AS Mustapha

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sadiqmustapha@gmail.com

Department of Geology & Mining,
Ibrahim Badamasi Babangida University, Lapai, Niger State, Nigeria.

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Diagenetic and Reservoir Quality Evaluation of Cenomanian Yolde Sandstone Facies in the Gongola Basin, Upper Benue Trough, NE, Nigeria

*AS Mustapha[1], I Yusuf[1], NG Obaje[1, 2], RG Oladimeji[3]
[1]Department of Geology & Mining, Ibrahim Badamasi Babangida University, Lapai, Niger State
[2]Chair Professor, Nigeria National Petroleum Company Limited
[3]Department of Geological Sciences, Osun State University-Oshogbo, Osun State, Nigeria

*** Corresponding author email address**: sadiqmustapha@gmail.com

ABSTRACT

Potential petroleum systems of the Chad Basin and Upper Benue Trough are made up of sandstone facies of the Bima and Yolde Formations as potential reservoir rocks. There are several literatures on the Bima sandstone reservoir facies, but scanty on the Yolde Formation especially on its reservoir quality. This study focuses on the diagenetic and reservoir quality assessment of the Yolde sandstone to assess its potential as a reservoir rock through integrated approach by the combination of field observations, sedimentological studies, petrography and petrographic image analysis (PIA), geochemical; X-ray Diffraction (XRD) and scanning electron microscope (SEM). Geological field observations reveal six (6) sandstone lithofacies that includes; the trough cross bedding (TCBL), massive sandstone (MSSL), hummocky crossed bedding (HCBL), herringbone sandstone (HSL), massive bioturbated (MBSL) and parallel laminated (PTSL) sandstone lithofacies. Results from sedimentalogical study indicate that the Yolde sandstone lithofacies are generally medium to coarse grains, moderate to poorly sorted sediments. Findings from integration of petrography, scanning electron microscopy (SEM), X-ray Diffraction (XRD) analysis also confirm sedimentalogical results and highlight textural immaturity, mechanical, chemical grain compaction, quartz overgrowth and cementation and clay minerals; illite, kaolinite, and smectite (montmorillonite) are mainly present authigenic clays that thus reduce and obliterates intergranular pore spaces through precipitation, cementation and pore-filling. Petrographic image analysis (PIA) indicate that the porosity within the different Yolde sandstone lithofacies vary from 0.17 to 0.30%. The reservoir quality of the sandstones in the study area appears to be moderately poor due to the intensive diagenetic alterations that have resulted from effect of burial compaction, presence of angular-to-sub angular grains, precipitation, cementation and blockage of pore throats interconnectivity by quartz overgrowths and other authigenic clay minerals which have significantly obliterated larger volume of pore attribute distribution within the variable sandstone lithofacies. These outcomes may have potential implications on reservoir deliverability that have contributed to exploration failure in part of the Gongola and Chad Basin where some exploration wells drilled were dry, because of the inability to transmit moveable oil fluid into the wellbore.

Keywords: Gongola sub-basin, Yolde Formation, Yolde sandstone lithofacies, Reservoir quality, Upper Benue Trough, Reservoir diagenesis, Eodiagenesis, Mesodiagenesis, Telodiagenesis.

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INTRODUCTION

The Upper Benue Trough is a geological basin located in Nigeria that has attracted significant attention from the oil and gas industry due to recent oil & gas discovery in Kolmani River well in the Upper Benue Trough- Gongola arm (Abubakar et al., 2019). The Yolde Formation is a prominent geological formation known to contain sandstone lithofacies that could potentially hold significant amounts of oil and gas (Obaje, 2009). The geological assessment and characterization of the reservoir quality of the Yolde Formation hold significant importance in understanding its contributions to exploration failure in the part of the basin. However, reevaluation of the Yolde Formation reservoir quality parameters is crucial for the evaluation of its potential as a hydrocarbon reservoir- holding the ability to store and transmit hydrocarbon fluid into wellbore.

In petroleum exploration, reservoir quality is one of the main controlling factors on hydrocarbon prospectively (Worden et al., 2020). Therefore, it is important to have a detailed understanding of the factors that controls reservoir quality in order to assist with the appraisal of the economic feasibility of hydrocarbon discoveries. Reservoir quality in sandstone rocks is controlled by several interconnected factors such as mineral composition, pore water chemistry, diagenetic events, temperature, fluid flow, depositional environment, tectonic setting, time, burial depth, uplift process, geothermal gradient, and subsurface pressure (Selley, 1997). Rock properties and reservoir quality of sandstones call for a deliberate focus on depositional, shallow diagenetic and deep burial diagenetic processes. Initial rock properties such as grain size, mineral composition initial porosity and permeability are dependent on processes associated with the source area and the environment of deposition. Subsequent evolution of these properties is influenced by diagenesis, a continuously active process during which sedimentary mineral assemblages react to equilibrate within an environment of altering temperature, pressure, and chemistry conditions (Morad, 2003). This study attempts to investigate the reservoir quality of the Yolde potential reservoir sandstone in the Upper Benue Trough to determine its possible contribution to reservoir deliverability and its petrophysical property distribution in the basin within the different sandstone lithofacies

GEOLOGICAL SETTING

The Upper Benue Trough is made up of two arms, the Gongola Arm and the Yola Arm (Figure 1). In both arms of the basin, the Albian Bima Sandstone lies unconformably on the Precambrian Basement. This formation was deposited under continental conditions (fluvial, deltaic, lacustrine) and is made up of coarse to medium grained sandstones, intercalated with carbonaceous clays, shales, and mudstones. The Bima Sandstone was subdivided by Carter et al. (1963) into a Lower, Middle and Upper Bima.

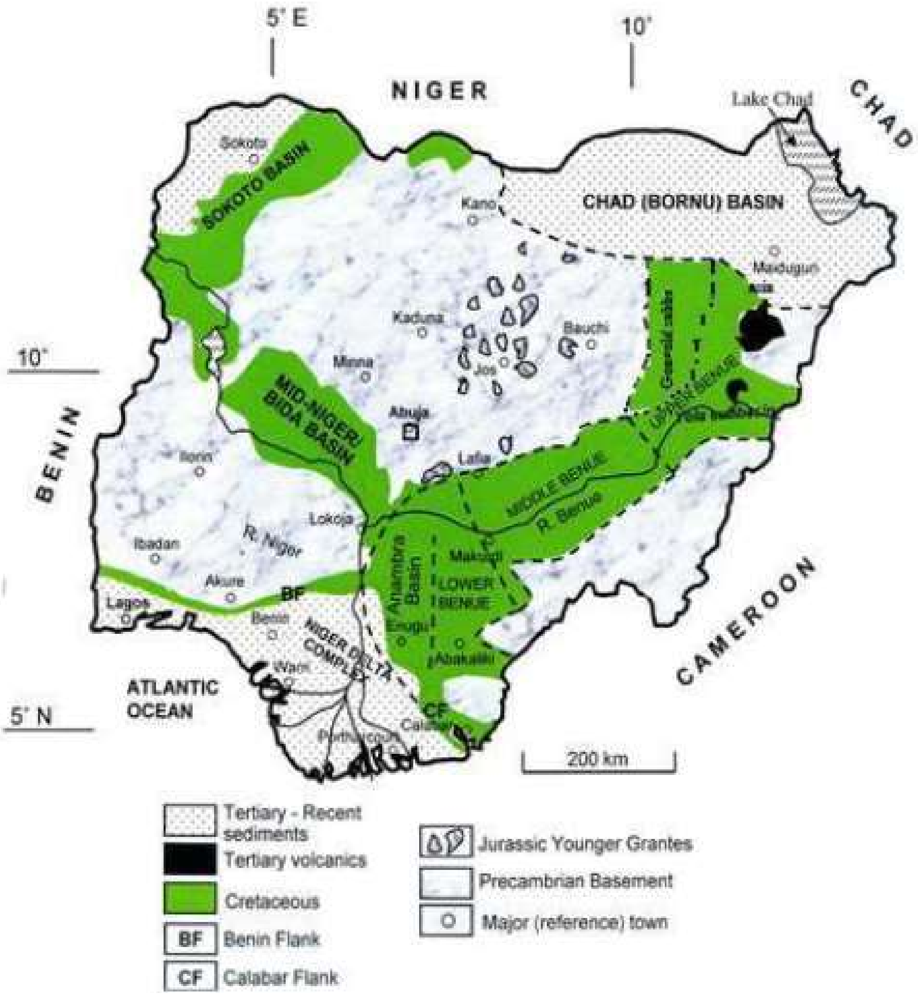

Fig 1: Map of Nigeria showing the Upper Benue Trough amongst other sedimentary basins in Nigeria (after Obaje, 2009)

The Cenomanian Yolde Formation lies conformably on the Bima Sandstone. This formation of Cenomanian age represents the beginning of marine incursion into this part of the Benue Trough. The Yolde Formation was deposited under a transitional/coastal marine environment. In the Gongola Arm, the laterally equivalent Gongola and Pindiga Formations and the possibly younger Fika Shale lie conformably on the Yolde Formation. These formations represent full marine incursion into the Upper Benue during the Turonian – Santonian times.

The Santonian was a period of folding and deformation in the whole of the Benue Trough. Post-folding sediments are represented by the Keri–Keri Formation of Tertiary age and the continental Gombe Sandstone of Maastrichtian age. The Gombe Sandstone is lithologically similar to the Bima Sandstone, attesting to the re- establishment of the Albian palaeoenvironmental condition.

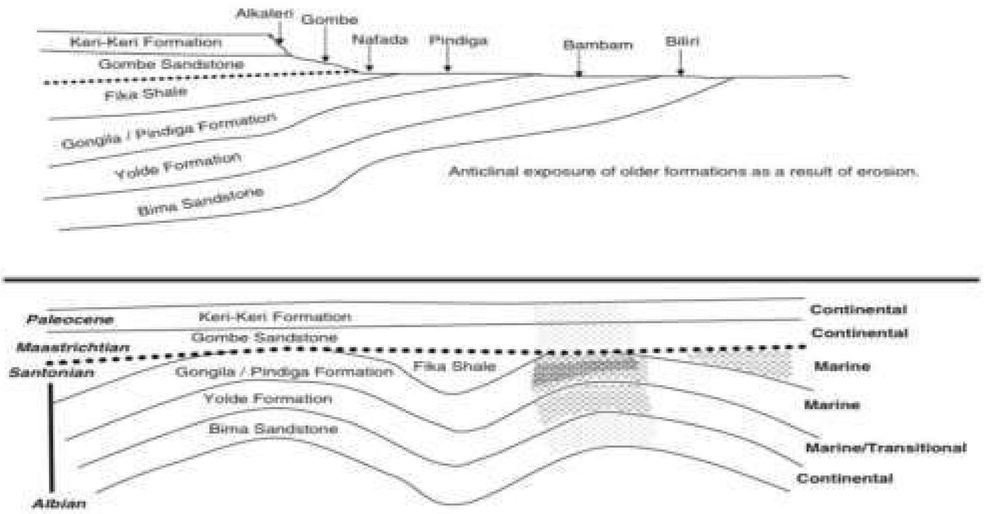

Fig 2: Stratigraphic successions in the Upper Benue Trough; Gongola Arm (after Obaje 2009)

MATERIALS AND METHODS

Mapping of sections of the Yolde Formation outcrop at the Pantami River channels in the Gongola Basin in Gombe town was logged to record data on the lithological variations, texture and sedimentary structures. Investigations followed by sedimentalogical and petrographic studies for grain descriptions and distribution, petrographic image analysis (PIA) for pore space, matrix and grain mass quantification. Geochemical investigation used in evaluation include the Scanning Electron Microscopy (SEM) to visualize pore attribute geometry as effected by the mineral digenetic alterations in an undisturbed state and X-ray diffraction (XRD) to confirm minerals visualized from the SEM micrographs.

RESULTS AND DISCUSSION

Facies Analysis

At the Patami River section, the Yolde and Pindiga formations outcrop along the channel. The Cenomanian Yolde sandstone lithofacies was lithologically characterized into their variable sub lithofacies based on textural and sedimentary structure characteristics. From the studies, six (6) sub

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lithofacies of the Yolde sandstones were identified as; 1) the trough cross bedding (TCBL) 2) massive sandstone (MSSL) 3) hummocky crossed bedding (HCBL),4) herringbone sandstone (HSL), 5) massive bioturbated (MBSL) and 6) parallel laminated (PTSL) sandstone lithofacies.

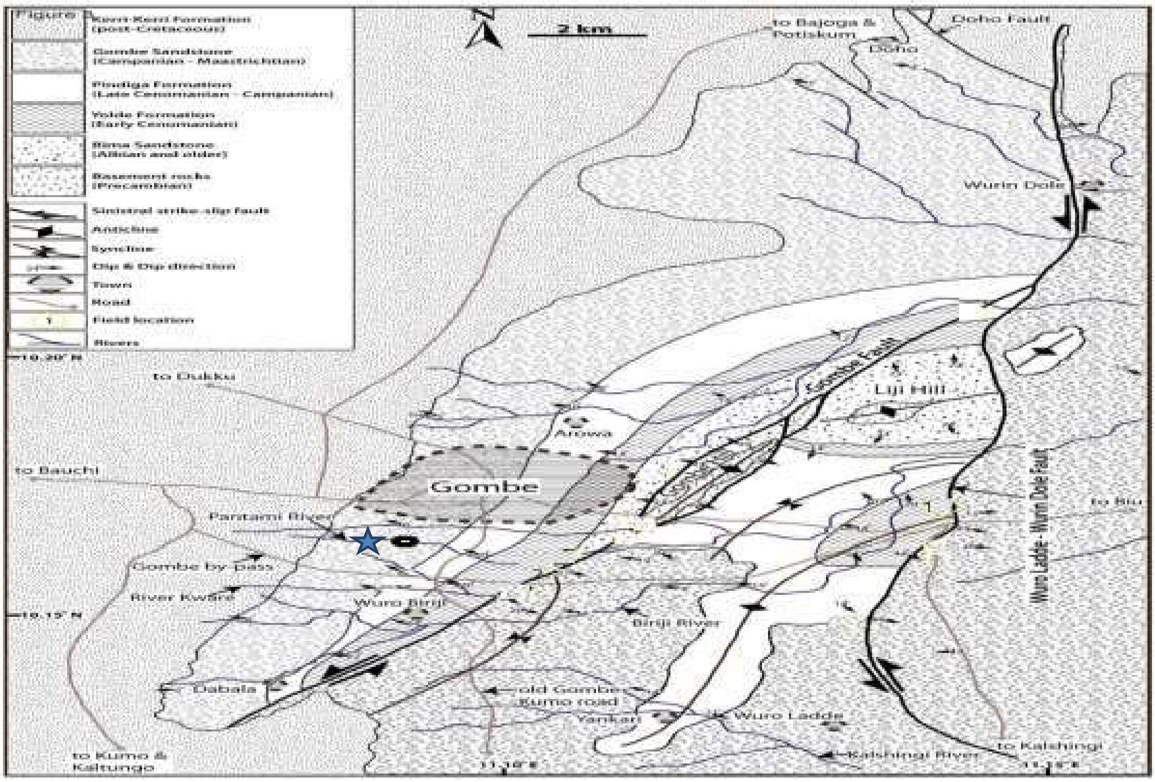

Fig 3 Map of the study area denoted in blue star (modified after Jolly et al., 2015)

Massive Bioturbated Sandstone Facies (MBSL)

This facie units measures about 3cm to 22cm thick and exhibits a light brownish yellow colour, bioturbated, fine to medium grain sandstone (fig 4A). It shows trace fossils that includes vertical and planolites burrows. The facie lacks other visible sedimentary structures, but moderate intense bioturbation which hindered interpretation of depositional processes, and thus may suggest a high energy deposition process within a generally low energy deposition (Walker and plint,1992, Bhattacharya et al. 2000 and Bhattacharya, 2006).

Massive Sandstone Facies (MSSL)

This sandstone unit is about 5cm to 11cm thick, light brownish yellow color, fine to coarse grained sandstone with very moderate bioturbation at the base (Fig 4B). The facies was probably deposited on bars by stream floods. Also, this occurrence of massive type sandstones in fluviatile and estuarine environments in braided rivers (Martin and Turner 1998), may be associated with channelized flood flows around bars.

Herringbone Cross Stratification Facies (HSL)

The facie unit is about 5cm in thickness and brownish in colour, moderately sorted coarse grained sandstone (Fig 4C). This facie features is usually associated with moderately to high energy environment indicative of tidal deposits which give rise to bi-directional cross stratification (Friedman 1967).

Hummocky Cross Stratification Facies (HCBL)

The facie is characterized by buff colored, hummocky cross stratified, fine to medium grain well sorted sandstone (Fig 4D). Hummocky cross stratification is indicative of storm and wave influenced deposition, it is interpreted to represent high energy storm process with strong wave influence (Harms et al., 1975, Duke et al., 1991).It is characterized by undulating sets of cross-laminae that are both concave-up (swales) and convex-up (hummocks). The cross-bed sets cut gently into each other with curved erosion surfaces. (Harms, et al., 1975, 1982) suggested that this structure is formed by strong surges of varied direction that are generated by relatively large storm waves, strong storm wave action first erode the seabed into low hummocks and swales that lack any significant orientation. Duke et al. (1991) suggest that hummocky cross beds originates by a combination of unidirectional and oscillatory flow related to storm activity.

Parallel Laminated Sandstone Facies (PTSL)

The facie units vary in thickness between 3cm and 7cm, characterize by fine grained, well sorted grain assemblages. It is produced by less severe or short lived fluctuation in sedimentation condition (Fig 4F). Lamination produced by alternating layers of fine and coarser grain sediment, are probably the most common kind (Boggs, 1995). This facie represent the tidal bottom current deposited during late stage of force regression in a distal slope setting (Miall, 2000 and Catuneanu, 2006).

Trough Cross-Bedded Sandstone (TCBL)

The facie consist of brown and buff trough cross bedded coarse-grained sandstones, though at times conglomeratic. It occurs in the lower section. It occurs in coarse grained sandstone. The cross-bedded units are 10cm to 2m thick (Fig 4D). The facie was probably formed by migrating sinuous crested dunes or mega ripples. Miall (1977, 1978) reported that trough cross-bedding in braided channels are formed by sinus crested dunes or mega-ripples.

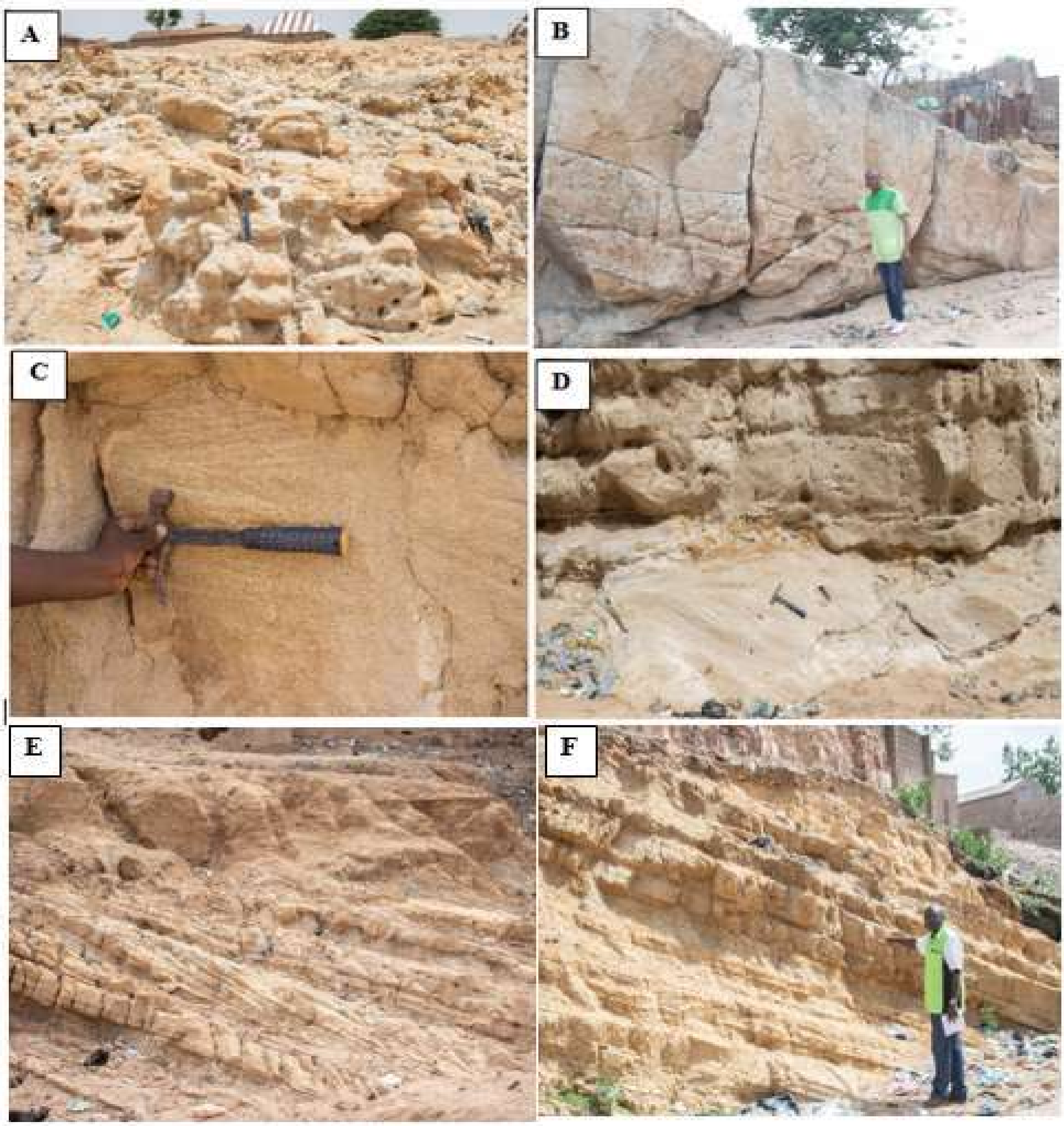

Fig 4: Exposure of Cenomanian Yolde sandstone sub-lithofacies **(A).** Massive bioturbated (MBSL) **(B).**massive sandstone (MSSL), **(C)** Herringbone sandstone (HSL), **(D)** hummocky crossed bedding (HCBL), **(E)** Trough cross bedding (TCBL) and **(D)** parallel laminated (PTSL) sandstone lithofacies

The granulometric analysis results of six samples of the Yolde sub-lithofacies analyzed are presented in Table 1. The fluctuations in the values of granulometric analysis result suggest change in energy of the depositional condition. The trend generally varies from poorly to moderately sorted as it reflects high energy and rework sediment during transport and in these respect agree with the river sand. According to Friedman 1967, these properties indicate rapid deposition by fluvial processes. The values of skewness vary from positive to very positively skewed and this is due to the fact that much of the silts and clay were removed by marine current indicative of fluvial condition (Friedman 1967). Very little geologic information could be derived from kurtosis (Friedman 1967).

Table 1: Grain size distribution of selected samples from the variable Yolde sandstone lithofacies

Sample	Mean	Sorting	Skewness	Kurtosis
L5A	0.57 coarse sand	0.49 moderately sorted	0.18 positively skewed	0.66 platykurtic
L2B	0.57 coarse sand	0.57 moderately sorted	0.96 very positively skewed	1.26 leptokurtic
L4B	0.87 coarse sand	0.86 moderately sorted	0.54 very positively skewed	2.03 very leptokurtic
L50	1.38 medium Sand	1.46 poorly sorted	0.46 very positively skewed	0.74 mesokurtic
L4I	0.73 coarse sand	0.98 moderately sorted	0.53 very positively skewed	1.60 very leptokurtic
L3N	0.58 coarse sand	1.05 poorly sorted	0.97 very positively skewed	1.77 very leptokurtic

Microscopy and Reservoir quality

Petrographic description reveals both mono and polycrystalline medium to coarse grain of quartz and feldspar minerals. It also shows several occurrences of grain fractures. The mineral grains vary from angular--sub angular in size and shape; angular grains undergo a different style of compaction indicative of degree of angularity reflect the textural immaturity. It exhibits abundant compacted quartz and feldspar (Fig 5a) indicated by suturing joining (Fig 5b) as result of pressure-solution during early burial compaction depicted by blue and green arrows. The grain assemblage also varies from planar contact to convex/concave contact. It also reveal trace of feldspar dissolution that enhance secondary porosity (Fig 5b) and quartz overgrowth (Fig 5c) that lead to reduction of intergranular pore spaces. The intergranular pore spaces are obliterated by pore-filling siderite that cements detrital grains in blue arrows (Fig 5b-c).The sandstone composes of quartz cement which involve the precipitation of silica within the pore spaces as the quartz cement fills the pore spaces it reduces the interconnectivity of the pores, impeding fluid flow, they develop as syntaxial overgrowth on detrital quartz grains and seems to develop at temperatures greater about 80 degree (Ajdukiewicz and Lander, 2010). The SEM shows a Pore filling siderite mineral (blue) obliterating pore attribute and hairy like illite (blue) (Fig 5d)

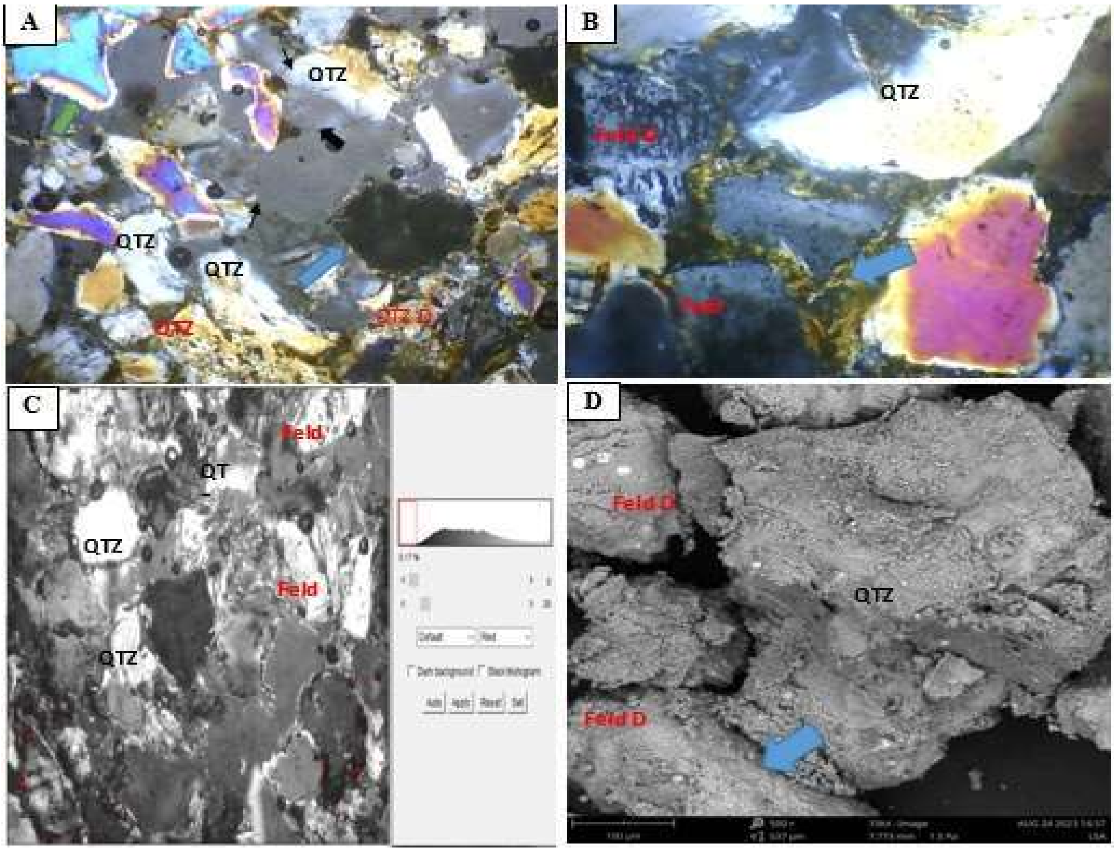

Fig 5 Thin section & SEM photomicrographs of Yolde sandstone (A) compaction in black arrows, pore-filling siderite in blue arrows, feldspar dissolution in yellow arrow, quartz overgrowth in green arrow, feldspar dissolution in yellow arrow (B) pore-filling siderite in blue arrow (C) Threshold image mapping porosity (D) SEM image showing pore-filling siderite and illite

Presence of quartz overgrowth partially filled the intergranular spaces (green arrows) which have been identified as one of the causes of porosity loss in sandstone reservoir of various basins (Walderhaug et al., 1996). Thus, all these contribute to alter high tortuosity that lay a very crucial role in permeability variation; a high tortuosity pore shape indicates an increase in pore surface area and decrease in permeability (Amaefule et al, 1993). Porosity value as threshold from the petrographic image analysis in the sample is 0.17%.

The petrographic description reveals both the mono and polycrystalline medium to fine grain of quartz and feldspar minerals that exhibit occurrence of grain fracture in red arrows (Fig 6a, b). The grains are generally moderately sorted with grains of quartz and feldspar exhibiting intensive intergranular compaction indicated by suturing as result of pressure-solution during early burial compaction depicted by black arrow (Fig 6a, b). The grains are compacted and also vary from angular-to- sub angular as angularity reflect degrees of textural immaturity in this sample. The sandstone exhibits of quartz cement through quartz overgrowth (Fig 6b) which involves the precipitation of silica within the pore spaces as the quartz cement fills the pore spaces as it reduces pore sizes and interconnectivity of the pore spaces (Yusuf and Eswaran, 2019). However, this is identified as responsible for porosities loss or obliteration in this sandstone reservoir of various basins (Walderhaug, 1996). It also shows that kaolinite contribute to pore-filling indicated by red arrow and illite in blue arrow (Fig 6d) respectively. Thus, the combined effect are blockage and pore-lining of the intergranular pore spaces that affects physical properties of a reservoir with respect to pore sizes, pore tortuosity and pore throats connectivity. Porosity values as threshold from the petrographic image analysis (PIA) in the sample is at an average of 0.20% composition

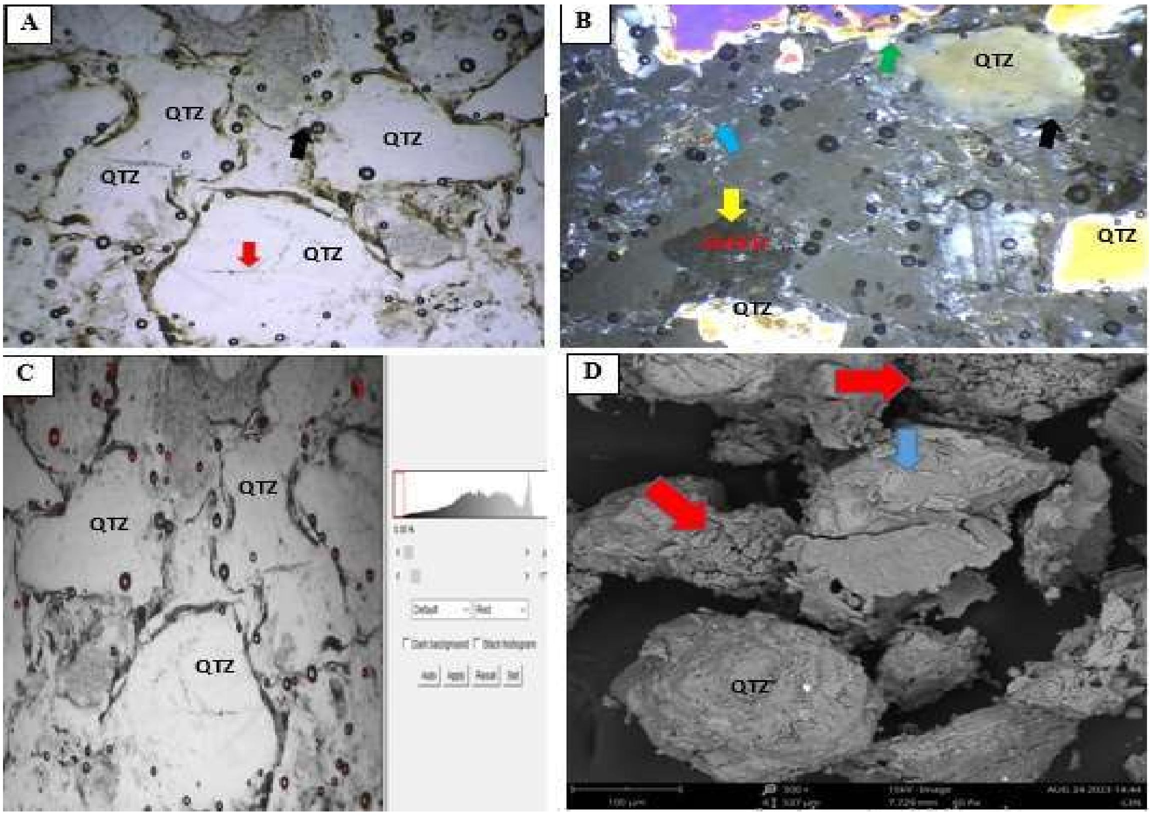

Fig 6 Thin section & SEM photomicrographs of Yolde sandstone (A) compaction in black arrow, fractures in red arrow (B) occurrence of pore filling siderite in blue arrows, feldspar dissolution in yellow arrows, quartz overgrowth in green arrow, compaction in black arrow (C) Threshold image mapping porosity (D) SEM image showing kaolinite (red arrow) and illite (blue arrow) completely filling a pore

The mineralogical analysis reveals that the most abundant mineral is quartz 42%, kaolinite is the second-highest mineral 33%, illite is third 21% while montmorillonite is 3.2% and muscovite is 0.9% as shown in (Fig 8). Kaolinite, illite and montmorillonite are identified clay minerals. The combined percentage of illite, kaolinite, and montmorillonite is very high (55.9%) (Fig 8), indicating a predominance of clay minerals in the reservoir composition. The clay minerals poses significant challenges for reservoir quality due to the potential for formation damage, reduced pore sizes, pore plugging and contribute to permeability reduction and variation confirming microscopy findings.

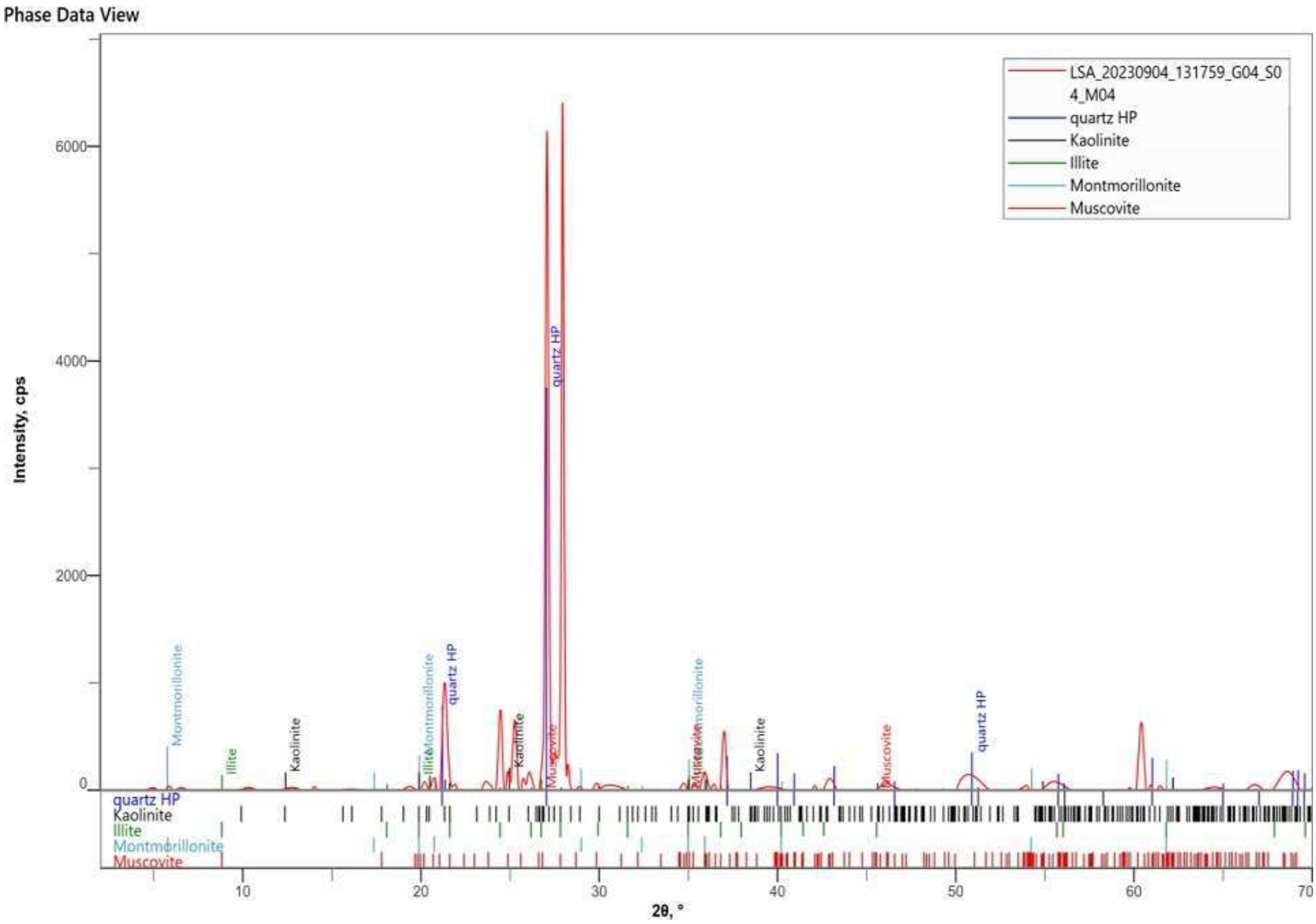

Fig 7 X-ray diffractogram of Yolde Formation sandstone showing the presence of the illite, kaolinite and montmorillonite

Digenetic phase and Reservoir quality evaluation

A diagenetic process governs reservoir properties distribution, and includes extent of compaction, cementation and dissolution of framework grains and cements (Salem et al., 2000). Mechanical compaction is visible deformation styles, fracture development and type of degree grain-to-grain contact across the entire sub lithofacies. Fractures are observed within grains from these sandstones (Figs 5-6). It may have fractured under the influence of overburden stress of overlying Pindiga, Gombe sandstone and Kerri Kerri formation respectively. This style of mechanical compaction is dominant in the first 1000 m and can continue to depths of 2000 – 4000 m's with the reduction of primary porosity (Worden et al., 1997). The long, concavo-convex and suture contacts; pressure solution along quartz to quartz contacts and deformation of ductile grains all confirm chemical compaction effects (Figs 5-6). The growth of quartz overgrowth and cements is here considered as a mesodiagenetic event due to the presence of concavo-convex and suture contacts which were related to the compaction phase. The pore solutions become enriched in silica which is precipitated as overgrowth as contributor to porosity and permeability reduction during progressive burial in sandstone reservoirs (Worden and Morad 2000).

The precipitation at this stage is ascribed to contribute to development of authigenic pore-filling clays, such as kaolin, illite and smectite (montmorillonite) minerals, which have a detrimental effect on reservoir quality by blocking primary intergranular pore space (Figs 5-6). However, the quartz cementation and clay authigenesis intensely influence the quality of sandstone reservoirs by modifying the nano-to macroscale reservoir properties (Worden and Morad, 2003) associated dissolution of unstable framework grains such as feldspars especially K feldspar in sandstones occurs over depth ranges of 1.5 to 4.5 km, temperature ranges from 50 to 150 degree (Wilkinson et al., 2001).

Impact on reservoir quality

Diagenetic alteration in the sandstone lithofacies, includes the mechanical compaction, chemical and quartz cementation, have significantly modifies the porosity of the sandstones of the cenomanian Yolde sandstone lithofacies more than the primary depositional features (grain size and sorting). The cementation in the reservoir sandstone is the main diagenetic mechanism that reduces pore spaces and volume distribution (Figs 5-6). The key porosity impeding cements precipitated in the early diagenetic phase of the reservoir sandstone where intergranular pore spaces filled by the quartz cements and kaolinite which have diminished the reservoir potentiality: Quartz cementation, typically initiating at temperatures greater than 80°C, is the main cause of porosity reduction during progressive burial in sandstone reservoirs (Worden and Morad, 2000). As the quartz cement fills the pore spaces it reduces the interconnectivity of the pores, impending fluid flow within into a wellbore.

The chemical compaction due to overburden pressure as sediments undergoes burial that have result in closer packing, sutured contacts and tight/packed rock pattern formation within the sandstone (Figs 5-6). The concentration of effective stress at points of grain-to-grain contact, leads to an increase of the solubility of the material along that surface. Subsequently, the dissolved silica precipitates on adjacent grain surfaces, which experience a lower degree of stress. These features obliterate all intergranular pore spaces or either completely diminished pore throats or decrease pore size. Thus, all shown features (fracture development and type of degree grain to grain contact) of mechanical compaction reduce the reservoir quality of the reservoir sandstone: many fractures are observed within grains from these sandstones.

Primary intergranular pore spaces are filled by authigenic clay minerals (kaolinite, illite and smectite (montmorillonite) minerals obliterating intergranular pore space (Figs 5-6) as a pore-filling mineral. It affects the distribution and interconnectivity of potential effective pore space that are the main parameter in fluid storage and transmitivity in a reservoir rock. The randomly scatter authigenic clay minerals within pore wall potentially alters pore tortuosity resulting from the effect of their roughness impacted on the pore-walls. This will potentially contribute to lower the ease of fluid transitivity (permeability) within the reservoir rock or into the future wellbore in the basin. Overall, intergranular pore-filling of pore space, pore throats by carbonate cement and alteration of pore walls by fine grained siderite will potentially destroy pore interconnectivity and invariably will have negative potential on effective porosity distribution and permeability of the reservoir rock.

CONCLUSION

The Cenomanian Yolde Formation sandstone lithofacies have been mapped and characterized into sub lithofacies along the Pantami River section. The identified variable sub lithofacies are further subjected to sedimentalogical studies, petrographic description, petrographic image analysis (PIA), scanning electron microscopy (SEM) and X-ray Diffraction (XRD) to evaluate diagenetic features and their impact on reservoir quality of the investigated samples. Geological field mapping and logging identifies six (6) sandstone lithofacies namely; the trough cross bedding, massive sandstone, hummocky, herringbone and massive bioturbated sandstone lithofacies.

Sedimentalogical studies indicate the Yolde sandstone lithofacies are generally medium to coarse grains, moderate to poorly sorted sediments. Also, results from integration of petrography, scanning electron microscopy (SEM), X-ray Diffraction (XRD) analysis also confirm sedimentalogical results and highlights textural immaturity, mechanical, chemical grain compaction, quartz overgrowth and cementation and clay minerals; illite, kaolinite, and smectite (montmorillonite) are mainly present authigenic clays that thus reduces and obliterates intergranular pore spaces through precipitation, cementation and pore-filling. The petrographic image analysis (PIA), indicate that the porosity within the different Yolde sandstone lithofacies vary from 0.17 to 0.30%. The reservoir quality of the sandstones in the study area appears to be moderately poor due to the intense diagenetic alterations that have resulted from burial compaction, presence of angular-to-sub angular grains, precipitation, cementation and blockage of pore throats by quartz overgrowths and other authigenic clay minerals present within the Yolde sandstone lithofacies have significantly obliterated larger volume of pore attribute distribution within the variable sandstone lithofacies. However, these outcomes may have contributed to exploration failure in part of the basin segments where exploration wells are drilled, because of the inability of moveable oil into the wellbore.

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