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Petrographic analysis of the sandstones and mudstones in Alice, Eastern Cape Province, South Africa: Implications for groundwater potential

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Abstract: The potential for the aquifers' storability in Alice, comprising of rocks of the Beaufort Group, Karoo Supergroup, was examined based on mineralogical and diagenetic implications of sandstones and mudstones**.** This investigation is focused on SEM+EDX analysis, petrographic study, porosity, and density determination. The SEM+EDX and petrographic studies showed that the rocks are fractured, porous, and contain minerals like quartz, feldspar, lithics, mica, kaolinite, calcite, illite. The primary diagenetic processes that affect the groundwater storage of the rocks are cementation by authigenic minerals, minerals replacement, dissolution of minerals, and recrystallization. The existence of fractured and dissolution pores improves the groundwater storage capacity. Ten rock samples were selected for density and porosity measurements. The porosity result shows that mudstone has the highest porosity value of 2.56 %, while sandstone has the lowest porosity of 0.85 %. This is due to numerous pore spaces within the mudstone than the sandstone. The density of the mudstone ranges from 2.5763 – 2.6978 g/cm^3, while the density of the sandstone ranges from 2.5908 – 2.6820 g/cm^3. The secondary porosity is the main porosity for the reservoir rocks. The pores and fractures observed in the rocks act as channels for groundwater, which influence the aquifers' storability in the study area. The techniques used in this research efficiently understand the factors that control the aquifers' storability to assist with groundwater exploration.

Keywords: groundwater; diagenetic processes; density; porosity; aquifer

INTRODUCTION

Water is the primary source of life because humans, animals, and plants all require water to survive. To maintain food security, feed animals, start industrial production, preserve biodiversity, and protect the environment, water is required. (Chakkaravarthy and Balakrishnan, 2019). Nature supplies a copious amount of water, but getting access to it in excellent quality and quantity is challenging (Sirhan et al., 2011). Groundwater is found within the fracture and pores of rocks in the subsurface (Adagunodo et al., 2018).

Water insecurity can be worsened by drought. According to Finnigan (2017), drought affects more people than any other disaster. Four hundred and eleven million people were affected by disasters in 2016, while 94 percent experienced drought (Finnigan, 2017). While this is a growing concern worldwide, South Africa is regarded as a country with a water crisis (Mckenzie et al., 2013). The water quality and availability in South Africa are influenced by the problems of an expanding economy, increased urbanization, and lack of infrastructure (Weaver et al., 2017). According to calculations, 64% of homes in South Africa lacks access to potable water, while 35% of municipal water is lost due to leakages

(Viljoen and van der Walt, 2018). However, the use of surface water resources has already reached its lower limit (Woodford and Chevallier, 2002).

The Eastern Cape is among the provinces in South Africa facing many challenges such as lack of water supply, extreme poverty, and food uncertainty (Baudoin et al., 2017). These distressing situations have overwhelmed the people struggling to provide basic requirements for their families in difficult conditions (Chakona and Shackleton, 2018). Alice, a town in the Eastern Cape Province of South Africa, is no exception to the above mentioned concerns. The municipality provides piped water to Alice town daily. The municipality's total dependence on water supply will prolong the water scarcity challenge experienced in Alice. Hence, there is a need to consider the potential of groundwater to supply the basic needs of many people in the study area.

However, it is necessary to examine and know the aquifer system to access groundwater. Most of the Eastern Cape areas are underlain by rocks of the Karoo Supergroup. The Eastern Cape aquifers are categorized as secondary types in which their water-bearing properties were enhanced during secondary processes, which includes fracturing, faulting, and dolerite intrusions (Fourie, 2003). There is very little knowledge of the rock's porosity and permeability, which are greatly influenced by the above mentioned secondary processes in the study area. Therefore, understanding aquifer storability through petrographic, density, and porosity studies will help to predict the potential of groundwater accumulation in the study area.

Petrographic studies are crucial for determining the porosity and permeability of the mudstones and sandstones (Ajdukiewicz and Lander, 2010; Baiyegunhi et al., 2017; Bilal et al., 2022). Many researchers have shown that diagenetic alterations in siliciclastic rocks influence reservoir quality by changing the primary porosity and permeability of the rocks (Giles and Marshall, 1986; Bloch et al., 2002; Worden and Burley, 2003; Baiyegunhi et al., 2017; Chima et al., 2018; Bilal et al., 2022 and Makulana et al., 2022). The relationship between fracture, fault, pores, and groundwater potential has been investigated and reported by these researchers (Solomon, 2003; Mpofu et al., 2020; Owolabi et al., 2021).

The physical rock properties, such as density and porosity, are critical in rock science as they help to determine the characteristics of the lithology in which the rocks are found (Baiyegunhi et al., 2014). Density depends largely on the age and depth of burial, composition, cementation, the porosity of the rocks, types of pore-fluid, and various tectonic settings (Reynolds, 1997). There are three most important types of density: dry density, wet density, and grain or particle density (Reynolds, 1997). Porosity is described as the voids within a rock. The sizes and distributions of voids can affect the smooth flow of fluids within the rock based on the channels' isolation in the rock owing to the cementation of the grains (Dandekar, 2006). The density and porosity measurements of the rocks will help determine whether the rocks will allow storage or passage of groundwater in areas with groundwater potential.

This research aim is to investigate the factors that influence the groundwater storage capacity of sandstones and mudstones. The study will further contribute additional knowledge on the diagenetic processes and how they influence the rock's quality as potential aquifers. These will provide valuable information needed for the proper exploration of groundwater in Alice.

Description of the study area

The study area is situated in the Eastern Cape Province, South Africa, about 120 km due west of East London, with a latitude of 32°47'20''S to 32°46'50''S and longitude of 26°50'25''E to 26°51'40''E (Figure 1). The Eastern Cape Province has a surface area of roughly 170 000 km^2, covering about 14% of South Africa's land area (Statistics South Africa, 2011). Mrubata (2012) reported that the area is considered to have semi-arid conditions, with an average rainfall of 500 mm/year. The average monthly temperature varies from 1.5 to 2.5 °C, with the average winter temperature reaching 21 °C and the average summer temperature reaching 28 °C (Amathole District Municipality, 2011). Alice is the capital of Nkonkobe Municipality, where the production of livestock and vegetables characterizes small-scale agriculture. Forestry, tourism, and the production of wool and sheep are additional economic activities. The Tyume River (Figure 1), which flows from the top of the Amathole Mountain in Hogsback, passes through the lower coastal slope down to Alice Town through several communities (Sibanda et al., 2013). The river is used for various domestic activities.

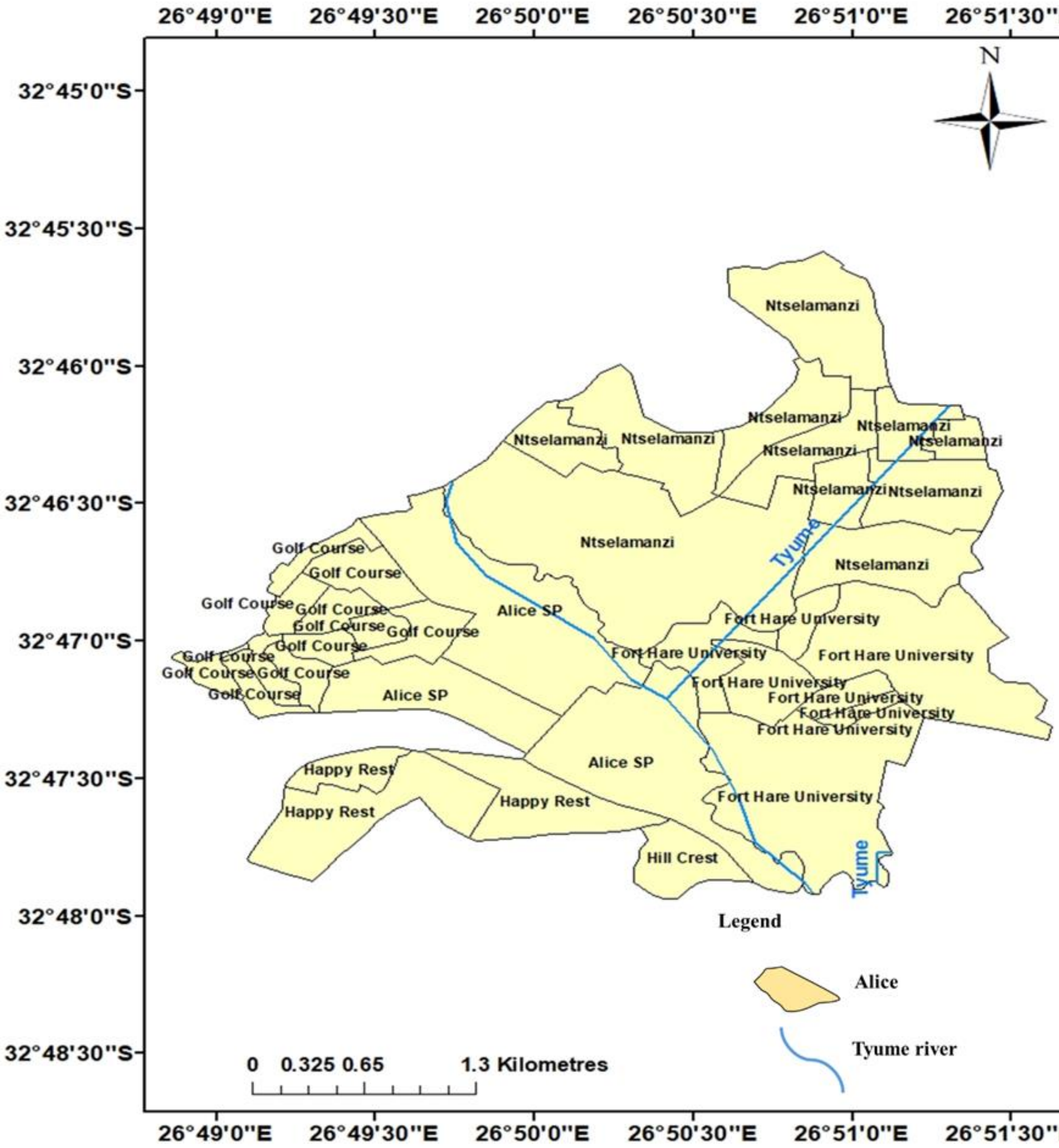


Figure 1: Map of the study area showing the Tyume river.

GEOLOGY

Geologically, Alice is within the Beaufort Group, Karoo Supergroup, the large stratigraphic sequence in the Eastern Cape, South Africa. The Karoo Supergroup originated from the Gondwana Supercontinent (Catuneanu et al., 1998). The majority of the continental deposits of the Karoo Supergroup are categorized under the Beaufort Group, which are formed from a significant part of the sediments deposited by the rapidly rising Cape

Fold Belt (Johnson et al., 1997). The glacial sediments of the Dwyka Group marked the earliest and lowest sedimentary deposits of the Karoo Supergroup (Table 1). The group comprises mudstone, shale, and diamictite (Schluter, 2008). The total thickness of this group is about 600 m - 700 m (Johnson et al., 2006). The Dwyka Group is overlain by the post-glacial Ecca Group, consisting mainly of shale and turbidites, followed by the Beaufort and Stormberg Groups (Johnson et al., 2006). Lastly, the Karoo sedimentary series is covered by the Drakensberg Group. This group consists of very thick basalts (Johnson et al., 2006). Since Alice is located in the Beaufort Group, the geology section will emphasize the Beaufort Group more.

Table 1. Lithostratigraphy of the Karoo Supergroup in the Eastern Cape Province (Johnson et al., 2006).

Supergroup	**Group**	**Subgroup**	**Formation**	**Member**	**Lithology**
KAROO	STORMBERG		Drakensberg		Basalt Pyroclastic-Deposits
			Clarens		Sandstone
			Elliot		Red Mudstone Sandstone
			Molteno		Coarse Sandstone Khaki & Grey Shale Coal Measures
	BEAUFORT	TARKASTD	Burgersdorp		Mudstone Sandstone Grey Shale
			Katberg		Sandstone, Red Mudstone Grey Shale
		ADELAIDE	Balfour	Palingkloof	Red Mudstone Sandstone Grey Shale
				Elandsberg	Sandstone Siltstone
				Barberskrans	Sandstone khaki shale
				Daggaboersnek	Grey Shale Sandstone Siltstone
				Oudeberg	Sandstone Khaki Shale
			Middleton		Shale Sandstone Red Mudstone
			Koonap		Grey Sandstone Shale
			Waterford		Sandstone Shale
			Fort Brown		Shale Sandstone

	ECCA	Ripon	Sandstone Shale
		Collingham	Grey Shale Yellow Claystone
		Whitehill	Black Shale Chert
		Prince Albert	Khaki Shale
		Dwyka	Diamictite Tillite Shale

The Beaufort Group comprises of greenish-grey mudstones, a bluish-grey, lenticular, tabular, fine-to medium-grained sandstone, and reddish-maroon (Visser, 1995). The group includes the upper Tarkastad Subgroup and the lower Adelaide Subgroup (Catuneanu et al., 1998). The Adelaide Subgroup is made up of three formations: Koonap, Middleton, and Balfour Formations. The Koonap Formation consists of sandstones and greenish silty mudstones, and the Middleton Formation comprises greenish-grey mudstones interbedded with sandstones and dark red. Lastly, the Balfour Formation, roughly 1,600 m, 1,300 m, and 2,000 m thick, is a fining-upward sequence of fine-grained sandstones and mudstones (Johnson et al., 1996). The Balfour Formation comprises of five units, namely the Oudeberg Member sequentially overlain by the Palingkloof, Elandsberg, Barberskrans, and Daggaboersnek Member (Johnson et al., 1996).

Alice is stratigraphically within the Daggaboersnek Member of the Balfour Formation, part of the Beaufort Group in the Karoo Supergroup (Figure 2). The local geology of the study area is made up of sedimentary rocks, such as shale, alternating siltstone, mudstone, and sandstone, and further intruded by Karoo dolerite in the forms of dykes and sills (Oghenekome, 2012). This area of study is denoted by fractured aquifers typical within the Karoo Supergroup (Usher et al., 2004). These fractures serve as a passage for groundwater and play a crucial role in the aquifer's general geometry. The shallow Karoo aquifer systems are less than 300 m and supply local communities via boreholes that are usually less than 150 m in depth for farming and domestic use (Rosewarne et al., 2013).

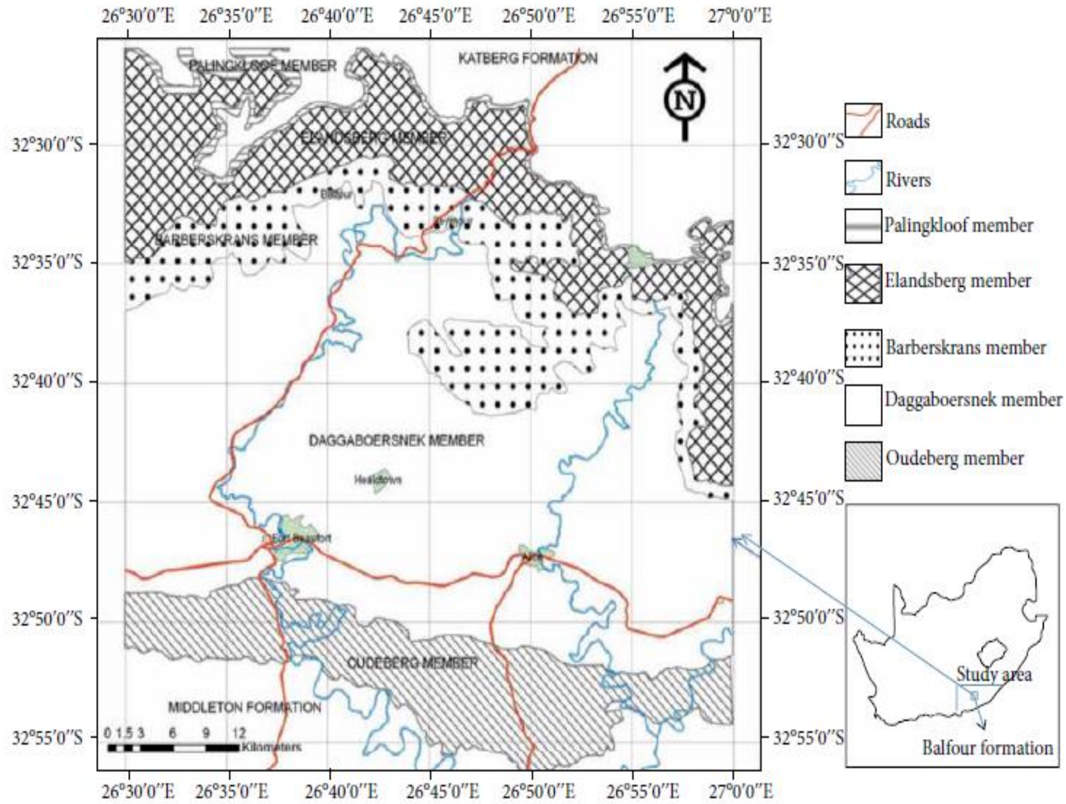


Figure 2. Detailed geological map of Alice (Katemaunzanga and Gunter (2009); Baiyegunhi and Gwavava (2016).

METHODOLOGIES

A total of 30 representative sandstone and mudstone samples were taken from outcrop exposure in the research area and subjected to petrographic microscopy and scanning electron microscopy (SEM) analyses. Ten (10) rock samples comprising sandstone and mudstone were selected for density and porosity measurements.

Petrographic studies

The thin sections petrographic examination used to categorize the mineralogical composition, and rock texture of the sandstones and mudstones was done using an optical Olympus BX51 microscope equipped with an Olympus DP72 camera. Photographs of the different minerals and rock textures discovered on the thin sections were taken and further analyzed to determine the rock types, diagenetic characteristics, grain size variation, cement texture, grain roundness, and sorting. For the SEM, the sandstones and mudstones fragments were cleaned, gold-coated, and examined with a scanning electron microscopy (SEM) machine (Model: JEOL JSM-6390LV, JEOL, Tokyo, Japan)) in a working condition of 15 KV equipped with an Energy Dispersive X-ray microanalyzer (EDX, JEOL JSM-6390SEM, JEOL, Tokyo, Japan). The combination of SEM+EDX was used for the analysis of the pores and fracture, recrystallization effect, diagenetic textures, as well as cement type, mineral, and chemical composition with their percentages. The petrographic study results were used to investigate the porosity and permeability of sedimentary rocks, which have a significant influence on the groundwater storage in Alice.

Procedures for measuring the density of rock samples

Several techniques, like buoyancy determined volume, direct volume measurement, and gas pycnometer, can evaluate the density of rock samples in the laboratory (Reynolds, 1997). In this research, an Adam electronic weighing balance was used to determine the rock densities. This equipment has a measurement range of seventeen units, including pound gram, grain, carat, newton, kilogram, and ounce. The equipment was well balanced on a vibration-free laboratory bench. The hook point at the base of the equipment was positioned so that the laboratory bench hole was directly under it. The loop was fixed to the hook point at the bottom of the equipment through the laboratory bench hole to conveniently hold the rock sample when immersed in the water in the bucket. The equipment was leveled with the spirit level and adjustable feet to allow the bubble in the spirit level to be positioned at the center. A bucket full of water was put under the table so the rock sample on the loop could be submerged in the water without touching the bucket's edges and bottom during measurement (Figure 3). The equipment was connected to a power source. The equipment was given around thirty (30) minutes. Before the measurement began, the weighing device, battery level, and stability were examined and approved. The water density was determined by using a 25 ml density bottle. A water density of 0.9964 g/cm^3 was recorded and used while computing the rock's porosity and density. A thermometer was constantly used to monitor the temperature of the water throughout the experiment period since the water density value depends on its temperature and pressure. The density of water was determined in order to meet the requirement of the formulae to calculate the dry, wet, and particle densities.

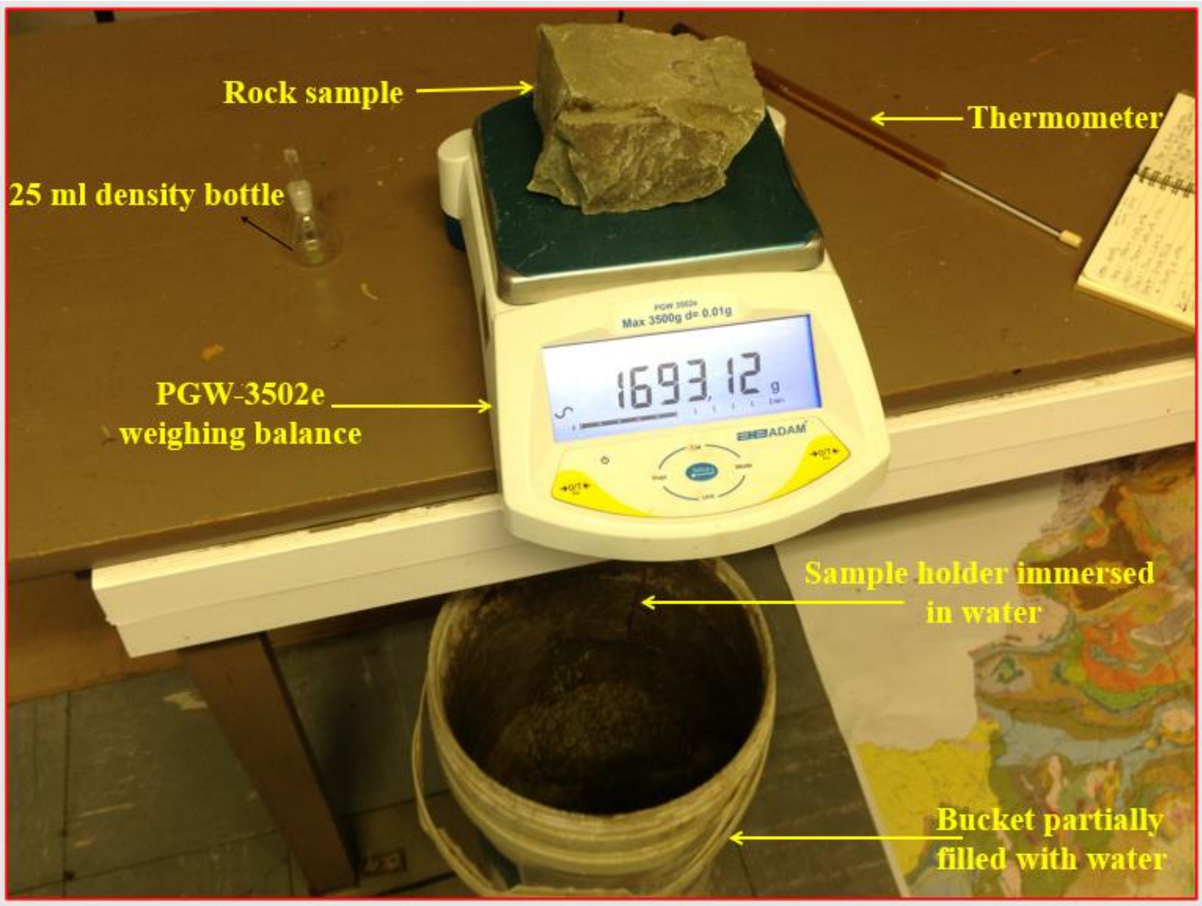


Figure 3. Photo demonstrating the use of Archimedes' Principle in rock samples measurement.

Determination of dry density

The rocks were kept in the sun for 72 hours to evaluate the samples' dry densities. The mass in the air (M_a) was noted after weighing the sun-dried sample on the Adam electronic weighing balance. The rocks were placed one after the other on the loop submerged in the water, and the displayed values were immediately noted to determine the submerged mass (M_b). For all the other dry samples, this procedure was repeated. The dry density is calculated using:

$$\text{Dry density}(\rho_{dry}) = \left(\frac{M_d}{M_d - M_s}\right) \times \rho_w \ , \tag{1}$$

1

where M_d is the dry rock's mass in the air; M_s is the mass of rock submerged in water and ρ_w is the water density.

Determination of particle density

To evaluate the particle density, the rocks were kept in a container filled with water for more than 48 hours to allow the pores to be occupied by water. The saturated mass (M_c) was determined by putting the soaked sample on the loop that was submerged in the bucket filled with water, and measurement was done. For all the other soaked samples, this procedure was repeated. The particle or grain density of the rock is calculated using:

$$\text{Particle or grain density } (\rho_{particle}) = \left(\frac{M_d}{M_d - M_w}\right) \times \rho_w \ , \tag{2}$$

2

where $\rho_{particle}$= particle density; M_d = mass of dry rock in the air; M_w= mass of wet rock in water and ρ_w is the water density.

Determination of porosity

Porosity (Φ) is defined as the ratio of the volume of the pore spaces (V_f) to the total volume (V) of the rock (equation 3)

$$\text{Porosity } (\Phi) = \frac{V_f}{V} \tag{3}$$

Meanwhile,

$$\rho_{dry} = \rho_{particle}(1 - \Phi) \tag{4}$$

$$\text{Porosity } (\Phi) = \left(1 - \frac{\rho_{dry}}{\rho_{particle}}\right) \tag{5}$$

Otherwise, it is generally calculated using:

$$\textbf{Porosity } (\boldsymbol{\Phi}) = \left(1 - \frac{\rho_{dry}}{\rho_{particle}}\right) \times 100\ \% \tag{6}$$

Determination of wet density

It is defined as the addition of the dry density (ρ_{dry}) with the product of porosity (Φ) and water density (ρ_w). The rock was soaked in water for a lengthy time, filling all the openings with water. The wet density of the rock is calculated using:

$$\text{Wet density } (\rho_{wet}) = \rho_{\text{dry}} + (\phi \times \text{Density}_{\text{water}}) \;, \tag{7}$$

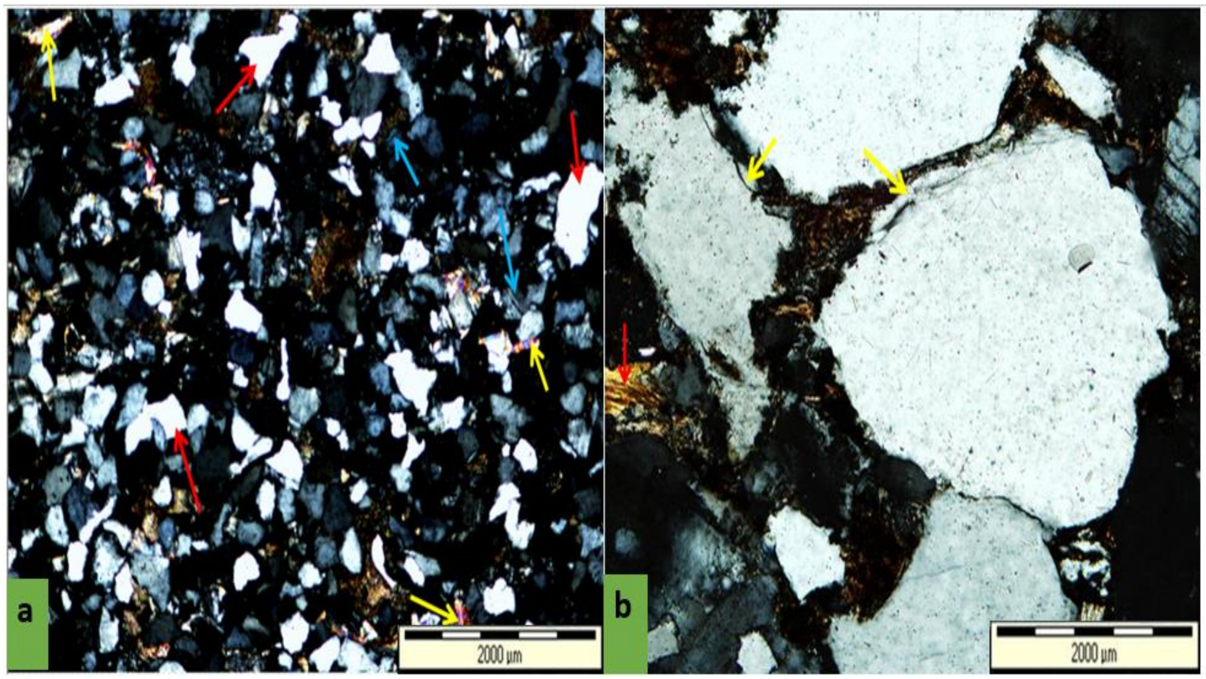
where $\boldsymbol{\rho_{wet}}$ = wet density; $\boldsymbol{\rho_{\text{dry}}}$ = dry density; Φ = porosity; $\boldsymbol{V_f}$ = volume of voids.

RESULTS AND DISCUSSION

Mineral compositions

Quartz

Quartz was observed abundantly within all the sandstone samples. The most common crystal structure for quartz is monocrystalline (Figure 4a). The monocrystalline quartz grains, which also occur as an overgrowth, show uniform to moderately undulose extinction (Figure 4b). The quartz grains mostly vary from subangular to subrounded. In addition, the quartz grains are free of inclusions. The recrystallization that occurred at the grain edge of quartz grains led to the development of pores (Figure 4c) as observed under the SEM+ EDX analysis.



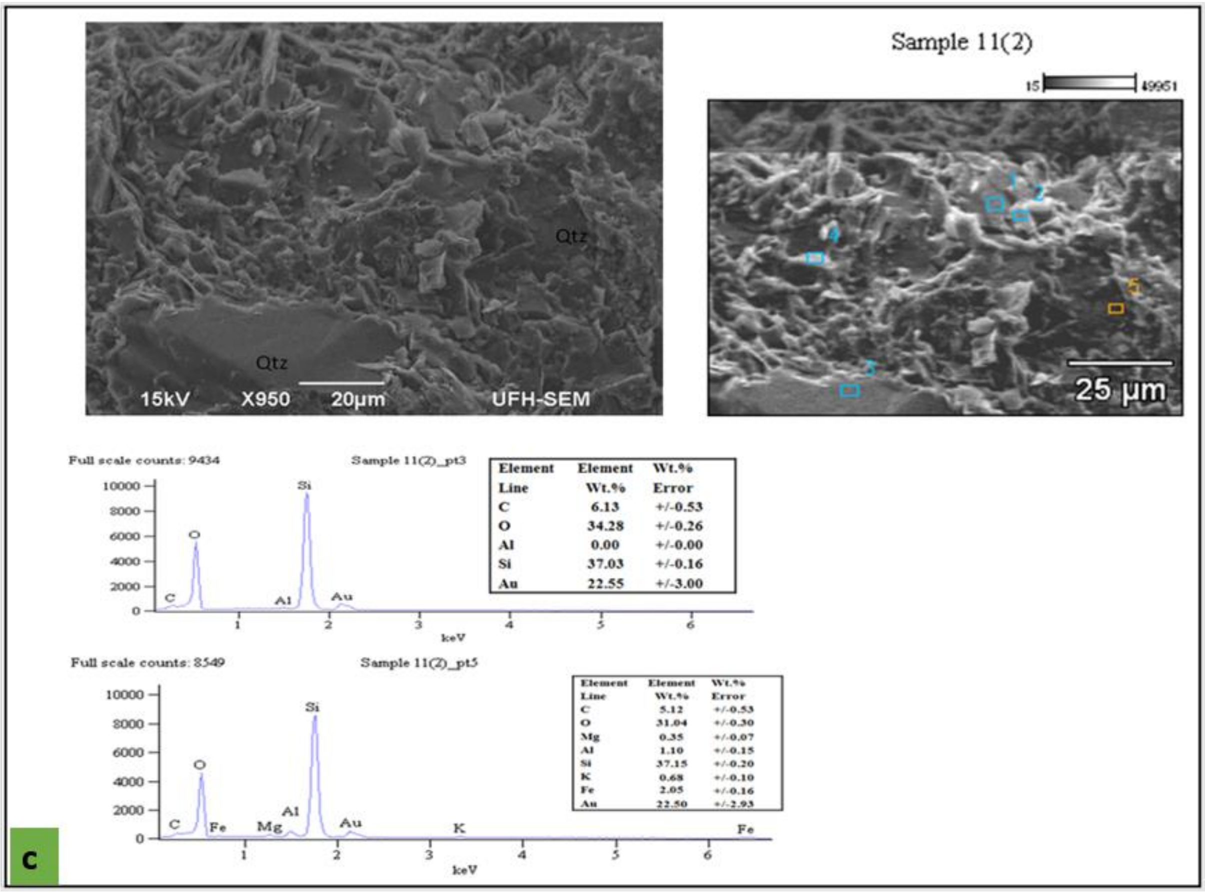


Figure 4. Petrographic study of sandstone displaying: (a) quartz grain (red arrows), plagioclase (blue arrows), and muscovite grains (yellow arrows); (b) quartz overgrowth (yellow arrow) and muscovite grains (red arrow); (c) Scanning electronic microscopy (SEM) photomicrograph and the EDX graphs indicating quartz composition of Si and O rich (SiO_2) with various elements present in quartz grains at points 3 and 5.

Feldspar

The second most common mineral found in the rocks with different grain types and sizes is feldspar. It exists in both authentic and detrital forms. The various types of feldspar minerals which can be seen in the thin sections are plagioclase and alkali (microcline and orthoclase) feldspars. Plagioclase can be identified through the albite twinning of grey and black lines (Figure 5a). Microcline can be found in a few places, and it underwent recrystallization to albite (Figure 5b). Furthermore, it exhibits cross-hatch twinning while albite grains have parallel twinning. Some of the plagioclase grains have been broken apart due to compaction (Figure 5c). The orthoclase grains exhibit perthite texture with minor twinning (Figure 5d). The feldspar grains vary from subangular to subrounded, though few are slightly changed to illite.

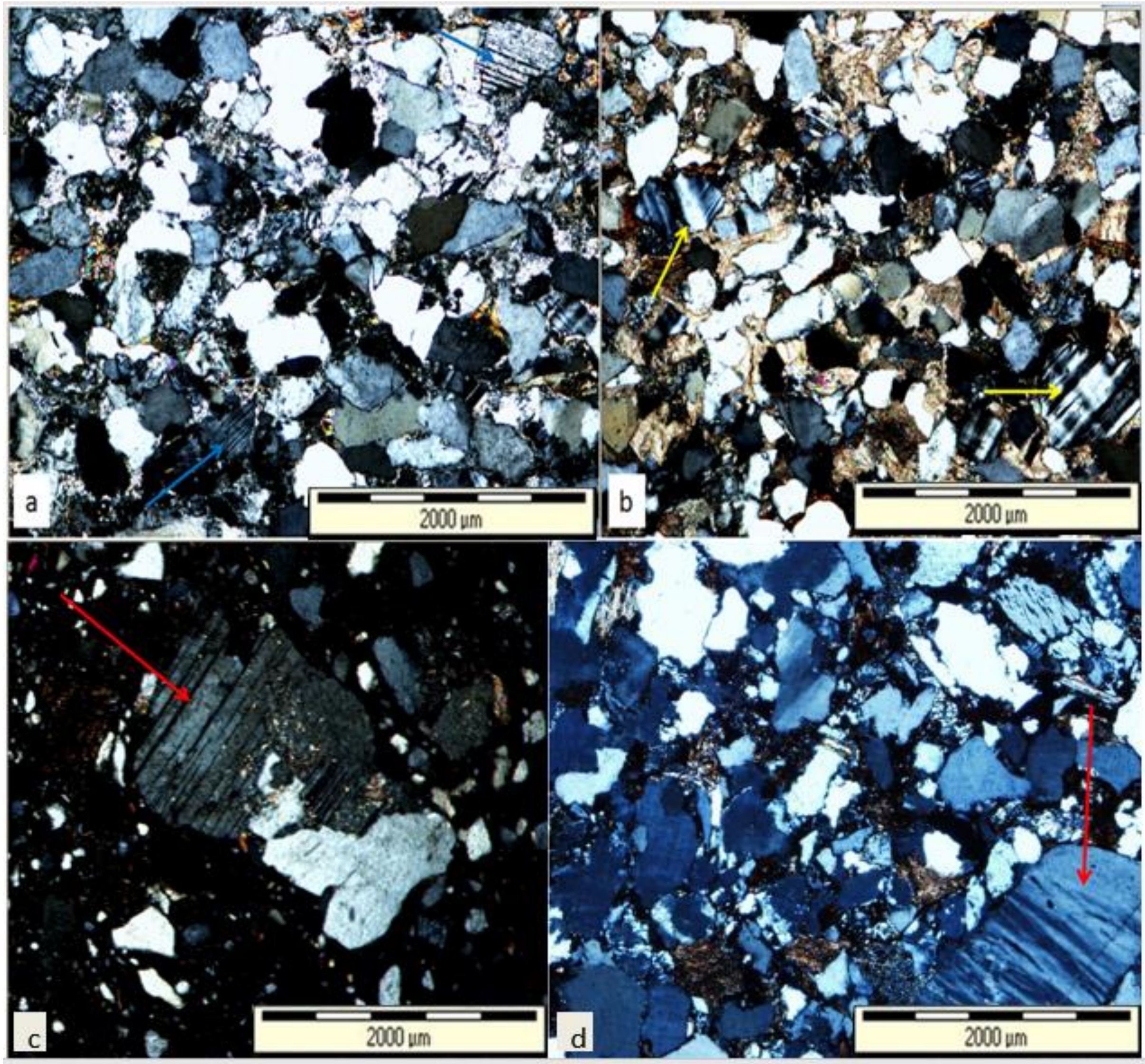


Figure 5. Thin section analysis illustrating: (a) Plagioclase feldspar (blue arrows); (b) Microcline partially altered to albite (yellow arrow); (c) Feldspar which has been broken (red arrow) along cleavage; (d) Perthitic texture of feldspar (red arrow).

Lithics

These are referred to as rock fragments which are eroded and broken to sand size and later form lithic sand grains. They are considered unstable in sedimentary environments and serve as provenance indicators for sediments. The types of lithics that were observed in the thin section of the rock samples are sedimentary, metamorphic, and volcanic types (Figure 6a-c). They occur as subangular to subrounded grains.

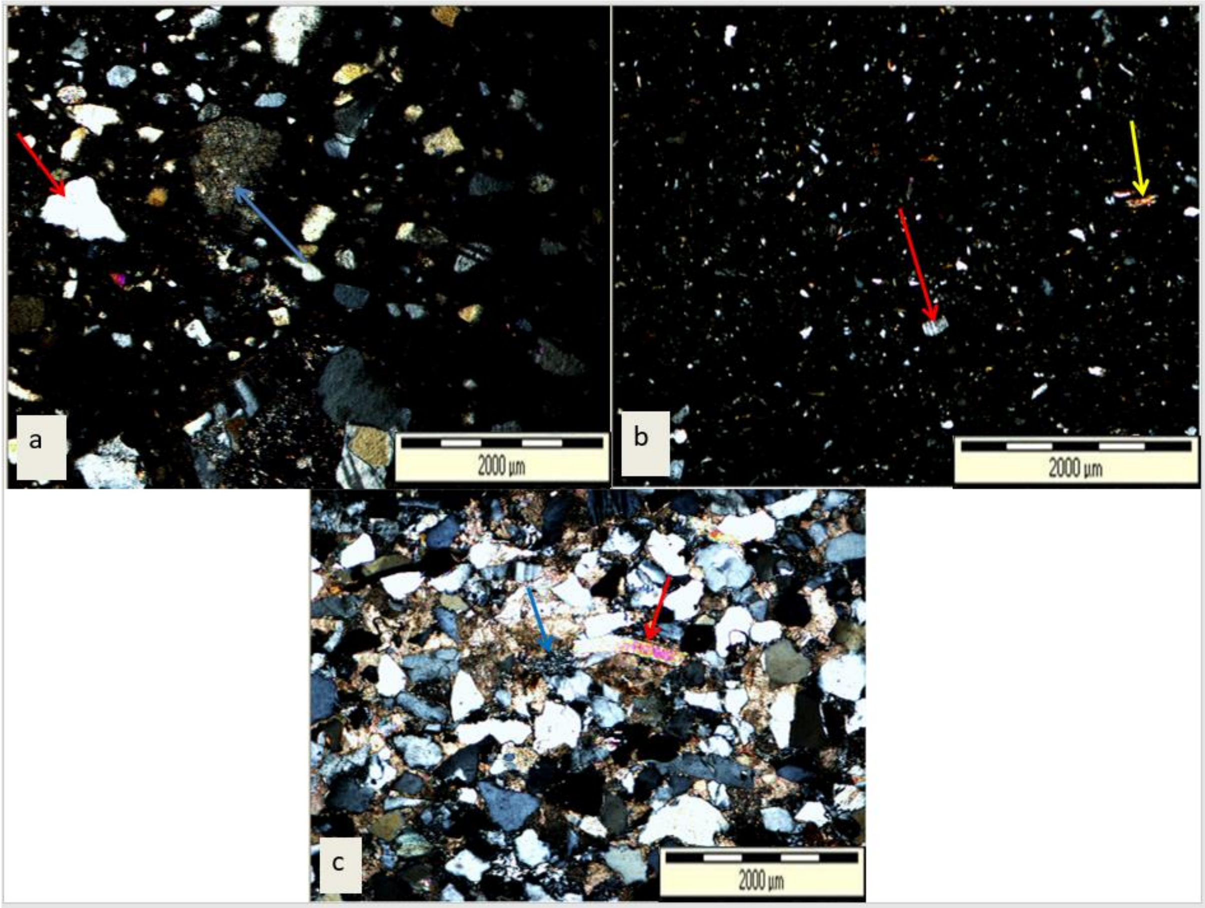


Figure 6. Thin section analysis showing: (a) Metamorphic lithic (blue arrow) and poorly sorted quartz grains (red arrow); (b) Mudstone showing quartz (white points), feldspar (red arrow), and muscovite (yellow arrow); (c) Volcanic lithic (blue arrow) with detrital quartz (white), feldspar (yellow arrow) and muscovite (red arrow).

Mica

The two types of mica observed in the study area rocks are muscovite and biotite, with a more frequent occurrence of muscovite than biotite. Chemically, muscovite is more stable in a depositional environment when compared with biotite. Hence, it can be well retained. Among the common detrital accessory framework minerals, this mineral was recognized for its perfect cleavage and combination of many colors such as blue, yellow, and red (Figure 7a-c).

Among other grains and matrix, muscovite flakes are distinctly parallel or squeezed flat (Figure 7a). Sometimes, the detrital muscovite grains are fractured and occur as an elongated flaky shape with boundaries that are well defined (Figure 7b). The fracture suggests that high overburden pressure resulted in the recrystallization. The recrystallization of clay during diagenesis resulted to the development of mica minerals which can be observed in the clay matrix (Figure 7c).

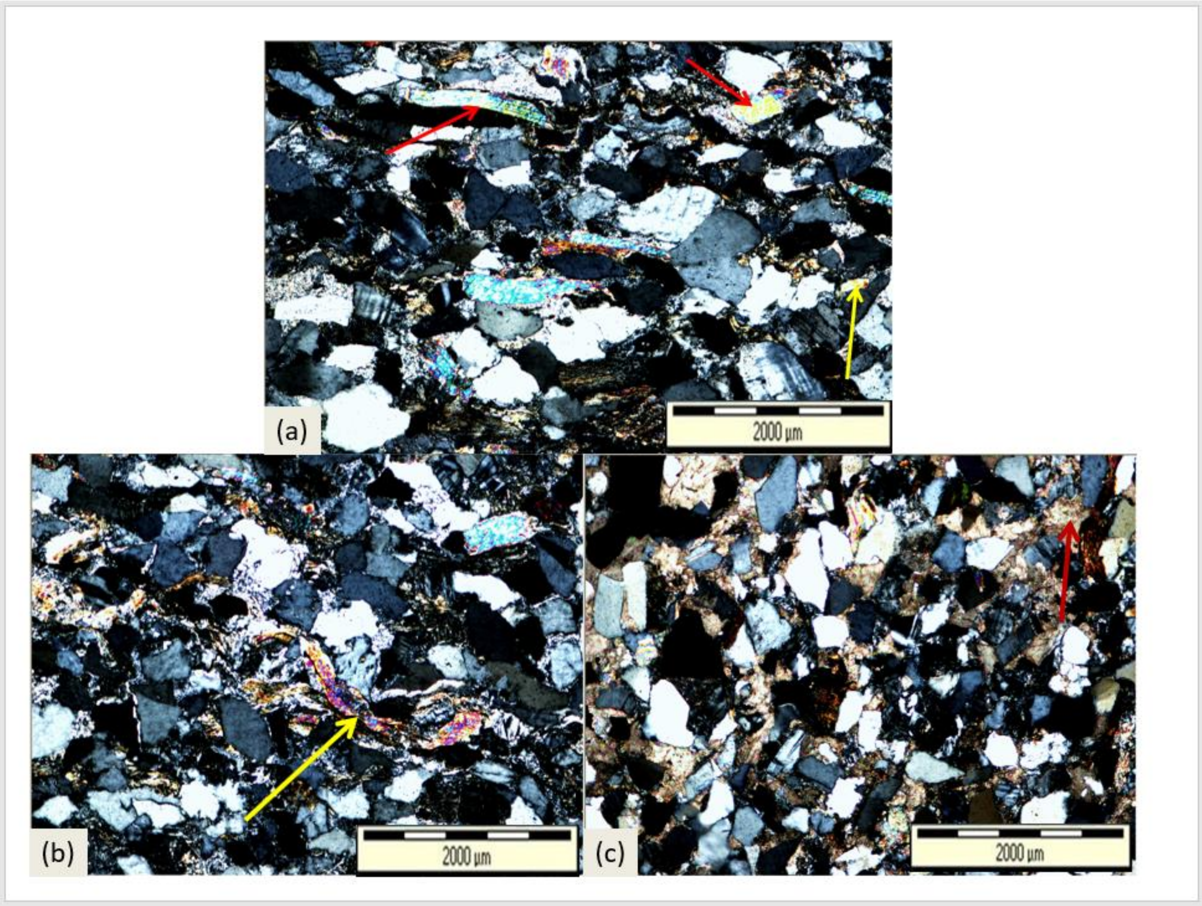


Figure 7. Petrographic image displaying: (a) Biotite (yellow arrow) and muscovite (red arrows); (b) Deformed muscovite flakes (yellow arrow); (c) Clay matrix which has been recrystallized to muscovite (red arrow).

Diagenesis of sandstones and mudstones

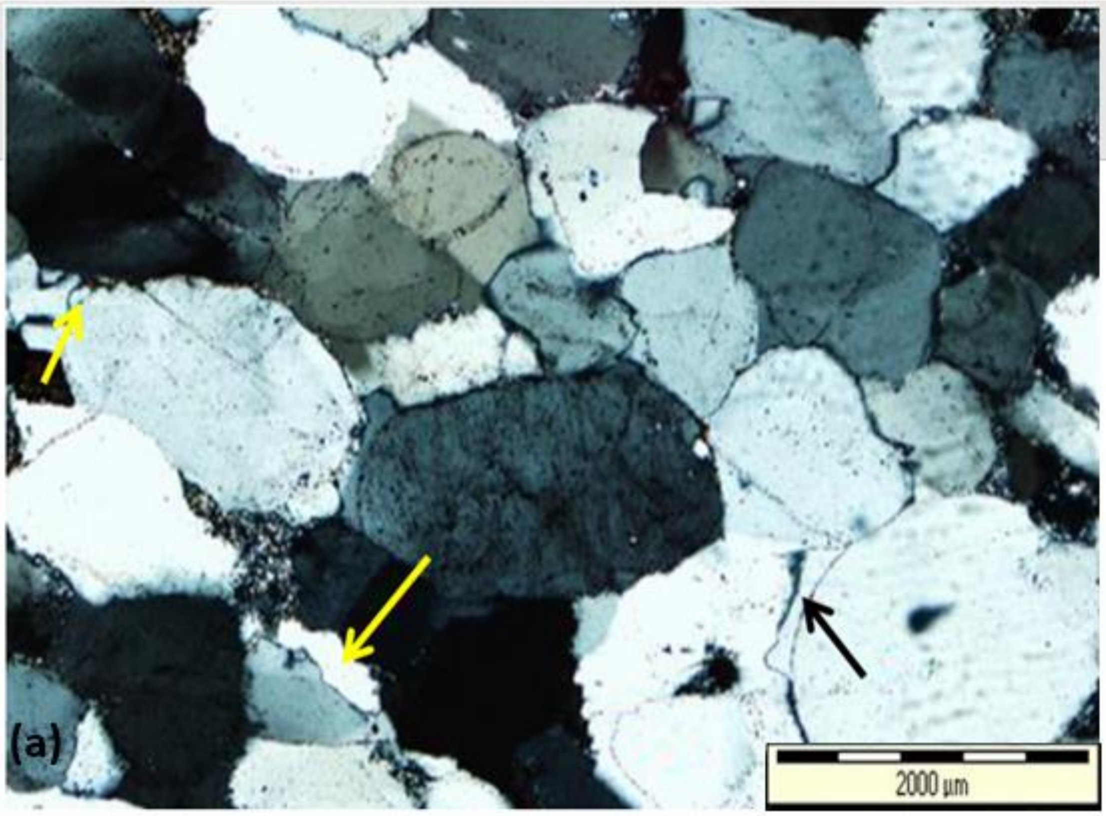
The following diagenetic processes have an impact on the sandstone and mudstone collected from the study area, and they are; cementation, mineral replacement, dissolution, and recrystallization.

Cementation

This is among the most significant processes which change loose sediments into consolidated rock, thereby decreasing the porosity level of rocks. The following kinds of cement were observed in the rock samples collected from the study area: calcite, quartz, feldspar, and authigenic clay mineral cement such as kaolinite and illite clay.

Quartz cement

This type of cement occurs in the rocks due to the precipitation of silica between grains into the openings. Figure 8a shows well-developed quartz overgrowths and cement identified in some pore spaces of the rocks. Therefore, it is formed in the rocks as pore-filling cement. The SEM+ EDX analysis (Figure 8b-c) reveals that the quartz primarily consists of silica and oxygen, while sodium, aluminum, and iron elements are present in small quantities. This is accurate in terms of the quartz chemical formula (SiO_2).


(a)
2000 µm

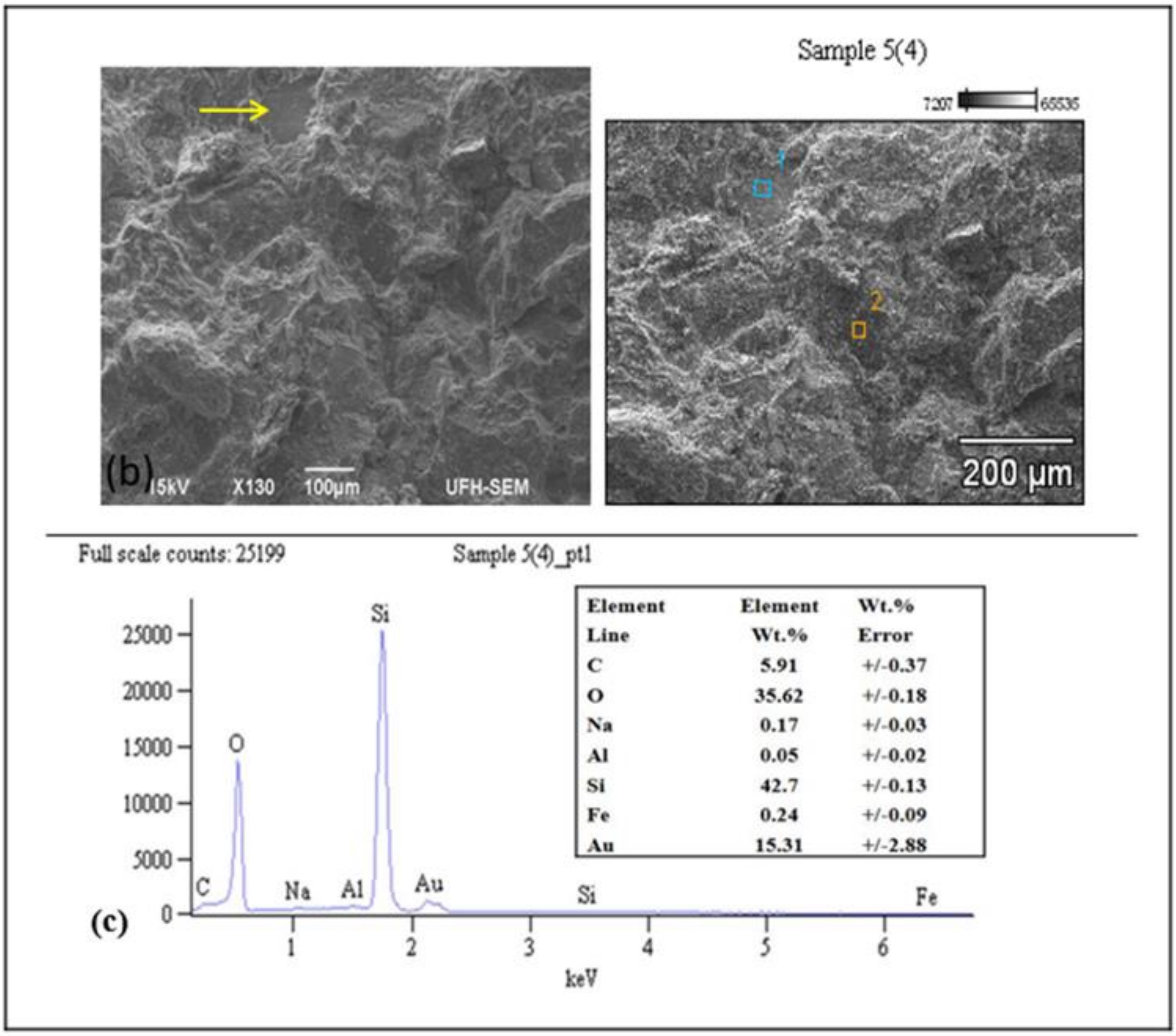


Figure 8. Thin section of sandstone illustrating: (a) quartz cement (yellow arrows) and quartz overgrowth (black arrow); (b) Scanning electron microscopy (SEM) photomicrograph indicating quartz grain (yellow arrow); (c) SEM+EDX graph indicating the composition of Si and O rich of quartz with various elements present in quartz grain at point 1.

Calcite cementation

This kind of cement was observed in the study area rock samples. It occurs as either pore-filling cement or as a replacing mineral of clay matrix. The cement was found not to dominate much of the analyzed samples. Calcite is precipitated in the openings and replaces quartz grains and matrix minerals, as seen in Figure 9. This mineral was also identified by studying the elements composed in EDX analysis. The observed elemental compositions of calcite correlate with the chemical formula of calcite ($CaCO_3$).

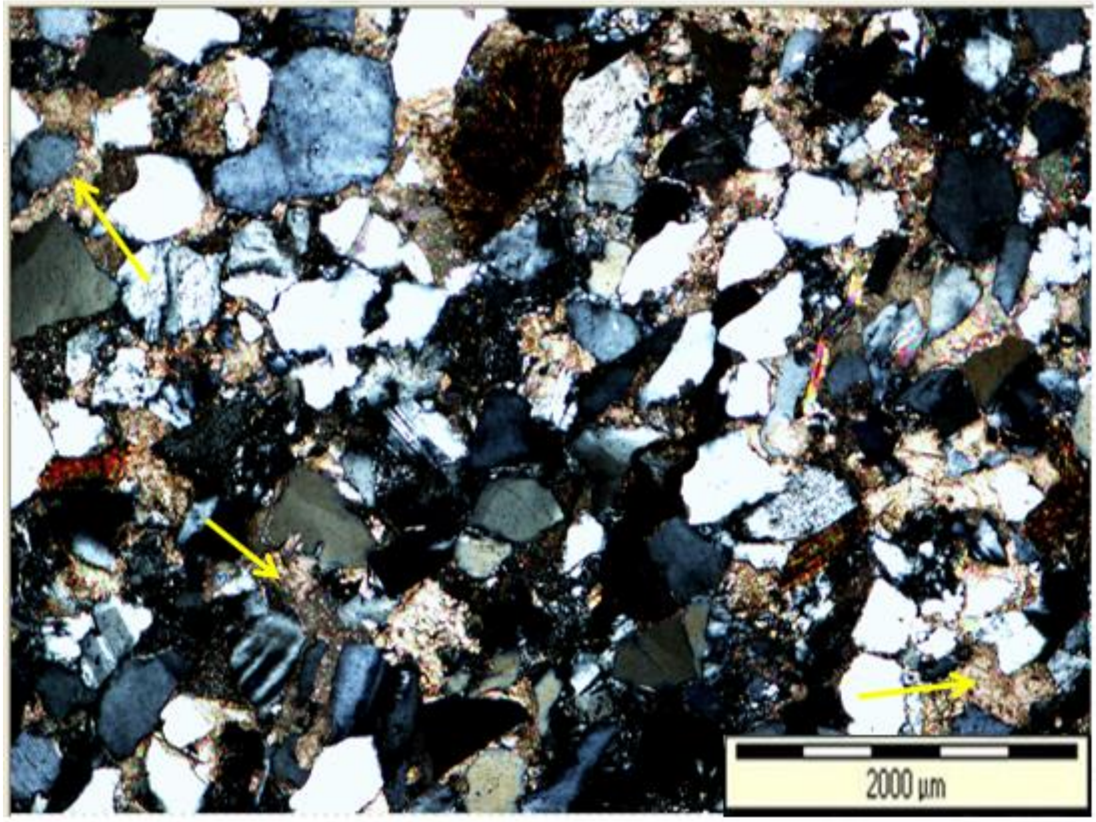


Figure 9. Thin section analysis illustrating calcite cement (yellow arrows) replacing quartz grains and clay matrix.

Clay cementation

Clay minerals (illite and kaolinite) are the main types of clay that serve as a means of cementation in rock samples. Most of the observed clay exists as pore-filling minerals, while some were found replacing the detrital grains. They might have been developed during the changing of one type of clay mineral to the other. Below are the descriptions of clay minerals observed during the SEM+EDX analyses:

Illite

This mineral was found as a pore-filling mineral (Figure 10a). Illitization generally takes place after kaolinite and smectite have been precipitated and also involves an influx of potassium at a greater temperature (Baiyegunhi et al., 2017). The observed illite occurs in a fabric shape. The EDX graphs (Figure 10a and b) show that the major elements found in the mineral are silica and aluminum, while other minor elements include iron, potassium, and magnesium. The observed elemental compositions of illite correlate with its chemical formula: $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2(H_2O)$.

Even though illitic clays are sometimes developed after kaolinite has been decomposed, kaolinite is not always decomposed when illitic cement are formed (Hurst and Irwin, 1982).

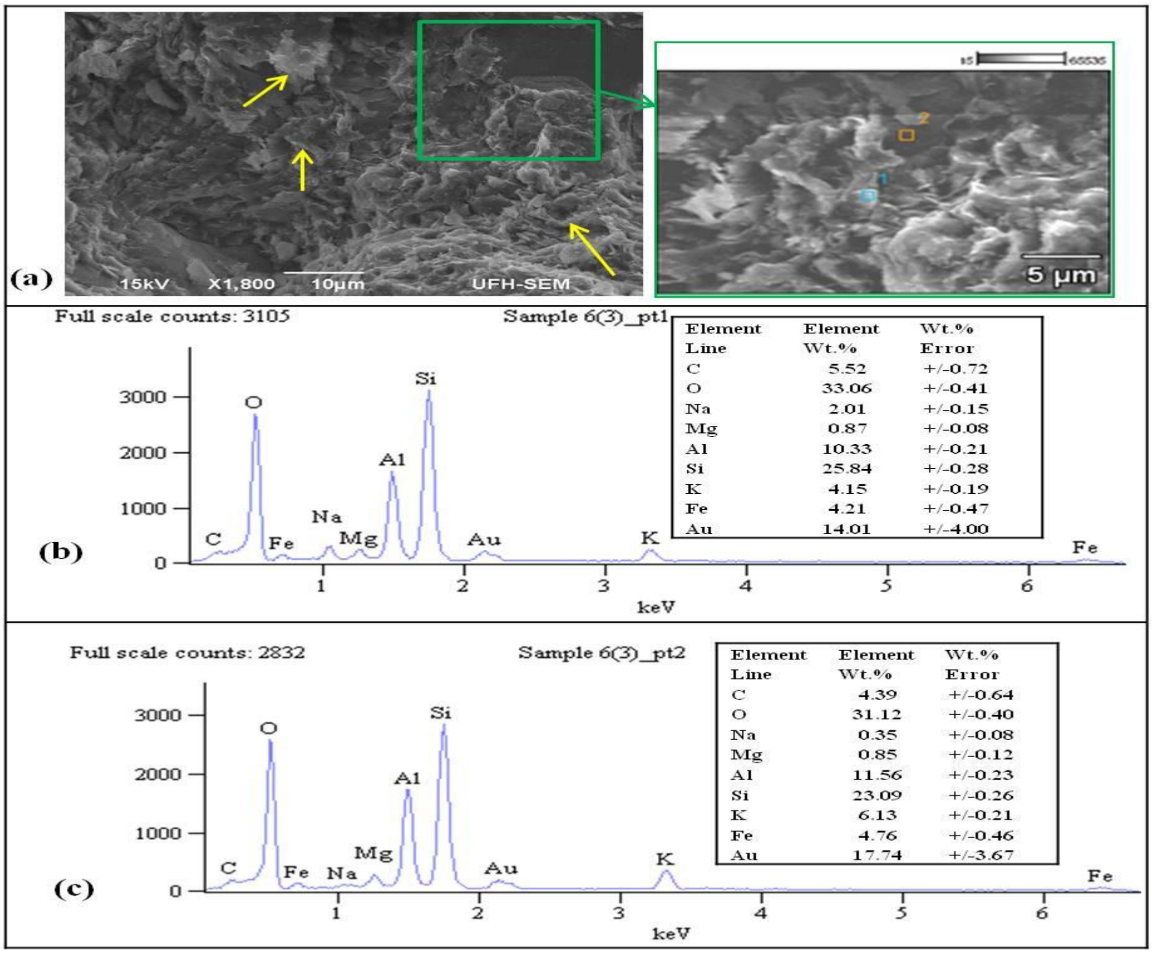


Figure 10. (a) SEM photomicrograph of sandstone displaying illite, which occurs in fibrous shape (yellow arrows); (b) SEM+EDX indicating the composition of various elements present in illite at point 1; (c) Graphs indicating the composition of various elements present in clay mineral cement at point 2.

Kaolinite

Kaolinite clay can be found in the rock samples as clay cement, which fills up the pore spaces. It also exists as a common replacement mineral, which replaces K-feldspar. Kaolinite may be originally detrital or authigenic. The detrital kaolinite is deposited through erosion and transportation from the continental surface, whereas the authigenic kaolinite is developed right in the depositional basin. The EDX graph (Figure 11) indicates that the mineral consists primarily of silica and aluminum with a small quantity of potassium and magnesium.

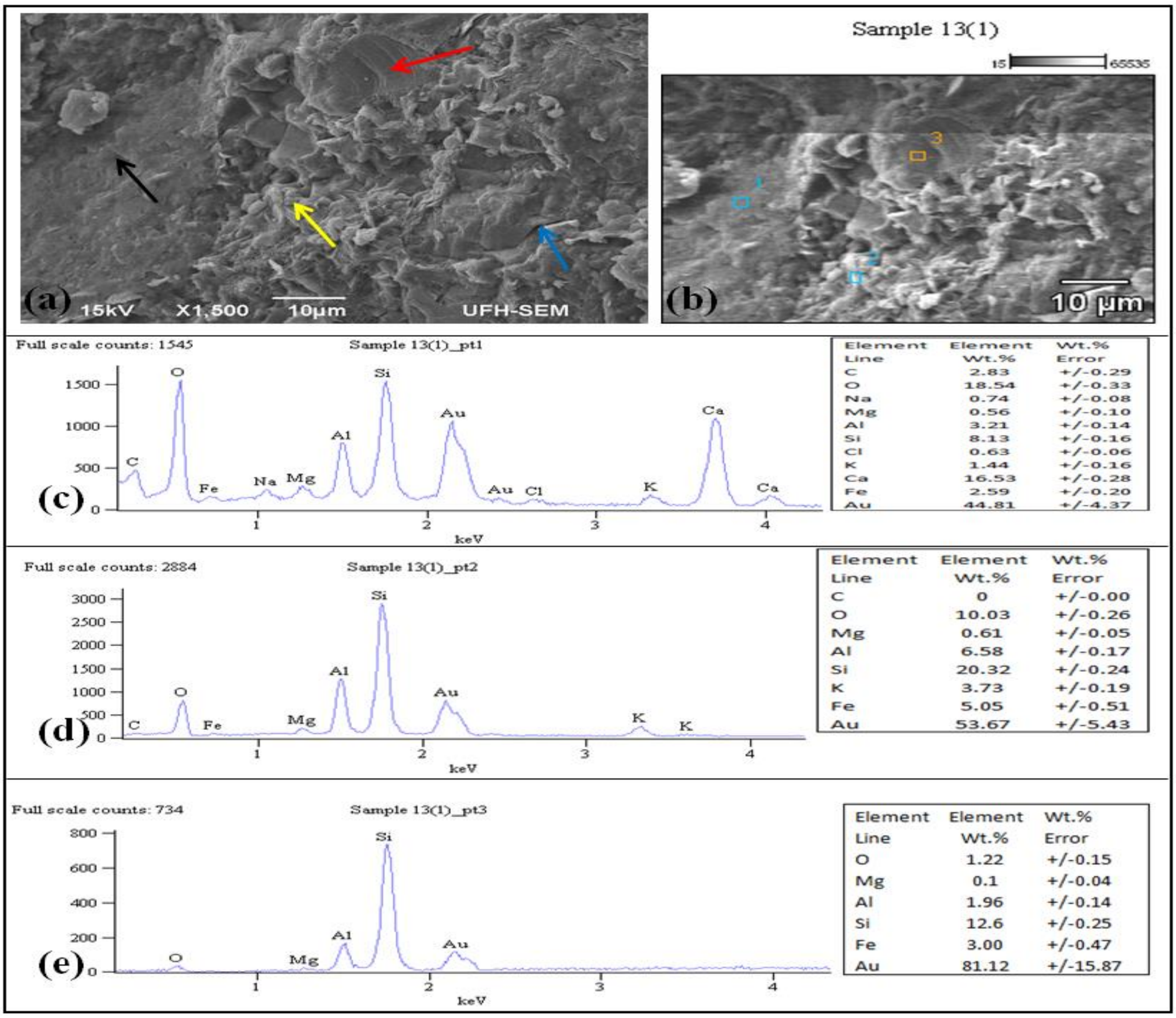


Figure 11. (a) SEM photomicrograph of sandstone indicating kaolinite cement (yellow arrow), quartz grain (red arrow), plagioclase grain consisting of Ca (black arrow), and intercrystalline pore/fracture, which can serve as water storage (blue arrow); (c) SEM+EDX indicating the composition of different elements found in plagioclase grain at point 1; (d) SEM+EDX graphs indicating the composition of different elements found in kaolinite cement at point 2; (e) The SEM+EDX analyses of sandstone showing kaolinite cement which are Si, Al, K and O rich. The Au peak was due to Au coating.

Feldspar cementation

This type of cement can be found in the study area. It occurs as pore-filling feldspar (Figure 12a). Feldspar cement acts as an authigenic opening-fill type of cement and depicts an early diagenetic mineral. This type of cement grew up from the mud, thereby filling the pore spaces. EDX graph, which is found in Figure 12b, shows the elemental composition of the described feldspar minerals.

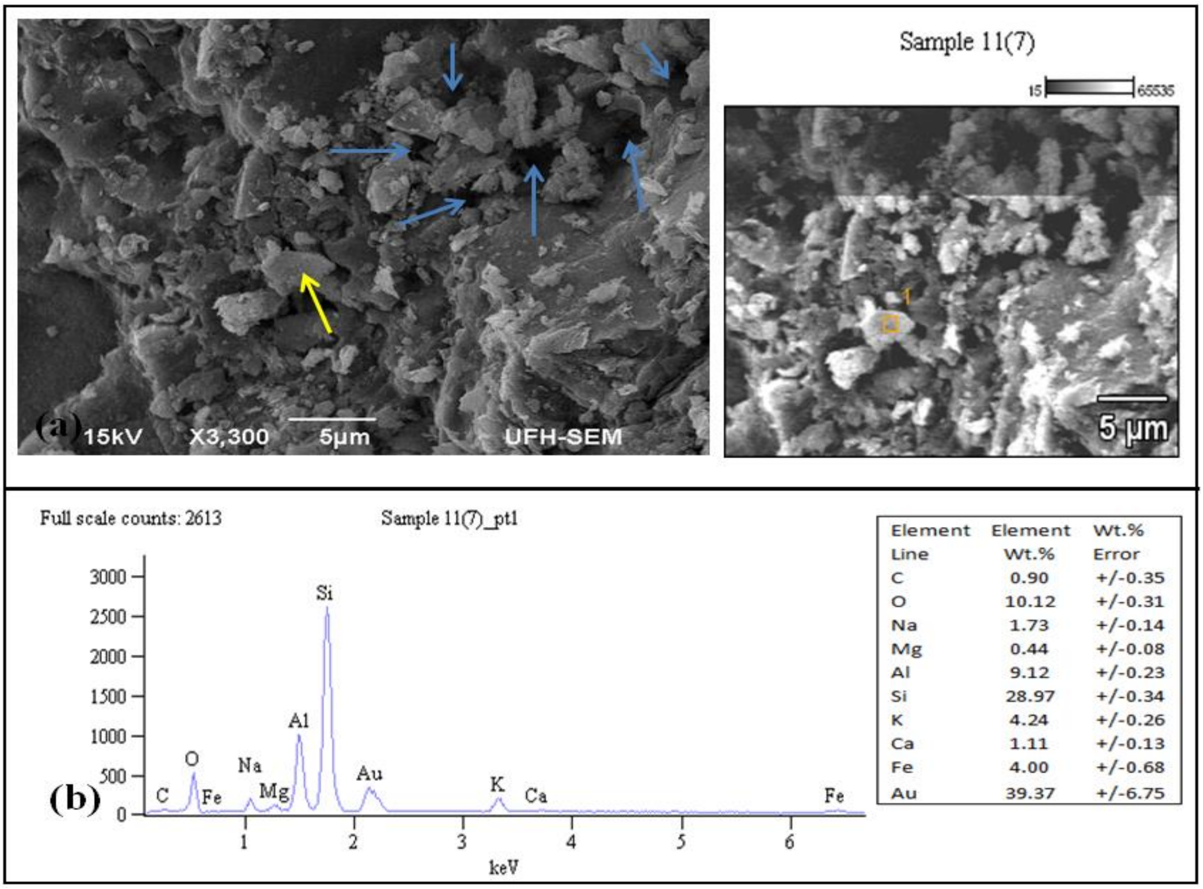


Figure 12. SEM image of mudstone from the study area indicating intergranular pores (blue arrow); (b) EDX graph indicating the composition of several elements existing in authigenic feldspar. The Au peak was due to Au coating.

4.6.1.2. Dissolution

Dissolution, as reported by Boggs (2014), includes removing all or part of existing minerals in a solution and creating a pore in the rocks, which can serve as groundwater storage. Dissolution causes a fracture in the analyzed rock samples (Figure 13). SEM+EDX results showed that some kaolinite was developed owing to the dissolution of K-feldspars, releasing silica, thereby offering a source of silica for the authigenic quartz development. The formation of authigenic quartz is also enhanced by the replacement and dissolution of feldspar to illite. Secondary porosity might have been developed due to this.

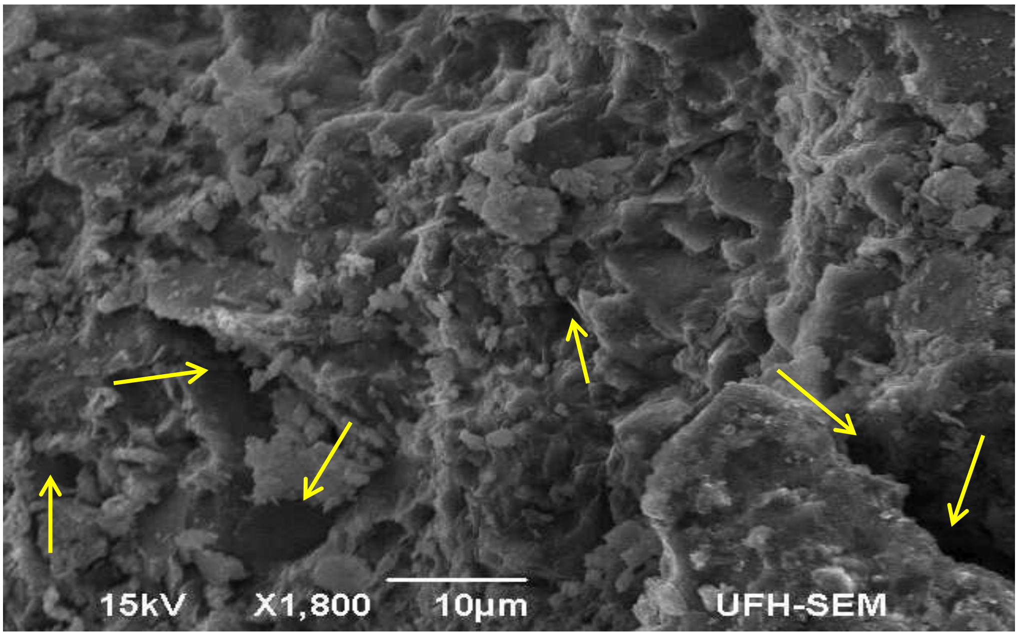
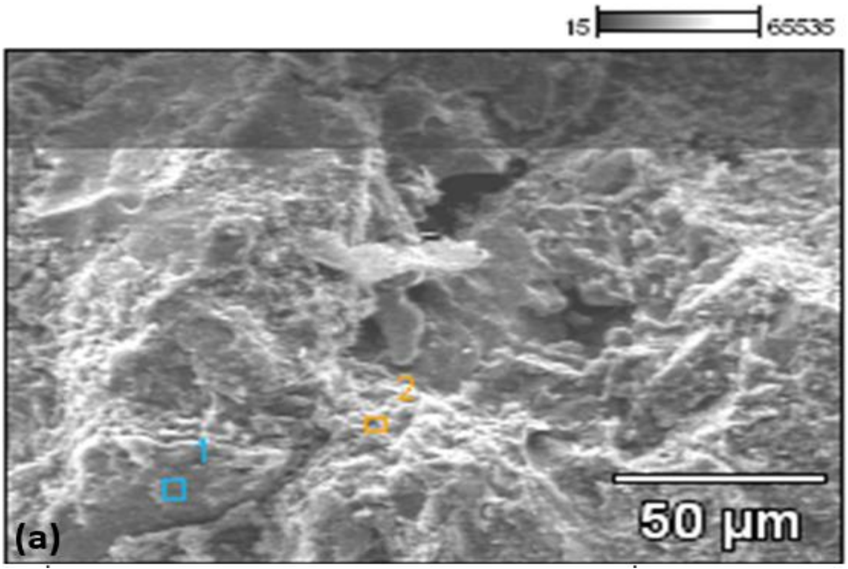


Figure 13. SEM image of mudstone from the study area indicating various dissolution pores/fractures (yellow arrows).

Recrystallization

This is a prevalent occurrence in the study area's rock samples. Recrystallization means changing the shape as well as the size of a specified mineral's crystals without changing the chemical composition or the mineral composition thereafter. Fine textures and micro-granular minerals can recrystallize into coarse textures when temperature and pressure rise with deep burial depth. Smectite and kaolinite progressively change to illite, later to sericite after recrystallization (Figure 14a). The findings of SEM+EDX showed that authigenic minerals such as quartz and feldspars overgrowths are the changed silicate mineral recrystallization. Also, it was observed in the rock samples that kaolinite transformed into illite. This may imply that, as a consequence of partial modification or recrystallization of kaolinite, illite and sericite were developed.

Sample 11(3)



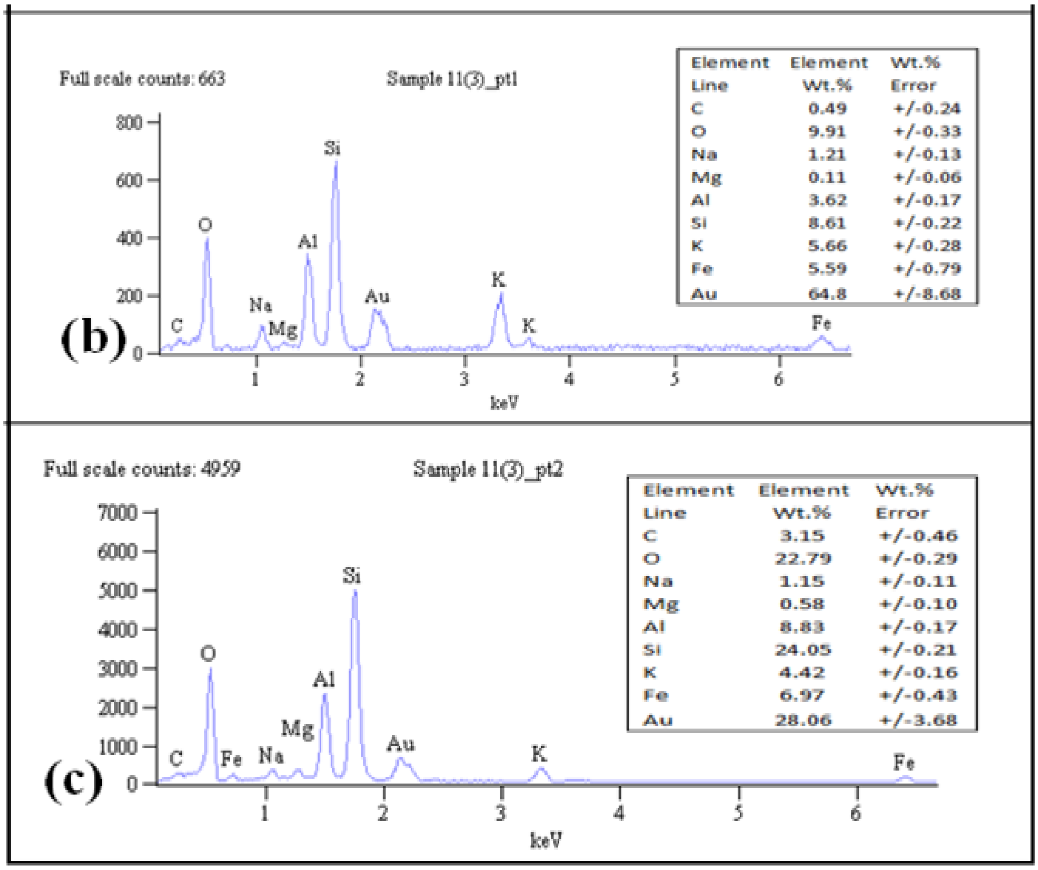


Figure 14. (a) SEM photomicrograph showing kaolinite (point 1), illite (point 2), and intergranular pores (yellow arrows); **(b)** EDX graph indicating the composition of various elements present in kaolinite at point 1; **(c)** Graph indicating the composition of various elements present in illite at point 2.

Mineral replacement

Mineral replacement takes place when void fluids are not in equilibrium with the rock fragments, hence enhancing solution-precipitation reactions (Worden and Burley, 2003). The texture and composition of rocks are changed during this process, and further fluid migration tends to enhance cementation. Temperature and pressure change after deep buried may be the reasons that caused mineral replacement from one to another. Secondary porosities could be developed during the replacement processes.

The findings of SEM+EDX showed that some cement and grains are replaced by authigenic minerals. Calcite replacing feldspar, clay matrix, and quartz (Figure 15) is a common process of replacement in the sandstones examined. The replacements of minerals in rocks identified throughout the analysis include calcite replacing quartz, clay matrix, and feldspar, along with kaolinitization and illitization. Plagioclase feldspar was the most affected. Feldspar mineral replacement with calcite promoted the development of openings in the rocks.

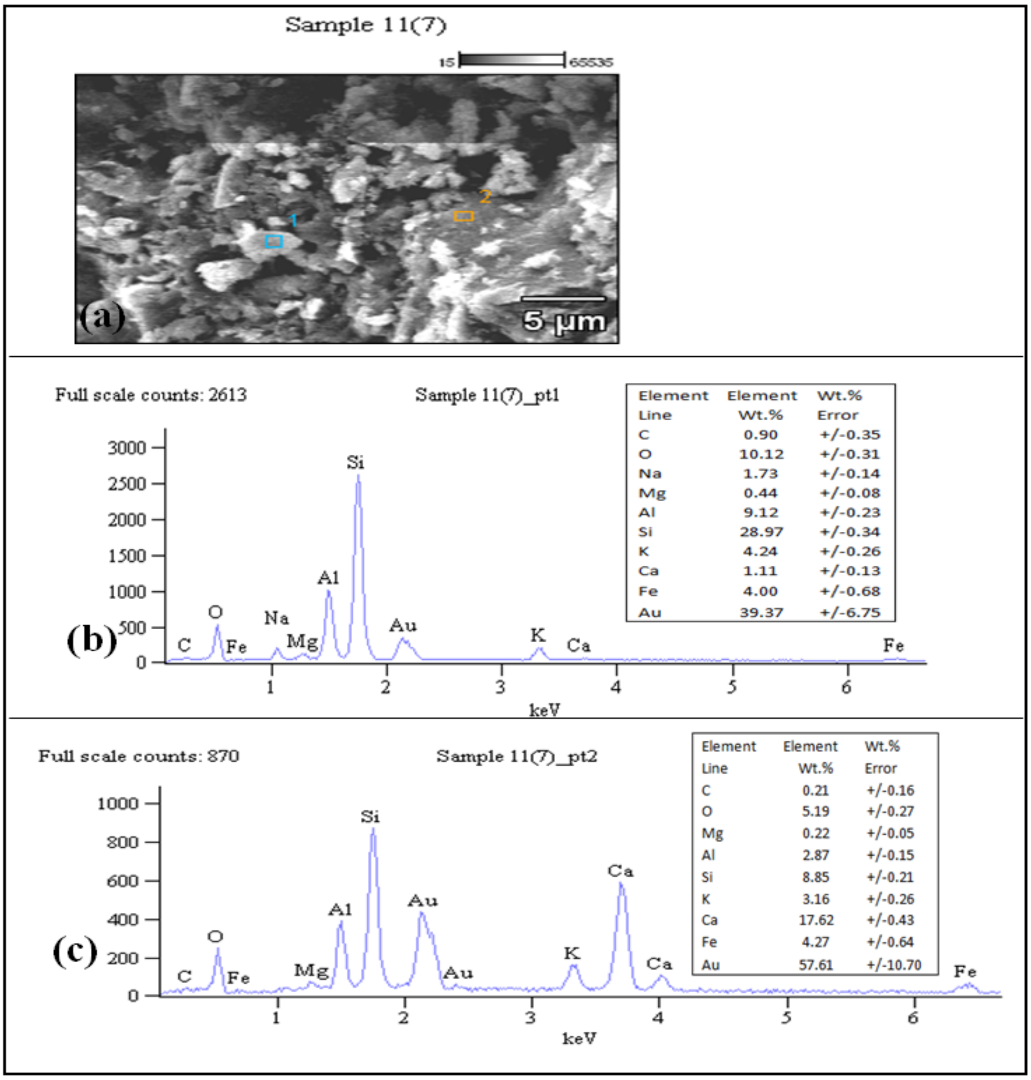


Figure 15. (a) SEM photomicrograph showing plagioclase feldspar (point 1) and calcite (point 2); (b) EDX graph indicating the composition of various elements present in plagioclase feldspar (point 1); (c) EDX graph showing the composition of various elements present in calcite replacing plagioclase (point 2).

Primary and secondary porosity

The important factors that examine the characteristics of the rock reservoir are porosity and permeability. Porosity is categorized into two major types, which are primary and secondary porosity. The primary pores develop during the sedimentation process, while secondary pores are created during diagenesis (following deposition) (Selley, 2000). The observations from SEM analysis of sandstones indicated the two types of porosity. The examined primary pores can be classified as intergranular and micro-pores (Figure 16a). The secondary pores are secondary dissolution pores and fractured pores (Figure 16b).

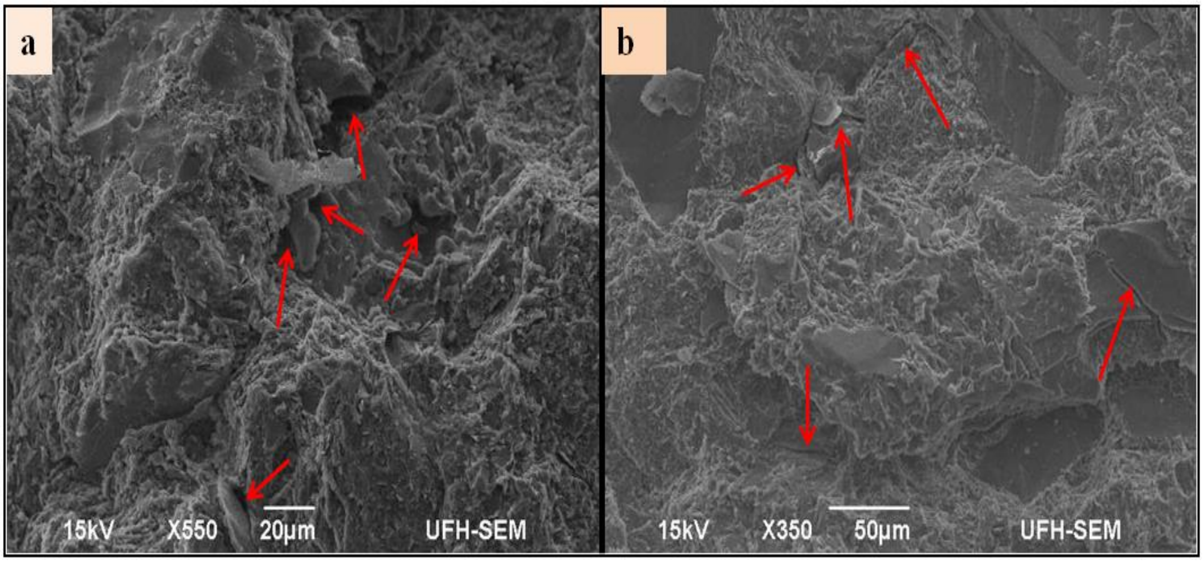


Figure 16. Scanning electron microscopy photomicrograph indicating (a) primary intergranular openin*gs* and secondary fracture (left 3 arrows along a crack) in sandstone (red arrows); (b) primary micro-pores in a sandstone collected from the study area (red arrows).

Implications of diagenesis for aquifer properties

The correlation between porosity and permeability, which can take several forms, is what determines the quality of an aquifer. The important characteristics of sedimentary rocks partly controlled by the grain packing, size, and shape are porosity and permeability (Baiyegunhi et al., 2017). As well, they play an important part in the diagenesis of sediments by regulating the flow of fluids through rocks. Petrographic investigation of the rocks showed primary and secondary porosity, hence suggesting groundwater potential. SEM shows that some of the rocks are influenced by fracturing and are characterized by a network of tiny fractures. The bedrock becomes more permeable through fractures, permitting more groundwater flow and storage. The presence of quartz cement and overgrowth in sandstones consequently decreased the porosity and permeability in the rocks because they destroy primary porosity. Regarding aquifer quality, the primary porosity was reduced by cementation and compaction, which was later increased by the dissolution of unstable minerals such as feldspars. The porosity and permeability of the majority of the rocks allow groundwater storage.

Density and porosity results

Table 2 below shows the dry density, wet density, particle density, and porosity measurements.

Table 2. Density and porosity results of the collected rock samples (S represents sandstone and M represents mudstone).

LITHOLOGY	DRY DENSITY (g/cm^3)	WET DENSITY (g/cm^3)	PARTICLE DENSITY (g/cm^3)	POROSITY (%)
S1	2.6065	2.6151	2.6289	0.85
S2	2.6083	2.6223	2.6454	1.40
S3	2.6168	2.6340	2.6625	1.72
S4	2.5908		2.6205	1.13

		2.6021		
S5	2.6278	2.6480	2.6820	2.02
M1	2.6351	2.6499	2.6748	1.48
M2	2.6284	2.6404	2.6602	1.20
M3	2.5763	2.6011	2.6417	2.48
M4	2.6287	2.6544	2.6978	2.56
M5	2.6152	2.6336	2.6641	1.84

The porosity range of the sandstones falls within 0.85 - 2.02 %. The wide range in porosity is due to differences in the number of voids. Some sandstones with low porosity are highly lithified, while those with higher porosity have many voids. The mudstones have a porosity range of 1.20 – 2.56 %. The small mud grains increase the surface area, which can facilitate porosity.

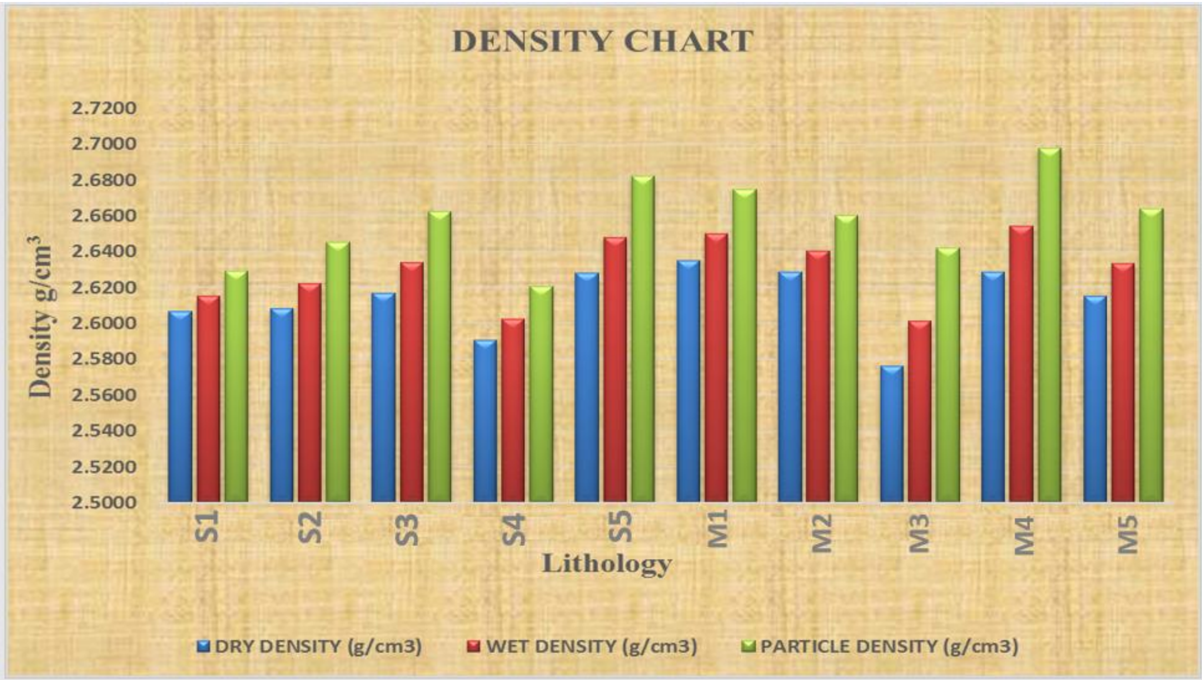


Figure 17. Bar chart showing densities of the rocks (S represents sandstone and M represents mudstone).

From the Figure above (Figure 17), the dry density, wet density, and particle density values vary between 2.5763 - 2.6351 g/cm^3, 2.6011 – 2.6544 g/cm^{3,} and 2.6205 - 2.6978 g/cm^3, respectively. The mudstone has the highest wet density of 2.6544 g/cm^3.

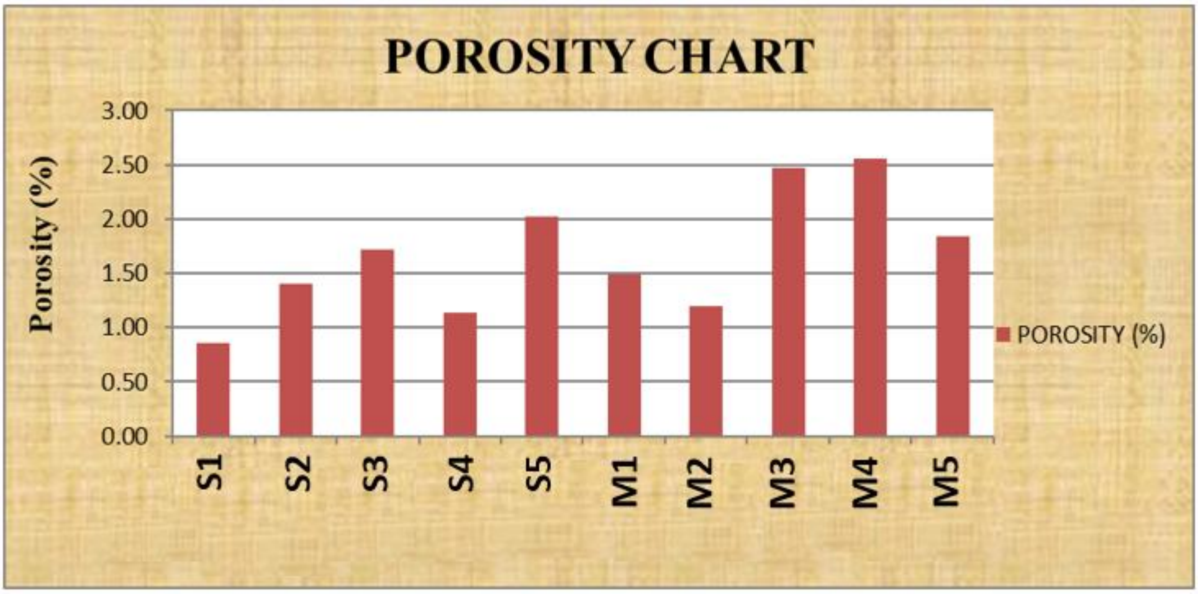


Figure 18. Bar chart of porosity of the rocks (S represents sandstone and M represents mudstone).

Figure 18 shows the estimated porosity of rocks comprising mudstone and sandstone. The porosity values range from 0.85 – 2.56 %. The mudstone has the highest porosity of 2.56 %, while the sandstone has the lowest porosity of 0.85 %.

Rocks from the Daggaboersnek Member have densities that vary between 2.5763 to 2.6978 g/cm^3. The porosities vary between 0.85 – 2.56 %. These density and porosity values of rocks from the Balfour Formation fall within the ranges of 1.5 – 2.8 g/cm^3 and 1 – 10% that have been reported by many researchers (Johnson et al., 2006; Baiyegunhi and Gwavava, 2016; Baiyegunhi and Gwavava, 2017) who have investigated the formations that make up the Karoo Supergroup in South Africa. Furthermore, it was observed that mudstone has the highest porosity value of 2.56 %, which is due to the presence of numerous pore spaces within the mudstone. The findings corroborate the results of Liuji (2011), who drilled a borehole around the study area and reported that some weathered mudstone fragments were found in the samples at a depth of 65 m, whereby the highest water yield of 36000 l/h was recorded.

CONCLUSION

This paper has reported a geological assessment of Alice's groundwater. The study shows the significant value of this method as viable methods for investigating the factors that influence the groundwater storage capacity of the research area rocks and other areas where applicable. Rock types directly impact an area's groundwater, as easily fractured rock would increase secondary porosity and permeability. Porosity types present in the research area are mainly composed of the primary and secondary intergranular pores, dissolution, and fracture openings. Increased bedrock porosity due to fractures allows for more groundwater to flow through and be stored. Also, fractured areas are incredibly productive with excellent storage potential (Pietersen et al., 2011). The quality of the reservoir is generally improved by the occurrence of dissolution pores and fractures in the rocks. Petrographic analyses show that the rocks contain minerals like calcite, feldspar, lithics, mica, kaolinite, quartz, and illite. The primary diagenetic processes which affect the groundwater storage of the rocks are recrystallization, minerals replacement, dissolution of minerals, and cementation by authigenic minerals. The dissolution of feldspars to illite after diagenetic change led to the formation of secondary pores, thus enhancing groundwater flow. Conversely, diagenetic process, such as cementation (quartz, feldspar, illite, and kaolinite), tends to reduce the porosity and permeability of the rocks. Density and porosity measurements revealed that the sandstones have a density range between

2.5908 – 2.6820 g/cm³ with a porosity of 0.85 - 2.02 %, and mudstones vary in density from 2. 5763 – 2.6978 g/cm³ with porosity of 1.20 – 2.56 %. The mudstone has the highest porosity values than sandstone in the research area, which is contradictory to the normal concept that sandstone has a higher porosity than mudstone, which indicates that secondary porosity is the main porosity for the reservoir rocks in the research area. It is recommended that the study area should be investigated more by geophysical methods (magnetic and electrical resistivity methods) to identify potential groundwater areas for borehole sites. This will assist the exploration of groundwater in this era of water scarcity.

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