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Pre-Cenozoic Petroleum System Evaluation from the Aruah Islands Outcrops

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Abstract

A geological field work in Aruah Islands as part of Joint Study in Rupat Area was conducted in 2020 for an evaluation of Greater Central Sumatra Basin hydrocarbon potential. The island is located about 68 kilometers from port of Bagan Siapiapi, situated at the border of Indonesia's territory and Malaysia in Malacca Strait.

Field observation and rock samples collection were done to provide new data set. The geological field work visited three islands, they are Jemur, Sarang Elang, and Labuhan Bilik Islands. Stratigraphic measured section, structural geology measurement, and sample collection were the main geological field works and conducted at the Jemur Island. The islands lithology is sedimentary assemblage, no granite or crystalline limestone found as originally expected. The sedimentary lithology is dominated by amalgamated quartz sandstone beddings succession with (black) shale interbeds. It is interpreted as dominantly deep-water mass-transport deposits. The outcrop's total measured thickness is approximately 360m thick of stratigraphic record with total of 18 hand specimens were collected. Homoclinal folding structure with general dip above 45o was observed as the result of tilted (compressional) tectonic regime. High degree of fractures density is dominated by pure shear (extensional) tectonic regime. Field interpretation suggested a lithology of Pre-Cenozoic basement, as part of Sibumasu Terrane (fragment of Gondwana Supercontinent, Metcalfe, 2014) that becoming microplate basement of northeastern part of Central Sumatra Basin. Laboratory analyses are included geochemistry, biostratigraphy, petrography, and mineralogy examinations.

Pre-Cenozoic basement lithology implies an opportunity for presence of reservoir and source rock that potentially becomes a possible secondary petroleum system in the Rupat Area (Greater Central Sumatra Basin).

(+) Presence of sandstones as poor to medium quality reservoir.
(+) Presence of black shale as possible source rock type lithology.
(-) Geochemistry analyses so far do not support capability of the black shale as productive source rock. Further data acquisition is required to provide more comprehensive geochemistry analysis.

Outcrop Location in the Context of Regional Geology

Situated in the greater Central Sumatra Basin partially northern area, the Aruah Islands is located on the Malacca Strait. The islands are on the trend of Pre-Cenozoic lithology which is exposed as outcrop in Jemur, Sarang Elang, and Labuhan Bilik Islands. (Figure 1)

The geological field trip guided by University of Padjajaran Team was intended to study the lithology of outcrops and take rock samples for laboratory analysis.

Figure 1: *Aruah Islands is located about 85 kilometers from port of Bagan Siapiapi, situated at the border of Indonesia's territory and Malaysia in Malacca Strait.*

Field observation and interpretation of Aruah Islands lithology was suggesting likely as Pre-Cenozoic basement outcrop. According to Metcalfe (2017) this basement is a part of Sibumasu Terrane (Siam, Burma, Malaysia, Sumatra)[1]. Based on regional study by Metcalfe (2013) of the Sibumasu Terrane, the microplate was a part of Gondwana super continent and have been drifting toward northern position from its original location.[1]

Geoseismic arbitrary cross cection from west to east suggests that Aruah Outcrop could be correlated trough "seismic trend" with either Pre-Cenozoic Basement or as part of Paleogene Syn-Rift Pematang. (Figure 2)

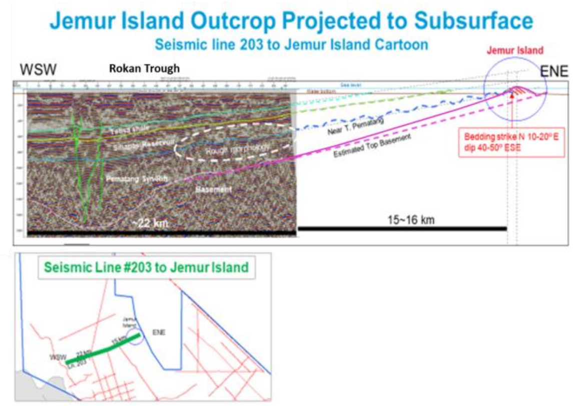


Figure 2: *The 40-50^{O} bedding dip measured in the Jemur Island outcrops might be equivalent to interpreted options, they are:*

- *Near Top Pematang Group (Paleogene section) – interpreted blue horizon, or*
- *Older than Pematang Group or as Pre-Cenozoic Basement section – interpreted purple horizon.*

Geological Field Trip General Findings

The Aruah Island is likely as basement outcrop but based on field observation at all 3 islands, the island is not composed by granite or crystalline limestone as originally expected, but in the fact the outcrops indicate all sedimentary rocks with clear texture and bedding structures.

Geological Structures Observation

Observation and measurement of geological structures (Figure 3) is likely dominated by two tectonic regimes; they are:

- The general bedding strike of the north-south (N10^{O}E - N20^{O}E) trending sedimentary rocks forms a homoclinal fold structure that tilts eastward. The dip is generally above 45^O east dipping homoclinal structures indicating the presence of compressional tectonics.
- The east-west and north-south direction joint structures, both are extensional (pure shear tectonic prints) with silicate filling.

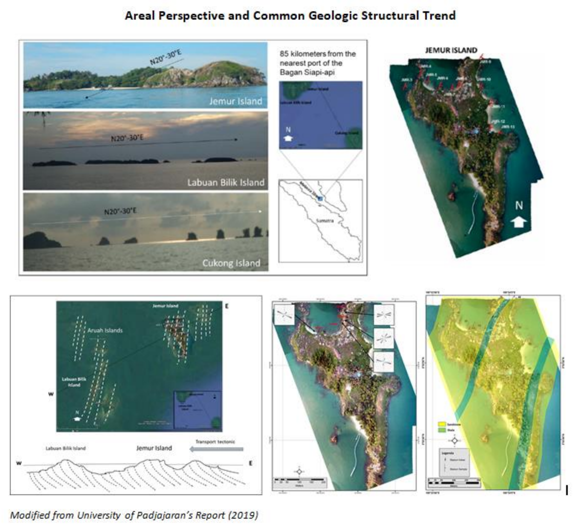


Figure 3: *The main field works were at Jemur Island, with quick spot checks at several islands. General bedding strike NE-SW trend, with common dip of above 45^O east dipping indicating the presence of compressional tectonic.*

Lithology and Field Stratigraphy Observation

Stratigraphic measured section was conducted at the outcrops performing description of lithology (Figure 4) as follow:

- The islands lithology is a sedimentary assemblage, no granite or crystalline limestone found. Field observation and interpretation was suggesting deep marine turbidite system deposit.
- Amalgamated quartz sandstone beddings succession with (black) shale interbeds. Outcrop's total measured thickness ~600m (20 hand specimens collected). Geochemical, biostratigraphy and petrographic examinations were completed in the University Padjajaran, Lemigas, and Rumbai laboratories.

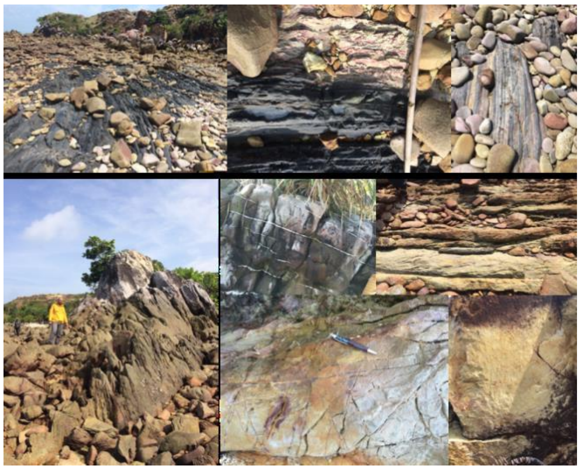


Figure 4: *The Aruah Island is likely as basement outcrop, but it is not granite or crystalline limestones. Field observation found all sedimentary rocks: Amalgamated quartz sandstone beddings succession with (black) shale interbeds.*

Sedimentary Structures Description

Very thick clean sandstone succession (Figure 5 & 6) with approximately total 600 m thickness was observed with condition high compacted with fine to coarse size of dominantly quartz grain with pebble fragments as result of offshore to deep water slope sediments and preserving indication of:

- High-density turbidite sedimentary structures (such as intra-formational fold or slump; and fluid-escape structures as dismembered coarse-grained sand injected into the relatively fine-grained sandstone),
- Sandy substrate-offshore deposits sedimentary structures (such as convolution and contorted lamination, current-ripples, and bioturbation), and
- Traction carpet sedimentary structure that be indicated by graded bedding with relict of pebble band.

Figure 5: *Very thick bedded coarse-grained quartz sandstones consist of vertically-stacked sandstone amalgamation indicated by the amalgamation surfaces.*

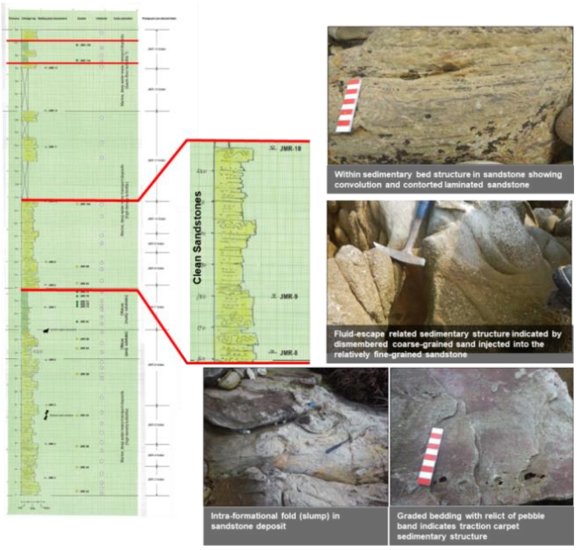


Figure 6: *Thick clean sandstone succession with condition high compacted with fine to coarse size of dominantly quartz grain act as potential reservoir as up to medium quality of porosity.*

Two thick black shale intervals were observed indication of muddy substrate-offshore deposits, characterized by mudstones, black-reddish shale couplets with local bituminous seams (Figure 7).

The first thick black shale interval is located in a bay where seawater pools at high tide. The thickness of the greyish-black substrate-offshore deposits shale interval is about 30 m with alternating fine-grained sandstones with chert intercalations and several number of coal-bituminous seam layers at the lower section, and dominantly massive black shale at the upper section.

Various sedimentary structures were observed in the shale layers such as current-ripple laminated sandstone in association with convolute lamination, and parallel laminated shale and siltstone couplets.

The second interval of shale is located at the bottom of the coastal cliff which is covered by tidal sea water with a thickness of about 20 m. The dominance of greyish black shale with sandstone layering has a parallel laminated shales and siltstone couplets sedimentary structure.

The lithological columns of the two shale intervals can be depicted in Figure 8.

Facies Interpretation

Field interpretation suggested a hypothesis of lithology as Pre-Cenozoic basement as interpreted as part of Sibumasu Terrane, with alternatively, it is possibly part of the Paleogene Pematang Group that was deposited in association with the syn-rift and pre-rift intervals.

Observation and interpretation of Aruah Islands lithology was suggesting a deep marine turbidite system deposit with possibility as diamictites. A measured section was traversed at the north and the northeast part of the island giving approximately 360 m thick stratigraphic record. Ten sandstone samples together with eight shale samples were collected from the outcrops. (Figure 9)

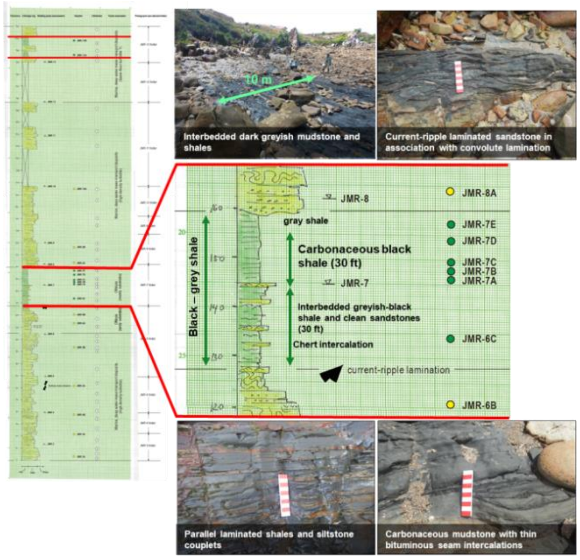


Figure 7: *Two thick black shale intervals act as potential source rock. Bituminous seams indicate organic content in the shale.*

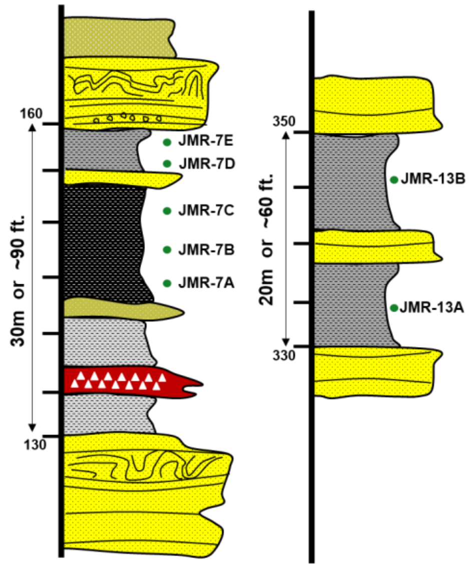


Figure 8: *Two thick black shale intervals act as potential source rock.*

The stratigraphic succession could consequently be divided into three major facies associations (Sunardi et.al, 2019) [3], they are:

- (Facies-1) high-density turbidite, very thick to massive coarse sandstones.
- (Facies-2) sandy substrate-offshore deposits, interbedded convoluted, current-ripple laminated, and bioturbated sandstones.
- (Facies-3) muddy substrate-offshore deposits, interbedded dark-greyish laminated mudstones, black to reddish and greyish shale couplets.

The sedimentary rocks consist of predominant very thick sandstone beds with shale and mudstone interbeds, with proposed six major lithofacies as follow:

- (Lithofacies-1) disturbed sandstones (sandstone showing soft-sediment deformation structures, sand injection, fluid-escape structures, and graded bed sandstones)
- (Lithofacies-2) banded and plane-stratified sandstones
- (Lithofacies-3) cross-stratified sandstones
- (Lithofacies-4) current-ripple laminated sandstones
- (Lithofacies-5) sandstones showing burrows and biogenic structures
- (Lithofacies-6) shale and mudstones (laminated mudstones, reddish mudstones, black shale couplet with thin bituminous seams).

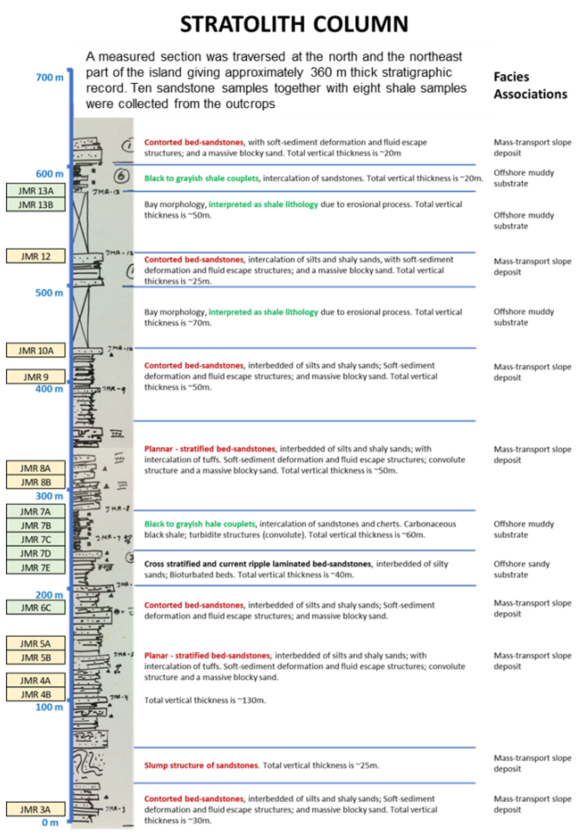


Figure 9: *Stratolith Column shows succession of 3 major facies associations with 6 lithofacies.*

Laboratory Analysis Result

Based on biostratigraphy and petrography analyses, it is concluded that the black shale rocks exposed on surface at the Aruah Islands are considered as age of Mesozoic sandstone and carbonaceous shale lithology. But the geochemistry analyses so far do not fully support the opportunity as possible secondary petroleum system of presence self-source-rock in the Rupat Block.

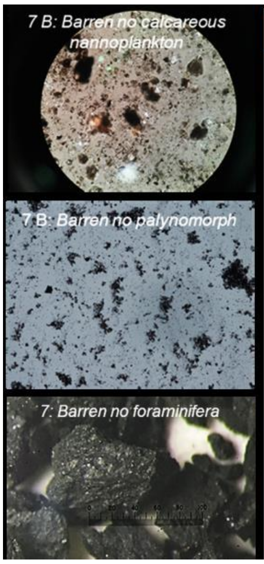
Biostratigraphy Analysis

Age determination is challenging, due to all samples of carbonaceous shale are barren from micro planktonic/benthic *foraminifera*, and nano plankton (Graha and Lemigas, 2019). Biostratigraphy analysis (Figure 10) suggests the Black Shales exposed on surface are interpreted as Paleogene or older age lithology since no nano fossil found due to probably over maturation or degradation process.

Calcareous nano plankton interpretation indicates mostly barren, but in the 13B samples was found a minor *Sphenolithus cf. moroformis* (NP12-NN9 / Early Eocene – Lower Part of Late Miocene). Lemigas biostratigrapher suggested it is not that species.

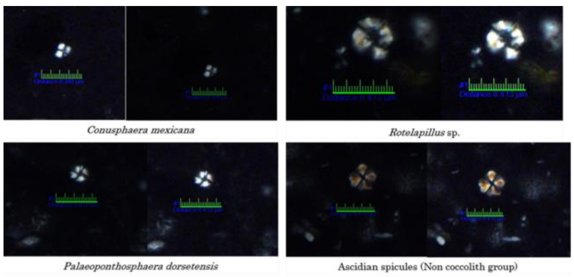
But based on University of Padjajaran's report (2019), palynology analysis at the 5 samples found several nano fossil species as determined age of Mesozoic (within Jurassic to Cretaceous Period). The observed non fossils are *Conusphaera Mexicana*, *Rotelapillus sp.*, *Palaeoponthosphaera dorsetensis*, and *Ascidian spicules*. (Figure 11).

Other age dating methods is not recommended due to no igneous/volcanic samples were found, and degraded condition of samples.



NO	SAMPLES	ANALYSIS	RESULT
1	13A	PALY	barren
2	13B	NANO & PALY	Barren with a minor fossil found
3	7A	FORAM	barren
4	7B	FORAM / NANO & PALY	barren
5	7C	NANO & PALY	barren
6	7D	NANO	barren
7	7E	FORAM	barren
8	7F	FORAM	barren
9	6C	FORAM	barren
10	2	FORAM	barren

Figure 10: *The biostratigraphy analysis observed no nano fossil found due to probably over maturation or degradation process.*



Pollen Species	First occurance	Last occurance
Conusphaera mexicana	Within base Tithonian Stage (149.09-151.50Ma – late **Jurassic Period**)	Within top Tithonian Stage (145.01-148.35Ma – late **Jurassic Period**)
Rotelapillus sp.	Within top Albian (105-100Ma – **Cretaceous Period**)	Within top Holocene Stage – **Tertiary Neogene**
Palaeoponthosphaera dorsetensis	Within Late Bathonian Substage (166.07-166.49Ma – middle **Jurassic Period**)	Within Tithonian Stage (145.01-152.06Ma – late **Jurassic Period**)
Ascidian spicules (Non coccolith group)	within base in Hettangian stage (145.01-201.30Ma - early **Jurassic Period**)	Extant **Recently**

Figure 11: *Palynology analysis found several nano fossils species as determined age of Mesozoic.*

Petrography & SEM (scanned electromagnetic microscope) Analysis

The analysis results show indication of sample degraded condition due to exposure to the surface as indicated by the oxidized process result (ferroan oxide mineral as fracture filling) and insitu secondary diagenesis (abundant kaolinite as dissolution pores filling). Partial carbonaceous materials were replaced by siderite.

The 'Aruah' sandstones are classified into quartz-arenite sandstones that mainly consist of coarse-silt to coarse-grained sands. Compactions are mainly represented by straight to concavo-convex grain contact with only local suture contact. Indication of any incipient metamorphism was not evidently observed.

Sandstone petrography analysis suggests relatively very poor to medium porosity (observed at 5-25%) - Figure 12. Diagenetic events in the sandstone sample can be described as follow:

- Compactions are mainly represented by straight to concavo-convex grain contact with only local suture contact.
- Indication of any incipient metamorphism such as interlocking quartz mosaic with serrated edges and other prominent alteration were not evidently observed.
- The porosity types are classified into: moldic, intergranular, and intragranular, that can be differentiated into: fracture, shrinkage, and dissolution origin.

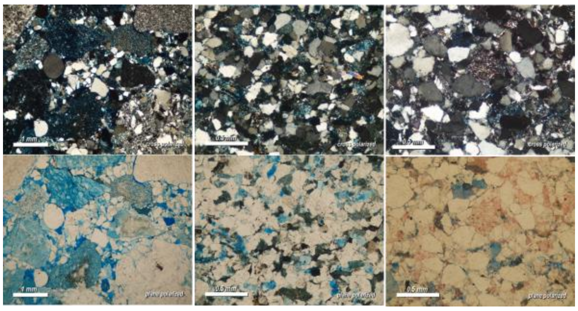


Figure 12: *Sandstone is observed as very poor to medium porosity mainly as intergranular type.*

Shale petrography analysis suggests oxidized process have been occurred and replacement of organic matters with ferrous oxide mineral probably as result of degradation of organic content (Figure 13). Diagenetic events in the shale samples can be described as follow:

- Partial organic and carbonaceous materials were replaced by siderite and pyrite.
- Cementation by ferroan oxide and quartz overgrowth
- Presence of ferroan oxide that filled most of fractures at the carbonaceous shale samples.
- Some mica fragments are found as clay/silt detrital without any lineation/foliation texture appearance as metamorphic indicator.

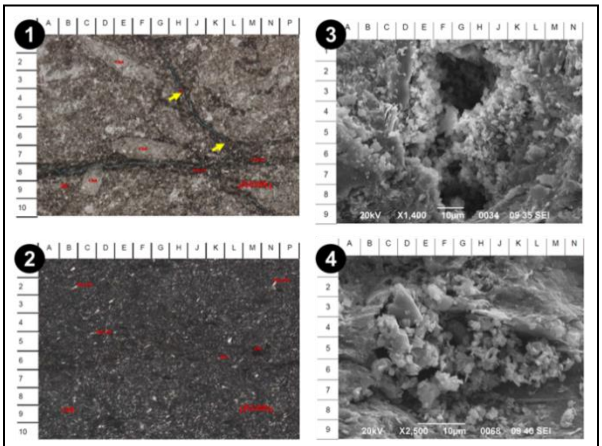


Figure 13: *Shale petrography describe an oxidized argillaceous coal (1) and Claystone (2) – detrital clay mixed with organic matter, with fragments of quartz and rocks. SEM sections show Silty Sandstone (3) composed by quartz and rock fragments, while Shale/argillaceous (4) composed by detrital clay mostly as illite and kaolinite, with fragments of quartz and carbonaceous materials.*

Based on petrography analysis, the lithology in the Aruah outcrops can be defined in the late diagenesis phase, which results in high degree of compaction for performing poor to medium quality of sandstone reservoir. Although the indication of incipient metamorphism is not evidently observed, therefore increasing of porosity may occur due to dissolution and presence of natural fractures.

AP140 Porosity and XRD Analysis

The measurements of AP140 porosity analysis show the samples as tight to poor quality sandstones (5-16 %) with porous shale (12-25%) with relatively low to medium clay mineral content (dominated by illite and kaolinite). (Table 1a).

The XRD (X-ray diffraction) measurements show the samples as tight to poor quality sandstones (5-16%) and relatively porous shales (12-25%) with low to medium clay mineral content (dominated by illite and kaolinite). Both are non carbonates. (Table 1b).

Sample#	Well	Sample No	Sample Description	API40 method		XRD analysis (RIR Method), value in wt%								
				grain density, gr/cc	Porosity, %	Quartz	plagioclase	K-Feldspar	Clay			carbonate		pyrite
									illite	kaolinite	chlorite	calcite	siderite	
1	Well SB	13B	Shale	2.65	17.5	59.8	3.5	2.2	21.3	7.6	1.6	2.0	2.0	
2		10A	Sandstone	2.66	12.5	90.0	2.3	2.5	3.2	2.0				
3		8B	Sandstone	2.64	8.2	90.0	2.8	3.0	2.3	1.9				
4		7F	Shale	2.63	22.1	83.7	2.0	1.8	3.7	7.2	1.6			
5		7E	Shale	2.68	17.3	73.5	2.9	3.0	14.0	6.1		0.5		
6		7D	Shale	2.68	16.1	77.0	4.1	3.2	9.0	4.7		2.0		
7		7C	Shale	2.62	12.0	80.1	5.7	6.0	6.9	1.3				
8		7B	Spl insufficient for porsity	NA	NA	83.7	3.4	3.6	6.0	3.3				
9		7A	Shale	2.68	24.9	86.3	2.7	2.8	4.4	3.8				
10		6C	Sandstone	2.66	16.3	85.0	2.5	2.0	4.9	5.6				
11		6B	Sandstone	2.64	16.4	86.0	4.3	3.9	3.1	2.7				
12		6A	Sandstone	2.64	16.4	89.0	2.1	2.2	2.2	4.5				
13		5B	Sandstone	2.67	10.1	86.1	2.7	2.2	4.5	3.5	1.0			
14		5A	Sandstone	2.66	6.0	86.1	2.7	2.2	4.5	3.5	1.0			
15		4B	Sandstone	2.71	12.5	88.7	2.0	1.5	5.1	1.8			0.9	
16		4A	Sandstone	2.64	6.8	93.0	2.0	1.7	1.5	1.8				
17		3A	Sandstone	2.64	9.6	89.5	1.9	1.6	3.6	3.4				
18		2	Sandstone	2.66	5.7	93.7	1.7	1.3	2.8	0.5				
19		1	Sandstone	2.67	5.8	92.0	1.7	1.9	1.9	1.0	1.5			

Sample matrix: Core chip sample
Methods:
Cleaning: Soxhlet extraction
Grain volume: Boyle's law grain volume porosimeter
Bulk Volume: Mercury bulk porosimeter
Bulk meneralogy: RIR method

Table 1: *AP140 Porosity Measurement (1a) and XRD Analysis (1b) in sandstone and shale samples.*

Geochemistry Analysis

Geochemistry samples were taken from both shale intervals. TOC (total organic carbon) and RockEvals Pyrolysis measurement performed in the Lemigas Laboratory at the selected outcrop samples to analyze organic richness, maturity, and interpreted environmental of deposition of potential source rock presence.

TOC was measured at 7 sample points and resulted various TOC values (0.2-3.7%) indicates approximately 100ft. thick of rich hydrocarbon source rocks potential (1.4-3.7%) at the middle part of First Black Shale interval. The other shale intervals indicate originally poor or have been degraded or even organic content has been reduced during diagenetic/maturation. (Table 2).

RockEval Pyrolysis at the 4 most higher TOC results a very low volatilized of free hydrocarbon (S1) content (<0.05 mg/gr) and generated hydrocarbon compound (S2) from pyrolysis of kerogen (<0.14 mg/gr). Total potential yield of hydrocarbon (PY=S1+S2) amount is very low (< 0.18 mg/gr). Plot of TOC versus S2 and HI (hydrogen index) of samples considered very poor potential as source rock. The sample based on plot of S2 vs. TOC and HI vs. OI can be defined as Kerogen Type 4 or inertinite/oxidized organic matter. (Figure 14).

Vitrinite reflectance (Ro) data clarify that the thermal maturity are in the late mature to over matured stage (3 samples have 3-4%Ro, but one sample has 1.15%).

Gas Chromatography (GC) done at 3 samples (Table 3) observes degradation level of organic matter. The analysis results show an indication of biodegraded samples due to exposure to surface. Even though the extracted rocks have undergone biodegradation but still leaves pristane and phytane compounds and a small portion of alkanes. (Figure 15).

The extracted rocks are estimated from pristane/phytane ratios to be derived from the source rock, which deposited in anoxic-suboxic of the associated aquatic depositional environment.

No.	Code Sample	Sample Type	General Lithology Description	TOC (%)	S_1	S_2	S_3	PY	S_2/S_3	PI	PC	Tmax (^0C)	HI	OI
1	JMR-7A	OC	Shale, med.gray-dark gray, very hard, Non Calcareous	0.34	-	-	-	-	-	-	-	-	-	-
2	JMR-7B	OC	Shale, dark gray, mod.hard, Non Calcareous	1.39	0.04	0.13	0.23	0.17	0.57	0.24	0.01	***	9	17
3	JMR-7C	OC	Shale, black, mod.hard, Non Calcareous	3.71	0.03	0.13	0.71	0.16	0.18	0.19	0.01	***	4	19
4	JMR-7D	OC	Shale, med.gray-dark gray, very hard, Non Calcareous	0.32	-	-	-	-	-	-	-	-	-	-
5	JMR-7E	OC	Shale, med.gray-dark gray, very hard, oxidated, Non Calcareous	0.41	0.03	0.11	0.19	0.14	0.58	0.21	0.01	***	27	47
6	JMR-13A	OC	Shale, med.gray-dark gray, very hard, oxidated, Non Calcareous	0.20	-	-	-	-	-	-	-	-	-	-
7	JMR-13B	OC	Shale, med.gray-dark gray, very hard, oxidated, Non Calcareous	0.44	0.03	0.10	0.31	0.13	0.32	0.23	0.01	***	23	71

Remarks :

TOC : Total Organic Carbon
S_1 : Amount of Free Hydrocarb
S_2 : Amount of Hydrocarbon re
S_3 : Organic Carbon Dioxide
PY : Amount of Total Hydrocarbons = $(S_1 + S_2)$
PI : Production Index = $(S_1/ S_1 + S_2)$
PC : Pyrolysable Carbon
Tmax : Maximum Temperature (^0C) at the top of S_2 peak
HI : Hydrogen Index = $(S_2/TOC) \times 100$
OI : Oxygen Index = $(S_3/TOC) \times 100$
NDP : No Determination Possible
D/C : Ditch Cuttings
*** : Erroneous reading Tmax due to lack of S_2

Table 2: *Organic richness based on TOC measurement and RockEval Pyrolysis for maturity analysis.*

OIL COMPOSITION AND GAS CHROMATOGRAPHY DATA

No	Sample ID	Sample Type	EOM(ppm)	SAT	ARO	NSO+Asp	Pr/Ph	Pr/nC17	Ph/nC18	CPI
				WT %						
1	JMR-7B	outcrop	82	15.58	2.60	81.82	1.40	1.16	3.36	-
2	JMR-7C	outcrop	282	2.00	3.00	95.00	2.20	1.86	2.24	-
3	JMR-7E	outcrop	66	5.71	2.86	91.43	1.02	0.83	1.25	-

Remarks
Pr : Pristane
Ph : Phytane
nC17 : normal Alkane C17
nC18 : normal Alkane C17
CPI : Carbon Preference Index [illegible]
Sat : Saturate Fraction
Aro : Aromatic Fraction
NSO : Non Polar Fraction

Table 3: *Gas Chromatography (GC) done at 3 samples observes degradation level of organic matter.*

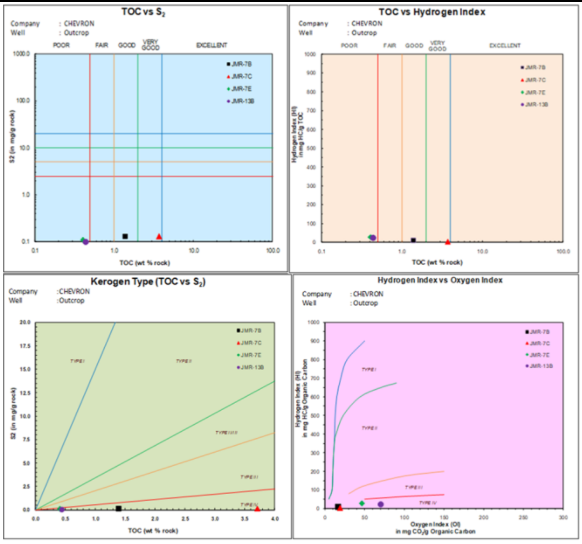


Figure 14: *Organic richness based on TOC measurement and RockEval Pyrolysis for maturity analysis.*

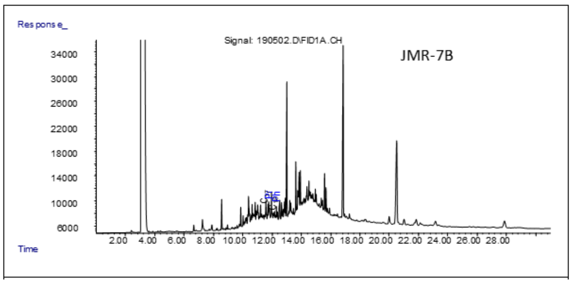


Figure 15: *Gas Chromatography (GC) indicates the samples are biodegraded due to exposure to surface .*

Gas Chromatography Mass Spectrometry (GCMS) results (Figure 16) show an indication of algae and higher plant species biomarkers which is deposited in transition area (estuarine).

- The steranes chromatogram (m/z 217) of JMR-7B, JMR-7C and JMR-7E samples shows clear regular sterane distribution with low indication of higher plant species biomarkers.
- The sterane configuration of C29>C27>C28 which is characteristic of mixed algae and higher plant organic matter.
- Low thermal maturity of hydrocarbons in the extract bitumens is very clearly demonstrated by the presence of the compounds 5a14a17a-sterane 20S which is relatively very low when compared with their 5a14a17a-sterane 20R conter-parts.
- Angiosperm derived biomarkers such as oleananes, C30 oleanoid triterpanes, and other terrestrial indicators, occur in very low concentrations to almost absent in the samples analyzed. This suggests only a minor contribution from terrestrial plants to the source kerogen.

- The dominant of C23 tricyclic terpane (peak no 5) indicate the extracted oil from rocks is produced by algae which deposited in shallow marine environments.
- Ts/(Ts+Tm) ratio (0.46-0.54) and Moretane/Hopane (0.11-0.15) give indicated low of thermal maturity. The possibility of immature sediments is new sediments formed simultaneously with the rework sediments.
- GCMS Biomarker of ion m/z 217 & m/z 191 and steranes show that 7B/7C samples come from same source and deposited in transition depositional environment.

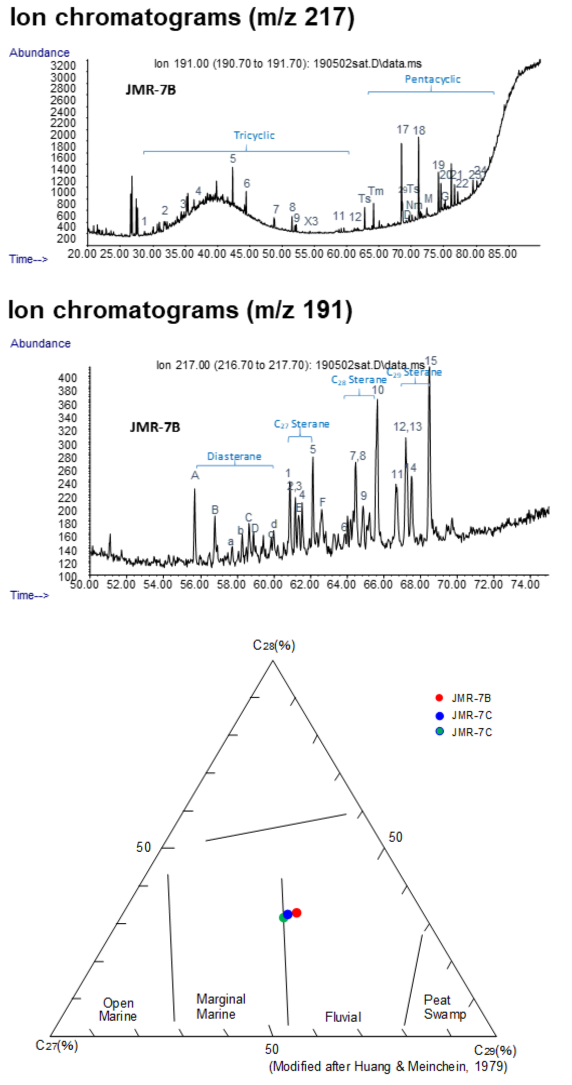


Figure 16: *Gas Chromatography Mass Spectrometry (GCMS) results show an indication of algae and higher plant species biomarkers which is deposited in transition area (estuarine).*

Geochemistry analysis result at the two Black Shale intervals (interpreted as Paleogene or Older lithology) indicates that the Black Shale exposed on surface as inertinite or probably has been over mature. It gives indication of very poor hydrocarbon source rocks potential.

Conclusions

Pre-Cenozoic basement lithology implies an opportunity for presence of reservoir and source rock that potentially becomes a possible secondary petroleum system in the Rupat Area (Greater Central Sumatra Basin).

(+) Presence of sandstones as poor to medium quality reservoir.

(+) Presence of black shale as possible source rock type lithology.

(-) Geochemistry analyses so far do not support capability of the black shale as productive source rock. Further data acquisition is required to provide more comprehensive geochemistry analysis.

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