# Exploration and exploitation of Tight gas reservoirs in Proterozoic Rohtas Limestone, Vindhyan Basin, India: Major challenges and Road ahead

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**Keywords**

Tight gas, dual porosity, stimulation

**Summary**

Meso-Proterozoic Son Valley sector of Vindhyan Basin, with encouraging thermogenic gas flow from several wells, has revealed substantial exploration potential from rocks more than one billion year old and any production to be established would be among the oldest in the world. Drilling of recent wells has opened up a new and regionally extensive Rohtas Limestone play in the Lower Vindhyan sequence of the basin. Though the very tight limestone with low production rate prevented the discovery well Nohta-B as well as subsequent wells from being commercial, the vast unexplored regional extent of the limestone reservoir represents a new opportunity in the basin. The organic activity has been documented in the form of thin algal layers and the sedimentary sequence is thermally over mature. Significant volume of gas appears to have been generated and migrated into reservoirs within multiple petroleum systems and may be available for exploration.

Thirteen exploratory wells have been drilled so far in Son valley. Initially drilled wells probed the large inversion structures like Jabera, Damoh and Kharkhari, out of which only well Jabera-A established presence of non-commercial thermogenic gas from stratigraphically deeper Jardepahar clastics. After the significant gas flow from shallower Rohtas Limestone from a well drilled in Nohta area, subsequent wells were targeted to this potentially prospective section only. Gas accumulations within strati-structural traps, both in Rohtas Limestone and immediately overlying Basal Kaimur Sandstone, have since been identified and may be characterized as unconventional pervasive tight reservoirs. Limestone in the upper portion of the Rohtas Formation is the key objective.

Recently acquired 3D seismic data indicate plays and leads that were not brought out by earlier 2D seismic based evaluation and drilling. Presence of both strata and non-strata bound fractures around faulted areas, where permeability has been enhanced by fracturing, may be the dominant feature controlling the flow of gas. The main obstacle to establishing commerciality of the discovery are ultra-low matrix porosity and permeability and identification of technically suitable well stimulation method. This paper presents success of exploration activities made so far as well as the major challenges and remedies by way of specific reservoir characterization, drilling and well stimulation technologies being implemented in the exploitation of the gas from these unconventional reservoirs to establish Vindhyan Basin as Category-I basin on the hydrocarbon map of India.

## Introduction

With the growing energy demand, natural gas is expected to emerge as the most preferred fuel in India. Use of natural gas in India's energy basket will increase from current 14% to an estimated 20% by 2025 (source: IEA, DGH). Profitable exploitation of domestic unconventional gas potential such as Shale gas, Coal Bed Methane (CBM) and tight gas could help India meet its growing energy demand. One prospective area with a significant tight gas resource potential exists in Son Valley, Vindhyan Basin, where presence of gas within Meso-Proterozoic Rohtas Limestone and immediately overlying Basal Kaimur Sandstone has been established in shallow depths of 1000-1600m through a number of recent exploratory wells within unconventional fractured tight gas reservoirs, having ultra low matrix porosities and permabilities and low reservoir pressure. Geochemical analyses indicate a thermogenic origin of the gas with rich methane content (82.68-92.39%) and presence of higher hydrocarbons up to pentane. Calorific Values of the gas are 865-970 BTU/ cubic feet, and as such, can be effectively used and monetized for industrial consumption. However, a viable commercial exploitation of this regionally extensive tight gas play is challenging, primarily in view of micro-Darcy range permeability of the reservoirs and sub economic gas flow rates. This paper highlights the major exploratory leads, challenges and suggests adopting a multidisciplinary technology driven approach which may lead to success in establishing commerciality and open up new opportunities in unlocking the tight gas resource potential of the Proterozoic Rohtas Limestone reservoir.

## Geological Set up

Proterozoic Vindhyan Basin in the Central part of India is situated between to mega tectonic elements: the Great Boundary Fault (GBF) to the north-west and Son-Narmada-Lineament (SNL) to the south. 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)**.**

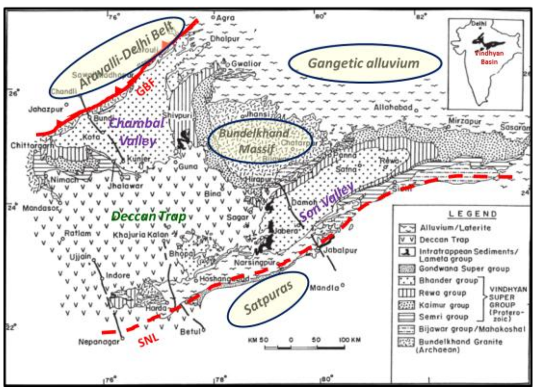


Fig.1 Geological Map of Vindhyan Basin (Prasad and Rao, 2006)

The basins fill, comprising 2-6 Km thick unmetamorphosed, varyingly deformed sedimentary succession, is divisible into carbonate dominated Lower Vindhyan (Semri Group) and clastic dominated Upper Vindhyan (Kaimur, Rewa and Bhander Groups) sequences, separated by a large hiatus. The Basin evolved through multiphase geological history from 1.65 Ga (?) to 0.55 Ga. Gravity-magnetic, seismic and exploratory well data in the ONGC exploration acreage of Son Valley reveal two major depositional lows: Jabera low to the south and Damoh low to the north. These depressions, showing half-graben morphology, originated in the initial phase of crustal extension and rifting. In the syn-rift phase, Karaundi Arenites, Arangi Shale, Kajrahat Limestone and part of Jardepahar formations were deposited. Transition from syn rift to post-rift phase occurred during late Jardepahar time. An initial compressive tectonic pulse during Post-Jardepahar time triggered slip reversals along major normal faults, initiating the process of structural inversions within Jabera, Damoh and Kharkhari lows. In the subsequent period of relative tectonic quiescence, Charkaria, Mohana, Basuhari and Rohtas sequences were deposited in a shallow marine environment. After the deposition of Rohtas Formation, a major phase of compressional deformation led to the culmination of major inversion structures, followed by a regional unconformity, leading to erosion of appreciable thickness of Rohtas Formation, over which, the Upper Vindhyan sequence was deposited (Fig.2).

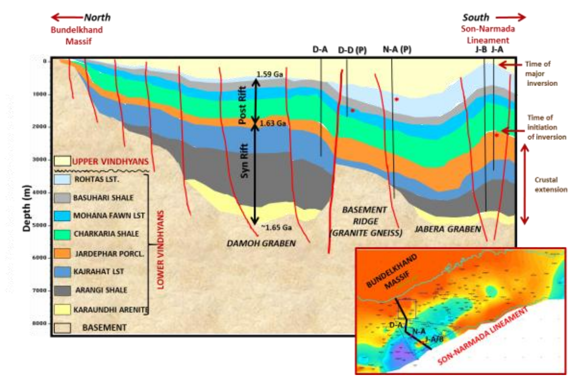


Fig.2 Geological cross section from Bundelkhand Massif to SNL

## Exploratory Leads

Based on 2D seismic data, thirteen vertical exploratory wells have so far been drilled in Son Valley. The initial stage of exploration was primarily targeted on major anticlinal features, with only partial success in establishing non-commercial gas from stratigraphically deeper Lower Vindhyan Jardepahar clastic reservoir in well Jabera-A, although subsequent wells drilled over Damoh and Kharkhari structures proved to be dry. The second stage of exploration (since 2011) saw a deliberate search for hydrocarbons in strati-structural plays, leading to significant exploratory success. Presence of gas in Upper Rohtas Limestone was established in well

Nohta-A followed by gas discovery through well Nohta-B, leading to a paradigm shift in exploration strategy, wherein shallower Rohtas and Kaimur plays emerged as primary exploration targets. To chase the shallow gas plays, seven exploratory wells were drilled in the Nohta-Damoh-Jabera corridor in last two years, which established multiple gas pools within Upper, Middle and Lower Rohtas and Mohana Fawn Limestone (Lower Vindhyan) as well as Basal Kaimur Sandstone (Upper Vindhyan).

From the view point of prospectivity of Rohtas Limestone, Nohta-Damoh sector has emerged as a major gas bearing corridor. This is a broad carbonate platform area and includes the rising flanks between Jabera and Damoh paleo lows. Wells on the inverted anticlines (Jabera-A, B, Damoh-A and Kharkhari-A) reveal poor prospectivity of Rohtas Limestone due to considerable erosion, less overburden and lack of seal integrity due to intense faulting near the structural crests. On the contrary, a considerable thickness of Rohtas Limestone is preserved in the Nohta-Damoh platform area deposited under carbonate mud flat environment in a relatively shallower bathymetry as compared to the Jabera and Damoh lows. Adequate source rocks are available within stratigraphically deeper syn-rift Arangi shale (TOC: 0.5-10.14% in Jabera-B) as well as younger Charkaria (TOC: 0.42-1.84%) and Basuhari Shale (TOC: 1.14-1.78%). Additionally, thick organic rich shale within Middle Rohtas and algal stromatolitic limestone exhibit fair to good source rock potential in wells Jabera-B (TOC: 1.14-1.78%), Nohta-C (TOC: 0.91-1.84%), Damoh-B (TOC:1.27-4.71%) and Damoh-C (TOC: 0.57-1.73%). Although the sedimentary sequences are thermally over matured with low remaining hydrocarbon generation potential (S2:0.01-1.1 mg HC /g rock), they might have generated hydrocarbon in the past which have charged the adjacent fractured reservoirs. Entrapment is mainly strati-structural with intra-formational shale and tight limestones / dolomitic layers providing vertical and lateral seals. Thus, Rohtas Formation in itself forms a viable petroleum system within this broad platformal part.

**Reservoir character**

Rohtas Formation, which encompasses the principal gas pools in the area, represents a typical rhythmite sequence of alternating mudstone and shale. Three lithological units within Rohtas Formation are clearly correlatable in all the drilled wells, of which the upper and lower units are dominantly mudstone with thin laminations of shale, whereas the middle unit is shale dominated with occasional thin beds of mudstone. Gas accumulation within five gas pools (two each in Upper and Middle Units and one in Lower Unit) have been established within fractured reservoirs. General matrix porosity is around 2-3%, while a realtively higher dual porosity (up to 5%) exist in areas having connected natural fractures. Petrophysical analysis of core samples reveal absolute air permeability in the range of 0.001 to 0.46 mD, while a relatively higher value of 3.2 mD is recorded in fractured samples. The core derived porosity vary from 0.5% to 4% and grain density around 2.7 gm/cc.

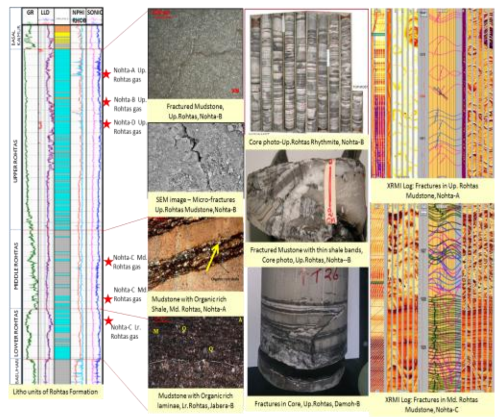


Fig.3 Reservoir character of Rohtas Limestone

**Major exploration and exploitation challenges and road ahead**

Developing a commercially viable exploration and exploitation strategy for the Rohtas tight gas reservoirs depends on adoption of suitable technologies that address the following challenges:

1. Reservoir characterization related with production drivers including pores/matrix, stress/fractures, mechanical rock properties and fluid distribution for locating productive sweet spots.
2. Realistic Formation Evaluation in view of uncertainties on Archie parameters and log derived porosities and saturations.
3. Challenges of Resource estimation and Reservoir engineering.

4. Formation damage during drilling and completion.
5. Cost effective advanced drilling, completion and stimulation technologies to increase efficiency of exploitation process.

**Locating Productive Sweet spots / Fracture Sets**

Rohtas gas pool in discovery well Nohta-B manifested in 2D seismic data as moderate to high amplitude and low frequency anomaly and the lead was chased by probing similar seismic anomalies through vertical exploratory wells based on 2D seismic evaluation. Recent API (470 SKM) of 3D seismic data in the area has enabled better characterization of the fractured reservoirs through advanced seismic attributes and fracture model. The gas bearing fractured reservoirs are characterized by moderate RMS amplitude (2 to 2.2K), medium to low seismic frequency (32-36 Hz), low P and S-wave impedance (P: 8-14K, S: 5.7-8.4 K) and Vp/Vs ratio of 1.4-1.7.

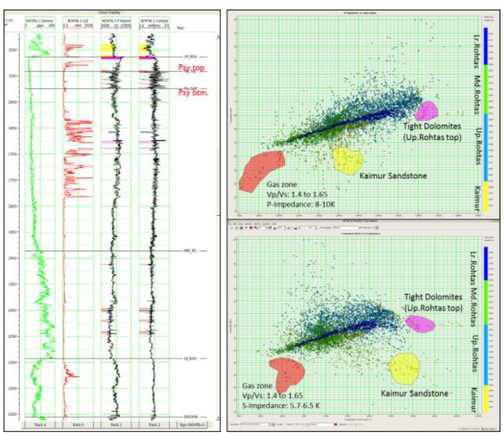


Fig.4 Impedance (P&S) and Vp/Vs response of Nohta-A gas zone in Upper Rohtas

A Discrete Fracture Network (DFN) Model, built with inputs from outcrop fracture / lineament trends, fracture intensity, orientation, stress directions from XRMI logs and 3D seismic ant track attributes, indicated four distinct permeability structure types: Strata bound Fracture Network (SFN), Non-strata bound Fracture Network (NSFN), Fault-fracture networks and matrix fractures (Fig.5). The matrix is tight with the lowest-scale (crystal-sized) permeable system represented by facies / diagenetic controlled fractures present over a large area. However, well productivity is governed to a large extent by reservoir permeability developed by matrix-fracture transfer (SFN and NSFN in close vicinity of fractures associated with fault network). Based on the DFN model, areas of better fracture porosities were identified at multiple gas bearing levels. (Fig.6).

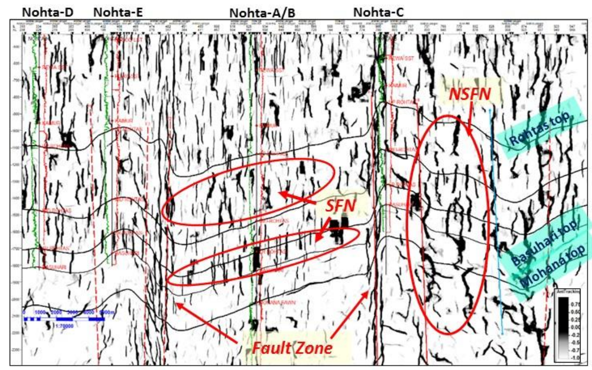


Fig.5 Vertical Ant track section depicting SFN, NSFN and fault induced fracture network within Rohtas Formation in Nohta-Damoh area.

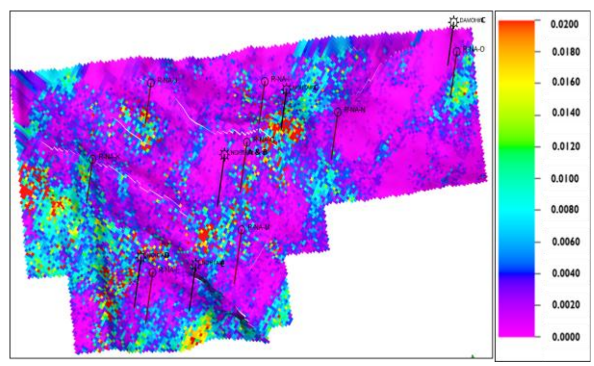


Fig.6 Computed Fracture porosity for Nohta-B gas bearing layer

Ant track attributes extracted along gas bearing layers reveal dominant fracture strike direction in Nohta-B area is NE-SW, while in Nohta-C area, there are two sets of conjugate fractures having strike orientations of NE-SW and NW-SE. High fracture density corridors, with two dominant fracture directions, are mapped in the areas to the east of Nohta-E, west of Nohta-D and NW of Nohta-B. Based on the results of DFN model and reservoir characterization through advanced 3D seismic attributes, it was possible to identify a number of fracture sets (Fig.7) which will be tested through subsequent drilling.

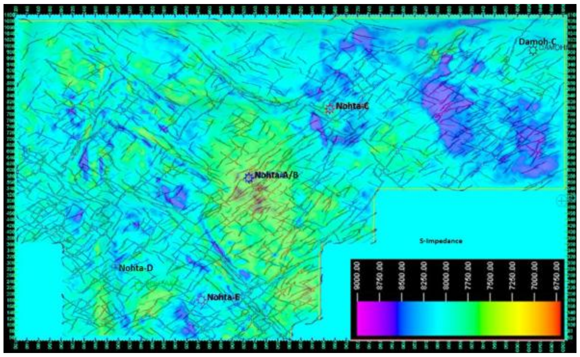


Fig.7 Prospective fracture corridors for Nohta-B gas bearing layer (Upper Rohtas) through ant track and S-impedance maps.

## Formation Evaluation

Most logging tools, developed to evaluate conventional reservoirs, often lose their sensitivity in ultra-low permeability, low-porosity reservoirs. In conventional reservoirs, the Relative Permeability of gas (Krg) starts decreasing at high water saturations, and at a wide range of water saturations, both water and gas can flow. However, in tight gas reservoirs, there is negligible effective permeability to either water or gas (Permeability Jail) over a broad range of water saturations and hence, neither gas nor water can flow. In tight reservoirs, Krg is negligible (Fig.8) at Sw more than 70%, (Robert Cluff, 2009). If the level of bound water is too high, there is a large difference between total water saturation ($S_{wt}$) and effective water saturation ($S_{we}$) which impedes flow of gas**.** Fig.9 illustrates two contrasting scenarios in Upper Rohtas tested zones of wells Nohta-B (flowed gas @ 4000 m3/day) and Damoh-B (no gas flow).

Estimated initial water saturations in Rohtas Limestone are generally high (70-80%). However, saturations calculated from logs suffer from limited availability of accurate "a", "m" and "n" parameters to calibrate resistivity logs. Accurate Rw data is often unavailable as, due to high capillary trapping effects, these zones do not produce free water. Due to above limitations of conventional logs, the zones of interest within Rohtas carbonate sections are usually interpreted based on gas shows observed during drilling and fractures identified from XRMI logs. A close monitoring of gas shows is critically important while drilling through these tight reservoirs.

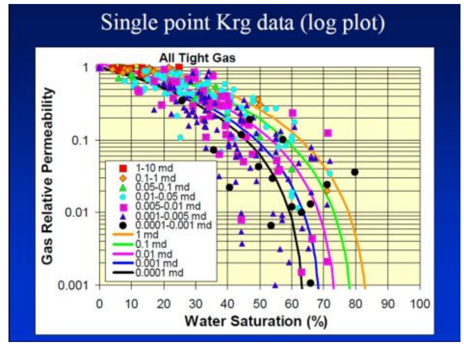


Fig.8: Log Plots showing relation between Relative Permeability of Gas and water Saturation in tight gas reservoirs. (Source: Robert Cluff, SPWLA Conference March 2009).

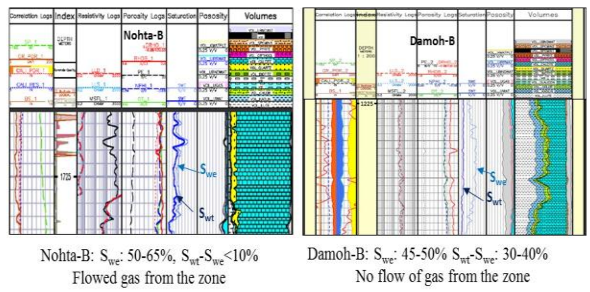


Fig.9: Paralogs of tested zones in Nohta-B and Damoh-B showing the effects of bound water on gas flow behaviour.

A better estimation of formation permeability, porosity and water saturation can be attained through extensive coring in reservoir sections for calibration with log derived petrophysical parameters. Special coring programs using radioactively traced (deuterium or tritium) fluids are recommended.

## Resource estimation and Reservoir engineering

Probabilistic resource estimation for the Rohtas tight gas play was carried out based on areal extent of seismic attributes and net fracture thickness derived from fracture model. However, a more realistic estimation of gas volume (GIIP) can only be achieved based on prolonged testing of existing gas wells through work over operations as well as sustained testing of additional wells. Conventional reservoir engineering methods (volumetric, material balance, decline curves and reservoir models) may not be adequate in evaluating Rohtas tight gas reservoirs. These low permeability reservoirs have a very slow response to pressure transient testing, so it is difficult to obtain dynamic reservoir properties. In view of limited number of well tests and production data available for Rohtas gas, a robust dual porosity reservoir simulation focused on fine-grid model of matrix-fracture transfer may provide reliable answers regarding placement of wells, best recovery process and its optimization as well as uncertainty analysis.

**Minimizing Formation damage**

Tight gas formations are highly susceptible to significant formation damage due to retention of aqueous fluids including water-based drilling mud filtrates, completion fluids, fracture fluids and spent acids which seal the fractures. Means of minimizing damage include use of gas or gas energized fluids, ultra-low fluid loss cross linked water based gel systems, underbalanced drilling and open hole testing and completion techniques.

**Suitable Drilling and Stimulation technologies**

Rohtas Tight gas reservoirs require operational efficiency to improve performance by:

1) ***Drilling slanted / high angle wells to produce at economic rates:*** Testing data of vertical wells exhibit sub commercial gas flow rate since these wells penetrate a few sporadic fractures at different levels. Drilling of cluster based slanted / high angle wells, orthogonal to number of SFN and NSFN is the most suitable option for future appraisal wells. Such well trajectories will intersect a large fractured drainage area of the reservoir resulting in an enhanced flow of gas and thereby establish commercial gas flow rate.

**2)** ***Significant well stimulation through Acid or hydraulic fracture treatment:*** Conventional hydraulic fracture technique may not be effective for low permeable Rohtas carbonate reservoirs. Some advanced fracturing techniques being used globally for tight carbonate reservoirs are:

1. Stimulated reservoir volume (SRV) acid fracturing in Chinese tight carbonate reservoirs, with good stimulation effect in pilot tests.
2. Fracturing by hydraulic pressure using cold $CO_2$ (less water and less acid), is an effective stimulation technique which eliminates potential formation damage and help in rapid clean up.
3. Multiple stage Acid Frac, Surgi Frac and Fibre Optic enabled Coil Tubing (FOECT) stimulation using Distributed Temperature Surveys (DTS) are some advanced stimulation techniques, used globally in both cemented and un-cemented vertical, deviated, and horizontal wells. Water less fracturing using formation compatible acids appears to be the most suitable stimulation method for Rohtas Limestone.

**Conclusions**

Significant thermogenic gas has been established through exploratory efforts within unconventional tight Rohtas carbonate reservoirs in Son Valley sector of Proterozoic Vindhyan Basin. 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. All new exploratory / appraisal wells are recommended to be precisely steered in slanted / high angle to cut across different fracture sets to ensure maximum contact with fractured reservoirs. Under balanced drilling, bare foot testing, open hole completions and appropriate well stimulation by multistage massive acid fracturing / $CO_2$ Frac /SRV/ Surgi Frac and DTS guided FOECT are some of the recommended technologies which can enhance gas recovery from these unconventional reservoirs.

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**Acknowledgements**

The authors are grateful to Director (Exploration) ONGC for his kind permission to publish this paper. The views expressed in the paper are of the authors only and not necessarily of the organization they represent.