A Review of the Heavy Mineral Provinces of the Paleogene Sediments, South-Eastern Nigeria: Factors Controlling the Distribution of the Heavy Minerals

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ABSTRACT

High-resolution heavy mineral analysis of the Paleogene sediments, south-eastern Nigeria, was used to delineate the heavy mineral provinces in the study area. Four heavy mineral provinces and two sub-provinces were identified based on the proportion of the ultra-stable minerals and the unstable high- and medium-grade metamorphic minerals. They include: i) the sandstone suite province and ii) the mixed suite province for the Imo Formation; iii) the Ameki Group province, and iv) the Ogwashi province which is delineated into Ogwashi 1A and 1B sub-provinces as a result of hydraulic differentiation.

The sandstone suite province is dominated by euhedral-subhedral zircon which suggests first-cycle detritus and mostly derived from granitoid rocks. The presence of the rounded zircon crystals indicates polycyclic or recycled pre-existing sediments. The mixed suite province records a high occurrence of garnet. The high counts of garnet, kyanite, and the presence of sillimanite, sphene, and staurolite suggest a high-amphibolite grade metamorphism. The Ameki Group province is characterized by tourmaline and apatite grains that occur as prismatic crystals, and rounded prisms, subrounded to rounded grains which suggest first cycle detritus to polycyclic origin. The Ogwashi province is strongly typified by sparse heavy mineral grains probably due to coarse nature of the sediments. Ogwashi province is categorized into Ogwashi 1A and 1B sub-provinces. The Ogwashi 1A sub-province is characterized by the absent of ultra-stable mineral rutile and the abundance of zircon, monazite and tourmaline which indicates basic igneous provenance whereas common occurrence of kyanite, staurolites, epidote minerals indicates input from metamorphic source. The Ogwashi 1B sub-province is dominated by zircon and rutile, and others are kyanite and tourmaline which also suggest mixed provenance. These heavy mineral distribution patterns are probably controlled river runoff, actions of tide and wave processes, erosion of adjacent terraces, and grain size that have probably been modified by hydraulic sorting.

(Keywords: high resolution, heavy minerals, ultrastable, ultra-stable minerals, provinces, Palegene, Niger Delta)

INTRODUCTION

Heavy mineral analysis has proven essential in terms of interpreting provenance of sedimentary rocks, mapping and delineating heavy mineral provinces, reconstructing ancient sedimentary routes, correlating unfossiliferous sedimentary strata, mining and exploration and forensic science (Lihou and Mange-Rajetzky, 1996; Mange and Otvos, 2005; Sevastjanove et al. 2012; Ekwenye et al., 2015). Integration of heavy mineral analysis with other techniques such as petrographic analysis, geochemistry, clay mineralogy, x-ray fluorescence (XRF), palynology as well as palaeocurrent studies provides very useful information on provenances (Hallsworth and Chisholm 2000, 2008; Zimmermann and Spalletti 2009; Tijani et al. 2010; Ekwenye et al. 2015).

Researchers have been able to delineate heavy mineral provinces based on mineralogical variations and heavy mineral distribution patterns in their study areas. Bengtsson and Stevens (1996) used the distribution patterns to interpret the transport pathways and the associated sediment sources for bottom sediment in the Skagerrak-Kattegat area. Mange and Otvos (2005) mapped the heavy mineral provinces of south-western Louisiana, using modern river samples and Quaternary samples. Okay and Ergün (2005) used the heavy mineral assemblages from Marmara Sea (an inland sea between the Mediterranean and Black seas) to define four heavy mineral provinces.

Numerous works on heavy mineral analysis and provenance interpretation of the south-eastern sedimentary basins in Nigeria such as the Benue-Abakaliki Trough and the Anambra Basin are recorded in Amajor (1987), Hoque (1977), Hoque and Ezeque (1977), Odigi (1986), and Tijani, et al. (2010). Heavy mineral studies of the Paleogene Niger Delta lithostratigraphic units are partly documented in Hoque (1977) and Nwajide (1980), where the authors only concentrated on the Nanka Formation.

Ejeh et al., (2015) studied the geochemical and heavy mineral characteristics of the Ogwashi Formation to unravel the provenance and tectonic setting. Ekwenye et al. (2015) also discussed the provenance study of the Paleogene sedimentary succession, however, delineation of heavy mineral provinces in the south-eastern Nigeria was not considered. Currently, there is no published work on the heavy mineral provinces of the Paleogene strata.

This research reviews these heavy mineral assemblages particularly the high-resolution heavy mineral analysis (HRHMA) to provide a framework for delineating heavy mineral provinces in the Paleogene Niger Delta as well as to document controlling factors affecting the distribution of the heavy minerals in the study area.

GEOLOGIC AND STRATIGRAPHIC SETTING

The separation of the African-South American plates during the Early Cretaceous led to the evolution of the Benue Trough, which is linked to the formation of the southern sedimentary basins and is well documented (Reyment, 1965; Murat, 1972; Nwachukwu, 1972; Olade, 1975; Kogbe, 1976; Petters, 1978; Wright, 1981; Benkhelil, 1982, 1989; Hoque and Nwajide, 1984). The Benue Trough is considered as part of the West and Central African Rift System (WCARS) that opened as a sinistral wrench complex (Benkhelil, 1989; Genik, 1993).

The evolution of the southern Nigerian sedimentary basins was controlled by three major tectonic phases. The first phase led to the formation of the Abakaliki-Benue Trough and the Calabar Flank. The second and third phases resulted in the sedimentation of the Anambra Basin/Afikpo Sub-basin and the Niger Delta respectively (Murat, 1972; Umeji, 2007).

The first phase is the Aptian/Albian - Santonian tectonic phase (Short and Stauble, 1967; Murat 1972). It commenced with major marine transgression from the Gulf of Guinea onto the Southern Benue Trough and reached the Middle Benue Trough, depositing the Asu-River Group (Figures 1 and 2) during the Aptian-Albian. Nwachukwu (1972) suggested a tectonic event during the Cenomanian in the Abakaliki Basin that resulted in the restriction of the Cenomanian Odukpani Formation (now known as Mfamosing Formation) to the Calabar Flank and the occurrence of lead-zinc mineralization in the Albian strata.

But Cenomanian sediments are said to occur in the Eze-Aku River section at Aka-Eze; Amasiri Sandstone, Umukwueke; Ibii and Ekukunella areas; Ezillo and Agala formations and other areas in the Central and Northern Benue Trough. During the Turonian transgression, the Eze-Aku Group and part of Awgu Formation were deposited (Benkhelil, 1986; Ojoh, 1992; Umeji, 2007). The Conanian regression culminated with the deposition of the Agbani Sandstone Member in the Abakaliki Basin. Sedimentation in the Abakaliki Basin was halted due to the Santonian thermo-tectonism (Figure 1).

The second phase is a Santonian compressional phase which resulted in the folding, faulting and uplifting the Abakaliki Basin to form an anticlinorium; displacing depocentres westward and eastward to form the Anambra and Afikpo basins. Sedimentary units of the Anambra Basin form a regressive offlap sequence, located on the continental crust and consist of the Nkporo Group and the Coal Measures, with the Nsukka Formation terminating sedimentation in the Anambra Basin (Nwajide, 2005).

The Anambra Delta Complex was terminated by an extensive Paleocene transgression (Whiteman, 1982). The third phase began in the late Paleocene with Niger Delta sedimentation (Short and Stäuble, 1967; Evamy et al., 1978; Nwajide, 2005). (Figure 2).

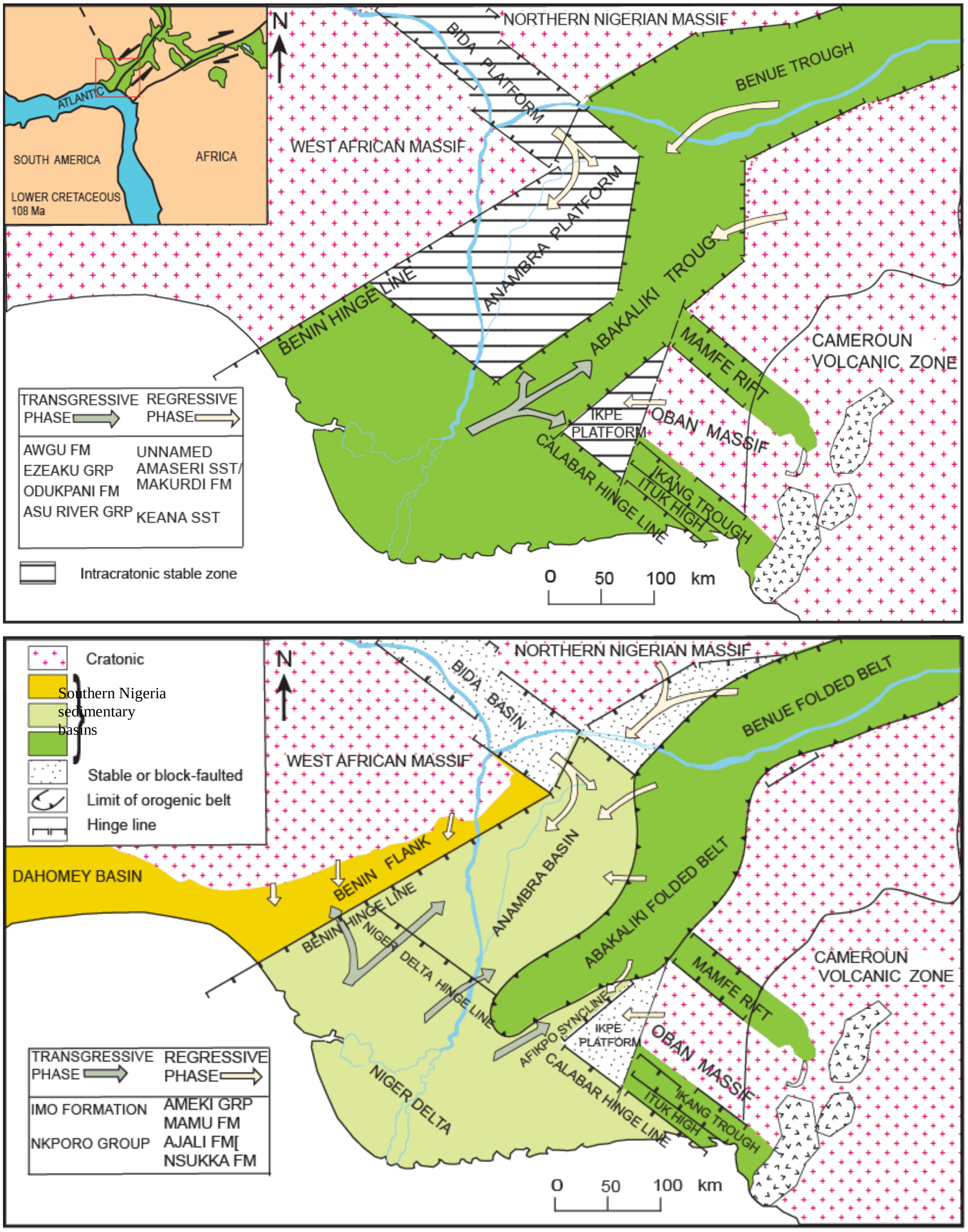

Figure 1: (A). Tectonic Map of South-East Nigeria, from the Albian to Santonian Ages. (B). Tectonic Map of South-East Nigeria during the Campanian to Eocene (redrawn and modified after Murat, 1972).

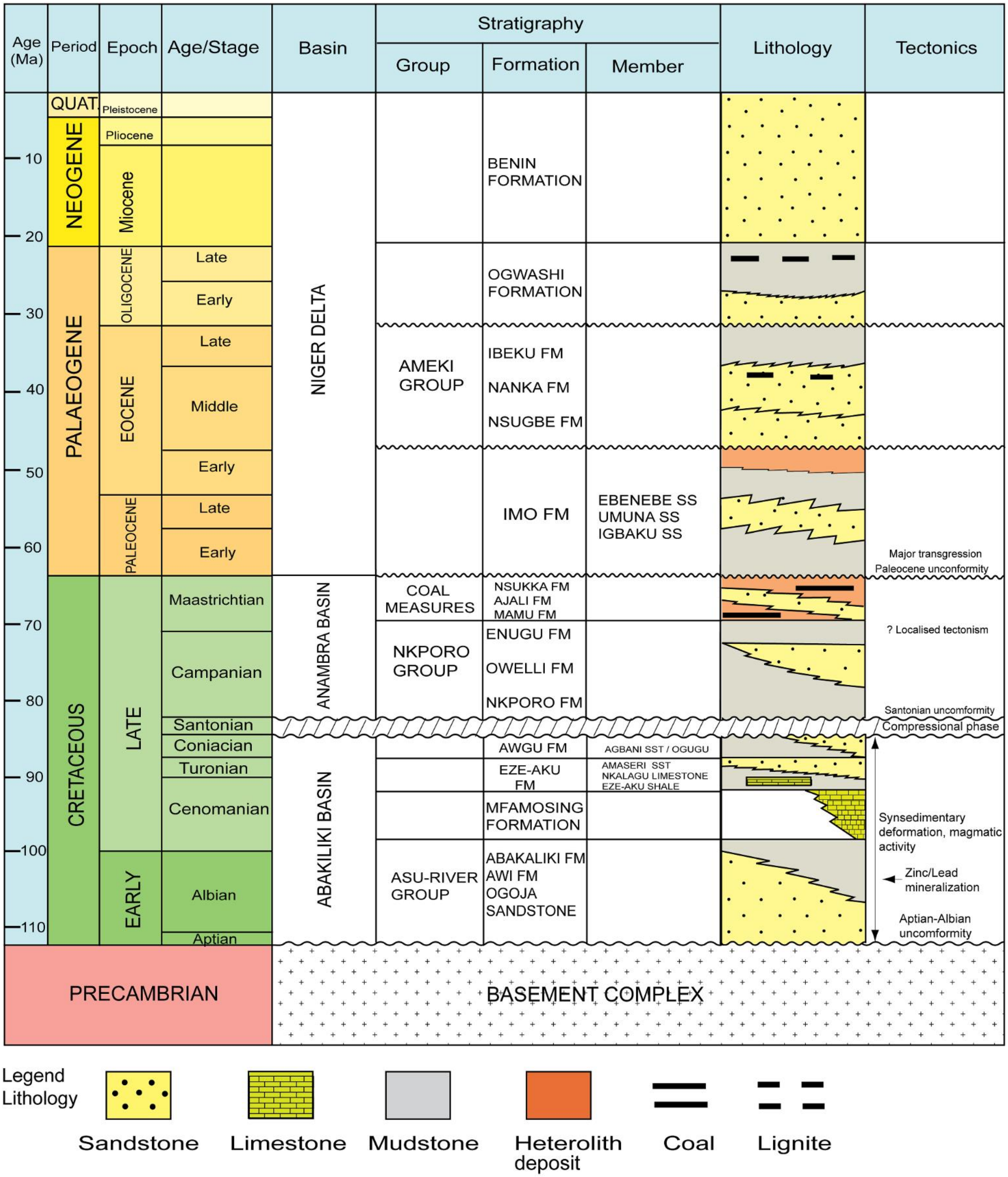

Figure 2: Stratigraphic Succession in the Anambra Basin and Outcropping Niger Delta (after Ekwenye et al., 2017).

The stratigraphic framework of the southern sedimentary basins is documented in several works, but to mention a few (Short and Stäuble, 1967; Nwachukwu, 1972, Murat, 1972; Oboh-Ikuenobe et al., 2005; Nwajide, 2013; Ekwenye et al., 2014; 2017).

A major transgression extends across the entire area of southern Nigeria during the Paleocene, terminating the advance of the Upper Cretaceous Delta and separating it stratigraphically from the modern Niger Delta which began to form in the Thanetian (Nwajide, 2005). Paleogene strata within southern Nigeria consist of a sedimentary succession that is thicker than 3500 m. These include the Imo Formation (~480 m – 1000 m), Ameki Group (~1400 m), and Ogwashi Formation (~250 m) (Simpson, 1955; Reyment, 1965; Dessauvagie, 1975; Jan du Chêne et al., 1978; Nwajide, 1980; Arua, 1986; Anyanwu and Arua, 1990; Oboh-Ikuenobe et al., 2005).

The Imo Formation is dated as Paleocene to Early Eocene (Table 1) based on based on macro and microfossils dinoflagellate cysts, miospore assemblages (Short and Stäuble, 1967; Oloto, 1992) (Reyment, 1965; Adegoke et al., 1980; Arua, 1980) and it is composed of blue-grey clays, black shales with bands of calcareous sandstone, marl, and limestone (Reyment, 1965). The Imo Formation is referred to as the oldest formation in the Niger Delta (Petters, 1991). The formation shows lateral variation into sandstone in certain places in south-eastern Nigeria and is characterized by sandstones units that are laterally equivalent - the Ebenebe, Igbaku and Umuna Sandstone. A foreshore-shoreface (Reijers et al., 1997) and delta front environment (Arua, 1990) have been suggested for the sandstone member of the Imo Formation. Ekwenye et al. (2014), however, interpreted the sandstone members as tidal sandwave deposits.

The Ameki Group comprises the Nsugbe Formation, Nanka Formation, and Ibeku Formation (formerly known as Ameki Formation) (Nwajide, 1980; Ekwenye et al., 2015), which are laterally equivalent. The Ibeku Formation consists of alternating sandy shale, clayey sandstone, fossiliferous shale (consisting of mollusks, foraminifera, and corals) and fine-grained argillaceous sandstone with thin limestone bands (Reyment, 1965; Arua, 1986). The age of the formation is assigned Middle Eocene (Lutetian) to Oligocene age (Berggren, 1960; Reyment, 1965, Oloto, 1984). Kogbe (1976) suggested Lutetian to Lower Bartonian age for the Ameki Group. The depositional environment has been interpreted as estuarine, barrier ridge-lagoon complex, and open marine, based on lithofacies interpretation and faunal content (Reyment, 1965; Adegoke, 1969; Arua, 1986; Mode, 2002). Nwajide (1980) interpreted the Nanka Formation of the Ameki Group as the deposits of a tidally influenced marine shoreline environment; whereas Ekwenye et al., (2017) interpreted the Ameki Group as tide-dominated estuarine environment. The Ameki Group is unconformably overlain by the Ogwashi Formation (commonly referred to as Ogwashi-Asaba Formation).

The Ogwashi Formation consists of alternating coarse-grained sandstone, lignite seams, and light coloured clays of continental origin (Kogbe, 1976) and it is assigned Middle Eocene to Miocene age (Reyment 1965; Jan du Chêne et al., 1978). Ekwenye and Nichols (2016) suggested a tidally influenced coastal plain environment for the Ogwashi Formation. Table 2 shows the summary of the stratigraphy of the Paleogene strata (Ekwenye et al., 2017).

Table 1: Correlation of Subsurface and Outcrop Formations of the Niger Delta (redrawn and modified after Short and Stäuble, 1967, Avbovbo, 1978).

Subsurface			**Outcrop**		
Youngest known age	Formation	Oldest known age	Youngest known age	Formation	Oldest known age
Recent	Benin	Oligocene	Recent	Benin	Miocene
Recent	Agbada	Eocene	Miocene Eocene	Ogwashi Formation Ameki Group	Eocene Eocene
Recent	Akata	Paleocene	Lower Eocene	Imo Formation	Paleocene

Table 2: Summary of the Facies Assemblages and Depositional Environments of the Paleogene Stratigraphy, SE Nigeria (after Ekwenye et al., 2014; 2016).

AGE	GROUP	FORMATION	MEMBER	FACIES ASSEMBLAGES/ INTERPRETATION	FACIES DESCRIPTION	DEPOSITIONAL ENVIRONMENT
OLIGO-CENE		OGWASHI FORMATION		FA 5: Coastal floodplain/mire	Mudstone, carbonaceous mudstone, claystone, gritty claystone and massive sandstone facies	Tidally influenced coastal plain
				FA 4: Coastal plain deposit	Mudstone, massive fine grained sandstone and variegated facies	
				FA 3: Tidal Channel deposit	Trough cross-bedded sandstone, planar cross-bedded sandstone, bioturbated sandstone, and current rippled laminated sandstone facies (Sr).	
				FA 2: Tidal Flat	Sandy heterolithic, bioturbated sandstone, and current rippled laminated sandstone facies.	
				FA 1: Fluvio-estuarine deposit	Conglomerate, trough cross bedded sandstone, planar cross bedded sandstone, herringbone cross stratified sandstone, bioturbated sandstone, and current rippled laminated sandstone facies.	
MIDDLE–LATE EOCENE	AMEKI	IBEKU FORMATION		FA 7: Estuarine Embayment (Open Estuarine)	Mudstone, shale, siltstone and nodular mudstone facies	Tide-dominated estuarine
				FA 5: Supratidal deposit	Variegated and mudstone facies.	
				FA 4: Tidal Flat	Current rippled laminated sandstone, wave-rippled laminated sandstone, siltstone, and mudstone facies.	
		NANKA FORMATION		FA 6: Tidal bar sands	Tabular cross-bedded sandstone, current rippled laminated sandstone, bioturbated sandstone, and sigmoidal cross-stratified sandstone.	
				FA 5: Supratidal deposit	Variegated and mudstone facies.	
				FA 4: Tidal Flat	Current rippled laminated sandstone, wave-rippled laminated sandstone, mud-draped tabular cross-bedded sandstone, siltstone, bioturbated sandstone, and mudstone facies.	
				FA 3: Tidal Channel	Tabular cross-bedded sandstone, mud-draped cross-bedded sandstone, trough cross-bedded sandstone, bioturbated sandstone, sigmoidal cross-stratified sandstone, herringbone cross-stratified sandstone, variegated and mudstone facies	
		NSUGBE FORMATION		FA 2: Tidally influenced fluvial deposit	Conglomerate, sandy heterolithic, muddy heterolithic, planar cross-bedded sandstone, herringbone cross-stratified sandstone, mudstone and bioturbated sandstone facies	
				FA 1: Fluvial deposit	Conglomerate, trough cross-bedded sandstone, planar cross-bedded sandstone, horizontally stratified sandstone and current rippled laminated sandstone facies.	
PALEO-CENE-EARLY EOCENE		IMO FORMATION	UPPER SANDSTONE	FA 5: Shelf deposit	Marl, fossiliferous shale, calcareous sandstone, non-calcareous sandstone, bioturbated sandstone and non-fossiliferous dark gray shale facies	Dominantly Shallow marine
				FA 4: Fluvial deposit	Structureless, coarse to medium grained sandstone facies	
			MIDDLE SANDSTONE	FA 3: Shoreface/Foreshore	Wave rippled laminated sandstone, current rippled laminated sandstone, fine grained bioturbated sandstone, horizontal bedded sandstone and dark gray fossiliferous facies	
			LOWER SANDSTONE	FA2: Offshore tidal sandwaves	Large scale planar cross-bedded sandstone, with subordinate planar cross-bedded sandstone, herringbone cross-stratified sandstone and trough cross-bedded sandstone facies	
				FA1: Offshore shale/mudstone	Gray shale to clayey shale facies.	

The Ogwashi Formation consists of alternating coarse-grained sandstone, lignite seams, and light coloured clays of continental origin (Kogbe, 1976) and it is assigned Middle Eocene to Miocene age (Reyment 1965; Jan du Chêne et al., 1978). Ekwenye and Nichols (2016) suggested a tidally influenced coastal plain environment for the Ogwashi Formation. Table 2 shows the summary of the stratigraphy of the Paleogene strata (Ekwenye et al., 2017).

These Paleogene formations are referred to as the lateral equivalents of the subsurface Niger Delta (Table 1). The Paleogene strata are diachronous and extend into the subsurface where they are assigned different formation names (Petters, 1991). The subsurface Akata Formation as a downdip continuation of the outcropping Imo Formation. The Akata Formation is characterized by monotonous dark-grey shale with local concentrations of sand, silt, plant materials and mica. The Agbada Formation is also referred to as the down-dip continuation of the outcropping Ameki Group and Ogwashi Formation (Kogbe, 1976; Short and Stäuble (1967).

METHODOLOGY

Detailed heavy mineral analytical method of the samples obtained from the study area is presented in Ekwenye et al., 2015. Figure 4 shows the sample location map of the study area. The heavy mineral analysis was carried out in the sediment processing and mineral separation laboratories at the Department of Earth Sciences, Royal Holloway, University of London.

A total of 27 unconsolidated sandstone samples were analyzed systematically. The procedures include sieve washing, decanting, drying and removal of highly magnetic grains using a bulk magnetic separator. Furthermore, heavy liquid separation involves using sodium polytungstate (SPT) solution (2.89 g/cm^3) used to remove quartz, feldspars and other light minerals from the sample, using funnel technique (Mange and Maurer, 1992). The separated heavy mineral fractions obtained were oven-dried and mounted on thin slides for mineral identification. About 200 (non-opaque) heavy minerals were counted per slide and the proposition of each mineral was calculated as a percent of the total weight of minerals counted for each sample (Morton and Hallsworth, 1994; Okay and Ergün, 2005). Opaque minerals are dominated by iron-oxide or leucoxene-coated grains and haematite but they are not discussed in this research. The following categories of mineral varieties were distinguished based on the high-resolution heavy mineral analysis method proposed by Mange-Rajetzky (1995).

Zircon: euhedral, subhedral, rounded colourless, rounded purple and grains with overgrowth.

Tourmaline: angular, prismatic, rounded prism, subrounded, rounded to well-rounded.

Apatite: prismatic, rounded prism, subrounded, rounded and spherical.

The high-resolution heavy mineral analysis focuses on the ultrastable heavy mineral suites such as zircon, tourmaline and apatite (Mange-Rajetzky, 1995). This method is based on the fact that numerous heavy mineral species have chemical, structural, colour, morphological and optical varieties that record signatures of crystallizing conditions in their parent rocks (Mange and Otvos, 2005). These properties make the mineral valuable indices of provenance.

RESULTS

Heavy Minerals of the Paleogene Sediments

Provenance of the sandstone member of the Imo Formation: The analyzed sediments contain diverse heavy mineral assemblages. The quantitative point-counting results for the heavy mineral composition of the Imo Formation are shown in Table 3. Table 4 shows the estimated heavy mineral composition in the Imo Formation (modified from Ekwenye et al., 2015). Figure 3 shows the proportion of zircon, tourmaline and apatite varieties in bar charts.

The heavy mineral suites consist of a high proportion of ultra-stable minerals zircon, tourmaline and rutile which occurs throughout the succession except in sample SAA-1 which has a very low grain count. Index minerals of high-grade metamorphic (HGM) rocks which include kyanite, sillimanite and andalusite occur in varying proportion throughout the succession. A high proportion of unstable heavy mineral medium-grade metamorphic minerals (MGM) (epidote group, garnet, sphene, staurolite, and hornblende) was encountered in all counts.

The lower Sandstone Member of the Imo Formation includes the Ebenebe Sandstone (SEB1, 2), the Igbakwu Sandstone (SNK1, 3) and the Umuna Sandstone (SAIM 2). Sediments of the lower Sandstone Member consist of similar heavy mineral assemblages dominated by rutile (20 - 50%), with a high count of zircon (10 - 30%), kyanite and tourmaline (<20%). Subordinate occurrences of epidote, pyroxene, staurolite and sillimanite (<10%) are observed. Andalusite, amphibolite and apatite counts (<2%) are very low. Monazite and garnet occur in trace amounts in a few samples. Dissolution is commonly observed in most of the unstable minerals.

Heavy Mineral Provinces: The spatial distribution of the certain minerals such as high-resolution heavy minerals (HRHM) (Mange-Rajetzky, 1995) such as zircon, apatite and tourmaline, index minerals of HGM and MGM shown on the location map in form of pie charts, allows the delineation of heavy mineral provinces (Mange and Otvos, 2005).

Table 3: Quantitative Point-Counting Results for Heavy Mineral Composition in the Imo Formation.

Sample Nos	Formation	Sandstone Member	Zrn	Tur	Apt	Mn	Rt	St	Sil	Kyn	Sp	Ep	Hb	Am	Grn	Act	And	Px	Oth	TOTAL
SEB-1	Imo Fm	Lower Sandstone	57	46	0	0	150	29	7	25	0	24	0	4	0	0	6	20	0	368
SEB-2	Imo Fm	Lower Sandstone	70	30	0	0	120	13	10	58	0	13	0	8	0	0	1	17	0	340
SNK-1	Imo Fm	Lower Sandstone	78	33	3	4	80	10	8	27	0	18	0	4	0	0	1	6	1	273
SNK-3	Imo Fm	Lower Sandstone	36	17	2	0	150	7	9	31	0	30	0	3	1	0	2	13	1	301
SAIM-2	Imo Fm	Lower Sandstone	60	24	0	0	85	7	10	54	0	16	0	6	0	0	2	5	0	269
SAA-1	Imo Fm	Lower Sandstone	9	9	5	0	18	4	12	39	0	12	2	5	0	0	2	11	4	132
SAA-3	Imo Fm	Upper Sandstone	44	15	2	0	127	5	8	34	0	17	0	0	0	0	3	38	1	294
SAA-4	Imo Fm	Upper Sandstone	74	14	4	0	183	4	3	40	5	6	0	0	1	0	0	16	1	351
SIAM-1	Imo Fm	Upper Sandstone	80	21	6	0	150	19	22	80	0	35	0	10	1	0	4	25	3	456
SIA-2	Imo Fm	Upper Sandstone	65	11	9	0	80	8	4	66	31	85	0	0	150	4	2	6	0	521
SOZ-3	Imo Fm	Upper Sandstone	51	19	7	0	80	10	7	60	40	110	0	3	150	1	2	11	6	557

Abbreviation: Zrn, Zircon; Tur, Tourmaline; Apt, Apatite; Rt, Rutile; St, Staurolite; Sil, Sillimanite; And, Andalusite; kyn, Kyanite; Sp, Sphene; Ep, Epidote Group; Px, Pyroxene; Hb, Hornblende; Am, Amphibole; Gr, Garnet; Mn, Monzite; Act, Actinolite; Oth, other heavy minerals.

Table 4: Summarized Results for Heavy Mineral Vomposition for the Imo Formation (modified after Ekwenye et al., 2015).

Formation/Member	Lower Sandtone Member						Middle Sandstone		Upper Sandstone Member		
Minerals/Sample No	SEB-1	SEB-2	SNK-1	SNK-3	SAIM-2	SAA-1	SAA-3	SAA-4	SIAM-1	SIA-2	SOZ-3
Zircon	*	††	††	*	††	††	*	††	*	*	•
Tourmaline	*	•	*	*	•	•	•	•	•	•	•
Apatite	o	o	*	•	o	•	•	•	•	•	•
Monazite	o	o	*	o	o	o	o	o	o	o	o
Rutile	††	††	††	††	††	*	††	‡	††	*	*
Sphene	o	o	o	o	o	o	o	o	o	o	o
Staruolite	•	•	•	•	•	•	•	•	•	•	•
Sillimanite	•	•	•	•	•	•	•	•	•	•	•
Kyanite	•	*	•	*	††	††	*	*	*	*	*
Epidote	•	•	•	*	•	•	•	•	•	*	*
Hornblende	o	o	o	o	o	•	o	o	o	o	o
Amphilbole	•	•	•	•	•	•	o	o	•	o	•
Garnet	o	o	o	•	o	o	o	•	•	††	††
Actinolite	o	o	o	o	o	o	o	o	o	•	•
Andalusite	•	o	•	o	•	o	o	o	o	o	o
Pyroxene	•	•	•	•	•	•	*	•	•	•	•
Unidentified	o	o	•	•	o	•	•	•	•	o	•

Greater than 50% ‡
50 - 20% ††
20-10% *
10-1% •
0% o

Parent rock: Acid Igneous /Plutonic; Regional Metamorphism; Contact Metamorphism; Basic Igneous

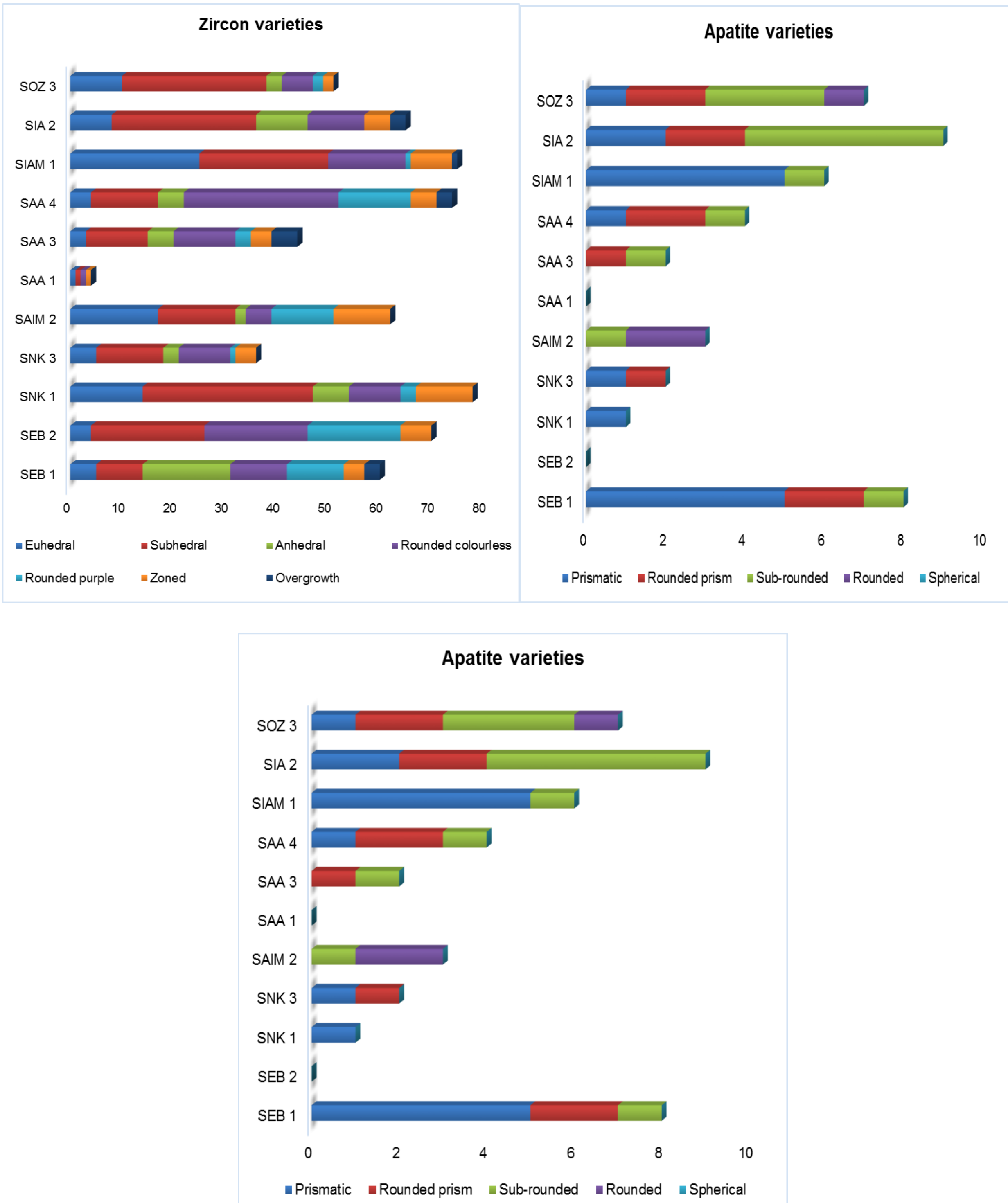

Figure 3: Proportion of Zircon, Tourmaline and Apatite Varieties (modified from Ekwenye et al., 2015).

Based on the heavy mineral trends, the provinces are discussed and grouped into a sandstone suite province and a mixed suite province (Figure 4). The sandstone suite province dominates the Imo Formation.

Sandstone Suite Province and Sediment Source Area: Provenance from the sandstone suite province characterizes the lower Sandstone, the middle and parts of the lower Sandstone members of the Imo Formation. It is characterized by medium to coarse grain heavy mineral assemblages that are dominated by rutile (Table 4). Other common mineral types are zircon, kyanite and tourmaline. A large number of the zircon grains are euhedral-subhedral; rounded colourless, zoned zircon and rounded purple coloured crystals are also well represented (Figure 3). Tourmaline varieties are dominated by sub-rounded to rounded crystals, although prismatic, rounded prismatic and angular crystals are common in some samples. Apatite occurrence is very low and the varieties vary from prismatic to sub-rounded crystals. In most samples from the lower sandstone province, heavy mineral suites such as kyanite, staurolite, and pyroxene show etch patterns, corrosion and hacksaw terminations, which suggest incipient dissolution processes due to contact with acidic fluid during diagenesis.

The high occurrence of euhedral-subhedral zircon crystals suggest first-cycle detritus and mostly derived from granitoid rocks (Lihou and Mange-Rajetzky, 1996). The presence of the rounded zircon crystals indicates polycyclic or recycled pre-existing sediments, whereby the grains have undergone multiple cycles of reworking during transportation. Although, Deer et al., (1982) noted that rounded zircon can also be derived as first-cycle detritus from metamorphic rocks that were formed from a sedimentary protolith. The occurrence of the rounded zircon crystals and euhedral-subhedral crystals in the lower sandstone province implies a mixed provenance. Similarly, the tourmaline varieties show high counts in the subrounded and rounded crystals as well as the angular and prismatic shape crystals also suggesting mixed provenance. The heavy mineral assemblages reflect sediment contribution mainly from a regional metamorphic terrain with considerable input from acid igneous or plutonic rocks (Table 4); as earlier interpreted by Ekwenye et al. (2015). Small amounts of sediment were shed from basic igneous rocks, as well as recycled sedimentary rocks.

Mixed Suite Province and Sediment Source Area: The mixed suite provenance is dominant in the upper Sandstone Member of Imo Formation, and the sedimentary units are characterized by mixed siliciclastic and carbonate material. The sudden high occurrence of coarse detrital grains of garnet (Table 4; Figure 4) suggests a different source area from the sandstone suite province.
Epidote group minerals (dominated by epidote, with more zoisite and fewer clinozoisite crystals), kyanite and zircon are relatively abundant (Table 4; Figure 4).

A higher sphene count confirms the additional source area. Tourmaline, pyroxene, apatite and staurolite are present and there are small amounts of actinolite present. Zircon varieties are dominated by euhedral-subhedral crystals (Figure 3). Rounded polycyclic colorless zircons are common but purple colorless zircons are not common. Tourmaline varieties are also dominated by angular and prismatic crystals; though subrounded tourmaline grains are common, rounded tourmaline grains are relatively rare. Similarly, apatite varieties are more commonly prismatic and subrounded rather than rounded crystals.

The dominance of euhedral-subhedral, prismatic-angular and subrounded crystals of the ultrastable mineral suite - zircon, tourmaline and apatite, suggests first-cycle detritus from acid igneous or plutonic parent rocks. About 20% of the heavy mineral suite is derived from acid igneous or plutonic rock which may probably infer the Pan African granitoids or the Older Granites as the source area. These granites occur in the Oban Massif, the Western Nigeria basement and Adamawa highlands (see Ekwenye, et. al. 2015). The high counts of garnet, kyanite and the presence of sillimanite, sphene and staurolite suggest a high-amphibolite grade metamorphism (Ekwueme and Onyeagocha, 1985; Ekwueme et al., 1991; Rahaman, 1976; Schlüter, 2006; Obaje, 2009). This accounts for about 70% of the heavy mineral suites (Table 4). This suggests that the sediments were probably derived dominantly from the magmatic-gneiss complex of the Oban massif and/or the magmatic-gneiss complex and the schist belt of the south-western Nigeria basement.

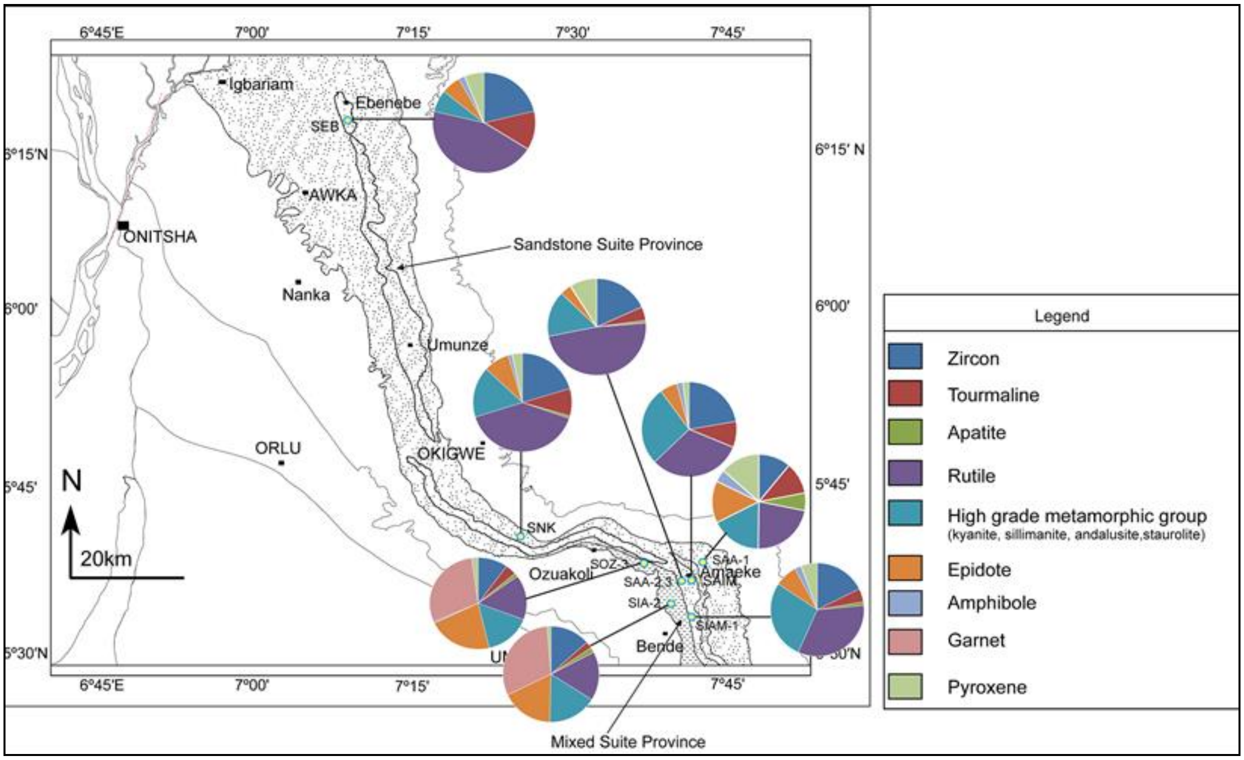

Figure 4: Heavy Mineral Composition of the Imo Formation Sandstone and Mixed Suite Provinces.

The schist belt in the south-western Nigeria includes high-grade amphibolites facies as well as low-grade greenschist facies (Rahaman, 1976; Obaje, 2009); this probably accounts for the minor occurrence of low-grade minerals such as actinolite in the mixed suite province.

Heavy Mineral of the Tide-Dominated Estuarine Ameki Group

The quantitative point-counting results for the heavy mineral composition of the Ameki Group are showed in Table 5. The heavy mineral compositions are further summarized into percentages and grouped into the various rocks as shown in Table 6.

The heavy mineral suites of ultra-stable minerals zircon, tourmaline and rutile, occur in the Ameki Group (Tables 5 and 6; Figure 5). Different proportions of heavy minerals are observed throughout the succession, these include index minerals of high-grade metamorphic (HGM) rocks which are kyanite, sillimanite and andalusite; unstable heavy mineral medium grade metamorphic minerals (MGM) such as epidote group and staurolite and accessory minerals such as monazite and brookite. Facies association 6 shows a relatively lower proportion of zircon and a higher proportion of rutile and kyanite when compared to the other facies associations (Table 6). The distribution of the heavy mineral suite across the Ameki Group is shown as a pie chart in Figure 6.

Ameki Group Province and Sediment Provenance

The Ameki Group province is characterized by predominantly ultra-stable minerals, with varying amount of apatite. Kyanite is relatively abundant in facies association 3 (tidal channel deposits) and 6 (tidal sand bar deposits). The heavy mineral suites vary from fine to coarse-grained crystals. Other heavy minerals such as pyroxene, staurolite and epidote group occur throughout the depositional facies, though in relatively low proportions. The spatial distribution of the heavy mineral assemblages in the Ameki Group (Figure 6; Tables 5 and 6) shows no variation to allow further delineation of heavy mineral provinces.

The proportion of the heavy mineral suite varies slightly probably due to the effect of tides that influenced sedimentation and hydraulic conditions which affected the grain sizes. Zircon varieties are dominated by euhedral-subhedral crystals, rounded polycyclic colorless crystals are relatively high, while zoned zircon crystals (Figure 5) are common throughout the depositional facies, though in moderate to low quantity. Zircons with overgrowths are common in facies association 1 and 2. Tourmaline crystals occur in varying proportions with prismatic, rounded prisms and subrounded varieties been common. Angular and rounded tourmaline grains occur in relatively low proportions. Apatite is not abundant in the heavy mineral suite, however, the quantity of prismatic, rounded prisms and subrounded grains are high compared to the spherical and rounded crystals.

The abundance of zircon, rutile and kyanite, with the common occurrence of pyroxene, tourmaline and staurolite reflect combinations of igneous and medium to high grade regional metamorphosed rocks. The high occurrence of euhedral-subhedral zircon suggests first-cycle detritus whereas the rounded colorless zircon crystals may indicate either polycyclic derivation or first cycle detritus from metamorphosed sedimentary rocks or as a result of magmatization. Zircon grains with overgrowths are associated with high-grade metamorphism, contact metamorphism or granitization (Speer, 1980; Lihou and Mange-Rajetzky, 1996).

A similar signature is observed in the tourmaline and apatite grains, where the prismatic crystals suggest first cycle detritus whereas the rounded prisms and subrounded to rounded grains may indicate a polycyclic origin. The basement complex is one of the petrological provinces supplying sediments to Nigerian sedimentary basins. The Western Nigerian Massif consists of four major petro-lithological units which are the migmatite-gneiss complex, the schist belts, the older granites and the undeformed acidic and basic dykes (Obaje, 2009). The massif is probably the major source area for the sediments in the Ameki Group province; another possible source is older sedimentary rocks from older formations such as Imo and Nsukka formations (Ekwenye et al., 2015).

Table 5: Quantitative Point-Counting Results for Heavy Mineral Composition in the Ameki Group and Ogwashi Formation.

Sample Nos	Group	Formation	Facies Ass.	Zrn	Tur	Apt	Mn	Rt	St	Sil	Kyn	Sp	Ep	Hb	Am	Grn	Act	And	Px	Oth	TOTAL
SNS 1	Ameki	Nsugbe Formation	FA 1	172	9	3	2	86	3	1	20	0	2	0	0	0	0	1	21	2**	320
SNS 3	Ameki	Nsugbe Formation	FA 1	148	11	1	1	63	3	1	27	0	1	0	0	0	0	0	28	1**	284
SUN 1	Ameki	Nanka Formatior	FA 2	120	13	0	0	8	13	0	8	0	6	0	0	0	0	1	2	1	172
SUN3	Ameki	Nanka Formatior	FA 2	56	14	2	0	25	4	0	2	0	3	0	0	0	0	0	1	0	107
SUM 1	Ameki	Nanka Formatior	FA 3	139	15	3	0	48	1	1	23	0	5	0	1	0	0	3	8	2*	247
SUM 2	Ameki	Nanka Formatior	FA 3	92	10	2	0	58	3	2	22	0	9	0	0	0	0	0	8	0	206
SNI 2	Ameki	Nanka Formatior	FA 3	110	3	0	0	17	2	7	45	0	3	0	4	0	0	0	6	4	201
SUM 3	Ameki	Nanka Formatior	FA 4	89	17	2	0	60	4	4	27	0	10	0	0	0	0	0	13	0	226
SUM 4	Ameki	Nanka Formatior	FA 4	89	10	3	0	11	2	0	7	0	2	0	0	0	0	0	2	1**	126
SIS 1	Ameki	Nanka Formatior	FA 5	57	8	1	0	107	8	7	80	0	3	0	4	0	0	3	23	1	302
SIK 1	Ameki	Nanka Formatior	FA 5	40	4	5	0	61	3	8	52	0	7	0	0	0	0	0	14	0	194
SOK1A*	Ogwashi	Ogwashi Fm	FA 1	20	3	0	5	0	0	0	5	0	0	2	0	0	0	0	0	0	35
SOK 1.1	Ogwashi	Ogwashi Fm	FA 1	46	6	1	0	34	1	1	21	0	4	0	0	0	0	0	2	0	116
SOK 1.2	Ogwashi	Ogwashi Fm	FA 1	30	12	4	0	80	4	5	71	0	7	0	0	0	0	0	29	0	242
SOK 1.4*	Ogwashi	Ogwashi Fm	FA 2	12	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	15
SOK 2.1*	Ogwashi	Ogwashi Fm	FA 2	25	3	0	0	7	2	0	9	0	5	0	2	0	0	0	0	0	53

2* **Brookite**
3** **Oxide**
SOK 1A* Samples with insufficient grains.
Fm - Formation

Table 6: Summarized Result for Heavy Mineral Composition for the Ameki Group and Ogwashi Formation (modified after Ekwenye et al., 2015).

Group/Formation	Nsugbe		Nanka Formation (Ameki Group)									Ogwashi Formation				
Minerals/Sample No	SNS 1	SNS 3	SUN 1	SUN 3	SUM 1	SUM 2	SNI 2	SUM 3	SUM 4	SIS 1	SIK 1	SOK 1A*	SOK1.1	SOK 1.2	SOK 1.4*	SOK 2.1
Zircon	‡	‡	‡	‡	‡	††	‡	††	‡	††	††	‡	††	*	‡	††
Tourmaline	•	•	•	*	•	•	•	•	•	•	•	•	•	•	o	•
Apatite	•	•	o	•	•	•	o	•	•	•	•	o	•	•	o	o
Monazite	•	•	o	o	o	o	o	o	o	o	o	*	o	o	o	*
Rutile	††	††	•	††	*	††	•	††	•	††	††	o	††	††	*	o
Staruolite	•	•	•	•	•	•	•	•	•	•	•	o	•	•	o	o
Sillimanite	•	•	o	o	•	•	•	•	o	•	•	o	•	•	o	o
Kyanite	•	•	•	•	•	*	††	*	•	††	††	*	*	††	•	*
Sphene	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Epidote	•	•	•	•	•	•	•	•	•	•	•	o	•	•	o	•
Hornblende	o	o	o	o	o	o	o	o	o	o	o	•	o	o	o	o
Amphilbole	o	o	o	o	•	o	•	o	o	•	o	o	o	o	o	•
Garnet	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Actinolite	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Andalusite	•	o	•	o	•	o	o	o	o	•	o	o	o	o	o	o
Pyroxene	•	•	•	•	•	•	•	•	•	•	•	o	•	•	o	o
Unidentified	•	•	•	o	•	o	•	o	•	•	o	o	o	o	o	o

Greater than 50% ‡
50 - 20% ††
20-10% *
10-1% •
0% o
SOK 1.4* Sample with insufficient heavy mineral grains.

Parent rock: Acid Igneous /Plutonic; Regional Metamorphism; Contact Metamorphism; Basic Igneous

Heavy Mineral of the Tidally Influenced Coastal Plain Ogwashi Formation

Table 5 also shows the quantitative point-counting results for the heavy mineral composition in the Ogwashi Formation. Table 6 shows the summarized heavy mineral composition, which is grouped into various parent rocks. The proportions of zircon, tourmaline and apatite varieties are shown on the bar charts (Figure 5).

The heavy minerals composition and varieties are also shown as pie charts in Figures 6. Ogwashi Formation has insufficient heavy mineral grains probably due to the coarse and conglomeritic nature of the sediments. The heavy mineral suite is high in zircon while tourmaline and rutile are relatively low to moderate in abundance and did not occur throughout the succession. Index minerals of high-grade metamorphic (HGM) rocks such as kyanite occur throughout the depositional facies, sillimanite occurs only in facies association 1. Heavy minerals of medium-grade metamorphic (MGM) suite such as epidote group, staurolite, and hornblende occur in very low counts in the depositional facies.

Heavy Mineral Provinces and their Provenance

The spatial distribution of minerals such as high-resolution heavy minerals (HRHM) such as zircon, apatite and tourmaline, index minerals of HGM and MGM allows the delineation of heavy mineral provinces (Mange and Otvos, 2005). Based on the occurrences and trends of the heavy minerals, single province, Ogwashi is delineated into Ogwashi 1A and 1B sub-provinces, due to the slight variation observed within the province which may be as a result of hydraulic differentiation.

Ogwashi 1A Sub-province and Sediment Sources: The Ogwashi 1A sediments are characterised by zircon-monazite-kyanite assemblage, with subordinate staurolite, epidote and hornblende occurring in some sediments (Table 6). The ultrastable mineral rutile is noticeably absent in this province. Numerous zircon grains are euhedral-subhedral; rounded colorless and zoned zircon crystals are also well represented (Figure 5).

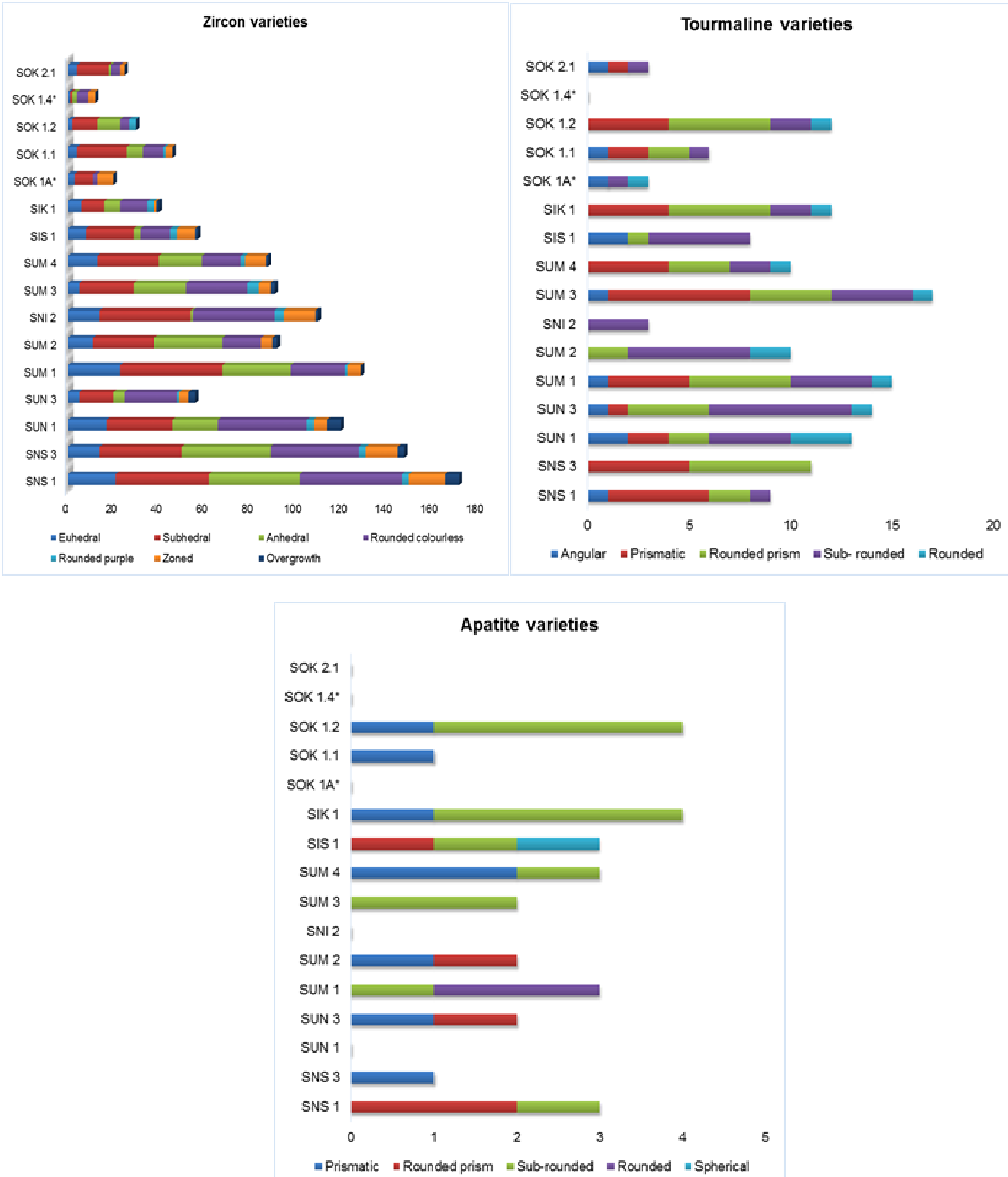

Figure 5: Proportion of Zircon, Tourmaline, and Apatite Varieties in Bar Charts.

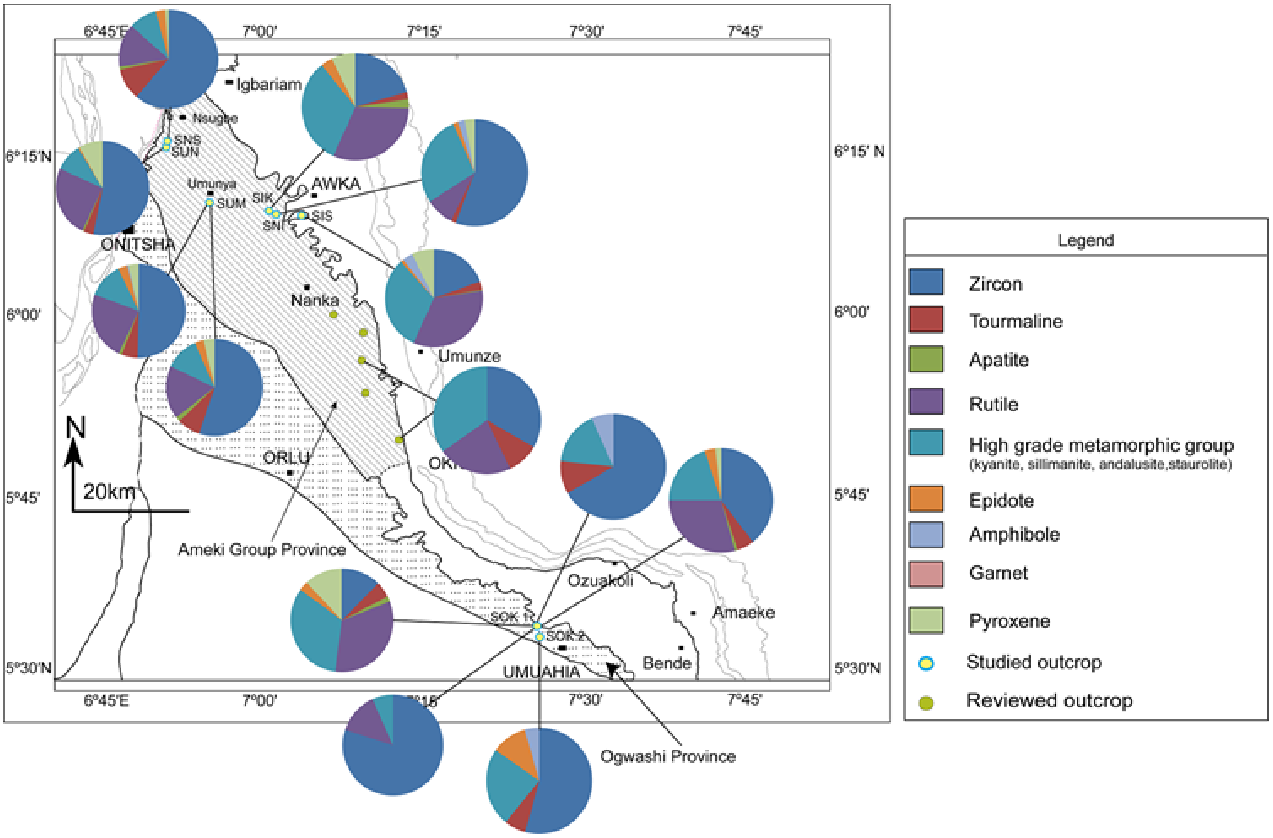

Figure 6: Heavy Mineral Composition of the Ameki Group and the Ogwashi Provinces.

Tourmaline varieties are dominated by sub-rounded to rounded crystals, although angular crystals are observed as well. Prismatic and sub-rounded apatite morphologies occur in very low proportions. The paucity of apatite grains may have been caused by acidic leaching (Lihou and Mange-Rajetzky, 1996) or sediment reworking. The abundance of zircon, monazite and tourmaline (>50 %) in the heavy mineral suites indicate basic igneous rocks are the ultimate parentage. Less than 50% of the heavy mineral suite (such as kyanite, staurolites, epidote) indicates input also from metamorphic source.

Ogwashi 1B Sub-Province and Provenance Sources: Provenance from the Ogwashi 1B sub-province is characterised by medium grain heavy mineral assemblages that are dominated by zircon and rutile. Other common mineral types are kyanite and tourmaline (Table 6). Subordinate apatite, staurolite, sillimanite and epidote are observed. Many zircon grains are euhedral-subhedral; rounded colorless, and zoned zircon crystals are well represented (Figure 5). Tourmaline is dominated by prismatic and rounded prisms morphologies; sub-rounded crystals are common in some samples. Apatite occurrence is very low and the varieties include prismatic and sub-rounded crystals. A similar mixed provenance is also proposed for the Ogwashi 1B sub-province; zircon; the proportion of rutile, tourmaline, apatite, staurolite, sillimanite, kyanite and pyroxene is >20 and >50%.

The Oban Massif is differentiated into metamorphic rocks which consist of phyllites, schists, gneisses and amphibolites and intrusives which are charnockites, dolerites, granites, granodiorite, diorite, syenite, adamellite and pegmatite (Ekwueme et al., 1991). The mixed proportion of suites of minerals from metamorphic and igneous rocks suggests dominant source area to be the Oban Massif and probably Western Nigerian Massif. The occurrence of rounded and subrounded crystals of zircon and tourmaline may infer a contribution recycled sedimentary rocks. Although the Ogwashi province is subdivided into two provinces, this may not suggest different source rocks because of insufficient grains encountered in some of the rock samples.

DISCUSSION

Controlling Factors on Heavy Mineral Distribution Pattern

The possible factors controlling the heavy mineral distribution pattern at various geologic time during the Paleogene apart from provenance are river runoff, action of tide and wave processes, erosion of adjacent terraces and grain size which may be modified by hydraulic sorting.

The Niger Delta started to evolve in the early Paleogene when clastic river input is considered to have increased (Doust and Omatsola, 1990). This river runoff during the early Paleocene must have resulted to river input into the shelf, which led to the deposition of sandstone bodies reworked by tidal action to form tidal sandwaves (Ekwenye at al, 2015). The high occurrence of euhedral–subhedral heavy mineral grains such as zircon in the tidal sandwave deposits suggests their derivation from primary sources and an incipient mechanical abrasion, whereas tourmaline crystals are dominantly rounded to subrounded forms, which suggest either a polycyclic origin or a long exposure to dynamic processes prior to deposition (Cascalho and Fradique, 2007).

The upper Sandstone Member of Imo Formation interpreted as wave influenced mixed siliciclastic and carbonate shelf deposit is dominated by subangular to subrounded garnet and epidote group minerals. Zircon and Tourmaline minerals are dominated by euhedral-subhedral crystals (Figure 3). The controlling factor affecting the heavy mineral distribution is probably wave action and erosion from adjacent terraces. The palaeoclimatic condition during the Paleogene is semi-humid to humid climate (Ekwenye et al., 2015); this probably contributed to the weathering of a nearby source (most likely the magmatic-gneiss complex of the Oban massif); in which the weathered sediments were transported and deposited by wave process.

The middle–late Eocene Ameki Group commenced with fluvial deposit which became inundated by marine water during transgression to form an estuary. Palaeocurrent readings from sediments of the fluvial deposit suggest north-easterly source (Ekwenye, et al., 2017). Heavy mineral distribution within the Ameki Group suggests that the fluvial sands must have discharged into the estuary by fluvial process and the sediments were reworked by the tidal processes. The distribution of the heavy minerals river sands appears to be consistent with the heavy mineral content of the estuarine sands, although the estuarine sands show more enrichment in kyanite, which may be as a result of marine influence. The dominant input is suggested to be fluvial influx whereby the drainage basin feed the estuary through fluvial transport whereas the subordinate input is oceanic through tidal transport.

Outcrops of the Oligocene Ogwashi Formation is poorly exposed; the lithofacies of the formation are conglomerate, very coarse to medium-grained sandstone, claystone, lignites beds and carbonaceous mudstone. Sediments of the tidally influenced coastal plain of the Ogwashi Formation exhibit low counts or low concentration of heavy minerals in the sand-sized grains. Factors affecting the low concentration of heavy minerals in sediments include provenance, sedimentary processes and post-depositional dissolution (such as diagenetic dissolution) (Mange and Maurer, 1992; Morton and Hallsworth, 1999). Garzanti and Andò, 2007 demonstrated that heavy mineral concentration in medium to fine sand fractions is poor compared to very fine sand or coarse–silt fractions (which has a strong concentration of heavy minerals) due to hydraulic sorting with respect to transport mode.

The matrix to clast–rich conglomerate and poorly to moderately sorted bioturbated sandstone of facies associations 1 and/or 2 of the Ogwashi Formation have been interpreted as fluvio-estuarine to tidal channel deposits. The absent of ultra-stable mineral rutile in the Ogwashi 1A sub-province (Tables 5, 6) may not necessarily be due to post-depositional dissolution because the Paleogene strata are poorly consolidated and have not undergone deep burial (Nwajide, 2013). Provenance and hydraulic sorting are the most probably controlling factors affecting the heavy minerals distribution in the sandstone facies of the Ogwashi Formation. Although sediments of this sub-province are enriched with euhedral-subhedral zircon, rounded to subrounded zircon, tourmaline and apatite are well represented. Similarly, sediments of Ogwashi 1B sub-province show high counts of euhdedral-subhedral zircon crystals and prismatic tourmaline crystals and the rounded crystal of the aforementioned minerals are well represented (Figure 5). These suggest that the source may probably be a close by pre-existing sedimentary terraces and probably oceanic input, as well as contributions from the basement complexes such as Oban Massif due to the occurrence of monazite, which rarely occurred in the older Paleocene-Eocene sediments. Monazite occurs as a weathering product from high-graded metasedimentary rocks or granite intrusive rocks (Horton and Zullo, 1991) such as pegmatites.

This study shows that the distribution of heavy mineral suites in the Paleogene sediments of south-east Nigeria is controlled mainly by sedimentary processes (such as river, tide and wave actions as well as hydraulic sorting) and provenance.

CONCLUSIONS

Four main provinces namely: the sandstone suite province and the mixed suite province for the Imo Formation; the Ameki Group province and the Ogwashi province were delineated based on the proportion of the ultra-stable minerals and the unstable high- and medium-grade metamorphic minerals. The distribution of these heavy mineral suites within the Paleogene sediments of the study area is probably controlled by factors such as river influx, tide and wave actions, erosion of adjacent terraces as well as hydraulic sorting. The sandstone suite province is dominated by rutile, zircon and kyanite. The mixed suite province accounts for high occurrence of coarse garnet grains; common minerals are epidote group minerals and kyanite. The controlling factor affecting the heavy mineral distribution in the Imo Formation is mainly provenance, wave action and erosion from adjacent terraces.

The spatial distribution of the heavy mineral assemblages in the Ameki Group showed no variation mainly due to the influence of both fluvial Influx and tide action during sedimentation and the effect of hydraulic sorting of grains. Similarly, sediments from Ogwashi Formation lack sufficient heavy minerals probably due to hydraulic differentiation. Provenance is also an important factor that affected the proportion and availability of certain heavy mineral suites in the study area. This effected the presence and high count of heavy minerals such as garnet, rutile, epidotes, sphene and monazite in certain provinces.

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