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Diagenetic Study Based on Petrography: Implications for Sandstone Porosity of the Peunasu Formation, Pulau Nasi, Aceh

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Abstract

Diagenetic studies observe the process of changing sedimentary deposits into sedimentary rocks. This study is critical because it relates to the quality of rock porosity, which can be filled by fluid. The analysis of the Peunasu Formation is interesting because previous researchers considered that the Tertiary sedimentary rocks in the Northwest Aceh Basin are equivalent to rock units in the petroleum system in the North Sumatra Basin and Mergui Basin. Meanwhile, studies on the Peunasu Formation, a tertiary sedimentary rock, still need to be completed. Therefore, this study was carried out to determine the characteristics and diagenetic processes in the sandstone of the Peunasu Formation. The method used is petrographic observation, which identifies the composition of rocks along with textures such as grain size, roundness, sorting, grain contact, and porosity. The results are that the Peunasu Formation sandstone is classified as sublitharenite, lithic greywacke, and litharenite. The diagenetic regime is mesogenesis. In the mesogenesis stage, the sandstone of the Peunasu Formation experiences compaction, cementation, and dissolution. The porosity of the Peunasu Formation sandstone, as determined by the percentage of pores, exhibits a range of 0.5% to 16.8%, categorizing it as ranging from negligible to moderate. Compaction reduces the intergranular porosity, while the dissolution of grains contributes to the formation of secondary porosity.

Introduction

Sandstone is formed from sediment deposition through the diagenesis process. This process determines the characteristics of rock. The diagenetic level of the rock will be reflected in the texture, type of cementation, mineral composition, and porosity. Understanding the diagenesis of sandstone is crucial because the study relates to the quality of rock porosity, which can store water, oil, and gas if its porosity is sufficient. Previous researchers frequently conducted diagenetic studies on sandstone to investigate its porosity concerning reservoir conditions. In pre-Cenomian sandstones, for example, the dissolution of unstable grains during diagenesis creates secondary porosity, so these sandstones have good reservoir characteristics [1]. Meanwhile, diagenesis studies on Aptian sandstones and conglomerates in the Campos Basin show that secondary porosity comes from the dissolution of rock components and fractures [2]. Sandstones with dissolution and clay mineral grain coatings present high primary and secondary porosity, while sandstones cemented with quartz or carbonate cement tend to have poor porosity [3]. On the other hand, adding clay minerals during diagenesis reduces porosity because they fill the intergranular pore, causing the Halang Formation sandstone to have low potential as a hydrocarbon reservoir [4]. In addition, several researchers studied diagenesis to determine sandstone's temperature conditions and burial depth [5], [6]. In the Triassic sandstones of the Kanikeh Formation, this diagenetic study interpreted that they were formed at 95^0C – 120^0C with depths of 2700 m – 4000 m [6]. Therefore, the author considers the diagenesis study necessary for observing the quality of the reservoir.

The diagenesis study involved an analysis of the components – such as minerals, cement, and matrix – as well as the texture found in sedimentary rocks. The object was on both clastic sedimentary rocks, including mudstone [7], sandstone and conglomerate [2], and non–clastic sedimentary rock [8]. The rocks studied were either exposed to outcrops at the surface or on the subsurface [3]. The methods applied primarily included petrographic observation using a polarizing microscope [1], [9], and, in some cases, scanning electron microscopy (SEM) [7]. On the other hand, the diagenesis study utilized geochemical and isotopic methods [10], even integrating well-log data with petrographic observations [3]. For surface-exposed outcrops, rock samples were collected for microscopic analysis. Sedimentary rocks, including sandstone, exhibit textures and components that can be observed under a polarizing microscope. In contrast, the texture and mineralogical composition of claystone are not observed through polarizing microscopy; consequently, the SEM technique was applied for detailed analysis. Sometimes, geochemical methods can be added to identify types of clay not visible microscopically, and isotope methods are used to determine the age of diagenetic events [10]. On the other hand, diagenetic studies of sedimentary rocks subsurface can be conducted through logging measurements, which provide porosity information. If a core sample is available, it can be analyzed petrographically and integrated with porosity log data [3]. Based on the description, it can be concluded that diagenetic studies necessitate a method capable of observing the texture and components of sedimentary rocks. Consequently, the primary method used is the petrographic technique with a polarizing microscope. Scanning electron microscopy (SEM) and geochemical methods may be applied if the rock samples cannot be analyzed with a polarizing microscope, while well-log data are applied for studies involving subsurface objects.

This research was carried out on the Peunasu Formation sandstone, which was formed in a forearc basin [11]. This formation is Late Oligocene to Early Miocene in age [12], [13]. The research location is on Pulau Nasi, intersected by the Aceh Fault segment with a fault plane trending N 70^0E cutting the Peunasu sandstone unit [14], [15]. Some recent studies have referred to this basin as the Northwest Aceh Basin [13], while others have called it the Breuh Basin [16]. In the past few decades, research on petroleum systems has primarily focused on the North Sumatra basin [17]. However, in the Northwest Sumatra Basin, Tertiary sedimentary rocks are equivalent to rock units included in the petroleum system of the onshore North Sumatra Basin in the southeast and the offshore Mergui Basin in the northeast [13]. Therefore, our study aims to investigate the sandstones in this part of the Northwest Sumatra Basin, focusing on the Peunasu Formation. Over the past decade, limited new geological information has been available, prompting our research to provide new insights into the Peunasu Formation. Therefore, our investigation of the Peunasu Formation sandstone aims to provide information on diagenetic processes, including its porosity condition. Analyzing this porosity is necessary to determine whether the sandstone can store fluids and could be used as a reference for future research related to the Peunasu Formation sandstone. Since this study focuses on sandstone, the appropriate method is petrographic observation using a polarizing microscope.

Geologic Setting

The tectonic evolution of Sumatra Island began with the subduction of the Indian Ocean Plate in the Eocene age. The result is the formation of sedimentary basins (Figure 1). This phase continued with the formation of horsts and grabens in the early to late Oligocene. Regional subsidence also occurred then so that it can be distinguished between the mountain range and the back arc and forearc basins. In the early Miocene, regional subsidence was faster than the uplift of the Mountain Range, and transgression occurred until the Middle Miocene [18]. During this phase, the sediments that form the Peunasu Formation sandstone were deposited in the forearc basin [11]. Then, it continued with the regression stage in the Late Miocene to the Recent [18]. The Peunasu Formation consists of reef limestone overlying micaceous sandstones, laminated siltstones, and mudstones, whose depositional environment ranges from open marine to paralic-fluvial [12], [13]

Method

The study was conducted at Ujung Eumpee, Pulau Nasi (Figure 2), with sampling points presented in Table 1.

Table 1. Sampling points coordinate

Location	Coordinates	Outcrop code
Ujung Empee, Pulau Nasi	5°36′18″N 95°11′39″ E	PS A
	5°36′18″N 95°11′38″ E	PS B
	5°36′20″N 95°11′33″ E	PS C
	5°36′18″N 95°11′32″ E	PS C1
	5°36′18″N 95°11′37″ E	PS D1
	5°36′18″N 95°11′29″ E	PS D2
	5°36′19″N 95°11′35″ E	PS G
	5°36′21″N 95°11′34″ E	PS G1
	5°36′20″N 95°11′32″ E	PS J

Nine outcrop samples were prepared into thin sections for microscopic analysis (Figure 3). The study examines the composition and percentage of clasts, as well as the texture of the sandstone. Clastic compositions are identified, including quartz grains, lithic fragments, feldspar, and muscovite mica. Quartz types, such as undulating monocrystalline and polycrystalline quartz, are identified. Observations also cover matrix presence and cement type.

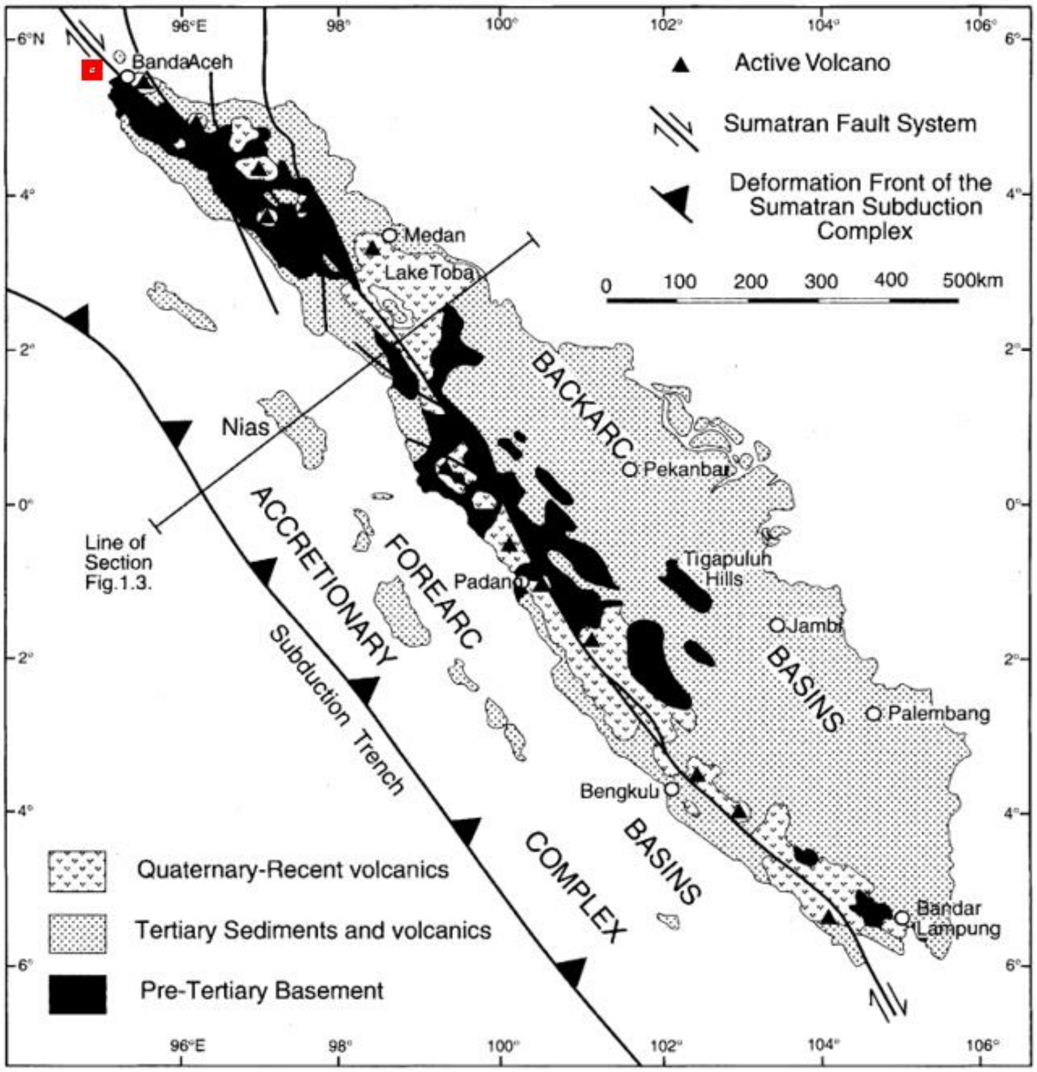

Figure 1. Map of Sumatra showing the Tertiary backarc, fore-arc, and intra-arc basins [11] The research location is marked in red color.

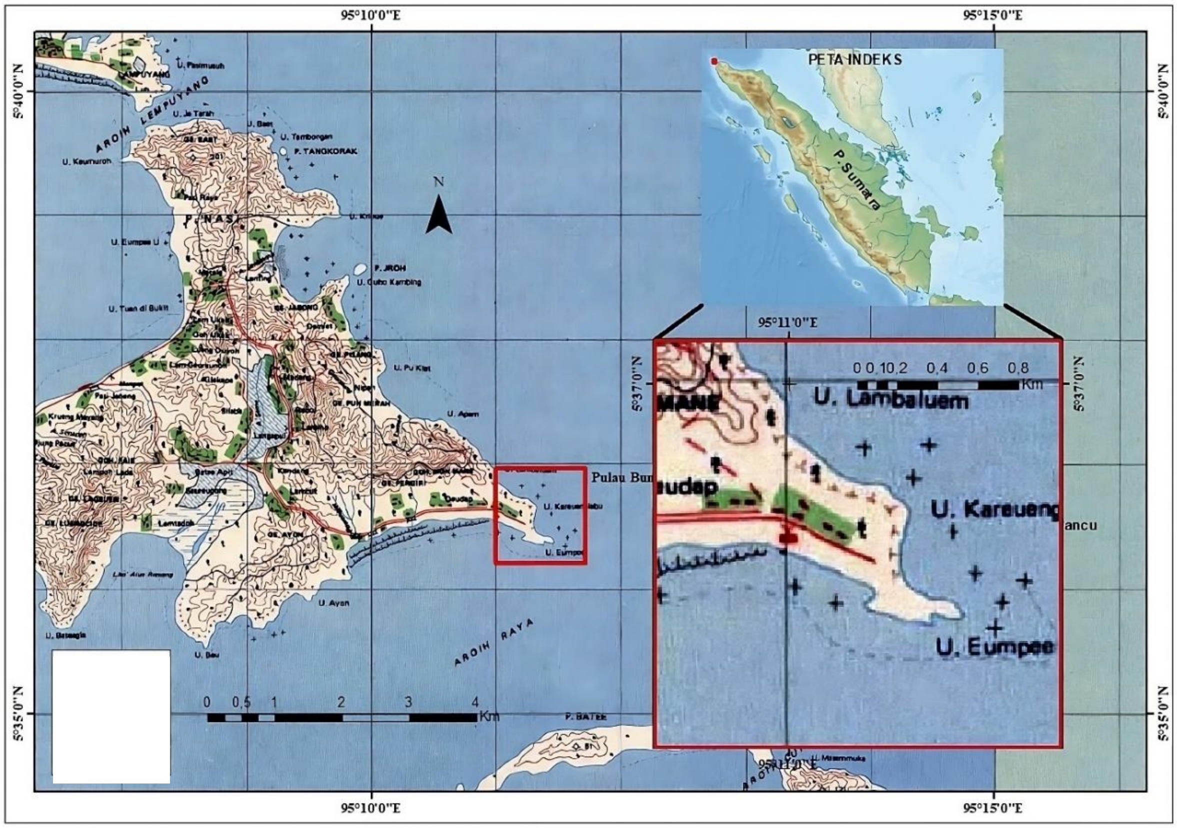

Figure 2. For the research location map, see the red box.

Figure 3. Photographs of sandstone outcrops from the Peunasu Formation.

There are two methods for petrographic observation using a polarizing microscope: plane-polarized light (PPL) and cross-polarized light (XPL) (see Figure 4). These two observation techniques complement each other in identifying rock constituents. Using XPL observation, minerals that compose rocks—such as quartz, lithic fragments, and matrix—can be clearly distinguished (refer to Figure 4). In addition, during PPL observation, oxide cement is easily recognizable due to its blackish-brown color (see Figure 4).

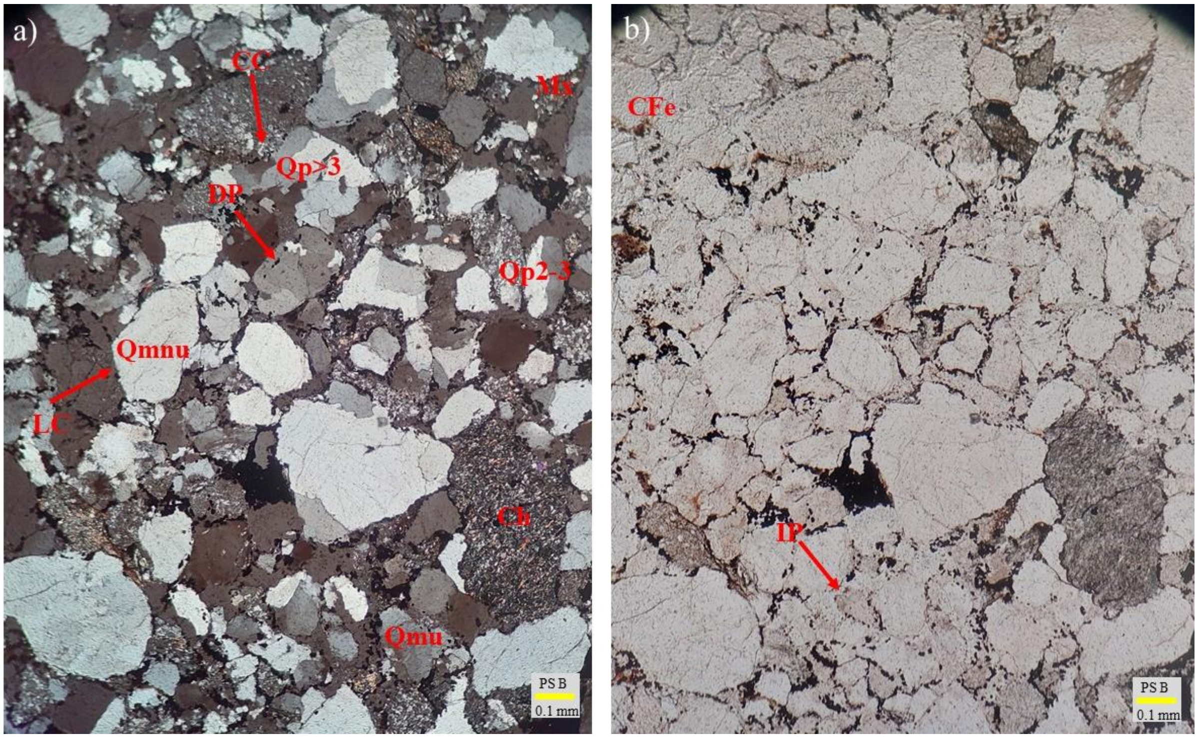

Figure 4. Two methods of microscopic observation: (a) cross-polarized light (XPL), (b) plane-polarized light (PPL). Grains will be more easily observed in XPL, while oxide cement is easily observed in PPL.

The petrographic analysis involves examining the texture of sedimentary rocks, including aspects such as grain size, sorting, roundness, grain contact, and porosity. When using a polarizing microscope, a scale is available to measure the size of mineral grains. Determining grain size is essential for classifying sedimentary rocks, as it can be referenced using the Wentworth scale [19], which is provided in Supplementary information. Furthermore, we observe the sorting texture, which denotes the variation in grain size found within sedimentary rocks. A relatively uniform grain size indicates a very well sorting, whereas considerable non-uniformity in grain size is indicative of poor sorting [20], [21]. A textural comparison chart that delineates various degrees of sorting is provided in Supplementary information.

Roundness texture is determined by the degree of mineral roundness. A mineral is described as having a well-rounded texture if it is more rounded. On the other hand, if the mineral has an angular shape, it is referred to as having a very angular texture [22]. Image of grains used to estimate the roundness of sedimentary grains can be found in Supplementary information. Additionally, grain contact texture is assessed by observing the interaction between grains [23]. A diagram illustrating these grain contacts is also included in Supplementary information.

The last texture analyzed is porosity. It is identified using a mica comparator under a microscope. In XPL observation, it is characterized by a consistent color that does not change when the sample table is rotated. The difference between grains and porosity can be seen in Figure 5.

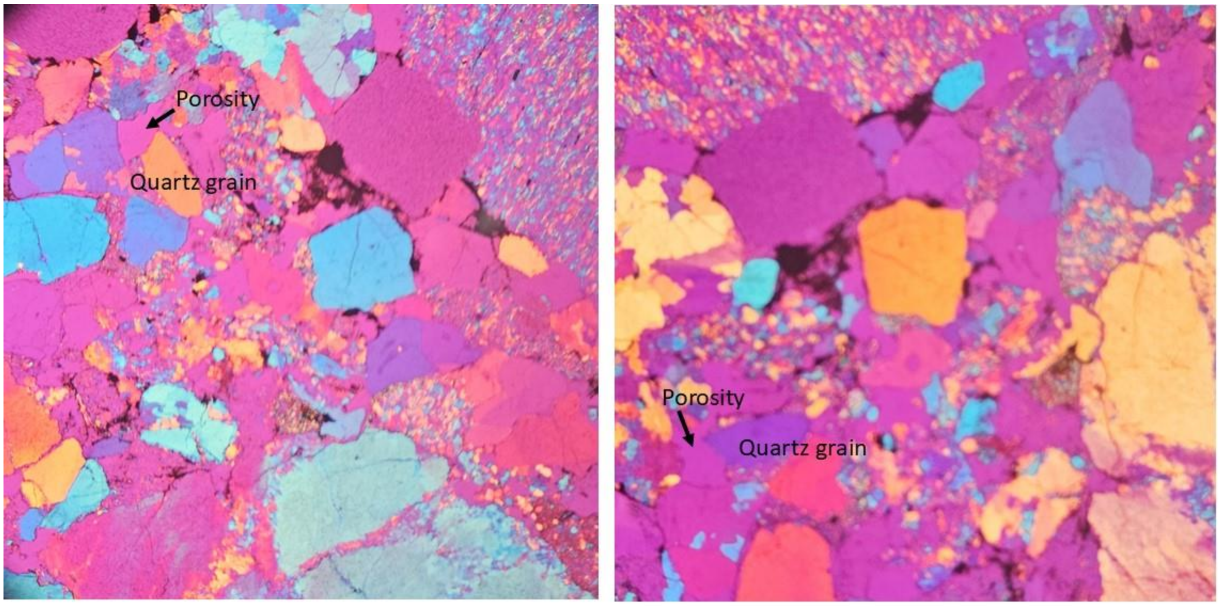

Figure 5. The distinction between porosity and grains can be observed using a mica comparator. In the initial observation (**Left**), porosity appears purple while the quartz grain is yellow. After rotating the sample position **(Right)**, porosity retains its color, but the quartz grain shows a color change.

The further phase of the research involves capturing photographic images of thin section samples to quantify the proportions of clastic grains, matrix, cement, and porosity. This quantitative analysis will be conducted utilizing the point-counting technique. The point–counting method, commonly used in petrography, was employed to estimate these components' volume by randomly placing points on minerals in the thin section and identifying the minerals. The number of points for each mineral was then stated as a percentage of the total. We used the *Jmicrovision* software to digitally count points in thin-section images, achieving accurate quantification with 1,500 points, covering all minerals in each sample [24].

Figure 6 provides an example of the results from our point counting. In this figure, each monocrystalline quartz mineral (Qm) is marked with red point. Similarly, other minerals are marked with specific colors. The Jmicrovision software automatically calculates the percentage of points assigned to each mineral. As a result, we obtain the percentages for quartz, lithic minerals, muscovite, matrix, cement, and porosity, which is attached in Supplementary information.

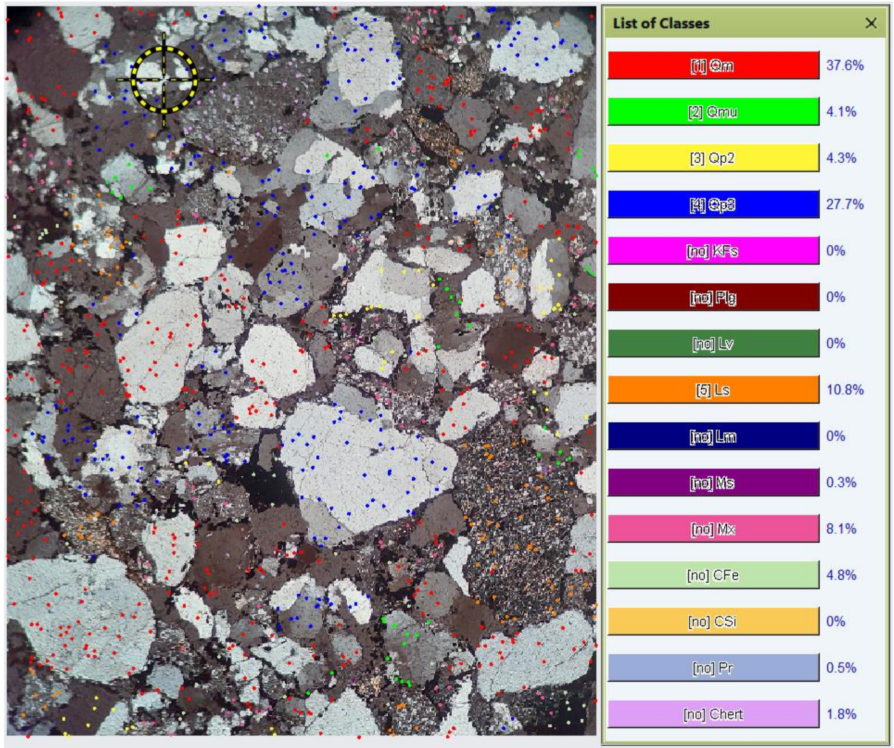

Figure 6. An example of the results of point counting.

The next phase of the research involves describing the rock type. According to the Wentworth scale [19], this sedimentary rock is classified as sandstone. We will use the QFL diagram [25] to determine the specific classification of the sandstone. This diagram includes the components of quartz, feldspar, and lithic fragments, which together should total 100%. Since the total percentage of these three components does not equal 100%, we will normalize the percentages of quartz, feldspar, and lithic fragments. The results of our normalization are provided in Supplementary information.

Figure 7 presents a QFL diagram, which categorizes three sections based on the percentage of the matrix present in the rock. The diagram's usage accounts for the matrix in the rock. When the matrix ranges from 0% to 15%, the arenite section of the diagram is utilized. For a matrix between 15% and 75%, the Wacke section is applicable. If the matrix exceeds 75%, the mudrock section should be applied. For instance, sample PS B has a matrix of 8.1%, so we refer to the arenite section of the diagram. By inputting the normalized values of quartz, feldspar, and lithic fragments, we identify the sandstone type as sublitharenite. This process is similarly applied to the other samples.

Result

The sandstone of the Peunasu Formation is characterized by a whitish-yellow color and coarse sand grain size, as shown in Figure 3. According to the QFL classification diagram (Figure 7), it is categorized as sublitharenite, lithic greywacke, and litharenite based on the percentage of matrix presence and the normalized percentages of quartz, feldspar, and lithic fragments. If the matrix percentage is less than 15%, it is classified as arenite; if it is between 15% and 75%, it is classified as wacke; and if it exceeds 75%, it is classified as mudrock. The results of the petrographic analysis for each sample are presented in Supplementary information, while the normalized results of quartz, feldspar, and rock fragments can be found in Supplementary information. Thin-section photographs are provided in Supplementary information.

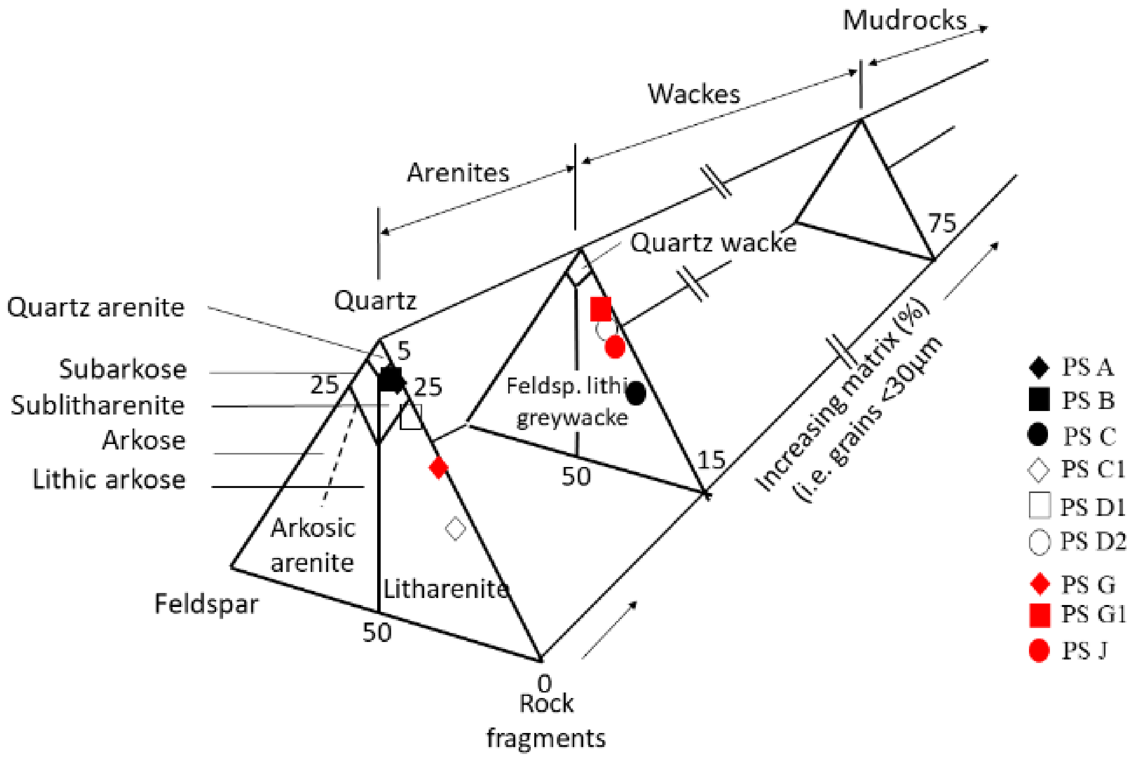

Figure 7. Classification of the Peunasu Formation sandstone [25]. The sample code is PS A, B, C, C1, D1, D2, G, G1, and J.

Sublitharenite. This sandstone is fragment-supported and has a medium sand size (0.25 mm – 0.5 mm). It is between poorly and moderately sorted as well as subangular to subrounded roundness. The composition includes 8.1% - 12.3% matrix and 71.9% - 86.3% grain. The grain comprises 61.9% - 73.7% quartz and 10% - 12.6% lithic fragments. The quartz is non-undulating and undulating monocrystalline and polycrystalline, with 2-3 units per grain and more than three units per grain. The lithic fragments present are sandstone and chert (Figure 8). Another mineral present is muscovite mica, which has 0.3% - 2.9%. The cement is iron oxide, indicated by a brownish color on the grain rim and filling between the grains. It can be observed in the parallel-polarized light (PPL). The porosity ranges from 0.5% - 8.6%. The types of porosity observed are intergranular porosity (see Figure 8) and porosity due to dissolution, revealing cavities within the minerals or along the mineral rims (see Figure 8).

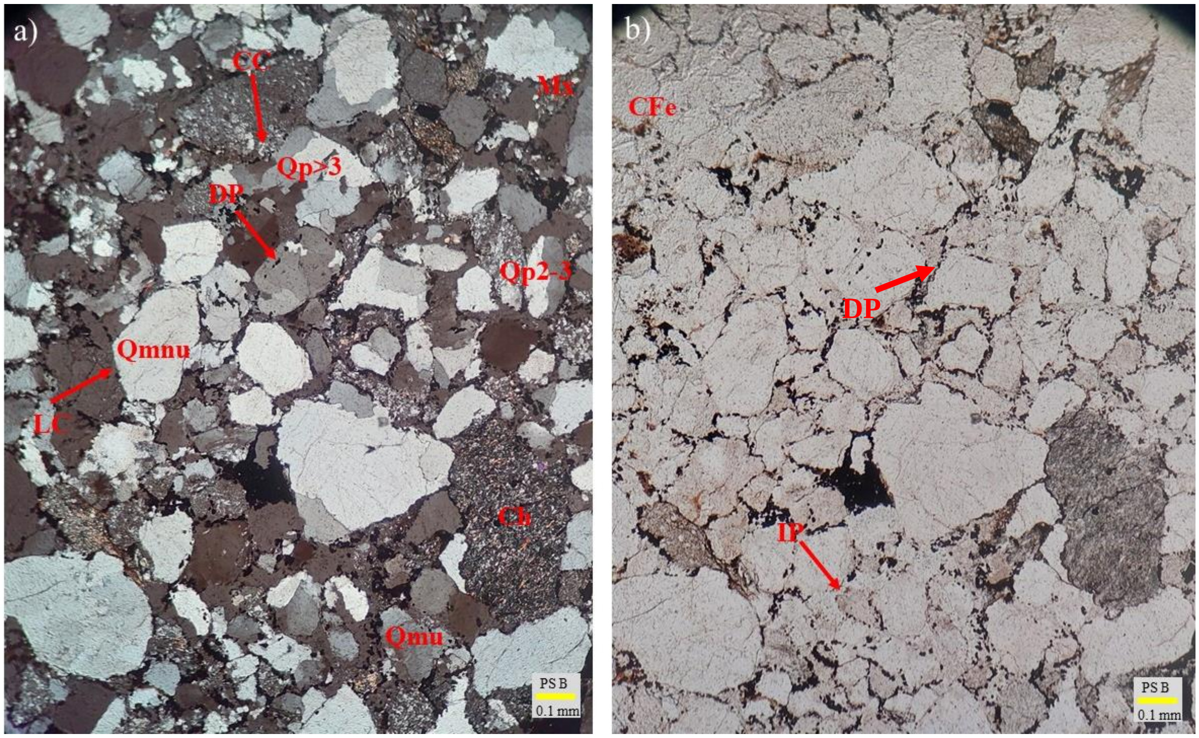

Figure 8. Sublitharenite sandstone samples with moderate sorted, long contact (LC) to concave-convex contact (CC) a) PS B observed in cross-polarized light (XPL), b) PS B observed in parallel-polarized light (PPL). (Qmu = Undulating monocrystalline quartz; Qmnu = non-undulating monocrystalline quartz; Qp2-3 = Polycrystalline quartz with 2 – 3 unit per grain; Qp>3 = Polycrystalline quartz with more than 3 unit per grain; Ch = Chert; Mx = Matrix; CFe = iron oxide cement; IP = Intergranular porosity; DP = Dissolution porosity)

Lithic greywacke. This sandstone is fragment-supported and has a medium sand size (0.2 mm – 0.5 mm). It is between poorly and moderately sorted as well as subangular to subrounded roundness. The composition includes 16.5% - 20.4% matrix and 72.7% - 79.5% grain. The grain comprises 34.3% - 56.3% quartz and 18.4% - 39.2% lithic fragments. The quartz is non-undulating and undulating monocrystalline and polycrystalline, with 2-3 units per grain and more than three units per grain. The lithic fragments are sandstone, schist, and chert (Figure 9). Additionally, 0.5% - 1.6% of muscovite mica. The cement present includes iron oxide and a small amount of silica cement. The porosity ranges from 1.8% - 8.3%. The types of porosity observed are intergranular porosity (see Figure 9) and porosity due to dissolution, as shown in Figure 9, where a section of the quartz has dissolved.

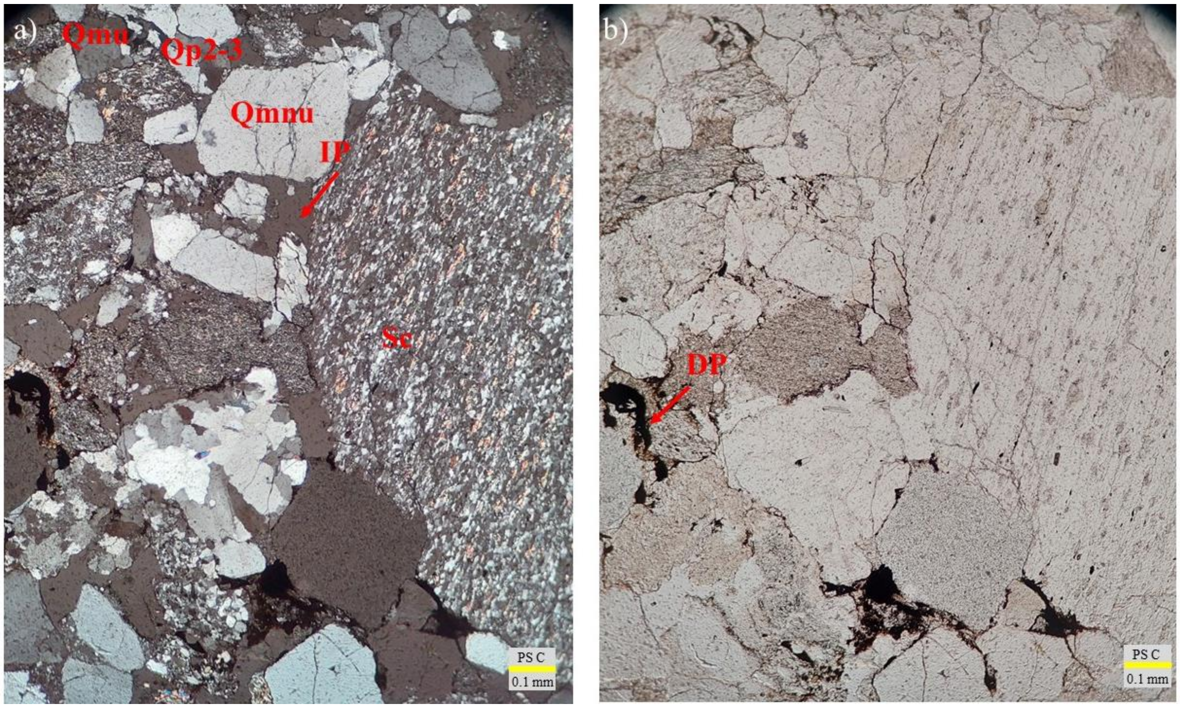

Figure 9. Lithic greywacke sandstone samples with poorly sorted, a) PS C observed in XPL, b) PS C observed in PPL. (Qmu = Undulating monocrystalline quartz; Qmnu = Non-undulating monocrystalline quartz; Qp2-3 = Polycrystalline quartz with 2 – 3 units per grain; Sc = Schist; IP = Intergranular porosity; DP = Dissolution porosity).

Litharenite. This sandstone is fragment-supported and has a medium sand size (0.2 mm – 0.25 mm). It is between poorly and moderately sorted as well as subangular to subrounded roundness. The composition includes 5% - 11.8% matrix and 70.9% - 85.9% grain. The grain consists of 43.9% - 57.1% quartz and 16.7% - 37.2% lithic fragments. The quartz is non-undulating and undulating monocrystalline and polycrystalline, with 2-3 units per grain and more than three units per grain. The lithic fragments are sandstone, schist, and chert (Figure 10). Additionally, 0.4% - 2.2% of muscovite mica. The cement present includes iron oxide and a small amount of silica cement. The porosity ranges from 3.8% - 16.8%. The types of porosity observed are intergranular porosity (see Figure 10) and porosity due to dissolution, as shown in Figure 10, where a section of the quartz has dissolved.

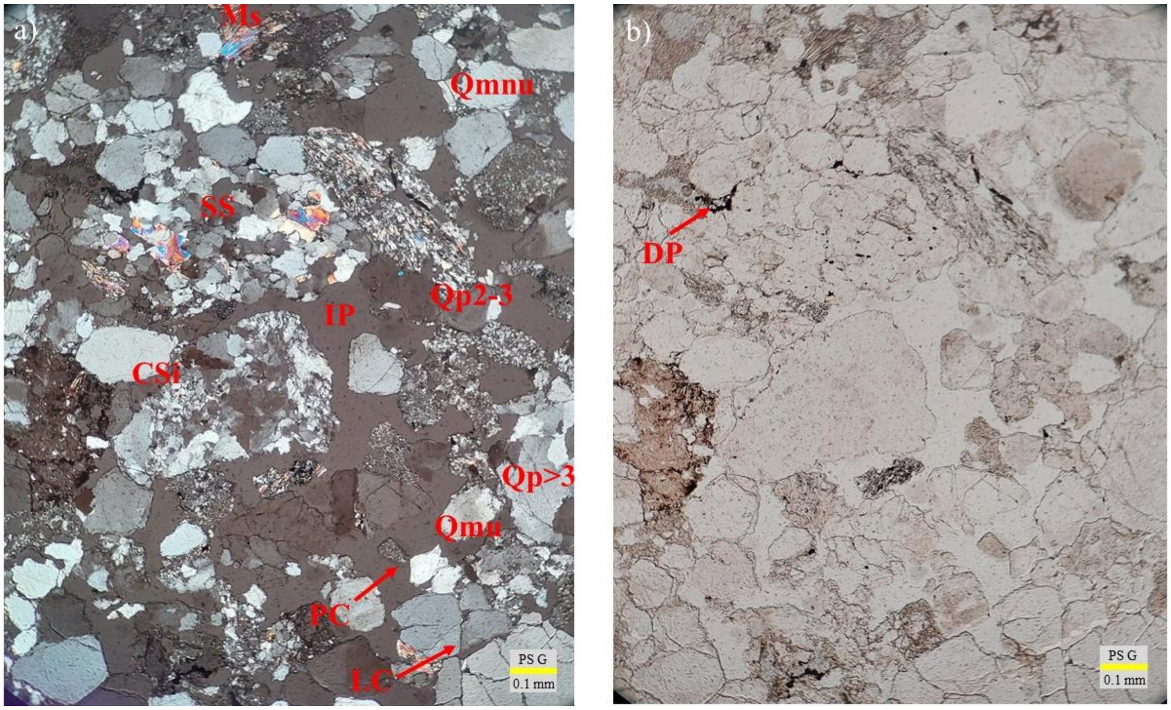

Figure 10. Litharenite sandstone samples with moderate sorted, point contact (PC) to long contact (LC) (a) PS G observed in XPL, b) PS G observed in PPL. (Qmu = Undulating monocrystalline quartz; Qmnu = non-undulating monocrystalline quartz; Qp2-3 = Polycrystalline quartz with 2 – 3 unit per grain; Qp>3 = Polycrystalline quartz with more than 3 unit per grain; SS = Sandstone; Ms = Muscovite; Csi = Silica cement; IP = Intergranular porosity; DP = Dissolution porosity)

Discussion

According to thin section observations, the Peunasu Formation sandstone has a matrix of more than five percent, thus indicating that the sandstone is still at the immature stage [26]

Diagenesis is a physical, chemical, and biological process that changes loose sediment into sedimentary rock by changing its texture and mineralogy. The diagenesis process is divided into stages: eogenetic, immature mesodiagenetic, semi-mature mesodiagenetic, mature mesodiagenetic and super mature mesodiagenetic [27]. In addition, diagenetic processes are also classified based on burial into early shallow subsurface (Group A) and late deep subsurface (Group B and Group C) [28]. Another classification divides diagenesis stages into eogenesis (shallow burial), mesogenesis (burial diagenesis) involving compaction, cementation, dissolution, replacement, and authigenesis, and the final stage, telogenesis [10]. The diagenetic processes observed in the sandstone of the Peunasu Formation are compaction, cementation, and dissolution.

Compaction

Sandstone typically goes through a compaction process, transforming loose material into sedimentary rock. However, the degree of compaction varies for each rock. Compaction can be observed in the contact texture between grains. The more intense the compaction, the more the grains stick together until they form a suture contact [22]. Peunasu sandstone exhibits point and long contact (Figure 10), and some samples exhibit concave-convex textures (Figure 8). The point contact in these samples indicates that compaction is early. On the other hand, the long and concave-convex grain contact suggests that compaction is progressing to an intermediate stage [23].

Cementation

The Peunasu sandstone contains silica cement, present in samples PS C1, PS D1, PS D2, and PS G, ranging from 0.1% to 0.9%. Cement in sandstone is primarily derived from the minerals it comprises. Quartz or silica cement is typically present. Quartz cement forms during burial diagenesis at temperatures above 70^{0}C [10]. The presence of quartz cement in the Peunasu sandstone is minimal in percentage and is only present in a few samples. On the other hand, the cement that is generally present in every Peunasu Formation sandstone sample is iron oxide cement. Its presence is in the range 0.2% - 5.8%. Some iron oxides form in environments where oxidation is an early stage of the diagenesis process before undergoing significant compaction. The red pigment in sandstone layers comes from diagenetic processes and is the main result of changes within layers of silicate materials after deposition [29]

Dissolution

The quartz grains depicted in Figure 8 dissolve, revealing cavities within the minerals or along the mineral rims. In some cases, dissolution can lead to partial mineral dissolution, as shown in Figure 9, where a section of the quartz has dissolved. Dissolution may occur near the earth's surface due to water, resulting in secondary porosity [29].

Porosity

According to petrographic observations, the Peunasu Formation sandstone has a 0.5% - 16.8% porosity. These porosities can be classified as negligible to moderate porosity [30]. The compaction process aims to reduce porosity, but porosity may increase in samples with grain dissolution. We conclude that the porosity of the Peunasu sandstone is influenced by compaction and dissolution. Intensive compaction reduces intergranular porosity, while dissolution of grains creates secondary porosity.

Diagenetic Regime

The diagenetic compaction, cementation, and dissolution processes in the Peunasu Formation sandstones indicate that the diagenetic regime is mesogenesis [10]. In some samples, intergranular contact from points to extended contact indicates that burial occurred early. Meanwhile, some other samples have long to concave-convex contact, indicating that the rock is compacting to an intermediate stage [23]. The presence of quartz cement, which is still very small and only in some samples, also indicates that the diagenesis stage is mesogenesis with burial at a depth of 1 - 2 km and a temperature of 30^{0}C - 70^{0}C [10]. This condition supports the burial stage, which is still early. Other evidence, such as the presence of oxide cement and dissolution, is like the conditions at the beginning of diagenesis. However, mesogenesis is divided into several stages [31]. Secondary porosity is associated with the mature a mesogenesis stage, with temperature conditions of 80^{0}C to 95^{0}C and a depth of 2 km to 3 km [31]. The Peunasu sandstone has not reached the mature B mesogenesis stage as in the Kanikeh Formation sandstone [29] The Kanikeh sandstone is interpreted to have formed at a depth of 3 km to 4 km and a temperature of 95^{0}C – 120^{0}C. This sandstone has reached mature B mesogenesis due to bending muscovite mica [29]. In contrast, the muscovite mica minerals in the Peunasu sandstone do not show bending (see Figure 10), indicating that the burden has not reached the mature B stage like the Kanikeh Formation sandstone. Despite quartz overgrowth, it is interpreted as an authigenic mineral formed at the mature a mesogenesis stage, like the Seblat Formation sandstone [32]

Conclusion

The diagenetic stage of the Peunasu Formation sandstones is mesogenesis, which involves compaction, cementation, and dissolution. In the mesogenesis stage, this sandstone undergoes initial burial stages at a depth of around 1 – 2 km with a temperature of less than 70^0C. The porosity in the sandstone in the Peunasu Formation is affected by two factors: compaction and dissolution. This results in porosity ranging from negligible to moderate. The rock's pore quality is unsuitable for a fluid reservoir.

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