured host rock, Strata bound fracture network (SFN), Non strata bound fracture network (NSFN) and Fault induced tectonic fractures have been identified which control the gas flow behavior. Identification of these fracture systems is critically important to facilitate future target selection for assessing the gas flow potential of these tight carbonate reservoirs.

Introduction

With the days of conventional hydrocarbons maturing, the industry is consciously shifting its focus towards unconventional and tight hydrocarbon plays in challenging and frontier areas. Recent successful exploration for tight gas plays in geologically oldest Proterozoic Vindhyan Basin in India revealed that ultra-low porosity and micro-Darcy permeability Rohtas carbonate reservoirs, with significant natural fracture systems, may emerge as a significant gas play. Genetic characterization of the fractured carbonate reservoirs in terms of geological controls and geomechanical attributes is a key challenge in view of strong heterogeneities at various scales from outcrop, seismic, logs to microscopic levels. Nevertheless, a detailed characterization of the natural fracture distribution is critically important in such tight and low permeability reservoirs since even a small enhancement in permeability is sufficient for significant flow of gas from such reservoirs. In this study, we present the results and interpretation of our work on the geological controls on fracture formation, identification of mechanical stratigraphy comprising distinct geomechanical units and types of fracture permeability systems within different units of Rohtas Formation.

Geological and tectonic setting

Proterozoic Vindhyan Basin in the central part of India is situated between the Great Boundary Fault (GBF) to the north-west and Son-Narmada Lineament (SNL) to the south. The Bundelkhand Massif, located in the north-central part of the basin, divides it into two sectors: Chambal Valley to the west and Son Valley to the east (Fig.1). The basin fill in Son Valley constitutes 2-6 Km thick shallow marine sedimentary succession, comprising carbonate dominated Lower Vindhyan (Semri Group) and clastic dominated Upper Vindhyan (Kaimur, Rewa and Bhander Groups) sequences, separated by a large hiatus (Fig.2). The basin initiated by basement related rift tectonics, which formed a number of horst and grabens. Two main fault trends are evident, faults parallel to the SNL (E-W to ENE-WSW) as well as along NW-SE aligned oblique faults. Three major tectonic blocks are evident in Son Valley: Udaipur-Tendukhera Block, Jabera-Damoh Bock and Satna-Rewa-Kaimur Block (Fig.3). In later phase of evolution, compressional reactivation of pre-existing extensional faults under the influence of wrench related strike–slip movement resulted in the formation of inversion structures like Damoh and Jabera. There are evidences of an initial compressive pulse during post-Jardepahar time leading to the initiation of structural inversions and finally a major compressive event during post-Rohtas time led to culmination of major inversion structures.

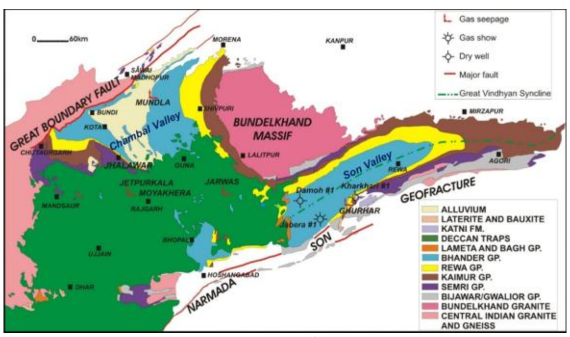

Fig.1 Geological map of Vindhyan Basin

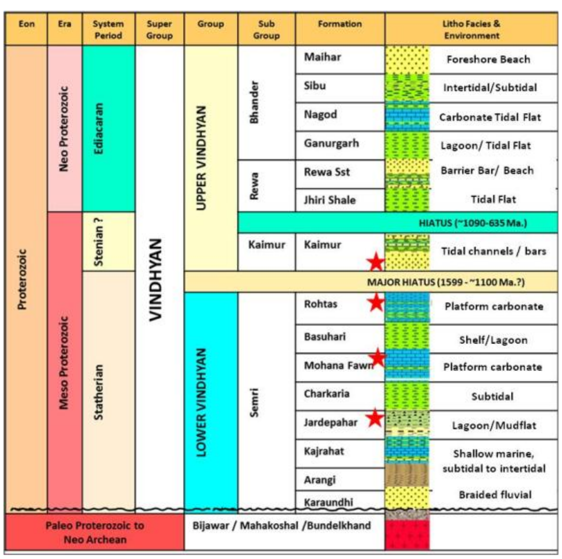

Fig.2 Stratigraphy of Son Valley, Vindhyan Basin

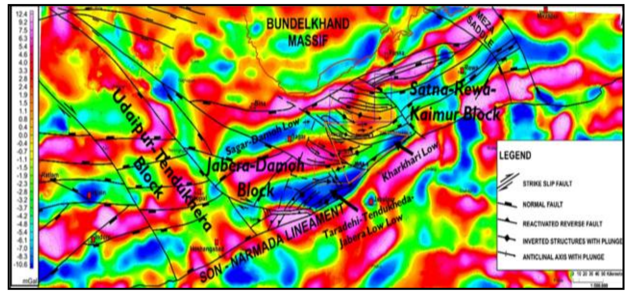

Fig.3 Tectonic map superimposed on Residual gravity map of Vindhyan Basin (source: KDMIPE)

Factors controlling fracture distribution

The spatial distribution of fractures and their intensity within Rohtas Limestone is controlled by following parameters:

Tectonic control

Lineament and fracture data generated on outcrop studies by earlier workers (Banerjee et.al, 2002, Samal et.al 2005) were analyzed and two major trends of lineaments found: ENE-WSW (Parallel to SNL) & NNW-SSE (Oblique/ cross trends). Lineament intensity is maximum near axis of Vindhyan syncline. Southern margin close to SNL is tectonically more disturbed. Lineament directions observed within different formations of Lower Vindhyan from field traverses were plotted and their principal stress directions were determined (Fig. 4). There are two preferred fracture directions within Kajrahat and Jardepahar formations (almost NE-SW and NW-SE) with the inferred maximum horizontal compressional stress direction being 96^0-97^0 (σ1) and. The fracture trend within Charkaria Formation shows a minor variation with maximum horizontal compressional stress direction (σ1) being 84^0. This may be attributed to minor fluctuation in stress regime at the end of Jardepahar tectonic event. At Rohtas-Basuhari-Mohana Fawn levels, the fracture trends show a considerable scattering. The maximum horizontal compressive stress direction change significantly to 112^0 (σ1). This may be related to the phase of most intense tectonic pulse at the end of Lower Vindhyans.

Analysis of image logs (XRMI) and available conventional cores of drilled wells to identify fracture intensity, aperture, dip and strike orientations and inferred stress directions revealed that different units of Rohtas Formation exhibit two dominant sets of fractures formed during multiple tectonic episodes (Fig.5). The inferred maximum horizontal compressive stress direction is ENE-WSW (80-87.5^0) to E-W (92.5-97^0) and minimum horizontal stress direction is N-S to NNW-SSE (350^0 to 07^0).

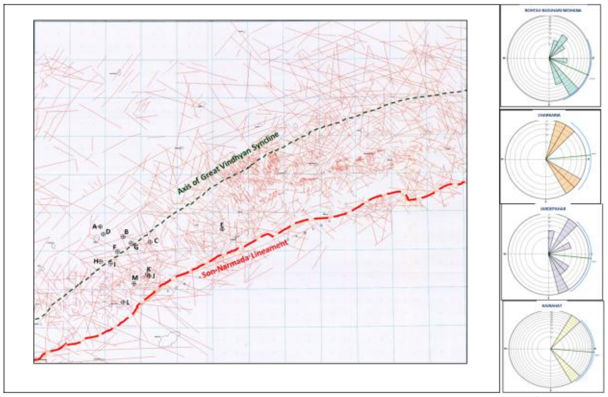

Fig.4 Outcrop Lineament map (source: KDMIPE) and inferred stress directions within Lower Vindhyan

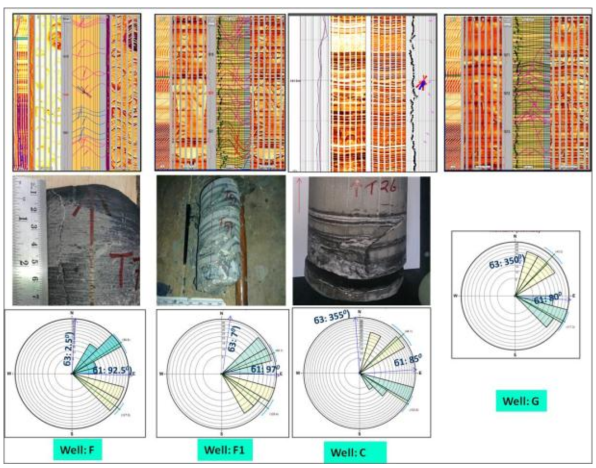

Fig.5 Inferred stress directions from XRMI logs and cores of drilled wells

3D seismic attributes clearly bring out distribution and intensity of natural fractures is influenced by the position with respect to major fault zones / fault intersections. Wells drilled close to intersection of major faults (well G), show considerable increase in fracture intensity and variation in stress direction (Fig.6).

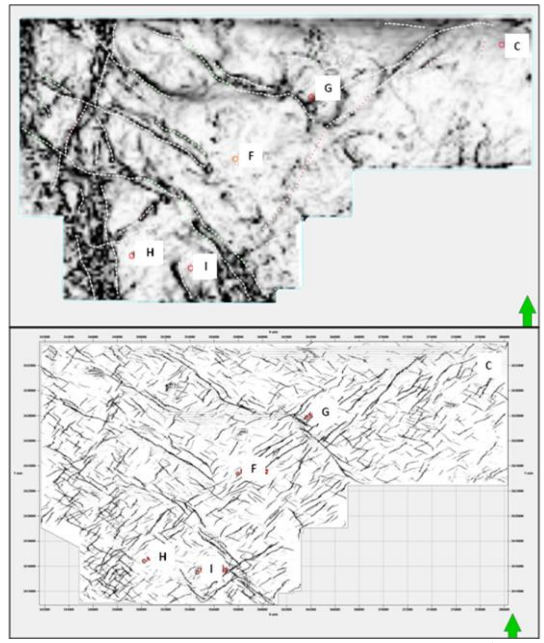

Fig.6 Variance (top) and ant track (bottom) showing the influence of major faults on fracture distribution

Facies control

The concept of facies control on fracture occurrence and mechanical stratigraphy, subdividing stratified rocks into discrete mechanical units defined by geomechanical properties such as tensile strength, elastic stiffness and brittleness has been emphasized by workers like Laubach (2009), Bettroti (2007). Distinct and diagnostic geomechanical properties occur in stratified rocks under the influence of depositional composition and diagenetic processes which have a strong influence on fracture pattern. Facies appear to be important controlling factors for the fracture intensity and spatial distribution within different lithological sub units within Rohtas Formation. The sequence within Rohtas Limestone represents a typical rhythmite composed of several facies deposited in a carbonate platform set up. The Upper and Lower Rohtas units are composed of mudstone, dolomitic layers with interbeds of shale while the Middle Rohtas unit is dominated by shale with frequent thin interbeds of mudstone and argillaceous limestone (Fig.7).

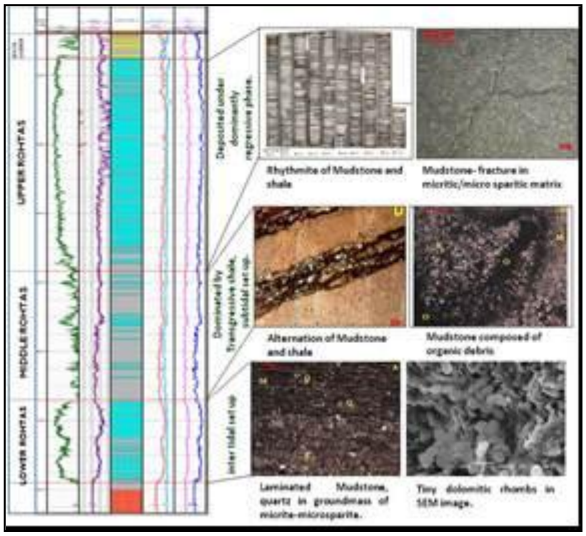

Fig.7 Facies and depositional set up of sub units within Rohtas Formation

At small-scale, porosity profile, depending on the initial sedimentary facies and the early diagenesis, controls the distribution of the mechanical properties along a facies sequence. It is observed that the deformation is differently expressed within each bed, forming several small-scale mechanical units. Given the fact that sedimentary facies have evolved laterally and vertically throughout the platform area, and that the early diagenesis also changes with the depositional environment, initial mechanical properties of rocks will change during these evolutions. In addition, lateral facies changes such as the presence of laterally limited lenses of dolomite within a mudstone affect the vertical fracture connectivity. In general, the interfaces of the intermediate- and large-scale mechanical units are located at all major lithologic and faciologic changes. During deformation, fracturing is only controlled by the mechanical properties acquired during early diagenesis.

Mechanical Stratigraphy

One of the key objectives of the present study is to evolve a mechanical stratigraphy approach that interprets discrete mechanical units within the stratified sequence of Rohtas Formation defined by geomechanical properties of different litho-facies. For the above study, parameters like Young's modulus (E), Poisson ratio (μ) and uniaxial compressive strength (UCS) obtained from rock mechanical tests conducted on the core samples of Rohtas Formation at National Institute of Rock Mechanics (NIRM) was analyzed in conjunction with electrolog derived parameters.

Based on the rock mechanical properties and facies character, three distinct Mechanical Units (MU) have been identified within Rohtas Formation (Fig.8).

MU-1:

This MU is present at the top of Upper Rohtas unit represented by 40-50m thick hard dolomitic layer which might have originated due to solution activities by meteoric water during period of hiatus at the top of this sequence. The characteristic parameters are low GR (20-30 API), low NPHI (0 to 0.2), high UCS (25-30K psi), very high Young's Modulus (70-90 GPa) and Poisson's Ratio ranging from 0.15 to 0.25. At few places separation between Stoneley and Elastic Stoneley indicates possible presence of fractures within this brittle MU.

MU-2:

High fracture density intervals within Upper Rohtas unit define MU-2 with facies association of gray to dark gray, massive mudstone composed of micrite, microsparite, minor detrital quartz grains, and partially dolomitized at places with interlaminations of dark gray, incipiently fissile, micaceous, silicified and occasionally feebly-calcareous shale. This MU is characterized by low GR (30-60 API), low NPHI (0 to 0.5), high UCS (25-30K psi), high Young's Modulus (60-80 GPa) and higher Poisson's Ratio (0.25 to 0.35) relative to the rocks above and below. Clear separation is evident in these intervals between stoneley and elastic stoneley which indicates possible presence of fractures/permeability. Such brittle rocks having higher young's modulus and higher Poisson's Ratio have been observed consistently within Upper Rohtas formations in most of the drilled wells and most of the gas bearing zones are confined within these higher fracture density and intensity MU.

MU-3:

There is another distinct mechanical unit (MU-3) in the lower part of Middle Rohtas Unit where high density fractures have been observed in most of the drilled wells. This unit is characterized by thin interlaminations of contrasting litho facies: dominantly dark gray calcareous shale alternating with siltstone and sparitized mudstone. These intervals have higher GR (>100 API), higher NPHI (0.1 to 0.15), moderate to high UCS (15-25K psi), lower Young's Modulus (30-50) and lower Poisson's Ratio (0.2 to 0.25) relative to the MU-1 and 2 within Upper Rohtas. Consistent higher density and intensity of fractures occurrence have been observed in this MU which is attributed to association of contrasting mechanical facies. Siltstone and mudstone with high rupture strength has a higher Poisson's Ratio but lower Young's Modulus, while calcareous shale with less rupture strength have a lower Poisson's Ratio but higher Young's Modulus. Therefore, under identical tectonic stress conditions, calcareous shale with less rupture strength is more brittle and prone to produce fractures.

Reservoir implications

Occurrence of four types of Permeable Fracture Systems has been identified within Rohtas Formation. They are:

Fractured host rock (matrix): In relatively less deformed areas, the fracture intensity and connectivity are usually controlled by the facies / diagenetic heterogeneities rather than by the deformation linked to tectonic episodes. They represent the lowest-scale (crystal-sized) permeable system.

Strata bound Fracture network (SFN): They are characterized by fractures terminating along the margins of mechanical layers like bed boundaries. The fracture spacing is regular and increases with mechanical layer thickness. These confined fracture systems are major targets for gas accumulation.

Non-strata bound Fracture network (NSFN): They are formed by irregularly spaced fractures displaying either lengths lesser than bed thickness, or cross cutting more than one mechanical layer.

Tectonic Fractures: Fractures related to fault zone are characterized by a clustered spatial distribution and occur as the longest permeable system extending from deeper to shallow stratigraphic units and play a critical role as effective conduits for hydrocarbon migration and also connect the individual fracture sets within each mechanical unit. The different permeable fracture types can be clearly deciphered on seismic ant track attribute sections (Fig. 9).

The overall hydraulic behavior of fluid flow is a cumulative measure of the fluid transfer from matrix to the SFN or NSFN, which, in turn, interact with the fault network. The most productive wells are situated in proximity to faults and zones close to the junction of conjugate fault / fracture systems. Selectively identifying and targeting the MUs within Upper and Middle Rohtas units with higher density/ intensity fracture intervals by drilling high angle wells and selective stimulation will enable maximum contribution from all the above permeability structures over a larger a large contact area for gas flow within the reservoir.

Conclusions

Genesis of multi scale natural fracture systems within unconventional tight Proterozoic Rohtas gas reservoirs is controlled by tectonic forces as well as facies association, depositional composition and diagenetic processes.

Analysis of tectonic stress directions from outcrop lineaments, seismic discontinuity attributes and XRMI logs of drilled wells reveal two dominant sets of fractures within different units of Rohtas Formation formed during multiple tectonic episodes along SNL and oblique fault systems. The inferred maximum horizontal compressive stress direction is ENE-WSW (80-87.5^0) to E-W (92.5-97^0) and minimum horizontal stress direction is N-S to NNW-SSE (350^0 to 07^0)

Based on geomechanical parameters like Young's modulus (E), Poisson ratio (μ), and uniaxial compressive strength (UCS), three distinct Mechanical Units (MU) have been identified. MU-1 and 2 within Upper Rohtas unit depict typical brittle rock fractures while MU-3 within Middle Rohtas unit represent fracturing under the influence of contrasting mechanical facies with different rupture strengths.

Four distinct fracture systems are identified in the area based on seismic discontinuity attributes. They are: 1) Fractured host rock, 2) Strata bound fracture network (SFN), 3) Non strata bound fracture network (NSFN) and 4) Fault induced tectonic fractures. Effective fluid transfers between the different fracture permeability systems are considered as a primary driver which controls the gas flow behavior of these unconventional tight reservoirs.

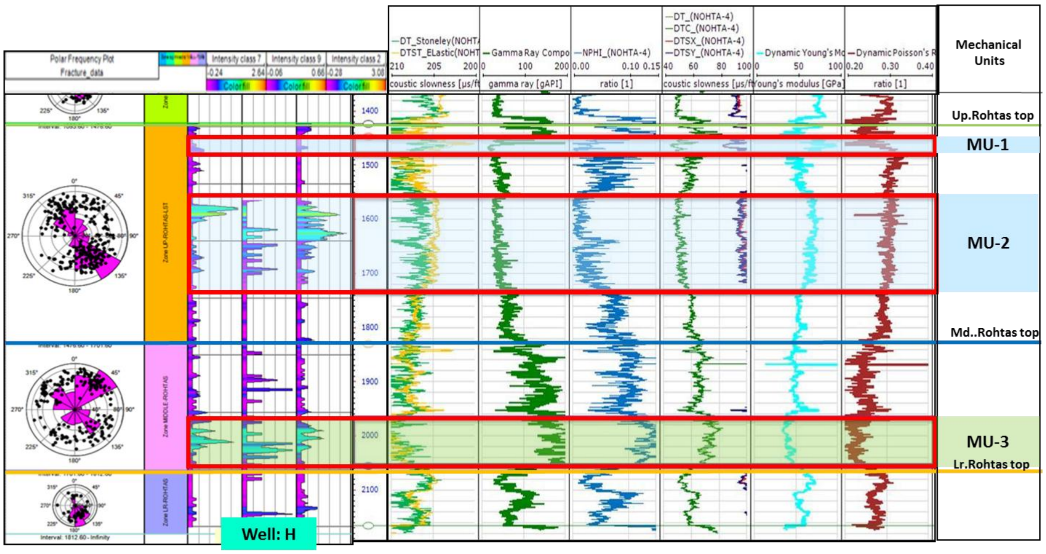

Fig.8 Mechanical Units within Rohtas Formation

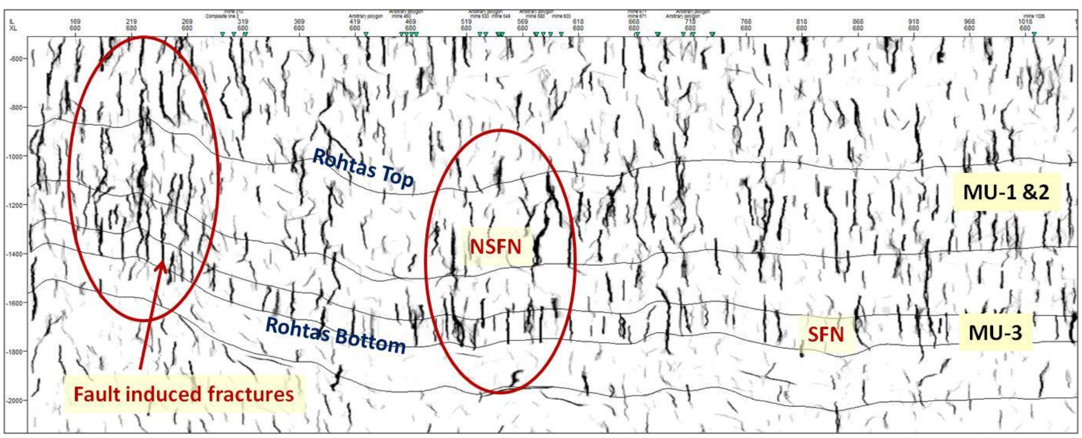

Fig.9 Seismic ant track section depicting fracture types

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