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Diagenetic Study of Sandstone Sediments in Parts of Anambra and Afikpo Basins, Southeastern Nigeria

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Abstract
The evaluation of textural and petrophysical properties of sandstone sediments formed the basis of determining degree and history of diagenesis of sediments in the study area. These two factors have the potential to affect reservoir qualities of sandstones deposited in parts of Anambra and Afikpo Basins. Preliminary field study showed that the sandstone sediments are liable to moderately consolidated and detailed petrographic analysis in thin sections revealed early diagenetic effects including precipitation of chamosite, pyrite and hematite minerals on the grains and as cement along point-floating contacts. Observed deeper burial effects included physico-chemical compaction and formation of Illite and Quartz overgrowths. Important post-burial effects observed in some of the sandstones included sutured contacts and the dissolution of Ankerite, Quartz and Labile grains. Average porosity values of 32.5, 27.0, 26.6, 22.1, and 20.8% obtained from modal analysis for the Ajali, Afikpo and Amasiri sandstones, Manu and Nkporo formations, respectively showed moderately high porosities irrespective of the observed diagenetic effects. The values compared favorably with known hydrocarbon producing reservoirs of the world. The Ajali sandstone sediments, however, have the best petrophysical qualities because the sandstones are virtually cement-free, with significant portion of its primary porosity retained and generally have undergone the least mechanical compaction evident from floating and point contacts of the accompanying grains. Compaction and precipitation of authigenic quartz and clay minerals were some of the diagenetic changes responsible for porosity reduction, while the dissolution and replacement of framework minerals observed in some of the samples enhanced porosity.

Keywords: Sandstone, Diagenesis, Reservoir quality, Anambra Basin, Afikpo Basin

1.0 Introduction
Sandstone diagenetic analysis has attracted renewed interest over the past few decades. In such studies original composition, burial depth, temperature and pore-water chemistry have been highlighted as the main factors influencing diagenetic changes in sandstones (Carrigy & Mellon, 1964; Blatt, 1979; Hayes, 1979; Vavra, 1983). The evaluation of reservoir qualities of sediments (sandstones) in parts of the southeastern Nigerian sedimentary basins have also been undertaken by many scholars. These studies focused mainly on provenance, sandstone geometry and depositional environments (Amajior, 1987; Hoque, 1977; Odigie, 2011). Similarly, outcrop-based reservoir characterization was studied in the western Orogande Basin (New Mexico) using stratigraphic, petrographic and petrophysical techniques (Patrick et al., 2002). They documented that the distribution of porosity and permeability within reservoir systems is dependent on depositional and diagenetic facies. Diagenesis in sandstones usually starts with pore space reduction due to compaction, then rim alteration as a result of cementation and later, pore-filling and alteration with cement. And finally, the transformation of the mineral phases in more deeply buried sandstones (Wilson & Pittman, 1977). The present study will similarly highlight the prevailing factors responsible for sandstone diagenesis in sediments deposited in parts of the Anambra and Afikpo Basins. It will also provide a comprehensive information on the diagenetic history of the cretaceous sediments in the basins. This will provide the required platform for a more objective assessment of the reservoir qualities of the sediments in the light of renewed interest in hydrocarbon prospects of Nigeria's inland basins. The study will thus characterize the reservoir rocks in the study area in order to ascertain their potentials to host hydrocarbons.

The study area lies between Longitudes 6°50' and 7°50' E, and Latitudes 5°40' and 6°15' N, covering Ohaifa, Abiriba, Uturu, Okigwe, Ihube, Lenu, Lokpanta and Afikpo (Figure 1; Table 1). The area presents the best hydrocarbon productive trends in the Southern Nigerian sedimentary basins (Abyibo and Ogbe, 1978) based on some shows...
and seepages already recorded (Odigi, 2002; Nwajide, 2005; Onyekuru & Iwungha, 2010; Odigi, 2011).

1.1 Geological History of the Study Area

The tectonic evolution of Southeastern Nigeria may be traced back to Late Jurassic when conventional currents in the asthenosphere caused the break-up of the African Plate and left the Benue Trough as an aulacogen, a failed arm of Triple Rift junction (Burke, et al., 1972; Olade, 1975). Hoque and Nwaigide (1985) summarized the tectonic evolution into the riftting, trough, deformation and platform stages (Figure 2).

The accumulation of thick sediments of the Albion Asu River Group, Turonian Eze Aku Shale and Awgu Shale in the trough led to the development of instability at the base of faulted crustal blocks which culminated in large-scale folding with fold axes parallel to the trend of the trough. The lips of the trough began to sag forming the Anambra Basin and the Afikpo Syncline. The depressed platforms of Anambra and Afikpo Basins became major depocentres after the Santonian Orogeny.
Table 1: Coordinates of Sampling Locations in the Study Area.

<table>
<thead>
<tr>
<th>Outcrop Description</th>
<th>Formation</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Outcrop section at km 8 Along Afikpo-Uturu Road near Abakiliki Junction</td>
<td>Amaesiri Sandstone</td>
<td>N6° 03'</td>
<td>E7° 44'</td>
</tr>
<tr>
<td>2. Outcrop section Near Leru Junction</td>
<td>Nkporo/Mamu Formation</td>
<td>N5° 55'</td>
<td>E07° 24'</td>
</tr>
<tr>
<td>3. Outcrop section at McGregor Hill Near Ebonyi Hotels</td>
<td>Afikpo Sandstone</td>
<td>N6° 05'</td>
<td>E7° 45'</td>
</tr>
<tr>
<td>4. Outcrop section at km 76 on the Enugu-bound side of the Enugu-Port Harcourt Expressway</td>
<td>Mamu Formation</td>
<td>N5° 51'</td>
<td>E07° 21'</td>
</tr>
<tr>
<td>5. Outcrop section km 65 along Uturu-Afikpo Road</td>
<td>Mamu Formation</td>
<td>N5° 49'</td>
<td>E07° 24'</td>
</tr>
<tr>
<td>6. Outcrop section at Ohafia-Asaga (I)</td>
<td>Mamu Formation</td>
<td>N5° 41'</td>
<td>E07° 39'</td>
</tr>
<tr>
<td>7. Outcrop section at Ohafia-Asaga (II)</td>
<td>Ajali Sandstone</td>
<td>N5° 47'</td>
<td>E07° 37'</td>
</tr>
<tr>
<td>8. Outcrop section at Okoko - Illem Village</td>
<td>Ajali Sandstone</td>
<td>N5° 49'</td>
<td>E07° 35'</td>
</tr>
<tr>
<td>9. Outcrop section at km 75 along Enugu – Port Harcourt Road</td>
<td>Ajali Sandstone</td>
<td>N5° 48'</td>
<td>E07° 20'</td>
</tr>
<tr>
<td>10. Outcrop section near km 65 Uturu-Afikpo Road</td>
<td>Ajali Sandstone</td>
<td>N5° 45'</td>
<td>E07° 24'</td>
</tr>
<tr>
<td>11. Outcrop section at Ilpankwu Quarry near Ilube</td>
<td>Ajali Sandstone</td>
<td>N5° 43.778'</td>
<td>E07° 24'</td>
</tr>
</tbody>
</table>

Figure 2. Tectonic map of Southeastern Nigeria (After Murat, 1972).
Sediments of about 4000 m-thick were deposited in the basins in environments ranging from marine through paralic to fluvial. The entire Campanian-Eocene lithic fills in the Anambra Basin and Afikpo Syncline is divisible into three main transgressive-regressive cycles (Reynolds, 1965). These cycles correspond to major marine incursions in the Late Campanian, Paleocene and Eocene, representing second order depositional sequences (Murat, 1972). The sedimentary successions in the basins consist of the Campanian Nkporo Group (Nkporo Shale, Afikpo Sandstone, Enugu Shale, etc.), Campanian-Maastrichtian Mamm Formation, overlain by the Maastrichtian Ajali Sandstone. Others include the Maastrichtian - Paleocene Nsukka Formation (~350 m), Paleocene Imo Formation (~1000 m) and the Eocene Akfor Formation (~250 m)(Nwajide, 2005: Table 2; Figure 1).

2.0 Materials and Method

2.1 Thin Section Analysis
Thirteen (13) fresh representative sandstone samples collected from sections of some of the lithostratigraphic units in the two basins (including Anasiri Sandstone, Afikpo Sandstone, Nkporo Shale, Mamm Formation and Ajali Sandstone) were randomly selected and prepared for thin section microscopy. The analysis was done in the Mineralogy Laboratory of the Department of Geology, University of Port Harcourt (UNIPORT), Rivers State.

Sample preparation started with the impregnation of friable samples with resin before cutting. Each of the samples was later mounted on the polished side on a glass slide. The mounted sample was ground with a coarse abrasive and later washed with water before manual grinding until the slide was fine or thin enough for individual mineral identification. The slide was thereafter thoroughly washed with water and allowed to dry before covering with a cover slip. The modal analysis (point-counting method), according to Ingersoll et al. (1984) and Osae et al. (2006) was adopted for the study.

2.2 X-Ray Diffraction Analysis
The X-Ray Diffraction (XRD) analysis of five sandstone samples in the study area was evaluated at the National Geoscience Research Laboratory Centre, Kaduna. The analysis was carried out using EMPYREAN XRD by PANALYTICAL with Copper anode and radiation at 40 kV and 55 mA, which runs at a rate of 20. The diffractometer was equipped with PC-APD in-built diffraction software which produced the diffraction signatures.

The analysis generally involved the isolation of clay fractions in sandstone samples, glycolation (using ethylene glycol in desiccators) to allow expanding clays to be conveniently investigated and heating to 375 °C to collapse Smectite and Illite-Smectite fractions which leaves other clay fractions unaffected, while the Kaolinite fraction of clay minerals is destroyed as temperature rises to 550 °C.

3.0 Results and Discussion
3.1 Lithostratigraphic Study
A total of 11 outcrop sections were investigated. The predominant rock types in the studied sections are sandstone, mudstone and shale. Sedimentary structures observed include planar and trough cross beds, slump and load structures, ripple and cross laminations, bioturbation including Skolithos and Ophiomorpha ichnogenera (Figures 3 and 4).

Results of Thin Section Petrography
The results of the thin section study for representative sandstone samples of the studied lithostratigraphic units is presented as photomicrographs (Figures 5 - 9). The texture of the sandstones ranged from medium to coarse grained, poorly to moderately well sorted and generally sub angular to subrounded.

The modal composition of Quartz is more than 85% of the minerals in the studied samples (Table 2). The quartz grains are dominated by monocrystalline varieties. Feldspar is minor, but constitutes up to an average of 2% of the modal composition. Void fillers (cement) are comprised of iron oxide. Other fillers include Kaolinite, Sericite and silt-sized Quartz. Mica and some opaque minerals.

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<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mami</td>
<td>70</td>
<td>Cl St Fs M s Cs Gv</td>
<td>Bioturbated Red Sandstone</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td>Permic mudstone</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td></td>
<td>Siltstone/shale-sandstone interbeds with fumarolized top</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td></td>
<td>Thick X-beded sandstone with burrows, Ophiomorpha, top bed shows reactivation surface</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
<td>Intensely burrowed top (scoliths), erosive base with black shale with thin medium sand intercalations</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td></td>
<td>Well sorted, ripple-top, bioturbated, large-scale trough-beded sandstone with interbeds of burrowed (scoliths)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>Siltstone/shale interbeds</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td>Micritic fossiliferous Limestone</td>
</tr>
</tbody>
</table>

Mami

<table>
<thead>
<tr>
<th>Mami</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
</tr>
</tbody>
</table>

Nkporo

<table>
<thead>
<tr>
<th>Nkporo</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3. Lithology of Nkporo/Mami sections at Leru (Anambra Basin).
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ajali Sandstone</td>
<td>12</td>
<td></td>
<td>coarse, mega-rippled, lenticular sandstone.</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>Coarse-pebbly angular and poorly sorted sandstone.</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td>Fine-medium, ripple laminated sandstone.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>Coarse-grained, planar cross-bedded sandstone, intensely bioturbated with ophiomorpha ichnogenera.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>Pebble channel deposit with scoured erosional base.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>Fine-silty, ripple to cross laminated sandstone.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td>Planar cross-bedded, fine grained sandstone.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td>Pinkish-white, silty sandstone with mud drapes.</td>
</tr>
</tbody>
</table>

Figure 4: Litholog of Ajali Sandstone at the Ohafia-Asaga Road Cut Section (Afikpo Syncline).
Figure 5. Photomicrographs of fresh quartz-dominated thin sections of Ajali Sandstone
(A) Coarse angular poorly sorted sandstone (Okoko from) X 40 (B) Moderately well sorted quartz grains with flakes of opaque minerals in a clay matrix (Uturu Okigwe) X 40
(C) Well sorted sandstone with quartz grains showing point contact (Uturu) X 64
(D) Well sorted, sub-angular sandstone with abundant quartz grains (Iuba) X 40.

Figure 6. Photomicrographs of thin sections of Mamu Formation Samples (X 40)
(A) Poorly sorted coarse grained sandstone. Compaction and dissolution is evident as shown by presence of slippage between grains, quartz overgrowth and embayed edges (red arrows).
(B) Moderately well sorted angular sandstone dominated by quartz grains showing point contact.

Figure 7. Photomicrographs of thin sections of Nkporo Formation (X 40).
(A & B) Poorly sorted and coarse grained SST with quartz grains enclosed in kaolinite matrix. Compaction is evident from the micro fractures on quartz grain (Fig. 10 A). Dissolution contact is evident in sutured contacts and severely corroded and embayed margin of quartz grains (red arrows in A & B) in support of compaction and a special chemical environment. Also note that the pore-filling grain replacement ankerite (Am) has also undergone extensive dissolution.
The Ajali Sandstone sediments generally have a dominance of subangular to subrounded monocry stalline quartz. The ferruginized variety is composed of quartz of similar morphology but with iron oxide as void fillers (Figure 5). The Mamu Formation samples are comprised of both the poorly sorted, coarse grained and the moderately well sorted, angular sandstone varieties. The sediments are dominated by quartz grains that display point contacts (Figure 6). The sandstone samples from Nkporo Formation were so rich in quartz (Figure 7). Less quartz dominated varieties had been observed in other parts of the study area (Odigi, 2011). Quartz grains are also mainly monocry stalline. Feldspar occurs as microcline. Lithic grains of mudstone, siltstone and minor carbonates make up the rock fragments. Opaque minerals occur as accessories. The sandstone is coarse grained and commonly matrix supported. Poor-sorting and more significant strained quartz grains in the Ajali Sandstone sediments (Figure 8) distinguishes it from those of Nkporo Formation. Further, the Amaesiri Sandstone samples on the other hand, are comprised of interlocking mosaic of detrital quartz grains with little clay content, but a concentration of opaque materials along some grain boundaries (Figure 9). The average porosity values of the studied sandstone samples ranged from 21.6 - 32.5% (Table 3). The sediments of the Ajali Sandstone and those of the pre-Santonian Amaesiri Sandstone sediments have
the highest and lowest porosity values, respectively. The sediments of the Mamu and Nkporo Formations, with average porosity values of 27.0 and 26.6 %, respectively have moderate porosity values. The relatively low average porosity value (22.1 %) recorded for the Afikpo Sandstone, a Member of the Nkporo Group is attributed to poor sorting as a result of high matrix content in a framework of conglomerates and coarse grained sandstones. This condition is most likely to be a function of depositional processes than diagenesis. The lowest average porosity value recorded for sediments of the Amasiri Sandstone has however, been attributed to the effects of mechanical compaction due to burial. Older sediments (sandstones) are more susceptible to the effects of burial arising from high overburden pressure and thermal effects.

**Results of X-Ray Diffraction Analysis**

X-Ray diffraction patterns of the clay mineral species in the study area were obtained from strongest reflection peaks which were converted from 20 angles to d-spacing. Identification of the clay mineral species was based on comparison with the Index book of X-Ray Powder Diffraction File (PDF) and the American Mineralogist Crystal Structure Database (AMCSD). References were also made to similar works done by several authors on clay mineralogy (Agbanum and Ene, 1990; Allam et al., 2009).

Kaolinite and quartz constitute the dominant minerals identified in the study. Quartz is identified in all the diffractogram at basal reflection of 4.256 Å, 3.34 Å, 2.45 Å, and 2.28 Å (Figures 10a-e). For purposes of enhancement, however, and especially to recognize and evaluate the percentage intensity of other clay minerals in the samples, the “stick pattern” of diffraction signature was utilized (Figures 11a-d). Kaolinite is recognized at basal spacing of 2.34 Å, 2.56 Å, 3.58 Å, 4.18 Å, 4.46 Å and 5.17 Å. The basal spacing at 3.58 Å and that at 7.17 Å are the most intensive. The peaks remain unaffected on glycolation but destroyed on heating at temperatures above 550 °C (Miliot, 1970). Kaolinite is ubiquitous in all the sandstones. Dickite is identified by the basal reflection at 7.16 Å in the Ajali Sandstone. Illite is identified by the basal spacing at 1.89 Å, 2.38 Å, 2.50 Å and 2.56 Å. The 2.50-2.56 Å have relatively higher intensity. On glycolation, Illite is essentially non-expanding. Illite is more predominant in the Afikpo Sandstone, Mamu Formation and Nkporo Formation sediments. The basal reflections of chlorite are recorded at 1.49 Å, 2.19 Å, 2.38 Å, 3.58 Å and 7.17 Å. Iron-rich chlorite generally gives a very strong reflection at 7.0-7.12 Å. The peaks are not affected on glycolation and heating up to 550 °C (Rahman et al., 2005). Chlorite is more predominant in the Afikpo Sandstone and Nkporo Formation sediments. Montmorillonite was recorded at basal spacing of 1.48 Å, 1.99 Å and 2.2 Å.

Figure 10 a. X-Ray diffractogram of Ajali Sandstone (Uturu-Alikpo Road).
Figure 10b. X-Ray diffractogram of Mamu Formation (Km 76 Enugu-Port Harcourt Road).

Figure 10c. X-Ray diffractogram of Afikpo Sandstone (McGregor Hill-Afikpo).

Figure 10d. X-Ray diffractogram of Nkporo Formation (Luru).

Figure 10e. X-Ray diffractogram of Amaesiri Sandstone (Afikpo-Uturu Road).
Evidence of Diagenesis from Thin Section Petrography and XRD

Various diagenetic alterations affected the sandstones that crop out in the study area. The features observed are related to compaction, authigenic cementation and secondary porosity.

Compaction
The effects of compaction were observed in most of the sandstones in the basins, typified with the slightly strained quartz grains with long contacts. Houseknecht (1987) related similar diagenetic effects to two processes or degrees of compaction.

Mechanical and chemical compaction.
The former which involved low to intermediate degree of compaction accounts for the fracturing of rigid grains, micro fractures or Boehm Lamellae in grains (Figures 10a-d), while the latter, a strong to very strong degrees of compaction resulted in the formation of dissolution patterns like straight and sutured contacts (Figure 7).

The sandstones in the study area also exhibited low to intermediate pressure solution probably due to evenly spread stresses and shallow burial. The highest degree of pressure solution was observed in the sandstone units of the interbedded sandstone and shale facies of the Nkporo Formation (Figure 7). Poor sorting observed in some of the sandstones due to substantial amounts of detrital matrix arising from mechanical compaction also have the capacity to reduce primary porosities of the basal units of the Nkporo Formation and the Afikpo Sandstone in the study area (Figure 7).

Authigenesis
Evidence of the formation of new minerals in the sandstones was manifested as overgrowths of cementing, recrystallization and replacement minerals. These effects were observed in the quartz and clay minerals:
Quartz

Overgrowths occurred as silica jackets on quartz grains and identified in thin sections as part of the grain lying outside the dust line. The dust line occurs as discontinuous bubbles or minute inclusions between the grains and the cement (Riches et al., 1986). Though poorly outlined in the photomicrographs, they were however, vividly recognized in the thin sections of the Manu and Nkporo Formation samples (Figures 6 and 7). It was also observed that the inclusions occur close to pore spaces and evidence of preferential enlargement of the overgrowths were however, not observed. The increase of pH due to chemical degradation of clay minerals in the interbedded sandstone/shale facies of the Nkporo Shale may be due to insufficient replacement of the silica charged water and thus the cessation of quartz cementation in the studied sandstones (Thompson 1959; Bole & Frank 1979).

Authigenic Clay

The authigenic clays constituted the orthomatrix in the pore spaces of the studied sandstones. They were essentially kaolinitic clay. According to Bucke and Mankin (1971), the development of kaolinite presupposes the availability of the following: sufficient porosity or permeability to allow the migration of interstitial water to provide growth space, the presence of K-feldspar to provide Al and Si ions, partly degraded illite as K acceptor and the presence of organic matter to maintain low pH. This condition is expected in the interbedded sand/shale units of Nkporo and Manu Formations with a lot of organic matter contents.

The preponderance of kaolinite in sandstone samples in the study area is therefore, indicative that these conditions were prevalent during the alteration of sandstones. Units AJSU 10, AJSU 11 of Ajali Sandstone sediments and units AKF 1 and AFK 6 of the Alikpo Sandstone sediments recorded significant Kaolinite species. In most cases, however, the kaolinite is colorless, clear and uniform in appearance making identification and discrimination from the detrital matrix under the petrographic microscope very easy.

Cementation

Compatible cementation of silica to detrital quartz occurred abundantly in the studied sandstone. Incompatible cementation also existed between quartz and clay, while in some other samples pore spaces were filled with iron oxide cement.

Quartz-Silica

Quartz-silica cement formed a coherent boundary in the Nkporo Formation and the Pre-Santonian Amaesiri Sandstone. The study showed that silica formed as incompletely welded contacts between grains, with cement being slightly visible. Unlike clear meniscus cement, the grains are not in contact with each other. The cementation probably resulted from precipitation of silica into pore spaces.

Iron Oxide Cement

Iron oxide cement formed abundantly in the Ajali Sandstone and Manu Formation sediments. The oxides commonly filled voids and cemented other grains. Iron oxide cement occurred as reddish brown coatings on some of the sandstones and in some cases, masks the color of the matrix giving it reddish coloration. Bole and Frank (1979) related iron oxide cement to smectite-illite transformations, while Wescot (1983) considered the oxidation of pyritic shale as source of iron oxide.

Silica-Clay Cement

Incompatible cementation was observed between kaolinitic clay and quartz grains. This is probably due to the antipathetic relationship between quartz cements and detrital clay minerals (Riches et al., 1986). Crystal development of quartz is inhibited where quartz and clay occur together (Thompson, 1959).

Diagenetic History of Sandstones in the Study Area

The evaluation of relative sequence of diagenetic events in the studied sandstone sediments was based on the textural relationships between grains and diagenetic features. Dapples (1962) explained that according to the type of chemical reactions and the major sequences of occurrence, three diagenetic stages are recognizable: the first stage is more or less the early stage of diagenesis and involved the episode of sediment accumulation, reworking and early burial. This stage is primarily an oxidation-reduction action (Fe$^2+$ Fe$^3+$) and characterized by mineral transformation such as Hematite + Illite $\rightarrow$ Glaucinite, Hematite + Chlorite $\rightarrow$ Chamosite. In marine depositional environments where reducing conditions prevail, the formation of pyrites is particularly pronounced. In non-marine depositional environments where oxidizing conditions commonly prevail, little pyrites are formed. Instead iron oxides are commonly produced, creating red-beds. Formation of kaolinitic clays and precipitation of quartz and...
calcite cements may take place also in the non-marine realm. This Redoxomorphic stage had earlier been linked in the study area with the occurrence of Chamosite in the pyritic nodules of the Mamu Shale units overlying the Nkporo Formation at Leru (Nwajide and Reijers, 1996c) and the characteristic ferruginized sandstone units in the Ajali Sandstone and Mamu Formation. The other evidence of early diagenesis in the studied sections is the preponderance of kaolinitic which also is indicative of environments whose temperature regimes did not exceed 150 °C (Keller, 1970); the second stage (Locomorphic Stage) is the intermediate stage of diagenesis. This stage is characterized by replacement of one mineral by another without the mineral entering into mutual reactions (Dapples, 1962). Other important processes during this stage include: physical compaction, chemical compaction (pressure solution), cementation, dissolution by pore fluid and clay mineral authigenesis. Some of these features were observed in the sediments of the Mamu and Nkporo Formation; the third stage (Phyllosomorphic) is the late stage of diagenesis and involved the origin of micas mainly as transformation products of clay minerals. The stage more or less overlapped with the zeolite and chlorite stages of deep burial or low metamorphism. Mica development is essentially due to temperature increase. Advanced diagenesis is often indicated by widespread occurrence of Illite (Nagtegaal, 1978). From these observations, the studied sandstone sediments in the study area are in early to intermediate stages of diagenesis. Similarly, the classification scheme of Schmidt and McDonald (1979) was used to discriminate three other stages of diagenesis namely Eogenesis, Mesogenesis and Telogenesis. All the stages were substantially observed in the studied samples. Eogenesis occurred near the sediment surface where fluid chemistry are mainly controlled by the depositional environment. Mesogenesis commenced at greater depth where sediments were effectively sealed from the predominant influence of surface agents. Telogenesis represented uplift-related diagenesis. The observed eogenetic minerals in the study area are Pyrite and Chamosite in the Mamu and Nkporo Formations and hematite in the Ajali Sandstone sediments. Odigi (2011) had recognized grain-rimmed Illite-Smectite, Glauconite and early siderite in the study area. As burial depth increased during the Cenomanian and Maastrichtian periods, temperature and pressure also increased and interstitial fluids no longer had active influence on sediment diagenesis. During this mesogenetic regime, physical-chemical compaction became more significant due to framework orientation and silica dissolution at point contacts between quartz grains and quartz overgrowths. It is during this period that the included fluids as earlier noted had been completely liberated from the interbedded sandstone/shale units due to physical compaction at a more elevated temperatures greater than 70 °C – 80 °C. The mesogenetic regime also results in the formation of Illite (Burley, 1986). The entire proto Niger Delta sediments later underwent major uplift and deformation during the Late Maastrichtian structuring episode (Odigi and Amajor, 2009c). The telogenetic regime is thought to be linked to these events with attendant freshwater flushing to depths of at least 700 m and widespread dissolution of quartz and feldspar grains (Figures 6b and 7a-b). Related to this fresh water flushing episode was the creation of secondary pores through the dissolution process, formation of Kaolinite by labile grain alteration, a second generation of quartz overgrowth and later precipitation of barite and calcite cement.
Iron-oxide → quartz → chlorite → illite → kaolinite

This sequence is similar to the diagenetic sequences observed for sandstones of the Belly River Formation (Issaugui, 1983) and those in parts of Southern Benue Trough (Aguma, 1990).

A summary of the diagenetic history of sandstones in the study area is presented in Figure 12.

Clay Mineral Authigenesis and its Implication on Reservoir Quality

The authigenic clay minerals in the studied sandstones included Kaolinite, Illite, Illite-Smectite mixed layer and Chlorite. Kaolinite is the most ubiquitous and usually forms cement that fills the pores around detrital grains. Kaolinite poses production problems in sandstone reservoirs. This has been attributed to the fact that it attaches itself to host grains and the large-sized individual crystals leads to the migration of fines in reservoirs. Therefore, fluid turbulence within the pore can rip the delicately attached Kaolinite from the substrate especially in areas of high fluid turbulence such as close to the well bore. Loosened Kaolinite migrates to the pore throat where it lodges and acts as a check valve because of the large size of the individual crystals (David, 1980).

During the period of intermediate to late burial diagenesis, pore-filling Illite formed at expense of Kaolinite. Illite constitutes pore-bridging clays (Odigi, 2011). During this stage also, Illite is associated with Smectite. Illite-Smectite and Kaolinite are the first cements precipitated from the dissolution of grains during post-dating quartz overgrowth.

Some of the pores in the Nkporo Formation are secondary, originating from the dissolution of detrital Feldspar, Quartz and Ankerite. Quartz and Kaolinite overgrowth, however, have reduced the porosity substantially. Again, the generation of secondary porosities in the Nkporo Formation sediments would not raise permeability significantly, because most of the dissolution processes generated intragranular pores.

![Fig. 12. Summary of diagenetic events in the study area (modified after Odigi 2011)](image-url)
Conclusion

The major diagenetic features observed in the study area include: compaction, authigenic clay mineral transformation, authigenic cementation and secondary porosity by dissolution. The sandstones from the study area are mainly at the early to intermediate stages of diagenesis corresponding to redoxomorphic and loomorphomorphic stages. Uplift-related diagenesis is also significant as evidenced by widespread dissolution of quartz and feldspar grains in older sediments. The implications of these diagenetic changes on reservoir quality are essentially porosity loss and reduction in permeability as a result of compaction, pore throat blockage due to authigenic clay minerals, substantial secondary porosities associated with dolomite, and extension of observed dissolution processes produced intragranular pores. The average porosity values ranging between 21.6 - 32.5% for the sandstone sediments in the study area, however, compare favorably with porosity values of known producing reservoirs in the world, irrespective of the observed diagenetic effects.

References


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