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A Provenance Study of the Paleogene Lithostratigraphic Units of the Niger Delta: An Insight into the Plate-Tectonic Setting

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Abstract

Integrated heavy-mineral analysis and paleocurrent characteristics of the outcropping Paleogene strata of the Niger Delta Basin, southeastern Nigeria were studied in order to reconstruct the provenance, with an emphasis on the sandstone maturity and tectonic setting. The depositional environment of the strata in the study area is a shallow marine to shoreline deposit, which records the transgressive and regressive episodes of three outcropping Paleogene strata (Imo, Ameki, and Ogwashi formations). The regional paleocurrent pattern shows predominance of bimodal WNW and ENE paleoflow directions with a high to medium variance. The integration of the heavy minerals and paleocurrent analyses show a mixed provenance of low- to high-grade metamorphic, igneous and reworked older sedimentary sources that lie southwest, southeast and east of the study area. The major source terrains are the Oban Massif and pre-Santonian sedimentary units of the Southern Benue Trough to the southeast and east, as well as the gneisses and schists' belt of the West African Massif to the southwest of the study area. The zircon-tourmaline-rutile (ZTR) index indicates that sandstones are mineralogically immature to mature, while the triangular plot of MF-MT-GM suites shows that the sediments were deposited in a mature passive continental margin on the stable craton of the African plate.

Keywords: Heavy minerals, mineralogical maturity, provenance, tectonic setting, Paleogene, Niger Delta

1. Introduction

The Paleogene strata consisting of the Imo, Ameki and Ogwashi formations of the Niger Delta Basin have been widely studied and varying interpretations on the environment of the deposition of these formations have been documented (Reyment, 1965; Short and Stauble, 1967; Adegoke, 1969; Arua, 1986; Nwajide and Hoque, 1979; Nwajide 1980; Reijers et al., 1997; Oboh-Ikuenobe, 2005; Odunze and Obi, 2011; Ekwenye et al., 2014; 2017; Ekwenye and Nichols, 2016). The stratigraphic succession in the Niger Delta Basin in the southeastern part of Nigeria begins with the Paleogene Imo Formation of the Late Paleocene to the Early Eocene age (Reyment, 1965; Arua, 1980). The Imo Formation is succeeded conformably by the Ameki Group (Nsugbe, Nanka and Ameki formations) of the Early to the Middle Eocene age (Reyment, 1965; Adekoge, 1969; Oloto, 1984), while the Ameki Group is conformably overlain by the Ogwashi Formation of the Middle Eocene to the Oligocene age (Jan du Che`ne et al., 1978; Reyment, 1965).

The nature and abundance of heavy minerals are widely used in sedimentological studies of sandstone provenance, and when combined with paleocurrent data, can provide useful clues on sediment dispersal patterns (Hussain et al., 2004; Fossum et al., 2019). Heavy minerals are very useful in interpreting source rock geology as some of the minerals have a restricted paragenesis, and are diagnostic of specific source lithologies. Few studies on heavy-mineral and petrographic analyses have been carried out on the Paleogene formations. The provenance of the successions was interpreted to be of a mixed origin, and the paleoclimatic conditions at the time of deposition are suggested to be semi-humid to humid conditions (Nwajide, 1980; Ekwenye et al., 2015). These works, however, did not determine the relationship between heavy-mineral assemblages and the tectonic setting of these formations. This research presents detailed heavy-mineral interpretation for the Paleogene sedimentary strata, and also uses the integrated study of the depositional facies, paleocurrent analysis and heavy-mineral assemblages to improve the understanding and reconstruct the paleoenvironment and provenance of the Paleogene formations of the Niger Delta Basin. This study also documents, for the first time, the mineralogical maturity and the tectonic setting of the Paleogene strata, based on heavy-mineral data.

2. Tectonic Setting and Basin Evolution

The Niger Delta Basin was formed along a failed arm of a triple junction system that originally developed during the separation of the South American from the African plates during the Late Jurassic to Early Cretaceous (Burke et al., 1972; Whiteman, 1982). Three major tectonic episodes which occurred during the Aptian-Albian, Santonian and Eocene times controlled the formation of the Southern Nigerian basin complex, as a result of the displacement of the axis of the main basin, giving rise to the formation of three successive basins (Fig. 1). These three tectonic phases formed the three sedimentary phases which include the Abakaliki-Benue phase (Aptian-Santonian), Anambra-Afikpo phase

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(Campanian-Mid Eocene), and the Niger Delta phase (Late Eocene-Pliocene) (Short and Stauble, 1967; Murat, 1972; Obi et al., 2001).

The first tectonic phase of the Aptian–Santonian times resulted in the movement along the NE-SW trending fault that forms the rift-like Abakaliki-Benue Trough (Short and Stauble, 1967), while on the southeastern margin, the movement along the NW-SE trending faults or hinge line formed the Calabar Flank, within which sedimentation was similar to that in the Southern Benue Trough. The second tectonic phase coincided with the structural deformation of the Abakaliki-Benue Trough and the formation of the Anambra Basin and the Afikpo Syncline during the Santonian-Maastrichtian time. The down-faulting of the Anambra Platform to the west of the Abakaliki Trough formed the Anambra Basin, whereas, on the eastern margin of the trough, a down-warping rather than faulting occurred, and led to the formation of the Afikpo Syncline. The third tectonic phase occurred towards the end of the Eocene as a result of a major earth movement which caused another structural inversion that raised the Anambra Basin and shifted the depocentre down dip (southwards) to form the petroliferous Niger Delta Basin (Obi et al., 2001; Nwajide, 2013).

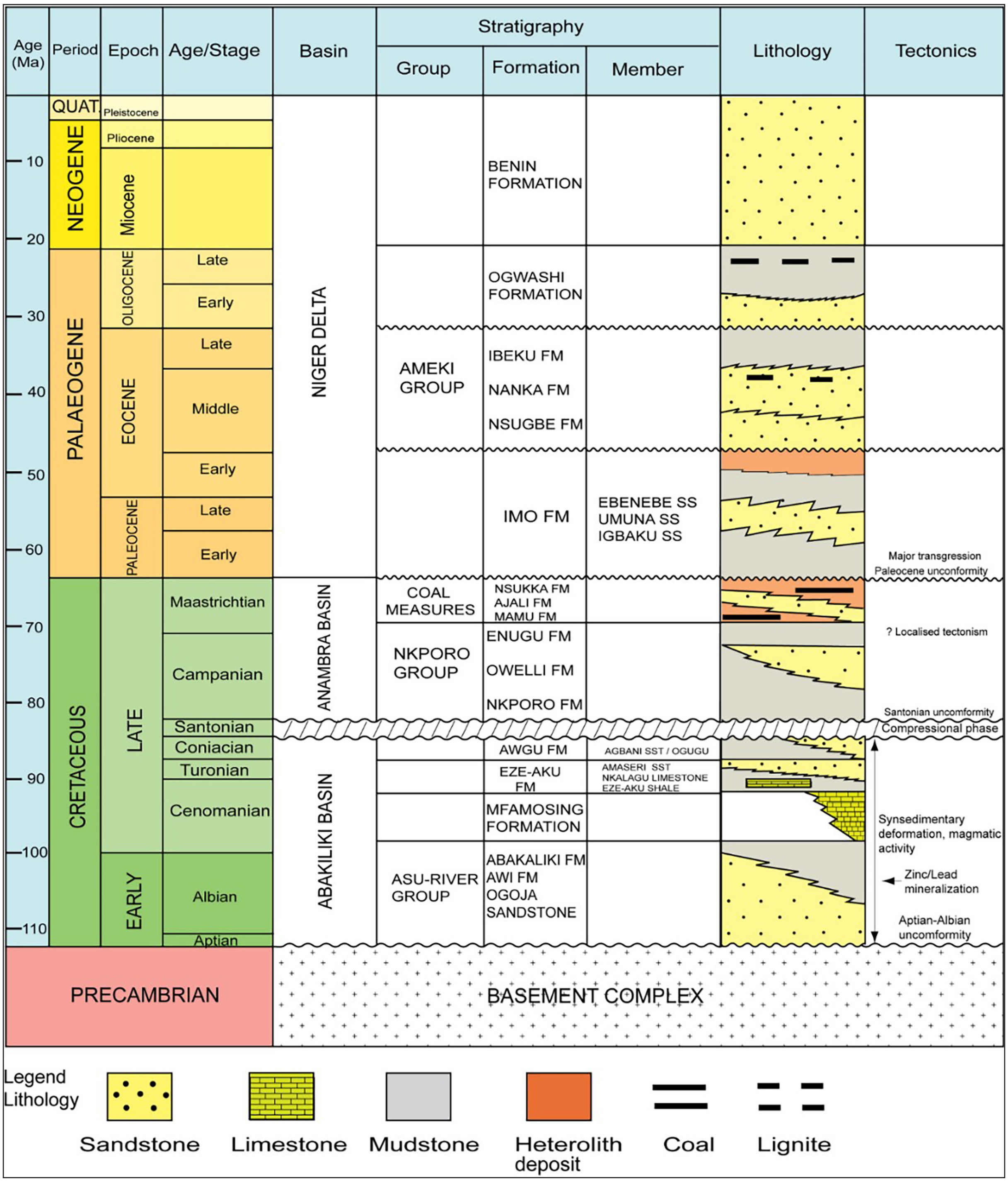


Figure 1. Stratigraphy of the Early Cretaceous-Cenozoic outcropping strata in the Southern Benue Trough, Anambra Basin and Niger Delta Basin (after Ekwenye et al., 2016).

3. Stratigraphic Setting

The detailed study of the stratigraphic units of the southern Nigerian sedimentary basin was first carried out by Reyment (1965). These Paleogene sediments (Fig. 1) were initiated when the Anambra Basin sedimentation was terminated by an extensive Paleocene transgression (Kogbe, 1989).

The Imo Formation consists of blue-grey mudstones and shales and black shales with bands of calcareous sandstone, marl, and limestone (Reyment, 1965). Ostracods and foraminifera biostratigraphy (Reyment, 1965), and microfauna recovered from the basal limestone unit (Adegoke et al., 1980; Arua, 1980) indicate a Paleocene age for the formation. Whiteman (1982) stated that the Imo Formation is the basal unit of the Niger Delta Complex. The Imo Formation has three Sandstone Members – the Ebenebe, Igbaku and Umuna Sandstones which are interpreted as tidal sand waves (Ekwenye et al., 2014). The lateral equivalent of the outcropping Imo Formation in the subsurface Niger Delta is the Akata Formation (Table 1; Short and Stauble, 1967; Maron, 1969; Avbovbo, 1978).

The Ameki Group consists of a series of a highly fossiliferous grayish-green sandy-clay with calcareous concretions and white clayey sandstones. The Ameki Group consists of the Nsugbe, Nanka, and Ameki formations (Nwajide, 1980), which are lateral equivalents. The age of the formation has been considered to be either Early Eocene (Reyment, 1965) or Early to Middle Eocene (Berggren, 1960; Adegoke, 1969). The thickness of Ameki Group is estimated to be around 1,400 m in some places. The depositional environment of the Ameki Group was observed as a barrier ridge-lagoon complex, open marine and a tide-dominated estuarine environment, based on the lithofacies interpretation and faunal content (Adegoke, 1969; Nwajide, 1979; Arua, 1986; Ekwenye et al., 2017). Fayose and Ola (1990) suggested that the sediments were deposited in marine waters between the depths of 10 m and 100 m.

The Ogwashi Formation consists of white, blue and pink clays, coarse-grained and cross-bedded sandstones, carbonaceous mudstones, shales and seams of lignite (Kogbe, 1976). An Oligocene-Miocene upper flood plain environment of deposition has also been detected (Short and Stauble, 1967). The Ogwashi Formation was re-interpreted as a tidally-influenced coastal plain system (Ekwenye and Nichols, 2016). The Ameki Group and the Ogwashi Formation are correlative lateral equivalent of Agbada Formation in the subsurface Niger Delta (Table 1).

Table 1. Outcropping and subsurface units of the Cenozoic Niger Delta Basin (modified from Maron, 1969).

<table>
<tr><th>Age</th><th>Present Niger Delta</th><th colspan="2">Outcropping Units - Reyment (1965)</th><th>Subsurface Units - Short and Stauble (1967)</th><th>Characteristics</th></tr>
<tr><td>Miocene - Present</td><td>Continental (fluviatile) deposits, mainly sands</td><td colspan="2">Benin Formation</td><td>Benin Formation (Afam Clay Member)</td><td>Cross-bedded, coarse pebbly continental sands, with clay lenses and lignites, has marine shale breaks with foraminifera, ostracods and mollusca</td></tr>
<tr><td>Oligocene - Miocene</td><td rowspan="4">Mixed continental brackish water and marine deposits, sands and clays</td><td colspan="2">Ogwashi Formation</td><td rowspan="4">Agbada Formation</td><td>Clays, silts and sands with thin to thick lignite seams</td></tr>
<tr><td rowspan="3">Middle Eocene</td><td rowspan="3">Ameki Group</td><td>Ameki Fm.</td><td>Mainly sands with some conglomerate bands</td></tr>
<tr><td>Nanka Fm.</td><td>Calcareous clays and silts with thin shelly limestone, rich in foraminifera</td></tr>
<tr><td>Nsugbe Fm.</td><td>Calcareous clays and silts with thin shelly limestone, rich in foraminifera, mainly sands, minor silt and clay intercalations</td></tr>
<tr><td rowspan="3">Late Paleocene - Early Eocene</td><td rowspan="3">Marine deposits mainly clays</td><td rowspan="3">Imo Formation</td><td>Igbaku Sst.</td><td rowspan="3">Akata Formation</td><td rowspan="3">Blue-grey shales with sand lenses, marls and fossiliferous limestones, sandstone members - Ebenebe, Umuna and Igbaku Sandstones; shales with foraminifera and ostracods</td></tr>
<tr><td>Umuna Sst.</td></tr>
<tr><td>Enenebe Sst.</td></tr>
</table>

4. Methodology

4.1 Field Mapping

Detailed field description and measurements of fifteen outcrop sections ranging in thicknesses from 5 to 50 metres were carried out based on the essential parameters for studying sedimentary rocks in the field, including textural characteristics, measurements of strikes and dips, vertical and lateral distributions of lithofacies, stratigraphic types, spatial distribution of the physical sedimentary and biogenic structures, and lateral extent of outcrops (Fig. 2). These essential parameters have been used to delineate the different facies successions and associations. Important sedimentological parameters (bed thickness, lithology, physical and biogenic structures, intensity of bioturbation, and type of basal contacts) were inputted in the SedLog 2.1.4™ software to create the sedimentary logs (Fig. 3). Detailed measurements of the azimuth and dip of cross-beds were taken in the field to be used in interpreting the paleocurrent directions of the sediments of the different strata.

4.2 Heavy-Mineral Analysis

Twenty-three disaggregated sandstone samples were taken from five different locations across the three formations within the study area for heavy-mineral analysis. Fourteen samples were obtained from the Imo Formation, while three and six samples were obtained from Ameki and Ogwashi formations, respectively. The sandstone samples were sieved and separated into grain size fractions using sieve mesh of 250, 180, 150, 125, 90, and 63 microns. Ten grams of disaggregated sandstone samples retained in the 125 micron sieve were soaked in a sodium metahexaphosphate (calgon) solution, and were, then, washed thoroughly with distilled water and oven-dried. Krumbien and Pettijohn (1938) gravity method of extracting and separating heavy minerals has been effectively used to separate and extract these heavy minerals using bromoform ($CHBr_3$) (liquid with density of 2.89). They were rinsed with acetone, oven-dried, and mounted on slides using Canada balsam. About 200 point counting of the non-opaque mineral assemblages was done in the Petrology Laboratory of the University of Nigeria Nsukka, using a petrological microscope. Photomicrographs of salient features of the heavy minerals were taken.

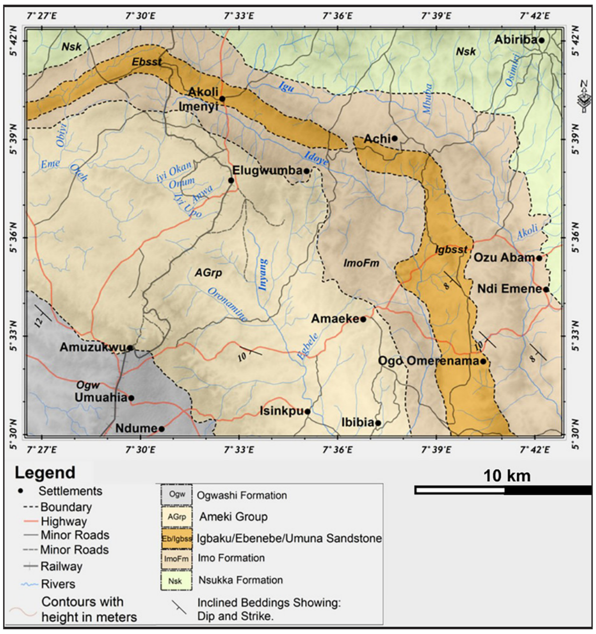
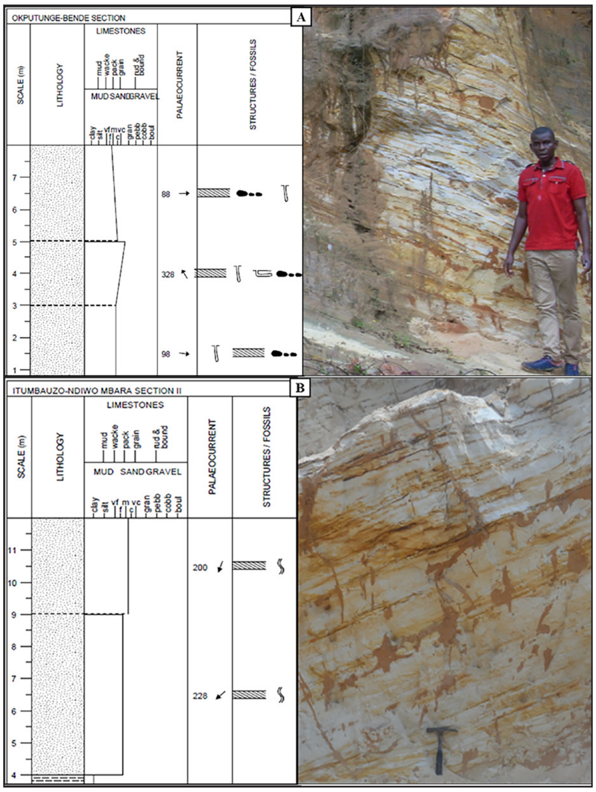


Figure 2. Detailed geological map of the study location in the Umuahia-Bende area of the Niger Delta, southeastern Nigeria (modified from Nigerian Geological Survey Agency, 2009).



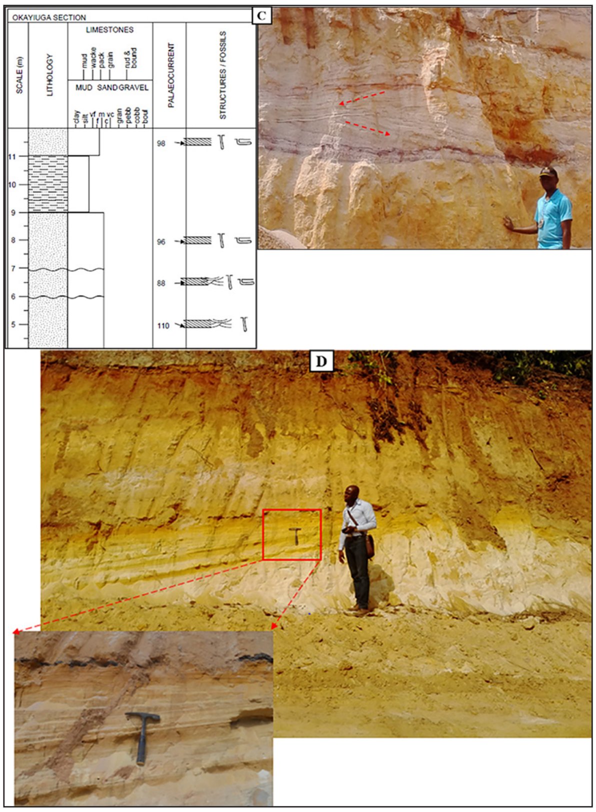


Figure 3. **(A)** Litholog and outcrop photo of the Imo Formation at Okputunge-Bende showing large-scale planar cross-bedded sandstone; **(B)** Litholog and outcrop photo of the Imo Formation at Itumbauzo-Ndiwo showing large-scale planar cross-bedded sandstone; **(C)** Litholog and outcrop photo of the Ogwashi Formation at Okaiuga showing bi-directional, trough cross-bedded sandstone; **(D)** Outcrop photo of the Imo Formation at Idima Abam road cut section showing planar cross-bedded sandstone.

5. Results and Interpretations

5.1 Paleocurrent Analysis

The methodology and applications of paleocurrent analysis have been studied and reviewed by several authors (Tanner, 1955; Kuenen, 1957; Selley, 1968; Potter and Pettijohn, 1977; Tucker, 2003). In this study, the paleocurrent data were obtained from planar cross-beds measured from five different locations in the Imo, the Ameki, and the Ogwashi formations. The parameters of the azimuth data of each location from the three formations were grouped and plotted as rose diagrams (Fig. 4). In order to determine the dominant (mean) directions and variability, and the data were treated as vectors. The variance is a measure of the variability of the flow direction. Variance values in the range of 6000 and above suggest shallow marine environments, while variance values ranging between 2000 and 6000 indicate fluvio-deltaic sands (Potter and Pettijohn, 1977). Long and Young (1978) suggested that variance values greater than 4000 indicate a marine shelf environment. Paleocurrent parameters, vector patterns, and interpretations of the cross-bedded sandstones in this study are summarized in (Table 2).

The paleocurrent vector patterns of the Imo Formation (Figs. 4a-c) are characterized by a bimodal-oblique pattern that is oriented sub-parallel to the ancient shoreline, while that of the Ameki Formation (Fig. 4d) is characterized by a bimodal-bipolar pattern, which indicates a strong tidal current influence with modes perpendicular to the shoreline. The paleocurrent pattern of the Ogwashi Formation (Fig. 4e) is characterized by a unimodal pattern with small dispersion, oriented perpendicularly to the ancient shoreline.

The mean vector azimuth computed from the paleocurrent parameters indicates a southwesterly and easterly directions for the sediments of Imo and Ogwashi formations, while the Ameki Formation exhibits a southeasterly direction. From the rose diagram, the provenance or sediment source of the study area suggests that the sediments were derived from different source directions. The sediment sources of the Imo Formation indicate ESE and SW directions. The sediment source of the Ameki Formation is in the NW direction, whereas that of the sandstones of the Ogwashi Formation is from WSW (Figs. 4a-e).

The variability values fall within the range of 235 to 36000 (Table 2) which suggests a dominantly shallow marine shelf environment with a tidal influence for the Imo Formation (3803–35,600), while that of the Ameki Formation (4321) suggests shallow marine/estuarine environments, and the Ogwashi Formation showed relatively low variability values (235), which are indicative of fluvio-deltaic/estuarine environments (Potter and Pettijohn, 1977; Long and Young, 1978). These results are largely in consonance with the results of the facies analysis and the depositional environments of these three formations, where the paleocurrent data were measured, and they support the interpretations.

Table 2. Paleocurrent parameters, vector patterns and interpretations of the cross-bedded sandstones in the study area.

Formation	Locality	MVA	Variance	Vector Strength	Vector Pattern	Environment of deposition
Imo	Idima-Abam	243.33°	3802.91	2.35	Bimodal-oblique pattern showing strong tidal current influence that is parallel to the shoreline	Tide-dominated deltaic environment
	Okputunge-Bende	212.27°	21,320.73	3.49	Bimodal-oblique pattern showing strong tidal current reversal influence that is oriented or parallel to the shoreline	Shallow marine shelf environment
	Itumbauzo-MbaraNdiwo	97.00°	35,596.29	2.95	Bimodal-oblique pattern showing strong tidal current reversal influence that is normal to the shoreline	Shallow marine shelf environment
Ameki	Ozu-Item	175.42°	4321.88	3.57	Bimodal-bipolar and perpendicular pattern which shows strong tidal current influence with modes perpendicular to the shoreline	Tide-dominated estuarine environment or shallow marine environment
Ogwashi	Umuahia (Okaiuga sand mining pit)	90.60°	235.96	4.53	Unimodal pattern with low variability	Fluvio-deltaic environment

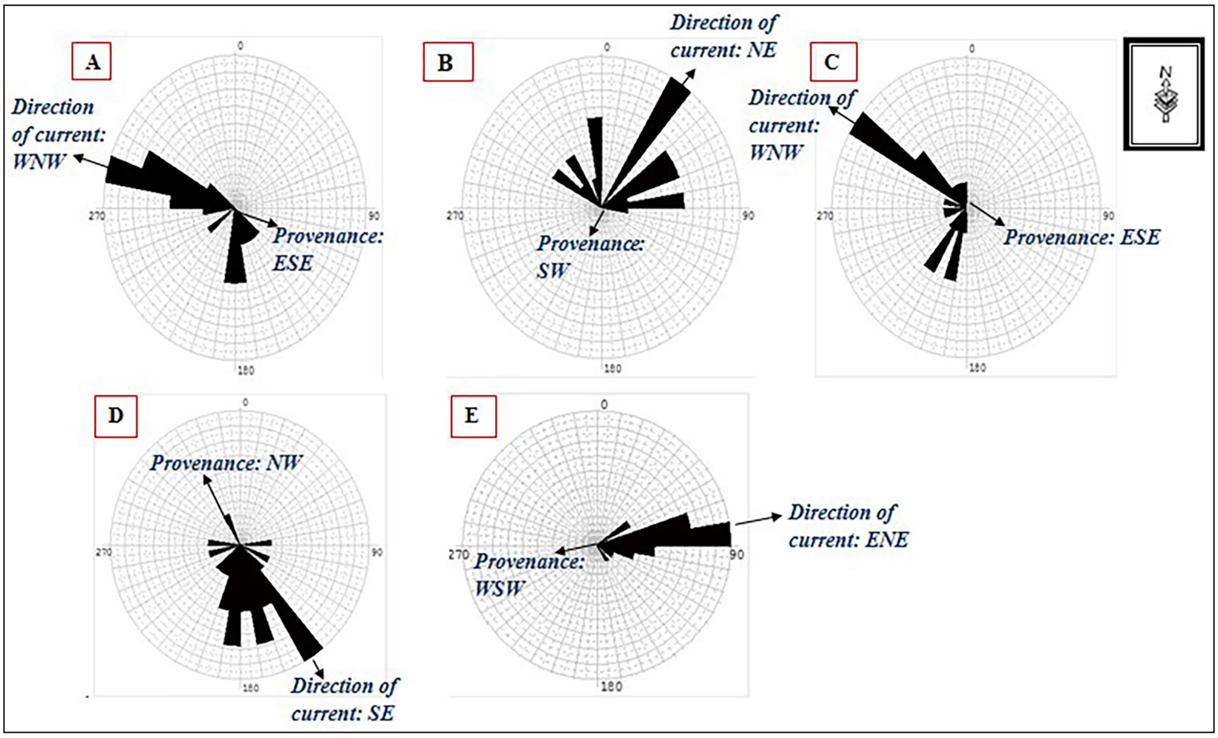


Figure 4. Rose diagrams of the study area at different locations for the three formations: **(A)** Idima-Abam (Imo Fm. – n = 20), **(B)** Okputunge-Bende (Imo Fm. – n = 25), **(C)** Itumbauzo-Ndiwo (Imo Fm. – n = 25), **(D)** Ozu-Item (Ameki Fm. – n = 25), and **(E)** Okaiuga Sandstone mining pit (Ogwashi Fm. – n = 22). n = number of grouped azimuth measurements.

5.2 Heavy-Mineral Analysis

Most of the sediments from the study area are medium- to coarse-grained and poorly consolidated sediments, except for a few samples from the Ameki Formation which contain a high proportion of fine-grained sediments that are not suitable for heavy-mineral analysis. Thus, only three viable samples were obtained from the Ameki Formation. The zircon-tourmaline-rutile (ZTR) maturity indexes of all the samples were also calculated and classified following the Hubert (1962) scheme (Table 3). Results show that zircon, tourmaline, rutile, apatite, garnet, staurolite, epidote, kyanite, sillimanite, sphene, pyroxene, and andalusite form the major non-opaque heavy-mineral suites, while magnetite, hematite, and limonite form the major opaque mineral suites of the sandstone samples (Figs. 5-6). Tables 4- 6 show the relative percentage of the abundance of the main heavy-mineral suites of the Imo, Ameki, and Ogwashi formations, while Fig. 7 shows the histogram plots of their relative abundance and ZTR indices.

The percentages of opaque minerals relative to non-opaque minerals are lower in the Imo Formation and the Ameki Formation samples, while the samples from the Ogwashi Formation showed a high percentage of opaque minerals compared to the non-opaque minerals. The sandstone samples of the Imo Formation, Ameki Formation, and Ogwashi Formation are rich in ultrastable heavy minerals (zircon, tourmaline and rutile), which consist of 60% of the entire non-opaque heavy minerals identified. The enrichments of zircon, tourmaline and rutile is due to the mechanical and chemical stability of these ultrastable heavy minerals during the periods of transport, deposition and diagenesis compared to the abrasion of unstable minerals such as the kyanite, sillimanite, pyroxene, hornblende, and andalusite during transport, deposition and diagenetic changes. The ultrastable heavy minerals show different colours ranging from colourless, deep-red, to brownish-yellow colours, which suggests different source rocks (Figs. 5-6). Zircon, tourmaline, and rutile grains retain all their depositional characteristics with no signs of modification due to chemical dissolution processes. These features confirm their stability during burial diagenesis.

Table 3. Mineralogical maturity based on zircon-tourmaline-rutile (ZTR) indices (modified from Hubert, 1962).

Maturity	Immature	Sub-mature	Mature	Super mature
ZTR index (%)	< 50	50 - 70	70 - 90	> 90

Rutile is the most fairly abundant of all the transparent heavy-mineral grains. On average, it constitutes 31% of all the heavy minerals in the studied sandstone samples in the study area (Tables 4- 6). Most of the rutile grains are short prismatic, angular to sub-angular, and rounded shapes. Zircon grains form 24% of all the transparent heavy-mineral suites of all the studied sandstone samples (Tables 4-5). The zircon grains from the three formations range from euhedral to subhedral as well as from rounded to well-rounded, and a few prismatic crystals (Figs. 5-6). The Tourmaline grains show the dominance of prismatic, rounded prismatic and sub-rounded to rounded shapes. The Imo Formation has predominantly euhedral and angular to sub-angular heavy-mineral grain shapes, while the Ameki and Ogwashi formations have more sub-rounded to well-rounded grain shapes.

The metastable heavy-mineral suites, which include staurolite, apatite, garnet, sillimanite, kyanite, sphene, epidote, hornblende, andalusite, and pyroxene, consist of 39% of the non-opaque heavy minerals, occurring in varying proportions throughout the three formations. These metastable heavy minerals occur in most sandstone samples from the Imo Formation (Table 4, Fig. 7a). Sphene, hornblende, andalusite, and pyroxene were present in most of the Imo Formation sandstone samples, but were noticeably absent in almost all of the samples from the Ameki Formation (Table 5, Fig.7b) and the Ogwashi Formation (Table 5, Fig.7c).

Table 4. Heavy-mineral composition of representative samples of the Imo Formation. Zrn - Zircon; Tur - Tourmaline; Apt - Apatite; Spn - Sphene; Rt - Rutile; St - Staurolite; Sil - Sillimanite; Kyn - Kyanite; Ept - Epidote Group; Grn - Garnet; Hb - Hornblende; And - Andalusite; Px - Pyroxene.

Sample ID.	Formation	Location	Zrn	Tur	Apt	Spn	Rt	St	Sil	Kyn	Ept	Grn	Hb	And	Px	Total %
ID/L2/01	Imo Fm.	Idima-Abam	8.6	3.8	5.6	1.8	25.3	7.8	2.7	18.3	2.7	10.2	0.4	2.3	9.8	100
ID/L2/02	Imo Fm.	Idima-Abam	10.4	3.6	3.5	1.0	38.2	6.6	3.4	15.4	2.0	12.1	0	0	3.8	100
ID/L2/03	Imo Fm.	Idima-Abam	15.4	6.7	2.5	0	32.7	3.6	4.8	17.6	3.6	6.2	0	1.3	4.2	99.9
NW/L4/02	Imo Fm.	Ndiwo-Itumbauzo	6.8	4.4	1.8	0.8	52.8	8.3	4.9	8.4	1.2	2.3	0	1.0	4.0	100
NW/L4/03	Imo Fm.	Ndiwo-Itumbauzo	12.5	5.5	0.6	0	40.9	7.1	8.3	10.7	4.8	4.8	0.8	2.2	0	100
NW/L5/01	Imo Fm.	Ndiwo-Itumbauzo	9.3	2.9	3.2	0	47.3	4.8	3.8	9.5	9.8	7.3	0	0	0	100
NW/L5/02 (B)	Imo Fm.	Ndiwo-Itumbauzo	14.6	8.8	5.6	0	37.8	5.0	5.3	13.1	4.3	1.6	0	0	2.6	100
NW/L5/02 (T)	Imo Fm.	Ndiwo-Itumbauzo	12.7	1.5	4.7	0	48.8	3.2	2.6	11.5	7.4	2.6	1.0	0.3	3.7	100
NW/L6/01	Imo Fm.	Ndiwo-Itumbauzo	5.3	7.9	3.3	2.0	30.6	5.3	5.1	16.4	5.4	11.5	0	0	6.8	100
NW/L6/02	Imo Fm.	Ndiwo-Itumbauzo	8.7	2.6	2.0	1.5	32.5	8.7	3.8	18.9	6.3	2.0	1.8	0.5	8.5	99.9
NW/L6/03	Imo Fm.	Ndiwo-Itumbauzo	11.8	3.2	1.7	2.8	27.4	6.2	2.6	13.2	12.8	6.1	0	0	9.2	100
OKP/L3/01	Imo Fm.	Okputunge-Bende	18.2	1.9	4.9	0	39.2	2.1	4.8	10.9	7.5	2.8	1.2	0	6.5	100
OKP/L3/02	Imo Fm.	Okputunge-Bende	15.3	4.6	2.3	0	30.7	5.5	6.9	16.2	4.2	3.4	0	0	9.1	100
OKP/L3/03	Imo Fm.	Okputunge-Bende	14.5	3.5	5.2	0	34.9	8.0	3.3	9.9	9.3	5.7	1.6	0	3.7	100

Table 5. Heavy-mineral composition of representative samples of the Ameki and the Ogwashi formations. Zrn - Zircon; Tur - Tourmaline; Apt - Apatite; Spn - Sphene; Rt - Rutile; St - Staurolite; Sil - Sillimanite; Kyn - Kyanite; Ept - Epidote Group; Grn - Garnet; Hb - Hornblende; And - Andalusite; Px - Pyroxene.

Sample ID.	Formation	Location	Zrn	Tur	Apt	Spn	Rt	St	Sil	Kyn	Ept	Grn	Hb	And	Px	Total %
OZI/L9/01	Ameki Fm.	Ozu-Item	36.3	5.2	2.8	0	31.8	0.4	4.7	14.0	3.3	0	0	0	1.3	99.8
OZ/L10/01	Ameki Fm.	Ozu-Akoli	26.5	6.7	6.3	0	35.7	5.7	1.3	12.7	2.3	1.6	0	0.5	0.7	100
OZ/L10/02	Ameki Fm.	Ozu-Akoli	43.2	3.8	4.6	0	29.3	3.5	2.6	9.5	0.6	0	0	0	1.1	100
OK/L15/01	Ogwashi Fm.	Okaiuga	45.2	10.9	6.3	0	20.3	0	3.6	8.5	0	4.5	0	0	0	100
OK/L15/03	Ogwashi Fm.	Okaiuga	32.9	6.2	0	0	26.6	2.8	2.7	23.8	1.8	3.2	0	0	0	100
OK/L15/05	Ogwashi Fm.	Okaiuga	47.3	2.6	2.2	0	19.7	1.6	1.5	17.9	4.2	2.9	0	0	0	99.9
OK/L15/06	Ogwashi Fm.	Okaiuga	57.7	3.2	1.7	0	18.2	1.3	2.1	10.3	1.4	1.3	0	0	0	100
OK/L15/07	Ogwashi Fm.	Okaiuga	64.2	1.6	0	0	10.6	3.6	0.7	6.5	4.6	6.3	0	0	1.8	100
OK/L15/08	Ogwashi Fm.	Okaiuga	35.5	7.8	1.6	0	9.3	0.8	5.6	24.7	9.8	2.0	0	0	0	100

Table 6. Maximum, minimum, and average percentage of the main non-opaque heavy minerals.

Non-Opaque Minerals	Imo Formation			Ameki Formation			Ogwashi Formation		
	Max. %	Min. %	Ave. %	Max. %	Min. %	Ave. %	Max. %	Min. %	Ave. %
Zircon	18.2	5.3	11.7	43.2	26.5	35.3	64.2	32.9	47.1
Tourmaline	8.8	1.5	4.4	6.7	3.8	5.2	10.9	1.6	5.4
Apatite	5.6	0.6	3.4	6.3	2.8	4.6	6.3	0	2.0
Sphene	2.8	0	0.7	0	0	0	0	0	0
Rutile	52.8	23.3	37.1	35.7	29.3	32.3	26.6	9.3	17.5
Staurolite	8.7	2.1	5.9	5.7	0.4	3.2	3.6	0	1.7
Sillimanite	8.3	2.6	4.5	4.7	1.3	2.9	5.6	0.7	2.7
Kyanite	18.9	8.4	13.6	14	9.5	12.1	24.7	6.5	15.3
Epidote	12.8	1.2	5.8	3.3	0.6	2.1	9.8	0	3.6
Garnet	12.1	2.0	5.6	1.6	0	0.5	6.3	1.3	3.4
Hornblende	1.8	0.4	0.5	0	0	0	0	0	0
Andalusite	2.3	0	0.5	0.5	0	0.2	0	0	0
Pyroxene	9.8	0	5.1	1.3	0.7	1	1.8	0	0.3

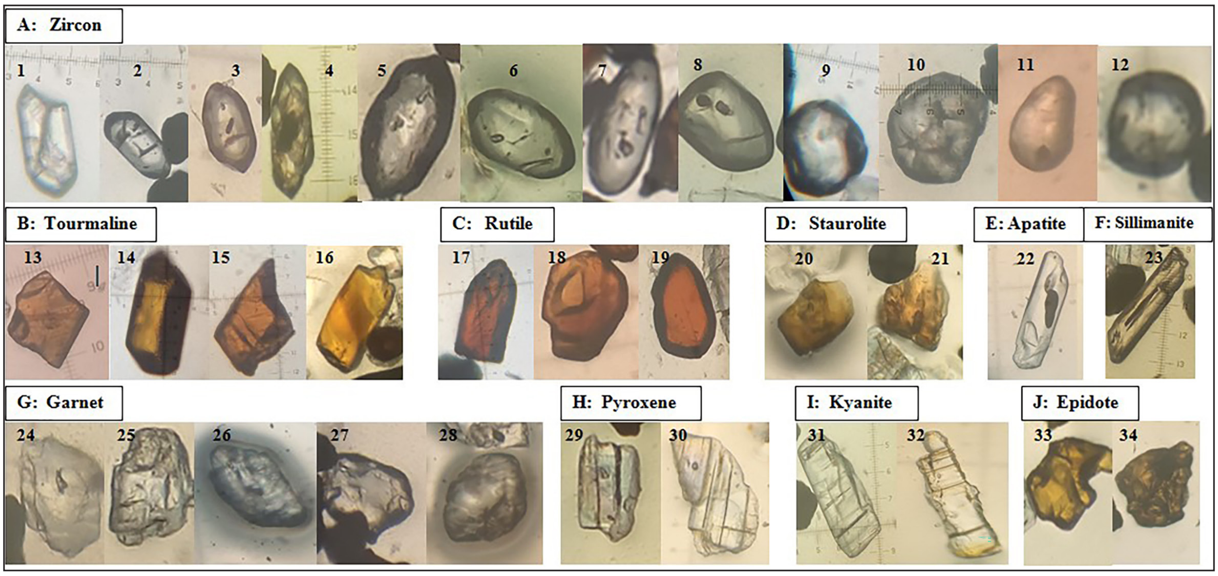


Figure 5. Photomicrographs of selected non-opaque heavy-mineral suites from sandstone samples within the study area. **(A)** 1 - 6 show euhedral zircon grains with zoning, while 7 - 12 show well-rounded polycyclic zircon grains; **(B)** 13 – 16 show prismatic tourmaline grains; **(C)** 17 – 19 show euhedral and well-rounded oblong form rutile grains with well-developed pyramidal terminations; **(D)** 20 – 21 show prismatic and angular shape staurolite grains; **(E)** 22 shows long slender prisms of apatite grains; **(F)** 23 shows sillimanite grain with parallel cleavage fragments; **(G)** 24 - 28 show sub-rounded to rounded garnet grains; **(H)** 29 – 30 show pyroxene grains with parallel cleavage fragments; **(I)** 31 – 32 show elongated kyanite grains; and **(J)** 33 – 34 show irregular, angular, and equant grains of epidote group. (Scale bar is 3 mm).

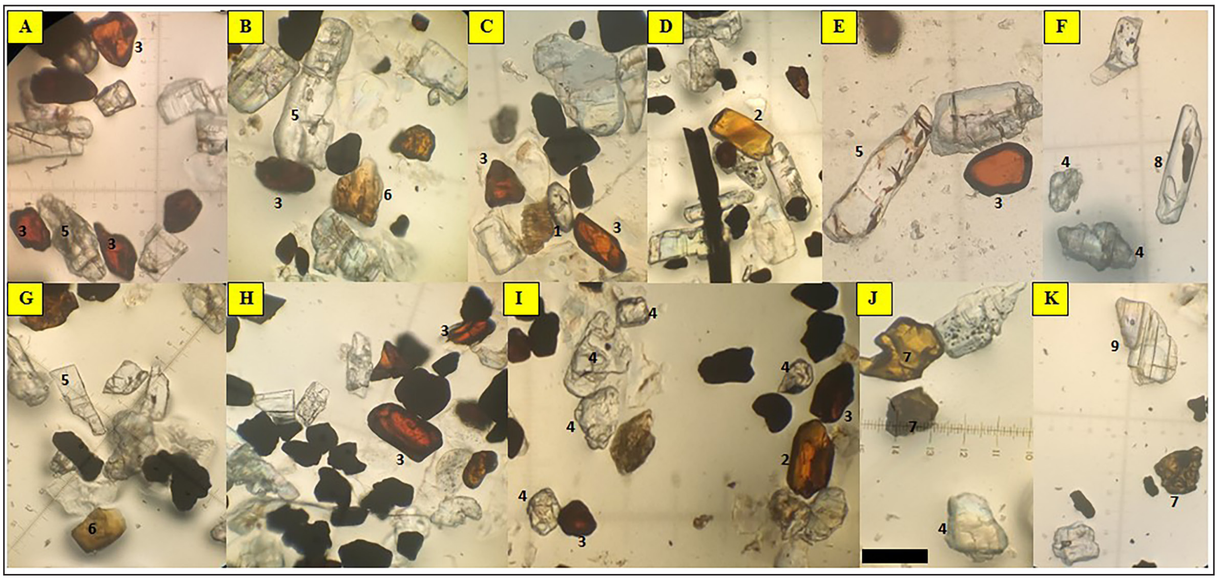


Figure 6. Selected photomicrographs of heavy-mineral suites from sandstone samples of the Paleogene sediments (Imo, Ameki and Ogwashi formations). Transparent heavy minerals dominate, but opaque heavy-mineral grains (dark) probably magnetite, hematite and limonite are also present. Numbered labels represent different minerals **(A)** 3 - rutile, 5 - kyanite; **(B)** 3, 5, 6 - staurolite; **(C)** 1 - zircon, 3; **(D)** 2 - tourmaline; **(E)** 3, 5; **(F)** 4 - garnet; 8 - apatite; **(G)** 5, 6; **(H)** 3; **(I)** 2, 3, 4; **(J)** 4, 7 - epidote; **(K)** 7, 9 - pyroxene. (Scale bar is 3mm).

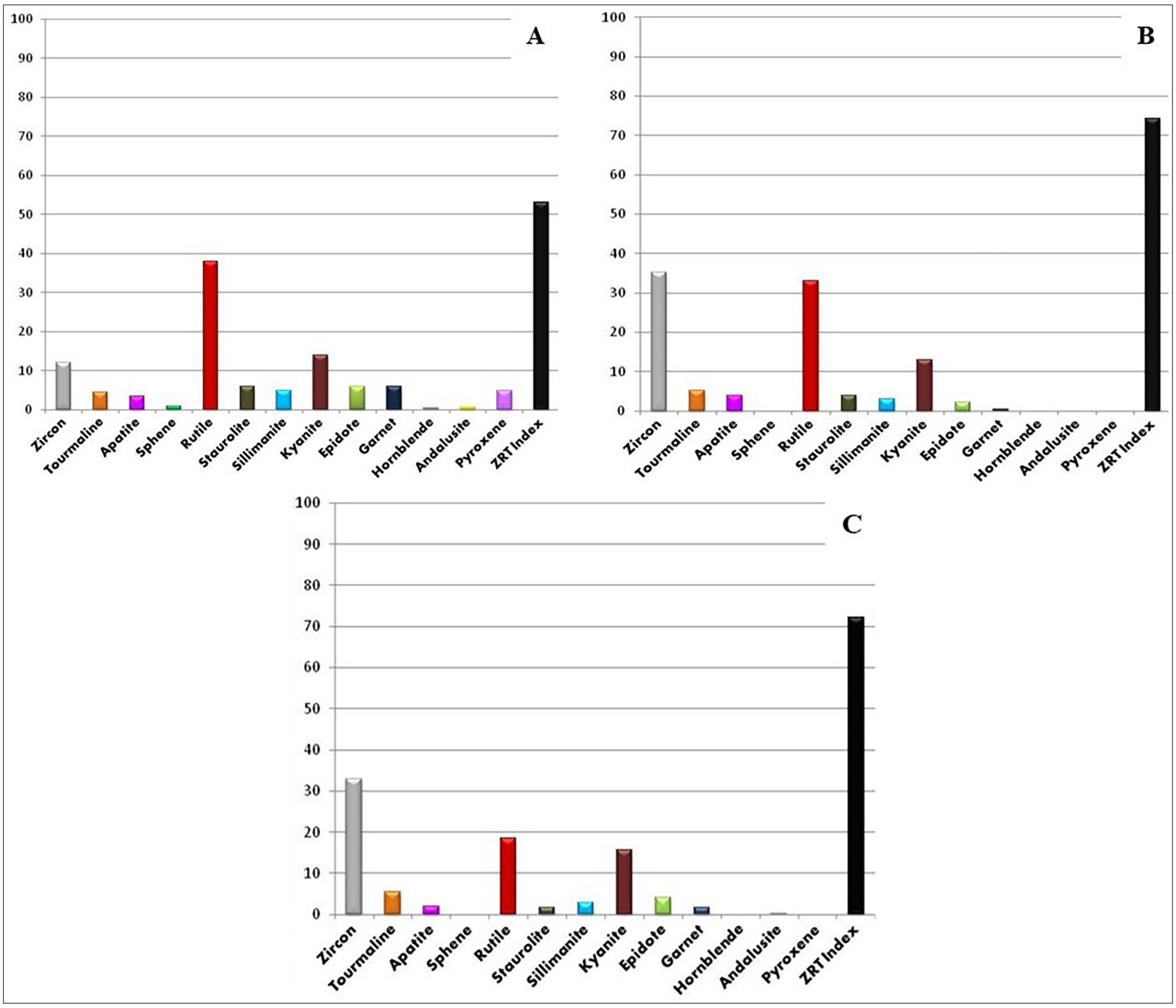


Figure 7. Distribution bar charts of the average percentages of the different non-opaque heavy-mineral assemblages and their ZTR indices for the three Paleogene formations sandstone samples. **(A)** Imo Formation; **(B)** Ameki Formation; and **(C)** Ogwashi Formation.

6. Discussion

6.1 ZTR Heavy-Mineral Index as an Indicator of Sandstone Mineralogical Maturity

In the process of weathering, transportation, and deposition, unstable minerals are progressively destroyed, concentrating the stable ones. A stable mineral index, commonly used to determine the abundance of stable minerals in sandstones, and referred to as the zircon-tourmaline-rutile (ZTR) index, is employed in this study (Hubert, 1962; Table 7). The ZTR-maturity index analysis of the sandstone samples of the three formations within the study area shows that the Imo Formation sandstone samples vary from 37.7% to 64%, with an average of 53%; the Ameki Formation sandstone samples vary from 68.9% to 76.3%, with an average of 73%, while the Ogwashi Formation sandstone samples vary from 52.6% to 79.1%, with an average of 70% (Tables 6-7). This indicates that the sediments are mineralogically immature to mature. The general concept is that there is an increase in the ZTR index with the increasing geological age of the sediments as a result of the progressive dissolution of the unstable minerals (Hubert, 1962), but this is not the case with the Imo Formation, which has the lowest ZTR index on average, due to a higher percentage of metastable heavy minerals (Table 7).

Based on Folk (1980) and Pettijohn et al. (1987) petrographic classification of sandstones, Ekwenye et al. (2015) classified sandstone samples of the Imo Formation into submature arkosic arenite to sub-arkose, while the Ameki Formation and Ogwashi Formation sandstones were classified into mature sub-litharenite, sub-arkose and quartz arenite. This classification of the Imo Formation is reflected in its average ZTR index of 53% (submature), while the Ameki Formation and the Ogwashi Formation sandstone samples have a higher average ZTR index of 73% and 70%, respectively (i.e. mature). A possible reason why the Imo Formation has a lower ZTR index could be that the Imo Formation sandstones were deposited after a short distance of transportation and rapid deposition. This is characterized by their predominantly euhedral and angular to sub-angular heavy-mineral grain shapes, while Ameki and Ogwashi formations have more sub-rounded to well-rounded grain shapes, which were deposited after a longer distance of transportation, farther away from the source rocks. Therefore, the higher a sandstone sample tends towards quartz arenites, the higher its ZTR-maturity index will be (Hubert, 1962). This is because most of the non-stable mineral grains in the sandstone samples have undergone chemical dissolution, while retaining the stable mineral grains (quartz, zircon, tourmaline and rutile), which dominates the sandstone samples of the Ameki Formation and Ogwashi Formation classified as sub-litharenite, sub-arkose, and quartz arenite (Ekwenye et al., 2015).

6.2 Relationship between Heavy-Mineral Assemblage and Tectonic Setting

The relationship between tectonic setting and sediment composition has been studied by several authors (Dickinson and Suczek, 1979; Pettijohn, et al., 1987; Nechaev and Isphording, 1993). The relationship between heavy-mineral assemblages and tectonic environments was evaluated using the triangular plot of interrelationship of the MF-MT-GM suites in the studied sediments, according to Nechaev and Isphording (1993). "MF" indicates common heavy minerals of mafic magmatic rocks (i.e. the total content of pyroxene, hornblende and olivine), "MT" indicates common heavy minerals of basic metamorphic rocks (total content of epidote, garnet and pale-coloured and blue green amphibole), while "GM" indicates accessory minerals of granitic and silicic metamorphic rocks (zircon, tourmaline, staurolite, kyanite, andalusite, monazite, and sillimanite).

The results show that the Imo Formation has an average MF of 9.5%, MT of 19.8% and GM of 70.7%; and the Ameki Formation has the average MF of 1.6%, MT of 4.2% and GM of 94.1%; while the Ogwashi Formation has the average MF of 0.3%, MT of 8.6% and GM of 91.1% (Table 7). The plotting of the heavy-mineral assemblages of these three formations on the MF-MT-GM triangular plot of Nechaev and Isphording (1993), as shown in Fig. 8, indicates that these sandstone samples fall within the field of mature passive continental margins, characterized by a high percentage of heavy minerals derived from acidic igneous and regional metamorphic rocks, as a result of sediments' reworking, and deep weathering in regions with no active tectonic events (Nechaev and Isphording, 1993). The results of the data plotted are in line with earlier studies of the Niger Delta Basin as a rifted Atlantic-type and a mature passive continental margin basin which resulted from the thermal contraction of the lithosphere (Sleep, 1971; Steckler and Watts, 1978; Ofoegbu and Onuoha 1990).

According to Nechaev and Isphording (1993), heavy-mineral assemblages of the continental margins far from the volcanic areas contain GM values greater than MF values, as clearly seen in Table 7. Also, according to Dickinson and Suczek (1979), Ingersoll and Suczek (1979), and Valloni and Maynard (1981), the provenance of passive continental margin sediments has a wide range of variability – quartz, feldspars, and some lithic fragments, as well as zircon, tourmaline and rutile dominate in the sediments found in passive continental margin sediments. The data plotted in Fig. 8 show that the heavy-mineral suites of the three formations were derived from a passive continental margin of the Niger Delta Basin, and indicate a mixed provenance of acidic igneous and metamorphic sources, which are dominated by a high proportion of GM compared to MF suites.

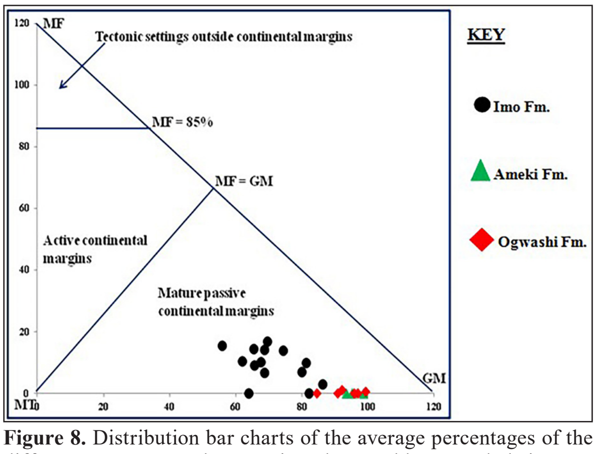


Figure 8. Distribution bar charts of the average percentages of the different non-opaque heavy-mineral assemblages and their ZTR indices for the three Paleogene formations sandstone samples.

Table 7. ZTR indices and MF, MT, and GM percentages of the studied sandstone samples of the three formations in the study area. MF, MT, GM calculated after Nechaev and Isphording (1993).

Formation	Sample ID.	ZTR Index %	Ave. ZTR Index %	MF%	MT%	GM%	Ave. MF%	Ave. MT%	Ave. GM%
Imo Fm	ID/L2/01	37.7	53	15.3	19.4	65.3	9.5	19.8	70.7
	ID/L2/02	52.2		6.6	24.61	68.8			
	ID/L2/03	54.8		6.6	15.5	77.9			
	NW/L4/02	64.0		9.7	8.5	81.8			
	NW/L4/03	58.9		1.4	16.9	81.7			
	NW/L5/01	59.5		0	36.1	63.9			
	NW/L5/02(B)	61.2		4.7	10.7	84.6			
	NW/L5/02(T)	63.0		10.1	21.5	68.4			
	NW/L6/01	43.8		10.7	26.5	62.8			
	NW/L6/02	43.8		16.7	13.4	69.9			
	NW/L6/03	42.4		14.1	29	56.8			
	OKP/L3/01	59.3		13.8	18.4	67.8			
	OKP/L3/02	50.6		14	11.7	74.4			
	OKP/L3/03	52.9		8.9	25.2	65.9			
Ameki Fm	OZI/L9/01	73.3	73	2.0	5.1	92.9	1.6	4.2	94.1
	OZ/L10/01	68.9		1.2	6.7	92.1			
	OZ/L10/02	76.3		1.7	0.9	97.4			
Ogwashi Fm	OK/L15/01	76.4	70	0	6.2	93.8	0.3	8.6	91.1
	OK/L15/03	65.7		0	6.8	93.2			
	OK/L15/05	69.6		0	9.1	90.9			
	OK/L15/06	79.1		0	3.5	96.5			
	OK/L15/07	76.4		2	12.2	85.8			
	OK/L15/08	52.6		0	13.7	86.3			

6.3 Provenance Evaluation and Tectonic Setting

The heavy-mineral suites (Tables 4- 6) identified in the Paleogene sediments of the Niger Delta Basin revealed that the ultrastable heavy-mineral grains are euhedral to subhedral, as well as rounded to well-rounded and a few prismatic crystals, while the metastable heavy minerals have prismatic, angular to subangular and irregular shape (Figs. 5-6). The euhedral and angular to subangular morphology probably indicates short transportation and rapid deposition derived from igneous sources, while the sub-rounded to the well-rounded shape zircon, tourmaline, and rutile indicate a moderate to long transportation from reworked sedimentary sources (Poldervaart, 1955). The presence of brown and pale brown varieties of tourmaline indicates that the sediments were derived from a metamorphic provenance (Blatt et al., 1980), while the prismatic, yellow and brown-colored tourmaline, indicates the derivation of sediments from granitic and pegmatic rocks (Krynine, 1946). The relative abundance of different varieties of zircon, tourmaline, and rutile of different morphology suggests that these heavy minerals came from a mixed provenance of igneous, metamorphic, and reworked older sedimentary rocks, while the occurrence of sillimanite, kyanite, andalusite, staurolite, and hornblende, as accessory minerals in this assemblage (Tables 4-5), clearly suggests a parent rock affiliation to an area of medium- to high- grade metamorphism of aluminum-rich pelitic rocks (Nockolds et al., 1978). The percentages of the contribution of the different associated parent rocks to the three formations were calculated based on their associated heavy-mineral assemblages (Table 8). In the Imo Formation, acidic igneous and/or recycled sedimentary rocks contributed 20.2%, basic igneous rocks contributed 5.1%, with the regional metamorphic rocks being the greatest contributor with 73%, and contact metamorphic rocks with 0.5%. The Ameki Formation is sourced predominantly by regional metamorphic rocks (53.1%), with a significant contribution from acidic igneous and/or sedimentary rocks (45.1%), while the Ogwashi Formation is sourced predominantly from acidic igneous and/or sedimentary rocks (Table 8).

Ekwenye et al. (2015) noted that the orogenic recycling of the sedimentary rocks corresponds to the Santonian tectonic events, which resulted in the folding and uplifting of the Abakaliki area to form Abakaliki anticlinorium and the subsequent formation of Anambra and Afikpo depocentres. The anticlinorium became one of the sediment sources for the Cretaceous Anambra and Afikpo basins. The compositional maturity and dominance of the stable heavy minerals indicate a lack of tectonism during the Paleogene and moderate to high-energy conditions during sedimentation. It can be concluded that the Paleogene sediments in the study area were deposited after a short- to long-distance transportation from the source areas to the deposition sites.

Th plot of the paleocurrent data shows that the Paleogene sediments of the Niger Delta Basin in the study area were transported from southeasterly and southwesterly source terrains (Fig. 4). The paleocurrent modes are mainly a bimodal pattern except for the Ogwashi Formation which shows a unimodal pattern with little dispersion. The northwesterly to southeasterly and northeasterly to southwesterly distribution of the paleocurrent modes suggests that the source could be the high- to medium- and low-grade metamorphic terrain of the Obudu Plateau (Adamawa Highlands) and Oban Massif, which consists of magmatic-gneiss complex rocks (Ekwueme, 2006), and/or the magmatic-gneiss complex and schist belt of the West African Massif, as well as recycled sedimentary rocks from the Anambra and Afikpo basins (Fig. 9).

Table 8. Summary of the associated parent rock percentages of contribution of heavy minerals to the three formations. Each parent rock is the percentage sum of the associated heavy minerals. Acid igneous and/or sedimentary rock (zircon + tourmaline + apatite + sphene); regional metamorphic rock (rutile + staurolite + sillimanite + kyanite + epidote + hornblende + garnet); contact metamorphic (andalusite); Basic igneous (pyroxene).

Formation	Acid Igneous and/or Sedimentary	Regional Metamorphic	Contact Metamorphic	Basic Igneous
Imo Fm	20.2%	73%	0.5%	5.1%
Ameki Fm	45.1%	53.1%	0.2%	1%
Ogwashi Fm	54.5%	44.2%	0%	0.3%

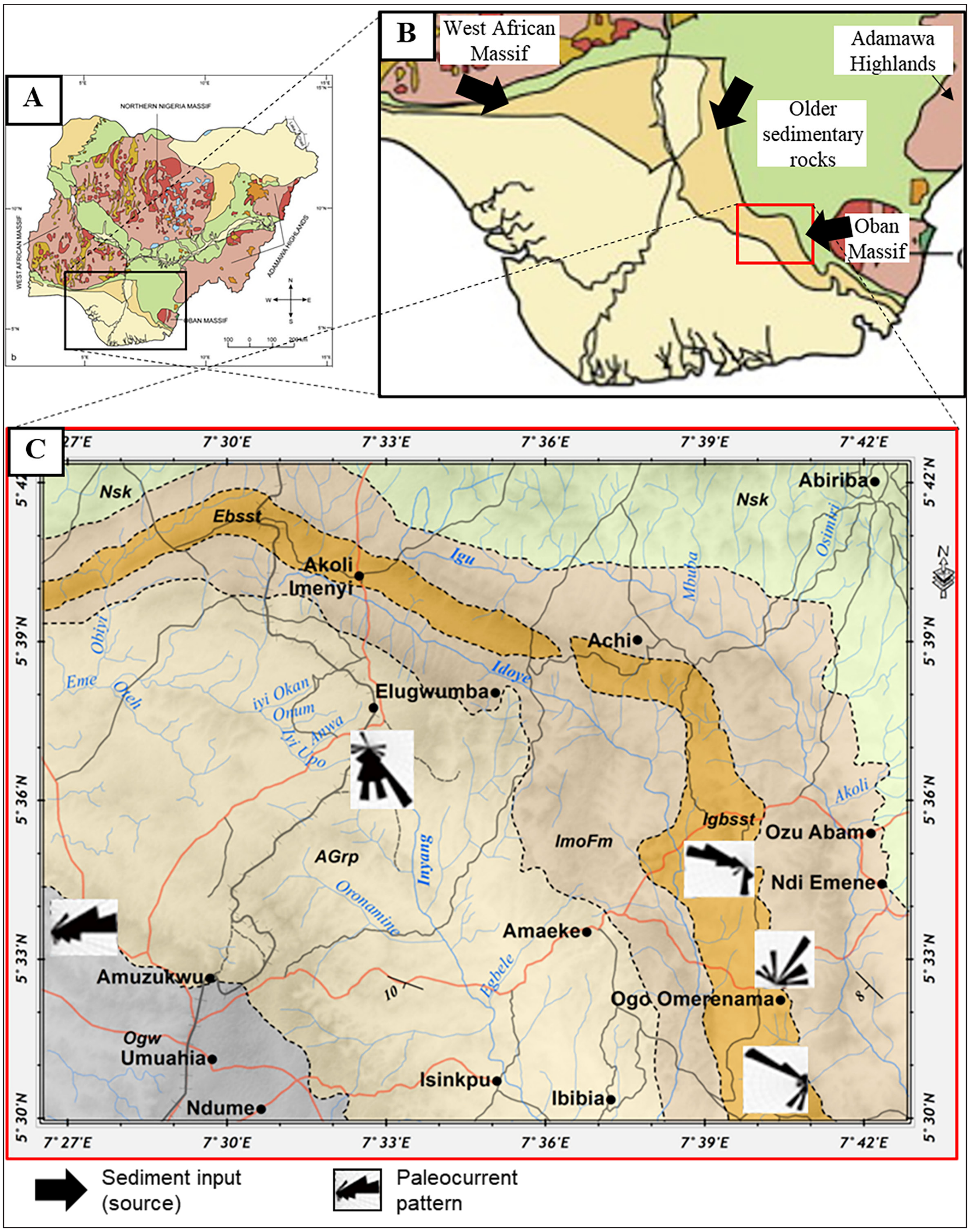


Figure 9. (A) Inset geologic map of Nigeria (after Nigerian Geological Survey Agency, 2009); **(B)** Zoom in on the southern part of Nigeria showing the basement complex and older sedimentary rocks distribution **(C)** Detailed geologic map of the study showing paleocurrent patterns.

5. Conclusions

This study has examined the provenance and tectonic setting of the Paleogene strata exposed at the southeastern part of the Niger Delta. The petrographic study shows the occurrence of zircon, tourmaline, and rutile of different forms, suggesting a mixed provenance from igneous, metamorphic, and reworked older sedimentary rocks, while the occurrence of sillimanite, kyanite, andalusite, staurolite, and hornblende heavy minerals in this assemblage clearly suggests a parent rock affiliation to an area of medium- to high-grade metamorphic rock sources.

The mineralogical maturity of the sandstones were calculated from the ZTR maturity index, with the ZTR index increasing in the younger sediments of Ameki and Ogwashi formations, which have a high proportion of stable heavy minerals and are submature to mature, while the older sediments of the Imo Formation have an almost equal stable and metastable heavy- mineral species, and a ZTR- maturity index range of immature to submature.

The plot of MF-MT-GM suites indicates that the sandstone units of the Paleogene strata occur within the mature passive continental margin on a stable craton of the African plate in the Niger Delta. This could be attributed to the dominance of stable heavy-mineral species, after a medium to a long distance of transportation from a source area lacking active tectonism, to the site of deposition.

The paleocurrent and provenance analyses indicate that the depositional systems of the Paleogene formations derived their detritus mainly from the metamorphic and granitic basement complex rocks of the Oban Massif and the Obudu Plateau (Adamawa Highlands), east and southeast, as well as the gneisses and schists' belt of the West African Massif from the northwest and west of the study area, whereas the regional paleocurrent analysis shows the predominance of bimodal WNW and ENE paleoflow, with a high to medium variance.

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