Journal of Geology and Mining Research Vol. 3(10), pp. 265-280, October 2011
Available online at http://www.academicjournals.org/JGMR
ISSN 2006 – 9766 ©2011 Academic Journals

Full Length Research Paper

Diagenesis and reservoir quality of cretaceous sandstones of Nkporo formation (Campanian) southeastern Benue trough, Nigeria

Minapuye I. Odigi

Department of Geology, University of Port Harcourt, Port Harcourt, Nigeria. E-mail: isaacodigi@yahoo.com.

Accepted 11 January, 2011

The Afikpo Basin of southeastern Benue trough represents an elongate NE-SW oriented depocenter located north-west of the Oban Massif. During Campanian-Maastrichtain times, two parallel facies belts of basal sandstones of the Nkporo formation were developed in a wide range of alluvial fan complex, tidal channel and deltaic environments. Detailed petrological study of the unit by thin section, scanning electron microscopy and isotopic analysis reveals that early diagenetic effects include the precipitation of siderite, and illite-smectite rims. Deep burial effects include physico-chemical compaction and the formation of quartz overgrowths, siderite, illite/illite-smectite and ankerite. Involved fluids were in part connate meteoric water derived from compaction of the underlying freshwater beds. Important post burial effects, controlled by deep meteoric influx from the surface, were ankerite and labile grain dissolution and formation of kaolinite, calcite and dawsonite, the formation of dawsonite reflecting eventual stagnation of the aquifer. Precipitation of authigenic quartz overgrowth and crystallization of cementing material are some of the diagenetic changes responsible for porosity reduction. On the other hand, dissolution and replacement of framework minerals enhance the porosity as well as permeability. Reservoir quality varies from marginal to intermediate in the west to poor in the east, with predictable trends being directly linked to depositional environment and diagenesis.

Key words: Benue trough, Nkporo formation, fan delta complex, fan delta fan, cretaceous, clay minerals, reservoir quality, diagenetic history and alteration.

INTRODUCTION

Over the past decade, the study of sandstone diagenesis attracted renewed interest. These have demonstrated that factors influencing diagenetic changes in sandstones include original composition, burial depth, temperature, and pore-water chemistry (Carrigy and Mellon, 1964; Blatt, 1979; Hayes, 1979; Vavra, 1983). Sandstone diagenesis proceeds through several systematic steps starting with pore space reduction by compaction, followed by compaction, alteration rim cementation, followed by pore –fill cementation, and alteration, and transformation of mineral phases in more deeply buried sandstones (Wilson and Pittman, 1977). It is for this reason that porosity and permeability decrease downward in sedimentary sequences. Selective dissolution at depth may cause development of secondary porosity within sandstones (Schmidt and McDonald, 1979). Sedimentary facies and porewater composition influence the growth-form and the distribution of authigenic clays (Bjorlykke et al., 1979). Diagenesis and reservoir quality of Oligocene sandstones in the North Belridge Field California have been documented by Taylor and Soule (1993) and Susanne et al. (2008).

The Benue trough is an intra-continental rift basin characterized by tectonic and magmatic activities during Cretaceous times.

The Benue trough can be subdivided into Lower, Middle and Upper parts (Figure 1) that were affected by Santonian tectonic activity. Regional Santonian compression deformed the “Benue Trough proper”

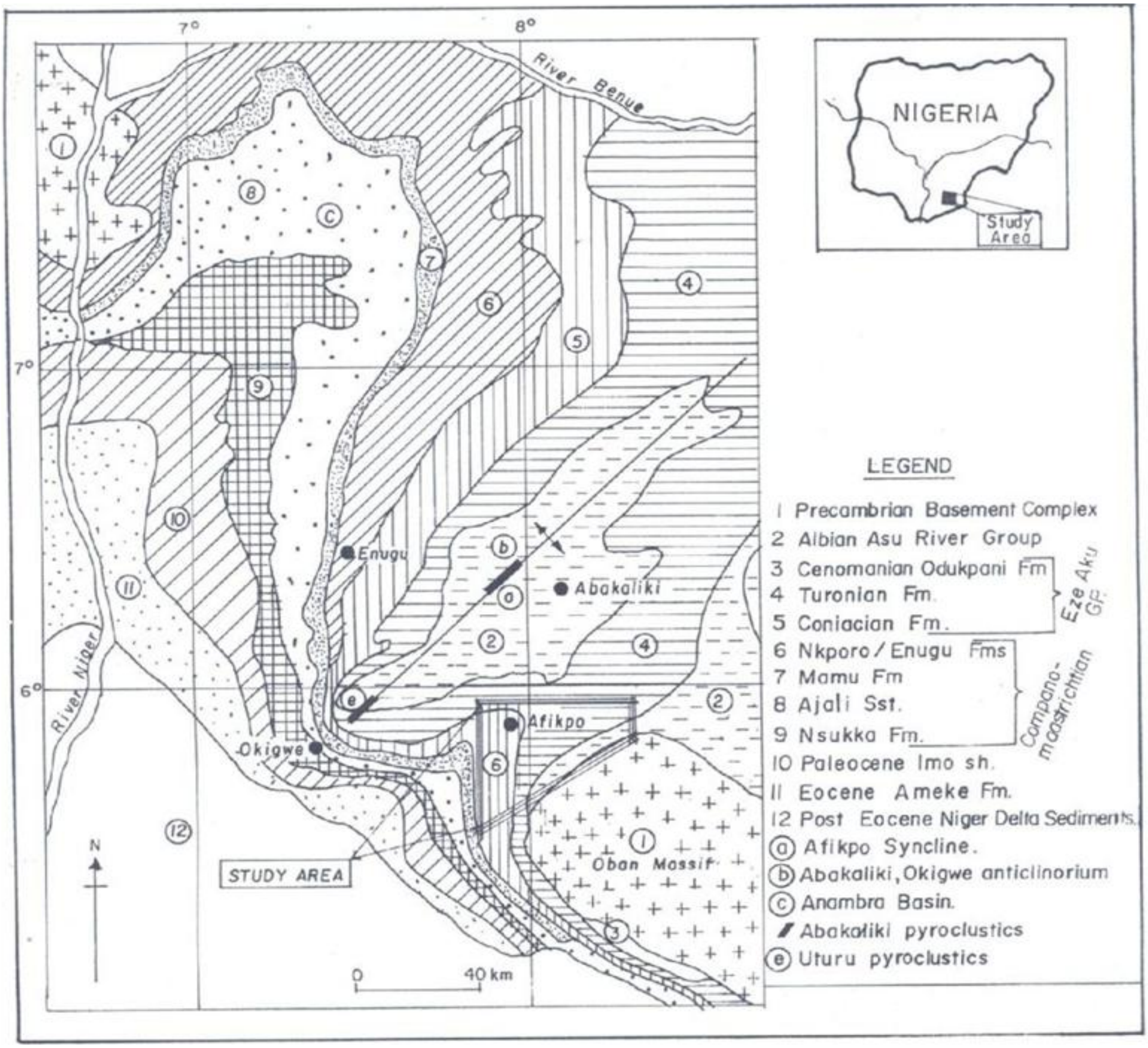

Figure 1. Geological map of Southern Benue trough showing the study area.

inverting the main depocenter of the Abakaliki Trough and subsequently creating the Anambra and Afikpo Basins to the north-west and south-east respectively (Murat, 1972; Benkhelil and Guiraud, 1980; Benkhelil, 2001). The Santonian tectonics differentiated the sedimentary successions into pre- and post Santonian packages. The post Santonian successions are Campanian-Maastrichtian in age (Reyment, 1965); they occur both in the Anamabra and Afikpo basins respectively. In the Afikpo basin, the Campanian-Maastrichtian succession comprises the Nkporo, Mamu, Ajali and Nuskka Formations. The Nkporo Formation rests on the post Santonian unconformity plane and consists basically of sandstones, shales and coal which accumulated during the Early Campanian.

The Nkporo formation of the Afikpo basin is considered to be relatively a good source rock (Odigi, 2007), and has been rated an oil and gas prone basin that is worthy of attention. Oil seeps have been reported in the post-Santonian sediments northwest of Usumtong

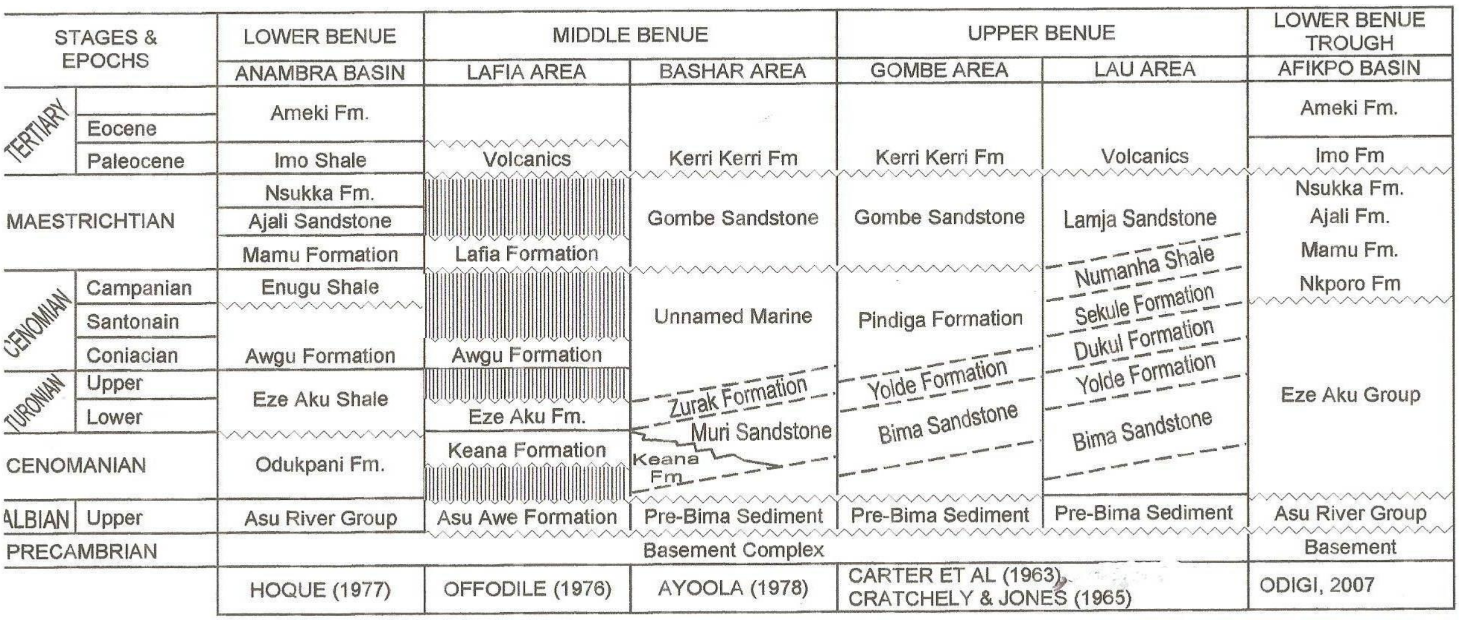

Figure 2. Stratigraphic successions in the Benue trough of Nigeria.

and Ozziza-Amate. The seeps occur in the basal unit of the post-Santonian sandstones which rest on the unconformity plane of the folded Eze-Aku Group.

Very little is known about the diagenesis of the post Santonian sandstones in this tectonic domain where rifting, deformation and high heat flow from magmatic activity should play an important role in diagenesis. Some of the studies on the sandstones in the Benue Trough were focused on framework components studies (Amajor, 1987, 1989; Hoque, 1976, 1977; Odigi and Amajor, 2008a).

The purpose of this paper is to discuss the diagenesis of the sandstone units of the Nkporo formation in relation to sedimentary facies and the influence of growth-form and the distribution of authigenic clays; and existing link between diagenesis and reservoir quality, which enable the characterization of the sandstones.

GEOLOGICAL SETTING AND STRATIGRAPHY

The Benue trough is a linear NE-SW trending intra-continental basin. Structurally it consists of a series of N-E trending transform fault system, anticlines and synclines. In the Afikpo basin, transform faulting was reactivated during late Maastrichtian terminal tectonic event (Odigi and Amajor, 2009c). The basin was modified by sinistral strike-slip activity.

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. The detailed stratigraphic succession is presented in Figure 2. The Nkporo formation in the Afikpo syncline area thins towards the NW and SE at the trough margins of the basin. The Mamu formation lies conformably upon the Nkporo Formation. The Nkporo Formation is the basal formation of the Campanian-Maastrichtian sediments, and is relatively undisturbed but intruded by igneous rocks. High geothermal gradients prevail in this area close to the intrusives. Simple synsedimentary growth faults and tectonic structures such as folds and slike-slip faults are present in the Afikpo subbasin (Odigi, 2007).

DEPOSITIONAL FRAMEWORK

The post-Santonian Nkporo formation Campano-Maastrichtian sequence is subdivided into four lithofacies associations: alluvial fan complex, estuarine, tidal channel and fan delta front can be identified which together suggest the depositional setting of the Nkporo formation. In plan view the fan delta front, estuarine and tidal channel facies occur in the eastern while the alluvial fan complex deposits predominate in the western sector (Figure 3). The Nkporo formation forms a belt that roughly parallels the trend of the Benue Trough. The Campano-Maastrichtian facies are flanked in the north and south by older strata belonging to the pre-Santonian Abakaliki trough. Stratigraphically, the alluvial fan

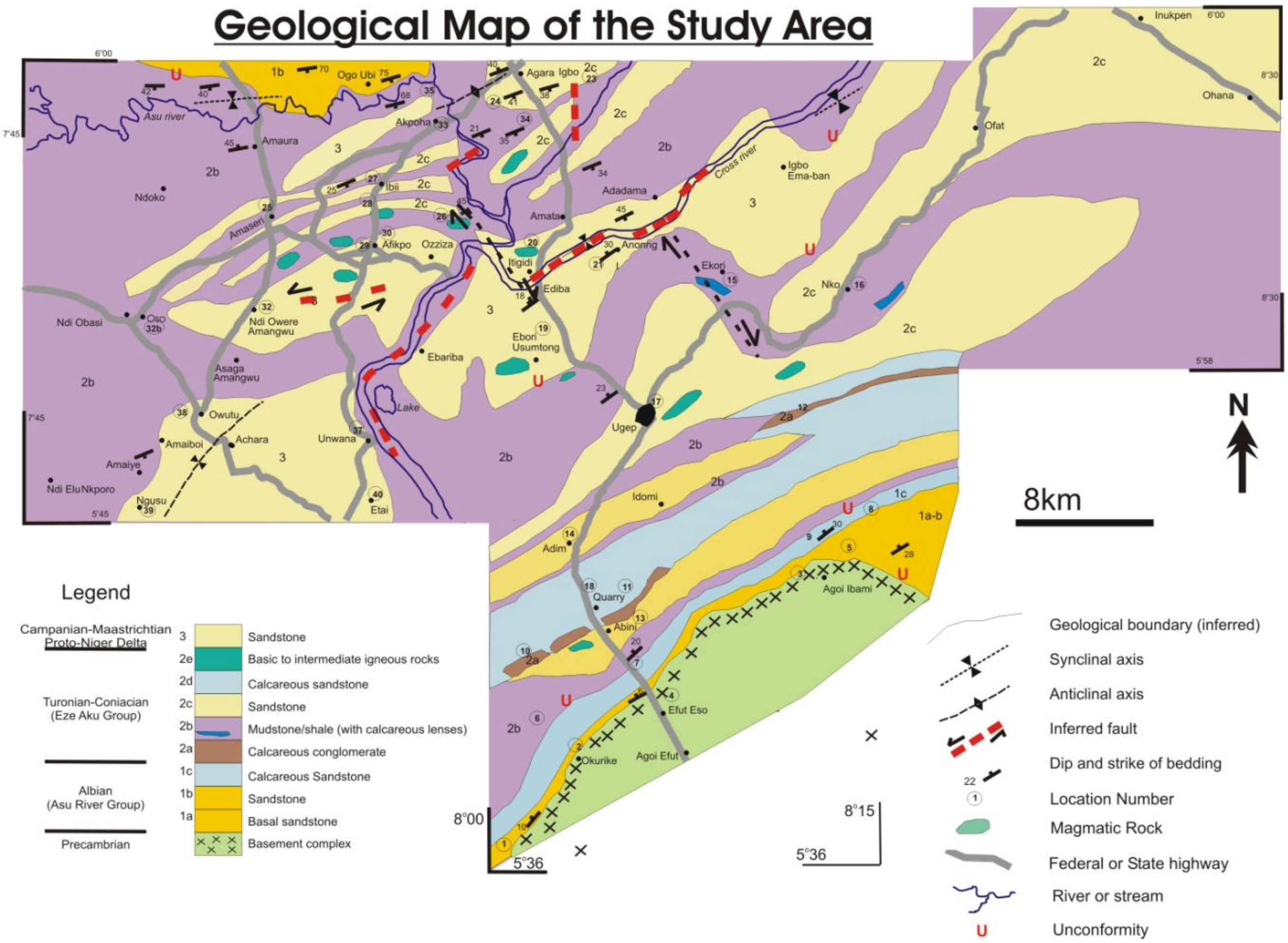

Figure 3. Geological map of the study area.

deposits tend to be transitional to the estuarine, tidal channel sediments and the fluvial –dominated fan delta complex. In the Afikpo, Akpoha and central parts of the Afikpo basin where Campano-Maastrichtian sequence occurs, the fan delta front facies, and alluvial and fluvial depositional systems are volumetrically more important. The tidal channel facies are more prominent in the eastern part of the basin. In vertical successions, the alluvial fan and tidal channel sandstones form the base and overlain by mouthbar deposits showing a coarsening upward profile which records the progradation of the delta. The basal unit of the Nkporo formation is referred to as Afikpo Sandstone (Reyment, 1965); deposited by high energy currents associated with an increase in transgressive activity. From the top of the non-marine to transgressive deposits, low energy, frequently offshore, fine micaceous sediments coarsen upwards into nearshore, medium to coarse, clean sands occur which represents coastal progradation over a shallow shelf.

BURIAL HISTORY

Reconstruction of the burial history of the Nkporo Formation was carried out using stratigraphic data. The Afikpo basin has experienced two major cycles of subsidence and uplift. The first subsidence episode during the early Campanian resulted to the burial of the sandstones of the Nkporo formation. Compression induced –positive inversion of the basin fill terminated this episode and by late Maastrichtian had led to exposure of the unit over the present day Campanian-Maastrichtian outcrop area. Elsewhere in the Anambra basin west of the Afikpo basin it remained deeply buried. Renewed subsidence during the early Maastrichtian heralded commencement of the second burial episode during which more of the sediments of the Afikpo basin accumulated. Terminal Cretaceous uplift, the second major uplift episode, had led to the removal of most Campanian-Maastrichtian section in the southern Benue Trough. The Campanian-Maastrichtian sediments including the Afikpo Sandstone, have been exhumed over the central part of the basin.

METHODOLOGY

Twenty eight sandstone samples were collected from three lithofacies units-alluvial fan, tidal channel and fan delta front of the Nkporo Formation in several outcrop locations. Thin sections were prepared for all sandstones using blue impregnation resin to highlight porosity. Slides containing Ca, Fe and Mg carbonates were stained with alizarin red-S and potassium ferricyanide, and a number were stained with sodium cobaltinitrite to aid K-feldspar identification. Modal analyses were performed on most sandstone by counting 500 points per slide.

Orientated clay fraction X-ray diffraction (XRD) analyses were routinely carried out on each sample to enable precise identification of the clay minerals present. Superimposed traces for air-dried, glycolated (vapour 12 h at 25ºC) and heated (1 h at 375ºC) oriented clay preparations additionally enabled an interpretation of the relative abundances of clay mineral species occurring in each sample using the method of Weir et al. (1975). Illite-smectite compositions were determined by comparing illite-smectite peak positions with those given in Hower (1981). Copper Kλ radiation was used for all XRD analyses.

Scanning electron microscopy (SEM) was performed on 12 sandstone samples selected following the thin-section study. This work yielded important supplementary data on the nature of authigenic clay minerals and porosity. Authigenic clay minerals were identified using SEM. The relative values of porosities and permeabilities were determined directly from SEM measurements.

The preparation of samples for stable isotope analysis follows that described by McCrea (1950). Small amounts of whole-rock samples were grounded for 15 min in a ball mill, and 10 to 100 mg subsamples, depending on the estimated carbonate content, were taken for $^{13}C/^{12}C$ and $^{18}O/^{16}O$ analysis. Carbon dioxide was extracted from samples by reacting with excess 100% orthophosphate acid in *vacuo* at a constant temperature of 25.2 + 0.05°C. $\delta^{18}O$ was calculated using the constant $\alpha^{18}CO_{2\ Calcite}$ =1.01025 (Friedman and O'Neil, 1977) and $\alpha^{18}CO_{2\ dolomite}$ = 1.011 (Sharma and Clayton, 1965).

Isotopic analysis was performed on a VG-903 triple collector mass spectrometer. Results are quoted on the conventional del (δ) scale in per (%) deviation from PDB standard. The normal analytical precision of duplicate analysis is better than +0.1% for both $\delta^{13}C$ and $\delta^{18}O$.

RESULTS

Mudrocks

The mudrock clay mineralogy is dominated by discrete illite, low-expandability (allevardite ordered) illite-smectite and kaolinite. Chlorite is locally present as a very minor constituent in the north. The proportion of illite and illite-smectite increases significantly at the expense of kaolinite of kaolinite east of the outcrop area. Constituent non-clay detrital minerals are quartz, K-feldpar, plagioclase and mica. Authigenic minerals detected are pyrite and siderite. Siderite, isotopically analyzed in one marine mudstone sample gave δ^{13} C and δ^{18} O values of 30.0 and 8.5% respectively (Odigi and Amajor, 2009b).

Sandstones

Texture

The sandstones range from fine to very coarse-grained, but dominantly medium-grained. The sandstones of the alluvial fan and tidal channel are poorly sorted and commonly matrix-supported rather than grain-supported while the deltaic sandstones have cleaner sands and well sorted.

Framework grains

The sandstones from the Nkporo formation are rich in quartz. Approximately 75% are quartz arenites according to the classification of Folk et al. (1970). Feldspathic and subarkosic varieties are common in the western part of the trough. In the east of the study area, sandstones are enriched in quartz by up to 16% compared with those of the west.

Quartz grains are mainly monocrystalline and non-undulatory with subordinate amount of polycrystalline quartz grains. The dominant feldspar is albite, and minor microcline. Lithic grains of mudstones, siltstone and carbonate occur as rarities suggestive of carbonate source rocks. Accessories include euhedral zircon, rutile, ilmenite and magnetite.

Diagenetic minerals

The diagenetic and framework minerals recognized are shown in Figure 5.

Quartz: Authigenic quartz occurs in form of microcrystalline and crystalline aggregates in the pores and as syntaxial overgrowths on detrital quartz grains and thus affects the porosity and permeability of the sandstones. The average percentage of syntaxial overgrowths is 49.40%. Overgrowths are best developed in the highly quartzose sandstones located over the central (Ozziza) area of the Afikpo basin, and are lacking in those sandstones containing percentages of detrital matrix and in which framework grains are rimmed by authigenic clay.

Calcite: Although quite common, authigenic calcite is not a pervasive cement in the sandstone. It typically occurs as a pore-fill and grain replacement in well-defined, sporadically developed zones with vertical dimensions of up to several meters. Calcite cement occurs in 2% of the pore space. Stained thin sections revealed the presence of both non-ferroan and ferroan varieties.

Dawsonite: Dawsonite is though rare in sedimentary rocks worldwide, and is widely distributed in the sandstones where it partially in-fills pores, and replaces mainly labile framework grains. Unlike calcite, it occurs widely in the study area. Recorded abundances range between 9 to 13.4% of the samples. Dawsonite is confined solely to sandstones of marine affinity (Baker, 1991).

Ankerite: Very minor amounts < 1% of the samples are present in sandstones throughout the interval studied. Abundances rarely exceed 4% and range up to a recorded maximum of 10%.

Siderite: Siderite in trace proportions is also very common in the outcrop samples. Abundances greater than 2% of the samples and ranging up to a recorded maximum of 23% are rare and spatially limited. Siderite occurs as a partial replacement of feldspars, rock fragments and micas.

Feldspar*:* Feldspar cements are present in the arkoses and subarkosic sandstones of the sandstones. Like quartz, feldspar cement occurs as syntaxial overgrowths on detrital grains. Altered plagioclase grains leave ragged, etched grain as oversized secondary pores.

Kaolinite: Authigenic kaolinite is very common in the sandstone analyzed. Absolute abundances commonly exceed 8% of the samples and it has a range of about 15% throughout the interval over the outcrop area. In the east of the outcrop area, kaolinite abundance decreases with values less than 2% of the samples. It typically forms randomly orientated, delicate booklet and accordion-like, loosely to densely packed aggregates of euhedral pseudo-hexagonal plates, which line and infill scattered pores and replace labile feldspar grains.

Illite: The sandstones from the upper and lower part of the lithostratigraphic units show much higher percentages of illite. Illite cements form-interstratified species which reflect the composition of the porewaters of the sandstones. Illitization of early diagenetic kaolinite requires K, which is derived from mainly from dissolution of K-feldspar. Other diagenetic clays locally present in trace amounts are chlorites.

Smectite/illite: Mixed-layer illite-smectite and discrete illite occur in the sandstone west of the study area. Illite-smectite forms meshworks of irregular crinkled flakes orientated perpendicular to grain surfaces. Authigenic illite-smectite and illite occurs as a product of labile grain alteration, typically forming in this situation a pore-filling cellular or honeycomb structure in which crystals are either sheet-like or more commonly exhibit no well developed morphology. The identification and interpretation of the mixed-layer clays is important as it forms the only expanding component in the reservoir.

Smectite: Minor amounts of smectite are present in a few samples obtained from outcrops close to the Abakaliki anticlinorium where igneous rocks of basic to ultra basic character occur. Bentonitic clays have also been recognized along the Abakaliki anticlinorium. Except for these occurrences, all smectites detected in sandstones are related to near-surface weathering processes.

Stable isotope composition

A summary of the isotope results for carbonates is presented in Figure 4 and Table 1. Further details on these results can be found in Odigi and Amajor (2009b).

DISCUSSION

Paragenesis

The relative timing of the major diagenetic minerals in the sandstone analyzed was inferred from their textural relations as observed in thin section and SEM.

Illite-smectite rims pre-date physical compaction, quartz overgrowths overlying illite-smectite grain rim (Figure 5a). Accordingly, they are regarded as a very early precipitate. Siderite is enclosed within ankerite, and ankerite is enclosed within calcite (Figure 5b), indicating that siderite was the earliest and calcite was the latest of these carbonates to precipitate. Dawsonite has grown on and around calcite, indicating that dawsonite is the earliest carbonate, a fact substantiated by the occurrence in one sample of fracture-filling dawsonite cross-cutting an area extensively cemented with calcite (Figure 5c). Dawsonite abuts euhedral quartz overgrowths (Figure 5d) as do all the other carbonates with the exception of a

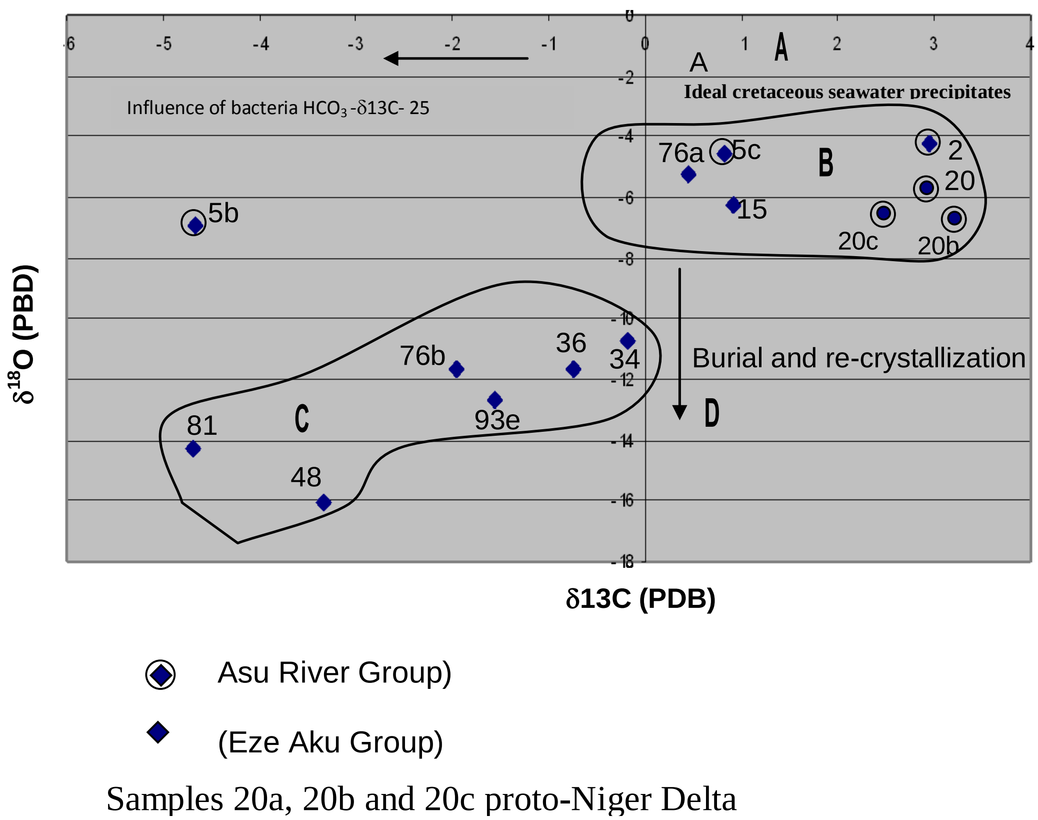

Figure 4. Plot of $\delta^{12}C$ (PDB) vs. $\delta^{12}O$ (PBD) for Asu River Group, Eze-Aku Group and Proto-Niger Delta sandstones. Carbon and Oxygen stable isotopic composition of calcite from Cretaceous sandstones. The isotopic compositions of cements have been modified from seawater (Cretaceous) by dissolution, precipitation and re-crystallization during burial. This had led to a more negative shift in $\delta^{18}O$ values. $\delta^{18}O$% 0 to –4 refers to equilibrium with seawater warm temperatures ^{18}O% axis refers to increase in temperature or input of fresh water $\delta^{18}O$.

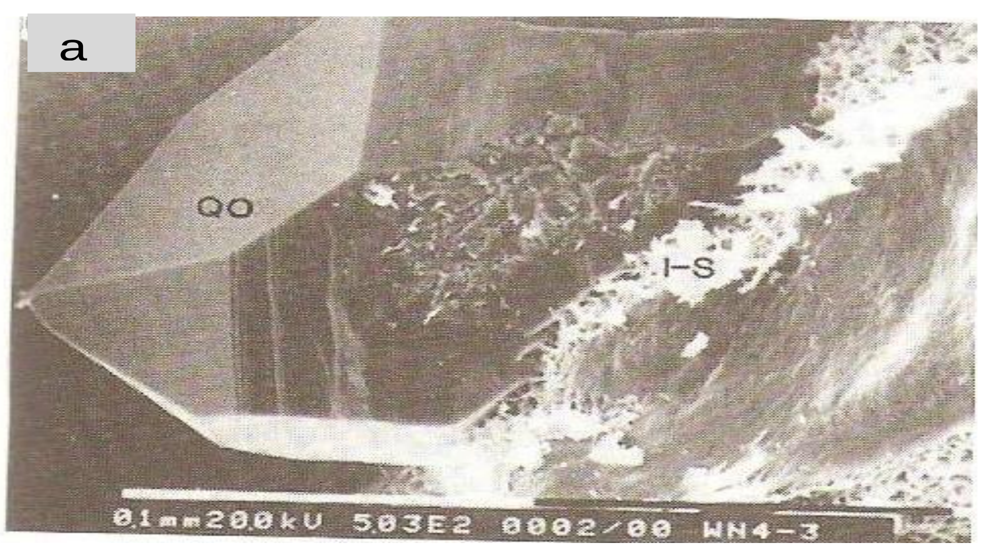

Figure 5a. Equant quartz overgrowth (QO) overlying illite-smectite (I-S) grain rim.

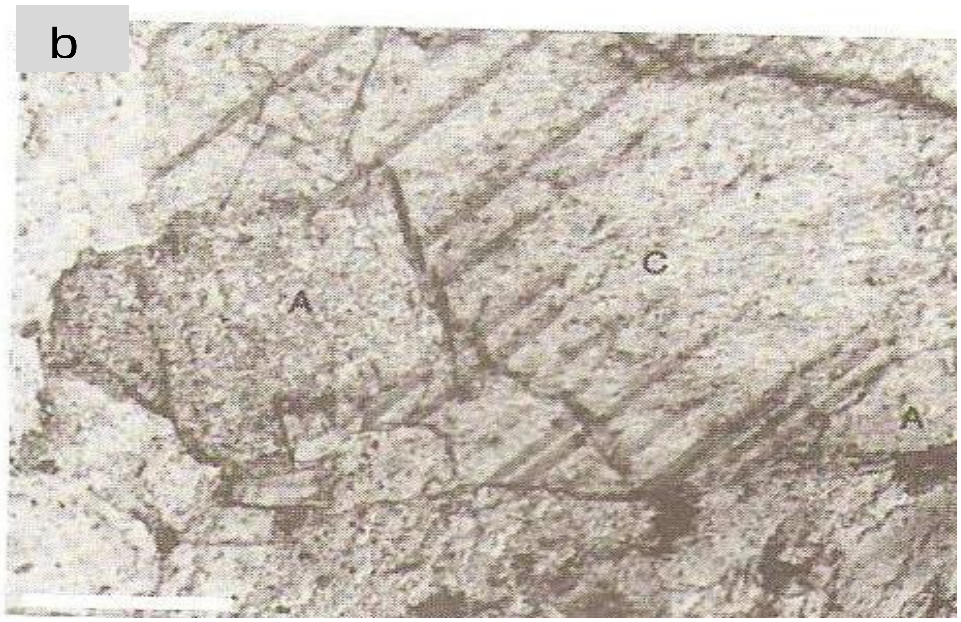

Figure 5b. Calcite (C) enclosing ankerite (A) indicating calcite is the latest minerals.

Figure 5c. Microfault, with associated fracture gouge (FG) and partially infilled by Dawsonite.

minor early siderite cement, relationships which suggest that the carbonates for the most part post-date quartz overgrowths. Kaolinite occupies spaces made available by ankerite dissolution (Figure 5e) and it is enclosed by calcite (Figure 5f) indicating that it post-dates ankerite and pre-dates calcite. Kaolinite is also partly enclosed by

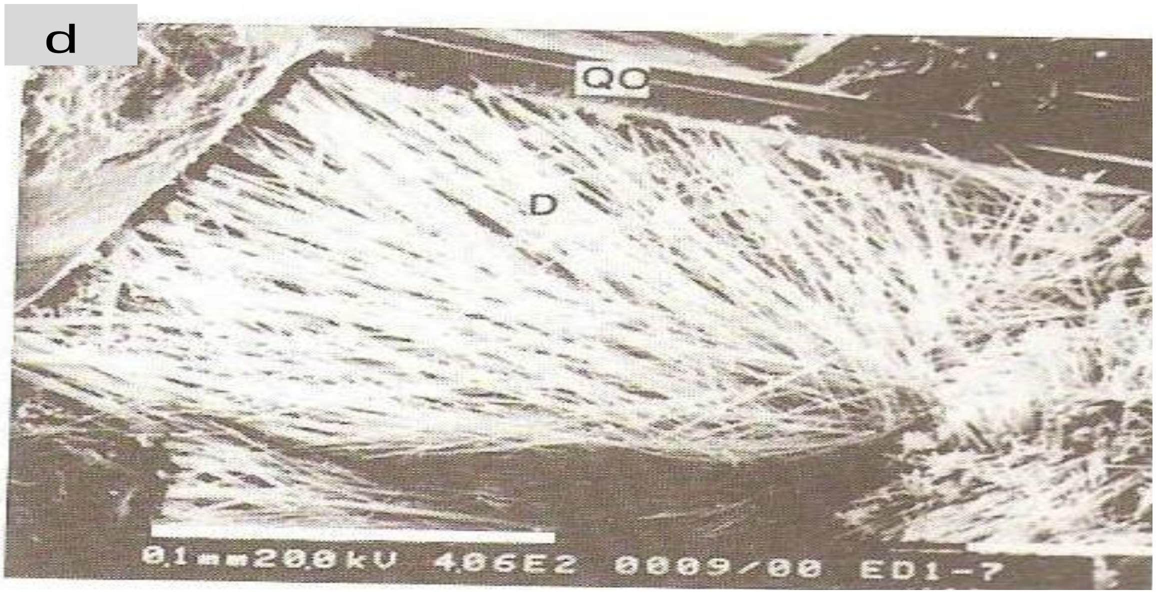

Figure 5d. Pore-filling dawsonite (D), showing typical fibrous habit, abutting quartz overgrowths (QO).

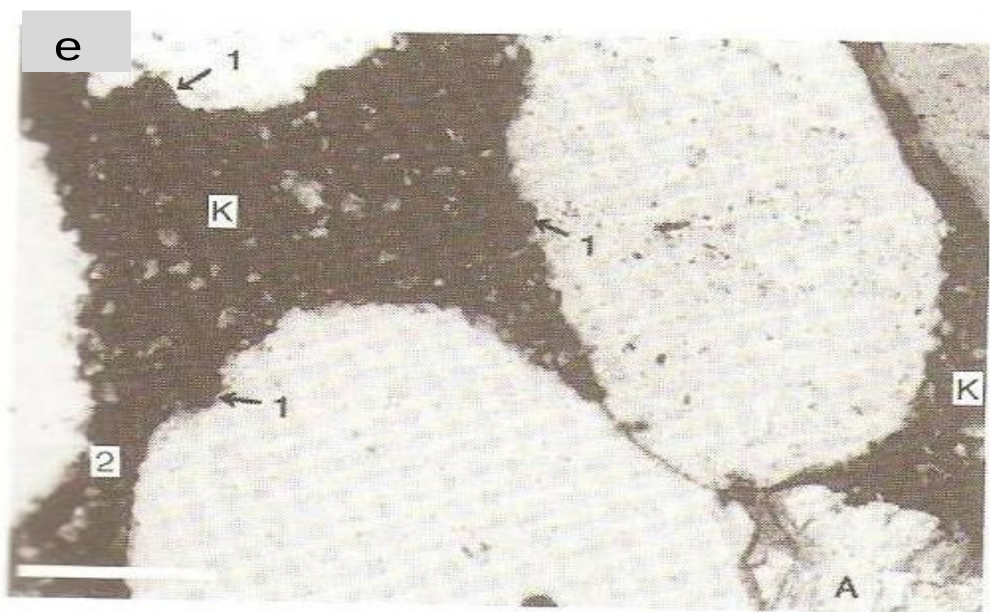

Figure 5e. Ankerite-Kaolinite relationship. Pore-filling/grain-replacement ankerite has undergone extensive dissolution (note remnant-A). kaolinite (K) has precipitate in its place. Severely corroded and embayed margin of quartz grain(1), elongated areas between adjacent quartz grains(2), and presence of small ragged patch of oxidized ankerite are strong evidence for ankerite decementation having occurred.

quartz overgrowths (Figure 5g) suggesting that either the two minerals are synchronous or that kaolinite pre-dates an episode of quartz overgrowth formation. Barite includes ankerite and replaces kaolinite indicating that it post-dates these minerals. Secondary grain dissolution pores are surrounded by welded quartz grains, detrital

Figure 5f. Calcite (c) engulfing kaolinite (K) pore fill.

Figure 5g. Booklets engulfed by quartz growth (QO). Relation interpreted to indicate that the two are coeval overgrowth is the latest phase.

matrix and undeformed and intact illite-smectite rims (Figure 5h) suggesting that they post-date compaction. Some are partially infilled by dawsonite, indicating formation prior to dawsonite precipitation.

Diagenetic history and alteration

Diagenesis here is divided into three regimes, eogenesis, mesogenesis and telogenesis, in accordance with the

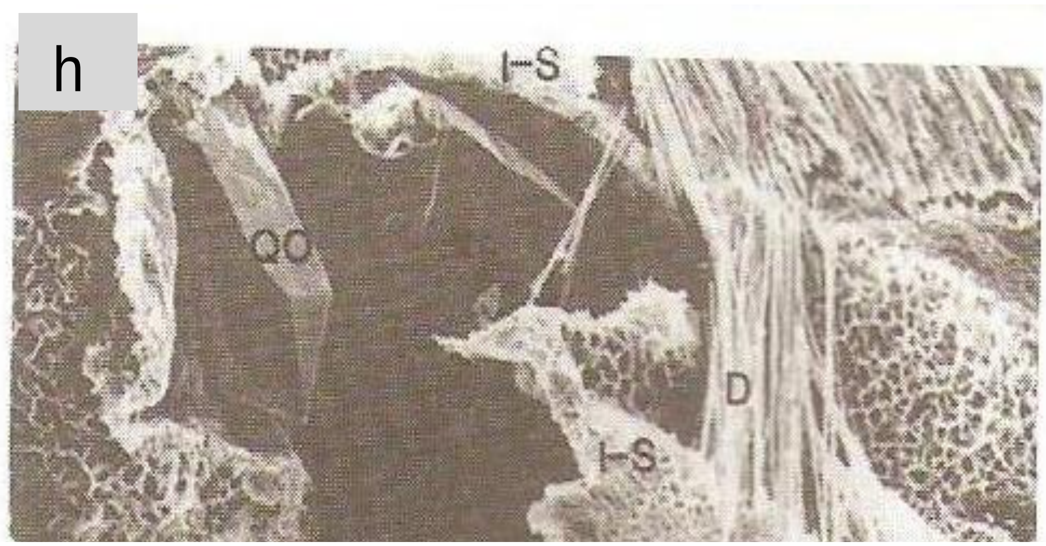

Figure 5h. Secondary pore defined by illite-smectite (I-S) rims which developed prior dissolution to dissolution of pore-precursor grain. Quartz overgrowth (QO) has since developed inside. Except for partial collapse produced artificially during sample preparation, pore has not been physically deformed indicating it and quartz overgrowth developed subsequent to compaction. Dawsonite (D) also present; (a), (d), (f), (g) and (h) are scanning electron photomicrographs; scale bars in (b), (c) and (e) = 0.2 mm.

Table 1. Carbon and oxygen isotopic composition of Cretaceous sandstone cements form the study area.

Sample	Formation	δ^{13}O (PDB)	δ^{18}O(PBD)
02	Asu River Group	2.96	-4.22
5B	Asu River Group	-4.66	-6.91
5C	Asu River Group	0.82	-4.57
15	Eze-Aku Group	0.91	-6.26
34	Eze-Aku Group	-0.75	-11.67
36	Eze-Aku Group	-0.81	-10.75
48	Eze-Aku Group	-3.34	-16.03
76A	Eze-Aku Group	0.46	-5.23
76B	Eze-Aku Group	-1.96	-11.62
81	Eze-Aku Group	-4.68	-14.31
93E	Eze-Aku Group	-1.56	-12.66
20a	Proto-Niger Delta	3.01	-4.45
20b	Proto-Niger Delta	2.98	-6.89
20c	Proto-Niger Delta	2.50	-6.30

Source. Odigi and Amajor (2010).

classification scheme of Schmidt and McDonald (1979). Eogenesis occurs at or near the sedimentation surface where fluid chemistries are mainly controlled by the depositional environment. Mesogenesis commences at greater depths where the sediment is effectively sealed from the predominant influence of surface agents. Telogenesis represents (uplifted related diagenesis) the regime at or near the surface following effective burial where surficial meteoric waters are brought into circulation displacing pre-existing pore fluids. The major eogenesis mineral recognized in the sandstone studied is grain-rimming illite-smectite. Requiring high cation concentrations, which would not have characterized groundwaters in the non-marine environment due to the humid paleoclimate at the time of deposition; this mineral could only develop in sandstones which accumulated in normal marine environments. Other eogenetic minerals recognized in the marine sandstones are glauconite, pyrite and an early siderite. Despite the presence of intraformational unconformities and the potential of gravity-driven, lateral seaward migration of meteoric water from emergent intrabasinal areas to the west, marine sandstones show no evidence of early fresh water flushing. No eogenetic minerals could be recognized in the non-marine sandstones due to overprinting by later diagenetic effects.

As burial depth increased during the Campanian and Maastrichtian, temperatures and pressures become higher coupled with the effect of magmatic activity, and depositional pore waters no longer had an active influence on sediment diagenesis. Entering the mesogenetic regime, physico-chemical compaction became significant due to framework grain reorientation and silica dissolution at contacts between quartz grains. No early carbonate cements were present to hinder the process. Assuming sandstones were always hydrostatically pressured prior to maximum burial during the Late Maastrichtian, most grain-to-grain contact dissolution probably occurred during the Maastrichtian in response to accumulation of the thick Maastrichtian to Paleocene units and concomitant substantial temperature increase.

Siderite, ankerite, illite-smectite/illite pore fill and quartz overgrowth formation, as well as compaction, probably took place in the mesogenetic regime. Involved fluids would have been liberated from underlying and overlying mudstones as a result of physical compaction and, at temperatures above 70 to 80°C, resulting to the formation of illite (Burley, 1986). Water responsible in the precipitation of carbonates and transformation of illite-smectite rims to a more illite-rich composition was expelled from the underlying and overlying older Eze-Aku and proto-Niger Delta sediments respectively.

The entire proto Niger Delta sediments underwent major uplift and deformation during the Late Maastrichtian structuring episode (Odigi and Amajor, 2009c). Thought to be linked to this event and attesting to freshwater flushing to depths of at least 700 m in the telogenetic regime is the widespread dissolution of ankerite and concomitant precipitation of kaolinite in areas vacated by the ankerite (Figure 5e). Related also to this freshwater flushing episode was the creation of secondary pores through labile grain dissolution, formation of kaolinite by labile grain alteration, a second generation of quartz overgrowth development and, later, the precipitation of barite and calcite cements. Calcites are also relatively depleted in ^{18}O, reflecting precipitation from meteoric waters (Odigi and Amajor, 2009b). A summary of the diagenetic history of the sandstones of the Nkporo Formation is presented in Figure 6.

Diagenesis, clay minerals and reservoir quality

As shown by Odigi (2007), diagenetic clay minerals play a very important role in determining the reservoir quality of river-dominated, tidal channel and alluvial sandstones in the Afikpo subbasin. The general diagenetic characteristics of the sandstones and the major factors that control their occurrence are summarized below.

The first stage of clay-mineral diagenesis was characterized by the formation of kaolinite (Figure 5F) at the expense of feldspars. Authigenic quartz occurs intimately associated with kaolinite. Most of the present porosity is secondary, originating from dissolution of detrital feldspar grains. However, growth of kaolinite and quartz reduced this porosity. Formation of secondary porosity may not significantly have raised permeability, since most feldspar dissolution porosity in the outcrop seems to be intragranular.

During the period of intermediate to deep burial diagenesis, pore-filling illite formed mainly at the expense of kaolinite. The illitic clays also occur as pore- bridging clays. The progressive stages of illite development from intermediate to deep burial are illustrated in Figures 5 B, C, D and E. In the intermediate burial stage, illite is associated with smectite, mixed-layer illite-smectite I/S and subordinate amount of kaolinite. Authigenic clays in the sandstones studied occur as illite, illite-smectite and kaolinite. They form cements around the detrital minerals. Ilite and illite-smectite clays are the first cement, precipitated from the dissolution of grains, post-dating quartz overgrowths. These early-formed clay films play an important role during burial diagenesis. They may act as crystallization nuclei for the formation of new clay minerals or for the transformation of old clay minerals to new.

It would appear from this evidence that there is a trend of illite-smectite to illite transformation with depth. This trend is similar to that observed by Odigi (1986) in the sandstones of the Agbada formation of the Tertiary Niger Delta and appears to be a gradual dehydration process with increasing burial depth.

The tidal channel sandstones contain kaolinite clays. Deltaic sandstones contain illite, chlorite and kaolointe clay minerals that are authigenic in character. The identification of the mixed-layer clay is important as it forms the only expanding component in the sandstone reservoir.

Diagenetic processes related to the burial of the

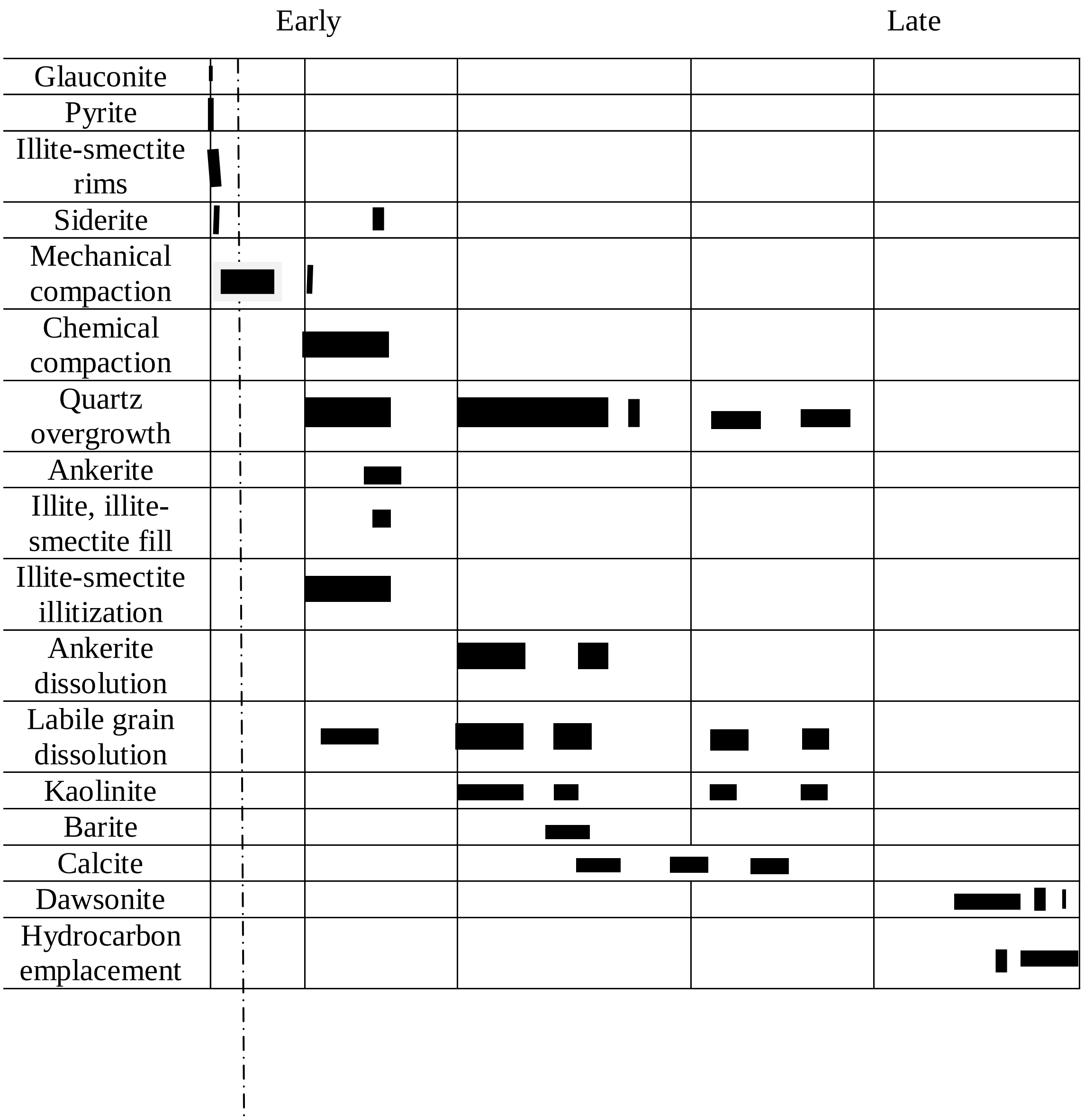

Figure 6. Summary of diagenetic event in the Nkporo sandstone.

sandstones are controlled by the interplay of various factors, instance differences in the depth of burial within relatively short distances, and the proximity of igneous intrusives, and the availability of ions, which may crystallize as cement that is detrimental to reservoir quality, or may go into solution and so enhance it. These ions may have originated in the overlying Mamu formation as well as in the underlying older Eze-Aku strata. The area occupied by the sandstones of the Nkporo formation have lower permeability and was subjected to deeper burial and more pronounced tectonic activity during the end of Cretaceous (Odigi and Amajor, 2009c). This resulted in the formation of fibrous interstitial illite and illite-smectite in the sandstones (Figures 5C and E), whereas the less-deeply and more steadily buried area of higher permeabilities in the northeast with bulky kaolinite as the dominant diagenetic interstitial clay mineral (Figure 5F). The low permeability in the more deeply buried sandstones is attributed to the intricate network of the diagenetically-formed interstitial illite-smectite and illite whiskers, which increase the tortuosity in the interstitial pore space. The inherent

Table 2. Average feldspar, kaolinite and illite contents, and relative porosity, permeabilities and burial stages of Nkporo sandstones.

Contents	Feldspar	Kaolinite	Illite	Poro	Perm	Burial stages
Feldspathic sandstone	7.5	1.5	0.8	Marginal	Marginal	Shallow
Kaolinitic sandstone	0.4	7.1	0.7	Interm	Interm	Interm
Illitic sandstone	1.3	0.8	8.4	Marginal	Marginal	Deep

Poro- porosity, Perm-permeability.

morphology of the illite, concomitant blocking of throats, has the predominant influence on the sandstone permeability.

Facies development and reservoir geometry

Three environment of deposition were identified for the sandstones of the Nkporo formation (Odigi, 2007); all which maintained distinct characteristics during most of time of deposition. Three facies associations were recognized: Facies A include fluvial deposits that show fining upward trend, Facies B are tidal channel deposits that were formed as a result of subsidence and transgressive erosion and Facies C fan delta front show coarsening-upward sequences from lower to upper shoreface. The facies B is identified by the single criterion of bundle sequences and double mud drapes. The sequence show fining upward trends with fine-grained restricted marine sediments on top.

Reservior quality versus clay mineral diagenesis

In order to appraise the regional effect of clay mineral diagenesis on the reservoir quality of the sandstone of the Nkporo Formation, the sandstones were divided into three groups representing the following mineralogical differences (Odigi and Amajor, 2008a):

Group 1: (Feldspathic sandstones): feldspar/ (kaolinite + illite) – tidal channel sandstones.
Group 2: (Kaolinitic sandstones: kaolinite/(feldspar + illite) – tidal channel sandstones.
Group 3: (Illitic sandstones): illite and illite-smectite (feldspars + kaolinite) – fan deltaic sandstones. Sediments were sourced from K-feldspar-poor sources during the maximum progradation of the Campanian-Maastrichtian, and sandstones deposited at this time are sandstones exposed to illitization and have better permeability at deep burial than reservoir sandstones that initially contained more K-feldspar.
Group 4: (Kaolinitic sandstones): Kaolinite +Feldspar - fluvial sandstones.

Secondary porosities are enhanced by labile (mainly feldspar) grain dissolution. Feldspar dissolution has obliterated nearly all-primary porosity. Poor to marginal reservoir quality exists in sandstones associated with the deltaic system, which mainly developed in the western part of the study area. East and West of the outcrop area where the sandstones of the Nkopro formation occur; the lack of labile grain dissolution pores in the area reflects the absence of secondary porosity. The presence of illite-smectite clays has led to the preservation of medium to good reservoir quality by inhibiting formation of quartz overgrowths and grain-grain contact dissolution (Figure 5E).

The sandstones of the Nkopro formation that are identified have “marginal to intermediate relative” porosity and permeability values (Table 2) compared to many other sandstones reservoirs. The fluvial channel and deltaic facies are likely to have greater reservoir potential at the time of deposition. Lowry and Jacobsen (1993) measured porosities of 44% and permeability’s of 40 darcys for such sandstones. The pore throats in the sandstones can be restricted or blocked by the movement of kaolinite clay particles, which occur as loosely attached or free aggregates in the pore space. This form of permeability reduction can account for up to 30% of the observed reduction.

Previous petrographic and diagenetic studies of the post-Santonian sandstones have shown that kaolinite and illite are the most frequently occurring authigenetic clay minerals in the Campanain-Maastrichtain sandstones (Odigi, 2007). These studies also show that the sandstones are characterized by three main stages of authigenic clay minerals:

(a) An early diagenetic-clay coating around detrital grains, (b) formation of kaolinite at intermediate burial depth, and (c) growth pore-filling illite at the deepest burial stage.

Conclusions

The diagenetic history of the sandstones of the Nkporo formation can be directly linked to depositional environment, sedimentary facies, initial composition and burial depth. Rossel (1982) and Seemann (1982) used authigenic clay mineral suites to predict the reservoir quality of sandstones from the southern North Sea. Similarly, the authigenic clay suites recognized in the sandstones of the Nkporo formation are used to predict the sandstone reservoir quality.

Eogenetic effects include formation of pyrite, siderite and illite-smectite rims. Mesogenetic effects were physic-chemical composition and the formation of quartz overgrowths, siderite, illite/illite-smectite pore-fill and ankerite. Involved fluids were a mixture of fresh and marine connate water and clay mineral-bound water. Late Maastrichtian structuring uplift subsequently placed the sandstones in the telogenetic regime where it underwent flushing by deeply circulating meteoric water. In response, ankerite was extensively dissolved and kaolinite was precipitated in its place. Other effects of this flushing included the creation of grain-dissolution secondary porosity and precipitation of barite and calcite. Possibly during the Early Paleocene, active meteoric water flushing of the sandstones ceased to the south and east of the outcrop area. Trapped meteoric water stagnated chemically and became enriched in sodium bicarbonate.

Reservoir qualities in the sandstones of the Nkporo formation are clearly related to depositional facies, environment, and diagenesis. Depositional environment had its most profound control on reservoir quality by way of dictating initial sediment composition, texture and pore fluid composition. This is shown by:

(i) The increase in detrital quartz east of the outcrop area; and (ii) differences in reservoir quality between the lower and upper basal units.

In the west, diagenesis was developed in a fluvio-deltaic environment whereas in the east, it is controlled by tidal environment.

It is concluded that the poor sandstone reservoir quality generally characterizes the sandstones of the basal Nkporo Campanian-Maastrichtian sandstones, mainly resulting from compaction of poorly sorted sediment combined with precipitation of minor amounts of diagenetic minerals during shallow burial thereby reducing primary porosity.

Although the reservoir properties of the sandstones varies from intermediate to poor, it is suggested that intermediate to good properties may be found in certain areas within the Nkporo Campanian-Maastrichtian succession in Anambra subbasin.

ACKNOWLEDGEMENTS

This study forms part of a PhD research project supervised by Professor L.C. Amajor. The author wish to thank Mr. Cornelius Veltkamp, the Chief Laboratory Technologist in-charge of the SEM Laboratory, Department of Earth Sciences, University of Liverpool, UK for his assistance with the use of the Philips XL 30 equipment.

REFERENCES

Amajor LC (1987). Paleo current, petrography and provenance analysis of the Ajali Sandstone (Upper Cretaceous), south Benue trough, Nigeria. J. Sedim. Geol., 54: 47-60.

Amajor LC (1989). Petrography and provenance characteristics of Albian and Turonian sandstones, southeastern Nigeria. In: The Benue trough a Structure and Evolution (ed. Ofoegbu C.O): Fried, Vieweg & Sohn, Berlin., pp. 39-57.

Baker JC (1991). Diagenesis and reservoir quality of the Aldebaran Sandstone, Denison trough, east-central Queensland, Australia. Sedim., 38: 819-838.

Benkhelil J (2001). The structure and sedimentology of the Lower Benue trough, Nigeria. nIgerian Min. & Geoscience Soc. (NMGS) Conmfernce Abstr., pp. 1-48.

Benkhelil J, Guiraud M (1980). La Benoue (Nigeria). Une chaine intracontinentale de style atlasique. C.R Acad. Sci, Paris, 290: 1517-1520.

Bjørlykke K, Elverhoi A, Malm O (1979). Diagenesis of part of the Brent Sand formation (Middle Jurassic) of the northern North Sea Basin. J. geol. Soc. London, 135:73-82.

Blatt H (1979). Diagenetic processes in sandstones. In: Aspects of Diagenesis (Ed. Scholle PA, Schluger PR) Spec. Soc. Econ. Paleont. Miner; Tulsa., 26: 141-158.

Burley SD (1986) The development and destruction of porosity within Upper Jurassic reservoir sandstones of the Piper and Tartain Fields, Outer Moray Firtrh, North Sea. Clay Mineral., 21: 649-694.

Carrigy MA, Mellon GB (1964). Authigenic mineral cements in Cretaceous and Tertiary Sandstones of Albert. J. Sedim. Petrol., 34: 461-472.

Folk RF, Andrew PB, Lewis DW (1970). Detrital rock classification and nomenture for use in New Zealand. J. Geol. Geophys., 13: 937-968.

Friedman I, O'Neil JR (1977). Compilation of stable isotope fractionation factors of geochemical interest. In: (Fleischor M. ed.) Data of Geochemistr (6^{th} ed.) U.S Geol. Surv. Prof., p. 440.

Hayes JB (1979). Sandstone diagenesis- hole truth. In: Aspects of Diagenesis (ed. Scholle PA, Schluger PR) Spec. Soc. Econ. Paleont. Miner. Tulsa., 26: 127-140.

Hoque M (1976). Significance of textural and petrographic attributes of sandstones, southern Nigeria. J. Geol. Soc. Ind., 77: 514-521.

Hoque M (1977). Petrographic differentiation of tectonically controlled Cretaceous sedimentary cycles, southeastern Nigeria. Sedim Geol., 17: 235-245.

Lowry P, Jacobsen T (1993). Sedimentological and reservoir characteristics of a fluvial-dominated delta front sequence: Ferroan Sandstone Member (Turonian), Eastern –Central Utah, USA. In: Ashton M (ed) Advances in Reservior Geology. Geol. Soc. London, Sp. Publ., 69: 81-101.

McCrea JM (1950). The isotopic composition of carbonates and a paleotemperature scale. J. Chem. Phys., 18: 849-857.

Murat RC (1972). Stratigraphy and paleogeography of the Cretaceous and Tertiary in Southern Nigeria. In: (eds. Dessauvage FFJ, Whiteman AJ) African Geology. University Press Ibadan. pp. 251-268.

Odigi MI (1986). Mineralogical and geochemical studies of Tertiary sediments from the eastern Niger Delta and their relationship to petroleum occurrence. J. Petrol. Geol., 10(1): 101-114.

Odigi MI (2007). Facies Architecture and Sequence Stratigraphy of

Cretaceous formations, southeastern Benue trough, Nigeria. Unpublished PhD Thesis University of Port Harcourt., p. 312.
Odigi MI, Amajor LC (2008). Petrology and geochemistry of sandstones in the Southeastern Benue trough, Nigeria: Implications for provenance and tectonic setting. Chin. J. Geochem., 27(4): 384-3394.
Odigi MI, Amajor LC (2008b). Origin of carbonate cements in the Cretaceous sandstones from southern Benue Trough, Nigeria. J. Sci. Afr., 7(2): 101-118.
Odigi MI, Amajor LC (2010). Geochemistry of carbonate cements in the Cretaceous sandstones, southern Benue trough, Nigeria: implications for the geochemical evolution of formation waters. J. Afr. Earth Sci., 57: 213-226.
Odigi MI, Amajor LC (2009c). Brittle deformation of the Afikpo Basin, SE Nigeria: Evidence for a Terminal Cretaceous Extensional regime in the Lower Benue Trough. Chin. J. Geochem., 28(4): 369-376.
Reyment RA (1965). Aspects of the geology of Nigeria. University of Ibadan Press, Nigeria., pp.1-14.
Rossel NC (1982). Clay mineral diagenesis in Rotligend Aeolian Sandstones of the Southern North Sera. Clay Miner., 17: 69-77.
Schmidt V, McDonald DA (1979). The role of secondary porosity in the course of sandstone diagenesis. In: Aspects of Diagenesis (Ed. by Scholle PA, Schluger PR) Spec. Publs. Soc. Econ. Paleont. Miner., 26: 175-207.
Seemann U (1982). Depositional facies, diagenetic clay minerals and reservoir quality of Rotliegend sediments in the southern Permain Basin (North Sea): A review. Clay Miner., 17: 55-67.
Sharma T, Clayton RN (1965). Measurement of $^{18}O/^{16}O$ ratios of total oxygen carbonates. Cosmochim. Acta, 29: 1347-1353.
Susanne G, Worden RH, William D (2008). Diagenesis and reservoir quality of Miocene sandstones in the Vienna Basin, Austria. Marine Petrol. Geol., 25(8): 681-695.
Taylor TR, Soule CH (1993). Reservior characterization and diagenesis of the Oligocene 64-zone Sandstone, North Belridge Field, Kern County California, USA. AAPG Bull., 77(9): 1549-1566.
Vavra CL (1983). Mineral reactions and control on zeolite facies alteration in sandstone in central Transantaractic Mountains, Antaractica (Abs). Bull. Am. Ass. Petrol. Geol., 67: 563.
Weir AH, Ormerod EC, Mansey IMI (1975). Clay mineralogy of sediments of the Western Nile Delta. Clay miner., 10: 370-386.
Wilson MD, Pittman ED (1977). Authigenic clays in sandstones: recognition and influence on reservoir and paleoenvironmental analysis. J. sedim. Petrol., 47: 3-31.