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

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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

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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 Oeta-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.

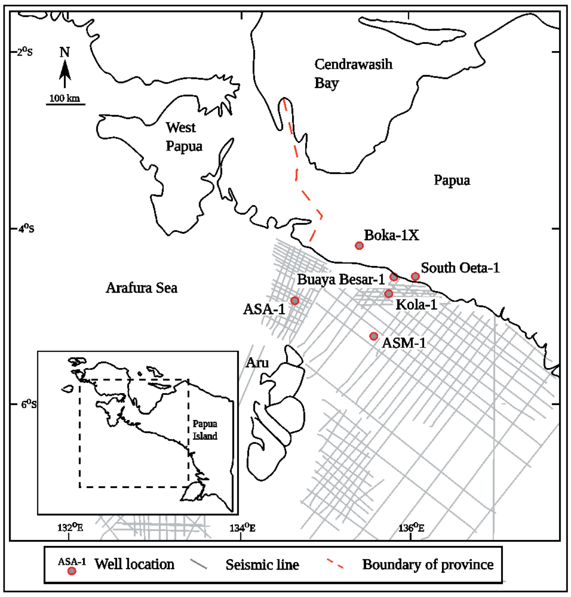

Figure 1. Map displaying several wells and seimic lines within the studied area (Ministry of Energy and Mineral Resources, Indonesia, 2019), all of these wells drilled are plugged and abandoned (Aldha and Ho, 2008).

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).

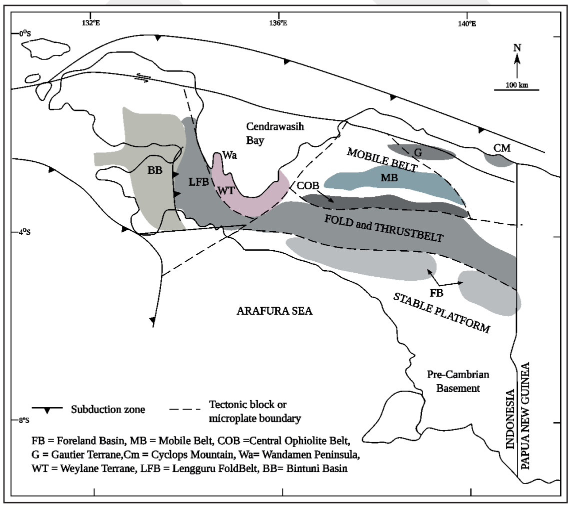

Figure 2. Map displaying tectonic features of Papua (Western Part of New Guinea) comprising Stable Platform, Fold and Thrust Belt, Mobile Belt, and Paleogene arcs and oceanic terranes (after Hill and Hall, 2003; Baldwin *et al.*, 2012; Davies, 2012).

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 Klasafet 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

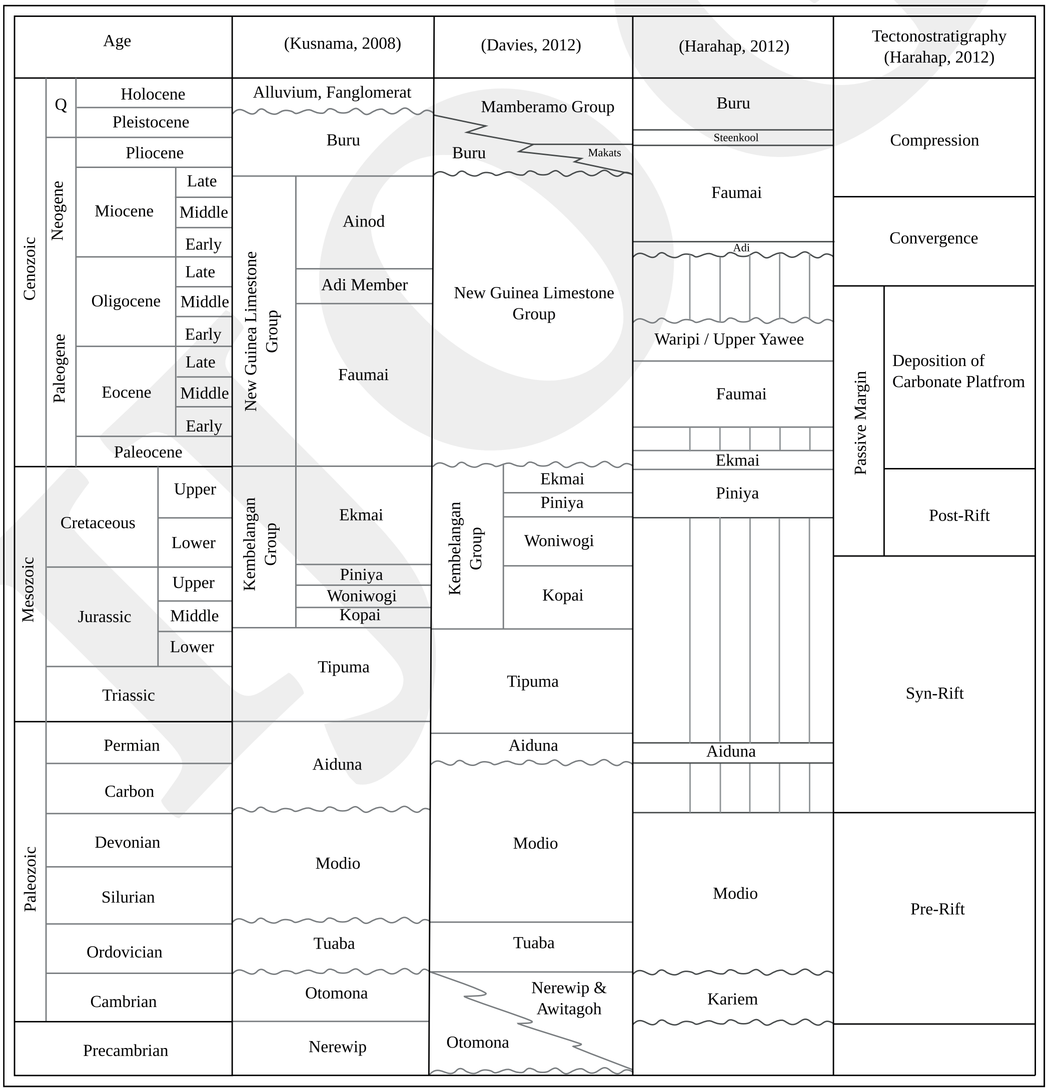

Figure 3. Stratigraphic column of Papua (Western Part of New Guinea) which has experienced five tectonic evolution stages: 1. Pre-Rift, 2. Syn-Rift, 3. Post-Rift or Passive Margin, 4. Convergence, and 5. Compression (after Kusnama, 2008; Davies, 2012; Harahap, 2012).

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_{17} ratio (Pr/nC_{17}), phytane/nC_{18} ratio (Ph/nC_{18}), pristane to phytane ratio (Pr/Ph), hopane to sterane ratio (hop/ster), carbon isotope composition, and C_{27-29} steranes.

The present study comprises four main analyses, those are the quantity, quality and maturity of organic matter, and the source of hydrocarbon. The quantity of organic matter was performed by plotting values of TOC, S1, S2, and S1+S2 against depth. In this assessment, samples were eliminated as potential source rocks if they contained TOC and S1 < 0.5, S2 < 2.5, and S1+S2 < 2. The quantity of organic matter is determined by plots of TOC against S2 and TOC against S1+S2. The TOC against S2-HI, HI against OI, S2/S3 against depth plots were applied in order to determine the organic matter types. The maturity of organic matter was identified by plotting Ro, TAS, SCI, Tmax, and PI against depth and HI and PI against Tmax plots. All of the analyses were performed by using geochemical parameters from Batten (1976), Smith (1983), Peters (1986), Peters and Cassa (1994), and Hunt (1996). Identification of hydrocarbon source was conducted using a plot of Pr/nC_{17} against Ph/nC_{18} (Peters *et al*., 2005), plot of hopane/sterane against Pr/Ph (Syamsuddin *et al*., 2019), plot of $\delta^{13}C$ value of saturated fraction against $\delta^{13}C$ value of aromatic fraction of carbon isotope composition (Sofer, 1984), and C_{27-29} steranes ternary diagrams (Huang and Meinschein, 1979).

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 Permian 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 reachs 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 Permian 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 S2 and 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	S2	Tmax (°C)	Production Index (PI)	Potential Yield (S1 + S2)	Hydrogen Index
	from		to			(mg/g)					
Tertiary	566.9	-	630.9	Sh/Sltst	0.88	0.12	0.86	428	0.12	0.98	98
	758.9	-	822.9	Sh/Sltst	0.84	0.04	0.35	427	0.10	0.39	42
	887.0	-	951.0	Sh/Sltst	0.91	0.05	0.38	428	0.12	0.43	42
	1079.0	-	1143.0	Shale	0.71	0.03	0.38	427	0.07	0.41	54
	1207.0	-	1271.0	Shale	0.78	0.03	0.35	429	0.08	0.38	45
	1371.6	-	1414.3	Shale	0.65	0.02	0.26	429	0.07	0.28	40
	1542.3	-	1584.9	Shale	0.66	0.04	0.41	426	0.09	0.45	62
	1712.9	-	1755.6	Sh/Sltst	0.82	0.06	0.44	432	0.12	0.50	54
	1841.0	-	1883.6	Sh/Sltst	0.98	0.03	1.71	426	0.02	1.74	174
	1969.0	-	2011.6	Sh/Sltst	0.83	0.04	0.97	428	0.04	1.01	117
	2097.0	-	2139.7	Shale	0.71	0.05	0.83	429	0.06	0.88	117
	2267.7	-	2310.3	Shale	0.63	0.02	0.48	428	0.04	0.50	76
	2435.3	-	2462.7	Shale	0.69	0.07	0.93	429	0.07	1.00	135
	2712.7	-	2734.0	Shale	0.68	0.02	0.41	429	0.05	0.43	60
Cretaceous	3096.7	-	3118.0	Shale	0.47	0.08	0.43	428	0.16	0.51	91
	3139.4	-	3160.7	Shale	0.48	0.04	0.18	431	0.18	0.22	38
	3182.1	-	3203.4	Shale	0.41	0.02	0.25	429	0.07	0.27	61
	3224.7	-	3246.1	Shale	0.56	0.02	0.37	426	0.05	0.39	66
	3267.4	-	3288.7	Shale	0.54	0.05	0.51	431	0.09	0.56	94
	3310.1	-	3331.4	Shale	0.64	0.02	0.36	432	0.05	0.38	56
	3352.7	-	3374.1	Shale	0.55	0.03	0.37	429	0.08	0.40	67
	3374.1	-	3395.4	Shale	0.53	0.01	0.31	428	0.03	0.32	58
	3395.4	-	3416.8	Shale	0.55	0.01	0.35	426	0.03	0.36	64
	3416.8	-	3438.1	Shale	0.56	0.02	0.41	427	0.05	0.43	73
	3438.1	-	3459.4	Shale	0.91	0.02	0.45	431	0.04	0.47	49
	3459.4	-	3480.8	Shale	1.15	0.01	0.31	433	0.03	0.32	27
	3480.8	-	3502.1	Shale	1.00	0.01	0.32	432	0.03	0.33	32
	3502.1	-	3523.4	Shale	0.99	0.01	0.27	430	0.04	0.28	27
	3523.4	-	3544.8	Shale	1.03	0.01	0.23	431	0.04	0.24	22
	3544.8	-	3566.1	Shale	1.13	0.02	0.31	432	0.06	0.33	27
	3566.1	-	3587.4	Shale	0.93	0.01	0.31	433	0.03	0.32	33
	3587.4	-	3608.8	Shale	0.82	0.04	0.36	433	0.10	0.40	44
	3608.8	-	3630.1	Shale	0.92	0.04	0.37	436	0.10	0.41	40
	3630.1	-	3651.4	Shale	0.71	0.05	0.57	439	0.08	0.62	80
	3651.4	-	3672.8	Shale	0.48	0.04	0.28	430	0.13	0.32	58
	3672.8	-	3694.1	Shale	0.55	0.14	0.82	434	0.15	0.96	149
	3694.1	-	3715.5	Shale	0.61	0.01	0.17	435	0.06	0.18	28
	3715.5	-	3736.8	Shale	0.78	0.01	0.22	431	0.04	0.23	28
	3736.8	-	3758.1	Shale	0.54	0.01	0.16	434	0.06	0.17	30
	3758.1	-	3779.5	Shale	0.43	0.01	0.28	433	0.03	0.29	65
	3779.5	-	3800.8	Shale	0.41	0.01	0.21	436	0.05	0.22	51
	3800.8	-	3822.1	Shale	0.34	0.01	0.19	432	0.05	0.20	56
	3826.7	-	**	Carb. Clst	0.67	0.04	0.37	432	0.10	0.41	55
	3828.5	-	**	Shale	0.78	0.04	1.16	436	0.03	1.20	149
	3822.1	-	3843.5	Shale	0.39	0.01	0.32	438	0.03	0.33	82

* Sh = shale, Sltst = siltstone, Carbon = carbonaceous, Clst = claystone

Table 2. TOC and Rock-Eval Pyrolysis Data for the Kola-1 Well from Permian to the Total Depth, SR-1

Age	Sample Depth (m)			Lithology	TOC (Wt.%)	S1	S2	Tmax (°C)	Production Index	Potential Yield (S1 + S2)	Hydrogen Index
	from		to			(mg/g)			(PI)		
Permian	3834.9	-	***	Shale	3.43	0.78	5.63	442	0.12	6.41	164
	3838.0	-	***	Shale	2.68	0.27	3.15	448	0.08	3.42	118
	3838.6	-	***	Shale	3.45	0.97	9.50	444	0.09	10.47	275
	3846.5	-	***	Shale	2.94	0.17	5.09	445	0.03	5.26	173
	3843.5	-	3864.8	Shale	0.46	0.01	0.32	434	0.03	0.33	70
	3864.8	-	3886.1	Shale	0.90	0.03	0.81	444	0.04	0.84	90
	3878.8	-	**	Clst	1.34	0.07	0.90	441	0.07	0.97	67
	3898.3	-	**	Shale	0.99	0.02	0.98	449	0.02	1.00	99
	3886.1	-	3907.5	Shale	1.24	0.04	0.83	443	0.05	0.87	67
	3910.8	-	**	Clst	0.78	0.04	0.56	443	0.07	0.60	72
	3907.5	-	3928.8	Shale	1.36	0.06	1.00	442	0.06	1.06	74
	3928.8	-	3950.1	Shale	1.27	0.04	0.95	443	0.04	0.99	75
	3950.1	-	**	Shale	1.69	0.05	0.87	442	0.05	0.92	51
	3950.1	-	3971.5	Shale	1.33	0.07	1.07	443	0.06	1.14	80
	3971.5	-	3992.8	Shale	0.83	0.02	0.59	445	0.03	0.61	71
	3992.8	-	4014.2	Shale	0.75	0.02	0.44	446	0.04	0.46	59
	4014.2	-	4035.5	Shale	1.34	0.03	1.12	440	0.03	1.15	84
Indeterminate	4035.5	-	4056.8	Shale	0.41	0.01	0.25	435	0.04	0.26	61
	4056.8	-	4078.2	Lst	0.15						
	4078.2	-	4099.5	Lst	0.14						
	4099.5	-	4120.8	Lst	0.19						
	4120.8	-	4142.2	Lst	0.21						
	4142.2	-	4145.2	Lst	0.12						
	4166.6	-	4184.8	Dol	0.05		0.02	442	0.00	0.02	40
	4248.8	-	**	Dol	0.50	0.06	0.09		0.40	0.15	18
	4248.8	-	4270.2	Dol	0.11	0.01	0.04		0.20	0.05	36
	4248.8	-	4270.2	Clyst/Sltst	0.14	0.01	0.06		0.14	0.07	43
	4257.4	-	**	Dol	0.22	0.03	0.21	437	0.13	0.24	95
	4259.8	-	**	Dol	0.23		0.13		0.00	0.13	57
	4270.2	-	4291.5	Shale	0.04		0.01		0.00	0.01	25
	4339.4	-	**	Dol	0.23	0.01	0.16		0.06	0.17	70
	4334.2	-	4358.6	Dol	0.17	0.06	0.18	380	0.25	0.24	106
	4334.2	-	4358.6	Sh/Sltst	0.19	0.21	0.74	382	0.22	0.95	389

* Dol = Dolomite, Lst = Limestone, Sh = shale, Sltst = Siltstone, 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

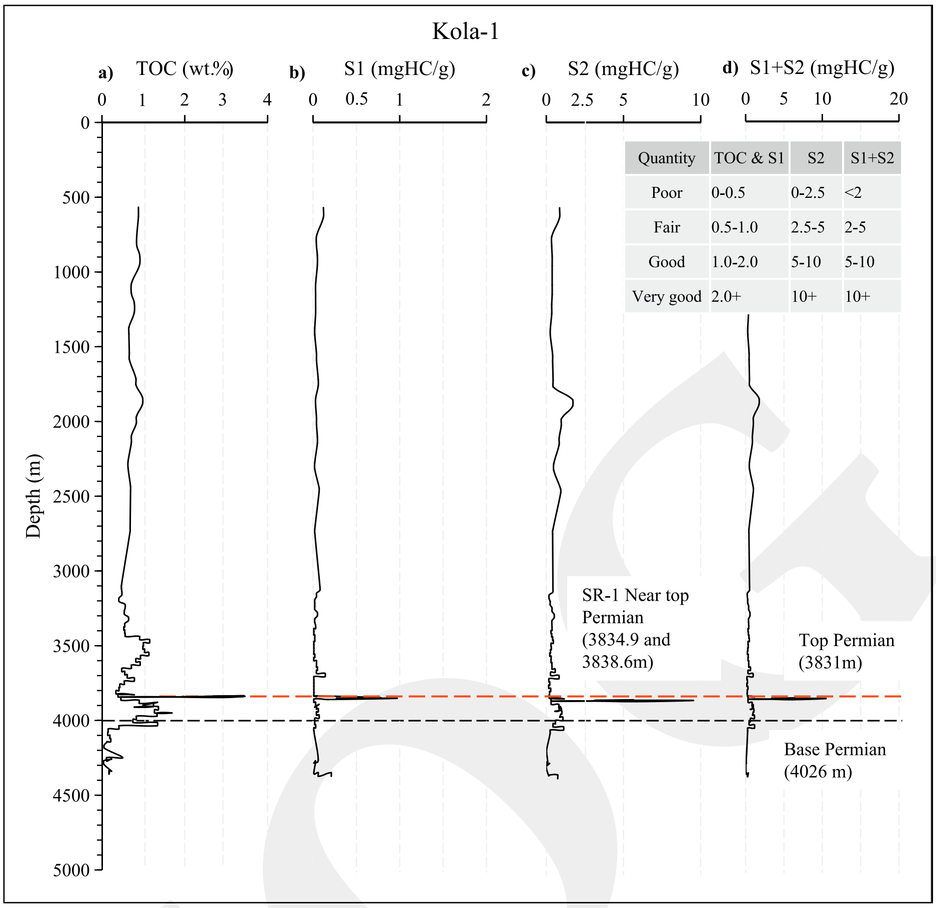

Figure 4. Assesment for organic matter quantity from the Kola-1 well using plots of: a) TOC against depth, b) S1 against depth, c) S2 against depth, and d) S1+S2 against depth. From these plots, it can be suggested the source rock interval is identified from 3834.9 to 3838.6m which is marked as SR-1.

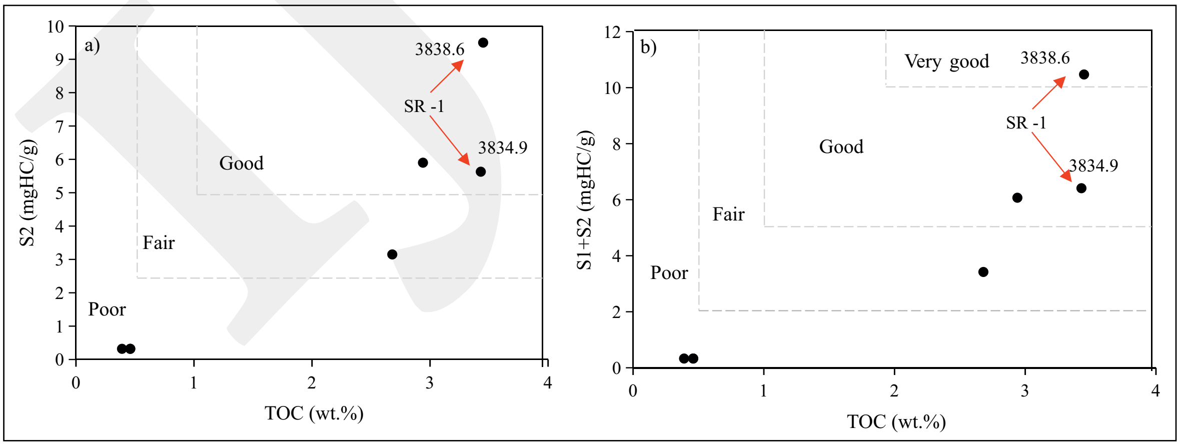

Figure 5. Plots of: a). TOC against S2 and, b). TOC against S1+S2 sugesting SR-1 as a good to very good source rock.

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).

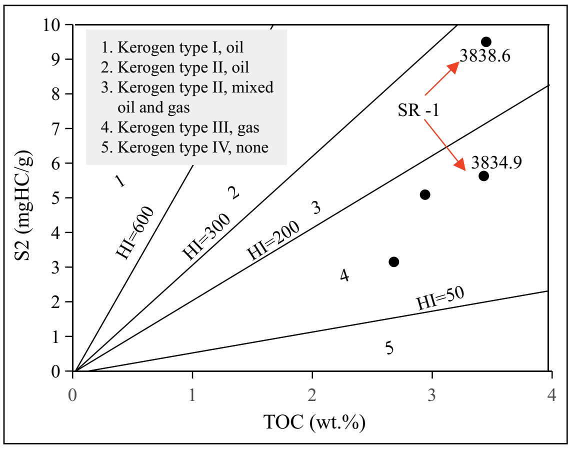

Figure 6. Plots of TOC against S2 presenting SR-1 contains type III and IV kerogen with H1 value from 164 - 275 mg HC/g TOC.

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
	from		to			S1	S2							
Tertiary	917.4	-	1127.7	Clyst	0.11									2-2.5
Mesozoic	1371.6	-	1584.9										0.35	3
	1734.0	-	1880.6										0.36	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	4.5
Permian	2615.1	-	2764.5	Clyst	0.60	0.21	0.33	432	0.39	0.54	55	120		
	2764.5	-	2813.3	Clyst	0.95	0.97	1.66	430	0.37	2.63	175	94	0.6	5
	2904.7	-	2983.9	Clyst	0.69	0.25	0.25	440	0.50	0.50	36	789		
	2983.9	-	3060.1	Clyst	1.14	0.29	0.59	429	0.33	0.88	52	74	0.63	5-5.5
	3060.1	-	3136.3	Sltst	0.74	0.48	0.94	429	0.34	1.42	127	167		
				Clyst	0.95	1.01	3.39	430	0.23	4.40	357	92		
	3136.3	-	3197.3	Lst	0.25									
	3197.3	-	3282.6	Lst	0.17									
	3282.6	-	3374.1	Lst	0.14									
	3374.1	-	3486.9	Sltst	0.38								0.71	5
				Clyst	1.20	0.37	0.94	420	0.28	1.31	78	200		
	3486.9	-	3572.2	Lst	0.21									
	3572.2	-	3639.3	Lst	0.20									
	3654.5	-	3688.0	Lst	0.23								0.74	5.5-6
	3688.0	-	3730.7	Lst	0.18									
	3730.7	-	3773.4	Clyst	0.30									
	3773.4	-	3806.9	Clyst	0.40								1.63	8.5-9
Pre-Permian	3806.9	-	3819.1	Clyst	0.20									

* Clyst = claystone, Lst = limestone, Sltst = siltstone

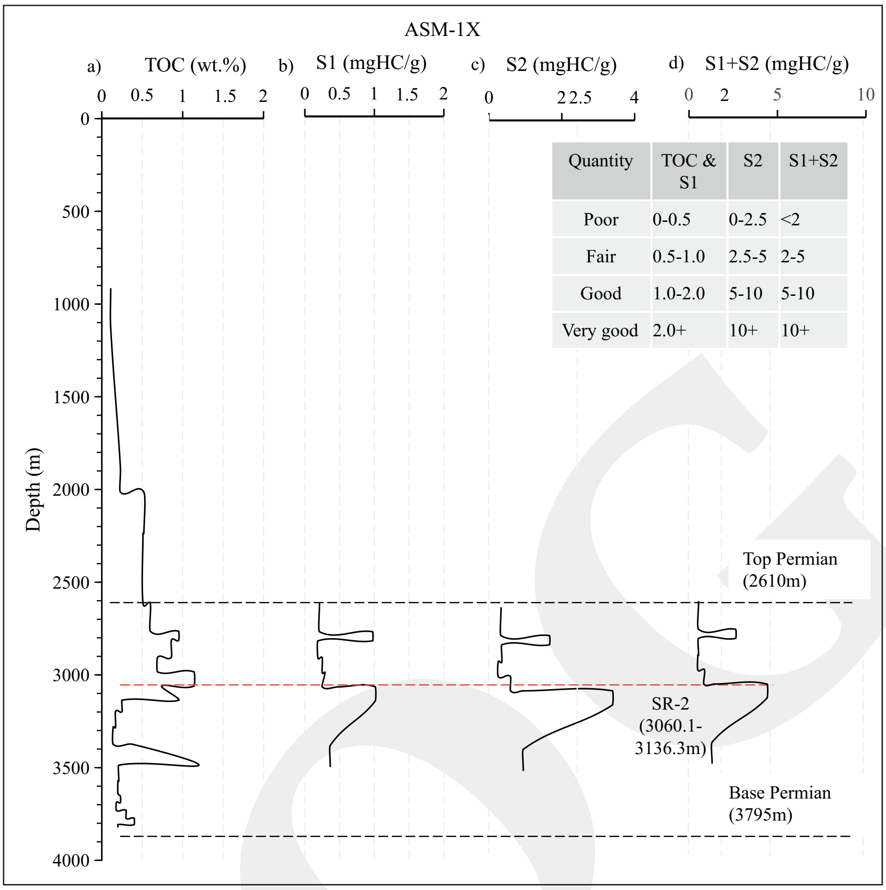

Figure 7. Assesment for organic matter quantity from the ASM-1X well using plots of: a) TOC against depth, b) S1 against depth, c) S2 against depth, and d) S1+S2 against depth. These plots identified potential source rock intervals from 3060.1 to 3136.3m which is marked as SR-2.

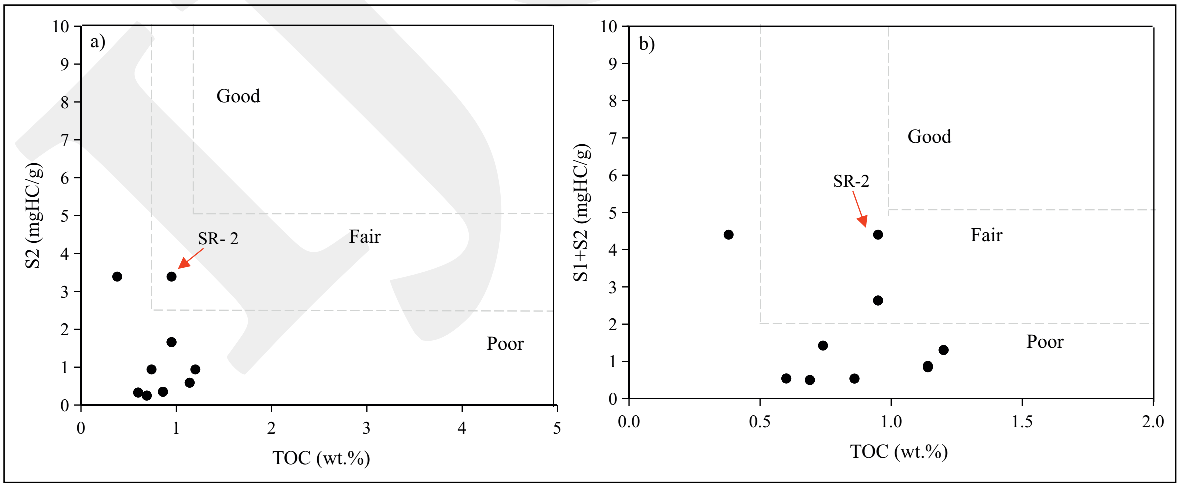

Figure 8. Plots of: a). TOC against S2 and, b). TOC against S1+S2 suggesting SR-2 as fair source rock.

(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^{o}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

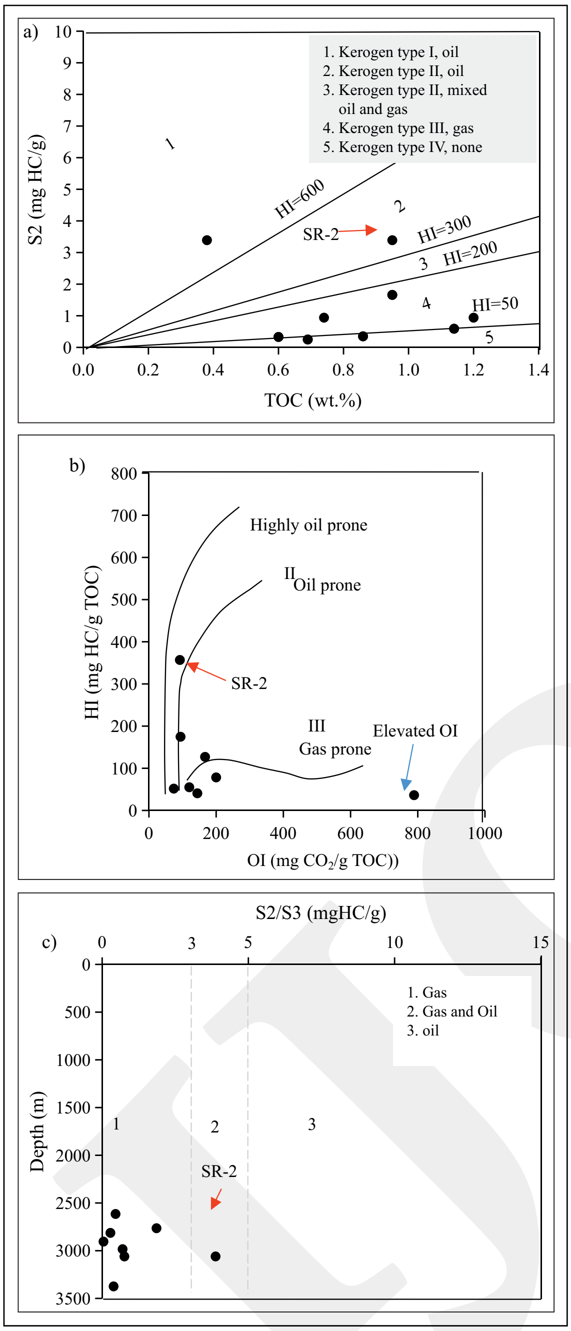

Figure 9. Plots: a). A plot of TOC against S2-HI indicating SR-2 contains type II kerogen with HI value of 357 mg HC/g TOC, b). HI against OI suggesting SR-2 as an oil prone kerogen, and c). S2/S3 against depth suggesting SR-2 will generate gas and oils when reach maturity.

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 %**
	from		**to**	
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

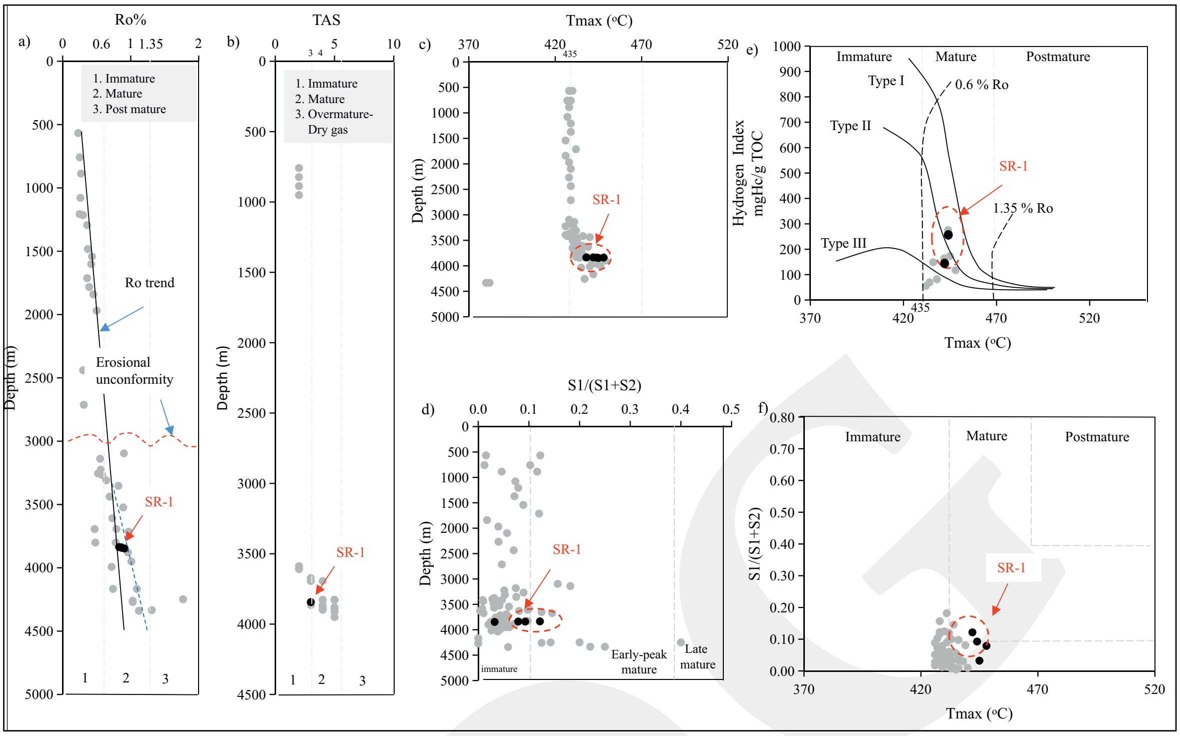

Figure 10. a) A plot of % Ro against depth presenting SR-1 has reached maturity, this plot has two different trends which possibly affected by an erosional unconformity that made % Ro value below uncorformity has higher values than expected, b) a plot of TAS against depth indicating SR-1 is within the 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.

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

Age	Sample Depth (m) from		to	TAS
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

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 $\delta^{13}C$ value of saturated fraction against $\delta^{13}C$ value of aromatic fraction of carbon isotope composition (Figure 13), it can be noted this interval is a terrigenous 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

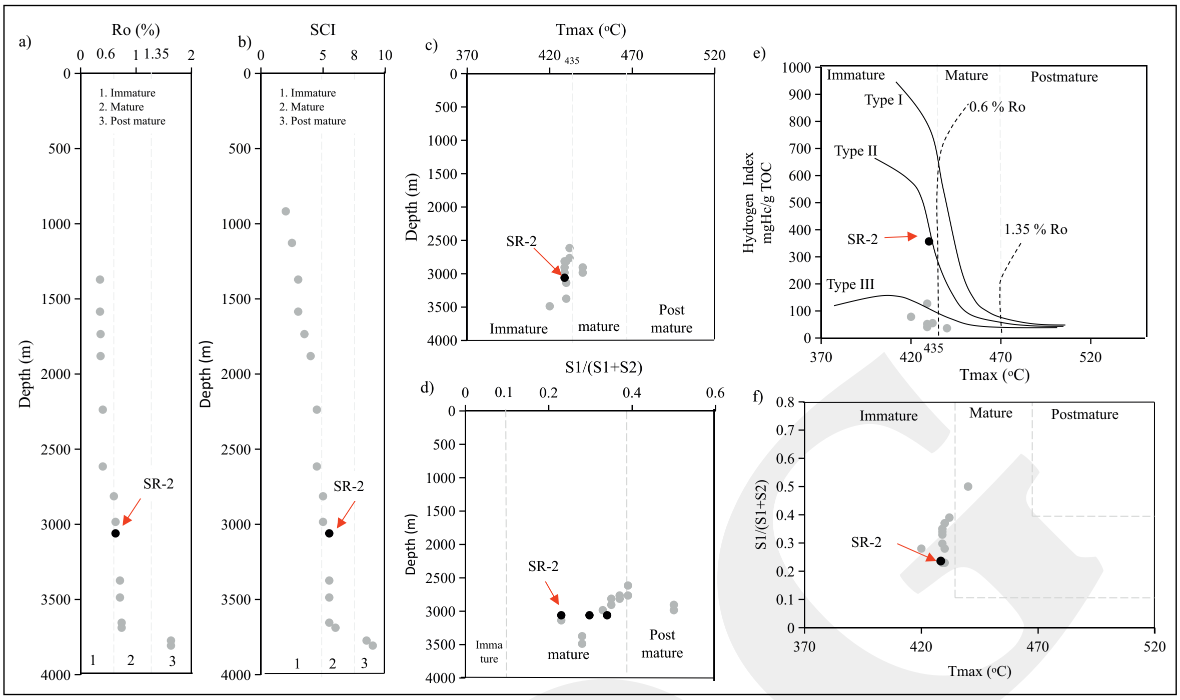

Figure 11. Plots of: a). % Ro against depth indicating SR-2 has reached maturity level, b). SCI against depth assigning SR-2 has reached maturity level, c). Tmax against depth indicating SR-2 is within the immature zone, d). PI against depth assigning SR-2 has reached maturity level, e). HI against Tmax-Ro 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.

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

Depth	N-alkanes			Carbon isotopes			steranes			hop/ster
	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	$\delta^{13}C_{saturated}$	$\delta^{13}C_{aromatic}$	CV	C_{27}	C_{28}	C_{29}	
3843.5	3.6	0.58	0.15	-27.29	-24.54	2.91	35.42	24.4	41.1	5.76

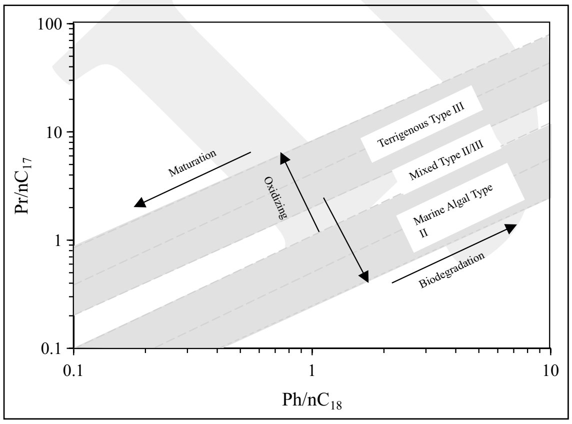

Figure 12. A Plot of Pr/nC_{17} against Ph/nC_{18} reflecting SR-1 containing type III kerogen with terrigenous input and has reached maturity level.

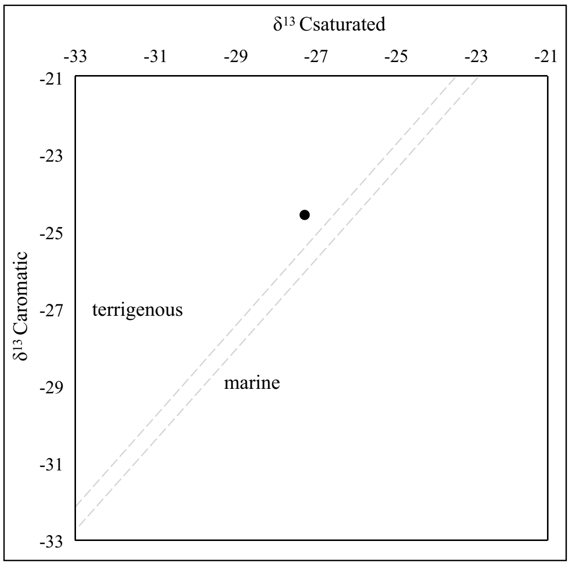

Figure 13. A plot of $\delta^{13}C$ of saturated fraction against and $\delta^{13}C$ of aromatic fraction from carbon isotope indicating SR-1 as source rock with terrigenous input.

of C_{27-29} steranes suggests that this source rock was deposited in a bay or estuarine environment (Figure 15). The estuarine deposit of Permian age

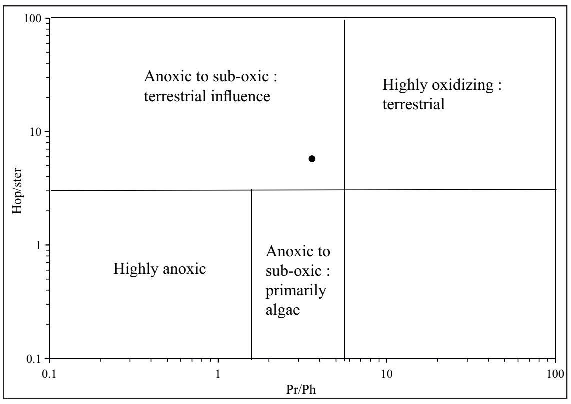

Figure 14. A plot of hopane/sterane against Pr/Ph assigning SR-1 was deposited in the anoxic to suboxic condition with terrestrial influence.

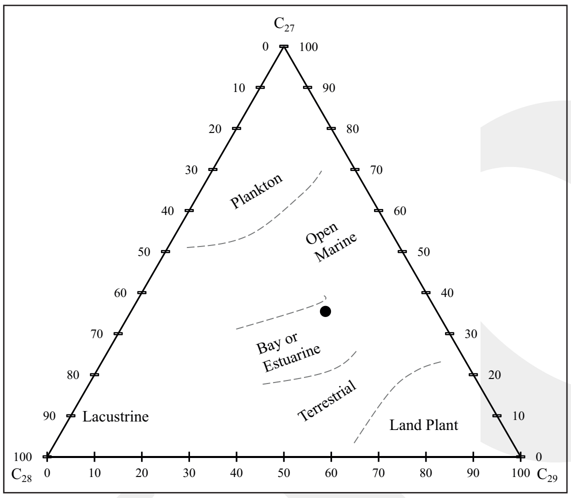

Figure 15. Ternary diagrams of C_{27-29} steranes indicating SR-1 was deposited in the bay or estuarine environment.

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 S2 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 Tmax value which assigns this interval as immature source rock. The difference between the analysis results are probably related to factors that affect Tmax 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.

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References

Aldha, T. and Ho, K.J., 2008. Tertiary hydrocarbon in NW Arafura Shelf, offshore south Papua; Frontier area in eastern Indonesia. *Proceedings of Indonesian Petroleum Association, 32nd Annual Convention and Exhibition,* Jakarta, IPA08-G-144, 9pp.

Allen, P.A. and Allen, J.R., 2005. *Basin Analysis, Principles and Applications, Second Edition*. Blackwell Publishing, 549 pp.

Baldwin, S.L., Fitzgerald, P.G., and Webb, L.E., 2012. Tectonics of the New Guinea region. *Annual Review Earth Planetary Sciences*, 40, p. 495-520. DOI:10.1146/annurev-earth-040809-152540.

Batten, D.J., 1976. Use of transmitted light microscopy of sedimentary organic matter for evaluation of hydrocarbon source potential. 4th International Palynology Conference, Lucknow. *In*: Smith, P.M.R. (ed.) 1983, *Spectral correlation of spore coloration standards*. Geological Society of London Publications, 12, p.289-294.

Boyd, R., Dalrymple, R.W., and Zaitlin, B.A., 2006. Estuarines and Incised-Valley Facies Models, SEPM Special Publication, 84, p.171-237. *In*: Posamentier, H.W. and Walker, R.G. (eds.), *Facies model revisited*. Society for Sedimentary Geology, Tulsa, 525pp.

Davies, H.L., 2012. The geology of New Guinea - the Cordilleran margin of the Australian continent, Earth Sciences, University of Papua New Guinea. *Episodes*, 35 (1), p.87-102.

Dow, W.G., 1977. Kerogen studies and geological interpretations. *Journal of Geochemical Exploration*, 7, p.79-99. DOI: 10.1016/0375-6742(77)90078-4.

Foresman, J.B., Perkins, E.H., Froideveaux, C.M., and Morris, D.A., 1972. Geologic study of the onshore Arafura Sea contract area: West Irian, Indonesia. Phillips Petroleum Company, Exploration Projects Group, Surface Projects Section Report (unpublished). *In*: Kendrick, R.D. and Hill, K.C., 2002. Hydrocarbon play concept for the Irian Jaya fold belt. *Proceedings of Indonesian Petroleum Association, 28th Annual Convention and Exhibition*, Jakarta, p.353-367.

Gao, X., Wang, P., Li, J., Wang, M., and Ma, W., 2019. Influencing factors of the Tmax parameter in Rock-Eval pyrolysis. *IOP Conference Series: Earth and Environmental Science,* 360 012011. DOI:10.1088/1755-1315/360/1/012011.

Harahap, B.H., 2012. Tectonostratigraphy of the southern part of Papua and Arafura Sea, Eastern Indonesia. *Indonesian Journal of Geology*, 7 (3), p.167-187. DOI: 10.17014/ijog.7.3.167-187.

Hill, K.C. and Hall, R., 2003. Mesozoic-Cenozoic evolution of Australia's New Guinea margin in a West Pacific context. *Geological Society Australia Special Publication 22 and Geological Society America Special Paper,* 372, p.265-289.

Huang, W.Y. and Meinschein, W.G., 1979. Sterols as ecological indicators. *Geochimica et Cosmochemica Acta*, 43, p.739-745.

Hunt, J.M., 1996. *Petroleum Geochemistry and Geology, Second Edition*, W.H. Freeman and Company, 743pp.

Katz, B.J., 1983. Limitations of 'Rock-Eval' pyrolysis for typing organic matter. *Organic Geochemistry*, 4, p.195-199. DOI: 10.1016/0146-6380(83)90041-4.

Kendrick, R.D. and Hill, K.C., 2002. Hydrocarbon play concept for the Irian Jaya fold belt. *Proceedings of Indonesian Petroleum Association, 28th Annual Convention and Exhibition*, Jakarta, p.353-367.

KNOC-PT. GEOSERVICES, 2006. Source rock analysis and geochemical characterization (unpublished internal report). *In*: Aldha, T. and Ho, K.J. (eds.), 2008. Tertiary hydrocarbon in NW Arafura Shelf, offshore south Papua; Frontier Area in Eastern Indonesia. *Proceedings of Indonesian Petroleum Association, 32nd Annual Convention and Exhibition*, Jakarta, IPA08-G-144, 9pp.

Kusnama, 2008. Stratigrafi daerah Timika dan sekitarnya. *Jurnal Sumber Daya Geologi,* 14 (4), p.202-222.

Livsey, A.R., Duxbury. N., and Richards, F., 1992. The geochemistry of Tertiary and Pre-Tertiary source rocks and associated oils in eastern Indonesia. *Proceedings of Indonesian Petroleum Association, 21st Annual Convention and Exhibition*, Jakarta, p.500-520.

Ministry of Energy and Mineral Resources, Indonesia, 2019. *ESDM One Map Indonesia*, https://geoportal.esdm.go.id/peng_umum/.

Panggabean, H. and Hakim, A.S., 1986. Reservoir rock potential of the Paleozoic-Mesozoic sandstone of the southern flank of the Central Range, Irian Jaya. *Proceedings of Indonesian Petroleum Association, 15th Annual Convention and Exhibition*, Jakarta, p.461-476.

Peck, J.M. dan Soulhol, B., 1986. Pre-Tertiary tensional periods and their effect on the petroleum potential of eastern Indonesia. Proceedings Indonesian Petroleum Association, 15th Annual Convention and Exhibition, Jakarta, p.341-369.

Peters, K.E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis. *American Association of Petroleum Geologists, Bulletin*, 70, p.318-329.

Peters, K.E. and Cassa, M.R. 1994, Applied source rock geochemistry. *In*: Magoon, L.B. and Dow, W.G. (eds.), *The Petroleum system - from source to trap*. AAPG Memoir, 60, p.93-120.

Peters, K.E., Walters, C.C., and Moldowan, J.M., 2005. *The Biomarker Guide, Biomarkers and Isotopes in the Environment and Human History*. Cambridge University Press, 1155pp.

Smith, P.M.R., 1983. Spectral correlation of spore coloration standards. *Geological Society of London Publications*, 12, p.289-294. DOI: 10.1144/ GSL.SP.1983.012.01.29.

Sofer, Z., 1984. Stable carbon isotope compositions of crude oils: Application to source depositional environments and petroleum alteration. *American Association of Petroleum Geologist, Bulletin*, 68 (1), p.31-49.

Subroto, E.A. and Noeradi, D., 2008. Petroleum system of the Paleozoic and Mesozoic formation intervals in the northern Arafura Sea, Papua, Indonesia. *8th Middle-East Geoscience Conference Exhibition (GEO 2008)*, Bahrein, 1p. (Abstract only)

Sulaeman, A., Sjapawi, A., and Sosromiharjo, S., 1990. Frontier exploration in the Lengguru fold belt Irian Jaya, Indonesia. *Proceedings of Indonesian Petroleum Association, 15th Annual Convention and Exhibition*, Jakarta, p.85-105.

Syamsuddin, E., Jamaluddin, Maria, Shehzad, K., and Wahyuni, S., 2019. Bio-markers based oil to source rock correlation and paleo-environmental interpretation: A case study from Talang Akar Formation, South Sumatra Basin, Indonesia. *Journal of Physics, The*

3rd International Conference on Science. DOI:10.1088/1742-6596/1341/8/082023.

Sykes, R. and Snowdon, L.R., 2002. Guidelines for assessing the petroleum potential of coaly source rocks using Rock-Eval pyrolysis. *Organic Geochemistry*, 3 p.1441-1455. DOI: 10.1016/S0146-6380(02)00183-3.

Tyson, R.V., 1995. *Sedimentary Organic Matter*, *Organic facies and palynofacies*. Springer-Science+Business Media, B.V., 615pp.

Ufford, A., 1996. *Stratigraphy, structural geology, and tectonics of a young forearc-continent collision, western Central Range, Irian Jaya (western New Guinea), Indonesia* [Doctoral dissertation]: Austin, Texas, The Univesity of Texas, 421pp.