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The Characteristics of Arun Carbonate Reservoir and Its Implication To Optimize the Most Potential Gas Resource Zones In the Arun Gas Field, Aceh, Indonesia

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Abstract - Since the discovery of major oil and gas reserves in carbonate rocks in the Middle East, carbonate reservoirs became important to the petroleum industry. Carbonate rocks have covered only 20% of the sedimentary rock records. However, carbonate reservoirs hold 50% of the world petroleum reserves. Arun Carbonate Reservoir is one of the biggest proven retrograde gas reservoirs in the world. After more than thirty years of production, Arun Carbonate Reservoir had an initial gas in place of 14.1 TCF residual hydrocarbon gas. The issue makes Arun Carbonate Reservoir became an interest to be studied for the development and production of hydrocarbon in other carbonate reservoirs in Indonesia. One of the fundamental topics to be studied is the characteristics of Arun Carbonate Reservoir itself. The characteristics of carbonate reservoir usually cause a lot of geologic and engineering problems in the development and production of hydrocarbon reserves. This paper aims to identify the characteristics of Arun Carbonate Reservoir and its implication to optimize the most potential gas resource zone in Arun Gas Field, Aceh, Indonesia. The data from sixteen wells have been examined through several multidiscipline studies: geophysics (well logging), geology (facies, lithology and diagenetic analyses), and petrophysics (core analysis). The result of this study shows that Arun Carbonate Reservoir (N5-N8) contains limestone 92%, 5% dolomite, and 3% dolomitic limestone (or other), and petrophysically have 16% porosity and 13.5 md permeability in average. Arun Carbonate Reservoir is divided into four facies (Reef, Near Reef, Lagoon, and Middle Shelf). Of four facies in Arun Carbonate Reservoir, only two facies which can be categorized as productive facies: Reef and Lagoon Facies. The potential zones of hydrocarbon resource have vertically been documented in Arun Carbonate Reservoir.

Keywords: Arun, carbonate, reservoir, gas, resource, petrophysics

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Introduction

Petroleum system consists of four essential elements in the occurrence of hydrocarbon. One of the essential elements is the occurrence of reservoir (Praptisih and Kamtono, 2014b). For a petroleum geoscientist, reservoirs are porous and permeable rock bodies that contain commercial amounts of hydrocarbons (Ahr, 2008). After the World War I, when drilling resulted in the discovery of major oil and gas reserves in carbonate rocks in the Middle East, carbonate reservoirs became important to the petroleum industry (Chilingarian *et al*., 1992). Carbonate rocks make up only 20% of the sedimentary rock records, but carbonate reservoirs hold approximately 50% of the world petroleum reserves (Mazzullo, 2004; Chopra *et al*., 2005; Ahr, 2008; Schon, 2011).

Today, prudent management of petroleum industries is interesting and competitive to find a potential carbonate reservoir. But in many cases, the geological and engineering problems arise in the development and production of hydrocarbon reserves in carbonate reservoirs. These problems are mainly caused by unique characteristics of carbonate reservoir rocks (Chilingarian *et al*., 1992). Unlike most sandstone reservoirs which are typically single-porosity systems (*i.e*. interparticle pores) of relative uniform (homogeneous) nature, reservoirs in carbonate rocks are commonly multiple-porosity systems that characteristically impart petrophysical heterogeneity to the reservoirs (Chilingarian *et al*., 1992; Mazzullo, 2004; Lindsay, 2010). In short, pore systems in carbonates are much more complex than siliciclastics (Choquette and Pray, 1970; Lucia, 1995; Moore, 2001; Ahr, 2008).

Carbonate porosity values also do not always correspond closely to permeability (Ahr, 2008). Lucia (2007) stated that no relationship between porosity and permeability in carbonate rocks without including pore-size distribution. The distribution of porosity and permeability in relation to carbonate reservoir is controlled by characteristics of carbonate reservoir itself (Chilingarian *et al*., 1992; Wardlaw, 1976; Mazzullo, 2004; Praptisih and Kamtono, 2014a).

Indonesia has a lot of carbonate rock formations which are potential to become reservoirs. One of those potential reservoirs in Indonesia is Arun Carbonate Reservoir, which has ever been recorded to have giant retrograde gas reserves in the world (Afidick *et al*., 1994). Arun Carbonate Reservoir is characterized by abnormally high pressure of 7100 psig (49 MPa) at 10,000 feet (3048 m), and initially contained 16.2 x 1012 scf (459 x 109 std m^3) gas in place (Soeparjadi, 1983). Since 1977 until 2013, more than 99% of the expected ultimate gas recovery has been produced and Arun Carbonate Reservoir had an initial gas in place of 14.1 TCF residual hydrocarbon gas (Avida *et al*., 2013).

Despite gas production which is relatively high, the processes of development and production in Arun Carbonate Reservoir had some problems, such as declining reservoir pressure, lost well capacities, declining production rate, *etc*. These problems are geologically caused by the characteristics of Arun Carbonate Reservoir itself.

Referring to the above enlightenment, it is very essential to identify the characteristics of Arun Carbonate Reservoir. The main reason to study the characteristics of Arun Carbonate Reservoir is to find the most potential gas resource zone in Arun Gas Field, Aceh, Indonesia. The results of this study are expected to be a reference for the development and production of hydrocarbon in other carbonate reservoirs.

Geological Setting

This research is located in Arun Gas Field, Aceh Province, North Sumatra, Indonesia. Arun Gas Field (Figure 1) is one of the hydrocarbon fields in North Sumatra Basin. The North Sumatra Basin is a back-arc basin of Tertiary age bounded to the east by onlap onto the Malacca Platform and to the southwest by Barisan Mountain uplift. The North Sumatra Basin was initially subject to Late Eocene rifting that formed the north-south horsts and grabens. A quiescent phase of basin sag, with widespread carbonate deposition and reef growth during the Late Oligocene and Early Miocene, followed the rifting (Barber *et al*., 2005).

Fauzi *et al*. (2017) stated that during Oligocene time a thick transgressive sequence of black claystone (Bampo Formation) was deposited, particularly in the topographic lows. The Lower Miocene was a time of maximum marine ingression. However, rapid subsidence had ceased and the rate of deposition was minimal. Marls and very calcareous shales, rich in planktonic

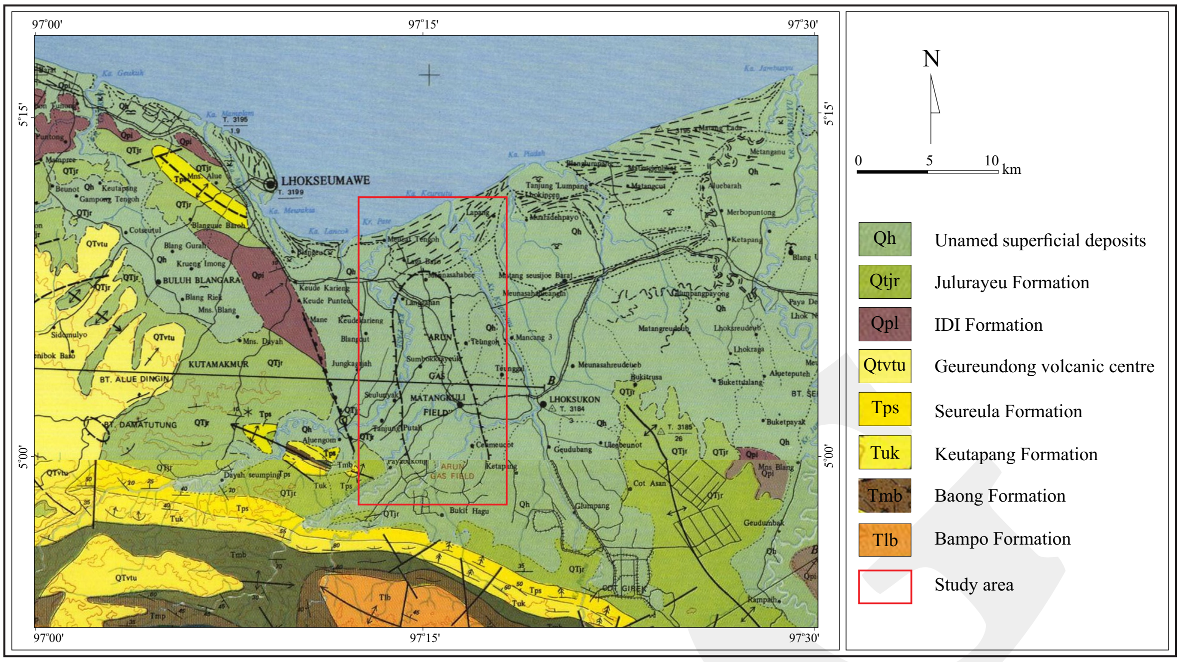

Figure 1. Regional geology map of Arun Gas Field (Fauzi *et al*., 2017; modified of Keats, 1981.,*et al* and Cameron *et al.,* 1983).

foraminifera, became the dominant sediments (Peutu Formation).

Environmental conditions were also ideal for the development of reefs and other biogenic limestones (Arun Limestone). The period of quiescence continued through the Middle Miocene with the deposition of shales (Baong Formation). These shales became the seal of the Arun Reef and contributed most, if not all, hydrocarbons found in this area. Based on well data, the stratigraphy of Arun Field from the oldest to the youngest is shown in Figure 2.

The object of this research is Arun Limestone. Based on Figure 2, Arun Limestone is time-stratigraphically to the Peutu Formation. Arun Limestone is mainly Lower to Middle Miocene in age. Arun Limestone overlain by Baong Formation is responsible for sourcing and sealing the hydrocarbon in Arun Limestone.

Methods and Material

The data were obtained through several multidiscipline studies: geophysics (well logging), geology (sedimentology, stratigraphy, diagenesis), and petrophysics (core analysis). The data have been collected, drawn, re-analyzed, and compared to previous research data to reach the present understanding of Arun Carbonate Reservoir characteristics including lithology, facies, porosity, and permeability. These data have been correlated to each other and presented in zonation to know the distribution of Arun Carbonate Reservoir characteristics.

More than 6,000 feet of cores have been taken in Arun Gas Field and sixteen wells (4305.5 feet core sections) were examined in detail for this study. The lithology and facies in this study are derived by core description and petrographic analysis in the laboratory. It was continuously compared to wireline log data such as gamma ray log, resistivity log, and sonic log to know the vertical distribution of lithology and facies in each well studied. Wireline logging is very important in petroleum study, because its set represents certainly a short-term economy, and can generate approximately 90% of the information extracted from a well (Serra, 2003).

In this research, porosity is determined by visual methods and laboratory measurements. Permeability is measured in the laboratory by

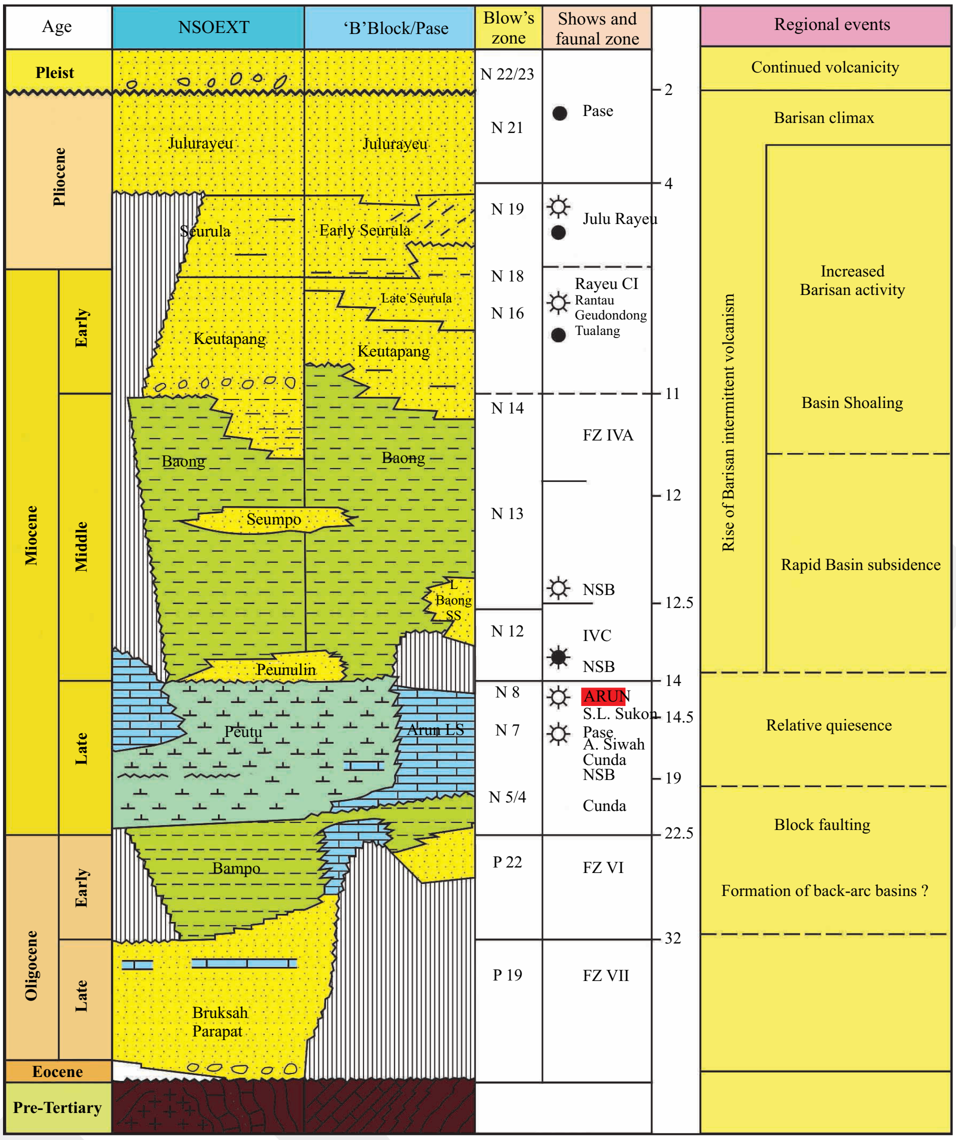

Figure 2. Stratigraphy of Arun Gas Field (modification after Atmadibrata, 1988).

encasing a sample of known length and diameter in an air-tight sleeve (the Hasseler Sleeve) in a horizontal position. Lucia (2007) said that visual methods of measuring total porosity were estimated by visual inspection of core slabs using a low-power microscope. Visible porosity in thin section can be measured by point counting visible pores or by using image analysis software to calculate pore space.

Measurement of porosity of rock samples in the laboratory requires knowing the bulk volume and either its pore volume or the volume of the matrix material. Bulk volume is measured by volumetric displacement of a strongly nonwetting or by direct measurement of a regularly shaped sample. Pore volume can be obtained in a number of ways (mineral volume, He expansion, Hg injection, *etc.*).

Results and Discussions

Lithological Characteristics of Arun Carbonate Reservoir

The result of previous study from Arun-A2 shows that Arun Carbonate Reservoir consists of coral skeletal limestone 47.8%, foraminiferal skeletal limestone 16.7%, calcarenitic limestone

13.7%, micrictic limestone 16.7%, and dolomite 5.3% (Soeparjadi, 1983). The result of this study from sixteen cored wells shows that Arun Carbonate Reservoir dominantly consists of 92% limestone, 5% dolomite, and 3% dolomitic limestone (or other). The lithological percentage of each well is shown in Table 1.

Based on core description and petrographic analysis, the lithology of Arun Carbonate Reservoir can be divided into four major rock types: coral boundstones and coral encrusting-red-algae boundstones, mixed skeletal packstones, benthonic foram mixed skeletal packstones to wackstones, and benthonic-planktonic foram packstones.

Facies Characteristics of Arun Carbonate Reservoir

The Arun Carbonate Reservoir comprises three main lithofacies which are interpreted with regard to depositional environments those are Reef Facies, Near Reef Facies, and Lagoon Facies. The percentage of these facies is shown in Table 2 and the distribution of these facies is shown in Figures 3 and 4.

<u>Reef Facies</u>

Reef Facies include various types of boundstones, most of which are coral boundstones and coral encrusting-red-algae boundstones (Figure 5). These formed in shallow water by the growth and accretion of various types of coral and red algae to create a wave-resistant bathymetric feature that affected sedimentation on and around it. Basically, fossil reefs are skeletal remains of part of a diverse marine ecosystem. Based on the examination of core samples from sixteen wells, 39% of Arun Cores consist of various types of boundstone.

<u>Near Reef Facies</u>

The characteristics of Near Reef Facies are coarse, poorly sorted deposits of skeletal packstone, and mixed with branches and plates of corals (Figure 6). Basically, this rock type consists of coral fragments floating in a muddy sand matrix of skeletal packstone and commonly rich in large benthic foraminifera. This facies is distinguished from Reef Facies by a dominance of sediment over framebuilders such as corals.

Table 1. Lithological Percentage of Arun Carbonate Reservoir

No	Core Well	Core Section	Limestone		Dolomite		Dolomitic Limestone	
			ft	%	ft	%	ft	%
1	A-2	662	628	95	34	5	0	0
2	A-3	199	169	85	0	0	30	15
3	A-5	152	128	84	0	0	24	16
4	A-6	331	324.5	98	3	1	3.5	1
5	A-7	891	891	100	0	0	0	0
6	A-9	28	28	100	0	0	0	0
7	A-10	115	115	100	0	0	0	0
8	A-11	86	86	100	0	0	0	0
9	A-13	14	14	100	0	0	0	0
10	A-26	29	29	100	0	0	0	0
11	A-42	179	179	60	57	32	15	8
12	A-46	218	218	100	0	0	0	0
13	A-52	461.5	431.5	93	0	0	30	7
14	A-53	172	172	100	0	0	0	0
15	A-54	658	624	95	32	5	2	0
16	A-59	90	66	73	22	24	2	2

Table 2. Facies of Arun Carbonate Reservoir Based on Core Examination

No	Core Well	Core Section	Reef Facies		Near Reef Facies		Lagoon Facies		Other Facies	
			ft	%	ft	%	ft	%	ft	%
1	A-2	662	269	40.63	57	8.61	334	50.45	34	5
2	A-3	199	45	22.61	55	27.64	99	49.75	-	-
3	A-5	152	41	26.97	24	15.79	87	57.24	-	-
4	A-6	331	43	12.99	53	16.01	235	71.00	-	-
5	A-7	891	306.5	34.40	203	22.78	381.5	42.82	-	-
6	A-9	28	-	-	-	-	-	-	-	-
7	A-10	115	115	100.00	0	0.00	0	0.00	-	-
8	A-11	86	86	100.00	0	0.00	0	0.00	14	100
9	A-13	14	0	0.00	0	0.00	0	0.00		
10	A-26	29	0	0.00	0	0.00	0	0.00		
11	A-42	179	15	8.38	8	4.47	156	87.15		
12	A-46	218	88	40.37	63	28.90	67	30.73	-	-
13	A-52	461.5	140.5	30.44	278	60.24	43	9.32	-	-
14	A-53	172	112	65.12	0	0.00	60	34.88	-	-
15	A-54	658	240	36.47	41	6.23	377	57.29	-	-
16	A-59	90	65	72.22	25	27.78	0	0.00	-	-

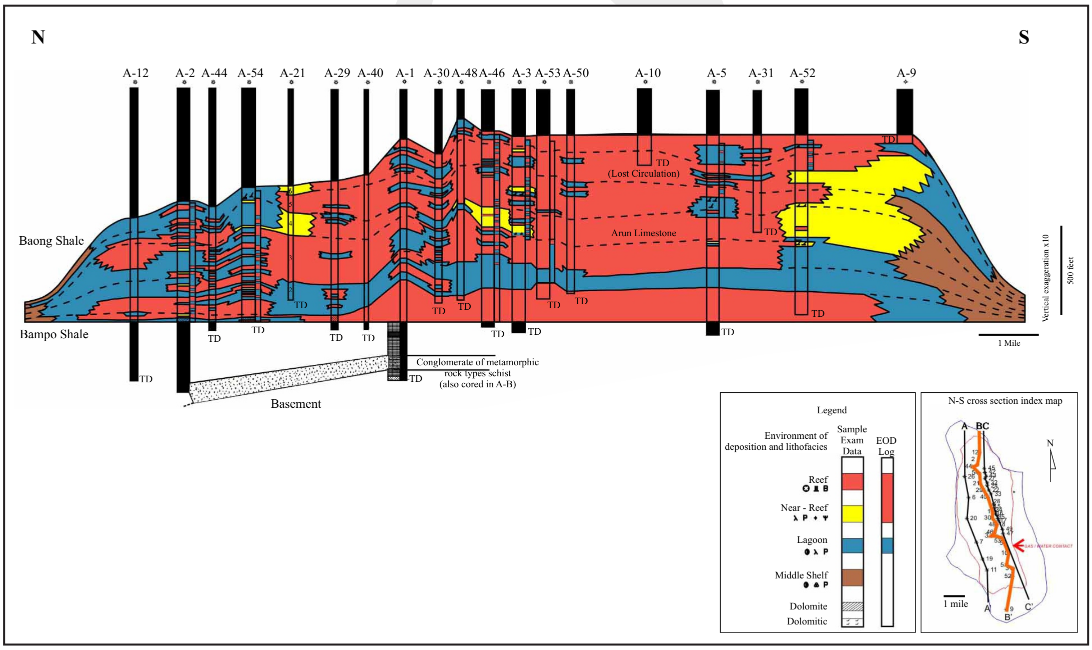

Figure 3. Vertical distribution of Arun Carbonate Lithofacies, Arun Field, North Sumatra Basin.

Near Reef Facies account for 14% of the total Arun Carbonate Complex.

Lagoon Facies

The deposit comprises foraminifera skeletal packstones characterized by moderately deep water sedimentation occurring between patch reefs (Figure 7). Certain large benthic foraminiferas are characteristics of moderately deep lagoon environments. These include mainly species of Operculina and Cycloclypeus. Within the Arun Carbonate Complex,

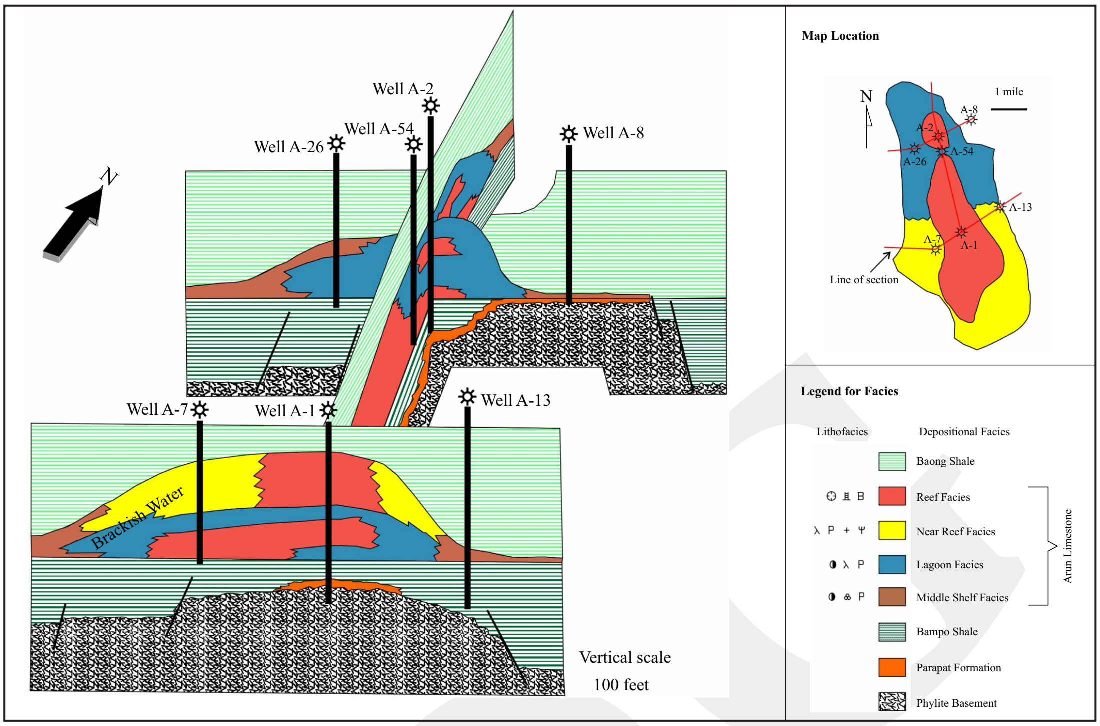

Figure 4. Fence diagram of Arun Carbonate Facies, Arun Field, North Sumatra Basin.

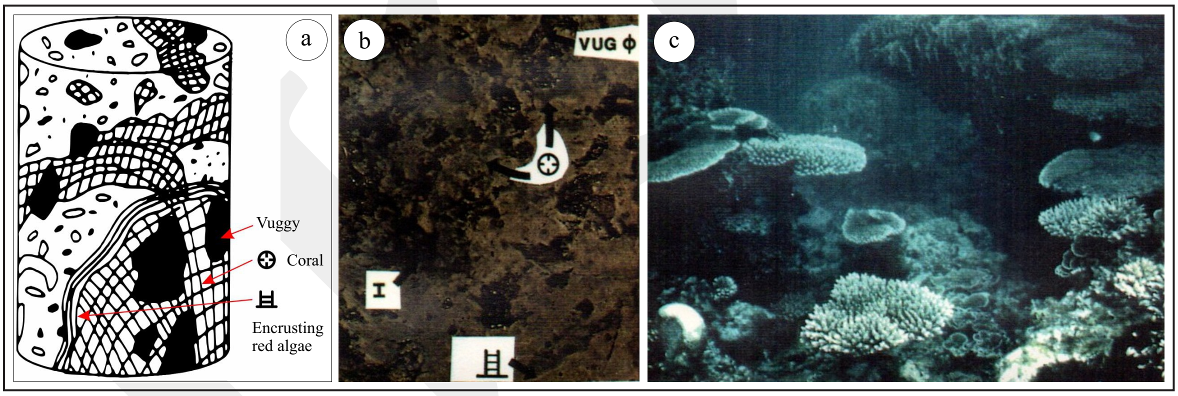

Figure 5. Sketch of Reef Facies from core sample (a); photomicrograph of carbonate (b), and current sedimentation (c) (modification after Jordan, 1989).

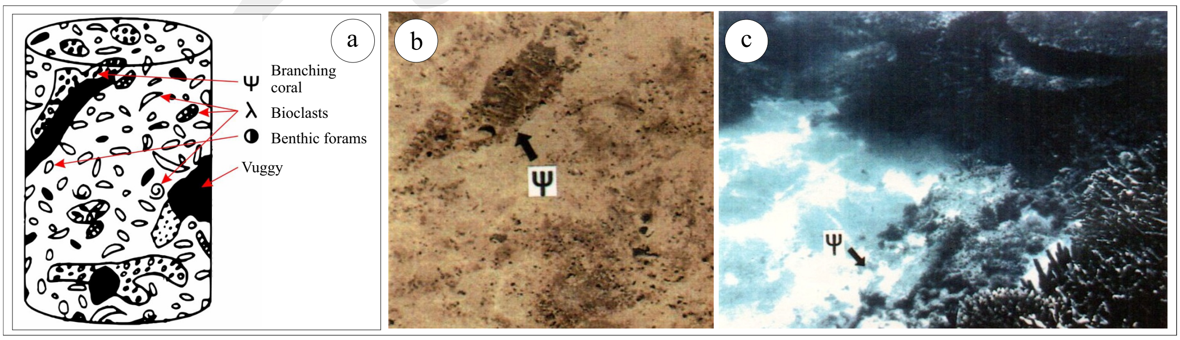

Figure 6. Sketch of Near Reef Facies from core sample (a); photomicrograph of carbonate (b); and current sedimentation (c) (modification after Jordan, 1989).

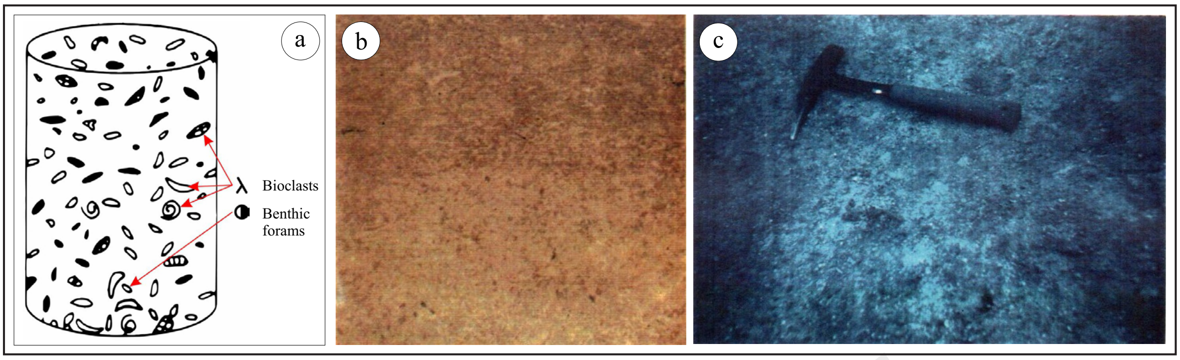

Figure 7. Sketch of Lagoon Facies from core sample (a); photomicrograph of carbonate (b); and current sedimentation (c) (modification after Jordan, 1989).

Lagoon Facies account for 33% of the cored interval studied.

Petrophysical Characteristics of Arun Carbonate Reservoir

The result of petrophysical analysis in this research is divided into two parameters: porosity and permeability. Porosity and permeability are an important rock property, because it is a measure of the potential storage volume for hydrocarbons and relate to the rate at which hydrocarbons can be recovered (Lucia, 2007). The value of porosity and permeability in this study is examined by visual and core analysis method in the laboratory.

Arun A-2 is one of the most representative well studies in this research. It is caused by complete core samples from the top to the bottom of Arun Carbonate Reservoir. The detailed of porosity and permeability values of Arun A-2 are displayed in Table 3. Porosity values throughout the Arun Carbonate Reservoir are ranging from 1% to 33% and 16% on the average. Based on qualitative classification by Archie (1952), the average porosity of Arun Carbonate Reservoir is categorized to have a good quality. Permeability values throughout the Arun Carbonate Reservoir are ranging from 1 to 60 md and 13.5 md on the average. This reservoir permeability average can be graded as moderate permeability based on the following classification of North (1985).

Based on core and thin section observation, the porosity types of Arun Carbonate Reservoir can be divided into macroporosity and microporosity. The types of macroporosity (Figure 8) in Arun Carbonate Reservoir are vuggy, moldic, intraparticle, fracture, and breccia porosities (Figures 8a- e, respectively). Macroporosity is account for approximately 25% of the total porosity. In Arun Carbonate Facies, macroporosity is significantly distributed in Reef Facies and Near Reef Facies, with slightly distributed in Lagoon Facies and Middle-Shelf Facies. Based on routine core logging determination, the amount of vuggy porosity in Arun Carbonate Reservoir is 21%.

Microporosity (intercrystalline porosity) in Arun Carbonate Reservoir usually occurs as microspar matrix of recrystallized lime mud. Microporosity is account for approximately 75% of the total porosity present in all of Arun Carbonate Facies. Micropores are 2-4 μ across (Figure 9) and have complex microrhombic shapes due to being enclosed by 3-4 μ size rhombs of calcite.

Potential Gas Resource Zone in Arun Carbonate Reservoir

The potential gas resource zone in Arun Carbonate Reservoir is delineated by lithology, facies, and porosity distribution. Based on physical characteristics, of four Arun Carbonate Facies, only two facies which can be categorized as productive facies. The first one is Reef Facies which consist of 17.5% porosity and 189.6 md permeability on the average. The second one is Lagoon Facies comprising of 14.6% porosity and 45.6 md permeability on the average.

Table 3. Porosity and Permeability of Arun A-2 Core Samples (Zone 1 - 5)

Facies	Zone	Sample No.	Depth (Feet)	Horizontal Permeability (md)	Porosity (%)
Reef and Near Reef Facies	Zone 1	1	9543.30	5.2	22.1
		2	9554.40	131	29.2
		3	9560.00	10	22.1
		4	9573.10	58	28.5
	Zone 2	5	9586.40	1003	18.2
		6	9604.30	9.1	21.2
		7	9614.40	4.4	19
		8	9627.80	3.2	15.4
		9	9637.70	5.1	15.9
		10	9646.50	1.2	13.7
		11	9653.00	11	21.9
		12	9664.00	11	16.8
	Zone 3	13	9678.60	4.8	21.9
		14	9688.30	5.5	23.2
		15	9698.90	10	19.4
		16	9708.50	1.3	10
		17	9719.00	3.3	20.4
		18	9724.30	69	27.9
		19	9742.50	5.5	17.5
	Zone 4	20	9770.50	79	22
		21	9792.60	4.2	22.4
		22	9802.10	8.8	20.7
		23	9812.10	11	22.7
		24	9819.20	5.5	23.3
		25	9827.60	4.5	21.2
		26	9831.80	3	19.4
		27	9848.50	1	4.8
Lagoon Facies	Zone 5	28	9866.40	41	23.2
		29	9871.30	10	19.4
		30	9878.40	4.4	18.6
		31	9901.20	3.3	18.8
		32	9914.30	2.5	17.8
		33	9933.10	1.5	13.6
		34	9948.40	2	17.1
		35	9969.00	1.6	16.5
		36	9983.00	1.2	13
		37	10009.60	0.65	8.8
		38	10012.80	5.2	11.4

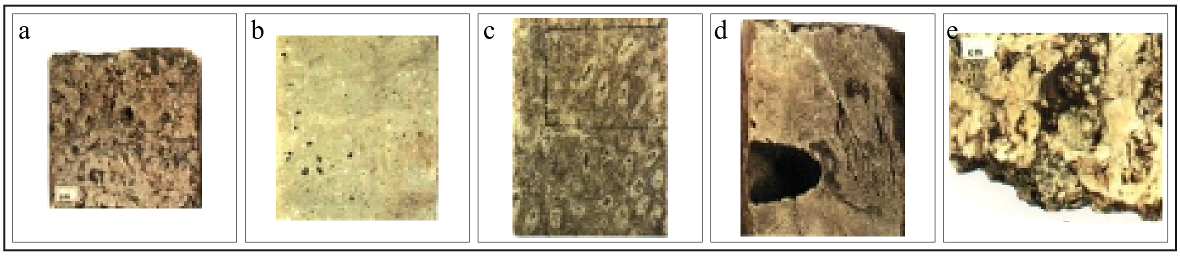

Figure 8. Macroporosity types of Arun Carbonate Reservoir (Jordan, 1989) (a. Vuggy porosity; b. Moldic porosity; c. Intraparticle porosity; d. Fracture porosity; e. Breccia porosity).

Figure 9. Photomicrograph of microporosity of Arun Carbonate Reservoir from Arun A-7 core sample, under SEM mode (Jordan, 1989).

Although the Reef Facies consist of the largest macroporosities, the microporosities of Lagoon Facies are also important in the Arun Carbonate Reservoir. The great majority (more than 90%) of the porosity in Lagoon Facies is the type of microporosity. Microporosity in Lagoon Facies (13.14%) is significantly higher than microporosity in Reef Facies (7.01%). On the contrary, macroporosity in Reef Facies (10.49%) is significantly higher than macroporosity in Lagoon Facies (1.46%), because Arun Reef Facies are exposed causing meteoric diagenesis in the Middle Miocene (Figure 10). Kong *et al*. (2016) stated that the diagenesis process was continuously active as the ambient environment evolved in term of uplift cycle of basin history. Basically, the value of average porosity between Reef and Lagoon Facies is not much different. The significant variable distinguishing productivity of reef and Lagoon Facies is microporosity, macroporosity, and permeability. Based on gamma ray log, porosity log, and compared to lithological characteristics, Arun Carbonate Reservoir can be divided into seven zones (Figure 11; Tables 3 and 4).

Referring to the porosity and permeability data of Arun A-2 core samples (Tables 3 and 4), the zones which have the highest to lowest porosities are Zone 1 (25.48% porosity in average), Zone 3 (20.04%), Zone 4 (19.56%), Zone 2 (17.76%), Zone 5 (16.20%), Zone 6 (11.02%), and Zone 7 (9.56%). The zones which have the highest to lowest permeability are Zone 2 (131 md on the average), Zone 1 (51.5 md), Zone 7 (15.6 md), Zone 4 (14.6 md), Zone 3 (14.2 md), Zone 5 (6.7 md), and Zone 6 (1.2 md). In short, the potential gas resource zones in Arun Carbonate Reservoir are derived from Reef Facies zones (Zones 1, 2, 3, 4, and 7) and Lagoon Facies zones (Zones 5 and 6).

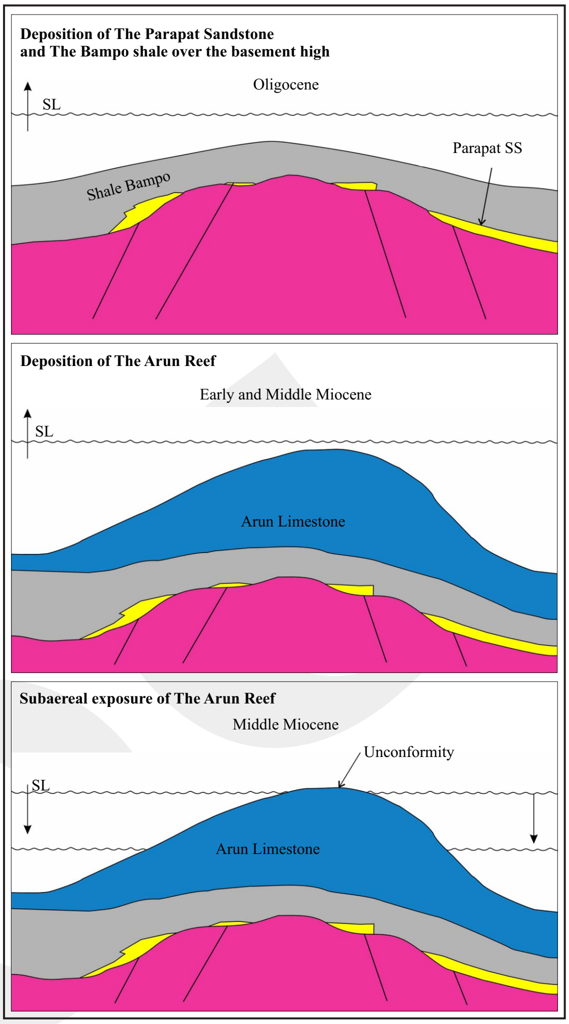

Figure 10. Subaerial to aerial exposure process resulted in macroporosity, in Arun Carbonate Reservoir (modification after Jordan, 1989).

Based on plotting core analysis data of Arun A-2 (Figure 12), the porosity is not correlated to vertically distribution of Reef and Near Reef Facies in Arun Carbonate Reservoir. It is probably caused by its complexity of secondary porosity distribution due to diagenetic processes when Arun Carbonate was exposed in the surface. On the other hand, the value of porosity in Lagoon Facies (Figures 12 and 13) decreases due to the increase of depth.

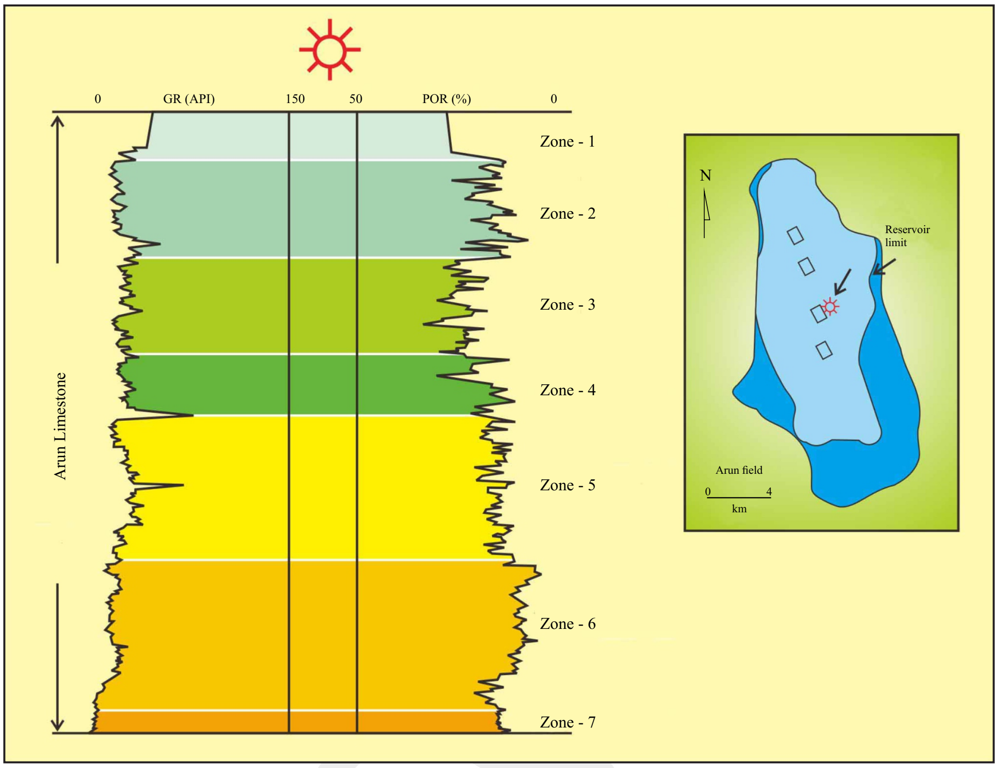

Figure 11. Porosity zones of Arun Carbonate Facies (modification after Atmadibrata, 1993).

Table 4. Porosity and Permeability of Arun A-2 Core Samples (Zone 6 - 7)

Facies	Zone	Sample No.	Depth (Feet)	Horizontal Permeability (md)	Porosity (%)
Lagoon Facies	Zone 6	39	10023.60	1.5	16.4
		40	10033.90	3.9	18.6
		41	10042.80	0.8	10.5
		42	10063.80	1	13
		43	10069.50	0.16	4.6
		44	10083.40	0.31	4.8
		45	10095.20	0.71	10.7
		46	10110.40	1	9.6
Reef Facies	Zone 7	47	10122.10	27	13.6
		48	10138.20	2.8	13.5
		49	10157.40	0.9	13
		50	10173.20	1	5.1
		51	10177.00	77	6.2
		52	10186.30	0.1	4.7
		53	10196.60	0.1	9.9
		54	10200.60	*	10.5

In the case of permeability value, Atmadibrata (1993) stated that permeability data in Arun Carbonate Reservoir were distributed irregularly, both in vertical permeability (Kv) and horizontal permeability (Kh). On the basis of relationship of Kv and Kh in Arun Carbonate Reservoir (Table 5), Zone 1 is dominantly affected by Kv; Zone 4 relatively consists of Kv and Kh; and the other zone is dominantly affected by Kh. The relationship of Kv and Kh is useful to improve the knowledge of gas resource flow in Arun Carbonate Reservoir (Atmadibrata, 1993).

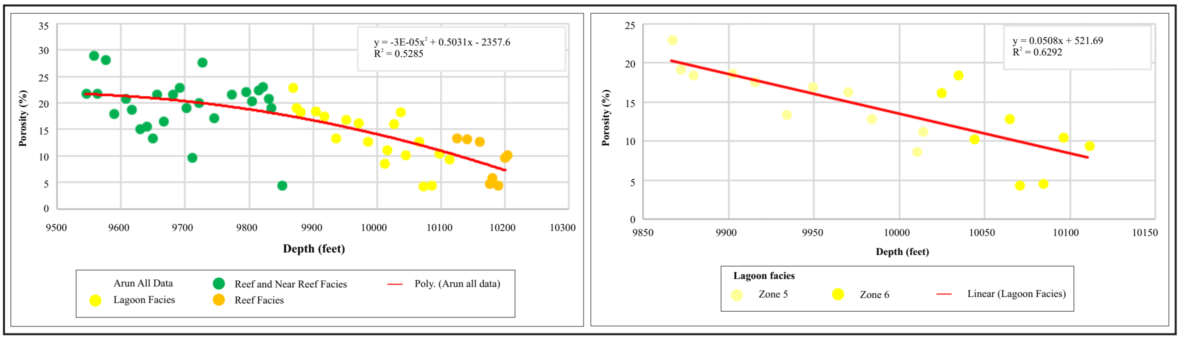

Figure 12. Relationship of porosity and depth in Arun Carbonate and specific on Lagoon Facies.

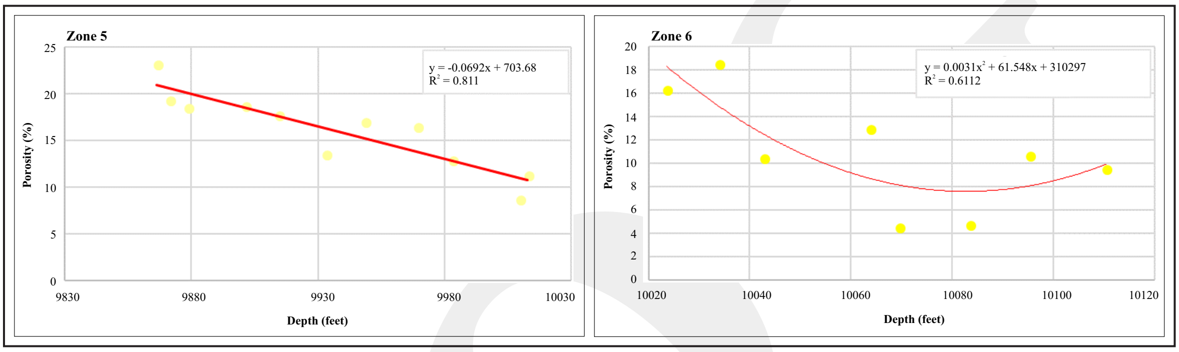

Figure 13. The relationship between porosity and depth (Zone 5 and Zone 6).

Table 5. Relationship of Vertical and Horizontal Permeability in Arun Carbonate Reservoir (modification after Atmadibrata, 1993)

Zone	Type	Slope = b	Intercept = a	Equation	Kv/Kh
1	Full Core	0.87	0.19	Log Kv = 0.87 Log Kh + 0.19	1.57
2	Full Core	1.20	-0.29	Log Kv = 1.20 Log Kh - 0.29	0.51
3	Full Core	1.19	-0.30	Log Kv = 1.19 Log Kh - 0.30	0.51
4	Full Core	0.92	-0.02	Log Kv = 0.92 Log Kh - 0.02	0.96
5 and 6	Full Core	1.25	-0.24	Log Kv = 1.25 Log Kh - 0.24	0.57
7	Full Core	1.05	-0.32	Log Kv = 1.05 Log Kh - 0.32	0.47

Conclusions

Arun Carbonate Reservoir consists of four main lithofacies which is interpreted with regard to lithology and depositional environments; those are 1. Reef Facies characterized by the occurrence of coral boundstones and coral encrusting-red-algae boundstones, 2. Near Reef Facies characterized by skeletal packstone and mixed branches and plates of corals, 3. Lagoon Facies characterized by mixed benthic and planktonic foram packstones to wackstones, and 4. Middle-Shelf Facies characterized by benthic and planktonic foram packstones.

The study of petrophysics shows that the porosity value of Arun Carbonate Reservoir is 16% on the average, while the average permeability value is 13.5 md. The porosity types of Arun Carbonate Reservoir are divided into intercrystalline microporosity 75% and macroporosity 25% (including vuggy, moldic, breccia, and fracture porosity).

However, only two of them which can be categorized as productive facies based on their porosity and permeability, those are Reef Facies and Lagoon Facies. The potential gas resource zonation in Arun Carbonate Reservoir is derived from Reef Facies zones (Zones 1, 2, 3, 4, and 7) and Lagoon Facies zones (Zones 5 and 6). The significant variable distinguishing productivity of Reef Facies zones and Lagoon Facies zones are microporosity, macroporosity, and permeability.

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References

Afidick, D., Kaczorowski, N.J., and Srinivas B., 1994. Production Performance of a Retrograde Gas Reservoir: A Case Study of the Arun Field. *SPE-28749-MS*. Asia Pacific Oil and Gas Conference and Exhibition, Melbourne, Australia. DOI: 10.2118/28749-MS

Archie, G.E., 1952. Classification of Carbonate Reservoir Rocks and Petrophysical Considerations. *AAPG Bulletin,* 36 (2), p.278-298. DOI: 10.1306/3d9343f7-16b1-11d7-8645000102c1865d

Atmadibrata, R.M.R. and Joenoes, S., 1993. Vertical Horizontal Permeability Relationship: Arun Reservoir. *SPE-25362-MS*, Asia Pacific Oil and Gas Conference and Exhibition, Singapore. DOI: 10.2118/25362-MS

Atmadibrata, R.M.R., 1988. Top of Abnormal Pressure Zone Prediction in the Arun Field, North Sumatra. *PIT. IAGI XVII*, Jakarta.

Avida, H., Auzan A.S., and Deli P.U., 2013. Aceh Operation Mature Field Management: Arun Assets Consolidation and North Sumatra Offshore (NSO) Liquid Handling. *SPE-165929-MS*, Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia. DOI: 10.2118/165929-MS

Barber, A.J., Crow, M.J., and Milsom, J.S. 2005. Sumatra: Geology, Resources, and Tectonic Evolution. *Geology Society Memoirs,* 31, London, 289p. DOI: 10.1017/s0016756806212974

Cameron, N.R., Bennett, J.D., Bridge, D.McC., Clarke, M.C.G., Djunuddin, A., Ghazali, S.A., Harahap, H., Jeffery, D.H., Kartawa, W., Keats, W., Ngabito, H., Rocks, N.M.S., and Thompson, S.J., 1983. *Geologic Map of the Takengon Quadrangle, Sumatra, scale 1:250.000.* GRDC, Bandung.

Chilingarian, G.V., Mazzullo, S.J., and Rieke, H.H., 1992. *Carbonate Reservoir Characterization: A Geologic - Engineering Analysis, Part I*, Elsevier, Amsterdam, 638p. DOI: 10.1016/s0376-7361(96)80023-9

Chopra, S., Chemingui, N., and Miller, R., 2005. An Introduction to this Special Section Carbonates. *The Leading Edge May*, p.488-489. DOI: 10.1190/1.1926805

Choquette, P.W. and Pray, L.C., 1970. Geological Nomenclature and Classification of Porosity in Sedimentary Carbonates. *AAPG Bulletin,* 54, p.207-250. DOI: 10.1306/5d25c98b-16c1-11d7-8645000102c1865d

Fauzi, R.R., Atmadibrata R.M.R., Muslim, D., and Sophian, R.I., 2017. Physical and Geomechanical Characteristics of Keutapang Formation in Arun Gas Field, North Sumatra, Indonesia. *Proceedings the 2nd Joint Conference of Utsunomiya University and Universitas Padjajaran*, Japan.

Jordan C.F., 1989. The Geology of the Arun Reservoir: Depositional and Diagenetic History of a Miocene Patch Reef Complex, North Sumatra, Indonesia. *Mobil Research & Development Corporation*, Unpublished Report.

Keats, W., Cameron, N.R., Djunuddin, A., Ghazali, S.A., Harahap, H., Kartawa, W., Ngabito, H., Rocks, N.M.S., Thompson, S.J., and Whandoyo, R., 1981. *Geologic Map of the Lhokseu-*

mawe Quadrangle, Sumatra, scale 1:250.000. GRDC, Bandung.

Kong, L., Wan, M., Yan, Y., Zou, C., Liu, W., Tian, C., Yi, L., and Zhang, J., 2016. Reservoir Diagenesis Research of Silurian Longmaxi Formation in Sichuan Basin, China. *Journal of Natural Gas Geoscience,* I, p.203-211. DOI: 10.1016/j.jnggs.2016.08.001

Lindsay, R.F., 2010. Carbonate Porosity Families and Their Reservoir Potential, Louisiana USA. *AAPG Annual Convention and Exhibition*.

Lucia, F.J., 1995. Rock Fabric Petrophysical Classification of Carbonate Pore Space for Reservoir Characterization. *AAPG Bulletin,* 79, p.1275-1300. DOI: 10.1306/7834d4a4-1721-11d7-8645000102c1865d

Lucia, F.J., 2007. *Carbonate Reservoir Characterization.* 2nd edition Springer-Verlag, Berlin, 342p. DOI: 10.1007/978-3-540-72742-2

Mazzullo, S.J., 2004. Overview of Porosity Evolution in Carbonate Reservoirs. *Kansas Geological Society Bulletin,*79 (1-2)*,* p.1-19.

Moore, C.H., 2001. Carbonate *Reservoirs: Porosity Evolution and Diagenesis in a Sequence Stratigraphic Framework*. Elsevier, Amsterdam, 444p.

North, F.K., 1985. *Petroleum Geology*. Allen & Unwin, London, 607p.

Praptisih and Kamtono, 2014a. Hydrocarbon Host Rock Characteristics of Cibulakan Formation at Palimanan Area, Cirebon, West Java. *Buletin Sumberdaya Geologi,* 9 (1), p.27-40.

Praptisih and Kamtono, 2014b. Carbonate Facies and Sedimentation of the Klapanunggal Formation in Cibinong, West Java. *Indonesian Journal on Geoscience,* I (3), p.175-183. DOI: 10.17014/ijog.v1i3.196

Schon, J.H., 2011. *Physical Properties of Rocks: A Workbook. Handbook of Petroleum Exploration and Production*, Elsevier, UK, 481p.

Serra, O., 2003. *Well-log and Geology*. Elsevier Science Publishing Company inc. USA, 468p.

Soeparjadi, R.A., 1983. Geology of the Arun Gas Field. *SPE Paper No. 10486*. Presented at Offshore South East Asia Conference, Singapore.

Wardlaw, N.C., 1976. Pore geometry of carbonate rocks as revealed by pore casts and capillary pressures. *AAPG Bulletin,* 60, p.245-257. DOI: 10.1306/83d922ad-16c7-11d7-8645000102c1865d

Wayne, M.Ahr., 2008. *Geology of Carbonate Resevoirs: The Identification, Description and Charaterization of Hydrocarbon Reservoirs in Carbonate Rocks.* Willey, New Jersey, 289pp. DOI: 10.1002/9780470370650