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RESEARCH

Hydrocarbon generative potential and thermal maturity of newly discovered coal seams from Bapung Coalfield, Meghalaya, India: Rock-Eval pyrolysis and organic petrographic analysis

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Abstract
The present study systematically investigates a newly discovered coal seam in Bapung Coalfield, Meghalaya, on eighteen samples to determine the origin of organic matter, thermal maturity, hydrocarbon richness, and petroleum generation potential(GP). The data obtained from the geochemical study show that the samples contain a significant quantity of organic matter, and free hydrocarbon value suggests excellent source rock potential. Similarly, the hydrocarbon richness value ranges from 68.10 to 588.63, demonstrating an emphatic possibility for oil and gas generation in all studied samples. T_{max} and Ro% data of studied sediments indicate that most of the analysed samples are thermally immature, and some of them attain maturity (oil window) for petroleum generation but is not able to produce hydrocarbon at the commercial level. The pseudo Van Krevelen (HI Vs OI) and TOC Vs released hydrocarbon yield diagrams show that organic matter is mainly Type II and II–III kerogens, thus can be contemplated as a fair oil source and gas/oil source rock. Excellent positive correlations were found between oil yield ($R^2=0.99$) and vitrinite ($R^2=0.98$) with conversion (%), signifying its suitability for liquid hydrocarbon generation in future. Overall the results indicate that the formation (source rock) can generate hydrocarbon and may produce oil and gas through gasification and liquefaction.

Keywords Bapung Coalfield · Coal · Rock-Eval pyrolysis · Northeast India · Geochemical analysis

1 Introduction

The last few decades have witnessed hydrocarbon exploration and exploitation activity in many basins worldwide (Islam, 2014; Ma & Holditch, 2015; Thakur et al., et al. 2020). India is also paying close attention to the utilization and exploration of hydrocarbon resources available in Indian coalfields. In addition, several scientific studies and R & D activity have also been conducted in various coalfields to assess the hydrocarbon generation potential (Ghosh et al., et al. 2022; Gogoi et al., et al. 2008; Kala et al., et al. 2022; Kumar et al., et al. 2017). The Government of India (GOI) wants to unlock the hidden potential of various coalfields by supporting the government's policy of self-sufficiency in energy, which has led to the creation of several state-owned oil and gas companies, such as Oil and Natural Gas Corporation (ONGC), Oil India Limited (OIL), and GAIL (India) Limited (Geological Survey of India, 2017; Singh et al., et al. 2018). As a result, many oil and gas fields have been discovered in various parts of the country, including Mumbai High, Cambay, Krishna–Godavari Basin, and the Barmer Basin (Banik et al., et al. 2021; Boruah et al., et al. 2022; Singh et al., et al. 2021). Rock-Eval pyrolysis is a prominent modality for the assessment of the source rock to determine the organic matter type, composition, nature, organic richness and thermal maturity of petroleum generation potential organic matter type and thermal maturity of any source rock (Kumar et al., et al. 2015; Nath et al., et al.

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2023; Ojha et al., et al. 2011; Panwar et al., et al. 2022). Previously many studies conclude that if a sufficient amount of hydrogen is present, there is a strong possibility of liquid and gaseous hydrocarbon generation in source rock (Dembicki Jr, 2009; Nath et al., et al. 2022, 2023; Panwar et al., et al. 2021a, 2021b).

Originally it was thought that coal could not generate viable oil pools commercially. Still, subsequent research and the demand for increasing hydrocarbon consumption showed that coal has the potential to generate and expel significant oil (Ahmed et al., 2009; Durand & Paratte, 1983; Hedberg, 1968; Hunt, 1991; Shah, 2021; Shah & Abdullah, 2017; Welte & Tissot, 1984; Wilkins & George, 2002). As per observation found by Hunt (1991), the stipulations for producing and expelling oil and gas are that: The coals must have a H/C ratio of more than 0.9, hydrogen indices of more than 200 mg HC/g TOC by Rock-Eval pyrolysis and liptinite more than 15%. According to Wilkin and George (Wilkins & George, 2002), per hydrous vitrinite has the potential to generate hydrocarbon liquids during natural coalification. Oil-prone coal deposits have been reported worldwide (Boreham et al., 2003; Fleet Andrew & Scott Andrew, 1994; Hendrix et al., 1995; Macgregor Duncan, 1994; Noble et al., 1991; Ogala, 2011; Powell & Boreham, 1994). Research for the distribution of oil-prone coals in time reveals that it belongs to deposits of the Jurassic to Paleogene age (Wilkins & George, 2002). The study area is shown in Fig. 1. The area is bounded by latitudes 25° 22′ N to 25° 25′ N and longitudes 92°18′ E to 92°21′ E. The hydrocarbon potential of coal resources of Paleogene coals of North-East-India has been studied previously by Mishra (Misra, 1992) and Singh & Singh (Singh & Singh, 2001) based on optical and some geochemical properties. This study includes the entire coal deposits of northeast India, but this specific field was not included.

The novelty of the present study is to conduct a systematic investigation on a newly discovered coal seam in Bapung Coalfield, Meghalaya, to determine the origin of organic matter, thermal maturity, hydrocarbon richness, and petroleum generation potential (GP) of source rock. In addition, geochemical and petrographic data were also utilized to find their effect on hydrocarbon generation, liquefaction and gasification behaviour of source rocks. Presently limited scientific papers are accessible in the Bapung Coalfield. Hydrocarbon exploration and exploitation activities are still in the initial stages (R & D) in Meghalaya. This analysis may support future petroleum exploration in Meghalaya, NE, India.

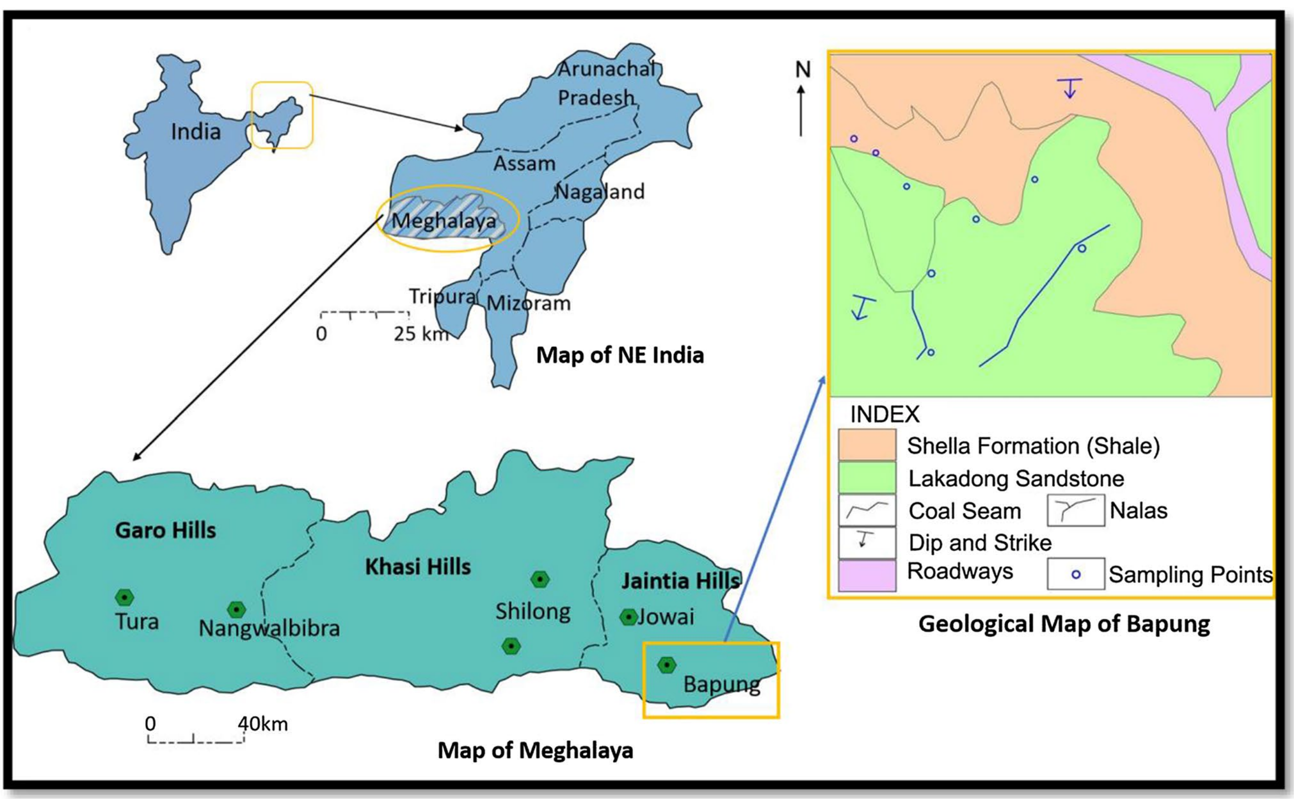

Fig. 1 Geological Map of the Bapung Coalfield (after GSI, 2013)

2 Geological setting

The Bapung Coalfield in the Jaintia Hills of Meghalaya is placed on the Jowai-Badarpur NH-44. Physiographically it is a part of the Meghalaya plateau, composed of solid crystalline Precambrian rock. Stratigraphically the coalfield belongs to the Eocene age. Lakadong Sandstone, a Member of Shella Formation of Jaintia Group, is the broad subdivision. The coal seams are rested upon sandstone and shales, which are the principal rock types of the area. In some places, coal seam lies over carbonaceous shale. Three coals seams were known to exist earlier, but a new seam was recently discovered from which samples were collected. This new seam, probably seam no. 4, is persistent in nature and at places resting over sandstone. The seam looks almost horizontal but shows some dipping character at places. The dip direction is commonly towards NE. The stratigraphic succession of the Bapung Coalfield is given in Table 1 (after GSI, 2013). Shell Formation is predominantly developed, including four coal seams, including NEW SEAM. This seam is not persistent in nature and at places associated with carbonaceous shale bands. The associated sandstone is medium-grained and brown, while shale is greyish-white. This seam is nearly horizontal and shows a dip amount of 2° to 3° with a common dip direction towards SE. The present NEW SEAM is in working condition only while the other three are exhausted. The modified Stratigraphic succession after the (India, 2009) and geological detail study are already conducted by Nath and Kumar (Nath & Kumar, 2022).

3 Materials and methods

3.1 Sample collection and experimental methods

Fresh coal from the working exposures and quarry sections was collected for analysis, as shown in Fig. 1. Details of the organic petrography of all the samples are available in Table 2. The collected sample was finally crushed to the − 3 + 0.5 mm size for better liberation using a double-roll crusher. The samples were crushed and screened through British Standard Specification 72 mesh size (− 212 µm size) and then utilized for conventional organic geochemical analysis Fig. 2. These geochemical analyses, Rock-Eval pyrolysis, and Micro-petrographic analysis were conducted at Keshava Deva Malaviya Institute of Petroleum Exploration, Dehradun, India.

3.2 Rock-Eval pyrolysis and TOC analyses

The present study used Rock-Eval 6 analyzer (Vinci Technologies, 2003) for source rock analysis. Rock-Eval pyrolysis (REP) has been described by many researchers (Behar et al., et al. 2001; Hazra et al., et al. 2017; Lafargue et al., et al. 1998). REP is a significant way to determine hydrocarbon generation from any source rock (Hazra et al., et al. 2016, 2019, 2021). The REP experiment is completed in two steps; pyrolysis and oxidation of a sample (5–10 mg each). In the first step, pyrolysis is performed under an N_2 atmosphere, and the temperature is maintained at 300 °C. Free hydrocarbons without cracking of kerogen (S_1 in mg HC/g rock) or lightly bound hydrocarbons present in the sample were released and quantified simultaneously by the Flame Ionization Detector (FID). Further temperature is increased from 300 to 850 °C, with a constant heating rate of 25 °C/min. Hydrocarbons are generated from the cracking of kerogen releases (S_2 in mg HC/g rock) and are simultaneously quantified by FID. The quantity of CO_2 and CO generated (S_3) from the breaking of chemical groups (carboxyl and oxygen containing compounds) at 300 to 390 °C in the sample and detected by an infrared (IR) detector.

In the second step, oxidation of pyrolysis residue is performed under the air atmosphere at 850 °C to determine total organic carbon (TOC). Primary parameters are TOC (wt. %) content, S_1 (free hydrocarbon amount), S_2 (remaining hydrocarbon generation potential of organic matter in the temperature range of 300–850 °C), and T_{max} is the Rock-Eval temperature, where the maximum release of hydrocarbons from pyrolysis occurs). The secondary parameters investigated are HI (Hydrogen index), GP (Genetic potential), PI (Production index) and OI (Oxygen index) which are calculated from primary parameters.

Table 1 Stratigraphic successions of Bapung Coalfield

Age	Formation	Member	Lithology
Eocene	Shella Formation (Sylhet Formation)	Lakadong Sandstone Member	Medium to coarse grained ferruginous quartzitic sandstone, containing thin coal seams, carbonaceous shales and occasionally thin clay bed
Unconformity			
Archaean	Gneissic Complex		Gneisses and Granites

Table 2 Geochemical results of the analysed coal samples from Bapung Coalfield

S. no	TOC Wt%	TOCo Wt%	S_1 mg/g	S_2 mg/g	S_3 mg/g	PI mg/g	PIo mg/g	S_2/S_3 mg/g	HI mg/g	HIo mg/g	OI mg/g	G'P mg/g	*f*	T max (°C)
1	65.20	67.10	22.12	205.12	0.44	0.09	0.02	466.18	313.83	429.83	0.67	227.24	0.36	417
2	70.25	72.02	25.10	200.12	0.45	0.11	0.02	444.71	284.17	428.31	0.63	225.22	0.44	418
3	75.28	75.49	21.20	282.54	0.48	0.06	0.02	588.62	372.95	398.82	0.64	303.74	0.09	425
4	74.19	74.61	10.47	265.64	0.90	0.03	0.02	295.16	355.95	401.32	1.20	276.11	0.15	414
5	60.40	61.72	13.10	212.35	0.92	0.05	0.02	230.81	350.37	417.56	1.51	225.45	0.22	428
6	82.26	82.44	16.58	210.12	1.12	0.07	0.02	187.60	254.24	412.78	1.35	226.70	0.48	440
7	80.25	80.67	18.20	199.52	2.73	0.08	0.02	73.08	247.38	382.60	3.38	217.72	0.44	428
8	79.25	79.28	14.86	300.21	1.92	0.04	0.02	156.35	378.26	384.97	2.41	315.07	0.02	425
9	60.02	61.48	16.10	189.20	1.35	0.07	0.02	140.14	314.07	390.25	2.24	205.30	0.26	445
10	85.52	85.09	14.25	170.25	2.50	0.07	0.02	68.10	197.49	391.08	2.90	184.50	0.59	441
11	60.20	61.79	20.10	202.20	2.62	0.09	0.02	77.17	335.65	416.17	4.34	222.30	0.27	435
12	75.15	76.11	23.90	225.15	1.82	0.09	0.02	127.70	299.44	415.54	2.42	249.05	0.37	434
13	76.16	76.86	14.36	220.00	1.79	0.06	0.02	122.90	288.20	384.81	2.34	234.36	0.33	418
14	78.12	78.56	14.50	236.60	1.80	0.05	0.02	131.44	302.84	383.75	2.30	251.10	0.28	420
15	69.12	70.30	15.25	221.50	1.62	0.06	0.02	136.72	318.96	406.71	2.33	236.75	0.29	423
16	68.52	69.70	12.10	222.12	1.22	0.05	0.02	182.06	322.07	407.81	1.76	234.22	0.28	425
17	72.12	73.32	9.58	210.12	1.65	0.04	0.02	127.34	289.96	402.28	2.27	219.70	0.36	429
18	73.10	74.19	8.62	215.15	1.72	0.03	0.02	125.08	292.60	402.56	2.33	123.77	0.36	430

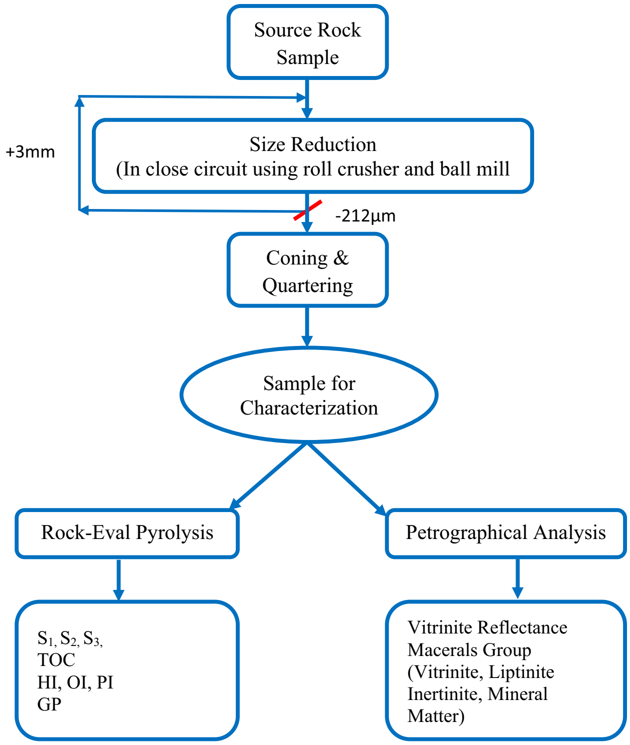

Fig. 2 Workflow adopted for the present investigation

3.3 Petrographic analysis

Coal mainly comprises organic matter such as vitrinite, inertinite, liptinite, and mineral matter. Organic matters (Macerals) are identified based on the ICPP classification system (International Committee for Coal, 1998, 2001). The undersize of mesh size-18 samples was employed to prefabricate polished particulate mount for petrography. Micro-petrographic analysis was done under reflected light attached to the microscope (model Leitz MPV-2) in conjunction with the oil immersion lens. Micro-petrographic analysis was conducted to determine the maturity, kerogen type and quality of organic matter in source rock (Banerjee et al., et al. 2022; Misra et al., et al. 2020; Peters & Cassa, 1994). However, some researchers utilized the same technique to estimate GP in a different type of source rocks (Kumar et al., et al. 2018; Misra et al., et al. 2019; Sharma et al., et al. 2018). Previously many researchers successfully used the correlation developed by Jarvie et al. (Jarvie et al., et al. 2007) and Peters et al. (Peters et al., et al. 2005) to assess the Hydrogen index original (HI_O), the conversion factor (f) and total organic carbon original (TOC_O) contents of the source rock samples.

The Claypool equation was used to calculate HI_O:

$$HI_O = \frac{(\%L^{mmf} \times 750)}{100} + \frac{(\%V^{mmf} \times 450)}{100} + \frac{(\%I^{mmf} \times 125)}{100} \quad (1)$$

Jarvie et al. (2007) has used Type I, Type II, Type III and Type IV hydrogen and *%L*, *%V*, *%I*.

Where I^{mmf}, L^{mmf} and V^{mmf} are vol. (%) of inertinite, liptinite and vitrinite on a mineral matter-free basis.

Conversion factor (*f*) of the organic matter calculated by:

$$f = 1 - \frac{HI_{PD}\{1200 - [HI_O * (1 - PI_O)]\}}{HI_O\{1200 - [HI_{PD} * (1 - PI_{PD})]\}} \quad (2)$$

where HI_{PD} and HIo represent the present day and original hydrogen index. PI_{PD} and PIo (The assumed value of 0.02) is the present day and original production indexes.

The original total organic carbon (TOC_O) contents are calculated by:

$$TOC_O = \frac{83.33(HI_{PD})TOC_{PD}}{[HI_O(1-f)(83.33 - TOC_{PD}) + (HI_{PD})(TOC_{PD})]} \quad (3)$$

where TOC_{PD} and TOCo represent the present day and original total organic carbon.

The Petrographic analysis result can also be used to determine oil yield and conversion of macerals into hydrocarbon. Guyot (Guyot, 1978) applied the ''petrofactor'' to predict reactivity in the liquefaction process of coal. Jin and Shi (Jin & Shi, 1997) studied the effect of various maceral present in different coal ranks and found a correlation between coal conversion into oil and oil yield. As given below:

$$RF = 1000\,R\max / RM \quad (4)$$

$$\text{Conversion}(\%) = 0.2\,RM + 76.6 \quad (5)$$

$$\text{Oil - yield}(\%) = 0.22\,RM + 44.8 \quad (6)$$

where *R*max is the maximum reflectance of vitrinite, RM is reactive macerals.

4 Results and discussions

4.1 TOC and pyrolysis

REP is a significant way to determine any source rock's hydrocarbon generation potential and organic matter (OM). Based on REP and TOC analysis, the results of the studied samples are shown in Table 2, the total organic carbon (TOC) wt. % indicates organic richness (OM) for any source rock. It was strongly suggested by Hunt (1996) that if the TOC in clastic rocks is greater than 1.0 wt. % than rocks were considered as source rocks. The samples have TOC content lying on the higher side ranging from 60.02 to 85.52 wt. % with mean values of 72.50 wt. %. Overall, analysed samples indicate that most samples possess excellent TOC contents. According to Hunt (Hunt, 1996) migration index (S_1/TOC) is generally used as an indicator for the identification of indigenous and migrated petroleum (Hunt, 1996; Shah & Abdullah, 2017; Shah et al.,et al., 2019).

Previous researchers (Bordenave, 1993; Shah et al., 2019) also demonstrate that at least 5 mg HC/g S_2 is necessary for significant petroleum generation. Free (S_1) and released hydrocarbon (S_2) yielded values for the studied samples ranging from 8.62 to 25.10 mg HC/g rock and 170.25 to 300.21 mg HC/g rock. The graph between S_1 vs TOC shows all samples are indigenous (Fig. 3). Whereas the S_2 vs TOC graph plot (Fig. 4) reveals that the formation has excellent petroleum generating potential. Generation potential (GP: $S_1 + S_2$) for various source rocks has been determined by many researchers, which illustrated that coal (OM > 50%) is a significant source of hydrocarbon (Das et al., 2021; Hakimi et al., 2018; Nath et al., 2022; Panwar et al., 2021a, 2021b). All studied samples' generation potential (GP) values vary from 184.50 to 315.07 mg HC/g rock, making them excellent for hydrocarbon generation.

4.2 Thermal maturity

The thermal maturity of studied source rocks samples was determined by three maturity indicators, i.e., T_{max} values, production index (PI) and Vitrinite reflectance (%Ro) (Panwar et al., et al. 2017a, 2017b; Welte & Tissot, 1984). REP was also employed to calculate the maturity of the studied samples. The result showed that the Tmax values of the analyzed samples are found between 414 and 445 °C (Table 2)

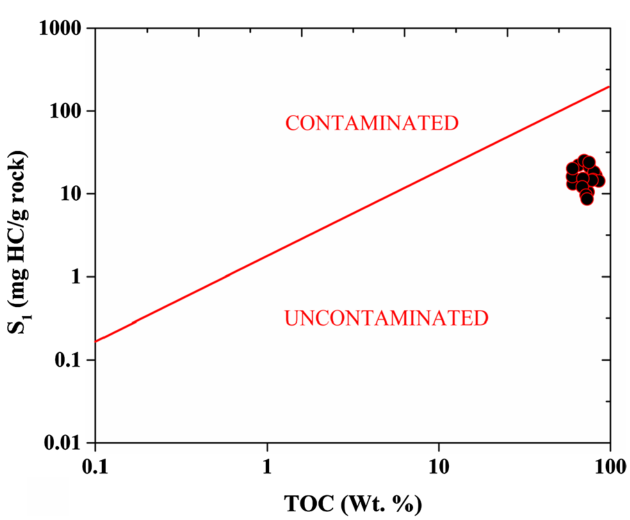

Fig. 3 Relation between S1 and TOC of the analyzed coal samples from Bapung Coalfield (After Hunt, 1996)

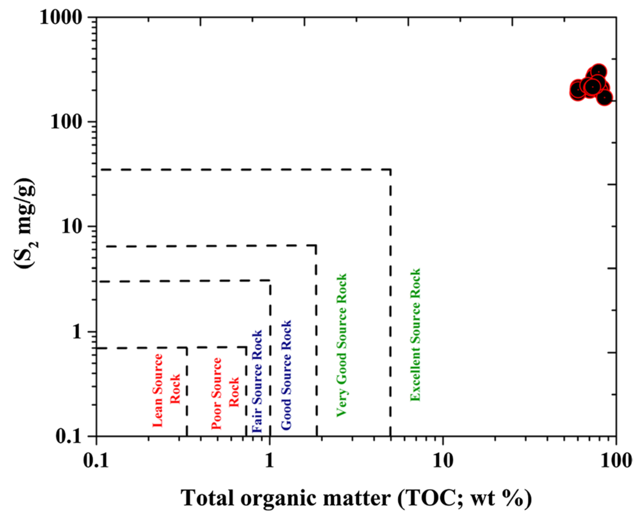

Fig. 4 Relation between S2 and TOC of the analyzed coal seams from the Bapung Coalfield (After Hunt, 1996)

and depict an immature to mature stage for hydrocarbon generation, as shown in Fig. 5 (Hazra et al., et al. 2017; Jarvie, 2012; Panwar et al., et al. 2020).

Previous studies show that source rocks with vitrinite reflectance (Ro%) value higher than 0.55 are mature in nature (Al-Matary et al., 2018). The analyzed coal samples illustrate that vitrinite reflectance (Ro%) values vary between 0.57 and 0.67 Ro% (Average value 0.62) (Table 3), which shows that liquid and gaseous hydrocarbon could be generated. (Bordenave, 1993; Lewan, 1998; Lewan & Ruble, 2002; Osli et al., 2019; Peters & Cassa, 1994).The results verified by the cross-plot of T_{max} and Ro% illustrate that the studied samples were thermally mature in nature for gaseous hydrocarbon, as presented in Fig. 6 (Osli et al., 2021; Shalaby et al., 2021).

Free hydrocarbon (S_1) and total hydrocarbon generation yield ($S_1 + S_2$) were used to estimate the production index (PI). The PI value reveals the maturity of organic matter (OM) in the source rock (Peters & Cassa, 1994; Welte & Tissot, 1984). Previous researchers (El Nady et al., 2015; Espitalie et al., 1985; Hunt, 1996; Peters & Cassa, 1994) believed that a low production index (PI < 0.01) value signifies immaturity or extreme post mature organic matter. In contrast, high production index (PI > 0.40) indicates a mature stage or contamination by migrated hydrocarbons or oil-based mud. The analyzed source rocks samples have a value of PI varying between 0.038 and 0.11, demonstrating that samples mainly were from immature and early-mature oil window (Hadad & Abdullah, 2015; Pandey et al., 2018). Furthermore, the cross-plot between T_{max} and production index data showed the same level of thermal maturity in studied samples, which lies in immature and early-mature oil window (Fig. 7) and is consistent with VR (%Ro) data.

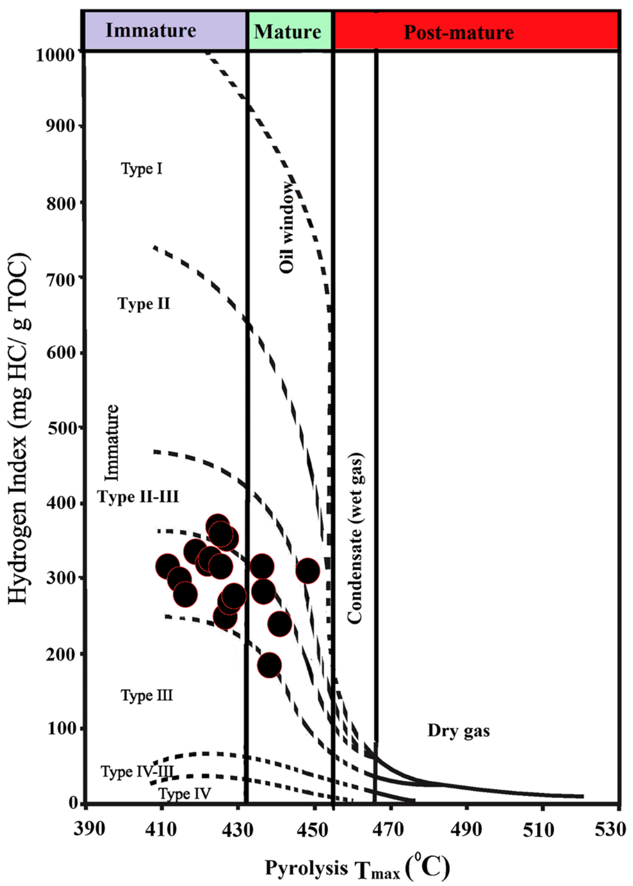

Fig. 5 HI vs Tmax cross plot showing kerogen types for the analyzed coal samples in the study area (After Hunt, 1996)

4.3 Kerogen and organic matter

Dispersed organic matter (OM) in source rocks is known as kerogen. Commonly, optical microscopic and physicochemical methods are used to classify kerogen types. Kerogen is categorized into four types based on chemical composition and OM: Type I, Type II, Type III and Type IV. The above classification is also useful for understanding the type of hydrocarbon generation possible in source rocks.

Tmax has various variations for kerogen Type I, Type II, and Type III (Espitalie et al., 1977; Shah et al., 2019). The HI value of source rocks samples varies from 199 to 379 mg/gTOC with a low oxygen index (< 5), implying coals are capable of generating oil and mixed oil and gas (Fig. 5). In the current investigation, the kerogen types extant in the studied samples of the Bapung Coalfield cognized from the modified Van Krevelen diagram (Fig. 5) demonstrate that the samples endue kerogen of type II/III (mixed organic matter) and might be competent to produce mixed oil and gaseous hydrocarbons. The plot between HI and OI alludes that all studied samples have significantly low OI values (< 5 mg CO_2/g TOC). Both plots HI and OI and S_2 Vs TOC (Figs. 8 and 9) are in good agreement with Van Krevelen diagrams interpretation, implying that the presence of admixed type II–III and type II kerogen in all samples and could be expected to procreate mainly oil with gas. The organic petrography study shows that vitrinite is the dominant maceral, and inertinite and liptinite are in smaller quantities. Thus it will indicate it may produce gas with liquid hydrocarbon.

Table 3 Results of Maceral analysis, conversion and oil yield for source rocks samples from Bapung Coalfield

S. no	Vitrinite (%)	Liptinite (%)	Inertinite (%)	Ro (%)	Conversion (%)	Oil yield (%)	RM (%)
1	87.12	3.47	9.41	0.66	94.72	64.73	90.59
2	86.88	3.35	9.77	0.66	94.65	64.65	90.23
3	81.16	1.61	17.23	0.62	93.15	63.01	82.77
4	82.03	1.56	16.41	0.62	93.32	63.19	83.59
5	84.01	3.13	12.87	0.58	94.03	63.97	87.13
6	82.78	3.00	14.22	0.58	93.76	63.67	85.78
7	76.74	1.31	21.95	0.67	92.21	61.97	78.05
8	77.49	1.30	21.21	0.67	92.36	62.13	78.79
9	79.05	1.34	19.62	0.59	92.68	62.48	80.38
10	79.36	1.30	19.33	0.59	92.73	62.55	80.67
11	85.26	2.25	12.49	0.61	94.10	64.05	87.51
12	85.21	2.18	12.61	0.61	94.08	64.03	87.39
13	76.00	2.05	21.95	0.65	92.21	61.97	78.05
14	75.64	2.07	22.29	0.65	92.14	61.90	77.71
15	83.30	1.76	14.94	0.63	93.61	63.51	85.06
16	83.84	1.65	14.51	0.63	93.70	63.61	85.49
17	82.84	1.29	15.87	0.57	93.43	63.31	84.13
18	83.02	1.24	15.74	0.57	93.45	63.34	84.26

Ro vitrinite reflectance (%); *V* vitrinite (%); *L* liptinite (%); *I* inertinite (%); *RM* reactive macerals

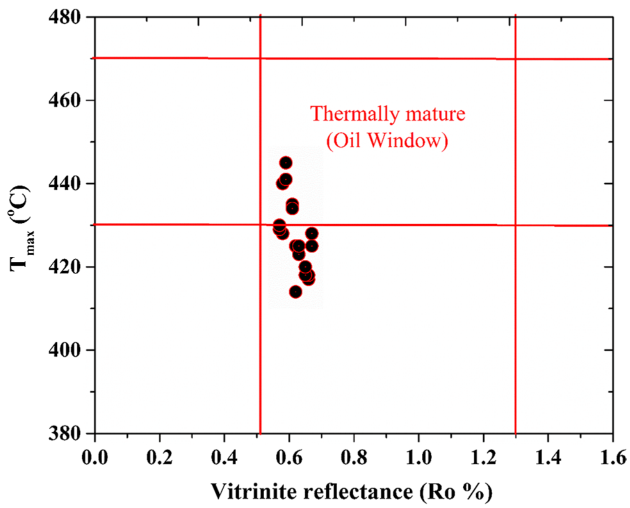

Fig. 6 Relation between Tmax and Ro (%) of the analyzed coal seams from the Bapung Coalfield (After Kumar et al., 2018)

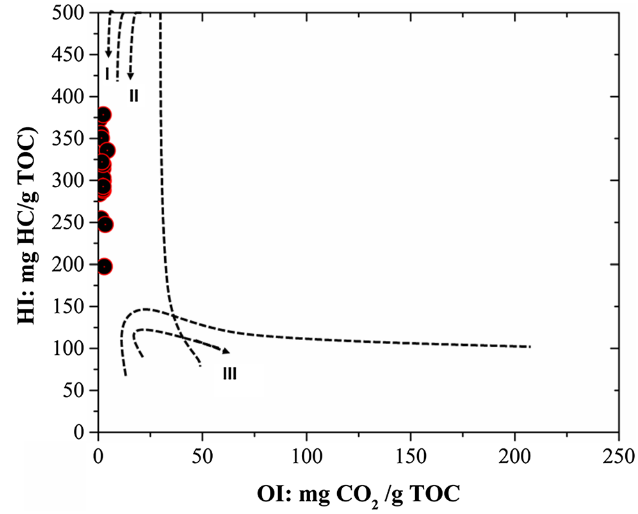

Fig. 8 Relation between HI and OI of the analyzed coal seams from the Bapung Coalfield (After Misra et al., 2019)

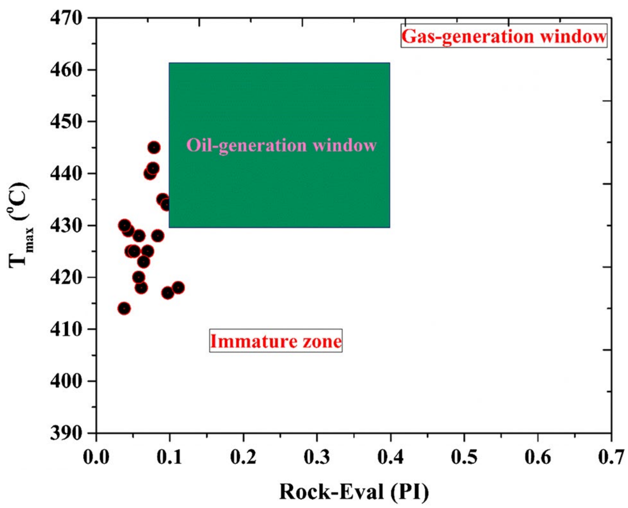

Fig. 7 Relation between Tmax and PI of the analyzed coal seams from the Bapung Coalfield (After Varma et al. 2019)

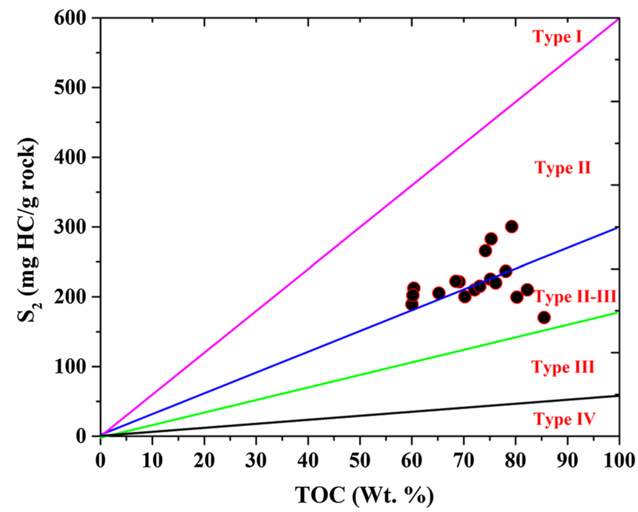

Fig. 9 Relation between S2 and TOC of the analyzed coal seams from the Bapung Coalfield after Panwar et al. (2019)

4.4 Evaluation of hydrocarbon generation and liquefaction

The generation potential (GP) and liquefaction potential of source rocks like coal and shale are documented in many previous studies (Singh, 2012, 2022; Singh et al., et al. 2013). Recently, several works have been carried out which reveal that liquefaction potential is significantly influenced by nature, degree of maturation, hydrogen content, structure, environments of deposition and quantity of organic constituents (Akanksha et al., et al. 2020; Panwar et al., et al. 2021a). Organic Hydrogen index (HIo) and original total organic carbon (TOCo) calculated (Jarvie et al., et al. 2007; Peters et al., et al. 2005) by equations vary from 382 to 430 mg/g TOC and 61.48–85.09 wt.%, respectively, promulgate pithy conversion of kerogen (OM) into liquid and gaseous hydrocarbons during the maturation of source rock.

TOCo and present day total organic carbon (TOC_{PD}) demonstrates reliability in OM or carbon conversion into prominent hydrocarbons. Existing studies illustrate that an excellent positive correlation ($R^2 = 0.997$) is established between TOCo and $TOC_{PD,}$ as revealed in Fig. 10. It might be due to a minimum or no tectonic and associated disfigurement impacts over the coal seams bed (Kumar et al., 2018). The fraction conversion of the OM into liquid or gaseous hydrocarbons (*f*) varies from 0.02 to 0.48, specifying the

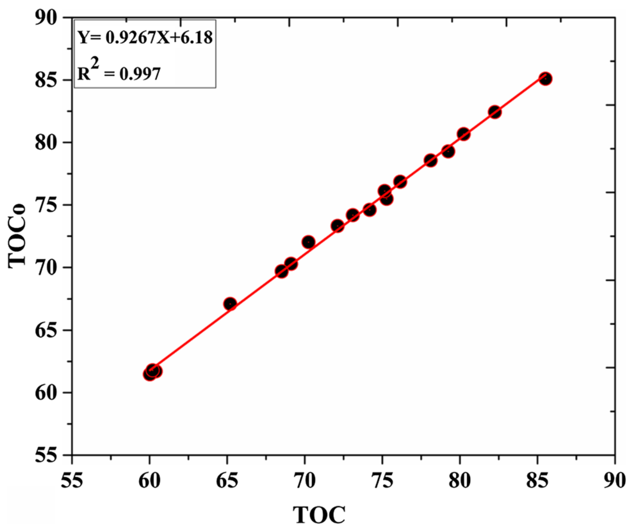

Fig. 10 Relation between TOC and TOCo of the analyzed coal seams from the Bapung Coalfield after Kumar et al., (2018)

prominent expulsion of hydrocarbons from the studied samples (Jarvie et al., 2001; Misra et al., 2019).

The order of oil generating potential for any source rock is followed as alginate > resinite > cutinite > sporinite > suberinite > vitrinite > inertinite (Bhattacharyya, 2021; Rajak et al., 2021). Vitrinite macerals have little potential for liquid hydrocarbon and prone for gaseous hydrocarbon. Many researchers suggested that vitrinite rich source rock is suitable for the generation of gaseous hydrocarbon (; Panwar et al., 2017a; Petersen, 2006). The petrographic analysis observed for the Bapung Coalfield has already been published as a separate paper (Nath & Kumar, 2022). Vitrinite and liptinite macerals are generally known as reactive macerals (RM) and dominantly impact liquefaction potential in coal (Li et al., 2022; Singh et al., 2017). Previous results attributed that bituminous rank coals with 60% reactive macerals were suitable for liquefaction (Cudmore, 1977; Given et al., 1975; Panwar et al., 2017a, 2017b; Singh et al., 2016; Wilkins & George, 2002). The studied samples illustrate a considerable quantity of reactive macerals, ranging from 86.81 to 94.63 wt % (Table 3). The ample quantity of reactive macerals in coal (> 70 wt %) makes it suitable for hydrocarbon generation. Earlier studies also depicted that lignite and bituminous rank coals have high reactive macerals, sulphur and volatile matter suitable for liquefaction (Singh et al., 2012, 2013; Suárez-Ruiz & Crelling, 2008). The study illustrates that coals from Bapung Coalfield have significant potential for conversion (92.14–94.72%) to oil and oil yield (61.90–64.73%), as shown in Table 3, making it apposite for liquid hydrocarbon generation (Singh, 2022). The cross-plot confirms the current result between total organic carbon (TOC) and S_2. Excellent positive correlations were found between oil-yield vs conversion (%) (R^2 = 0.99) and vitrinite Vs conversion (%) (R^2 = 0.98) with conversion (%) as shown in Figs. 11 and 12. Further, inertinite (R^2 = 0.99) maintains a negative propensity with conversion (%), point towards its privative role in liquefaction process as shown in Fig. 13.

5 Conclusions

Conventional energy resources (oil and gas) have played a critical role in India's economic development and will likely remain an imperative energy source in the future. There are several reasons to be optimistic about its future prospects, including the growing energy demand, largely untapped reserves, policy support, technological advancements, and

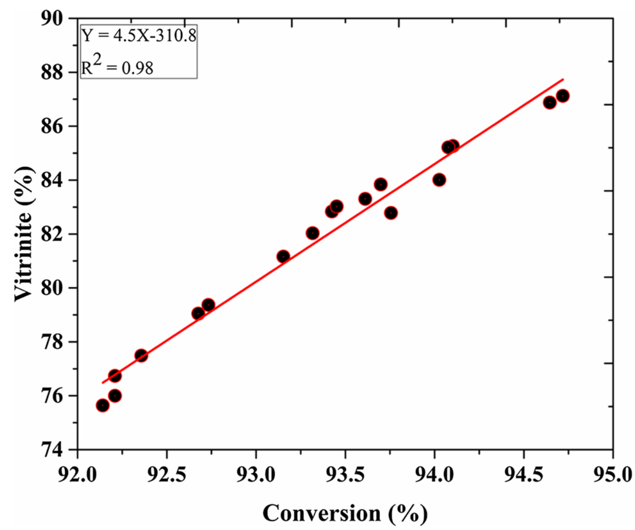

Fig. 11 Conversion vs vitrinite maceral for studied samples

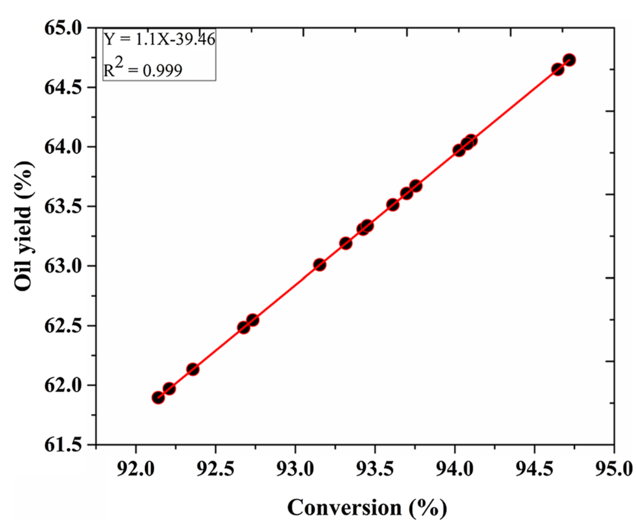

Fig. 12 Conversion Vs oil yield for studied samples

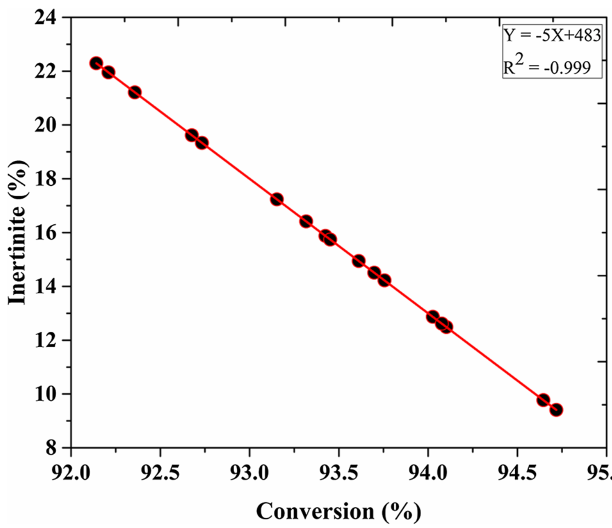

Fig. 13 Conversion vs inertinite maceral for studied samples

energy diversification. GOI has taken various initiatives to promote Coalbed methane (CBM), Coal mine methane (CMM) and Shale gas exploration and production in NE India. In 2020, the government announced a new policy framework for exploring and exploiting CBM, which provides various incentives to attract investment in NE India. As a result, many oil and gas fields, such as Naharkatiya, Moran, and Hugrijan fields, have been discovered by India's largest state-owned oil and gas companies, ONGC and OIL. However, it is essential to utilize unconventional energy resources such as Coalbed methane (CBM), Coal mine methane (CMM), Shale gas, Gas hydrate, etc., to unlock the full potential of hydrocarbon exploration, exploitation and exploitation production in India. This analysis may support future petroleum exploration in Meghalaya, NE, India.

Based on evaluation techniques petroleum generative potential of the study area located in Meghalaya, NE India, was evaluated, and the findings are summed up in the following way.

- The existing investigation data obtained from the geochemical study impart that the samples have a significant quantity of organic matter (TOC > 50 wt. %), and free hydrocarbon value suggests excellent source rock potential. Similarly, the hydrocarbon richness value ranges from 68.10 to 588.63, demonstrating an emphatic possibility for oil and gas generation in all studied samples.
- The quantity of various macerals such as Vitrinite, Liptinite, and Inertinite on a dry mineral matter-free basis (dmmf) shows the studied samples' excellent source rock generation potential.
- Excellent optimistic correlations have been found amid Vitrinite and Oil-yield with a value of ($R^2 = 0.98$) and ($R^2 = 0.99$), respectively, with conversion (%) signifying its suitability for liquid hydrocarbon generation in future. Further, more inertinite ($R^2 = 0.99$) establishes a pessimistic connection with Conversion (%), pointing towards its negative role in the liquefaction process.
- Tmax (414–445 °C) and Ro% (0.57–0.67) data of studied sediments indicate that the formation has most of the samples immature in nature, and some of them attain maturity (oil window) for petroleum generation but is not able to produce hydrocarbon at the commercial level.
- Modified van Krevelen diagram (OI Vs HI) and TOC Vs released hydrocarbon (S_2) yield intimate that mainly Type II and Type II–III kerogens, with HI values varying from 199 to 379 mg HC/g TOC and thus can be contemplated as fair oil source and gas/oil source rock. The plot between HI versus Tmax also evaluated the above results.
- The fraction conversion of the organic matter to hydrocarbons (f) varies from 0.02 to 0.48, specifying the prominent expulsion of hydrocarbons from the studied samples. The plot between TOCo Vs TOC_{PD} demonstrates that a strong positive correlation ($R^2 = 0.997$) existed and illustrates the conversion of OM into hydrocarbons.
- The chief input obtained from the plot between S_1 Vs TOC confirmed that all perusal samples belong to indigenous hydrocarbons, and there is no contamination by migrated hydrocarbons or oil-based mud. Overall the results indicate that the formation (source rock) can generate hydrocarbon and may produce oil and gas through gasification and liquefaction.

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Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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