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Coalbed Methane Potential of The Muara Enim Formation in The South Sumatera Basin as a Source of Natural Gas

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Abstract: Identification of aromatic hydrocarbon fraction by biomarker analysis was carried out to determine the geochemical characteristics of the coal samples from the Muara Enim formation in the South Sumatra basin for potential coalbed methane (CBM) exploration and production. Biomarker analysis using gas chromatography-mass spectrometry (GC-MS) shows the distribution of naphthalene, phenanthrene, and pentacyclic polyaromatic triterpenoid compound groups. The high abundance of 1,2,5- and 1,2,7-trimethylnaphthalene (TMN) compounds indicates that the organic matter in the coal samples mostly originated from higher Angiosperm plants that were deposited in a terrestrial and oxic environment. This terrestrial depositional environment was also indicated by the dominance of the 1,6- and 1,7- dimethylphenanthrene (DMP) compounds. The low maturity of the analyzed coal was indicated by the dominance of less stable isomers over more stable isomers. The identification of 2- and 1- methylphenanthrene (MP) biomarkers that are associated with type II and type III kerogens in relatively high abundance indicates that the analyzed coal samples tend to produce oil and gas. However, the lower abundance value of 2,7-dimethyl-1,2-(isopropylpenteno)-1,2,3,4-tetrahydrochrysene compared to 1,2,4a,9-tetramethyl-1,2,3,4,4a ,5,6,14b-octahydropicene indicates that the coal samples from the Muara Enim formation possess a higher potential to produce gas than oil. In addition, the high vitrinite content in the samples is related to type III kerogen, which shows that the coal is more gas-prone than oil-prone. The obtained methylphenanthrene index (MPI) value of 0.99 indicates moderate maturity of coal. These implicatons show that the analyzed coal can be exploited for its CBM gas content.

Keywords: *Coalbed methane, coal, biomarker, aromatic hydrocarbon, GC-MS analysis, Muara Enim.*

1. Introduction

Coalbed methane (CBM) is a rare natural gas found in coal seams. This gas is trapped in the coal matrix in the form of bubbles or dissolved in water and released into the surrounding sediment during compaction at shallow depths and low temperatures (Gao et al., 2020). A ton of coal typically produces 250–500 cubic feet of methane gas but can produce 250,000–500,000 Btu when burned. This energy potential makes CBM suitable for use as a fuel (Gao et al., 2020). Furthermore, CBM can be extracted from coal deposits without having to conduct coal mining. CBM is an environmentally friendly fuel because it does not produce sulfur oxides, nitrogen, or other toxic materials. The carbon dioxide gas emissions produced by CBM are less than those produced by the direct combustion of conventional coal fossil fuels in steam power plants. The development of CBM by the coal mining industry in Indonesia has a positive impact on the environment by reducing in-situ gas content during the exploitation process, which can also improve industrial safety conditions (Huang et al., 2019).

Indonesia has the largest coal reserves in the Asia-Pacific region and is one of the largest coal-producing countries in the world. As of 2020, the total coal resources in Indonesia reached 143.73 billion tons, with coal reserves reaching up to 38.80 billion tons (ESDM, 2020), which accounts for 3.7% of the world's reserves. Most Indonesian coal is low- and medium-calorie, which posses a lower economic value than high-calorie coal (Nugroho, 2017). Furthemore, many of the largest coal reserves are located in the South Sumatra Basin. This basin is a tertiary basin that includes the Lahat, Lemat, Talang Akar, Baturaja, Gumai, Lower Palembang, Kasai and Muara Enim formations. The Muara Enim formation has coal bearings that were formed in the Late Miocene to Early Pliocene eras (Amijaya et al., 2006; Darman, 2000; Kim et al., 2017; Stanford, 2013; Yasin et al., 2021).

Knowledge on the origin of CBM is a prerequisite for formulating an effective and successful CBM exploration strategy (Martini et al., 2008; Scott et al., 1994). Biogenic CBM is produced through microbial decomposition of organic matter in coal at low temperatures (usually less than 56 °C). In contrast, thermogenic CBM is produced from thermal decomposition of organic matter in coal, primarily at temperatures above 100 °C at which methanogenic microbial activity becomes biochemically impossible (Hunt, 1979; Rice & Claypool, 1981). The exploration of biogenic CBM should be focused on shallow and thermally immature coal seams that possess larger fractures which can result in a faster gas extraction process. In contrast, thermogenic CBM is more likely to accumulate in deeper and more thermally mature coal seams, where the network of open fractures are

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limited (McIntosh et al., 2008; Rice, 1993; Strapoć et al., 2007). Furthermore, the production of mixed CBM (thermogenic and biogenic) require complex exploration and production strategies based on the local geological and hydrological conditions. Thus, successful CBM exploration largely depends on studying the origin of coal seam gas (Dai et al., 2009; Faiz & Hendry, 2008; Flores et al., 2008; Rice, 1993; Scott et al., 1994; Whiticar, 1999).

Biomarker analysis can be carried out to identify the origin of coal seam gas for CBM exploration. Aromatic hydrocarbon biomarkers with naphthalene, phenanthrene and pentacyclic aromatic triterpenoid structural frameworks indicate that the organic matter originate from terrestrial higher plants. Isomers such as 1,2,5-TMN and 1,2,7-TMN can be used as indicators of coal deposition environments (Burhan et al., 2020; Jiang & George, 2019; Wang et al., 2022). The presence of methylphenanthrene biomarkers can be used to determine the type of kerogen on the van Krevelen diagram. The presence of 3-MP, 2-MP, 9-MP and 1-MP isomers potentially determines whether coal is a gas producer (gas-prone) or oil producer (oil-prone). Kerogen types I and II are oil-prone, whereas kerogen type III is gas-prone (El-Sabagh et al., 2018; Zhang & Li, 2018).

The biogenical formation of CBM with the help of bacteria requires a group of methoxylated aromatic compounds (MACs) or compounds that have methoxy groups to carry out methanogenesis and produce methane gas. Methanosarcinales bacteria convert MACs into methane gas in coal seams. These MACs are derivatives of lignin found in plant wood tissue and are often buried in humic coal sediments, so these compounds can be considered biogenic markers of CBM (Mayumi et al., 2016). In this article, geochemical characterization of the coal samples extracted from the Muara Enim formation is conducted by aromatic biomarker analysis and discusses the implications of the biomarker analysis to determine the origin of organic matter, depositional environment and coal maturity for CBM exploration and production.

2. Method

Sample

The coal samples in this study were extracted from the Muara Enim mine in Rambutan Field, South Sumatra Basin, which were formed in the Cretaceous-Early Tertiary period. The samples taken at a depth of 503.7 m with a layer thickness of 10.67 m were included in the sub-bituminous rank.

Method

A total of 10 g of finely ground coal sample was extracted in a dichloromethane/methanol solvent (97:3 v/v) for 16 h. The solvent mixture was evaporated and the asphaltene and maltene were separated using an excess n-hexane solvent (Theuerkorn et al., 2008). The maltene extract was fractionated by thin layer chromatography using silica gel GF_{254} in an *n*-hexane solvent to separate aliphatic and aromatic hydrocarbon fractions. Furthermore, the aromatic hydrocarbon fraction was analyzed for its components by Gas Chromatography-Mass Spectrometry (GC-MS) using Agilent 122-5561 with an HP-5MS column type (60 µm x 250 µm x 0.33 µm). The carrier gas was helium, the flow rate was set to 1 mL/min and the mass spectrometer was conditioned at an energy of 70 eV. The operating temperature was initiated at 70 ℃ and kept isothermal for 1 minute and then increased to 180 °C at a rate of 10 °C/min. The temperature was increased again to 315 °C at a rate of 4 °C/min and kept isothermal for 30 min. The mass spectrometer was operated in full-scan mode. The biomarker structure was identified based on specific m/z fragmentograms, retention time patterns and by comparing the mass spectrum with reference data published by previous researchers.

3. Results and Discussion

Coal Classification

The analyzed coal sample had a calorific value of 5669 cal/gram, which is equivalent to the subbituminous coal rank (Sharma et al., 2019). This subbituminous coal ranking is in accordance with the results of the proximate analysis carried out by (Sosrowidjojo, 2013). The results include, among others, a low vitrinite reflectance (Ro = 0.31–0.49%) which indicate subbituminous rank, high moisture content (21%), low ash content (5.6 – 19.8%), volatile matter of the seams in the range of 29.3–45.8%, fixed carbon content less than 80% weight (daf) and a maximum fixed carbon of 46.54%.

Identification of Aromatic Hydrocarbon Fraction Biomarkers

The biomarker structure of the aromatic hydrocarbon fraction was identified based on specific m/z fragmentograms, mass spectra and comparing the results with previous publications (Buckley et al., 2021; Burhan et al., 2019; Gan et al., 2023; Lima et al., 2023; Synnott et al., 2021; Zheng et al., 2023). The biomarkers identified were naphthalene, phenanthrene and aromatic pentacyclic triterpenoid compounds (Figure 1 and Table 1).

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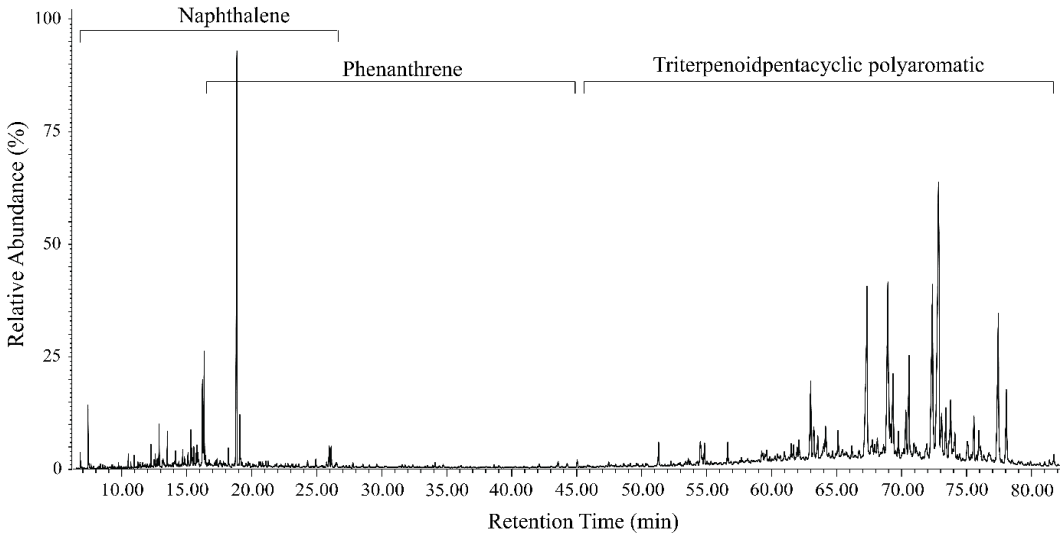

Figure 1. Total ion chromatogram (TIC) of aromatic hydrocarbon compounds

Table 1. Abundance of naphthalene, phenanthrene and pentacyclic polyaromatic triterpenoid compounds

Naphthalene			Phenanthrene			Polyaromatic pentacyclic triterpenoid		
Compounds	*m/z*	% abundance	Compounds	*m/z*	% abundance	Compounds	*m/z*	% abundance
2-MN	142	33.85	3-MP	192	10.63	C_{27} triaromatic-8,14-secotriterpenoid	169	100
1-MN	142	66.15	2-MP	192	38.56	C_{28} triaromatic-8,14-secotriterpenoid	183	100
(2+1)-EN	156	1.33	9-MP	192	23.53	2,9-dimethylpicene	306	100
(2,6+2,7)-DMN	156	10.09	1-MP	192	27.29	1,2,9-trimethylpicene	320	100
(1,3+1,7)-DMN	156	12.58	2,6-DMP	206	3.42	2,2,9-trimethyl-1,2,3,4-tetrahydropicene	324	63.8
1,6-DMN	156	65.52	(1,3+2,10+3,9+3,10)-DMP	206	8.7	1,2,9-trimethyl-1,2,3,4-tetrahydropicene	324	36.2
(1.4+2.3+1.5)-DMN	156	6.5	(1,6+2,9)-DMP	206	37.02	8,14-triaromatic secolupane	145	76.36
1,2-DMN	156	3.99	1,7-DMP	206	29.35	8,14-triaromatic secooleanane	145	23.64

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Naphthalene			Phenanthrene			Polyaromatic pentacyclic triterpenoid		
Compounds	*m/z*	% abundance	Compounds	*m/z*	% abundance	Compounds	*m/z*	% abundance
1,3,7-TMN	170	2.36	2,3-DMP	206	5.11	1,2,4a,9-tetramethyl-1,2,3,4,4a,5,6,14b-octahydropicene	257	89.02
1,3,6-TMN	170	13.91	(1,9+1,4)-DMP	206	10.48	2,7-dimethyl-1,2-(isopropylpenteno)-1,2,3,4-tetrahydrochrysene	257	10.98
(1,4,6+1,3,5)-TMN	170	7.16	1,8-DMP	206	5.93			
2,3,6-TMN	170	7.08	(1,3,6+1,3,10+2,6,10)-TMP	220	8.82			
1,2,7-TMN	170	23.08	(1,3,7+2,6,9+2,7,9)-TMP	220	15.96			
(1,6,7+1,2,6)-TMN	170	6.38	(1,3,9+2,3,6)-TMP	220	10.46			
1,2,4-TMN	170	28.17	(1,6,9+1,7,9+2,7,3)-TMP	220	14.6			
1,2,5-TMN	170	11.85	1,3,8-TMP	220	12.28			
			2,3,10-TMP	220	8.51			
			1,6,7-TMP	220	9.98			
			1,2,8-TMP	220	19.39			

MN = Methyl Naphthalene MP = Methyl Phenanthrene

EN = Ethyl Naphthalene DMP = Dimethyl Naphthalene

DMN = Dimethyl Naphthalene TMP = Trimethyl Naphthalene

TMN = Trimethyl Naphthalene

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The presence of alkyl naphthalene in the coal samples is produced by the precursor β-amyrin, which comes from higher Angiosperm plants (Ding et al., 2022; Li et al., 2022). The higher abundance of 1-MN compared to 2-MN is shown in Figure 2 and Table 1. Structurally, the stability of α-substituted 1-MN is lower than that of β-substituted 2-MN. Therefore, the low maturity of the analyzed samples is indicated by the higher abundance of 1-MN compared to 2-MN (Abdullah et al., 2021; Burhan et al., 2019, 2020; Killops & Killops, 2005; Zetra et al., 2016). However, to determine the organic geochemical characteristics, such as maturity, source of organic compounds and depositional environment, it is necessary to conduct other biomarker analysis on the samples.

Dimethylnaphthalene (DMN) compounds can be used to indicate coal maturity based on differences in isomer intensity. The abundance of 1,6-DMN compounds was higher than that of other DMNs, namely 1,2-DMN and 2,6+2,7-DMN (Figure 2). The thermal maturity of the coal samples can be determined from the abundance value of the identified isomers. The high intensity of the 1,6-DMN peak, which is a less stable isomer compared to 2,6+2,7-DMN and 1,2-DMN, indicates immature coal. Therefore, the dominance of 1,6-DMN compounds over 1,2-DMN and 2,6+2,7-DMN in the samples indicates that the coal samples are immature (Fang et al., 2019; He et al., 2019; Killops & Killops, 2005; Wang et al., 2022; Zetra et al., 2016).

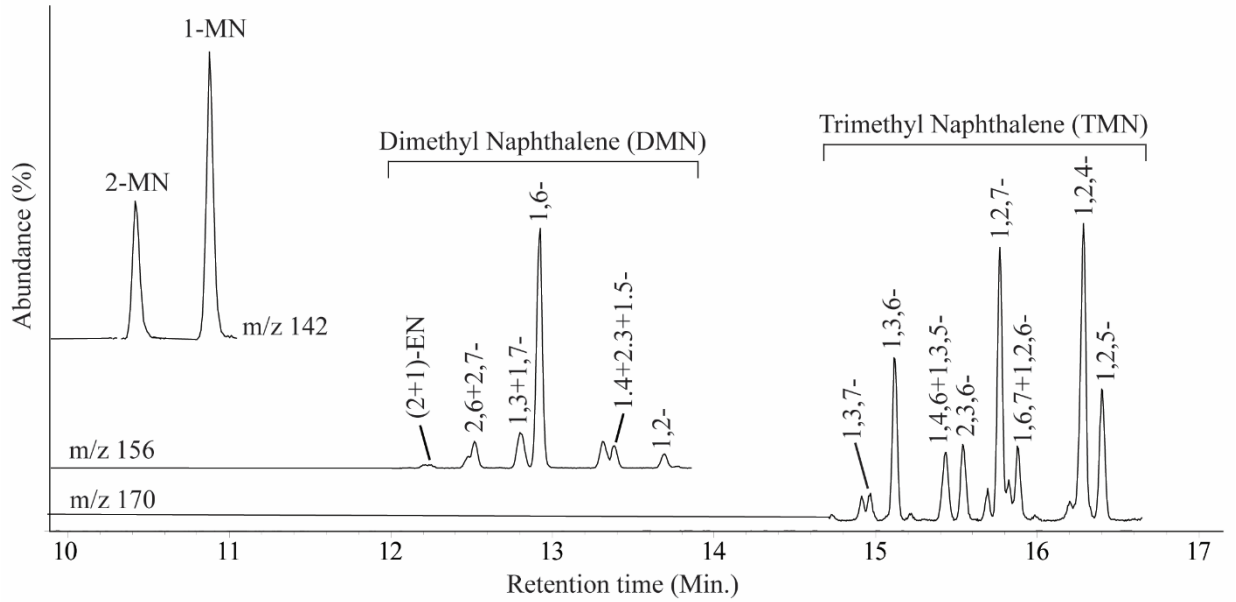

Figure 2. The presence of naphthalene-derived compounds

Another alkyl naphthalene compound in the coal samples that was analyzed was trimethylnaphthalene (TMN). In Figure 2 and Table 1, it can be seen that the isomers 1,2,4-TMN and 1,2,7-TMN have higher abundance values than the other isomers. The higher abundance of less stable isomers indicates the low maturity of the sediment samples (Aboglila et al., 2019; Li et al., 2022). Compounds 1,2,7-TMN and 1,2,4-TMN are less stable isomers compared to 1,2,5-TMN. Therefore, the higher abundance of compounds 1,2,4-TMN and 1,2,7-TMN compared to 1,2,5-TMN indicates immature samples. The presence of the isomers 1,2,5-TMN and 1,2,7-TMN in the analyzed CBM samples also indicates an oxic depositional environment, which were produced through the degradation of β-amyrin compounds as precursors (Burhan et al., 2019). In addition, the formation of 1,2,5,6-TeMN and 1,2,5-TMN compounds in the coal samples indicates the presence of bacterial input via bacteriohopanetetrol as a precursor (Ogungbesan & Adedosu, 2020; Qiao et al., 2021; Rontani et al., 2017).

The cadalene and isocadalene compounds identified based on the m/z 183 fragmentogram are naphthalene derivatives formed through the depolymerization of polycadinene derived from higher plant resins (Zakrzewski & Kosakowski, 2021). These two isomers have the potential to be used as indicators of coal maturity because isocadalene compounds originate from the isomerization of cadalene through thermal enhancement. The deeper the coal deposition environment, the higher the abundance of isocadalene compounds. Therefore, the lower abundance of isocadalene compared to cadalene indicates that the coal samples are immature (Li et al., 2022).

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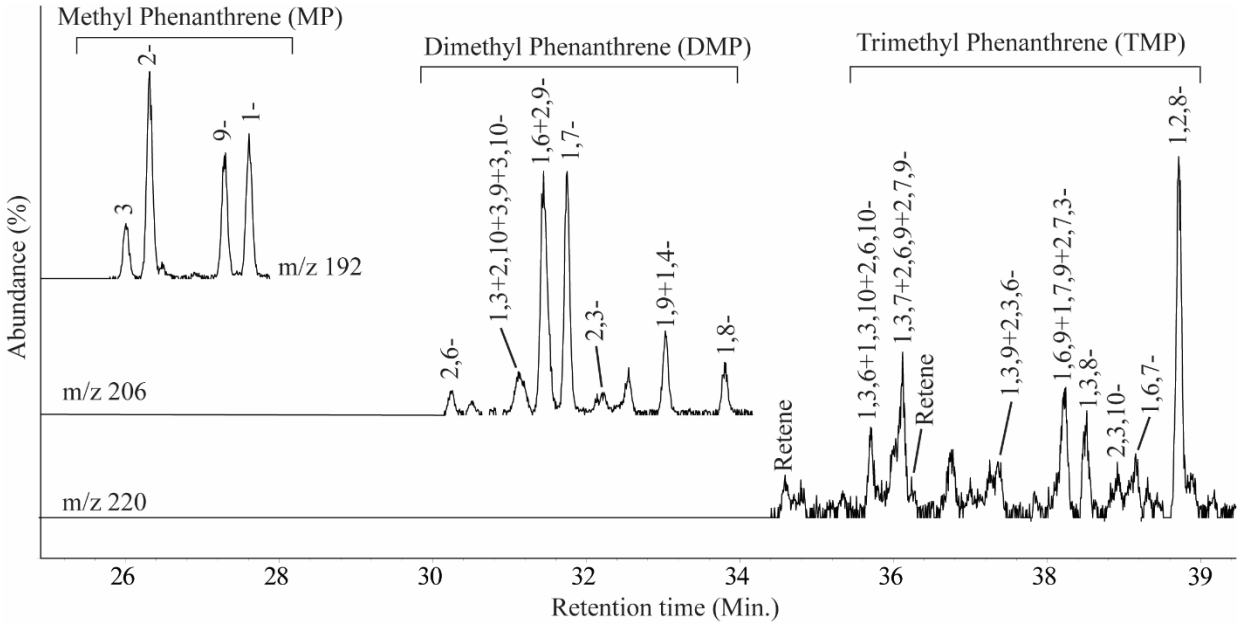

Figure 3. The presence of phenanthrene-derived compounds

The distribution of methylphenanthrene (MP) is shown in Figure 3 and Table 1, with the higher peak of 2-MP indicating a higher abundance. Furthermore, 9-MP and 1-MP showed similar abundance values, with 1-MP having a slightly higher abundance value. The low abundance of 3-MP, which is relatively more stable than 1-MP and 9-MP, indicates the low maturity of the analyzed samples. However, the high abundance of 2-MP, which is a more stable isomer compared to 1-MP and 9-MP, also indicates high maturity (Ayu et al., 2021). To further analyze the maturity of the coal samples, the methylphenanthrene index (MPI) value was used as an indicator of maturity (Sharma et al., 2022; Zheng et al., 2023). The MPI index is a quantitative maturity indicator calculated from the abundance of MP isomers in organic sediments. An MPI value < 0.8 indicate sediments with low maturity, an MPI value in the range of 0.8–1.0 indicate medium maturity, while an MPI value > 1.0 indicate mature sediments (Abdullah et al., 2021; Akinlua et al., 2023; He et al., 2019). The results show an MPI of 0.99, indicating medium-maturity coal.

The presence of MP biomarkers can be used to determine the type of kerogen on the van Krevelen diagram. The presence of 3-MP, 2-MP, 9-MP and 1-MP isomers can potentially determine whether coal, as a source rock, tends to produce gas (gas-prone) or oil (oil-prone). Type I and type II kerogens are oil-prone, whereas type III kerogen are gas-prone. The abundance of 1-MP is related to type III kerogen, the abundance of 9-MP is associated with type II and type III kerogens, while 2-MP and 3-MP are related to type II and type III kerogens (El-Sabagh et al., 2018; Zhang & Li, 2018). The identification of 2-MP and 1-MP biomarkers with relatively high abundance indicates that the analyzed coal samples tend to produce both oil and gas because these MP biomarkers are associated with type II and type III kerogens.

This type II and III kerogen classification is supported by the high vitrinite content in the Muara Enim formation located in the Rambutan Field in the South Sumatra basin (Sosrowidjojo & Sagha, 2009; Zajuli et al., 2017). This high vitrinite content is related to type III kerogen, which is more susceptible to gas than oil. The tendency toward gas- and oil-prone coal in the Muara Enim formation has also been reported by several previous researchers (Sosrowidjojo & Sagha, 2009; Zajuli et al., 2017). In addition to Angiosperm plants as the source of organic matter in the analyzed Muara Enim coal samples, there was also a small amount of organic matter originating from Gymnosperm plants which was identified by the presence of 1-MP and 1,7-DMP biomarkers (Bechtel et al., 2020; Jiang & George, 2019).

Based on the m/z 206 fragmentogram (Figure 3), the distribution of dimethylphenanthrene (DMP) compounds exhibited the highest abundance in the α-isomers such as (1,6+2,9)-DMP and 1,7-DMP. The α-isomer has low stability. Therefore, its high abundance indicates low maturity of the samples (Lima et al., 2023; Zheng et al., 2023). Coal with αβ-substituted DMPs such as 2,9-DMP and 1,9-DMP indicate type II kerogen, which tends to produce oil (oil-prone). Therefore, the presence of 2,9-DMP and 1,9-DMP in the analyzed coal samples indicates that the CBM coal samples possess type II kerogen properties (oil-prone). However, proximate analysis and gas composition in the samples showed high vitrinite and high methane gas content (96.55%), indicating the potential for the coal samples to also produce gas (Sosrowidjojo & Sagha, 2009; Zajuli et al., 2017). In addition, the abundance of 1,6-DMP and 1,7-DMP in the analyzed samples also indicates that the coal was deposited in a terrestrial environment (Lima et al., 2023; Zheng et al., 2023).

The distribution of trimethylphenanthrene (TMP) isomers identified based on the m/z 220 fragmentogram shows the low maturity of the analyzed coal samples. This is indicated by the low intensity of the 2,3,6-TMP peak, which is a more stable isomer than the other isomers, as shown in Figure 3 and Table 1. In addition to being an indicator of maturity, the origin of organic matter in sediment samples can be determined by the presence of TMP isomers. The isomer with the highest abundance, namely

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1,2,8-TMP, is produced by the precursor β-amyrin, which is abundant in higher terrestrial plants. Therefore, the abundance 1,2,8-TMP is an indicator of the terrestrial environment (Jiang & George, 2019; Ogungbesan & Adedosu, 2020).

A low abundance of another biomarker, namely retene, was also exhibited in the analyzed coal samples using the m/z 218 fragmentogram. Retene can be used as an indicator of organic matter originating from Gymnosperm plants, because retene is produced from abietic acid, a major constituent of coniferous plants which are a group of Gymnosperms (Ghosh et al., 2022; Jurek & Kowalski, 2022; Simoneit et al., 2020). Therefore, the identification of retene compounds in low abundance indicates that the organic matter in the coal samples did not only originate from Angiosperm plants but a small amount of organic matter in the coal samples also originated from Gymnosperm plants.

The presence of C_{27} triaromatic-8,14-secotriterpenoid and C_{28} triaromatic-8,14-secotriterpenoid compounds were identified using the m/z 169 and m/z 183 fragmentograms, respectively (Figure 4). The presence of these biomarkers indicates terrestrial source of organic compound because these biomarkers are produced from β-amyrin, a typical precursor of Angiosperm plants (Fadhliah et al., 2020; Wang et al., 2022). Therefore, the C_{27} triaromatic-8,14-secotriterpenoid and C_{28} triaromatic-8,14-secotriterpenoid compounds produced through triterpenoid aromatization during the diagenesis stage in the Miocene era are related to coals that are immature (Fadhliah et al., 2020; Wang et al., 2022).

Other biomarkers, namely 3,3,7-trimethyl-1,2,3,4-tetrahydrochrysene (m/z 274 fragmentogram), 2,2,9-trimethyl-1,2,3,4-tetrahydrochrysene (m/z 257 fragmentogram), 2,2,9-trimethyl-1,2,3,4-tetrahydropicene (m/z 324 fragmentogram) and 1,2,9-trimethyl-1,2,3,4-tetrahydropicene (m/z 324 fragmentogram), were exhibited to be highly abundant. All of these biomarkers indicates organic matter originating from Angiosperm plants, further indicating the extent of Angiosperm vegetation during the Miocene period (Burhan et al., 2019; Jiang & George, 2019). Furthermore, compounds 2,9-dimethylpicenes and 1,2,9-trimethylpicenes were identified based on the m/z 306 fragmentogram and m/z 306 fragmentogram, respectively. Compound 2,9-dimethylpicenes was exhibited to be more abundant than 1,2,9-trimethylpicenes (Table 1). The compound 1,2,9-trimethylpicenes is derived from α-amyrin, while 2,9-dimethylpicenes is derived from the full aromatization of β-amyrin and are isomers of each other (Jiang & George, 2019; Killops & Killops, 2005). These compounds may also be produced by the microbial aromatization of triterpenoid during diagenesis. This indicates that the dehydrogenation reaction of triterpenoid to produce polyaromatic hydrocarbon compounds does not require a long time and high temperature (Ding et al., 2022; Körmös et al., 2021). Therefore, considering that the Muara Enim coal samples are immature, the identified polyaromatic pentacyclic triterpenoid compounds are suspected to be an indication of Angiosperms.

The presence of triaromatic compounds that underwent ring opening and monoaromatic pentacyclic triterpenoids observed in the partial m/z 145 fragmentogram indicate the presence of 8,14-triaromatic secolupane and 8,14-triaromatic secooleanane compounds in the samples (Fadhliah et al., 2020; Wang et al., 2022). The compounds found in the coal samples that were formed in the Miocene era are thought to have formed due to changes in the hopanoid framework by bacteria, followed by aromatization reactions that occurred during the diagenesis stage. Therefore, the presence of these compounds is an indicator of immature samples (Abdullah et al., 2021).

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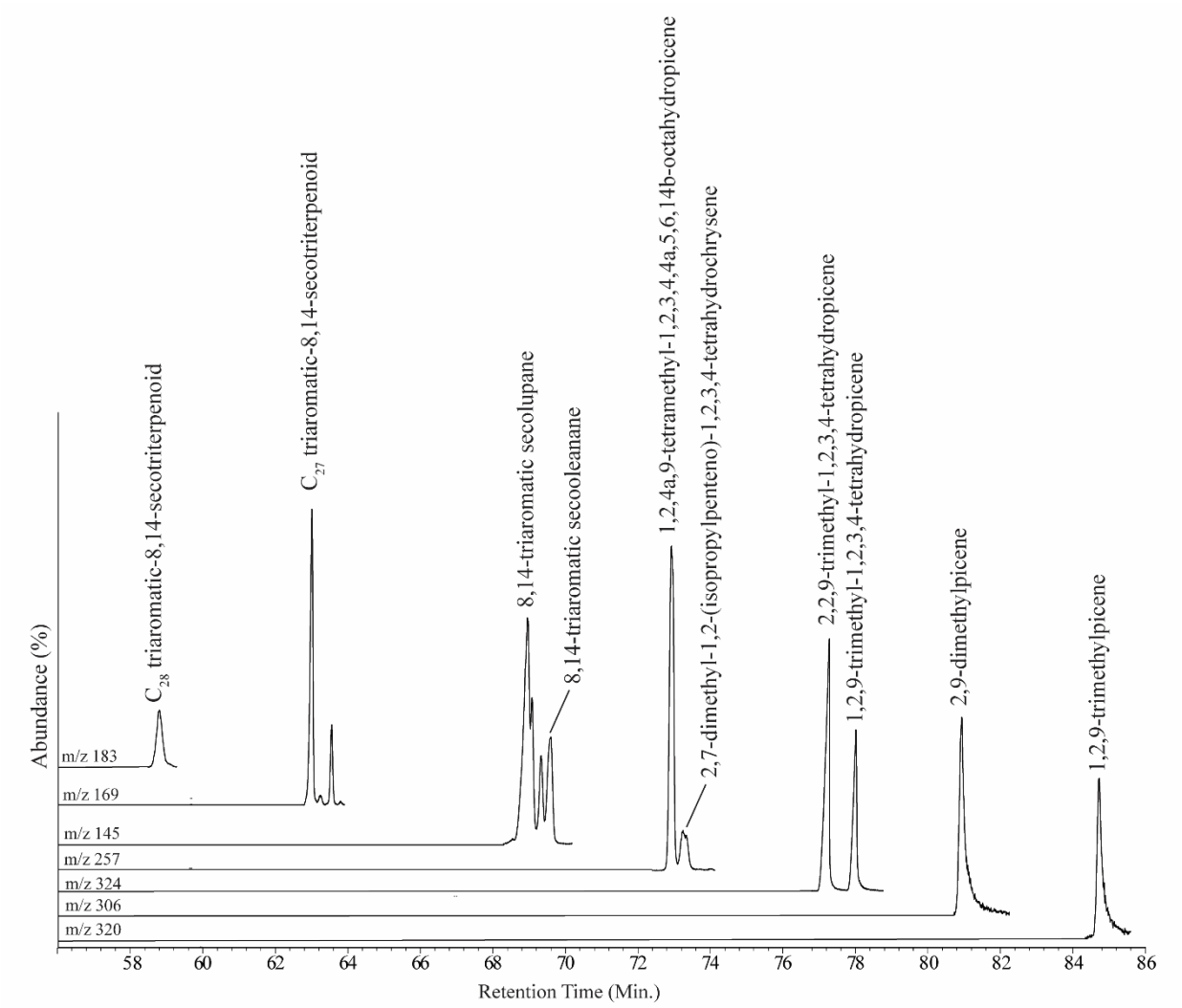

Figure 4. The presence of Polyaromatic pentacyclic triterpenoid-derived compounds

Biomarkers that are indicators of Angiosperm plants, namely the molecule 1,2,4a,9-tetramethyl-1,2,3,4,4a,5,6, 14b-octahydropicene and the compound 2,7-dimethyl-1,2-(isopropylpenteno)-1,2,3,4-tetrahydrochrysene with a triaromatic ursane framework, were observed in the m/z 257 fragmentogram (Burhan et al., 2019; Jiang & George, 2019; Zetra et al., 2016). The high abundance of the compound 2,7-dimethyl-1,2-(isopropylpenteno)-1,2,3,4-tetrahydrochrysene is an indicator of coal that has not yet been produced (Burhan et al., 2019). Furthermore, due to the analyzed coal samples being immature and associated with type II and type III kerogens, the coal samples possess the potential to produce gas (gas-prone) and oil (oil-prone). However, the relatively low abundance value of 2,7-dimethyl-1,2-(isopropylpenteno)-1,2,3,4-tetrahydrochrysene compared to 1,2,4a,9-tetramethyl-1,2,3,4,4a ,5,6,14b-octahydropicene indicates that coal within the Muara Enim formation has a higher potential to produce gas than oil (Burhan et al., 2019).

4. Conclusion

The geochemical implications of the results of biomarker analysis on the Muara Enim coal samples can be used to determine the origin of organic matter, depositional environment and coal maturity. The identification of naphthalene, phenanthrene and pentacyclic aromatic triterpenoid in high abundance indicates the that main origin of organic matter is Angiosperm plants. However, the presence of retene in low abundance shows that a small amount of organic matter in the samples originated from Gymnosperm plants. The dominance of 1-MN isomers compared to 2-MN, the higher abundance value of 1,6-DMN compared to 2,6+2,7-DMN, the higher abundance values of 1,2,4-TMN and 1,2,7-TMN compounds compared to 1,2,5-TMN and the dominance of cadalene compared to isocadalene indicate the low maturity of the coal samples. The MPI value of 0.99 which was calculated from the abundance of MP isomers in organic sediments indicates that the coal samples possess a moderate maturity level. The presence of MP biomarkers was used to determine the type of kerogen based on the van Krevelen diagram. The results show that the MP biomarkers exhibited in the coal samples are associated with type

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II and type III kerogens, indicating that the coal samples tend to produce oil (oil-prone) and gas (gas-prone). However, the high content of vitrinite and methane gas of the coal samples is related to type III kerogen, indicating the samples are more likely to produce gas (gas-prone) than oil (oil-prone). This is further supported by the low abundance of the compound 2,7-dimethyl-1,2-(isopropylpenteno)-1,2,3,4-tetrahydrochrysene compared to 1,2,4a,9-tetramethyl-1,2,3,4,4a,5,6,14b-octahydropicene in the samples which indicates that the Muara Enim coal samples possess more potential to produce gas than oil. The presence of biomarkers, namely 1,2,8-TMP, C_{27} triaromatic-secotriterpenoid, C_{28} triaromatic-8,14-secotriterpenoid, indicate a terrestrial depositional environment and humic coal. Finally, Angiosperm plants as the main origin of the organic matter in the samples are also indicated by the presence of 1,2,4a,9-tetramethyl-1,2,3,4,4a,5,6, 14b-octahydropicene and 2,7-dimethyl-1,2-(isopropylpenteno)-1,2,3,4-tetrahydrochrysene compounds with a triaromatic ursane framework.

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6. References

Abdullah, E. S., Ebiad, M. A., Rashad, A. M., El Nady, M. M., & El-Sabbagh, S. M. (2021). Thermal maturity assessment of some Egyptian crude oils as implication from naphthalene, phenanthrene and alkyl substituents. *Egyptian Journal of Petroleum*, *30*(1), 17–24. https://doi.org/10.1016/j.ejpe.2020.12.004

Aboglila, S., Abdulgader, A., Albaghdady, A., Hlal, O., & Farifr, E. (2019). Biomarker Ratios and Stablecarbon Isotopes to Describe Crude Oils Characteristics in the Murzuq Basin (Libya). *Advances in Research*, *December*, 1–12. https://doi.org/10.9734/air/2019/v18i330094

Akinlua, A., Dada, O. R., Usman, F. O., & Adekola, S. A. (2023). Source rock geochemistry of central and northwestern Niger Delta: Inference from aromatic hydrocarbons content. *Energy Geoscience*, *4*(3), 100141. https://doi.org/10.1016/j.engeos.2022.100141

Amijaya, H., Schwarzbauer, J., & Littke, R. (2006). Organic geochemistry of the Lower Suban coal seam, South Sumatra Basin, Indonesia: Palaeoecological and thermal metamorphism implications. *Organic Geochemistry*, *37*(3), 261–279. https://doi.org/10.1016/j.orggeochem.2005.10.012

Ayu, M. W. P., Burhan, P., & Zetra, Y. (2021). Analisis Biomarka Minyak Mentah Sumur Tua Blok Cepu, Formasi Wonocolo, Jawa Timur. *Jurnal Sains Dan Seni ITS*, *9*(2), 1–6. https://doi.org/10.12962/j23373520.v9i2.56936

Bechtel, A., Chekryzhov, I. Y., Pavlyutkin, B. I., Nechaev, V. P., Dai, S., Vysotskiy, S. V., Velivetskaya, T. A., Tarasenko, I. A., & Guo, W. (2020). Composition of lipids from coal deposits of the Far East: Relations to vegetation and climate change during the Cenozoic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *538*(April 2019), 109479. https://doi.org/10.1016/j.palaeo.2019.109479

Buckley, S., Power, R. C., Andreadaki-Vlazaki, M., Akar, M., Becher, J., Belser, M., Cafisso, S., Eisenmann, S., Fletcher, J., Francken, M., Hallager, B., Harvati, K., Ingman, T., Kataki, E., Maran, J., Martin, M. A. S., McGeorge, P. J. P., Milevski, I., Papadimitriou, A., … Stockhammer, P. W. (2021). Archaeometric evidence for the earliest exploitation of lignite from the bronze age Eastern Mediterranean. *Scientific Reports*, *11*(1), 1–11. https://doi.org/10.1038/s41598-021-03544-w

Burhan, R. Y. P., Chairacita, A. M., Zetra, Y., & Mutiara, E. (2019). Biomarking Study of Aromatic Hydrocarbon Fraction Crude Oil Tarakan, North Kalimantan. *Jurnal Teknik ITS*, *8*(2), 4–10. https://doi.org/10.12962/j23373539.v8i2.49743

Burhan, R. Y. P., Zetra, Y., & Amini, Y. A. (2020). Paleoenvironmental And Maturity Indicator Of Cepu Block Oil, Wonocolo Formation, East Java Indonesia. *Jurnal Teknologi*, *5*, 173–182.

Dai, J., Ni, Y., Zou, C., Tao, S., Hu, G., Hu, A., Yang, C., & Tao, X. (2009). Stable carbon isotopes of alkane gases from the Xujiahe coal measures and implication for gas-source correlation in the Sichuan Basin, SW China. *Organic Geochemistry*, *40*(5), 638–646. https://doi.org/10.1016/j.orggeochem.2009.01.012

Darman, H. (2000). An outline of the geology of Indonesia. *Lecture Notes in Earth Sciences*, *116*(August), 1–31. https://doi.org/10.1007/978-3-540-77076-3_1

Ding, W., Hou, D., Gan, J., Zhang, Z., & George, S. C. (2022). Aromatic hydrocarbon signatures of the late Miocene-early Pliocene in the Yinggehai Basin, South China Sea: Implications for climate variations. *Marine and Petroleum Geology*, *142*(March), 105733. https://doi.org/10.1016/j.marpetgeo.2022.105733

El-Sabagh, S. M., El-Naggar, A. Y., El Nady, M. M., Ebiad, M. A., Rashad, A. M., & Abdullah, E. S. (2018). Distribution of triterpanes and steranes biomarkers as indication of organic matters input and depositional environments of crude oils of oilfields in Gulf of Suez, Egypt. *Egyptian Journal of Petroleum*, *27*(4), 969–977. https://doi.org/10.1016/j.ejpe.2018.02.005

DOI:https//doi.org/10.22452/mjs.vol44no4.7
Malaysian Journal of Science 44(4): 65-76 (December 2025)

ESDM. (2020). Handbook of Energy & Economic Statistics of Indonesia. *Ministry of Energy and Mineral Resources Republic of Indonesia*. https://www.esdm.go.id/en/publication/handbook-of-energy-economic-statistics-of-indonesia-heesi

Fadhliah, A., Zetra, Y., Wahyudi, A., & Burhan, R. Y. P. (2020). Biomarka sebagai Indikator Sumber Asal Usul Senyawa Organik Minyak Mentah Blok Cepu, Formasi Wonocolo, Bojonegoro, Jawa Timur. *Jurnal Sains Dan Seni ITS*, *9*(2), 37–42. https://doi.org/10.12962/j23373520.v9i2.58293

Faiz, M., & Hendry, P. (2008). Microbial Activity in Australian CBM Reservoirs. **Adapted from Oral Presentation at AAPG Annual Convention, San Antonio, TX, April 20-23, 2008*, *80033*, 32.

Fang, R., Littke, R., Zieger, L., Baniasad, A., Li, M., & Schwarzbauer, J. (2019). Changes of composition and content of tricyclic terpane, hopane, sterane, and aromatic biomarkers throughout the oil window: A detailed study on maturity parameters of Lower Toarcian Posidonia Shale of the Hils Syncline, NW Germany. *Organic Geochemistry*, *138*, 103928. https://doi.org/10.1016/j.orggeochem.2019.103928

Flores, R. M., Rice, C. A., Stricker, G. D., Warden, A., & Ellis, M. S. (2008). Methanogenic pathways of coal-bed gas in the Powder River Basin, United States: The geologic factor. *International Journal of Coal Geology*, *76*(1–2), 52–75. https://doi.org/10.1016/j.coal.2008.02.005

Gan, H., Gong, S., Tian, H., Wang, H., Chen, J., Ma, Q., Liu, K., & Lv, Z. (2023). Geochemical characteristics of inclusion oils and charge history in the Fushan Sag, Beibuwan Basin, South China Sea. *Applied Geochemistry*, *150*(February), 105598. https://doi.org/10.1016/j.apgeochem.2023.105598

Gao, L., Schimmelmann, A., Mastalerz, M., Schatzel, S. J., & Su, D. W. H. (2020). The origin of coalbed methane. In *Coal Bed Methane: Theory and Applications* (2nd ed.). Elsevier Inc. https://doi.org/10.1016/B978-0-12-815997-2.00001-9

Ghosh, S., Dutta, S., Bhattacharyya, S., Konar, R., & Priya, T. (2022). Paradigms of biomarker and PAH distributions in lower Gondwana bituminous coal lithotypes. *International Journal of Coal Geology*, *260*(July), 104067. https://doi.org/10.1016/j.coal.2022.104067

He, C., Huang, H., Wang, Q., & Li, Z. (2019). Correlation of Maturity Parameters Derived from Methylphenanthrenes and Methyldibenzothiophenes in the Carboniferous Source Rocks from Qaidam Basin, NW China. *Geofluids*, *2019*. https://doi.org/10.1155/2019/5742902

Huang, Q., Liu, S., Wang, G., Wu, B., & Zhang, Y. (2019). Coalbed methane reservoir stimulation using guar-based fracturing fluid: A review. *Journal of Natural Gas Science and Engineering*, *66*(September 2018), 107–125. https://doi.org/10.1016/j.jngse.2019.03.027

Jiang, L., & George, S. C. (2019). Biomarker signatures of Upper Cretaceous Latrobe Group petroleum source rocks, Gippsland Basin, Australia: Distribution and geological significance of aromatic hydrocarbons. *Organic Geochemistry*, *138*, 103905. https://doi.org/10.1016/j.orggeochem.2019.103905

Jurek, K. J., & Kowalski, A. (2022). Origin of Carpathian ozokerite deposits: determined from biomarkers and aromatic hydrocarbons distributions. *Fuel*, *310*(PB), 122357. https://doi.org/10.1016/j.fuel.2021.122357

Killops, S., & Killops, V. (2005). *Introduction to Organic Geochemistry* (2nd editio). Blackwell Publishing Ltd.

Kim, J. H., Lee, D. H., Yoon, S. H., Jeong, K. S., Choi, B., & Shin, K. H. (2017). Contribution of petroleum-derived organic carbon to sedimentary organic carbon pool in the eastern Yellow Sea (the northwestern Pacific). *Chemosphere*, *168*, 1389–1399. https://doi.org/10.1016/j.chemosphere.2016.11.110

Körmös, S., Sachsenhofer, R. F., Bechtel, A., Radovics, B. G., Milota, K., & Schubert, F. (2021). Source rock potential, crude oil characteristics and oil-to-source rock correlation in a Central Paratethys sub-basin, the Hungarian Palaeogene Basin (Pannonian basin). *Marine and Petroleum Geology*, *127*(January). https://doi.org/10.1016/j.marpetgeo.2021.104955

Li, Z., Huang, H., & George, S. C. (2022). Unusual occurrence of alkylnaphthalene isomers in upper Eocene to Oligocene sediments from the western margin of Tasmania, Australia. *Organic Geochemistry*, *168*(April), 104418. https://doi.org/10.1016/j.orggeochem.2022.104418

Li, Z., Huang, H., Yan, G., Xu, Y., & George, S. C. (2022). Occurrence and origin of perylene in Paleogene sediments from the Tasmanian Gateway, Australia. *Organic Geochemistry*, *168*(November 2021), 104406. https://doi.org/10.1016/j.orggeochem.2022.104406

Lima, B. D., Martins, L. L., Pereira, V. B., Franco, D. M. M., dos Santos, I. R., Santos, J. M., Vaz, B. G., Azevedo, D. A., & da Cruz, G. F. (2023). Weathering impacts on petroleum biomarker, aromatic, and polar compounds in the spilled oil at the northeast coast of Brazil over time. *Marine Pollution Bulletin*, *189*(February). https://doi.org/10.1016/j.marpolbul.2023.114744

DOI:https//doi.org/10.22452/mjs.vol44no4.7
Malaysian Journal of Science 44(4): 65-76 (December 2025)

Martini, A. M., Walter, L. M., & McIntosh, J. C. (2008). Identification of microbial and thermogenic gas components from Upper Devonian black shale cores, Illinois and Michigan basins. *American Association of Petroleum Geologists Bulletin*, *92*(3), 327–339. https://doi.org/10.1306/10180706037

Mayumi, D., Mochimaru, H., Tamaki, H., Yamamoto, K., Yoshioka, H., Suzuki, Y., Kamagata, Y., & Sakata, S. (2016). Methane production from coal by a single methanogen. *Science*, *354*(6309), 222–225. https://doi.org/10.1126/science.aaf8821

McIntosh, J., Martini, A., Petsch, S., Huang, R., & Nüsslein, K. (2008). Biogeochemistry of the Forest City Basin coalbed methane play. *International Journal of Coal Geology*, *76*(1–2), 111–118. https://doi.org/10.1016/j.coal.2008.03.004

Nugroho, H. (2017). Coal as the National Energy Supplier Forward: What are Policies to be Prepared? *Jurnal Perencanaan Pembangunan: The Indonesian Journal of Development Planning*, *1*(1), 1–13. https://doi.org/10.36574/jpp.v1i1.3

Ogungbesan, G. O., & Adedosu, T. A. (2020). Geochemical record for the depositional condition and petroleum potential of the Late Cretaceous Mamu Formation in the western flank of Anambra Basin, Nigeria. *Green Energy and Environment*, *5*(1), 83–96. https://doi.org/10.1016/j.gee.2019.01.008

Qiao, J., Grohmann, S., Baniasad, A., Zhang, C., Jiang, Z., & Littke, R. (2021). High microbial gas potential of Pleistocene lacustrine deposits in the central Qaidam Basin, China: An organic geochemical and petrographic assessment. *International Journal of Coal Geology*, *245*(July), 103818. https://doi.org/10.1016/j.coal.2021.103818

Rice, D. D. (1993). *Composition and Origins of Coalbed Gas* (Vol. 98, Issue 93, pp. 9885–9907). American Association of Petroleum Geologists. https://doi.org/10.1306/St38577C7

Rice, D. D., & Claypool, G. E. (1981). *Generation , Accumulation , and Resource Potential of Biogenic Gas '*.

Rontani, J. F., Galeron, M. A., Amiraux, R., Artigue, L., & Belt, S. T. (2017). Identification of di- and triterpenoid lipid tracers confirms the significant role of autoxidation in the degradation of terrestrial vascular plant material in the Canadian Arctic. *Organic Geochemistry*, *108*, 43–50. https://doi.org/10.1016/j.orggeochem.2017.03.011

Scott, C. D., Woodward, C. A., & Scott, T. C. (1994). Mechanisms and effects of using chemically modified reducing enzymes to enhance the conversion of coal to liquids. *Fuel Processing Technology*, *40*(2–3), 319–329. https://doi.org/10.1016/0378-3820(94)90154-6

Sharma, R., Jha, S. K., Pal, S., & Shrivastava, J. P. (2022). Organic molecules based palaeoenvironmental inferences and U mineralization in Palaeoproterozoic Bijawar basins of Central India. *Applied Geochemistry*, *147*(October), 105489. https://doi.org/10.1016/j.apgeochem.2022.105489

Sharma, S., Saxena, A., & Saxena, N. (2019). *Introduction to Gas Hydrate, In: Unconventional Resources in India: The Way Ahead*. SpringerBriefs in Petroleum Geoscience & Engineering. https://doi.org/10.1007/978-3-030-21414-2

Simoneit, B. R. T., Oros, D. R., Karwowski, Ł., Szendera, Ł., Smolarek-Lach, J., Goryl, M., Bucha, M., Rybicki, M., & Marynowski, L. (2020). Terpenoid biomarkers of ambers from Miocene tropical paleoenvironments in Borneo and of their potential extant plant sources. *International Journal of Coal Geology*, *221*(December 2019), 103430. https://doi.org/10.1016/j.coal.2020.103430

Sosrowidjojo, I. B. (2013). Coal Geochemistry of the Unconventional Muaraenim Coalbed Reservoir , South Sumatera Basin : a Case Study From the Rambutan Field. *Indonesian Mining Journal*, *16*(2), 71–81.

Sosrowidjojo, I. B., & Sagha, A. (2009). *International Journal of Coal Geology Development of the fi rst coal seam gas exploration program in Indonesia : Reservoir properties of the Muaraenim Formation , south Sumatra*. *79*, 145–156. https://doi.org/10.1016/j.coal.2009.07.002

Stanford, C. E. (2013). Coal Resources, Production and Use in Indonesia. In *The Coal Handbook: Towards Cleaner Production* (Vol. 2). Woodhead Publishing Limited. https://doi.org/10.1533/9781782421177.2.200

Strapoć, D., Mastalerz, M., Eble, C., & Schimmelmann, A. (2007). Characterization of the origin of coalbed gases in southeastern Illinois Basin by compound-specific carbon and hydrogen stable isotope ratios. *Organic Geochemistry*, *38*(2), 267–287. https://doi.org/10.1016/j.orggeochem.2006.09.005

Synnott, D. P., Schwark, L., Dewing, K., Percy, E. L., & Pedersen, P. K. (2021). The diagenetic continuum of hopanoid hydrocarbon transformation from early diagenesis into the oil window. *Geochimica et Cosmochimica Acta*, *308*, 136–156. https://doi.org/10.1016/j.gca.2021.06.005

Theuerkorn, K., Horsfield, B., Wilkes, H., di Primio, R., & Lehne, E. (2008). A reproducible and linear method for separating asphaltenes from crude oil. *Organic Geochemistry*, *39*(8), 929–934. https://doi.org/10.1016/j.orggeochem.2008.02.009

DOI:https//doi.org/10.22452/mjs.vol44no4.7
Malaysian Journal of Science 44(4): 65-76 (December 2025)

Wang, Q., Huang, H., He, C., Li, Z., & Zheng, L. (2022). Methylation and demethylation of naphthalene homologs in highly thermal mature sediments. *Organic Geochemistry*, *163*(September 2021), 104343. https://doi.org/10.1016/j.orggeochem.2021.104343

Whiticar, M. J. (1999). *Carbon and hydrogen isotope systematics of bacterial formation and oxidation of methane*.

Yasin, C. M., Yunianto, B., Sugiarti, S., & Hudaya, G. K. (2021). Implementation of Indonesia coal downstream policy in the trend of fossil energy transition. *IOP Conference Series: Earth and Environmental Science*, *882*(1). https://doi.org/10.1088/1755-1315/882/1/012083

Zajuli, M. H. H., Panggabean, H., Hendarmawan, & Syafri, I. (2017). Hubungan Kelompok Maseral Liptinit dan Vitrinit dengan Tipe Kerogen Relationship Between Liptinite and Vitrinite Maceral Groups with Kerogen Type of Hydrocarbon Source Rock on The Shale of Upper Kelesa Formation in Kuburan Panjang, Riau. *Jurnal Geologi Dan Sumberdaya Mineral*, *18*(1), 13–23. http://jgsm.geologi.esdm.go.id

Zakrzewski, A., & Kosakowski, P. (2021). Impact of palaeo-wildfires on higher plant parameter revealed by new biomarker indicator. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *579*(April). https://doi.org/10.1016/j.palaeo.2021.110606

Zetra, Y., Sosrowidjojo, I. B., & Perry Burhan, R. Y. (2016). Aromatic biomarker from brown coal, Sangatta coalfield, East Borneo of middle miocene to late miocene age. *Jurnal Teknologi*, *78*(6), 229–238. https://doi.org/10.11113/jt.v78.8822

Zhang, M., & Li, Z. (2018). Thermal maturity of the Permian Lucaogou Formation organic-rich shale at the northern foot of Bogda Mountains, Junggar Basin (NW China): Effective assessments from organic geochemistry. *Fuel*, *211*(5268), 278–290. https://doi.org/10.1016/j.fuel.2017.09.069

Zheng, T., Zhang, Q., & Deng, E. (2023). Applications of low molecular weight polycyclic aromatic hydrocarbons (PAHs) and diamondoids ratios/indices on the maturity assessment of coal-bearing source rock: Insight from mature to overmature Longtan Shale. *International Journal of Coal Geology*, *269*(November 2022), 104209. https://doi.org/10.1016/j.coal.2023.104209

DOI:https//doi.org/10.22452/mjs.vol44no4.7
Malaysian Journal of Science 44(4): 65-76 (December 2025)