Challenges & Outcome of Hydrocarbon Exploration in Frontier Basins; A case analysis of Son valley, Vindhyan Basin, India

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Summary

For around past three decades continuous efforts were taken for upgrading the Vindhyan basin to a Category II basin. In this period several exploratory wells have been drilled in the area and presence of gas has been proven without doubt. The thermogenic gas discovered from here with upto 90% Methane having high calorific value (865-970 BTU/cubic feet in Rohtas play) has driven explorationist to keep looking for better prospect in the basin. Several challenges were resolved and new innovative techniques and exploration strategies have been applied in the basin. This paper outlines the exploratory works carried out in the basin by ONGC and the outcome associated with them.

Introduction

The Vindhyan Basin is the largest among all the ‘Purana Basins’ and second largest among all the Proterozoic basins of the world (Chakraborty, 2006). As per Directorate General of Hydrocarbons, the basin covers an area of 162,000 km^2 out of which 80,000 km^2 is covered by the Deccan Trap and 10,000 km^2 substantially thick rocks have also been estimated under the Gangetic alluvium (Mathur, 1965; Jokhan Ram et al., 1996) *(Figure 1)*. Vast quantity of sediments were deposited in this intra-cratonic rift basin in the Proterozoic period resulting in 2-6 km thick sequence of alternating sandstone, Limestone, Shale, Dolostone, conglomerates and few occurrences of Porcellanite. Gypsum & halite are also reported. It should be noted that in spite of being so old, these rocks do not show much signs of metamorphism or even intense structural deformation except for few instances of deformation adjacent to the basin borders. There are also enough evidences that suggest that the initial sedimentary structures are well preserved in these rocks, including ripple marks, flute-cast marks etc. The environment of deposition of these sediments have been inferred as shallow marine to fluvial environment and is estimated to have taken place between 1650 Ma to 650 Ma (Various authors and Ray et.al, 2003).

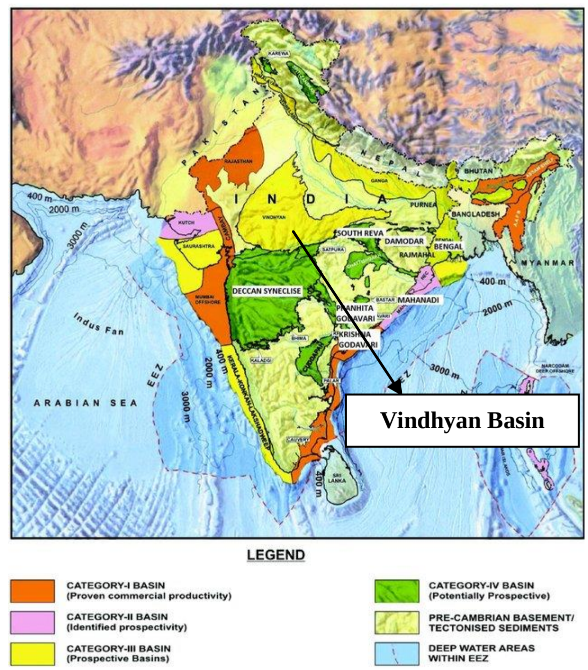


Figure 1: Sedimentary basins of India (after DGH).

Rocks of Vindhyan Basin outcrop in two sectors; Chambal valley in the NW and Son valley in the SE on either sides of Bundelkhand massif (*Figure 2)*. Towards south, they are overlain by Deccan Volcanics. The Vindhyan sediments mostly overlie rocks of Bundelkhand massif, Mahakoshal Group and Bijawar Group. The basin is bounded by Great Boundary Fault (GBF) in the NW and Son-Narmada Lineament (SNL) in the South. The Northern and NE parts wedge under Gangetic Alluvium. The stratigraphy is divided into Lower and Upper Vindhyans by a basin wide unconformity and its laterally correlatable conformities (Chakraborty et.al, 2012). Rocks of Lower Vindhyan are classified as Semri Group whereas rocks of Upper Vindhyan are grouped into 3, namely Kaimur, Rewa and Bhander

Insight into hydrocarbon exploration in Son valley of Vindhyan Basin

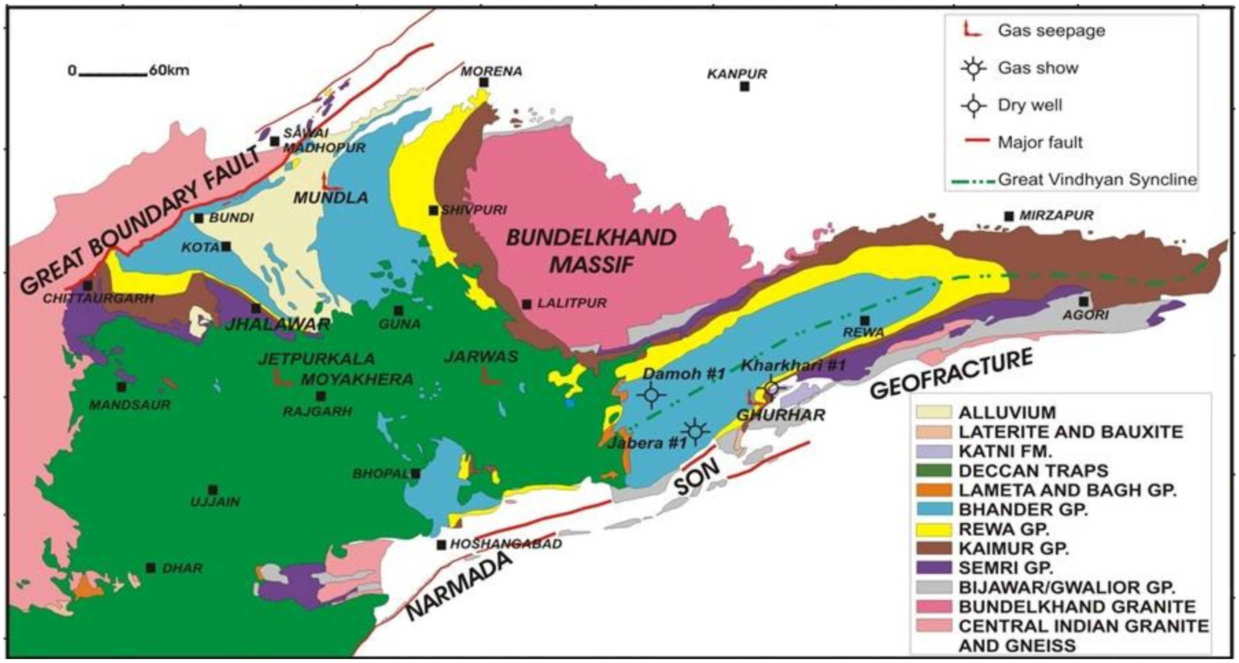


Figure 2: Geological Map of Vindhyan Basin

EAST VINDHYAN BASIN (SON VALLEY)					
DAMOH-REWA AREA (After Srivastava et al. 1983)				MIRZAPUR-ROBERTGANJ AREA (After Sastri & Moitra 1984)	
STRATIGRAPHY			Thickness Mt.	STRATIGRAPHY	
LAMETA FM.				SUB-RECENT LATERITE	
			Unconformity		
BHANDER SUBGROUP	HAVELI FM.	MAIHER SST	87		
		SIRBU SHALE	80		
	BETWA FM.	NAGOD LST	112		
		GANURGARH SHALE	45		
REWA SUBGROUP	ADHESAR FM.	GOVINDGARH SST	55		
		JHIRI SHALE	34		
	ADWA FM	ASAN SST	64	KAIMUR GROUP	DHANDRAUL SANDSTONE
		PANNA SHALE	34		MANGESAR FORMATION
KAIMUR SUBGROUP	CHURK FM.	DHANDRAUL QRTZ.	185		BIJAIGARH SHALE
		SOMAN SCARP SST.	140		GHAGHAR SANDSTONE
	RAMPUR FM.	BIJAIGARH SHALE	34		SUSNAI BRECCIA
		DOMARKHOKA QRTZ.	95		SASARAM SANDSTONE
			Unconformity		
SEMRI GROUP	ROHTAS FM	BHAGAWAR SHALE	420	ROHTAS SUBGR.	BHAGAWAR SHALE
		ROHTAS LST			ROHTASGARH LST
	KHEINJUA FM.	BASUHARI (GLAUCONITIC) SST.	320		RAMPUR GLAUCONITE
		MOHANA (FAWN) LST	207		SALKHAN LST
		CHARKARIA (OLIVE) SHALE	561	KHEINJUA SUBGR	KOLDAHA SHALE
	CHOPAN FM.	JARDEPAHAR PORCILLINITE	555	PROCEL SUBGR	DEONAR PORCELLINITE
		KAJARAHAT LST	335	MIRZAPUR SUBGROUP	KAJARAHAT LST
					ARANGI FORMATION
		BASAL CONGLOMERATE			DEOLAND FORMATION
			Unconformity		
BIJAWAR GROUP				BIJAWAR / MAHAKOSHAL GROUP	
BUNDELKHAND GNIESS				BUNDELKHAND GNIESS	

Stratigraphic Nomenclature, Son Valley (ONGC) & H/C occurrence			
AGE	GROUP	SUB GROUP	FORMATION
MESO TO NEO PROTEROZOIC	UPPER VIMDHYAN	BHANDER	MAIHAR SANDSTONE
			SIRBU SHALE
			NAGOD LIMESTONE
			GANURGARH SHALE
		REWA	REWA SANDSTONE
			JHIRI SHALE
		KAIMUR	KAIMUR SANDSTONE ★
UNCONFORMITY			
PALEO PROTEROZOIC	LOWER VIMDHYAN	SEMRI ★	ROHTAS LIMESTONE ★
			BASUHARI SHALE
			MOHANA FAWN LIMESTONE
			CHARKARIA OLIVE SHALE ★
			JARDEPAHAR PORCELLANITE ★
			KAJRAHAT LIMESTONE
			ARANGI SHALE
			KARAUNDHI ARENITE
UNCONFORMITY			
EARLY PROTEROZOIC	BIJAWAR GROUP		
ARCHEAN	BUNDELKHAND GNEISS		

Figure 3: Stratigraphy of Vindhyan Basin

Insight into hydrocarbon exploration in Son valley of Vindhyan Basin

Groups *(See figure 3 for detailed stratigraphy)*. Lower Vindhyan has prominent limestone thickness compared to Upper Vindhyan sequence, explaining the depositional environment itself. Mc. Arthur basin of Australia which has indicated gas and dead oil from late Paleo-Proterozoic to early-Mesoproterozoic sediments are equivalent to Son Valley sector of Vindhyan basin where too gas discovery has been reported. This provides an impetus to further explore the Vindhyan basin, especially in the Son valley sector where at present all the attention is focused on.

Structure & tectonics

As mentioned earlier, Vindhyan Basin is associated with two major structural features namely GBF in the NW and SNL in South. Basin geometry in the Son Valley is characterized by an ENE-WSW trending synclinal depression (Chakraborty, 2006). The axis of the syncline is slightly curved (convex towards north) and plunges gently towards west. It has been observed that the sediment thickness is high closer to the SNL and thin towards Bundelkhand massif. The SNL is characterized by intense structural deformation of the Lower Vindhyan sediments in its northern vicinity and exhibits tight folds, both normal and reverse faults, mylonitization and strike-slip movements concomitant to Vindhyan sedimentation and even during post Vindhyan times (Pandey, 1971). Based on gravity anomaly maps, the basement in Son valley has been characterized as having several horst and graben structures which in ideal case would be suitable locations for hydrocarbon generation and accumulation. Most of these form half grabens. Simple fault block tectonics and wrench related complex flower and inversion structures are notable. Structures mapped in Jabera and Damoh are part of regional inversion trend and are linked to wrench related strike slip movement along SNL (Singh & Srivastava, 2013).

Petroleum Systems

The South Eastern margin of Bundelkhand massif is surrounded by several step faults and they have been envisaged as favorable trapping condition for hydrocarbon accumulation. Apart from these, few up dip truncations against regional unconformities may also be considered as part hydrocarbon plays. Overall, it can be inferred that the trapping mechanism in the basin is strati-structural with good reservoir facies and efficient cap rocks.

From the inputs of exploratory drilling and structural interpretations four petroleum systems have been envisaged based on facies analysis and hydrocarbon occurrences (Paul, S. et.al, 2013). They are as listed below;

- Arangi-Kajrahat-Jardepahar
- Arangi- Jardepahar -Jardepahar
- Charkaria-Chorhat-Rampur
- Rampur-Rohtas-Rohtas

Arangi shales are considered to be the most prominent source rocks (TOC 0.5-10.14%) and they are possibly charging Kajrahat & Jardepahar formations. Charkaria Shale (TOC 0.42-1.84%) and Rampur Shale (TOC 1.14-1.78%) are also presumed to be of considerable source rock potential. Charkaria shale may also be considered as the source of Mohana Fawn limestone as well.

Rohtas very often shows characteristics of a separate petroleum system in itself with intercalating organic rich and stromatolitic lagoonal shale layers acting as source as well as cap rock. Well D-3 helped establish presence of multiple gas pays within entire Rohtas Formation. D-3 also confirmed gas accumulation within Basal Kaimur Sandstone. Gas samples from Rohtas Limestone are methane rich (82.68-92.39%) with presence of higher hydrocarbons up to pentane. Samples of Kaimur gases are also similar to those of Rohtas in terms of methane content and even isotopic values, pointing to same source. Gas samples of Mohana Fawn have 81% methane but have lower carbon isotopic value as compared to Rohtas & Kaimur. Jardepahar gases show low methane (47.29%) towards Jabera region and are not correlatable with shallower gases whereas In Hatta area they show a notable variation upto 87.89% methane. All these are of thermogenic origin.

Exploration History

The first wild cat well, A-1 of Vindhyan Basin was spud in 1990 at Jabera, Damoh – M.P. with a target depth of 3500m. The objective of the well was to acquire stratigraphic information, thickness & source potential of Vindhyan sediments in M.P. and to test the Hydrocarbon potential of Jabera dome. Fortunately the production testing resulted in gas bearing zones though non-commercial in Charkaria Shale and Jardepahar Porcellanite. Object-III of this well produced gas at the rate of 2000-3000 cu.m/day. This result emphasized the need of further exploratory activities in Vindhyan Basin in both Son as well as Chambal valleys and till date more than 25 exploratory wells have been drilled in the basin. Of these wells most of them have been identified as gas bearing and few had gone dry. Commerciality of gas is yet to be established in Vindhyan Basin (except in one well) and further efforts are on to achieve the same. Drilling of these wells has helped identify different reservoir facies precisely and major reservoirs identified are Rohtas Limestone, Mohana Fawn Limestone, Jardepahar Porcellanite and Kajrahat Limestone though gas indication has been obtained from Charkaria shale as well as Kaimur sandstone. Of these, the most promising as of now has been Rohtas and Jardepahar. Rohtas limestone shows development of secondary fracture porosity which are gas charged and similar traits were observed in Mohana Fawn limestone as well. Similarly, Jardepahar Formation with alternating siltstone/sandstone with occasional limestone was expected to have good reservoir facies. They have porosity in range upto 4% including fracture porosity and are likely to be higher in areas proximal to major faults and fracture zones.

Initial exploration in Son valley was limited to Damoh-Jabera-Katni block focusing on structural features like Jabera dome, Damoh High. Two major fault bounded grabens in the area are the Jabera graben in south and Damoh graben in north, separated by the intervening Nohta horst. Wells D-1 & D-2 led to gas discovery in Rohtas formation and this opened up a new play for exploration at shallow depth. Later the exploration also spread to NELP block towards Hatta, on the northern rising flank of Damoh graben where the sedimentary sequences show a monoclonal rise towards the Bundelkhand Massif with a number of fault bounded strati-structural closures.

Positive outcome of exploratory drillings

The lead of very first well flowing gas at 3000 cu.m/day was followed by a series of exploratory wells in the basin. Several of these wells have flowed gas during their production testing. Of all the wells drilled in Son Valley, only two have been declared dry and all others are either gas bearing or a few even gas discovery wells. Well B-2 was recently declared as a gas discovery. It was drilled with an aim of assessing the potential of Mohana fawn Limestone, Jardepahar Porcellanite and Kajrahat Limestone. All the zones in Jardepahar formation that were identified for testing proved to be gas bearing. Further, Object-II flowed gas at the rate 54080 cu.m/day through 5 mm bean at 2100 psi *(Figure 4)*. All other objects flowed gas to the flare line although at very low pressure. Object-II has helped establish commercial scale gas reservoir in the region and also justifies the need to revamp the E&P activities in the region with greater vigor.

Figure 4: Gas flaring at well B-2

Challenges to commercial viability

Being one of the oldest basin in the world and after being subject to very high levels of compaction, it is natural for the rocks of Vindhyan Basin to be devoid of hydrocarbons as anybody would have expected. But this is not the case as it has been proven without doubt that there is presence of hydrocarbon in the basin that exists in the thermogenic gas window. Commerciality of these gas pools are not yet established due to various reasons like;

- Gas accumulations happened in tight unconventional reservoirs having very low porosities ranging from 1-5% and ultra-low permeability. In most cases the primary porosity in limestone has been destroyed by dolomitisation, the grade of which is higher towards Northern side than Jabera or Damoh. Micro fractures enhance the effective porosity to certain limit and it has been noted that gas occurrence is mostly confirmed where the well penetrates through a highly fractured zone

- Very low reservoir pressure which is mostly hydrostatic and restricts productivity. This has caused many wells being not able to sustain the flow of gas and due to lack of pressure even flow studies could not be carried out.
- Hard and compact formations in which drilling is a time consuming and difficult task with Rates of penetration as low as 300 min/m in the upper Rewa sandstone often resulting in frequent mud cuts and string failures during conventional rotary drilling.
- Logs of Vindhyan reservoirs do not show characteristic Neutron-density cross over even where presence of gas is confirmed and hence conventional logs have limitations in identifying hydrocarbons in Vindhyan Basin.

Innovative efforts and way forward

As mentioned above, the major challenge encountered in Vindhyan Basin is the very hard and compact nature of sandstones encountered. Certain sections are so hard and abrasive that they look more like a quartzite than normal sandstones. During conventional drilling frequent change of bits and string failure was very common. To overcome this, two methods were employed. Firstly the harder Upper Vindhyan clastics were designated to be drilled by using Air Hammer drilling rig which proved to be very effective in terms of improved ROP and reduced time of drilling. Though the drawback remains that air hammer drilling does not use mud system and hence real time monitoring of the presence of gas in not possible. Further, the lower Vindhyan, reservoir sections were drilled by turbo drilling which uses PDC bits and SDMM (Steerable Down hole Mud Motor) which again results in improved rates of penetration and also enables directional drilling by using MWD tools.

As discussed in previous section, conventional logs are of limited use in this basin hence advanced image logs (FMI, XRMI etc.) are captured in the wells drilled here and these logs give a clear idea about the orientation and intensity of sub surface micro fractures around the borehole section. Based on them zones can be identified precisely *(Figure 5 & 6)*.

It was observed that gas was encountered in most cases where the bore hole had intersected a highly fractured zone. Hence focus was on to achieve drilling wells that intersects fractures. Thus it was important to have a clear idea of the subsurface fracture intensity, orientation etc. The same was attained by preparation of Ant track maps using seismic attributes for different reservoir levels and based on them well trajectories were planned so as to connect maximum fractures to the bore *(Figure 7)*.

Further, Hydraulic fracturing including both acid & proppant jobs were also carried out in few wells and is still on going and point towards confirmed presence of Gas in the basin.

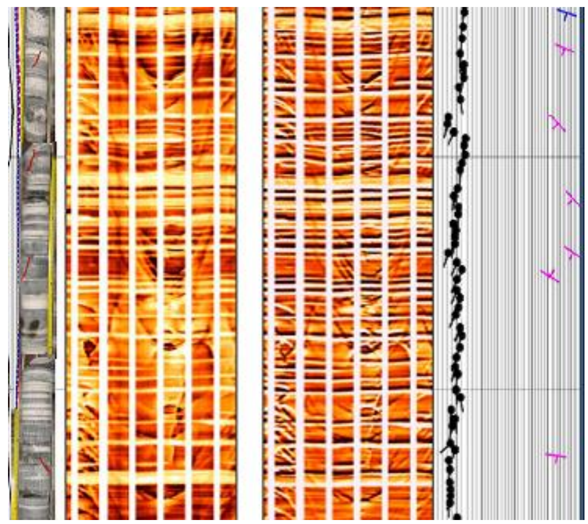


Figure 5: XRMI logs compared to conventional cores of same depth, showing same trends of fractures

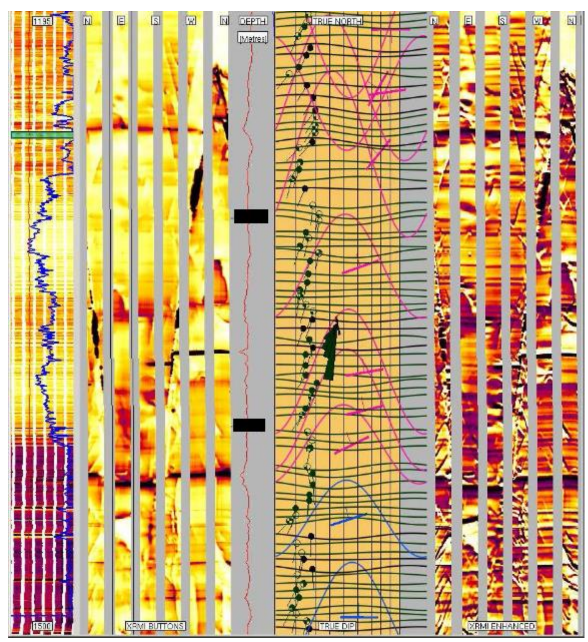
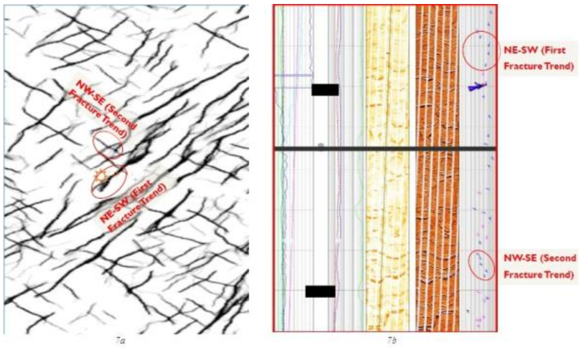


Figure 6: Heavily fractured zone with fracture strike orientation from NE-SW to E-W direction

Insight into hydrocarbon exploration in Son valley of Vindhyan Basin



Figures 7(a), Ant track depth surface prepared from seismic attributes showing two trends of fractures, (b), XRMI logs for the same depth showing similar trends of fractures

Looking ahead, Vindhyan Basin looks promising provided high angle/horizontal wells are drilled in more promising locations so as to encounter more fracture networks and connecting more drainage area and thus optimize the flow of gas. This can be actively pursued once the 3-D seismic study of the desired area is completed. Weathered and fractured basements of this basin are yet to be explored and they may be considered future targets. Further stimulation by means of massive HF or acid frac jobs are envisaged which may open up the fracture porosity.

Conclusions

Future exploration in Vindhyan Basin is focused towards achieving more commercial scale gas discoveries. This is expected to be fulfilled by the application of advanced technologies like Discrete Fracture Network (DFN) model, Ant tracks etc. Precise identification of fracture corridors of gas accumulation can be done by using Image logs integrated with real time gas show data recorded by Mud Logging Unit (MLU) during drilling. Further, preparation of Geomechanical/static models help is assessing and planning advanced stimulation techniques like HF and acid frac jobs in high angle wells which are essential in the basin considering very low formation pressure.

References

Chakraborty, C., 2006. Proterozoic intracratonic basin: the Vindhyan example. Jour. Earth Sys. Sci., v. 115, p. 3-22.

Chakraborty, P.P., Sarkar, S., Patranabis Deb, S., 2012. Tectonics and Sedimentation of Proterozoic Basins of Peninsular India. *Proc Indian natn Sci Acad*, 78 No., 3 September 2012, pp. 393-400.

Pandey, S.N., 1971. Development of dome and basin structure due to interference of major folds of the southern margin of the Vindhyan Basin. Deptt. Of App. Geol., Univ. of Saugar, Vol. 39 A, No. 1

Paul, S., Bisht, B.S., Raturi, V.C., Jaiswal, S., 2013. Exploring frontiers through sequence stratigraphic approach: Vindhyan basin case study. Abstract of paper, 10th Biennial conference, Society of Petroleum Geophysicist,

Ram, J., Shukla, S.N., Pramanik, A.G., Varma, B.K., Chandra, G. and Murthy, M.S.N., 1996. Recent investigations in the Vindhyan basin: implications for basin tectonics. Mem. Geol. Soc. India, v. 36, p. 267-286.

Ray, J.S., Veizer, J., and Davis, W.J., 2003. C, O, Sr and Pb isotope systematics of carbonate sequences of the Vindhyan Supergroup, India: age, diagenesis, correlations and implications for global events; *Precamb. Res.* **121**, pp. 103–140.

Ray, J.S., 2006. Age of the Vindhyan Supergroup: A review of recent findings. J. Earth Syst. Sci. v.**115**, pp. 149–160

Singh, D.N., Srivastava, D.K., 2013. What after Nohta? Exploration strategy in Frontier Basins. Ongc Bulletin, Vol. 48 (3), Special Issue

Various internal reports and texts of Ongc

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