Fractured Reservoir characterization of Jardepahar Porcellanite Formation in Hatta area of Son valley,Vindhyan Basin

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Keywords

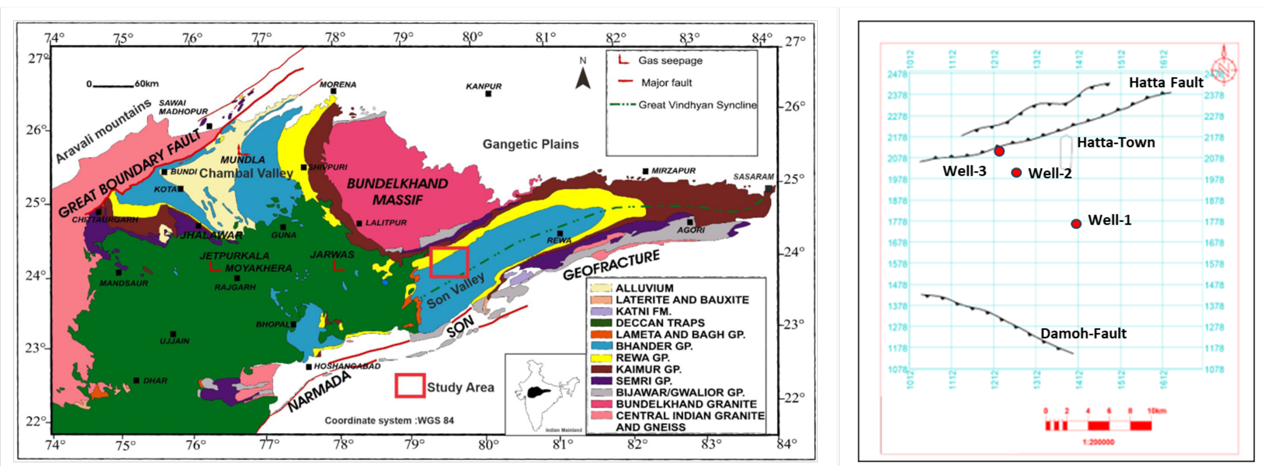
Proterozoic, AVAZ, VVAZ, DFN, Vindhyan Basin, Tight reservoir, Jardepahar Porcellanite

Abstract

The Proterozoic Vindhyan sequences exhibit extremely low porosity and permeability, with fractures serving as the primary channels for fluid flow. The present work focuses on characterizing the fractures to gain a deeper understanding of the reservoir properties specific to the Jardepahar Formation in the area through Discrete Fracture Network (DFN) modeling and specialized AVAZ/VVAZ fracture processing techniques. DFN modeling and AVAZ/VVAZ analysis provide insights into fracture intensity, direction, as well as porosity and permeability values.

This study aims to comprehend fracture behavior, geological origins, and spatial distribution. Furthermore, it aids in identifying areas within the basin with a high density of fractures, which are potentially rich in hydrocarbon resources. The investigation reveals that the depth component of permeability plays a vital role in determining fluid flow due to the presence of steeply dipping fractures. Further, the study highlights the importance of the Damoh structural high as a noteworthy prospect for hydrocarbon exploration due to the significant contribution of fractures aligned with the Damoh fault in the discovery well.

Introduction



a) b)

Figure 1: (a) Base Map of Son Valley showing study area in red square (b) Location map of the study area showing seismic and wells

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The basin has evolved through a poly-phase geological history. Initial tectonic evolution of the basin is controlled by basement related rift tectonics, which formed a number of horst and grabens. In later phase of tectonic evolution, the basin witnessed episodic compressional events (Ram, 1996). Some earlier workers have opined of an initial compressive pulse during post-Jardepahar time, followed by relative tectonic quiescence and finally a major compressive event in post Rohtas time (end of Lower Vindhyan).

Vindhyan Basin is divided into the Son valley sector to the East and Chambal valley to the West (**Figure 1a**). The Basin fill in the Son Valley constitutes a considerable thickness of about 2 to 6 km of varyingly deformed sedimentary succession, which is divisible into carbonate dominated Lower Vindhyan and clastic dominated Upper Vindhyan sequences separated by a considerably long unconformity. (**Figure 2**). Lower Vindhyan sediments mainly constitutes seven major stratigraphic units having alterations of limestone and shale sequences (presence of sandstone is relatively low) interrupted by a volcanic event in between leading to deposition of Jardepahar Porcellanite which has proven to be prospective with gas discovery in Well-2 **(Figure 1b)**. The basal part of Lower Vindhyan (Semri Group) consists of Arangi, Kajrahat, Jardepahar and Charkaria formations, representing an alternating transgressive-regressive depositional cycle in the shallow 'Purana' sea (Chakraborty, 2006; Ojha et al., 2021) with carbonate build up (Kajrahat) followed by a period of sub-marine and sub-aerial volcanism (Jardepahar Porcellanite) and overlain by a thick regionally pervasive transgressive shale deposit (Charkaria Shale). These together constitute the petroleum system for Well-2 gas zones.

Arangi shale is considered to be potential source rock which is organically rich (TOC: 0.5-10.14 %). Jardepahar Porcellanite Formation predominantly comprises of volcano-clastic sediments with alternation of shale, siltstone and limestone whereas Kajrahat Limestone Formation is predominantly carbonate. The Charkaria Olive shale is of regional extent and is acting as a seal in the study area. The sedimentary sequences of the basin are highly compacted and tight in nature leading to the Formation of unconventional tight reservoirs having low porosity and ultra-low permeability.

This present study was taken up following the gas discovery in one of the wells of the Hatta area. In quest for early monetization and prospectivity assessment, it is imperative to have detailed fracture study to understand hydrocarbon producibility in tight reservoirs. Fractures in subsurface give rise to variation in seismic velocity as well as in amplitudes with azimuths in P-P reflection seismic data (Thomsen, 1988). Extracting these fracture parameters (fracture density and orientation) (Lynn et al., 1996) are now in trend and technology have been developed to utilize this property in recent times (Li, 1999; Gray et al.,1999; Hall et al., 2000; Lynn et al., 1996; MacBeth and Lynn, 2001). Amplitude variation with azimuth (AVAZ) and velocity variation with azimuth (VVAZ) are such study which are carried out for extracting fracture parameters such as intensity and orientation.

Newly processed ES-360 PSDM seismic data, drilled wells and fractures oriented special processing (AVAZ/VVAZ) data are utilized in the present study to decipher fractured reservoir characterization.

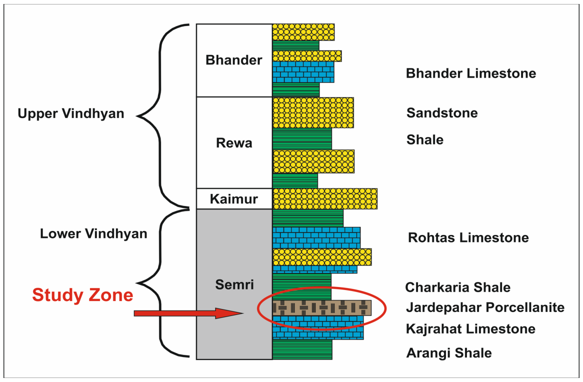

Figure 2: General stratigraphy of the area (Panwar et al., 2022).

Basic theory

AVAZ (Amplitude Vs Azimuth) and VVAZ (Velocity Vs Azimuth) are key seismic methods for

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performing fracture estimation in the subsurface using ES360 Reflection angle azimuth gathers. Azimuth present in seismic datasets are often used for fractured reservoir analysis. The fracture produced anisotropy (mainly HTI), which causes azimuthal variation in amplitude as a function of offset/reflection angle, as well as moveout variations in amplitude as a function of azimuth, which are a reflection of the anisotropic velocity field. Azimuthal data captures these anisotropic effects and provides the means for fracture characterisation. Anisotropic velocity analysis is a critical step when processing seismic data with azimuth and is basic elements in fractured reservoir characterisation. These velocities are also required for Amplitude Vs. Azimuth (AVAZ) Inversion & Analysis in order to 'flatten' the data. Output volumes characterize sub-surface fracture networks. Attribute maps are also generated to analyse fracture's orientation and intensity. Ideal data for this study will have coverage of all azimuths and high angle (large offset) with good foldage. 3D siesmic data of Hatta area has narrow to moderate azimuth and moderate angle coverage up to (~40˚). Delta Alpha indicates the intensity of the fractures; ORT Azimuth indicates the direction normal to the fractures and Alpha Slow indicates Delta V/Vrms in output results.

On the other hand, a Discrete Fracture Network (DFN) modelling is a representation of a fractured rock mass that consists of a network of interconnected fractures. The DFN works by simulating the behavior of fluid flow, mechanical deformation, or other processes within the fractured rock system. The DFN starts with the representation of fractures within the rock mass which are typically represented as planar or curvilinear features in three-dimensional space. The geometry of the fractures is captured using parameters such as orientation, length, aperture, and connectivity. The fractures within the DFN are interconnected to form a network. The connectivity represents how fractures intersect, overlap, or interact with each other and determines the flow paths and channels for fluids or the transmission of stresses within the rock mass. Each fracture in the DFN is assigned properties such as aperture, its width ,its length and permeability. These properties are essential for modeling the behavior of the fractures and their interaction with fluids. A computational mesh is generated to discretize the DFN geometry. The mesh consists of nodes and elements that cover the fractures and the rock mass surrounding them. This mesh allows for the numerical representation of the DFN within a simulation or analysis framework. DFN model provides fracture porosity, permeability and flow parameters in each directions. The DFN model is at last calibrated and validated by comparing the simulation results with field measurements. This helps ensure the accuracy and reliability of the DFN model and its ability to represent the real-world behavior of the fractured rock system.

Methodology

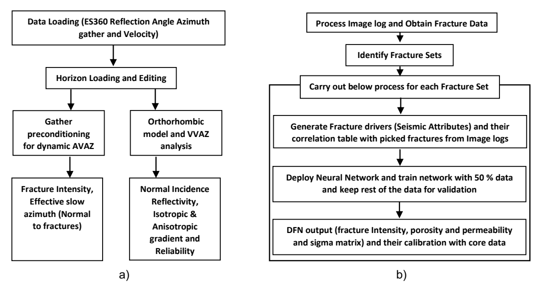

Figure 3: a) Flow chart of AVAZ/VVAZ processing. b) Flowe chart of DFN modelling

In the present study, a DFN Model was built in PETREL software using structural attributes inputs derived from 3D PSDM seismic data volume. Workflow of AVAZ/VVAZ study and DFN modelling is mentioned in **Figure 3**. Subsequently, fracture data from image logs of 3 wells Well#1, Well#2 and Well#3 (**Figure 4**) to generate DFN, were used as input. Before going for DFN process, Structural model was prepared and then it was used for DFN modelling. As per the workflow, once the DFN modelling is finished, results were calibrated using existing core data in nearby wells.

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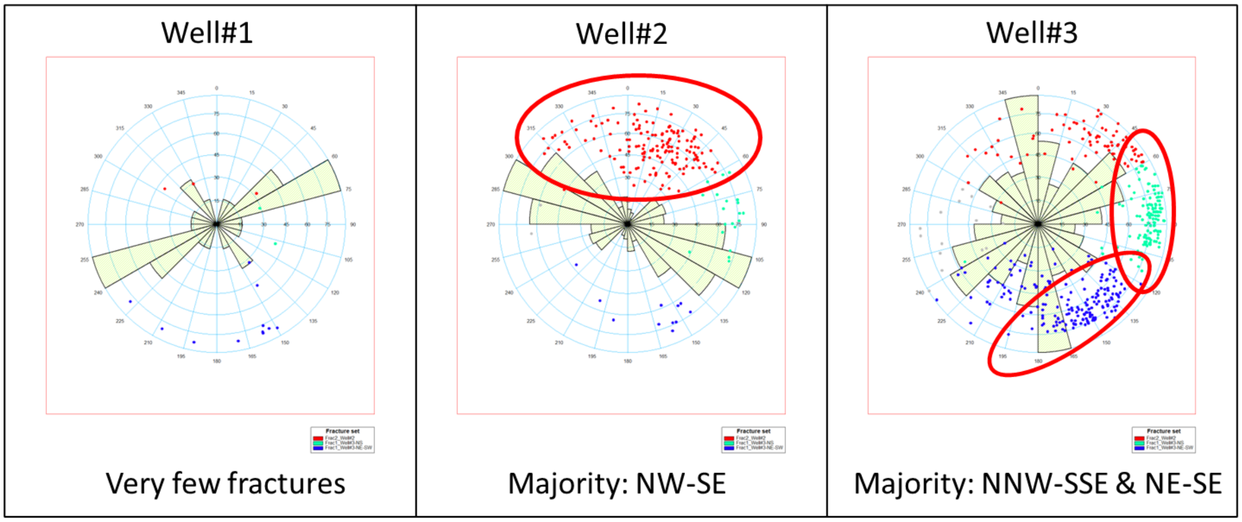

Figure 4: Well#1 shows very few fractures, Well#2 shows mainly NW-SE trending fractures and Well#3 shows 2 set of fractures (NNW-SSE & NE-SW).

Results and Discussion

VVAZ analysis and AVAZ Inversion, characterized the fracture intensity and fracture directions, which are in line with borehole image log (XRMI) and production data. VVAZ Delta Alpha Intensity Attribute Map at Jardepahar Top shows (**Figure 6a**) the presence of fractures in Well#2 well whereas absence or relatively low fractures intensity are seen in Well#3. Reliability Map shows the confidence of results obtained from study (High reliability corresponds to high confidence) (**Figure 6b**). VVAZ ORT Azimuth Map at Jardepahar Top shows azimuthal coverage of fractures present in the area (**Figure 6c**). High Delta alpha values represents high fracture intensity. AVAZ anisotropy gradient map at Jardepahar Top (which correlates to fracture density (**Figure 13c**), indicates that Well#2 and nearby area are more susceptible to have high fracture density as compare to Well#1 area. Since positive and negative both values in AVAZ attribute are desirable, thereby, area near to Well#2 and northern flank of Damoh inversion structure becomes prospective. DFN study also corroborates the results.

In our study, in Hatta area, we have identified 3 fractures set which are NE-SW, NW-SE and NNW-SSE. NE-SW fracture set is well correlated to Major fault North of the area whereas NW-SE fractures are also, quite correlatable to Damoh fault (interpreted faults are seen in all maps). NNW-SSE or N-S fractures are only seen in Well#3 and have less presence further South (**Figure 4**). After analyzing fracture drivers, we have identified above mentioned fault associated with fractures in volumes of fracture drivers (**Figure 5**). **Figure 4** shows that fractures present in abundant in Well#2, is scarcely present in Well#3 which is NW-SE. And on the other hand, fracture presents in Well#3 has 2 different fracture set, one is NNW-SSE and other one is NE-SW. While performing neural network for each fracture set, good correlation (more than 30%) (**Figure 5**) between few seismic drivers and fractures is observed, hence produced results have good confidence. Since distribution of wells are skewed hence high confidence is seen only in the areas located close to the wells and as we move further away the confidence lessens. Fracture set wise fracture intensity values are extracted along a composite section passing through Well#1, Well#2 and Well#3 (**Figure 8**). Results of DFN study are shown in **Figure 9** and also plotted as histogram in **Figure 10**. **Figure 11a** shows that intensity of Well#2 equivalent fractures (NW-SE) is good near Well#2 area as well as near Damoh fault.

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Correlation table

Correlation type: Linear

	Distance from Faults	Chaos	Gradmag	Maxcurv	Var	Mincurv	Dominant_Freq	Envelope	AntTrack-Frac2-Well#2	AntTrack-Frac1-Well#3-NW-SE	AntTrack-Frac1-Well#3-NS	Frac2-Well#2	Frac1-Well#3-NS	Frac1-Well#3-NE-SW	Distance from Faults
Distance from Faults	1.0000	0.1733	0.0373	0.2380	0.1551	0.3079	0.0929	0.0146	0.3475	0.1354	0.571	0.3264	0.1040	0.1180	1.0000
Chaos	0.1733	1.0000	0.4140	0.2050	0.2898	0.5222	0.2804	0.1069	0.3158	0.1513	0.269	0.0294	0.1191	0.1827	0.1733
Gradmag	0.0373	0.4140	1.0000	0.1639	0.1236	0.2102	0.4005	0.1033	0.1735	0.2234	0.076	0.0662	0.2437	0.0933	0.0373
Maxcurv	0.2380	0.2050	0.1639	1.0000	0.1416	0.2272	0.1692	0.6067	0.5271	0.0412	0.369	0.1041	0.0198	0.1514	0.2380
Var	0.1551	0.2898	0.1236	0.1416	1.0000	0.0774	0.1610	0.4809	0.2792	0.1174	0.056	0.1181	0.1763	0.3285	0.1551
Mincurv	0.3079	0.5222	0.2102	0.2272	0.0774	1.0000	0.1172	0.0243	0.2628	0.1514	0.310	0.1521	0.1000	0.0095	0.3079
Dominant_Freq	0.0929	0.2804	0.4005	0.1692	0.1610	0.1172	1.0000	0.0043	0.2179	0.1236	0.133	0.0404	0.3036	0.1158	0.0929
Envelope	0.0146	0.1069	0.1033	0.6067	0.4809	0.0243	0.0043	1.0000	0.5460	0.0814	0.363	0.0983	0.1584	0.1469	0.0146
AntTrack-Frac2-Hatta#3	0.3475	0.3158	0.1735	0.5271	0.2792	0.2628	0.2179	0.5460	1.0000	0.0490	0.743	0.2414	0.1408	0.2578	0.3475
AntTrack-Frac1-Hatta#4-NW-SE	0.1354	0.1513	0.2234	0.0412	0.1174	0.1514	0.1236	0.0814	0.0490	1.0000	0.131	0.0485	0.0868	0.0495	0.1354
AntTrack-Frac1-Hatta#4-NS	0.5712	0.2690	0.0764	0.3693	0.0564	0.3108	0.1332	0.3639	0.7430	0.1318	1.000	0.4080	0.0824	0.0609	0.5712
Frac2_Hatta#3	0.3264	0.0294	0.0662	0.1041	0.1181	0.1521	0.0404	0.0983	0.2414	0.0485	0.408	1.0000	0.0200	0.0887	0.3264
Frac1_Hatta#4-NS	0.1040	0.1191	0.2437	0.0198	0.1763	0.1000	0.3036	0.1584	0.1408	0.0868	0.082	0.0200	1.0000	0.3527	0.1040
Frac1_Hatta#4-NE-SW	0.1180	0.1827	0.0933	0.1514	0.3285	0.0095	0.1158	0.1469	0.2578	0.0495	0.060	0.0887	0.3527	1.0000	0.1180
Total	0.7247	0.7923	0.6752	0.8575	0.6778	0.8022	0.6537	0.8375	0.8730	0.4453	0.864	0.5137	0.5959	0.5990	1.0000

Figure 5: Correlation table between different Fracture drivers and fracture sets

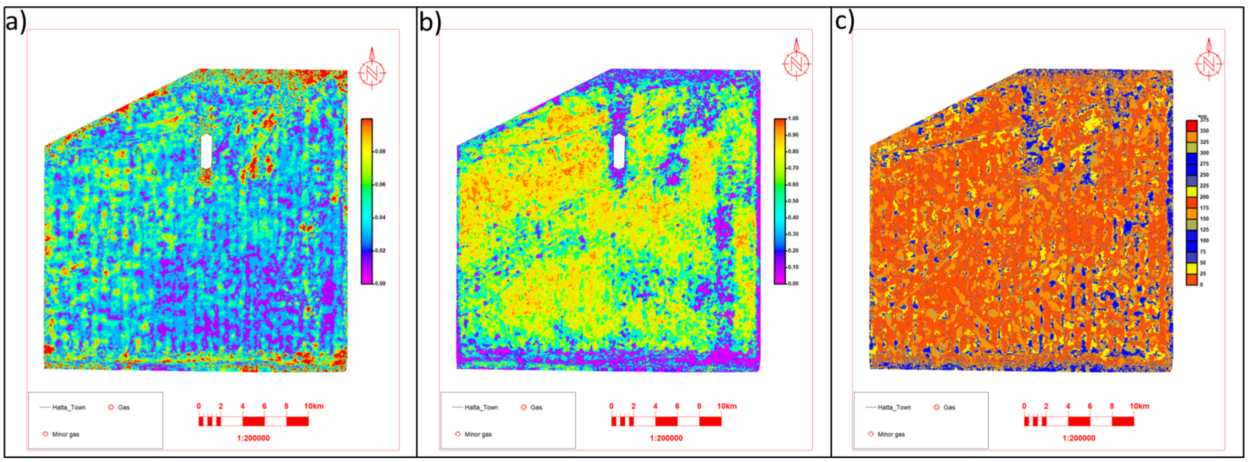

Figure 6: a) VVAZ Delta Alpha Intensity Map at Jardepahar Top. b) VVAZ Reliability Map at Jardepahar Top. c) VVAZ ORT azimuth Map at Jardepahar Top.

	Fracture Dip	Fracture Dip Azimuth	Fracture Aperture (mm)
Fracture Set 1 (Hatta#4 -NS)	Mean : 74.59°	Mean : 88.51°	Mean: 0.99 Std: 0.43 Min: 0.02 Max: 2.25
Fracture Set 2 (Hatta#3)	Mean : 62.46°	Mean : 162.70°	Mean: 1.03 Std: 0.68 Min: 0.00 Max: 2.81
Fracture Set 3 (Hatta#4 -NESW)	Mean : 61.21°	Mean : 19.29°	Mean: 0.92 Std: 0.48 Min: 0.01 Max: 1.91

Figure 7: Fracture Data from Well#1, Well#2 and Well#3

Well#1 comes in fracture shadow zone (**Figure 11**). N-S fractures of Well#3 in Jardepahar Formation as seen in **Figure 11b** are mostly present in northern part of the acreage that is also corroborated in seismic drivers. **Figure 11c** show that intensity of NE-SW fractures in Jardepahar Formation are mostly towards north fault of Hatta area which is a major fault at rising flank of basin and near Northen rising flank of Damoh structure (due to weak zone near Damoh inversion structure).

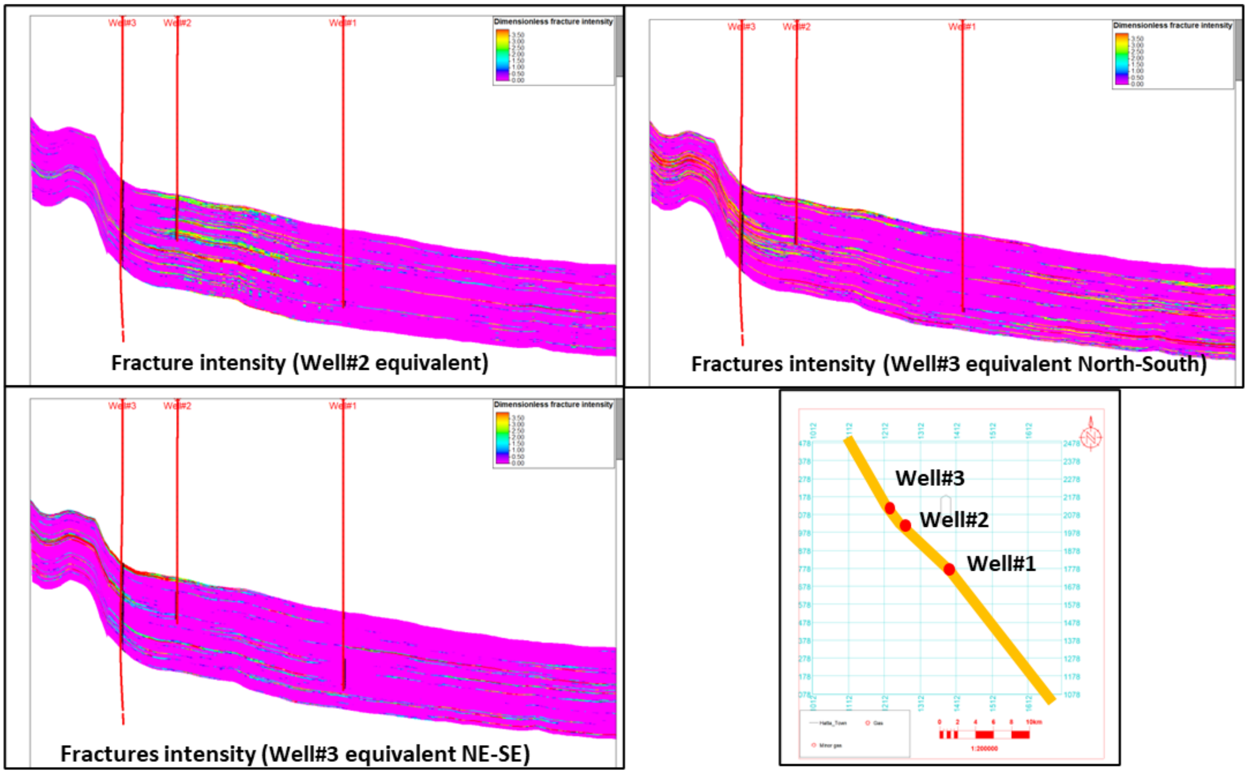

Figure 8: Fracture intensity is shown in composite section crossing Well#1, 2, 3

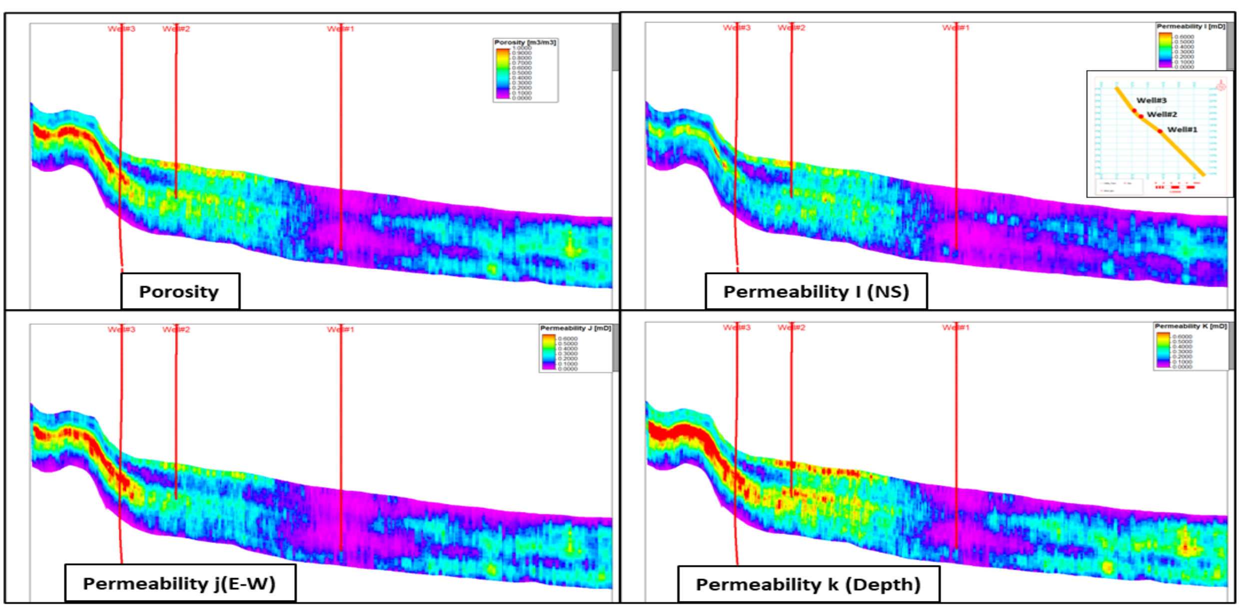

Figure 9: Results of DFN shown in composite section crossing Well#1, 2, 3

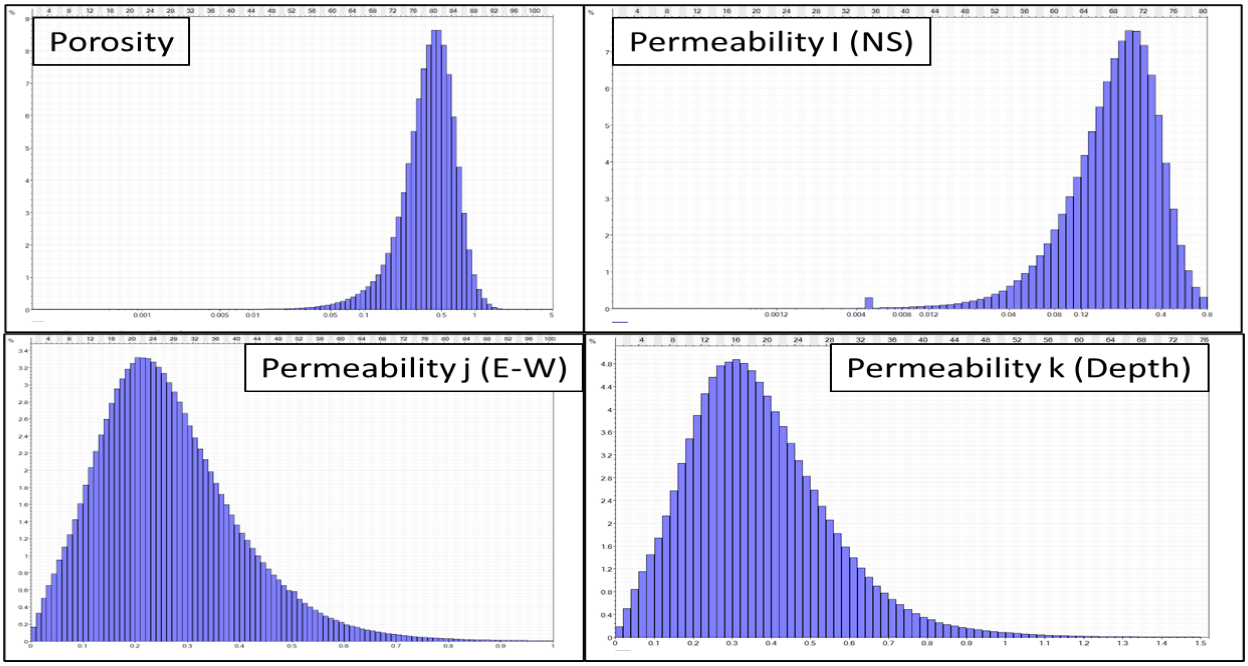

Figure 10: Histogram of results obtained from DFN (permeability in 'mD' and porosity in '%')

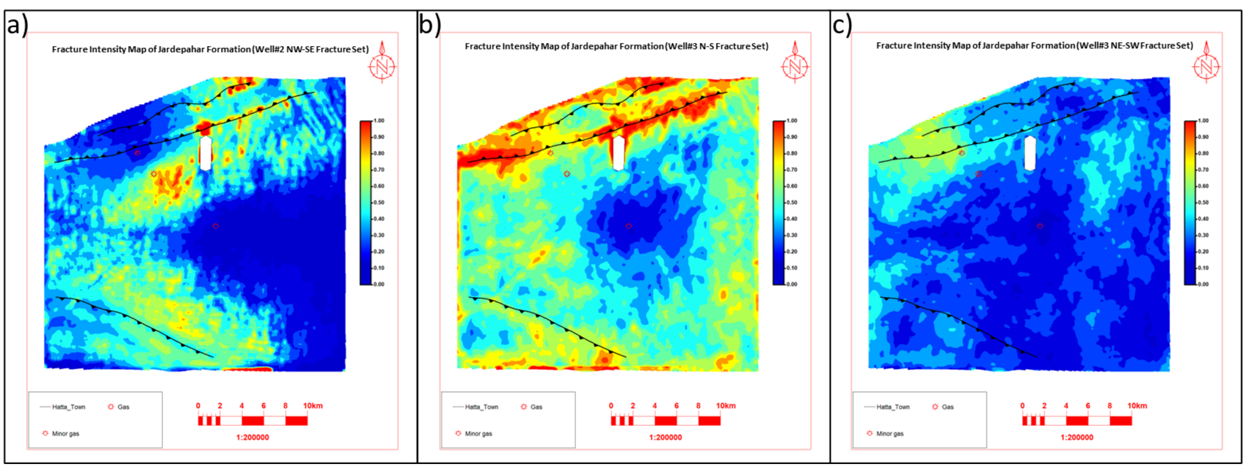

Figure 11: a) Fracture intensity Map of Jardepahar Formation (Well#2 NW-SE Fracture Set) b) Fracture intensity Map of Jardepahar Formation (Well#3 N-S Fracture Set) c) Fracture intensity Map of Jardepahar formation (Well#3 NE-SW Fracture Set)

Permeability and porosity simulation has been carried out after DFN modelling. Permeability (E-W component) in Jardepahar Formation is focused towards north (**Figure 12a**). Horizontal components of permeability have less bearing in deciding actual flow of hydrocarbon since fracture are more than 60° dipping (**Figure 7**). Therefore, depth component is important to study. **Figure 12c** shows that in

Jardepahar Formation in depth component of permeability is dominantly focused in north of the Hatta area as well as near Damoh Fault. Permeability (N-S component) in Jardepahar Formation is equally focused towards north as well as near Damoh fault (**Figure 12b**). Total porosity map of Jardepahar Formation also shows that area near northern slope of Damoh high is as important as northern part of Hatta area (**Figure 12d**).

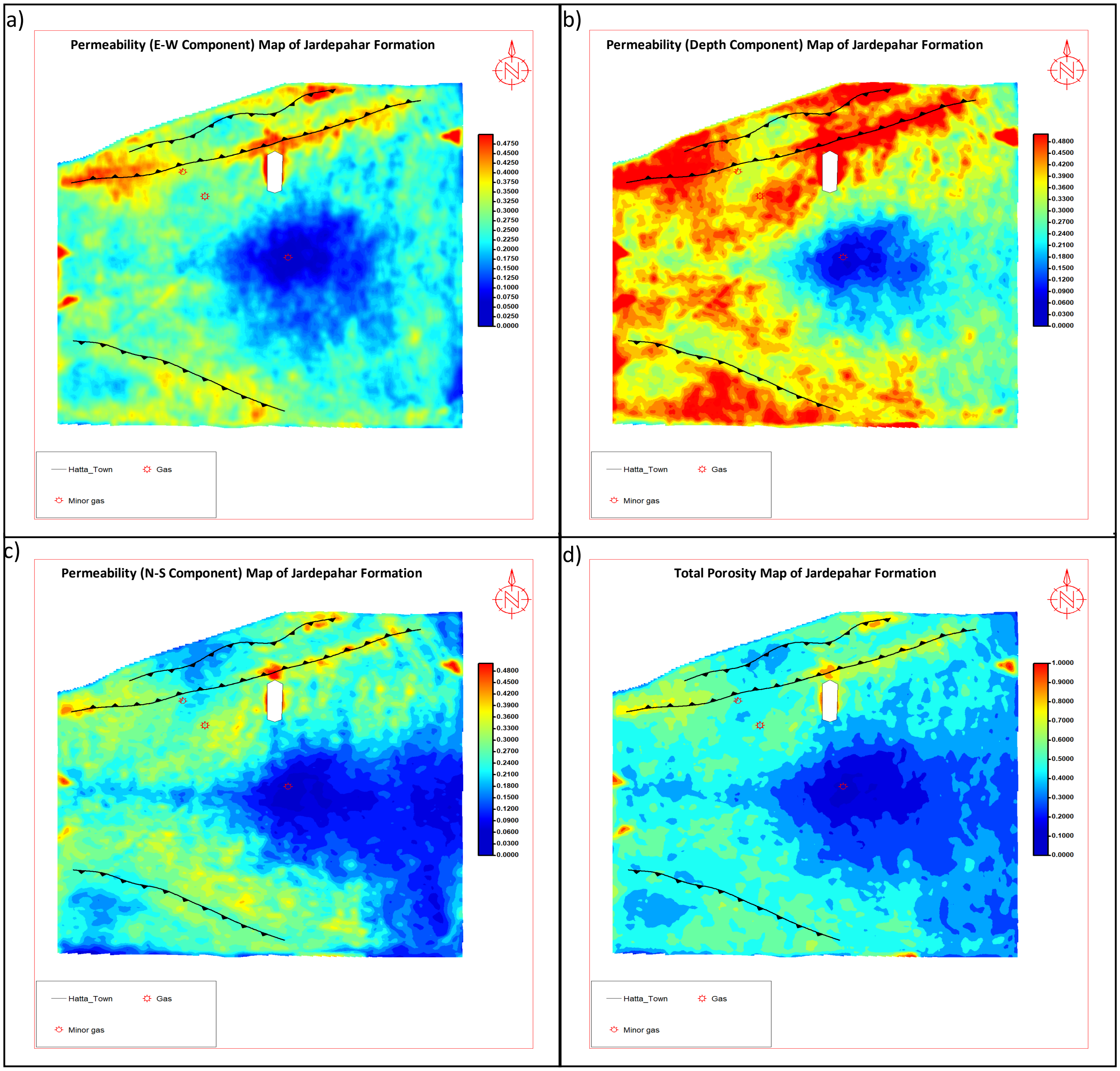

Figure 12: a) Permeability (E-W component) Map of Jardepahar Formation b) Permeability (Depth component) Map of Jardepahar Formation c) Permeability (N-S component) Map of Jardepahar Formation d) Total Porosity Map of Jardepahar Formation

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Conclusions

Vindhyan Basin consists closely packed Proterozoic sediments with occluded primary porosity. Secondary porosity is developed in the form of fracture developed preferentially. Therefore, study of fracture behavior and their distribution becomes important for ascertaining hydrocarbon prospectivity. As per the Prospectivity perception based on present detailed interpretation, incorporating structural refinement based on new 3D ES360 PSDM data, structural modelling, Discrete Fracture Network modelling (DFN), special fracture processing data (AVAZ/VVAZ) and incorporating data of exploratory wells Well#1, Well#2 and Well#3, northern rising flank of basin and northern rising flank of Damoh inversion structure in southern part of the area appears to be most promising in terms of fracture driven secondary porosity for probing the hydrocarbon potential of Jardepahar play**.** Prospective locales are encircled for each attribute. Common area in all attributes will have highest chance of finding suitable prospective zone. (**Figure 13**)

DFN study has brought out that porosity is in the range of 0-5 % where mean value is equal to 0.43 % and standard deviation equals to 0.21. On the other hand, permeability values in 3 major directions also have been brought out by the study. N-S horizontal permeability is between 0 to 0.8 mD where mean is 0.23 mD and standard deviation is 0.133 mD. E-W horizontal permeability is between 0 to 1 mD where mean is 0.26 mD and standard deviation is 0.135 mD. Most important, depth component of permeability (due to high dip of fractures) values is between 0 to 1.5 mD where mean is 0.37 mD and standard deviation is 0.18 mD (**Figure 10**).

Three major fracture sets also have been mapped and observed in Hatta area which correlates to three major faults seen in integrated data interpretation. ENE-WSW fracture set correlated to major north bounding ENE-WSW trending faults whereas WNW-ESE fracture set correlates well to Damoh fault. Since both the faults are deep seated into basement hence these fractures are envisaged to have present up to younger (Rohtas) formations. One more fault set, NNW-SSE (N-S), are also observed in seismic data which are extended from Jardepahar to basement. Similar to that NS trending fracture sets are observed in Well#3. The Well#2 was drilled on a northern flank of the basin in the northern part of the acreage and gave very promising results. Hence it was envisaged that Well#3 will have more fractures than Well#2. While drilling Well#3 gave high pressure gas shows and indicated presence of good quality fractures (quantity) in Jardepahar as well as in Kajrahat Formation from image log.

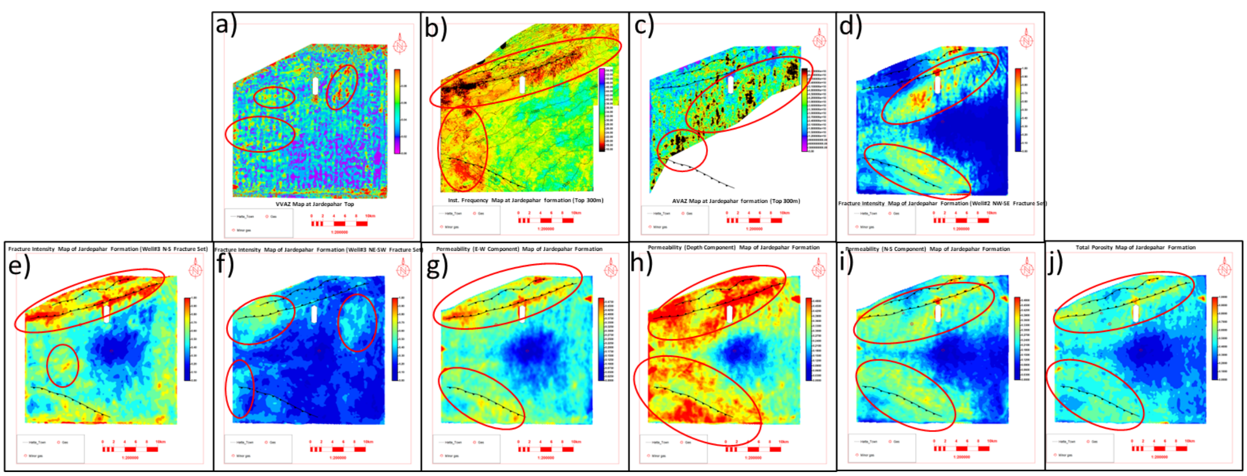

Fig. 13: Prospective locales are encircled in red in respective attribute maps.

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