Evaluation of Hydrocarbon Source Rock Potential and Organic Geochemistry in North Arafura Shelf, Papua (Indonesia)

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Manuscript received: May, 14, 2019; revised: January, 16, 2020; approved: January 26, 2021; available online: August, 22, 2021

Abstract - The results of this study identified two potential source rock intervals of Permian age in the North Arafura Shelf area of Papua, Indonesia. The first potential source rock interval (SR-1) was identified at 3834.9 m to 3838.6 m depth within the Kola-1 well, which is believed to be good to very good potential source rock with TOC in the range of 2.94 to 3.4 wt %, S1 0.78 to 0.97 mg HC/g, and S2 5.63 to 9.5 mg HC/g. The source rock is composed of type II and III kerogens with HI in the range of 164 to 275 mg HC/gTOC and reached the maturation stage with Ro of 0.83 - 0.86%, Tmax of 442 - 444°C, and Production Index (PI) of 0.09 - 0.12. The second potential source rock interval (SR-2) is at 3060.1 - 3136.3 m depth in the ASM-1X well and has fair potential to be source rock with TOC of 0.95 wt %, S1 of 1.01 mg HC/g, and S2 of 3.39 mg HC/g. This source rock has type II kerogen with a HI value of 357 mg HC/g TOC and has reached maturation as indicated by a Ro value of 0.63%, Tmax of 430°C, and PI of 0.23. Biomarker analysis revealed SR-1 is type III kerogen with terrigenous input and was deposited in an estuarine environment.

Keywords: source rock, biomarker, Permian, eastern Indonesia

How to cite this article:
Sabra, E., 2021. Evaluation of Hydrocarbon Source Rock Potential and Organic Geochemistry in North Arafura Shelf, Papua (Indonesia). Indonesian Journal on Geoscience, 8 (3), p.401-416. DOI: 10.17014/ijog.8.3.401-416

INTRODUCTION

Background
The studied location is in eastern Indonesia, which is considered to be an exploration frontier for hydrocarbons. Several wells were drilled within the area (i.e. ASM-1X Wells, Kola-1, ASA-1, Buaya Besar-1, and South Octa-1), but all are plugged and abandoned (Aldha and Ho, 2008) (Figure 1). However, poor documentation of source rocks in this area may lead to further unsuccessful exploration. Previous studies have been conducted regionally, in order to investigate the source rock potential (Peck and Soulhol, 1986; Sulaeman et al., 1990; Livsey et al., 1992; Kendrick and Hill, 2002; Aldha and Ho, 2008; Subroto and Noeradi, 2008). Unfortunately, none of these studies have applied comprehensive source rock evaluation in smaller, more discreet areas.

The present study intends to investigate the source rock potential based on the evaluation of quantity, quality, and maturity of organic matter within a specific area. In addition, several biomarker parameters will be used to determine the source of hydrocarbons. The goal is that these results will provide guidance for future exploration endeavors.

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Geological Settings

Papua comprises four main tectonic regions: 1. Stable Platform, 2. Fold and Thrust Belt, 3. Mobile Belt, and 4. Paleogene arcs and oceanic terranes (Hill and Hall, 2003) (Figure 2), experienced five tectonic stages: 1. Pre-Rift, 2. Syn-Rift, 3. Post-Rift or Passive Margin, 4 Convergence, and 5. Compression (Harahap, 2012).

The Pre-Rift stage is characterized by the deposition of Silurian-Devonian Modio, Kemum, and Kora Formations, followed by non-deposition and erosion in the Early Devonian with marine transgression and then followed by folding, slight metamorphism, and uplifting of the Kemum Formation during the Late Devonian or possibly as late as the Early Carboniferous (Harahap, 2012).

The Syn-Rift phase is manifested by the extension and rifting during the Carboniferous to Permian that led to deposition of the fluvial deltaic Aiduna Formation (Ufford, 1996; Kusnama, 2008; Harahap, 2012), which has been identified as an oil and gas source rock (Subroto and Noeradi, 2008). The Syn-Rift phase is thought to have occurred under an arid climate with volcanic activity; the fluvial red-bed dominated Tipuma Formation is conformable with the overlying Triassic-age Aiduna Formation (Kusnama, 2008; Harahap, 2012).

The Post-Rift stage began in the Jurassic, which is characterized by the deposition of Kembelangan Group (Harahap, 2012), sediments that consist of four formations: the Kopai, Woniwogi, Piniya, and Ekmai (Panggabean and Hakim, 1986; Kusnama, 2008). Foresman et al. (1972) stated that the Kopai and Piniya Formations are the highest quality potential source rocks within the Waghete map sheet area. The Kopai Formation is composed of medium- and fine-grained sandstone (Ufford, 1996), conformably overlain by the sandstone dominated Woniwogi Formation (Panggabean and Hakim, 1986; Kusnama, 2008). Overlying the Woniwogi Formation, the Piniya Formation has been described as laminated and massive mudstones and siltstones interbed with fine-grained sandstone. This formation is conformably overlain by the Late Cretaceous Ekmai Formation consisting of coarse- to fine-grained sandstones (Ufford, 1996). The Post-Rift stage is followed by uplift and erosion of the southern platform of Papua in the Late Cretaceous and Paleocene, and then by the deposition of the New Guinea Limestone during the Eocene (Hill and Hall, 2003).
The convergence phase corresponds to the uplift of Papua, erosion and deposition of clastics into the foreland, the drop in sea level during the Oligocene, and collision of the Australian Plate with Southeast Asia in the Late Oligocene-Early Miocene that allowed the deposition of deep marine KlasiFet Formation (Harahap, 2012).

The compression stage occurred during the Late Miocene to Pleistocene which is attributed to the deposition of the Steenkool and Buru Formations (Harahap, 2012). The Buru Formation has been identified as a source rock with good potential and is characterized by TOC in the range of 1 - 3%, HI between 200 and 300, and a dominated type III kerogen (KNOC, 2006). Vitrinite reflectance indicated that shallow parts of this formation were immature, while the deeper parts had reached maturation stage (Aldha and Ho, 2008). The stratigraphic succession is summarized in Figure 3.

### Data and Methods

The data used in this paper were acquired from the Kola-1 and ASM-1X wells. A total of 182 data points were collected for source rock evaluation, consisting of 140 data from Kola-1 well, 42 data points from ASM-1X well, and 6 from other wells. The data were processed using standard geochemical and geophysical methods.

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**Figure 3. Stratigraphic column of Papua (Western Part of New Guinea) which has experienced five tectonic evolution stages: 1. Pre-Rift, 2. Syn-Rift, 3. Post-Rift or Passive Margin, 4. Convergence, and 5. Compression (after Kusnama, 2008; Davies, 2012; Harahap, 2012).**
from the ASM-1X well, and 1 data point was used from Kola-1 well having biomarker analysis. The source rock evaluation was not applied to coaly (coals, shaly coals, and coaly mudstones) lithologies, due to their separated guidelines for source rock evaluation (Sykes and Snowdon, 2002).

The parameters used for quantity and quality of organic matter analysis include the total organic carbon (TOC), free hydrocarbon (S1), remaining potential (S2), carbon dioxide (S3), hydrogen index (HI), and oxygen index (OI). The thermal alteration scale (TAS), spore colouration index (SCI), temperature of maximum pyrolysis (Tmax), production index (PI), and vitrinite reflectance (% Ro) were also carried out in order to determine the maturity of source rock. Identification of hydrocarbon source was performed using parameters including pristane/nC\textsubscript{17} ratio (Pr/nC\textsubscript{17}), phytane/nC\textsubscript{18} ratio (Ph/nC\textsubscript{18}), pristane to phytane ratio (Pr/Ph), hopane to sterane ratio (hop/ster), carbon isotope composition, and C\textsubscript{27-29} steranes.

**Results and Discussions**

**Quantity and Quality of Organic Matter**

Most of the samples within the Kola-1 well have TOC values higher than 0.5 % and S2 values lower than 2.5 mg HC/g, which means most of these samples have sufficient organic matter but low genetic potential to generate hydrocarbon (Tables 1 and 2). The samples that can be suggested as potential source rocks are identified at Permain age from 3834.9 m to 3838.6 m depth and marked as the first potential source rock interval (SR-1) (Figures 4a, b, c, d). This interval is characterized by TOC of 2.94 - 3.4 wt.%, S1 of 0.78 - 0.97 mg HC/g rock, and S2 of 5.63 - 9.5 mg HC/g rock, which is suggestive of good to very good source rock. This conclusion is also confirmed by plots of TOC against S2 and TOC against S1+S2 (Figures 5a, b). SR-1 has HI values from 164 to 275 mg HC/g TOC which means this source rock contains kerogen type II and III and will generate both oil and gas when it reaches peak maturity. A plot of TOC against S2-HI also confirmed the organic matter type of this interval (Figure 6).

The TOC values higher than 0.5 wt.% within the ASM-1X well are identified at Permain age only and the potential source rocks interval is found at 3060.1 - 3136.3m depth (Table 3) assigned as the second potential source rock interval (SR-2) (Figures 7a, b, c, d). SR-2 has a TOC value of 0.95 wt.%, S1 of 1.01 mg HC/g rock, and S2 of 3.39 mg HC/g rock, which is indicative of fair source rock and confirmed by plots of TOC against S1+S2 (Figures 8a and b). SR-2 has a HI value of 357 mg HC/g TOC, which is indicative of kerogen type II and will generate oil predominantly when reaches maturation window. The characteristics of this source rock are confirmed by plots of TOC against S2-HI and HI against OI (Figures 9a and b).
### Table 1. TOC and Rock-Eval Pyrolysis Data for the Kola-1 Well from Tertiary to Cretaceous Age, SR-1

| Age    | Sample Depth (m) | Lithology | TOC (Wt.%) | S1 (mg/g) | S2 (mg/g) | Tmax (°C) | Production Index (PI) | Potential Yield (S1 + S2) | Hydrogen Index |
|--------|-----------------|-----------|------------|-----------|-----------|-----------|-----------------------|----------------------------|----------------|
| Tertiary | 566.9 - 758.9   | Sh/Shltst | 0.88       | 0.12      | 0.86      | 428       | 0.12                  | 0.98                       | 98             |
| Tertiary | 887.0 - 1079.0  | Sh/Shltst | 0.84       | 0.04      | 0.35      | 427       | 0.10                  | 0.39                       | 42             |
| Tertiary | 1079.0 - 1207.0 | Sh/Shltst | 0.91       | 0.05      | 0.38      | 428       | 0.12                  | 0.43                       | 42             |
| Tertiary | 1371.6 - 1542.3 | Sh/Shltst | 0.71       | 0.03      | 0.38      | 427       | 0.07                  | 0.41                       | 54             |
| Tertiary | 1542.3 - 1712.9 | Sh/Shltst | 0.78       | 0.03      | 0.35      | 429       | 0.08                  | 0.38                       | 45             |
| Tertiary | 1841.0 - 1969.0 | Sh/Shltst | 0.90       | 0.03      | 1.71      | 426       | 0.02                  | 1.74                       | 174            |
| Tertiary | 2097.0 - 2267.7 | Sh/Shltst | 0.83       | 0.04      | 0.97      | 428       | 0.04                  | 1.01                       | 117            |
| Cretaceous | 3096.7 - 3139.4 | Sh/Shltst | 0.71       | 0.05      | 0.83      | 429       | 0.06                  | 0.88                       | 117            |
| Cretaceous | 3224.7 - 3267.4 | Sh/Shltst | 0.63       | 0.02      | 0.48      | 428       | 0.04                  | 0.50                       | 76             |
| Cretaceous | 3435.3 - 3459.4 | Sh/Shltst | 0.69       | 0.07      | 0.93      | 429       | 0.07                  | 1.00                       | 135            |
| Cretaceous | 3310.1 - 3352.7 | Sh/Shltst | 0.64       | 0.02      | 0.36      | 432       | 0.05                  | 0.43                       | 60             |
| Cretaceous | 3374.1 - 3437.4 | Sh/Shltst | 0.55       | 0.03      | 0.37      | 429       | 0.08                  | 0.40                       | 67             |
| Cretaceous | 3402.1 - 3495.4 | Sh/Shltst | 0.53       | 0.01      | 0.31      | 428       | 0.03                  | 0.32                       | 58             |
| Cretaceous | 3495.4 - 3523.4 | Sh/Shltst | 0.55       | 0.01      | 0.35      | 426       | 0.03                  | 0.36                       | 64             |
| Cretaceous | 3542.4 - 3544.8 | Sh/Shltst | 0.56       | 0.02      | 0.41      | 427       | 0.05                  | 0.43                       | 73             |
| Cretaceous | 3546.8 - 3578.7 | Sh/Shltst | 0.59       | 0.02      | 0.31      | 432       | 0.03                  | 0.32                       | 33             |
| Cretaceous | 3587.4 - 3608.8 | Sh/Shltst | 0.82       | 0.04      | 0.36      | 433       | 0.10                  | 0.40                       | 44             |
| Cretaceous | 3608.8 - 3630.1 | Sh/Shltst | 0.92       | 0.04      | 0.37      | 436       | 0.10                  | 0.41                       | 40             |
| Cretaceous | 3630.1 - 3651.4 | Sh/Shltst | 0.71       | 0.05      | 0.57      | 439       | 0.08                  | 0.62                       | 80             |
| Cretaceous | 3651.4 - 3672.8 | Sh/Shltst | 0.48       | 0.04      | 0.28      | 430       | 0.04                  | 0.28                       | 27             |
| Cretaceous | 3672.8 - 3694.1 | Sh/Shltst | 0.55       | 0.14      | 0.82      | 434       | 0.15                  | 0.96                       | 149            |
| Cretaceous | 3694.1 - 3715.5 | Sh/Shltst | 0.61       | 0.01      | 0.17      | 435       | 0.06                  | 0.18                       | 28             |
| Cretaceous | 3715.5 - 3736.8 | Sh/Shltst | 0.78       | 0.01      | 0.22      | 431       | 0.04                  | 0.23                       | 28             |
| Cretaceous | 3736.8 - 3758.1 | Sh/Shltst | 0.54       | 0.01      | 0.16      | 434       | 0.06                  | 0.17                       | 30             |
| Cretaceous | 3758.1 - 3779.5 | Sh/Shltst | 0.43       | 0.01      | 0.28      | 433       | 0.03                  | 0.29                       | 65             |
| Cretaceous | 3779.5 - 3800.8 | Sh/Shltst | 0.41       | 0.01      | 0.21      | 436       | 0.05                  | 0.22                       | 51             |
| Cretaceous | 3800.8 - 3822.1 | Sh/Shltst | 0.34       | 0.01      | 0.19      | 432       | 0.05                  | 0.20                       | 56             |
| Cretaceous | 3822.1 - 3843.5 | Sh/Shltst | 0.39       | 0.01      | 0.32      | 438       | 0.03                  | 0.33                       | 82             |

* Sh = shale, Slst = siltstone, Carbon = carbonaceous, Clst = claystone
Compared to SR-2 kerogen type, which is discussed above, a plot of S2/S3 against depth is different, which suggests SR-2 will generate oil and gas (Figure 9c). This difference is probably due to the increasing value of S3 that will reduce the value of S2/S3. The increasing value of S3 can be identified by the presence of elevated OI values which are usually associated with carbonate mineral densities (Figure 9b) (Katz, 1983). Therefore, the plot of S2/S3 against depth is not applied for this case.

### Maturity of Organic Matter

The first potential source rock interval (SR-1) has Ro values in the range of 0.83 to 0.86 % (Table 4) reflecting that it has entered the oil window and reached peak maturity (Figure 10a). This interval has TAS value 3/4 with yellow - yellowish orange and orange - dark brown fluorescence (Table 5), which is indicative of marginally mature to mature oil generation (Smith, 1983) (Figure 10b). Based on Tmax values that range from 442 - 444°C, SR-1 is regarded as an early stage of oil generation.
Figure 4. Assessment for organic matter quantity from the Kola-1 well using plots of: a) TOC against depth, b) S1 against depth, c) S2 against depth, and d) S1+S2 against depth. From these plots, it can be suggested the source rock interval is identified from 3834.9 to 3838.6m which is marked as SR-1.

Figure 5. Plots of: a) TOC against S2 and, b) TOC against S1+S2 suggesting SR-1 as a good to very good source rock.

Stage mature source rock (Figure 10c). PI values of 0.09 - 0.12 are inconclusive and indicate that this interval could be either immature or a mature source rock (Figure 10d). However, the relationship between HI-Tmax and Ro, does suggest that this source rock is within the mature zone of type II and III kerogen (Figure 10e). In addition, a Tmax-PI plot is also inconclusive and indicates that SR-1 could be either immature or a mature source rock (Figure 10f).
Taking into account all maturity parameters discussed above, the SR-1 well intervals are most likely within an immature to early mature stage, although vitrinite reflectance (Table 4) does suggest this interval could be a fully mature source rock, entering into peak maturity. The high % Ro, however, is possibly affected by an erosional unconformity (Figure 10a). Vitrinite reflectance values below an erosional unconformity may have higher values than expected (Dow, 1977). Therefore, the % Ro is not applied for this source rock in this case.

A vitrinite reflectance value of 0.63 % suggests that the second potential source rock interval

Table 3. TOC, Rock-Eval Pyrolysis, and Petrographic Data for the ASM-1X Well, SR-2

| Age         | Sample Depth (m) | Lithology | TOC (Wt.%) | mg/g | Tmax (°C) | Production Index (PI) | Potential Yield (S1 + S2) | Hydrogen Index | Oxygen Index | Mean Ro% | SCI |
|-------------|------------------|-----------|------------|-------|-----------|-----------------------|--------------------------|-----------------|--------------|----------|-----|
| Tertiary    | 917.4 - 1127.7   | Clyst     | 0.11       |       |           |                       |                          |                 |              |          | 2.25 |
| Mesozoic    | 1371.6 - 1584.9  | Clyst     | 0.35       |       | 0.35      | 3                     |                          |                 |              |          | 3    |
|             | 1734.0 - 1880.6  | Clyst     | 0.36       |       | 0.36      | 3.5-4                 |                          |                 |              |          | 3.5-4|
|             | 1880.6 - 2014.7  | Lst       | 0.23       |       |           |                       |                          |                 |              |          |      |
|             | 2014.7 - 2237.2  | Clyst     | 0.52       |       |           |                       |                          |                 |              |          |      |
|             | 2237.2 - 2615.1  | Clyst     | 0.51       |       |           |                       |                          |                 |              |          | 0.4  |
|             | 2615.1 - 2764.5  | Clyst     | 0.55       |       | 0.55      | 5                     |                          |                 |              |          | 5    |
| Permian     | 2764.5 - 2813.3  | Clyst     | 0.93       | 0.95  | 0.97      | 1.66                  | 430                      | 0.37            | 2.63         | 175     | 94  |
|             | 2904.7 - 2983.9  | Clyst     | 0.69       | 0.69  | 0.25      | 0.25                  | 440                      | 0.50            | 0.50         | 50      | 78  |
|             | 2983.9 - 3060.1  | Clyst     | 1.14       | 1.14  | 0.29      | 0.59                  | 429                      | 0.33            | 0.88         | 52      | 74  |
|             | 3060.1 - 3156.3  | Slst      | 0.74       | 0.74  | 0.48      | 0.94                  | 429                      | 0.34            | 1.42         | 127     | 167 |
|             | 3156.3 - 3317.3  | Lst       | 0.25       |       |           |                       |                          |                 |              |          |      |
|             | 3197.3 - 3282.6  | Lst       | 0.17       |       |           |                       |                          |                 |              |          |      |
|             | 3282.6 - 3374.1  | Lst       | 0.14       |       |           |                       |                          |                 |              |          |      |
|             | 3374.1 - 3486.9  | Slst      | 0.38       |       |           |                       |                          |                 |              |          | 0.71 |
|             | 3486.9 - 3572.2  | Lst       | 0.25       |       |           |                       |                          |                 |              |          |      |
|             | 3572.2 - 3639.3  | Lst       | 0.20       |       |           |                       |                          |                 |              |          |      |
|             | 3654.5 - 3688.0  | Lst       | 0.23       |       |           |                       |                          |                 |              |          | 0.74 |
|             | 3688.0 - 3730.7  | Lst       | 0.18       |       |           |                       |                          |                 |              |          | 5.5-6|
|             | 3730.7 - 3773.4  | Clyst     | 0.30       |       |           |                       |                          |                 |              |          |      |
|             | 3773.4 - 3806.9  | Clyst     | 0.40       |       |           |                       |                          |                 |              |          | 1.63 |
| Pre-Permian | 3806.9 - 3819.1  | Clyst     | 0.20       |       |           |                       |                          |                 |              |          | 8.5-9|

* Clyst = claystone, Lst = limestone, Siltst = siltstone
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(E. Sabra)

Figure 7. Assessment for organic matter quantity from the ASM-1X well using plots of: a) TOC against depth, b) S1 against depth, c) S2 against depth, and d) S1+S2 against depth. These plots identified potential source rock intervals from 3060.1 to 3136.3m which is marked as SR-2.

Figure 8. Plots of: a). TOC against S2 and, b). TOC against S1+S2 suggesting SR-2 as fair source rock.

(SR-2) has entered the oil window and is at an early mature stage (Figure 11a), but a SCI value of 5.5 indicates that SR-2 may be fully mature, though not at optimum maturity for oil generation (Figure 11b). In contrast, based on a Tmax value of 430°C, SR-2 would be considered as immature source rock (Figure 11c). A PI value of 0.23 would assign this source rock to a mature stage that has
entered the oil window (Figure 11d). From a HI-Tmax plot with % Ro, it can be noted this interval would be considered to be within the immature zone of type II kerogen (Figure 11e) and a PI-Tmax plot suggests that this source rock is in the immature – mature zone (Figure 11f).

Table 4. Vitrinite Reflectance (% Ro) Data for The Kola-1 Well, SR-1

| Age    | Sample Depth (m) | Mean Ro % |
|--------|------------------|-----------|
| Tertiary | 566.9 - 630.9    | 0.23      |
|         | 758.9 - 822.9    | 0.25      |
|         | 887.0 - 951.0    | 0.27      |
|         | 1079.0 - 1143.0  | 0.26      |
|         | 1214.9 **        | 0.30      |
|         | 1207.0 - 1271.0  | 0.25      |
|         | 1294.2 **        | 0.36      |
|         | 1483.1 **        | 0.37      |
|         | 1541.0 - 1584.9  | 0.43      |
|         | 1601.7 **        | 0.42      |
|         | 1712.9 - 1755.6  | 0.36      |
|         | 1783.1 **        | 0.39      |
|         | 1841.0 - 1883.6  | 0.45      |
|         | 1969.0 - 2011.6  | 0.50      |
|         | 2439.6 **        | 0.30      |
|         | 2712.7 - 2734.0  | 0.31      |
| Cretaceous | 3096.7 - 3118.1  | (0.90)    |
|         | 3139.4 - 3160.7  | 0.55      |
|         | 3224.7 - 3246.1  | 0.56      |
|         | 3255.2 **        | 0.52      |
|         | 3267.4 - 3288.7  | 0.58      |
|         | 3310.1 - 3331.4  | 0.64      |
|         | 3352.7 - 3374.1  | (0.82)    |
|         | 3438.1 - 3459.4  | 0.69      |
|         | 3523.4 - 3544.8  | (0.89)    |
|         | 3608.8 - 3630.1  | 0.73      |
|         | 3694.1 - 3715.5  | (0.79)/0.47|
|         | 3715.5 - 3736.8  | (0.97)    |
| Permian  | 3800.8 - 3822.1  | (0.78)/0.48|
|         | 3836.6 ***       | (0.83)/0.55|
|         | 3838.0 ***       | 0.86      |
|         | 3842.9 ***       | 0.87      |
|         | 3847.4 ***       | 0.91      |
|         | 3878.8 ***       | 0.96      |
|         | 3950.1 **        | (1.01)    |
|         | 3992.8 - 4014.2  | 0.72      |
| Indeterminate | 4166.6 - 4184.8  | 0.74/(1.09)|
|         | 4259.8 **        | 1.03      |
|         | 4248.8 - 4270.2  | 1.77      |
|         | 4270.2 - 4291.5  | 1.03      |
|         | 4334.2 - 4358.6  | 1.31      |
|         | 4339.4          | 1.12      |

*( ) = Reworked vitrinite
In summary, Tmax values assign SR-2 into an immature source rock stage, which differs from the other analyses that indicate these source rocks are at least in a stage of maturity. This difference is probably owing to factors that affect Tmax pyrolysis data, such as soluble organic matter and the effect which minerals may have (Gao et al., 2019). Additional studies would be necessary in order to properly assess the Tmax values.

**Source of Hydrocarbon**

Biomarker data are represented in Table 6. SR-1 has a Pr/nC$_{17}$ ratio of 0.58 and a Pr/nC$_{18}$ ratio of 0.15, assuming type III kerogen with terrigenous input. These results would suggest this interval is a mature source rock (Figure 12), which is in agreement with the assessment from the TOC-S2 plot with HI. From a plot of the δ$^{13}$C value of saturated fraction against δ$^{13}$C value of aromatic fraction of carbon isotope composition (Figure 13), it can be noted this interval is a terrestrial source rock with a CV (canonical value) of 2.91. Based on a hopane/sterane-Pr/Ph plot, it can be assumed this source rock was deposited in an anoxic - suboxic environment with terrestrial influence (Figure 14). The ternary diagram

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**Table 5. Thermal Alteration Scale Data for The Kola-1 Well**

| Age     | Sample Depth (m) | TAS |
|---------|------------------|-----|
|         | from to          |     |
| Tertiary| 758.9 - 822.9    | 2   |
|         | 887.0 - 951.0    | 2   |
| Cretaceous| 3587.4 - 3608.8 | 2   |
|          | 3672.8 - 3694.1 | 3-3/4 |
| Permian | 3826.7 - **      | 4/5 |
|          | 3828.5 - **      | 4-4/5 |
|          | 3843.5 - 3864.8 | 3/4 |
|          | 3878.8 - **      | 4/5-5 |
|          | 3898.3 - **      | 4/5-5 |
|          | 3910.8 - **      | 5   |
|          | 3950.1 - **      | 5   |

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Figure 10. a) A plot of % Ro against depth presenting SR-1 has reached maturity, this plot has two different trends which possibly affected by an erosional unconformity that made % Ro value below unconformity has higher values than expected, b) a plot of TAS against depth indicating SR-1 is within the immature to mature zone, c) a plot of Tmax against depth indicating SR-1 has reached maturation window, d) a plot of PI against depth assigning SR-1 is within the immature - mature zone, e) a plot of HI against Tmax-Ro indicating SR-1 is contain of type II kerogen and has reached maturity, f) a plot of PI against Tmax reflecting SR-1 is within the immature – mature zone.
Figure 11. Plots of: a) % Ro against depth indicating SR-2 has reached maturity level, b) SCI against depth assigning SR-2 has reached maturity level, c) Tmax against depth indicating SR-2 is within the immature zone, d) PI against depth assigning SR-2 has reached maturity level, e) HI against Tmax-Ro indicating SR-2 contains type II kerogen and within the immature zone, f) PI (S1/(S1+S2)) - Tmax reflecting SR-2 is within the immature - mature zone.

Figure 12. A Plot of Pr/nC_{17} against Ph/nC_{18} reflecting SR-1 containing type III kerogen with terrigenous input and has reached maturity level.

Figure 13. A plot of δ^{13}C of saturated fraction against and δ^{13}C of aromatic fraction from carbon isotope indicating SR-1 as source rock with terrigenous input.

Table 6. GC, GC-MS, and Carbon Isotop Data for SR-1

| Depth  | Pr/Ph | Pr/nC_{17} | Ph/nC_{18} | δ^{13}C_{saturated} | δ^{13}C_{aromatic} | CV | C_{27} | C_{28} | C_{29} | hop/sterol |
|--------|-------|------------|------------|---------------------|------------------|----|-------|-------|-------|------------|
| 3843.5 | 3.6   | 0.58       | 0.15       | -27.29              | -24.54           | 2.91| 35.42 | 24.4  | 41.1  | 5.76       |
is unusual and speculative, and would be needed to be confirmed through other analyses and placed within a palaeogeographic context.

**Factor Controlling High-Quality Source Rocks**

The estuarine environment and anoxic to suboxic condition are presumably the factors that led to the good quality of SR-1, because estuarine settings contain sediments with abundant organic matter which, of course, is conducive to the formation of source rocks (Allen and Allen, 2005; Boyd et al., 2006). In addition, anoxic conditions will confine the activity of bacteria that will damage organic matter as well as inhibit scavenging fauna causing bioturbation (Allen and Allen, 2005). Finally, the water column would be more anoxic and thus will allow the preservation of organic matter with high hydrogen content, which is reflected by the high $S_2$ value (Tyson, 1995).

**CONCLUSIONS**

This study assesses potential source rocks using pyrolysis and biomarker data and has identified two potential source rock intervals of Permian age which are marked as SR-1 and SR-2. SR-1 is identified in the 3834.9 m to 3838.6 m depth within the Kola-1 well, which is possibly good to very good source rock. This source rock is of type II and III kerogen with HI values ranging from 164 to 175 mg HC/g TOC. All maturity parameters used for SR-1 indicate this source rock is within the immature - early mature stage, except for % Ro value which suggested this interval is a fully mature source rock and has reached peak maturity. This difference is probably affected by an erosional unconformity which made % Ro values below the unconformity higher than expected.

SR-2 is identified from 3060.1 m to 3136.3 m depth within ASM-1X well, which is possibly a fair source rock. This interval is composed of type II kerogen with a HI value of 357 mg HC/g TOC. All maturity parameters used indicate SR-2 has entered the oil window and is in an early mature stage, except for the $T_{max}$ value which assigns this interval as immature source rock. The difference between the analysis results are probably related to factors that affect $T_{max}$ data pyrolysis such as soluble organic matter and the effect which minerals may have.

Biomarkers data assign SR-1 as a mature source rock, which contains type III kerogen and has terrigenous input, which is in agreement with the results from pyrolysis data. This data also suggest SR-1 as a source rock which was deposited in a bay or estuarine environment with anoxic to suboxic condition.

Further studies are required in order to determine if the source rocks were really deposited...
within an estuarine environment. However, the result of this study provides insight on the possible stages of source rocks, which may decrease exploration risk within the studied area, and can be used as a guide in basin modeling for further exploration. In spite of the source rocks that are identified in the immature – mature phase, the deeper, down dip source-rock intervals are expected to have higher maturity stages, as long as there are no facies changes. Therefore, further studies on the distribution and thickness of source rocks can be refined in order to determine the depths and position to focus future exploration efforts.

**ACKNOWLEDGEMENTS**

The author would like to acknowledge the Centre for Geological Survey and Patra Nusa Data of Ministry of Energy and Mineral Resources for assessing data. Special thanks to Rakhmat Fakhruddin who has given suggestions and discussion in writing the manuscript, and three anonymous reviewers for their comments, which greatly improved the quality of this paper. Finally, thanks for the editorial staff of this journal for input and corrections.

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