Integrated Geoscientific Interpretation and Petroleum System Modelling (PSM) Studies in Chhattisgarh Basin

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Keywords

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Abstract

Proterozoic basins are the least studied for hydrocarbons because of the paucity of data leading to an inadequate understanding of the tectonic events that shaped the basin architecture, sedimentation history, and original depositional boundaries, which in turn limits the assessment of the elements and processes of the petroleum system in the basins. The Proterozoic witnessed the most profound biological and geochemical change in Earth's history. In parallel with the development of complex ecosystems, changes in continental configuration and plate tectonics have been proposed as important factors influencing climate and biogeochemical cycling. However, the geologic record in the Indian basins offers little evidence for this, as much of the sedimentary column has already been eroded in the last 500 million years. The atmospheric and marine conditions under which the Proterozoic basins formed are very different from present-day conditions, which are not yet fully known. However, the recent discovery of gaseous hydrocarbons in the Son Valley in the Vindhyan Basin and Neoproterozoic oil in the Bikaner-Nagaur sub-basin of the Rajasthan Basin has increased interest and exploration efforts in Proterozoic basins.

Introduction

Peninsular India hosts a number of Proterozoic basins; the largest is the Vindhyan basin (Category II), followed by the Ganga, Cuddapah, and Chhattisgarh basins (Category III). The other smaller basins are Bikaner-Nagaur, Bastar, Khariar, Ampani, Sukma, Pakhal-Penganga, Bhima and Kaladgi (Figure 1). The present study focuses on the Chhattisgarh basin, an intracratonic sag basin in the Bastar craton, which contains a Meso-Neoproterozoic sedimentary package 1500-3000 m thick. Tectonically, the basin is divided into two sub-basins: Hirri (west) and Baradwar (east), which are separated by a middle subsurface ridge, the Sonakhan Greenstone Belt (SGB), a relict of the Paleoproterozoic greenstone belt (Figure 2). To date, various geological, geophysical, and geochemical investigations have been conducted in the basin to constrain the basin geology, tectonic fabric, and structural architecture. However, in order to pursue hydrocarbon exploration, these studies are insufficient and inconclusive, and further specialized studies are needed to understand and evaluate the possibility of the presence of petroleum systems in the basin.

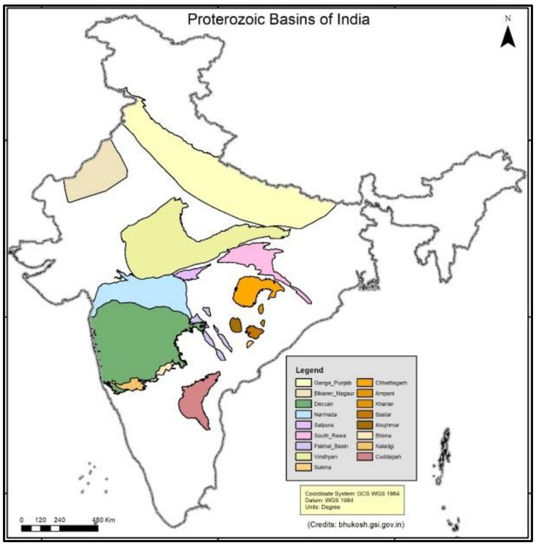


Fig.1: Distribution of Proterozoic basins over Indian Peninsula (Courtesy: DGH, India)

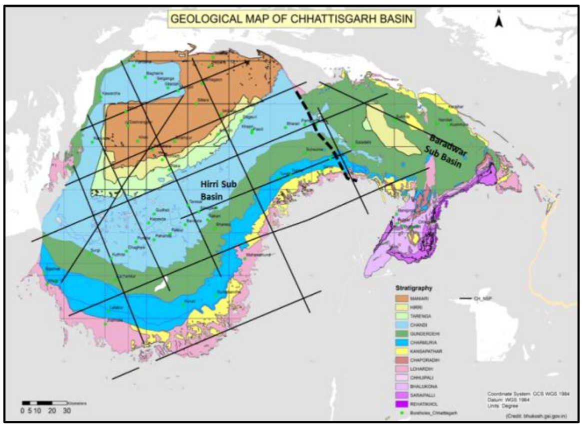


Fig.2: Geological Map of Chhattisgarh Basin with available NSP data and boreholes by GSI included in the study (Courtesy: bhukosh.gsi.gov.in)

Geological Setting and Stratigraphic Framework

Chhattisgarh is a concavo-convex intracratonic basin formed by subsidence and minor gravity faulting during the Precambrian. The basement consists of Archean granites and gneisses with associated metavolcanic-metasedimentary belts. The EGMB (Eastern Ghats Mobile Belt) on the eastern side is a high-grade metamorphic belt separated from the Bastar craton by a major thrust known as the "Sileru shear zone" (Ptranabis-deb et al., 2020).

The Chhattisgarh Basin is the third largest Proterozoic basin in India with an area of 33 000 km2 and hosts a 2300 m thick mixed siliciclastic–carbonate–phosphorite-evaporite sequence. The sedimentary sequence was deposited mainly in two sub-basins – the Hirri to the west and the Baradwar to the east, separated by an uplift of the Paleoproterozoic Sonakhan greenstone belt. Some sediment was also deposited in two protobasins known as Singhora and Barapahar, which lie on the southeastern margin of the Baradwar subbasin.

Lithostratigraphically, the Chhattisgarh Supergroup is divided into four groups in the order of deposition – Singhora, Chandarpur, Raipur and Kharsiya (Table 1). The Singhora and Chandarpur groups are predominantly siliclastic, while the Raipur and Kharsiya groups represent a Siliciclastic-Carbonate succession deposited in varied tectono-sedimentary conditions, ranging from an active basin subsidence phase with the development of aluvial fans to a shallow shelf environment terminating at a passive margin setup (Mukherjee et al., 2014.

Hirri sub-basin (Western part) (covers ~25000 km2)		**Age**	**Baradwar sub-basin** (Eastern part) (covers ~8000 km2)	
Alluvium/Laterite/Gondwana Supergroup /Intrusive rocks				
Formation	**Major lithology**		**Formation**	**Major lithology**
Raipur Group		**Neoproterozoic**	**Kharsiya Group**	
Maniari (>300 m)	Gypsiferous purple shale and dolomite		Nandeli	Gypsiferous purple shale and dolomite
Hirri (150 m)	Stromatolitic dolomite and black shale		Sarnadih	Sandstone and conglomerate
			Raipur Group	
Tarenga (>300 m)	Argillaceous dolomite; Dhamda tuff and Kusmi Member shale		Churtela	Purple shale and Sukhda tuff
Chandi (670 m)	Stromatolitic limestone-dolomite with Deodongar Member sandstone-shale		Chandi	Dolomite/stromatolitic limestone
Gunderdehi (>300 m)	Calcareous shale with Dotapar Member sandstone		Gunderdehi	Calcareous shale with stromatolitic limestone
Charmuria (260 m)	Flaggy limestone, shale with Sirpur Member tuff (?) and Ranidhar Member cherty limestone		Sarangarh	Flaggy limestone and shale
		Mesoproterozoic		
Chandarpur Group (130 m)			**Chandarpur Group (130 m)**	
Kansapathar	Quartz arenite		Kansapathar (150 m)	Quartz arenite
Chaporadih	Glauconitic sandstone/ silt stone and black shale		Chaporadih (600 m)	Glauconitic sandstone/ silt stone and black shale
Lohardih	Subarkose with basal conglomerate		Lohardih (150 m)	Subarkose with basal conglomerate
			Singhora Group	
			Saraipali (>300 m)	Shale, tuff (1405 Ma) and Stromatolitic limestone with sandstone and basic intrusive
			Rehatikhol (30–75 m)	Sandstone with conglomerate
Older basement		**Archaen/ Paleoproterozoics**	**Older basement**	
(Rocks of Dongargarh Supergroup, Chilpi Group, Iron ore Group, Amgaon Group)			(Rocks of Raigarh–Surguja metamorphic belt, Sonakhan Group, Sambalpur Granites)	

Table 1: Stratigraphy of Chhattisgarh Basin (modified after Mukherjee, et al., 2014)

Basic Workflow, Modelling Inputs and Calibration

The present study represents a result of integrating all available geological and geophysical information into Petroleum System(s) Modeling in the Chhattisgarh Basin. The 2D NSP data were interpreted (Figure 3) and time structure maps were prepared at six stratigraphic levels, i.e., Basement, Singhora Group, Chandarpur Group, Charmuria Formation, Gunderdehi Formation and Chandi Formation. For depth conversion, a velocity model was used, which was created from drilled wells in the Vindhyan and Ganga basins with penetration in Proterozoic sequences, and then depth structure maps were created. Isopach maps were also produced to give an idea of the total thickness of sediments and the temporal distribution of depositional foci in the basin (Figure 4).

A static 3D geologic model was created for the entire basin area based on interpretation of the NSP 2D seismic data supported by geologic outcrop data, borehole data, and DEM. Initially, 2D petroleum system modeling (PSM) was performed along a composite NSP line encompassing the Hirri and Baradwar sub-basins to understand the history of the basin and quantify the erosional thickness of the various geologic formations. Based on the results of the 2D modeling, a 3D PSM was performed for the entire basin. The basic workflow followed for the study is given in Figure 5.

Inputs required for modeling included assigning boundary conditions such as basal Heat Flow, Paleowater depth, and sediment-water interface temperatures (SWIT) (Figure 8) and assigning petroleum system elements (source, reservoir, seal, and overburden) to different layers in the model. Modeling also requires geochemical inputs in the form of source rock type, quality, and quantity (e.g., kerogen type, TOC, HI, and source kinetics). Source rock layers (speculative) are assigned using available geochemical data along with lithologic information, depositional environment, and facies association (Figure 6). Two component Kerogen-oil-gas kinetics, i.e., Behar_et_al (1997) TI and Behar et. al. (1997) TII, are assigned to source layers. The distribution of activation energies for the above kinetics is shown in Figure 7.

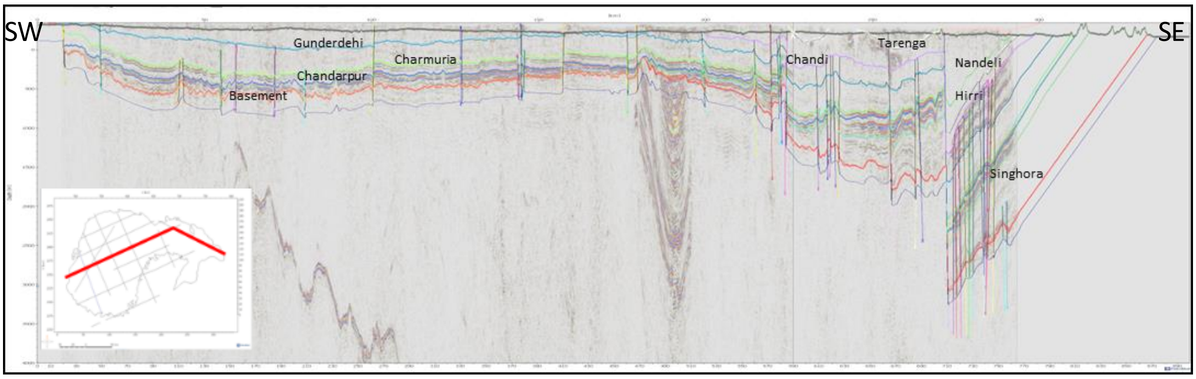


Figure 3: Interpreted seismic of an NSP composite line used in the study

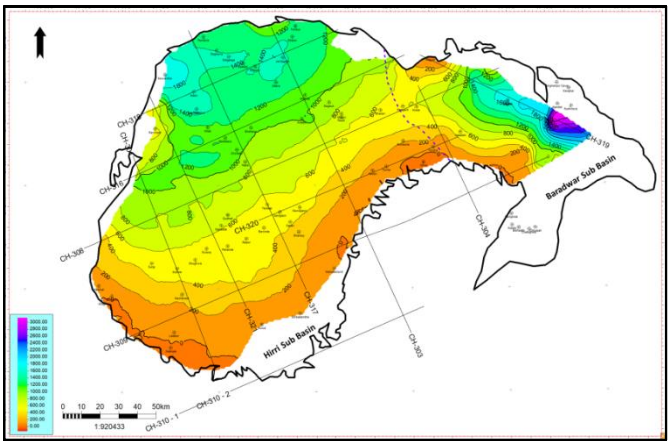


Figure 4: Isopach map of the total sedimentary package

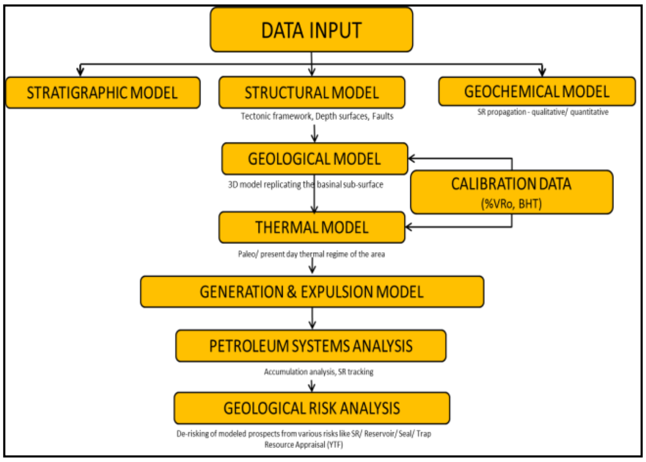


Fig.5: Basic workflow followed for the PSM Study

Name	Color	Lithology Value	Kinetics	TOC Mode	TOC Value [%]	TOC Map	HI Mode	HI Value [mgHC/gTOC]	HI Map	Petroleum System Elements
Neoproterozoic_Shale		Shale (typical)								Seal Rock
Neoproterozoic_Limestone		Limestone (shaly)								Seal Rock
Neoproterozoic_Sandstone		Sandstone (typical)								Reservoir Rock
Neoproterozoic_dolomite		Dolomite (typical)								Reservoir Rock
Neoproterozoic_Shale_SR		Shale (typical)	Behar_et_al(1997)_TII(PB)	Value	5.00		Value	600.00		Source Rock
Tarenga_Shale		Shale (typical)								Seal Rock
Tarenga_dolomite		Dolomite (typical)								Reservoir Rock
Chandi_Limestone		Limestone (shaly)								Seal Rock
Chandi_Limestone_SR		LimestoneSR	Behar_et_al(1997)_TII(PB)	Value	5.00		Value	600.00		Source Rock
Chandi_Sandstone		Sandstone (typical)								Reservoir Rock
Gunderdehi_Shale		Shale (typical)								Seal Rock
Gunderdehi_Limestone_SR		LimestoneSR	Behar_et_al(1997)_TII(PB)	Value	5.00		Value	600.00		Source Rock
Charmuria_Limestone		Limestone (shaly)								Seal Rock
Chandarpur_Sandstone		Sandstone (typical)								Reservoir Rock
Chandarpur_Shale_SR		Shale (typical)	Behar_et_al(1997)_TI(GRS)	Value	5.00		Value	600.00		Source Rock
Singhora_Shale		Shale (typical)								Seal Rock
Singhora_Sandstone		Sandstone (typical)								Reservoir Rock
Singhora_Shale_SR		Shale (typical)	Behar_et_al(1997)_TI(GRS)	Value	5.00		Value	600.00		Source Rock
Singhora_felds_arenite		Sandstone (arkose, typical)								Reservoir Rock
Singhora_conglomerate		Conglomerate (typical)								Underburden Rock
Basement		Granite (> 1000 Ma old)								Underburden Rock

Fig.6: Assignment of petroleum system elements (source layers are highlighted in green)

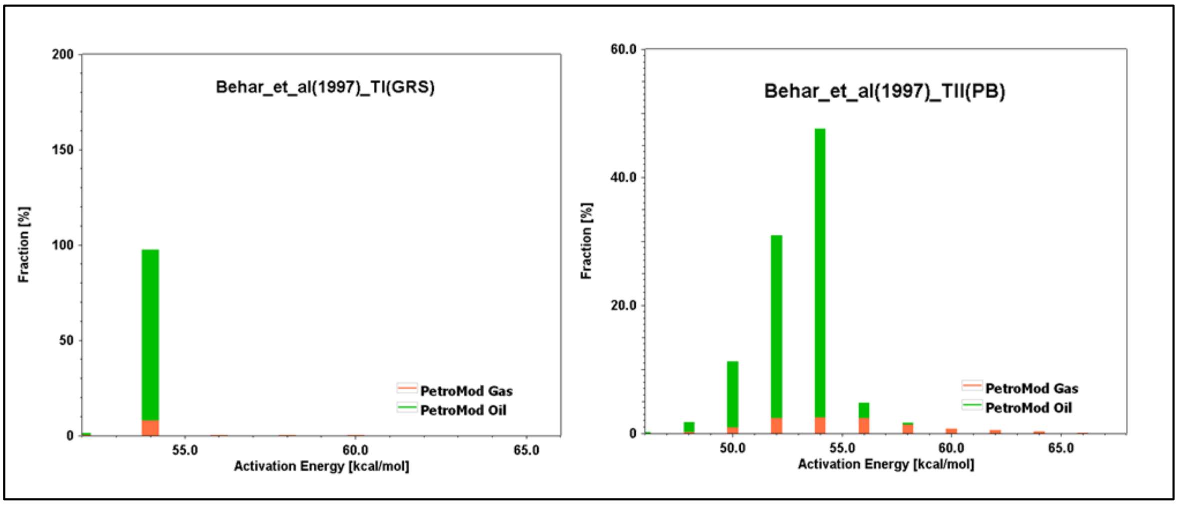


Fig.7: Distribution of activation energies for the kinetics used in the study; Behar_et_al (1997) _TI (left) & Behar_et_al (1997) _TII (right) (Magoon, LB. et al, 1994)

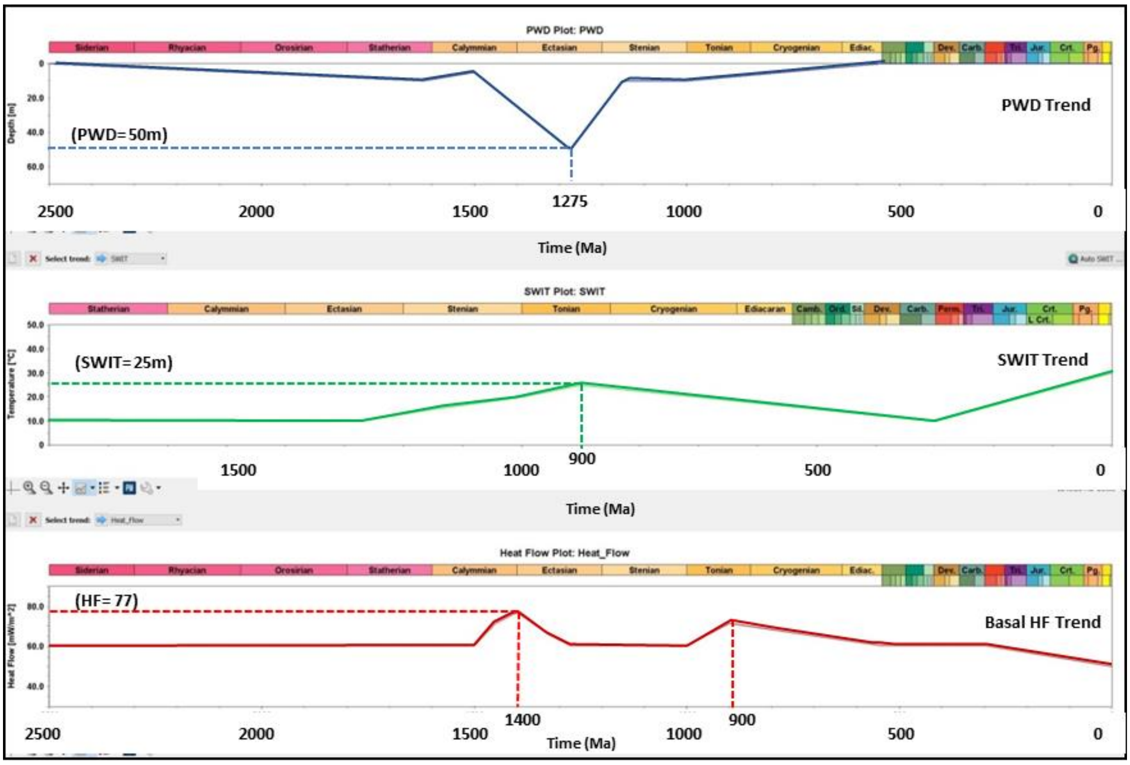


Figure 8: Boundary Condition (Paleowater depth, Sediment-water interface temperature, Basal heat flow) tables and trends used in the model

Igneous intrusion events and erosion reconstruction were also critical to the modeling. Based on published information and regional basin understanding, two intrusion events at 1400Ma and 900 Ma were included in the model. Approximately 5 km of Neoproterozoic sediment erosion was reconstructed.

As no direct calibration dataset was available, outcrop-based rock density values, geothermal gradient observed in the drilled wells from Vindhyan basin for thermal calibration (Figure 9) and Raman Spectroscopy data converted to vitrinite reflectance for maturity calibration were considered (Figure 10). The equation used for calculation of equivalent VRo (%) from Raman band parameters is as follows:

VRo eq (%) = d(G-D) *0.0537 - 11.21 (Liu, D. et al., 2013)

where, (G-D) refers to Raman inter-peak in terms of Raman shift.

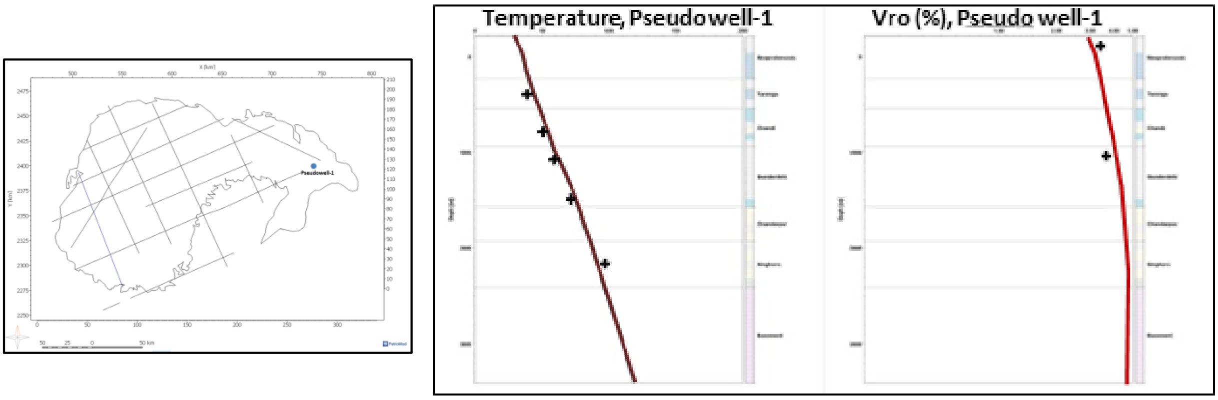
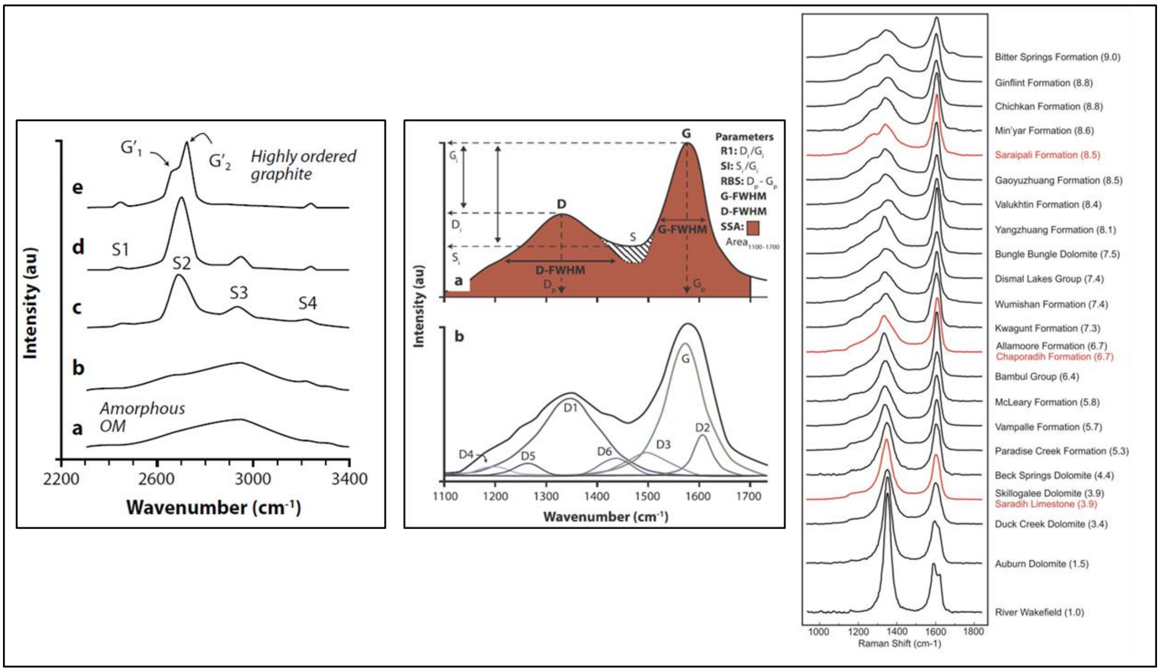


Fig.9: Thermal and Maturity Calibration at Pseudowell-1



Sample_No.	Latitude	Longitude	X	Y	Microfossils	Formations	VRo eq (%)
1	21 14 30.53 N	82 58 05.25 E	704243.46	2350181.5	Tappania plana	Saraipalli shale	1.8391
2	21 14 30.53 N	82 58 05.25 E	704243.46	2350181.5	Satka colonialica	Saraipalli shale	2.9131
3	21 33 59.33 N	83 29 47.62 E	758533.14	2386915.02	Valeria lophostriata	Chaporadih Formation	2.8594
4	21 14 30.53 N	82 58 05.25 E	704243.46	2350181.5	Ptrospermopsimorpha	Chaporadih Formation	2.6983
5	21 43 31.40 N	83 07 36.16 E	719977.97	2403943.55	Navifusa robustus	Chaporadih Formation	2.8057
6	21 43 31.40 N	83 07 36.16 E	719977.97	2403943.55	Oscillatoriopsis obtusa	Saradih Limestone	3.7186
7	21 42 36.75 N	83 08 02.53 E	720759.07	2402272.91	Oscillatoriopsis obtusa	Saradih Limestone	3.7186
8	21 43 31.40 N	83 07 36.16 E	719977.97	2403943.55	Biocatenoides spherula	Saradih Limestone	3.5038

Figure 10: Raman spectroscopic data used for maturity calibration. Top Left: shows how Raman bands of OM change with increasing maturity. Top right: shows Raman Index of Preservation (RIP) values of Chhattisgarh Organic-walled microfossils together with existing studies from the different fossiliferous localities. Bottom table: lists out the sample points and their equivalent VRo values.

Modelling Results and Analysis

In order to assess the likelihood of the existence of a petroleum system and associated risks in the basin, PSM results were synthesized and critically analyzed. As indicated by the modelled Rock maturity overlay (Figure 10), the majority of sedimentary sequences have reached the Dry Gas to Overmature window (Figure 11) and the source layers have undergone >99% transformation at present. The modelled source layers show only marginal transformations until 1000 Ma. By 800 Ma, 50% TR is achieved, and by 600 Ma, 90% TR is achieved. Inferred from the TR-Time curve (Figure 12), peak transformation and expulsion occurred between 1000 and 600 Ma ago. Before the end of the Neoproterozoic, all source layers appear to have reached the Critical Moment. As a result of such a long and multiphased evolutionary history, it is difficult to determine the timing of trap formation. Thus, the timing of trap formation has been constrained considering the major tectonic episodes in the basin evolution

1) initial basin opening phase at around 1600Ma which resulted in evolution of basin margin normal faults,
2) tectonic event at around 1400Ma manifested in the form of numerous tuffs and intrusives, and
3) another major tectonic event at Meso-Neoproterozoic boundary at 1000Ma which resulted in massive granitic intrusions along with formation of reverse and strike-slip faults (noticeably affected eastern part of the basin i.e., Baradwar sub-basin) owing to Eastern Ghat Orogeny.

In all possibilities, the events of structuration predate the timing of attaining of critical moment in the basin. In this scenario, suitable traps might have existed during the generation and expulsion of hydrocarbons (also assuming good quality reservoirs). As the basin has seen a long episode of uplift and erosion during post Neoproterozoic, risk of preservation of hydrocarbons over a very long geological time still exists.

The results of the study is summarized and presented in the PSE chart (Figure 13).

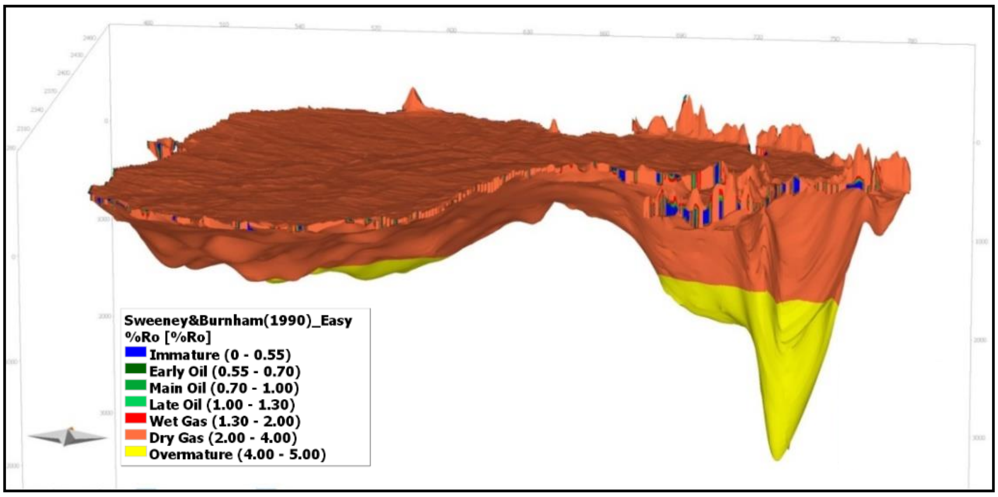


Fig.11: Rock Maturity model (3D) of Chhattisgarh Basin

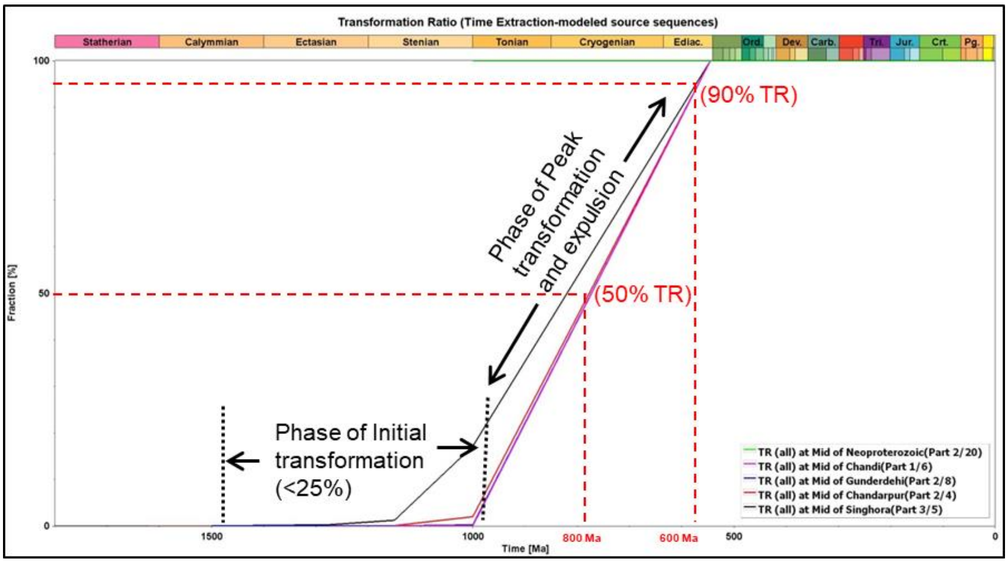


Fig.12: Time extraction of TR for modeled source rocks

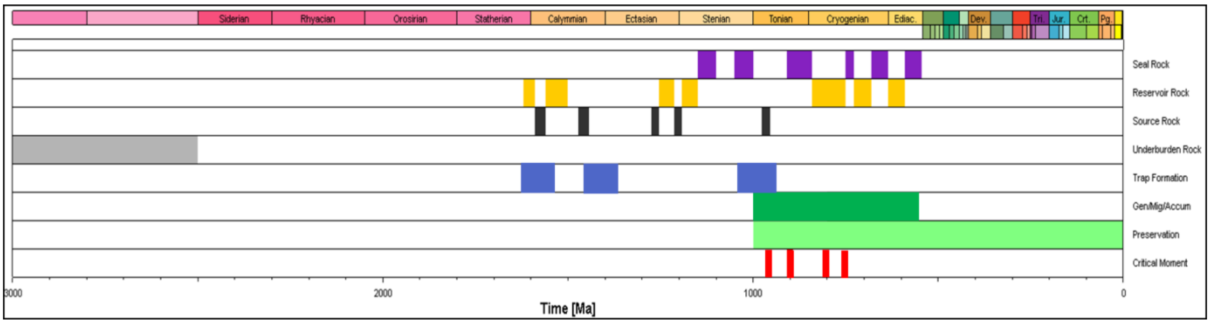


Figure 13: PSE Chart for Chhattisgarh Basin depicting temporal relation of petroleum system elements and processes in conjunction with preservation time and critical moment

Constraints

Available data in the basin is limited to surface geological data and indirect subsurface geophysical data. Wells have not yet been drilled and the boreholes drilled by GSI are only a few meters deep. This limits the understanding of basin geology, stratigraphy and tectonic evolution. The NSP data recently acquired is limited to the western part of the basin and leaves out the Eastern sub-basin which is tectonically more complex and disturbed. The geochemical data collected and studied so far includes surface microbial activity and adsorbed gas anomalies, Rock-eval analysis. All these studies indicate meagre gaseous hydrocarbon concentrations in the sample and very low organic matter richness (TOC= 0.13-0.02 %) except only one TOC value of 1.75% in Hirri shale sample (Kalpana et al, 2010 and Prasanna et al, 2008). This does not necessarily warrant presence of good source rocks in the basin. Moreover, there are porosity reportings of less than 4% from Chandarpur formation. This indicates the quality of reservoir rocks has been degraded though time due to drastic reduction of porosity owing to deep burial and physico-chemical compaction and cementation.

Conclusions

- While this study suggests a possible petroleum system in this basin, it is based on sparse data, a number of assumptions, and speculative elements of the petroleum system. However, more specific sedimentological and geochronological studies are needed in these basins to minimize uncertainties related to age of deposition, true thickness of formations and depositional boundaries, source rock quality and organic matter preservation, reservoir quality, sealing potential, and the effects of orogenic and epiorogenic episodes on hydrocarbon preservation.
- In the absence of calibration datasets such as Vitrinite reflectance (VRo%), additional multidisciplinary scientific data/methods such as Illite crystallinity / Kubler's index, Raman spectroscopy / Raman preservation index, fluid inclusion studies, etc. will be needed to quantify erosion, rock maturity, and paleothermal conditions. These scientific approaches will be instrumental in improving the robustness of Basin and Petroleum System models in the future.

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