Petroleum and Coal

Article **Open Access**

Geology and the Impact of Diagenesis on the Reservoir Quality of the Permian Sandstone of the Ecca Group in Borehole KZF-1

Ronaldo Malapana, Mahlatse Manthepeng Ntake, Sibusiso Maseko, Mokgadi Koketjo Teffo, Tsibula Juliet Sekantsi and Christopher Baiyegunhi*

Department of Geology and Mining, University of Limpopo, Private Bag X1106, Sovenga 0727, Limpopo Province, South Africa

Received May 29, 2023; Accepted September 20, 2023

Abstract

Despite the fact that the Ecca Group in the southern Main Karoo Basin is considered as a significant region for hydrocarbon exploration and exploitation, there is still lack of knowledge on the diagenesis of the sandstones of the Ecca Group. Hence, the impact of diagenesis on the quality of sandstone as a reservoir for hydrocarbon in the basin is not well understood. In this study, petrographic, scanning electron microscope with energy dispersive x-ray (SEM+EDX), and x-ray diffraction (XRD) analyses were performed on representative sandstones samples from the Ecca Group in borehole KZF-1 to investigate the impact of diagenesis on the reservoir quality of the sandstones. Petrographic studies show that the sandstones are mostly well-sorted, medium-grained and can be classified as lithofeldspathic wacke. In addition, petrographic and XRD analysis revealed the dominance of quartz and feldspar. Clay minerals are the most common cementing materials in the sandstones. The SEM and EDX examinations revealed that smectite, kaolinite and illite are the major clay minerals that act as pore-filling matrix and pore lining rim-cement. The diagenetic processes that have significantly impacted the sandstones are cementation, compaction, recrystallization and to some extent, dissolution. The sandstones were subjected to moderate-intense mechanical and chemical compaction during its progressive burial. Intergranular pores, secondary dissolution and fractured pores are well developed in the sandstones. Primary intergranular pores are reduced as a result of intense compaction and cementation. Most of the primary pores have been destroyed by the same process that resulted in generation of the pseudomatrix of wackes. However, Small amount of secondary porosity occurred in the rocks. The presence of fractured and dissolution pores tends to enhance reservoir quality. Most of the secondary pores are very small and isolated, resulting in very low porosity and permeability, which also resulted in poor-medium potential reservoir quality.

Keywords*: Diagenesis; Sandstone; Porosity; Permeability; Ecca Group.*

1. Introduction

Diagenesis is a significant concept used in sedimentary studies. It influences the porosity and permeability of the sedimentary rocks, as well as their reservoir properties [1-5]. Other factors such as composition, texture and, permeability along with porosity of sandstones are largely influenced by the depositional environment [6-7]. Sandstones are one of the most abundant and important sedimentary rocks because of the reservoir properties they possess [8-9]. These properties are largely influenced by the extent and intensity of diagenesis [5]. The use of geochemical data and geological investigation are key aspects in the identification of sandstones as reservoirs [10]. In addition, [11-12] elaborates that these techniques reveal the internal structures of sandstones including porosity, permeability, grain size, and the mineralogical composition. When determining the effectiveness of a sandstone reservoir, factors such as pore varieties, porosity, and permeability should be considered [7,13]. The primary factor influencing commercial viability during hydrocarbon exploration and development is reservoir quality, which is influenced by diagenesis [9,14].

The Ecca Group has been an area of interest in exploration geology as it is renowned for the large reservoirs of hydrocarbons. Sedimentation of the Ecca Group occurred in several environments. The first sediments of this group were deposited in deep marine environments and the final sediments were deposited in lacustrine environments [15]. Similarly, this group has rocks of different grain sizes, indicating that the rocks have been transported by varying rate of flow. Several studies by [3,5,7,15] were conducted on the stratigraphy and diagenesis of the Ecca Group. However, to date, there is limited data pool on the effects of diagenesis on the reservoir quality of the sandstones in the Ecca Group. As a result, this study was carried out to fill this research gap. Petrographic studies and several analytical techniques including (scanning electron microscope with energy dispersive x-ray (SEM+EDX), and x-ray diffraction (XRD)) were employed on sandstones samples in borehole KZF-1. These methods were used to investigate the impact of diagenesis on the reservoir quality of the sandstones, which is the main aim of this study. Furthermore, this study will aid in broadening the understanding of diagenetic characteristics and factors influencing the reservoir properties. Borehole KZF-1 is located in the Tankwa area of the Western Cape, South Africa. Geographically, it is situated on longitude 32°50'30.4"S and latitude 19°44'33.0"E (Figure 1).

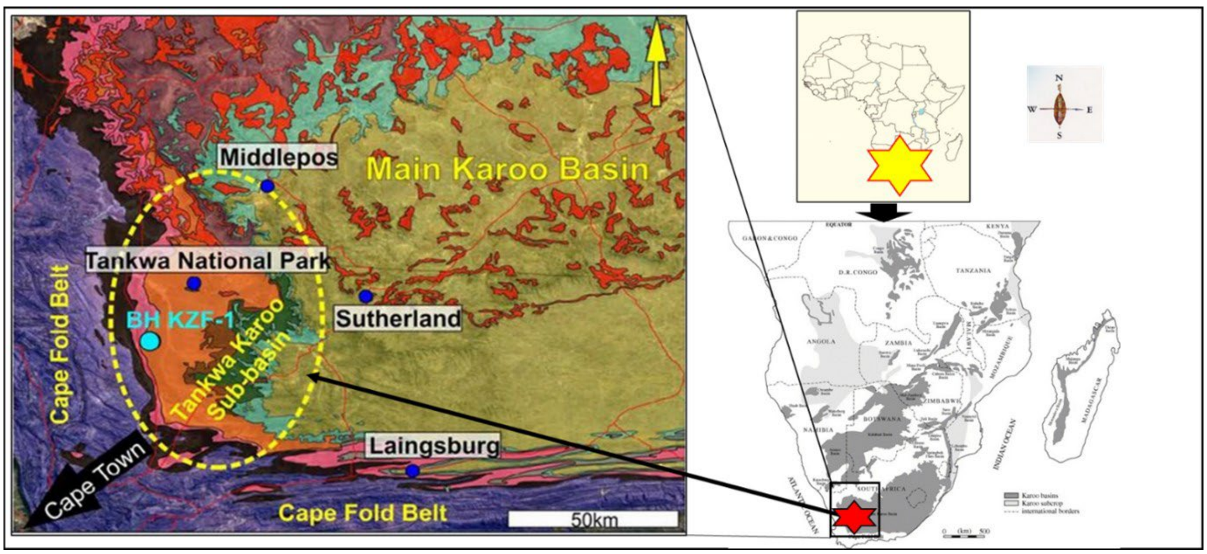

Figure 1. Simplified map showing the location of the Borehole KZF-1 in Western Cape around the Tankwa area, at coordinates 32°50'30.4"S 19°44'33.0"E (modified after [16]).

2. Geology settings

The Main Karoo Basin is one of the most complex basins due to its diverse rock types. In South Africa, this basin encompasses over 700,000 km^2 of South African terrain [17]. Economically, it hosts the largest reserves of coal and other hydrocarbons in this country. The Ecca Group is the centralised zone for the coal deposits. The majority of the coal reserves are hosted by the Vryheid Formation; however, there are minor occurrences of these reserves in both the Beaufort and Stormberg Groups [18]. A study by [19] indicates that the Karoo basin was controlled by the shift and change in both tectonism and climate. This demonstrates a broad transition from cold and semi-arid environments during the early Karoo times to warmer and hotter temperatures with erratic precipitation in the late Karoo times. The climatic conditions and tectonic activities are also reflected by the stratigraphic units of the Karoo Supergroup, namely, the Dwyka, Ecca, Beaufort and Stormberg Groups, respectively. These traverse from the freezing climate of the Dwyka, through the marine of the Ecca Group, till the semi-arid conditions of the Stormberg series [19].

The tectonic activities during Gondwana times formed the Cape Fold Mountains in the south and the Karoo regions in the north which in turn influenced sedimentation of the Karoo Supergroup [20]. The extension of Gondwana and the accumulation of sediments in the Karoo

Sea in the north of the Cape Mountains contributed to the Main Karoo Basin of South Africa. This also caused uplifts in Cape Fold and part of the Karoo Basin [19-20]. Amid the Ecca times, tectonism was intense, causing a resurgence of the movement of the northern part (i.e., South Africa) away from poles, thus melting the Dwyka glacial [17,19, 21-23]. Additionally, the Ecca sediments continually sank between crustal faults terrane and the absence of features such as syn-rift sedimentary wedges and unconformities imply considerable upper plate expansion. The Main Karoo Basin is believed to be a retro-arc foreland basin which formed below the Gondwana supercontinent, behind an extended magmatic arc and fold-thrust belt of the Palaeo-Pacific [19].

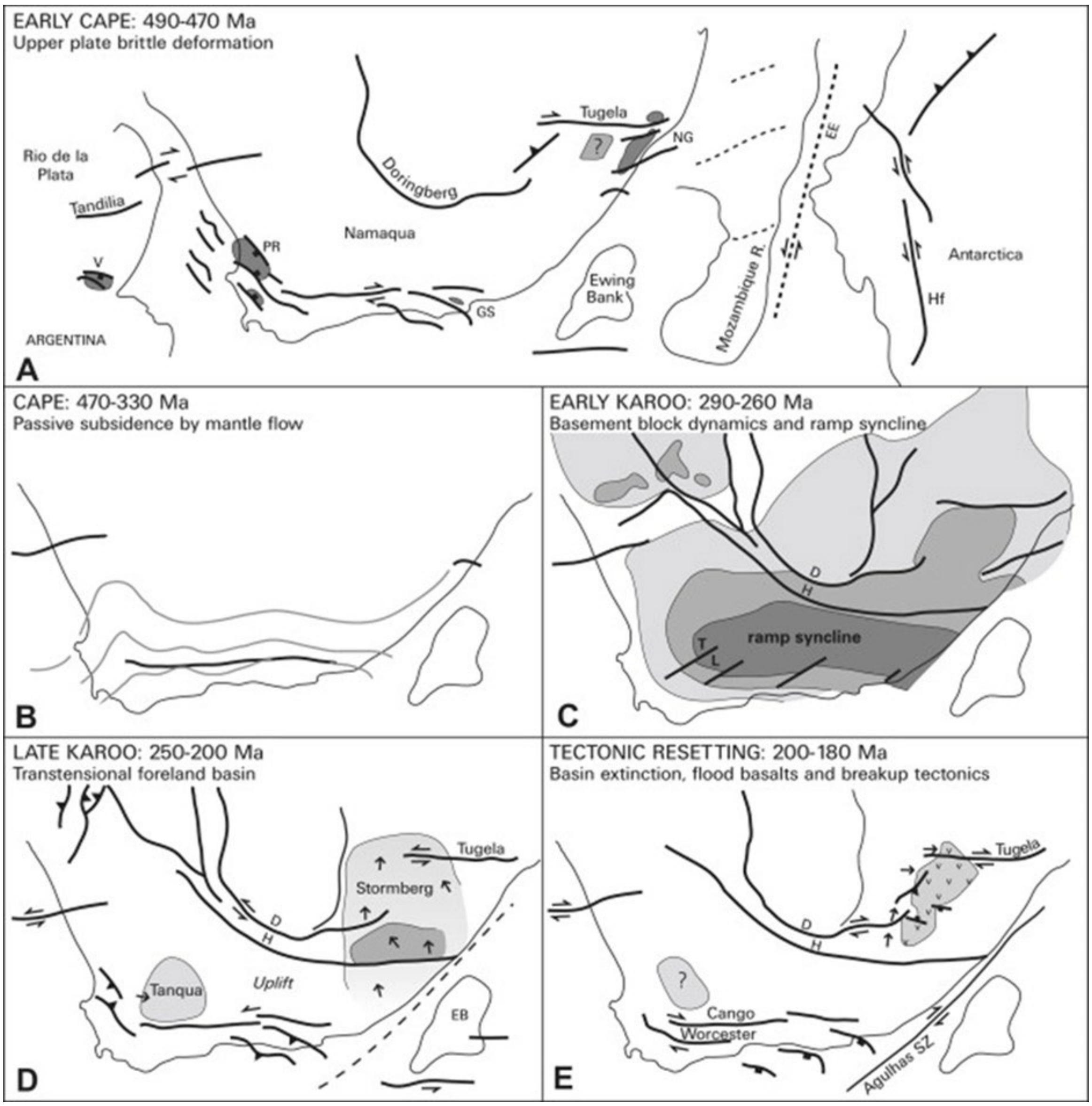

Figure 2. Tectonism of Karoo basin and Cape Fold (after [24-25]).

The Karoo Supergroup's sedimentary and volcanic suites were deposited between the Late Carboniferous to the Early Jurassic periods [18]. The Ecca Group is a boundary between the Carboniferous Lower Dwyka Group and the Upper Late Permian-Middle Triassic Group, dominating the Early-Middle Permian era [18] (Figure 3). In the southern margin of the Main Karoo Basin, the Ecca Group reaches its maximum thickness of 3000 m [22] whilst it gets thinner in the northern margin.

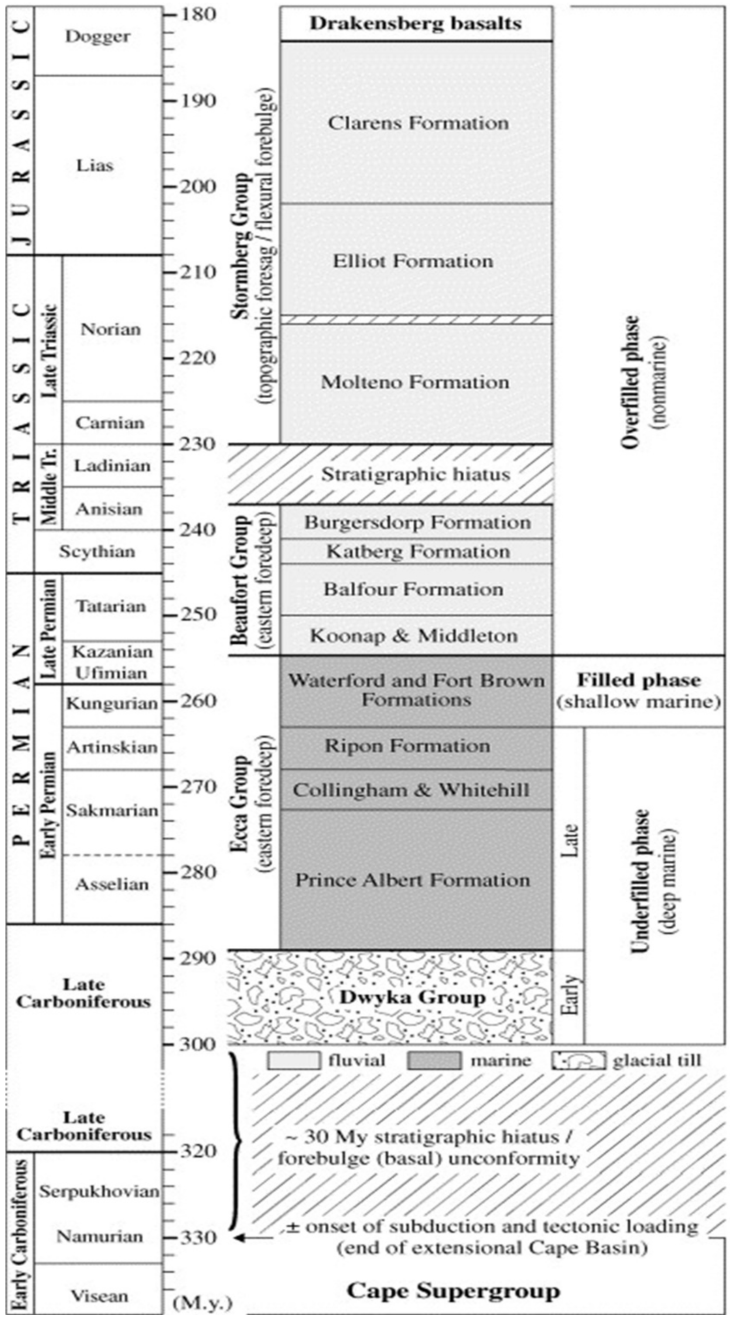

Figure 3. Simplified stratigraphy of the Karoo Supergroup showing different formations of the different groups (after [32]).

The Ecca Group is stratigraphically made up of different formations, namely, the Prince Albert, the Collingham, Whitehill, the Ripon, Waterford and the Fort Brown Formations. The age of the formations varies as per U/Pb dating. The age ranges from 289-225 Ma, 279-275 Ma, 281-270 Ma and 275-257 Ma for the Prince Albert, Whitehill, Collingham and Ripon Formations, respectively [26-28]. The 120 m thick Prince Albert Formation is largely dominated by mudstone, grey shales, and thin sandstone strata, with occasional dropstones near the base [1,17,19,29-30]. Prince Albert sediments, excluding the dropstones, indicate quiet environments and low depositional energy during their transportation. The Collingham Formation of the Ecca Group has overburden sediments of mudrocks, tuffs, siltstones, and sandstones, associated with distal submarine turbidite facies with an average thickness of 30m [22,31]. The Whitehill Formation is made up of weathered white to black carbonaceous shale with chert bands. This formation was deposited in seawater, oxygen-free environment and it comprises a thickness of 70 m [17,19]. It loses its distinguishing character as it moves northeast and can be linked to coal-bearing strata in the Vryheid Formation [18]. The Ripon Formation is characterized by sandstones with some shale [31]. According to [32], the Ripon Formation originated in a shallow marine to the deltaic environment, while the Fort Brown Formation developed in a large continental edge lacustrine environment (Figure 3). In the other basins, sandstones and mudstones predominate, with sandstones being generally fluvial and mudstones being lacustrine [19].

3. Methodology

Thin sections of thirteen borehole KZF-1 samples were examined under an optical microscope to assess mineral compositions, textures, grain shape and size. The samples were then used to prepare thin sections which were used for petrographic studies. The samples and thin sections were analysed using scanning electron microscopy (SEM) (Model: JEOL JSM-6390LV) set to 15 KV and Energy Dispersive X-Ray micro-analyser (EDX). These analyses were used for elemental and mineral composition of the examined samples. SEM was also used to explore clay minerals, dissolution effects, quartz overgrowth, diagenetic textures, pore geometry, and other related diagenetic textures. Secondary electron imaging (SEI) and backscattered electron imaging (BSE) were used to give high resolution images which display the elemental distribution within the sample. XRD was carried out at the Council for Geoscience to determine the mineral compositions of the sandstones. The XRD measurements were carried out on a Bruker XRD D8 Advance (Model: V22.0.28) at a room temperature of 25°C, with the samples scanned at a rate of 2° 2θ per minute from 2° to 70° (wavelength of 1.5406).

4. Results and interpretations

4.1. Stratigraphy of the Ecca Group in KZF-1 borehole

The Ecca Group in borehole KZF-1 encompasses the Prince Albert, Whitehill, Collingham, and the Tierberg Formations (Figure 4). The borehole is 671 m deep and it includes part of the basal Dwyka Group and the 648 m deep Ecca Group. The Prince Albert Formation is the first and oldest formation of the Ecca Group and it has a thickness of about 180 m. It is dominated by greyish shale and fine-grained sandstone; in addition, it also contains grey-green tuff with black matchstick-like needles in places, as well as calcite veins. Overlying the Prince Albert Formation is the Whitehill Formation, which is about 47.55 m. This formation is dominated by black carbonaceous shales, with brecciated rocks containing quartz fragments. Above the Whitehill is the 77.9 m thick Collingham Formation. It is dominated by dark-greyish shale, black shale, greyish shale, fine-grained sandstone, and tuff material. The youngest formation in the borehole KZF-1 is the Tierberg Formation, with a thickness of 344.55 m. It is dominated by shales of defined and undefined bed along with massive shales with carbonate concretions, fined grained sandstone interbeds, and minor layers of rhythmite.

4.2. Mineral composition

4.2.1. Petrography and modal composition

The modal composition results show that the dominant minerals in the sandstones are quartz, feldspars, and lithic fragments (Table 1). The matrix content is greater than 15% in all formations, signifying that the sandstones are wacke [33].

The percentage of quartz in the sandstone is about 40%. The sandstone is dominated by monocrystalline quartz with about 3% of polycrystalline quartz (Table 1 and Figure 6a and b). The colour of quartz is white but may vary as the stage is rotated thus displaying the mineral at different angles (extinction angle). The quartz and feldspars are medium to fine grained, which implies that the studied sandstones are medium to fine-grained (Figures 5b and Figure 6c). The percentage of feldspars in the sandstone is greater than 15% (Table 1).

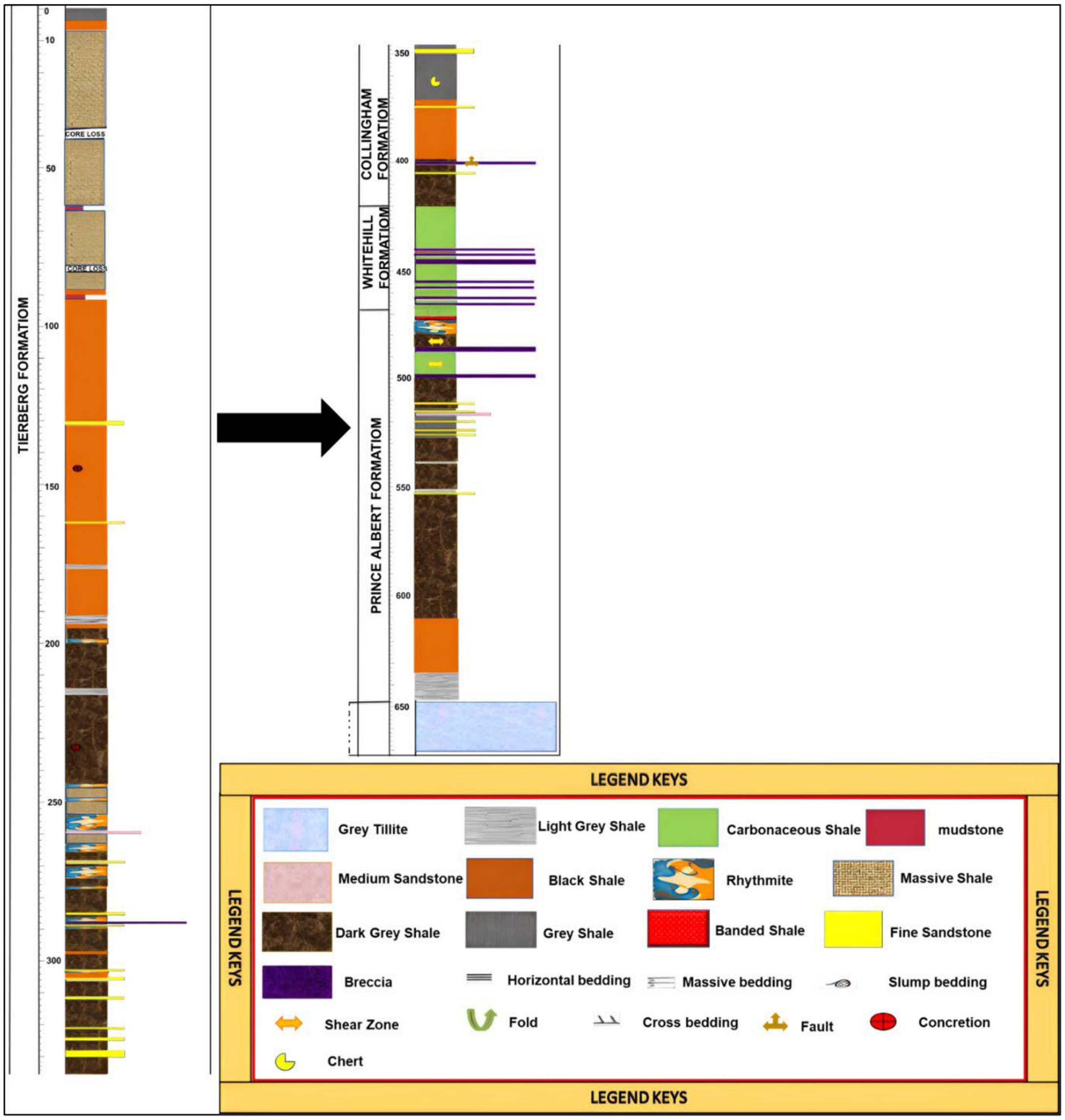

Figure 4. (a) Stratigraphic column of the Ecca Group in borehole KZF.

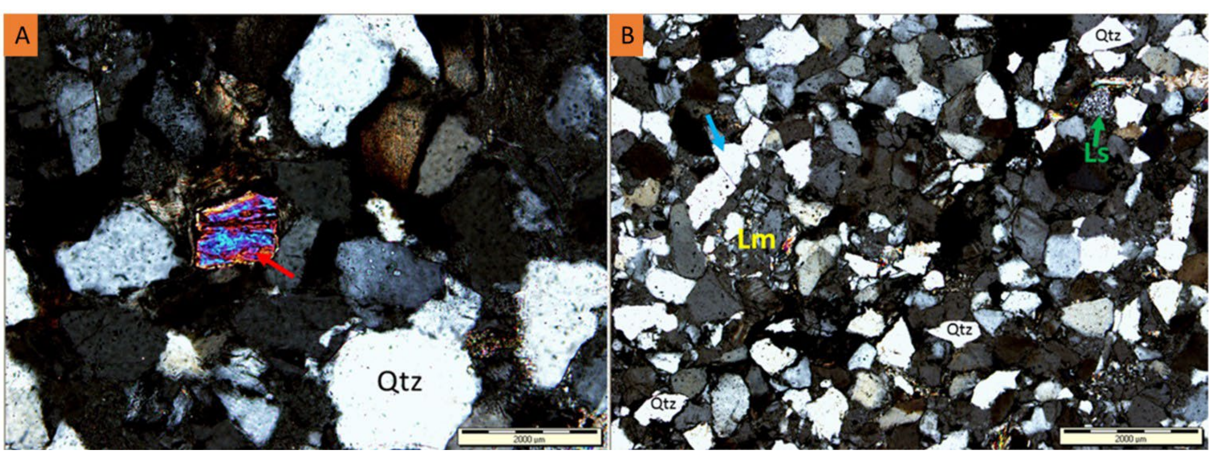

Figure 5. (a) Photomicrograph of sandstone mineral grains showing sub-angular shape grains of low sphericity. (b) Photomicrograph shows a packed arrangement of grains of almost similar sizes in the sandstone of the Ecca.

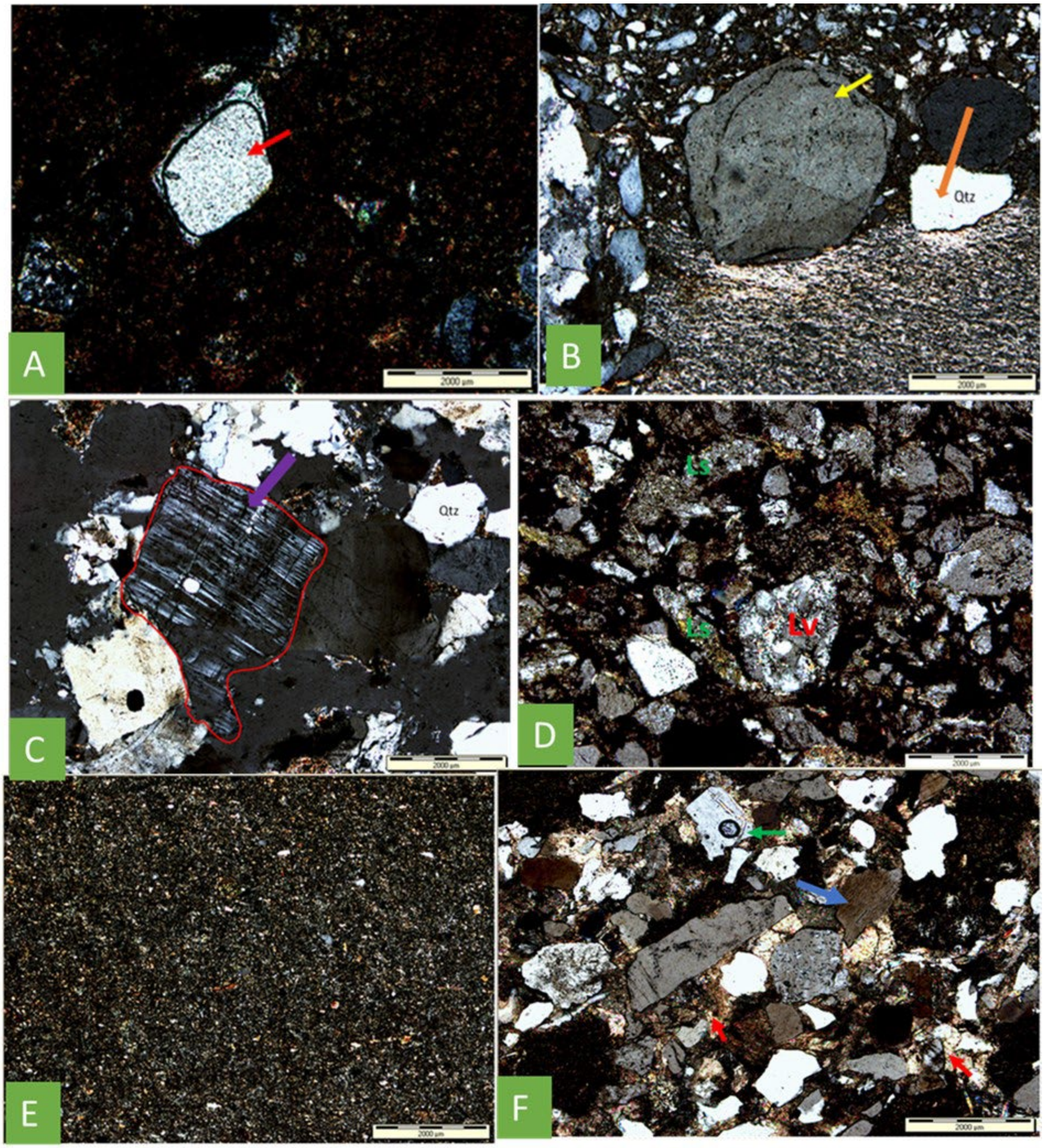

Figure 6. (a) and (b) Photomicrograph of sandstone showing quartz grains. The red arrow representing polycrystalline quartz (Qp) and gold arrow representing mono-mineralized quartz (Qm). The variation in the colour of quartz from white to greyish to black is due to the angle of extinction, (c) sandstone displaying feldspar grain (dark-purple arrow) in the rock, which show form of twinning around its regions. (d) Photomicrograph image of sandstone showing a large lithic fragment (dark red arrow) surrounded by quartz and matrix material. (e) Thin section photomicrograph of sandstone showing muscovite (blue arrow), shows inner fractures of cleavage aligned parallel to elongation. (f) Photomicrograph of sandstone showing matrix minerals.

Feldspar colour properties ranges from white, grey to black, this differs due to percentage of the calcium and potassium in the feldspar. The dominating feldspars are plagioclase feldspars which shows twinning (Figure 6c, Figure 6d). The content of lithic fragments (Figure 6d) exceeds the feldspar material, by a percentage greater than 20%. The shapes of lithics range from rounded to well rounded (Figure 6d). The brown to dark coloured micas in the sandstone occur in low quantities, but they display perfect cleavage parallel to their elongation, in addition (Figure 6e). The shape of the grains displays a sheet-like structure with sharp edges, displaying angular characteristics. These minerals are not hard; therefore, they are easily altered. The most observed micas in sandstone are biotite mica and muscovite (Figure 6e). The matrix minerals range from 18-26% (Table 1) in the studied sandstones (Figure 6f). The abundant clay minerals include kaolinite, montmorillonite, and illite.

4.2.2. Elemental composition

The results from x-ray diffraction show dominance of quartz, plagioclase feldspars and kaolinite mica (Table 2). The total proportion of quartz in the sandstones ranges from 18-38 weight percent (wt.%), plagioclase 10-20 wt.%, and micas 2-17 wt.%. Clay minerals include kaolinite, smectite, and chlorite and they range between 7-38 wt.%, 1-33 wt.% and 3-14 wt.%, respectively. Illite (1-6 wt.%) is only found in the sandstone of the Tierberg Formation, while microcline is concentrated in lower quantity in the Tierberg and Prince Albert Formation. Furthermore, sericite occurs in lower wt.% in the Prince Albert Formation. The heavy minerals (garnet, hematite, and zircon) are in trace amounts. Pyrite is concentrated in the Whitehill Formation, while occurring in trace amounts in the other formations.

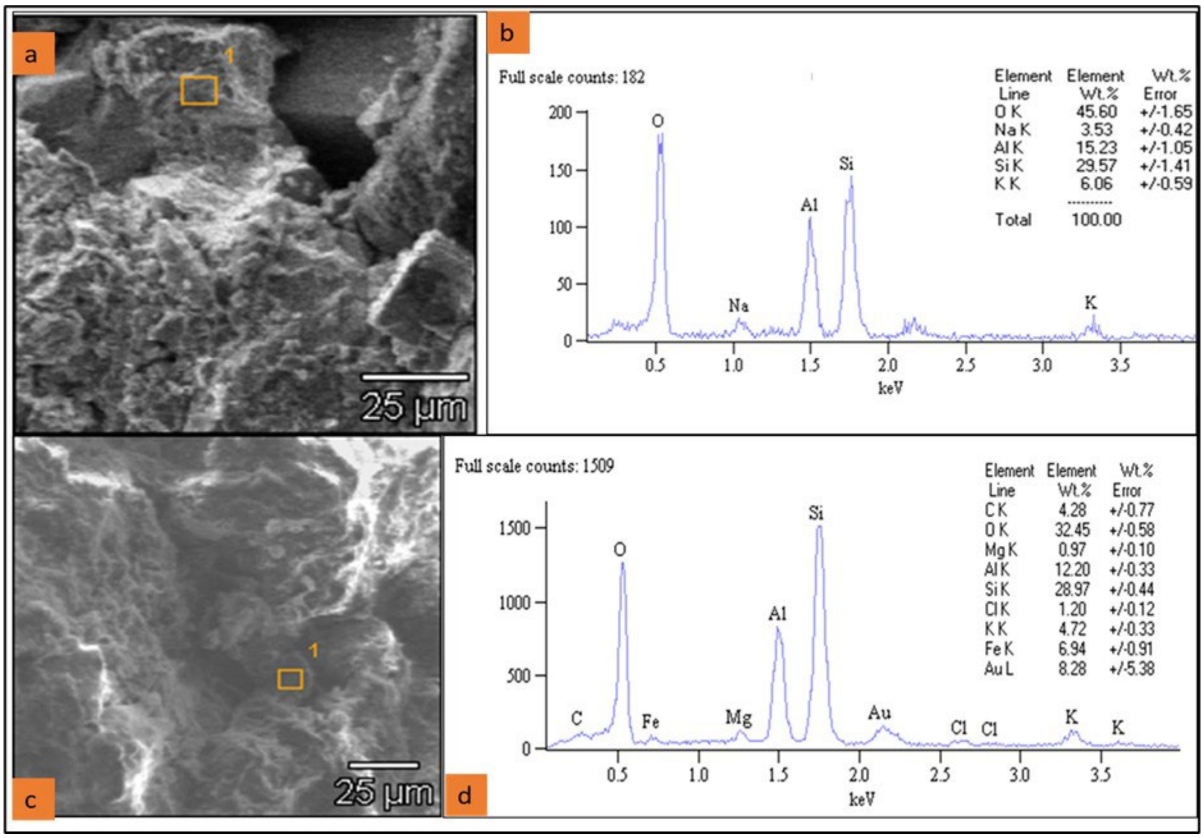

Figure 7. (a) SEM of kaolinite picked at point 1, (b) EDX diagram of kaolinite at point 1 showing its elemental composition, (c) SEM of illite picked at point 1 at image and (d) EDX diagram of illite showing its elemental composition.

Kaolinite is greyish to whitish in colour and it appears like pages of books under an SEM (Figure 7a). The clay minerals are dominated by major minerals, Si, and Al while minor minerals such as K and Na appear in low weight percent (Figure 7b). Under SEM, illite appears intact and it is whitish to greyish in colour with fibrous shapes (Figure 7c). The illite is dominated by a variety of minerals including major elements (Si, Al, Au) and minor elements (Mg and Fe with less than 7 wt.%) (Figure 7d). Smectite appears greyish to white under SEM

(Figure 9a). The elemental percentage differs greatly considering that clay minerals have various elements within them. The smectite is dominated by Si and Al, with some minor elements of Fe and K (Figure 8b). The Al has an approximated weight percentage of 18 wt. %. Si is 25 wt. % while the minor elements, i.e., Fe and K have 5 wt. % and 7 wt. %, respectively.

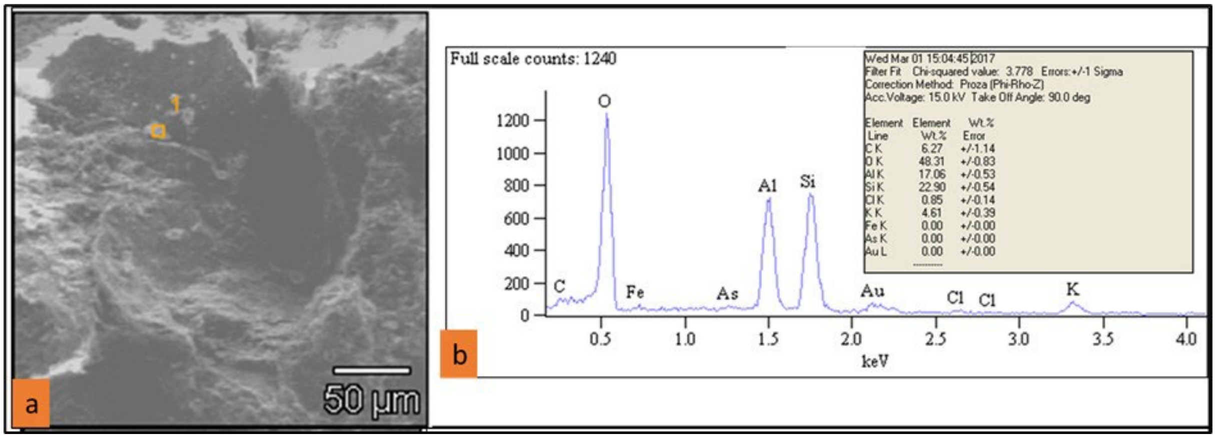

Figure 8. (a) SEM image of smectite and (b) EDX of smectite.

4.3. Sandstone classification

The Ecca Group is dominated by fine to medium sandstone (Figure 5b). According to [34] and [35] the sandstone is classified as lithofeldspathic wacke (Figure 9a) and as lithic wacke (Figure 9b).

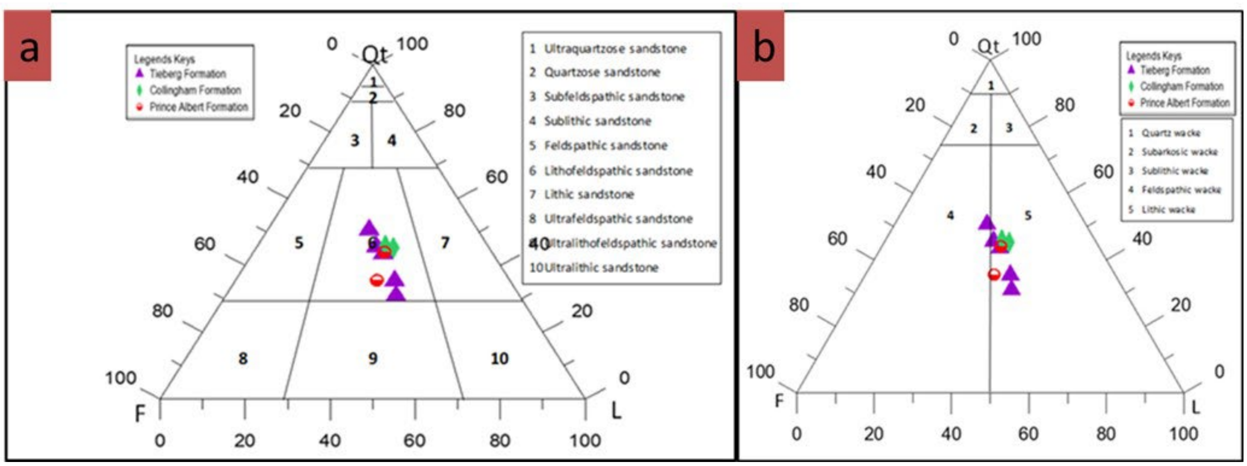

Figure 9. (a) Qm-F-L ternary diagram of sandstone data presented in Table 1, (after [34]) and (b) Qt-F-L ternary diagram of sandstone data shown in Table 1, (after [35]).

4.4. Diagenetic processes

4.4.1. Compaction

Compaction makes the distance between the buried sediments or grains decrease [36-37]. The sandstones of the Ecca Group show grains that are intermediately in contact with each other, that indicate point and long compaction based on [38] compaction level classification (Figure 10a and b).

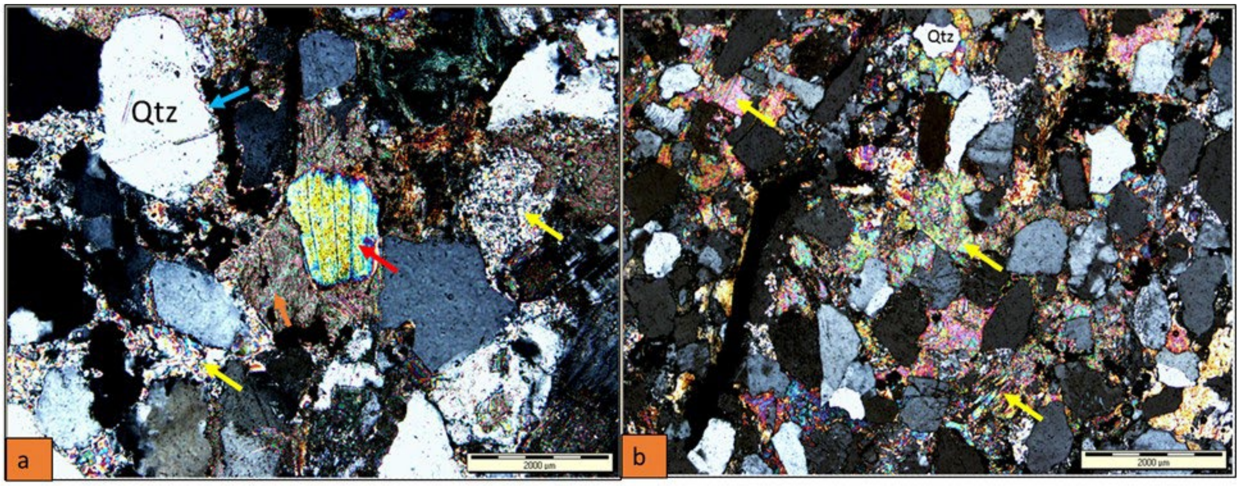

Figure 10. Sandstone photomicrographs showing (a) long and (b) point compaction

4.4.2 Cementation

Quartz cement. The cement of quartz occurs as an overgrowth (Figure 11a). Quartz appears greyish with a prismatic to hexagonal shape (Figure 11b). Quartz cement occurs mostly in the sandstone of the Tierberg and Whitehill Formations.

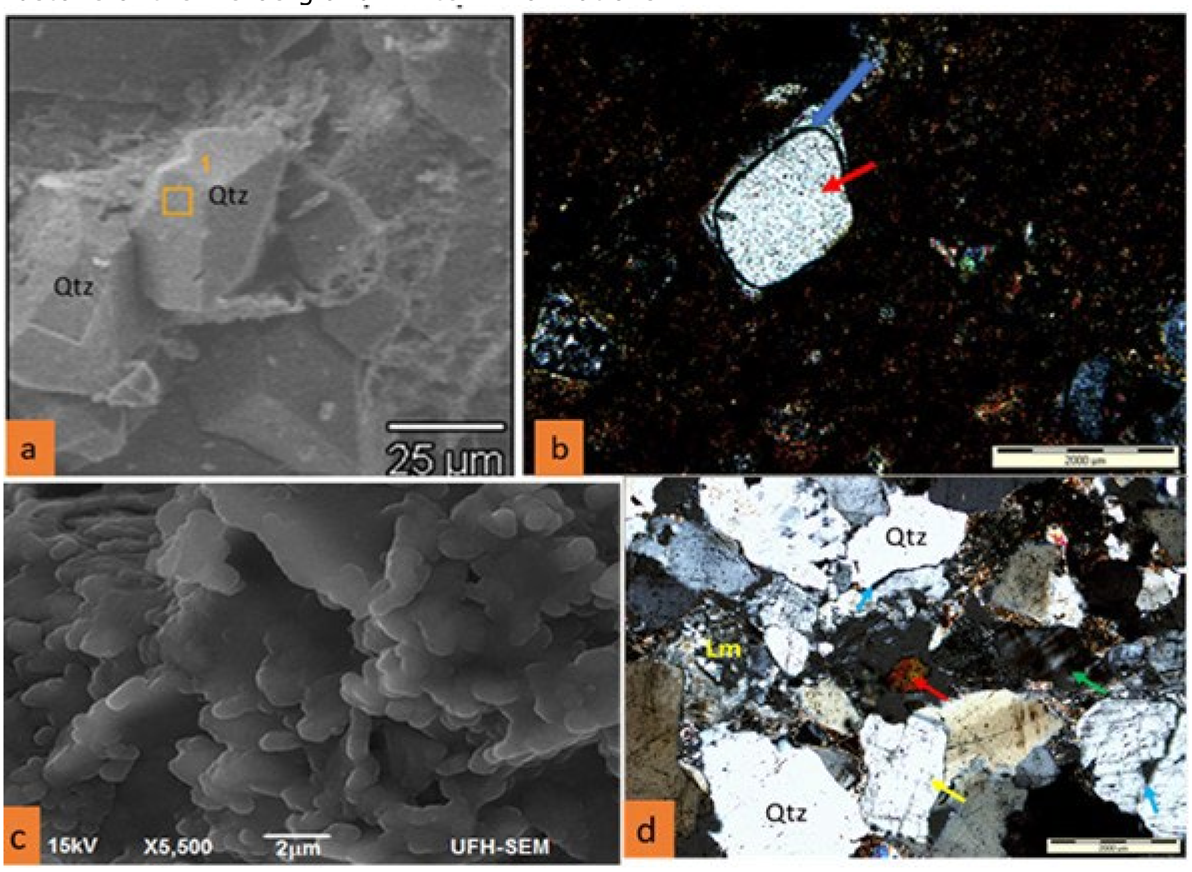

Figure 11. (a) SEM of quartz showing overgrowth, (b) photomicrograph of a quartz showing overgrowth, (c) Recrystallization of smectite flakes to pelletic and fibrous illite, and (d) Photomicrograph of a sandstone sample showing dissolution within the boundaries of quartz, feldspars, and micas.

Feldspar cement. Feldspars appear to be altered by clay minerals and therefore occur in minute amounts. They occur as pore fillings and lining with albite being the most abundant feldspar cement (Figure 6f).

Kaolinite cement. The sandstones of upper part of the Tierberg Formation are dominated by cement of kaolinite (Figure 7c). They occur as infill (Figure 7a and b) through precipitation and as linings through alterations. The kaolinite cement is dominated by silicon and aluminium.

Illite cement. Illite cement in this part of the Ecca sandstones occurs specifically at the Tierberg Formation. The composition of illite is dominated by silica and aluminium with low values of potassium and sodium. Illite accommodates other heavy elements such as iron and magnesium (Figure 7d).

Carbonate cement. Carbonate cement mostly occur as either calcite or dolomite, which are dominated by magnesium and calcium. The XRD of this sample shows that the carbonate representative is dolomite (Figure 6b, Table 2). Calcite cement act as both the primary and secondary pore infills (Figure 6b).

4.4.3. Replacement

Replacement occurs when a mineral precipitate is replaced by another mineral. Feldspar minerals in the sandstones are replaced by kaolinite (Figure 6c).

4.4.4. Dissolution

The removal of all or some of the previously present minerals in solution is known as dissolution and it leaves pores in the rocks [39]. The dissolution of k-feldspars results in kaolinite formation (Figure 11c). This process weakens the grains along the boundaries usually creating fractures appearing in a dark colour with mica within the fractured zones (Figure 12c and d).

4.4.5. Recrystallization

Recrystallization is a diagenetic process that involves the alteration of a mineral grain's shape and size but retains the mineral composition [40]. Figure 6c shows a grain of feldspar, which is changing its shape and size. The change in the shape and size of the feldspars can also be noticed at the boundaries (Figure 6c). Smectite and illite under SEM show that the smectite flakes are changed into pelitic and fibrous illite (Figure 11c).

4.5. Reservoir properties

The pore spaces within the sandstones is filled (Figures 12a and b), however the porosity is also variable (Figures 12c, d, e, and f). The porosity is shown as micro-cracks (Figure 12c and d) and others in form of hollows or round spaces in between the grains (Figure 12e and f). Micro-cracks are usually a sign of external stress and represents secondary porosity. Intercrystalline pores occur as authigenic minerals of clays and calcite as they do within a crystal (Figure 12a). Figure 12a and b represents poor permeability whilst Figure 12c, d, e, and f represent good permeability.

4.6. Diagenetic stages

4.6.1. Early diagenesis

Early diagenesis refers to the initial stage of diagenesis which occurs in the depositional environment at relatively shallow depths (a few meters to tens of meters). Processes affecting early diagenesis include temperature, time, mineralogy, the orientation of grains, and pore characteristics. Cementation, compaction, and bioturbation occur at this stage. At this stage, compaction is less intense because greater depth constitutes greater pressure. Mechanical compaction occurs at this stage, whereby, lithics, mud intra-clast, and glauconite are mainly involved (Figure 6d and 11b). Dissolution processes occur in the case of kaolinite and carbonate grains. Due to the abundance of the framework of feldspar, through dissolution, the feldspar grains are replaced by kaolinite clay minerals. Meteoritic fluids or a wet climate stimulate the dissolution of carbonate grains through the introduction of carbonate minerals such as calcium and magnesium. Cementation at the initial stage of diagenesis is brought upon by the precipitation of clay minerals, quartz and feldspar overgrowth, carbonate, and haematite. The sediments' modest lithification is typically brought on by cementation. According to [41], clay mineral cement includes illite, kaolinite, chlorite, and smectite (Figures 8a). The clay mineral cement is influenced by the compaction and fluid introduction, from which the clay matrix is mainly altered to cement.

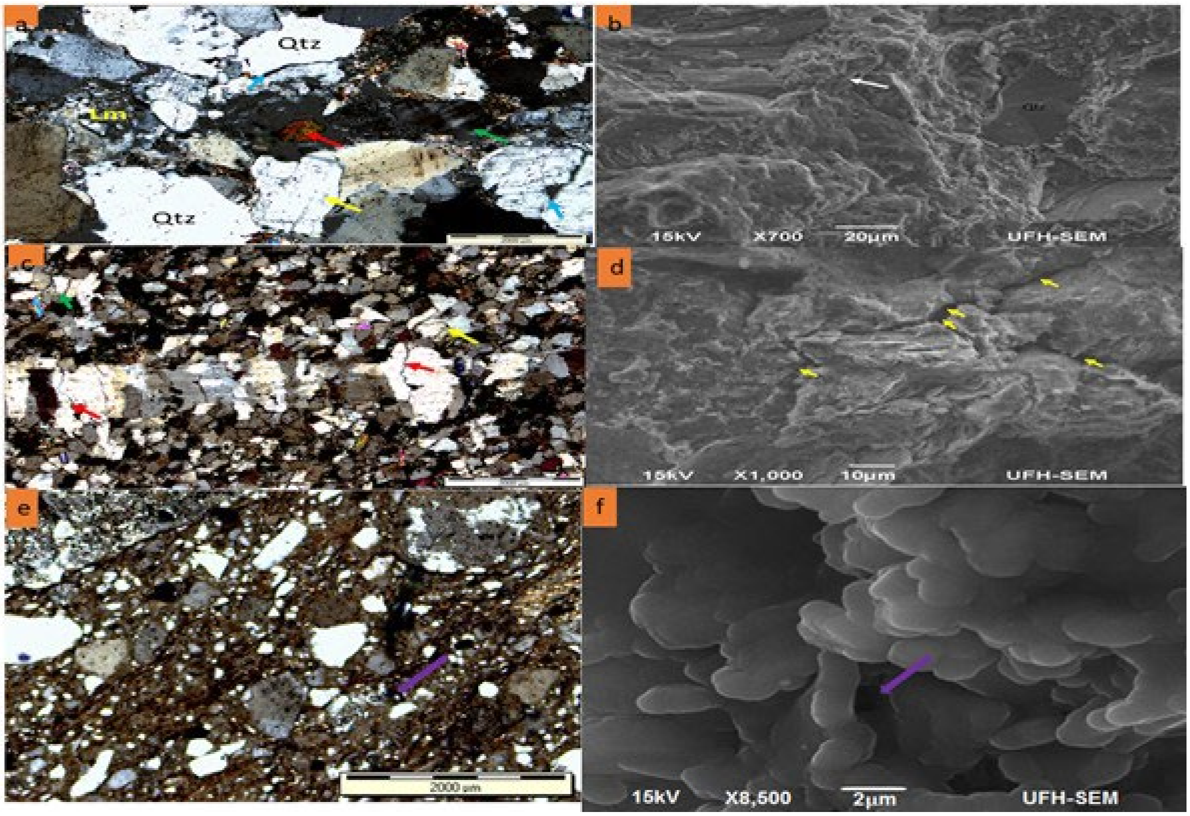

Figure 12 (a) and (c) are petrographic images of studied sandstone showing cracks along and inside grains displaying intergranular and intragranular pores, (b) shows an SEM image of illite, kaolinite and quartz crystals displaying poor permeability with no traces of pores (d) SEM image of illite shows cracks/fractures between grains, petrographic image (e) and SEM image of Illite and smectite (f) respectively shows hollow pores spaces within the grains of the sandstone.

4.6.2. Burial diagenesis

Diagenesis that occurs under deeper burial, at higher temperatures and pressures with altered pore-water compositions is referred to as burial diagenesis [42]. Processes that occur at this stage of diagenesis include dissolution, compaction, recrystallization, replacements, and cementation. Increased temperature and pressure results in more compacted and tighter grains within the rock thus displaying a concavo-convex structure (Figure 11d). Compaction creates cracks within or along the grains, especially those of quartz and feldspars. Greater temperature, pressures, and fluids triggered chemical changes in the rock. Plagioclase acts as the source of albite through the process of albitization, for which the plagioclase has high Ca^{2+}-rich plagioclase along with Na^{+}, through grain cracks this then forms albite. The Ca^{2+} and Al^{3+} are sources of smectite, illite, and dolomite cement. The presence of smectite at this stage of diagenesis inhibits quartz overgrowth. Traces of replacements of feldspar by calcite through mineral replacement process (Figure 11d). Illite cement occurs through the alteration of smectite (Figure 11c) or kaolinite with increased temperatures and depth.

4.6.3. Uplift-related diagenesis

After the process of burial diagenesis, the buried sediments may find their way to the surface due to uplift through meteoritic waters. Dissolution, replacement, and oxidation processes take place at this stage; however, compaction and recrystallization seldom occur due to lower pressures. The uplift of rocks allows for the infiltration of oxygen in minerals whilst at the same time the presence of iron in some minerals may trigger the process of oxidation. This is reflected by reddish to pinkish stains on the affected samples. Pyrite mineral through the process of oxidization changes to gypsum. Figure 6f shows matrix with traces of yellow-goldish pyrite which is replaced to form haematite/gypsum minerals when oxygen is introduced. Through the dissolution process, smectite is converted to illite whilst iron and magnesium from smectite are used as by-products to naturally create illite [43]. Feldspars are altered through dissolution, resulting in clay minerals such as kaolinite. The compaction level during uplift may cause the fracturing or alteration of stronger grains such as quartz and feldspars.

5. Discussion

The stratigraphy of the Ecca Group (Figure 4) indicates that the sandstones in this study are mainly medium grained. This implies that the sandstone may have been transported by low to medium energy. Low depositional energy triggers cementation and mineral replacement thus closing pore spaces between sandstones. This negatively impacts the reservoir qualities. The analysed sandstones contain minor structures which reveal that porosity and permeability are low in the sandstone. The modal composition reveals that the sandstones are dominated by quartz and lithics. These remain stable during late diagenesis thus stopping pores from forming. Textural characteristics of sedimentary rocks play a significant role in porosity and permeability. The key primary textures include grain size, grain shape, and mineralogy. While most of these factors are significant for porosity, effective porosity is the major identifier of permeability. Effective porosity is defined as the interconnected pores that are in sedimentary rocks [44]. Primary and secondary porosity are the two forms of porosity that are distinguished [44-45]. According to [44], primary porosity occurs during the lithification of the rock after deposition, while secondary porosity occurs immediately after deposition and lithification. Primary porosity yields both inter-granular (Figure 12f) and intra-granular grains (Figure 12d). Secondary porosity on the other hand results in fractured and inter-crystalline grains (Figure 12c).

Petrographic studies indicate textural characteristics (i.e., grain size and shape) which play a role in the reservoir quality of the sandstones. The sandstones with angular shape grains (Figure 11d) display low porosity which negatively impacts the reservoir quality. This is because the grains are closely packed. The rounded grains show high porosity which impacts the reservoir properties positively. The size of the grains is important, however, the arrangement in grains (i.e., sorting) is much more essential. A well-sorted, fine-grained rock displays high porosity and permeability because the grains are not well connected (Figure 5b). It has been noted by [41] that well-sorted sandstones tend to contain higher porosity throughout burial than less-sorted sandstones. The degree of sorting can be attributed to the flow energy levels. The sandstones reflect intermediate to high energy flow which is as a result of equal grain size distributions (Figure 5b).

An intermediately compacted rock has fewer pores and low permeability (Figure 10a and b). This is due to the fact that during early diagenesis, more minerals are able to act as cement as the pressure is lower. The increase in cement minerals decreases the reservoir quality of the rock. The influence of compaction on pore reduction in the braided channel sandstones is clearly reflected due to the abundance of deformable components and calcite cement, as well as sorting [46]. The sandstones are severely fractured as they were subjected to high pressures (this is reflected by the grain borders). This has increased the porosity but not the permeability (Figure 12c). The mineral composition of the sandstones can also be a driving force in porosity and permeability levels of the rocks. The sandstones of the Ecca Group are dominated by quartz which is a hard mineral and is not easily altered. This has resulted in the sandstones exhibiting low porosity and permeability levels. Feldspars (k-feldspar) mainly promote the formation of illite which decreases permeability. Micas also decrease both porosity and permeability through chemical compaction.

The XRD and SEM+EDX results indicate that authigenic quartz, feldspar, kaolinite, smectite, and illite are the major cement types in the sandstone. The formation of cement is proof that feldspar dissolution and alteration took place. Kaolinite has a unique lattice structure that can protect inter-crystalline micro-pores and increase reservoir space. However, intercrystalline micropores and dissolution can make up for the loss of pores brought on by cementation [47-48]. The moderate content of kaolinite displays high levels of secondary pores (Figure 8a). An increase in the kaolinite content could impact reservoir porosity negatively. The Ecca Group sandstones are dominated by kaolinite which decreases their pores and permeability. Feldspar cementation occurs as overgrowth and occupies the voids which lower the permeability. Quartz occurs as overgrowth which impact porosity and permeability negatively (Figure 11b); however, some authors have indicated that quartz overgrowth does not contribute to reservoir quality [46].

The sandstones of the Ecca Group contain less than 10% of voids, and these voids are mainly attributed to secondary porosity (Figures 11c and d). The triggering factor for secondary porosity is the dissolution of various minerals such as silica, clay, rock fragments, and carbonates minerals. This plays a crucial role on the reservoir quality [46,49-50]. The dissolution of feldspar acts as a key factor in the increase of secondary porosity when silica is precipitated (11d and 12c). This dissolution is caused by faults and high reservoir quality rocks where acidic waters could infiltrate. The aluminium silicates extensively dissolve at temperatures between 80 and 120°C during which the levels of organic acid and pore fluids are high [52]. During the dissolution processes, the formation of quartz overgrowth [52-54] closes the intragranular pores in the sandstones thus decreasing the reservoir quality (Figure 11a and b). Though carbonate minerals are not abundant, they occur as cement in the Whitehill Formation. The carbonates are mainly derived from rock fragments, fossils and Ca-bearing feldspars and they mainly occur as cement [49]. Sandstones with low carbonates minerals enhances the pores and permeability.

Replacement of minerals has a positive impact on the reservoir quality. In cases where micas replace feldspars during late diagenesis, more pores are formed and permeability is greatly affected. The Ecca sandstones contain muscovite micas which greatly impacts the reservoir quality of the Ecca Group (Figure 6e). According to [41], a well-sorted rock tends to display high porosity, this agrees with studies done on the sandstones which have revealed that grains do not occupy the spaces between each other. Cementation negatively affects the reservoir properties due to infill of pores, but [46] has shown that cementation through carbonate minerals does not contribute to the reservoir properties. Dissolution in the analysed sandstones shows a decrease in reservoir properties as a result of low percentage of pores which were infilled post dissolution. This agrees with studies conducted by [53-54] indicating that dissolution decreases pores and permeability.

6. Conclusions

This study was conducted to unravel the diagenetic properties of the sandstones in borehole KZF-1 of the Ecca Group. From the petrographic studies, it was revealed that the sandstones of these groups are wacke. The sandstones were subjected to three main stages of diagenesis, namely the early, burial and uplift diagenetic stages. The main diagenetic processes that have affected the rocks are cementation, mechanical compaction, recrystallization, replacement, and dissolution. The primary porosities (inter- and intra-granular pores and intercrystalline pores) are reduced due to intense mechanical compaction and clay mineral infills. The feldspars after diagenetic modification, tectonism and differential compaction have led to the formation of secondary pores. These diagenetic processes occurred during both burial and uplift-related diagenetic stage when meteoric water influx was abundant. Conversely, the diagenetic processes also resulted in production of some diagenetic products such as clay cements (e.g. smectite filling and lining) which reduced the porosity. Generally, there is no single diagenetic process that solely controlled the pattern of porosity within the rocks. The main types of cements (clay minerals and quartz) as well as compaction have collectively controlled the porosity and the reservoir quality of the rocks. Petro-physically, the reservoir quality of the Ecca Group ranges from poor to medium. The presence of fractured and dissolution pores has enhanced the reservoir quality of the sandstones. However, the low porosity as well as the isolated nature of the pores (low permeability) makes them unfavorable producers of hydrocarbons.

References

[1] Kim JC, Lee YI and Hisad KI. Depositional and compositional controls on sandstone Diagenesis, the Tetori Group (Middle Jurassic–Early Cretaceous), Central Japan. Sedimentary Geology, 2007; 195 (3-4), pp.183-202.
[2] Gier S, Worden RH, Johns WD, and Kurzweil H. Diagenesis and reservoir quality of Miocene sandstones in the Vienna Basin, Austria. Marine and Petroleum Geology, 2008; 25 (8): 681-695.
[3] Taylor TR, Giles MR, Hathon LA, Diggs TN, Braunsdorf NR, Birbiglia GV, Kittridge MG, Macaulay CI, and Espejo IS. Sandstone Diagenesis and reservoir quality prediction: Models, myths, and reality. AAPG bulletin, 2010; 94 (8): 1093-1132.
[4] Zou C, Zhu RK, Wu ST, Yang Z, Tao SZ, Yuan XJ, Hou L, Yang H, Xu C, Li D, and Bai B. Types, characteristics, genesis and prospects of conventional and unconventional hydrocarbon accumulations: taking tight oil and tight gas in China as an instance. Acta Petrolei Sinica, 2012; 33 (2): 173-187.
[5] Monsees AC, Busch B, and Hilgers C. Compaction control on Diagenesis and reservoir quality development in red bed sandstones: a case study of Permian Rotliegend sandstones. International Journal of Earth Sciences, 2021; 110 (5): 1683-1711.
[6] Almond JE, de Klerk B, and Gess R. Palaeontological heritage of the Eastern Cape. Unpublished technical report prepared for Heritage Western Cape, 2008; 7-8.
[7] Li Y, Fan A, Yang R, Sun Y, and Lenhardt N. Sedimentary facies control on sandstone reservoir properties: A case study from the permian Shanxi Formation in the southern Ordos basin, central China. Marine and Petroleum Geology, 2021a; 129: 105083.
[8] Feng J, Cao J, Hu K, Peng X, Chen Y, Wang Y, and Wang M. Dissolution and its impacts on reservoir formation in moderately to deeply buried strata of mixed siliciclastic–carbonate sediments, northwestern Qaidam Basin, northwest China. Marine and Petroleum Geology, 2013; 39 (1): 124-137.
[9] Dar QU, Pu R, Baiyegunhi C, Shabeer G, Ali RI, Ashraf U, Sajid, Z, and Mehmood M. The impact of Diagenesis on the reservoir quality of the early Cretaceous Lower Goru sandstones in the Lower Indus Basin, Pakistan. Journal of Petroleum Exploration and Production Technology, 2021; 1-16.
[10] Avseth P, Jørstad A, van Wijngaarden AJ, and Mavko G. Rock physics estimation of cement volume, sorting, and net-to-gross in North Sea sandstones. The Leading Edge, 2009; 28 (1): 98-108.
[11] Kelly J, Parnell J, and Chen HH. Application of fluid inclusions to studies of fractured sandstone reservoirs. Journal of Geochemical Exploration, 2000; 69: 705-709.
[12] Worden RT, and Barclay SA. Internally-sourced Quartz cement due to externally-derived CO2 in sub-arkosic sandstones, North Sea. Journal of Geochemical Exploration, 2000; 69: 645-649.
[13] Dutton SP, and Loucks RG. Diagenetic controls on evolution of porosity and permeability in lower Tertiary Wilcox sandstones from shallow to ultradeep (200–6700 m) burial, Gulf of Mexico Basin, USA. Marine and Petroleum Geology, 2010; 27 (1): 69-81.
[14] Zhang Y, Lv D, Wang Y, Liu H, Song G, and Gao J. Geological characteristics and abnormal pore pressure prediction in shale oil formations of the Dongying depression, China. Energy Science & Engineering, 2020; 8 (6): 1962-1979.
[15] Nyathi N. Stratigraphy, sedimentary facies and diagenesis of the Ecca Group, Karoo Supergroup in the Eastern Cape, South Africa. Doctoral dissertation, University of Fort Hare, 2014; 1-137.
[16] Geel C, and Bordy EM. Palaeo-environmental and provenance reconstruction of the Lower Permian mudstones (lower Ecca Group) in the main Karoo Basin, South Africa. Journal of African Earth Sciences, 2021; 182: 104303.
[17] Johnson MR, Anhauesser, CR, and Thomas RJ. The Geology of South Africa. Geological Society of South Africa, 2006; 2-7.

[18] Johnson MR, Van Vuuren CJ, Hegenberger WF, Key R, and Show U. Stratigraphy of the Karoo Supergroup in southern Africa: an overview. Journal of African Earth Sciences, 1996; 23 (1): 3-15.
[19] Catuneanu O, Wopfner H, Eriksson PG, Cairncross B, Rubidge BS, Smith RMH, and Hancox PJ. The Karoo basins of south-central Africa. Journal of African Earth Sciences, 2005; 43 (1-3): 211-253.
[20] Wopfner H. Tectonic and climatic events controlling deposition in Tanzanian Karoo basins. Journal of African Earth Sciences, 2002; 34 (3-4): 167-177.
[21] Catuneanu O, Hancox PJ, and Rubidge BS. Reciprocal flexural behaviour and contrasting stratigraphies: a new basin development model for the Karoo retroarc foreland system, South Africa. Basin research, 1998; 10 (4): 417-440.
[22] Catuneanu O, Hancox PJ, Cairncross B, and Rubidge BS. Foredeep submarine fans and forebulge deltas: orogenic off-loading in the underfilled Karoo Basin. Journal of African Earth Sciences, 2002; 35 (4): 489-502.
[23] Baiyegunhi TL, Liu K, Gwavava O, and Baiyegunhi C. Classification and Diagenetic Characteristics of the Cretaceous Sandstones in the Southern Bredasdorp Basin, Offshore South Africa. Acta Geologica Sinica-English Edition, 2021; 95 (5): 1695-1713.
[24] Jacobs J. and Thomas RJ. Himalayan-type indenter-escape tectonics model for the southern part of the late Neoproterozoic–early Paleozoic East African–Antarctic orogen. Geology, 2004; 32 (8): 721-724.
[25] Tankard A, Welsink H, Aukes P, Newton R, and Stettler E. Tectonic evolution of the Cape and Karoo basins of South Africa. Marine and Petroleum Geology, 2009;26 (8): 1379-1412.
[26] Bangert B, Stollhofen H, Lorenz V, and Armstrong R. The geochronology and significance of ash-fall tuffs in the glaciogenic Carboniferous-Permian Dwyka Group of Namibia and South Africa. Journal of African Earth Sciences, 1999; 29 (1): 33-49.
[27] McKay MP, Weislogel AL, Fildani A, Brunt RL, Hodgson DM, and Flint SS. U-PB zircon tuff geochronology from the Karoo Basin, South Africa: implications of zircon recycling on stratigraphic age controls. International Geology Review, 2015; 57 (4): 393-410.
[28] Fildani A, Weislogel A, Drinkwater NJ, McHargue T, Tankard A, Wooden J, Hodgson D, and Flint S. U-Pb zircon ages from the southwestern Karoo Basin, South Africa—Implications for the Permian-Triassic boundary. Geology, 2009; 37 (8): 719-722.
[29] Geel C, Schulz HM, Booth P, deWit M, and Horsfield B. Shale gas characteristics of Permian black shales in South Africa: results from recent drilling in the Ecca Group (Eastern Cape). Energy Procedia, 2013; 40: 256-265.
[30] Cole DI and Johnson MR. Prince albert formation. Catalogue of South African Lithostratigraphic Units. South African Committee for Stratigraphy, 2005; 8: 33-36.
[31] Geel C, De Wit M, Booth P, Schulz HM, and Horsfield B. Palaeo-environment, diagenesis and characteristics of Permian black shales in the Lower Karoo Supergroup flanking the Cape Fold Belt near Jansenville, eastern Cape, South Africa: Implications for the shale gas potential of the Karoo Basin. South African Journal of Geology, 2015; 118 (3): 249-274.
[32] Rubidge BS. 27th Du Toit Memorial Lecture: re-uniting lost continents–fossil reptiles from the ancient Karoo and their wanderlust. South African Journal of Geology, 2005; 108 (1): 135-172.
[33] Pettijohn FJ, Potter PE, and Siever R. Petrography of common sands and sandstones. In Sand and Sandstone. Springer, New York, NY, 1987; 139-213.
[34] Dickinson WR, Beard LS, Brakenridge GR, Erjavec JL, Ferguson RC, Inman KF, Knepp RA, Lindberg FA, and Ryberg PT. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geological Society of America Bulletin, 1983; 94(2): 222-235.
[35] Folk RL. Petrology of Sedimentary Rocks Hemphill Publishing Co. Austin, TX, 1974; 182.
[36] Bjørlykke K. Principal aspects of compaction and fluid flow in mudstones. Geological Society, London, Special Publications, 1999a;158 (1): 73-78.
[37] Bjørlykke K. An overview of factors controlling rates of compaction, fluid generation and flow in sedimentary basins. Growth, dissolution and pattern formation in geosystems, 1999b; 381-404.
[38] Boggs S. Principles of sedimentology and stratigraphy. Prentice Hall. New Jersey, 2012; 652-674.
[39] Boggs Jr S, and Boggs S. Petrology of sedimentary rocks. Cambridge university press, 2009;.21-25.

[40] Chima P, Baiyegunhi C, Liu K, and Gwavava O. Diagenesis and rock properties of sandstones from the Stormberg Group, Karoo Supergroup in the Eastern Cape Province of South Africa. Open Geosciences, 2018; 10 (1): 740-771.
[41] Folk RL. Henry Clifton Sorby (1826–1908), the founder of petrography. Journal of Geological Education, 1965; 13 (2): 43-47.
[42] Boggs S. Principles of Sedimentology and Stratigraphy. Prentice Hall. New Jersey, 1995; 765-774.
[43] Chamley H. Clay minerals. In Clay sedimentology. Springer, Berlin, Heidelberg, 1989; 3-20.
[44] Selley RC. Applied sedimentology. Elsevier, 2000; 45-120.
[45] Murray RC. Origin of porosity in carbonate rocks. Journal of Sedimentary Research, 1960; 30 (1): 59-84.
[46] Li J, Zhang X, Tian J, Liang Q, and Cao T. Effects of deposition and Diagenesis on sandstone reservoir quality: A case study of Permian sandstones formed in a braided river sedimentary system, northern Ordos Basin, Northern China. Journal of Asian Earth Sciences, 2021b; 213: 104745.
[47] Fan A, Yang R, Lenhardt N, Wang M, Han Z, Li J, Li Y, and Zhao Z. Cementation and porosity evolution of tight sandstone reservoirs in the Permian Sulige gas field, Ordos Basin (central China). Marine and Petroleum Geology, 2019; 103: 276-293.
[48] Xiao D, Jiang S, Thul D, Lu S, Zhang L, and Li B. Impacts of clay on pore structure, storage and percolation of tight sandstones from the Songliao Basin, China: implications for genetic classification of tight sandstone reservoirs. Fuel, 2018; 211: 390-404.
[49] Ma B, Cao Y, and Jia Y. Feldspar dissolution with implications for reservoir quality in tight gas sandstones: evidence from the Eocene Es4 interval, Dongying Depression, Bohai Bay Basin, China. Journal of Petroleum Science and Engineering, 2017; 150: 74-84.
[50] Shao X, Pang X, Jiang F, Li L, Huyan Y, and Zheng D. Diagenetic characteristics and reservoir quality in tight gas sandstones: A case study of the Shanxi Formation in the north-eastern Ordos Basin, China. Geological Journal, 2019; 54(6): 3257-3271.
[51] Surdam RC, Crossey LJ, Hagen ES, and Heasler HP. Organic-inorganic interactions and sandstone Diagenesis. Aapg Bulletin, 1989; 73 (1): 1-23.
[52] Kim Y, and Lee YI. Diagenesis of shallow marine sandstones, the Lower Ordovician Dongjeom Formation, Korea: response to relative sea-level changes. Journal of Asian Earth Sciences, 2004; 23 (2): 235-245.
[53] Peltonen C, Marcussen Ø, Bjørlykke K, and Jahren J. Clay mineral diagenesis and quartz cementation in mudstones: The effects of smectite to illite reaction on rock properties. Marine and Petroleum Geology, 2009; 26 (6): 887-898.
[54] Worden RH and Morad S. Quartz cementation in oil field sandstones: a review of the key controversies. Quartz cementation in sandstones, 2000; 1-20.

To whom correspondence should be addressed: Ronaldo Malapana, Department of Geology and Mining, University of Limpopo, Private Bag X1106, Sovenga 0727, Limpopo Province, South Africa; e-mail: malapaneron@gmail.com