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Impact of Texture and Diagenesis on Reservoir Quality of Some Pre-Santonian Sandstones (Asu River Group and Eze-Aku Formation), Southern Benue Trough, Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author RAO designed the study and wrote the protocol in conjunction with author AWM. All authors together performed the statistical analysis, managed the analyses of the study and prepared the first draft of the manuscript. Author EEO managed the literature searches while all authors read and approved the final manuscript.

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ABSTRACT

This research presents a detailed study of the pre-Santonian sandstones of the Asu River Group and the Eze-Aku Formation exposed in southeastern Nigeria. Intensive field studies complimented with laboratory thin section petrography, X-ray diffraction (XRD), porosity and permeability studies were carried out to determine the main controls on reservoir properties of these sandstones. Results revealed that the reservoir rocks within the study area consist of consolidated, 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 porosity in the studied reservoir sediments was determined petrographically and ranged from 3.00 – 6.00; the permeability values determined from the porosity vs grain size plot 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,

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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 in the study area.

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

1. INTRODUCTION

Sediments are generally subjected to changes from the time of deposition till they become lithified sedimentary rocks. The degree to which this happens depend on the dominant geological processes acting on them [1]. Among these processes include, physical, chemical, and biological processes which act on the sediments to transform them into rocks. The combined effects of bioturbation, burial, compaction, cementation and chemical reactions between rocks collectively known as diagenesis play a major role in modifying the properties of the rock and this determines its suitability as a potential reservoir rock. It is therefore necessary to understand how these processes influence the properties of the rock. Therefore, knowledge of the gross sediment heterogeneity and petrophysical properties is important and aids exploration and exploitation activities.in the course of the evolution of the Benue Trough, clastic and carbonate deposition were distributed across the basin, these were controlled by transgressive – regressive episodes as well as epeirogenetic movements in places [2]. Sandstone facies of Asu river Group and Eze-Aku Formation both of the Southern Benue Trough is 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. Therefore, this paper considers the impacts of textural features and diagenesis of pre-Santonian sandstones of the Southern Benue Trough. 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 [3], it is necessary to determine the reservoir properties of the sand bodies.

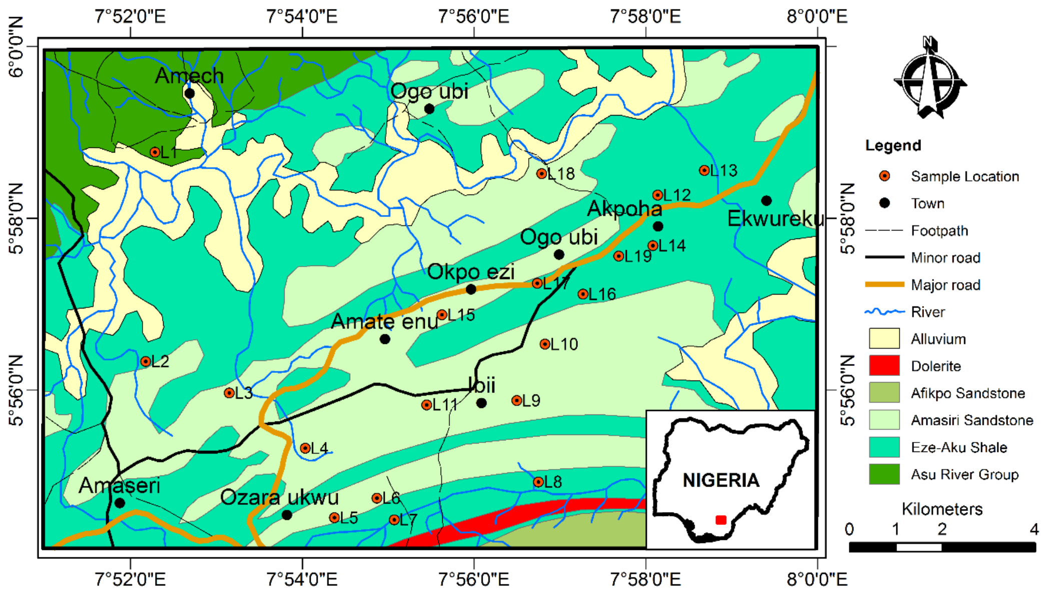


Fig. 1. Location map of the study area

2. TECTONIC SETTING AND BASIN EVOLUTION

The Southern Benue Trough is a part of the megastructure that runs northeast across Nigeria from the reaches if the Gulf of Guinea into the zone popularly referred to as West and Central Africa Rift System (WCARS). Within Nigeria, the Benue Trough is estimated to extend for about 1000 km in length and 250 km in its widest width [4,5]. In its southern part, the Niger Delta is seen to overly 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 [2,4,6,7,8].

Basically, this controlled the sedimentary evolution in concert with eustatic movement leading to transgressive-regressive phases [2,9-12]. 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, Asu River Group, 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. These sediments grade northwards to form platform carbonates of the Arufu and Gboko Formations [6,10,11,13]. 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. These sediments are characteristic of tidal shelf to deep marine turbidite depositional model [14]. These sediments ultimately belong to the Eze-Aku Group [4] or the Cross-River Group of Petters and Ekweozor [15]. 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 [5]. The Paleogene saw the progradation of the Niger Delta which has continued to regress since the Eocene times [16].

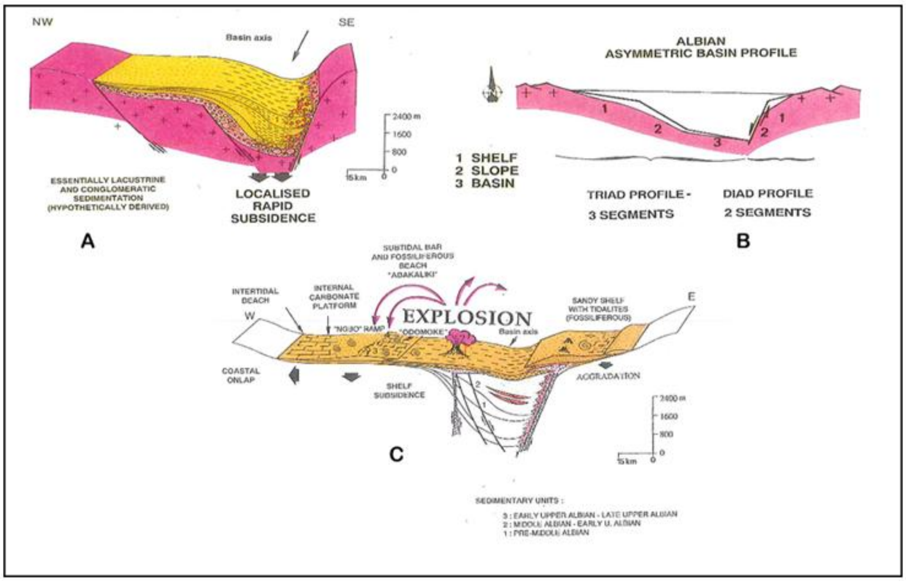


Fig. 2. Illustration of the basin forming process (after Ojoh [4])

3. 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. The first account by Reyment [6] have been revised largely (Table 1) as a result of later exposed outcrop sections and new information from drill cores resulting from research carried out by oil companies and tertiary institutions. Among such notable studies were those of Petters and Ekweozor [15], Amajor [11] and Ojoh [4].

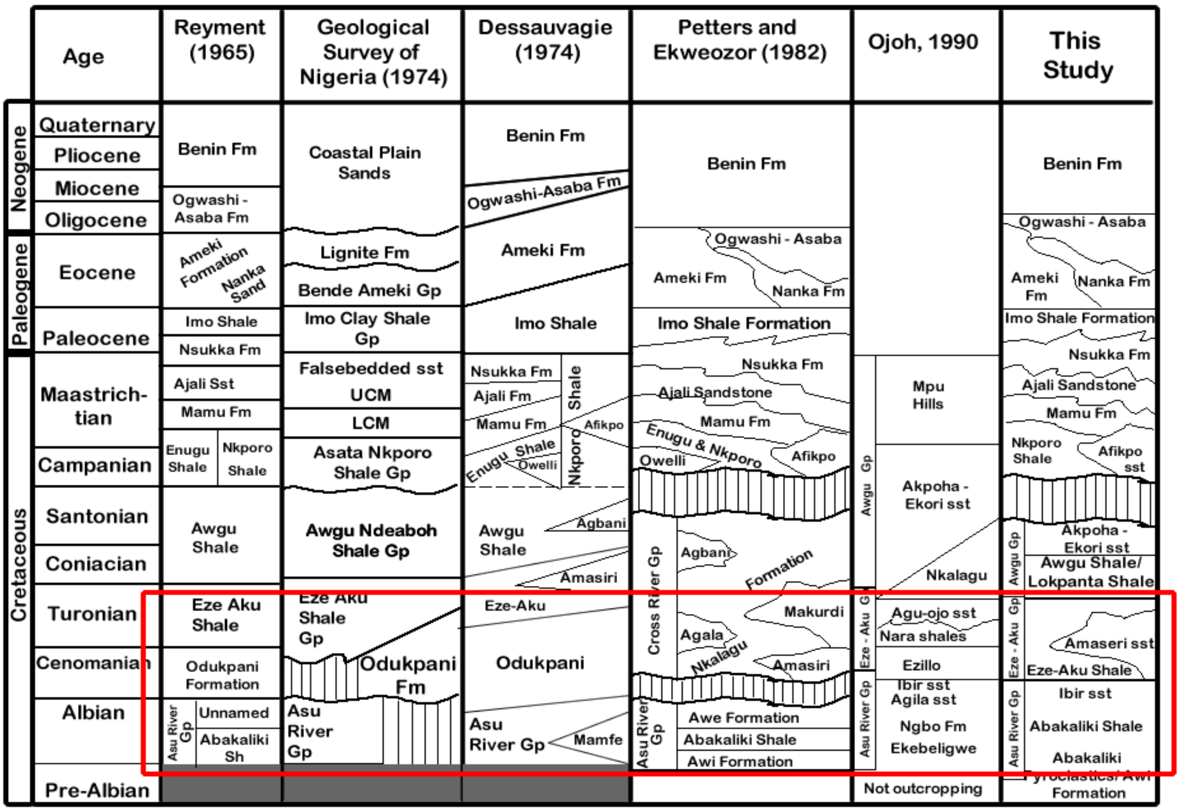
3.1 Asu River Group (Albian)

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 Reyment [6], 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 [17] although this is merely a hypothesis, it is yet to be fully confirmed. The sediments of the Asu River Group in Abakaliki are arkosic and non-fossiliferous conglomerates associated with the Abakaliki shales and pyroclastics. Ojoh [4] 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 [18], while the Ngbo Formation, Agila and Ibir (Late Albian) contain more sands and changes from shelf to near shore environment.

3.2 Eze-Aku Group (Cenomanian-Turonian)

Cenomanian sediments within the Benue Trough was assigned to the Odukpani Formation consisting predominantly of shales and limestones of shallow marine shelf environment [6,19]. Although some authors think that the

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



Cenomanian is absent in Abakaliki Basin; Nwachukwu [7] attributed the absence of the Cenomanian to a possibly slight folding phase within this area. Ojoh [18] 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 [6,19]. 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 [20], Agala Sandstones [2], Konshisha Section, Amasiri Sandstones [19] and the Agu-Ojo Sandstones [18], are deposits laid by a short-localised 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.

4. 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 compositionally included shales, siltstones and medium – coarse grain sandstones (Figs. 3 and 4) were found to be bedded (Fig. 3a) and observed to be 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). Burrow structures observed in the sediments were carefully studied and identified and their impact on reservoir properties was noted.

Fig. 3. Field representation of outcrops of Asu River Group and Eze-Aku Group (a) Weathered siltstone bed (b) Dipping siltstone Unit (c) Medium grained sandstone (d) Poorly sorted coarse-grained sandstone

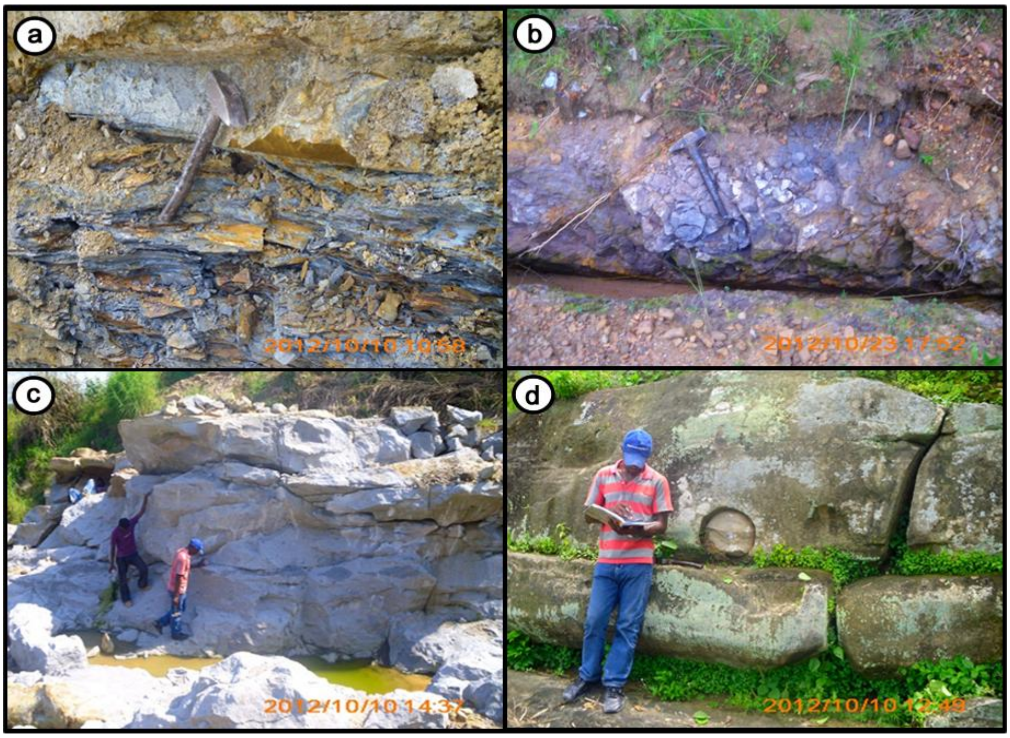


Fig. 4. (a) Fissile grey shale facies at Marlum quarry, Ibii (b) Underlying grey shale facies having a sharp contact with the overlying sandstone. (c) Siltstone section at Julius Berger quarry, Akpoha (d) Highly indurated medium grained sandstone at Ugo Ubi

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 then 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.

5. RESULTS AND INTERPRETATIONS

The results from petrographic analysis are presented in Table 2. The result shows the percentage distributions of the framework components (quartz, felspar and rock fragments) within the sandstones and their porosity/permeability values. Supplemented 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. Mineralogical composition of sandstone is critical to reservoir quality development as contrasting framework grains tend to behave differently with burial diagenesis.

Based on Folk's classification scheme [21], the sandstones of the Albian Asu River Group (Ibii Sandstones) and Turonian Eze-Aku Group (Amasiri Sandstones) are classified as Arkoses (Fig. 5). Quartz and feldspar grains are the main framework constituents, with rock fragments occurring in minor quantities. The proportion of the quartz grains ranges from 63-68% in the studied sandstone samples (Table 2). Feldspars (Albite and Microcline) exceed 16% in the studied samples. Some feldspars and quartz grains exhibit internal dissolution to form secondary porosity while others alter to form kaolinite and illite. Mica (biotite and muscovite) abundance was observed to be between 1% to 3% (Table 2).

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

		Framework grains					**Cement**		**Textural properties**			**Reservoir properties**	
FORMATION	**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

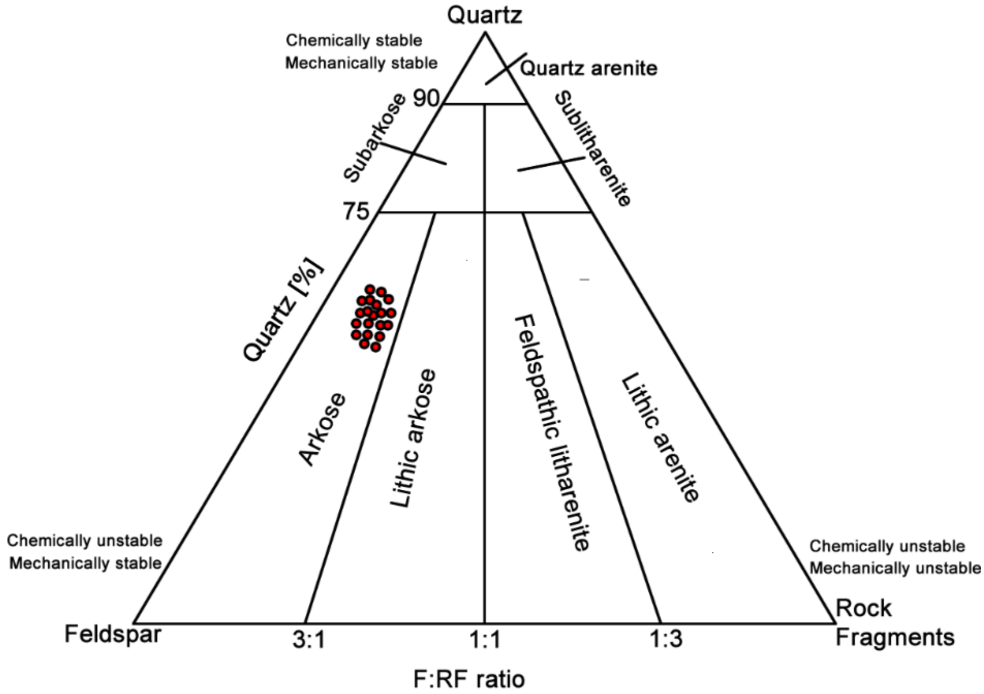


Fig. 5. Ternary plot showing position of the studied samples in Folk's sandstone classification (Folk [21])

5.1 Texture

Textural parameters that affect the reservoir properties include sorting, shape and grain size. The texture ranges from coarse to very fine grained, sub angular to sub rounded, moderately to poorly sorted sandstones (Fig. 6a-d). Compaction in sandstones composed predominantly of non-ductile grains, 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 [22]. However, Houseknecht [23] made clear his position that fine grain sandstone preserves little porosity even where they contain small total volume of quartz cement, therefore the grainsize 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 [24] noted that the quartz grains were of granitic source from the Oban massif which has already undergone diagenetic processes.

5.2 Clay Minerals

The presence of clay sized particles and clay minerals to a large degree contributes 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/serpentinite, Illite and chlorite and a list of other minerals that are closely associated with the clay mineral phase (Table 3).

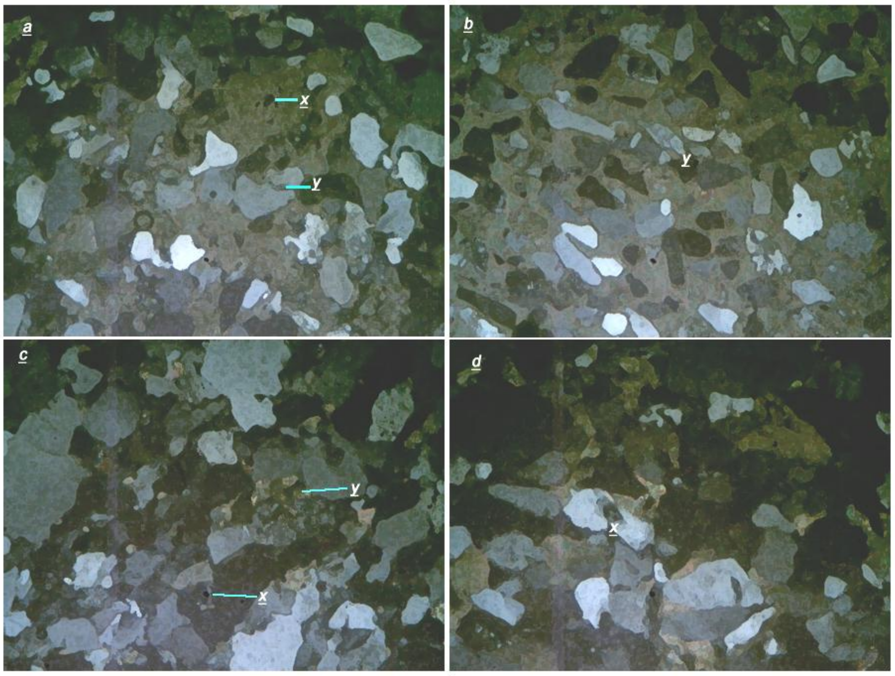


Fig. 6a-d. Photomicrograph of studied samples taken under cross polarized light illustrating subangular to subrounded poorly sorted grains and porosity types.
(*x – intragranular; y - intergranular*).

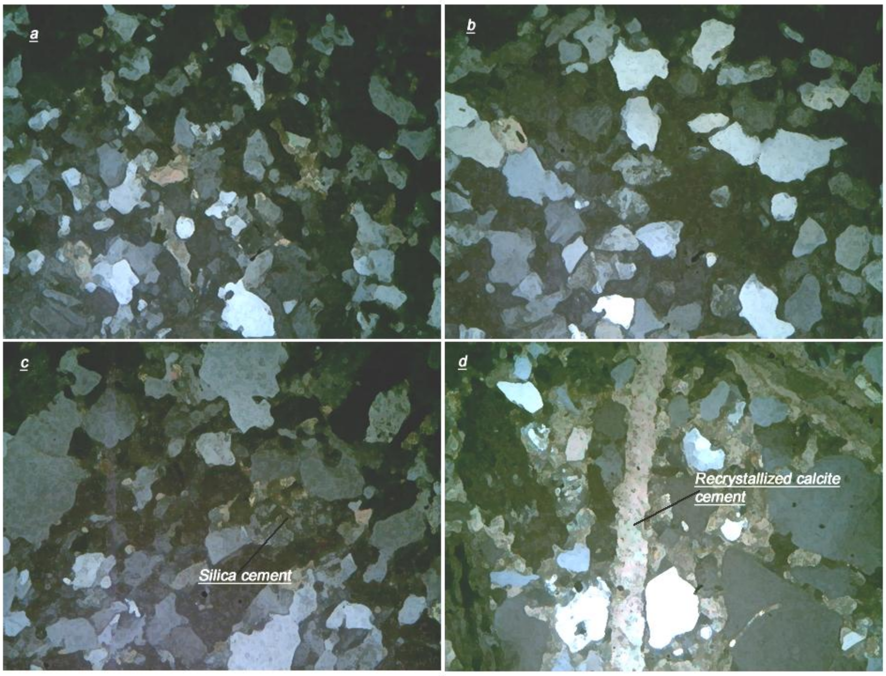


Fig. 7a-d. Photomicrograph of studied samples taken under cross polarized light showing mineralogical constituents (quartz), silica cement and calcite cement

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 chrysolite 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 [25]. The breakdown of the unstable ductile minerals (feldspar and lithics) in the studied samples resulted in the precipitation of these fine grained (clay) minerals.

5.2.1 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.

5.2.2 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 [26].

5.2.3 Illite

The presence of illite indicates an increase in burial depth of investigation [27]. The samples analysed 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.

5.2.4 Chlorite

XRD analysis reveal 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. The presence of chlorite in the study area has the highest effect in destroying the reservoir properties of the sediments.

5.3 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) [3]. This mechanism results in porosity and permeability loss by reducing the pore spaces and sand body thickness [28]. 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 [29]. The degree of compaction is 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.

5.4 Discussion

The mineralogy and textural parameters of the sediments of the Albian Asu River Group and Turonian Eze-Aku Formation have undergone significant diagenetic modifications such as compaction, precipitation of authigenic minerals and dissolution of framework grains. 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 is brought about by chemical precipitation from pore solution. The cementing materials were precipitated 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, mechanical infiltration, and authigenesis. 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.

5.4.1 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 syndepositional or post-depositional processes [30]. 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. 8).

Comparing the values obtained for these petrophysical properties with the reservoir sands field appraisal of Selley [32], 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.

5.4.2 Bioturbation

Burrowing organism displaces and mix sedimentary grains by burrowing, feeding and relocating the sediments. They secret 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 [33]. Burrows can alter the geochemistry of a substrate, acting as focal point for the colonization of microbes and mineralization which may consequently drive early diagenetic processes and add to sedimentary heterogeneity [34]. The burrow structures observed in the study area include *Ophiomorpha* burrows, plant fragment, *Planolites* and *Gyrolithis* (Fig. 9).

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 by directly interact with their substrate to modify the sorting and mineralogy of the near burrow environment (Table 3).

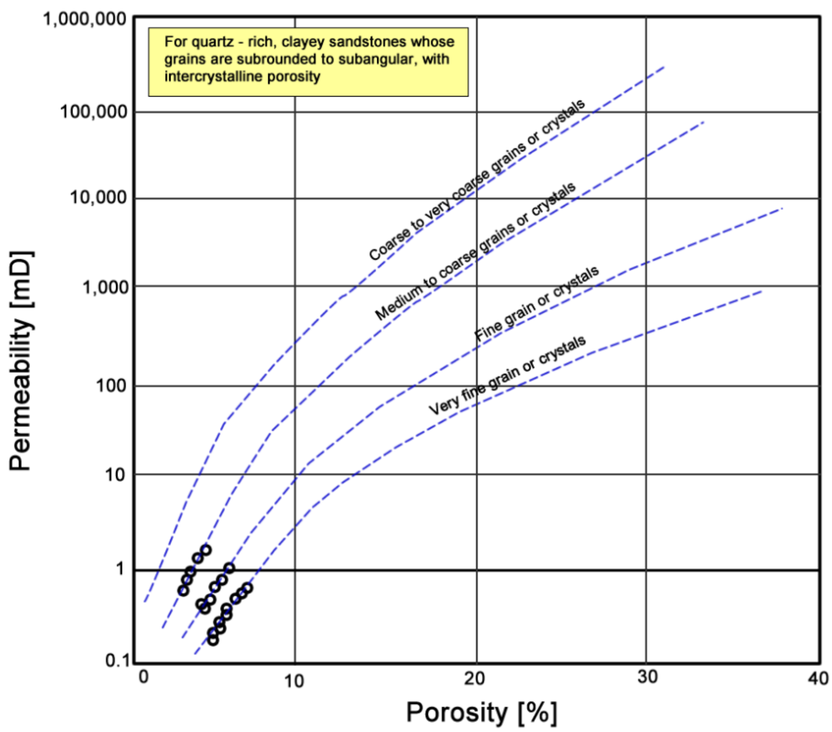


Fig. 8. Permeability determination from porosity against grain size plot (after Coalson [31])

Fig. 9. Icnofossils, (a) *Ophiomorpha* burrow observed at Ibir (b) Plant fragment at Akpoha (c) *Gyrolithis* at Ibir (d) *Planolites* at Ibir

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, developed secondary porosity during burial through dissolution
: Silica	moderately common but develop secondary porosity by dissolution.	
: Dissolution	Unstable minerals in the study area undergo dissolution as burial depth increases leading to secondary porosity development.	
Bioturbation	Minor to Intense: displace grains rearrangement through burrowing activities as well as filling the pore spaces in rocks.	Porosity and permeability destroyed

Measurements of the common trace fossils in the study area show that the burrow diameter of these traces remain constant throughout the succession. This suggests that they were created by adult organisms probably in an equable paleoenvironmental setting.

6. SUMMARY/CONCLUSION

This research was based on petrographic, porosity/permeability, and XRD studies of the Turonian Eze-Aku Formation and middle Albian Asu River Group sediments. These are generally characterized by very fine to coarse grain size, moderately to poorly sorted, sub angular to sub rounded, grey to dull white sediments. The sediments are predominantly arkosic, composed mainly of quartz, feldspar and other components, with silica, and calcite occurring as cementing materials.

XRD analysis also revealed that kaolinite, mixed clay kaolinite/serpentine (dickite, nacrite, chrysotile, antigorite, lizardite and halloysite), and Illite, are the most frequently occurring detrital clay minerals in the Albian - Turonian sandstones while chlorite occur in minor quantity and that the first stage of clay mineral diagenesis was characterized by the formation of kaolinite at the expense of feldspars (Fig. 10). Cement and grain dissolution have been known to occur as a result of water flushing [27] by deeply circulating meteoric water, thereby enhancing the porosity of the sediments.

During the period of intermediate to deep burial diagenesis, pore-filling illite formed mainly at the expense of kaolinite. Silicate minerals recorded are mordenite, sanidine, sepiolite minerals which are hydrous aluminosilicates formed from the weathering of hydrothermal vein deposits or the alteration of feldspathoid-like minerals. The porosity and permeability values recorded show that the reservoir quality of the Albian Asu River Group and Turonian Eze-Aku Formation range from poor to moderate. It also shows that sedimentological controls and depositional facies play a fundamental role on reservoir quality. Dissolution of feldspar and quartz grains result in the development of secondary porosity and enhanced the porosity of the studied sandstone sediments.

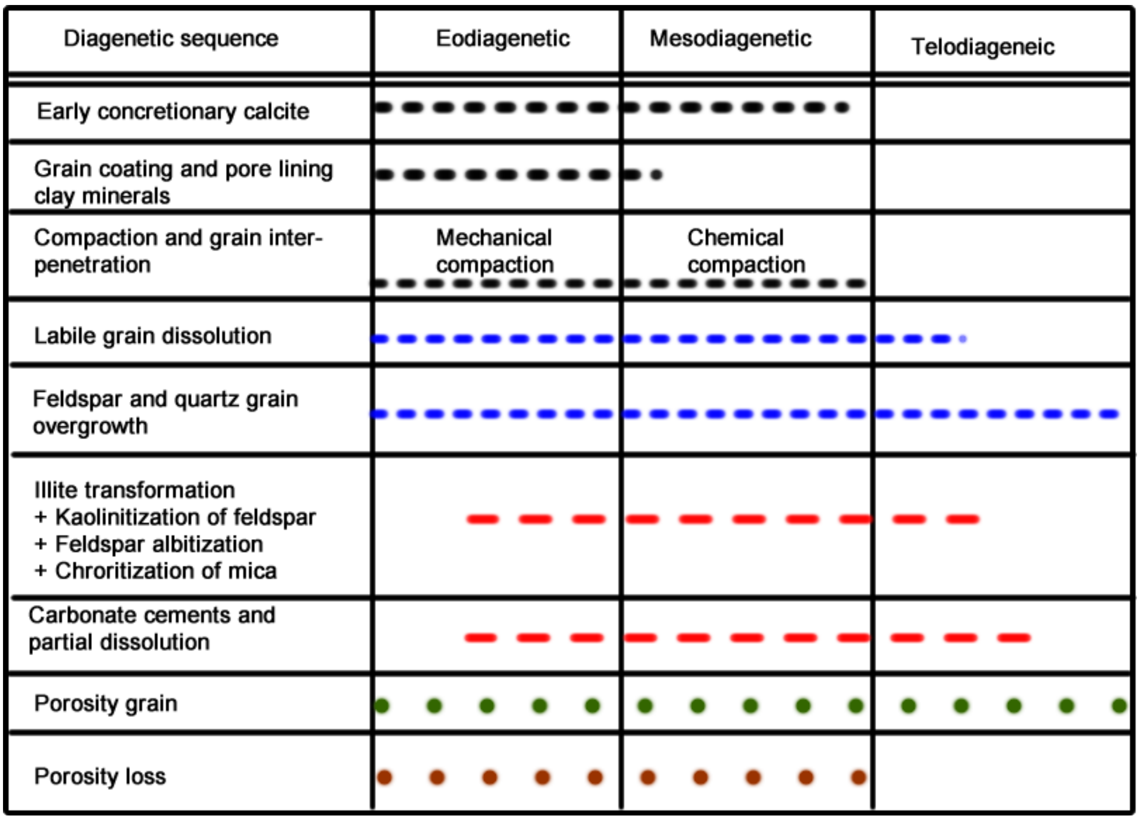


Fig. 10. Summary of the diagenetic events in sediments of Southern Benue Trough

In conclusion, the sediments have experienced significant burial diagenetic processes that have strongly influenced their reservoir quality. Compaction, cementation (silica, and calcite), dissolution of unstable minerals, pressure solution and bioturbation have been recognized as the major processes resulting in the reservoir quality modification in the area.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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