INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Geochemical Characteristics and Origin of Crude Oils from Sunda and Asri Basins, Indonesia

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Manuscript received: February 15, 2024; revised: June, 28, 2024;
approved: September, 27, 2024; available online: December, 8, 2024

Abstract – The Sunda and Asri Basins are back-arc basins located SE of Sundaland at the present day. These basins contain Cenozoic sediments deposited in a Paleogene half-graben system. This rifing was followed by sagging during the Neogene associated with a north-south major fault system in the eastern part. The Sunda and Asri Basins constitute significant petroliferous basins in Indonesia which have produced more than a billion barrels of oil equivalent. Some studies conducted focus on geochemistry only in Sunda or Asri Basins, but a comprehensive geochemical study integrating data from both basins have never been conducted. This is the first paper to integrate the geochemical characteristics and the origin of crude oils from Sunda and Asri Basins. A total of eighteen crude oils were investigated to delineate their characteristics. The results provide an explanation about the origin of the organic matter and the genetic relationship between crude oils from Sunda and Asri Basins, and their probable source rocks. This study presents an in-depth geochemical characterization. The crude oils were classified as aliphatic oils, as indicated by their high saturated hydrocarbon fractions (>50 %). The API gravity values of the crude oils range from 25.3 to 39, and their sulfur content was low (0.01 %). Geochemistry analysis reveals a novel interpretation of crude oils originating from shale source rock deposited under oxic-suboxic conditions. Sunda and Asri crude oils exhibited relatively similar stable carbon compositions. The modest concentrations of biomarker 18α(H)-oleanane (OL) indicate that the source age is younger than Late Cretaceous. The crude oil in the Sunda and Asri Basins were charged from source rocks that reached early to peak maturity. The results of the current study strongly indicate the differentiation in lacustrine organofacies of crude oils from the Sunda and Asri Basins. The source rock for these crude oils were shales from the Paleogene syn-rift Banuwati Formation.

Keywords: geochemical characteristics, biomarker, stable carbon isotope, organofacies, lacustrine-sourced crude oils

How to cite this article:
Priyanto, B., Subroto, E.A., Kesumajana, A.H.P., Susanto, V., and Suryanto, D.A., 2024. Geochemical Characteristics and Origin of Crude Oils from Sunda and Asri Basins, Indonesia. *Indonesian Journal on Geoscience*, 11 (3), p.437-454. DOI: 10.17014/ ijog.11.3.437-454

Introduction

The study of geochemistry is a multidisciplinary field between geology, chemistry, and physics. It enables geoscientists in the oil and gas industry to understand the chemical composition of rocks and fluids as it forms the basis for understanding the origin, migration, and accumulation of hydrocarbons. One aspect of geochemistry that is particularly relevant to the oil and gas industry is the study of biomarkers. Biomarkers are significantly useful to determine the source and migration of hydrocarbons. This assists in oil-to-source rock correlation and in understanding the genetic link between the oil generated to its potential source rock.

Indonesia's back-arc basins, including the present day back arc of Sunda and Asri Basins,

are significant oil-producing regions. The Sunda and Asri Basins are located southeast of Sundaland and approximately 150 km from Jakarta, the capital city of Indonesia (Figure 1). Hydrocarbon exploration in the Sunda Basin began with the discovery of the giant "C" field in 1969, found with the fifth exploratory well. To date, the field has produced over 170 million barrels from Talangakar reservoir, and therefore has the largest cumulative production in the Java region. Following exploration success in the Sunda Basin, a hydrocarbon discovery was successfully made in the Asri Basin at "I" field in 1987. As of today, these basins have numerous oil and gas discoveries with the total cumulative production exceeding 1,700 million barrels of oil equivalents, according to current operator.

Despite the significant number of discoveries and ongoing production from these basins, there is relatively limitation in conducting comprehensive research on geochemical analysis for both Sunda and Asri Basins since some studies conducted focus on geochemistry only in Sunda or Asri Basins. For instance in previous studies, *e.g*. Molina (1985), studied the distribution of hydrocarbons in the Sunda Basin using n-alkane chromatogram patterns, isoprenoid and n-alkane ratios. Prayitno *et al*. (1992) described the division of source rock and petroleum based on n-alkane chromatograms, isoprenoid, and n-alkane ratios in the Sunda Basin, whereas Sukanto *et al*. (1998) explained the geochemical analysis in the Asri Basin uses gas chromatography (GC). Moreover, Sosrowidjojo (2011) employs multiple biomarker parameter ratios from gas chromatography-mass spectrometry (GC-MS) to describe the distribution of hydrocarbons in the Sunda and Asri Basins in relation to the platform locations, but does not define the hydrocarbon origin in detail. Therefore, insufficient attention has been given, thus far to conclusively determine the organofacies type and oil-source source rock origin in these basins.

For this study, the geochemical data were obtained from the current operator, enabling us to conduct a comprehensive analysis of the geochemistry of crude oils. This analysis allow us to determine the organofacies type and the origin of crude oils in the Sunda and Asri Basins. This paper offers a thorough assessment of the current state of understanding about the geochemical characteristics and the origin of crude oils in these basins.

Geological Setting

The Sunda and Asri Basins are categorized as back-arc basins at the present day. They are located behind a volcanic arc on Java Island, and were filled with Cenozoic sediments. Its geological setting has been described by several researchers, *e.g.* Bushnell and Temansja (1986), Prayitno *et al*. (1992), Aldrich *et al*. (1996), Noble *et al.* (1997), Sukanto *et al*. (1998), Sribudiyani *et al*. (2003), Doust and Noble (2008), Hall *et al*. (2009), Metcalfe (2011). The Paleogene interval is the period of formation of the Sunda and Asri Basins, and is characterized by syn-rift sedimentary deposits. Both basins are characterized by Paleogene half-grabens with a north-south major fault trend in the eastern part, and continued by loading during the Neogene. Reactivation along these faults is critical for trap development, such as three-way closures, faulted structures, and complex stratigraphic or structural traps.

The Sunda and Asri Basins can be divided into periods of pre-rift, syn-rift, and post-rift (Figure 1). The pre-rift basement is pre-Tertiary, and consists of various nonsedimentary rocks, such as granite, granodiorite, schist, slate, and marble. In the Eocene/Early Oligocene (Paleogene), rifts were formed predominantly by north-south oriented faults in the eastern part of the basins as a result of tensional stresses. These rifts were characterized by subsidence, resulting in grabens along the rift border faults. In the syn-rift phase, the first sediment fill was deposited overlying the rock of the basement, characterized by sedimentary rock with conglomerate, shale, sandstone, and alluvial fan deposit to the margin of the basin, known as The Banuwati Formation. This formation is important and is characterized by lacustrine shale deposits containing rich organic materials. The thickness of the Banuwati Formation is approximately 1,500 m and 1,000 m in the

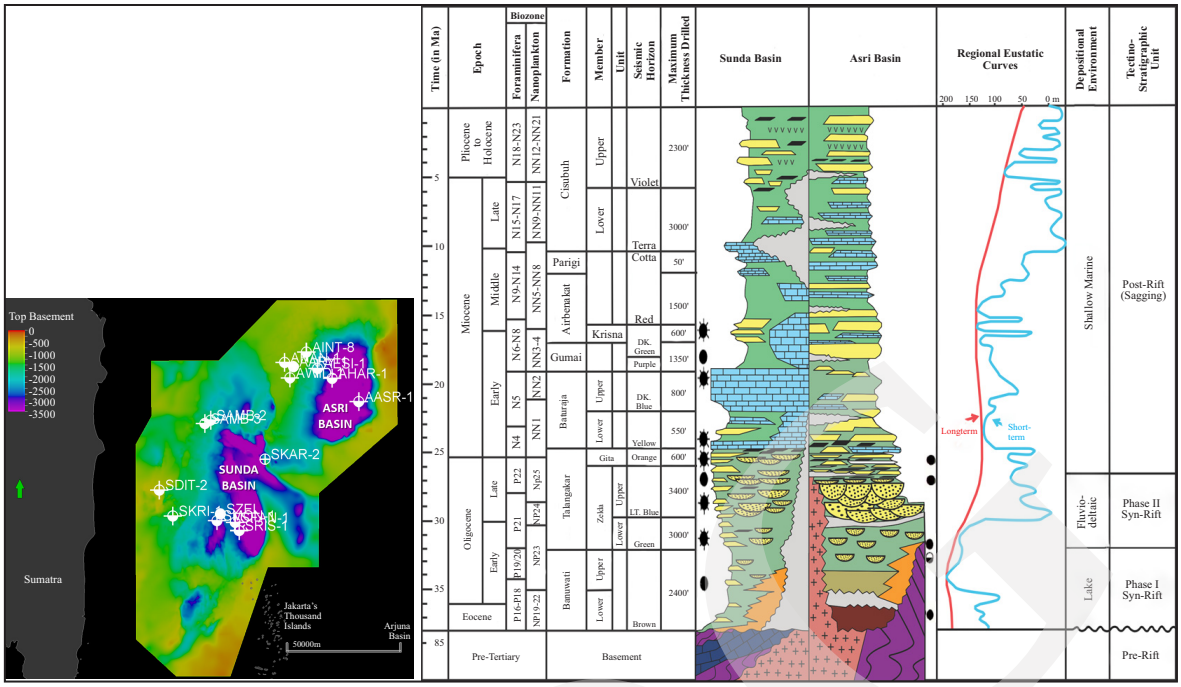

Figure 1. Location of the studied area, the top basement depth map (in meters) and well data used in this study (left figures). The stratigraphy of Sunda and Asri Basins is modified after Prayitno *et al*. (1992) and Sukanto *et al*. (1998). The Banuwati Formation was deposited in the Paleogene (Eocene-Oligocene) syn-rift (right figures).

Sunda and Asri Basins, respectively. Overlying the Banuwati Formation is the Zelda and Gita members of the Talangakar Formation, deposited in Late Oligocene-Early Miocene. The Zelda and Gita Members are characterized predominantly by fluvial to deltaic environment with sandstone, siltstone, shale, and interbedded coal lithology. Sandstone from the Talangakar Formation serves as the main reservoir. The Baturaja Formation, predominantly composed of limestone in marine settings, was deposited above the Talangakar Formation because of the rise in the sea level. During Middle Miocene post-rift phase, the Gumai Formation was deposited, consisting of claystones and minor sandstones. This formation functioned as a regional seal rock. The Gumai Formation is then overlain by the Late Miocene-Holocene Airbenakat and Cisubuh Formations.

Data and Methods

To define the organofacies and the origin in the Sunda and Asri Basins, eighteen crude oils and two rock samples were used for this study. The crude oils consist of ten samples from the Sunda Basin and eight samples from the Asri Basin, while the two rock samples were from wells in the Sunda Basin. The data were sourced from proprietary geochemical reports provided by the block operator. These reports, while not publicly available, have undergone rigorous internal quality control measures. These data were subjected to a comprehensive suite procedures and analyses as described by Tissot and Welte (1984), Peters (1986), Zumberge *et al*. (2005), and McCarthy *et al*. (2011). Briefly, crude oil compositions were evaluated by liquid chromatography (LC) and separated into saturated hydrocarbons, aromatic hydrocarbons, nitrogen-sulfur-oxygen (NSO) compounds, and asphaltene, which were run through a silica gel column. The saturated hydrocarbons, nC_{5+}, were analyzed by gas chromatography (GC).

The combination of gas chromatography with a spectrometer, gas chromatography-mass spectrometry (GC-MS), provides instrumentation for the resolution and detection of biomarkers.

GC-MS was used to identify and to quantify the biomarkers (*e.g.* bicyclic alkanes, terpanes, and steranes) in the nC_{15+} branched/cyclic and aromatic hydrocarbon fractions. Stable carbon isotope compositions were also determined.

For the crude oil maturity evaluation, the carbon preference index (CPI) was calculated using the ratio of peak heights for odd to even numbers n-alkanes in the range of nC_{24} - nC_{34} (Bray and Evans, 1961) using the following equation:

$$CPI = \left(\frac{nC_{25}+nC_{27}+nC_{29}+nC_{31}+nC_{33}}{nC_{26}+nC_{28}+nC_{30}+nC_{32}+nC_{34}} + \frac{nC_{25}+nC_{27}+nC_{29}}{nC_{24}+nC_{26}+nC_{28}+nC_{30}+nC_{32}} \right) + nC_{31}+nC_{33} \times 0.5 \quad \text{.....(1)}$$

The aromatic biomarkers methylphenanthrene (MP) and phenanthrene (P) were also used in the interpretation of maturity using the Methylphenanthrene Index, MPI (Radke *et al.* 1982; Radke 1988) using the following equation:

$$MPI = \frac{1.5\,[(2\text{-MP}) + (3\text{-MP})]}{P + (1\text{-MP}) + (9\text{-MP})} \quad \text{..... (2)}$$

The crude oils used in this study were excellent, because they represent geographic distributions (Figure 1).

Results

Tables 1 and 2 show the geochemical and biomarker data available for crude oils, including the crude oil from the last SFAN-2 well drilled in the Sunda Basin on 2021. The rock data covering the total organic carbon (TOC) and rock-eval pyrolysis measurement used to assess the quantity, quality, and thermal maturity of the organic matter within the rocks such as S1, S2, Tmax; then the hydrogen index (HI) was calculated (Table 3).

API Gravity and Sulfur Content

The API (American Petroleum Institute) gravity and sulfur composition of Sunda and Asri crude oils were relatively similar. The average API degree value of 36.2 within range between 32 to 39, Sunda crude oils exhibit a low sulfur content, averaging 0.09 %. In comparison, Asri crude oils demonstrated an average API degree value of 32.34, varying from 25.3 to 38.7, and maintained a similarly low average sulfur content of 0.08 %. According to Hunt (1995), the API gravity of crude oil is a useful indicator of its thermal maturity. The crude oil analyzed in this study had low sulfur content (Table 1), which is consistent with the medium to high API gravity

Table 1. Geochemical Data for Crude Oils Used in this Study; Blue Texts are Data from Sunda Basin and Green Texts are Data from Asri Basin

No	Well	Depth (meter)	Basin	Reservoir Age	API (°)	S (%)	Oil Composition (wt %)				$\delta^{13}C$ (‰)		CV
							Sat	Aro	NSO	Asp	Sat	Aro	
1	SAMB-2	-	Sunda	L. Oligocene	38.8	0.03	70.4	15.6	5.4	8.6	-20.9	-21.6	-6.78
2	SAMB-3	-	Sunda	L. Oligocene	39	0.14	87.8	5.7	0.9	5.6	-21.2	-21.3	-5.29
3	SDIT-2	-	Sunda	-	-	-	56.6	20.1	13.9	9.4	-	-	-
4	SFAN-1	3374	Sunda	L. Eocene - E. Oligocene	-	-	79.0	13.8	4.2	3.0	-	-	-
5	SFAN-2	-	Sunda	L. Oligocene	-	-	97.9	1.8	0.1	0.2	-21.2	-23.3	-9.74
6	SKAR-2	-	Sunda	-	-	-	-	-	-	-	-	-	-
7	SKRI-1	1261	Sunda	-	35	-	-	-	-	-	-19.9	-19.3	-5.06
8	SMON-1	2696	Sunda	L. Eocene - E. Oligocene	-	-	78.8	13.2	3.4	4.6	-	-	-
9	SRIS-1	2733	Sunda	L. Oligocene	-	-	-	-	-	-	-20.2	-19.9	-4.72
10	SZEL-E10	3305	Sunda	L. Oligocene	32	-	-	-	-	-	-20.4	-20.4	-4.81
11	AARY-1	1228	Asri	-	35	-	81.7	9.7	3.0	5.6	-19.7	-20.4	-7.11
12	AASR-1	1652	Asri	L. Oligocene	-	-	53.2	29.2	16.4	1.2	-	-	-
13	AESI-1	2131	Asri	L. Oligocene	-	-	64.3	24.1	7.0	4.6	-	-	-
14	AHAN-1	1012	Asri	E. Miocene	25.3	-	72.5	20.8	2.2	4.5	-20.4	-22.2	-9.32
15	AHAR-2	3767	Asri	L. Eocene - E. Oligocene	-	-	-	-	-	-	-19.4	-19.6	-6.08
16	AINT-8	1025	Asri	L. Oligocene	28.3	-	75.3	15.2	3.3	6.2	-	-	-
17	AMAN-1	2473	Asri	L. Eocene - E. Oligocene	38.7	0.11	81.6	12.2	3.5	2.7	-	-	-
18	AWID-1	1131	Asri	L. Oligocene	34.4	0.05	70.6	6.6	21.3	1.5	-19.3	-20.9	-9.22

API = American Petroleum Institute (gravity), S = Sulfur, Sat = Saturate, Aro = Aromatic, NSO = Nitrogen Sulfur Oxygen, Asp =Asphaltene
CV= Canonical Variable = -2.53 $\delta^{13}C_{Sat}$ + 2.22 $\delta^{13}C_{Aro}$ -11.65 CV>0.47 terrestrial and CV<0.47 marine or non-marine algal (Sofer, 1984)

Table 2. Biomarker Data from Sunda and Asri Crude Oils

No	Well	GC			m/z 123 Bicyclic Alkanes	m/z 191 Terpanes						m/z 217 Steranes				Aromatic	
		Pr/Ph	Pr/ nC_{17}	Ph/ nC_{18}	CPI	D/HD	C_{26}/C_{25} TT	Tm/Ts	C_{29}/ C_{30}H	C_{31} HH/ C_{30} H	C_{35}/ C_{34} HH	C_{27}	C_{28}	C_{29}	(C_{29} 20S)/ (20S+20R)	MPI	%Rc
1	SAMB-2	3.21	0.66	0.20	1.07	1.22	1.44	0.24	0.34	0.23	0.35	50.00	18.42	31.58	0.51	0.72	0.83
2	SAMB-3	3.87	0.41	0.11	1.09	1.02	1.23	0.25	0.55	0.25	0.38	55.56	17.78	26.66	0.51	0.83	0.90
3	SDIT-2	2.28	1.29	0.57	1.01	-	-	0.44	0.70	-	-	56.44	17.18	26.38	0.55	0.48	0.69
4	SFAN-1	3.08	0.34	0.11	1.05	-	-	-	-	-	-	-	-	-	-	-	-
5	SFAN-2	2.72	0.33	0.13	1.08	-	1.37	0.20	0.55	0.26	0.41	64.20	12.80	23.00	0.46	0.44	0.66
6	SKAR-2	3.41	-	-	-	-	-	0.36	0.41	0.31	0.44	-	-	-	-	0.35	0.61
7	SMON-1	3.71	0.52	0.15	1.06	-	-	-	-	-	-	-	-	-	-	-	-
8	SRIS-1	2.33	-	-	-	-	1.28	0.20	0.65	0.21	-	-	-	-	-	-	-
9	SZEL-E10	-	-	-	-	1.05	-	0.37	0.68	0.26	0.41	-	-	-	-	-	-
10	AARY-1	2.73	0.27	0.12	1.07	0.98	-	0.26	0.49	0.22	0.40	46.30	18.50	35.20	0.56	0.65	0.79
11	AASR-1	3.77	1.66	0.41	1.06	-	1.57	0.45	0.91	0.20	-	39.74	24.32	35.94	0.37	-	-
12	AESI-1	3.19	0.91	0.31	1.07	-	-	-	-	-	-	-	-	-	-	-	-
13	AHAN-1	2.79	0.59	0.29	1.04	0.96	1.31	0.60	0.73	0.32	0.36	42.93	23.23	33.84	0.52	0.29	0.59
14	AHAR-1	-	-	-	-	-	-	0.68	0.67	-	-	45.10	17.60	37.30	0.35	-	-
15	AHAR-2	2.28	0.63	0.28	1.05	0.57	1.22	0.35	0.50	0.33	0.42	46.60	18.50	34.90	0.59	0.65	0.79
16	AINT-8	2.95	1.03	0.38	1.07	0.73	-	0.56	0.73	0.28	0.41	51.30	23.10	25.60	0.54	0.32	0.59
17	AMAN-1	1.87	0.50	0.17	1.07	0.94	-	0.31	0.42	0.21	0.29	38.50	30.10	31.40	0.67	0.50	0.70
18	AWID-1	2.68	0.37	0.14	1.06	-	-	-	-	-	-	51.00	19.00	30.00	-	-	-

Pr = Pristane Ph = Phytane CPI = Carbon Preference Index D = Drimane HD = Homodrimane TT = Tricyclic Terpane Tm = Trisnorhopane
Ts = Trisnorneohopane H = Hopane HH = Homohopane MPI = Methylphenanthrene Index Rc = Calculated Vitrinite Reflectance

Table 3. Geochemical Data of the Rock Used in this Study

No	Well	Depth (m)	Formation	Lithology	TOC (wt%)	S1 (mg/g rock)	S2 (mg/g rock)	Tmax (°C)	HI
1	SRIS-1	3212	Banuwati	Shale	4.88	4.70	11.59	445	238
2	SZEL-14	2801	Banuwati	Shale	2.85	1.38	14.24	449	500

TOC = Total Organic Carbon, S1= Free Hydrocarbons, S2 = Pyrolysable Hydrocarbons, Tmax = Temperature S2 Maximum
HI= Hydrogen Index (S2/TOC x 100)

values, indicating that the crude oils came from mature source rock. According to Peters *et al*. (2005), sweet crude oils have a sulfur content of less than 0.42 %, whereas sour crude oils have a sulfur content more than 0.5 %. The crude oil collected from Sunda and Asri Basins were determined to be sweet crude oils.

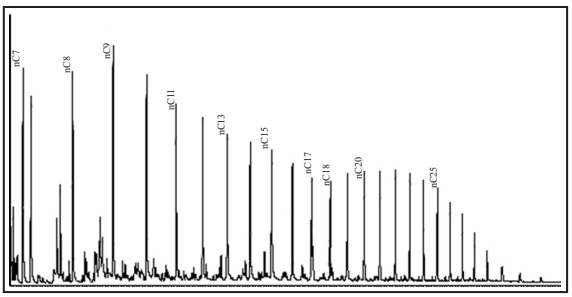

Figure 2. Representative gas chromatogram (GC) from the newest SFAN-2 crude oil drilled in 2021. The GC displays a bimodal peak with the dominance of short-chain n-alkanes (nC$_7$ - nC$_{15}$) relative to long-chain n-alkanes (nC$_{20}$ - nC$_{30}$).

Crude Oil Hydrocarbon Fractions

The crude oils were fractioned into aromatic, saturated, nitrogen-sulfur-oxygen (NSO), asphaltene compounds, and their relative proportions are presented in Table 1. Saturated and aromatic hydrocarbons represent significant fractions of crude oil and relatively low NSO and asphaltene components in Sunda and Asri crude oils. Crude oils dominate the saturated fraction, ranging from 53.2 to 97.9 % (Table 1), and are classified as paraffinic to high-wax oils (Tissot and Welte, 1984).

Biomarker Characteristics

This study investigated the biomarkers of normal alkanes, isoprenoids, bicyclic alkanes, terpanes, hopanes, and sterane components. Table 4 a lists all the identification for bicyclic alkanes with m/z 123, terpanes with m/z 191, and steranes with m/z 217 used in this study. Table 2 summarizes the biomarkers used in this study to identify the depositional environment.

Normal Alkanes and Acyclic Isoprenoids

Normal alkanes and acyclic isoprenoids (such as pristane, Pr; phytane, Ph) are saturated hydrocarbons ranging from nC$_5$ to nC$_{38}$. The n-alkane distributions are bimodal, with short-chain n-alkanes (nC$_7$ - nC$_{15}$) dominating over long-chain n-alkanes (nC$_{20}$ - nC$_{30}$) and the highest concentrations of n-alkanes occurred between

Table 4. Peak assignments in the m/z 123, m/z 191, and m/z 217 mass fragmentograms.

(m/z 123) peak no.	Compounds	Compounds abbreviation
15	8β(H)-drimane	C_{15} drimane
16	8β(H)-homodrimane	C_{16} homodrimane
(m/z 191) peak no.		
19-28	Tricyclic terpane	C_{19}-C_{28} tricyclic terpane
Ts	18α(H),22,29,30-trisnorneohopane	Ts
Tm	17α(H),22,29,30-trisnorhopane	Tm
BNH	17α(H),21β(H),28,30-bisnorhopane	BNH
29	17α(H),21β(H),30-norhopane	C_{29} hopane
OL	18α(H)-oleanane	OL
30	17α(H),21β(H)-hopane	C_{30} hopane
31S	17α(H),21β(H)-homohopane	C_{31}(22S)
31R	17α(H),21β(H)-homohopane	C_{31}(22R)
GM	Gammacerane	GM
32S	17α(H),21β(H)-homohopane	C_{32}(22S)
32R	17α(H),21β(H)-homohopane	C_{32}(22R)
33S	17α(H),21β(H)-homohopane	C_{33}(22S)
33R	17α(H),21β(H)-homohopane	C_{33}(22R)
34S	17α(H),21β(H)-homohopane	C_{34}(22S)
34R	17α(H),21β(H)-homohopane	C_{34}(22R)
35S	17α(H),21β(H)-homohopane	C_{35}(22S)
(m/z 217) peak no.		
21	5α(H),l4β(H),l7β(H)-pregnane	C_{21} sterane
22	5α(H),l4β(H),l7β(H)-homopregnane	C_{22} sterane
A	13β(H),17α(H)-diasterane (20S)	C_{27} diasterane
B	13β(H),17α(H)-diasterane (20R)	C_{27} diasterane
27	5α(H),14α(H),17α(H)-sterane	C_{27} sterane
28	5α(H),14α(H),17α(H)-sterane	C_{28} sterane
29	5α(H),14α(H),17α(H)-sterane	C_{29} sterane
*	Methylsterane	C_{30} 4-methylsterane

nC_8 and nC_{10} (Figure 2). As described in the following subsection that Sunda and Asri crude oils originated from matured sourced rock, then this bimodal peak due to organic material origin (Peters *et al*., 2005).

The concentration of pristane was higher than phytane in every crude oil in the GC. The Pr/Ph ratios of all crude oils ranged from 1.87 to 3.87 (Table 2). Additionally, Table 2 reveals that the ratios of isoprenoids to n-alkanes range between 0.27 and 1.66. The amount of isoprenoids compared to n-alkanes based on Pr/nC_{17} and Ph/nC_{18} ratios has also been calculated in the range 0.27-1.66 of Pr/nC_{17} and 0.11-0.57 of Ph/nC_{18} (Table 2).

The m/z 123 Bicyclic Alkanes

The m/z 123 bicyclic alkane mass fragmentograms of Sunda and Asri crude oils were observed for characterization and showed the presence of bicyclic alkanes (*e.g*. 8β(H)-drimane and 8β(H)-homodrimane) (Figure 3a). The ratio of 8β(H)-drimane to 8β(H)-homodrimane was calculated to be in the range of 0.57 to 1.22 and is summarized in Table 2.

The m/z 191 Terpanes

Terpanes and hopanes were detected in the m/z 191 mass fragmentograms of Sunda and Asri crude oils. The m/z 191 mass fragmentograms showed high proportions of hopanes relative to the tricyclic terpanes (Figure 3b). The biomarkers of tricyclic terpanes were dominated by C_{21} tricyclic terpane and decreased toward C_{19} tricyclic terpane. The ratio of tricyclic terpanes were also calculated (Table 2). In this study, the crude oil had high C_{26}/C_{25} tricyclic terpanes ratio value (>1.0) in the range of 1.22-1.57 (Table 2).

The hopane biomarkers were dominated by the significant presence of trisnorneohopane (Ts) over trisnorhopane (Tm), minor presence of 18α(H)-oleanane (OL), relatively low peak of 17α(H),21β(H),28,30-bisnorhopane (BNH), minor peak of gammacerane (GM), and considerable amount of homohopanes (C_{31} - C_{35}) (Figure 3b). Tm lower than Ts (Tm/Ts <1.00) was calculated and summarized in Table 2, with their ratio values ranging from 0.34-0.91 (Table 2). The homohopane distributions are dominated by the C_{31} homohopane, and generally decrease

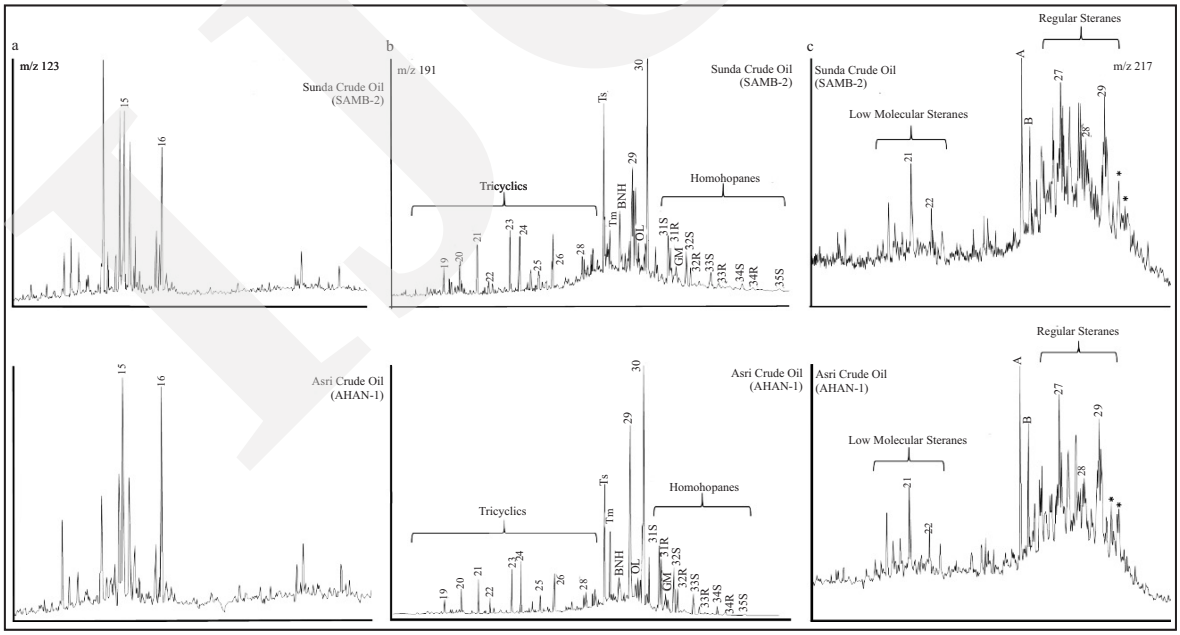

Figure 3. Representative of m/z 123, m/z 191, and m/z 217 mass fragmentograms of Sunda and Asri crude oils. The crude oils from Sunda and Asri relatively have similar characteristics. Peak assignments are given in: (a) The bicyclic alkanes distribution in the m/z 123 mass fragmentograms (left figures); (b) The terpanes and hopanes distribution in the m/z 191 mass fragmentograms (middle figures); (c) The steranes distribution in the m/z 217 mass fragmentograms (right figures). * = C_{30} 4-methylsterane.

toward the C_{35} homohopane. The homohopane ratios, such as C_{31} homohopane/C_{30} hopane and C_{35}/C_{34} homohopane, were calculated and are summarized in Table 2.

The m/z 217 Steranes

The m/z 217 mass fragmentograms of the saturated hydrocarbon fractions of Sunda and Asri crude oils were observed for characterization. They showed the relative dominance of regular C_{27}-C_{29} steranes over low-molecular steranes (such as C_{21} sterane, pregnane; C_{22} sterane, homopregnane), higher diasterane (C_{27} diasterane) over C_{27}-C_{29} steranes, and the presence of C_{30} 4-methylsterane (Figure 3c). The relative abundances of C_{27}, C_{28}, and C_{29} steranes were also calculated with a high proportion of C_{27} (39.74-64.2 %) compared to regular C_{29} (23-38.5 %) and C_{28} (12.8-30.1 %) steranes (Table 2). The maturity ratio, for example C_{29} sterane 20S/(20S+20R), was also calculated (Table 2).

Stable Carbon Isotope

The stable carbon data was used in crude oil evaluation. The crude oils have $\delta^{13}C$ saturate values ranging from -19.30 to -21.2 ‰, and $\delta^{13}C$ aromatics ranged from -19.3 to -23.3 ‰ (Table 1). The comparison between $\delta^{13}C$ saturate and aromatics were utilized for crude oils characterization.

Discussions

Biodegradation of Crude Oils

The biodegradation of crude oils by microbial activity can modify the composition of crude oils in the reservoir (Wenger *et al*., 2001; Peters *et al.*, 2005). Primary biodegradation was checked and indicated no or minor biodegradation in all crude oils, which contain a complete suite of n-alkanes of low-molecular-weight and acyclic isoprenoids in the GC (Figure 2). This finding is consistent with the low concentrations of NSO components compared to hydrocarbon fractions in all crude oil (Hughey *et al*., 2007) (Table 1). Furthermore, the reservoir temperature from several drill stem test (DST) of various wells was measured above 80° C in this study, making bacteria commonly unable to live at such temperatures (Wenger *et al*., 2001).

Crude Oils Maturity

The maturity of crude oil from the Sunda and Asri Basins was primarily evaluated using specific biomarker and nonbiomarker parameters, as presented in Tables 1 and 2.

The calculated CPI values ranged from 1.01 to 1.09 (Table 2), suggesting that Sunda and Asri crude oils originated from a relatively mature source rock. The calculated vitrinite reflectance (Rc) from the MPI values (Boreham *et al*., 1988; Radke, 1988) of Sunda crude oils is in the range between 0.61 and 0.90 with an average of 0.74, while Asri crude oils have an average Rc value of 0.69 with a range value of 0.59 to 0.79 (Table 2). The crude oil maturity indicators (Rc) accessed from MPI and combined with C_{29} sterane 20S/(20S+20R). As the maturity of MPI is generally constant, the reservoir hydrocarbon fluids record the source maturity in terms of high-concentration components (methylphenanthrenes, as MPI) and reservoir maturity with low-concentration components C_{29} sterane 20S/(20S+20R) (Curiale, 2002). The Sunda and Asri crude oils originated from source rocks that reached early to peak maturity (Figure 4).

The ratio of biomarkers Ts and Tm is also used as a maturity indicator (Waples and Machihara, 1991; Peters *et al*., 2005), because Ts is more stable during thermal maturation than Tm. Therefore, Tm/Ts ratio generally decreases with increasing maturity (Waples and Machihara, 1991; Peters *et al*., 2005). The higher Ts than Tm peak in all crude oils reflects the same interpretation of a matured source rock (Figure 3b).

Nonbiomarker parameters, such as API gravity and sulfur, have also been used to evaluate the level of thermal maturity of crude oils (Table 1). The sulfur content varies strongly with the maturity of crude oils (Wenger *et al*., 2001). The levels of sulfur in crude oil decrease with increasing maturity, whereas the API gravity values increase (Kennicutt and Brooks, 1988). The medium API ranged from 25.3° to 39° API, and had a low sulfur content (<0.01%) as shown in Table 1, further

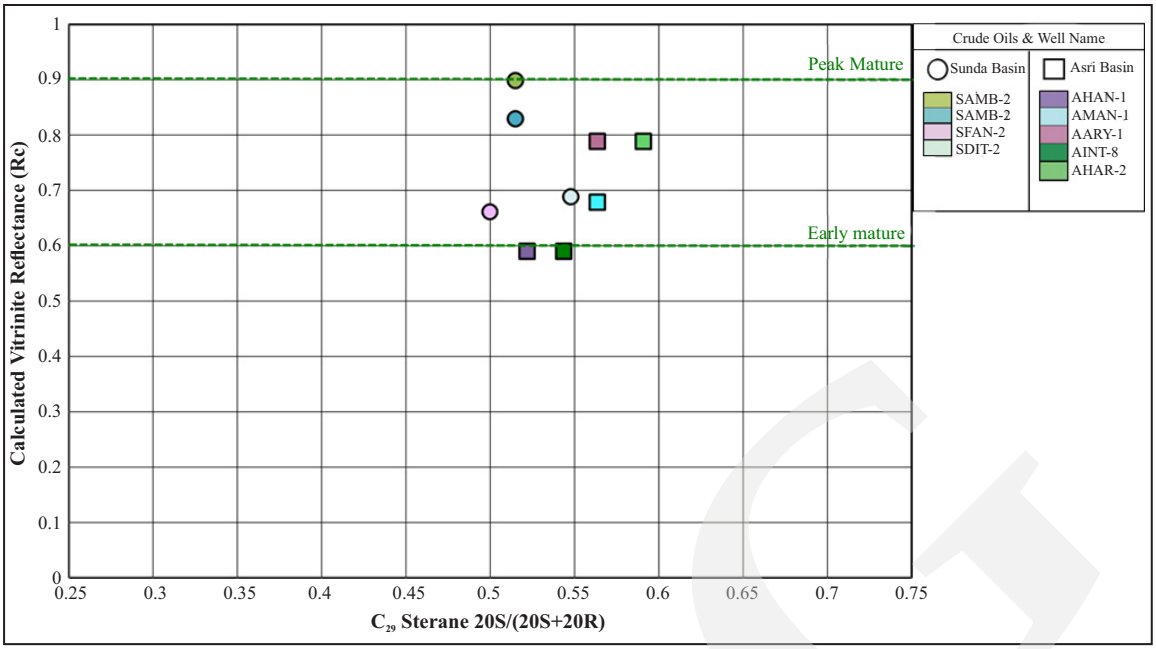

Figure 4. The calculated vitrinite reflectance estimated from MPI (Radke *et al*., 1982; Radke, 1988) for the source rock at the time of generation of crude oils versus C_{29} steranes 20S/(20S+20R), for Asri and Sunda crude oils (after Curiale, 2002).

suggesting that the crude oils were generated from mature source rock. This finding was consistent with previous biomarker observations.

Stable Carbon Isotope and Origin of Organic Matter

The stable carbon isotope composition of crude oils can be used to differentiate the depositional environment of their source rocks, and to determine the genetic relationship between crude oils and their potential source rocks (Sofer, 1984). A Sofer diagram of the bulk values of $\delta^{13}C$ saturate and $\delta^{13}C$ aromatics was used to differentiate marine crude oils from terrigenous (fluvial-deltaic) crude oils. The plot of the $\delta^{13}C$ saturate and aromatic fractions showed a relatively good cluster family of Sunda and Asri crude oils and their potential source rock (Figure 5). In addition, the canonical variable (CV) can be used to identify the depositional environment (CV > 0.47 terrestrial and CV < 0.47 marine or nonmarine algae), with CV= -2.53 $\delta^{13}C_{Sat}$ + 2.22 $\delta^{13}C_{Aro}$ -11.65 (Sofer, 1984). All crude oils showed low CV values (<0.47) ranging from -4.72 to -9.74, summarized in Table 1, which indicated algal origin of the organic matter. The limited rock sample of the Banuwati Formation (only from SRIS-1 well) has relatively similar carbon isotope canonical variable to those of the Sunda and Asri crude oils (Figure 5).

In contrast to the Sunda and Asri Basins, crude oils from the nearby Arjuna Basin exhibit isotopically lighter compositions (Figure 5). This disparity aligns with previous interpretations suggesting that Arjuna Basin oils originated from fluvial-deltaic source rocks (Napitupulu *et al*., 2000), whereas the Sunda and Asri oils are inferred to be derived from lacustrine sources. The distinct isotopic signatures likely reflect differences in the organic matter input and depositional environments of the respective source rocks. Fluvial-deltaic settings typically receive a greater influx of isotopically lighter terrestrial organic matter, leading to lighter isotopically composition compared to lacustrine environments, which often have a higher proportion of algal input, therefore have heavier isotopically composition.

A Novel Interpretation of Sunda and Asri Crude Oils from an Oxic-suboxic Environment

The acyclic isoprenoid composition of pristane (Pr) and phytane (Ph) can be used to interpret

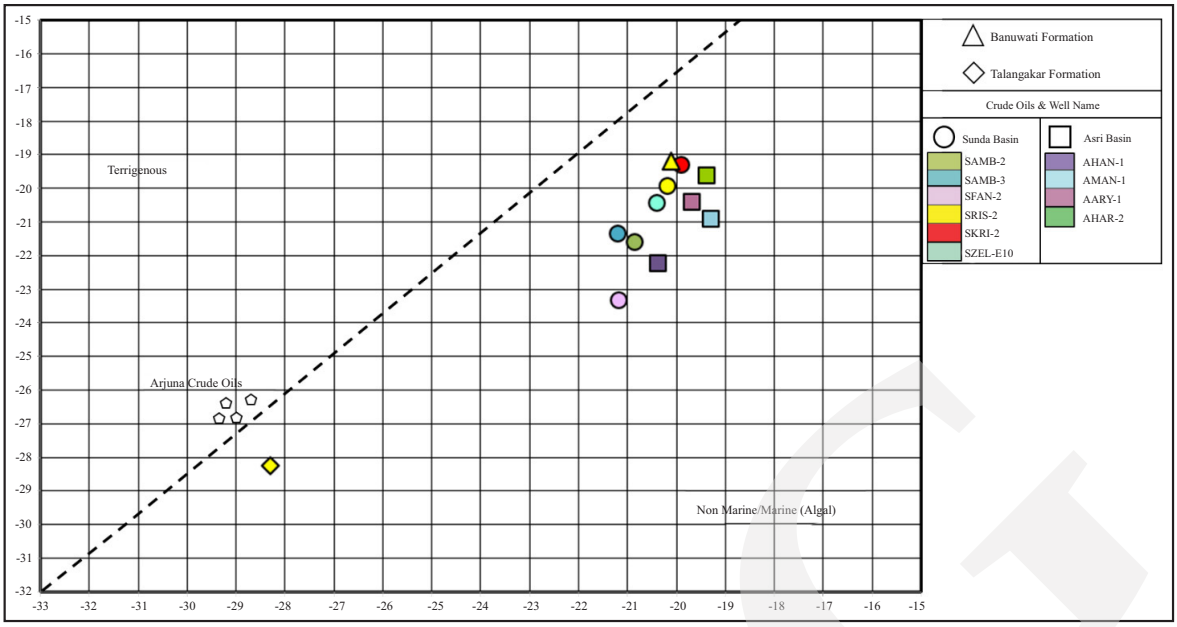

Figure 5. Plot of $\delta^{13}C$ saturate and $\delta^{13}C$ aromatic shows that algal organic matter dominated all crude oils and the rock samples. The dashed line represents the best-fit separation for 339 worldwide crude oil analyzed by Sofer (1984) where $\delta^{13}C_{aromatic} = 1.14\ \delta^{13}C_{saturate} + 5.46$. All shown values of the canonical variable (CV <0.47; Table 1) are consistent with algal organic matter.

depositional conditions (anoxic versus oxic) (Didyk *et al.*, 1978). Sunda crude oils had an average Pr/Ph ratio value of 3.07, ranging from 2.28 to 3.87, while Asri crude oils had an average Pr/Ph ratio value of 2.78, ranging from 1.87 to 3.77 (Table 2). The high Pr/Ph ratios (>1) of the crude oils also indicate that organic matter was preserved under oxic-suboxic conditions (Connan and Cassou, 1980; Peters *et al*., 2005). Homohopane biomarkers can be used to interpret anoxic versus oxic conditions during source-rock deposition (Peters *et al*., 2005). The crude oils had relatively low homohopane indices (Table 2), suggesting oxic-suboxic conditions. This is consistent with the relatively low C_{35}/C_{34} homohopanes ratio and low C_{31} homohopane/C_{30} hopane ratio (Peters and Moldowan, 1991; Peters *et al*., 2019) (Figure 6). The relative abundance of diasteranes and low-molecular steranes over regular steranes can also be used for source-rock depositional settings (Wang *et al.*, 2015). The crude oils have relatively high diasteranes and dominant regular steranes over low-molecular steranes, also suggesting oxic-suboxic conditions (Figure 3c).

Interestingly, Sunda and Asri oils have moderate BNH peaks. Although the origin of these biomarkers is not completely understood, BNH is frequently found in source rocks deposited under anoxic conditions (Peters *et al*., 2005). However, as the biomarkers suggest that Sunda and Asri oils were generated from oxic-suboxic conditions, the authors argue that BNH could also be found in oxic-suboxic conditions. This study aims to challenge the conventional understanding that significant crude oil resources in the Sunda and Asri Basins are produced from source rocks deposited entirely in anoxic environments (Prayitno *et al*., 1992; Sukanto *et al*., 1998). The authors present a novel interpretation of the Paleogene syn-rift Banuwati Formation, which contains lacustrine shales deposited in an oxic-suboxic environment. Although these shales were not deposited in an anoxic environment, they produced enormous amount of crude oils, providing a counter example to the old interpretation.

Organofacies of Crude Oils

In this study, the depositional paleoenvironment and conditions of the organic matter input of the source rock that expelled the crude oils were primarily based on the biomarker and nonbiomarker results, as presented in the

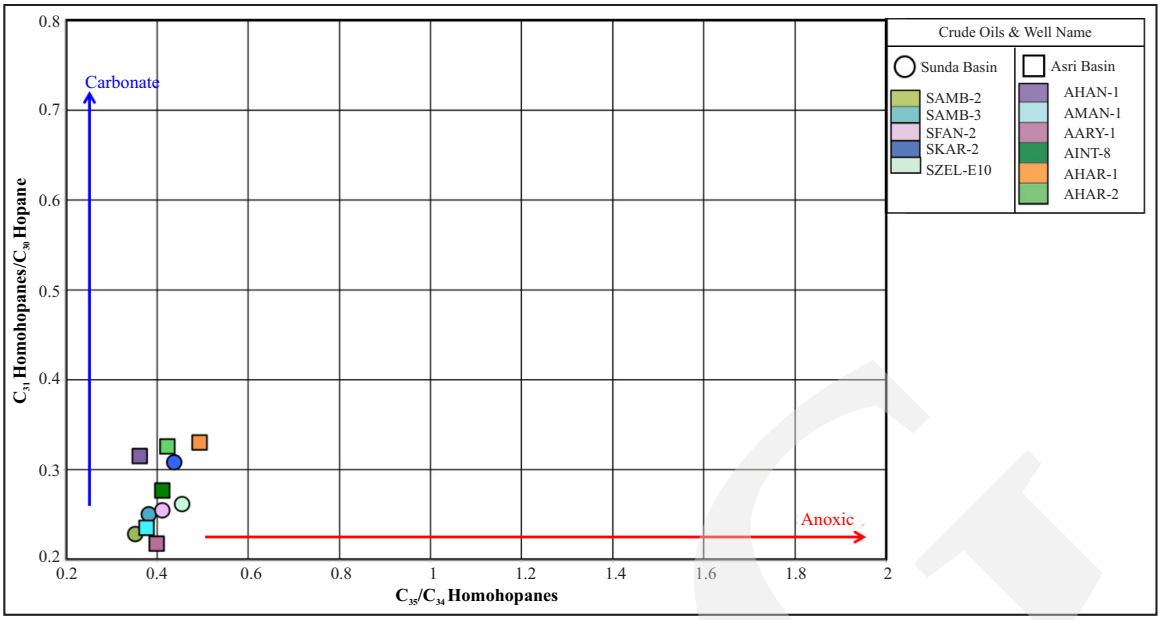

Figure 6. Lower C_{35}/C_{34} homohopanes and C_{31} homohopane/C_{30} hopane indicate more oxic−suboxic conditions and more clastic (shale) input during source rock-deposition (after Peters *et al.*, 2005, 2019).

previous subsections. Sunda and Asri crude oils strongly suggest the characteristics of lacustrine organofacies. The n-alkane distributions of the saturated hydrocarbons for the crude oil were characterized by a predominance of low to moderate molecular weight compounds in the GC, suggesting a high contribution of nonhigher plants organic matter input (*e.g.* algae; Tissot and Welte, 1984). Gas chromatograms displayed a bimodal peak in the n-alkanes (Figure 2). This bimodal peak has also been reported in GC analyses of crude oils derived from lacustrine source rocks, such as those found in the Central Sumatra Basin, Indonesia (Robinson, 1987; Katz and Lin, 2014); the Uinta Basin, USA (Ruble *et al.*, 2001); and the Bohay Bay Basin, China (Huang *et al.*, 2003).

The predominantly low CV values (<0.47) shown in Table 1 and the bulk values of the $\delta^{13}C$ saturated and aromatic fractions (Figure 5) suggest the algal origin of organic matter (Sofer, 1984). The C_{29} norhopane/C_{30} hopane ratio was used to predict the source organic facies (carbonate versus shale lithology) (Clark and Philp, 1989; Subroto *et al.*, 1991; Peters *et al.*, 2005; Al-Khafaji *et al.*, 2018; Hartono *et al.*, 2023), a higher concentration of C_{30} hopane compared to C_{29} norhopane is suggested of the shale source-rock (C_{29}/C_{30} H <1.0; Figure 3b; Table 2). The environmental interpretation used bivariate plots of C_{29}/C_{30} hopanes and C_{35}/C_{34} homohopanes biomarker ratio, indicating possible lacustrine shale or coal (Peters *et al.*, 2005) (Figure 7). The relatively strong biomarker parameters in determining the lacustrine environment are the C_{26}/C_{25} terpanes ratio, in which lacustrine is usually characterized by a higher concentration of C_{26} over C_{25} tricyclic terpanes *(Zumberge, 1987; Peters et al.*, 2005). The lacustrine crude oils are best distinguished using C_{31} homohopane/C_{30} hopane in combination with other parameters, such as the C_{26}/C_{25} tricyclic terpanes and the canonical variable from stable carbon isotope measurements *(Peters et al.*, 2005). The C_{26}/C_{25} tricyclic terpanes and C_{31} homohopane/C_{30} hopane ratio suggest lacustrine shale environment deposition (Peters *et al.*, 2005) (Figure 8). This interpretation was aligned with all Sunda and Asri crude oils having relatively higher C_{26} and C_{21} tricyclic terpanes content than those of C_{25} and C_{19} tricyclic terpanes, respectively (Figure 3b).

The depositional paleoenvironment and the origin of organic matter can also be indicated from the m/z 217 mass fragmentograms of the saturated hydrocarbon fraction of all crude oils. The relatively high diasteranes over regular ster-

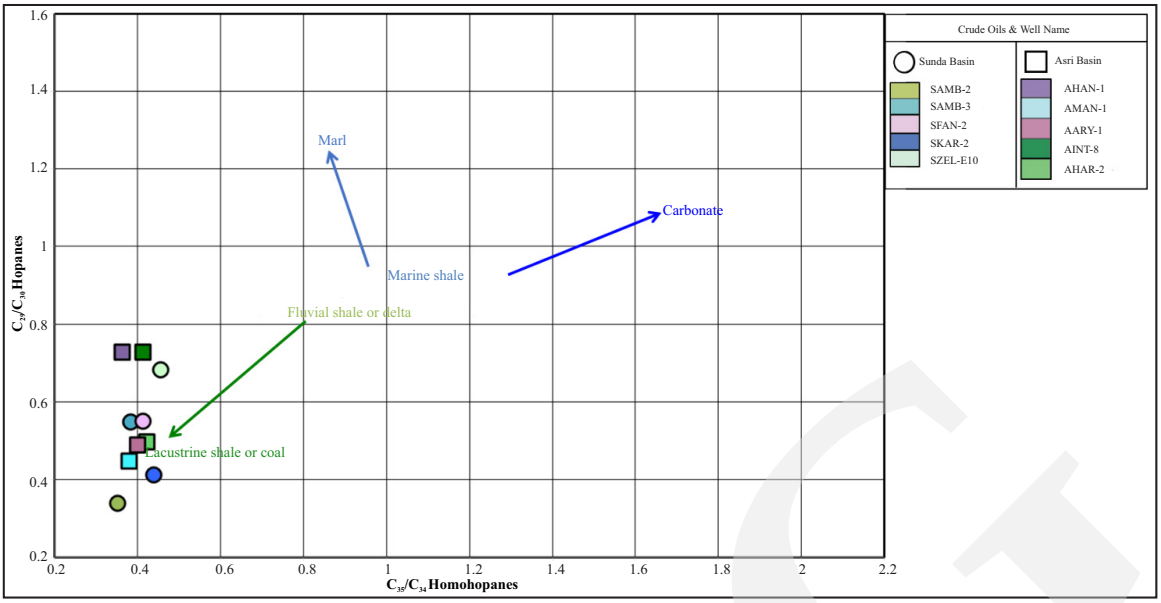

Figure 7. Plot between the ratio of C_{29}/C_{30} hopanes and C_{35}/C_{34} homohopanes. The assigned lithologies are based on > 500 global crude oil used to predict the source rock depositional environment (after Peters *et al.*, 2005). The environmental interpretation indicated possible lacustrine shale or coal.

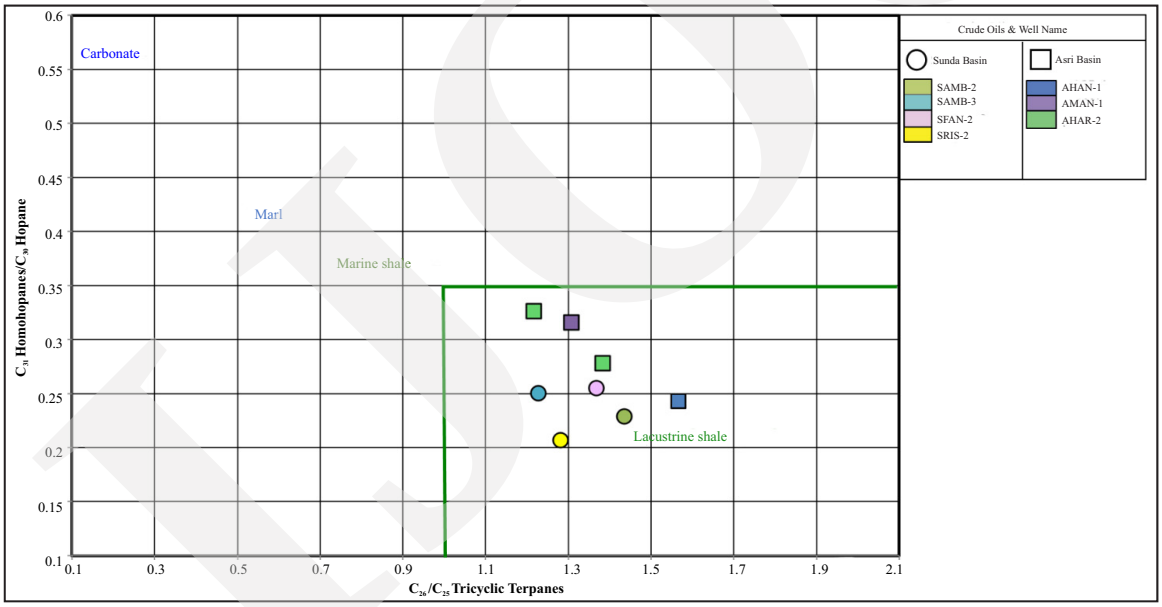

Figure 8. Plot between the ratio of C_{26}/C_{25} tricyclic terpanes *vs*. C_{31} homohopane/C_{30} hopane. The assigned lithologies are based on > 500 global crude oil generated from known source rock (after Peters *et al*., 2005). The lacustrine crude oils from lacustrine source-rock indicate high C_{26}/C_{25} tricyclic terpanes and low C_{31} homohopane/C_{30} hopane.

anes also support a clay-rich source rock (Wang *et al*., 2015) (Figure 3c). The saturated hydrocarbon fraction is characterized by a relatively high abundance of C_{27} regular steranes compared to C_{28} and C_{29} regular steranes (Figure 3c; Table 2). This can also be indicative of planktonic-algal or planktonic bacterial organic matter (Peters *et al.*, 2005; Xu *et al*., 2019) as indicated by the regular the sterane ternary diagram (Figure 9; Huang and Meinschein, 1979; Al- Khafaji *et al*., 2018; Xu *et al.*, 2019). Most of the samples relatively are located in the same plot (Figure 9), except from SFAN-2 plot in planktonic algal which possibly related to marine depositional environment. How-

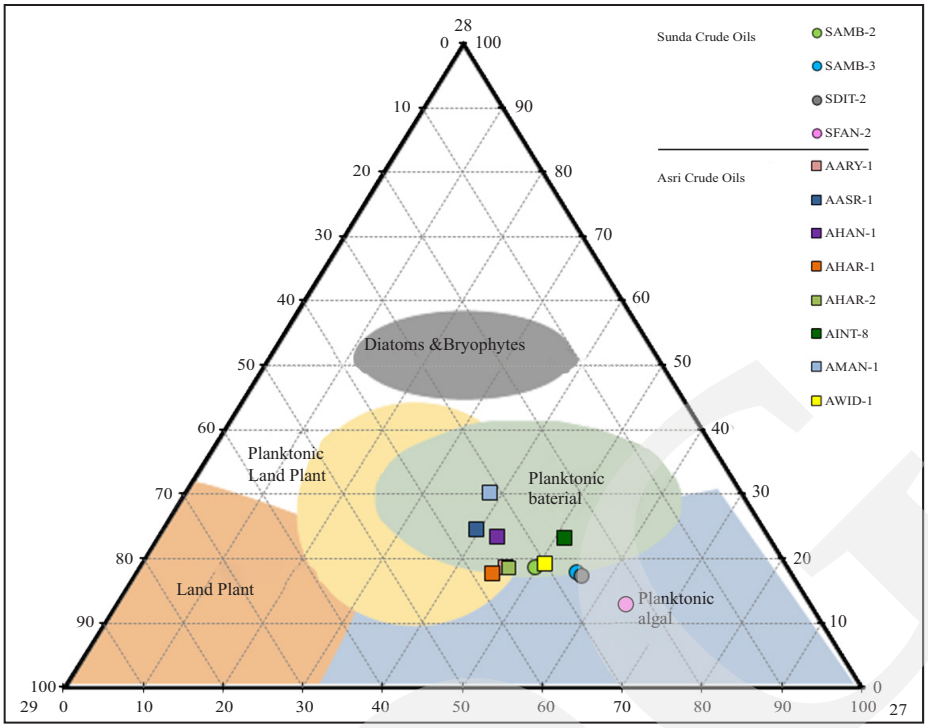

Figure 9. C_{27}-C_{28}-C_{29} regular sterane diagram for indicating the relationship between sterane compositions in relation to organic matter input and depositional environment (adapted from Huang and Meinschein, 1979; Al-Khafaji *et al.*, 2018; Xu *et al*., 2019). The Sunda crude oils are relatively more algal origin than Asri crude oils.

ever, SFAN-2 has C_{26} higher than C_{25} tricyclic terpanes, presence the C_{30} 4-methylsterane, and exhibits consistently low sulfur content supporting a nonmarine depositional environment. The presence of C_{30} 4-methylsterane is often abundant in lacustrine sediments and crude oils (Robinson, 1987; Summons *et al*., 1992). The C_{30} 4-methylsterane observed in m/z 217 steranes in all crude oils from The Sunda and Asri Basins also support the interpretation of a lacustrine environment (Figure 3c). Lacustrine can be subdivided into deep lacustrine, shallow lacustrine, and fluvial-lacustrine (Longley *et al*., 1990). The possibility of different lacustrine organofacies in crude oils from the Sunda and Asri Basins can be seen as an interesting pattern in the C_{27}-C_{28}-C_{29} steranes diagram (Figure 9). This pattern suggests that the lacustrine environments of the Sunda and Asri Basins have relatively different organic matter compositions. The Sunda crude oils are more influenced by algal origin, typically, common in shallow to deep lacustrine environments. Whilst Asri crude oils tend to be expelled from source rocks that are relatively more influenced by higher plants that are usually common in fluvial-lacustrine settings (Figure 9). This difference can be explained by the Asri Basin being located further north and closer to the main Sundaland compared to the Sunda Basin in the southern area.

The presence of bicyclic alkanes (high peak of 8β(H)-drimane and 8β(H)-homodrimane) in m/z 123 indicates the contribution of bacterial organic matter and some terrigenous higher plants input to the source rock (Noble *et al.*, 1986; Peters *et al*., 2005; Ji *et al*., 2016) (Figure 3a). Abundant bicyclic alkanes with relative abundances of 8β(H)-drimane and 8β(H)-homodrimane have also been reported from the Tertiary lacustrine source-rock in Qaidam Basin, China (Luo *et al.*, 1991). The contribution of higher plant material input to the sediments was also observed in the m/z 191 mass fragmentograms, as suggested by the minor occurrence of OL (Figure 3b). The presence of OL biomarker also implies that the source age was younger than Late Cretaceous (Moldowan *et al*., 1994).

Crude Oils to Source Rock Correlation

The crude oils in the Sunda and Asri Basins are characterized as sweet, paraffinic to high wax, lacustrine crude oils. In this study, the genetic link between crude oil and its potential source rock was investigated using biomarkers and carbon isotopes. The rock sample from the Banuwati Formation suggests to have carbon isotope values that are relatively similar to Sunda and Asri crude oils.

In contrast, the carbon isotopes of the Talangakar Formation showed a much lighter composition (Figure 5). This character was also supported by GC and m/z 191 mass fragmentograms. The characteristics of crude oil biomarkers in this study were relatively similar to those of the Banuwati Formation (Figure 10). The Banuwati Formation is classified as a very good source rock because of its high TOC (>2 wt%), S2 (>10 mg/g rock), HI (>200), and Tmax (>435°C) (Dembicki Jr., 2009, 2017), as summarized in Table 3. This formation was recently reassessed by Priyanto *et al.* (2023), consisting predominantly of algal organic material and classified as a Type I source

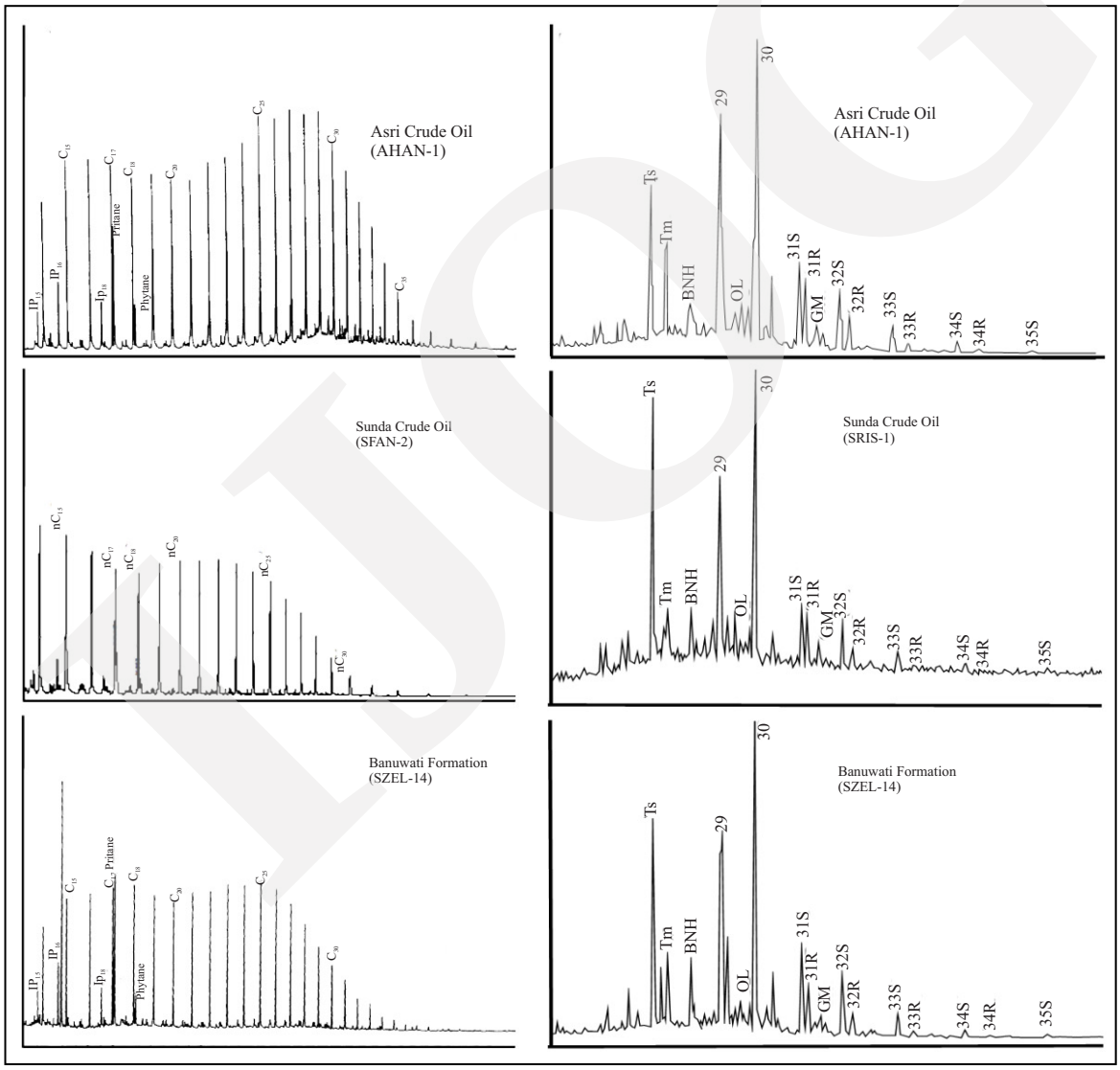

Figure 10. Representative of biomarker characteristics. The left figures indicate a comparable relatively bimodal GC patterns between the Asri and Sunda crude oils to Banuwati Formation. The right figures show several characteristics such as Ts higher than Tm, the homohopanes generally decrease toward the C_{35} homohopane, higher concentration of C_{30} hopane compared to C_{29} norhopane. The Sunda and Asri crude oils exhibit relatively similar biomarker characteristics to the Banuwati Formation source rock.

rock both in Sunda and Asri Basins. In summary, the Paleogene syn-rift oxic-suboxic Banuwati Formation is a proven source rock for the crude oils in this study.

Conclusions

This study presents a detailed and systematic investigation of the geochemical characteristics and origin of crude oils from the Sunda and Asri Basins, Indonesia. The results show that:

- Crude oils were generated from early to peak mature source-rocks based on biomarker maturity ratios and nonbiomarker data.
- The geochemical analyses reveal a differentiation in lacustrine organofacies between the Sunda and Asri Basins. The Sunda Basin exhibits geochemical signatures indicative relatively deeper lacustrine, while the Asri Basin reflects a relatively shallower lacustrine environment.
- The crude oils from the Sunda and Asri Basins originated from the oxic-suboxic shale source- rock of the Paleogene syn-rift Banuwati Formation.
- The importance of considering a more comprehensive range of depositional environments when evaluating source rock potential indicates that oxic-suboxic environments may be more productive than previously thought. The Banuwati Formation serves as a regional example of this potential, and expands the understanding of petroleum systems in the syn-rift systems.

Acknowledgements

The authors would like to thank the PERTAMINA EP Management and Subsurface Exploration Team (Region 2/Area 2), who provided background geological data and permission for this research to be published. The authors also thank the anonymous reviewers for improving the original manuscript and the editors for publishing this paper.

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