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Depositional environments, diagenesis and reservoir development of Asu River Group Sandstone: Southeastern lower Benue Trough, Nigeria

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ABSTRACT

The continental to deltaic Asu River Group in the Afikpo basin, south-eastern Nigeria, is mainly composed of arkosic sandstones with minor proportion of volcanic rock fragments and calcareous subarkosic sandstones. The arkosic sandstones are cemented mainly by calcite with minor quartz cement; while the calcareous sandstones have calcite as major cements. Petrographically, the sandstones and calcareous sandstones can be divided into four facies: the basal conglomerate to coarse grained sandstones, medium-fine grained sandstones deposited in a fluvial non-marine environment; calcareous siltstones and calcareous subarkosic sandstones. The calcareous sandstones are bioclastic grainstones and packstones respectively deposited in a estuarine to shallow shelf marine environment. Petrographic investigations indicate that diagenetic processes which have modified the Awi and Awe Formations respectively include micritization, cementation, dissolution, neomorphism and compaction. The calcareous sandstones have undergone diagenetic alteration under low temperatures and pressures. Alteration started with pore-space reduction by compaction and was followed by pore-filling cement. Dissolution at the surface, however, has caused secondary porosity. The sandstones have a lower porosity due to a higher degree of cementation. The higher porosity in the calcareous sandstones is due to dissolution of feldspars; and are better sorted and more loosely packed. The diagenetic history can be divided into three stages: marine, near surface, and burial. Each of these is characterized by differing degrees of porosity formation and cementation. Porosity in the Asu River Group is general either primary (intergranular and intragranular) or secondary, enhance by dissolution and fracturing (during tectonic movement) of the calcareous sandstones. It varies from zero to 6.5% (based on visual estimation) and includes both fabric – selective and non fabric-selective types. Fabric-selective porosity includes mouldic, intergranular and intragranular types. Difference in porosity within the facies is attributed to variations in the nature of the diagenetic fluids with depth. Dissolution in the Asu River Group probably reflects circulation of aggressive fluids which were undersaturated with respect to calcite (presumably meteoric waters). An influx of meteoric waters can be linked to exposure of the Asu River Group Cenomanian uplift. The outcrop reservoir quality studies can be used as a model in the predicting of the extent of diagenesis and reservoir quality in the subsurface Niger Delta.

INTRODUCTION

There are undiscovered petroleum deposits in the Lower Benue Trough of Nigeria, and this had created considerable interest in the sandstone reservoirs in the area.

Successful exploration efforts require an accurate knowledge of several formation parameters, including depositional environment and diagenetic history. Information presented in this paper includes a study of the various types of cements in sandstones and chronology. Depositional environment is also discussed, along with its possible effect on diagenesis.

The reduction of porosity in sandstones by compaction and cementation during early burial has been well documented (Galloway, 1979; Hayes, 1979; Boles and Franks, 1979: Mathisen, 1984; Reed et al; 1993; Tang et al;

1997 and Bashari, 1998). Mathisen (1984) noted that non-marine sandstones in the central part of the Cgayan Basin (Northern Luzon, Philippines) contain significant amounts of secondary porosity, which were formed at shallow depths as a result of diagenesis. The end result of diagenesis in terms of reservoir quality therefore depends not only on the detrital composition of sandstone, but also on the amount and composition of the fluids introduced into or removed from the system (Stenecipher and May, 1990; Bjorlykke et al; 1986; Bjorlykke, 1988; Bjorlykke, 1989; Bjorlykke and Egeberg, 1993). Each of these factors can be related in part to the depositional facies concerned.

The objective of this research is to describe the diagenesis of the siliclastic and calcareous sandstones from outcrops of the Lower Cretaceous Asu River Group located in the Afikpo Basin, South-eastern Benue Trough, Nigeria (Fig.1). Special attention is paid to the effect of depositional environments to the distribution of authigenic minerals, and to the paragenetic sequence and reservoir quality developed as a result of diagenesis within the two lithostratigraphic intervals identified of the Asu River Group.

REGIONAL GEOLOGY OF SOUTH EASTERN NIGERIA

The evolution of sedimentary basins in South-Eastern Nigeria followed the opening of the South Atlantic and the break-up of the South American and West African plates in late Jurassic times (Fig.2). The pro-basin of the Benue Trough was the failed arm of an RRR triple junction which extended from the Northern limits of the Niger Delta Basin to the Chad area in the NE.

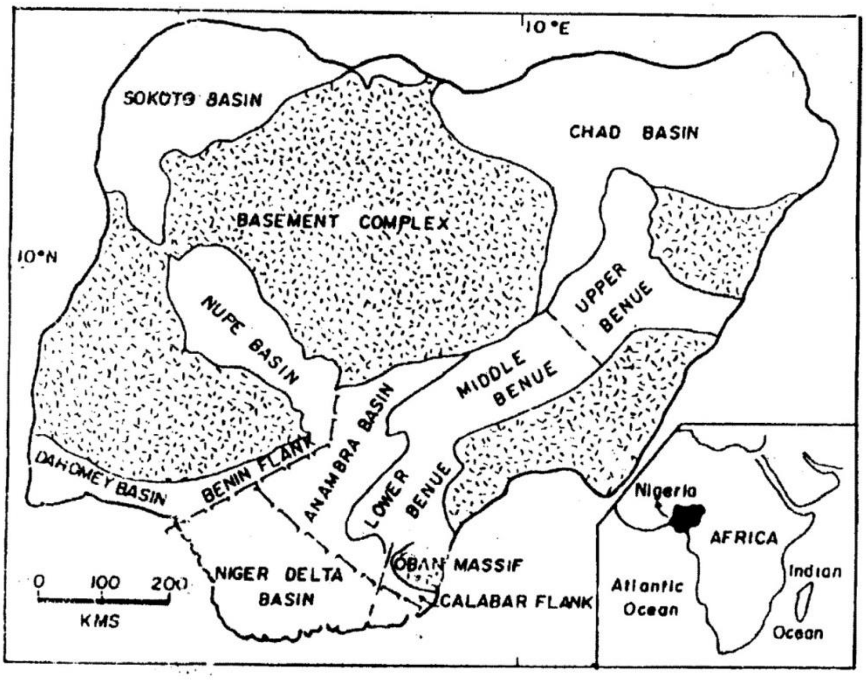


Fig. 1: Map of Nigeria Showing the location of the Benue Trough (Basin) and South-Eastern sedimentary basins

A review of the tectonic framework of the inland sedimentary basin of Nigeria has demonstrated that the Benue Trough system was indeed a rejuvenation of existing basement fractures. Wrench movements along these faults resulted in blocks faulting and formation of several sedimentary basins. The Benue Trough system had in the past been conveniently subdivided into the lower, middle and upper Benue Trough. However recent aeromagnetic and gravity data across the entire system has demonstrated the distinct nature of these basins each with its well defined sedimentary succession and separated by positive anomaly areas. Sediment thicknesses of up to 8km have been recorded in some of these basins within the Trough (Ofoegbu, 1985).

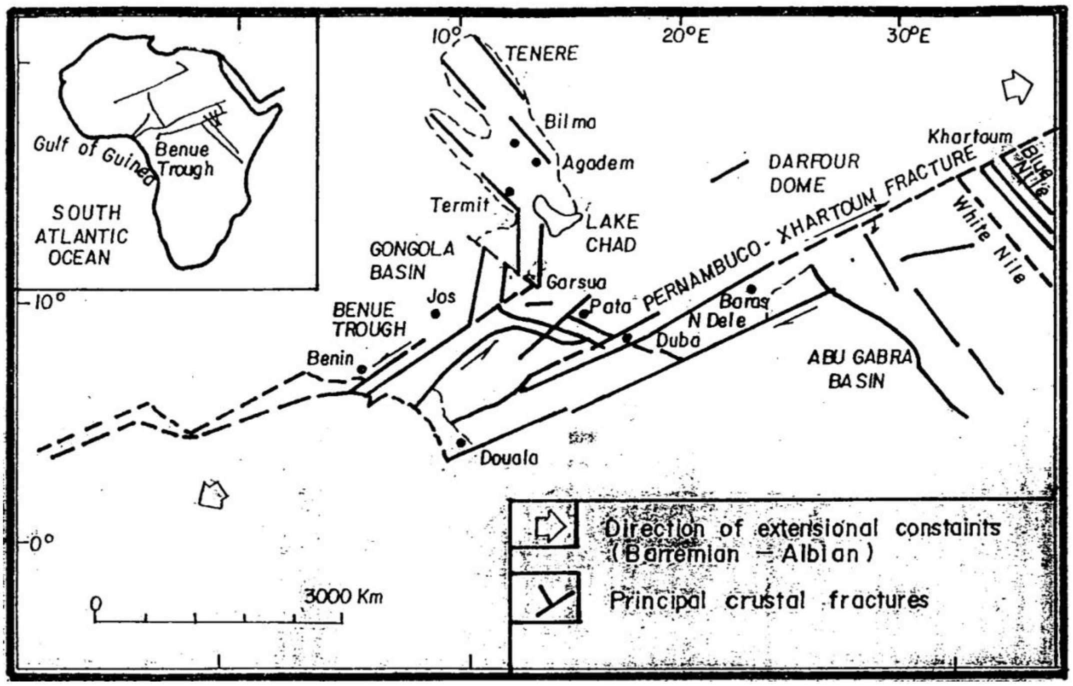
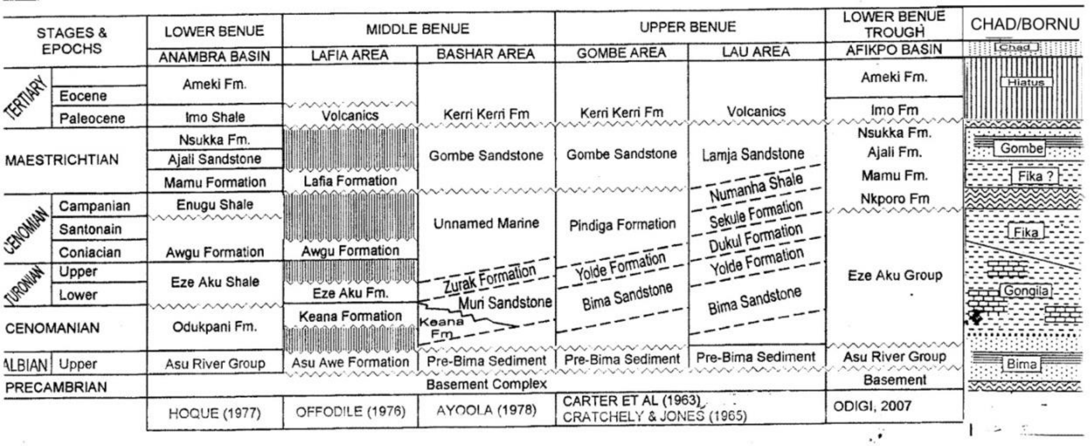


Fig. 2 Regional Structural map showing the major fracture subsystems in the West and Central African region (after Popoff, 1988)

In South-eastern Nigeria they include the Abakaliki, Anambra and Afikpo basins, as well as other minor basins such as the Calabar flank and Mamfe Embayment which together from the lower Benue Trough. The Paleogene basin has been influenced mainly by the later generation transform faults (Charcot, Chain, Ascension & St. Pauls) which emanate from the mid-Atlantic ridge system and now extend only into the Tertiary basin. Up to 12km sediments have been deposited within the central part of the Niger Delta basin, much of which is above oceanic basement.

GEOLOGY AND STRATIGRAPHY OF THE AFIKPO BASIN

The Benue Trough is a linear NE-SW trending intra- continental basin. The Cretaceous succession in Nigeria is exposed in the Benue Trough (Fig.3). The Benue Trough is about 85-90 km wide fault-bounded depression containing up to 6000 m of slightly too strongly deformed Cretaceous sedimentary and volcanic rocks.



STAGES & EPOCHS		LOWER BENUE	MIDDLE BENUE		UPPER BENUE		LOWER BENUE TROUGH	CHAD/BORNU
		ANAMBRA BASIN	LAFIA AREA	BASHAR AREA	GOMBE AREA	LAU AREA	AFIKPO BASIN	Chad
TERTIARY		Ameki Fm.					Ameki Fm.	Hiatus
	Eocene							
	Paleocene	Imo Shale	Volcanics	Kerri Kerri Fm	Kerri Kerri Fm	Volcanics	Imo Fm	
MAESTRICHTIAN		Nsukka Fm. Ajali Sandstone Mamu Formation	Lafia Formation	Gombe Sandstone	Gombe Sandstone	Lamja Sandstone	Nsukka Fm. Ajali Fm. Mamu Fm.	Gombe Fika ?
CENOMIAN	Campanian	Enugu Shale		Unnamed Marine	Pindiga Formation	Numanha Shale	Nkporo Fm	
	Santonain					Sekule Formation	Eze Aku Group	Fika
	Coniacian	Awgu Formation	Awgu Formation			Dukul Formation		
TURONIAN	Upper	Eze Aku Shale	Eze Aku Fm.	Zurak Formation	Yolde Formation	Yolde Formation		Gongila
	Lower			Muri Sandstone	Bima Sandstone	Bima Sandstone		
CENOMANIAN		Odukpani Fm.	Keana Formation	Keana Fm				
ALBIAN	Upper	Asu River Group	Asu Awe Formation	Pre-Bima Sediment	Pre-Bima Sediment	Pre-Bima Sediment	Asu River Group	Bima
PRECAMBRIAN		Basement Complex					Basement	
		HOQUE (1977)	OFFODILE (1976)	AYOOLA (1978)	CARTER ET AL (1963) CRATCHELY & JONES (1965)		ODIGI, 2007	

Fig. 3 Stratigraphic Successions in the Benue Trough of Nigeria

The sedimentary fill in the Afikpo basin is divided into three tectonic -stratigraphic mega sequences the Asu River Group, Eze-Aku Group and proto-Niger Delta succession (Fig. 3). In the south-eastern Nigeria the oldest sedimentary rocks overlying the Precambrian Basement complex rocks are non-marine to marine sediments of Early-Mid Albian in age. The Albian Asu River Group is dominantly shale with siliclastic and calcareous sandstones. The oldest sedimentary sequence is of a conglomeratic to arkosic sandstone, overlain by shales, lower and upper regressive sandstones. The lower and upper sandstone bodies are regarded by Petters and Ekweozor (1982) as Awi and Awe Formations respectively. The Asu River Group is overlain unconformable by the Eze Aku

Group, while the Eze-Aku Group is also overlain by the proto-Niger Delta deposits. The proto-Niger Delta basin comprise of Campian-Maastrichtian and Paleocene sediments which are post-unconformity formations.

Three mega sequences: Asu River Group, Eze-Aku Group and the proto-Niger Delta sediments have been intruded by basic rocks during the three tectonic events, namely Cenomanian, Santonian and Maastrichtain times (Odigi, 2007; Odigi & Amajor, 2009).

ASU RIVER GROUP LITHOFACIES

The base of the Asu River Group is marked by an angular unconformity. Overlying the succession is an extensive intrabasinal conglomeratic unit, leach limestone and hard ground surface of Mid Cenomanian age. The Asu River Group sequence can be subdivided into three main lithofacies units from base to top: Awi Formation consists of cross-bedded basal sandstone and bioclastic grainstone, while the Awe Formation is rich in both benthonic and planktonic forams and consists of packstone-grainstone, and bioclastic and planktonic forams (Fig.4). Each of the lithofacies contains siliclastic materials.

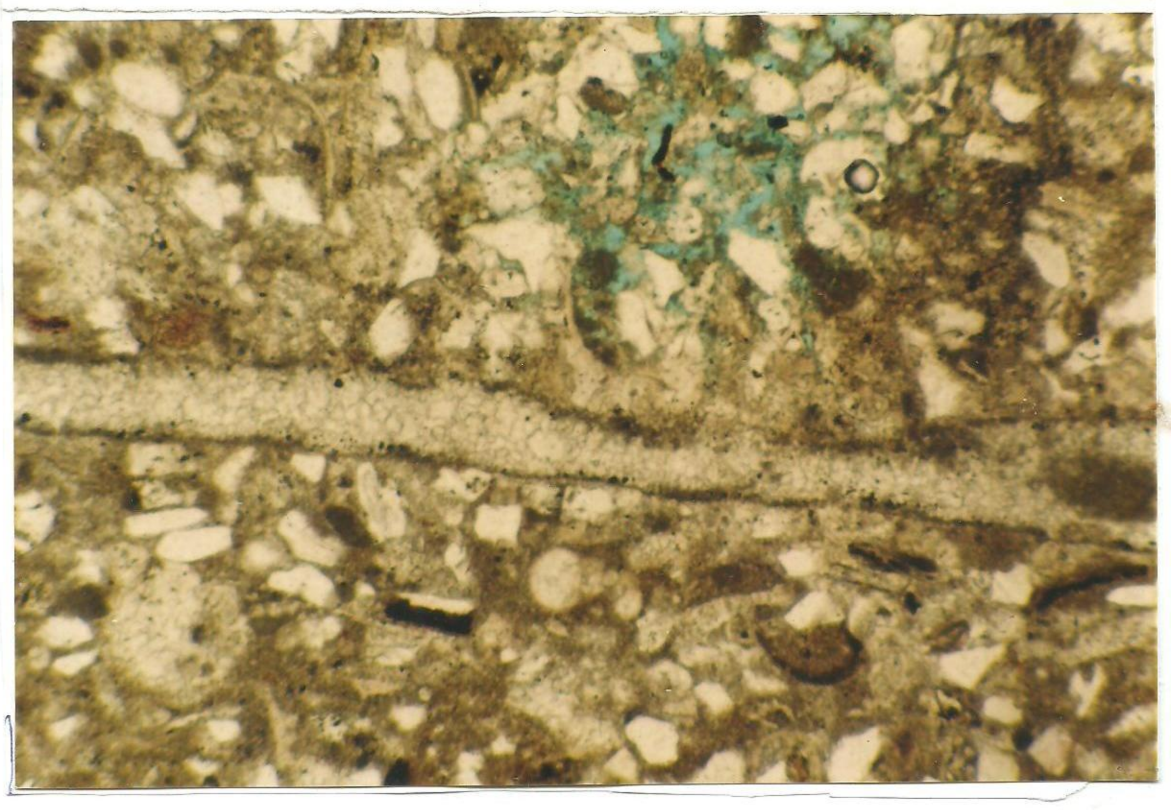


Fig.4 Photomicrograph of polished thin section, of calcareous sandstone of Awe Formation showing crinoids spine, ooids and foraminifera.

The Awi facies is interpreted to represent fluvial to estuarine, near shore depositional system, with high energy grain stone bars. The Awi Formation is classified as arkosic sandstone with a cyclic finning upward sequence bounded by an unconformity surface. The presence of apatite in the Awi sandstone suggests saline marine environment of deposition. The marine portion of the Awi sandstones are fossil-rich with finning upward texture. The Awe facies is composed of packstone and wackstone carbonate material was deposited in a low energy location.

MATERIALS AND METHODS

Sample collection from the Asu River Group outcrops was based on sedimentological and pre-existing stratigraphic documentation of the localities, supplemented with field observations and logs. Fresh collected samples were sliced and examined in the laboratory prior to sample selection for petrographic and geochemical analysis. Samples were selected for staining, thin-section petrography, scanning electron microscopy (SEM) and backscatter scanning electron microscopy BSEM. Thin sections were impregnated with epoxy, left uncovered and polished. Secondary electron image analysis (SEI) was carried out on freshly fractured, stub-mounted sample coated with gold. Some samples were carbon coated and examined on the SEM using backscattered imaging (BEI). The SEM data, CL images and the BEI were combined to differentiate between detrital quartz and authigenic quartz, and porosity. SEM-CL analysis of polished thin sections allowed a detailed view of cements and their host detrital quartz grains (with the host detrital grain typically exhibiting a brighter luminescence), which would otherwise may remain undetected by convectional optical petrographic analysis or BSEM backscatter analysis.

PETROGRAPHY

Detrital petrography

Various types of detrital minerals were identified; and they are as follows:
Quartz:-Quartz constitutes the most abundant grain type recorded in the samples, forming more than 73% of the detrital component. They are typically sub-angular to angular monocrystalline grains (Fig. 5), being occasionally sub-rounded. These grains are abundant and have uniform to slightly extinction optical property. Grains of this type frequently contain lines of fluid, and, less commonly, solid inclusions (apatite and rutile needles). These grains conform in character to the “common” quartz category of Folk (1980), and are debatably considered to be plutonic in origin. Monocrystalline grains, with highly strained extinctions, compromise approximately 10% (visual estimation) of the quartz component, and possibly derived from metamorphic rocks.

Polycrystalline quartz grains rarely exceed 5% of the detrital quartz component. Four common varieties, characteristic of primary metamorphic sources, have been recognized:

a) Recrystallised quartzites, composed of equant interlocking quartz crystals.
b) Sheared quartzites, consisting of strained, lenticular sub-crystals with well defined crenulated boundaries.
c) Recrystallised compose grains, comprising of sub-equant crystals with undulose to sutured boundaries.
d) Composite grains, composed of two or three strained sub-crystals with poorly defined, diffuse crystal boundaries.

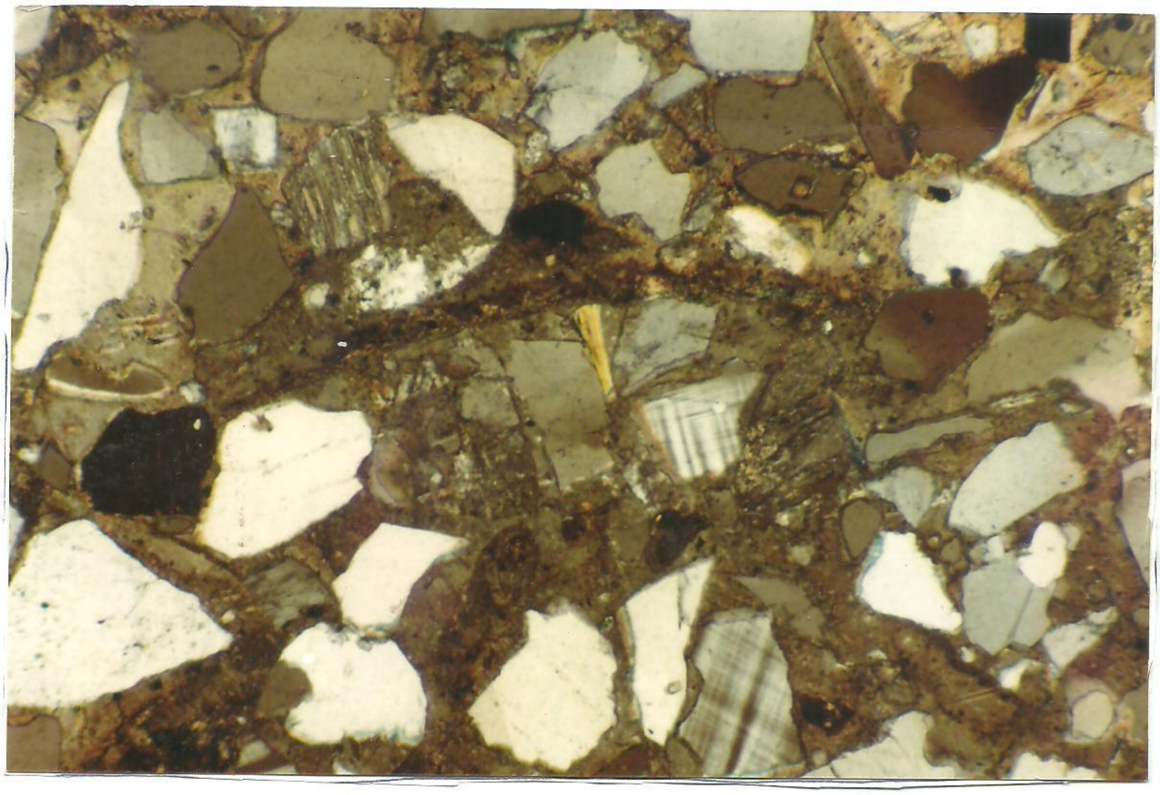


Fig. 5 Photomicrograph of polished thin section, of calcareous sandstone of Awe Formation showing detrital K-feldspar.

Feldspars:- Detrital feldspars occur in quantities rarely exceeding 10% of the detrital suite, and are present in all the samples studied (Fig.5). The dominant feldspar type is plagioclase-albite with multiple lamellar albite twins. Microcline is the alkali feldspar present. Feldspar is seen to be altered to illite and kaolinite. Provenance and primary depositional controls effectively account for significant differences in the distribution of feldspar grains. Secondary grain dissolution and partial to complete replacement by authigenic kaolinite, however, is locally responsible for the variation of albite feldspar content of these sediments to observed levels. Alteration of feldspar occurs along cleavage planes, resulting to secondary porosity. Thin section petrography supplemented with backscatter scanning electron microscopic (BEI) analyses shows that the feldspar content consists of albite, microcline, microperthite and myrmekite grains (Fig. 5).

Lithic Fragments: This suite of constituents comprises mainly of sedimentary lithologies, which rarely forms less than 1% of the detrital component. Mudstone intraclasts form constitute the most common lithic fragments, occurring as dense grains. Other fragments of sedimentary origin are restricted to rare siltstone grains.

Micas: Detrital micas form a minor and variable component in these samples; their distribution being controlled by primary factors. Micas are found, not more than 1% in the samples associated with low energy sedimentary environments, particularly interdistributary bay, distal mouth bar, offshore facies. Muscovite and biotite are the commonest forms, detrital chlorite occurs rarely.

Heavy Minerals and Detrital Opaques: These grains rarely comprise more than 1% of the detrital component. Generally only stable heavy minerals were recorded in the thin-section, dominated by sub-angular (occasionally euhedral) of zircon (Fig.6A), garnet and andalusite, apatite, zircon (zoned and fractured), tourmaline, rutile, sphene, monazite, and spinel with inclusions. Opaque grains consist of pyrite and iron minerals. Detrital heavy mineral grains easily identified from their extremely bright SEM backscatter electron images, with X-ray spectra fingerprinting used to confirm elemental compositions: zircon-yielding Zr and Si; rutile-Ti only and chromite – Cr, and Fe.

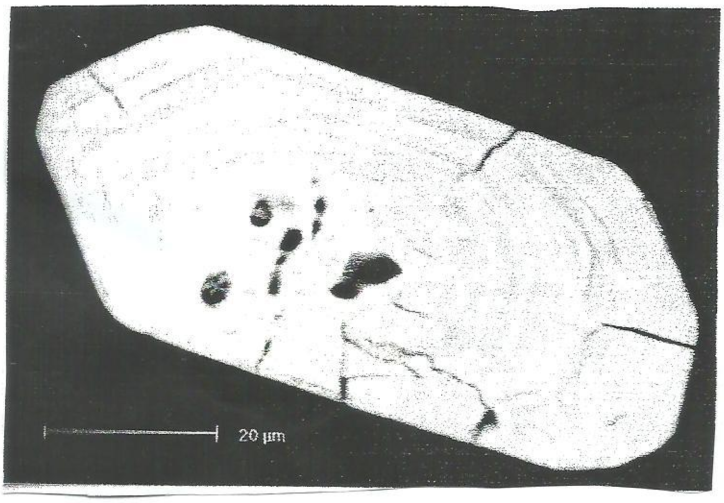


Fig. 6A. BSEM Photomicrograph of polished thin-section of zoned euhedra Zircon crystal from Awi Sandstone

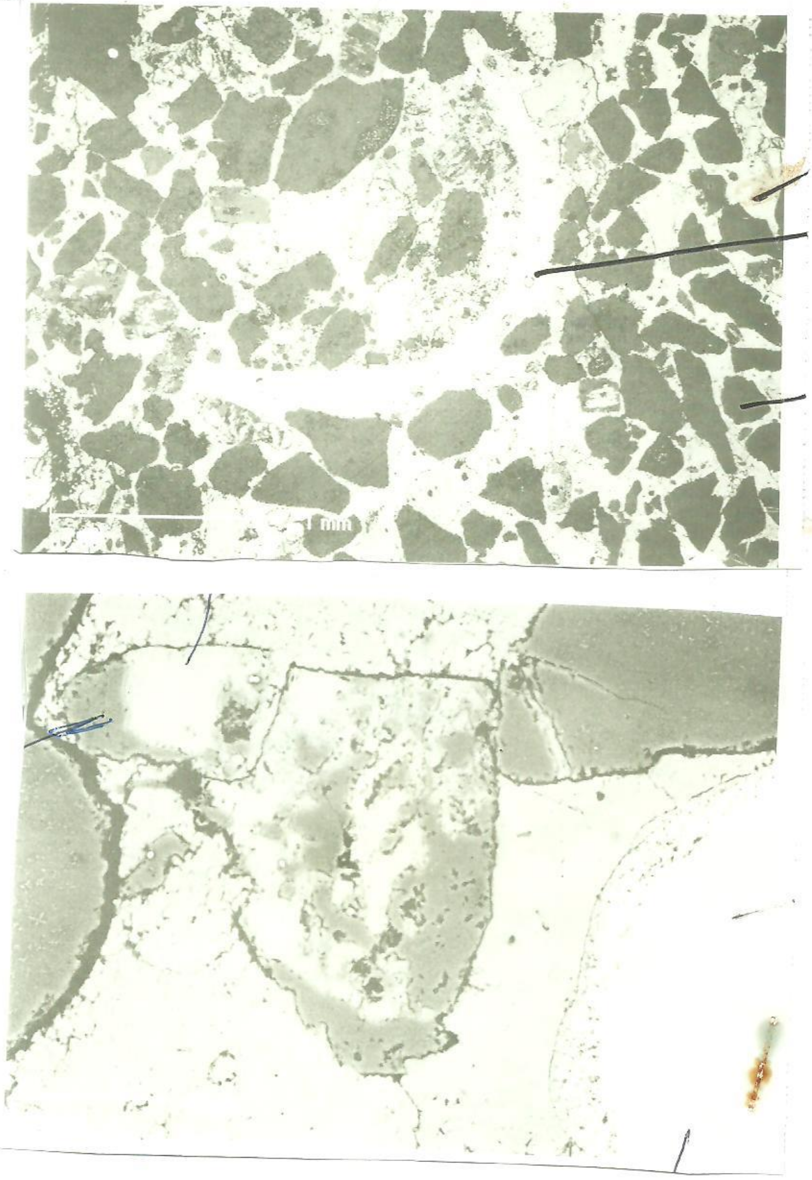


Fig. 6B. BSEM Photomicrograph of polished thin-section of Brachiopod shell and Fish tooth.

Allochems: The siliclastic carbonate rocks have been classified according to Folk (1959 and 1962) and Dunham (1962). The packstone and grainstone allochems consists of ooids, peloids and bioclastics grains, with intraclasts. The occurrence of bioclasts is restricted to calcareous sandstones; which can be divided into non-sketal and skeletal grains. They include micritised plant remains, fragmented molluscs, brachiopods, echinods, fish tooth and foraminifera (Fig. 6B). The non-skeletal grains are ooids and peloids that are spherical-ellipsoidal in shape and have been micritised; the micrite envelope defines a bivalve shell that has dissolved away. Formerly aragonite molluscs shell is replaced and preserved as calcite spar crystals. Example of well preserved shell does occur in the packstones/grainstones of the Early and Late Albian sandstones. The calcite spar forms uniform coarse grain size and it is generally inclusion free while the oolitic and peloidal grainstones tend to form a fine-grained drusty mosaic.

Glauconite: Glauconitic, occurring as well as rounded, pelleted grains is recorded in a small number of samples from delta progradational and nearshore.

Detrital clays: Detrital clays are significantly small in amount in the sandstones. Detrital clays occur in some of the sandstones sample. Their compositions are typically mixed, being mainly of kaolinite, chlorite, smectite and illite (based on secondary electron SEM analysis and associated EDS X-ray spectra fingerprinting) and they occasionally form a primary porosity occluding the matrix, but mainly manifests itself as partial tangential grain coatings on other detrital framework grains (mainly quartz and feldspar). Abundance of detrital clays from authigenic clay mineral phases by optical petrographic thin-section analysis for modal point count data was difficult, and certainly involved considerable judgement show typical detrital clay coatings on detrital framework grains.

SUMMARY OF PETROGRAPHIC CHARACTERISTICS OF FACIES TYPES IN THE ASU RIVER GROUP

Facies Type A (Aptian-Neocomian) basal conglomeratic sandstone include typical fluvial deposits; however, such deposits have been observed to be heavily weathered lying unconformable on the basement complex at Agoi Ibami and Okurike. Macroscopic examination of the samples reveals the presence of angular quartz, partially altered feldspar, tourmaline fragments and patches of kaolinite.

Optical petrographic analysis shows that samples from Agoi Ibami are non calcareous sandstones whereas calcareous sandstones were encountered at Okurike. Textually, most of the sandstones are immatured. In the majority of the sandstones, the grains are angular to subangular and are poorly sorted, with grain-supported fabric. In the calcareous sandstones, calcite cement forms a floating grain texture. Mineralogically, the sandstones are arkosic to subarkosic in composition. The most volumetrically significant authigenic minerals in these sandstones are calcite, siderite, apatite, pyrite, illite and kaolinite. Pore-filling types of illite are observed.

Facies Type B at Okurike, are interpreted as estuarine channel deposits which show fining-upward trends with coarse grained texture. SEM analysis shows the following detrital minerals: quartz, microcline, albite, illite, kaolinite, brachiopod shell and zircon; authigenic minerals include calcite and pyrite. The mineralogical composition of the sands is similar to the sandstones of facies A.

Facies Type C, exhibit coarsening upward sequence trend from lower to upper shoreface deposit that are calcareous. Facies C belongs to the upper shoreface. Detrital and authigenic minerals of this facies identified by SEM analysis are as follows: albite, anorthite, microcline and zoned zircon; stressed calcite and aggregation of calcite forming matrix. Texturally, the sandstones are immatured and compositional matured. Grain size varies from coarse to medium grained sand, moderately sorted, loosely packed and matrix supported fabric.

Facies Type D, this is the lower part of the coarsening- upward sequence of the shoreface deposits; which is calcareous. The following detrital authigenic minerals were identified: skeletal grains, microcline coated with kaolinite, illite, smectite and calcite, albite, quartz, pyrite and calcite forming cement. Texturally, the grains are angular to subangular and the grain size varies from medium to fine sand forming a moderately sorted, matrix supported fabric similar to that in facies C. Mineralogically, the sands are similar to those in facies C.

AUTHIGENIC MINERALS

Quartz cement – Authigenic quartz and feldspar overgrowth cements are believed to have developed contemporaneously and as such are considered synchronous within the paragenesis of these sandstones. Evidence for this is based on textural relationship between these two overgrowth cement phases. Quartz (SiO_2) overgrowth cements within Asu River Group sandstones are typically syntaxial, subhedral to euhedral in form and exhibit both compromise and free growth boundaries (Fig.7). They are best developed in the Early Albian Awi Formation than in the Middle to Late Albian Awe Formation. Increased abundance of quartz overgrowth cements is commonly associated with the coarse grained sandstone unit (which tend to have a higher abundance of detrital quartz grains). Where detrital quartz grains are loosely packed, carbonate cement and authigenic clays may occlude intergranular porosity. Quartz cement normally requires a nucleus to precipitate. Secondary quartz in sandstones forms syntaxial overgrowths on detrital grains where they are free of clay coats; complete coats will prevent nucleation of quartz (Bashari,1998). The presence of detrital clay coats may be responsible to the inhibition of quartz cements.

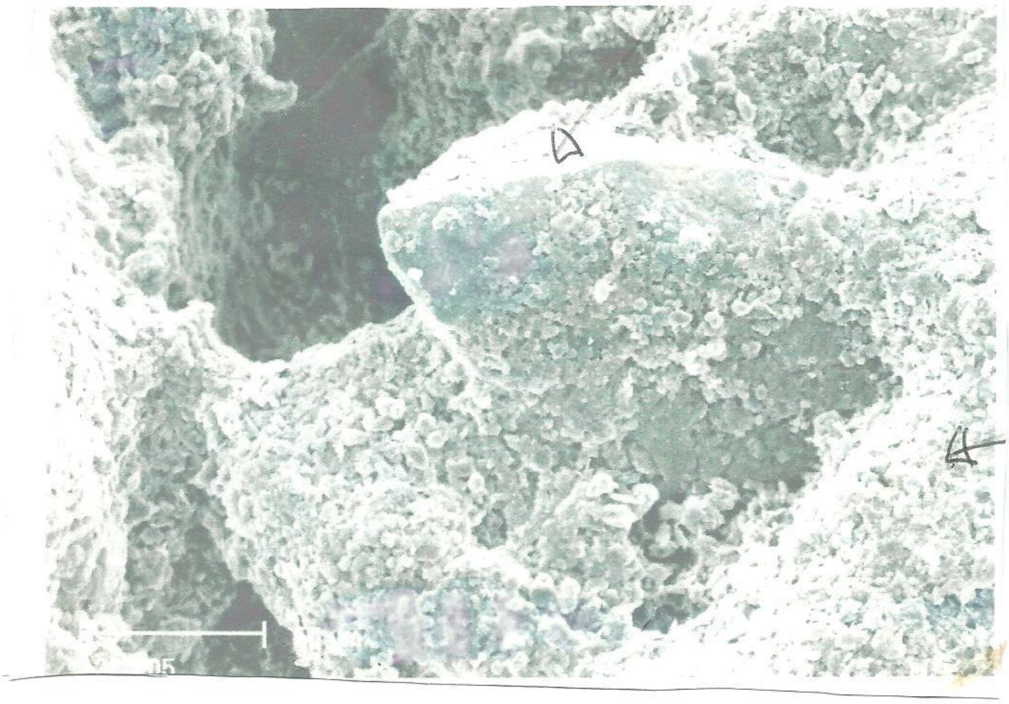


Fig. 7. SEM of Awe Sandstone showing syntaxial quartz overgrowth.

Carbonate cements are present in the Asu River Group, and occur in volumetric proportions of up to 3%. Calcite is the principle type of carbonate cement. Calcite is commonly present as a fine, medium – to coarse-grained, poikilotopic pore filling cement (Fig. 8). Calcite cements in the Asu River Group have been produced by the replacement of albite which is different from the calcite of the matrix. It is the more common of the authigenic carbonate minerals and is present in the Middle to Late Albian calcareous sandstones. Drusty calcite spar is another type of cement that occurs in both the Early Albian and Middle to Late Albian calcareous sandstones show types of carbonate cements.

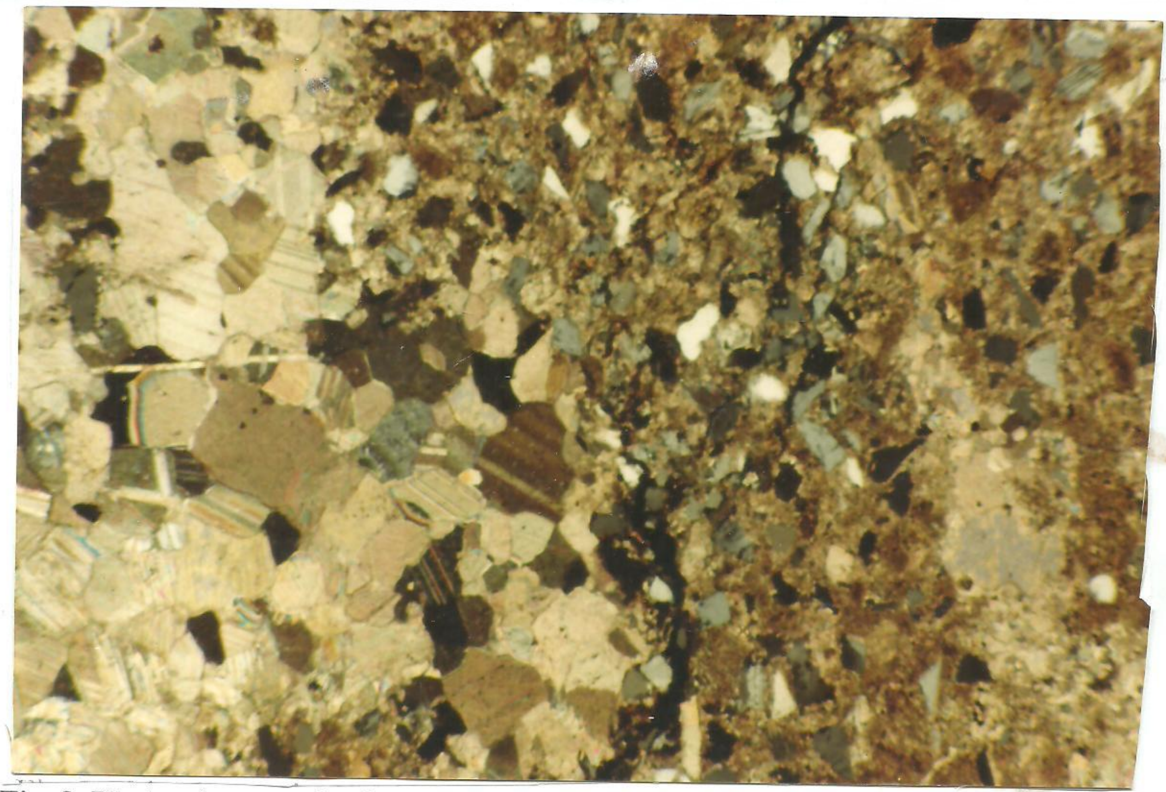


Fig. 8 Photomicrograph of polished thin-section of arkose sandstone from Asu River Group, showing poikilotopic calcite LHS and microsparry and sparry calcite RHS.

Staining of rock samples revealed that the dominant cement is the ferroan calcite (blue-purple) throughout Asu River Group. The type of cement is dependent of sedimentogical characteristics of the formations sampled. For example, the calcite-cemented formations can be sub-divided into four 'micro-type' dependent upon their sedimentological context:

i) Generally intensively bioturbated; moderately sorted with microsparry to mosaic pore filling calcite.
ii) Formations containing shell fragments; high content of bioclastic fragments (>30%) with mosaic to blocky calcite.
iii) Formations with no apparent association to particular facies; subarkosic to arkosic with calcite cement replacing feldspar.
iv) Carbonate formed during late stage of cementation following significant burial; forming blocky to poikilotopic ferroan calcite.

Absence of feldspar growth is observed in the four carbonate formations. Although overgrowths on feldspar can occur at any time during diagenetic history of the sediment, the absence of it in the samples analysed indicate that the diagenetic alteration of the clastic grains in the Asu River Group has been minimal prior to cementation. Thus, cementation must have occurred very early in the diagenetic history.

Siderite
Siderite is present in the Late Albian calcareous sandstones in proportions up to 1% of the whole rock volume, and typically occurs in the fine to siltstone facies. It was identified by its rhombohedral habit. Together with abundant iron, the siderite typically contains minor magnesium.

Pyrite
Pyrite (Fe_2S) is believed to be a late phase coarsely crystalline authigenic mineral to develop in the Early Albian calcareous sandstones containing brachiopod shell. Pyrite also occurs in the Late Albian calcareous sandstones as framboidal aggregates, spherical grains, and partial replacement of organic materials associated with siltstone and mudstone laminae, and irregularly shaped grains that replace silicates of all types. It is the first authigenic mineral phase to develop in the formation. Pyrite is present as trace amounts. The occurrence of pyrite throughout the calcareous sandstones of the Asu River Group indicates shallow marine reducing environment.

Compaction

Mechanical and chemical compaction is evident in the calcareous sandstones of the Late Albian suggesting the Cenomanian deformation. They occur as preferred orientation of early formed carbonate and broken zircon grains or completely or partially dissolved feldspars.

DISCUSSION

"Early" Diagenesis

Early diagenetic reactions occurring in coarse-grained clastic or mixes-elastic sediments are frequently characterized by a complex association of solution generating processes which are controlled by a wide range of potential variables (Burley et al; 1985 and Crowley, 1988).

The effects of specific variables (notably primary mineralogy and hydrological factors) are likely to accentuate in equatorial, paralic environments due to the frequent changes in depositional conditions over small lateral and vertical distances. The juxtaposition of siliclastics and mixed-siliclastics with fine-grained, organic-rich sediments, and the potential for repeated changes in the pore fluid chemistry of rechargeable aquifers, suggest that reaction should result to varied diagenetic mineralogy. The following diagenetic products were identified:

(a) **Detrital clays**: The earliest diagenetic product recognised in the formations are the occurrence of immediate post-depositional clays; which occur as tangential grain coatings.

(b) **Alteration of Detrital Micas:** Diagenetically modified sheet silicate grains are a common feature in the Asu River Group samples studied. Micas are responsible for significant porosity reduction, both compactional grain deformation and the precipitation of pore occluding authigenic phases with the release of a wide range of cations (notabale K, Na, Mg, Fe, Ti, Al, Si) during mica decomposition. Authigenic pyrite, siderite, illite, chlorite, kaolinite and tiatanium oxide phases are recorded as diagenetic products which can be related to the alteration of mica.

Feldspar diagenesis

The purpose of this section is to document the results of the study into the diagenetic modification of detrital feldspar component of the calcareous sandstones. Petrographic analysis permits the following feldspar or feldspar-related diagenetic fabrics to be recognized.

a) Fresh, unaltered plagioclase grains showing well defined albite twinning.
b) Fresh, unaltered microcline and untwined orthoclase.
c) Untwined albite grains consisting of sub-parallel, inclusion-rich and inclusion free feldspar lamellae, compared to the fabric described by Middleton (1972).
d) Untwinned albite grains growing blocky to tabular patterns of alternating turbid, inclusion-rich, and clear, inclusion-free feldspar, similar to textures reported by Gold (1987).
e) Untwinned and, less commonly, albite twinned feldspar grains partially to completely enclosed by authigenic kaolinite.
f) Authigenic kaolinite cement which occludes oversized, grain dissolution porosity.

The observed range of diagenetic products outlined above can be logically be related to the decomposition of feldspars.

"Late" Diagenetic carbonate cements:- Deep burial carbonate cements (ferroan calcite, ankerite) occur as "late" pore occluding phases in many siliclastic and mixed-carbonate sequences (see Boles, 1978; Land and Dutton, 1978; Burley, 1984; Franks and Forester, 1984; Kantorowicz, 1985; Boles and Ramseyer, 1987; Land and Fisher, 1987). The frequent recognition of characteristically Fe-rich carbonates, which typically post-date quartz cementation and the generation of secondary porosity (e.g. see Table 1 of Franks and Forester, 1984), implies a recurrent relationship between the precipitation of "late" ferroan calcite and ankerite cements, and the evolution of pore fluid chemistry during burial diagenesis. Relatively little, however, is known about the potential sources of cement components, although such information is of particular importance to the understanding of mass transfer within sedimentary basins.

(a) Both ferroan calcite and ankerite occur as "late" (post-quartz cementation) diagenetic phases in the sediments. However, the precise timing of cement precipitation, based on available textural relationships, is difficult to resolve, due to the generally mutual exclusive distribution of individual carbonate cement phases.

Examination of samples containing “late” authigenic carbonates permits the identification of two cement types on the basis of petrographic characteristics:

a) poiklotopic calcite spar – Type 1
b) euhedral calcite spar- Type 2

Type 1 cement: This cement type is characterized by (100-1000µm), large euhedral, poikiotopic ferroan calcite spar, which replaces both detrital grains and pre-existing authigenic cement phases. The type 1 cement is found in both the Early to Late Albian sediments. The distribution of Type 1 cement is restricted to bioturbated, heterolithic, offshore marine siltstones associated with coarsening upward and estuarine channel deposits.

Textural relationships, revealed by thin-section petrography, show that Type 1 cements post-date quartz cementation. Complete porosity occlusion by calcite cementation precludes further refinement of cement stratigraphy, due to the absence of textual relationships with other “late” cement phases.

Type 2 cement – This category of “late” carbonate cement is characterized by (50- 200 µm),euhefral, ferroan calcite spar, which have drusty fabric, found in echinoid spine. It is associated with fin-grained to hetrolithic facies.

PARAGENETIC SEQUENCE

This brief section is intended, simply to outline the main features of the sandstone diagenesis for the Asu River Group.

Petrographic investigations indicate that diagenetic processes which have modified the Awi and Awe Formations respectively include micritization, cementation, dissolution, neomorphism and compaction. These processes are discussed below as are the relationship between porosity and diagenesis in the Asu River Group.

The digenetic evolution of the Asu River Group can be summarized by the following, general sequence:
a) Commenced with the micritization as a result of boring by micro-organism
b) Mechanical compaction resulting to fracturing of bioclast and micas.
c) Alteration of unstable detrital grains and precipitation of facies-controlled, redox-dependent pyrite, Fe-rich carbonates and clay minerals (chlorite, illite, kaolinite).
d) Fractures
e) Formation of quartz overgrowths
f) Precipitation of Fe-rich calcite (coarse blocky and poikilotopic calcite, drusty calcite).
g) Albitisation and kaolinitisation of detrital feldspar
h) Precipitation of Fe-rich carbonates (notably ankerite).

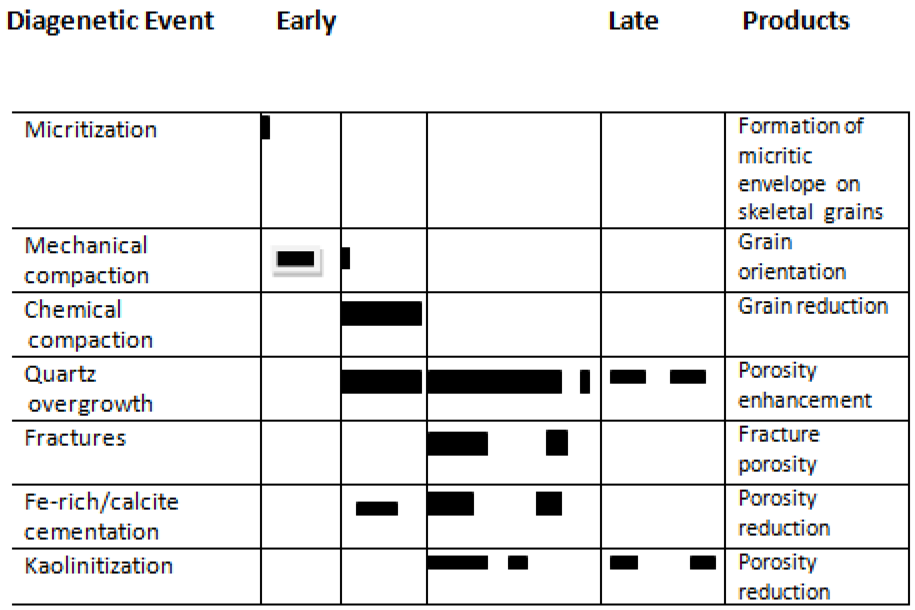
DIAGENESIS AND RESERVOIR PROPERTIES

Porosity in the Asu River Group is general either primary (intergranular and intragranular) or secondary, enhance by dissolution and fracturing (during tectonic movement) of the calcareous sandstones. It varies from zero to 6.5% (based on visual estimation) and includes both fabric – selective and non fabric-selective types. Fabric-selective porosity includes mouldic, intergranular and intragranular types.

Porosity is at a maximum in the nummultic packstone facies of the Awe Formation, decreases in the wackstone-packstone facies and is lowest in the grainstone facies of the Early Albian Awi Formation. Intensive subaerial dissolution within the nummultic facies during early diagenesis resulted in significant porosity development. Reduction in porosity is due to mainly due to cementation and compaction.

Reservoir quality in these sandstones reflects both detrital sediment texture and the calcite cement. For any given grain size, permeability is highest in the better sorted samples and lower where the original sediment was more poorly sorted. During diagenesis dissolution of skeletal grains gave rise to secondary porosity and through tectonic movements fractures are produced. It varies from zero in the Early Albian to 10% in the Late Albian (based on visual estimation) and it is mainly non-fabric selective pores spaces. Non-fabric selective type is mainly the fracture type. Primary porosity was lost during carbonate cementation.

Table 1: Diagenetic sequence in the Asu River Group



The matrix is between 2.5 – 0% and is composed of kaolinite, smectite and illite clays; and micrite (microcrystalline calcite). Most of the matrix fill the pore spaces and reduce the porosity which range from 10 – 0%.

Diagenetic sequence and Porosity Development

The diagenetic history can be divided into three stages: marine, near surface, and burial. Each of these is characterized by differing degrees of porosity formation and cementation.

Table 2: Diagenesis, porosity development and reservoir characteristics of the Asu River Group

Lithotypes	Diagenetic events	Porosity development	Reservoir characteristics	
Awl Fm	Basal conglomeratic Sandstone, poorly sorted, angular quartz With partially altered feldspar	Quartz overgrowths and kaolinite calcite cement associated with illite and kaolinte in Some sandstones	Generally poor Primary porosity	porosity 1.5% Qz Rf F 78 1 21
Awl Fm	Coarse-medium Grained calcareous sandstone, mod, sorted, with bioclast.	Calcite cement assoc with illite and kaolinite, pyrite Calcite replaces feldspar	zone of very poor porosity	porosity 0. 3% Qz Rf F 80 0 20
Awe Fm	Upper shoreface, moderately sorted loosely packed Coarse-medium grained	Physical compaction, stressed calcite blocky to poililotopic ferroan calcite	Poor to moderate porosity, porosity due to Fracturing	Porosity 6.5% Qz Rf F 90 - 10
Awe	Lower shorface, poorly sorted, With abundant Detrital clays. Forams Present. Fine grained	Late formed calcite k-feldspar rapped by Calcite, illite, smectite	Secondary porosity from dissolution of feldspar	Porosity 3% Qz Rf F 88 - 12

Qz: Quartz
RF: Rock fragment
F: Feldspar

Early marine diagenesis

This stage involved micritizataion and precipitation of early-marine rim cements. Micritization predominates in the Awe Formation and was caused by boring of micro-organisms. Primary porosity is largely unaffected by cementation. The cements of the Awi and Awe Formations were precipitated originally as high-magnesium calcite, indicating that the formations were affected by early marine diagenetic processes. The Awe Formation contains neomorphosed echinoid spines and micritized envelopes around bioclasts of planktonic forams. Micritized envelopes play an important role during early marine diagenesis by maintaining the shape of an aragonite bioclastic grains after its dissolution. Coarsening upward sequence in a lime mud/micrite and the replacement of aragonite by calcite are features of early marine diagenesis in the upper sections of the Asu River Group. The presence of phosphatic bioclasts in the Awi Formation suggests a high saline condition.

Near-Surface Diagenesis

This stage mainly involves carbonate dissolution. Dissolution is a common feature in the upper part of the Awe Formation and it is the main diagenetic process responsible for the creation of secondary porosity the wackstone-packstone and packstone-grainstone facies.

Burial Diagenesis

This was a porosity-occlusion phase with some fracture porosity development. Porosity general decreases with depth and both primary and secondary porosity were destroyed as a result of cementation and compaction. The Awi Formation suffered more over burden pressure than the Awe Formation; this is evident from the presence of broken bioclasts in the Awi Formation.

Difference in porosity within the facies is attributed to variations in the nature of the diagenetic fluids with depth. Dissolution in the Asu River Group probably reflects circulation of aggressive fluids which were under saturated with respect to calcite (presumably meteoric waters). An influx of meteoric waters can be linked to exposure of the Asu River Group Cenomanian uplift. Alteration may have taken place in the vadose zone or in the upper part of the actively circulating phreatic zone. Precipitation of non-ferroan calcite cement in the Awi Formation may be ascribed to this period.

CONCLUSION

The non-marine and marine sandstones of the Lower Cretaceous Asu River Group in the SE lower Benue Trough of Nigeria are divisible lithostratigraphically into Awi and Awe intervals separated by an interval of Abakaliki shale. Three lithostratigraphic intervals can be identified: the Awi Formation an arkosic basal conglomeratic unit at the base; Abakaliki Shale a sequence dominated by dark shales and sandstones in the middle; and Awe Formation a section dominated by calcareous arkosics at the top. Overlying the succession is an extensive intrabasinal conglomeratic unit, leached limestone bed and hardground surface of Mid-Cenomanian age.

Petrographically, the sandstones and calcareous sandstones can be divided into four facies: the basal conglomerate to coarse grained sandstones, medium-fine grained sandstones deposited in a fluvial non-marine environment; calcareous siltstones and calcareous subarkosic sandstones. The calcareous sandstones are bioclastic grainstones and packstones respectively deposited in an estuarine to shallow shelf marine environment.

Petrographic investigations indicate that diagenetic processes which have modified the Awi and Awe Formations respectively include micritization, cementation, dissolution, neomorphism and compaction. The calcareous sandstones have undergone diagenetic alteration under low temperatures and pressures. Alteration started with pore-space reduction by compaction and was followed by pore-filling cement. Dissolution at the surface, however, has caused secondary porosity. The sandstones have a lower porosity due to a higher degree of cementation. The higher porosity in the calcareous sandstones is due to dissolution of feldspars; and are better sorted and more loosely packed.

Decrease in clay content is recorded in the calcareous sandstones. Difference in clay mineralogy can be explained by the difference in permeability and fluid flux, with high permeability occurring in the calcareous intervals with secondary porosity. Porosity is best developed where there is alteration of feldspar, early silicification that has enhanced grain support and which has minimised the effects of late compaction.

The diagenetic history can be divided into three stages: marine, near surface, and burial. Each of these is characterized by differing degrees of porosity formation and cementation. Porosity in the Asu River Group is general either primary (intergranular and intragranular) or secondary, enhance by dissolution and fracturing (during tectonic movement) of the calcareous sandstones. It varies from zero to 6.5% (based on visual estimation) and includes both fabric – selective and non fabric-selective types. Fabric-selective porosity includes mouldic, intergranular and intragranular types.

Porosity is at a maximum in the nummultic packstone facies of the Awe formation, decreases in the wackstone-packstone facies and is lowest in the grainstone facies of the Early Albian Formation. Intensive subaerial dissolution within the nummultic facies during early diagenesis resulted in significant porosity development. Reduction in porosity is due to mainly due to cementation and compaction.

Difference in porosity within the facies is attributed to variations in the nature of the diagenetic fluids with depth. Dissolution in the Asu River Group probably reflects circulation of aggressive fluids which were under saturated with respect to calcite (presumably meteoric waters). An influx of meteoric waters can be linked to exposure of the Asu River Group Cenomanian uplift. Reservoir quality in this sandstone reflects both detrital sediment texture and the calcite cement. The outcrop reservoir quality studies can be used as a model in the predicting of the extent of diagenesis and reservoir quality in the subsurface Niger Delta.

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REFERENCES

[1] Ayoola, E.O.(**1978**) Sedimentology of the Middle Benue Trough, Nigeria. Unpublished Ph.D Thesis, University of London, 200pp.
[2] Boles, J.R and Franks, S.G (**1979***) J.Sed.Petrol*; 49, p55-70
[3] Carter, J.D; Barber, W. And Tait, E.A.(**1963**) The geology of the Adamawa, Bauchi and Bornu provinces in Northern Nigeria. Bull. Geol. Surv. Nigeria.No.30.
[4] Cratchley, C.R and Jones, G.P. (**1965**) An interpretation of gravity anomalies of the Benue Trough. Overseas Geol. Surv; No.1, pp1-26.
[5] Crowley, S.E (**1988**) Aspects of diagenesis of the Great Limestone cyclothem. Unpublished Ph.D Thesis, Uni.Liverpool, UK, p201.
[6] Bashari, A. (**1998**) Diagenesis and reservoir development of sandstones of in the Triassic Rewan Group, Bewen Basin, Australia, v.21(4). pp445-467
[7] Burley, S.D; Kantorowicz, J and Waugh, B (**1985**) Clastic diagenesis. (eds. P.J Brenchhley and B.P.J Williams) In: Sedimentology: Recent Development and Applied Aspects. Geol. Soc.London. Spec. Publ.18,p189-228.
[8] Bjorlykke, K. and Egeberg, P.K.(**1993**). *AAPG Bull,*77,pp1536-1548.
[9] Bjorlykke, K; Aagaard, P; Dypvik, H; Hastings, D.S. and Harper, A.S (**1986**) Diagenesis and reservoir properties of Jurassic sandstones from the Haltenbanken area, offshore mid Norway. In; Spencer,A.M. et al (eds) Habitat of Hydrocarbons on the Norwegian Continetal Shef, p275-286. Graham and Trotman, London.
[10] Bjorlykke, K (**1988**) Sandstone diagenesis in relation to preservation, destruction and creation of porosity. In: Diagenesis (eds G.V.Chillingar & K.H. Wolf) Elsevier, Amsterdam,pp 555-587.
[11] Bjorlykke, K (**1989**) Sedimentology and Petroleum Geology. Springer-Verlag, Berlin, 370p.
[12] Boles,J.R. (**1978**) *Mineral Petrol.* 63.pp13-22.
[13] Boles, J.R. and Ramseyer, K. (**1987**) *AAPG Bull*. 71, pp1475-1487.
[14] Burley, S.D.(**1984**) Patterns of diagenesis in the Sherwood Sandstone Group (Triassic) United Kingdom. Clay Minerals, 19,pp403-440.
[15] Dunham, J.B (**1962**) *AAPG Mem*, 1,p108-121.
[16] Folk, R.F (**1959**) *AAPG Bull*, 43,pp1-38.
[17] Folk, R.F. (**1962**) Spectral subdivision of limestone types. In: Ham W.E. (ed) Classification of Carbonate rocks. AAPG Memoir, 1,pp62-84.
[18] Folk, R.F (**1980**) Petrology of Sedimentary Rocks. 2ND Edition.pp1`90 Hemphill, Texas.
[19] Franks, S.G and Forester, R.W (**1984**). Relationships among secondary porosity, pore-fluid chemistry and carbon dioxide. AAPG Memoir 37,pp63-79.
[20] Galloway, W.E (**1979**) Diagenesis control of reservoir quality in arc-derived sandstones: implications for Petroleum exploration. In: Aspects of Diagenesis Society of Economic Paleontologists and Mineralogists Special Publ. 26 (eds. P.A. Scholle and P.R. Schluger) Tulsa, OK, pp251-262.
[21] Gold, P.D (**1987**) *J.Sedim. Petrol*. 57,p353-362.
[22] Hayes, J.B. (**1979**) Sandstone diagenesis-whole truth. In Aspects of diagenesis (ds.P.A. Scholle and P.R. Schluger) SEPM Special Publication 26,pp 127-140.
[23] Hoque, M (**1977**) Petrographic differentiation of tectonically controlled Cretaceous sedimentary cycles, southeastern Nigeria. Sed. Geol., v.17,pp235-245.
[24] Kantorowicz, J.D.(**1985**) *Sedimentology,* 32, pp833-853
[25] Land, L.S. and Dutton, S.P.(**1978***) J.Sedim. Petrol*.48,pp1167-1176.
[26] Land, L.S and Fisher, R.S. (**1987**) *Geol. Soc.London. Spec. Publ*.36, pp219-236.
[27] Middleton, G.V. (**1972**). *Sedim.Petrol*. 42, pp341-349.

[28] Mathisen, M.E (**1984**) Diagenesis of Plio-Pleeistocene Nonmarine sandstones, Cagayan Basin, Phillippines. Early Development of secondary porosity in Volcanic sanstones. In (eds. McDonald, D.A. & Surdam, R.C) Clastic diagenesis. AAPG Memoir 37, pp.177-193.
[29] Odigi,M.I (**2007**) Facies and Sequence Stratigraphy of Cretaceous formations, Southeastern Benue Trough, Nigeria. Ph.D Thesis. Uni. Port Harcourt. 300pp.
[30] Odigi, M.I and Amajor, L.C (**2009**) Brittle deformation of the Afikpo Basin, SE
[31] Nigeria: *Chinese J. Geochm*. V.28, no.4,pp.369-376.
[32] Ofoegbu, C.O (**1984**) *Geologischen Rundschau*, 73, p1007-1017.
[33] Offodile, M.E.(**1976**) The geology of the Middle Benue Trough, Nigeria. Palaeont. Inst.Univ.Uppsala, Sp. Publ.no4.166p.
[34] Popoff, M (**1988**) Evolution des basins et des environment sedimentaires cretaces du fosse de la benoue (Nigeria) BCRDP, v.11, pp 174-177.
[35] Petters , S.W. and Ekweozor, C.M.(**1982a**) *AAPG. Bull*; v.66, pp.1141-1149.
[36] Reed, J.K; Gipson, M and Neese, D.G (**1993**). *J.Petrol. Geol*; 16 (1) pp89-108.
[37] Stenecipher, S.A. and May, J.A.(**1990**) *AAPG Memoir* 49, pp25-44.
[38] Tang, Z; Parnell, J. And Longstaffe, F.J.(**1997**). *AAPG Bull*; 81, pp 1843-1865.