SANDSTONE ROCK PERMEABILITY: IMPACTS OF CLAY MINERALS AND PHYSICO-CHEMICAL VARIABLES

Muhammad Azfar Mohamed, Mohd Shukry Said

Department of Petroleum Engineering, Universiti Teknologi PETRONAS, Malaysia

Email: azfar.mohamed@utp.edu.my

ABSTRACT

Sandstone is one of the most common reservoir rocks found in sedimentary basins throughout the world. It exhibits porous and permeable characteristics. Clay matrix can usually found in sandstone pores. However, the presence of clay minerals that are very fines in the porous media tends to reduce its petrophysical properties as a reservoir rock. The reservoir properties of sandstone are evaluated, and the effect of clay minerals on the reservoir quality is being determined. This study portrays the effect of different pH levels ranging from 3-12.5 and the impact of salinity on the formation of damage in siliciclastic rocks, leading to the reduction of permeability which is regularly overlooked. This research aims to achieve an in-depth understanding of the relations of clay minerals and the effect of chemicals to the reservoir, particularly in sandstone reservoirs. From this finding, this research will comprehend how clay minerals will affect the petrophysical properties of the reservoir. The permeameter and porosimeter (POROPERM), scanning electron microscopy (SEM), and X-ray diffraction (XRD) analyses will be conducted to identify the petrophysical parameters of sandstone. SEM analysis to be run to accurately determine the location of the clay minerals within the sandstone matrix. X-ray diffraction (XRD) to be run to quantify the amount of clay mineral and to check the whole rock by diagnostic treatment to identify the type of clay minerals.

Keywords: sandstone, permeability, clay minerals, saline solution, formation damage

INTRODUCTION

Sandstones are vital hydrocarbon-bearing reservoir rocks which have high variability in texture and composition and may be deposited in various depositional environments. Clay minerals tend to exist in almost all sandstone rocks. It is very significant to know the amount and type of clay within the sandstone to have a greater understanding flow; it would affect the reservoir qualities.

Sandstone is categorised as siliciclastic sediment. The lithification of sand forms it under high pressure, made of sand-sized particles larger than 0.063 mm and less than 2 mm. The grain size indicates the energy of the transporting agent where turbulent water carries large particles and wind carries fine dust. Quartz is the predominant mineral due to its durable nature with a fraction of other minerals such as feldspar, clay, and mica. Since the silica content is very high, sandstones are often referred to as a siliciclastic rock. The fact that silica dissolves in an aqueous solution frequently at high temperature and high pH value made its importance in enhancing oil recovery.

Problem Statement

Due to its tendency to migrate, clay minerals cause severs permeability reduction by plugging interconnecting pores [1]. These very fine-grained clay minerals usually exist in sandstone and some carbonate formation. It is very mobile in very high freshwater saturation environments. For clay minerals, the types, percentage, and dispersion in sandstone have a major effect on the petrophysical qualities of a sandstone reservoir. Both detrital and authigenic clay minerals have been proven to cause a severe reduction in permeability. This happens by the very fine-grained particles of clay which fills the small pores. The fluid pressure will increase to maintain flow. This phenomenon will decrease the permeability of the rock. For most oil and gas fields, low salinity fluids have been linked heavily as the main cause of formation damage by clay minerals. The higher saturation of low salinity fluids is proportional to the reduction of reservoir quality.

Objectives

This project aims to study how different pH levels in saline solutions would affect the permeability in sandstone reservoirs. To achieve the objective, the following sub-objectives were designed,

1. To understand the relation between clay minerals and physicochemical properties in sandstone reservoirs.
2. To understand the impact of clay minerals on the reservoir qualities.

Literature Review

Sandstones

Sandstones are vital hydrocarbon-bearing reservoir rocks with high variability in texture and composition and may be deposited in various depositional environments. Sandstone is a common reservoir rock found in sedimentary basins throughout the world. Sandstone is composed of sand-sized mineral grains which bind the sand grains together and the spaces between them are occupied by a matrix of clay-sized particles. Clay minerals tend to exist in almost all sandstone rocks. It is very significant to know the amount and the type of clay within the sandstone to understand how it would affect the reservoir qualities.

Sediments are loose particles such as sand and silt that originate from weathering and erosion. Siliciclastic sediments are formed of grains of quartz and feldspar derived from the weathering of pre-existing rock. These sediments are transport and deposit by water, wind and ice. Sedimentary rock is made up of sediments that have undergone a lithification process which transforms sediments into solid rock through compaction and cementation [3]. The pressure of overlying sediments

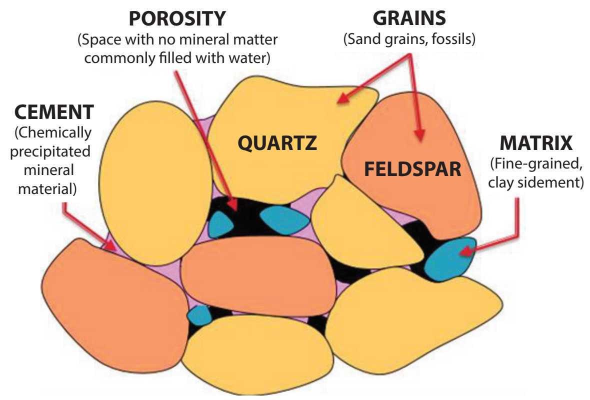

Figure 1 Components of sandstone [2]

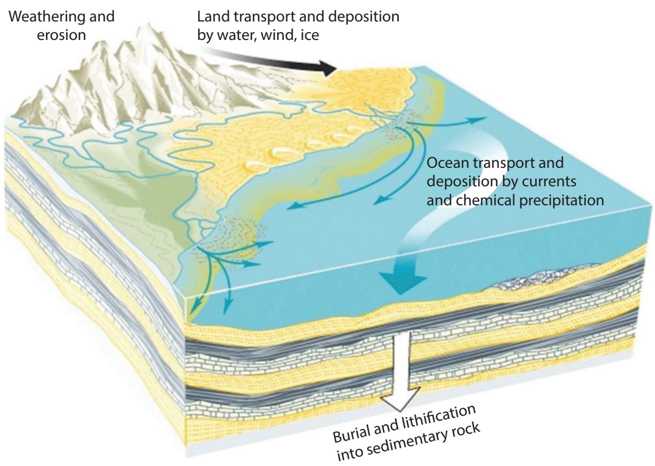

Figure 2 Sedimentation Processes [2]

Table 1 Particle size classification for detrital rocks [4]

SEDIMENTARY ROCK ANALYSIS AND CLASSIFICATION						
STEP 1: What is the rock's composition?		STEP 2: What are the rock's textural and other distinctive properties?			STEP 3: Rock Name(s)	
DETRITAL (CLASTIC)	Mainly rock fragment or mineral grains (quartz, feldspar, clay) weathered from other rocks	Mainly grave (>2 mm)		Rounded grains	CONGLOMERATE	
				Angular grains	BRECCIA	
		Mainly snad *1/16 - 2 mm)		Mostly quartz grains	QUARTZSANDSTONE	SANDSTONE
				Mainly feldspar and quartz	ARKOSE	
				Sand is mixed with much silt and/or clay (mud)	GRAYWACKE	
		Mainly Mud (<1/16mm)	Mostly slit (<1/256 - 1/16 mm)	Breaks into blocks or layers	SILTSTONE	MUDSTONE
			Mostly clay (<1/256 mm)	Crumbles or breaks into blocks	CLAYSTONE	
				Fissile (splits easily)	SHALE	

packs the grains and squeezes water from pores by compaction, while in cementation, pore spaces fill with a binding agent are precipitated from circulating water. Therefore, sandstone is formed when sand is buried under successive layers of sediment.

Sandstone is categorised as siliciclastic sediment. The lithification of sand forms it under high pressure, made of sand-sized particles larger than 0.063 mm and less than 2 mm. The grain size indicates the energy of the transporting agent where turbulent water carries large particles and wind carries fine dust. Quartz is the predominant mineral due to its durable nature with a fraction of other minerals such as feldspar, clay, and mica. Since the silica content is very high, sandstones are often referred to as a siliciclastic rock. The fact that silica dissolves in aqueous solution frequently at high temperature and high pH value enhances oil recovery.

Mineralogical composition of reservoir rock affects the relationship between reservoir minerals and interfacial properties such as wettability and surface charge. Clean quartz consists of negatively charged surface tend to adsorb organic bases from the solution, which is positively charged. The negative charged in solution will not be adsorbed due to the identical charge on the quartz surface. Anderson [5] mentioned that the quartz remain water-wet due to typical reservoir pH for sandstone is around five, which under natural condition. Majority of the minerals like quartz, sulphates and carbonates are strongly water-wet whereas sulphur, graphite and coal are weak water-wet or even oil-wet.

Clay Minerals

According to Barton and Karathanasis [6], clay mineral is clarifying as a group of aluminosilicates with a size of less than 2 mm. Clay minerals similarities with quartz, feldspar, and mica in the aspect of its chemical and structural composition. Johnston and Beeson [7] study show that the permeability of oil sandstone would reduce after contact with fresh water. The flow of fluid across the pores becomes difficult because clay minerals consist of micro-porosity, which is ineffective and isolating pores. The presence of clay in a small amount can reduce the permeability in sandstone, and residual water saturation in reservoir zones will be increased.

Kaolinite is easily dispersed and movable in the matrix as it is a non-swelling clay. This type of clay is developed in soils created under a frequent amount of rainfall environment, having very good drainage in the soil, and containing low pH fluids. For underwater basins, it is normally found at shallow waters. Kaolinite is a white coloured soft mineral. It composes of hydrous silicate of aluminium that represents the main mineral in kaolin which shaped by the disintegration of orthoclase feldspar. Kloprogge [8] mentioned a layered silicate mineral known as a 1:1 clay which layer structure composed of a single tetrahedral sheet connected to a single octahedral sheet. The other groups are known as 2:1 clay which is formed by stacking of 2 tetrahedral sheets with an octahedral sheet between them. Kaolinite group includes kaolinite, halloysite, dickite and nacrite. A few authors suggest incorporating serpentine group due to structural matches [9].

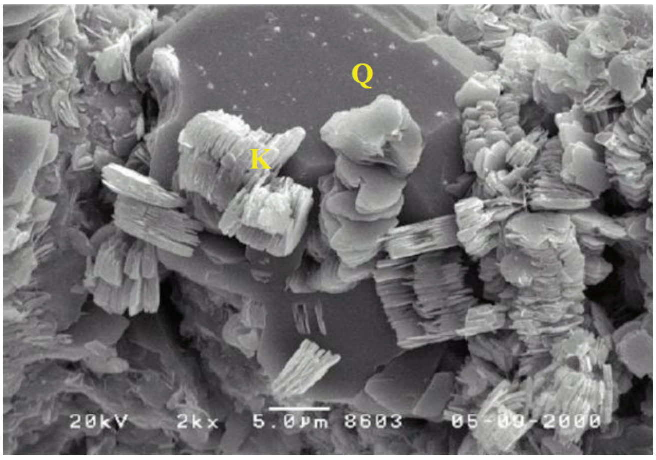

Figure 3 Authigenic quartz and kaolinite plates under SEM magnification [10]

Due to having a significant value of cation exchange capacity, smectite clays tend to swell and disperse easily and better at absorbing Na+ ions. It comprises montmorillonite, nontronite, pyrophyllite, saponite, sauconite, talc and vermiculite. The Figure 4 illustrates the smectite atomic structure.

Illite is composed of a non-expanding clay-sized alumino-silicate mineral. Illite's structure constitutes of Tetrahedron-Octahedron-Octahedron-Tetrahedron layers. According to Anderson [5], it the most abundant clay minerals amongst all by 50 percent. It tends to weather at high elevations having mild atmospheres and then transported to the sea by wind interactions.

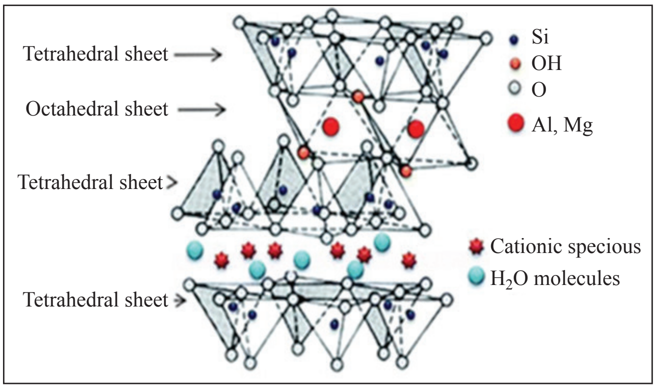

Figure 4 Smectite Atomic Structure [11]

Under high pH conditions, illite is formed when potassium and aluminium are weathered. Under high temperatures, illite will undergo a transformation into muscovite. Another variety of illite, which is glauconite, is very well known as an iron-rich mineral and is formed during sedimentation. However, glauconite as very vulnerable to weathering agents.

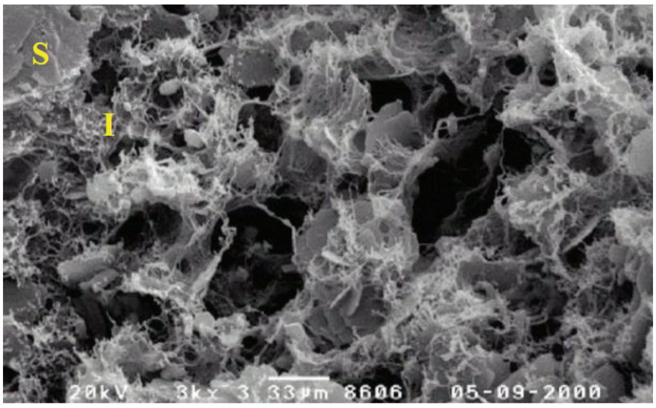

Figure 5 Sandstone and illite crystals under SEM magnification [10]

Reservoir Qualities

In a reservoir rock exists pores within its bulk volume. These pores can transmit and store fluids in the rock. Porosity is the ability of the rock to store fluids in the reservoir. Porosity is determined by using the following equation,

$$\text{Ø} = \frac{V_{pore}}{V_{bulk}} = \frac{V_{bulk} - V_{matrix}}{V_{bulk}} = \frac{V_{bulk}\left(\frac{W_{dry}}{\rho_{matrix}}\right)}{V_{bulk}} \quad (1)$$

where,

V_{pore} = pore volume

V_{bulk} = bulk rock volume

V_{matrix} = volume of solid particles composing the rock matrix

W_{dry} = total dry weight of the rock

ρ_{matrix} = mean density of the matrix minerals.

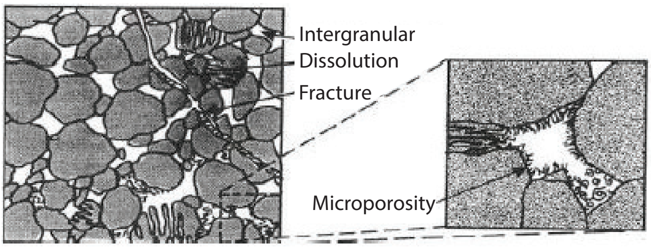

Figure 6 Porosity in sandstone reservoirs [12]

Permeability is the capability of the formation to transmit fluids. A higher permeability value indicates the ability of the rock to flow fluid at a better rate. The directional movement and flow rate of the reservoir fluids into the formation been controlled by the permeability that shows the importance of a reservoir. Henry Darcy derived the formula for a fluid to flow through a porous medium by deriving an empirical formula for the fluid flow interactions in a rock formation [13]. The Darcy Equation, as described below:

$$Q = \frac{kA(P_i - P_o)}{\mu L} \quad (2)$$

where:

Q = the flow rate (cm3/s or m3/s)

P_o = the outlet fluid pressure (dynes/cm2 or Pa)

P_i = the inlet fluid pressure (dynes/cm2 or Pa)

μ = the dynamic viscosity of the fluid (poise or Pa.s)

L = the length of the tube (cm or m)

k = the permeability of the sample (darcy or m2)

A = the area of the sample (cm2 or m2)

The type of permeability can be divided into two, which are absolute permeability and effective permeability. Absolute permeability is the ability for a single-phase fluid to flow in permeable rock. Effective permeability characterises as the permeability for all liquids, which is dependent on the saturation of the fluid and more than one fluid is present. Moreover, relative permeability is affected by the different phase properties such as their saturation, viscosity, and capillary pressure between the phases.

Formation Damage

In the industry, it is the impairment in the reservoir's ability to produce and store its hydrocarbon content due to wellbore fluids used throughout its production life cycle. It is harmful in terms of optimal production as it reduces the relative near-wellbore region permeability. These very fine particles may resolve to a significant reduction in permeability, even so in a short interval [14]. Galal et al. [15] stated that hydrocarbon formations always have fine particles and minerals presented in the rock matrix, and it is supported by Civan [16]. In short, it is very important to have a thorough understanding of the mechanism of formation damage and how to control its impact reservoir production efficiency. Clay content is one of the major factors determining the formation damage in a reservoir [17]. Although there are many ways the formation can be damaged, our focus is to evaluate the relationship between the clay minerals and the pH value of the fluid injected into the formation. The physical and chemical characteristics of sand are directly affected by clay minerals. [18]. Clay minerals to be observed in terms of swelling, deflocculating, migration, and dispersion of very fine-grained particles [19].For illite and kaolinite have lover cation exchange capacity (CEC) value and inhibit non-swelling properties, likewise for smectite having a high CEC [20].

Depositional Environment

The marine sedimentary successions in the Sandakan Formation of N.E. Sabah Basin display a variety of facies characteristics. They were deposited through interaction and dynamic processes of tidal and wave processes as proven by the facies characteristics. The rock successions provide a good example of wave-storm dominated shoreface deposits that can readily be studied in the recent outcrop. Analysis of facies characteristics and facies associations have contributed to paleoenvironmental reconstruction.

The stratigraphic succession of the study area revealed that the sandstone facies are forming 70% of the overall successions, and the remaining 30% of succession represented by mudstone facies. Sandstone facies mostly is dominated by massive HCS sandstone successions suggest that there is a huge amount of sedimentary supply during depositional processes. Mudstone facies is dominated by interbedded mudstone and sandstone, suggest that there are major changes between two different depositional environments.

Based on the documented eight sedimentary facies and four facies associations, *c*, following the Konjing (2015) model [21] in Figure 7 below. The model commonly

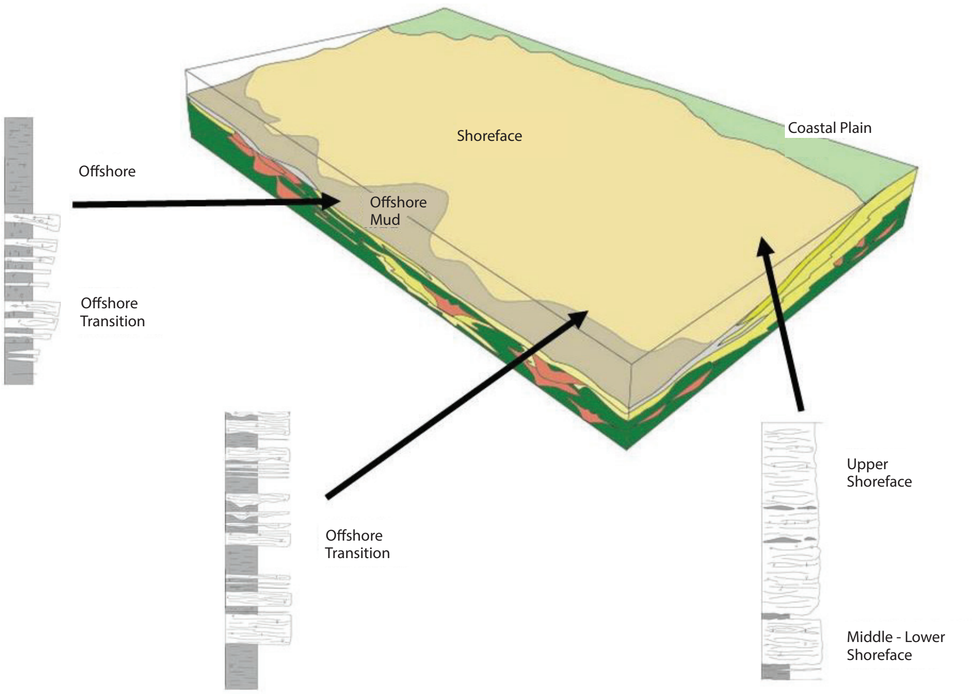

Figure 7 Conceptual model of wave-storm dominated shallow marine-shoreface complex, comprises sub environments ranging from upper, middle to lower shoreface and offshore succession (modified from Konjing [21])

comprises sub environments ranging from upper, middle to lower shoreface and offshore succession [22].

The vertical succession of the Sandakan Formation comprises repetitive cycles of wave-storm dominated shoreface succession with the bedding gradually thickening upward. Wave-storm dominated succession is characterised by upper shoreface, lower to middle shoreface, and offshore transition. These facies succession formed in various thickness ranged from 1 m reaching up to 45 m thick. wave-dominated shoreface environment in general characterised by offshore, followed by lower shoreface, middle shoreface, upper shoreface and end with foreshore facies association [23]. Fortunately, most of the facies association existed in the studied outcrop, except foreshore facies association which is no field evidence found.

The intensity of bioturbation activity within the shoreface deposits is varies, depending upon the degree of storm influence. The storm-wave dominated shoreface deposits present the increase in the intensity of bioturbation from upper to lower shoreface deposits but maintained low intensity of bioturbation in the offshore transition to offshore deposits. Minimal preservation of bioturbation activity is favoured by high intensity and frequency events. In contrast, low intensity and less frequent storms permit through the homogenisation of the tempestites and accumulation of thick fair-weather intervals [24]. In storm-dominated conditions, only deeply penetrating traces such as Ophiomorpha may be preserved as tempestites become progressively more cannibalistic [24].

EXPERIMENTAL PROCEDURE

This section explains the methodology undertaken to conduct this study. The study is performed in two stages. Firstly, the literature review was performed to gather relevant information on the topic. Then, petrographic and laboratory analyses to be performed to characterise the clay content in the sandstone reservoir by its petrophysical properties such as porosity and permeability. The quality of the reservoir is evaluated by relating the petrophysical parameters.

Core Preparation

To remove any traces of oil and other materials in the core sample, core cleaning must be done by using a Soxhlet Extraction apparatus. This apparatus is the most common method for cleaning the sample and usually used by most laboratories.

Procedure,

1. 400 ml of a 50%/50% by volume of a toluene/methanol mixture was prepared, and the mixture placed in the volumetric flask.
2. The volumetric flask and the solvent mixture were placed in the heating mantle.
3. Reflux core chamber was attached to the volumetric flask.
4. The condenser was attached to the reflux core chamber.
5. The water source was connected to the lower part of the condenser, and a hose was attached to the upper part of the condenser that will serve to evacuate the water.
6. The heating mantle was turned on by setting it with the appropriate condition (depending on the amount of solvent being used)
7. Leave the reflux process to continue until no more colour change can be seen in the condensed solvent mixture (this may take many hours or even days)

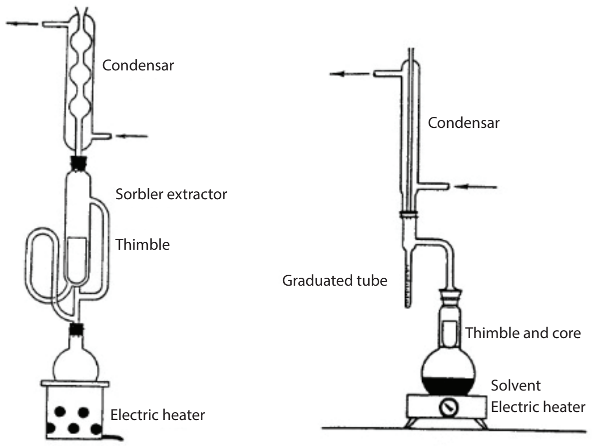

Figure 8 (a) Soxhlet apparatus , (b) Dean-Stark apparatus [25]

Once the core samples are cleaned, it will be dried in an oven to remove the remaining connate water inside the pores. The drying procedure is critical when hydratable minerals are present because interstitial water must be eliminated without alteration of minerals. Drying is commonly performed in a regular oven at temperatures 60°C and 40% relative humidity to prevent the clay and other soft minerals from damage.

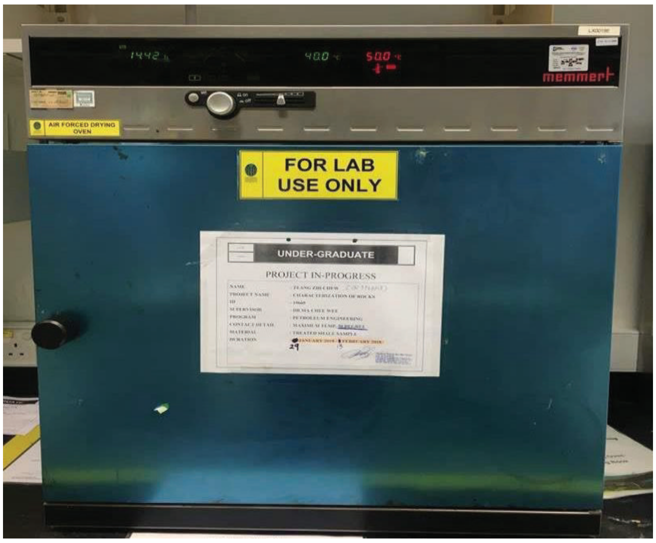

Figure 9 Air forced drying oven

Petrographical Evaluation

Petrographical analysis is vital in determining the mineralogy abundance and distribution. Houseknecht [26] stated that information regarding reservoir quality and homogeneity be obtained through petrographic analysis.

Scanning electron microscopy (SEM) is a technique used a scanned electron beam to analyses the surface structure and chemical composition of a sample. The backscattered electrons are used to identify the different types of mineral phases based on density. Various ranges of electron signals are emitted at the specimen surface due to the interaction of the beam with the sample. The electronic signals produced are translated as an image of the specimen's surface. Electron microscopy is performed at high magnifications in the range of 1000-5000 times, which generates high-resolution (Figure 10).

X-ray powder diffraction is most widely used for the identification of crystalline species in a material (e.g. minerals, inorganic compounds) and the phase. Besides, it is also used to calculate the clay or silt ratio, which is useful for shaly sand analysis [27]. XRD can be used to determine the mineralogy of rock samples and the percentage of clay compassion. XRD can also determine the degree of crystallisation and different phases with identical compositions.

Petrographical Evaluation

The petrophysical analysis of the sandstones was studied using the Helium Poroperm. This instrument is used to determine the pore characteristics in the rock. The theory utilised in the experiment is that the system pressure is proportional to the volume of helium being forced into the pores and thus produce pressure-volume curves. The volume of helium flows into the empty pore's spaces of the core samples.

For this project, the core samples are analysed by using Poroperm Coval 30. The Poroperm Coval 30 can determine the porosity and the permeability of the sandstone core by injecting Helium gas into the core samples at a maximum confining pressure of 400 psi.

Figure 10 Scanning Electron Microscopy set up

Figure 11 X-ray powder diffraction machine

Figure 12 POROPERM Coval 30

Figure 13 The acidic and basic solution in a glass bottle

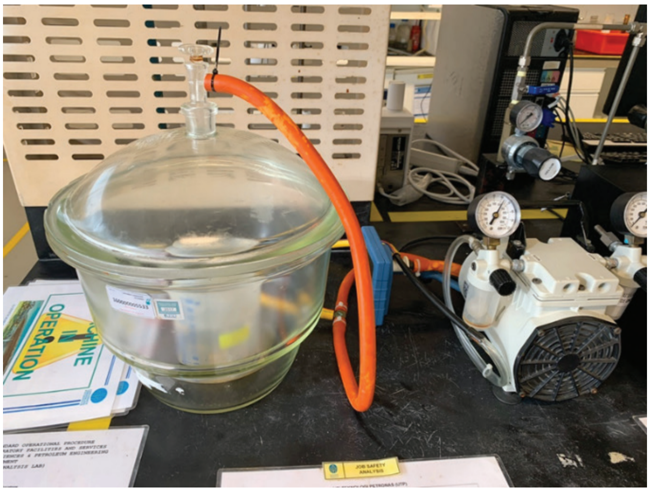

Figure 14 Setup for core flooding using glass desiccator and vacuum pump

The specific amount of materials mixed into the saline solution are shown in Table 2 below. The pH for the acidic solution is pH 3, and the basic solution is pH 12.

Table 2 Composition of saline solutions

Type of Solution	HF 48% (ml)	KOH 56.11 (g/mol)	NaCl (g)	Distilled water (mL)	pH
Acidic	1.8	-	5	993.5	3.0
Basic	-	4.3	5	990.7	12.0

Five cores are being saturated with the acidic solution and another five cores into the basic solution in glass desiccators. The glass desiccator is equipped with a vacuum pump.

It can be observed that bubbles are releasing from the core when the vacuum pump is turned on. This is due to the reason that the pore spaces inside the core are being sucked out and displaced by the solution. The core samples are saturated for 24 hours. This is to ensure the core samples are fully and completely saturated with the solution. While carrying this step, the glass had to be ensured that it is securely confined. This is to make sure that no air is entering the container and the vacuum pump can work well.

RESULTS AND DISCUSSION

For this chapter, we will relate the effectiveness of our methodology to achieve the expected results to meet our objectives. This project aims to quantify the percentage of clay content inside the sandstone matrix and see its interactions with the acid and basic solutions that we prepared. To achieve the relationship of the clay content percentage and porosity and permeability of the rock, the sample mineralogy has been studied and identified thoroughly by some experiments which are XRD analysis and SEM analysis. As the results from the analysis, the clay mineral content can be justified in the sample.

Scanning Electron Microscopy Analysis

The Scanning Electron Microscope (SEM) produced images that illustrate the pore structure, pore network and intergranular micro-porosity of these samples.

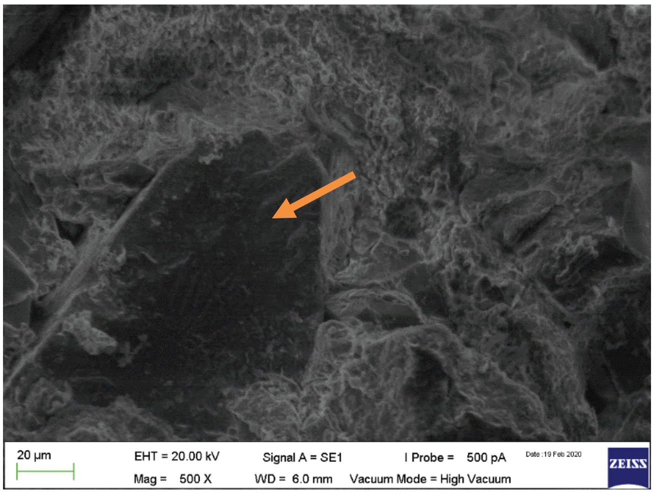

Figure 15 Overview of quartz in Alpha sandstone

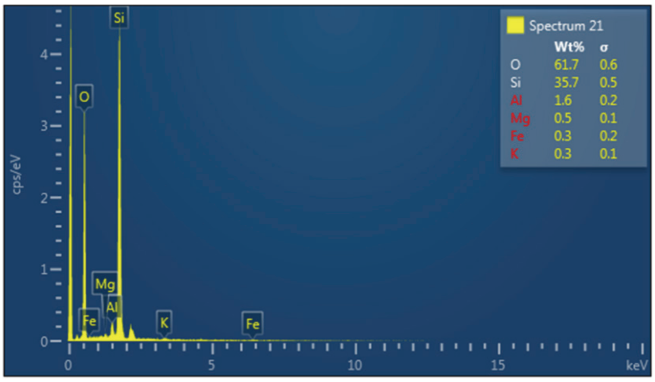

Figure 17 Spectrum 17 EDX

For this experiment, we want to determine the sandstone's composition inside the core by observing the micrography using Energy Dispersive X-Ray Spectrum (EDX).

Spectrum analysis was performed on the four (4) sandstone samples to study the mineral composition present in the samples. Quartz (SiO_2) is a mineral predominantly composed of silicon and oxygen elements, but traces of carbon were also discovered in the sample. For Spectrum 17, silica and oxides were the main constituents with weightage percentage of 58.7% and 33.3% respectively, as shown in Figure 17. Hence, it shows that Quartz (SiO_2) was found in Alpha sandstone sample. Moreover, quartz mineral was observed in the Electron Image, as shown in the Figure 16.

Kaolinite is the most common mineral that exists in a clay formation. Kaolinite often found near the oxidised surface where it has altered from hydrous aluminium silicates such as feldspar the general formula for the kaolinite Al2Si2O5(OH)4. Kaolinite was observed in the Hess sandstone sample at spectrum 26, which shown in Figure 18 and Figure 19. Spectrum 26 analysis graph stated that oxides were the main constituents with weightage percentage of 59.2%, silicon (20.9%) and aluminium (19.5%) respectively, as shown in Figure 20. All these minerals made up clay and act as the cementing materials.

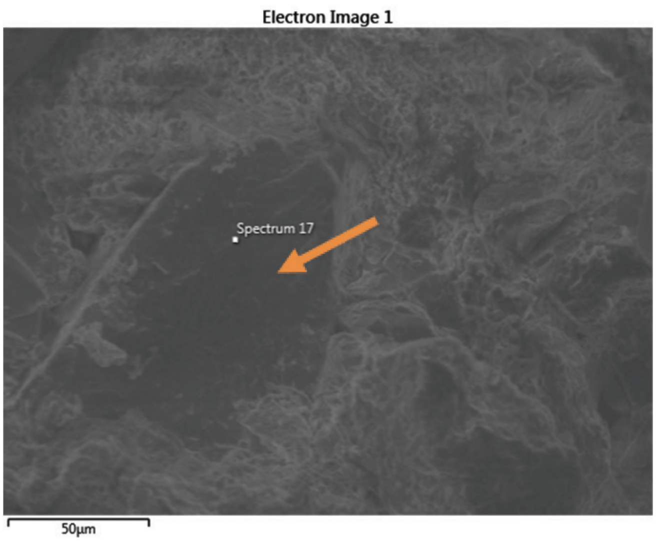

Figure 16 Spectrum 17 at 50 µm

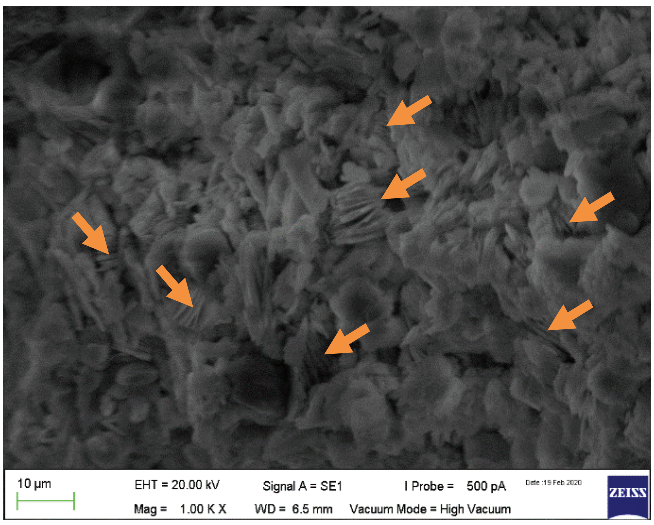

Figure 18 Overview of kaolinite in Hess sandstone

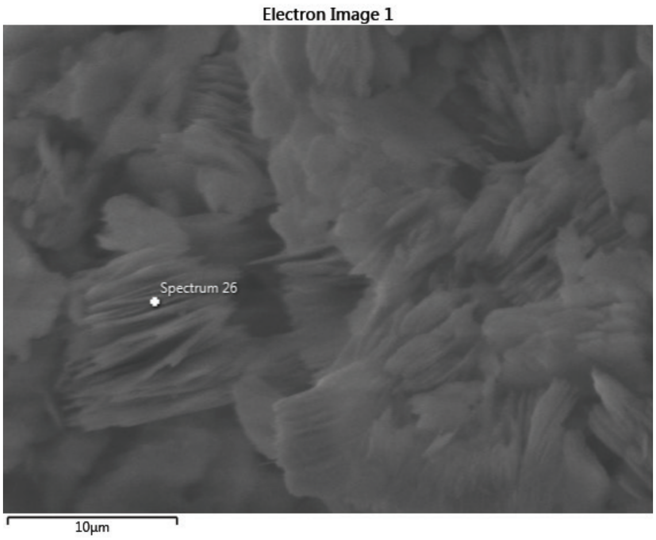

Figure 19 Spectrum 26 at 10 µm

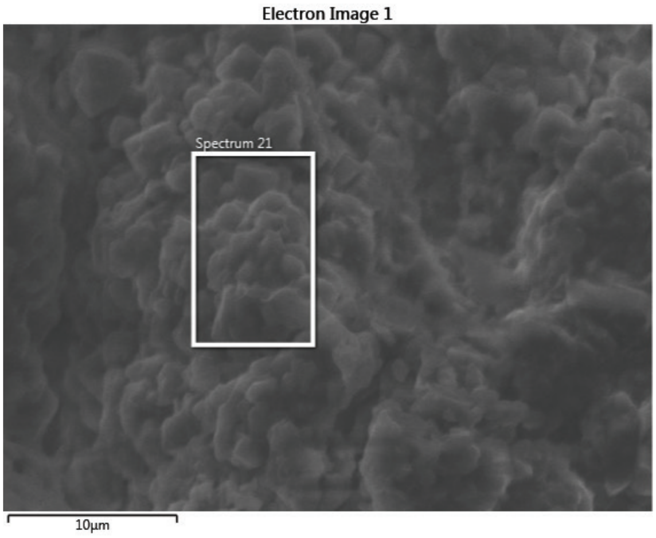

Figure 21 Spectrum 21 at 10 µm

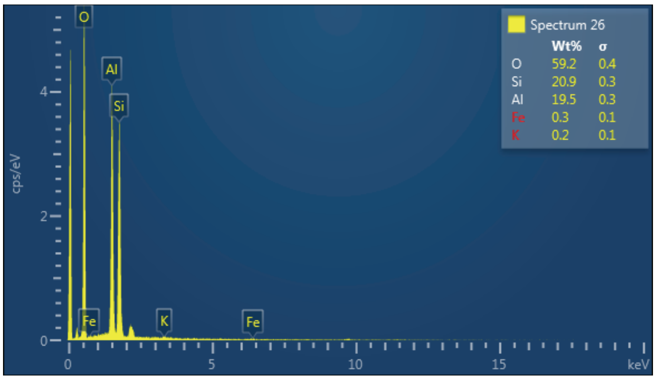

Figure 20 Spectrum 26 EDX illustrates the weightage of kaolinite elements

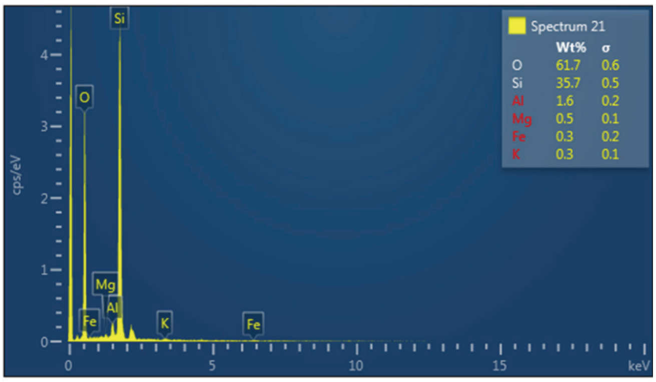

Figure 22 Spectrum 21 EDX illustrates the weightage of illite elements

In shale rocks, illite clay is its main element. It has a similar structure of muscovite but insufficient in alkalis with less Aluminium substitution for Silicone. Calcium (Ca) and Magnesium (Mg) can substitute for Potassium (K) due to possible charge imbalance. Therefore, illite and mica muscovite exists in the formation. The Figure 21 shows the image of illite.

X-Ray Diffraction Analysis

Powdered samples of Alpha & Bravo sandstones were run through the X-ray diffraction (XRD) equipment to identify the type of minerals in the sandstone core plug. From the machine, we can get the peaks for each mineral inside the rock and to be interpreted using HIGH SCORE software. The database from the International Centre for Diffraction Data (ICDD) was matched and fitted with the peaks to allocate different minerals to the subsequent peaks. The results show that the composition of the rock mostly consists of silicon oxide, which indicates quartz minerals. In contrast, clay minerals were found to be the least minerals in the samples, as shown below.

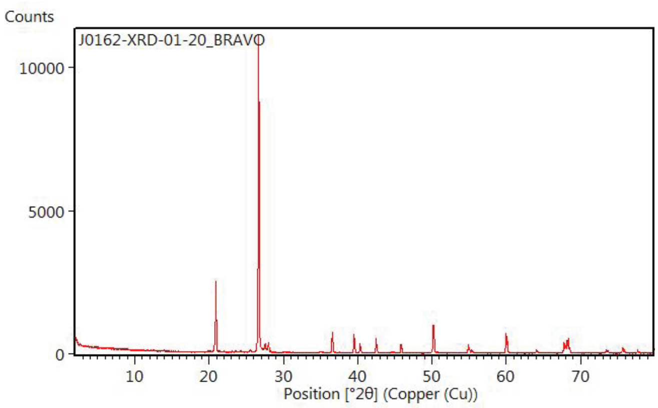

Figure 23 Mineral composition of Alpha sandstone

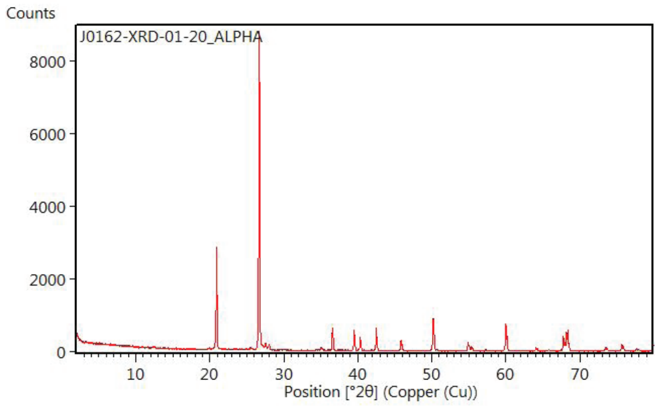

Figure 24 Mineral composition of Bravo sandstone

Porosity and Permeability Analysis

In this research, we use the POROPERM equipment to determine the reservoir qualities of the sandstone core plugs. The porosity of the sample is determined by the ratio of the bulk volume and the pore volume (Equation 1). Bulk volume is the total volume of the core plug, and the pore volume is the void spaces inside it. For this machine, we used Helium gas as it has a lower error due to gas slippage inside the pores due to its smaller particle size.

Ten (10) sandstone core each were run through the POROPERM equipment. The average length, diameter and weight for all core sample were measured using a Vernier calliper.

The average of Klinkenberg permeability values of fine and medium grain sandstone samples are 0.337 mD and 94.053 mD. Since the type of rock has been known as consolidated rock, it can be characterised as fresh sandstone corresponds with Bear's [28] classification of rock types by permeability value, as shown below.

The reservoir quality index (RQI) is an empirical relationship which relates the porosity and permeability of a reservoir [29]. It is useful to identify and categorise reservoir rock quality and heterogeneity. The RQI value is calculated by using the effective porosity and permeability of each sandstone samples. The RQI equation is shown below.

$$RQI\,(microuns) = 0.0314\sqrt{\frac{k(mD)}{(franc)}} \tag{3}$$

where

RQI = Reservoir quality index in the micrometre
k = permeability in millidarcy
φ = Porosity

The reservoir quality index (RQI) values shown in Table 4 indicate the initial petrophysical properties of all sandstone cores. In general, when the RQI value is more than 0.1, it shows that the rock containing clean sandstone and well sorted. In contrast, high content of mud, fine-grained and moderately sorted sand exhibit low RQI values which are less than 0.1. This proves that we have high clay content in our sandstone core plugs. The table below shows the changes in the RQI for all sandstone cores after injecting acid or basic solutions. Based on the results we have obtained, the core injected with basic solutions is a more significant change compared to acidic solutions.

There are two possibilities on how the clay minerals are affecting the cores. It is either caused by the swelling of clay or the fine migration within the pores during the injection. However, we can say that the impact of clay swelling can be ignored as our SEM and XRD results indicate a low percentage of the

Table 3 Permeability values of different sandstones

<table>
<tr><td>Permeability</td><td colspan="4">Pervious</td><td colspan="4">Semi-Pervious</td><td colspan="5">Impervious</td></tr>
<tr><td>Unconsolidated Sand & Gravel</td><td colspan="2">Well Sorted Gravel</td><td colspan="3">Well Sorted Sand or Sand & Gravel</td><td colspan="4">Very Fine Sand, Silt, Loess, Loam</td><td colspan="4"></td></tr>
<tr><td>Unconsolidated Clay & Organic</td><td colspan="4"></td><td colspan="2">Peat</td><td colspan="3">Layered Clay</td><td colspan="4">Unweathered Clay</td></tr>
<tr><td>Consolidated Rocks</td><td colspan="4">Highly Fractured Rocks</td><td colspan="3">Oil Reservoir Rocks</td><td colspan="2">Fresh Sandstone</td><td colspan="2">Fresh Limestone, Dolomite</td><td colspan="2">Fresh Granite</td></tr>
<tr><td>κ (cm^2)</td><td>0.001</td><td>0.0001</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td><td>10^{-8}</td><td>10^{-9}</td><td>10^{-10}</td><td>10^{-11}</td><td>10^{-12}</td><td>10^{-13}</td><td>10^{-14}</td><td>10^{-15}</td></tr>
<tr><td>κ (millidarcy)</td><td>10^{+8}</td><td>10^{+7}</td><td>10^{+6}</td><td>10^{+5}</td><td>10,000</td><td>1,000</td><td>100</td><td>10</td><td>1</td><td>0.1</td><td>0.01</td><td>0.001</td><td>0.0001</td></tr>
</table>

Table 4 Initial RQI for all sandstone sample

Sample	Solution Injected	He porosity, φ (%)	Klinkenberg Permeability, K_{air} (mD)	*RQI* (*μm*)
ALPHA	Basic	9.001	50.511	0.0744
BRAVO	Basic	10.87	87.789	0.0892
CHARLIE	Basic	10.062	70.74	0.0833
DELTA	Basic	11.851	0.857	0.0084
ECHO	Acidic	11.33	61.271	0.0073
GOLF	Acidic	11.752	0.475	0.0063
HESS	Acidic	9.724	94.053	0.0977
JAC	Acidic	12.599	48.809	0.0618
13.7	Acidic	4.564	46.194	0.0999
TOB	Basic	10.269	0.337	0.0057

swelling type of clay inside the core sample. The clay causes the damage inside the core migrated within the pores (primarily kaolinite). This is due to the cation's interactions with the solution. The clay being deflocculated and coagulated is what caused the core damage in this study.

CONCLUSION AND RECOMMENDATION

The first objective of this study was to determine the relation between clay minerals and physico-chemical properties in sandstone reservoirs. Basic solutions have a greater impact on the reservoir qualities compared to acidic solutions. For both injections, the time and injection rate play a significant role in the drop of permeability. The longer and higher the injection rate, the faster the core plug be affected by the solution. The damage inside the core is caused by the clay migrated within the pores (primarily kaolinite). This is due to the cation's interactions with the solution. The clay being deflocculated and coagulated is what caused the core damage in this study.

The second objective is to evaluate the impact of clay minerals on the reservoir qualities. This formation presents moderately low porosity ranging from 4.56% to 12.59% but relatively low permeability values ranging from 3.89 mD to 30.5 mD. The consistency of porosity values for all samples is due to the similarity of grain size and grain sorting of the sandstone. The inconsistency of permeability values is due to the sediment composition like clay minerals. The reservoir quality index (RQI) value is very useful to categorise the reservoir rock quality. When RQI value is more than 0.1, it shows that the rocks containing clean sandstone and well-sorted whereas when RQI value is less than 0.1, it indicates a high content of mud, fine grain and moderately sorted. In this experiment, the reduction of the reservoir qualities can be caused by the swelling of clay or fine migration within the pores. However, we can say that the impact of clay swelling can be ignored as our SEM and XRD results indicate a low percentage of the swelling type of clay inside the core sample.

Based on our findings related to clay minerals interaction within a sandstone reservoir, the following recommendations are suggested for further improvements to be conducted in the future:

a. Increase the number of samples to obtain a deeper understanding of petrophysical characteristics of a basin or formation and to provide more accurate and reliable results.
b. As the reservoir properties may be changed over the depth, diagenesis should be considered to determine its effect on the reservoir quality. Diagenesis is all chemical and physical changes sediment during and after lithification such as the chemical alteration of feldspar to form a clay mineral.

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