International Journal of Geosciences, 2023, 14, 792-811
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

# Characterization of Sandstone Reservoir at Bokor Formation, Kampot Province, Kampong Som Basin, Onshore Cambodia

**Vechheka Oeur[1], Chanmoly Or[1*], Chandoeun Eng[2], Sopheap Pech[1,2], Lytheng Thorng[1], Sreymean Sio[1,2], Ratha Heng[1,2]**

[1]Research and Innovation Center, Institute of Technology of Cambodia, Phnom Penh, Cambodia
[2]Faculty of Geo-Resources and Geotechnical Engineering, Institute of Technology of Cambodia, Phnom Penh, Cambodia
Email: *or.moly@itc.edu.kh

**How to cite this paper:** Oeur, V., Or, C., Eng, C., Pech, S., Thorng, L., Sio, S. and Heng, R. (2023) Characterization of Sandstone Reservoir at Bokor Formation, Kampot Province, Kampong Som Basin, Onshore Cambodia. *International Journal of Geosciences*, **14**, 792-811.
https://doi.org/10.4236/ijg.2023.148042

**Received:** July 20, 2023
**Accepted:** August 27, 2023
**Published:** August 30, 2023

Copyright © 2023 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

## Abstract

Kampong Som Basin is a Paleozoic-Mesozoic sedimentary basin located in southern Cambodia. While the sandstone of the Bokor Formation is expected to be the reservoir for hydrocarbon accumulation. Hence, this study aims to define the properties, quality, and factors that control reservoir rock quality. Sandstones of the Bokor Formation are sampled and analyzed using a helium porosimeter, nitrogen permeameter, polarized light microscope, and scanning electron microscope (SEM) to check the porosity, permeability, minerals, pore geometry, and clay minerals that influence the reservoir quality. According to the result of petrography analysis described by thin section, the sandstone samples from Bokor formation are classified as quartz arenite that composes mainly of quartz, rock fragment, mica-flake, and sericite with connected and unconnected pores of 50 μm to 500 μm with interparticle pore type. Sandstones in this formation have porosity values ranging from 6.55% to 13.19%, and permeability values ranging from 10 mD to 60 mD. The statistics of porosity and permeability of sandstone reservoirs indicate low porosity and permeability that are suggested to be fair reservoir rock for hydrocarbon accumulation. SEM results indicate that there are three types of authigenic clay minerals involving such as kaolinite, illite, and chlorite. In addition, the pore geometry, quartz overgrowth, dissolution of quartz and felspar grain filling in pore space, compaction, replacement diagenesis processes, and cementation presence of clay minerals are the main controlling factors of the sandstone reservoir from the Bokor Formation. Furthermore, this area exhibits sedimentary structures such as planar cross-bedding, cross-bedding, parallel lamination, normal grading, massive, wavy, and reverse graded bedding, which indicates these lithofacies may be deposited in shallow marine envi-

ronments.

## Keywords

Sandstone, Reservoir rock, Bokor Formation, Kampong Som Basin, Depositional Environment, Hydrocarbon Reservoir

## 1. Introduction

The sandstone reservoir characteristics and associated controlling factors in non-marine sedimentary environments have long been of great scientific and productive interest. Generally, the sandstone reservoirs mainly result from fluvial-deltaic deposits and developed in response to sediment supply, paleoclimate, lacustrine fluctuations, and tectonic movements [1]. The interaction of the factors influencing sandstone reservoir characteristics and revealing associated controlling factors in different tectonic settings, sedimentary environments, or diagenesis stages will produce different sandstone reservoir characteristics and clarify different controlling factors. Hydrocarbon reservoir characterization is very important to define a reservoir model that incorporates all characteristics of the reservoir such as the quantity of storage and ability to flow hydrocarbon. Porosity and permeability are the main parameters that evaluated the reservoir rock properties including pore space and ability flow [2]. Reservoir quality and heterogeneity are significant factors in affecting the accumulation process of hydrocarbon resources with porosity and permeability being the key parameters to assess reservoir quality. Original reservoir porosity and permeability are primarily controlled by tectonic and depositional evolution history, which determine the mineral composition, grain size, roundness and sorting. Subsequent diagenetic processes occur after burial, which may play opposite roles in changing the porosity and permeability. To be specific, the diagenetic mechanisms controlling the reservoir quality mainly include compaction, cementation, dissolution, and authigenic clay minerals [3]. Thus, an understanding of these parameters or geological terms is very important to characterize hydrocarbon reservoirs.

Sedimentary basins in Cambodia are subdivided into seven basins. In the onshore region, there are Tonle Sap, Kampong Som, Khorat, Preah, Chhung, and Svayrieng basins whereas only the Khmer basin is offshore [4]. This study focuses on the reservoir characteristics, reservoir quality, and the factor that controls the quality of hydrocarbon accumulation in Bokoor Formation where located in the Teuk Chou district, Kampot province, South-western part of the Kampong Saom Basin (**Figure 1**). The Kampong Som basin is considered a foreland basin covering a total area of ~28,000 km$^2$ offshore and ~12,000 km$^2$ onshore [4]. Bokor Mountain (referred to as Phnom Bokor) is considered the youngest sedimentary layer of Bokor formation having good reservoir rock that comes from the deposition of sediment during the Mesozoic. The Masozoic

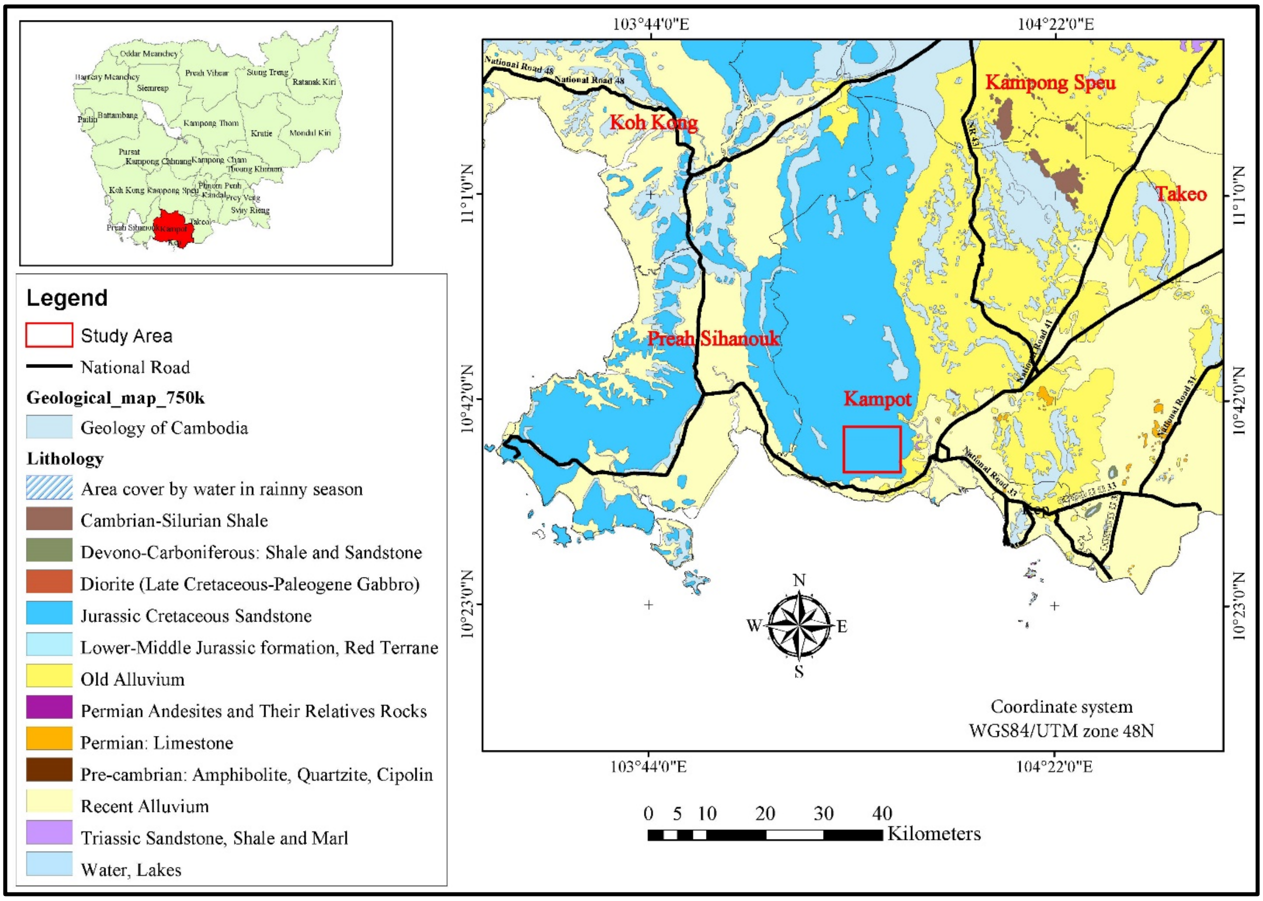


**Figure 1.** Geological map of the study area in Kampot province, Southeast Cambodia. The red rectangle is the area at Bokor Formation.

consists of Upper Jurassic Cretaceous successions for oil generation, also Upper Triassic to Middle Jurassic, and Upper Jurassic to Cretaceous sequences where expected as a reservoir for oil generation and deposit [4]. According to the unpublished locations of Angkor Resources Company in 2019, there are oil and gas seep and multiple oil and gas seeps have been discovered on the subsurfaces of some sedimentary locations at the Bokor Formation and mostly on many positions in Phnom Bokor areas. Those oil and gas seeps also contain the hydrocarbons of thermogenic origin after testing the most interesting location for conducting petroleum exploration [5].

Bokor Mountain is a natural hill location situated in Teuk Chhou District, Kampot province, southeast of Cambodia with 1075 m high above sea level. The locations have many sedimentary outcrops dominantly by sandstone facies, one of the siliciclastic sedimentary rocks with good hydrocarbon accumulation for the potential of petroleum exploration [6]. From previous research on the Kampong Som onshore basin, there is no more discovery on sandstone characterizations, especially on the sedimentary outcrops of Phnom Bokor where dominated by sandstone and clay sediment lithofacies. However, details characterization of sandstone reservoir as well as depositional environment have yet been documented. Furthermore, during oil and gas exploration, the characterization of sandstone reservoir and depositional environment are the crucial factor that controlled on reservoir quality and reservoir heterogeneity. Therefore, it is critical for this study to improve understanding of characterization of sandstone reservoir and depositional environment of sandstones in the Kampong Som basin.

## 2. Methodology and Materials

Nine samples were collected from Bokor Formation after observation of the stratigraphic column obtained during geological fieldwork. The specimen samples were collected by hammer, mobile rotary drilling, and chisel. Sandstone samples including labeled BKSS03, BKSS06, BKSS07, BKSS09, BKSS10, BKSS15, BKSS18, BKSS19, and BKSS21, were collected during the construction stratigraphy column. The sandstone samples are analyzed through physical properties, petrography, petrophysics, and scanning electron microscope (SEM-EDS) analysis in order to obtain both qualitative and quantitative results.

### 2.1. Lithofacies and Stratigraphy Measurement

The stratigraphic column must be included information, such as rock units, the thickness of lithology, sedimentary structure, grain size, sorting, geological structure, dip and strike, coordinate, composition, photo of the outcrop, and sample number. Importantly, it is required to note the date, place, and specialty of formation to easily recognize the recorded information after finishing geological fieldwork. In this study, stratigraphy measurement was carried during geological field investigation in Bokor Formation by observing the outcrop of the sedimentary rock. The data collection will be summarized in sedimentary template by using Corel drawing program. The equipment that was used in this field including: Notebook or sedimentary template, GPS, Compass, Jacob staff, Hand lens and geological hammer. Stratigraphy measurement revealed the different types of sedimentary structures at Bokor formation are recognized as planar cross-bedding, cross-bedding, parallel lamination, normal grading, massive, wavy and reverse graded-bedding. Lithological characteristics of each rock unit and associated sedimentary structure (**Figure 2**).

According to stratigraphy measurement, there are two lithofacies, sandstone and claystone at Bokor formation. Phnom Bokor is one part of Kampong Som basin deposited by post-rift Jurassic to Cretaceous sediments mainly sandstones and clay sediment formation [4] [7]. Such interesting locations for hydrocarbon exploration, a geological fieldwork also conducted to Phnom Bokor location to clearify more evident to such as lithofacies, sedimentological structure and stratigraphy of sedimentary rock at there. As conduction geological fieldwork, sedimentary facies, structure and stratigraphy have been recorded as shown in (**Figure 2**). The sedimentary outcrops at Phnom Bokor having depth extension around 140 meters starting from location's coordinate 401207; 1174169 with planar strike N2010 and dip 330. Lithology at their composed mainly sandstone

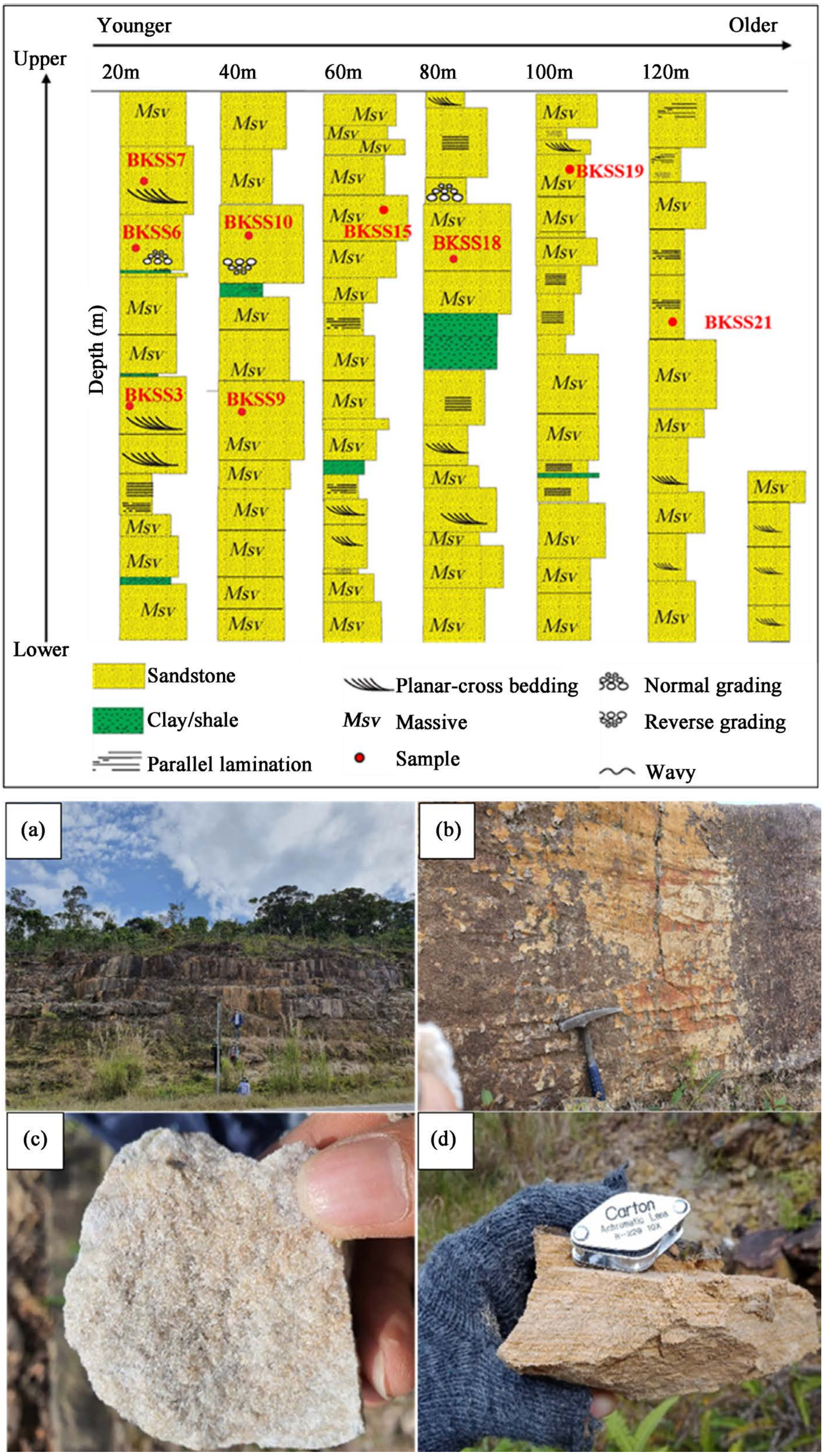


Figure 2. Stratigraphy column of Bokor formation describes the sedimentary texture, sedimentary structure and two lithofacies type of sandstone and claystone. (a) is the outcrop photos of the Bokor Formation. (b) is the sedimentary structure of planar cross bedding. (c) and (d) show the sandstone and claystone samples that collected from outcrop.

inter bedded with some strongly weathered sandy clays and clay sediments (**Figure 2**). Most sandy clay to clay sediments have total depth less than 10 meters. Some of clay sediments having gray color with wavy sedimentary structure (depth 2.0 m to 2.3 m) while other clay sediments have white to gray color that mostly massive structures and some are parallel lamination structures. There has no any geological structure was found on the sedimentary outcrop. Sandstone is the most abundant rock sediment of the study location. Finely to coarse grain and some highly matrix, that some having white, milky, gray and pink colors, sandstones under weekly to strong weathering condition. Most sandstone are occurred as massive, parallel lamination, planar cross-bedding, normal grading and some are reverse grading as primary sedimentary structures during deposit. Each sample having noticed clearly on out-crop locations.

For BKSS03, 18˚ planar cross-bedded structure, medium grain sandstone with light pink color containing clay lens along with 1 - 1.5 cm width. BKSS06 is fining grain upward as normal shorting, about 1 cm quartz grain, fine to medium grain size having white color sandstone. BKSS07 founded as fine grain mixed with less than 1 cm of subrounded, fined grain, well sorted, white-light pink, 2 m bed-set cross-planar bedding sandstone. BKSS09 is white pink medium grain size, massive structure with 0.4 to 0.7 m bed set, containing 0.1 to 1 cm grain size. BKSS10 is coarsening upward grading structure as coarse sand, grey white, thin layer mixed with fine sand. BKSS15 is fine-medium, moderate matrix, weathering color, light brown, laminated (287˚/15) while BKSS18 is fine grained sandstone, highly weathering, pink color, highly matrix with massive structure. BKSS19 indicated medium-coarse grain, white sandstone, moderated shorting, and subangular to subrounded. BKSS21 are mainly composed of white color, medium to coarse grain, subangular, poorly sorted, and mass structure.

### 2.2. Petrography Analysis

Petrography is a method to analyze samples based on the color observation of minerals under the Optical Microscope. This method provides qualitative information about mineral composition, texture, relative porosity, and the diagenetic process. There are nine sandstone samples (BKSS03, BKSS06, BKSS07, BKSS09, BKSS10, BKSS15, BKSS18, BKSS19, and BKSS21) were cut into the standard petrographic sample are prepared for petrography analysis. They were glued with a glass slide thin section using struts specifics resin, and blue-dyed powder mixed with a curing agent in a ratio of 10:1. Thin section samples were analyzed with a transmitted light microscope using Cross Polarized Light (XPL) and Plane Polarized Light (PPL) under Optical Microscope (Model: ECLIPSE CI-POL.B) and determine mineral percentage base on comparison chart estimation.

### 2.3. Petrophysics Analysis

Petrophysics is carried out to determine the rock's ability to store the fluid and allow for their movement within the reservoir, which were presented as porosity and permeability, respectively. Seven core sandstone samples (BKSS03, BKSS06, BKSS07, BKSS09, BKSS10, BKSS15, and BKSS18) were prepared to test both porosity and permeability for the measurement under the TPI-219 helium porosimeter and TKA-209 nitrogen permeameter that represents the reservoir quality at Bokor formation.

### 2.4. Scanning Electron Microscope Analysis (SEM-EDS)

There are three sandstone samples are prepared for scanning electron microscope analysis. Scanning electron microscope (SEM-EDS) is a method that provides qualitative information about pore geometry, locating and identified mineral, particularly clay mineral that use to determine based on their microstructure properties. SEM-EDS works by using high energy focus on beam electron. When beam electron hits the sample, it causes secondary electrons to be released from sample which are detected to provide an image based on the topography of the surface. In addition, EDS is also evaluated with SEM which is called SEM-EDS (JMS IT 500) analysis. In this study, thin section of sandstone samples was prepared and coated with platinum to determine type of clay mineral and also define pore size, pore type and pore connected in bulk sample. In addition, SEM-EDS analysis has been conducted at the Nanostructure and Chemical Analysis laboratory, Institute of Technology of Cambodia (ITC), Cambodia.

## 3. Results and Discussions

### 3.1. Petrography Analysis

Based on the result of petrography analysis, sandstones from the Bokor Formation are classified into Quartz Arenite (**Figure 3**), Pettijohn *et al*'s classification

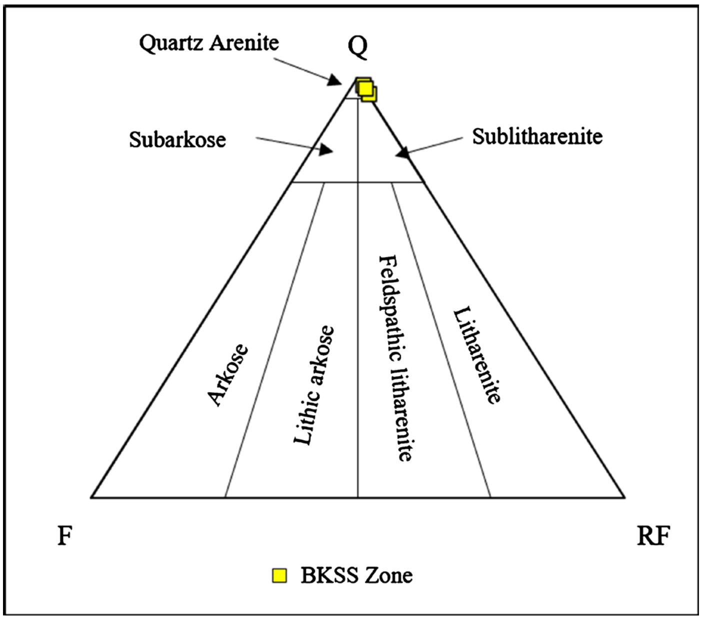


**Figure 3.** Sandstone classification at Phnom Bokor location following the Pettijohn *et al.*, 1973 [8].

[8]. The sandstones are mainly composed of different minerals such as quartz and rock fragment. The abundant of clastic grain is quartz which is composed of both monocrystalline and polycrystalline that components ranging from 95% to 97% with an average composition of about 96%. The monocrystalline quartz is dominated in the sandstone samples rather than polycrystalline quartz which is almost 95% of monocrystalline quartz grain. The monocrystalline of quartz grains varies from sub-angular to sub-rounded grain shape (**Figure 4(c)** and **Figure 4(d)**) and (**Figure 4(e)** and **Figure 4(f)**), partially low to high spherical, and poorly to well sorted, which have a grain size ranging from 100 μm to 300 μm. Polycrystalline quartz grains are composed of two or more crystals (**Figure 4(g)** and **Figure 4(h)**). The crystal boundary of polycrystalline quartz often be obscured due to recrystallization, but extinction characteristics generally indicate the polycrystalline nature. The boundary between the crystals of polycrystalline quartz may be straight or sutured [1] (**Figure 4**). A few quartz grains have numerous vacuoles as indicated by their cloudy appearance. Photomicroscope also indicates that the amount of quartz grains slides past each other and packed tighter or penetrated one another causing concavo-convex grain contact and sutured contact (**Figure 4**). Furthermore, some quartz grain shows grain fracturing with a small amount of clay filling.

Lithic grains (rock fragments) are found to be the most abundant to feldspar among the detrital components. The range of total lithic grains is 2% to 4% with an average of 3% which are presented as fine-grained material with grey to white color in XPL and light brown color in PPL (**Figure 4**). Lithic sedimentary grains are found to be more abundant than lithic metamorphic grains (**Figure 4**). Very few traces of lithic volcanic grains are found. The lithic sedimentary grains consist of mainly sand/siltstone fragments with little chert and argillite shale (**Figure 4**). Among the lithic metamorphic grains, schist mica-schist and graphite-mica-schist are common. In this case, it indicates that it may be eliminated by the dissolution that is replaced by the clay matrix during the diagenesis [1] [9].

Clay matrix is recognized based on the fine-grained material deposited between larger particles, such as quartz, feldspar, and rock fragment. Under the microscope, the matrix commonly has dark grey color in XPL and dark brown in PPL (**Figure 4**). Clay matrix is also seen to be present in Bokor sandstone which is identified by its fine-grained material and bright color in XPL. There was less amount of matrix contained in the sandstones which could be considered as clean sandstone with less than 15% of the matrix [8]. This less amount of matrix is indicated that the pore throats are less resulting in the loss of interparticle pores influenced by matrix [10]. Matrix is the second dominant component in the sandstone samples in composition.

However, it also presents deformed mica-flake as bending between quartz grain contacts (**Figure 4(a)** and **Figure 4(b)**). The quartz grains and mica flake in the center of the view are surrounded by numerous small crystals with low relief and show first order grey interference colors. Thus, this is evidence of mechanics

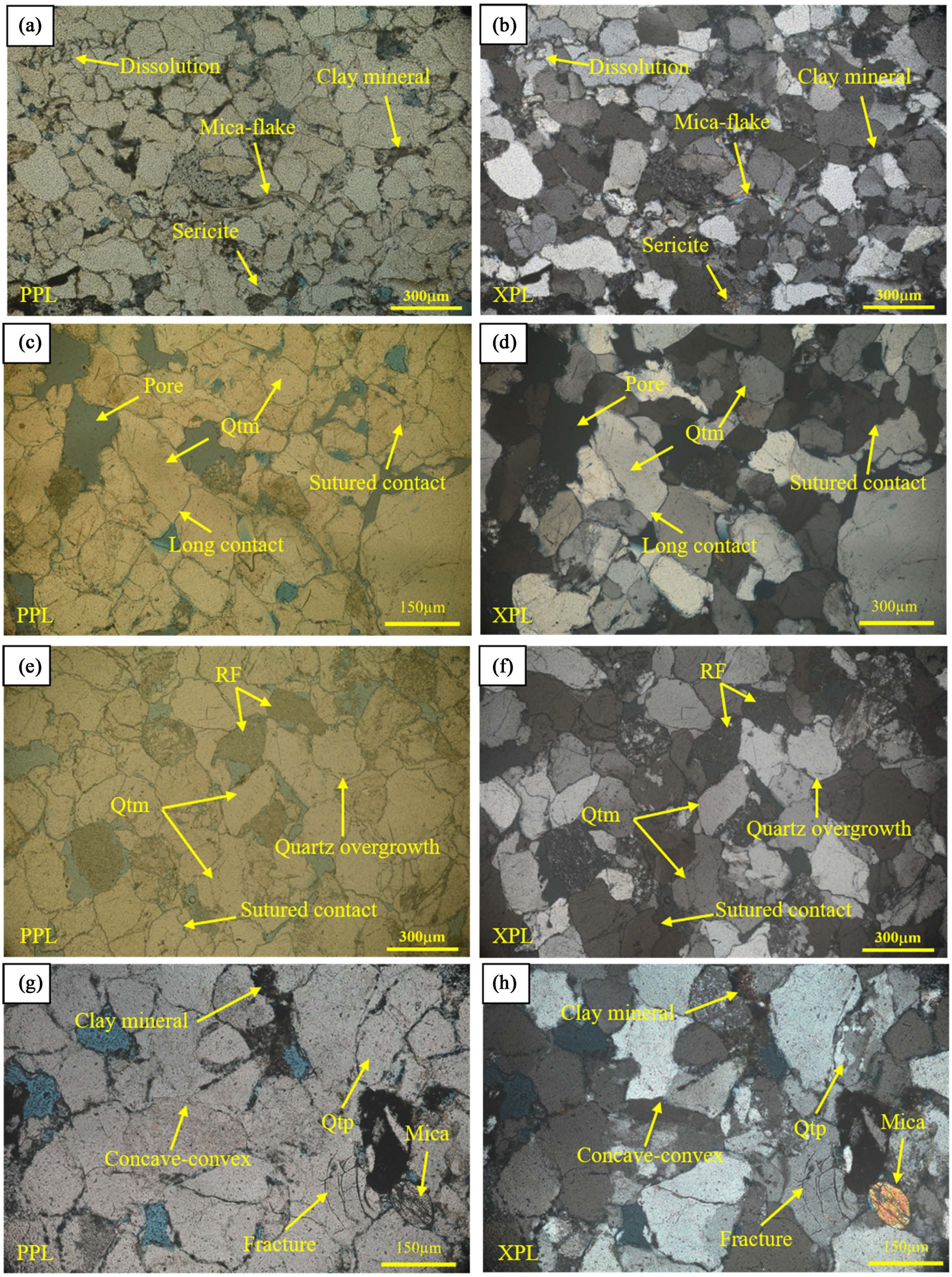


**Figure 4.** Photomicrographs of sandstones from Bokor formation. The left and right sides are images observed in PPL and XPL, respectively. (a) and (b) indicated dissolution of quartz grain, clay mineral, mica-flake, and sericite cement. (c) and (d) showed interparticle pores, monocrystalline quartz, sutured contact, and long contact. (e) and (f) displayed rock fragments, monocrystalline quartz, sutured contact, and quartz overgrowth. (g) and (h) indicated clay mineral, concave-convex, polycrystalline quartz, mica, and fracture. RF: Rock fragment, Qtm: Monocrystalline quartz, Qtp: Polycrystalline quartz.

and pressure dissolution that occurred during the diagenesis phase caused by a loss in the primary porosity of sandstone [11]. Silica dissolved during the process may be precipitated as cement away from grain contacts, leading to the destruction or occlusion of porosity (**Figure 4**) [1]. Mica generally occurs along partings, laminae, or bedding planes and frequently shows bending due to compaction (**Figure 4(g)** and **Figure 4(h)**).

Pore relative porosity in sandstones could be analyzed under petrography analysis using photomicrograph in plane-polarized light (PPL) and cross-polarized light (XPL) views (**Figure 4**), for qualitative interpretation of the reservoir rock properties. The observation under the thin section microscope is essential for the identification of pore type, pore connectivity, and pore size which could be used to identify the factor controlling reservoir quality. Based on the results of the sandstone reservoir from the Bokor Formation indicated the pore size ranges from 50 μm to 500 μm with interparticle pore type (**Table 1**). The pore spaces are primary pores that contribute to the increased porosity and their pore throats are well connected between one pore to another pore, thus the texture is tended to produce high permeability for hydrocarbon reservoirs. In addition, the pores are also unconnected with each other that is corresponding to authigenic clay precipitated by filling in the pore, which leads to reduce the permeability of the fluid to flow and porosity for the hydrocarbon reservoir.

## 3.2. Petrophysics Analysis

The results of porosity obtained from the helium porosimeter shows the seven sandstones from Bokor Formation contain a porosity value between 6.55% to 13.19% with an average of 9.80%, which there are four sandstones indicated that poor reservoir rock, and three sandstones showed fair reservoir rock (**Figure 5**). Based on these data and the classification of North, 1985, it is classified into fair porosity [12]. On the other hand, the absolute permeability measuring from the

**Table 1.** The characteristic of pore type, pore size, and pore connected of sandstone samples at bokor formation.

| Location | Sample ID | Pore type | Pore connectivity | Pore size |
|---|---|---|---|---|
| | BKSS03 | Interparticle | Unconnected | 100 - 200 |
| | BKSS06 | Interparticle | Connected | 80 - 320 |
| | BKSS07 | Interparticle | Unconnected | 50 - 150 |
| | BKSS09 | Interparticle | Connected | 100 - 400 |
| **Phnom Bokor** | BKSS10 | Interparticle | Unconnected | 50 - 150 |
| | BKSS15 | Interparticle | Connected | 100 - 500 |
| | BKSS18 | Interparticle | Unconnected | 100 - 200 |
| | BKSS19 | Interparticle | Unconnected | 50 - 130 |
| | BSKK21 | Interparticle | Connected | 100 - 540 |

core samples are range from 10 - 60 mD with an average of 36 mD. Based on these data and the classification of Koesoemadinata, 1980, the permeability is classified as fair to good reservoir quality for fluid flow [13] (**Figure 6**). The differences of permeability values of Bokor formation may be influenced by grain packing, grain sorted, and clay mineral content which occurred during diagenetic stage.

### 3.3. Scanning Electron Microscope Analysis (SEM-EDS)

The observation three samples such as BKSS03, BKSS06, and BKSS09 under SEM analysis is important for the identification of pore type, pore connectivity, and pore size which influences the reservoir quality and heterogeneity. Moreover, SEM analysis can also identify the structure of clay minerals that mostly fill

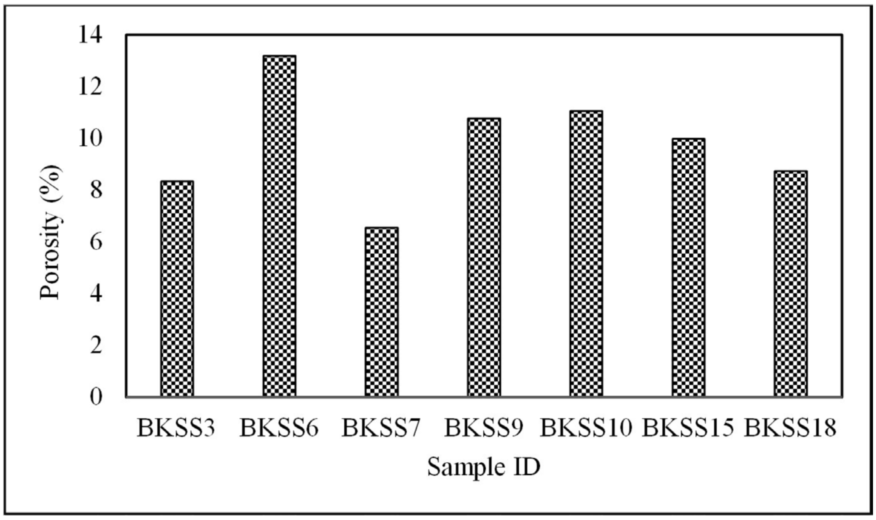


**Figure 5.** Summary result of porosity obtained from helium gas injection of sandstones at bokor formation.

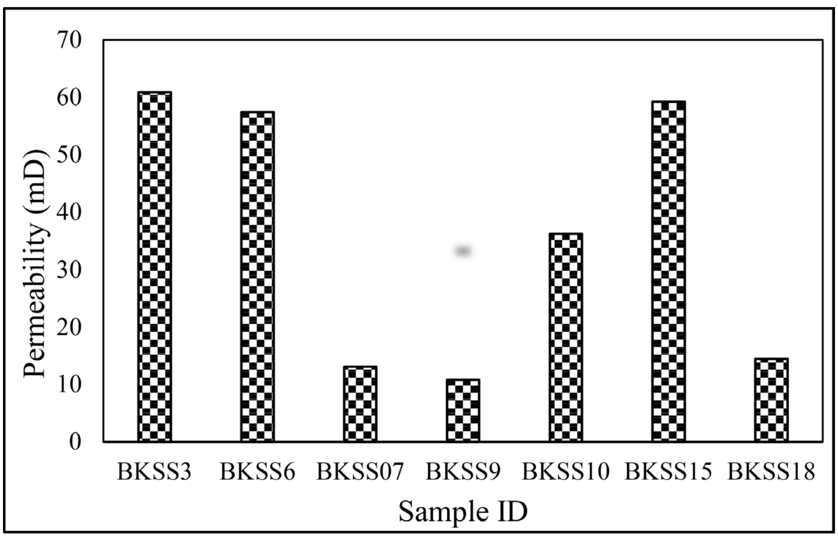


**Figure 6.** Summary result of permeability after Klinkenberg correction for sandstones at bokor formation.

into inter-particle pore or coating on detrital grain mineral. Based on the results, most of pore type are inter-particle pore that are mostly connected and unconnected (**Table 1**). Moreover, there are three types of clay mineral, such as kaolinite, chlorite, and illite (**Figure 8**), which partly formed in pores and coated on quartz grain (**Figure 7**).

#### 3.3.1. Pore Type

Based on the scanning electron microscope analysis (SEM), pore type, pore connected and pore size of three sandstone samples such as BKSS03, BKSS06, and BKSS09, the pore size of Bokor formation sandstones is varied from ~1 - 200 μm. This is because most of pores are inter-particle pore (**Figure 7**) and the pore network is also poorly connected that is corresponding to authigenic clay precipitated by filling in the pore throat leading to decrease porosity and permeability (**Figure 7**).

#### 3.3.2. Clay Mineral Structure and Composition

Clay mineral is the most common cement in sandstones. It occurred in sandstone by pore filling and coating on detrital grain mineral. Most of clay minerals are the result of the alteration of quartz and lithic fragments. The dissolution of quartz grain and feldspar grain produces secondary porosity and authigenic clay mineral formed as cement between the grains. Kaolinite, illite, and chlorite are the major clay minerals that act as cementation in sandstone in this study area [14].

According to SEM analysis, kaolinite is the most common clay mineral presented almost all sandstone samples at Bokor formation. (**Figure 8(a)**) show that the pore is filled by kaolinite and coating with quartz grain. It is identified by vermicular booklets crystals that are filled in both primary and secondary pore, high inter-crystalline microporosity. On the other hand, kaolinite also observed by coating of detrital quartz grain due to SEM-EDS analysis showed chemical composition Al, Si, and O (**Figure 8(a)**. In addition, Illite is the second most abundant clay mineral in all sandstone. It occurred as pore filling especially in pore throat between grains (**Figure 8(b)**). Under SEM images, illite formed as vermicular stacked similar to kaolinite because it occurred by transformation from kaolinite and smectite through to illitezation process. The characteristic of smectite can transform to illite through the process illitezation. It contains magnesium (Mg) and iron (Fe) by the process of illitezation; and it releases this chemical composition depending on initial chemical composition of rock, which is indicated in SEM-EDS of chemical composition as O, Al, Si and K (**Figure 8(b)**). Moreover, the chlorite clay exists in the succession as pore-filling cement and as grain-coatings on authigenic minerals (**Figure 7(c)**). It occurs as scattered crystals, as rims on quartz overgrowths and is intergrown with authigenic kaolinite (**Figure 7(f)**) and (**Figure 8(c)**). In some samples, chlorite is also present as grain-coatings on kaolinite. The chlorite clay is the one of the common authigenic minerals present in the samples. SEM image shows that the

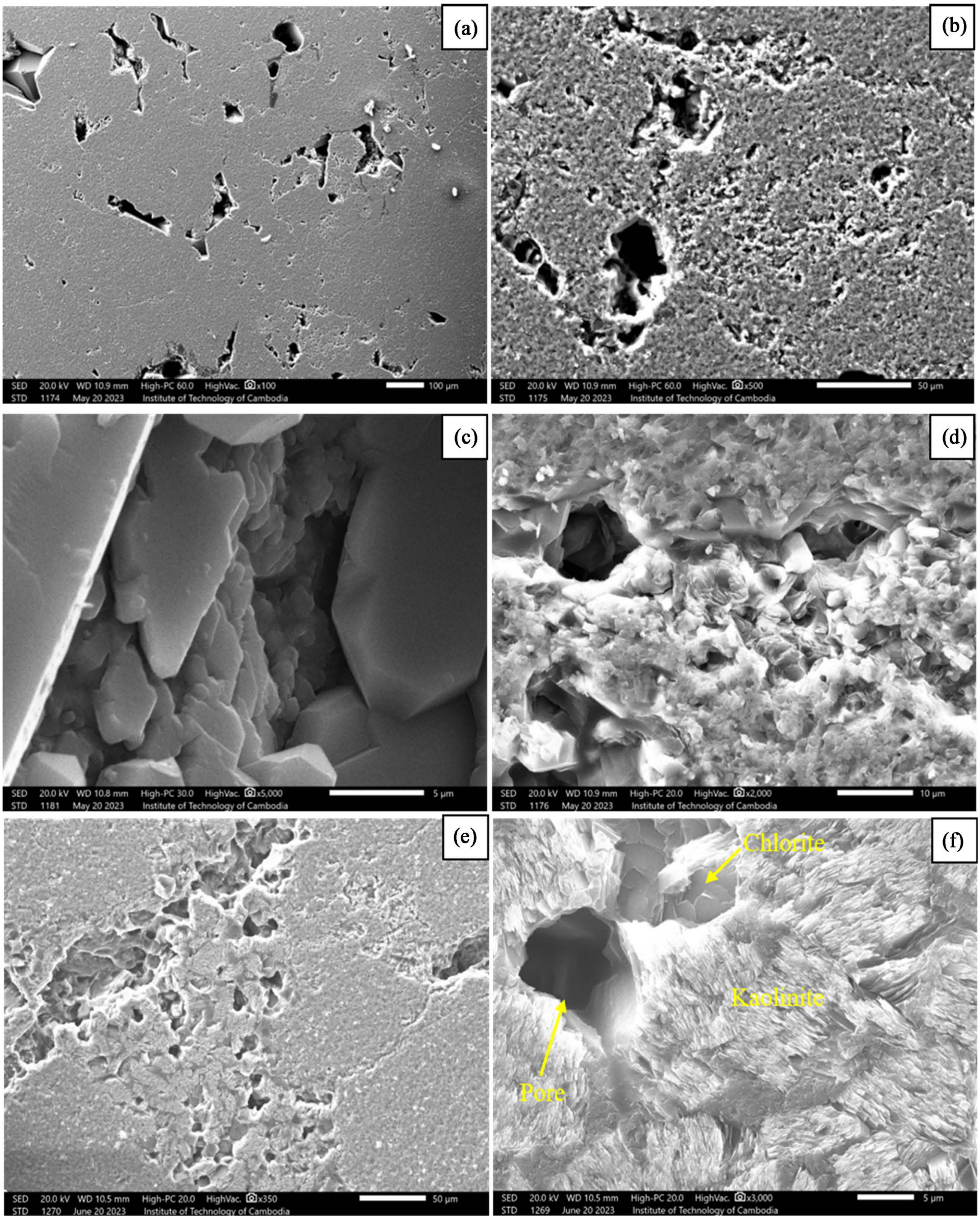


**Figure 7.** SEM image display pore of sandstone in Bokor Formation. (a) and (b) showed about primary pore and secondary pore coating and filling of clay mineral, quartz cement, and quartz crystalline in pore space. (c) indicated quartz grain and quartz crystalline filling in pore space. (d) Clay mineral filled in interparticle pore. (e) showed about the interparticle pore replacement by authigenic clay. (f) indicated of kaolinite grain coating and filling in pore, and chlorite filling in pore space.

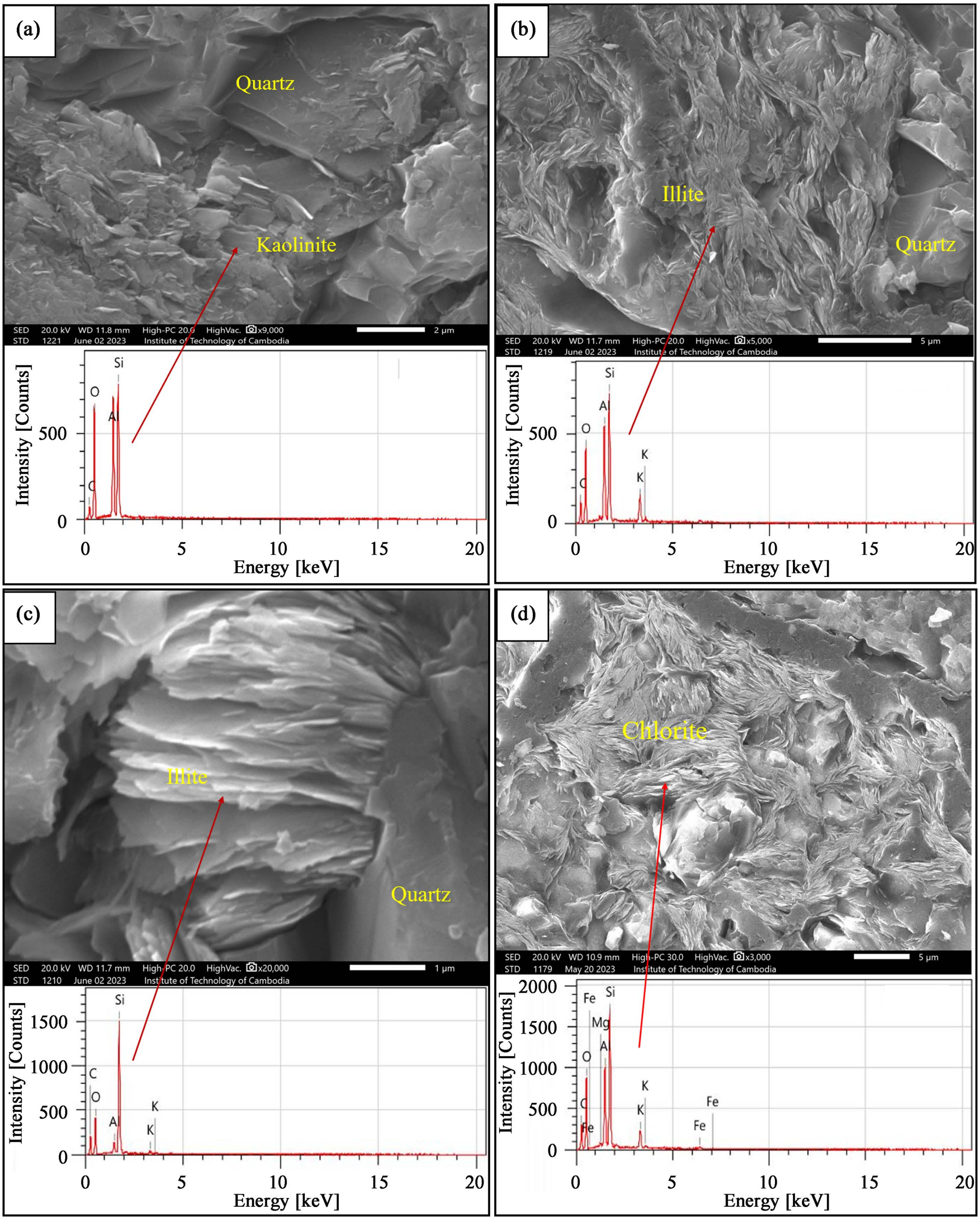


Figure 8. SEM images showing clay mineral at Bokor Formation. (a) Kaolinite coat on detrital grain with quartz and filled in pore with showing vermicular booklet structure. (b) and (c) Illite growth in pore throat and formed as vermicular stacked similar to kaolinite. (d) Chlorite coat on detrital grain. SEM-EDS is below of image showed about the chemical composition of clay, kaolinite, illite, and chlorite of sandstone.

chlorite crystals have euhedral and sub-euhedral shapes and are arranged in rosette pattern (**Figure 7(f)**) and (**Figure 8(c)**). The crystals are arranged perpendicular to the detrital grains thus they tend to face the pore spaces. It is possible that the chlorites were formed in the late stage of the diagenetic process under intense temperature and pressure. The SEM-EDS analysis showed chemical composition Mg, Fe, Al, Si, K, and O (**Figure 8(c)**). Elements such as silicon, aluminum and potassium were released from dissolved detrital grains to form some potassium and aluminum salts. Some of the magnesium could have been supplied from the breakdown of ferromagnesian minerals into pore waters. Chlorite is a common cement in channel sandstones and the Fe released as can be observed from SEM-EDS analysis (**Figure 8(c)**) resulted in the formation of iron-chlorite in reducing environments.

## 4. Discussions

Through the data analysis from stratigraphy, petrography, petrophysics and scanning electron microscope (SEM) analysis, the reservoir properties and depositional environment of sandstones at the Bokor formation of the south-east Kampong Sam sedimentary basin can be characterized. Moreover, this data provided the information to reveal the factors that control on reservoir rock.

### 4.1. Reservoir Quality

Based on the result of petrophysics analysis, the relation between porosity and permeability is made in the context of various aspects to find a reliable relation between porosity and permeability. (**Figure 9**) shows the porosity and permeability relation of sandstones at Bokor formation. Regard to this plot, it shows a low correlation for all sandstones at Bokor formation which is interpreted as poor to fair porosity for reservoir rock and fair to good permeability for fluid

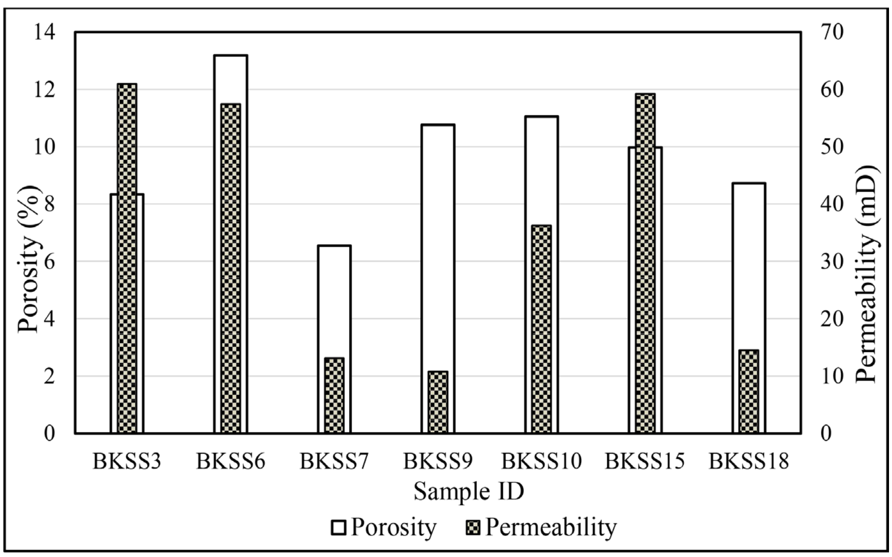


**Figure 9.** The relationship between helium porosity and nitrogen permeability of all sandstone in bokor formation.

flow [12] [13]. This is because these sandstones have different properties such as pore size, pore connectivity. According to the result of porosity and permeability, the reservoir properties of the Bokor formation have low porosity and permeability, averaging 9.80% and 36 mD, respectively (**Figure 9**). Therefore, the particle size and properties of clay minerals impact the relationship between porosity and permeability. In addition, the porosity and permeability values are suggested to be a fair reservoir quality. This is because most of the pores are mostly contributed from the isolated pores which their pore throats are interparticle pore and unconnected to well connected with pore size between 50 μm to 500 μm (**Figure 4** and **Table 1**).

## 4.2. Reservoir Heterogeneity (Factor Control Reservoir)

Based on petrography analysis, most of the sandstones at Bokor formation are identified by interparticle pores that have a pore size range of ~50 μm to 500 μm, and pore throat between grains are poorly connected to well-connected pores (**Figure 4**). This is because grain sizes are medium to coarse grain, well-sorted with sub-angular to sub-rounded. During the diagenetic stage, the grain packing is well arranged and produced more interparticle pore in bulk samples. Therefore, the porosity and permeability values in Bokor sandstones are increased when grain packing is well arranged by producing more interparticle pores [15]. The effects of diagenetic processes on the sandstone of the Kampot formation include the reduction of porosity by compaction and cementation as well as, the enhancement of porosity by dissolution [16]. The best quality rocks are characterized by medium to coarse grain size, good sorting with high percentages of detrital quartz, and low percentages of matrix and cement (quartz and calcite). Most quartz in sandstones occurs as subangular to subrounded monocrystalline fragments. Grain contact changes from dominantly floating to the point, long contact, and concavo-convex shapes due to the progressive burial and compaction effect. The detrital quartz grain contacts are transformed from point to long and concavo-convex contacts due to severe mechanical compaction, which reduces permeability [17]. In addition, the large amount of authigenic clay mineral, kalinite, illite, and chlorite in isolated pore, pore lining and pore throat also reduced porosity and permeability (**Figure 7** and **Figure 8**), However, there are some cases which large amount of clay in pore-throat has reduced permeability. Clay minerals in sandstone commonly altered from quartz grains, feldspar grains dissolution and rock fragments. Clay minerals are usually considered detrimental to the quality of sandstone reservoirs, as they can clog pores and some clay minerals advocate chemical compaction [18]. Most clay minerals formed where rocks are in contact with water, air, or steam in many conditions such as weathering, erosion and also diagenesis [19]. Hence, the properties of pore size, pore type, and pore network and clay mineral are influenced on both porosity and permeability. Monocrystalline quartz under the influence of increasing pressure and temperature, uncorrelated single-crystal quartz gradually transforms into corrugated quartz, polygonal quartz (quartz exhibiting well-defined extinction bands with sharp boundaries), and finally changes to polycrystalline quartz [20]. Presence of secondary quartz overgrowths around primary quartz grains will make reduction in pore space due to pressure solution [21]. Grain contact types also reveal some diagenesis mechanism reflecting influence of pressure solution suggested the key evidence of compaction and consolidation on the sandstone [14]. Long grain contact, concave-convex and sutured contacts are identified on the thin section's photos (**Figure 4**). Long grain contact and concave-convex grain contact indicate the sandstones have undergone substantial compaction indicate intermediate depths whereas Sutured contacts indicate diagenesis and deep burial [14]. The concave-convex and sutured contacts are mostly representative of intense compaction and pressure dissolution process during deep burial diagenesis [14]. The effect of detrital grain size and grain sorting on permeability and helium are indistinct comparing to other data point [22]. clay minerals in these samples may trapped in the small necks of pores provide increased fluid pressure to maintain flow, reducing the overall permeability of porous systems. The occurrence of quartz overgrowth is influenced on the lost of primary porosity due to the development of new crystalline and widespread close to inter-granular contact [2]. In some cases, quartz overgrowth can retard or prevent porosity lose from mechanical compaction by increasing grain size [23]. In the Bokor formation, there are more positive correlation between quartz overgrowth and primary porosity. Most of sandstones at Bokor formation have quartz overgrowth which grain size are medium to coarse grain (**Figure 4(e)** and **Figure 4(f)**) and have been tightly compacted (**Figure 4**). In this case, Bokor formation sandstones may be affected by high temperature of geothermal gradient and high pressure from overburden pressure. Thus, the positive correlation of quartz overgrowth and primary porosity reveal that porosity can be increased with increasing of quartz overgrowth. The compaction is prevented by quartz overgrowth; that causes primary porosity to be stable. Deposition of quartz overgrowths is recognized in many studies as a mechanism for porosity loss in sandstones.

### 4.3. Depositional Environment

The depositional environment of the sandstone samples in Bokor formation have been interpreted based on the detail study of the stratigraphic log, and petrography analysis. The sandstone lithofacies at Bokor formation consist of sedimentary structures, such as planar cross-bedding, cross-bedding, parallel lamination, normal grading, massive, wavy and reverse graded-bedding, which indicates these lithofacies may be deposited in shallow marine environment [24] [25]. Moreover, the result of petrography analysis showed sandstones are quartz arenite which are dominant of quartz mono and polycrystalline over 95%. The highly content of this quartz is suggested as shallow marine sandstone. Furthermore, sandstone in Bokor formation contain grain size from medium to coarse-grained, which is caused by high energy and rapid flow condition in shallow marine environment [25] [26] [27]. In addition, the characteristic of cross-bedding with normal and revers graded are related with increasing current and wave velocity that occurred near the surface [24] [26] [28]. On the hand, quartz overgrowth of sandstone facie at Bokor formation usually formed in shallow marine diagenetic environment and in the early diagenetic stage under temperature greater than 100˚C [20], it occurred as syntaxial overgrowth by growing continue from quartz grain, and the result is given quart grain more euhedral crystal face as well as the increase in grain size [16]. Clay minerals in sandstone commonly altered from feldspar grains dissolution, quartz grains and rock fragments. The dissolution occasionally occurred at shallow depth by meteoric water [24].

## 5. Conclusions

The study on the characterization of sandstone reservoir in the Bokor formation of the Kampong Som basin was successfully completed. The insight results of petrography, petrophysics, and SEM-EDS derived from this study are interesting to understand reservoir properties and controlling factors on reservoir rock (heterogeneity). The main findings of this study can be concluded as follow:

- The sandstones in Bokor formation mainly consist of quartz (95.19% to 97.83%), and rock fragment (2.17% to 4.81%), which is classified into Quartz Arenite.
- The sandstone in this study area is relatively low porosity and permeability, 9.80% and 36 mD in average, respectively. It is potentially fair reservoir quality for hydrocarbon accumulation.
- Three types of clay minerals are identified in sandstone in the Bokor formation such as kaolinite, illite, and chlorite.
- Pore geometry, clay mineral, quartz overgrowth, and diagenesis processes are the controlling factors on sandstones reservoir quality in the Bokor formation.
- As a result of the mineral composition and sedimentary structures, the sandstone samples from the Bokor formation could have been deposited in a shallow marine environment.

## Acknowledgements

The work was funded by Cambodia Higher Education Improvement Project (Credit No. 6221-KH). The authors would like to thank Dr. Yos Phanny and Ms. Chea Monyneath for advice and support of SEM analysis in Nanostructure and Chemical Analysis Laboratory, Institute of Technology of Cambodia, and government officers of General Department of Petroleum, Ministry of Mine and Energy for fieldwork supports.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References


[1] Xu, W., Deng, H. and Wang, Y. (2021) The Sandstone Reservoir Characteristics and Controlling Factors of Shanxi Formation and Lower Shihezi Formation in Southeastern Ordos Basin. *Geological Journal*, **56**, 1673-1698. https://doi.org/10.1002/gj.4019

[2] Bukar, M., Worden, R.H., Bukar, S. and Shell, P. (2021) Diagenesis and Its Controls on Reservoir Quality of the Tambar Oil Field, Norwegian North Sea. *Energy Geoscience*, **2**, 10-31. https://doi.org/10.1016/j.engeos.2020.07.002

[3] Yang, J., Qi, N., Lu, S., Wang, M., Lu, M. and Xia, Y. (2021) Reservoir Characterization and Geological Controls of the Lower Cretaceous Sandstones in the Northern Wuerxun Sag, Hailar Basin, China. *Journal of Petroleum Science and Engineering*, **205**, Article ID: 108771. https://doi.org/10.1016/j.petrol.2021.108771

[4] Vysotsky, V.I., Rodnikova, R.D. and Li, M.N. (1994) The Petroleum Geology of Cambodia. *Journal of Petroleum Geology*, **17**, 195-210. https://doi.org/10.1111/j.1747-5457.1994.tb00126.x

[5] Mao, C., Yasuhiro, Y. and Matsuoka, T. (2014) A Preliminary Assessment of Geological $CO_2$ Storage in Cambodia. *International Journal of Greenhouse Gas Control*, **30**, 19-33. https://doi.org/10.1016/j.ijggc.2014.08.016

[6] Ganat, T.A.A.O. (2020) Physical Properties of Reservoir Rocks. In: Ganat, T.A.A.O., Ed., *Fundamentals of Reservoir Rock Properties*. Springer, Cham, 1-4. https://doi.org/10.1007/978-3-030-28140-3_1

[7] Fyhn, M.B.W., Pedersen, S.A.S., Boldreel, L.O., Nielsen, L.H., Green, P.F., Dien, P.T., Huyen, L.T. and Frei, D. (2010) Palaeocene—Early Eocene Inversion of the Phuquoc-Kampot Som Basin: SE Asian Deformation Associated with the Suturing of Luconia. *Journal of the Geological Society*, **167**, 281-295. https://doi.org/10.1144/0016-76492009-039

[8] Pettijohn, F.J., Potter, P.E. and Siever, R. (1973) Sand and Sandstone. Springer, Berlin. https://doi.org/10.1007/978-1-4615-9974-6

[9] Al-Ramadan, K., Hussain, M., Imam, B. and Saner, S. (2004) Lithologic Characteristics and Diagenesis of the Devonian Jauf Sandstone at Ghawar Field, Eastern Saudi Arabia. *Marine and Petroleum Geology*, **21**, 1221-1234. https://doi.org/10.1016/j.marpetgeo.2004.09.002

[10] Chen, Z., Zhou, C., Chen, X., Zhu, Y. and Zhu, Y. (2020) Evaluation of the Matrix Influence on the Microscopic Pore-Throat Structures of Deep-Water Tight Sandstone: A Case Study from the Upper Triassic Chang 6 Oil Group of the Yanchang Formation in the Huaqing Area, Ordos Basin, China. *Interpretation*, **8**, T763-T776. https://doi.org/10.1190/INT-2020-0036.1

[11] Atkins, J.E. and McBride, E.F. (1992) Porosity and Packing of Holocene River, Dune, and Beach Sands. *AAPG Bulletin*, **76**, 339-355. https://doi.org/10.1306/BDFF87F4-1718-11D7-8645000102C1865D

[12] North, F.K. (1985) Petroleum Geology. Allen & Unwin Australia, Sydney.

[13] Koesoemadinata, R.P. (1980) Geologi minyak dan gasbumi. Penerbit ITB, Bandung.

[14] Chima, P., Baiyegunhi, C., Liu, K. and Gwavava, O. (2018) Diagenesis and Rock Properties of Sandstones from the Stormberg Group, Karoo Supergroup in the Eastern Cape Province of South Africa. *Open Geosciences*, **10**, 740-771. https://doi.org/10.1515/geo-2018-0059

[15] Lai, J., Wang, G., Wang, Z., Chen, J., Pang, X., Wang, S., Zhou, Z., He, Z., Qin, Z. and Fan, X. (2018) A Review on Pore Structure Characterization in Tight Sand-

stones. *Earth-Science Reviews*, **177**, 436-457. https://doi.org/10.1016/j.earscirev.2017.12.003

[16] Baiyegunhi, C., Liu, K. and Gwavava, O. (2017) Diagenesis and Reservoir Properties of the Permian Ecca Group Sandstones and Mudrocks in the Eastern Cape Province, South Africa. *Minerals*, **7**, Article 88. https://doi.org/10.3390/min7060088

[17] Shalaby, M., Hakimi, M., Abdullah, W. and Islam, M.A. (2016) Implications of Controlling Factors in Evolving Reservoir Quality of the Khatatba Formation, Western Desert, Egypt. *Scientia*, **15**, 129-146. https://doi.org/10.46537/scibru.v15i0.39

[18] Worden, R.H. and Morad, S. (1999) Clay Minerals in Sandstones: Controls on Formation, Distribution and Evolution. In: Worden, R.H. and Morad, S., Eds., *Clay Mineral Cements in Sandstones*, Wiley-Blackwell, Hoboken, 1-41. https://doi.org/10.1002/9781444304336.ch1

[19] Foley, N.K. (2009) Environmental Characteristics of Clays and Clay Mineral Deposits. https://doi.org/10.3133/70220359

[20] Boggs Jr, S. (2009) Petrology of Sedimentary Rocks. 2nd Edition, Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511626487

[21] Heidari, M., Momeni, A.A., Rafiei, B., Khodabakhsh, S. and Torabi-Kaveh, M. (2013) Relationship between Petrographic Characteristics and the Engineering Properties of Jurassic Sandstones, Hamedan, Iran. *Rock Mechanics and Rock Engineering*, **46**, 1091-1101. https://doi.org/10.1007/s00603-012-0333-z

[22] Monsees, A., Busch, B. and Hilgers, C. (2021) Compaction Control on Diagenesis and Reservoir Quality Development in Red Bed Sandstones: A Case Study of Permian Rotliegend Sandstones. *International Journal of Earth Sciences*, **110**, 1683-1711. https://doi.org/10.1007/s00531-021-02036-6

[23] Wang, M., Yang, Z., Shui, C., Yu, Z., Wang, Z. and Cheng, Y. (2019) Diagenesis and Its Influence on Reservoir Quality and Oil-Water Relative Permeability: A Case Study in the Yanchang Formation Chang 8 Tight Sandstone Oil Reservoir, Ordos Basin, China. *Open Geosciences*, **11**, 37-47. https://doi.org/10.1515/geo-2019-0004

[24] Siddiqui, N., Abd Rahman, A.H., Sum, C., Yusoff, W.I. and Ismail, M. (2017) Shallow-Marine Sandstone Reservoirs, Depositional Environments, Stratigraphic Characteristics and Facies Model: A Review. *Journal of Applied Sciences*, **17**, 212-237. https://doi.org/10.3923/jas.2017.212.237

[25] Heng, R., Pech, S., Sio, S., Eng, C. and Or, C. (2022) Study on Organic Identification of Black Shale in Bokor Formation, Kampot Province, Cambodia. *International Journal of Oil, Gas and Coal Engineering*, **10**, Article 4. https://www.sciencepublishinggroup.com/journal/paperinfo?journalid=268&doi=10.11648/j.ogce.20221004.11

[26] Goro, I., Jibrin, B.W., Waziri, N. and Idris Nda, A. (2014) Characterization of a Massive Sandstone Interval: Example from Doko Member of Bida Formation, Northern Bida Basin, Nigeria. *Universal Journal of Geoscience*, **2**, 53-61. https://doi.org/10.13189/ujg.2014.020203

[27] Allen, J.R.L. (1965) A Review of the Origin and Characteristics of Recent Alluvial Sediments. *Sedimentology*, **5**, 89-191. https://doi.org/10.1111/j.1365-3091.1965.tb01561.x

[28] Harms, J.C., Southard, J.B., Spearing, D.R. and Walker, R.G. (1975) Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences. *SEPM Society for Sedimentary Geology*, **2**. https://doi.org/10.2110/scn.75.02