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CHLORITE AUTHIGENESIS AND ITS EFFECTS ON RESERVOIR POROSITY IN THE EARLY CRETACEOUS BIMA SANDSTONE, YOLA SUB-BASIN, NORTHERN BENUE TROUGH, NIGERIA

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ABSTRACT

The effects of chlorite on sandstone reservoirs have received more attention recently. Deeply buried sandstone reservoirs are prone to diagenetic alterations due to the presence of clays thereby affecting their reservoir quality (porosity). The effects of chlorite authigenesis on reservoir porosity are yet to be fully understood, and these create uncertainties in reservoir exploration of the fluvial reservoir in the basin. The Early Cretaceous Bima Sandstone which is divided into the Lower and Upper Members was deposited in a braided river to alluvial fan settings. An integrated approach, including thin-section petrography, Scanning Electron Microscopy (SEM) and X-ray diffraction (XRD) analyses was employed in the study with the aim of determining the effects of different chlorite occurrences on reservoir quality (porosity). Sandstone reservoir quality depends on both depositional parameters like grain size, sorting and matrix content as well as diagenetic alterations. Chlorite formation involves the availability of precursor clays like smectite, kaolinite and berthierine as the material base and dissolution of detrital grains to provide Fe and Mg ions. Two types of authigenic chlorite occurrences were observed in this research; the grain-coating chlorite and the pore-filling chlorite. The study shows that chlorite sourced from smectite-dominant clays occurs as grain-coating thereby inhibiting quartz overgrowth, whereas chlorite formed from kaolinite are found as pore-fillings which leads to deterioration of reservoir porosity.

Keywords: Chlorite, Diagenetic, Grain-Coating, Porosity, Sandstone

INTRODUCTION

The continental Bima Sandstone is presently one of the most important petroleum reservoir and exploration target in the Nigerian inland sedimentary basins. The influence of authigenic chlorite has become a very important element in understanding the reservoir diagenetic alterations and its impact. Authigenic chlorite has both positive and negative influences in the quality of a deeply buried sandstone reservoir (Charlaftis et al., 2020, Cao et al., 2018). Although, the effects of chlorite on reservoirs are yet to be fully understood, its occurrence is a significant factor for reservoir exploration (Cao et al. 2018). In this research, two types of authigenic chlorite occurrences; grain coating and pore-filling were observed and evaluated.

Grain-coating chlorite has a positive influence in reservoirs by inhibiting the nucleation of quartz overgrowth thereby preserving the primary porosity (Tillman and Almon, 1979; Ehrenberg, 1993; Huang et al., 2004; Berger et al., 2009; Dowey et al., 2012). Chlorite also occurs as pore fillings which has a negative influence on reservoirs (Porter and Weimer, 1982; Nadeau, 2000; Islam, 2009; Smith et al., 2013).

Sandstone reservoir quality depends on both depositional characteristics like grain size, sorting and matrix content (Bello et al., 2021; Lai et al., 2016; Hakimi et al., 2012), and diagenetic modifications (Morad et al., 2010; Ma et al., 2017). As such, excellent reservoirs are those with large grain size, well sorted, and having low detrital matrix (Hakimi et al., 2012). However, getting clean sandstones free from diagenetic influence is somewhat impossible; as such understanding the origin and influence of these diagenetic elements is very important in exploration activities. Two most important issues concerning the formation mechanism of chlorite need to be understood: the formation conditions of chlorite, and the origin of different occurrences. Dowey et al. (2012) stated that chlorite coats generally develop in littoral, fluvial, and delta, whereas Baker et al. (2000) showed that chlorite coats indicate a marine-influenced deltaic facies. Few works have been done on chlorite occurrence in this basin (Bello et al., 2022). This present work is aimed at presenting the different occurrences of chlorite in the continental Bima Sandstone, their sources and impact on reservoir quality.

Geological background and stratigraphic setting

The Benue Trough (Fig. 1 A and B) is an elongate intracratonic structure that forms part of a mega-rift basin found within the West and Central African Rift System (WCARS) that extends NNE-SSW for about 800 km long and 150 km wide (Obaje, 2009), and consists of sedimentary package between 4,000 to 6,000 m of Cretaceous-Tertiary sedimentary units (Akande *et al.*, 2011). It is arbitrarily divided in to the northern, central and southern portions based on tectonic, geographical, and stratigraphic components (Murat, 1972; Ford, 1981; Whiteman, 1982, Benkhelil, 1987, 1989; Ramanathan and Fayose, 1990). The Northern Benue Trough bifurcates into N-S trending Gongola sub-basin and E-W trending Yola sub-basin (Fig. 1). Hydrocarbon explorations within the west and central African rift system (WCARS) have proven to be positive with commercial discoveries made in Doba basin, SW Chad and Mugland basin in Sudan among others.

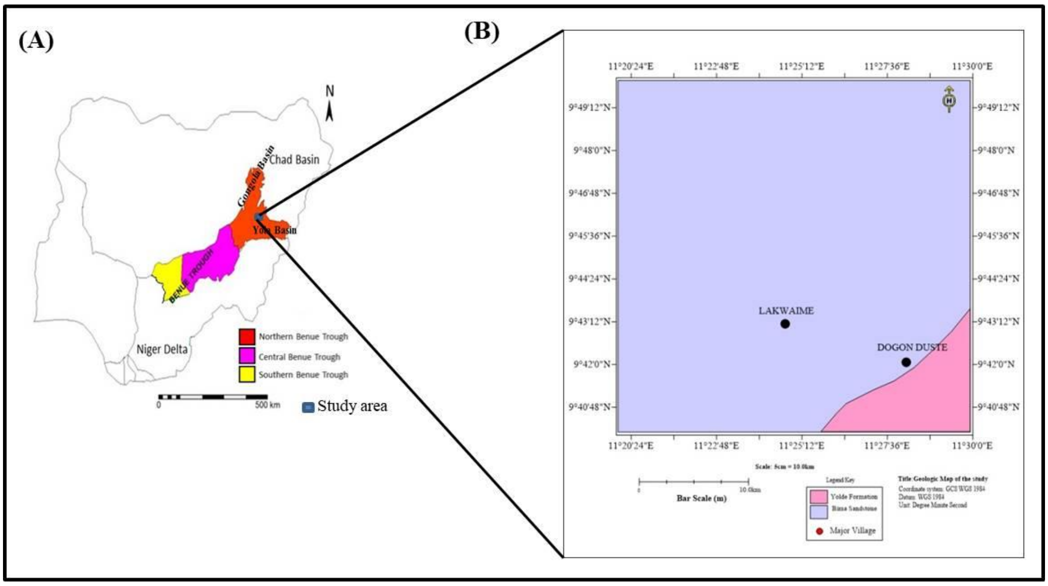

Figure 1: (A). Map of Nigeria showing the Benue Trough (adopted from Bata et al., 2018). (B) Geological map of the study area.

The Early Cretaceous Bima Sandstone in the Benue Trough has been proven to be a viable petroleum reservoir. It is the basal unit, which makes it unarguably the oldest formation in the basin that rests nonconformably on the Precambrian Basement Complex (Cater et al., 1963). The formation was deposited under continental conditions, mostly in the braided river and alluvial fan settings (Benkhelil, 1989; Guiraud, 1990). Tukur et al., (2015) subdivided the formation into two; the Lower and Upper members based on sedimentological data (Fig 2).

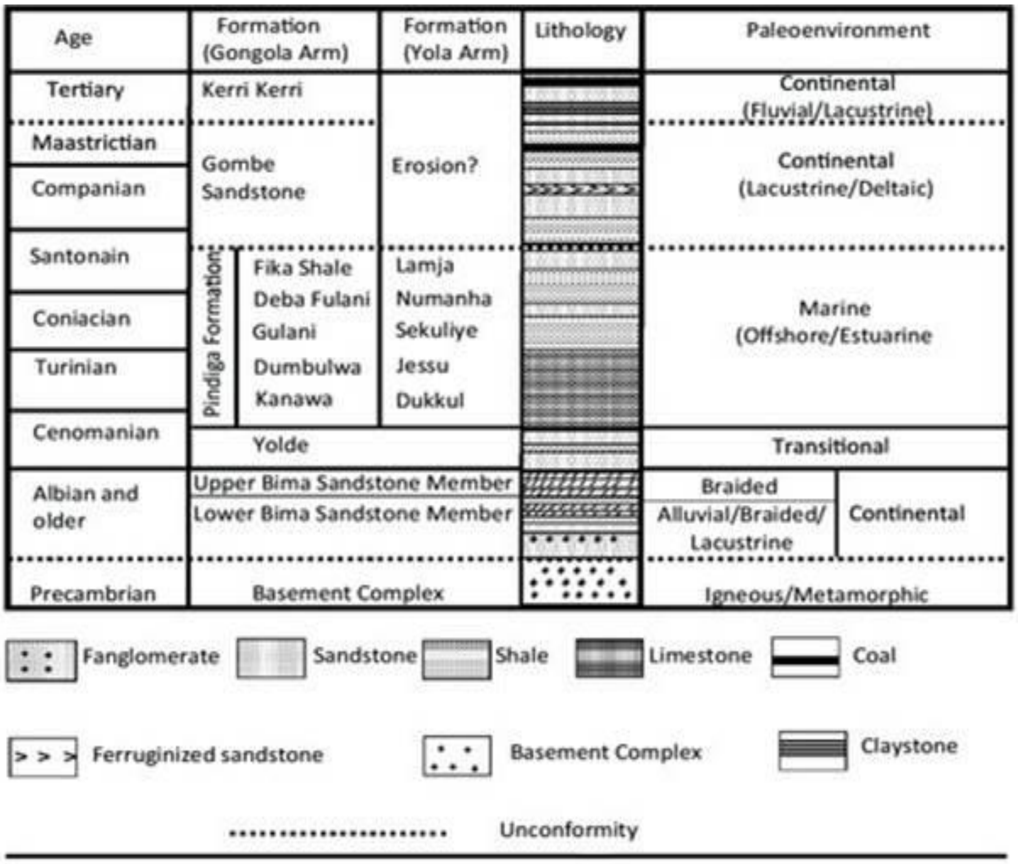

Figure 2: Stratigraphic succession of the Northern Benue Trough (after Tukur et al., 2015)

MATERIALS AND METHODS

A total of 10 sandstone samples from some selected outcrop exposures of the Lower and Upper members of Bima Sandstone in Yola Sub-basin, Northern Benue Trough, NE Nigeria were selected and subjected to quantitative investigation aimed at understanding the distribution and the effects of authigenic chlorite occurrences on reservoir quality (porosity).

Petrography

Thin sections were prepared and studied using petrographic microscope to see the textural as well as mineralogical components. Some of the samples were impregnated using blue resin to highlight pore spaces. Quartz and feldspars dominate the samples, with biotite occurring as subordinate mineral (Fig. 3. A-D). Modal point count analysis was conducted using JMicroVision 1.3.1 software based on 300 counts per sample to determine the detrital and authigenic components, and pore space properties.

SEM/EDS Analyses

Scanning Electron Microscopy and Energy Dispersive Spectrometry (SEM/EDS) analyses were done to study the textural relationship, clay mineral types and their composition, mode of occurrence, and diagenetic alterations (Fig. 4 A-D). This was done on polished thin sections prepared and studied under an SU70 Hitachi scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectrometer (EDS). The scanning electron microscope analysis was done under an accelerated voltage of 20 kV and a measured beam current of 0.6 nA after coating the samples with a thin layer of gold. SEM/SEM-EDS were used in confirming the identities of framework grains and clay minerals.

XRD Analysis

Bulk X-Ray Diffraction (XRD) analysis was conducted using Malvern PANalytical Empyrean Cu LFF HR diffractometer with Cu kα1 radiation at a wavelength of 1.5406 Å and X-ray tube voltage and current set at 40 mA and 5kV respectively. It was done to quantify sandstones framework constituents and also complement the petrographic point-count data following the setup of Amao *et al.,* (2022). About 5 g of crushed and powdered sandstone sample using the Retsch RM 200 mill for about 5-7 min was obtained. Before each run, the mill was cleaned with ethanol. The samples show chlorite occurrences in both lower and upper members of Bima sandstone (Fig. 5 A & B).

RESULTS AND DISCUSSION

Formation conditions of Chlorite

Previous studies have shown that formation of chlorite requires the presence of precursor clay mineral (including smectite, kaolinite, and berthierine) as the material base and dissolution of detrital grains to provide Fe and Mg ions (Cao et al., 2018). The studied sandstones contain framework grains, diagenetic clays, and pores space characteristics This indicates that chlorite could be formed in sandstones that are rich in biotite and mud intraclasts (Figs. 3 A-D) which act as sources of Fe and Mg (Luo et al., 2009).

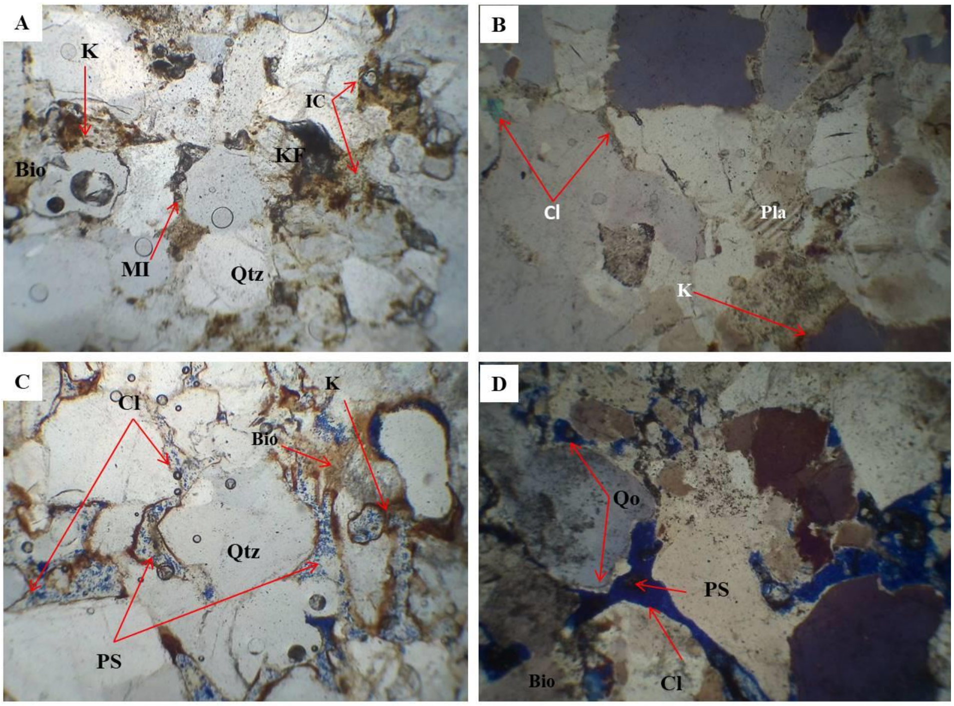

Figure 3: Photomicrograph (A-D). (A) Qtz=quartz, KF=potassium feldspar, Bio=biotite, MI=mud intraclasts, IC=illitic clays (B) Cl=chlorite, Pla=plagioclase and K=kaolinite (C) blue resin impregnated sample, PS=preserved pore space, Cl=grain-coating chlorite, Qtz=quartz (D) blue resin impregnated sample, Qo=quartz overgrowth, Cl=grain-coating chlorite, PS= preserved pore space.

The reservoir rocks have two principal sources of clay minerals; the fluvial system that deposited the sediments, and the alteration of clastic particles. The fluvial system has clay minerals carried as suspended loads in rivers and lakes which normally get deposited as the transporting medium becomes weak and cannot transport the sediments further. In such cases, clays held in suspension usually provided by weathering of the parent rocks, fed into the river system by rainwater will begin to settle on the sands earlier deposited. While the clastic units will subsequently be subjected to diagenetic alterations giving rise to some clays like kaolinite, smectite and illite which subsequently transform to chlorite (Figs. 4 A-D). Chlorite can be sourced from original layered silicate minerals (illite, kaolinite, and smectite) when Fe-Mg rich fluid invades a formation basically due to the difference between formation pressure and interstitial fluid of the adjacent formation (Hillier et al., 1996).

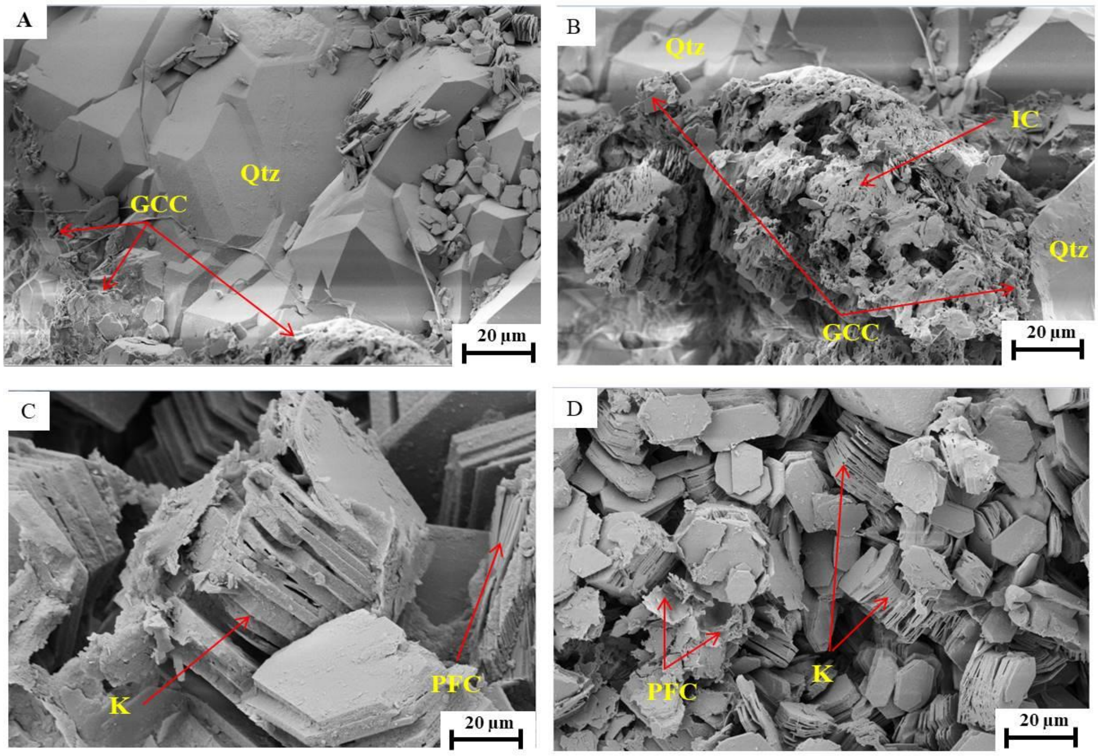

Figure 4: Mode of occurrence of various clay minerals in the Upper Bima Member (A & B) and Lower Bima Member (C & D). (A) Grain-coating chlorite (GCC) which inhibits quartz (Qtz) overgrowth. (B) Transformation of illitic clays into grain-coating chlorite (GCC). (C) Transformation of kaolinite (K) in to pore-filling chlorite (Cl). (D) Transformation of kaolinite (K) in to cabbage-head pore filling chlorite (PFC)

The XRD result shows that samples with kaolinite, illite and biotite have chlorite occurrences, and these are found in both the Lower and Upper Bima Sandstone Members (Fig. 5 A & B).

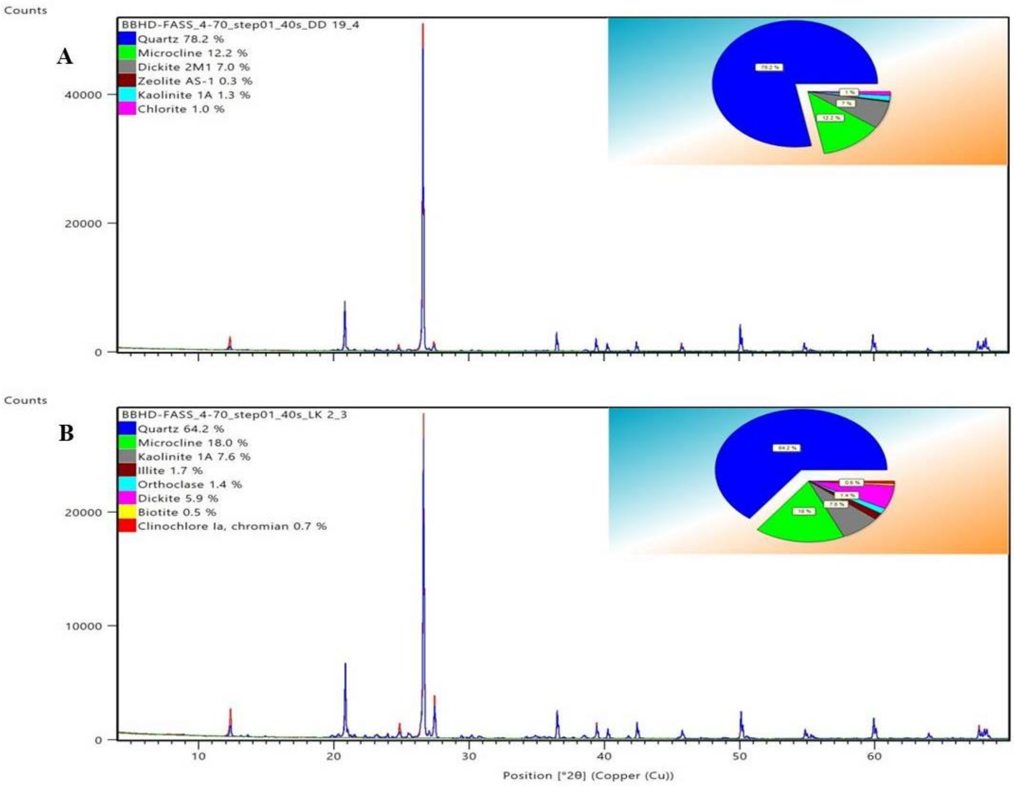

Figure 5: XRD analysis data (A) Chlorite occurs as Clinochlore la in Upper Bima Sandstone Member (B) Chlorite in the Lower Bima Sandstone Member.

Clay mineral precursors in the samples

Smectite precursor

Smectite has not been directly detected in the samples, however, its presence has manifested petrographically in the form of clays with greenish to brown birefringence that occur as detrital matrix (Figs. 3 A and 4 B) indicating illitic clays from smectite (Shaw and Conybeare, 2003; Bahlis and De Ros, 2013; Bello et al., 2021). Bloch et al. (2002) have pointed out that chlorite is developed from smectite reacting with iron oxide and saline pore waters. Also, the development of chlorite from a tri-octahedral smectite requires a local source of aluminum or the loss of excess silica (Chang et al. 1986). Examples of chlorite-smectite occurrence can be found in Central Graben of the UK North Sea (Humphreys et al., 1989), Santos Basin, Brazil (Anjos et al., 2003), North German Basin (Gaupp et al., 1993; Hillier et al., 1996; Platt, 1994). Chloritized smectite forms continuous coatings along the intergranular grain contact (Morad et al., 2000).

Kaolinite precursor

Kaolinite has been detected in virtually all the studied samples of Bima Sandstone. It has gradually transformed into chlorite during diagenesis (Figs. 3 A & B, and 4 C & D). A mixed-layer chlorite-kaolinite has been reported in a sandstone reservoir on the Norwegian Continental Shelf (Hillier and Velde 1992). Chlorite can be formed in sandstones that are rich in biotite and mud intraclasts (Fig. 3 A) which act as sources of Fe and Mg (Luo et al., 2009). Other sources of Fe and Mg include finely crystalline, grain coating Fe-oxide pigments that are usually associated with grain-coating infiltrated clays (De Ros et al., 1994). As such, the presence of chlorite in the sandstone samples of Lower and Upper Bima Sandstone Members can be attributed partly to kaolinite as precursor clay mineral.

Chlorite occurrences and their effects on porosity

Grain-coating chlorite

Grain-coating chlorite (GCC) is observed in the studied samples of Bima Sandstone. The spatial distribution of chlorite perpendicular to the framework grain surface as rims of pseudohexagonal crystals opposite quartz cement (Figs. 4 A & B) inhibits the precipitation of quartz overgrowths in sandstone. As such, chlorite coatings aid in the preservation of porosity and permeability in deep sandstone reservoirs (Pittman et al., 1992; Ehrenberg, 1993).

Pore-filling chlorite

Pore-filling chlorites can be sourced from rocks rich in kaolinite which occur within the pores. The rocks of the study area are also rich in biotite and mud intraclasts which will provide the Fe and Mg needed for chlorite formation (Fig 3 A & C). The XRD results (Fig. 5 A & B) show the presence of chlorite in the studied samples of Bima Sandstone. The pore-filling chlorite (PFC) in the samples can be attributed to form mostly from kaolinite (Fig. 4 C & D) that have possibly been flooded with Fe and Mg rich fluids.

CONCLUSION

In conclusion, the sediments of both the Lower and Upper Bima Sandstone Members have clay minerals that can serve as precursor for chlorite formation. The presence of authigenic chlorite in the samples is suggested to have evolved from smectite (via illite-smectite reaction), and kaolinite. The grain-coating chlorite occurrence was from smectite clays sourced via illite-smectite reaction whereas the pore-filling variety most likely sourced from kaolinite, and this is because the kaolinite occupies the intergranular spaces. The influence of chlorite on the reservoir quality (porosity) could be either positive or negative and, this depends on its occurrence. In the studied samples, grain-coating chlorites are found mostly in the Upper Bima Sandstone Member. They partly coat the grains (quartz) which are expected to enhance the mechanical strength of the rocks. This has played a significant role in preventing contact between detrital quartz surface and pore water, thus preserving the intergranular spaces by preventing compaction and nucleation of authigenic quartz. The pore-filling variety on the other hand, has a negative effect on the reservoir. This is because most of it is sourced from kaolinite found within the pore spaces, thereby destroying the initial intergranular porosity.

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