PaperID **AU392**

Author **SANTANU MUKHERJEE , ONGC LTD. , India**

Co-Authors **SURYANSH SUYASH and N K PUNJRATH**

DFN model for naturally fractured Rohtas carbonate reservoirs of Proterozoic Vindhyan Basin and its validation with recent well data.

Abstract

This paper presents an integrated approach of Discrete Fracture Network (DFN) modeling for naturally fractured Rohtas tight carbonate reservoirs in Proterozoic Vindhyan Basin. The model is generated through analysis and integration of multi-source data including outcrop lineament, litho-facies, electro-facies, petrophysical and geomechanical properties derived from cores and image logs and 3D seismic based depth and fault surface grids, from which the structural framework of Geocellular Model (GCM) was built. Geological heterogeneities in terms of facies and porosity distribution was modelled and up scaled throughout 20.9 million cells of GCM in a 200m X 200m grid. Variance, ant track and other structural discontinuity attributes, extracted from 3D seismic data, enabled detection of intensity and distribution of sub-seismic fractures in space and time. Final DFN model, generated by up scaling facies and fracture properties in the 3D GCM grid, led to estimation of fracture porosity for different sets. The generated DFN model was used to finalize trajectories of new inclined wells for better fracture connectivity. Drilling results of new wells have validated the model. The DFN model is ready to be used as input for optimizing well stimulation / fracking and completion scenarios and for generating dynamic simulation model for the fractured reservoir.

Keywords: Naturally fractured carbonate reservoirs (NFCR), Discrete fracture network model (DFN)

Introduction

Although modelling of naturally fractured carbonate reservoirs (NFCR) is extremely challenging because of their inherent heterogeneities, a rigorous characterization integrating multi-source and multi-scale data is critically important for evaluating the spatial variability in length, density and aperture of the fractures, which govern the fluid flow behaviour and is, in turn, a vital input for deriving a predictive dual porosity reservoir simulation model. Present study was undertaken for a comprehensive fracture characterization and Discrete Fracture Network (DFN) modelling of natural fracture networks occurring within ultra-tight Proterozoic Rohtas Limestone reservoir in Nohta-Damoh area, Son Valley, Vindhyan Basin.

Rohtas Limestone Formation comprises typical rhythmite sequence of repetitive dolomitic mudstone, stromatolitic mudstone and shale facies occurring at a depth range of 600 -1200m subsea with an average thickness of 450-700m across Nohta-Damoh area, regionally thickening from north to south. Rohtas Limestone is the youngest formation of Lower Vindhyan sequence (comprising carbonate-shale-volcaniclastics of Semri Group), overlain unconformably by a clastic dominated Upper Vindhyan sequence (Kaimur, Rewa and Bhander groups).The formation has three broad litho-units. The upper and lower units are dominantly limestone with thin laminations of shale and argillaceous matter, whereas the middle unit is dominantly shaly / argillaceous in nature with intervening beds of limestone. The poly phase tectonic evolution of this part of the basin is controlled by two dominant tectonic grains, viz. ENE-WSW trending Son-Narmada Lineament (SNL) and an oblique NW-SE trend. The basin initiated with basement related rift / syn rift phase followed by post-rift compressional events and inversion tectonics. Extensive faults and natural fracture systems are distributed in the reservoirs due to multiple tectonic episodes.

Based on 2D seismic evaluation, ten vertical exploratory wells were drilled and tested in Rohtas Formation and presence of sub-commercial thermogenic gas was established within all three units as well as Basal Kaimur sandstone unit overlying the Rohtas Formation. The matrix porosity of the reservoirs is typically in the range of 2-4% and permeability 0.01 to 0.5 mD, stressing the importance of natural fracture network on gas accumulation and flow. Recent acquisition of 3D seismic data has enabled better characterization of the fractured reservoirs and based on 3D DFN model, three new inclined wells, cutting across the fracture network, were recently drilled. In this paper, we describe an integrated approach, from outcrop fracture trends to petrophysics, rock mechanics, well cores and 3D seismic data evaluation for fracture characterization, DFN modelling and validation of the model with results of recently drilled wells.

Methodology

Building a representative, multi-scale fracture model of the reservoir implies a correct assessment of the components and properties of fractures (fracture scale, major fracture corridors, fracture sets, strike, dip angle, aperture, porosity and density) as well as their possible variability. This was achieved through an integrated workflow combining the analysis of geological data (outcrop, cores, logs including borehole image, facies types and geomechanical properties), 3D seismic data (3D GCM with depth surfaces, fault networks, discontinuity attributes like ant track) and up scaled facies and fracture properties in model.

Outcrop Lineament and fracture trends: Lineament and fracture data generated by earlier workers on outcrop studies and remote sensing images indicate maximum lineament intensity near axis of Vindhyan syncline. Another notable observation is that the southern margin close to SNL is tectonically more disturbed with occurrence of extensive fault and fracture density. Field and image interpretations reveal dominantly two sets of lineaments with strike directions ENE-WSW (parallel to SNL) & NNW-SSE (oblique/ cross trends), most of which coincide with surface faults, topographic breaks and straight segments of drainage. Field observations bring out conjugate shear fractures with two consistent strike orientations (55^0 and $125^0 \pm 5^0$) Most of these fractures exhibit conspicuous shear manifestations like slickensides, mylonites and polished surfaces (Samal and Mitra 2006). An almost E-W oriented maximum horizontal compressive stress is deduced from the direction of acute bisectrix of the two conjugate fractures from the rose diagram of strike frequency plot (Fig.1).

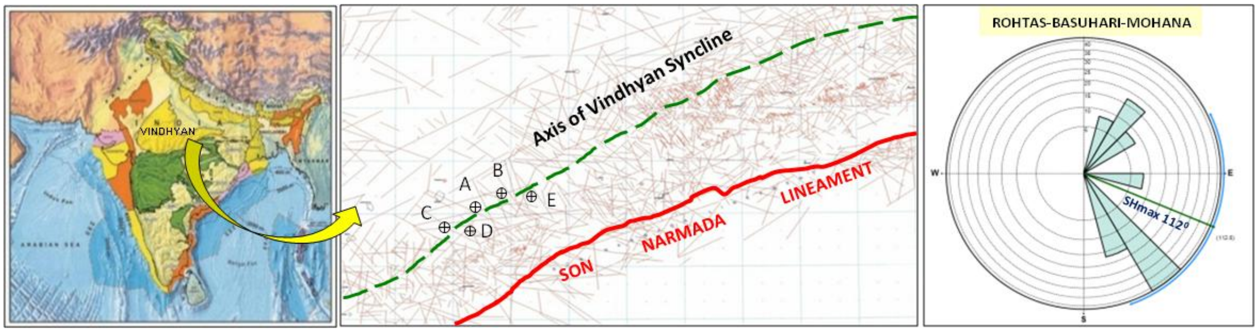
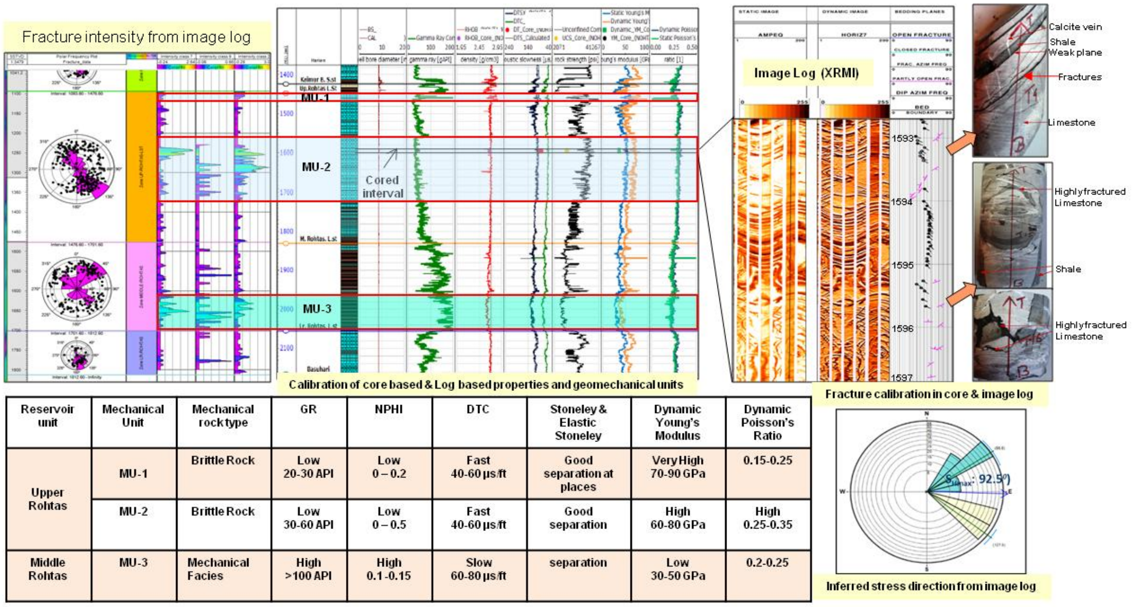


Fig.1 Outcrop Lineament map and inferred stress directions within Rohtas-Basuhari-Mohana formations

Core and well log analysis: Cores available in 4 vertical wells and electrologs (including image logs) of 5 wells (wells A, B, C, D & E) were analysed to identify litho-facies, electro-facies, geomechanical properties, fracture intensity, aperture, dip and strike orientations and inferred stress directions (Fig.2). Conjugate shear fractures within different units of Rohtas Formation exhibit two dominant strike directions: ENE-WSW to NE-SW (mean: $57^0 \pm 5^0$) and NW-SE (mean: $126^0 \pm 5^0$). Fracture intensity properties based on image log data analyses were computed and intensity logs were generated for each fracture set. Maximum horizontal compressive stress direction is inferred to be ENE-WSW ($80\text{-}87.5^0$) to E-W ($92.5\text{-}97^0$). This is supported by consistent bore hole breakouts at mean azimuth of 1 to 13°observed in logs of all six wells (6-pad image logs and six-arm caliper log), based on which azimuth of SH_{max} is constrained to be 90-103°± 10°. Thus, analysis of stress direction from image logs corroborates field observations. National Institute of Rock Mechanics (NIRM) conducted tri-axial tests, UCS and tensile strength tests for Rohtas Limestone on core samples of four wells. UCS measured from core tests were calibrated with log based petrophysical properties (compressional sonic, Young's modulus, Poisson's ratio) using modified Militzer equation. UCS values of limestone and shale within Rohtas Formation range from 25-30K psi and 12-15K psi respectively. Another notable observation is that formation of multi scale natural fractures are controlled by tectonic forces as well as facies association. Three distinct Mechanical Units (MU) have been identified within the stratified sequence of Rohtas Formation defined by geomechanical properties of different litho-facies (Mukherjee and Punjrath, 2017). MU-1 and MU-2, within Upper Rohtas, exhibit typical brittle rock fracture characteristics. MU-3 within Middle Rohtas unit depict fracturing under the influence of depositional composition and diagenetic changes within interlaminations of contrasting litho facies: calcareous shale alternating with siltstone and sparitized mudstone, having different rupture strengths, which impart distinct geomechanical properties to this unit. A preferential occurrence of fractures is noticed within MU-2 and MU-3 of Rohtas Formation.



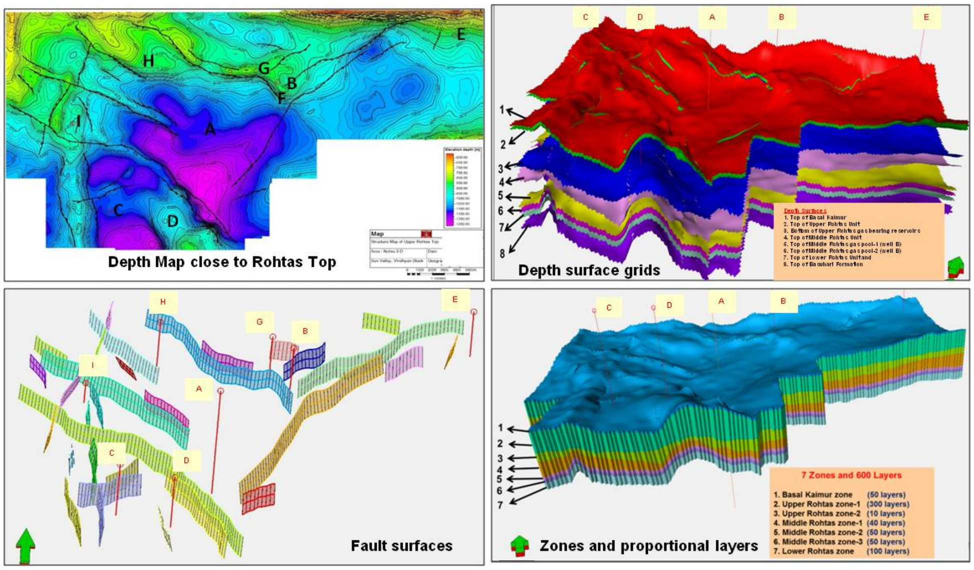
Reservoir unit	Mechanical Unit	Mechanical rock type	GR	NPHI	DTC	Stoneley & Elastic Stoneley	Dynamic Young's Modulus	Dynamic Poisson's Ratio
Upper Rohtas	MU-1	Brittle Rock	Low 20-30 API	Low 0 – 0.2	Fast 40-60 µs/ft	Good separation at places	Very High 70-90 GPa	0.15-0.25
	MU-2	Brittle Rock	Low 30-60 API	Low 0 – 0.5	Fast 40-60 µs/ft	Good separation	High 60-80 GPa	High 0.25-0.35
Middle Rohtas	MU-3	Mechanical Facies	High >100 API	High 0.1-0.15	Slow 60-80 µs/ft	separation	Low 30-50 GPa	0.2-0.25

Fig.2. Calibration of fracture strike, intensity, geomechanical properties and inferred stress direction from core and image log of well C and identification of three distinct Mechanical Units within Rohtas Formation.

Analysis of 3D seismic data: 3D pre-stack time migrated (PSTM) seismic data covering an area of about 460 Km^2 was used for mapping of key horizons and faults, which constituted major inputs for building the 3D GCM. The structural framework model was built by using eight seismically mapped depth surface grids (tops of Upper, Middle and Lower Rohtas, Basal Kaimur and Basuhari formations, tops of two known gas pools within Middle Rohtas unit and bottom of Upper Rohtas gas bearing reservoirs) along with 31 pillar gridded fault surfaces and well tops. Based on the facies from well logs, the entire interval from Basal Kaimur top to Rohtas bottom was divided into seven zones and 600 fine layers (50 in Basal Kaimur, 310 in Upper Rohtas, 140 in Middle Rohtas and 100 in Lower Rohtas units).These layers were generated in a proportional relation to the bounding surfaces and were assigned to the geological layers. The framework model consists of 200x200m grid and 20.9 million cells (Fig.3).

As noise distorts the image and makes the task of geological feature detection and interpretation difficult, a pre-conditioning of the input PSTM 3D seismic data was carried by frequency filtering to eliminate incoherent background noise events followed by dip guided structural smoothing. The resultant volume was used for extracting various seismic discontinuity attributes (Chopra and Marfurt, 2007) such as variance, curvature, amplitude contrast and dip illumination for detection of seismic discontinuities and to clearly understand the position and orientation of the major faults at different levels (Fig.4). Two major fault sets have been identified which define the broad structural disposition within the 3D area. The most dominant fault orientation in the area is NW – SE and the other trend is along NE–SW to ENE–WSW direction. In addition to the above, a set of cross faults, oriented in NNE–SSW to almost N-S direction are observed in the western part of the study area.

Variance volume generated from pre-conditioned seismic data was subjected to edge enhancement and ant track volume was realised by following a number of passive and active iterations which clearly brought out presence and distribution of sub-seismic faults and fractures. The fracture strike orientations derived from the ant track attributes at different depth intervals were calibrated with observed fracture data derived from image logs of all wells within the 3D area which showed a high degree of correlation, thereby validating the ant track volume was used , which for visualizing the track derived fracture trends.



vertico-lateral fracture distribution and continuityprovided valuable insight in identifying prominent fracture corridors with The sweet spots of higher fracture porosity at different levels (Fig.4).

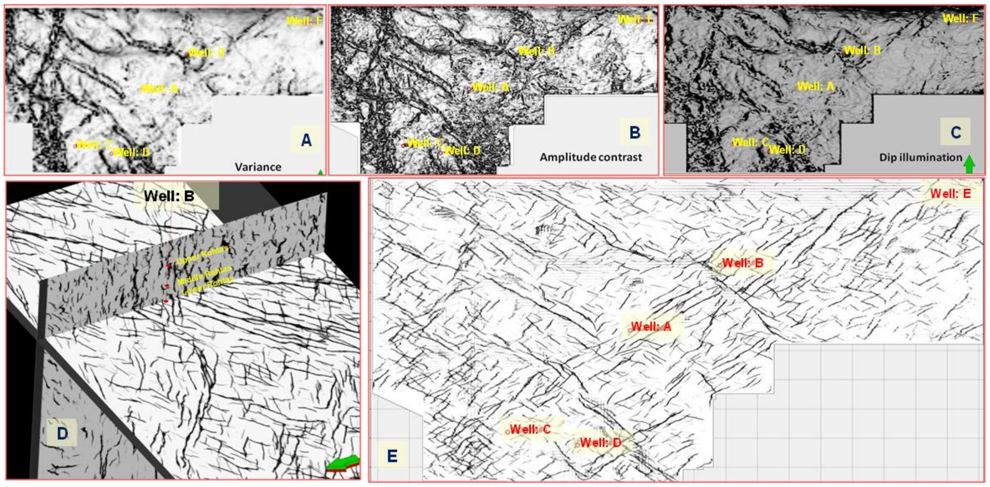


Fig.3. 3D structural framework model for Rohtas Formation

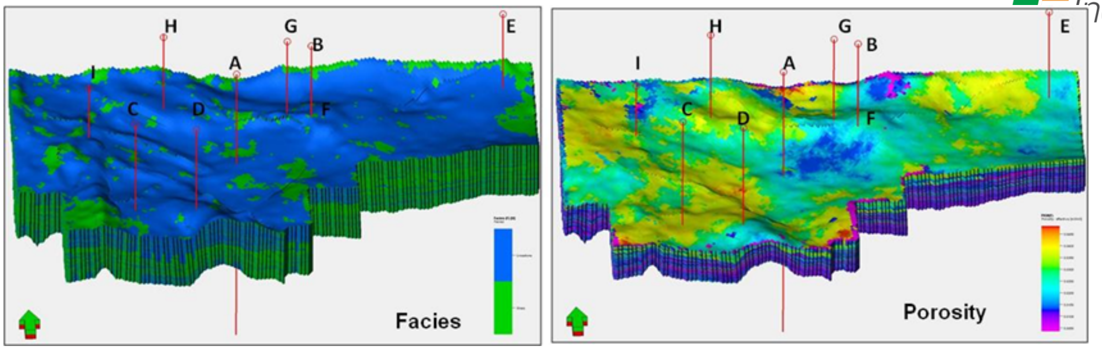


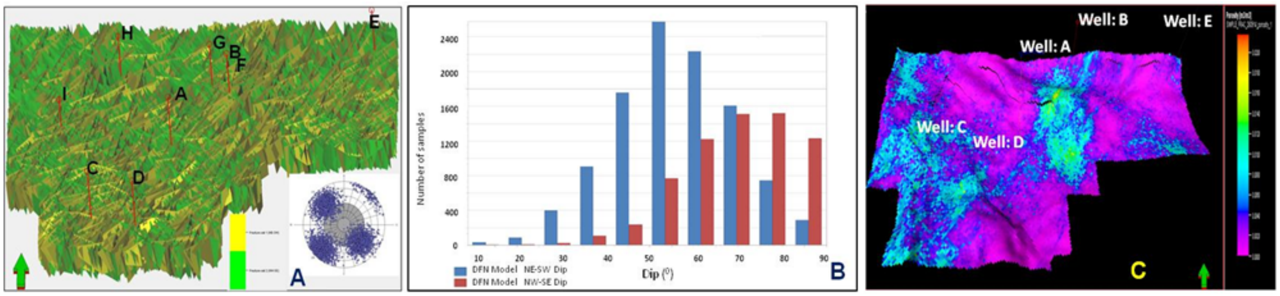
Fig.4. A: variance, B: amplitude contrast and C: dip illumination at Rohtas top. D: Ant track chair display showing fracture distribution at the top of gas zone in well B (Middle Rohtas). E: Ant track stratal slice close to the top of Upper Rohtas gas bearing zone in well A.

Generation of Discrete Fracture Network Model (DFN)

Using commercial modelling software, 3D GCM for Rohtas Formation was generated with eight depth surfaces, 31 pillar gridded fault surfaces, seven zones and 600 layers in 200m X 200m grid. Processed log data of 5 wells were used for building the well model with petrophysical parameters like facies and primary porosity of different reservoirs close to the bore hole. Facies logs of wells were scaled up and propagated throughout the 3D grid geo-statistically using variogram to analyse the related geological uncertainties (Fig.5).

Fig.5. 3D view of facies and porosity distribution within Upper Rohtas Unit

Two sets of conjugate fractures having strike directions of NE-SW and NW-SE constitute the dominant fracture sets. Fracture intensity was derived for each fracture set from the counts on image logs and then assigned fracture aperture values from XRMI interpretation and core observations in most of the wells. During generation of DFN, mean aperture was taken as 1mm and standard deviation 0.001. The fracture sets were up scaled and populated in entire 3D volume with the help of 3D ant track attribute as fracture drivers and a discrete fracture network was evolved (Fig. 6a). The final fracture model was used to obtain continuum approximation of reservoir fracture properties like dip, strike, aperture and fracture porosity for the different fracture sets. It has been observed that NW-SE strike fractures are dominant and have higher fracture dips (70^0 and higher) than NE-SW strike fractures which have average dips of 45-60^0 (Fig. 6b). Fracture porosities were estimated for different layers within Rohtas Formation from the DFN fracture porosity model, which revealed maximum fracture porosity of 1.8-2% with average value 0.6-1% (Fig. 6c).



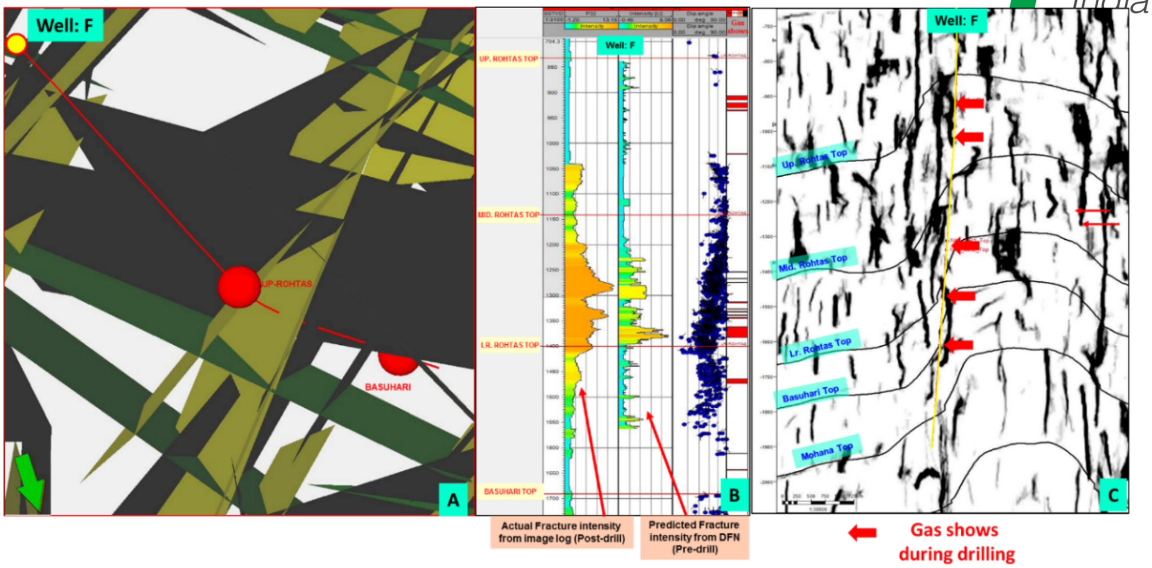


Fig.6. A: major frac
fractures. C: Fractu

Validation of DFN Model

Previously drilled vertical exploratory wells penetrated only a few of the high dip fractures. Based on the present DFN mode, four new deviated wells (F, G, H and I) were identified for drilling to maximize number of fracture intersections along the well path. Well trajectories were optimized based on DFN model along with geomechanical considerations of critically stressed fractures and present day stress field. Three of these wells have been drilled and logged. In order to test the validity of the DFN model, facture intersection and fracture intensity along well bore, envisaged from DFN model, was compared with the fractures occurrences and intensity interpreted from image logs of these wells. It is observed that fracture intersection and intensity predicted from the DFN model are in agreement with the actual observations from the image logs. Further, appreciable gas shows were observed during drilling through the fractured intervals as envisaged. Thus, the drilling results of new wells have validated the generated DFN model. The comparison of DFN model and actual fracture data at well F is demonstrated in Fig.7.

Fig.7. A: DFN fracture intersection along well F. B: Comparison of fracture intensity predicted from DFN and actual in image log. C: Ant track section along well F showing gas shows at fracture intersections.

Conclusions

A robust methodology for multi-scale fracture modelling, integrating outcrop, cores, image logs, litho-facies, petrophysics, geomechanics and 3D seismic evaluation is presented for Rohtas fractured carbonate reservoirs. Field observations, core analysis, image logs and seismic ant track attributes consistently bring out two sets of conjugate shear fractures having strike directions of NE-SW and NW-SE and azimuth of SH_{max} is 90-103°± 10°. There are three Mechanical Units with distinct geomechanical properties and litho facies within Rohtas, with preferential fracture occurrence within MU-2 and MU-3. 3D Ant track attribute, validated with image logs of wells, led to mapping of fracture distribution. Final DFN model, generated by up scaling facies and fracture properties in the 3D GCM grid, enabled estimation of fracture porosity (maximum 1.8-2%) for different fracture sets. The NW-SE strike fractures are dominant and have higher fracture dips (70^0 and higher) than NE-SW strike fractures, having $45\text{-}60^0$ dips. The DFN model was used to identify position and trajectories of new inclined wells for better fracture connectivity. Drilling results of new wells have validated the model, which can be used for optimizing well design, stimulation and completion scenarios and for generating a reliable dual porosity reservoir dynamic simulation model.

References

Chopra, S and Marfurt, K.J., 2007, Attributes for fault-fracture characterization, 77th SEG Annual Meeting, Expanded Abstracts, 2007, pp.1520-1524.

Mukherjee, Santanu and Punjrath, N. K., 2017, Geological controls on mechanical stratigraphy and its impact on multiscale fracturing of unconventional carbonate reservoir: Rohtas Limestone Formation, Proterozoic Vindhyan Basin, India, 13th International Conference and Exposition on Petroleum Geophysics, SPG, Jaipur, 2017.

Samal, J. and Mitra, D. S., 2006, Field study of shear fractures – its tectonic significance and possible application in hydrocarbon exploration – an example from Vindhyan Basin, 6th International Conference and Exposition on Petroleum Geophysics, SPG, Kolkata, 2006.

Acknowledgements

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