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Lithofacies and Petrology of Sandstones from Outcrops at Kulen Area, Siem Reap Province, Cambodia

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Abstract: *Lithofacies and petrological studies of sandstones from outcrops at the Kulen area were carried out to understand the diagenetic processes, depositional process, and mineral composition of sandstones. Measurement of stratigraphic section and sandstone samples were conducted at three zones of Kulen area, Phnom Takhok (TK), Peah Ang Chub (PAC), and Phnom Mrech (PM) for this study. The sedimentological study provides the information of large -and small-scale variations in lithofacies, sedimentary structures, and rock textures. Petrography analysis is used to identify the mineral composition, diagenesis alteration, relative porosity, and classify the types of sandstones. The results demonstrated that Kulen area consists of lithofacies, such as cross-bedding and massive bedding sandstones, and black shale. Moreover, the zone presents the sedimentary structures as planar cross-bedding, cross-bedding, parallel lamination, normal and reverse graded -bedding. Furthermore, petrography analysis showed that sandstones of Kulen area are classified into quartz –arenite in PAC zone, sublith arenite in TK zone, and quartz wacke in PM zone with an average relative porosity of ~17% which indication as good reservoir quality. The diagenetic process includes compaction, cementation, replacement, and quartz overgrowth. Therefore, this study provided crucial information for further research on sandstone reservoir characterization, factors controlling its properties, and depositional environment.*

Keywords: Sedimentology; Petrology; Lithofacies; Mineral composition; Kulen area

1. INTRODUCTION

Sandstones are essential as a reservoir for oil and gas, about 50% of the world's petroleum reserve is estimated to accumulate in sandstone. The study on sedimentology and petrology of sandstones is important for hydrocarbon exploration and production because the lithofacies and their properties strongly influence reservoir qualities. Sedimentological study of sandstones provides an understanding of lithofacies, texture, and sedimentary structures, revealing depositional environments, and diagenesis. Sandstone is deposited from continental alluvial settings to marginal coastal areas affected by riverine, waves, and tidal processes to deep submarine regions. These depositional settings may result in sandstones with different properties including mineral composition, porosity, and diagenesis [1].

Sedimentary basins in Cambodia are subdivided into seven basins [2]. There are Tonle Sap, Kampong Saom, Khorat, Preah, Chhung, and Svayrieng basins in the onshore region, whereas only the Khmer basin is offshore [2]. Tonle Sap basin is one of the biggest sedimentary basins among six others, covered by Quaternary sediments overlying mainly terrigenous Mesozoic sediments exceeding 4000m in thickness potential for the hydrocarbon reservoir [2]. This basin has been explored for potential hydrocarbon reservoirs since 1996 with airborne gravity and magnetic survey [3]. From 2008-2013, the 2D seismic survey was conducted, and it is confirmed for promising with oil and gas accumulation. However, the lithofacies and properties of sandstones in this area have not been documented yet. In this study, we are focused on the lithofacies characterization and petrological studies of sandstones of three different zones (TK, PAC and PM Zones) at Kulen area where located at the northern part of Tonle Sap basin (Fig. 1).

For geological setting, Tonle Sap basin is a foreland basin-type, which covers an area of 23,800 km^2. It is generally occurred by tectonic activity [4]. There are several faults in Indochina due to the collision of India and Eurasia, and some have affected the southeastern part of Thailand and the southern part of Cambodia [4]. The basement is composed of deformed and metamorphosed Palaeozoic rocks, which are cropped out at

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the basin margins. Most of the basin is covered by Quaternary sediment, which overlies mainly by terrigenous Mesozoic sediments exceeding 4,000 m in thickness.

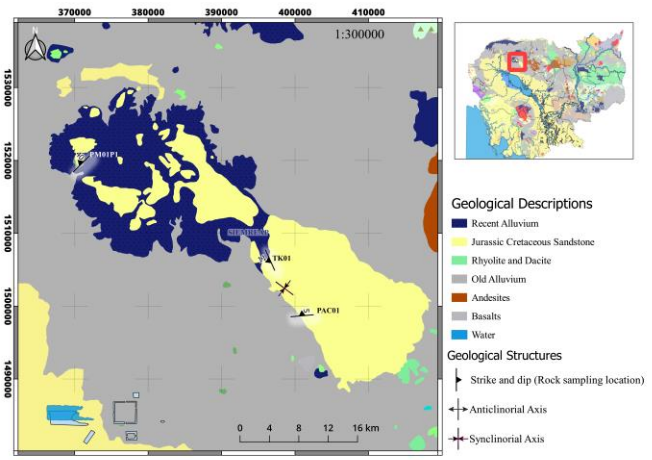

Fig. 1. Geological map of the study area. Red stars indicate three locations of sample collection in Kulen area.

Kulen zone is an area where located at the northern part of Tonle Sap basin. This zone composes mainly of young alluvium, Jurassic-Cretaceous sandstone, and Deveno-Carboniferous sandstone and shale (Fig. 1). The young alluvium deposited from the middle of the study area to the northwest part, while the Jurassic-Cretaceous sandstones were deposited mainly in the southeast of study area and continued forward to the Norwest part (Fig. 1). The Jurassic-Cretaceous sandstone may be the future target for hydrocarbon exploration in Kulen area. This study was selected the three locations, such as Phnom Mreach (PM Zone), Phnom Takok (TK Zone), and Phnom Preah ang Chub (PAC Zone) (Fig. 1) for conducting measurement of stratigraphy and collecting sandstone samples to understand their lithofacies and properties.

2. METHODOLOGY

2.1. Measurement of stratigraphic section (MS)

Measurement of stratigraphic section (MS) is a method to record rock strata, sedimentary structures, mineralogy, texture, grain size, and sorting. In this study, MS was carried out by observing and recording the character and attributes of the rock outcrop in the field. The data collection and interpretation, such as lithofacies, grain size and shape of sediments, and sedimentary structures were summarized within the stratigraphic logs (Figs. 2-4).

3.2. Petrography

Petrography is a method to analyze samples based on the color observation of minerals, size, shape, orientation under the Optical Microscope. This method provides qualitative information about mineral compositions, texture, sedimentary textures, relative porosity, and diagenetic processes. The thin sections of nine rock samples taken from the field were prepared using struers specifics resin, blue-dyed powder mixed with curing agent in the ratio 10:1. Petrographic thin sections of sandstones are conducted under Optical Microscope (Model: ECLIPSE CI-POL.B) and determine mineral percentage based on comparison chart estimation [5].

3. RESULTS AND DISCUSSION

3.1. Lithofacies

MS is a method to measure and describe a vertical stratigraphic section. It provides the information of lithofacies types, thickness of lithology, geological sequence of rock strata, dip, size, and texture of rock units at Kulen area. Moreover, the sedimentary structures are recognized as planar cross-bedding, cross-bedding, parallel lamination, normal and reverse graded-bedding. The lithofacies of Kulen area consists of cross-bedding and massive sandstones, black shale, and granite. The details of lithological characteristics of rock units at Phnom Takhok, Phnom Preah Ang Chub, and Phnom Mreah at Kulen area are demonstrated in Figs. 2-4.

Phnom Takhok (TK)

According to MS, there is only one lithofacies, cross-bedding sandstone in TK zone (Fig. 2). The thickness of the facies is about 14 m and is mainly composed of reddish-grey sandstones. The thickness of the lower part is around 9 m. It was distributed by medium-grained sandstone, well-sorted, and close packing matrix cement with planar cross-bedding dipping at ~11º degree NW incline with the thickness of each cross-bedding layer about ~10 to 20 cm (Fig. 2). The cross-bedding was from SSE toward NNW. On the other hand, the thickness of the upper part is around 5 m. It is composed of various grain sizes ranging from medium to coarse-grains, reddish-grey, normal, and reverses graded bedding showing trough cross-bedding, moderately–sorted with gravel inclusion forms disseminative in the layer.

There are two lithofacies at PAC zone, such as massive and cross-bedding sandstones, where both facies are deposited as the inter-bedded layer with a total thickness of 16 m (Fig. 3). The massive sandstone exposed approximately 1.5 ~2 m and some parts are weathering by oxidation (Fig. 3). These facies are mainly composed of fine to medium sand grains, sub-rounded shape, well-sorted, whitish-grey color with structureless trough cross-bedding. The main composition of this sandstone are homogeneously quartz bed consists mainly of quartz with fewer lithic fragments and mica. The homogeneous properties may be caused by the depositional at the lower flow regime [6].

Cross-bedded sandstone is deposited on the upper part, where the thickness of the layer is approximately 0.5 – 1.5m (Fig. 3). The Grain size of sandstone is varied from medium to coarse-grained with a reddish-brown color, moderately –sorted, and sedimentary structure exposed as cross-bedding locally containing inclined sand layer. Some parts of this facie show finning upward with gravel disseminated at bottom part whereas, other part appeared locally homogeneous properties.

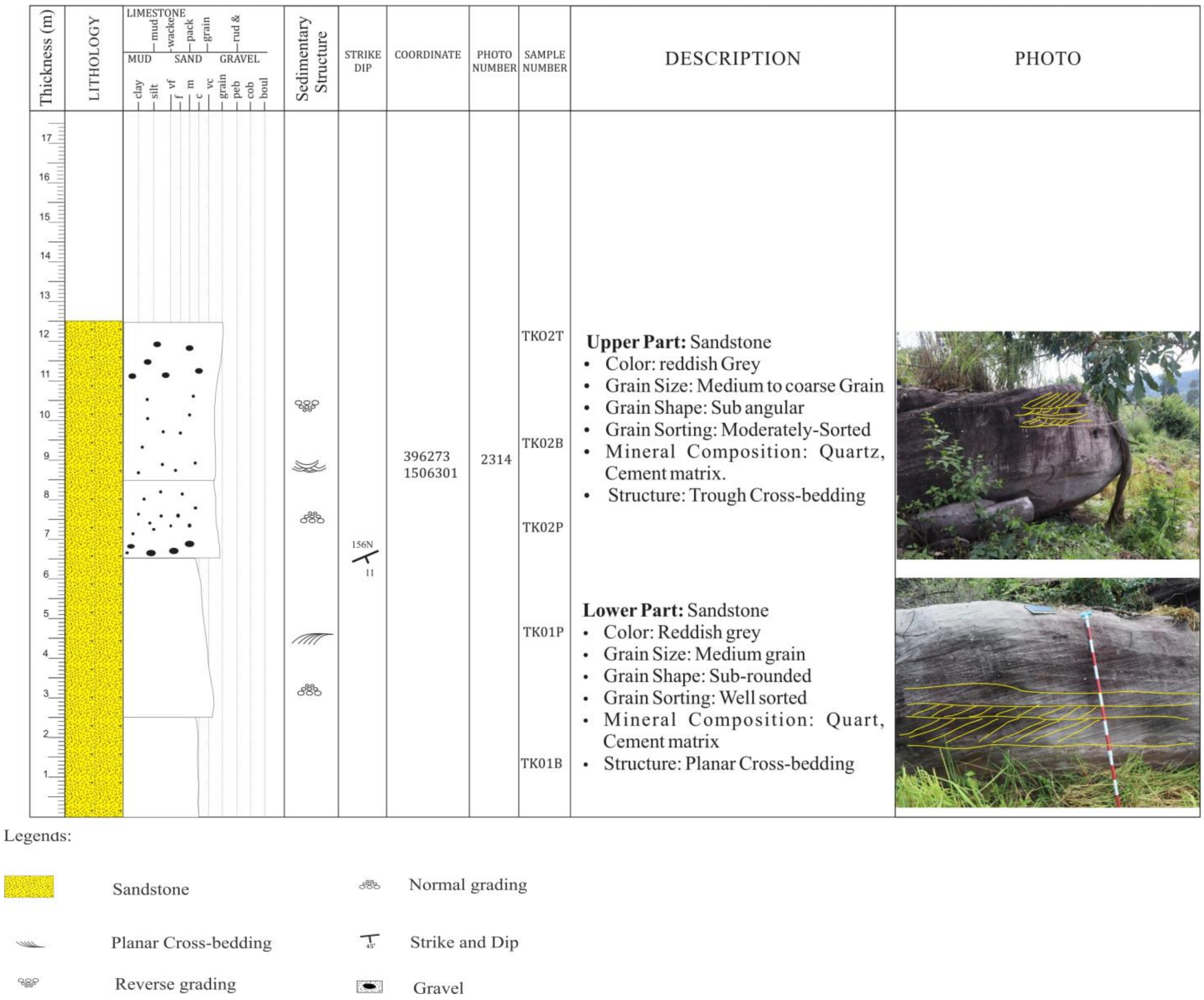

Fig. 2. Stratigraphy Log of sediment at TK Zone, Kulen Area.

Phnom Mreach (PM)

PM Zone has three lithofacies, including sandstone, black shale, and granite. Sandstone facies compose of fine-grained with matrix supported texture. Some parts of this facies are weathered and mixed into topsoil (Fig. 4). Sandstone facies is deposited on the upper part of the black shale facies with reddish-brown in color. Some sandstone layers discontinue due to the erosion caused by weathering. Moreover, the sedimentary structures of this lithology are characterized as laminated.

Black shale facies deposited with a thickness of 7– 8 m mixed with rock fragments, mud layer, and some parts were affected by weathering. There are two various sub-facies inside black shale facies that are deposited into 4 layers. The first and second layers were exposed as massive bedded black shale, whereas the third and fourth layers were exposed as laminated black shale (Fig 4). These black shale facies may deposit under a reducing environment that consists of organic material, sulfide material, leading shale to become black color [7].

Granite was deposited beneath the black shale facies at PM zone. This granite has whitish color. It comprises a thickness of about 10 m (Fig. 4). Some shale fragments were observed at the uppermost of white granite close to contact boundary. This is indicated that the white granite intrusion may be occurred pre-date shale deposit in this environment [8].

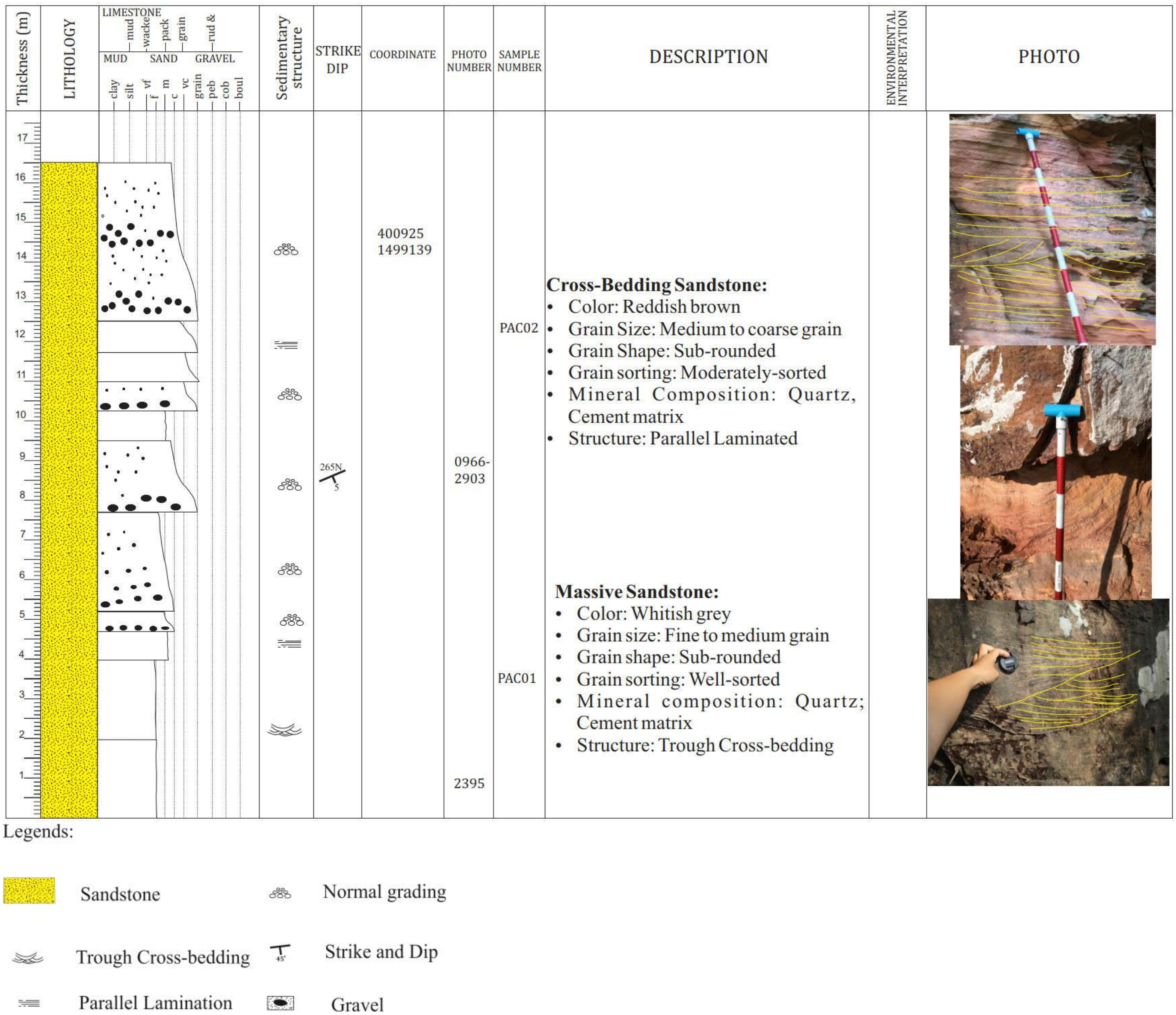

Fig. 3. Stratigrapic section at PAC, Kulen Area.

3.2 Petrographic Analysis

There are five samples from the TK zone, and two samples from PAC and PM zones were used to analyze with petrography. The results of petrographic analysis revealed that sandstones at Kulen area are composed of quartz, feldspar, lithic rock fragment and can be classified as quartz arenite, sublith arenite, and quartz wacke [5] (Figs. 5 and 6).

Phnom Takhok (TK)

Sandstones of the TK zone are classified into quartz arenite and sublith arenite (Figs. 5 and 6). The abundance of clastic grain is quartz, which composes of both monocrystalline and polycrystalline (Fig. 6A). Monocrystalline quartz grains vary from subangular to subrounded, partially low to high spherical, moderately and well-sorted (Fig. 6B). This indicates that some quartz grains are observed with straight to undulose extinction. These types may be derived from the plutonic origin [5]. The average quartz composition existed about 95% ranging from 93% to 97%. Polycrystalline grain is common for quartz and less common for mica sub-crystals, such as muscovite and biotite (Figs. 6B and C). Inside the interparticle pore volume, there are small crystals of biotite and muscovite, clay mineral, calcite cement, sericite, and iron oxide cement enclosed with quartz grain (Figs. 6B, C, and F). Additionally, sandstones of TK zone also present deformed mica-flake as bending between quartz grain contacts (Fig. 6C). Thus, this is evident of mechanics, and pressure dissolution occurred during the diagenesis phase caused by a loss in primary porosity of sandstone [9]. Lithic fragments observed in thin sections containing fragment of sedimentary, metamorphic, volcanic, and chert fragments that constitute an average of 4.13 % of volume percentage of framework grain (Figs. 6B and D). Photomicroscope also indicates that the number of quartz grains is slide pass each other and packed into tighter or penetrate one another, causing concavo-convex grain contact and sutured contact (Figs. 6D and E). Moreover, other observations of TK sandstone are presented as quartz overgrowth (Fig. 6E). Most samples showed quartz overgrowth along the detrital quartz grain, perpendicular to quartz grain. This quartz overgrowth may have occurred typically at a temperature greater than 100 ºC [10].

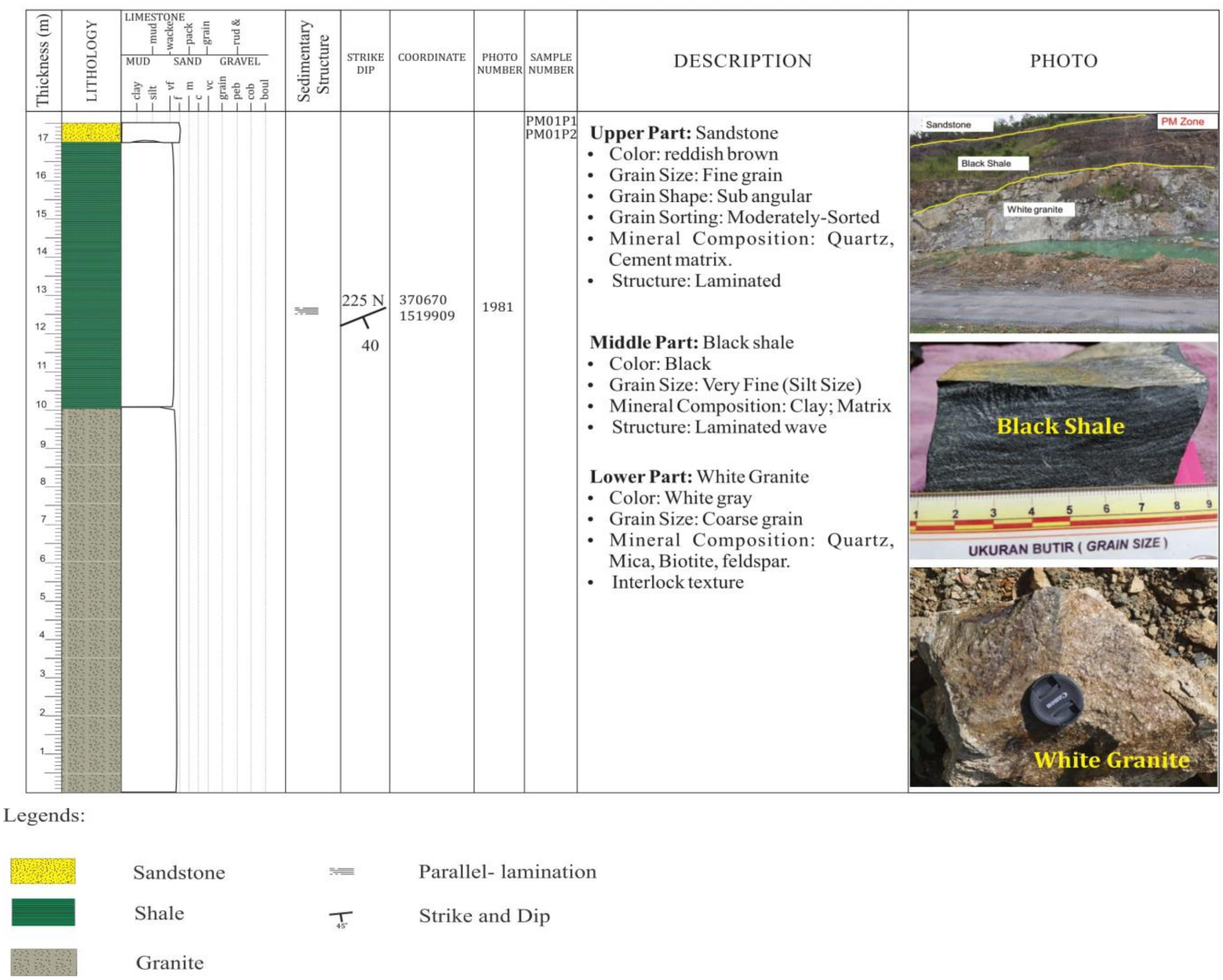

Fig. 4. Stratigrapic section at PM zone, Kulen Area

Generally, K-feldspars are the second abundant detrital grain in sandstone. However, based on the observation of the TK zone indicated that the amount of K-feldspar is absent due to the alteration or partly dissolved and produced pore volume for secondary cementation, filled by authigenic clay, mineral or produced the secondary porosity during early and late of digenetic process, respectively [11] (Fig. 6D).

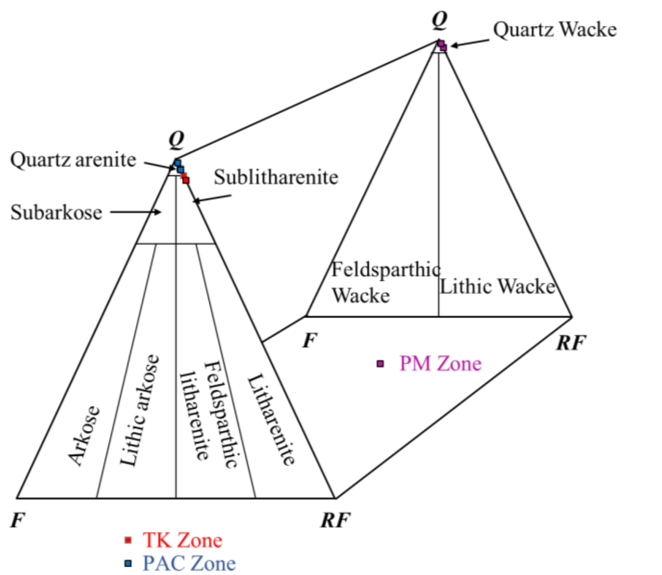

Fig. 5. Sandstone classification of three different zones, TK, PAC, and PM at Kulen formation [5].

Phnom Preah Ang Chub (PAC)

Sandstones of the PAC zone have similar properties to those at the TK zone, which is also classified into Quartz Arenites (Fig. 5). Over 95% of quartz grains are monocrystalline and polycrystalline that vary from medium to coarse-grained, moderately sorted, and high spherical grains.

Most of the monocrystalline quartz grains are clean, which shows undulose extinction and between grains. They are contacted tighter concave-convex, and some muscovite grain also deformed between quartz grains (Mica-flake) due to the pressure dissolution [10] (Figs. 7A and D). Some quartz grains show grain fracturing with a small amount of clay mineral filling that is the evidence of compaction process and consolidation [12]. Polycrystalline quartz grains are more than two sub-crystals. Most sub- crystals vary from medium to coarse-grained (Fig. 7A).

Quartz cement occurred in PAC sandstone that commonly refers to quartz overgrowth. The quartz overgrowth filled in the pore space by growing euhedral crystalline authigenic quartz (Fig. 7C).

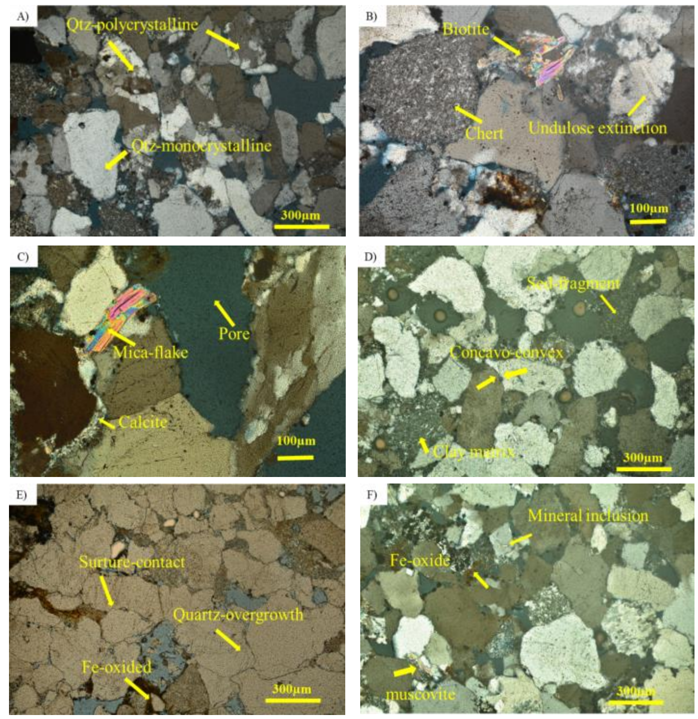

Fig. 6. Photomicroscope images of quartz arenite and sublitharenite of samples TK01P, TK01B, TK02P, TK02B, and TK02T. (A) Quartz mono and polycrystalline. (B) Photomicroscope shows texture of chert fragment, undulus extension, and biotite. (C), (D), and (E) Photomicroscope images display mica-flake, concavo-convex, and suture contact due to mechanical compaction and pressure dissolution. (F) Photomicroscope image indicates clay matrix replace by Fe-oxide.

The detrital feldspar grain is also absent in this zone which may intense to diagenetic alteration and the replacement of secondary cement. A minor amount of muscovite and biotite, sericite are also observed in this thin section samples (Fig. 7D). Photomicroscope also indicated the various types of rock fragments in PAC sandstone. There are sedimentary, chert, and volcanic fragments (Figs. 7B and C).

Phnom Mreach (PM)

Sandstones at the PM zone are different from those at TK and PAC zones. It is classified into quartz wacke (Fig. 5) due to the matrix content >15 % [5]. Moreover, the monocrystalline quartz grains are dominant, with an average of ~ 97.57 % of the total volume of grain framework. Most quartz grains are subangular and subrounded, poorly sorted, and high spherical.

Furthermore, the inter particles pores are dominantly filled by clay minerals, iron oxide, and sericite (Fig. 8A). The rock fragment of this sample is ~ 1.7% to 3.2%, with an average of 2.43% in sedimentary rock fragments. There is no feldspar mineral present in this sample. In such a case, it indicates that it may be eliminated by the dissolution that is replaced by the clay matrix during the diagenesis (Fig. 8B).

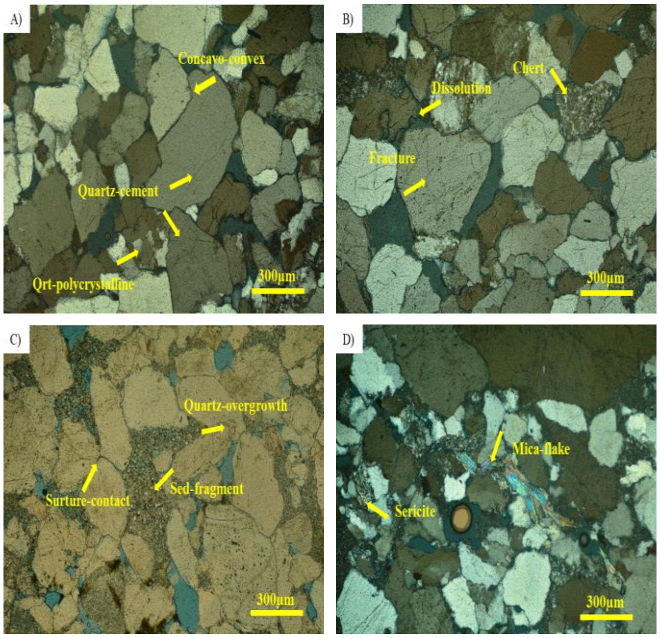

Fig. 7. Microphotograph of quartz arenite of PAC01 and PAC01 (A) and (D) Photomicroscope images display quartz cement overgrowth, mica flake (muscovite), and concavo-convex. (B) and (C) Photomicroscope images show sediment and chert fragment, fracture due to high compaction

Relative Porosity

The relative porosity of nine sandstone rock samples was determined by petrographic analysis for qualitative interpretation of the reservoir rock properties [13, 14] (Fig. 9). TK sandstone samples show high porosity ranging from ~11% - 25%, with an average of ~ 21%. The pores dominantly are primary pores and fewer secondary pores (Figs. 6 and 9), it classified into very good porosity for hydrocarbon reservoirs [13]. The primary porosity is mainly interparticle and well-connected pores (Fig. 6). Furthermore, the second porosity may contribute to this high due to the presence of micro-intercrystalline pores. The dissolution of the K-feldspar mineral may produce these pores. Moreover, the occurrence of quartz overgrowth is influenced by the loss of primary porosity due to the development of new crystalline and widespread close to inter-granular contact [15]. In some cases, quartz overgrowth can retard or prevent porosity loss from mechanical compaction by increasing grain size [16]. Most sandstones at TK and PAC have quartz overgrowth (Figs.7 and 8), which occurred as syntaxial overgrowth by growing to continue from quartz grain, and the result is given quart grain more euhedral crystal face as well as the increase in grain size from medium to coarse grain. Thus, the presence of quartz overgrowth may cause an increase in porosity. Quartz overgrowth is genrally formed in the early diagenesis stage under temperature greater than 100^0C, thus sandstones at TK and PAC zones may be tightly compacted and caused by high temperature of geothermal gradient and high overburden pressure. One sandstone sample (TK01B) has low porosity (Fig. 9), which is similar to those at the PM zone. This may be caused by the high content of clay minerals.

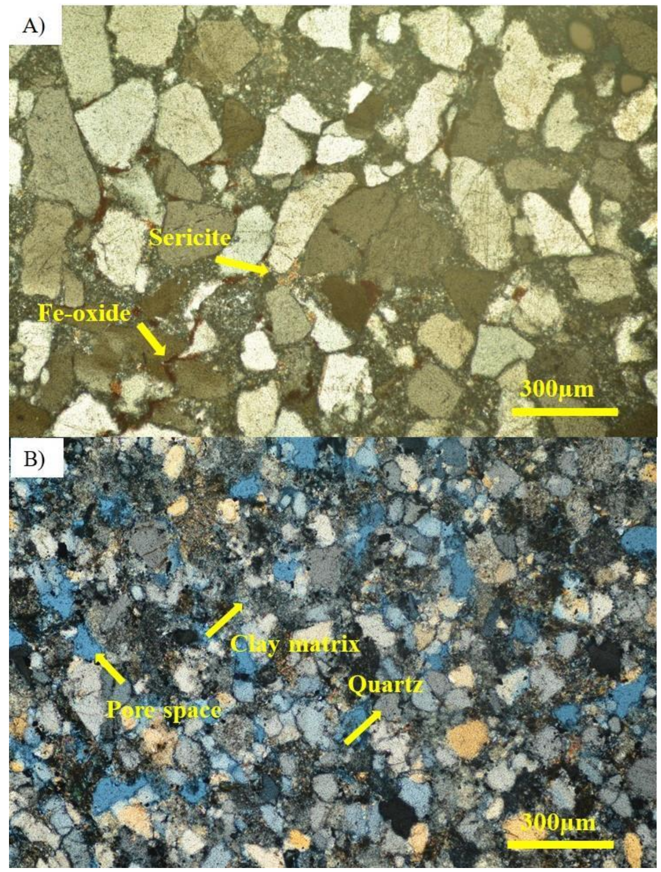

Fig. 8. Microphotograph of Quartz wacke of samples PM01P1 and PM01P2 (A) image shows Fe-oxide and sericite cement surround quartz grain. (B) Photomicroscope image displays dominantly of clay matrix.

Furthermore, the porosity of samples at the PAC zone is also classified into good reservoir rock with porosity ranging from ~9% to 17% and with an average of ~ 13%. On the other hand, sandstones at the PM zone have low and high porosity. Sample (PM02P2) has low porosity ~ 2%, which is indicated as poor reservoir rock (Fig. 9).

3.3. Sedimentary Process and Depositional Environment

The depositional environment of sandstones at Kulen area has been interpreted based on a detail examination of sedimentary structure, texture, lithologies, and facies association. The sandstone lithofacies at TK and PAC consist of sedimentary structures, such as cross-bedding and massive bedded (Figs. 2 and 3), which indicates these lithofacies may be deposited in a shallow marine environment. Moreover, the result of petrography analysis showed TK and PAC sandstones are quartz arenite which is dominant of quartz mono and polycrystalline over 95% (Fig. 5). The high content of this quartz is suggested as shallow marine sandstone. Furthermore, sandstone in both zones contains grain size from medium to coarse-grained, which is caused by high energy and rapid flow condition in a shallow marine environment [17,18]. This environment can produce sedimentary structures, such as cross-bedding, normal and reverse grade bedded, and fining upward that is observed in TK and PAC zones (Figs. 2 and 3). In addition, the characteristic of cross-bedding with normal and reverse graded are related to increasing current and wave velocity that occurred near the surface [18-20]. On the other hand, sandstone facies at PM zone is difficult to define depositional environment due to the unclear sedimentary structure of sandstone facies. In the case of black shale facies at PM zone deposited with thickness less than 10m, this generally refers to lacustrine deposit [21]. Therefore, the sandstone facies in the area is probably have the same depositional environment as black shale since it is fine-grained sandstone.

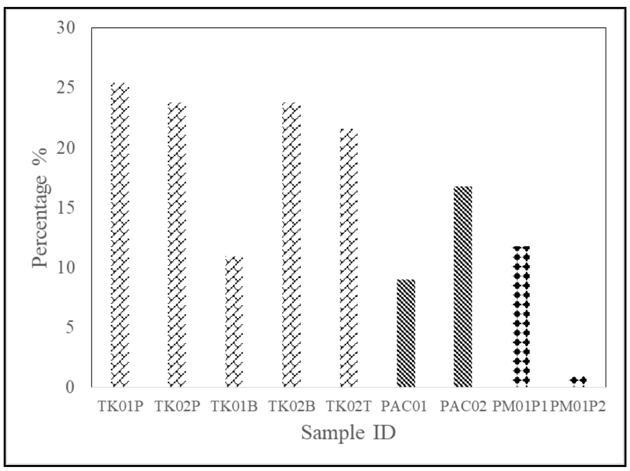

Fig. 9. Relative porosity of TK, PAC, and PM obtained from petrographic analysis

Moreover, the geological setting in Kulen area have occurred of syncline axis between gab of PM zone and TK, PAC zone. This is maybe the evidence showing that there is a subsidence event that occurred between both zones. In addition, at the PM zone, the granite has observed below black shale and the upper part of black shale was eroded finely sandstone. Thus, it is possible that PM zone was uplifted by doom structure of white granite which has higher elevation than PAC and TK zones. After geological time, it may be eroded break down into soil.

4. CONCLUSIONS

The stratigraphic measurement of outcrops and petrographic analysis of sandstones at Kulen area showed the types of lithofacies, sedimentary structures, mineral composition, relative porosity, types of sandstone, diagenetic processes, and depositional environment. The insights derived from this study are of interest to understanding sandstone properties, which is the main parameter for future hydrocarbon reservoir exploration. Our main findings are:

i. The sparial relationship of lithofacies at the three difference zones of Kulean area (PM, TK, and PAC) has beed constructed. There are cross-bedding sandstone facies at the TK zone, massive and cross-bedding sandstone facies at the PAC zone, and three lithofacies at the PM zone, sandstone, black shale, and granite. The Kulen area mainly consisted of planar cross-bedding, cross-bedding, parallel lamination, and normal and reverse graded-bedding sedimentary structures.
ii. Sandstones in Kulen area are mainly composed of mineral quartz with miner feldspar, and rock fragments which can be classified as quartz arenite, sublith arenite, and quartz wack.
iii. Sandstones of Kulen area consist of 17% of average relative porosity, which indicates a good hydrocarbon reservoir.
iv. The diagenetic process includes compaction, cementation, replacement, and quartz overgrowth, which may influence the quality of reservoir sandstones.
v. Sandstones at TK and PAC may be deposited in shallow marine due to the mineral composition (e.g., quartz arenite) and sedimentary structures (e.g., cross-bedding), while sandstone at PM may be deposited in the lacustrine environment according to analogy of shale facies.

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