



SEDIMENTOLOGICAL ATTRIBUTES OF SELECTED PRE-SANTONIAN SANDSTONES IN PARTS OF THE ABAKALIKI SUB-BASIN OF THE SOUTHERN BENUE TROUGH, NIGERIA: EVIDENCE FROM TEXTURAL ANALYSIS AND DIAGENETIC IMPRINTS

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ABSTRACT

Sedimentological studies of some pre-Santonian sandstones of the Asu River Group and the Eze-Aku Formation exposed in southeastern Nigeria were carried out. The study involved Intensive field work integrated with laboratory (Sedimentary petrography, X-ray diffraction (XRD), porosity and permeability determination). The study aims to determine the main controls on reservoir properties of these sandstones. The results revealed that the sandstone rocks within the study area comprised indurated sandstones that are poorly to moderately sorted, very fine–coarse grained arkosic arenites deposited in shallow to deep marine settings, associate with other non-reservoir lithologies (e.g. siltstones and shale). The sandstones depositional texture in many instances has been modified by biogenic structures that act to enhance the porosity of the sandstones. The porosity in the studied reservoir sediments ranges from 3.00 – 6.00; the permeability values range from 0.3mD – 3.5mD. X-ray diffractometry revealed that the following clay minerals constituted the major phase in the cementation of the sandstones viz kaolinite, mixed layer kaolinites (nacrite, dickite, halloysite, chrysotile, lizardite), illite, chlorite (corrensite) some silicates, carbonates and sulphate mineral groups. Compaction, cementation (carbonate, clay silica) bioturbations and dissolution of unstable framework grains are the principal diagenetic processes responsible for the modification of the reservoir quality of the sandstones within the study area.

KEYWORDS: Pre-Santonian; reservoir quality; porosity; permeability; cementation.

INTRODUCTION

The effects of diagenesis (bioturbation, burial, compaction, cementation and chemical reactions between rocks) is known to play a major role in modifying the properties of sedimentary rocks and thereby determines its suitability as potential reservoir rock. It is therefore necessary to understand how these processes influence the properties of the rock.

Knowledge of the sediment heterogeneity and its petrophysical properties appears to be important and aids exploration and exploitation activities at any given time. In the course of the evolution of the Southern Benue Trough, clastic sedimentation and carbonate deposition were distributed across the basin, these were controlled by transgressive – regressive episodes as well as epeirogenetic movements in places (Murat, 1972; Nyong & Ramanathan, 1985).

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Sandstone units of Asu River Group and Eze-Aku Formation, both of the Southern Benue Trough are the focus of this study (Fig. 1). During routine exploration, the risk is always greater if the effects of diagenetic processes are not properly understood. This alone can lead to erroneous reservoir volume calculations and impact on flow rate during production of such rock units. More often, reservoir quality decreases downward in sedimentary sequences, except in areas where they have been enhanced through dissolution of unstable minerals resulting in the development of secondary porosity. Since sandstone diagenesis proceeds through several steps beginning with pore space reduction by compaction, followed by pore-fill cementation and transformation of mineral phases in more deeply buried sandstone (Wilson and Pittman, 1977) as well as the impact of bioturbation to the

depositional fabrics, it is necessary to determine the reservoir properties of the sand bodies. Burrowing organism displaces and mix sedimentary grains by burrowing, feeding and relocating the sediments. They secrete mucus as they move through the sediments, use the mucus to trap organic matter or fine grains or incorporate detritus (mud/sand) to create a burrow wall or lining (Bromley and Ekdale, 2022). A thorough understanding of the sandstone unit is important and this can be achieved through reservoir characterization of outcrop analogues such as sedimentological, petrophysical (porosity-permeability relationship) and diagenetic studies. The general objective of this study is to evaluate the reservoir quality of some pre-Santonian sandstones by multiple techniques. This study is focused on the significance of sedimentary petrology and textural analysis and how they affect the poro-perm of potential reservoir units.

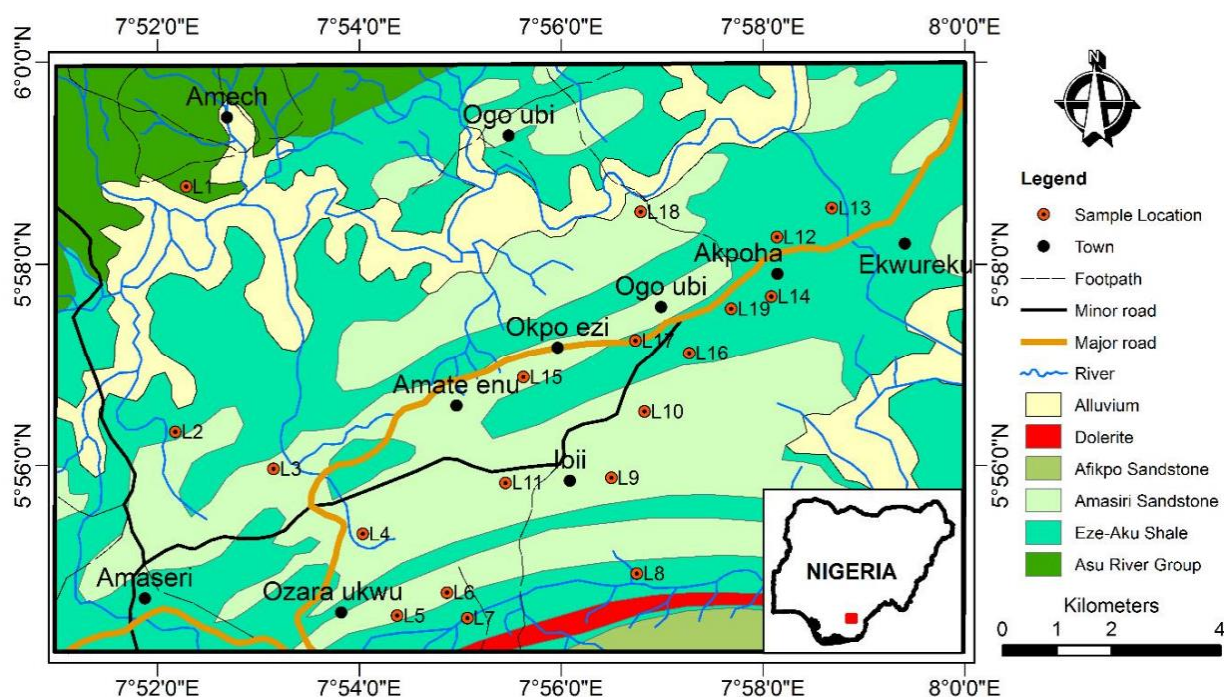


Figure 1: Geology and location map of the study area

Tectonic setting and basin evolution

The Southern Benue Trough is a part of the megastructure that runs northeast across Nigeria from the reaches of the Gulf of Guinea into the zone popularly referred to as West and Central Africa Rift System (WCARS), (Benkheilil, 1989; Fairhead & Binks, 1991; Tchouondo et al., 2026). Within Nigeria, the Benue Trough is estimated to extend for about 800 km in length and 250 km in its widest width (Ojoh 1990; Nwajide 2013). In its southern part, the Niger Delta is seen to overlie the basin and to the east and west it is delimited by Oban Massif and the Anambra Basin respectively.

Since the opening of the South Atlantic Ocean in latest Jurassic to early Cretaceous period, leading to the formation of the Benue Trough, the basin has undergone several tectonic modifications, some geographically restricted and others wide spread across the entire length of the basin (Reyment, 1965; Murat, 1972; Nwachukwu, 1972; Olade, 1975; Ojoh, 1990). Basically, these controlled the sedimentary evolution in concert with eustatic movement leading to transgressive-regressive phases (Murat, 1972; Adeleye 1975; Petters 1982; Amajor, 1987; Essien et al., 2018).

The basal sediments of the entire southeastern domain are made of pyroclastic materials and fluvial deposits of the Abakaliki pyroclastics and Awi Formation respectively, both accounting for the oldest deposits in the basin (Fig. 2). Record of marine sedimentation in the trough began

with thick sequence of limestones, shales and some calcareous sandstones forming part of the Asu River Group (Ibe and Okon 2021; Okon et al 2023). These sediments grade northwards to form platform carbonates of the Arufu and Gboko Formations (Petters, 1982; Anyiam and Mode 2008; Ojong et al 2018). There was a break in sedimentation with the ushering of the Cenomanian regression indicated by mudstones in the Calabar Flank area and sandstones in some parts of the Southern Benue Trough (Ibir Sandstone). The marine sedimentation resumed with the deposition of the Eze-Aku shales, Nkalagu Limestone and some sandstones in the Amasiri –

Ezillo areas. The Eze-Aku Formation is characteristic of tidal shelf to deep marine turbidite depositional model (Ojoh, 1990; Okoro and Igwe, 2014). As the transgressive phase peaked during the Coniacian times, Awgu Shales, Akpoha-Ekori Sandstones in the Southern Benue Trough and New Netim Formation in the Calabar Flank were deposited. A break in sedimentation throughout southern and Central Benue Trough occurred in the Santonian times recording a period of non-deposition, erosion, folding and basic magmatism. This led to the formation of the Abakaliki anticlinorium, thereby displacing the depocentre to the east and west giving rise to the Afikpo Syncline and the Anambra Basin respectively. During Late Campanian – Maastrichtian, the sea transgressed the entire southern Nigeria depositing the Nkporo Shale, Enugu Shale, Owelli Sandstone, Afikpo Sandstone, Lafia Formation and Otobi Sandstone (Nwajide, 2022). The Paleogene witnessed the progradation of the Niger Delta which has continued to regress since the Eocene times (Short and Stauble, 1967; Knox and Omatsola, 1989; Boboye et al., 2017)

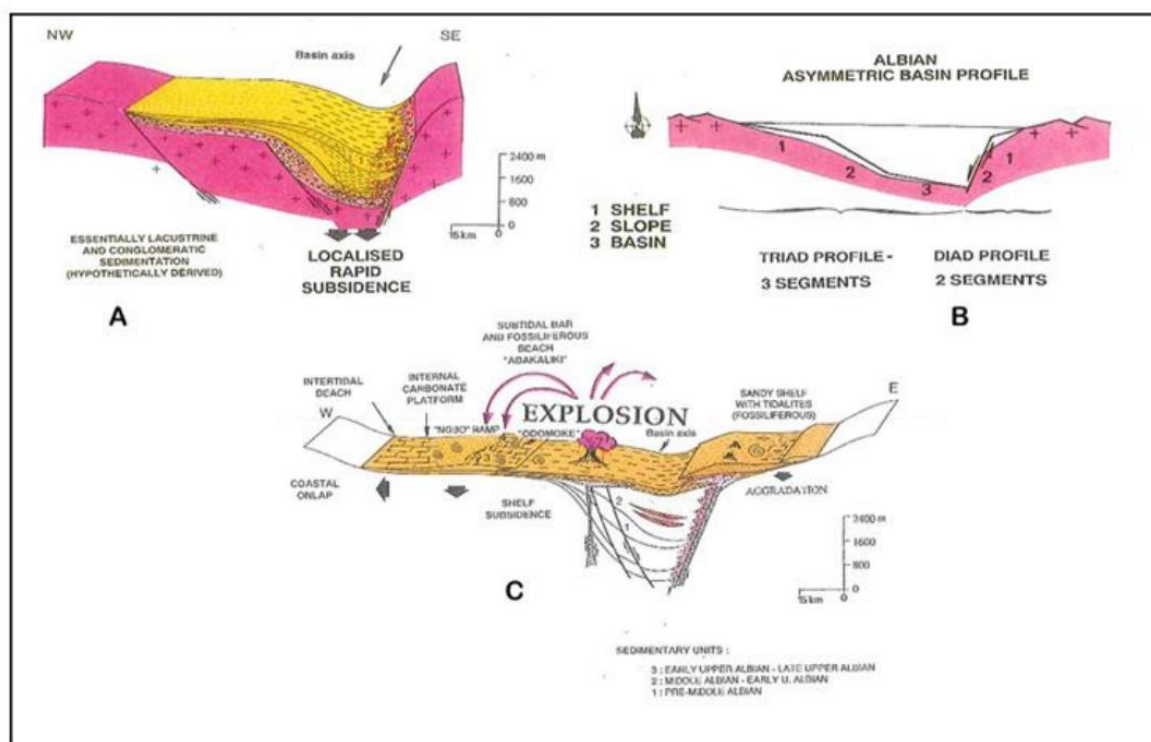


Figure 2: Illustration of the basin forming process (after Ojoh 1992)

Stratigraphic setting

The lithostratigraphic and biostratigraphic divisions of Southern Benue Trough has over the years been plagued with nomenclatural inconsistencies, however, a correlation of a selected few will largely aid discussion of the lithologies being considered in this study. first account by Reymont (1965) have been revised largely as a result of later exposed outcrop sections and new information from drill cores resulting

from research carried out companies and tertiary institutions (Table 1). Among such notable studies were those of Petters and Ekweozor (1982), Amajor, 1987 and Ojoh (1990).

Asu River Group (Albian)

The Asu River Group was deposited in the earliest stages of the basin formation process. Outcropping sediments are found around Abakaliki, Uturu and Okigwe, Amuri and Nkalagu. Outcrops of the Asu River group are also mappable within Mamfe Embayment and the Calabar Flank. According to Reymont (1965), the Asu River Group is associated with first marine transgression thought to be Albian in age. More recent studies believe that the marine incursion was much earlier than the Albian (Ukpong and Ekhalialu, 2018) although this is merely a

hypothesis, it is yet to be fully confirmed. The sandstones of the Asu River Group in Abakaliki are arkosic and non-fossiliferous with associated and interbedded pyroclastics and shales.

Ojoh (1990) divided the Group into four formations (Ekebeligwe, Ngbo, Agila and Ibir Sandstones) ranging from Late Albian to the Early Cenomanian (Table 1). The Ekebeligwe Formation (mid-Albian) was interpreted as deep marine based on the presence of mega slumps and turbidites, and from the foraminifera and ammonite assemblages found within this Formation (Ojoh, 1992), while the Ngbo Formation, Agila and Ibir (Late Albian) contain more sands and changes from shelf to near shore environment.

Table 1. Presentation of the stratigraphic reviews of the Southern Benue Trough

	Age	Reymont (1965)	Geological Survey of Nigeria (1974)	Dessauvagie (1974)	Petters and Ekweozor (1982)	Ojoh, 1990	This Study
Neogene	Quaternary						
	Pliocene	Benin Fm	Coastal Plain Sands	Benin Fm			Benin Fm
	Miocene				Benin Fm		
	Oligocene	Ogwashi - Asaba Fm		Ogwashi-Asaba Fm			Ogwashi - Asaba
Paleogene	Eocene	Ameki Formation	Lignite Fm	Ameki Fm	Ogwashi - Asaba		Ameki Fm
		Nanka Sand	Bende Ameki Gp		Nanka Fm		Nanka Fm
	Paleocene	Imo Shale	Imo Clay Shale Gp	Imo Shale	Imo Shale Formation		Imo Shale Formation
		Nsukka Fm					Nsukka Fm
Cretaceous	Maastrichtian	Ajali Sst	Falsebedded sst	Nsukka Fm			
		Mamu Fm	UCM	Ajali Fm	Ajali Sandstone		Ajali Sandstone
	Campanian	Enugu Shale	LCM	Mamu Fm	Mamu Fm		Mamu Fm
		Nkporo Shale	Asata Nkporo Shale Gp	Enugu Shale	Enugu & Nkporo		Nkporo Shale
Cretaceous	Santonian			Nkporo Shale	Owelli		Afikpo sst
	Coniacian	Awgu Shale	Awgu Ndeaboh Shale Gp	Awgu Shale	Agbani	Akpoha - Ekori sst	Akpoha - Ekori sst
				Amasiri	Formation	Nkalagu	Awgu Shale/ Lokpanta Shale
	Turonian	Eze Aku Shale	Eze Aku Shale Gp	Eze-Aku	Agala	Agu-ojo sst	Amasiri sst
Cretaceous					Makurdi	Nara shales	
	Cenomanian	Odukpani Formation	Odukpani Fm	Odukpani	Nkalagu	Ezillo	Eze-Aku Shale
					Amasiri	Ibir sst	Ibir sst
	Albian	Asu River Gp	Asu River Gp	Asu River Gp	Awbe Formation	Ngbo Fm	Abakaliki Shale
Pre-Albian		Unnamed			Abakaliki Shale	Ekebeligwe	Abakaliki
		Abakaliki Sh		Mamfe	Awbe Formation		pyroclastic Awbe Formation
						Not outcropping	

Eze-Aku Group (Late Cenomanian - Turonian)

Cenomanian sediments within the Benue Trough were assigned to the Odukpani Formation consisting predominantly of shales and limestones beds of shallow marine shelf environment (Kogbe, 1989). Although some authors think that the Cenomanian is absent in Abakaliki Basin; Nwachukwu (1972) attributed the absence of the Cenomanian to a possibly slight folding phase within this area. Ojoh (1992) established the presence of the Cenomanian in the Abakaliki Basin using pollen and spores. He placed the upper formations (Ibir and Agila

Sandstones) in the Early Cenomanian while the marine shales outcropping at Ezillo originally classified as part of the Eze-Aku shales was dated Late Cenomanian.

The upper members of the Eze-Aku Group are Turonian in age (Kogbe, 1989; Ibe and Okon 2021). A widespread transgression that occurred during this period deposited black shales with limestone and calcareous sandstones. This was the first transcontinental connection of the Tethys Ocean (present day Mediterranean Sea) with the Atlantic.

The Makurdi Sandstones (Nwajide and Reijers, 1996), Agala Sandstones (Murat, 1972), Konshisha Section, Amasiri Sandstones (Kogbe, 1989) and the Agu-Ojo Sandstones (Ojoh, 1992), are deposits laid by a short-localized regression that occurred during mid-Turonian period. Renewed transgression deposited some limestones on the platform areas (Nkalagu limestone and Waddatta limestones, although the latter formation name is not in use, it is now lumped up into the Eze-Aku Formation in the Central Benue Trough. Others include bluish grey shales with limestones and calcareous sandstones; and the presence of Turonian ammonites in some of these lithologic units establishes their membership within the Turonian Eze-Aku Group.

METHODOLOGY

Detailed field mapping of the study area was undertaken during which outcrop sections were mapped at road cuts and quarry sections. Outcrops were studied, various lithologies were identified and sedimentary contacts and different observed structures were delineated. The sediments which include shales, siltstones and medium – coarse grain sandstones (Figs. 3 and 4) were observed to be bedded (Fig. 3a), inclined (Fig. 3a-b) and indurated (Fig. 3c-d, 4b-d).

In the Marlum quarry at Ibir, the grey, highly fissile shales were seen to have sharp contact with the medium grain, highly compacted sandstones (Fig. 4a).



Figure 3: Field representation of outcrops of Asu River Group and the Eze-Aku Group (a) weathered siltstone bed, (b) Dipping siltstone unit, (c) medium grained sandstone (d) poorly sorted coarse grained sandstone

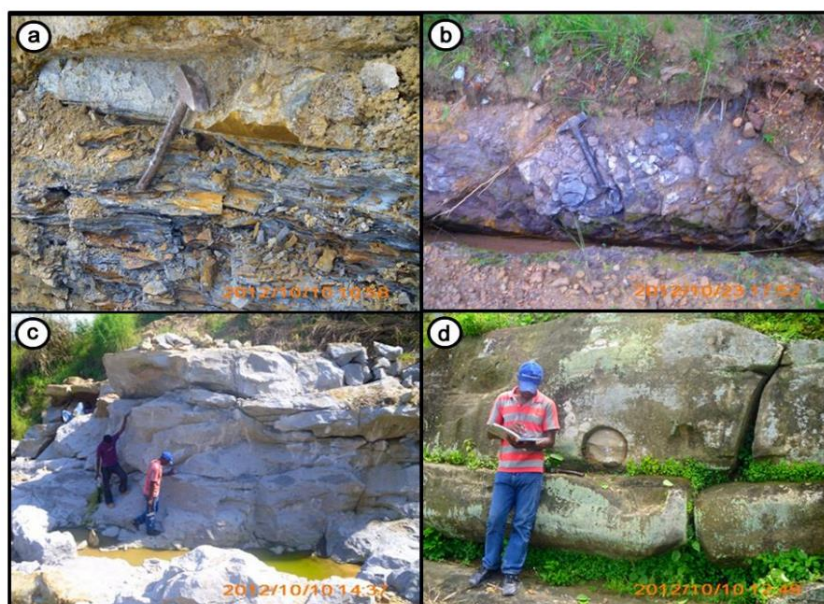


Figure 4. (a) Fissile grey shale facies at Marlum quarry, ibir (b) underlying grey shale facies having a sharp contact with the overlying sandstone (c) Siltstone section at Julius Berger quarry, Akpoh (d) highly indurated medium grained sandstone at Ugo Ubi

Burrow structures observed in the sediments were carefully studied and identified and their impact on reservoir properties was noted. Fresh samples were collected from good exposures for laboratory studies. Twenty (20) samples were selected for petrographic studies during which thin sections were prepared. This was used to determine their textural parameters (grain size, sorting and shape) and mineralogical composition (framework grains and cementing materials). Quantitative determination of porosity was carried out petrographically by point counting of voids between at least 200 grains in each of the thin section slides.

A plot of porosity against grain size was used to quantify the permeability values of the samples. Representative photomicrographs were taken to illustrate features described from the petrographic

studies. X-ray diffraction (XRD) analysis was carried out on sandstone samples from various locations to enable precise identification and relative abundance of the contained clay minerals and other silicates composition.

RESULTS AND INTERPRETATIONS

The results from petrographic analysis are presented in Table 2. The result shows the percentage distributions of the framework components (quartz, feldspar and rock fragments) within the sandstones and their porosity/permeability values. Complimented with XRD studies, the diagenetic processes such as compaction, cementation, dissolution, precipitation of authigenic clay minerals and other cementing materials responsible for reservoir properties modification was identified.

Table 2. Framework grains, cementing materials, texture and reservoir characteristics of the Albian Asu River group and Turonian Eze-Aku group

FORMATION	Framework grains					Cement		Textural properties			Reservoir properties		
	LOCATION	SAMPLE NO	QUARTZ (%)	FELDSPAR (%)	ROCK FRAGMENT (%)	MICA (%)	SILICA (%)	CALCITE (%)	SORTING	GRAIN SIZE	GRAIN SHAPE	POROSITY (% Total Volume)	PERMEABILITY (mD)
TURONIAN EZE--AKU FORMATION	Amaseri	1	65	20	8	2	5		Moderate	Medium-coarse	Sub rounded-Rounded	4.0	1.0
	Amaseri	2	62	22	10	3	3		Moderate	Very fine	Sub rounded-Sub angular	4.0	0.3
	Amaseri	3	65	21	9	1	4		Moderate	Very fine	Sub rounded-Sub angular	4.5	0.4
	Amaseri	4	67	18	10	2	3		poor	Medium-coarse	Sub angular - Angular	3.0	0.8
	Amaseri	5	64	22	10	2	2		Poor	Fine	Sub angular-Angular	4.0	0.6
	Amaseri	6	63	21	11	3		2	Moderate	very fine	Sub rounded-Sub angular	5.0	0.6
	Akpoha	12	62	21	10	2		5	Moderate	Fine	sub angular-angular	4.0	0.6
	Akpoha	13	65	19	9	3		4	Poor	Very fine	sub angular-angular	4.0	0.3
	Akpoha	14	64	21	10	2	3		Poor	Very fine	sub angular - angular	4.5	0.5
ALBIAN – EARLY CENOMANIAN ASU RIVER GROUP	Ibii	10	63	22	9	2	4		Poor	Very fine	Sub rounded-sub angular	4.0	0.3
	Ibii	11	62	22	9	3	4		Moderate	Very fine	Sub rounded- sub angular	4.5	0.4
	Ibii	7	64	23	8	2	3		Moderate	Very fine	Sub rounded- sub angular	5.0	0.6
	Ibii	8	60	24	9	2	5		Poor	Medium - coarse	sub rounded - angular	3.5	1.0
	Ibii	9	64	23	10	1	2		Poor	Medium - coarse	sub rounded-angular	4.5	2.5
	Amenu	15	62	20	9	2	5	2	Moderate	Fine	sub angular-angular	4.5	0.8
	Amenu	16	63	22	10	2		3	Poor	Medium-coarse	Sub rounded angular	5.0	3.5
	Amenu	17	64	25	7	1		3	Moderate	Very fine	sub angular-angular	6.0	0.8
	Amauro	18	63	22	9	2		4	Poor	Fine	sub rounded-angular	4.5	0.8
	Amauro	19	62	24	9	3	2		Moderate	Fine	sub rounded-rounded	5.0	1.5
	Amauro	20	64	20	10	3		3	Moderate	Very fine	sub rounded- sub angular	5.5	0.7

Based on Folk et al., (1970) classification scheme around Ibii (Albian Asu River Group) and the Amasiri sandstones (Turonian Eze-Aku Group) are classified as Arkoses (Fig. 5). Quartz and feldspar grains are the main framework constituents, with rock fragments occurring in minor proportions. The proportion of the quartz grains ranges from 63-68% while feldspars

(Albite and Microcline) exceed 16% in the studied samples (Table 2). Some feldspars and quartz grains exhibit internal dissolution to form secondary porosity while others alter to form kaolinite and illite. Total mica (biotite and muscovite) abundance was observed to be between 1% to 3% (Table 2).

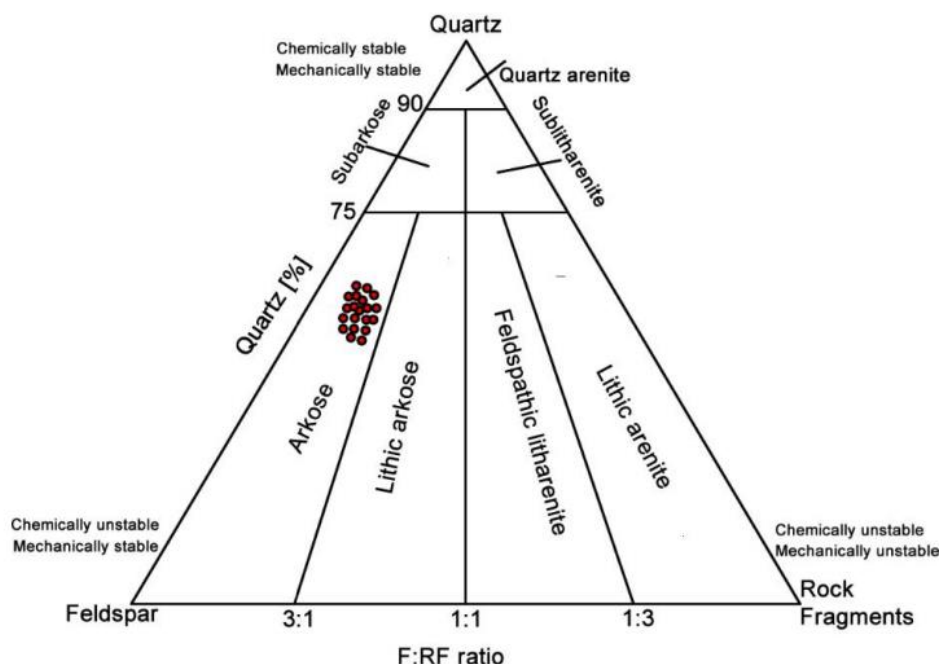


Figure 5. Ternary plot showing position of the studied samples in Folk's sandstone classification scheme (Folk 1975)

Texture

Textural parameters that affect the reservoir properties include sorting, shape and grain size. The texture ranges from coarse grained to very fine grained, sub-angular to sub-rounded, moderately to poorly sorted sandstones (Fig. 6a-d).

The encountered sandstone are predominately composed of non-ductile grains, thus compaction of such do not result in considerable reduction the volume of the framework components and thus pore-spaces. In the presence of variable grain sizes (poorly sorted sediments) therefore, the finer grains can significantly reduce the amount of pore spaces between coarse grains by grain reorientation during burial.

The diagenetic minerals encountered during this study include carbonate (calcite), and silica (quartz) cement. The carbonate cement constitutes a significant diagenetic product in the studied sandstone sediments occurring both as pore - fillings and as grain replacement in well-defined zones with dimensions up to several millimetres (Fig. 7a-d). It occurred as early diagenetic cement. The early precipitation of calcite cement inhibits the formation of later quartz overgrowth and alteration of feldspars to clay. Authigenic quartz occurred as microcrystalline and crystalline aggregate in the pores thus affecting the porosity and permeability of the sandstone. It has

been documented in earlier studies that quartz cementation is favoured by high concentration of silica in pore water at relatively low temperature (Worden and Burley, 2003).

However, Houseknecht (1992), made clear his position that fine grain sandstone preserves little porosity even where they contain small total volume of quartz cement, therefore the grain-size of the sediments have a contribution irrespective of the presence of silica cementation. Also, early clay coating can equally prevent quartz cement from growing, this time preserving porosity and permeability. Typically, from studies carried out on the provenance of the quartz within the study area, Odigi (2007) noted that the quartz grains were of granitic source from the Oban massif which has already undergone diagenetic processes.

Clay Minerals

The presence of clay sized particles and clay minerals to a large degree contribute to the overall diagenesis process. The area essentially voids-fillers and act as coating to framework grains in some cases. The clay mineral assemblages in this study is grouped into kaolinite, mixed layer kaolinite/serpentine, Illite and chlorite and a list of other minerals that are closely associated with the clay mineral phase (Table 3).

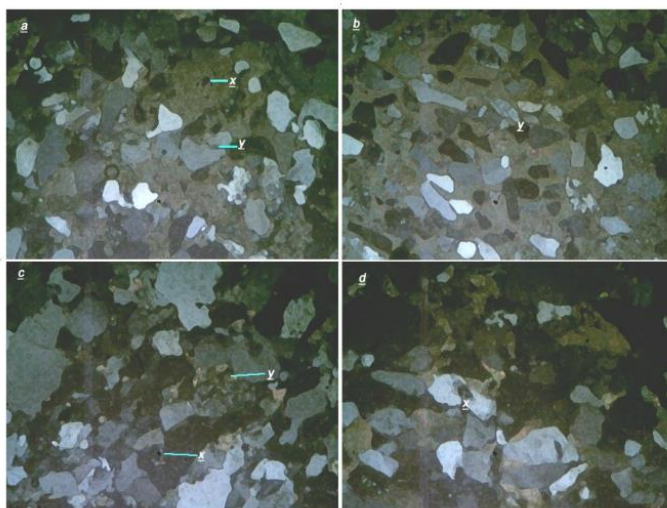


Figure 6. Photomicrograph of the studied samples taken under cross polarized light illustrating sub-angular to sub-rounded poorly sorted grains and porosity types (x=intragranular; y=intergranular)

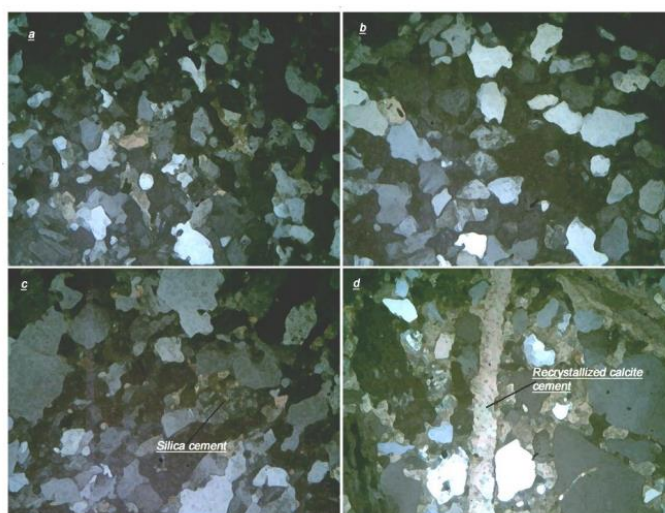


Figure 7: Photomicrograph of studied samples taken under cross polarized light showing mineralogical constituents (quartz), silica cement and calcite cement

Table 3. Diagenetic processes and reservoir potentials of the Turonian Eze-Aku Formation and middle Albian Asu River group

Diagenetic processes	Characterization of the Pre-Santonian Sandstones of the Southern Benue Trough	Reservoir potential
Mechanical compaction	Compaction: Moderate – High	
: Grain types	Moderate quartz content and ductile grain type	
: Size	Grain size: Coarse to very fine which allows for high compaction	Porosity and permeability destroyed
: Sorting	Sorting; moderate-poor attributes to moderate to high compaction	
: Shape	Shape: Subangular to sub rounded tolerate moderate compaction	
Chemical compaction	Compaction: High	
	High feldspar (>15%) and ductile lithic (>10%) content allows for high compaction.	
	Angular to subangular quartz grains permit moderate compaction through contact dissolution for compaction at later burial diagenesis.	Porosity and permeability destroyed
Cementation	Cementation: Moderate	
: Carbonate	> 1% carbonate lithics	destroys porosity and permeability, however,
: Silica	moderately common but develop secondary porosity by dissolution.	developed secondary porosity
: Dissolution	Unstable minerals in the study area undergo dissolution as burial depth increases leading to secondary porosity development.	during burial through dissolution
Bioturbation	Minor to Intense: displace grains rearrangement through burrowing activities as well as filling the pore spaces in rocks.	Porosity and permeability destroyed

Most fine grain materials (clay sized constituents) contained in the sediment composition are diagenetic products of the weathering of aluminosilicates. Some of the silicate minerals observed such as chrysotile, dickite, nacrite and halloysite (Table 3) reveal that the sediments are detrital deposits derived from alumina-rich rocks, while other silicate minerals such as mordenite, sanidine, sepiolite and lizardite are hydrous aluminosilicate formed from the weathering of hydrothermal vein deposits or the alteration of feldspathoid-like rocks (Hibbard, 2007). The breakdown of the unstable ductile minerals (feldspar and lithics) in the studied samples resulted in the precipitation of these fine grained (clay) minerals.

Kaolinite

Kaolinite is the most abundant type of clay mineral in the studied sediments with average amount of 11.23%. The abundance of kaolinite in the study area possibly indicates large amount of feldspar before dissolution and this might have been favoured by humid climate and chemical instability of the detrital minerals with respect to circulating acidic pore water (Wang et al., 2024; Onyekuru et al., 2026).

Mixed layer kaolinite/serpentine minerals

Mixed layer kaolinite-serpentine have been identified by XRD analysis with an average amount of 7.5% of the total rock volume. They occurred in form of nacrite, dickite, halloysite, chrysotile, and lizardite. These minerals probably originated from the transformation of clay detrital grains. These clays are the result of the feldspar transformation into kaolinite which occurs during burial by temperature increasing with depth (Worden & Morad, 2003).

Illite

The presence of illite indicates an increase in burial depth of investigation (Odigi, 2011). The samples analyzed recorded an average amount of 7.3% of the total rock volume. Kaolinite can be altered to illite when the pore water changes from acidic to alkaline conditions, and the transformation from kaolinite to illite might have been favoured by potassium ions from the dissolution of K=feldspar.

Chlorite

XRD analysis reveals the presence of chlorite, but in minor amount (4.8%).

This clay type also occurred in the form of Corrensite. The pore-filling chlorite might have been favoured by magnesium and iron ions released from volcanic activities of unstable grains and dissolution of carbonate cement during the late diagenetic stage (Worden & Morad, 2003). The presence of chlorite in the study area has the highest effect in destroying the reservoir properties of the sediments

COMPACTION

Compaction results in the reduction in bulk volume of the rock that occurs in response to some increased sediment thickness and of course the weight of buried sediments leading to (grain rearrangement, plastic deformation, dissolution and/or brittle deformation) (Wilson and Pittman, 1977). This mechanism results in porosity and permeability loss by reducing the pore spaces and sand body thickness (Tucker, 1993). During compaction, sand grains move closer together under the load of overburden or tectonic stress, destroying existing voids and expelling pore fluids in the process. Chemically and mechanically unstable grains such as clays, feldspar and rock fragment tend to compact faster than more stable grains such as quartz (Bloch and Helmond, 1995). The degree of compaction, as observed in Marlum Quarry, suggest that the indurated sandstone may have been strongly influenced by the burial history and lithology of the sandstone sediment. Poorly sorted sands with clay minerals tend to compact faster than well sorted sands. The compaction in the study area is observed to range from moderate to high as a result of the presence of moderate quartz grain content and other ductile grain types.

DISCUSSION

The mineralogy and textural parameters of the sediments of the Albian Asu River Group and Turonian Eze-Aku Formation reflects significant diagenetic modifications such as compaction, dissolution of some framework grains and precipitation of authigenic minerals. Compaction of the sediments started with burial and progressively

increased with depth. Further compaction resulted in the dissolution of feldspar and quartz grains resulting in the development of secondary porosity. Cementation, brought about by chemical precipitation from pore solution was observed to have being introduced under different pH conditions. The silica cement in the form of quartz overgrowth; precipitation of calcite minerals and the dissolution of feldspar to clays have significant influence on the reservoir quality of the sandstone units in the study area. Clay minerals are believed to have been introduced in the reservoir sands through biogenic activities, mechanical infiltration, and authigenesis. The XRD result showed that Kaolinite, mixed clay kaolinite/serpentine (dickite, nacrite, chrysotile, antigorite, lizardite and halloysite) and Illite are the most common detrital clay minerals in Albian - Turonian sandstones whereas chlorites occur in a minor amount also results indicated first stage of clay mineral diagenesis is represented by forming kaolinite at the expense of feldspars (Fig 8). Odigi (2011) noted that water flushing by deeply circulating meteoric water was responsible for cement and grain dissolution thereby enhancing the porosity of the sediments. Most pore-filling illite clay minerals form at the expense of kaolinite during the periods of intermediate to deep burial diagenesis. This study revealed that silicate minerals such as mordenite, sanidine, sepiolite minerals which are hydrous aluminosilicates are associated with weathering of hydrothermal vein deposits and/or the alteration of feldspathoid-like minerals, making the porosity and permeability values of the reservoir rocks of the Albian Asu River Group and Turonian Eze-Aku Formation to range from poor to moderate quality.

The relative paragenetic sequence of the diagenetic events based on the results of the petrographic microscopy, X-ray diffraction and reservoir properties determination includes: (a) early concretionary calcite (b) grain coating and pore lining clay minerals (c) compaction and grain interpenetration (d) labile grain dissolution (e) feldspars and quartz grains overgrowth (f) clay authigenesis (illite transformation, feldspars kaolinitization, feldspars albitization); (g) carbonate cementation and replacement (h) chloritization of micas (i) carbonate cement partial dissolution (j) porosity loss and gain.

Diagenetic sequence	Eodiagenetic	Mesodiagenetic	Telodiagenetic
Early concretionary calcite	•••••	•••••	
Grain coating and pore lining clay minerals	•••••	••	
Compaction and grain interpenetration	Mechanical compaction •••••	Chemical compaction •••••	
Labile grain dissolution	•••••	•••••	•
Feldspar and quartz grain overgrowth	•••••	•••••	•••••
Illite transformation + Kaolinitization of feldspar + Feldspar albitization + Chloritization of mica	•••••	•••••	•••••
Carbonate cements and partial dissolution	•••••	•••••	•••••
Porosity gain	•••••	•••••	•••••
Porosity loss	•••••	•••••	

Figure 8. Summary of the diagenetic events in sediments of the Southern Benue Trough

Reservoir evaluation

Porosity and permeability are the fundamental properties of a reservoir and are controlled primarily by textural attributes of grain size, sorting (grain size distribution) shape (sphericity), packing and other syn-depositional or post-depositional processes (Schmidt & Donald, 1999). Various techniques are employed in the evaluation of these properties. In this study, the porosity of the consolidated samples was evaluated

petrographically (Table 2). Porosity against grain plot was used to estimate the permeability values (Fig. 9). Comparing the values obtained for these petrophysical properties with the reservoir sands field appraisal of Selley (1985) the reservoir quality in the study area is classified as poor to fair. The poor to moderate sorting and highly compacted nature of the grains adds up to the poor reservoir quality.

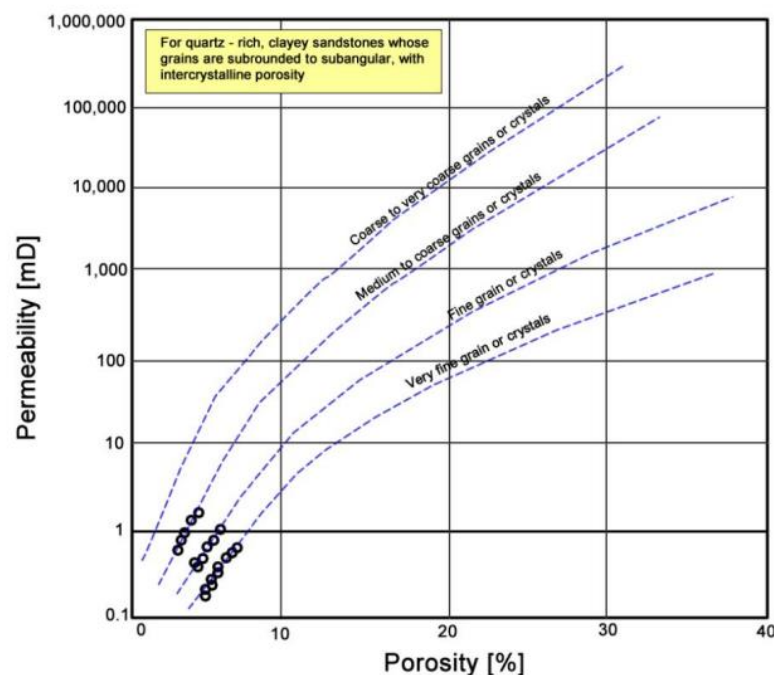


Figure 9: Permeability determination from porosity against grain-size plot (after Coalson, 1970)

Bioturbation

Bioturbation process may result in highly variable textures and structures with variable impact on the substrate porosities and overall geochemistry. Burrows act as focal point for the colonization of microbes and mineralization which may consequently drive early diagenetic processes and add to sedimentary heterogeneity (Pemberton & Gingras 2005; Anderskov & Surlyk 2012). The burrow structures observed in the study area include

Ophiomorpha, and *Gyrolithis* (Fig. 10). These burrows control porosity and permeability in two ways; first by mixing fines into clean sands or removing fines from muddy sand thereby introducing grain size contrast and thereby directly interacting with the substrate to modify sorting and mineralogy of the near burrow environment (Table 3). Measurements of the common trace fossils in the study area show that the burrow diameter of these traces remains constant throughout the succession. This suggests that they were created by adult organisms probably in an equable paleoenvironmental setting (Mode, 1997).



Figure 10: Ichnofossils (a) *Ophiomorpha* burrow observed at Ibir (b) Plant fragment at Akpoha (*Gyrolithis* at Ibir (d) *Planolites* at Ibir

SUMMARY AND CONCLUSION

The study was primarily based on petrographic, porosity/permeability and XRD analyses of the Eze-Aku Formation and middle Albian Asu River Group sediments. They are typically composed of very fine to coarse grain, moderately to poorly sorted, sub angular to sub rounded grey to dull white sediments. The sediments are mainly arkosic with quartz, feldspar and other components as the main constituents, whereas silica and calcite occur in them as cementing materials. The role of sedimentology and depositional facies is fundamental to the quality of the reservoir rocks. Secondary porosity development and enhanced porosity in this studied sandstone results from dissolution of feldspar grains. Diagenesis has been observed to be a significant process that influenced the reservoir quality in the study area. This has showcased in the degree of compaction, cementation (silica, and calcite), dissolution of unstable minerals, pressure solution and bioturbation

recognized as major processes that resulted in the modification of reservoir quality in the study area.

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