DIAGENETIC AND PROVENANCE STUDIES OF SANDSTONES IN PARTS OF ANAMBRA AND AFIKPO BASINS SOUTHEASTERN NIGERIA.

BY

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CERTIFICATION

This is to certify that this thesis has been read and approved as meeting the requirements of the Department of Geology, School of Sciences, Federal University of Technology, Owerri Imo State.

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This piece of work is dedicated to God Almighty - My Wonderful Provider, my ever-supportive parents for their patience, tolerance and assistance, Chidi Ikpegbu my kid brother and Ikechukwu Onunkwo my colleague both of blessed memory.
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ABSTRACT

The study of the textural and structural properties of sandstone sediments outcropping in parts of the Anambra and Afikpo Basins formed a basis for evaluating the diagenetic properties and source areas of the Cretaceous formations (Ajali, Afikpo and Amaesiri Sandstones, Mamu and Nkporo Formations) in the area. Preliminary field studies showed that the studied sandstone sediments were friable to moderately consolidated. Detailed petrological studies in thin sections revealed early diagenetic effects including the precipitation of chamosite, pyrite and hematite minerals exhibiting point-floating contacts in some of the sandstone samples. Observed deeper burial effects included physico-chemical compaction, formation of Illite and quartz overgrowths. Important post-burial effects observed in some of the sandstones, included dissolution of ankerite, quartz and labile grains. An average porosity of 32.5, 27.0, 26.6, 22.1, and 20.8% were recorded for the Ajali, Afikpo and Amaesiri Sandstones, Mamu and Nkporo Formations, respectively. These values compare favorably with known hydrocarbon producing reservoirs of the world. The Ajali Sandstone sediments, however, had the best qualities having retained a significant portion of their primary porosity, underwent the least mechanical compaction as evident from their floating and point contacts and were observed to be virtually cement-free. 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. Major elemental oxide analysis revealed samples with extreme depletion of mobile oxides and ferromagnesian minerals, which is suggestive of granitic origin for the sandstone samples. The heavy mineral suites comprising both the ultrastable (zircon, tourmaline and rutile) averaging about 70% of the non-opaque minerals and the semi-stable (kyanite, sillimanite, staurolite), is suggestive of mixed provenance of recycled sediments and Basement Complex rocks. This was further substantiated by the westernly and southwesternly paleocurrent directions recorded for the Ajali and Afikpo Formations. The Cameroun Basement Complex, the Oban Massif and Abakaliki Anticlinorium are the likely source areas for deposits in the basins.

Keywords: Diagenesis, provenance, reservoir quality, Anambra basin, Afikpo basin.
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CHAPTER ONE
INTRODUCTION

1.1 Background Information

Southeastern Nigeria is generally characterized by sediments of Cretaceous and younger ages. Oftentimes, the rocks bear evidence of their depositional environment, transporting medium, original mineralogical composition and transformational history. Such evidences can be reflected on the grain textures, sedimentary structures, and mineralogical composition. These indicators serve as tools for reconstructing ancient depositional environments as well as establishing provenance, transportational and the diagenetic history of sediments in the basins.

Diagenetic and provenance studies of sandstones in parts of southeastern Nigerian sedimentary basin have been undertaken by a number of scholars, notably the works of Amajor, (1987); Hoque and Ezepue, (1977), Nwajide and Hoque (1984); Ladipo (1988); Agumanu (1990); Odigi (1993); Samaila and Singh (2010); Odigi (2011). These studies focused on provenance sandstone geometry and depositional environments. Outcrop-based reservoir characterization was studied by Patrick et al (2002) in the western Orogrande Basin (New Mexico) using stratigraphic, petrographic and petrophysical techniques. They documented that the distribution of porosity and permeability within reservoir systems is dependent on depositional and diagenetic facies.

The study area presents very goodhydrocarbon productive trends in the southern Nigerian sedimentary basins (Avbovbo and Ogbe, 1978). The lower portion of the Nkporo Formation at the Leru section has profuse seepage of fluids suspected to be hydrocarbon on the shale /mudstone unit (Onyekuru and Iwuagwu, 2010). Oil seeps have also been reported in the post-Santonian sediments which rest on the unconformity plane of the folded Eze-Aku Group, northwest of Usumtong and Ozizza-Amante (Odigi, 2002, 2011).
Based on outcrop and petrographic analyses, the present study discusses and compares the prevailing factors responsible for sandstone diagenesis and cement paragenesis in parts of Anambra and Afikpo basins. It will provide additional information on the diagenetic history of sediments in the basins, which will enhance the assessment of sediment’s reservoir quality, in the light of increased interest in the Nigeria’s inland basins. The geochemical (using heavy minerals and major oxides composition) and paleocurrent analyses will attempt a provenance study of the sandstones in the area of study.

1.2 Justification of Study
The processes involved in the transformation of loose sediments into lithified sedimentary rocks are fundamental important geological processes in their own right and deserve to be studied as a theoretical academic discipline.

Numerous works have been published on the hydrocarbon prospectivity of southeastern sedimentary basins. (e.g.Agagu, 1978; Avbovbo and Ayoola, 1981; Agagu and Ekweozor, 1982; Ekweozor and Gormly, 1983; Akande et al., 1992; Unomah and Ekweozor, 1993; Akagbobi and Schmitt, 1998; Obaje et al., 2004; Olusola et al., 2009). Amongst the studied Inlandbasins of Nigeria, the Anambra Basin presents the best petroleum system in terms of formational source rock, reservoirs and seal lithology. Hence the need to establish a link between diagenesis and reservoir quality, in the basins to characterize the sandstones as potential reservoirs.

The study of porosity and permeability of rocks in the frontier basins especially the Anambra and Afikpo Basins is of prime importance in relation to the renewed search for oil and gas in the basins since the pore system is the main channel for movement as well as storage of fluids. Bernet et al.(2007) in the diagenetic study of Silurian quartz arenites in SE New York observed that primary porosity in sandstone samples was occluded by compaction, post-depositional cement, and infiltration or formation of matrix/pseudomatrix.
In the last 10 to 15 years, there has been considerable interest in diagenetic processes and their influence on properties of reservoir rocks. It has been realized that porosity, permeability and other reservoir properties are the result of both primary depositional facies and diagenetic alterations. Successful prediction of reservoir quality therefore depends on the understanding of diagenetic reactions and their controlling factors. The importance of clastic diagenesis to petroleum geology as a very strong driving force particularly to reservoir geology cannot be overemphasized.

Several authors over the years have utilized sedimentological studies with the associated primary and biogenic structures to deduce the provenance and characterize the depositional environment. However, it is pertinent to know that reliable provenance reconstruction can only be made with a combination of techniques. The study intend to incorporate geochemical tools in addition to the routine Paleocurrent analysis.

1.3 **Aim and Objectives**

The project is aimed at presenting an integrated assessment of sandstone diagenesis in some parts of southeastern Nigerian sedimentary basins, in order to understand clastic reservoir quality and its potential to host fluids.

The principal objectives of the study include the following:

- **Description of the texture and sedimentary structures of the different sandstone units using surface data (outcrop) and their field relationship.**
- **Granulometric analysis of the samples as a descriptive parameter to understand variability of samples with respect to hydrodynamic conditions, and textural characteristics.**
- **Comparison using Petrographic analysis (thin section) the features responsible for the diagenesis.** This shall also include among other things the distinction between mono and polycrystalline quartz as well as
variation in undulose extinction of quartz grains (Basu et al., 1975; Young, 1976; Tortsa et al., 1991)

- Diagenetic studies will also be focused on the destruction of primary porosity by compaction and precipitation of authigenic phases, as well as the abundance of matrix/pseudo matrix content.

- Determination of clay mineral transformation and distribution among the sandstones using XRD bulk mineral analysis. This shall serve as a guide to inferring the burial temperature, pressure environment and authigenic clay mineral transformation as it relates to diagenesis. (Hover et al., 1976; Boles and Frank, 1979)

- Determination of the provenance of the studied sandstones as well as the weathering conditions at the source area based on the paleocurrent data, major oxides and heavy mineral geochemistry.
CHAPTER TWO
LITERATURE REVIEW

2.1 Review of Related Literature

Numerous works on several aspects of geology has been carried out in the study area. The geology and stratigraphic disposition have been described by many workers (Reyment, 1965; Cratchley and Jones 1965; Murat, 1972; Petters and Ekweozo, 1982; Agumanu, 1986a, 1988, 1990; Nwajide et al., 1992; Reijers and Nwajide, 1997).

Published works on sandstone diagenesis in parts of the southeastern sedimentary basins include (Nwajide and Hoque, 1984; Agumanu, 1990; Odigi, 1993; Samaila and Singh, 2010; Odigi, 2011).

The study of diagenesis has been mainly observational science until recently when geologists and geochemists have obtained data on natural and artificial (laboratory) diagenetic chemical systems. Diagenesis has been restricted to those processes that cause lithification. Such a limited application however is arbitrary, artificial and impracticable. Over the past decade, the study of sandstone diagenesis attracted renewed interest. These studies have demonstrated that factors influencing diagenetic changes in sandstones include original composition, burial depth, temperature and pore-water chemistry (Blatt, 1979; Hayes, 1979). Sandstone diagenesis proceeds through several systematic steps starting with pore-space reduction by compaction, followed by pore-fill cementation, alteration, and transformation of mineral phases in some deeply buried sandstones (Wilson and Pittman, 1977). It is for this reason that porosity and permeability decrease downward in sedimentary sequences even though selective dissolution at depth may cause the development of secondary porosity within sandstones (Schmidt and McDonald, 1979).

Using the average total number of contacts per grain in a thin section, Taylor (1950) showed the usefulness in assessing the degree of compaction. He stated
that sutured contacts are due to local solution which produces wavy contact lines in the plane of the thin section, while long contacts are due mostly to pressure, noting that sandstones with packing that result in maximum porosity has a minimum number of long contacts.

Rittenhouse (1971) observed that sandstone containing ductile grain may undergo more intense mechanical compaction than those devoid of ductile grains and rich in quartz than feldspar and might loose porosity and permeability more rapidly (e.g. Greywacke).

From a study of complex diagenetic alteration, Aalto (1972), observed that irregular and microstylolitic contacts, pseudo grains, inclusion trains, and comb-like group of trains associated with strong undulosity, all reflect increase in deformational stresses and presence of special chemical environment.

Levandoski et al. (1973) while working in the Permian Lyon Sandstone of Colorado demonstrated the important role of cementation in petroleum geology, especially with regards to migration, accumulation, and storage of hydrocarbon in sandstone because it controls porosity and permeability. One interesting observation in their study was that solution and overgrowth in grains is absent where organic, iron oxide, and clay coating are thick and apparently have prevented the chemical interaction between the solutions and granular components.

Nagtegaal (1978) while relating burial diagenesis as a function of sandstone-framework stability observed that quartz-rich sandstones have higher grain strength and are less vulnerable to mechanical deformation. Arkoses and especially litharenites have, however lower framework stability and are more susceptible to deformation.

Schmidt and McDonald (1979a) while evaluating the role of secondary porosity in the course of sandstone diagenesis emphasized their importance as
exploration targets as they represent a level of optimum reservoir quality occurring at depth where primary porosity is often times no longer preserved. They interpreted this porosity to have been created by acid porewater at depth of about 3km supposedly derived mainly from maturing kerogen.

Using petrographic analysis, Agumanu (1990) discussed and compared the factors responsible for the diagenesis and cement paragenesis in Cretaceous Sandstones of the southern Benue Trough. According to him, both geologic and geochemical (pore fluid) factors aided the diagenetic processes: mechanical and chemical compaction, authigenesis, cementation and secondary porosity.

Odigi (1993) studied the petrography, diagenesis and reservoir development of sandstones in the Asu River Group, and showed that the sandstones and calcareous sandstones have undergone diagenetic alteration under low temperature and pressure. He further observed that alteration started with pore space reduction by compaction and was followed by pore-filling cement.

Akande and Erdtmann (1998) studied the burial metamorphism in Cretaceous sediments of the southern Benue Trough and Anambra Basin, Nigeria and utilized clay-mineral assemblages in sedimentary rocks and illite crystallinity to study burial diagenesis. They also used fluid-inclusion techniques to provide information on paleotemperature, pressure and composition of fluids formed during diagenesis.

Akande and Mucke (2003) used petrographic, X-ray diffraction, and microprobe analysis to describe the depositional environment and diagenesis of carbonates of the Mamu/Nkporo Formation, Anambra Basin, SE Nigeria. They were able to establish at least five diagenetic stages involving micritization, dissolution of the primary chamosite, replacement of chamosite by siderite cement, growth of blocky pre-existing minerals by goethite from textural and compositional evidence.
Agumanu and Enu (2003) studied the late Cretaceous clay distribution in the lower Benue Trough and its tectonic, diagenetic and paleoenvironmental implication. From their results, clay mineral distribution within the formations indicates that tectonics; environment of deposition and diagenesis (burial) controlled clay mineral types and their distribution pattern.

As noted by Obaje et al (2004), in the inland basins of Nigeria, the Anambra Basin presents the best naturalpetroleum system in terms of formational source rock, reservoir, and seal lithologies. Apart from interbedded marine sandstone facies in the Nkporo/Enugu shales, petroleum generated from the Nkporo/Enugu shale and Mamu coal source rocks have good reservoirs in the overlying clean quartz arenites of the Ajali Sandstone and other sandstone bodies.

Bernet et al (2007) using a combined scanning electron microscopy-cathodoluminiscence and optical microscopy (SEM-CL/OM) to study the diagenesis and provenance of Silurian quartz arenites in SE New York State, observed that about 10-15% of medium to coarse quartz sand grains showed evidence of an early inherited phase of quartz cement which is interpreted as an indication of recycling of quartz-rich sediments of the former Iapetus Passive margin.

Samaila and Singh (2010) carried out a study of porosity loss due to compaction in the Cretaceous upper Bima Sandstone NE Nigeria. The result of the work showed that apart from the isolated cases around the major faults, cementation played a bigger role in reducing the initial porosity of the sediments; compaction was generally responsible for the porosity reduction. The result also agrees with the earlier works done on other sandstone formations (Ehrenberg, 1989; Housekneccht, 1987).

With regards to the impact of sandstone diagenesis on reservoir quality, Borgohain et al (2010) in a study of the arenaceous units of Barail Group of an oilfield of upper Assam Shelf, India observed that precipitation of authigenic
mica, chert, quartz overgrowth and crystallization of cementing material are responsible for porosity reduction on one hand, while dissolution, and replacement of framework grains, intergranular fracturing and floating type of texture enhance the porosity as well as the permeability and make the reservoir sandstone highly productive.

The textural characteristics of siliciclastic units are products of weathering, transportation and sedimentary processes, while the compositions also depends on the primary chemical compositions of the source rock area and the tectonic setting of the depositional basins (Das and Haake, 2003; Jin et al., 2006). Hence composition of siliciclastic sedimentary rocks has been employed as sensitive indicator for provenance (Roser and Korch, 1986, 1988; Goetze, 1998; Cullers, 2000). Suites of heavy minerals are also used for source rock determination, in addition to paleocurrent analysis. Based on this, Amajor (1987) utilized paleocurrent and petrographic data to establish the provenance of the Ajali Sandstone deposited in the southeastern Anambra Basin, southeastern part of Anambra Basin, and showed that the sedimentary rocks on the Santonian Okigwe - Abakaliki Anticlinorium provided the major detritus, whereas minor contributions of the eastern Precambrian Basement block (Oban Massif) are confined along a narrow belt southeast of Alayi in the Afikpo Basin.

2.2 Environmental and Geological Setting

2.2.1 Location of the Study Area

Southeastern sedimentary basins are characterized by the lower Benue Trough, the Afikpo Syncline, bounded in the west by the Anambra Basin and the Niger Delta in the south. The study area is located between Longitudes 6°50’ and 7°50’E and Latitudes 5°40’ and 6°15’N(Fig. 2.0) The study area includes the following towns in southeastern Nigeria: Ohafia, Uturu, Okigwe, Ihube, Leru, Lokpanta and Afikpo.

2.1.2 Physiography

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The topography of southeastern Nigeria is generally undulating and punctuated by a few low hills here and there. This is in contrast to the northeastern parts where the relief is exaggerated by hills like the Lamuder and Ligri (Offodile, 1976)

The study area according to Nwajide(2006) is dominated by a cuesta-like landscape, an asymmetrical ridge, with its western end at the left bank of River Niger at Idah. From here it stretches northeastwards and, from close to the River Benue, turns south past Enugu to just north near Arochukwu at the right bank of the CrossRiver. Most of its scarp slope faces the CrossRiver plain. Its crest constitutes a long sigmoidal drainage divide between the AnambraRiver plain to the west and the CrossRiver catchment area to the east. The landscape stretching from the foot of the scarp face shows several isolated ridges some of which are parallel to the main axis of the cuesta. In the southwest of the area, the Awka-Orlu upland forms such cuestas, whose scarp face and dip slope gullies turned the area into badlands. The positive land forms are most probably erosional resistors left behind as the scarp face retreats westward at a rate estimated to be 9cm/1000 years (Obi et al., 2001). The dip slope of the cuesta is generally broadly undulating due to the activity of the headwaters of the Anambra and the ImoRivers, while smoothly grassed inselbergs characterize the cuesta crest (Fig. 2.0)

In the Afikpo area, sandstone hills and ridges are striking NE-SW with steep-sided valleys presupposed to be made of shale in the northern part of the basin. The set of sandstone ridges observed in the area have an estimated average elevation of about 250m while the intervening low-lying shale-dominated plains are about 100m above sea level. Drainage is controlled by the Cross-River and its tributaries especially Ebonyi drainage system.
Fig 2.0:  Location, Accessibility and Topographic map of the study area
2.2 Geological Setting

2.2.1 Tectonic Evolution

The tectonic evolution of southeastern Nigeria may be traced back to the late Jurassic when conventional currents in the asthenosphere caused the break-up of the African plate and left the Benue Trough as a failed arm of RRR Triple junction (Burke, 1972; Olade, 1975).

From the study of sedimentary and tectonic history of southeastern Nigeria, Nwajide and Hoque (1984) summarized the tectonic evolution into four stages as described below in chronological order of their origin and development.

Rifting Stage:
A graben-like depression is formed by crustal extension followed by rifting, with broad lip adjoining the western margin of the trough (Anambra platform) and a smaller lip on the southern edge (the Afikpo platform)(Fig 2.2).
**Trough Stage:**

The first marine transgression took place in Albian (or Aptian) times; the trough was widened and deepened. There was a mild deformational episode during the Cenomanian which restricted deposition only in southern part of the trough. The Cenomanian deformation was perhaps very local (Nwachukwu, 1972) and may have originated due to reactivation of the basin along basement faults.

**Deformation Stage:**

The accumulation of thick sediments 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 to form the Anambra Basin and the Afikpo Syncline. Large-scale alkaline basaltic volcanism took place. (Hoque, 1984).

**Platform Stage:**

The deformed and uplifted (Benue-Abakaliki) trough became a positive element to shed detritus; the depressed platforms of Anambra and Afikpo became the major depocenters. In environments ranging from marine to parallic to fluvial, about 4000m of Post-Santonian sediments were deposited in the Anambra Basin. They are largely undeformed, but broadly upwarped with a few degree of dip towards the cratonic margin of the trough.
2.2.2 Paleogeographic History and Basin Fill
Reyment (1965) described the stratigraphy of the different depositional basins in the country and created a large number of lithostratigraphic and biostratigraphic divisions. Murat (1970; 1972), Petters (1978) presented the paleogeographic description of the Cretaceous and Lower Tertiary in southern Nigeria based on major depositional cycles resulting from three main tectonic episodes (fig 2.3). The general Stratigraphic correlation as described by Nwajide (1990) is shown in Table 1 and graphically presented in Figure 2.4.
Fig 2.3: Cretaceous to Recent paleogeographic evolution of Nigerian rift

(from Petters, 1978).
Fig 2.4 : Maps showing (a) the geology (b) the regional framework of southeastern Nigeria and (c) the West African subregion and the location box of the study area. *(After, Akande and Erdmann, 1998)*
Table 1: Correlation chart for Early Cretaceous-Tertiary strata in Southeastern Nigeria and Niger Delta (*Modified from Nwajide, 1990*)

<table>
<thead>
<tr>
<th>Age</th>
<th>Basin</th>
<th>Stratigraphic Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligocene-Recent</td>
<td>Niger Delta</td>
<td>Ogwashi-Asaba Fm, Benin Formation</td>
</tr>
<tr>
<td>Eocene</td>
<td>Niger Delta</td>
<td>Ameki/Nanka Fm, Nsugbe Sandstone (Ameki Group), Agbada Formation</td>
</tr>
<tr>
<td>Thanetian</td>
<td>Niger Delta</td>
<td>Imo Formation, Akata Formation</td>
</tr>
<tr>
<td>Danian</td>
<td>Anambra Basin</td>
<td>Nsukka Formation</td>
</tr>
<tr>
<td>Maastrichtian</td>
<td>Anambra Basin</td>
<td>Ajali Formation</td>
</tr>
<tr>
<td>Campanian</td>
<td>Southern Benue Trough</td>
<td>Mamu Formation</td>
</tr>
<tr>
<td>Santonian</td>
<td>Southern Benue Trough</td>
<td>Agwu Formation</td>
</tr>
</tbody>
</table>

The critical factors that governed the paleogeographic evolution of the study area were the paleomorphology, the proximity of sediments source areas, regular incursions of the sea during the Campanian-Eocene and the paleo-circulation pattern (Nwajide and Reijers, 1996b). As deduced from Murat (1972), there was a gradual straightening of the coastline over the course of time. The funnel-shaped Anambra shelf probably generated two drift cells as opposed to the four independent cells of today’s Guinea’s current. In the Anambra Basin there were both a southwest-northwest-directed drift cell and a southeast-northeast-directed cells. Therefore, the converging flows pointing towards the apex of the embayment must have led to constriction and caused sedimentation dominated by stream waves and tides during those periods when the circulation was governed by transgressive tendencies. During pronounced regression (lowstand) phases, however, riverine input from the proto-Niger river
dominated, leading to a progressive closing of the funnel-shaped estuary and smoothing out of the coastline.

In line with Kogbe(1975) the paleogeographic history and basin fill of southern Nigeria including the Anambra and Afikpo Basins showing the nature and extent of trangressive, regressive phases as well as nature of sediments is summarized below.

**Albian**

The earliest documented marine transgression in Nigeria occurred during the middle Albian. Outcrops of Albian age are well developed in the Benue Trough where they generally outcrop in the core of the main anticline structures (Abakaliki Anticlinorium). Albian sediments constitute the Asu River Group and its lateral equivalents. The Asu River Group consists of olive brown sandy shales, fine-grained micaceous sandstones and micaceous mudstones. Bluish grey or olive brown shales, which weather to a rusty brown color, are also present. Although this sequence is poorly fossiliferous, there are occasional outcrops of thin Shelly limestone with presence of fossils like ammonite. The thickness is about 1,800m on the average (Obaje et. al. 1999). Asu River Group is Albian in age and was deposited under marine conditions (Whiteman, 1982).

The rich Ammonite fauna of this group include genera such as *Oxytropidoceras, Hystroceras, Mortinoceras, Elobiceras* and *Dipoloceras*. These fossils date the first marine inculcation in the Benue Trough as middle to late Albian.

**Cenomanian**

From available published information, the Cenomanian was a largely regressive stage in most parts of the country. Dated marine deposits of Cenomanian age are found in southeastern Nigeria in Odukpani Formation near Calabar as well as in the middle Benue valley. (Reyment 1965). In the Benue valley, the Cenomanian regression was characterized by extensive deltaic developments with the continued deposition of the Bima Sandstone (Carter et al., 1963).
**Turonian**

The generally continental conditions existing during the Cenomanian was terminated by marine transgression at the beginning of the Turonian. The sea invaded the interior of Nigeria from the Gulf of Guinea as far as the Benue valley (Furon, 1960; Murat, 1970).

The Turonian consist of fossiliferous marine series outcropping throughout the Benue Trough. The lower and middle Benue Trough are represented by the Eze-Aku Formation, which consist of hard grey and black calcareous shale, limestones and siltstones. The thickness varies, but may attain 1000m in some places (Reyment, 1965; Dessauvagie, 1975). Offodile(1976) recorded a thickness of 304.8m in the Oturkpo division and noted that the thickness ranges up to 609.6m toward the south. The formation is overlain by about 900m of bluish grey, bedded shale with some fine grained carbonaceous limestone beds (Agwu Shale) locally replaced by sandstone (Agbani Sandstone). Near Afikpo, the Eze-Aku shale grades locally into sandstone (Amaesiri Sandstone). Marine fauna such as ammonites, gastropods, pelecypods, and foraminifera characterize the formation (Fayose and de Klasz, 1976; Arua and Rao, 1978; Petters, 1978; Banerjee, 1980, 1981).

Murat (1972) and Banerjee (1981) have attributed the Eze-Aku Formation to deep marine clastic sediments while Umeji(1985) attributed it to a subtidal shelf environment.

**Coniacian-Santonian**

The regression that began in the Coniacian ended in the lower Benue Trough during the Santonian and the Abakaliki area emerged completely. The Anambra Basin remained paralic and the Enugu/Nkporo Shales were deposited. Clastic deposits were generated by erosion of the Abakaliki high and deltas formed along the margin of the Anambra Basin (Owelli/Otobi and Afikpo Sandstones).
The upliftment and folding of the Abakaliki Anticlinorium led to the exposure and subsequent erosion of the Coniacian, Turonian, and Albian formations. Consequent to this upliftment, two depressions were formed flanking the Abakaliki Anticlinorium. They consist of the wide Anambra Basin to the NW and the narrow Afikpo Syncline to the southeast. These depressions became the main foci of deposition during the Campanian to Paleocene.

**Campanian**

The Campanian began with a short marine transgression followed by a regression. In the South-eastern Nigeria, it marks the deposition of the Nkporo Group which reflects a funnel-shaped shallow marine shelf setting that graded into channeled low-energy marshes (Reijers, 1996). The concave inward shape of the coastline allowed a gradual filling by minor amounts of sediment brought in by short rivers, that were carried along by north-eastward converging longshore drifts. Behind poorly developed foreshores and shorefaces, extensive coastal swamps could be expected (Enugu Shale). Within the swamps, fluvial point bars were formed that were preserved as the Owelli Formation. The shallow open marine shelf sea was alternatively storm- and tide- dominated. (Reijers, 1996).

Planktonic foraminifera are generally rare but Agagu et al. (1985) identified some benthonic foraminifera such as *Bulimina Prolixa, Ammobaculites sp and Gavelinela sp*, and attributed the prevalence to a normal shelf environment. Reyment(1965) also described the Maastrichtian zone of *Libycoceras afikpoensis* in the Nkporo Formation while Agagu et al.(1985) from their benthonic foraminifera suggested a Campanian to Maastrichtian. The Owelli sandstone is unconformably overlying the Agwu shale (Reyment, 1965). The sandstone is typically thickly bedded and prominently tabular, planar and trough cross-bedded. It is poorly sorted, medium to coarse- grained to pebbly. Deposition is inferred to be point bars in meandering river system that drained the Abakaliki fold belt (Agumanu, 1993).
**Maastrichtian**

The broad shallow sea gradually became shallower during this period and the paralic sequence of the Mamu Formation was deposited (the Lower Coal Measure) as a narrow strip trending N-S from the Calabar Flank, swinging west round the Ankpa plateau and terminating at Idah near the River Niger (Geological Survey of Nigeria, 1987). The Mamu coastal plain was drier than previous swamp deposits. This formation was overlain by the continental sequence of the Ajali Sandstone which marks the height of the regression at a time when the coastline was still concave, albeit less “embayment-like”. Two converging littoral drift cells governed sedimentation and are reflected in tidal sand waves which are characteristic for Ajali Sandstone.

The Mamu Formation delineated here is stratigraphically synonymous to the Lower Coal Measures (Tattam, 1944; Simpson, 1954; Reyment and Barber, 1956). On surface sections, the Mamu Formation comprises of shales, fine sands, heteroliths of both lithologies and coal. The shales are dark and often splintery. They are interlaminated with fine sandstones and siltstones. They sandstones are dominantly fine, occasionally medium grained. The sandstones are mineralogically mature, being composed almost exclusively of quartz and the ultrastable heavy minerals: zircon, tourmaline, and rutile (Nwajide and Reijers, 1996b). Nwajide and Reijers,(1996c) recognized *Teichichnus sp and Ophiomorpha sp*. The subsurface shale interbeds contain *Ostracods sp*, and arenaceous foraminifera, mainly *Haplophragmoides*. The Mamu Formation is essentially marine, with a relatively short lasting paludal intermission during which mud deposition was promoted.

The Ajali Formation (Reyment, 1965), replaced such terms as the “Sandstone Series”, “White False-beded Sandstone” and “Eagle Rock Sandstone” (Bain, 1924) and the “False-beded Sandstone” (Tattam, 1944). Because of its characteristic friability and weak consolidation, the Ajali Formation is highly erodible and so it’s often exposed in gullies. They are fine to pebbly-grained,
poorly to fairly well-sorted and friable. Cross-stratification is ubiquitous and bioturbations is restricted to specific horizons. The unit is typically white in colour due to the dominant kaolin matrix. Red beds intervals are common.

The Ajali Formation is generally thought of as continental in origin (Grove, 1951; Reymet, 1965). However the bulk of the sedimentary structures reflect periodic reversal of tidal current directions separated by episodes of slack water (Banerjee, 1979; Amajor, 1987; Nwajide and Reijers, 1997).

The Nsukka Formation overlies the Ajali Formation conformably. The formation consists of an alternating sequence of laminated very fine-grained sandstone and siltstone. There are also brown and grey shales and sandy shales and mudstones, with fossiliferous limestone and shale occur within the formation around Item-Alaiyi, near Ohafia (Onyekuru, 2008). The friable Nanka Formation is well exposed in various localities in the central Anambra area and has been studied (Nwajide and Hoque, 1979; Nwajide, 1980). The friability and poor consolidation of the sandstone has rendered it particularly susceptible to erosion, resulting in spectacular gullies that have devastated vast areas south of Awka.

The depositional environment of the Nsukka Formation inferable from surface exposure appear similar to that of the Mamu Formation. Marine influence is however higher in the Nsukka Formation into the overlying marine Imo Formation. Ages ranging from Maastrichtian to Paleocene has been assigned to the Nsukka Formation (Simpson, 1954; Reymet, 1965)

**Paleocene**

The Nsukka Formation marks the onset of the Sokoto transgression (Murat, 1972) and documents a return to paludal conditions. Sedimentation was mainly of fluvial origin. However, at the height of transgressive phases it was punctuated by marine flooding reflecting continued convergence of two littoral-drift cells controlling shoreface sedimentation. The Imo shales reflect
shallow-marine shelf conditions in which foreshore and shoreface sands are occasionally preserved (Petters, 1981). The Imo Formation consists of blue-grey clays and shales and black shales with bands of calcareous sandstone, marl, and limestone (Reynment, 1965). Ostracod and foraminiferal biostratigraphy (Reynment, 1965), and microfauna recovered from the basal limestone unit (Arua, 1980) indicate a Paleocene age for the formation. Lithology and trace fossils of the basal sandstone unit reflect foreshore and shoreface or delta front sedimentation (Anyanwu and Arua, 1990 ;). The Imo Formation is the outcrop lithofacies equivalent of the Akata Formation in the subsurface Niger Delta (Short and Stauble, 1967; Avbovbo, 1978).

**Eocene**

Regression continued throughout the Eocene (Jones, 1964; Reynment ,1965). Lower and Middle Eocene deposits in the Gulf of Guinea include the clastic exposed Ameki and Nanka Formation The progradational Nanka Formation marks the return to regressive conditions. The outcropping deposits of the Eocene regression, which marked the beginning of the Niger delta progradation, constitute the Ameki Group which includes tidal facies and backshore as well as pro-deltaic facies. Well exposed, strongly asymmetric sandwave suggest the predominance of flood-tidal currents over weak ebb-reverse currents (Nwajide, 1979; 1980). The prograding shorefaces and river plain deposits are reflected in the subsurface deposits of the Agbada Formation in the northern depobelts of the Niger delta, whilst the marine Imo Shale equivalent in the subsurface is termed the Akata Formation.

The Ameki Group consists of the Nanka Sand, Nsugbe Formation, and Ameki Formation (Nwajide, 1979), which are laterally equivalent. The Ameki Formation outcrops in the study area, and is predominantly alternating shale, sandy shale, clayey sandstone, and fine-grained fossiliferous sandstone with thin limestone bands (Reynment, 1965; Arua, 1986). The age of the formation
has been considered to be either early Eocene (Reyment, 1965) or early middle Eocene. The depositional environment has been interpreted as estuarine, lagoonal, and open marine, based on the faunal content. White (1926), Interpreted an estuarine environment because of the presence of fish species of known estuarine affinity. Nwajide (1979) and Arua (1986) suggested environments that ranged from near shore (barrier ridge-lagoonal complex) to intertidal and subtidal zones of the shelf environments, whereas Fayose and Ola (1990) suggested that the sediments were deposited in marine waters between the depths of 10 m and 100 m.

It is quite possible that the basal beds of the Ogwashi-Asaba Formation are partly Oligocene in age (Kogbe, 1985). During the Miocene, the Niger Delta continued to build up and prograde seawards. There was a lowering of sea level during the Pleistocene. The River Niger cut wide valleys through its own delta. These troughs are being filled today as the sea level gradually rises. Figure 2.5 summarizes the geology of the study area.
Fig 2.5: Geologic Map of the study Area
CHAPTER THREE

MATERIALS AND METHODS OF STUDY

3.1 Field Study

The field study entailed a geological mapping of the study area. The mapping was completed within subsequent field trips that took four days and was basically aimed at examination of outcrop sections, the lithologic relationship in the outcropping profile, the nature of contacts, and the sedimentary structures. The attitude of the bed and other structural features were measured with the aid of Brunton/Silver compasses, while steel tape was used to measure the vertical thickness of the units. A geologic hammer was used for collection of samples followed by labeling and packaging.

Most parts of the study area are heavily vegetated and deeply weathered, thus fresh, exposed rock sections are restricted to some road cuts, ridges, quarries and erosional gullies. A total of ten (11) outcrop locations we areinvestigated during which a total of 35 carefully selected spot samples were collected for closer observation and laboratory analysis.

3.1.1 Lithostratigraphical Studies

Lithostratigraphic studies involved the following:

- Review of different aspects of works on the Sandstone units in the study area.

- Detailed geological mapping to examine outcrop sections and the lithofacies relationship in the outcropping profile, the nature of the breaks or boundaries within or between units, the sedimentary structures and sediment thickness.

- Bed-by-bed sampling to cover the representative samples in a section. Measurement of structural features such as dip and strike with a Silver
Compass. Material for paleocurrent analysis such as pebble and macro faunal imbrications, prod marks, were also examined.

- Description and sketching of lithologic logs of exposed rock sections to mimic grain size profiles and photographing of important features in the logged sections.
- All sampled locations were referenced to the base map using a Geographical position system (GPS).

3.2 Laboratory Study

3.2.1 Granulometric (Sieve) Analysis for Sand-size Particles.

Sieving is a method of mass measurement used in evaluating the size frequency distribution of sedimentary particles in the sand-size fraction -1Φ to 5Φ(0.062-2.00mm). This was carried out at the Department of Geosciences, Federal University of Technology, Owerri. The equipment for this analysis includes a set of sieves, an automatic sieve shaker, and a sensitive beam balance. Sandstones amenable to sieving are the loose and friable sandstones, poorly cemented calcareous and ferruginized sandstones.

Twenty six (26) sandstone samples selected for the analysis were first sun-dried. 50-130g of each sample was shaken in a nest of sieves arranged in full (Φ) intervals with an automatic sieve shaker for 15 minutes. The sand fractions retained in each sieve were then weighed and the weight recorded in a sieve analysis data sheet. The weight percents and cumulative frequency curves are presented graphically as histograms and cumulative frequency curves. The cumulative frequency curve was presented on probability (log) scales for the percentile ordinate of Friedman and Sanders(1978). Grain sizes of 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentile were obtained and were used to calculate the graphic mean, standard deviation, inclusive graphic skewness and graphic kurtosis for each sample. These calculations were based on formulae proposed by Folk and Ward (1957).
Statistical Grain Size Parameters Evaluated

Simple statistical techniques were used to evaluate the grain size distribution data. The principal form of analysis used for this study is the graphical methods, in which values derived directly from plotted cumulative curves are imputed into established formula. The derived values from the plots were used in calculations to determine some predetermined parameters. The principal parameters fall into four categories and they include

- Measure of average grain size (Mean)
- Measure of spread of the size around the average(Standard Deviation or Sorting)
- Measure of degree of asymmetry (Skewness) and
- Measure of degree of peakedness (Kurtosis). The parameters are necessary for the construction of scatter diagrams needed for environmental interpretation because size frequency distribution among sands sometimes correlate with their various origin and terminal environment of deposition (Boggs, 2006).

Average Grain Size

Three mathematical measures of average grain size are in common use. The mean, median and mode. The best graphic measure for determining the overall grain size is the Graphic Mean ($M_M$). It is computed from size of particles spread through a range of percentile values. It corresponds very closely to the mean as computed from moment method yet much easier to evaluate. It is much superior to the median because it is based on three points and gives a better overall picture. The formula used for calculating mean is given below:

$$M_M = \frac{\Phi_{16} + \Phi_{50} + \Phi_{84}}{3}$$
Sorting
This is a measure of the range of grain sizes present and the magnitude of the spread or scatter of these sizes around the mean size. The best measurement of this parameter is the Folk’s (1957) Inclusive Graphic Standard Deviation ($σ_I$). This formula includes 90% of the distribution and it is the best overall measure of sorting. The formula for calculating standard deviation is given below.

$$σ_I = \frac{Φ84 - Φ16}{4} + \frac{Φ95 - Φ5}{6.6}$$

Skewness
Skewness reflects sorting in the “tails” of a grain-size population. Populations that have tail of excess fine particle are said to be positively skewed or fine skewed i.e. skewed toward positive phi values. Populations with a tail of excess coarse particles are negatively skewed. The formula for calculating skewness is given below.

$$Sk = \frac{Φ84 + Φ16 - 2Φ50}{2(Φ84 - Φ16)} + \frac{Φ95 + Φ5 - 2Φ50}{2(Φ95 - Φ5)}$$

Kurtosis
Kurtosis ($K_G$) is related to both dispersion and the normality of the distribution. Kurtosis may be leptokurtic when the curve is strongly peaked, in which case have exceptionally good sorting of the central part of the distribution and may be platykurtic when the curve is flat showing poorly sorted sediments or those with bimodal frequency curve. The formula for calculating kurtosis is given below.

$$K_G = \frac{Φ95 - Φ5}{2.44 (Φ75 - Φ25)}$$
Multivariate Parameter

This statistical method was employed by Sahu (1964) to investigate the problems of discrimination between different processes and the depositional environments of sands using size distribution. He established several discrimination functions by multivariate analysis in order to distinguish between adjacent mechanism and the environments that have closely related energy conditions.

Multivariate parameter is also computed for the sandstones in the study area by:

\[ \text{Yu} = 0.2852 \text{Mz} - 8.760452 \sigma^2 - 4.8932\text{Sk} + 0.0482\text{KG}. \]

If the computed values of Yu > - 7.419, it is interpreted as shallow marine deposits while value of Yu < - 7.419 is interpreted as fluvial deposits.

3.2.2 Pebble Morphometric Analysis

The primary objective of pebble morphometric analysis is for paleo-environmental diagnosis. The samples used here are pebbles greater than 2.00mm in diameter. One basic requirement in pebble morphometric analysis is that the pebbles used for measurements must be stable and of one mineral species. Vein quartz pebbles satisfy these conditions and have been satisfactorily used for morphometric analysis. Dobkins and Folk (1970) used volcanic rock pebbles for pebble analysis in Tahiti Nui. Nwajide and Hoque (1982) employed quartz vein pebbles in the Makurdi Sandstone.

A total of 30 pebbles each from the Ajali and Afikpo Sandstones were picked for the analysis. The analysis was carried out in the Department of Geosciences, Federal University of Technology, Owerri. It involved the measurement of the three mutually perpendicular diameters of particles (> 2.00mm) using Venier Calipers namely: long (L), intermediate (I) and short (S) axes. The roundness of each pebble/particle was qualitatively estimated by noting the proportion of the maximum projection perimeter of the pebble that is convex (rounded), using
Sames (1966) pebble images for visual roundness. The dimensions are presented on a data sheet for morphometric analysis. The averages of L, I and S for the samples are computed and applied in the computation of pebbles morphometric parameters as follows:

- Flatness index, S/L (Lutig, 1962; Sames, 1966)
- Elongation index, I/L (Lutig, 1962; Sames, 1966)
- Maximum Projection Sphericity(S^2/LI)^{1/3} (Sneed and Folk, 1958).
- Oblate Prolate (OP) Index, \(\frac{10(L-I-0.5)}{(L-S)/(S/L)}\) (Dobkins and Folk, 1970)
- Form(L-I)/(L-S) (Dobkins and Folk, 1970)

### 3.2.3 Thin Section Petrographic Analysis

Thin section petrographic analysis is the primary technique for gathering detailed petrographic information. It was used to investigate petrographic characteristics of the sandstone units in the study area for the documentation of depositional and diagenetic fabric, matrix content, grain contact, roundness of quartz, sandstone maturity, porosity and mineralogy. Thirteen fresh samples of the sandstones in the studied area were selected for thin section petrography. The analysis was carried out at the Department of Geology, University of Portharcourt, River State. The friable samples were impregnated with resin before cutting. The samples were each mounted with polished side on a glass slide with araldite and Canada balsam. The mounted sample was ground on a lap wheel with a coarse abrasive and was later washed with water. This was followed by manual grinding with sludge of fine abrasive on a glass plate until the slide was fine or thins enough for individual mineral identification. The slide was then thoroughly washed with water and allowed to dry before covering with a cover slip. The point-counting method, according to Ingersoll et al. (1984) and Osae et al. (2006) was employed for quantitative compositional analysis of the different mineral grains. This has advantage of minimizing compositional dependence on grain sizes as sandstones of different sizes can be
compared. The modal analysis was also performed by counting more than 300 points per thin section as reported by Gazzi (1966) and Dickinson (1970), while the slides were examined under the flat stage of a petrological microscope and classified based on Folk (1974).

3.2.4 X-ray Diffraction (XRD) Analysis

X-ray powder diffraction (XRD) is a rapid analytical technique primarily used for phase identification of a crystalline material and can provide information on unit cell dimensions. X-ray diffraction is based on constructive interference of monochromatic X-rays and a crystalline sample. These X-rays are generated by a cathode ray tube, filtered to produce monochromatic radiation, collimated to concentrate, and directed toward the sample. The interaction of the incident rays with the sample produces constructive interference (and a diffracted ray) when conditions satisfy Bragg's Law \( n\lambda = 2d \sin \theta \). This law relates the wavelength of electromagnetic radiation to the diffraction angle and the lattice spacing in a crystalline sample. These diffracted X-rays are then detected, processed and counted. By scanning the sample through a range of 2θ angles, all possible diffraction directions of the lattice should be attained due to the random orientation of the powdered material. Conversion of the diffraction peaks to d-spacings allows identification of the mineral because each mineral has a set of unique d-spacings. Typically, this is achieved by comparison of d-spacings with standard reference patterns.

Five samples of the sandstones exposed at km 65 Uturu-Okigwe road, Leru, Km 75 along Portharcourt-Enugu road, and McGregor Hill 2km from Afikpo town, Afikpo were examined. The study generally involved the isolation of clay fractions in sandstone samples, glycolation (using ethylene glycol in dessicators) to allow expanding clays to be conveniently investigated and heating to 375°C collapses smectite and illite-smectite fractions while leaving
other clay fractions unaffected. Kaolinite faction is destroyed as the temperature gets to 550°C.

The analysis was carried out at the National Geoscience Research Laboratory Centre Kaduna with EMPRYEAN XRD by PANALYTICAL with Copper anode and radiation at 40KV and 55mA. The diffractometer was equipped with PC-APD in-built diffraction software which produced the diffraction signatures.

3.2.5 Major Elemental Oxide Composition

Eight samples were selected for geochemical analysis using X-ray fluorescence (XRF) method. This analysis was aimed at determining the elemental oxide composition of the selected samples from the study area. The analysis was carried out at the National Geoscience Research Laboratories Centre, Kaduna.

The samples were prepared by grinding into fine powder of mean particle diameter of 50μm in a Tungsten Carbide Spex Mill. 10g of each finely pulverized rock sample was moistened with 5-6 drops of a binder (10% solution of PVC in toluene) and was thoroughly homogenized in agate mortar and then allowed to dry. It was then pressed into pellet by a pressure of 10 tons using SPEDAC hydraulic press.

The elemental oxides composition of each pellet was obtained using the wavelength dispersion method. When the wavelengths of the elements were obtained, the observed wavelength patterns were interpreted and converted to oxide forms using a computer software program.

3.2.6 Heavy Mineral Separation

Heavy minerals are defined operationally as those with specific gravity greater than 2.85, the specific gravity of bromoform liquid used to separate them from lighter quartz, feldspar or calcite. They represent the accessory and varietal minerals of igneous and metamorphic rocks, which are much reduced in quantity (except for zircon and tourmaline) as they pass into sediments because they are chemically unstable and also considerably softer than quartz. Although over 100 different minerals have been recorded from sediments, they probably
form no more than 0.1-0.5% of the terrigenous fraction of sediments. Despite their small amount, they are of great value in studying provenance, transportation and weathering history of a sediment and correlation and paleogeographic studies.

Ten (10) disaggregated samples were carefully selected for heavy minerals separation. Each sample was boiled with dilute hydrochloric acid for about 15 minutes to eliminate calcareous materials and to clean the grains. The boiled samples were subsequently thoroughly washed with water to remove the acid effect; oven-dried and sieved through a 60-mesh sieve. The sieved fractions were then used for the heavy mineral separation analysis.

Bromoform of specific gravity of 2.85 was the heavy liquid used as the separating medium. 5g of each treated sample was taken and emptied into a separating funnel containing bromoform. The mixture was rigorously stirred and then allowed to settle. The separating funnel tap was then opened to allow all the heavy metals that settled to its stem to be flushed out into a filter paper fitted into a glass funnel in a conical flask. The separated heavy minerals were then washed with acetone (to remove the effects of the bromoform), oven-dried and then mounted on glass slides with Canada balsam.

Examination and identification of the heavy minerals were carried out under transmitted light flat stage petrographic microscope on the basis of their optical properties. The number, size and shape of the different opaque and non-opaque minerals were noted. Maturity index or “ZTR index” (Hubert, 1962) was calculated using the formula:

\[ ZTR = \frac{Zircon + Tourmaline + Rutile}{No \ of \ Non- opaque} \times 100 \]

The ZTR index is used as a scale for the estimation of the degree of modification of the entire heavy mineral assemblage of the selected rock sample from the study area.
CHAPTER FOUR

DATA PRESENTATION, RESULTS AND INTERPRETATION

4.1 Description of Lithostratigraphic Sections

4.1.1 Lithologic Description of Amaesiri Sandstone At Km 8 Along Afikpo-Uturu Road Near Abakiliki Junction.

The section is about 17m thick. Four units were altogether logged. The lowermost contact was not seen. The basal unit consist of highly weathered, laminated, grayish silty shale of about 1.5m thick. It is overlain by friable and whitish fine grained sandstone of about 4.5m thick. A sharp contact was established between this unit and the underlying silty shale unit. Overlying the fine grained sandstone, is a 4m thick yellowish brown, medium grained sandstone. The unit is overlain by a poorly sorted coarse grained sandstone about 4m thick. Figure 4.0 shows the legends as used in the descriptions, while figure 4.1 describes graphically the litholog of Amaesiri Sandstone.

![Legend for the Lithostratigraphic sections](image)

Fig 4.0: Legend for the Lithostratigraphic sections
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amaesiri</td>
<td>15</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Poorly sorted coarse grained sandstone</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Yellowish brown, medium grained sandstone.</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Friable and whitish fine grained sandstone with a sharp contact with the underlying unit</td>
</tr>
<tr>
<td></td>
<td>0m</td>
<td>Cs Gv</td>
<td>Highly weathered, laminated, grayish silty shale</td>
</tr>
</tbody>
</table>

Fig 4.1: Litholog of Amaesiri Sandstone at km 8 Afikpo-Uturu road.
4.1.2 Lithostratigraphic Description of Nkporo/Mamu Formation at Leru.

The section is exposed at Leru, about kilometer 72 along the Enugu-Portharcourt express way. The location is defined by Cartesian coordinates Latitude N5°55’180” and Longitude E07°24’60”. The major lithology is sandstone, mudstone and shale. Sedimentary structures observed include planar and trough cross-beds, ripple marks, Skolithos and Ophiomorpha ichnogenera.

The base of the section was presumed to start at an angular unconformity on top of the Eze-Aku Shale which was intruded by dolerites. This is evidenced by the scattered igneous boulders seen around the area (Nwajide and Reijers, 1996c).

The total logged section is about 70 m (Fig. 4.0). The basal part of the section consists of thinly laminated, micaceous, pyritic shale about 30m thick, with thin mudstone beds. Nwajide and Reijers(1996c) identified ostracods, gastropod, foraminifers and ammonites in the section. Onyekuru and Iwuagwu (2010) also identified the following fossils: *Haplophragmoides sp*, *ammobaculite sp*, *Bolivina anambra*, *Ammotium nwabium* etc. Upwards, there is a horizon composed of cm-scale beds of grey fossiliferous limestone. The succeeding section is covered by vegetation. The middle portion above the covered section is characterized by heterolith (sandstone/shale) bedding (Fig 4.3). Sandstone beds thicken up the section as can be seen in the road cut on the Portharcourt-bound side of the expressway. The sandstones are sideritic and also contain minor dawsonite and ankerite (Odigi, 2011). Their characteristic sedimentary structures are large-scale trough cross-bedding succeeded by wave-rippled lamination in the fine-sand facies. The shale/sandstone interbedding is overlain by a clean, medium grained, planar cross-bedded sandstone whose top is heavily burrowed (Figs. 4.4 and 4.5). The cross-beds dip at 4° in the direction of 214° azimuth. The section is overlain by rippled 1m thick interbedding of shale and siltstone. The unit is capped by a ferruginized firm ground which in turn is
overlain by mudstone bed containing ironstone concretions. Nwajide and Reijers (1996c) showed that in thin section, the ironstone consist of chamosite ooids in a groundmass of granular siderite and pyrite. A meter-scale, sandstone unit, presently ferruginized with reddish colour and profusely transverse by predominantly horizontal Ophiomorpha caps the Leru section (Fig. 4.6).

As noted by Onyekuru and Iwuagwu (2010), the bioturbated ferruginized red sandstone and the ironstone impregnated mudstone bed dip at $0^\circ$ and thus maintain an onlap contact with the lower dipping beds of the section marked by the ferruginized hardground. This probably form the boundary between the Mamu Formation and the underlying Nkporo Shale (Fig. 4.7).

The preservation of primary lamination suggests bottom anoxia as noted by the absence of bottom eating benthos. The deposition of lime mud is linked to deepening and prevalence of open marine setting in which occasional blooming may have caused (super) saturation in relevant carbonate component (Nwajide and Reijers, 1996c). Also, they note that the thick sand beds in the midsection indicate a marked shallowing to a marginal shallow marine environment. Subsequent deepening re-introduced reducing conditions as evidenced by the deposition of the shale unit, even though intermittent shallowing resulted in the wave-formed chamosite ooids.
**Formation**

<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mamu</td>
<td>70</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Bioturbated Red Sandstone.</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Pyritic mudstone</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Siltstone/shale/sandstone interbeds with ferruginized top</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Thick X-bedded sandstone with burrows (Ophiomorpha), top bed show reactivation surface.</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Intensely burrowed top (skolithos), erosive base with black shale with fine-medium sand intercalations</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Well sorted, rippled top part, bioturbated, large-scale trough-bedded sandstone, with interbeds of burrowed (skolithos),</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Siltstone-Shale interbeds</td>
</tr>
<tr>
<td>Nkporo</td>
<td>0</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Micritic fossiliferous Limestone</td>
</tr>
<tr>
<td></td>
<td>10m</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Thinline laminated, micaceous, pyritic shale with interbeds of calcareous mudstones concretions</td>
</tr>
</tbody>
</table>

**Fig 4.2:** Litholog of the Leru Section km 72 along Enugu-Portharcourt Road.

39
Fig 4.3: Sandstone/Shale interbeds at Leru section

Fig 4.4: Planar cross-bedded sandstone at Leru section

Fig 4.5: Intensely burrowed top of cross-bedded sandstone at Leru
Fig 4.6: Pyritic mudstone overlain by ferruginized Bioturbated Sandstone

Fig 4.7: Leru 1 section at Km 72 along Portharcourt-Enugu Road showing the onlap between the overlying Mamu Formation (white arrow) and underlying Nkporo Formation (yellow arrow) (note the variability in dip of the units)
4.1.3 Lithostratigraphic Description of Afikpo Sandstone At Megregory Hill Near Ebonyi Hotels

The section crops out along Uturu-Afikpo road about 2-3 km to Afikpo town. It has a lateral spread of about 30m and a vertical thickness of 9m. Six units altogether were described (Fig. 4.8). The Lower unit consist of a 0.5m thick medium-coarse indurated and intensely bioturbated whitish sandstone with abundant clay particles. The biogenic structures are straight and branched burrows notably skolithos and Ophiomorpha. The unit exhibited a sharp contact with the overlying 0.7m thick coarse-pebbly, poorly sorted sandstone. This unit also exhibits an internal fining upward motif with angular pebbles at the base. The overlying unit is a 1m thick planar-trough cross-bedded, fine-medium grained sandstone with trace pebbles, dipping at 2° in the direction of 200° Azimuth. The unit is also slightly bioturbated. A 2m thick unit comprising of internally graded whitish sandstone overlies the cross-bedded sandstone. Each unit starts with coarse-pebbly sandstone grading upward into medium to very fine sandstone. The overlying unit consist of intercalations of fine sandstone with intervening bands of laminated siltstone about 0.6m thick. The topmost unit consists of 2m thick very coarse poorly sorted sandstone with a band of imbricated cobbles at the base.
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afikpo Sandstone</td>
<td></td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Very coarse poorly sorted sandstone with imbricated cobbles at the base.</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>Intercalations of fine sandstone with beds of laminated siltstone.</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td>Internally graded whitish sandstone with coarse-pebbly base grading upward into medium to very fine sandstone.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>Planar-trough cross-bedded, fine-medium sandstone with trace pebbles. The unit is also slightly bioturbated.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>Coarse-pebbly, poorly sorted sandstone exhibiting a fining upward motif with angular pebbles at the base.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>Medium-coarse indurated whitish sandstone, heavily bioturbated with straight and branched burrows.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.8: Litholog of Afikpo Sandstone at Mcgregory Hill near Ebonyi hotels
4.1.4 Lithostratigraphic Description of Mamu Formation

- Lithostratigraphic Description of Mamu Formation at Km 76 on the Enugu-bound side of the Enugu-Portharcourt Expressway.

The location is situated at Latitude N5° 51’ and Longitude E07° 21’. The section was exposed as a road cut along the Enugu-Portharcourt road. It has a thickness of about 20m (Figs. 4.9 and 4.10) and a lateral extent of 60m. The lithology is composed of sandstone, shale, and siltstone. The lower part of the section begins with interbeds of ripple laminated sandstones, shale and siltstone about 5m thick. This unit is overlain by bioturbated fine-grained ferruginized sandstone about 2m thick. Also a 2m thick whitish-brown sandstone overlies the red sandstone unit (Fig. 4.10).

Traced laterally, farther down, the unit is overlain by a 5m thick dark grey fissile shale with lots of pyrite concretionary nodules and concentrations of carbonaceous materials at bedding surfaces. The upper contact with the overlying fine-medium, well sorted, well laminated (with lisengang structures) sandstone is sharp and marked by a ferruginized hardground(Fig 4.11). The base of the overlying sandstone is characterized by load cast structures (Fig. 4.12).
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ajali?</td>
<td>20</td>
<td>CI Si Fs Ms Cs Gv</td>
<td>Fine-medium grained, well sorted, well laminated Red ferruginized (lisengang structures) sandstone with load cast structures at the base.</td>
</tr>
<tr>
<td>Mamu</td>
<td>15</td>
<td>CI Si Fs Ms Cs Gv</td>
<td>Dark grey fissile shale with lots of concretionary nodules and concentrations of carbonaceous materials at the bedding surface.</td>
</tr>
<tr>
<td>Mamu</td>
<td>10</td>
<td>CI Si Fs Ms Cs Gv</td>
<td>Fine grained whitish-brown sandstone</td>
</tr>
<tr>
<td>Mamu</td>
<td>5</td>
<td>CI Si Fs Ms Cs Gv</td>
<td>Bioturbated fine-grained ferruginized sandstone</td>
</tr>
<tr>
<td>Mamu</td>
<td>0</td>
<td>CI Si Fs Ms Cs Gv</td>
<td>Interbeds of ripple laminated sandstones, shale and siltstone</td>
</tr>
</tbody>
</table>

Fig 4.9: Litholog of Mamu Formation at km 76 on the Enugu-Portharcourt road
Fig. 4.10: Road cut at Km 76 along Portharcourt-Enugu Road exposing the Mamu Formation.

Fig. 4.11: Close-up of Fig. 4.8 showing the sharp contact between an underlying pyritic shale and overlying ferruginized sandstone.

Fig. 4.12: Load structure (shown with arrow) at the contact between an underlying shale and overlying sandstone.
Lithostratigraphic Description of Mamu Formation at Km 65 along Uturu-Afikpo Road.

The location is situated at Latitude N50°49’781” and Longitude E07°24’174” and standing at elevation of 245m. The overall thickness of the logged section is about 8m (Fig. 4.13). The thickness gradually tappers off to the west and maintains a gradational contact with the Ajali Sandstone to the east. The overall lateral extent is about 30m. The lithology is comprised of siltstone and shale interbeds with thin coal seams. The beds dip 3° in the direction of 300° Azimuth.

Three units were described. The lower unit consists of interbeds of grey fissile shale and siltstone with concretionary nodules. The shale is sideritic with abundant plant fragments. Siderite accounts for the rusty brown weathering colour seen in the outcrops (Nwajide and Reijers, 1996c). The unit was punctuated by a thin seam of coal. A reddish-brown mudstone 1m thick overlies the coaly unit. The section is capped by a 2m thick siltstone unit.

Lithostratigraphic Description of Mamu Formation at the Ohafia-Asaga Section.

The section is located within Latitude N5°31’.06” and Longitude E07°40’73” and stands at elevation of 172m. The total thickness of the section is 8m (Fig. 4.14) and lateral extent of about 25m. The beds dip 2° in the direction of 295° Azimuth. The base of the unit consists of 4m thick bluish to dark grey laminated carbonaceous shale interbedded with thin siltstone laminae. The unit is highly fossiliferous with abundant dark gray concretions. The unit is overlain by a 3m thick light greyish mudstone.
<table>
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<th>Thickness (m)</th>
<th>Lithology</th>
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</thead>
<tbody>
<tr>
<td>Mamu</td>
<td>8</td>
<td>Si</td>
<td>Siltstone bed</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Ms</td>
<td>Reddish brown mudstone</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Cs</td>
<td>Thin coaly bed about 3cm thick</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Gv</td>
<td>Sideritic shale/siltstone beds</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td>Interbeds of grey fissile shale and siltstone with concretionary nodules.</td>
</tr>
</tbody>
</table>

Fig. 4.13: Litholog of Mamu Formation at km 65 Uturu-Okigwe road
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology Cl Si Fs Ms Cs Gv</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mamu</td>
<td>8</td>
<td>8</td>
<td>Light grey mudstone.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6</td>
<td>Concretionary and fossiliferous blue-dark grey laminated carbonaceous shale interbedded with thin siltstone laminae.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Fig 4.14: Litholog of Mamu Formation at the Ohafia-Asaga Section.
4.1.5 Lithostratigraphic Description of Ajali Sandstone

- Lithostratigraphic Description of Ajali Sandstone at Ohafia-Asaga Section.

The section is situated in a quarry about a hundred meters off Ohafia-Asaga road. It is described by Latitude N5° 37'.067” and Longitude E07° 50’.45”, and stands at elevation of 190m. Quarrying activity has exposed ample face of the formation making it easily accessible for logging. The lithology consists of moderately-poorest sorted, friable sandstone, mostly ferruginized with mud drapes on foresets of cross strata.

Nine units were altogether logged. The overall thickness of the section is about 12m (Fig. 4.15 and 4.16). The lower unit is a 0.6m thick fine-medium grained, planar cross-ripple bedded sandstone. The cross-beds dip 19-25° in the direction of 194° Azimuth. This unit is overlain by a 0.5m thick pinkish-white silty sandstone with mud drapes probably a slack deposit (Fig. 4.17). A 0.9m thick planar cross-bedded, fine grained sandstone with dip 23° in the direction of 200° Azimuth overlies the silty-sandstone unit (Fig. 4.18). The sandstone bed atop this unit is fine-silty, ripple to cross laminated sandstone. It has a thickness of 1.5m and whitish brown in colour. The upper part of the section is scoured forming a sharp erosional contact with the overlying pebble channel deposit. This depicts an increase in the competence of the depositional medium. The unit is 0.5m thick. Overlying the channel lag deposit is a 1.2m thick coarse grained, planar cross-bedded sandstone with dip of 5° in the direction of 170°. The upper part of the section is intensely bioturbated with vertical burrows of Ophiomorpha ichnogenera. The upper part of the section is comprised of fine-medium grained 0.6m thick ripple laminated sandstone, overlain by a band of coarse grained-pebbly (angular) and poorly sorted sandstone of 0.3m thick. This section is capped by a 3m thick coarse, mega-rippled, lenticular sandstone.
<table>
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<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>Ajali Sandstone</td>
<td></td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>10</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Fig.4.15: Litholog of Ajali Sandstone at Ohafia-Asaga Section.
Fig. 4.16: Panoramic view of Ajali Sandstone exposed at a quarry in the Ohafia-Asaga Section

Fig. 4.17: Silty sandstone with mud drapes/clast

Fig. 4.18: Planar cross-bedded sandstone
• Lithostratigraphic Description of Ajali Formation at Okoko-Item

The section is situated in Okoko-Item Village about 1km off Ohafia-Umuahia road. The road cut has exposed about 5m of the Ajali Sandstone. Three units were described (Fig. 4.19). A 0.5m thick fine-medium grained, moderately sorted, whitish, bioturbated sandstone constitute the lower unit. This was overlain by a 1.5m thick cross-bedded sandstone, medium to coarse grained with a thin mud drape capping the unit. The dip of the cross bed is 15° in the direction of 215° Azimuth. The top of the section is a medium-coarse, and bioturbated sandstone with a thickness of 2m. The section is covered by lateritic topsoil.

• Lithostratigraphic Description of Ajali Formation at Km 75 along Enugu-Portharcourt Road.

The location is an abandoned sandstone quarry site. The excavation has exposed about 5m of the section (Fig. 4.20). The section comprises of a basal 1.5m thick medium-coarse grained sandstone, exhibiting medium-scale herringbone-planar cross-bedding dipping between 4-7° in the directions of 120 and 300°, Azimuth (Fig. 4.21). Overlying this unit is 1m thick moderately sorted, ripple laminated sandstone. This unit is highly ferruginized with pronounced lisengang structures occurring as irregular shaped, contorted bands of iron oxide enclosing loose sands. The section fines upward with a 0.8m thick laminated, bioturbated, fine-silty sandstone with thin silty-muddy intercalation. The upper siltstone unit is heavily bioturbated with vertical burrows of Ophiomorpha. The unit is 0.5m thick. The section is capped with thick interbeds of siltstone and kaolinitic mudstone.
<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>5</td>
<td>Cl Si Fs Cs Gv</td>
<td>Medium-coarse, moderately sorted and bioturbated sandstone</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>Cross-bedded sandstone, medium to coarse grained with a thin mud drape capping the unit.</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>Fine-medium grained, moderately sorted, whitish and bioturbated sandstone</td>
</tr>
</tbody>
</table>

Fig. 4.19: Litholog of Ajali Sandstone at Okoko-Item, Abia State.
<table>
<thead>
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<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology Cl Si Fs Ms Cs Gv</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ajali Sandstone</td>
<td></td>
<td></td>
<td>Interbeds of siltstone and kaolinitic mudstone. Also bioturbated.</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>Siltstone unit, heavily bioturbated with vertical burrows of Ophiomorpha.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>Micro-laminated, bioturbated, fine-silty sandstone with thin silty-mud intercalation.</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>Moderately sorted, ripple laminated sandstone. With highly ferruginized and pronounced lisengang structures.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>Medium-coarse grained, moderately sorted sandstone, exhibiting medium-scale herringbone-planar cross-beds</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.20: Lithology of Ajali Sandstone at km 75 Enugu-Portharcourt Road at Ihube.
Fig. 4.21: Herringbone structure in the basal unit of the outcrop at Km 75, Ihube

- Lithostratigraphic Description of Ajali Sandstone near Km 65 Uturu-Afikpo Road.

This section is also located in an abandoned quarry site along Uturu-Afikpo road. The outcrop is near the contact between Ajali Sandstone and Mamu Formation at Km 65 along the same road. The section is defined by Latitude N5° 40.778’ and Longitude E07° 24.072’ and stands at elevation of 23m. The thickness of the section is about 10m thick (Fig. 4.22). The lower 2.5m of the section consist of very fine, ripple-laminated, and bioturbated sandy-siltstone. This lower unit is overlain by a 2m thick medium-coarse grained, bioturbated sandstone, and ripple laminated in some places. A 1.3m thick medium to coarse grain, cross-bedded sandstone with a dip of 20° in the direction of 185° Azimuth with mud drapes at forests overlies the ripple laminated sandstone. The overlying 1.5m thick unit consists of coarse grained sandstone that displays a fining upward motif that grades into ripple laminated sandstone with mud drapes. The unit exhibits a scoured erosional contact with the underlying cross-bedded sandstone. The topmost 1.5m thick unit consist of a medium-coarse grained, planar cross-bedded sandstone capped with kaolinitic mudstone and siltstone. The dip of the cross bed is 22° in the direction of 190° Azimuth.
<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>10</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Medium-coarse grained, planar cross-bedded sandstone capped with kaolinitic mudstone and siltstone.</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td>Coarse grained to pebbly bedded sandstone fining upward into ripple laminated sandstone with mud drapes at the top. The bottom of the unit is a scoured erosional base.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>Medium to coarse grain, cross-bedded sandstone capped with mud drape.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>Medium-coarse grained, bioturbated sandstone, and ripple laminated in some places.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>Very fine, ripple-laminated, and bioturbated sandy-siltstone.</td>
</tr>
<tr>
<td></td>
<td>0m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.22: Litholog of Ajali Sandstone near km 65, along Uturu-Afikpo Road.
• Lithostratigraphic Description of Ajali Sandstone at the Ikpankwu Quarry near Ihube.

The outcrop is a sandstone quarry about 1km from Ihube junction. It is about 12m thick with very steep face making access to the top units very difficult (Figs. 4.23 and 4.24). Five units were described. The section is underlain by very dark fissile and pyritic shale which was possibly a lateral continuation of the similar shale unit observed at Km 76 along the Enugu-Portharcourt road. The overlying unit is 3m thick, massive, poorly sorted coarse grained and poorly rounded sandstone. This unit is overlain by intercalations of very coarse poorly sorted sandstone with siltstone interbeds 1m thick. A coarse-pebbly, thick sandstone of about 0.7m thick overlie this unit. This unit is overlain by a 2m thick medium-coarse grained, cross-bedded, and moderately sorted sandstone. The cross-beds dip at 4° in the direction of 267° Azimuth. The top most unit consists of very thick intercalations of kaolinitic mudstone and siltstone.

Fig. 4.23: Outcrop section at the Ikpankwu quarry, near Ihube.

(note the underlying shale suspected to be Mamu Formation exposed by erosion)
<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>10</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Intercallations of bioturbated kaolinitic mudstone and siltstone.</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Medium grain, cross-bedded sandstone, bioturbated at the top.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Cs Fs Gv</td>
<td>Coarse-pebbly, angular 0.7m thick sandstone</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Poorly sorted coarse sandstone with siltstone interbeds</td>
</tr>
<tr>
<td>Mamu</td>
<td>0</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Massive, poorly sorted coarse, poorly rounded sandstone.</td>
</tr>
</tbody>
</table>

Dark fissile pyritic shale exposed by erosion, marking the base of the section

Fig. 4.24:  Litholog of Ajali Sandstone at Ikpankwu quarry, Near Ihube.
4.1.6 Lithostratigraphic Description of Ameki Formation.

- **Lithostratigraphic description of Ameki Formation at Ohulu Ekeoba, Umuahia**

The section is situated close to the NNPC mega station along the Enugu-Portharcourt road. The section has a lateral extension of 30m and a thickness of about 4m. The lithology consists of shale, limestone, and mudstone (Fig. 4.24b). The lower-most unit comprise of 2m thick dark grey fissile shale with concentration of plant remains at the bedding plane. The shale unit in the middle section contains ironstone nodules in places, interbedded with fine grained calcareous, light grey-greenish limestone beds. The overlying 0.5m thick unit is a lenticular bedded shale that weathers in blocks with siltstone interbeds. The topmost unit is a bioturbated mudstone unit.
<table>
<thead>
<tr>
<th>Formation</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ameiki</td>
<td>4</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Bioturbated mudstone</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Lenticular bedded shale with siltstone interbeds.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Shale with ironstone nodules in places, interbedded with fine grained calcareous, light grey-greenish limestone beds.</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Cl Si Fs Ms Cs Gv</td>
<td>Dark grey fissile shale with concentration of plant remains at the bedding plane.</td>
</tr>
</tbody>
</table>

**Fig. 4.24b:** Litholog of Ameiki Formation at Ohuhu Ekeoba, Umuahia.
4.2 Sedimentary Structures

Sedimentary structures are those features that are seen or studied best in outcrop rather than in handspecimen or thin section. (Pettijohn, 1975). Unlike textures, structures deals with larger organizational units and is most clearly seen in the field.

Primary sedimentary structures have been used as guides to the agent and/or environment of depositional (Shrock, 1948). In recent years directional structures have been utilized to map paleocurrents and to determine paleoslope and sedimentary strike (Potter and Pettijohn, 1963). Special attention has been given also to biogenic structures (Ichnofossils) as guides to depositional environment. Unlike body fossils, these structures are not susceptible to reworking or transport (Seilacher, 1964a).

Renewed interest in sedimentary structures has led to the publication of a number of monographs and articles on various aspect of the subject. Included here are the works of atlases of Khabakov(1962), Pettijohn and Potter; (1964) Ricci Lucch(1970).

Pettijohn(1975) broadly classified sedimentary structures into physical, chemical and biogenic structures. The study area have some striking structures belonging to the above mentioned categories that reflect diagenetic processes and their depositional milieu. Notable types of sedimentary structures in the study area include: cross stratifications, graded bedding, ripple laminations, reactivation surface, herringbone cross bedding, burrows, concretions and other ferruginized bodies.
4.2.1 Primary Sedimentary Structures

Parallel Laminations
Laminations are layers of sediments less than 1cm in thickness (Pettijohn, 1975). They tend to reflect in-phase waves, laminar flow, fluctuating conditions or variable low energy conditions and are more characteristic of fine-grained sediments.

The distinctiveness and degree of preservation of lamination is in part a rough measure of the quietness of the water in which the sediments accumulated. Hence, laminations often record deposition below wave base (Pettijohn, 1975). It is also probable that laminations may be destroyed by organisms that feed on organic matter contained in bottom mud. Repeated ingestion of mud results in thorough working over of sediments and destruction of laminations. Because this is nearly universal, the preservation of laminations therefore indicates either very rapid deposition or toxic bottom and suppression of benthonic fauna. Under the later condition, individual paper-like lamination may persist and be traceable over distances of several kilometers(Ricci Lucci, 1970). The parallel laminations observed in the Nkporo (NKP6U1 and NKP6U4) and Mamu Formations (MA8U2, MA8U4, MA8U7 and MA9U1) lend strength to their interpretation as anoxic bottom marine deposits.

Ripple Laminated/Mark
Ripple marks like cross-bedding, have proved useful in determining stratigraphic order, paleocurrent and indicating flow conditions (Pettijohn, 1957). Allen(1963; 1967) traced their origin to current flow over a bed of sand reaching a certain velocity as sand begins to move. Symmetrical mega ripples were observed on the ferruginized firm ground in the Nkporo/Mamu Formation contact at the Leru section. Ripple laminations were observed in the Nkporo Formation at the Leru section. This according to Hamblin(1962) were produced
by migration of ripples to produce small-scale cross-laminated layer. They are essentially internal structures.

**Cross Stratification**

Cross-stratification consists of packets or sets (Mckee and Weir, 1953) of laminae inclined to the principal bedding. These sets are generated by the growth and movement of bed forms such as ripples (Allen, 1963a;)

Pronounced cross-beds were the dominant sedimentary structures observed in the Ajali Sandstone. They were observed virtually in all the locations. Planar and trough cross-bedding were also observed in the Afikpo Sandstone, and Mamu Formation. Amajor(1987) recorded cross-strata range between 1.5 and 3cm in thickness.Mckee and Weir(1953) distinguished between cross-bedding which are foreset layers greater than 1cm in thickness and “cross-lamination” with foresets less than 1cm in thickness. Cross-beddings are characteristics of non-cohesive granular materials no matter their composition.

The scale of the cross-bedding in subaqueous deposits seems to be related to water depth (Allen, 1963). Jopling(1964) noted that the maximum angle of dip of cross-strata is related to current velocity and grain size, decreasing with increasing current velocity. The significance of cross-bedding has long been debated. However, several types of cross-beddings recognized by Mckeeand Weir (1953) may be more characteristics of certain environments than others. Low-angle (<12\(^{\circ}\)) planar cross-bedding is most common in beach and offshore bar deposits. Tabular planar cross-bedding of moderate angle (18-28\(^{\circ}\)) is most typical of delta foresets building into any type of water body. High-angle (24-34\(^{\circ}\)) wedge-planar cross-bedding is most common in aeolian dune deposits but can also occur in delta foresets.

Trough cross-bedding and festoon pattern reflect scour and fill and are most common in fluvial deposits but also occur in channels in tidal flats, and backshore beaches. Herringbone or Chevron cross-stratification comprises pairs
of sets, commonly tabular, in which the dip directions of the straight or concave upward cross-strata are mutually opposed (Conybeare and Crook, 1968). They are thought to be diagnostic of tidal channels as they reflect abrupt and complete reversal of current direction.

Amajor (1987) noted that the observed herringbone cross-stratification in the Ajali Sandstone are identical to those of low tidal flat sand deposits described by Klein (1970); Mackenzie (1972); and Reineck (1975).

In the study area, herringbone cross-stratification exist only in the Ajali Formation as observed at Km 75 along Enugu-Portharcourt road, where together with other cross-stratifications constitute the predominant sedimentary structures.

**Graded Bedding**

Graded beds are deposited by currents that carry a suspended load of sediment. Where the current velocity is more than sufficient to carry the entire load of sediment, it will scour the surface over which it flows. Friction will decrease the velocity of the lower part of the flow until the largest particles can no longer be carried, and are dropped to form a layer of the coarsest fragments from the suspended load. Graded beds thus are deposited from a waning current and may range in thickness from a centimeter or less to one or more meters. In general, the thicker the graded unit, the coarser the material at the base of the bed (Potter and Scheidegger, 1966). Grading is of several types however there is always an ideal or normal sequence of structures. This ideal cycle has come to be called the Bouma cycle as it was first most explicitly described by Bouma (1962).

The geologic significance of graded bedding and its recognition as distinguishing attribute of two contrasting facies were first clearly pointed out by Bailey (1936). It has been found exceptionally useful in determining the order of superposition in isoclinals folded and overturned strata.
Graded bedding was observed in the Afikpo Sandstone and was inferred to have been deposited out of a waning shallow current rather than turbidity current because of a rather constant sorting as a result of exclusion of fine materials from the bed (Pettijohn, 1957; Folks and Ward, 1957)

**Load Cast/Structures**

Load cast, more properly called “load pockets” are somewhat irregular bulbous features on the base of a sandstone bed that overlie shale bed (Pettijohn, 1957). Apparently, these structures are a product of unequal loading of the underlying hydroplastic mud and owe their origin to vertical readjustment, with downward motion of the sand and compensatory upward movement of mud. Load cast features were observed in the Mamu/Ajali Formation contact at kilometer 76, Enugu-Portharcourt road.

Load cast do not indicate any particular environment, although they tend to be more common in turbidite sequence. Their presence seems to reflect the hydroplastic state of the underlying mud. They apparently will not form on the bases of sand beds deposited on mud that have already been compacted prior to deposition of the sand.

**4.2.2 Biogenic Structures**

Biogenic sedimentary structures are features formed by activities of organic agencies. Interpreted broadly, biogenic structures can be considered to include the following: Bioturbation structures (burrows, tracks, trails, and root penetration structures), Biostratification Structures (algal stromatolites), Bioerosion structures, and Excrement (fecal casting). These are collectively called trace fossils and their study is referred to as ichnology. Although trace fossils record a particular activity of an organism, they are particularly useful in determining the environment in which the organism lived. The assemblage of such “trace fossils” has proved to be very good index of sedimentary facies and water depth. Trace fossils also yield information on the rate of sedimentation
and are guides to toxicity of bottom waters. They have also proved helpful in determining the stratigraphic order in steeply inclined or overturned beds (Pettijohn, 1957).

The interbedded sandstone in the Nkporo Shale of the Leru section is characterized by vertical burrows with skolithos and distinguished as vertical disposed, unbranched tubes filled with dark grey to black mud obviously derived from the superjacent mudrock. Horizontal Thallossinoides burrows were also observed. Onyekuru(2008) interpreted the Thalssinoides burrows seen in the sandstone-shale facies of the Nkporo Formation as indicative of shallow marine environment, relatively of low energy and rich in silt and organic matter.

Vertical and horizontal burrows identified as Ophiomorpha and Skolithos were observed in the Ajali Sandstone particularly in the upper mudstone facies. Similarly branched burrows were observed in the cross-bedded sandstone unit of the McGregor Hill, Afikpo section.

In line with Amajor,(1987) the presence of Ophiormorpha, Arenicola, and Skolithos trace fossils in the burrowed mudstone facies and the herringbone cross-strata observed in the Ajali Sandstone were obstacle to the hypothesis of fluvial origin of Ajali Sandstone on a regional scale. Frey et al (1978) noted that the Ophormorpha and arenicola characterize a range of environments. Arenicola was noted to have a world wide distribution and commonly inhabit the intertidal zone (Conybeare and Crook, 1968).

4.2.3 Chemical Sedimentary Structures

Chemical sedimentary structures are features formed sometime after deposition during sediment burial. These structures are largely of diagenetic origin formed by precipitation of mineral substances in the pores of semi-consolidated or consolidated sedimentary rocks or by replacement processes. Concretions are probably the most common kind of chemical sedimentary structures. They occur as irregular, rounded, or disk-shaped cemented hard masses of rock that