www.gondwanags.org.in
Research Article

ISSN : 2455-1953
JGSR
Journal of Geosciences Research
Vol. 8, No.2, July, 2023, pp. 100-109

Rock-Eval Pyrolysis and Petrographic Characteristics of Coals of Chintalapudi Sub-Basin, Pranhita-Godavari Basin, Southern India: Implication to Depositional Environment

S. Kiran and Kakoli Gogoi*

Geology Discipline, School of Sciences, Indira Gandhi National Open University, New Delhi-110068, India
*(*Corresponding Author, E-mail: kakoligogoi@ignou.ac.in)*

Abstract

The results of the Rock-Eval pyrolysis and petrological investigation carried out on coal samples from the Chintalapudi sub-basin of the Pranhita-Godavari basin have been discussedtoidentify the assessment of the maturity, type, and quantity of organic matter and interpret the depositional environment. Petrographically these coals are enriched in vitrinite (40.0%-60.7%) followed by liptinite (7.3%-26.0%) and inertinite (9.3%-24.0%) macerals.TOC concentrations range from 17.54% to 64.97%. S_1 ranges from 0.30% to 1.63% and S_2 ranges from 11.70% to 138.06% are considered to be good source rocks. The T_{max} values of the Chintalapudi sub-basin coals are found to be between 420°C to 428°C, indicating an immature source rock for the production of oil. The coal samples have an average HI of 157 mg HC/g TOC and VRo of 0.30% placing them in the Type III gas kerogen range. HI, and OI values reveal that the samples of organic matter composition mostly follow the evolutionary route of mixed Type II/III kerogens and are contributed by terrestrial plants which is the main source of the organic matter. The GI (1.67-5.95) and TPI (2.75-47.14)values favour the existence of wet moor with moderate to severe floods with short periods of alternateoxic and anoxic moor environments due to the high concentration of vitrinite that allowed for adequate tissue preservation.

Keywords: Kerogen, Rock-Eval Pyrolysis, Petrography, Chintalapudi Sub-basin

Introduction

Coal is believed to be an important source for the generation of oil and gas. The generation of oil-like substances in coal was recognised long ago (Brooks, 1970, Teichmuller, 1974). Source rocks are commonly shales and lime mudstones, which contain a significant amount of organic matter (Tissot, 1984).The rock with the ability to produce and expel sufficient hydrocarbons to create an accumulation of oil or gas is referred to be a petroleum source rock. Since coal contains more than 50% organic material, it is an important source rock for hydrocarbons (Singh, 2012). As a result, coal is regarded as a significant petroleum source rock, and there is debate about how petroleum compounds may be produced and released from coal (Wilkins and George, 2002). The quantity (organic richness), quality (kerogen type), thermal maturation generation capabilities, and distribution of the organic matter in the rock are the main factors used to evaluate the hydrocarbon source (Tissot, 1984; Waples, 1994).

In order to understand the heterogeneity of coal, coal petrography is a crucial technique. The petrographic composition of coal influences its physico-chemical characteristics, and the petrographic framework can also be used to anticipate coal's scientific behaviour and potential uses (Singh *et al.*, 2017a). Organic petrography and rock-eval pyrolysis are the techniques that are applied for the rapid assessment of the maturation and source characteristics of all types of organic matter. Organic petrography deals with the microscopically visible organic matter present in rocks and is the most effective method for determining the depositional environment, the source vegetation,and the maturation level of coal and its gas generation potential (Diessel, 1983; Flores, 2002; Kalkreuth *et al.*, 1991; Latif *et al.*, 2021). Many researchers have provided a thorough study of several geochemical parameters in evaluating the richness, maturity and quality of source rocks, vitrinite reflectance, maceral analysis, total organic content measurement, rock–eval pyrolysis, associations between maturity and hydrocarbon generation, as well as the depositional environment (Dow, 1977; Tissot and Welte, 1978; Thompson-Rizer, 1993; Law, 1999; Vandenbroucke and Largeau, 2007; Gogoi *et al.*, 2008; Salleh *et al.*, 2008; Sahoo and Gogoi, 2011; Phukan *et al.*, 2013; Jahan, 2016; Sharma *et al.*, 2016; Singh *et al.*, 2016a-b, 2017a-b; Mathews *et al.*, 2020; Gogoi *et al.*, 2020, 2021; Singh and Kumar, 2020; Kumar *et al.*, 2020; Singh *et al.*, 2022; Kar *et al.*, 2022). Quantitative and qualitative analyses of different kerogen types with the geochemical study of organic matter provide a better understanding of the generating potential (GP) of source rocks (Thompson and Dimbicki, 1986; Isabel, 2012). The present study is an attempt to identify the assessment of the maturity, type, and

(Received : 08 November 2022 ; Revised Form Accepted : 15 April 2023)
https://doi.org/10.56153/g19088-022-0129-29

quantity of organic matter and interpret the depositional environment based on the maceral and kerogen types of the coals of Chintalapudi Sub-basin (CSB) of the Pranhita-Godavari (PG) Basin.

Geological Setting

The Pranhita-Godavari Basin trending NNW-SSE lies between 79°15′ and 81°30′ longitudes and 16°45′ and 19°45′ latitudes. The basin extends a strike length of about 470 kilometres from Eluru on east of Andhra Pradesh to Boregaon in the NW in the state of Maharashtra. A major portion of the valley lies in the state of Telangana for about 350 km and is called as Pranhita-Godavari or Godavari Basin, while the adjacent part further northwest, falling in the state of Maharashtra is designated as Wardha valley. The initial work on the stratigraphy of the whole Godavari Basin was worked out by King (1872, 1881). Subsequent studies by many researchers have brought out a wealth of information on the stratigraphy on one or other rock units in different parts of the basin (Sengupta, 1970; Ramanamurty *et al.*, 1979; Ramanamurthy and Rao, 1987, 1996; Ramanamurty, 1985; Raja Rao, 1982; Srinivasa Rao, 1987; Lakshminarayana, 1991, 1995a-b, 1996; Lakshminarayana *et al.*, 1992; Raju, 1986; Kutty, 1969; Kutty *et al.*,1987; Srivastava and Jha, 1988, 1990; Dasgupta, 1993; Tewari, 2017). The Archean basement, Proterozoic sedimentaries, Palaeozoic-Mesozoic Gondwana sedimentaries and Upper Cretaceous-Tertiary Deccan Trap are the principal geological units of the Pranhita-Godavari Basin. Lower Gondwana group and Upper Gondwana group are two lithostratigraphically distinct groupings of sediments that constitute the Pranhita-Godavari Basin. Along the 470 km course of the rivers Pranhita and Godavari, the Gondwana deposits are spread out over the Precambrian platform. Godavari Sub-basin is in the northern sector, and the Kothagudem Sub-basin, Chintalapudi Sub-basin and the Krishna-Godavari Coastal Tract are in the southern sector (Raja Rao, 1982, Lakshminarayana, 1991; Lakshminarayana, 1995a-b). The generalised geological succession of the Pranhita-Godavari Basin is given in Table 1 (Lakshminarayana and Murti, 1990; Lakshminarayana, 1995).

Chintalapudi Sub-basin is transversely superimposed by the NE–SW oriented continental margin Krishna–Godavari coastal Basin (Lakshminarayana, 2002). The Talchir, Barakar, and Kamthi Formations make up the majority of the geologic sequence in the Chintalapudi Sub-basin. The Talchir sequence form the base of the Gondwana succession with a thickness of 200 to 370 metres, which also includes a shale sequence, fine-grained greenish sandstone, and a basal boulder bed (Lakshminarayana and Murti, 1990; Sarate, 2013, 2017, 2018). The generalised geological map of the area of the Chintalapudi Sub-basin along with the sample (borehole) locations is shown in Fig.1.

Materials and Methods

Samples have been collected from boreholes SVP 94 and SSP 428 coal mines from Chintalapudi Sub-basin of Pranhita- Godavari Basin (Fig.1) by taking the permission for field work and samples collection from Singareni collieries company limited (SCCL). The total depths of the bore hole SVP 94 and SSP 428 is ~118m and ~75m, respectively. Two major coal seams of Barakar Formation, Index 1 and Seam A had been encountered in the borehole SVP 94. Megascopically, the coals of Chintalapudi Sub-basin are dull to banded dull in nature as per the standard classification derived by Diessel (1965).

Petrographic investigations were conducted in compliance with the recommendations of ICCP (1963, 1971, 1975, 1998 and 2001) and Stach *et al.* (1982). For the petrographic study 10 selected samples were air dried and crushed to 1mm in size to prepare polished pellets. A Leica DM4P Fluorescence microscope has been used to study the coal petrography. The identification of macerals present in the polished coal pellets was carried out using a Leica DM4P Fluorescence microscope fitted with 50X and oil immersion. Images of the macerals have been taken through Leica Application Suit (LAS). The reflectance studies were generated on Microscope Photometry System (PMT IV) along with the software MSP200 after calibrating the instrument with the Zirconia (Vro 3.17%), Gadolinium-Gallium-Garnet (Vro 1.720 %), and Spinel (Vro 0.423%) standards.

To study the hydrocarbon maturity of coal, the Rock-Eval Pyrolysis is carried out on16 selected coal samples using the Rock Eval-6 apparatus. The method consists of the selection, detection and quantitative analysis of oxygenated and hydrocarbon-type compounds under an inert atmosphere using a Flame Ionization Detector (FID) detector and with programmed temperature (Espitalie *et al.*, 1977). FID signals are divided into S_1 and S_2 which are expressed in mgHC/g. S_1 refers to the free hydrocarbons which are present in the coal and S_2 refers to the hydrocarbons liberated during the thermal cracking of kerogen. A third peak (S_3) marks the

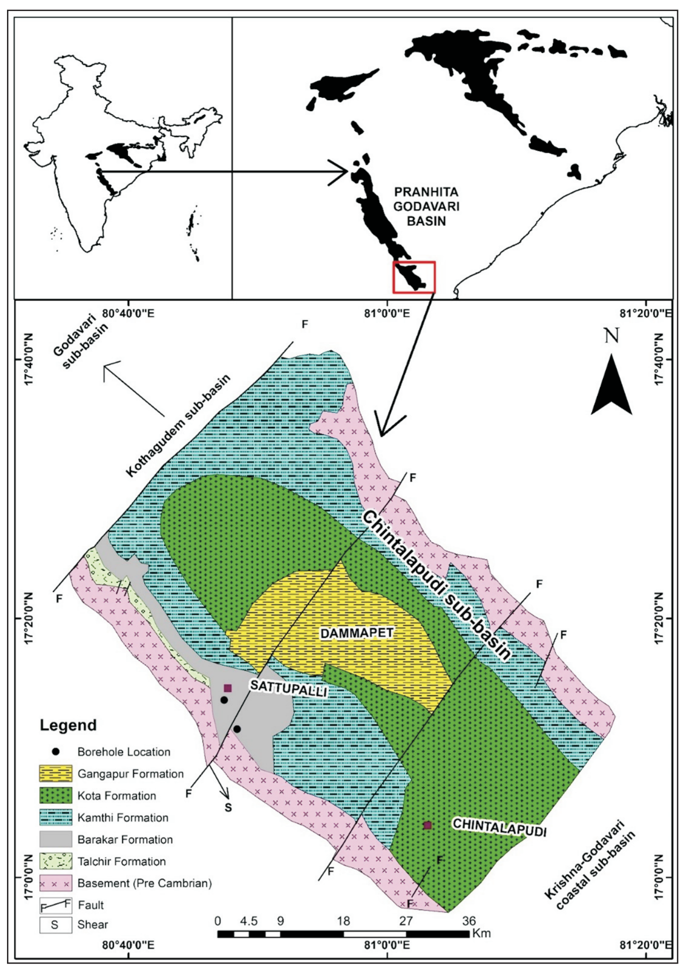

Fig.1. Geological map of the Chintalapudi Sub-basin with sample locations

Table 1: General Geological Succession of the Pranhita-Godavari Basin (*After* Lakshminarayana and Murti, 1990; Lakshminarayana, 1995)

Age	Super-group	Group	Formation	Lithology
Upper Cretaceous			Deccan Trap (65m)	Basaltic flows
				~~ Unconformity ~~~~~~
Early Cretaceous			Chikiala (300m)	Brown, red, and yellow to buff ferruginous sandstones with conglomerates and a few clay beds
				~~ Unconformity ~~~~~~
Jurrasic		UPPER GONDWANA	Kota (675m)	Pale brown sandstones with red clays with a few thin persistent limestone bands and local carbonaceous clays, thin coal bands, and pebble beds
				~~ Unconformity ~~~~~~
Middle to Upper Triassic			Maleri (1000m)	Alternate sandstones and clay beds, lime pellet rocks, and coarse buff sandstones with clay galls (Dharmaram). Coarse grain sandstones with clay galls and a few clay Intercalations (Bhimaram). Soft red mudstones with calcareous bands (Yerrapalli).
Upper Permian to Middle Triassic	GONDWANA			Upper Member (500 m) L-M Triassic Coarse-grained ferruginous sandstones with numerous clay clasts and pebbles of cherty siltstones and secondary hematitic bands.
				~~ Unconformity ~~~~~~
		LOWER GONDWANA	Kamthi (1700m)	Middle Member (1000 m) U-E Triassic Alternating sequence of medium-grained, white to greenish grey sandstones, and green calcareous clays. Lower Member (200 m) U Permian Medium to coarse-grained greyish-white calcareous sandstones with few coal seams and subordinate shales.
Middle Permian			Barren Measures (500 m)	Medium to coarse-grained, greenish grey to grey-white feldspathic sandstones with subordinate variegated clays and siltstones and carbonaceous shales.
Lower Permian			Barakar (300 m)	Medium to coarse-grained, grey-white sandstones with subordinate shales and a few workable coal seams. Lower part is pebbly with few shale bands.
Basal Permian			Talchir (350 m)	Fine grained sandstones, splintery green clays/shales, khaki coloured clays, pebble beds and diamictites
				~~ Unconformity ~~~~~~
Upper Proterozoic		Sullavai Group (645 m)		Medium to coarse-grained, white to brick red sandstones, at places quartzite and mottled shales
				~~ Unconformity ~~~~~~
Middle Proterozoic		Pakhal Group (3335 m)		Grey shales, phyllites, dolomites and marble and white to buff quartzites
				~~ Unconformity ~~~~~~
Archean				Granites, banded gneisses, blotte gneisses, hornblende gneisses, quartz magnetite schists, blotte schists, quartz and pegmatite veins.

Table 2: Macerals and mineral matter (%) present in the coals of CSB of the PG Basin

Macerals	Sample no.	SVP 94/3	SVP 94/4	SVP 94/10	SVP 94/12	SVP 94/15	SVP 94/20	SVP 94/21	SVP 94/22	SSP 428/3	SSP 428/10
Vitrinite	Collotelinite	26.7	32.7	32	56.0	21.3	46.7	50.7	47.3	42.7	46.3
	Vitrodetrinite	18.7	8.0	13	4.0	7.3	3.3	1.3	2.0	1.3	0.0
	Collodetrinite	3.3	6.7	13	0.7	11.3	5.3	2.7	1.3	4.7	11.7
	Total	48.7	47.3	57.3	60.7	40.0	55.3	54.7	50.7	48.7	58.0
Inertinite	Fusinite	9.3	2.7	9	6.0	16.7	4.7	10.7	6.0	20.7	11.6
	Semifusinite	4.0	8.0	3	4.0	6.0	1.3	3.3	8.0	1.3	6.3
	Inertodetrinite	2.7	2.7	3	0.7	1.3	3.3	2.7	2.7	0.7	2.8
	Total	16.0	13.3	15	10.7	24.0	9.3	16.7	16.7	22.7	20.7
Liptinite	Sporinite	1.3	6.7	7	5.3	3.3	7.3	10.7	6.0	4.0	1.3
	Cutinite	15.3	10.0	3	10.0	10.0	7.3	4.0	8.7	7.3	1.3
	Liptodetrinite	6.7	8.0	5	3.3	12.7	5.3	2.7	0.0	2.0	4.7
	Total	23.3	24.7	15	18.7	26.0	20.0	17.3	14.7	13.3	7.3
Mineral matter		12.0	14.7	13	10.0	10.0	15.3	11.3	18.0	15.3	14.0
Vitrinite reflectance (%)	VR min	0.23	0.23	0.22	0.24	0.27	0.27	0.2736	0.257	0.207	0.25
	VR max	0.48	0.48	0.48	0.39	0.44	0.41	0.366	0.472	0.488	0.373
	VRo	0.32	0.34	0.35	0.32	0.30	0.34	0.31	0.324	0.356	0.3
	GI	3.04	3.53	3.82	5.67	1.67	5.95	3.28	3.04	2.15	2.80
	TPI	6.67	4.62	2.75	47.14	3.49	6.13	11.98	15.33	11.98	4.43

amount (in mg) of CO_2 generated from 1g of coal. The infrared cell monitors the released CO and CO_2. This acquired data helps in determining the total organic carbon (TOC) or total mineral matter (TMC). Additional parameters *viz.* Productivity Index (PI) [$S_1/(S_1 + S_2)$]; Hydrogen Index (HI) [(100 x S_2)/TOC] and Oxygen Index (OI) [(100 x S_3)/TOC] are calculated to know the type and maturity of the organic matter.

Results and Discussion

Results achieved from the present study are discussed in terms of the following sub-sections: Petrographic Composition: maceral analysis and Rock-Eval Pyrolysis: quality of organic matter, maturity of organic matter. Further based on the maceral and kerogen types depositional environment is discussed.

Petrographic Composition

Results of petrographic composition are shown in Table 2.

Maceral Analysis

The microscopic data suggests that the coal of the Chintalapudi Sub-basin exhibits vitrinite dominance that ranges from 40.0% - 60.7% followed by liptinite (7.3% - 26.0%) and inertinite (9.3% -24.0%). The ability of coal to produce oil is directly correlated with its liptinite concentration in sediments and must have at least 15-20% liptinite (by volume) to be regarded as a source (Fowler *et al.*, 1991; Hunt, 1991; Mukhopadhyay *et al.*, 1991). Liptinites and perhydrous vitrinites have the potential to generate hydrocarbon liquids and are able to predict several environments of deposition (Wilkins and George, 2002). Therefore, when examining any sedimentary rock as a possible source rock for liquid hydrocarbons, the presence of liptinite macerals is the fundamental requirement (Stach *et al.*, 1982; Thompson *et al.*, 1985; Hunt, 1991; Mukhopadhyay and Hatcher, 1993; Hendrix *et al.*, 1995). The Vitrinite group of macerals recorded a high content than the Liptinite group of macerals. Liptinite group of macerals is represented by cutinite, sporinite and liptodetrinite with an average of 7.7%, 5.2% and 5.0%, respectively. Collotelinite is the most dominant maceral present in thick and thin bands in the coal with an average of 40.2% followed by collodetrinite accounting average of 6.1% and vitrodetrinite with an average of 5.9% (Table 2; Fig.2). Fusinite and semifinite macerals present with an average of 9.7% and 4.5%, respectively followed by inertodetrinite with an average of 2.3% (Table 2; Fig. 2). Fusinite and semi-fusinites are considered to be the product of peat fire (Sarate, 2013). Some mega sporinites are also recorded in some samples along with thick and thin-walled sporinites, appearing like elongated thread or spindle-shaped. Cutinite represents the waxy cuticles coating leaves and young

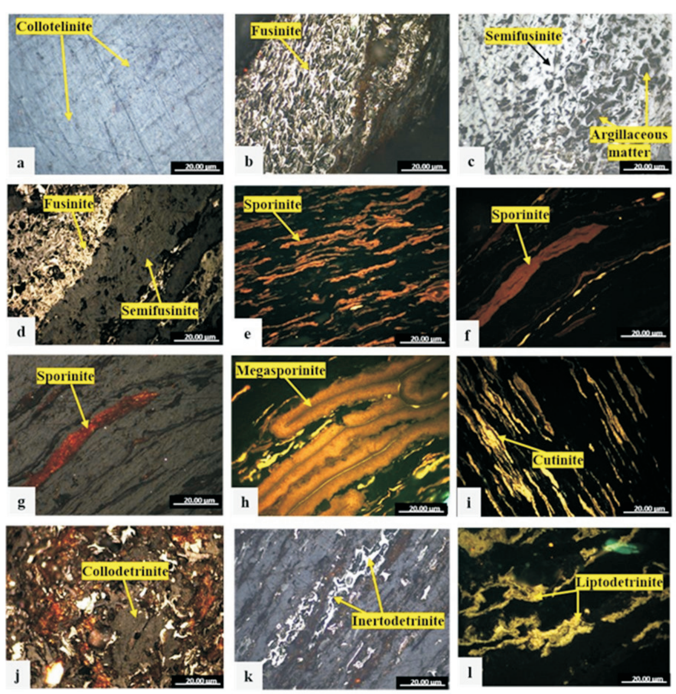

Fig.2. Photomicrographs (a) Collotelinite band; (b) Fusinite band; (c-d) Fusinite and Semifusinite filled with argillaceous matter; (e-g) Sporinite; (h) Megasporinite; (i) Cutinite; (j) Collodetrinite; (k)Inertodetrinite and (l) Liptodetrinite

Table 3: Rock-Eval pyrolysis data of coals of CSB of the PG Basin

Sample	S (mgHC/g)	S2 (mgHC/g)	S3 (mgHC/g)	Tmax °C	HI (mgHC/g)	OI (mgHC/g)	GP (mgHC/g)	PI	TOC (%)
SVP- 94/2	1.63	138.06	5.15	425	240	9	249	0.01	57.49
SVP- 94/3	0.3	35.32	3.72	426	77	8	8	0.01	46.09
SVP- 94/4	1.03	105.96	4.32	424	225	9	234	0.01	47.04
SVP- 94/6	1.51	120.92	5.37	421	216	10	226	0.01	55.93
SVP- 94/7	0.38	46.59	4.56	426	105	10	93	0.01	44.22
SVP- 94/12	0.52	42.6	5.78	426	91	12	12	0.01	46.82
SVP- 94/15	1.12	122.78	5.79	425	203	10	213	0.01	60.58
SVP- 94/17	0.3	11.7	1.77	421	47	7	54	0.03	24.92
SVP- 94/19	0.39	43.25	2.69	420	103	6	38	0.01	41.92
SVP- 94/20	1.38	110.27	6.75	427	170	10	180	0.01	64.97
SVP- 94/21	1.3	95.5	4.69	423	154	8	162	0.01	62.05
SVP- 94/22	1.14	73.03	4.14	423	126	7	133	0.02	58.14
SSP-428/2	0.74	46.5	1.61	428	143	5	5	0.02	32.51
SSP-428/3	0.43	38.03	1.64	423	148	6	154	0.01	25.73
SSP-428/5	0.58	44.88	1.22	428	179	5	5	0.01	25.02
SSP-428/6	0.34	48.81	0.97	426	278	6	113	0.01	17.54
Min.	0.30	11.70	0.97	420	47	5	5	0.01	17.54
Max.	1.63	138.06	6.75	428	278.2	12	249	0.03	64.97
Avg.	0.82	70.26	3.76	425	157	8	117	0.01	44.44

shoots while sporinite represents the external coats (exines) of pollens and spores (Falcon, 2013).The mineral matter which accounts for about 13.3% includes argillaceous matter, silicates, carbonates and pyrite. The argillaceous matter is also observed in the cavities of fusinites and semi-fusinites (Table 1, Fig 2)**.**The random vitrinite reflectance varies between 0.30% and 0.36% (Table 1) which suggests that the coal is of sub-bituminous rank as per the classification given by German and North American classification schemes (Teichmüller, 1987).

Rock-Eval Pyrolysis

Source-rock potential of the analysed samples has been evaluated on the basis of the quality, quantity, and maturity of the organic matter. The results of the samples are presented in Table 3.

The organic matter, which is usually expressed as total organic carbon (TOC wt%) and rock-eval pyrolysis was considered to find out the organic matter and analyse the source rock potential (Peters, 1986; Peters and Cassa, 1994; Waples, 1994). The coals of the Chintalapudi sub-basin recorded high TOC content ranging from 17.54% to 64.97%. S_1 ranges from 0.30% to 1.63% and S_2 ranges from 11.70% to 138.06% has been observed. S_2 expelled at maximum temperature during thermal cracking is a useful indicator to evaluate the generative potential of source rocks (Peters, 1986; Bordenave *et al.*, 1993). Rocks with S_2 values, of more than 5mg/gm of rock are considered to be good source rocks (Sharma *et al.*, 1987). The majority of the CSB coals with S_2 values exhibiting more than 5mgHC/g reveal that the samples are considered to be good source rocks. Tmax value of more than 435°C is considered to be a mature stage for oil generation. In the present study, the Tmax values range from 420°C to 428°C. Tmax is the value of the maximum temperature at which the S_2 hydrocarbons are expelled (Espitalie *et al.*, 1977). Further, the results have been plotted on HI *vs* OI, S_2 *vs* TOC, T_{max} *vs* HI, and T_{max} *vs* PI for precise interpretation of the quality and maturity of organic matter present in the coals.

Hydrocarbon generation potential and hydrogen index values (HI) *i.e.*, S_2 of rock-eval pyrolysis are indicative of the quality of organic matter. HI values of the present samples range from 47 mgHc/g TOC to 278 mgHc/g TOC. HI values between 150 – 300 HI mgHc/g TOC contain Type III kerogen than Type II and therefore, have marginal to fair potential for liquid hydrocarbons (Waples, 1985). The Organic matter with higher HI values (>200 mgHc/g TOC) is typically regarded as having the ability to produce liquid hydrocarbons (Hunt, 1991).

Quality of Organic Matter

The best approach for determining the genuine average HI and evaluating the hydrocarbon adsorption by the rock matrix is to plot S_2 *vs* TOC diagram (Langford and Blanc-work Valleron, 1990). The coal samples from the Chintalapudi Sub-basin that were tested had an average HI of 157 mg HC/g TOC, placing them in Type II/III gas kerogen range (Fig. 3).

The Van Krevelen (1961) method, which is based on atomic H/C *vs* O/C ratios, is the most widely used technique for the classification of organic matter in terms of kerogen typeand has been utilised to account for maturity effects when evaluating pyrolysis data. The cross plot of HI and OI of the coals of Chintalapudi Sub-basin in the modified Van Krevelen diagram represents both Type II and Type III kerogen (Fig. 4). The plot reveals that the samples of organic matter composition mostly follow the evolutionary route of mixed Type II and III kerogens,

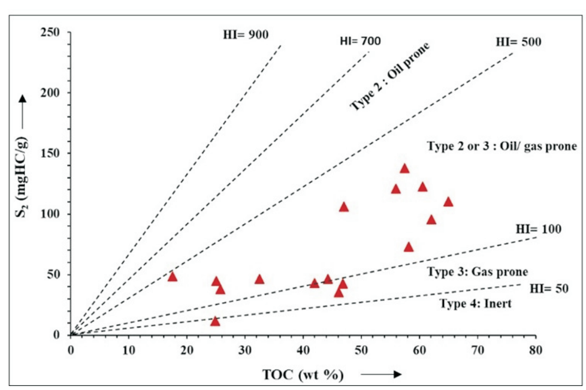

Fig.3. Total Organic Carbon (TOC) *vs* S_2 (*Modified after* Langford and Blanc-Valeron, 1990)

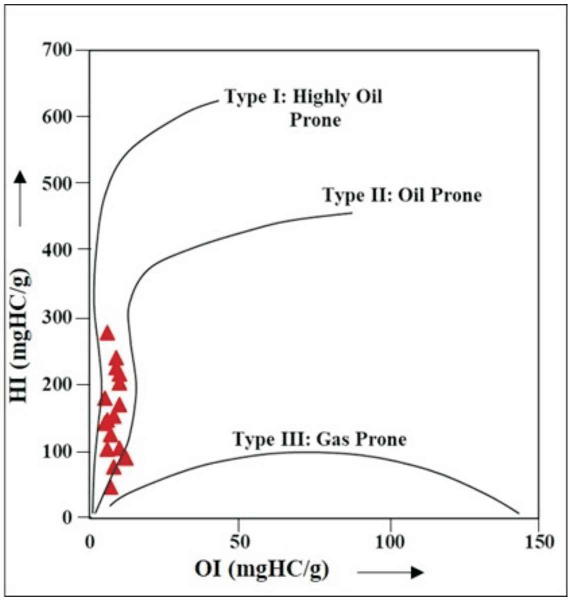

Fig. 4. Hydrogen Index *vs* Oxygen Index (*Modified after* Van Krevelen, 1961)

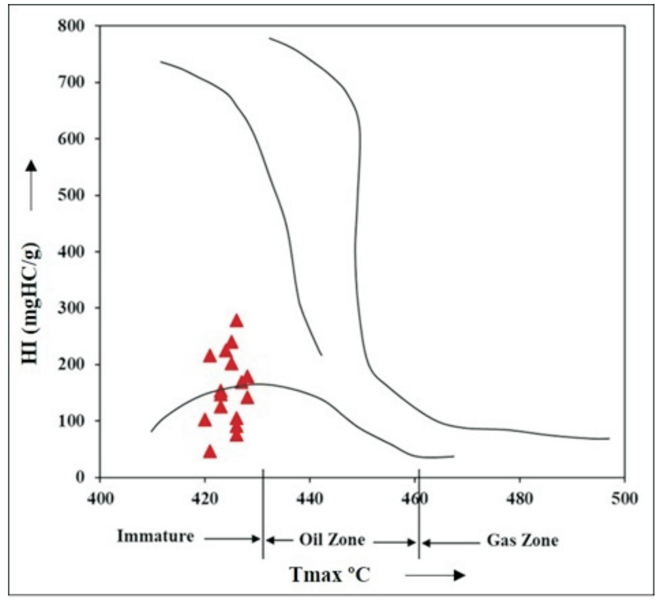

Fig. 6. The plot of Rock-Eval HI versus Tmax (*Modified after* Espitalie *et al.*, 1985)

which are both gas- and oil-prone. By pyrolysis, the generative potential coals were often over estimated and are best analysed by elemental analysis and organic petrography (Peters, 1986). The plot of TOC *vs* HI (Fig. 5) suggests that the increased HI and TOC values of the Chintalapudi sub-basin samples improved organic matter preservation at high TOC levels. The higher oxygen reduction produced by microbial respiration through the breakdown of organic materials may be the reason for this improved preservation (Jackson *et al.*, 1985).

Maturity of Organic Matter

The thermal maturity provides relevant information on the highest temperature (Tmax) and the depth at which the source rocks were buried. To assess the thermal maturity of coal samples, three parameters were used: Rock-eval T_{max}, Production Index (PI), and Hydrogen Index (HI). The T_{max} values of the Chintalapudi Sub-basin coals are found to be between 420°C to 428°C (Table 2), indicating an immature source rock for the production of oil. With an increase in the organic matter's maturity level, the T_{max} values rise as well.

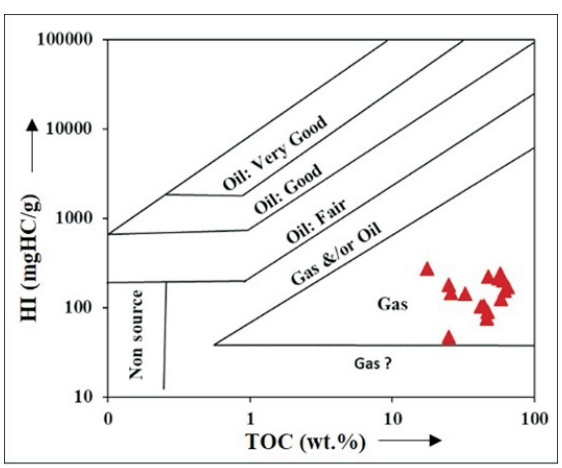

Fig. 5. Hydrogen Index (HI) *vs* Total Organic Carbon(TOC) (*Modified after* Jackson *et al.*, 1985)

Low T_{max} values (<430°C) obtained for the samples, refer that the organic matter associated with them is immature, which is also supported by HI *vs* T_{max} plot (*Modified after* Espitalie *et al.*, 1985; Fig. 6). The PI values of the coals of Chintalapudi Sub-basin (Fig.7) indicates immature sources for producing oil and mostly illustrate the immature nature of the organic matter (Peters, 1986; Sengular *et al.*, 2008).

Vitrinite reflectance (VRo) techniques in assessing kerogen maturity may in fact be based on a coincidence that is not always valid (Waples, 1985). Despite its weakness, vitrinite reflectance is the most popular technique for estimating kerogen maturity. A cross plot between HI versus VRo% of the present samples indicate that coals are of Type-III kerogen (Fig. 8) indicating that they are immature (Leythaeuser *et al.*,1980; Tissot and Welte, 1984).

Depositional Environment

Organic matter/facies provide information about the palaeobotanical context, the initial environment, and the depositional circumstances of the source area. As a result, these facies have been extensively employed to explain the evolution of peat swamps and characterise palaeo-vegetation (Diessel, 1982, 1986, 1992; Tyson, 1995; Batten, 1996; Mendonça Filho *et al.*,

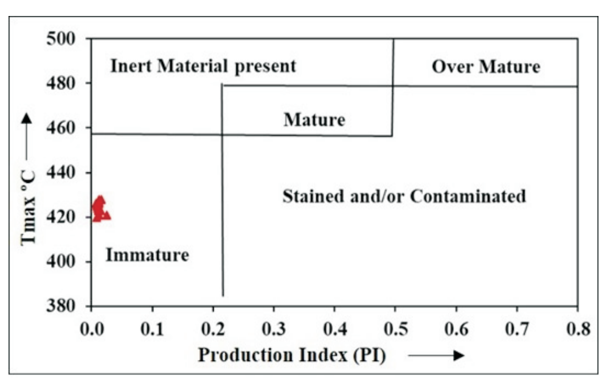

Fig. 7. The plot of Rock-Eval PI versus Tmax (*Modified after* Peters, 1986; Sengular *et al.*, 2008)

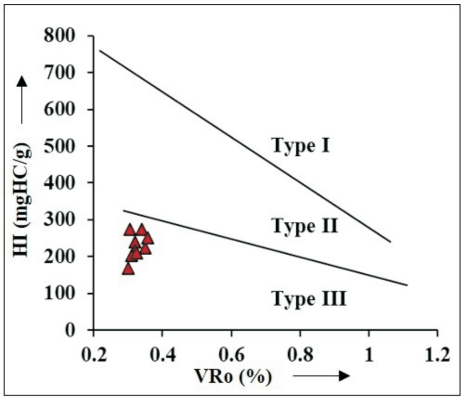

Fig.8. The plot of Rock-Eval HI *vs* VRo % (Leythaeuser *et al.*, 1980).

2011, 2012; Singh *et al.*, 2013, 2017b-c; Singh *et al.*, 2017a-b). The composition of the maceral and mineral matter in the seam profile can be used to infer how the peat or seam developed (Shearer *et al.*, 1994; Kalkreuth *et al.*, 1991). Peat developed in wet conditions has a high vitrinitisation or Gelification Index (GI) and high telovitrinite-based Tissue Preservation Index (TPI), whereas peat developed in dry conditions exhibits low GI and low telovitrinite-based TPI (Diessel, 1986). In the present study, TPI [(Telinite + Collotelinite + Semifusinite + Fusinite)/ (Collodetrinite + Macrinite + Inertodetrinite) and GI [(Vitrinite + Macrinite)/ (Semifusinite + Fusinite + Inertodetrinite)] have been calculated (Diessel, 1986).

The GI values ranges from (1.67-5.95) with an average of 3.49 and TPI values ranges from (2.75-47.14) with an average of 11.45 (Table 2). The facies model deciphered from the GI and TPI indices with (Fig. 9) displays that the coals of the Chintalapudi Sub-basin are formed in wet forest wetlands (Diesel, 1986). The presence of collotelinite in samples from the upper portion of the seam in high concentrations is a sign of biochemical gelification. High concentrations of fusinite and semi-fusinite are signs of woody vegetation and subsequent wildfire. However, the presence of sporinite, cutinite, and resinite, as well as an adequate amount of inertodetrinite support a moderate level of humification in these

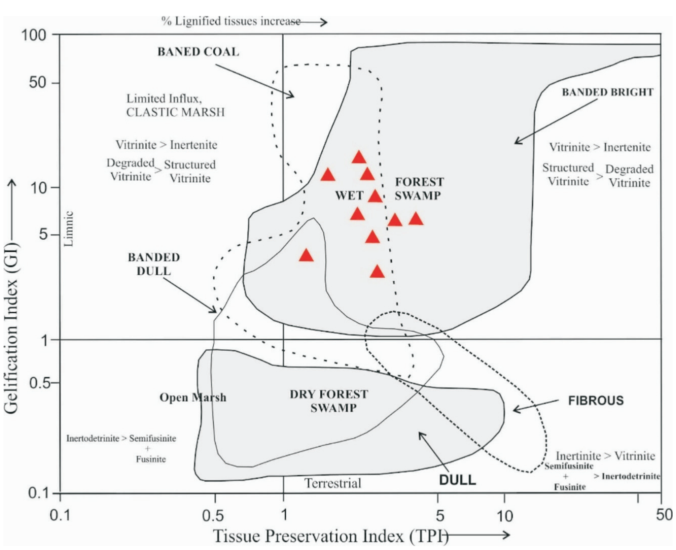

Fig. 9. Facies diagram based on Gelification Index (GI) and Tissue Preservation Index (TPI) (*Modified after* Diesel, 1986; Kalkreuth *et al.*, 1991; Singh *et al.*, 2012)

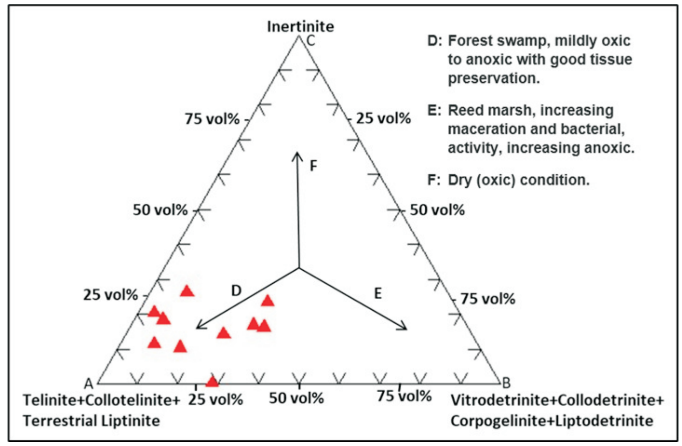

Fig. 10. Ternary diagram showing facies critical maceral associations (*After* Mukhopadhyay, 1986)

coals (Ligouis *et al.*, 1998). A low TPI indicates either a large-scale breakdown of wood due to widespread deterioration or a predominance of herbaceous plants in the swamp (Sutcu and Karayigit, 2009).Vitrinites develop in a relatively wet reducing environment, while inertinites develop in a relatively dry oxidising environment. As a result, there is a clear correlation between the swamp's water level and the condition where coal is formed (Li *et al.*, 2010). The coals of the Chintalapudi Sub-basin (Fig.10) were formed in forests and marshes with mildly oxic to anoxic environments that allowed for adequate tissue preservation (Mukhopadhyay, 1986). The present samples of the Chintalapudi Sub-basin suggest that the development of peat took place in a highly wet moor (Fig. 11) with intermittent moderate to high flooding conditions (Singh and Singh, 1996). The studied samples are relatively rich in vitrinite, this suggests that they formed in a deeper basin.

Conclusions

Chintalapudi Sub-basin exhibits vitrinite dominance that ranges from 40.0% - 60.7% followed by liptinite (7.3% - 26.0%) and inertinite (9.3% -24.0%). Liptinite group of macerals is represented by cutinite, sporinite and liptodetrinite with an average

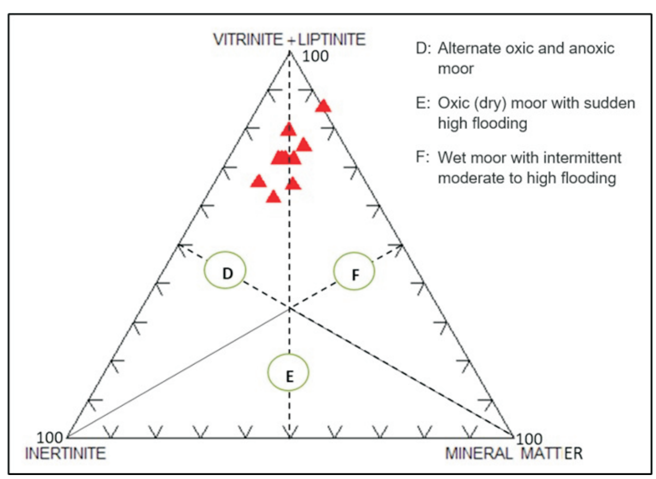

Fig. 11. Ternary facies diagram involving maceral and visible mineral matter contents (*After* Singh and Singh, 1996)

of 7.9%, 5.5% and 5.7%, respectively. Vitrinite reflectance suggests that the coal is of sub-bituminous rank. The majority of the CSB coals with S_2 values reveal that the samples are considered to be good source rocks. The coals have relatively medium reflectance values and high TOC levels reported in the coals of the Chintalapudi Sub-basin mostly contain type-II and type-III kerogen, mainly gas-prone with subordinate oil-generation potential. However, the coals are immature or in starting stage of maturation. The current coal deposits with the GI and TPI reveal the existence of wet moor with moderate to severe floods predominated for an extended period of time with short periods of alternate oxic and anoxic moor revealed by the facies diagram. The dominance of the vitrinite group of macerals is an indication that the coals were deposited during cold climate conditions.

Authors' Contributions

SK: Conceptualization, Data Collection and Data Generation, Investigation, Visualization, Formal Analysis, Writing-Original Draft, Reviewing and Editing. **KG:** Conceptualization, Data Collection and Data Generation, Investigation, Visualization, Supervision and Formal Analysis, Writing, Reviewing and Editing.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

The authors are thankful to Prof. P.K. Singh for extending the laboratory facilities for analytical works in the Department of Geology, Banaras Hindu University, Varanasi, and for his invaluable guidance, and expertise suggestions. The authors are also grateful to Prof. S. Phukan for permitting them to carry out analysis work in the Department of Geological Sciences, Gauhati University, Assam.

References

Batten, D.J. (1996). Palynofacies and palaeoenvironmental interpretation. *In*: Jansonius, J., Mc Gregor, D.C. (*Eds*.), Palynology: Principles and Applications. AASP, pp. 1011-1064.

Bordenave, M.L., Espitalié, L., Leplat, P., Oudin, J.L. and Vandenbroucke, M. (1993). Screening techniques for source rock evaluation. *In*: Bordenave, M.L. (*Ed.*), Applied Petroleum Geochemistry. Editions Technip, Paris, pp.217-278.

Brooks, J.D. (1970). The use of coals as indicators of the occurrence of oil and gas. Jour. Austral. Petrol. Prod. Explor. Assoc., v. 10, pp. 35-50.

Dasgupta, K. (1993). Some contributions to the stratigraphy of the Yerrapalli Formation, Pranhita-Godavari valley, Deccan, India. Jour. Geol. Soc. India, v. 42(3), pp.223.

Diessel, C.F.K. (1965). Correlation of macro-and micropetrography of some New South Wales coals. Proc. General, v.6, pp.669-677.

Diesel, C.F.K. (1986). On the correlation between coal facies and depositional environments. Proc. 20th Symposium of Department of Geology, University of New Castle, New South Wales, pp.19-22.

Diessel, C.F.K. (1982). An appraisal of coal facies based on maceral characteristics. Austral. Coal Geol., v. 4(2), pp.474-484.

Diessel, C.F.K. (1992). Coal-bearing Depositional Systems. Springer-Verlag, Berlin, pp.721.

Diessel, C.F. (1983). Carbonization reactions of inertinite macerals in Australian coals. Fuel, v. 62(8), pp.883-892.

Dow W. (1977). Kerogen studies and geological interpretations. Jour. Geochem. Explor., v. 7, pp.79-99.

Espitalie, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Pauletand, J. and Boutefeu, A. (1977). Methoderapide de caracterisation des roches meres, de leur potential petrolier et de leurdegred'evolution. Rev. Instit. Franc. Petrole., v. 32, pp. 23-42.

Falcon, R. (2013). The coal handbook, Chapter 3: Coal Petrography Wood-head Publishing Limited, 79p. DOI : 10.1533/9780857097309. 1.53

Flores, D. (2002). Organic facies and depositional palaeoenvironment of lignites from Rio Major Basin (Portugal). Internatl. Jour. Coal Geol., v.48, pp.181-195.

Fowler, M.G., Goodarzi, F., Gentzis, T., Brooks, P.W. (1991). Hydrocarbon potential of Middle and Upper Devonian coals from Melville Island, Arctic Canada. Org. Geochem., v.17(6), pp.681-694.

Gogoi, K., Dutta, M.N., and Das, P.K. (2008). Source rock potential for hydrocarbon generation of Makum coals, Upper Assam, India. Curr. Sci., v. 95, pp.233-239.

Gogoi, M., Kumar, T.S. and Phukan, S. (2020). Organic geochemistry, petrography, depositional environment and hydrocarbon potential of the Eocene coal deposits of west Daranggiri Coalfield, Meghalaya. Jour. Geol. Soc. India, v. 95(1), pp.84-94.

Gogoi, M., Walling, T., Thadoju, S.K., Mathur, N., Longkumer, L. and Phukan, S. (2021). Organic geochemistry and petrology of the coals in the Laisong Formation, Naga Schuppen Belt, NE India: Inferences on hydrocarbon potential and depositional environment. Geol. Jour., v.57(2), pp.707-726.

Hendrix, M.S., Brassel, S.C., Carroll, A.R. and Graham S.A. (1995). Sedimentology, organic geochemistry, and petroleum potential of Jurassic Coal Measures: Tarim, Junggar, and Turpan Bassins. AAPG, Bulletin v. 76, pp.952- 959.

Hunt, J.M. (1996). Generation of gas and oil from coal and other terrestrial organic matter. Organ. Geochem., v.17, pp.673-680

International Committee for Coal and Organic Petrology, ICCP (1998). The new vitrinite classification (ICCP System 1994). Fue1, v. 77, pp. 349-358.

International Committee for Coal and Organic Petrology, ICCP (2001) The new inertinite classification (ICCP System 1994). Fue1, v. 80 (4), pp. 459-471.

International Committee for Coal Petrology, ICCP (1963). International Handbook of Coal Petrography, 2nd Edition. CNRS. Academy of Sciences of the USSR, Paris, Moscow.

International Committee for Coal Petrology, ICCP (1971). International Handbook of Coal Petrography, 1st Supplement to 2nd Edition. CNRS, Paris.

International Committee for Coal Petrology, ICCP (1975). International Handbook of Coal Petrography, 2nd Supplement to 2nd Edition. CNRS, Paris.

Isabel S. (2012). Organic petrology: an overview. *In*: Al-Juboury, A. (*Ed.*) Petrology: new perspectives and applications, [Online] http://www.intechopen.com/books/petrology-new-perspectives-and applications/organic-petrology-an-overview.

Jahan, S. (2016). Preliminary assessment of the petroleum source-rock potential of upper Eocene Kopili shale, Bengal basin, Bangladesh. Thesis, Graduate Faculty of Auburn University, pp.1-98.

Jackson, K.S., Hawkins, P.J., and Bennet, A.J.R. (1985). Regional facies and geochemical evolution of the Southern Denison Trough. Austral. Petrol. Explor. Assoc. Jour., v. 20(1), pp.143-158.

Kalkreuth, W., Kotis, T., Papanicolaou, C., and Kokkinakis, P. (1991). The geology and coal petrology of a Miocene lignite profile at Meliadi Mine, Katerini, Greece. Internatl. Jour. Coal Geol., v.17(1), pp.51-67.

Kar, R., Phukan, S. and Baruah, H. (2022). Organic Geochemical

Assessment and Characterisation of Extra-Peninsular Gondwana Coal from Kalijhora Basin, Darjeeling District, West Bengal, India. Jour. Geol. Soc. India, v. 98(4), pp.505-515.

King, W. 1872. Notes on a new coalfield in south-eastern part of the Hyderabad territory. Rep. Geol. Surv. India 5, pp.41-44.

King, W. (1881). Geology of the Pranhita Godavari Valley: Mem. Geol. Surv. India, 18(3), pp.16.

Kumar, A., Singh, A.K., Paul, D. and Kumar, A. (2020). Evaluation of hydrocarbon potential with insight into climate and environment present during deposition of the Sonari lignite, Barmer Basin Rajasthan. Energy Clim. Change, v.1, 100006.

Kutty, T.S. (1969). Some contributions to the stratigraphy of the Upper Gondwana formation of thePranhita- Godavari Valley, Central India. Jour. Geol. Soc. India, v.10, pp. 33-48.

Kutty, T.S., Jain, S.L. and Chowdhury, T.R. (1987). Gondwana sequence of the northern Pranhita-Godavari Valley: its stratigraphy and vertebrate faunas.

Law, C.A. (1999). Evaluating source rocks. *In*: Beaumont, E.A. and Foster, N.H. (*Eds.*) Treatise of petroleum geology/handbook of petroleum geology: exploring for oil and gas traps. Am. Assoc. Petrol. Geol. Sp. Vol., Tulsa, Oklahoma, pp.1-41.

Lakshminarayana, G., Kutumba Rao, N. and Murti, K.S. (1992). Stratigraphy and Structural framework of the Gondwana Formations in the Pasra-Venkatapuram area, Godavari sub-basin. Proceedings Volume on National Workshop on Coal Exploration. Singareni Collieries Company Limited, Kothagudem, pp.30-45.

Lakshminarayana, G. (1996). Stratigraphy and structural framework of the Gondwana sediments in the Pranhita–Godavari valley, Andhra Pradesh. Gondwana IX. I. Oxford -IBH, New Delhi. ISBN: 81-204-1073-4, pp. 311–330.

Lakshminarayana, G. and Murti, K.S. (1990). Stratigraphy of the Gondwana formations in the Chintalapudi sub-basin, Godavari Valley, Andhra Pradesh. Jour. Geol. Soc. India, v.36(1), pp.13-25.

Lakshminarayana, G. (1995a). Gondwana sedimentation in the Chintalapudi sub-basin, Godavari valley, Andhra Pradesh. Jour. Geol. Soc. India, v.46, pp.375-383.

Lakshminarayana, G. (1995b). Stratigraphy and structural framework of the Gondwana sediments in the Pranhita- Godavari valley, A.P. Proceedings of IX Int. Gondwana Symp. Oxford IBH Publisher, New Delhi, v.1, pp.313-332.

Lakshminarayana, G. (1991). Stratigraphy sedimentation and economic potential of the Gondwana sediments in the Chintalapudi sub-basin, Godavari valley, Andhra Pradesh. Unpublished Ph.D thesis submitted to Nagarjuna University, pp.126.

Lakshminarayana, G. (2002). Sedimentary Facies and Stratigraphic Significance of Cumbum and Bairenkonda Type Sections of Nallamalai Fold Belt, Cuddapah Basin, Andhra Pradesh. Jour. Geol. Soc. India, v.59(2), pp.167-177.

Langford, F.F., and Blanc-Valleron, M.M. (1990). Interpreting Rock-Eval pyrolysis data using graphs of pyrolizable hydrocarbons vs. total organic carbon. AAPG Bull., v.74(6), pp.799-804.

Latif, K., Hanif, M., Shah, S.A. et al. (2021). Source rock potential assessment of the Paleocene coal and coaly shale in the Attock-Cherat Range of Pakistan. Jour. Petrol. Explor. Prod. Technol., v. 11, pp. 2299-2313. https://doi.org/10.1007/s13202-021-01172-8

Leythaeuser, D., Hageman, H.W., Hoblerbach, A. and Schaefer, R.G. (1980). Hydrocarbon generation in source beds as a function of type and maturation of their organic matter, a mass balance approach. *In*: Proceedings of the l0th World Petroleum Congress, Heyden.

Li, X., Zhuang, X.G., Zhou, J.B., Wang, H. and Ma, X.P. (2010). Coal facies analysis of thick coal seam of middle Jurassic Xishanyao Formation in the middle part of eastern Junggar coal field, Xinjiang. Geol. Sci. Tech., v.29(5), pp.84–88.

Ligouis, B., Lu, J. and Pils, J. (1998). Coal petrology and Rock-Eval pyrolysis of a coal seam in the Oligocene Molasse near Miesbach (Upper Bavaria, Germany): coal depositional environments. Bull. Soc. Geol. France, v. 169, pp. 381-393.

Mathews, R.P., Singh, B.D., Singh, V.P., Singh, A., Singh, H., Shivanna, M. and Chetia, R. (2020). Organo-petrographic and geochemical characteristics of Gurha lignite deposits, Rajasthan, India: Insights into the palaeovegetation, palaeoenvironment and hydrocarbon source rock potential. Geosci. Front., v.11(3), pp.965-988.

Mendonça Filho, J.G., Menezes, T.R. and Mendonça, J.O. (2011). Organic composition (palynofacies analysis). *In*: ICCP Training Course on Dispersed Organic Matter, pp.33–81.

Mendonça Filho, J.G., Menezes, T.R., Mendonça, J.O., Oliveira, A.D., Silva, T.F., Rondon, N.F. and Da Silva, F.S. (2012). Organic facies: palynofacies and organic geochemistry approaches. *In*: Panagiotaras, D. (*Ed.*), Geochemistry–Earth's System Processes, InTech, pp. 211–248.

Mukhopadhyay, P.K. (1986). Petrography of selected Wilcox and Jockson Group lignites from Tertiary of Texas. *In*: Finkelman, R.B. and Casagrada, D.J. (*Eds.*), Geology of Gulf Coast Lignites, Annual Meeting of Geological Society of America, Coal Geology Division Field Trip, pp.126-145.

Mukhopadhyay, P.K., Hatcher, P.G. and Calder, J.H. (1991). Hydrocarbon generation from deltaic and intermontane fluviodeltaic coal and coaly shale from the Tertiary of Texas and Carboniferous of Nova Scotia. Org. Geochem., v.17, pp. 765-783.

Mukhopadhyay, P.K. and Hatcher, P.G. (1993). Composition of coal. In: law BE, Rice DD (Eds.) Hydrocarbons in coal. Am. Assoc. Petrol. Geol. Stud. Geol., v.38, pp.79-118.

Peters, K.E. (1986). Guidelines for evaluating petroleum source rock using programmed pyrolysis. AAPG Bull., v.70(3), pp.318-329.

Peters, K.E., and Cassa, M.R. (1994). Applied source rock geochemistry: Chapter 5: Part II. Essential elements.

Phukan S, Hazarika S, Purohit, S. et al. (2013). Source rock potential and thermal maturity of coal deposits of the Langrin coalfield, West Khasi Hills, Meghalaya. South East Asian Jour. Sediment. Basin Res., v. 1, pp.45-49.

Raja Rao, C.S. (1982). Coalfields of India, Coal Resources of Tamilnadu, Andhra Pradesh, Orissa and Maharashtra. Geol. Surv. India, Bull. Series A, v. 45(2), pp.103.

Ramanamurty, B.V., Das, M., Michael, G.P., Kumaraguru, P. and Chaco, P.T. (1979). Report on regional assessment of coal deposits in parts of Chinnur area,Godavari valley coalfield, Adilabad district, A.P. Progress report, GSI.

Ramanamurty, B.V. (1985). A Gondwana sedimentation in Ramagundam-Manthani Area, Godavari Valley Basin. Jour. Geol. Soc. India, v.26 (1).

Ramanamurty, B.V., and Madhusudan, Rao (1987). A new classification of Lower Gondwana (Permian) Lithostratigraphy of Ramagundam Area, Godavari Valley Coalfield, A.P. Proc. Nat. Sem. Coal Resour. Ind, BHU, Varanasi, India. pp. 112-120.

Ramanamurthy, B.V., and Madhusudan, Rao, C. (1996). A new lithostratigraphy classification of Permian (Lower Gondwana) succession of Pranhita-Godavari basin with special reference to RamagundamCoalbelt, Andhra Pradesh, India. *In*: Gondwana nine proceedings of the IX Intern. Gondwana Symposium Hyderabad. New Delhi: Oxford and IBH Publishing Co., Pvt. Ltd, v.1, pp. 67-78.

Raju, P.R. (1986). Geology and hydrocarbon prospects of Pranhita-Godavari Graben. Jour. Assoc. Explor. Geophys., v.7(3), pp.131-146.

Salleh, Z., Awang Jamil S.A., Mohamed R.K., et al. (2008). Hydrocarbon generation potential of the coals and shales around the Eucalyptus Campsite area, Maliau Basin, Sabah. Bull. Geol. Soc. Malaysia, v.54, pp.147-158.

Sahoo, M. and Gogoi, K.D. (2011). Structural and sedimentary evolution of Upper Assam Basin, India and implications on hydrocarbon prospectivity. AAPG, 10315, pp.1-11.

Sarate, O.S. (2013). The deep-seated coal deposits of the Chintalapudi sub-basin, Godavari Valley coalfield, Andhra Pradesh, India and their petrographic significance. Jour. Palaeontol. Soc. India, v.58(2), pp.219-228.

Sarate, O.S. (2017). Petrography of coal seams from Belampalli coalfield, Godavari valley, Telangana state, India. Jour. Geosci. Res, v.2(1), pp.29-36.

Sarate, O.S. (2018). Petrographicappraisal of coal deposits from mallayyapalli area, mulugcoal belt, Godavari valley, Telangana state, india. Jour. Palaeontol. Soc. India, v.63(1), pp.127-136.

Senguler, I., Ayyildiz, T., Onal, Y. and Onal, M. (2008) Organic geochemical characterization and mineralogic properties of Mengen oil shale (Lutetian), Bolu-Turkey. Oil Shale, v.25, pp.359-375.

Sengupta, S. (1970). Gondwana sedimentation around Bheemaram (Bhimaram), Pranhita-Godavari valley, India. Jour. Sediment. Res., v. 40(1).

Shearer, J.C. and Clarkson, B.R., (1998). Whangamarino wetland: effects of lowered river levels on peat and vegetation. Internatl. Peat Jour., v. 8, pp. 52-65.

Sharma, A., Phukan S., Saikia B.K., et al. (2016). Geochemical evaluation of the hydrocarbon prospects of carbonaceous shale and coal of Barail Group, Upper Assam Basin. Internatl. Jour. Oil, Gas Coal Technol., v. 19, pp.263-282.

Sharma, S.K., Pal, M., Jha, B.K. and Venkatesh, V. (1987). Source rock potential for hydrocarbon generation in Barakar coals and carbonaceous shales. *In*: Proceedings of the National Seminar on Coal Research, India, pp.65-14.

Shearer, J.C., Staub J.R. and Moore, T.A. (1994). The Conundrum of Coal Bed Thickness: A Theory for Stacked Mire. Jour. Geol., v. 102(5), pp.611-617.

Singh, M.P., and Singh, P.K., (1996). Petrographic characterization and evolution of the Permian coal deposits of the Rajmahal basin, Bihar, India. Internatl. Jour. Coal Geol., v.29, pp.93-118.

Singh, P.K. (2012). Petrological and geochemical considerations to predict oil potential of Rajpardi and Vastan lignite deposits of Gujarat, Western India. Jour. Geol. Soc. India, v. 80(6), pp.759-770.

Singh, P.K., Singh, M.P., Prachiti, P.K., Kalpana, M.S., Manikyamba C., Lakshminarayana, G., Singh A.K. and Naik, A.S. (2012). Petrographic characteristics and carbon isotopic composition of Permian coal: Implications on depositional environment of Sattupalli Coalfield, Godavari Valley, India. Internatl. Jour. Coal Geol., v.90-91 pp.34-42.

Singh, P.K, Singh, M.P., Singh, A.K., et al. (2013). The prediction of the liquefaction behavior of the East Kalimantan Coals of Indonesia: An appraisal through petrography of selected coal samples. Energy Sourc., Part A, v. 35(18), pp.1728-1740.

Singh, P.K., Rajak, P.K., Singh, V.K., Singh, M.P., Naik, A.S., and Raju, S.V. (2016a). Studies on thermal maturity and hydrocarbon potential of lignites of Bikaner-Nagaur basin, Rajasthan. Energy Explor. Exploit., v.34(1), pp.140-157.

Singh, P.K., Singh, V.K., Rajak, P.K., Singh, M.P., Naik, A.S., Raju, S.V. and Mohanty, D. (2016b). Eocene lignites from Cambay basin, Western India: an excellent source of Hydrocarbon. Geosci. Front., v.7, pp.811-819.

Singh, P.K., Singh, V.K., Singh, M.P. and Rajak, P.K. (2017a). Paleomires of eocenelignites of Bhavnagar, Saurashtra basin (Gujarat), western India: petrographic implications. Jour. Geol. Soc. India, v.90, pp.9-19.

Singh, P.K., Singh, V.K., Rajak, P.K., and Mathur, N. (2017b). A study on assessment of hydrocarbon potential of the lignite deposits of Saurashtra basin, Gujarat (Western India). Internatl. Jour. Coal Sci. Technol., v.4(4), pp.310-321.

Singh, V.P., Singh, B.D., Mathews, R.P., Singh, A., Mendhe, V.A., Singh, P.K., Mishra, S., Dutta, S., Mahesh Shivanna M. and Singh, M.P. (2017b). Investigation on the lignite deposits of Surkha mine (Saurashtra Basin, Gujarat), western India: their depositional history and hydrocarbon generation potential. Internatl. Jour. Coal Geol., v.183, pp.78-99.

Singh, V.P., Singh, B.D., Singh, A., Singh, M.P., Mathews, R.P., Dutta, S., Mendhe, V.A., Mahesh, S., Mishra, S., (2017c). Depositional palaeoenvironment and economic potential of Khadsaliya lignite deposits (Saurashtra Basin), western India: based on petrographic, palynofacies and geochemical characteristics. Internatl. Jour. Coal Geol., v.171, pp.223-242.

Singh, V. P., Singh, B. D., Mathews, R. P., Singh, A., Mendhe, V.A., Mishra, S., Banerjee, M. (2022). Paleodepositional and Hydrocarbon Source-Rock Characteristics of the Sonari Succession (Paleocene), Barmer Basin, NW India: Implications from Petrography and Geochemistry. Natur. Resour. Res., v. 31(5), pp.2943-2971.

Singh, A.K. and Kumar, A. (2020). Assessment of thermal maturity, source rock potential and paleodepositional environment of the paleogenelignites in Barsingsar, Bikaner–Nagaur Basin, Western Rajasthan, India. Natural Resources Research, 29, 1283-1305.

Srinivasa Rao, T. (1987). The Pakhal Basin-a perspective on the Purana Basins of Peninsular India. Geol. Soc. India. Mem., v. 6, pp.161-187.

Srivastava, S.C. and Jha, N. (1988). A Lower Triassic palynoassemblages from Budharam area, Godavari Graben, Andhra Pradesh, India. Geophytology, v.18, pp.124-125.

Srivastava, Suresh C., and Jha, Neerja (1990). Permian-Triassic palynofloral transition in Godavari Graben, Andhra Pradesh. The Palaeobotanist, v. 38, pp.92-97.

Stach, E., Mackowsky, M. Th., Taylor, G.H., Chandra, D. and Teichmuller, R. (1982). Stach's Textbook of Coal Petrology, Gebrder Borntraeger, Berlin, 2nd Ed.

Sutcu, E. and Karayigit, A.I. (2009). Depositional environment and coal petrology of Afsin-Elbistan coals, Turkey. Geolines, v. 22, pp.73-86.

Teichmuller, M. (1974). Generation of petroleum like substance in coal seams as seen under the microscope. *In*: Tissot, B. and Bienner, F. (*Ed.*). Advanc. Org. Geochem. Techniq. Paris, pp.321-348.

Teichmüller, M., (1987). Organic material and very low grade metamorphism. *In*: Frey, M. (*Ed.*), Low Temperature Metamorphism. Blackie, Glasgow, pp. 114-161.

Tewari, R.C. (2017). Stratigraphic Simulation of Late Paleozoic Coal Bearing Cycles in Gondwana Basins of Eastern India using Continuous Time Markov Model. Jour. Geosci., v.2(1), pp.1-8.

Thompson, C.L. and Dimbicki, H. Jr. (1986). Optical characterization of kerogen and the hydrocarbon-generating potential of source rocks. Internatl. Jour. Coal Geol., v. 6, pp. 229-249.

Thompson Rizer, C.L. (1993). Optical description of amorphous kerogen in both thin sections and isolated kerogen preparations of Precambrian to Eocene shale samples. Precamb. Res., v.61, pp.181-190.

Thompson, S., Morley, R.J., Barnard, P.C. and Cooper, B.S. (1985). Facies recognition of some Tertiary coals applied to prediction of oil source rock occurrence. Mar. Petrol. Geol., v.2, pp.288-297.

Tissot, B.P. (1984). Recent advances in petroleum geochemistry applied to hydrocarbon exploration. Am. Assoc. Petrol. Geolog. Bull., v. 68, pp. 545-563.

Tissot, B.P. and Welte, D.H. (1978). Petroleum formation and occurrence. Springer, Verlag, Berlin, pp.81-91.Tissot, B.P. and Welte, D.H. (1984). Petroleum formation and occurrence. 2nd Editon, Berlin, Springer, 699p.

Tyson, R.V., (1995). Sedimentary Organic Matter; Organic Facies and Palynofacies. Chapman and Hall, London, 615p.

Van Krevelen, D.W. (1961). Coal: Typology - Chemistry - Physics - Constitution. Elsevier, The Netherlands, 1st edition.

Vandenbroucke, M. and Largeau C. (2007). Kerogen origin, evolution and structure. Org. Geochem., v.38, pp.719-833.

Waples, D.W. (1994). Maturity modelling: Thermal indicators, hydrocarbon generation, and oil cracking. Am. Assoc. Petrol. Geolog. Bull., v. 60, pp.285-306.

Wilkins, R.W. and George, S.C. (2002). Coal as a source rock for oil: a review. Internatl. Jour. Coal Geol., v. 50(1-4), pp.317-361. doi: 10.1016/s0166-5162(02)00134-9.