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Source Rock Characterization for Hydrocarbon Generative Potential and Thermal Maturity of Sutunga Coals, (East Jaintia Hill) Meghalaya, India: Petrographic and Geochemical Approach

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ABSTRACT

The study presents hydrocarbon generative potential and thermal maturity of the Paleogene coals from Sutunga, Meghalaya, India using petro-geochemical method. The petrographic examination showed that the analyzed samples contain abundant vitrinite group macerals (mean 71.8%) with a significant amount of the liptinite (17.4%) group maceral, while the concentration of inertinite group is less (3.1%). Vitrinite reflectance (0.38 to 0.69 %Ro_m), indicates that the rank of Sutunga coals as sub-bituminous 'B' to high volatile bituminous 'C'. The results obtained from rock-eval pyrolysis show that the hydrogen index (HI) ranges from 245 to 348 mg HC/g TOC and temperature at S_2 peak (T_{max}) is 412 to 441 ^{0}C. These coals contain Type III and Type II/III kerogen and are immature in nature. The total organic carbon (TOC) and S_2 yield of Sutunga coals vary from 27.5–93.3 wt%, and 86.0–300.1 mg HC/g rock respectively indicating its high potential for hydrocarbon.

INTRODUCTION

For last few decades coal and organic matter in sediments are being targeted for oil and gas (Kumar et al., 2020; Singh and Kumar, 2020; Singh et al., 2020; Pandey et al., 2018; Singh et al., 2013a; Singh, 2012; Wilkins and George, 2002; Singh and Singh, 1994a & b). Identification of organic components and study of their petro-geochemical properties provide information about their source characteristics (Pandey et al., 2018; Isabel, 2012). Petrographically, liptinite and vitrinite group macerals have main organic constituents that characterize the generation of liquid and lighter hydrocarbons (Singh and Kumar, 2017a; Singh et al., 2017; Singh et al., 2016a, b, & c). In addition, petrographic observation coupled with rock-eval pyrolysis data has been used for evaluation of thermal maturity of organic matter, rank, kerogen type and their hydrocarbon generation potential (Singh and Kumar, 2020; Singh and Kumar, 2018a; Singh et al., 2016a, b, & c; Hakimi et al., 2013;).

Generally, Palaeozoic coals have been considered as source rock for gas-prone hydrocarbon, whereas Cenozoic coals have potential to generate liquid hydrocarbons (Takahashi et al., 2020). In India, coals reserves occur in two stratigraphic horizons namely, Gondwana coals of Permian age (Palaeozoic) and Tertiary coal of Paleogene age (Cenozoic). About 99% coal production comes from Gondwana, whereas Paleogene coals contribute the remaining part (Indian Bureau of Mines, 2018). Cenozoic coals of India have received attention because of their high hydrocarbon potential than Palaeozoic coals (Petersen, 2005; Singh et al., 2016b). In North-Eastern region of India, Paleogene coal deposits occurs in states of Assam, Meghalaya, Arunachala Pradesh and Nagaland (Singh et al., 2013b; Mishra and Ghosh, 1996). Petro-chemical characteristics of coal deposits of North-Eastern region have been studied by several researchers for source rock characterization (Singh et al., 2013b; Singh et al., 2012; Singh and Singh, 2002; Mishra and Ghosh, 1996; Mishra, 1992). Whereas, the coals of Sutunga area got very limited attention which, as expected has not been evaluated specially as source rock for hydrocarbon generation.

In, the present study, petrographic analysis, Rock-Eval pyrolysis, proximate and ultimate analysis was performed to investigate the maturity of Sutunga samples and their hydrocarbon generation potential.

METHOD OF STUDY

Channel samples were collected from all exposed coal seams from the Sutunga. Coal samples possessing similar characters were clubbed together to make a 13 composite samples for petrographic and geochemical analyses. The samples were crushed to - 1 mm size for petrographic analysis and - 200 µm size for geochemical analysis.

The petrographic analysis was done following the methods described by ICCP (International Committee for Coal and Organic Petrology, 1975, 1998, 2001), and Taylor et al. (1998). For the precise identification of different macerals and mineral matter, the petrographic analysis was done using both normal incident white light as well as fluorescence light. The random vitrinite reflectance measurement was carried out as per the International Organization for Standardization (ISO 7404-5, 2009).

Proximate analysis of the samples was performed according to Bureau of Indian standard (BIS, 2003) to determine moisture, volatile matter and ash yield. The ultimate analysis was carried out as per ASTM D5373-08 (2008) to determine elemental compositions (C, H, N, S, O). Rock-Eval Pyrolysis was performed on 13 samples in order to determine maturity of organic matter and hydrocarbon source rock potential using Vinci Rock-Eval 6 pyrolizer following procedure described in Singh and Kumar (2018b). TOC (total organic carbon content) S_1 (free hydrocarbon), S_2 (remaining hydrocarbon), S_3 (amount of CO_2 produced during), T_{max} (the temperature at which the maximum release of hydrocarbons) were determined through pyrolysis. Further, hydrogen index ($HI = S_2 \times 100/TOC$), oxygen index ($OI=S_3\times100/TOC$), genetic potential ($GP=S_{1+}S_2$), production index ($PI=S_{1/}S_1+S_2$) were calculated from pyrolysis data.

RESULT AND DISCUSSION

Microscopic Constituents

Microscopically, coal of the Sutunga area contains macerals of all the groups, vitrinite, liptinite and inertinite. Vitrinite (61.3–79.9% with

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mean 71.8 %) is the dominant maceral group followed by liptinite (11.2–23.7% with mean 17.4%) and inertinite (1.2–5.3% with mean 3.1%) groups. Visible mineral matter ranges from 5.3–11.5% with mean 7.8%). The quantitative distribution of macerals with mineral matter (in vol%) and mean vitrinite reflectance $\%R_{om}$ of Sutunga samples is given in Table 1.

Proximate Analysis

Proximate analysis determines the weight percent of moisture, ash yield, volatile matter, and fixed carbon present in coals. From the utilization point of view, a high-quality coal should have a high amount of fixed carbon, a sufficient amount of volatile matter, but less amount of ash yield. The results obtained from proximate analysis reflects rank and grade. It is observed that, moisture content in Sutunga coals is low and varies from 2.1–5.7% with mean value 3.7% whereas, the concentration of ash ranges from 2.2–6.3%, mean 4.6% (Table 2). Volatile matter and fixed carbon vary between 40.1 and 46.1% with mean 42.7%, and 45.3 and 54.2% with mean 48.9% respectively. On the other hand, volatile matter varies between 42.8 and 49.9%, mean 46.6% while fixed carbon ranges from 49.6–57.2%, mean 53.4% (on dry ash free basis) (Table 2).

Ultimate Analysis

The elemental analysis gives the information about the elemental composition (carbon, hydrogen, nitrogen, sulphur, and oxygen) in weight percent. In Sutunga coals, carbon varies from 64.6–80.4 wt%, mean 73.7 wt% (d.a.f); hydrogen lies in between 3.2 and 5.8 wt%, mean 4.8 wt% (d.a.f); nitrogen between 0.2 and 1.0 wt%, mean 0.7 wt% (d.a.f); sulphur between 4.8 and 6.9 wt%, mean 5.9 wt% (d.a.f), and oxygen between 8.1 to 26.1 wt%, mean 14.9 wt% (d.a.f) (Table 4). H/C and O/C ratio in the study ranges from 0.57–0.98, mean 0.78 and 0.08–0.30, mean 0.16 respectively (Table 3).

Rock-Eval

The rock-eval result shows that the yield S_1, S_2, and S_3 ranges from 4.5–28.3 mg HC/g, 86.0–300.1 mg HC/g and 0.4–2.8 mg HC/g respectively. The wt% of TOC is ranging from 27.5–93.3. HI and OI calculated from the rock-eval data ranges from 245–348 mg HC/g TOC and 0–4 mg CO_2/g TOC respectively. On the other hand, T_{max} value ranges from 412–441 °C with calculated PI and GP values from 0.0–0.1 and 90.1–315.2 respectively (Table 4).

Table 1. Frequency distribution of maceral and mineral matter composition (in volume percent) under white incident light and blue irradiation with reflectance in coals of Sutunga coalfield, Meghalaya, North-East India

			Vitrinite (Vol. %)							Liptinite (Vol. %)			Inertinite(Vol. %)				Mineral Matter (Vol. %)				Reflectance
S. No.	Coalfield	Seam	Te	Co	Ge	Ca	Cd	Vd	Vt	Sp	Re	Lt	Se	Fu	Sc	It	Su	Cb	Ar	Mt	$\%R_{om}$
1			0.0	62.3	1.1	0.1	2.3	1.0	66.8	15.2	5.7	23.7	3.2	1.0	0.0	4.2	3.7	0.8	0.8	5.3	0.38
2			0.1	68.9	0.1	1.8	1.0	1.1	73	11.1	2.1	15.5	4.2	0.3	0.8	5.3	4.2	1.1	0.9	6.2	0.41
3	Sutunga	Top	0.3	66.6	1.1	0.7	0.5	1.0	70.2	13.7	5.1	20.2	1.1	0.7	0.6	2.4	5.2	0.3	2.0	7.5	0.45
4	Coalfield	Seam	0.7	74.5	0.0	0.5	0.2	0.7	76.6	6.9	5.5	13.1	0.7	0.2	0.3	1.2	6.6	0.5	2.0	9.1	0.51
5			0.5	63	0.5	1.6	0.1	0.2	65.9	12.9	5.3	20.1	1.7	0.1	0.7	2.5	7.4	2.9	1.2	11.5	0.62
6			0.0	66.4	0.0	1.0	1.7	0.6	69.7	10.1	5.2	17.2	3.1	0.2	1.1	4.4	4.4	3.4	0.9	8.7	0.63
7			0.4	58.3	2.1	0.2	0.1	0.2	61.3	17.5	5.5	23.1	3.5	0.1	0.7	4.3	8.1	2.1	1.1	11.3	0.65
8			0.3	69.0	0.0	0.1	2.1	0.5	72.0	11.9	6.2	18.2	1.7	0.2	1.0	2.9	4.5	2.2	0.2	6.9	0.62
9			0.8	68.4	0.0	1.3	1.0	0.2	71.7	13.5	5.5	19.0	0.7	0.8	0.5	2.0	3.3	2.7	1.3	7.3	0.58
10	Sutunga	Bottom	0.6	79.2	0.0	0.0	0.5	0.1	79.9	6.7	2.1	11.2	0.9	0.7	0.1	1.7	5.5	1.1	0.6	7.2	0.57
11	Coalfield	Seam	0.2	72.6	0.0	0.4	1.5	0.5	75.2	8.8	2.2	13.7	1.8	0.2	0.6	2.6	6.2	1.5	0.8	8.5	0.69
12			0.0	73.2	1.3	2.7	0.2	1.0	76.2	12.1	2.3	14.5	2.7	1.1	0.1	3.9	3.8	0.9	0.7	5.4	0.61
13			0.2	71.3	1.5	1.2	0.1	0.2	74.5	13.8	2.9	16.7	1.9	0.5	0.4	2.8	4.2	0.6	1.2	6.0	0.57
		Mean	**0.3**	**68.7**	**0.6**	**0.9**	**0.8**	**0.6**	**71.8**	**11.9**	**4.3**	**17.4**	**2.1**	**0.5**	**0.5**	**3.1**	**5.2**	**1.5**	**1.1**	**7.8**	**0.6**

Te-Tellinite; Co-Collotelinite; Ge-Gelinite; Ca-Corpohuminite; Cd-Collodetrinite; Vd-Vitrodetrinite; Vt-Total Vitrinite; Sp- Sporinite; Re-Resinite; Lt-Total Liptinite; Se-Semifusinite; Fu-Fusinite; Sc-Sclerotinite; It- Total Inertinite; Su-Sulphide; Cb-Carbonate; Ar-Argillaceous; Mt- Total Mineral Matter; $\%R_{om}$-Mean reflectance value

Table 2. Result of proximate analysis (Dry Basis) of coals of Sutunga coalfield, Meghalaya, North-East India

				Proximate constituents (Ar)					Dry basis			DAF basis		
S. N.	Coalfield	Coal seam	Sample No.	Moisture	Ash	Volatile matter	Fixed Carbon	Total	Ash	Volatile matter	Fixed Carbon	Volatile matter	Fixed Carbon	Total
1			1	2.1	3.2	40.5	54.2	100	3.3	41.4	55.4	42.8	57.2	100
2			2	3.2	5.1	42.3	49.4	100	5.3	43.7	51.0	46.1	53.9	100
3	Sutunga	Top	3	4.1	5.5	45.1	45.3	100	5.7	47.0	47.2	49.9	50.1	100
4	Coalfield	Seam	4	2.7	6.1	40.9	50.3	100	6.3	42.0	51.7	44.8	55.1	100
5			5	4.9	3.9	41.1	50.1	100	4.1	43.2	52.7	45.1	54.9	100
6			6	5.2	5.8	40.1	48.9	100	6.1	42.3	51.6	45.1	54.9	100
7			7	2.2	6.3	46.1	45.4	100	6.4	47.1	46.4	50.4	49.6	100
8			8	2.5	5.9	40.3	51.3	100	6.0	41.3	52.6	44.0	56.0	100
9			9	5.3	2.7	45.8	46.2	100	2.8	48.4	48.8	49.8	50.2	100
10	Sutunga	Bottom	10	4.8	2.2	44.6	48.4	100	2.3	46.8	50.8	47.9	52.0	100
11	Coalfield	Seam	11	3.7	5.3	43.2	47.8	100	5.5	44.9	49.6	47.5	52.3	100
12			12	2.8	4.9	44.9	47.4	100	5.0	46.2	48.8	48.6	51.3	100
13			13	5.7	2.7	40.1	51.5	100	2.9	42.5	54.6	43.8	56.2	100
			Mean	**3.8**	**4.6**	**42.7**	**48.9**	**100**	**4.8**	**44.4**	**50.9**	**46.6**	**53.4**	**100**

Ar= as received basis; Dr= Dry basis; DAF= Dry ash free basis;

Rank

Vitrinite reflectance is an important parameter for rank determination of organic matter. The volatile matter is also considered as a parameter for determination of rank of coals when used with vitrinite reflectance (Singh and Kumar, 2017b). The mean vitrinite reflectance of Sutunga coals varies from 0.38 to 0.69 %Ro_m (Table 1), indicating the rank of Sutunga coals as sub-bituminous 'B' to high volatile bituminous 'C' as per North American ASTM classification (ASTM D388-15, 2015). The average volatile matter and fixed carbon values are 46.6% and 53.4% respectively (Table 2). According to ASTM standard D388-12 (2012), Sutunga coals are classified as sub-bituminous 'B' to high volatile bituminous 'C'. The plot of reflectance data and volatile matter (d.a.f.) supports the about contention (Fig. 1a). Van Krevelen's coalification plot between atomic ratios H/C and O/C indicate a similar result (Fig. 1b).

Characterization of Organic Matter

Petrographic results reveal that vitrinite is the dominating maceral group and mainly contributed by collotelinite (Table 1). A significant content of liptinite is recorded in the coals while concentration of inertinite and mineral matter is low in comparison to other two maceral groups. The concentration of macerals has been used to define the source rock characteristics (Singh et al., 2013a; Taylor et al., 1998). According to Tissot and Welte (1984) and Taylor et al. (1998), the abundance of vitrinite, liptinite, and inertinite macerals gives the signature that source rock can be gas prone, oil/gas-prone, and inert respectively. In the study area, the high abundance of vitrinite maceral and a significant amount of liptinite maceral indicate that they are gas prone with mixed hydrocarbon (oil/gas prone) signature. The ternary plot, based on petrographic data proposed by Cornford (1979), indicates that these coals are formed of Type III kerogen and have generated gas and mixed hydrocarbon (Fig. 2a and b).

Hydrogen index (HI) can be used as a reliable parameter for the determination of kerogen present in the source rock (Tissot and Welte, 1984). The HI values more than 600 HC/g TOC indicate oil-prone kerogen type I (Bordenave, 1993) while the HI values between 300-600 HC/g TOC, 200-300 HC/g TOC, and 50-200 HC/g TOC indicate the presence of oil-prone type II kerogen, oil/gas-prone type II/III kerogen, and gas prone type III respectively (Tissot and Welte, 1984). The HI value ranges from 245-348 mg HC/g TOC (Table 4) and indicate type III kerogen (gas prone) and type II/III kerogen (oi/gas prone). The plot of HI with T_{max} and %R_{om} also indicates type II/III kerogen and presence of type III kerogen (Fig. 3a and b).

The elemental analysis gives the atomic ratios H/C (0.57-0.96, mean 0.78) and O/C (0.08-0.30, mean 0.16) for the Sutunga coals.

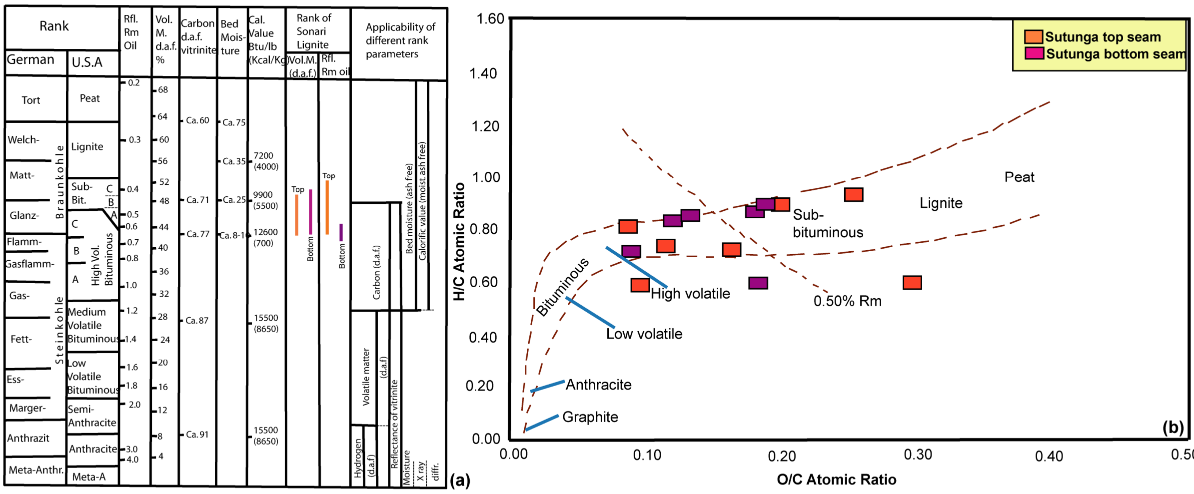

Fig.1. (a) Rank diagram based on reflectance and volatile matter content according to German (DIN) and North American (ASTM) classification, **(b)** the plot between atomic ratio H/C vs O/C showing rank of Sutunga coals

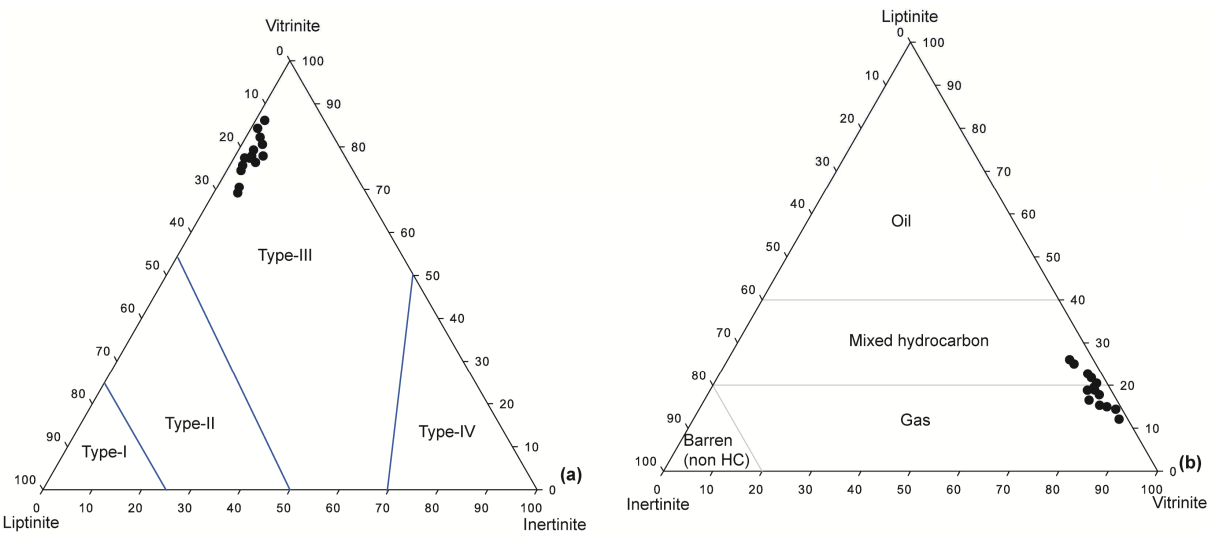

Fig.2. (a) Ternary plot of classification of kerogen type based on macerals (modified after Cornford 1979), **(b)** ternary diagram based on maceral composition indicating the hydrocarbon potential (after Tissot and Welte, 1984)

Table 3. Result of ultimate analysis of coals of Sutunga coalfield, Meghalaya, North-East India

			DRY BASIS					DRY ASH FREE BASIS					Atomic ratio	
S.N	Coalfield	Coal Seam	C%	H%	S%	N%	O%	C%	H%	S%	N%	O%	H/C	O/C
1	Sutunga	Top	62.5	3.1	4.9	0.9	25.2	64.6	3.2	5.1	0.9	26.1	0.60	0.30
2	Coalfield	Seam	66.2	4.9	5.4	0.8	17.4	69.9	5.2	5.7	0.9	18.4	0.89	0.20
3			73.0	4.4	5.9	0.4	10.5	77.4	4.7	6.3	0.4	11.1	0.73	0.11
4			75.3	3.6	4.5	0.5	9.8	80.4	3.8	4.8	0.5	10.4	0.57	0.10
5			65.3	5.2	5.8	0.6	19.0	68.1	5.4	6.0	0.6	19.8	0.96	0.22
6			69.1	3.9	5.6	0.7	14.9	73.6	4.2	5.5	0.8	15.9	0.68	0.16
7	Sutunga	Bottom	72.8	5.6	6.4	0.8	7.9	77.8	5.9	6.9	0.9	8.5	0.92	0.08
8	Coalfield	Seam	72.3	5.0	5.5	0.6	10.4	77.0	5.4	5.9	0.6	11.1	0.84	0.11
9			77.3	4.4	6.8	0.7	7.9	79.6	4.5	6.9	0.8	8.1	0.69	0.08
10			69.2	5.6	6.2	0.2	16.4	70.9	5.8	6.3	0.2	16.8	0.98	0.18
11			68.7	3.4	4.9	0.9	16.4	72.7	3.6	5.3	1.0	17.4	0.60	0.18
12			67.0	4.7	5.2	0.8	17.2	70.5	5.0	5.5	0.9	18.1	0.85	0.19
13			73.4	5.3	6.0	0.7	11.7	75.5	5.4	6.2	0.8	12.0	0.86	0.12
		Mean	70.2	4.6	5.6	0.7	14.2	73.7	4.8	6.0	0.7	14.9	0.78	0.16

C= Carbon; H= Hydrogen; N= Nitrogen; S= Sulphur; O= Oxygen

Table 4. Result of Rock-Eval pyrolysis of coals of Sutunga coalfield, Meghalaya, North-East India

S. No.	Coalfield	Coal seam	T_m (°C)	S_1(mg HC/g rock)	S_2(mg HC/g rock)	S_3 (mg HC/g)	PI	S_2/S_3 (mg/g)	TOC (Wt. %)	HI mg HC/(g TOC)	OI (mg CO_2/g TOC)	GP (mg/g)
1			415.0	4.5	86.0	0.4	0.0	204.7	28.8	265.0	0.0	90.1
2			425.0	5.9	79.3	0.5	0.0	158.5	27.5	245.0	0.0	100.1
3			441.0	7.5	89.3	0.4	0.0	217.7	29.3	250.0	0.0	102.4
4	Sutunga	Top	420.0	8.9	100.1	0.4	0.0	263.3	30.5	257.0	0.0	115.5
5	Coalfield	Seam	421.0	11.5	98.4	0.4	0.0	265.9	29.5	260.0	0.0	111.5
6			440.0	12.3	85.4	0.4	0.1	194.1	30.1	261.0	0.0	116.3
7			439.0	22.9	300.1	2.8	0.1	106.8	93.3	342.0	4.0	315.2
8	`		414.0	27.2	295.8	2.7	0.1	107.9	74.7	345.0	3.0	285.1
9			425.0	28.3	299.1	2.6	0.1	115.5	75.5	348.0	2.0	290.9
10	Sutunga	Bottom	430.0	21.5	288.3	2.3	0.1	124.8	60.3	347.0	2.0	289.3
11	Coalfield	Seam	429.0	18.7	245.7	2.8	0.1	88.1	69.7	340.0	4.1	254.6
12			412.0	18.3	278.3	2.2	0.1	126.5	79.5	348.0	4.1	270.1
13			437.0	19.5	268.7	2.4	0.1	114.3	80.3	339.0	3.5	311.2
		Mean	426.8	15.9	193.4	1.6	0.1	160.6	54.5	303.6	1.8	204.0

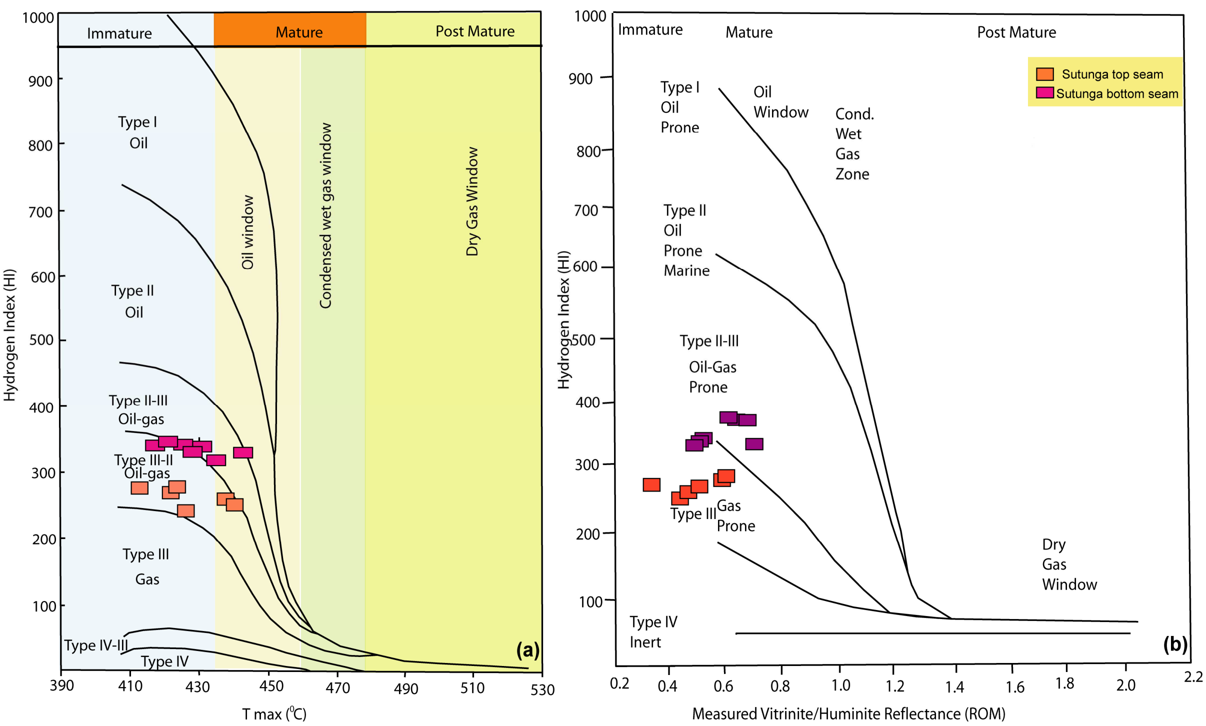

Fig.3. (a) Plots of classification of kerogen type and maturity based on Rock Eval-pyrolysis **(a)** HI vs. T_{max} data and **(b)** HI vs. $\%R_{om}$ (mean vitrinite reflectance)

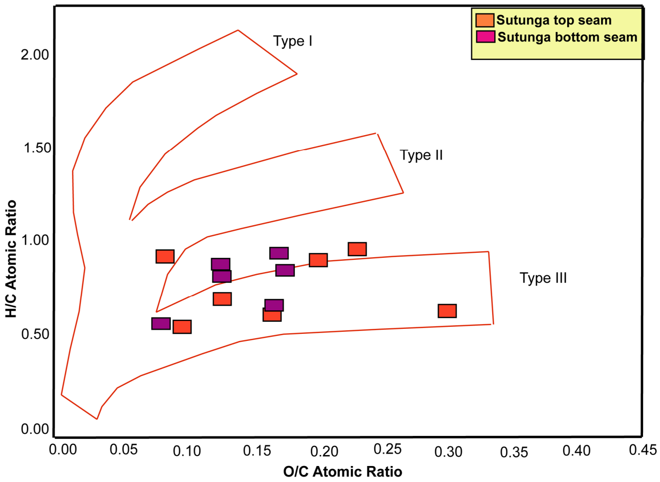

Fig.4. Plots of main kerogen type of the analysed coal samples, atomic H/C vs. O/C plot showing a kerogen type

The atomic ratio H/C can be used as an important aspect regarding source rock evaluation (Waples, 1985). These values indicate that coals of study area mainly contain oil/gas prone mixed kerogen with gas-prone type III kerogen (Fig. 4).

Thermal Maturity

For the assessment of generative potential of dispersed organic matter (coal), it is required to know their maturity (Waples, 1985). Vitrinite reflectance is used to know the maturity of source rock in the previous study and it is mainly dependent on the concentration of carbon and hydrogen in the sample (George et al., 1994). Based of reflectance value, the maturity has four stages starting from immature (less than 0.8 $\%R_{om}$), early gas (0.8-1.2 $\%R_{om}$), peak gas (1.2-2.0 $\%R_{om}$), and late gas (more than 2.0 $\%R_{om}$) (Petersen and Nytoft, 2006). The values of mean vitrinite reflectance varies from 0.38 to 0.69 $\%R_{om}$, indicating an immature to early mature stage (Fig. 3b). The T_{max} and PI are another reliable parameter for the maturity (Peters, 1986) though unreliable when the hydrocarbon yield (S_2) is below 0.2 mg HC/g rock. The values of T_{max} and PI varies from 412 to 441 °C with mean 426 °C and 0.0 to 0.1 with mean 0.1 (Table 4) indicating that the organic matter is immature to early mature in nature (Peters, 1986; Peters and Cassa, 1994). In addition, the plot of HI with T_{max} (Mukhopadhyay et al., 1995) and % R_{om}, also supports that these coals are thermally immature to early mature in nature (Fig. 3a and b).

Source Rock Potential

The potential of source rock for hydrocarbon generation of Sutunga coal was determined using parameters, TOC and S_2 yield. These are the widely used parameters for evaluation of source rock generative potential (Bordenave et al., 1993). The TOC and S_2 vary from 27.5-93.3 wt% and 79.3-300.1 mg HC/g rock respectively (Table 4). According to Peters (1986), TOC value more than four, indicates excellent source rock for hydrocarbon generation. The high values of S_2 indicate good source rock for hydrocarbon generation (Peters and Cassa, 1994). This contention is further supported by the genetic potential data which varies from 90.1-315.2 mg HC/g rock. HI value is high and ranges from 245-348 mg HC/g TOC. For the further classification, the cross plot of HI vs TOC and S_2 vs TOC was used (Fig. 5). These plots indicate source rock is gas prone (Fig. 5a) and display excellent hydrocarbon potential (Fig. 5b). In addition, the genetic potential (GP) is used for the source rock quality (Peters and Cassa, 1994; Tissot and Welte, 1984). The GP of the Sutunga coal samples ranges from 90.1 to 315.2 mg HC/g rock, indicating that these coals have potential for the hydrocarbon generation (Peters and Cassa, 1994).

CONCLUSIONS

The Paleogene coals of Sutunga from Meghalaya are mainly composed of vitrinite macerals with significant amount of liptinite macerals. These coals contain mainly type III gas prone kerogen with a little of mixed kerogen (type II/III) which are oil/gas prone. The plot of hydrogen index with T_{max} and mean vitrinite reflectance and ultimate plot (H/C *vs.* O/C) also indicates the presence of type II/III and type III kerogen. These plots also indicate that the source rock is thermally immature to early mature in nature. TOC and S_2 data indicate that Sutunga coals are excellent source rock for hydrocarbon generation. This contention is further supported by the genetic potential (GP) data.

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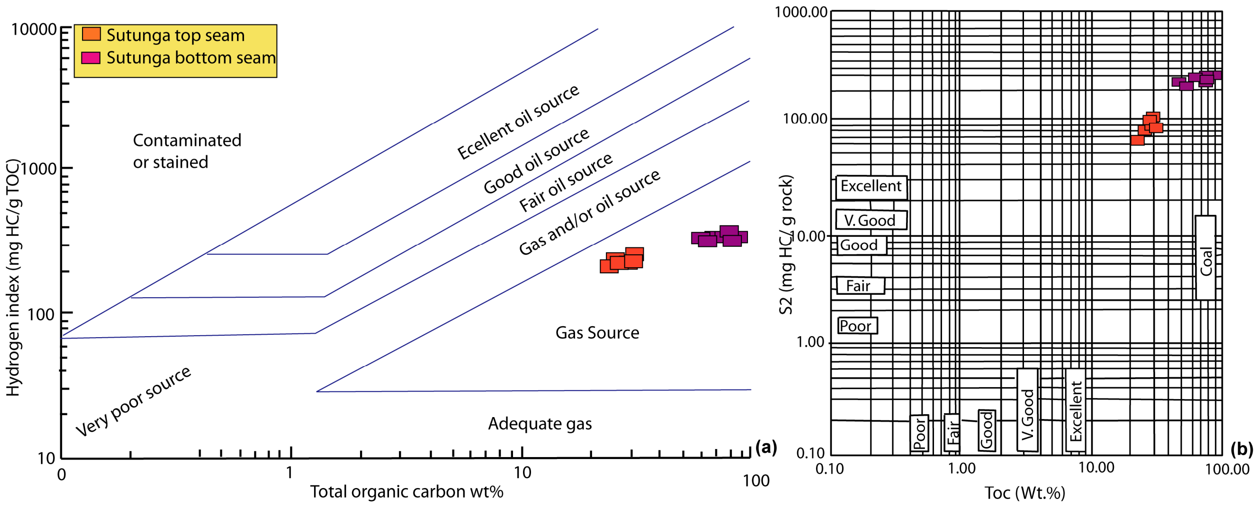

Fig.5. Source rock assessment of the examined samples from the Sutunga based on: **(a)** HI vs. TOC and, **(b)** cross-plot of S_2 vs. TOC.

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