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Reinterpretation of Salodik Group Performance Based on Facies and Diagenesis Approaches to Classify Reservoir Quality

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Abstract - An integrated study of several methods to characterize a carbonate reservoir provides a comprehensive result on carbonate facies and diagenesis. Therefore, a study on the Tertiary carbonate reservoir at the East Arm of Sulawesi area, Banggai – Sula Basin, is intended to determine the Salodik Group carbonate reservoir facies and diagenesis. Moreover, the purpose of this study is to determine the intensity and implication of syn-depositional or post-depositional processes, and to provide the reservoir final properties values, such as porosity and permeability to classify the reservoir quality. The methods of the study are based on carbonate fieldwork mapping to obtain samples on distributed traverses. Further analyses are the laboratory works to determine facies and diagenesis features on a more detailed scale. This study shows several facies, dominantly classified into reefal packstone, planktonic foraminifera packstone-wackestone, large foram packstone-mudstone, skeletal packstone-wackestone, planktonic-large foraminifera packstone-wackestone, and large foraminifera-red algae packstone. The dominant diagenesis processes are cementation and dissolution. Moreover, meteoric vadose and meteoric phreatic are predominantly the main diagenesis environment of Salodik Group formations. Furthermore, the dominant diagenesis stage is Eogenetic. The post-depositional process or the diagenetic processes, provides a more significant impact on carbonate reservoir properties than the syn-depositional process as shown on lithofacies texture. However, in general, from the younger to the oldest formation of Salodik Group, this shows a decreasing trend of reservoir properties due to the dominant cementation process in the oldest formation. Overall, the reservoir quality referring to porosity value is classified as negligible to excellent. While, based on permeability data, it is classified as the tight to good reservoir.

Keywords: Carbonate reservoir, Salodik Group, carbonate facies, diagenesis, porosity, permeability, reservoir quality

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Introduction

Background

The study of carbonate reservoirs according to Wayne (2008) comprises how to find, to extract, and manage the oil, gas usable water, or other resources they contain. Therefore, multiple studies had been conducted to manage and to characterize carbonate reservoirs. As the carbonate itself makes up about on-fifth to one-quarter of all sedimentary rocks in the stratigraphic record prior to Boggs (2009), studies have been commenced in carbonate reservoir comprising several scales, that include basin, reservoir, hand-specimen, and microscopic scale. Moreover, it is analyzed in more detailed scale by using Scanning Electron Microscope (SEM). However, although several previous studies and multi-methods had been used to characterize carbonate reservoirs, the complexity of this particular type of shallow marine reservoir, which is provided from the origin of the reservoir and structural geology, improves the difficulties of characterizing the carbonate reservoir. Another parameter which makes carbonate reservoir is more difficult to understand is the variety of the diagenesis. Diagenesis, according to Milliken (2003) is the physical and chemical changes that alter the characteristics of sediments after deposition. Moreover, according to Scholle and Ulmer-Scholle (2003), the most common diagenesis type comprises the cementation, dissolution, replacement, recrystallization, compaction, and fracturing.

One of the most complex carbonate gas reservoirs is the Salodik Group. This group based on previous study of Prabawa *et al*. (2020), is divided into equivalent formations, including Lower Tomori, Upper Tomori, and Minahaki Formations, and Mentawa Member. These formations of Salodik Group are affected by complexity of the geological setting of Banggai-Sula Microcontinent, where the formations are deposited. The geological setting was initially as the result of the collision of the Australian-Eurasian Plates. Moreover the complexity is also improved by the implication of Sorong Fault, which displaced the Banggai-Sula Microcontinent and collided with East Sulawesi (Guntoro, 1999). In order to analyze and characterize the Salodik Group, a study on Tertiary carbonate reservoir at East Arm of Sulawesi area, Banggai–Sula Basin, is intended to determine the diagenesis process and diagenesis environment of Salodik carbonate reservoir facies. Moreover, the purpose of this study is also to determine the intensity and implication of either syn-depositional or post-depositional processes, to provide reservoir final properties values, such as porosity and permeability by using multimethods.

Geological and Stratigraphical Settings

According to Darman and Sidi (2000), the Salodik Group was deposited in the Banggai-Sula Basin during Eocene–Pliocene. While Pertamina-BPPKA (1996) stated that it was deposited during Early Miocene to Late Miocene. Furthermore, Rusmana *et al.* (1993), decided that the Salodik Group was deposited during Early Eocene to Middle Miocene. The sample of Pertamina-BPPKA (1996) included borehole core sample, while Rusmana *et al*. (1993) obtained the samples during their fieldwork activity.

The Banggai-Sula Basin was originated from the collision of Australian northern margin at New Guinea with Eurasian Plate. According to Nugraha and Hall (2018), the collision among an Australia continental promontory, the Sula Spur, and the SE Asian margin of North Sulawesi volcanic arc began in the Early Miocene. Satyana and Purwaningsih (2011) emphasized the collision event of East Arm Sulawesi commenced in the Middle Miocene until Pliocene. Furthermore, this collision formed an obduction of the ophiolite series and thrusted eastwards over the microcontinent to form an imbricated collision zone at the East Arm of Sulawesi (Watkinson *et al*., 2011). The series of these tectonic events as illustrated on Figure 1 resulted in the majority faults of the East Arm characterized by imbricate thrusts. The thrust, particularly, the Banggai-Sula Zone and Ophiolitic Zone is marked by the Batui Thrust (Cornee *et al*., 1995) on the present day appearance at the area. The tectonic events are also marked the forming of Tomori Basin, which occupies the area of Morowali, North Morowali, and the offshore of Tolo Bay, East Arm of Sulawesi (Santy, 2016). As the targeted formation, Salodik Group is unconformably overlain by Nambo Formation, which consists of limestone with sandstone at the base. Based on the appearance of large foraminifera and planktonic foraminifera such as *Nummulites sp*., *Amphistegina sp*., *Lepidocyclina sp*., *Miogypsina sp*., and *Alveolinella sp*., the Salodik Group is dated as Eocene–Late Miocene in age. This group was generally deposited at a shallow marine (Rus-

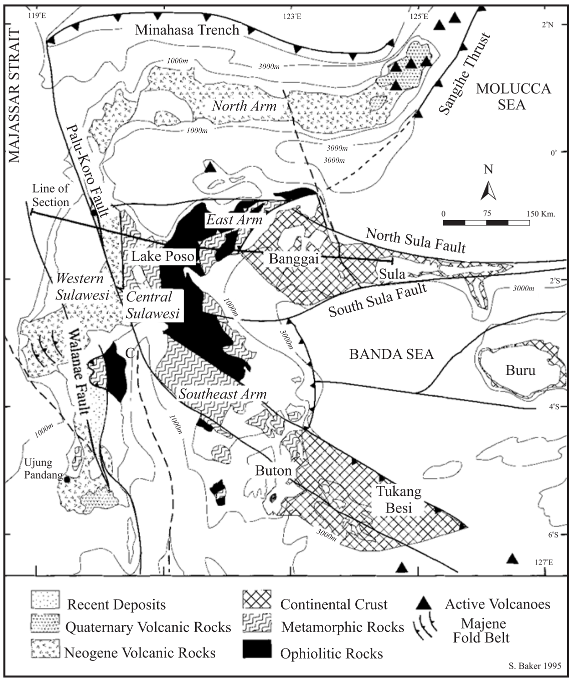

Figure 1. Regional structure of Sulawesi (Simandjuntak and Barber, 1996).

mana *et al*., 1993). Through the previous exploration drilling, subsurface Salodik Group is called as a group, divided into Tomori, Matindok, and Minahaki Formations, and Mentawa Member. The initial classification and detailing each of Salodik Group is illustrated on Figure 2 along with other formations in the region. The lower part of Tomori Formation consists of a thin basal clastic sequence succeeded by shelf carbonates, dated as Late Eocene–Early Oligocene in age. The middle and upper parts of Tomori Formation are Late Oligocene–Early Miocene in age with shelfal argillaceous limestones in the north of the basin, passing up into dolomitized limestones with coal interbeds. In the south, there are deeper water carbonates and few coal interbeds (Charlton, 1996). The Middle Miocene Matindok Formation conformably overlying the Tomori Formation, consists of claystone and sandstone with minor limestone and coal. It is conformably succeeded by the Late Miocene Minahaki Formation with shelf carbonate, and the Mentawa Member with pinnacle reefs in the north of the basin. It is suggested deepening of the palaeoenvironment to the south (Charlton, 1996).

Methods and Materials

Methods

The Salodik Group carbonate reservoir was primarily characterized based on a laboratory analysis. The laboratory analyses comprise thin section petrography, bulk mineralogy testing by using X-Ray Diffraction (XRD) technique, Scanning Electron Microscope-Secondary Electron (SEM-SE) method, and routine core analysis. The analyzed-rock samples at laboratory were obtained from geological fieldwork at the East Arm of Sulawesi (Rusmana *et al*., 1993). Five traverse paths and five stop-sites at the studied area were set to map the Salodik Group distribution. The traverse paths are Batui, Nambo, Teletubbies Hill, Salodik, and Balantak. This research also covered Bangketa-Bolaang, Kauru, Batutambung, Pagimana, and Peleng Island. Furthermore, each sample from all traverse paths were collected for the laboratory analysis.

The laboratory analysis used several advanced methods at P.T. Geoservices, Ltd. to characterize the reservoir, including polarizing petrography microscope, XRD, SEM, and routine core analysis. In this research, SEM Secondary Electron (SEM-SE) was used in order to identify the pores and cement based on the topographical images. XRD was used to quantify the mineral composition as well as to identify particular mineral to mark certain diagenetic, including ankerite, dolomite, aragonite, hematite. While the routine core analysis was to determine porosity and permeability values.

Materials

There are one hundred and nineteen thin sections for petrographic analysis, fifteen rock samples for SEM, XRD, and routine core analysis. In this study, the lithology classification is based on Dunham's (1962). The classification of the visual porosity based on petrography analysis refers to Choquette and Pray (1970), which distinguishes the porosity into fabric- and nonfabric selectives.

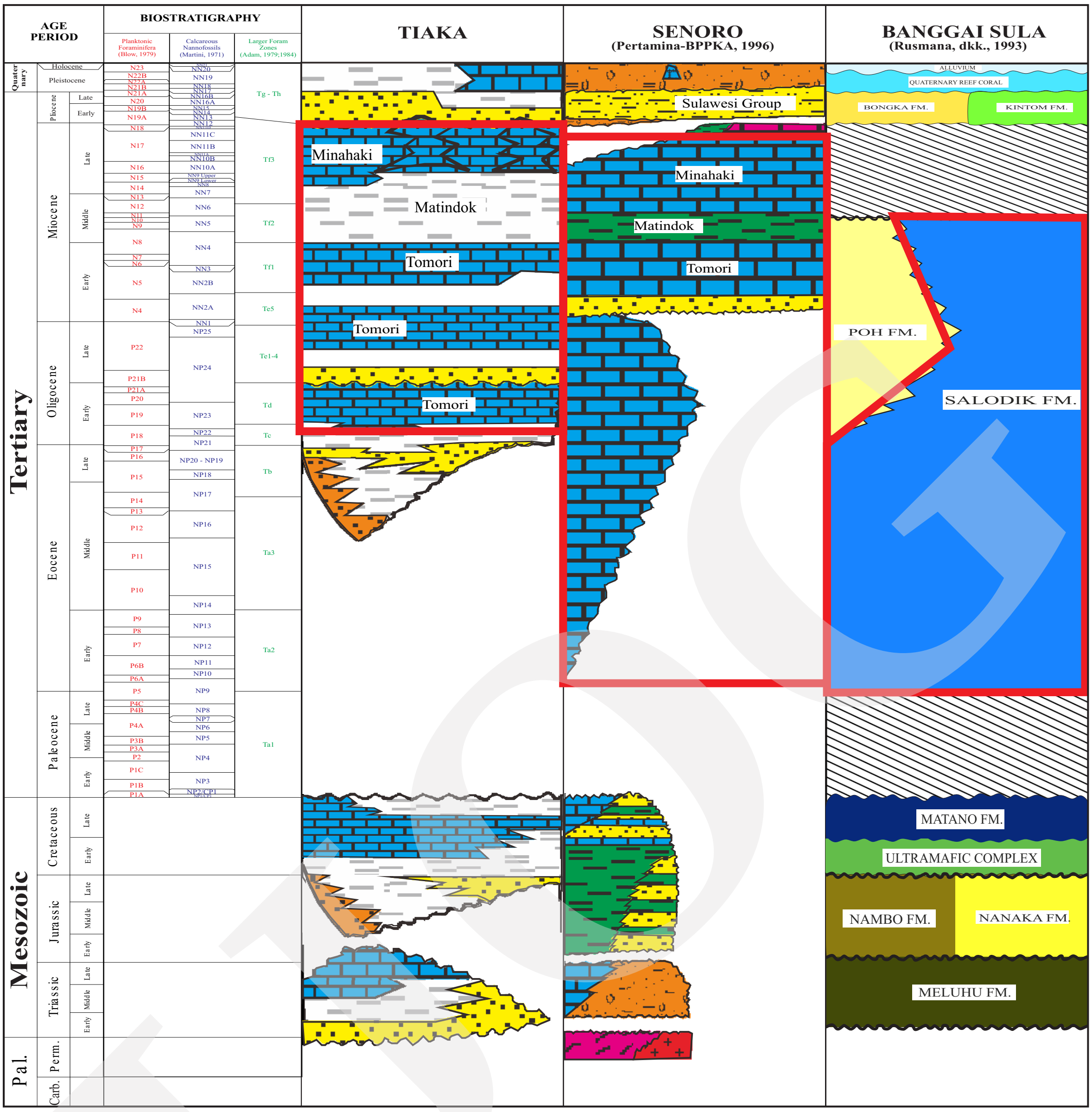

Figure 2. A comparison of East Arm Sulawesi regional stratigraphy according to previous studies by Pertamina-BPPKA (1996) and Rusmana *et al*. (1993). The Salodik Group carbonate reservoir is marked in the red shape.

Analysis and Result

Based on petrographic analysis of all thin section samples, the Salodik Group carbonate reservoir is classified into packstone (Figure 3a from BAL-13B), followed by wackestone (Figure 3b from BAL-2B). Both images are taken from Balantak traverse. On Figure 3a, more containments of grain, predominantly coral debris and large foram are recognized. On the other hand, Figure 3b shows micrite-dominated sample with coral debris as the main grain. On this figure, argillaceous material, the micrite, is observed filling the void space of coral debris. Several samples are classified into carbonate grainstone, mudstone, dolostone, and crystalline limestone. Nevertheless, this research also observed basalt, quartzite, and sublitharenite on the thin section samples.

The main composition of grains are coral debris (BAL-13B), red algae (BAL-12), mollusc (BAL-1B), bryozoa (BAL-23B), large foram (BAT-14A) including *Milliolid sp.* (BAL-23A, NAM-9) and *Alveollina sp.* (SAL-3), plank-

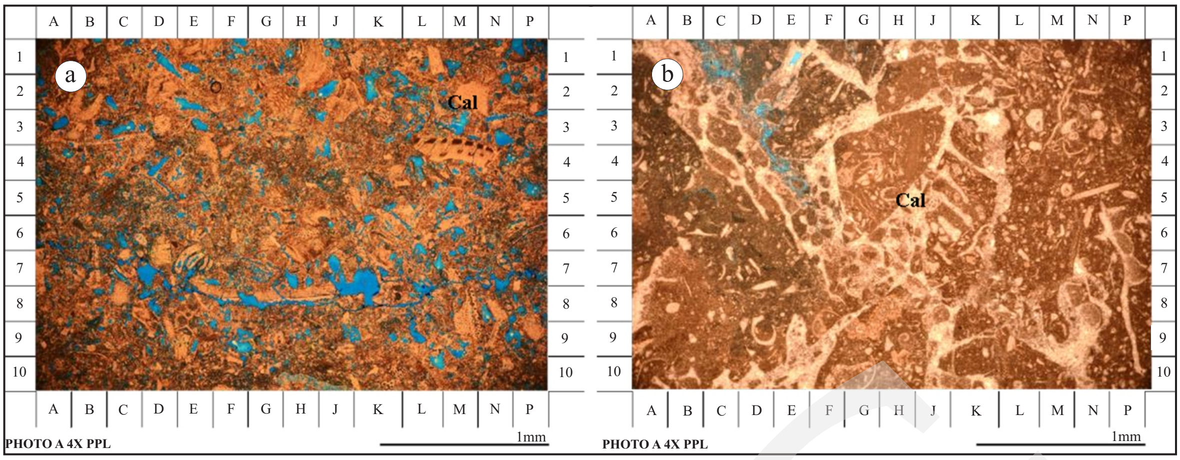

Figure 3. Photomicrographs of lithofacies: a). Packstone and b). Wackstone. Calcite (Cal) is predominantly replaced by the clastic materials (micrites).

tonic as benthic foraminiferas (BAL-23A). However, several less dominant minerals are quartz (monocrystalline) for instance in BAL-4, BANG-1A, clay minerals [including kaolinite, illite, and montmorillonite as most common clay mineral group according to Tucker (1991)] in BAT-19, PAG-2A as examples of its distribution, plagioclase in BAL-1B, and hematite in BAT-1A, NAM-19A, as well as in BAL-23A samples.

The fabric selective porosity or the primary porosity of Salodik Group comprises intergranular, intragranular, and moldic types, while the nonfabric selective porosity is secondary porosity, microvuggy, and fracture porosity. The fabric selective value is between 0.25–2.00%. On the other hand, higher visual porosity values are obtained from nonfabric selective, or the secondary porosity, with value of 0.25–6.00% of microvuggy porosity and 0.20–2.50% of fracture porosity.

According to XRD analysis (see Table 1), thirteen samples are classified into carbonate due to high amount of carbonate containment as the main composing mineral (90.0 to 98.8%). Calcite is predominantly the main carbonate minerals, followed by ankerite and dolomite. The other contents minerals are silicates, including quartz, potassium feldspar, clay minerals (dominantly in the form of illite), and iron oxide (in the form of hematite). Due to this condition, calcite is observed on petrographic analysis as a predominant mineral. Conversely, illite, hematite, or potassium feldspar can only be determined based on XRD method.

Overall, the result of routine core analysis data is shown in Table 2. All samples from Mentawa Member have higher reservoir properties than other formations. For instance, BANG-1A porosity and permeability values are 29.3% and 40,4mD respectively which are higher than PAG-2A of Minahaki Formation 3.8% porosity and 0,011mD permeability, NAM-19A of Upper Tomori Formation (15.5% porosity and 3.71mD permeability), and BAL-23A of Lower Tomori Formation, which has 4.5% porosity and 0.017mD of permeability. This Mentawa Member, nevertheless, has one anomaly of permeability data that shows the highest permeability value. It is obtained from PEL-7 sample, which has 72.5 mD. Moreover, this sample is including into the Minahaki Formation.

On the following result, the explanation is distinguished based on the lithification process. First, the syn-depositional process is represented in facies and reef system, while post-depositional process is represented by diagenesis.

Facies and Reef System

Mentawa Member consists of boundstone, and predominantly reefal packstone facies at Balantak area (Figure 4), while planktonic foraminifera packstone–wackestone is recognized at Nambo

Table 1. X-Ray Diffraction (XRD) Results of Each Formation from Salodik Group Reservoir

Sample ID	Clay Minerals			Carbonate Minerals					Other Minerals				
	Kaolinite	Illite	Montmorillonite	Calcite	Aragonite	Dolomite	Ankerite	Quartz	Plagioclase	K-Feldspar	Hematite	Cristobalite	Trydimite
BAL-4		2.3	0.7	86.3				7.3		2.0			1.4
BANG-1A		0.8		89.8			8.3	0.3					0.8
NAM-26C				93.5	2.7		2.6	1.2					
BAT-19		1.3		96.6				1.1					0.9
PAG-2A		1.3		93.5			1.3	3.0					0.8
TEL-20		1.1		96.7			1.3	0.2					0.7
BAL-8		1.7		97.1									1.3
PEL-7		1.1		98.0									0.9
BAL-1B	1.9	1.7		53.3				38.7	1.1	1.2			2.2
BAT-1A		1.1		97.0				0.6			0.4		0.9
NAM-19A				3.0		33.2	61.6				1.1	1.1	
KAUR-3		1.7		95.5			1.2	0.3					1.3
SAL-3		0.7		90.9			7.8	0..2					0.4
TEL-14		1.2		90.0				8.1					0.7
BAL-23A		3.0		94.5				0.5			0.8		1.2

Table 2. Routine Core Analysis on Porosity and Permeability of Salodik Group Resevoir

Sample ID	Permeability to Air (mD)	Klinkenberg Permeability (mD)	Helium Porosity (%)	Grain Density (g/cc)	Formation
BAL-4	0.520	0.494	17.000	2.700	
BANG-1A	40.400	38.340	29.300	2.700	Mentawa Member
NAM-26C	0.176	0.167	14.500	2.710	
BAT-19	0.510	0.484	18.300	2.700	
PAG-2A	0.011	0.010	3.800	2.710	
TEL-20	10.900	10.400	18.800	2.710	Minahaki Formation
BAL-8	0.014	0.013	2.400	2.720	
PEL-7	76.300	72.500	28.900	2.720	
BAL-1B	0015	0.014	1.800	2.710	
BAT-1A	1.860	1.770	19.000	2.710	Upper Tomori Formation
NAM-19A	3.710	3.520	15.500	2.720	
KAUR-3	0.037	0.035	9.300	2.720	
SAL-3	0.016	0.015	1.000	2.720	
TEL-14	0.323	0.306	10.100	2.730	Lower Tomori Formation
BAL-23A	0,017	0.016	4.500	2.720	

area (Figure 5). Both areas are mainly dominated by planktonic and benthic foraminifera with other consisting grains including echinoid, red algae, and mollusks. The reef system of these facies is outer–back reef at inner–middle sublittoral (Balantak area) and off reef at the middle sublittoral–bathyal (Nambo area) environments. The distribution of facies in Mentawa Member are illustrated on Figure 6.

Large benthic foraminifera packstone–mudstone at Batui area is the predominant facies of Minahaki Formation (Figure 7), although boundstone facies is also observed at several areas, represented by BAL-14 and BAL-16 samples. The large benthic foraminifera packstone– mudstone facies contains *Cyclopeus indopasificus* and *Lepidocyclina sp.* as the dominant species. Based on the observation on this area, this formation was

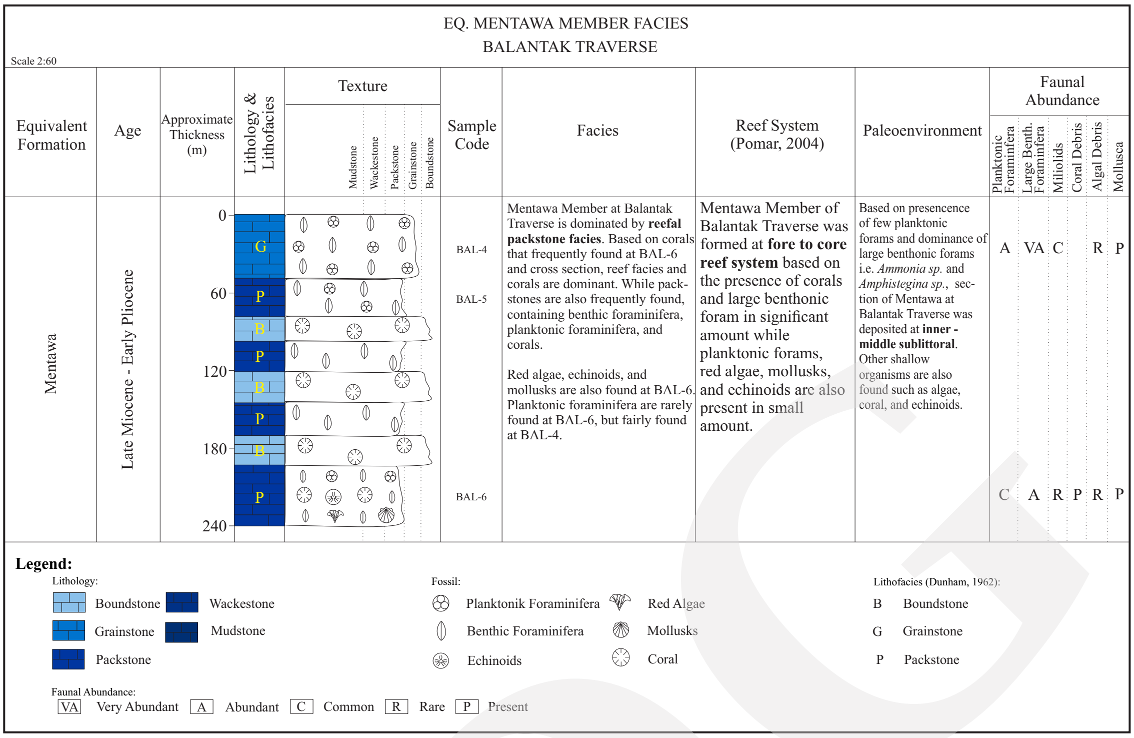

Figure 4. Mentawa Member facies profile at Balantak traverse.

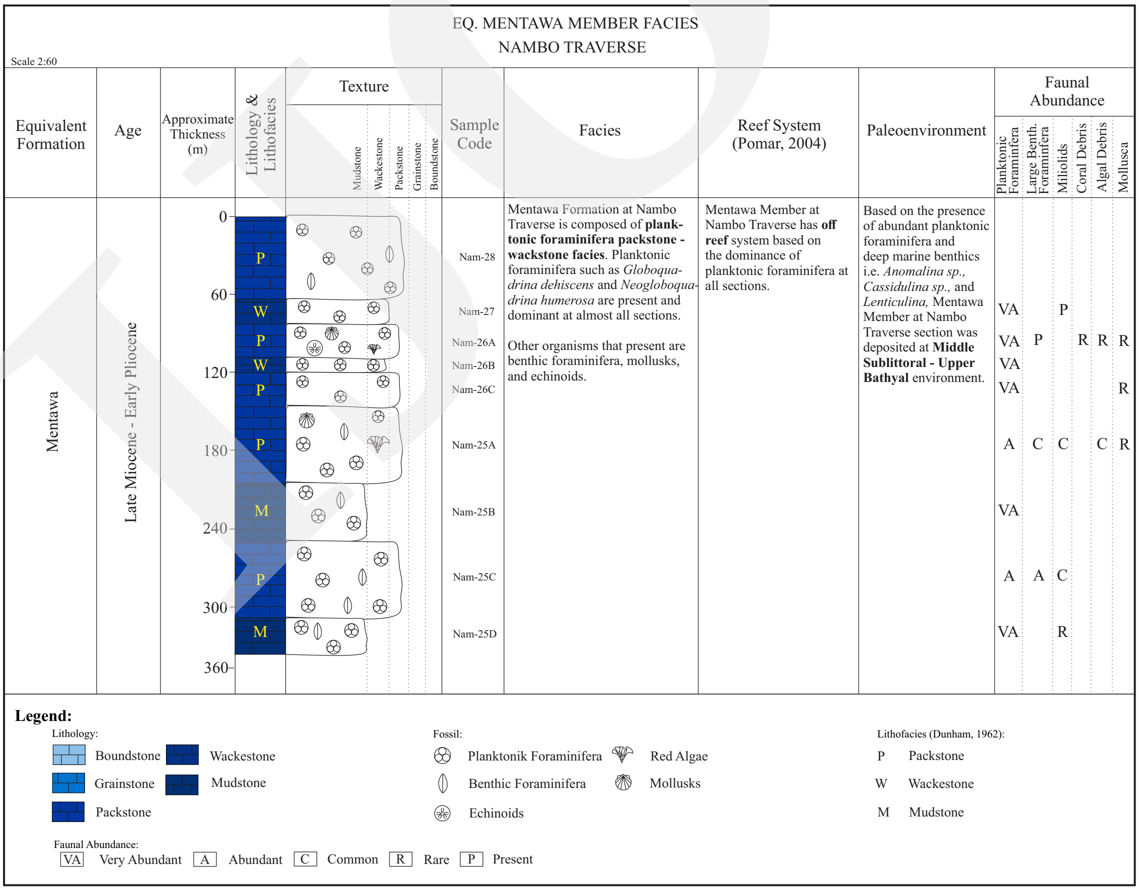

Figure 5. Mentawa Member facies profile at Nambo traverse.

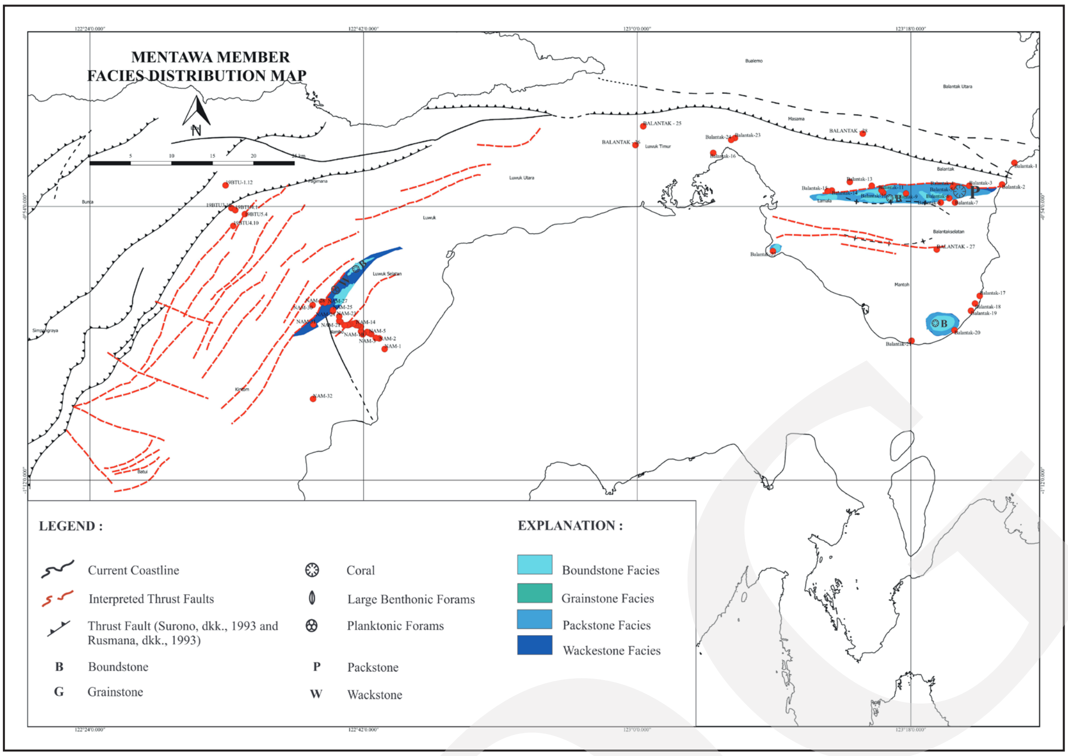

Figure 6. Planktonic foraminifera packstone-wackestone and reefal packstone facies of Mentawa Member distribution map and sample location.

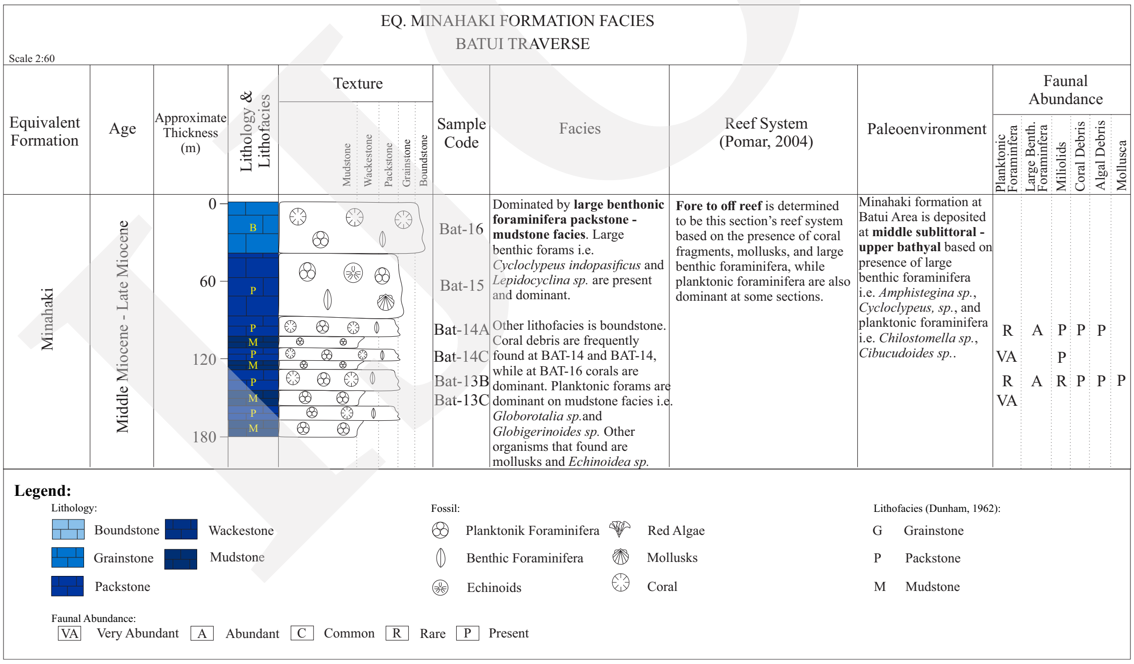

Figure 7. Minahaki Formation facies profile at Batui traverse.

deposited at fore to off reef, of a middle sublittoral–upper bathyal paleoenvironment. While in Balantak traverse area (Figure 8), the predominant facies is skeletal packstone–wackestone, composed of foraminifera, corals, echinoids, red algae, and mollusks. The distribution of carbonate facies in Minahaki Formation is shown on Figure 9. This formation, however, based on Balantak

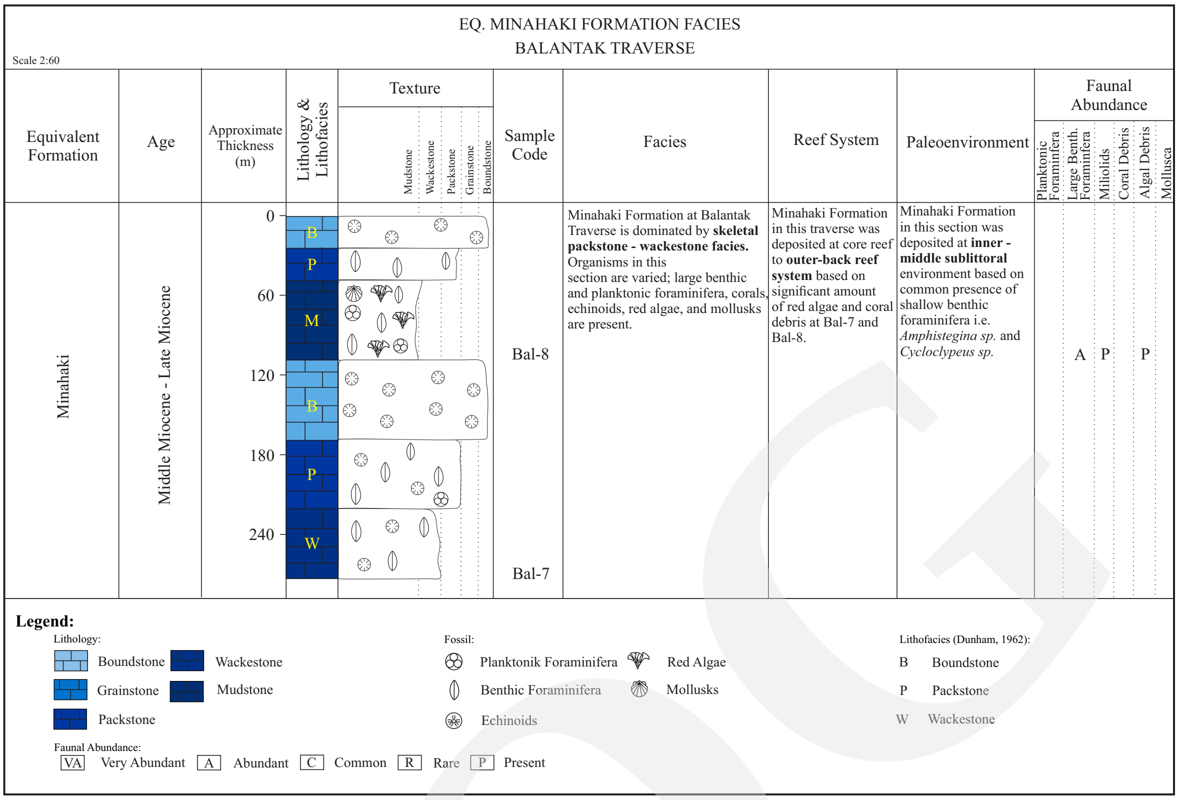

Figure 8. Minahaki Formation facies profile at Balantak traverse.

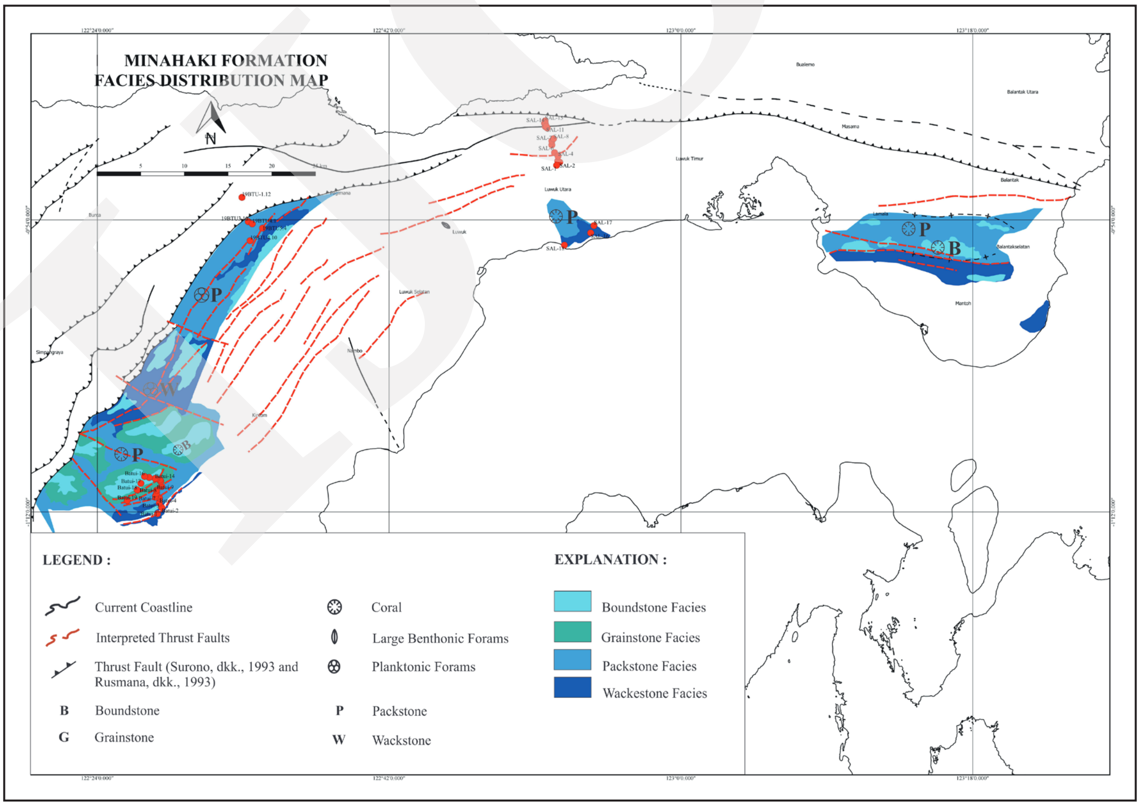

Figure 9. Skeletal packstone-wackestone facies and large benthonic foraminifera packstone-wackestone of Minahaki Formation distribution map and sample locations.

area observation, was deposited at the outer–back reef on inner–middle sublittoral.

The Upper Tomori Formation was observed at several areas, including Nambo, Batutambung, Teletubbies, and Balantak. Nambo is as the most representative traverse (Figure 10), the skeletal packstone–wackestone is the most dominant facies on this area, and predominantly consists of several organisms, such as foraminifera, coral, echinoid, brachiopod, and mollusks. Prior to the taken traverses, the distribution of this formation is illustrated on Figure 11. The reef system of this formation is core to fore reef deposited at inner–middle sublittoral.

The oldest observed formation in this research, the Lower Tomori Formation, was observed in the Salodik traverse area (Figure 12). Based on petrographic technique, *Alveolina sp*., *Amphistegina sp*., miliolid, and red algae are recognized. The predominant consisting facies is large benthic foraminifera–red algae packstone, furthermore its distribution is shown on Figure 13. This formation, is deposited at fore reef on inner–middle sublittoral paleo-environment.

The naming on the facies distribution map (Figures 6, 9, 11, and 13) is only based on the Dunham classification to represents the dominant lithofacies. Overall, according to the determined facies at each traverse and area, reefal packstone, planktonic foraminifera packstone-wackestone, large foram packstone-mudstone, skeletal packstone-wackestone, planktonic-large foraminifera packstone-wackestone, and large foraminifera-red algae packstone are the determined facies from all formations in Salodik Group carbonate reservoir as shown on, while the reef system is varied from back-reef to off-reef, and deposited predominantly at the inner to middle sublittoral (Table 3).

The reefal packstone as the first determined facies (Figure 4) is identified from Mentawa Member samples from Balantak traverse. From this traverse, skeletal packstone-wackestone facies of Minahaki Formation as shown on Figure

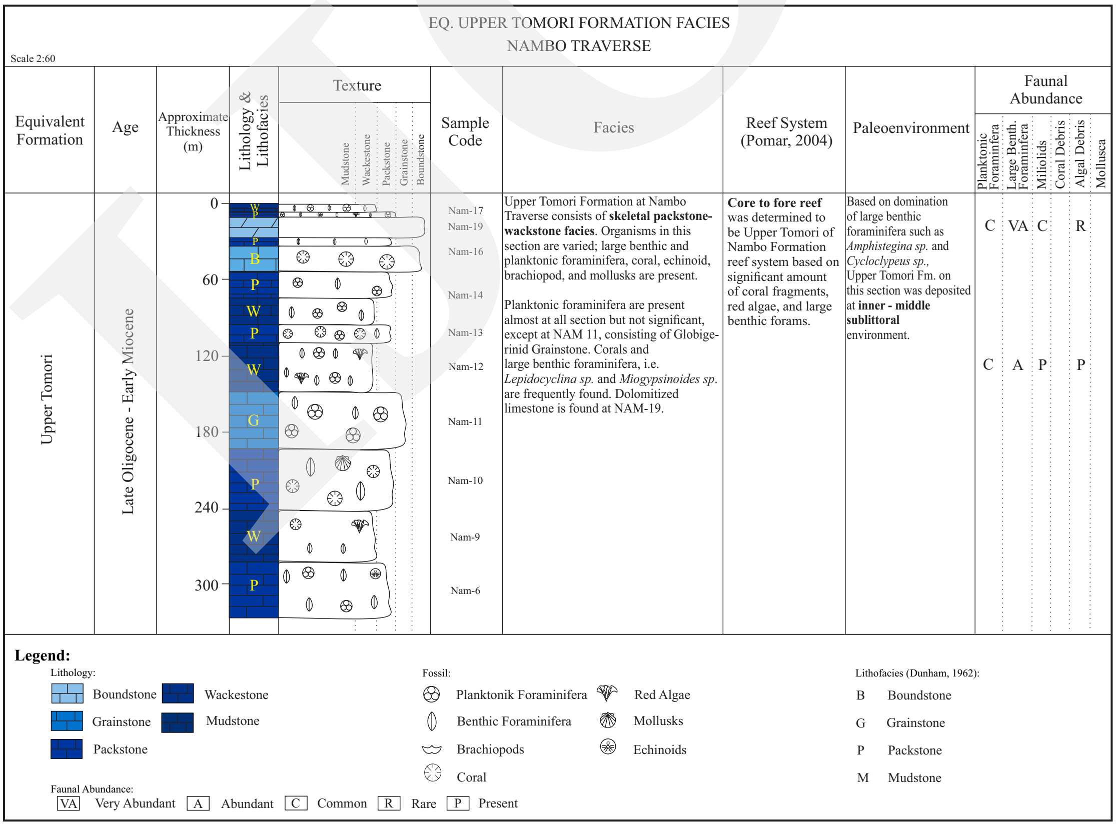

Figure 10. Upper Tomori Formation facies profile from Nambo traverse.

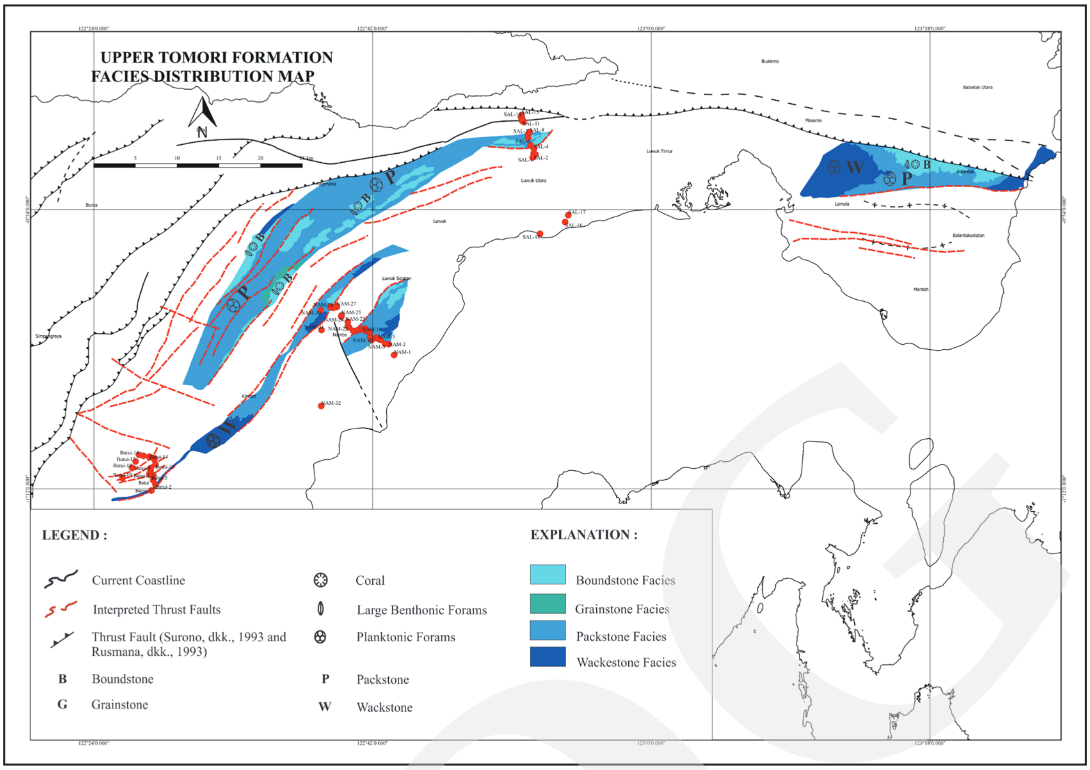

Figure 11. Skeletal packstone-wackestone facies of Upper Tomori Formation distribution map and sample locations.

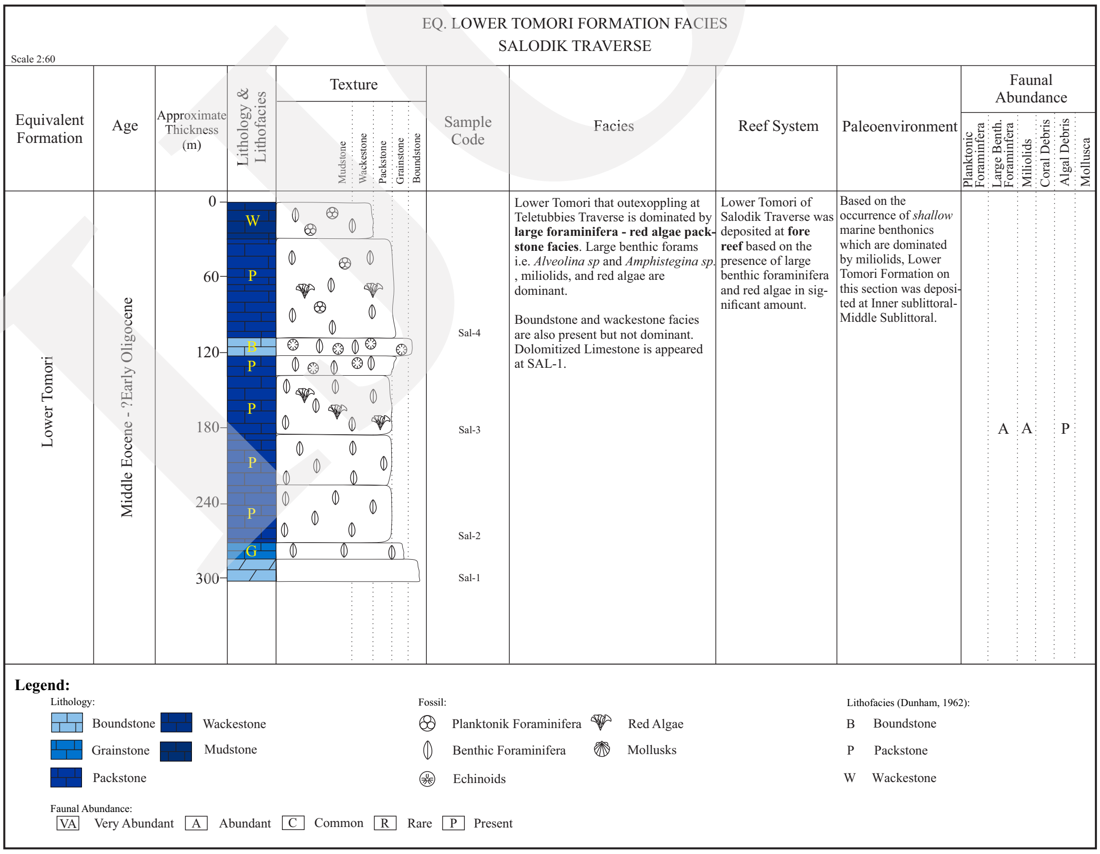

Figure 12. Lower Tomori Formation facies profile from Salodik traverse.

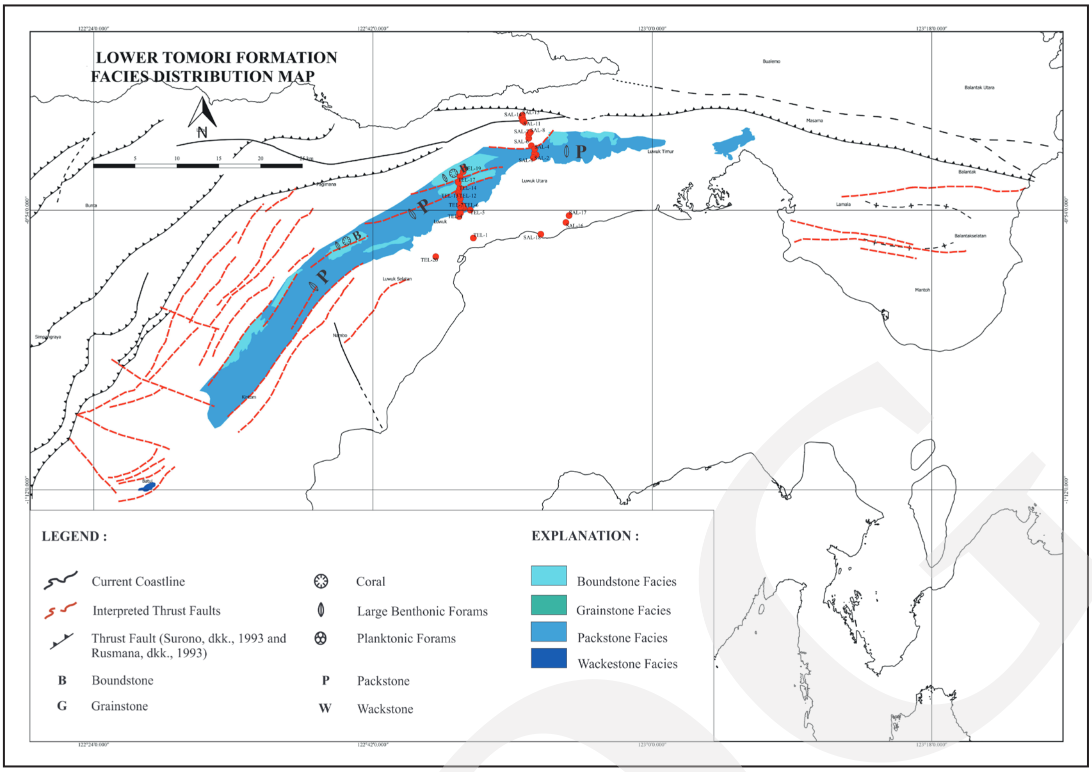

Figure 13. Large foraminifera-red algae packstone facies of Lower Tomori Formation distribution map and sample locations.

Table 3. Facies and Diagenesis of Each Formation in Salodik Group

Formation	Facies	Reef System	Depositional Environment	Diagenesis Feature	Diagenesis Environment	Diagenesis Stage
MentawaMember	Reefal packstone	Outer-backreef	Inner to middle sublittoral	Microvuggy	Meteoric vadose	Mesogenetic–Telogenetic
	Planktonic foraminifera packstone - mudstone	Off-reef	Middle sublittoral to upper bathyal	Equant calcitecement and microvuggy	Meteoric phreatic-vadose	Mesogenetc–Telogenetic
Minahaki Formation	Large benthic foraminifera packstone-wackestone	Fore-off reef	Middle sublitoral to upper bathyal	Equant calcitecement and microvuggy	Metoric phreatic–vadose	Mesogenetic–Telogenetic
	Skeletal packstone-wackestone	Outer-backreef	Inner to middle sub littoral	Equant calcitecement and microvuggy	Meteoric phreatic-vadose	Mesogenetic–Telogenetic
Upper Tomori Formation	Skeletal packstone-wackestone	Core-fore reef	Inner to middle sublittoral	Isopachous and/or equantblocky calcite cement	Meteoric phreatic	Mesogenetic–Telogenetic
Lower Tomori Formation	Large foraminifera-red algae packstone	Fore reef	Inner to middle sub littoral	Isopachous and/or equantblocky calcite cement	Meteoric phreatic	Mesogenetic–Telogenetic

8 was also determined. Nevertheless, the Minahaki Formation also consists of large benthic foraminifera packstone-wackestone facies, which was determined from Batui traverse (Figure 7). Another observed facies is planktonic foraminifera packstone-mudstone of Mentawa Member as well. This facies was determined from Nambo traverse (Figure 5), along with skeletal packstone-wackestone facies of Upper Tomori Formation (Figure 10). The older formation in this research are Lower Tomori Formation, consisting of large foraminifera red-algae packstone, which was

observed and determined from Salodik traverse sample as illustrated on Figure 12.

Based on lithofacies and fossil content at each facies, the reef system of Salodik Group is classified into back reef to off reef, although variation of several reef systems comprises outer reef, fore reef, and core reef. The core reef system is only classified from Upper Tomori Formation due to the dominance of boundstone lithofacies in this formation. Moreover, based also on fossil remnant, the depositional environment is distributed from inner sublittoral to upper bathyal. However, four of six facies were predominantly deposited at inner to middle sublittoral environment.

Diagenesis

Salodik Group dominant diagenesis features are cementation and dissolution. The first dominant diagenesis, cementation, is predominantly observed in the form of pore-filling equant calcite cement (Figures 14b, 15d, and 16b) and pore-bridging cement (Figures 15b and 17d). This diagenesis feature leads to significant reductions in porosity (Ali *et al*., 2010). On the other hand, the second dominant diagenesis feature is dissolution, in the form of microvuggy porosity (Figures 14a-c, and d, 15a and c, 16d, and 17a). This secondary porosity type enhances the reservoir property values. It was formed as the result of collision of Banggai-Sula with Sulawesi, which was responsible for further uplifted eastern arm of Sulawesi and implicated the development of reservoir properties (Husein *et al.*, 2018). Due to the dominant diagenesis, therefore the overall main diagenesis environment of Salodik Group reservoir is classified into meteoric phreatic-vadose. Moreover, the diagenesis stage is classified into mesogenesis-telogenesis (Choquette and Pray, 1970).

However, although the cementation and dissolution are mainly observed on each formation of Salodik Group, several other diageneses were also observed and marked the history of the post-depositional process of this carbonate reservoir.

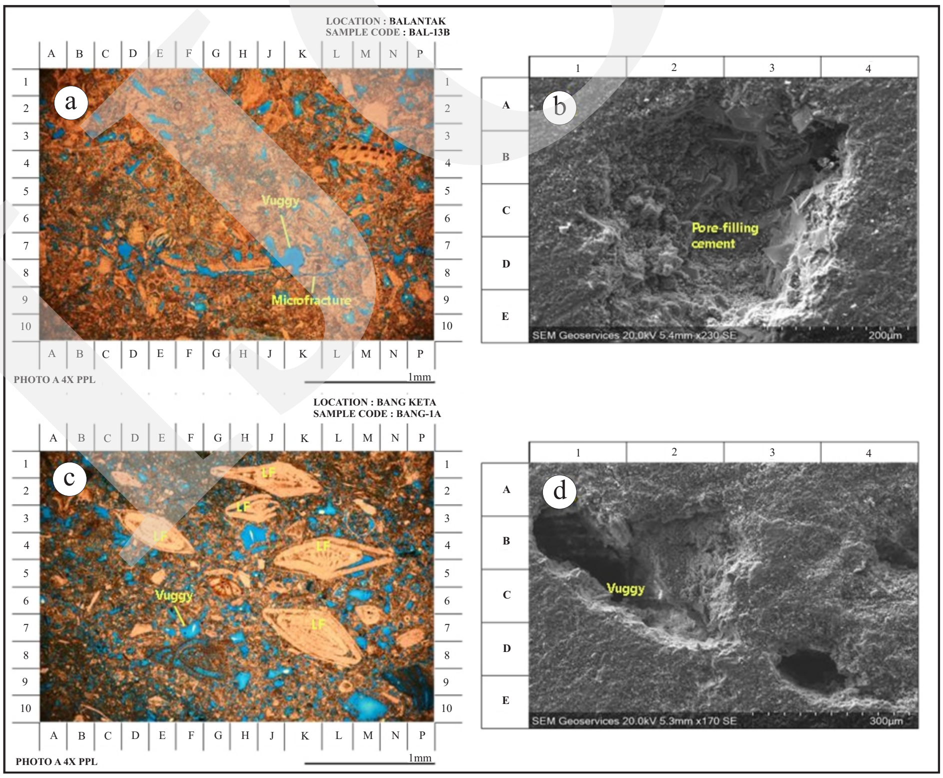

Figure 14. Photomicrographs of diagenesis analysis based on petrography and SEM techniques on BAL-13B and BANG-1A samples of Mentawa Members. (a), (c), and (d). show microvuggy porosity, while (b). shows pore-filling equant calcite. (a). also shows microfracture.

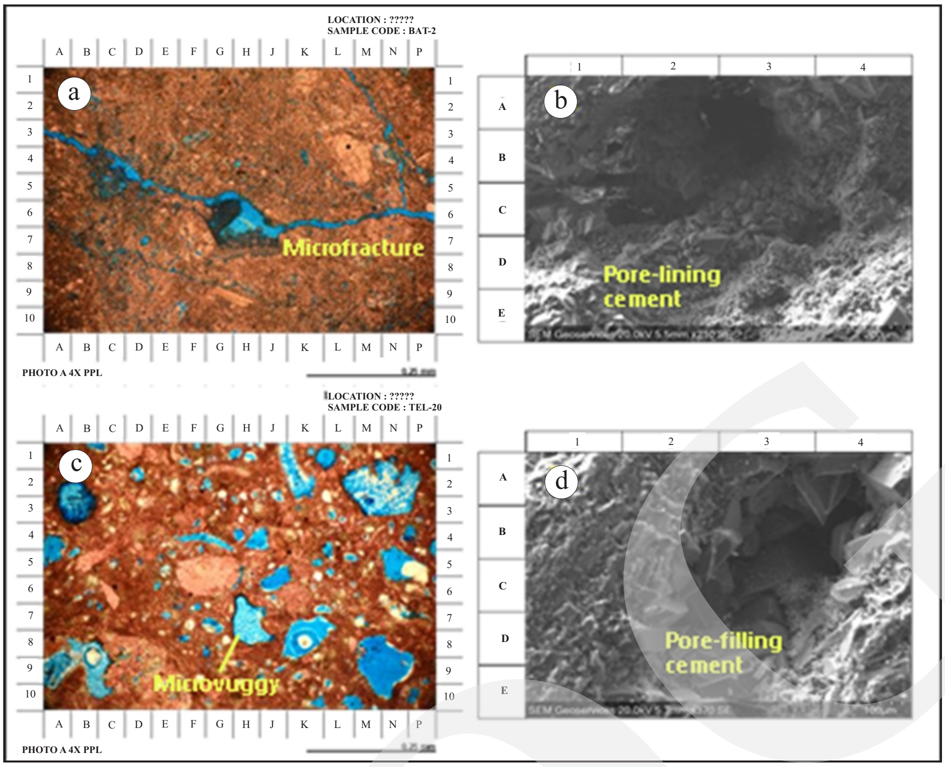

Figure 15. Photomicrographs of diagenesis features taken from BAT-2 and TEL-20 of Minahaki Formation samples, showing: (a). microfracture, (b). pore-lining equant calcite cement, (c). microvuggy porosity, and (d). pore-filling cement.

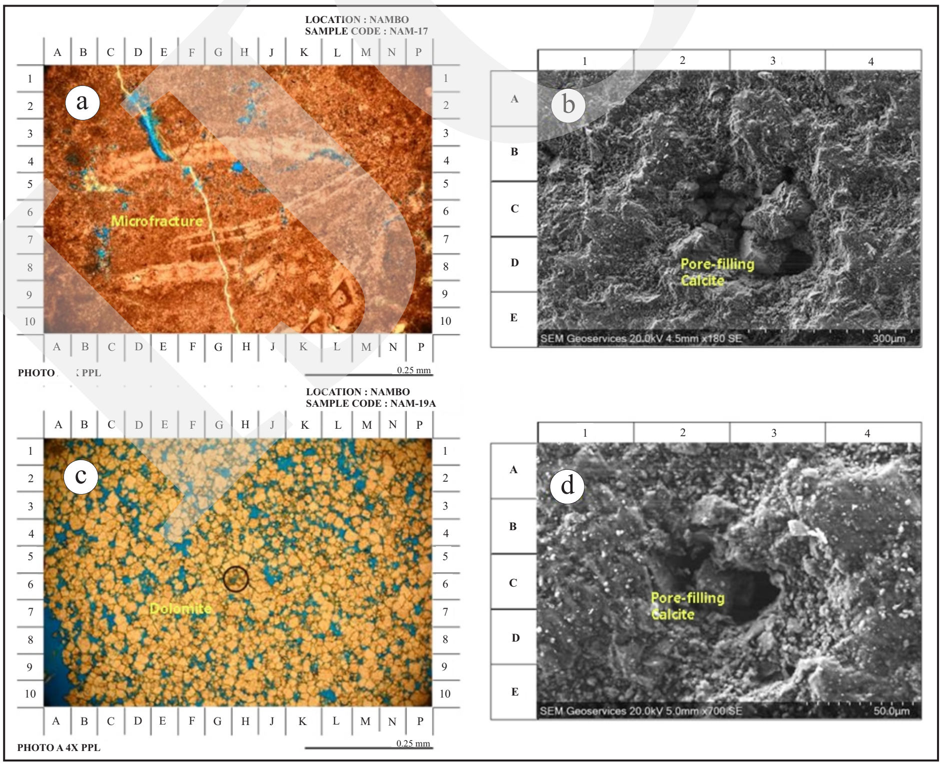

Figure 16. Photomicrographs showing diagenesis features taken from NAM-17 and NAM-19A of Upper Tomori Formation samples. (a). microfracture, (b) and (d). interpreted a pore-filling equant calcite cement, and (c). dolomite as the predominant composing mineral.

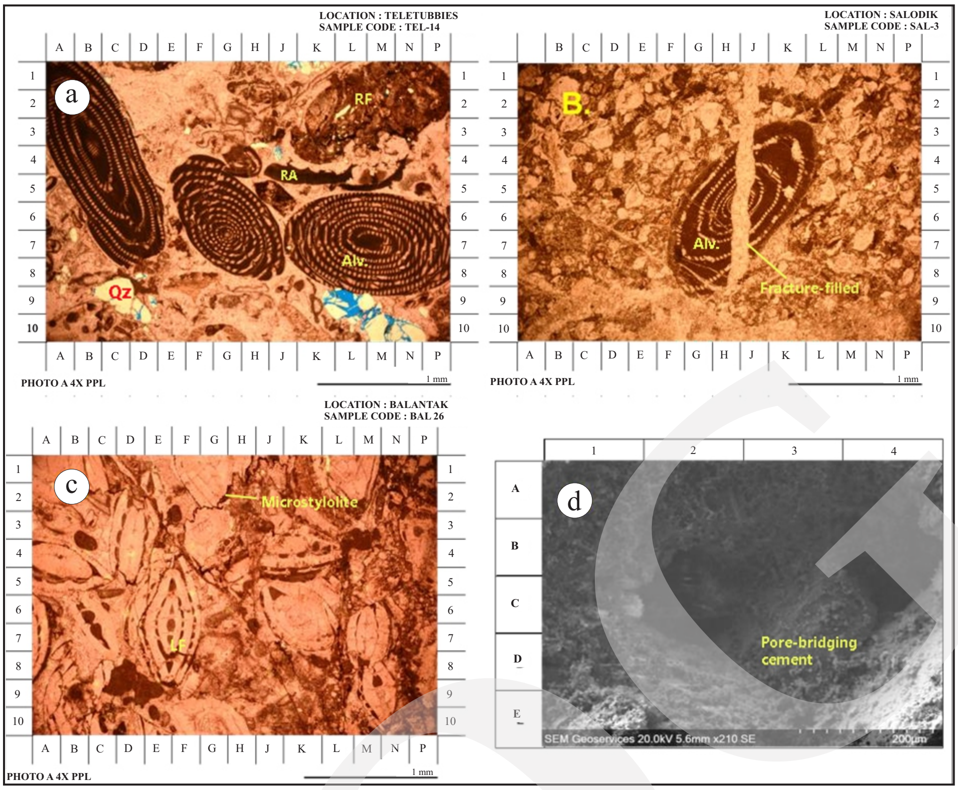

Figure 17. Photomicrographs of diagenesis features on TEL-14 and BAL-20 samples of Lower Tomori Formation. (a). microvuggy and detrital quartz (Qz) containment, (b). fracture-filled by calcite, (c). compaction feature including microstylolite, while (d). pore-bridging equant calcite cement.

The other diagenesis features observed on thin section and SEM are microfracture (Figures 14a and 15a) as well as compaction in the form of long to concave-convex contacts (Figure 17c) as a burial environment indicator. In Lower Tomori Formation, however, microfracture is filled with calcite (Figure 17b). Moreover, based on XRD data, ankerite as a significant deeper burial indicator was also observed at several formations.

The burial environment parameter, microfracture in particular was observed at all formations. Dolostone (Figure 16c) was only observed in Upper Tomori Formation based on a petrography analysis, which indicates a mixing zone. Nevertheless, according to XRD data on NAM-19A sample, it contains high amount of ankerite (61.6%) as another form of ferroan dolomite due to iron (Fe) for magnesium (Mg) substitution. One significant mark of the burial environment is the compaction in the Lower Tomori Formation, a further interpretation of Salodik Group is in accordance with ankerite presence at all formation based on XRD data. This mineral indicates iron (Fe) and manganese (Mn) enrichment. Furthermore, it provides significant data that all formations of Salodik Group had been through a deeper burial environment.

Anomalies of diagenesis data according to XRD result are due to the presence of quartz and aragonite. The occurrence of quartz was observed at all formations. This common silicate mineral is contained in Salodik Group consisting of formation between 0.2−8.1%. However, by integrating the XRD data of quartz with the thin section from Mentawa Member (BAL-4 sample) and Lower Tomori Formation (TEL-14 sample), the presence of quartz is only as detrital grain (Figure 17a), and it is not as a diagenetic or hydrothermal indicator. The second anomaly is the presence of aragonite in Mentawa Member. This mineral was detected by XRD on NAM-26C sample in amount of 2.7%. It indicates the remnant of syn-genetic diagenesis stage mineral.

Diagenesis of Salodik Group was also affected by the tectonic events in Bangga Basin, particularly the thrust faults. Due to this phenomenon, it is uplifted part of Salodik Group carbonate reservoir. Therefore, several diagenesis minerals are marked the weathering and oxidation process. These processes are marked by the presence of hematite and clay minerals, dominantly illite, in Upper and Lower Tomori Formation. These mineral amounts vary from 0.4−1.1% and 0.7−2.3%, respectively.

Discussion

The reservoir quality of Salodik Group is classified based on the porosity and permeability values. Furthermore, these values are the main parameter to be referred in the Koesoemadinata classification (1978) of the reservoir quality.

In this research, as explained in the facies and reef system section, the dominant lithofacies are packstone and wackestone. The common paradigm is these lithofacies having a high amount of porosity and permeability, particularly the packstone. It is due to packstone is composed of more grains than wackestone. Moreover, wackestone, which contains more micrite, has less void space due to grain size differences. This particular texture implicates the low value of reservoir permeability. However, reservoir property value change depends on the diagenesis of Lower Tomori Formation. This phenomenon occurs due to cementation and compaction of the formation shown on Figure 17. This figure shows how this particular oldest formation of Salodik Group does not have sufficient spaces for porosity to develop due to a tight contact of composing grains and/or carbonate cement presence. Moreover, the type of determined lithofacies does not provide significant impact on final reservoir values. Furthermore, it is also not the parameter to classify the reservoir quality.

Based on Table 4, the overall reservoir quality refers to porosity data which is classified into negligible to excellent. The porosity values are ranging from 0.50−29.30%. While the permeability data shows 0.01−76.30 mD, classified as tight−good. However, data on Table 4 shows only the younger formations in the Salodik Group, Upper Tomori Formation, and Lower Tomori Formation, which are classified as the better reservoirs. These formations are classified into negligible−reservoir based on the porosity. While based on the permeability, these younger formations are classified into tight−good reservoir. On the other hand, older formations, Upper Tomori and Lower Tomori Formations, are classified into negligible−good and negligible−fair reservoirs, respectively. Moreover, referring to the permeability data, these formations are classified into tight reservoirs. This phenomenon is due to diagenesis, which plays a significant role in the Salodik Group. The younger formations,

Table 4. Integrated Data of Facies, Routine Core, Dominant Diagenetic Environment, and Reservoir Quality of Each Formation in Salodik Group Carbonate Reservoir

Formation	Foram Zone	Thickness	Routine Core		Reservoir Quality (Koesoemadinata, 1978)		Diagenetic Environment
			Helium Porosity(%)	Permability (mD)	Porosity	Permeability	
Mentawa Member	N17− N19/Tf3	±240	0.50−29.30	0.01−40.40	Negligible−Excellent	Tight−Good	Meteoric Phreatic−Meteoric Vadose
Minahaki Formation	N12−N17/ Tf2-Tf3	±180	2.40−28.90	0.01−76.30	Negligible−Excellent	Tight−Good	Meteoric Phreatic−Meteoric Vadose
Upper Tomori Formation	P21−N8/ Te4-Tf1	±300	1.80−19.00	0.01−3.71	Negligible−Good	Tight	Meteoric Phreatic
Lower Tomori Formation	P10−P21/ Ta3−Td	±300	1.00−10.30	0.01−0.32	Negligible −Fair	Tight	Meteoric Phreatic

Mentawa Member and Minahaki Formation, are significantly affected by dissolution and cementation. Therefore, these formations are classified into meteoric phreatic and meteoric vadose. On the other hand, equant blocky cement is predominantly the main diagenesis of the older formations, the Upper Tomori and Lower Tomori Formations. Furthermore, this condition causes the reservoir properties to be lower than the younger formations in the Salodik Group.

Overall, from Mentawa Member to Lower Tomori Formation, the porosity and permeability decrease as shown on Table 4. However, one anomaly of the property value is shown where Mentawa Member to Minahaki Formation shows a decreasing reservoir property, particularly the permeability. It increases from the range of 0.01 −40.40 mD in Mentawa Member to 0.01−76.30 mD in Minahaki Formation. On the contrary, the porosity is slightly decreased as shown on the Table 4, from 0.5−29.30% in Mentawa Member to 2.4−28.9% in Minahaki Formation. It is due to the increasing of connecting pore in the reservoir.

The Salodik Group porosity and permeability, however, show a similar trend as shown on the crossplot porosity vs permeability (Figure 18). Moreover, it indicates that the dissolution process provides significant effects not only on porosity, but also on permeability as well.

The Salodik Group carbonate reservoir property is predominantly enhanced due to the post-depositional process, particularly the dissolution process in the form of microvuggy porosity. According to the visual porosity data based on thin-section petrography observation, microvuggy porosity is more dominant compared to fracture porosity as shown on Figure 19. Nevertheless, these formations had significantly been affected by cementation. Therefore, both formations have low property values. This figure also shows that the primary porosity is not well preserved. Moreover, younger formations of Salodik Group, Mentawa Member, and Minahaki Formation have less amount of well-preserved primary porosity. On the other hand, older formations, Upper Tomori and Lower Tomori Formations, have more well-observed primary porosity, although it is less than 50%.

This data shows post-depositional processes, and also work more intensely and affect the reservoir than syn-depositional process.

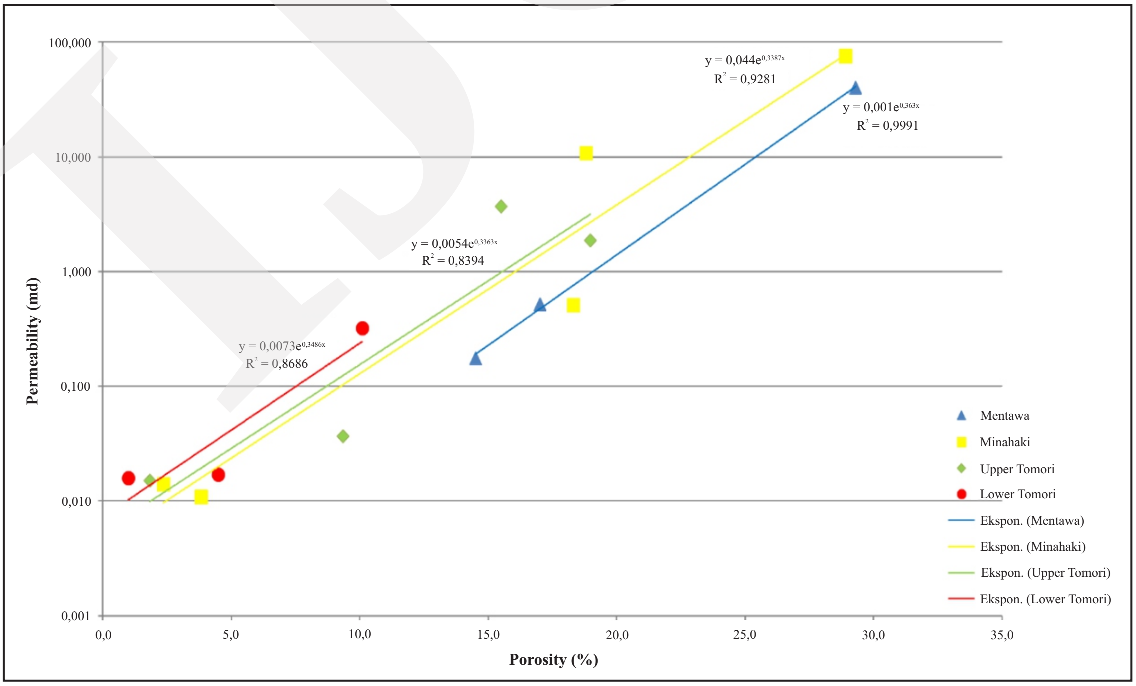

Figure 18. Scatter plot of porosity and permeability diagram.

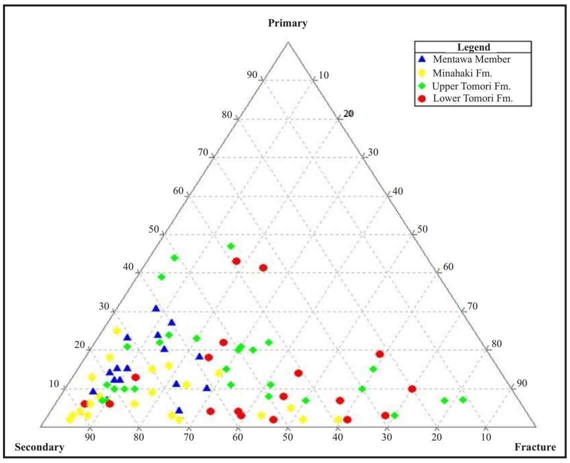

Figure 19. Visual porosity type plotting of all formations in Salodik Group. Secondary porosity (vuggy type) is more dominant than fracture and primary porosity.

Conclusions

Based on routine core data, porosity and permeability trends are in line with other results. The oldest formation, Lower Tomori Formation, has the lowest reservoir property value. It is primarily due to the post-depositional process in the form of equant calcite cementation. Therefore, it reduces the pore volume and the connecting pore throat. From the youngest to the oldest formations observed in this research, the reservoir property values of the Mentawa Member to the Lower Tomori Formation, overall decreases. However, an anomaly occurs at Minahaki Formation, where reservoir properties increases due to the presence of secondary porosity, enhancing porosity, and permeability values. This phenomenon also indicates the facies is less dominant than diagenesis. Overall, the reservoir quality referring to porosity value is classified as negligible to excellent. While based on permeability data, it is classified as tight to good reservoir.

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