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LESSON LEARN OF GEOCHEMISTRY OF HYDROCARBON GASES AND CO_2 IN MESOZOIC PETROLEUM SYSTEM OF PAPUA NEW GUINEA: IMPLICATION FOR THE FOLD BELT PLAY CONCEPT IN EASTERN PAPUA, INDONESIA

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Abstract - The potential of oil and gas discovery at the Fold Belt Play concept in eastern Papua could be learned from the multiple production fields in Papua New Guinea Fault and Thrust Belt area which has similar geological condition. Therefore, the geochemical characteristic of hydrocarbon gases and CO_2 at the Fold Belt Play concept is expected to be predictable by the analogy of those gases occurrence in Mesozoic petroleum system of Papua New Guinea Fault and Thrust Belt area. The hydrocarbon gases are of thermogenic origin, generated from Type II/III kerogen of Jurassic-Cretaceous source rock with gas maturity of about 1.2 to 2.0% Ro equivalent. The average CO_2 percentage in Mesozoic reservoir at Papua New Guinea is ~1.58%. The relatively light $\delta^{13}C$-CO_2 (-25.2 to -10.4‰) unequivocally confirm that the low volume of CO_2 is generated from kerogen maturation mechanism. For the Fold Belt Play concept in eastern Papua, the hydrocarbon gases are expected to have similar characteristic with the gases in Papua New Guinea. The low CO_2 may probably only be found at Northern Fold Belt due to the preservation of thin-skinned deformation that have the basal detachment surface in the Kembelangan Group (Kopai Formation). On the other hand, the Central and Southern Fold Belt are predicted to contain moderate to high volume of inorganic CO_2 migrated from Modio/Brug Dolomite.

Key words: the Fold Belt Play, Mesozoic petroleum system, analogous, Papua New Guinea, eastern Papua

Sari *– Potensi penemuan cadangan minyak dan gas pada konsep Fold Belt Play di Papua bagian timur dapat dipelajari dari banyaknya kehadiran lapangan migas berproduksi di area Papua New Guinea Fault and Thrust Belt yang secara umum memiliki kondisi geologi yang serupa. Dengan demikian, karakteristik geokimia gas hidrokarbon serta CO_2 pada konsep Fold Belt Play diharapkan dapat diprediksi melalui analog kemunculan gas tersebut pada sistem petroleum Mesozoikum area Papua New Guinea Fault and Thrust Belt. Hasil analog menunjukkan gas hidrokarbon yang hadir merupakan gas termogenik, dihasilkan dari batuan induk Jura-Kapur kerogen Tipe II/III dengan kematangan gas berkisar antara 1,2 dan 2,0% ekuivalen Ro. Rata-rata persentase volume CO_2 pada reservoir Mesozoikum di Papua Nugini adalah sekitar ~1,58%. Nilai $\delta^{13}C$-CO_2 yang relatif ringan (-25,2 hingga -10,4‰) mengonfirmasi bahwa CO_2 dengan volume rendah ini dihasilkan dari mekanisme pematangan kerogen. Untuk konsep Fold Belt Play di Papua bagian timur, gas hidrokarbon yang hadir diharapkan akan memiliki karakteristik yang sama terhadap gas dari Papua Nugini. Kandungan CO_2 rendah mungkin hanya dapat ditemukan di Northern Fold Belt karena adanya preservasi deformasi thin-skinned yang memiliki bidang gelincir sesar di Grup Kembelangan (Formasi Kopai). Di sisi lain, pada area Central dan Southern Fold Belt diperkirakan akan mengandung CO_2 anorganik dengan volume menengah hingga tinggi akibat migrasi CO_2 dari Formasi Dolomit Modio/Brug.*

Kata kunci*: Fold Belt Play, sistem petroleum Mesozoikum, analog, Papua Nugini, Papua bagian timur*

1. INTRODUCTION

Bird's Body of Papua Island (eastern Papua, Indonesia) is categorized as a remote and inaccessible "frontier" area that makes it lack of geophysical and geological data (Argakoesoemah and Hughes, 2017). Regionally, the geological setting of eastern Papua has many similarities with the basins in Papua New Guinea. Unfortunately, the number of discoveries was the least in eastern Papua inversely to the number of discoveries in Papua New Guinea e.g.: Hides, Kutubu, Heidina, Agogo, etc. (Kendrick and Hill, 2001; Argakoesoemah and Hughes, 2017). Several publications (Kendrick and Hill, 2001; Hill et al., 2004; Argakoesoemah and Hughes, 2017) were

studied for the geological setting of Papua New Guinea to build analogy of new petroleum system play concepts in eastern Papua. Argakoesoemah and Hughes (2017) have classified three types of petroleum system play concepts in eastern Papua: Fold Belt Play, Inversion Play, and Foreland Play (**Figure 1**). The Fold Belt Play concept is probably the most interesting compared to the others as most of the oil and gas fields in Papua New Guinea host this type of play in Pre-Tertiary reservoirs.

To build better decisions in exploration strategies, basin and petroleum system modeling is one of the fundamental tasks. To achieve that, the hydrocarbon geochemistry data became principal to produce an ultimate approach to the modeling. In addition, at this time the assessment of the occurrence of CO_2 needs to be considered in determining the exploration strategy policy. It is because CO_2 as non-hydrocarbon gas increases production costs due to the need for a cleaner energy vision (CCUS activity, carbon tax, etc.). Due to the lack of data to evaluate the hydrocarbon gas and CO_2 study in eastern Papua, this paper provides an analogous assessment of the hydrocarbon gas and CO_2 characterization of Papua New Guinea's gas fields as a preliminary evaluation of petroleum system in the Fold Belt Play concept, eastern Papua, Indonesia.

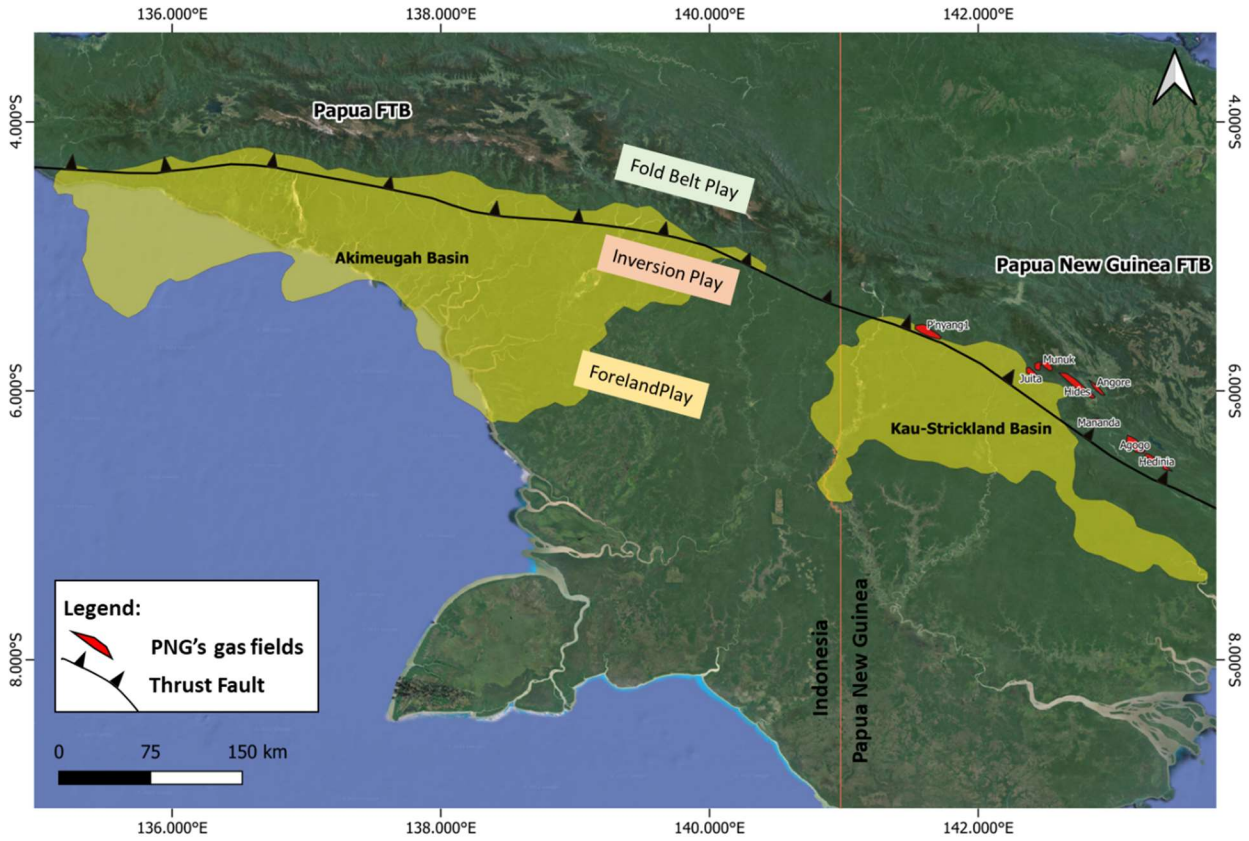

Figure 1. Geographic position of the three play concepts in eastern Papua, Indonesia: Fold Belt Play, Inversion Play, and Foreland Play. The multiple discoveries in Papua New Guinea FTB (Fold and Thrust Belt) also presented in this picture (adapted from Argakoesoemah and Hughes, 2017).

2. PRE-TERTIARY STRATIGRAPHY

The stratigraphic column (**Figure 2**) summarized in this paper is only the Pre-Tertiary sequences. Modio Dolomite (another name is Brug Dolomite) is assigned as the oldest sedimentary section penetrated by wells (Argakoesoemah and Hughes, 2017). This sequence was deposited during Silurian to Early-Middle Devonian, indicated by the preservation of Conodont fauna (Pieters et al., 1983). Argakoesoemah and Hughes (2017) claimed

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Modio/Brug dolomite as an economic basement in some wells which penetrated the sequence. It is supported by the statement of Kendrick and Hill (2001) that hydrocarbon shows in Modio/Brug Dolomite from Noordwest-1 well highlighted the possibility of fracture or vug/paleokarst development.

The Aiduna Formation was likely deposited in a paralic to very shallow marine environment with maximum thickness about 2000 m (Panggabean and Hakim, 1986). This Early - Late Permian formation is described as well bedded felspathic and micaceous fine to coarse-grained lithic sandstone interbedded with carbonaceous shale and siltstone, minor fossiliferous biocalcarenite and polymictic conglomerate. Coal seams up to 1.5 m occur although, most are less than 30 cm thick (Panggabean and Hakim, 1986).

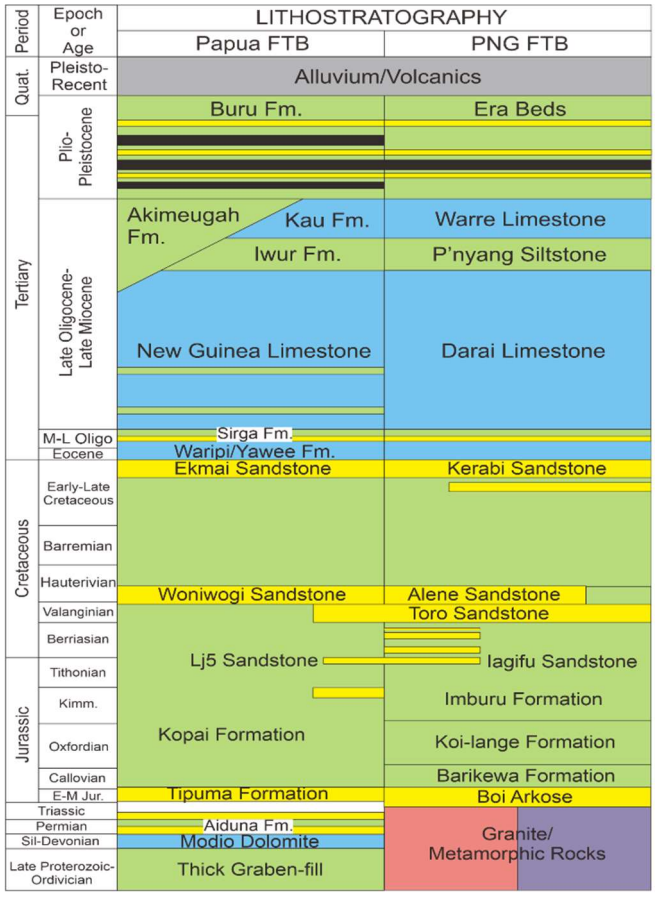

Figure 2. Generalized stratigraphic column of Papua FTB (Fold and Thrust Belt) and Papua New Guinea FTB (after McConacnie et al., 2000 in Kendrick and Hill, 2001).

The Triassic to Early Jurassic Tipuma Formation consists of maroon, green, grey to white feldspathic or tuffaceous lithic sandstone, minor red to grey micrite, arkose and polymictic conglomerate, volcanoclastic sandstone, and tuff (Panggabean and Hakim, 1986). The lack of organic matter and the highly oxidized state of the shale make the Tipuma Formation unlikely to be a source rock (Pieters et al., 1983).

The Kembelangan Group is a group of Kopai, Woniwogi, Piniya, and Ekmai Formations that rest disconformable on the Tipuma Formation (Pigram and Sukanta, 1982 in Pieters et al., 1983). The basal unit of Kembelangan Group of the Middle to Late Jurassic Kopai Formation, consists of predominantly of glauconitic quartz sandstone interbedded with siltstone and calcareous mudstone and with minor micaceous sandstone, "greensand", conglomerate, calcarenite, and calcilutite (Panggabean and Hakim, 1986). The Kopai Formation is conformably overlain by the Late Jurassic to Early Cretaceous Woniwogi Formation, comprising well bedded to massive glauconitic orthoquartzite (micaceous in part), with minor siltstone and thinly bedded black calcareous mudstone near the top (Panggabean and Hakim, 1986). Conformably overlying Woniwogi Formation is Piniya Mudstone. It is described as grey to black micaceous mudstone, glauconitic mudstone, minor muddy glauconitic quartz sandstone, and muddy siltstone, deposited in a shallow shelf during a marine transgression (Panggabean and Hakim, 1986). Late Cretaceous Ekmai Formation acts as the uppermost unit in Kembelangan Group. The formation consists predominantly of massive to thickly bedded glauconitic quartz sandstone, minor carbonaceous sandstone, siltstone, and mudstone, and was probably deposited in an inner shallow shelf environment (Panggabean and Hakim, 1986).

3. REVIEW OF THE FOLD BELT PLAY CONCEPT IN PAPUA PROVINCE

According to Argakoesoemah and Hughes (2017), the Fold Belt Play geologically extends from northwest to southeast along the Papua Fold and

Thrust Belt in the Bird's Body region and regionally extends across the Indonesia-Papua New Guinea international border to the east and merges with the Papua New Guinea Fold and Thrust Belt (see **Figure 1**).

Figure 3 is a schematic cross section of Bird's Body in the direction of NE-SW after Kendrick and Hill (2001). The Fold Belt Play is in the north part of the section and could be divided into three parts: Northern Fold Belt, Central Fold Belt, and Southern Fold Belt. Considering the presence of source rock, reservoir, and seal rock, the Northern and Central Fold Belt contain all of them. Discussing the Mesozoic petroleum system, Kendrick and Hill (2001) have formulated the candidates of source rocks in this type of play concept:

1) possibly, shale and thin coal within the Permian Aiduna Formation,
2) shale within the Middle Jurassic Kopai Formation, analogous to Papua New Guinea, and
3) shale of the Upper Cretaceous Piniya Formation, analogous to Papua New Guinea.

The potential reservoir rocks according to Kendrick and Hill (2001) are:
1) Early Turonian to Late Campanian Ekmai Formation,
2) lower Upper Cretaceous Woniwogi Formation,
3) the Kopai Sandstone,
4) the LJ5 Sandstone, and
5) brittle Silurian-Devonian Modio Dolomite.

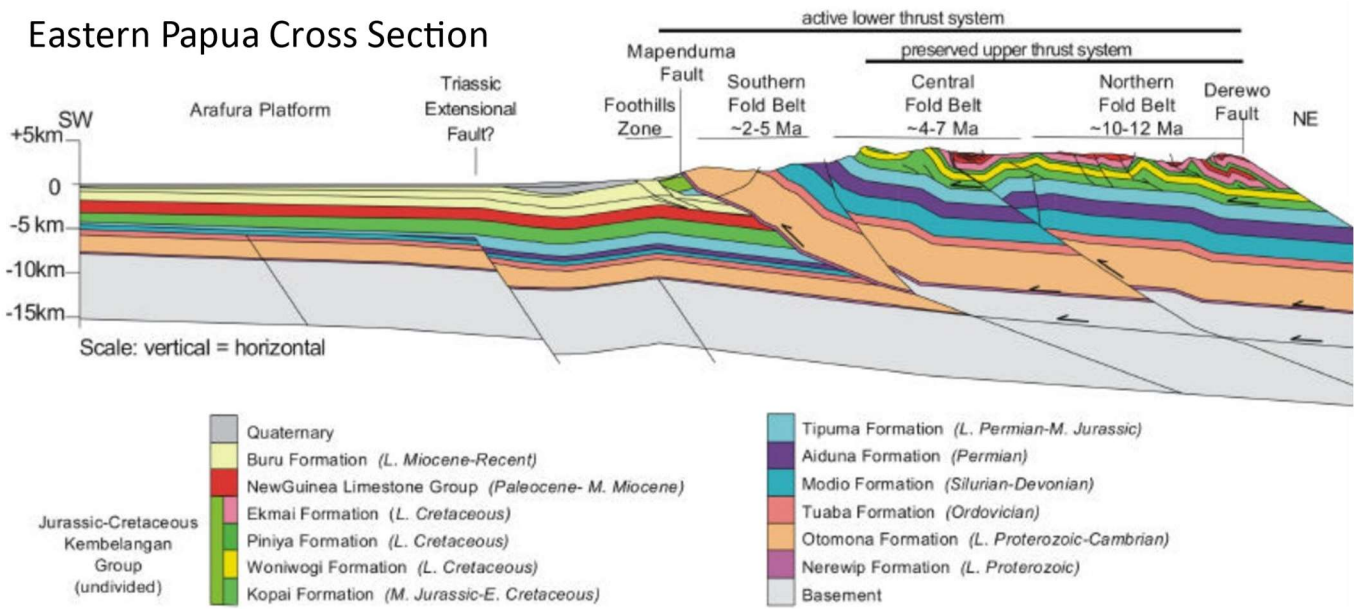

Figure 3. A schematic cross-section of Bird's Body, eastern Papua area shows the Fold Belt Play concept in the north (after Kendrick and Hill, 2001).

The best potential seal rocks are the Piniya and Kopai Formations, especially to the north where they are thickest. New Guinea Limestone Group may provide an adequate seal for Late Cretaceous Ekmai Formation (Kendrick and Hill, 2001).

The traps in the Fold Belt Play are product of thin-skinned (known as upper thrust system) and thick-skinned deformation (known as lower thrust system). The thin-skinned deformation was established during Late Miocene with the basal detachment fault interpreted in the Kembelangan Group (Kopai Formation). This thin-skinned could be found in the Northern Fold Belt area. Heading to the south, the deformation propagates to be thick-skinned, involving basement deformation. Thick-skinned deformation has started during Pliocene until Recent (Argakoesoemah and Hughes, 2017; Kendrick and Hill, 2001).

4. DATA AND METHODOLOGY

The data used in this paper are as many as 17 gas compositions (C_1, C_{2+}, and CO_2) collected from 5 gas fields in Papua New Guinea, reservoired in the Mesozoic sandstone **(Table 1).** Isotopes of $\delta^{13}C$ are taken from C_1 – C_3 to better understand characterization of the hydrocarbon gas. The $\delta^{13}C$-C_1 will be used to categorize the hydrocarbon gases, whether they are of thermogenic or biogenic origin. Cross plot of $\delta^{13}C$-C_1 and $\delta^{13}C$-C_2 after Milkov (2021) will be applied to approximate kerogen type information of the source rock. The $\delta^{13}C$-C_2 and $\delta^{13}C$-C_3 will be calculated using the equations from Berner and Faber (1996) gas maturity parameter to evaluate the maturation of source rock when generating hydrocarbon gases. Carbon isotopes from CO_2 are used to identify the origin of CO_2 itself, whether it's organic or inorganic. After that, the result of Papua New Guinea hydrocarbon gases and CO_2 interpretations later used as an analogy to the Fold Belt Play concept in Papua as a preliminary overview. The conclusion of the study is formulated after elaborating the geochemical study of gases analogous to Papua New Guinea and the geological conditions of the Fold Belt Play concept in eastern Papua, Indonesia.

Table 1. Data availability of this study (collected from GWIS (2012) and IHS (2019) reports)

No.	Field	Sample Number	Normalised Hydrocarbon (mol %)		CO_2 (mol %)	Isotope $\delta^{13}C$ (‰)			
			C_1	C_{2+}		C_1	C_2	C_3	CO_2
1	Agogo	1	97.83	2.16	3.59	-47.56	-31.16	-28.58	-16.62
2		2	72.20	27.80	0.90	-47.27	-31.1	-28.48	x
3		3	79.96	20.04	1.80	-48.28	-30.95	-27.69	x
4	Angore	1	94.47	5.53	1.60	-37.97	-25.04	-24.6	x
5		2	93.92	6.08	1.50	-37.77	-24.84	-24.77	-19.65
6	Hedinia	1	82.26	17.74	1.92	-44.69	-31.14	-28.51	-14.49
7		2	68.17	31.83	2.26	-42.07	-31.27	-28.58	-17.88
8	Hides	1	90.95	9.05	0.31	-42.55	-28.34	x	-17.97
9		2	88.16	11.84	0.31	-42.71	-28.43	x	-16.43
10		3	67.18	32.82	0.95	-38.87	-27.28	x	-25.15
11		4	89.54	10.46	0.37	-41.87	-28.65	-25.61	-11.18
12		5	87.94	12.06	0.37	-43.35	-28.43	-27.06	-12.58
13		6	89.27	10.73	0.30	-41.5	-29.1	-25.5	-10.44
14	SE Mananda	1	84.50	15.50	0.70	-39.7	-28.1	-21.7	-15.1
15		2	78.76	21.24	2.89	-36	-26.7	-23.8	x
16		3	81.35	18.65	4.29	-37	-27.1	-20.6	x
17		4	78.76	21.24	2.89	-36	-26.7	-23.8	x

5. RESULTS AND DISCUSSION

5.1 *Papua New Guinea's Hydrocarbon Gas Characterization*

The normalized hydrocarbon gases from Papua New Guinea's gas fields are categorized as methane-dominated gases with a range of C_1 about 67.18 – 94.47%. Isotope analysis of $\delta^{13}C$-C_1 indicates the gases are thermogenic origin (-48.28 to -36‰). **Figure 4** shows the kerogen type of source rock that produce the gases. The plots converge on the dividing line between Type II (shale-sourced) and Type III (coal-sourced) kerogens. Hence the plot suggests, the source rock of the hydrocarbon gases in Papua New Guinea's gas fields is of Type II/III kerogen.

The assessment of gas maturity has been conducted by using the equations of $\delta^{13}C$ from Berner and Faber (1996). The gas maturity calculation ranges from approximately 1.2 to 2.0% Ro equivalent, which means the source rock is already in the state of late-overmature stage.

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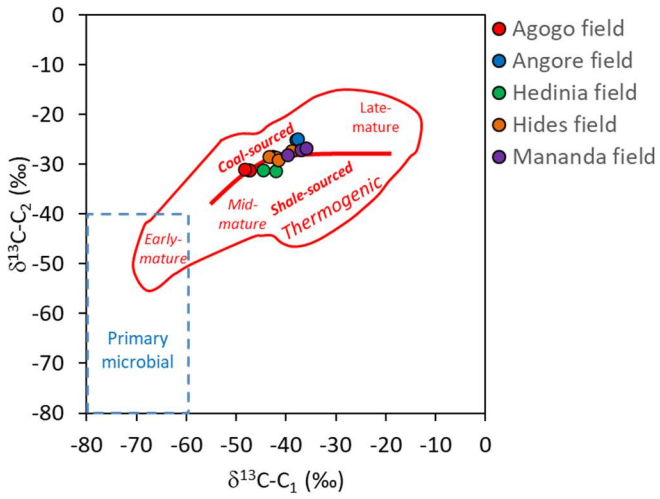

Figure 4. The mixing of Type II and III (known as Type II/III) kerogen is the source of hydrocarbon gases in Papua New Guinea (after Milkov, 2021).

5.2 *Papua New Guinea's CO_2 Characterization*

Seventeen samples from five gas fields contain only a small amount of CO_2. The value of CO_2 ranges from 0.30 to 4.29% volume (average ~1.58%), typical of small organic CO_2 volume. The hypothesis of organic CO_2 requires validation by evaluating the isotope of $\delta^{13}C$-CO_2. If the $\delta^{13}C$-CO_2 is lighter than -8‰ (such as -15 or -20‰), the CO_2 is confirmed to be generated from an organic mechanism (kerogen maturation or biogenic activity). Otherwise, if it is heavier than -8‰ (such as -5 or -2‰), the CO_2 is assigned as inorganic origin that could be generated from carbonate mineral dissolution or mantle degassing. The isotope values of $\delta^{13}C$-CO_2 from 11 samples of 5 gas fields in Papua New Guinea ranges from -25.2 to -10.4‰, unequivocally confirmed that the CO_2 gases were generated from the organic mechanism. Kerogen maturation is more likely the primary factor to generate the CO_2 since the gas maturity is already above 1.2% Ro equivalent, rather than biogenic activity mechanism. The reasons are explained in the following section.

There is no such condition for generating high volumes of CO_2 in Mesozoic petroleum system of the Papua New Guinea Fold and Thrust Belt. Carbonate sequence is absent below the Tertiary (look back to **Figure 1**) and mantle-degassing CO_2 cannot penetrate the reservoirs due to the tectonic regime in the research area being thin and thick-skinned deformations, resulted in detachment faults instead of deep-seated faults that penetrate the mantle. Secondly, the source rock is Type II/III kerogen instead of coal. Second, Hunt (1996) contended hydrocarbon gas that is produced from coal source rock would have heavier CO_2 isotope value than Type II or shale source rock. Moreover, there is no information that coal deposits propagate massively in Jurassic source rock at Papua New Guinea Fold and Thrust Belt.

5.3 *Lesson Learn for the Fold Belt Play Concept in eastern Papua, Indonesia*

Since the geochemical data of hydrocarbon and source rock in the Fold Belt Play area is limited and considering the similarity of the regional geology of the Fold Belt Play area and Papua New Guinea Fold and Thrust Belt, it could be predicted the gas in Fold Belt Play Mesozoic petroleum system will have similar characteristic with the gas in Papua New Guinea Fault and Thrust Belt Mesozoic petroleum system. The hydrocarbon gas may likely be thermogenic methane-dominated, generated from Type II/III kerogen with estimated maturity of late to overmature stage (above 1.00% Ro).

The occurrence of CO_2 in the Fold Belt Play concept majorly will have similar characteristic to Papua New Guinea Fault and Thrust Belt. The main source is organic CO_2 generated from kerogen maturation at late to overmature stage. Therefore, it will only be generated in a small amount of CO_2 (statistically, from Papua New Guinea is below 5%). Organic CO_2 from decarboxylation of coal from Aiduna Formation could be possibly found in the gas reservoir. These conditions could significantly be predicted to be found in Northern Fold Belt.

Since the main reservoir target is Jurassic-Cretaceous, the sequence older than Jurassic should be considered whether it might produce a high volume of inorganic CO_2 from carbonate dissolution. Modio/Brug Dolomite is the only carbonate sequence below Jurassic that possibly play a role as a producer of high volume of inorganic CO_2 from carbonate dissolution.

In retrospect, the tectonic evolution in the Fold Belt Play area, thin-skinned deformation interpreted to occur during the Late Miocene where the basal detachment fault possibly at the basal of Kembelangan Group (Kopai Formation). This thin-skinned deformation is preserved in the north area of Fold Belt Play concept (Northern Fold Belt). Heading to the south, the thin-skinned deformation propagates into thick-skinned deformation (basement involved deformation). Tectonically, the northern and southern area could be differentiated by the presence of fault that penetrate the Modio/Brug Dolomite all the way down to the basement and end in the detachment fault within the basement (see again **Figure 3**). Since the Northern Fold Belt retains only thin-skinned deformation with detachment fault in the basal of Kembelangan Group, inorganic CO_2 from Modio/Brug Dolomite is not expected to fill the Mesozoic reservoir as there are no fault to possibly act as a conduit. Thus, it is expected that Northern Fold Belt will only contain a small volume of organic CO_2 generated from kerogen maturation in the late to overmature stage of source rock maturation. On the other hand, the Central and Southern Fold Belt are predicted to contain moderate to high volume of inorganic CO_2 migrated from Modio/Brug Dolomite to the Mesozoic reservoir through the fault formed by thick-skinned deformation. Kendrick and Hill (2001) also proposed the brittle Silurian-Devonian Modoi/Brug Dolomite as a fractured basement reservoir. When the depth of this type of reservoir already experienced at least 150^{o}C (Kissin and Pakhamov, 1967 in Cooper et al., 1997), the probability is to contain a moderate to high level of CO_2 volume is greater.

6. CONCLUSION

The evaluation of geochemistry of hydrocarbon gases and CO_2 from Papua New Guinea's gas fields has given some analogous information. The expected hydrocarbon gases in the Mesozoic petroleum system Fold Belt Play concept are thermogenic methane-dominated of Type II/III kerogen source rock with estimated maturity of late to overmature stage (over 1.0% Ro). The low volume of organic CO_2 is expected to be found in the Northern Fold Belt due to the preservation of thin-skinned deformation in Kembelangan Group. Moderate to high levels of CO_2 volume generated from Modio/Brug Dolomite most likely to charge the reservoirs in Central and Southern Fold Belt.

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