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LIMESTONE FACIES AND DIAGENESIS ANALYSIS IN THE SOUTHERN OF GORONTALO PROVINCE, INDONESIA

Abstract. Strong tectonic effects have influenced the complexity of the geological conditions in the southern half of Gorontalo Province, Indonesia. As seen today, the raising of limestone into hills is one example. Furthermore, because it is located between the major volcanic and plutonic rocks, the distribution of limestone in the study area is quite distinctive. Most of the research related to limestone in the research area have only been conducted on a regional scale, therefore, a more in-depth analysis is required to gather the most up-to-date geological data. For this reason, this research aimed to look at the facies and diagenesis of limestones in the southern section of Indonesia's Gorontalo Province. Field surveys will be used to achieve the research objectives, including a megascopic study of limestone and petrographic analysis in the laboratory. The results revealed that Gorontalo Province's southern part's limestone facies are coralline floatstone. Based on the petrographic analysis, six different diagenesis processes occur in coralline floatstone. The six diagenesis processes include microbial micritization, initial calcite cementation, cementation, dissolution, neomorphism (inversion), and neomorphism (recrystallization). The research area's limestone diagenetic environment comprises three diagenesis environments: it begins with the diagenesis process in the marine phreatic zone, then turns into the meteoric phreatic zone, and ends with the diagenesis process in the meteoric vadose zone.

Key words: Diagenesis, Facies, Gorontalo, Limestone.

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ИНДОНЕЗИЯ, ГОРОНТАЛО ПРАВИНЦИЯСЫНЫҢ ОҢТҮСТІГІНДЕГІ ӘКТАСТЫ ФАСИЯЛАР ЖӘНЕ ДИАГЕНЕЗІСТІ ТАЛДАУ

Аннотация. Күшті тектоникалық әсерлер Индонезияның Горонтало провинциясының оңтүстік жартысындағы геологиялық жағдайлардың күрделілігіне әсер етті. Оның бір мысалы әктастың төбеге көтерілуі. Олар жанартаулық және плутондық жыныстардың арасында орналасқандықтан, зерттелетін аймақтағы әктастың таралуы айтарлықтай ерекшеленеді. Зерттеу аймағындағы әктасқа қатысты зерттеулердің көпшілігі тек аймақтық ауқымда жүргізілді, сондықтан ең өзекті геологиялық деректерді жинау үшін тереңірек талдау қажет. Осы себепті бұл зерттеу Индонезияның Горонтало провинциясының оңтүстік бөлігіндегі әктастардың фациялары мен диагенезін зерттеуді мақсат етті. Зертханада әктастарды мегаскопиялық зерттеу және петрографиялық талдауды қоса алғанда, зерттеу мақсаттарына қол жеткізу үшін далалық зерттеулер қолданылады. Нәтижесінде Горонтало провинциясының оңтүстік бөлігіндегі әктас фациялары маржанды флотта екенін анықталды. Петрографиялық талдау негізінде кораллин флоатста алты түрлі диагенез процесі жүреді. Алты диагенез процестеріне микробтық микротизация, кальциттің бастапқы цементтелуі, еруі, инверсия және қайта кристалдану жатады. Зерттеу аймағының әктас диагенетикалық ортасы үш диагенез ортасынан тұрады: ол теңіз фреатикалық аймағында диагенез процесінен басталып, кейін метеорлық фреатикалық аймаққа айналады және метеорлық вадоза аймағында диагенез процесімен аяқталады.

Түйін сөздер: диагенез, фация, горонтало, әктас.

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ИЗВЕСТНЯКОВЫЕ ФАЦИИ И ДИАГЕНЕЗИЧЕСКИЙ АНАЛИЗ НА ЮГЕ ПРОВИНЦИИ ГОРОНТАЛО, ИНДОНЕЗИЯ

Аннотация. Сильные тектонические эффекты повлияли на сложность геологических условий в южной половине провинции Горонтало, Индонезия. Как видно сегодня, поднятие известняка в холмы является одним из примеров. Кроме того, поскольку он расположен между основными вулканическими и плутоническими породами, распределение известняка на исследуемой территории весьма своеобразно. Большинство исследований, связанных с известняком в районе исследований, проводились только в региональном масштабе, поэтому для сбора самых современных геологических данных требуется более глубокий анализ. По этой причине это исследование было направлено на изучение фаций и диагенеза известняков в южной части провинции Горонтало в Индонезии. Для достижения целей исследования будут использованы полевые исследования, в том числе мегаскопическое изучение известняка и петрографический анализ в лаборатории. Результаты показали, что известняковые фации южной части провинции Горонтало представляют собой плавучий коралловый камень. На основании петрографического анализа в коралловом флоатстоуне происходят шесть различных процессов диагенеза. Шесть процессов диагенеза включают микробную микритизацию, начальную цементацию кальцита, цементацию, растворение, неоморфизм (инверсию) и неоморфизм (перекристаллизацию). Диагенетическая обстановка известняков района исследований включает три диагенетические обстановки: она начинается с процесса диагенеза в морской фреатической зоне, затем переходит в метеоритно-фреатический пояс и заканчивается процессом диагенеза в метеоритном аэрационном поясе.

Ключевые слова: диагенез, фация, горонтало, известняк.

Introduction. Diagenesis refers to the physical and chemical changes after sediment, or sedimentary rock is deposited. It does not contain metamorphism (Scholle & Ulmer-Scholle, 2003), a process involving high temperatures and pressures. Diagenesis can preserve information on the primary appearance, post-deposition history, pore water composition, and temperature. The key controllers of diagenesis are the composition and mineralogy of the sediments, the chemical composition of the pore fluids and the rate of fluid flow, the geological history of the deposits concerning burial, uplift and sea level change, the influx of pore fluids and climatic differences (Tucker & Wright, 1990).

Changes from one diagenesis environment to another may occur multiple times in the history of carbonate diagenesis. This can be determined using texture data that has been preserved to determine the sequence of diagenesis (Longman, 1980). Changes can occur in three main diagenesis environments: marine, meteoric, and burial, all of which have predictable processes throughout geological history (Wright et al., 2003; James et al., 2005; Wright & Cherns, 2008).

Carbonate rock diagenesis comprises six major processes: dissolution, cementation, neomorphism, dolomitization, microbial micritization, and compaction. In this case, the contributing variables are pressure, temperature, mineral stability, equilibrium conditions, water influx rate, time, and structural control (Tucker & Wright, 1990). Complex characteristics influence diagenesis processes in carbonate deposits, such as micritization, dissolution, compaction, cementation, dolomitization, and recrystallization. These criteria include primary mineralogy, depositional texture, porosity and permeability, pore water chemistry, oil saturation, and sedimentary basin tectonic development (Machent et al., 2007; Morad et al., 2012; Armelenti et al., 2016; Li et al., 2017; Seibel & James, 2017).

The chemistry of the pore water, which has the primary control over the diagenesis reaction, may vary widely. In near-surface conditions, diagenesis occurs in marine, meteoric, brackish, and hypersaline brines (Morad et al., 2012: 2019; James & Jones, 2015; Swart, 2015). The complexity of these controlling parameters makes perfect modeling of the role of diagenesis on the distribution and evolutionary pathways of reservoir quality in carbonate succession fraught with difficulties.

The regional stratigraphy of Gorontalo Province's southern part refers to a geological map of Tilamuta sheets on a scale of 1: 250,000 (Bachri et al., 1997) composed of several rock formations. In regional stratigraphic order, the oldest formation is the Tinombo Formation consisting of basalt lava, andesitic lava, volcanic breccia, intercalated sandstone, green sandstone, siltstone, red limestone, gray limestone, and a small amount of thermally recovered rock. The age of this rock unit is estimated to be between the Eocene and the Early Miocene. Above it, the Middle Miocene Bilungala Volcano Formation was created, consisting of volcanic breccia, tuff, and lava. The color of this lithology ranges from gray to dark gray. The Diorite Bone Formation, which includes diorite, quartz diorite, granodiorite, and adamelite, is estimated to be Middle Miocene in age. The Tinombo and Bilungala Volcano Formations were both cut through by this unit. Aside from that, there are variations in the composition of quartz diorite, granodiorite, and adamelite, with the main components being andesine, quartz, and hornblende. The Pinogu Volcano Formation, estimated to be of Pliocene-Pleistocene age, is not aligned. This formation consists of tuff, lapilli tuff, breccia, and lava. Volcanic breccias can be found in the Bone Mountains, Mount Mongadalia, and Pusian (Apandi & Bachri, 1997). The Reef Limestone Unit, formed unconformably in the Late Pleistocene-Holocene age, is the youngest formation. It is white and solid.

This unit has been elevated into hills, while others are still developing beneath the water. The uplift of numerous limestone facies in the Limboto Basin reaches 0.0699-0.0724 mm/year, demonstrating the tectonic influence of limestone uplift (Apandi & Bachri, 1997; Permana et al., 2019; 2021). Based on the preceding, the primary goal of this research is to investigate the facies and diagenesis of limestones in the southern region of Gorontalo Province.

Research materials and methods. The research material is a limestone outcrop in Gorontalo Province's southern part. The study area is a plateau (hills) has coordinates (0° 29' 25»-0° 30' 05» N and 123° 2' 25» 123° 03' 00» E) (Figure 1).

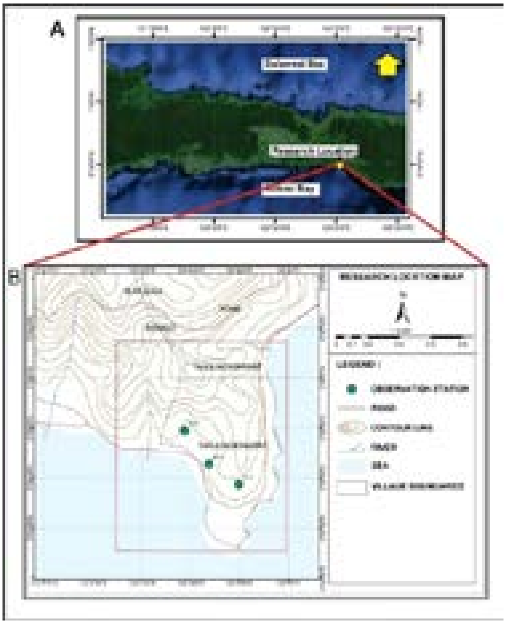

Figure 1. (A) The research location on the map of Gorontalo Province, (B) The research location is in the Tanjung Kramat area, Gorontalo City

A field survey and laboratory analysis was performed in this study. The focus of field surveys is the description and interpretation of limestone types and suitable sampling for laboratory analysis. The petrographic analysis is performed in the Geo Optics laboratory. The petrographic analysis stage begins with forming a thin section using the blocking method, which infiltrates the blue dye into the pores to distinguish the original rock pores from those formed during preparation (Dickson, 1966; Crabtree et al., 1984). Petrographic analysis was conducted with a Euromex 1053 binocular polarizing microscope equipped with a computer-connected camera (Tetley & Daczko, 2013; Serge & Senthilkumar, 2017; Ofulume et al., 2018). A petrographic analysis is very useful in determining the mineral composition of the rock and the kind of porosity, which allows the type of diagenesis to be determined. The interpretation of this type of diagenesis will assist in determining the diagenesis environment of the limestone after it has been formed or deposited (Maryanto, 2012; Arosi & Wilson, 2015).

Results and Discussion. A. Facies. The results of a field survey conducted at the research site in the southern portion of Gorontalo Province demonstrate the study's morphology in the form of limestone hills (Figure 2). Petrological analysis of limestone samples reveals white rock with poorly sorted, open-packed, floating grains in the matrix and a massive structure. The limestone is known as Coralline floatstone based on petrological analysis (Embry & Klovan, 1971). It contains coral fragments, quartz minerals, micrite, and sparite.

Figure 2. Coral limestone outcrops located in the hills of the southern part of Gorontalo Province

The petrological analysis results were then compared to the petrographic analysis using a polarizing microscope (Figure 3). The petrographic analysis revealed that the carbonate rock incision was brown, the interference color was dark brown, with a particle size of 0.1 - > 4 mm, an abundance of material measuring > 2 mm, up to 11%, and the rock texture was based on the relationship between the matrix's supported grains. There is a vuggy porosity with a 12 % abundance. There are skeletal fragments in the form of coral fragments, non-skeletal grains in the form of extraclase, non-carbonate grains in the form of volcanic lithic, quartz, plagioclase, and pyroxene minerals, as well as micrite and sparite, according to its composition. The limestone facies is known as Coralline floatstone (Embry & Klovan, 1971).

A detailed description of the rock composition, namely skeletal grain in the form of coral fragments (11 percent): on the parallel nickel appearance (//) it is brown, has a porous shape, > 4 mm in size, high relief, no pleocroism is visible, and has a sort of translucent transparency. The fragments are generally replaced by sparite (calcite), and the pores are filled with micrite due to micritization. The interference color varies in order II in the appearance of crossed nickel (X).

Non-skeletal grain in the form of extraclase (3%): on the appearance of parallel nickel (//) is colorless brownish, size 0.6 mm, high relief. In the appearance of cross-linked nickel (X), the interference color varies in order of 2. Because it has been heavily crystalline, the texture cannot be determined. It is considered an extraclase because it is more diegenic than other grains of rock origin.

Non-carbonate grains consist of 1. Andesite lithic (2%): on the appearance of parallel nickel (//), it is colorless brownish, on the appearance of nickel crossed (X), it has an interference color of yellowish black, size 0.8 mm, porphyroafanitic texture, the composition in the form of plagioclase, quartz with a base mass of glass material. 2. Quartz (2%): on the appearance of parallel nickel (//), it is colorless, 0.1 mm in size, conchoidal shape, translucent, low relief, no pleochroism, and no fracture. On the appearance of crossed nickel (X), it has an interference color of order 1 gray, wavy dark. 3. Plagioclase (2%): on the appearance of parallel nickel (//) colorless, 0.1 mm in size, a long prismatic shape, translucent, low relief, no pleochroism, one-way fracture. On the appearance of crossed nickel (X), it has an interference color of order 1 gray, Carlsbad twinning, and the darkening angle is $14-18^{o}$. 4. Clino-Pyroxene (2%): on the appearance of parallel nickel (//), it is colorless brownish, 0.2 mm in size, a short prismatic shape, translucent, low relief, no pleochroism, and no fracture observed. The crossed nickel (X) appearance has an orange interference color of order 2, and the darkening angle is $20-22^{o}$.

The matrix consists of 1. Micrite (63%): on the appearance of parallel nickel (//), it is dark brown-yellowish brown, mineral size < 0.1 mm, moderate relief, cleavage is not observed, no pleocroism is visible, and has a type of translucent transparency. On the appearance of nickel crossed (X), it has a golden brown color. 2. Sparite (15%): on the appearance of parallel nickel (//), it is colorless, size 0.1 - 0.4 mm, moderate relief, a fracture is not observed, bladed – equant shape, blocky structure, and meniscus. The appearance of crossed nickel (X) varies by order of two. It is composed of calcite. It results from pore filling, micrite recrystallization, or changing the composition of the shell or coral.

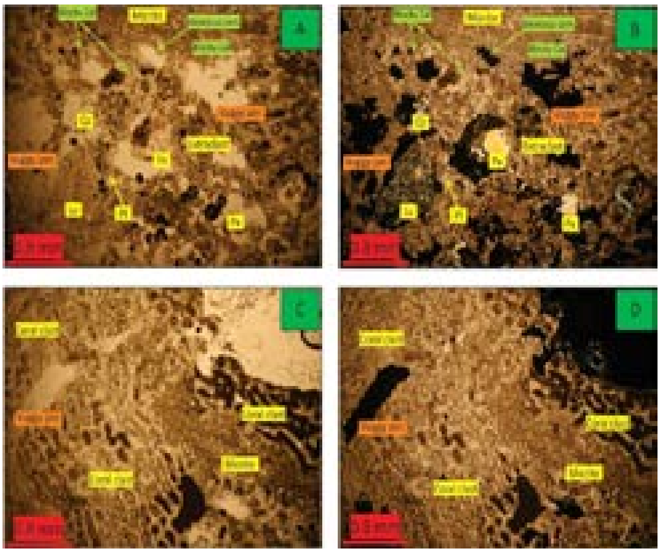

Figure 3. Petrographic analysis of rock samples showing the Coralline floatstone facies. Various types of diagenesis occur in the Coralline floatstone facies. (A) and (C) parallel nikol, (B) and (D) cross nikol

B. Diagenesis. Based on the petrographic study, six different diagenesis processes can occur in Coralline floatstone samples. Microbial micritization, initial calcite cementation, cementation, dissolution, neomorphism (inversion), and neomorphism (recrystallization) are the six processes that occur during diagenesis (Figure 3).

Microbial micritization is this process that occurs in the marine environment, and drilling activity can be carried out by organisms such as endolithic fungi, bacteria, and green algae or possibly red algae. The grain micritization process is indicated by replacing several skeleton grains with cloudy brown micrite that coats the granules. The cementation process in carbonate sediments is the main diagenetic process. It occurs when the pore-fluid is supersaturated with the cement phase, and there are no kinetic factors that hinder cement precipitation. The dissolving process requires a large volume of supersaturated water and is influenced by the selectivity of the matrix, grain shape, grain size, and skeleton properties. The neomorphism process consists of inverse, recrystallization, and coalescive neomorphism (aggrading/degrading neomorphism). Inversion is the change of one mineral to a polymorph, for example, the polymorphic transformation of aragonite to calcite and alteration of Mg calcite to calcite. While recrystallization is a change in crystal size without a change in mineralogy, for example, increasing/reducing the size of calcite crystals or the replacement (replacement) of tiny calcite crystals by larger calcite crystals (Folk, 1965).

It is possible to determine the diagenetic environment of the limestone in the study area based on petrographic analysis and diagenesis type determination using the classification (Longman, 1980), which includes three diagenesis environments: marine phreatic zone, meteoric phreatic zone, and meteoric vadose zone. The reconstruction of the history of limestone diagenesis in the southern part of Gorontalo Province is helped by the analysis of three diagenesis environments based on diagenesis type. Table 1 shows the research area's chronology or stages of limestone diagenesis.

Table 1. Stages of the diagenesis process that occurred based on relative time in limestones in the southern region of Gorontalo Province

Stages of the Diagenesis Process		Marine Phreatic Zone	Meteoric Phreatic Zone	Meteoric Vadose Zone
Relative Time				
1	Microbial Micritization			
2	Initial Calcite Cementation			
3	Cementation			
4	Dissolution			
5	Neomorphism (Inversion)			
6	Neomorphism (Recrystallization)			
7	Cement Structure Dominated by Blocky Structure			
8	Cement Structure Dominated by Meniscus Structure			
9	Vuggy Porosity			

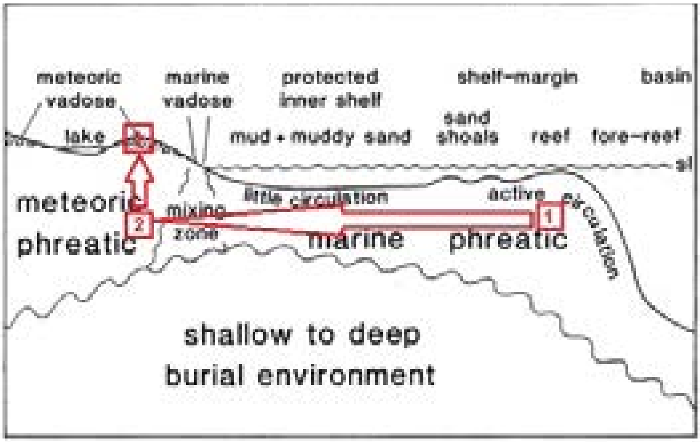

Figure 4. Environmental scheme of carbonate diagenesis in the Coralline floatstone facies in the southern area of Gorontalo Province (Tucker & Wright, 1990)

According to Table 1, the study area's chronology or stages of limestone diagenesis can be divided into three categories:

The major dissolving product in the matrix is cementation. The early steps of the diagenesis process take place in the marine phreatic zone. The process of microbial micritization and early calcite cementation characterize this stage.

The diagenesis process progresses to the second stage in the meteoric phreatic zone. The presence of a substantial dissolving process in the matrix and shell, with the matrix dominating, characterizes this stage. There is also a neomorphism process that involves inversion and recrystallization. Changes in shell composition or coral fragments into blocky calcite indicate an inversion. The process of nemorphism takes the form of recrystallization, as seen by the transformation of micrite to blocky calcite. The bladed equant form dominates the cement's morphology.

In the meteoric vadose zone, the diagenesis process reaches its third stage. The occurrence of a disintegrating process characterizes this stage. Vuggy porosity is formed as a result of this minor dissolving process. There was also a cementation process, as evidenced by the existence of a calcite cement pore filling with a meniscus structure. This is supported by the rock's cementation dominance and the presence of porosity due to extensive dissolution (Figure 4).

Conclusion. Several important conclusions can be taken from the results and discussion of facies analysis and limestone diagnosis studies in the southern portion of Gorontalo Province, including:

1. Coralline floatstone is the limestone facies found in the southern half of Gorontalo Province.

2. Based on the petrographic analysis, six different types of diagenesis processes occur in Coralline floatstone. Microbial micritization, initial calcite cementation, cementation, dissolution, neomorphism (inversion), and neomorphism (inversion) are the six diagenesis processes (recrystallization).

3. The limestone diagenetic environment in the study area consists of three diagenesis environments, which begin with the diagenesis process in the marine phreatic zone, then turn into the meteoric phreatic zone, and end in the diagenesis process in the meteoric vadose zone.

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