PETROGRAPHY AND HEAVY MINERAL STUDIES OF THE EOCENE SEDIMENTS IN AWKA AND ENVIRONS, SOUTHEASTERN NIGERIA: IMPLICATION FOR PROVENANCE

ABSTRACT

Petrography and heavy mineral techniques were employed in the study of the Nanka Formation in order to evaluate sediment provenance and tectonic setting. Petrographic study of the sands shows that quartz is the dominant mineral (64- 85%) with high monocrystalline to polycrystalline quartz ratio, feldspars vary from 1- 4%, rock fragments range from 1 to 15% whereas matrix is between 8 and 15%. The framework grains are medium to coarse in size, sub-angular to rounded and moderately well sorted to poorly sorted. Quartz grain abrasion and grain coating with iron oxide together with the framework grains that are devoid of cement are characteristics of the sands. The QFL ternary plot indicates that the sands are quartz arenites and sublitharenites. Maturity evaluation shows them to be texturally submature to mature and mineralogically submature to supermature. Heavy mineral assemblages consisting of zircon, tourmaline and rutile with sub-rounded to rounded grains were recovered from the sands. The QFL and QmFLt ternary plots of the sands indicate derivation from Craton Interior, Recycled Orogen and Quartzose recycled. Metamorphic and plutonic rocks of Oban Massif and the sedimentary rocks of the Benue Trough and Anambra Basin are suggested as parents. Weathering of the source rock took place under semi- humid to humid climatic conditions in a low relief.

Keywords: Petrography, Diagenesis, Maturity, Sands, Nanka, Heavy Mineral

1.0 Introduction

Framework modes of terrigenous sandstones reflect derivation from various types of provenance terranes that depend upon plate- tectonic setting (Dickinson *et al.,* 1983). Provenance analysis of sediments is aimed at reconstructing the parent- rock assemblages of sediments and the climatic- physiographic conditions under which sediments formed (Weltje and Eynatten, 2004). The technique of sandstone petrography has been utilized for sandstone classification, origin, tectonic environment, maturity stage, paleo- climatic condition of source area and sediment recycling (e.g Dickinson, 1970, 1985, 1988; Dickinson and Suczek, 1979; Pettijohn *et al.,* 1987; Basu, 1985; Weltje *et al.,* 1998; Weltje & Eynalten, 2004). Sandstone petrographic study provides insights into the abundance of its detrital components, such as quartz, feldspar, and lithic elements. These constituents are important in differentiating sediments originating from different tectonic terranes. Heavy mineral technique is also an effective tool in provenance studies. However, integration of both petrography and heavy mineral techniques provides a clue to proper evaluation, comparison and interpretation of sediment provenance.

Studies have been carried out on the lithofacies, textural attributes, ichnology, environment of deposition, sequence stratigraphy and reservoir properties of the Nanka Formation (e.g Nwajide, 1979, 1980; Nwajide and Hoque, 1979; Onuigbo *et al.,* 2010; Nwachukwu et al., 2011; Acra *et al.,* 2014; Oguadinma *et al.,* 2014; Odumodu and Mode, 2014; Ekwenye and Onyemesili, 2018; Ogbe and Osokpor, 2021). Ekwenye *et al.,* (2015) integrated petrography and heavy mineral techniques in the study of provenance of Paleogene strata in southeastern Nigeria.

This paper examines the petrography and the heavy mineral assemblages in sands of the Nanka Formation of the Niger Delta Basin, southeastern Nigeria. The objectives of this study are to determine the sand types, maturity stages, diagenesis and provenance of the sediments.

The Study Area

The study area, Awka and environs is situated within latitudes 06º 10'0" N and 06º 15'0" N and longitudes 07º 0'0"E and 07º 5'30" E and underlain by the Imo Formation and the investigated sediments of the Nanka Formation (Fig. 1). The two formations are part of the outcropping Niger delta (Short and Stauble, 1967).

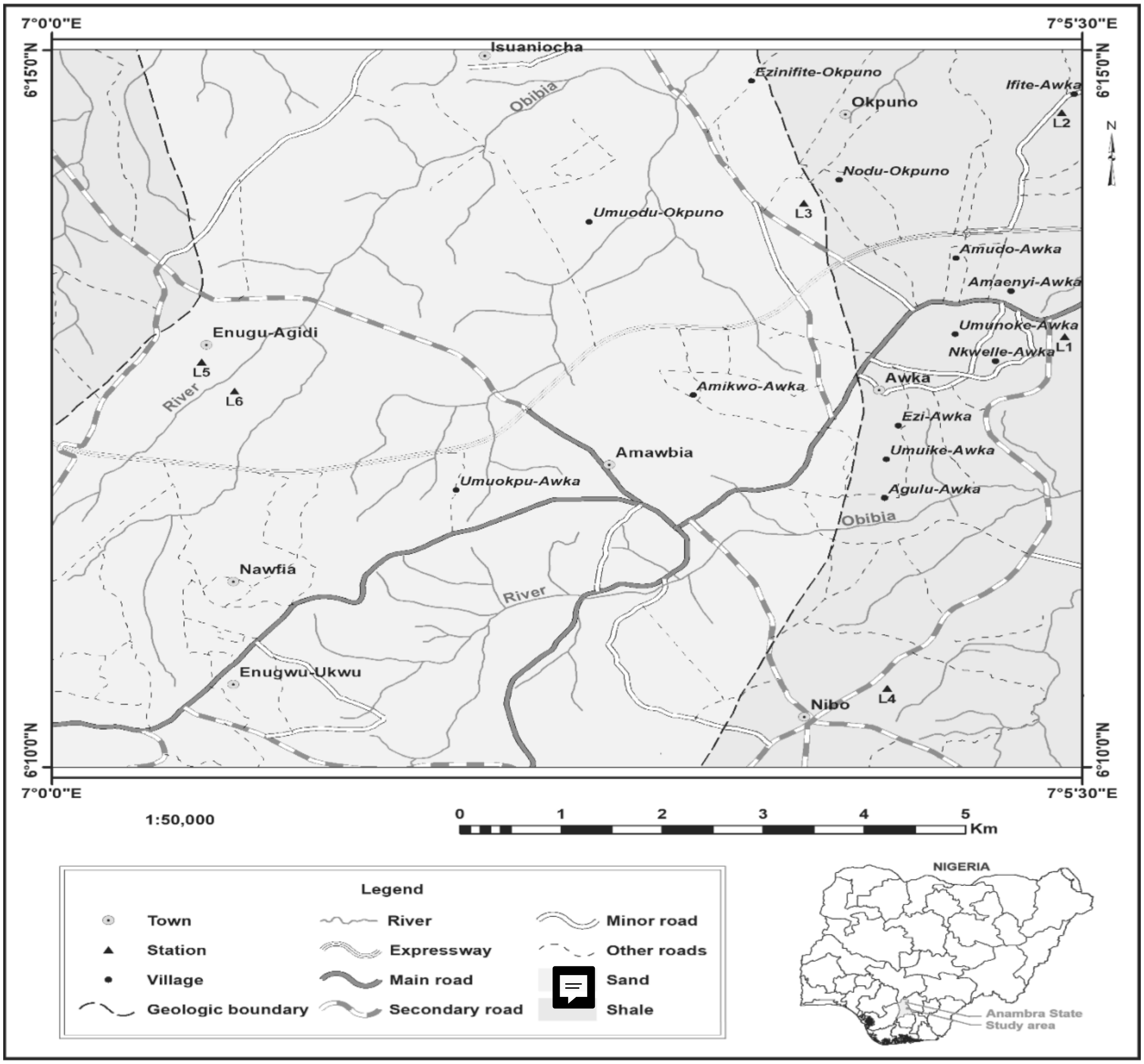


Fig. 1 Geologic map of the study area

2.0 Tectonics and Stratigraphic Setting

The emergence of the Niger Delta Basin is linked to the evolution of the Benue Rift as an aulacogen, a failed arm of a triple junction, which occurred during the breakup of Gondwana supercontinent and the opening of the southern Atlantic Ocean during the Jurassic period (Maron, 1969; Burke *et al.,* 1972; Nwachukwu, 1972; Olade, 1975; Wright, 1981; Benkhlil, 1982). The Benue Trough is a northeast-southwest oriented folding rift basin that traverses Nigeria (Chukwu- Ike, 1981; Ajakaiye *et al.,* 1986). The stratigraphy of the southern Nigeria sedimentary basins occurred within the framework of three tectonic sedimentary cycles (Hoque and Nwajide, 1984). The initial cycle, which span from the Aptian to Coniacian epochs resulted in the accumulation of syn-rift sediments in various habitats, including continental and shallow marine settings. The second cycle followed the Santonian folding and uplift of the sediments from the first cycle. Subsequently, both the Anambra Basin and the Afikpo sub-basin had a period of subsidence. The initiation of the third cycle occurred during the deposition of Campanian to early Paleocene facies within the Anambra Basin and Afikpo sub-basin, followed by the subsequent lateral migration of sediment into the basin's interior (progradation) throughout the late Paleocene to present-day, resulting in the formation of the contemporary Niger Delta Basin. Figure 2 is the stratigraphic succession in the Benue Trough, Anambra and the Niger Delta basins.

The Imo Formation is the basal lithostratigraphic unit of the outcropping part of the Niger Delta Basin. This is conformably overlain by the Ameki Group (Ameki, Nanka and Nsugbe formations). The Ameki Group is successively followed upwards by Ogwashi- Asaba and Benin formations (Nwajide, 2022).

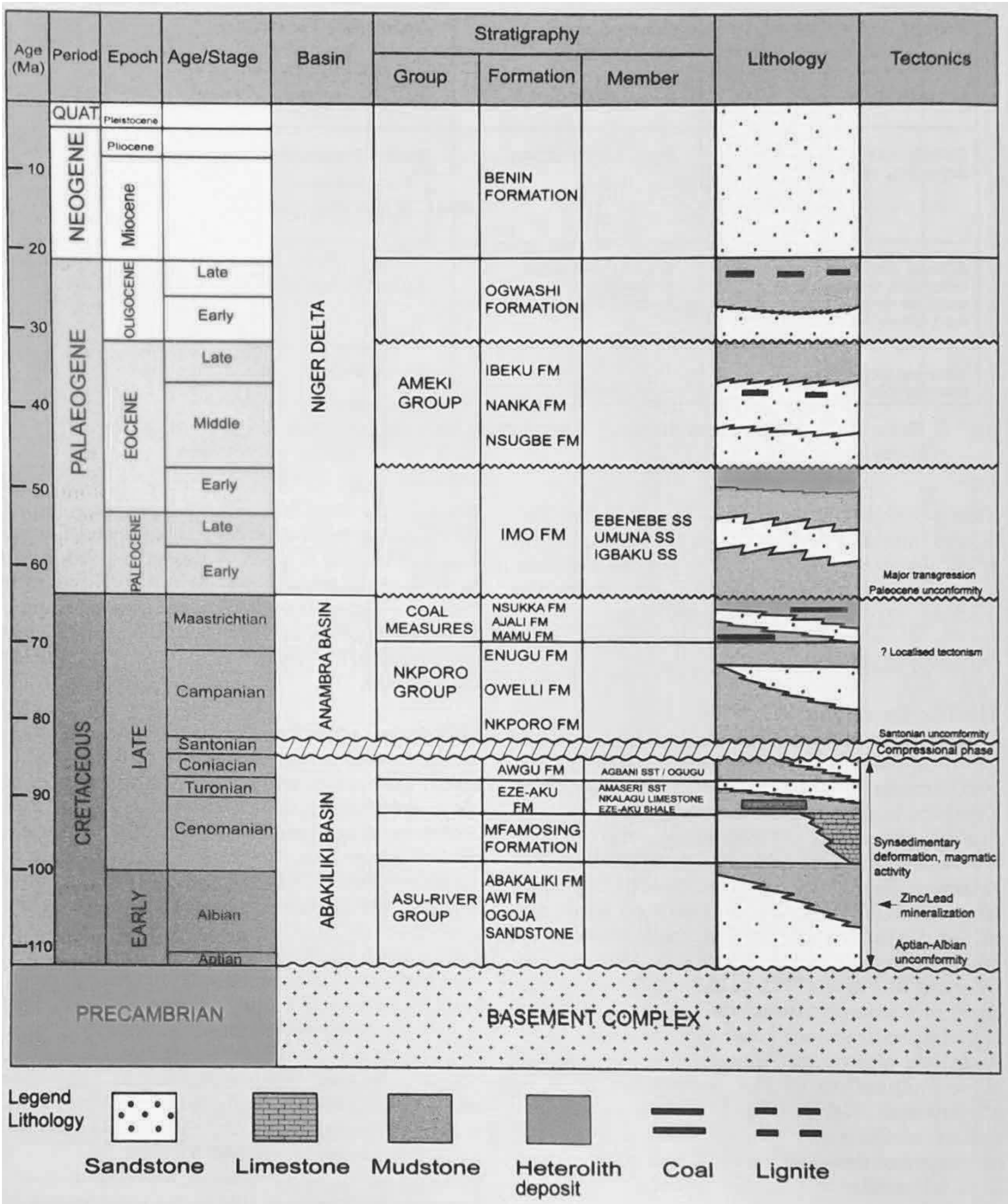


Fig 2: Stratigraphic succession in the Benue Trough, Anambra and Niger Delta basins (Ekwenye and Nichol, 2016).

3.0 Methodology

Sand samples collected from the outcrop sections of the Nanka Formation in the study area were subjected to petrographic and heavy mineral analyses. Samples for petrographic studies were prepared following the standard method of impregnation using epoxy resin, flattening using 600F Carborundum powder and resin bonding on the glass slide. Modal composition of the sand was estimated with petrographic microscope. Heavy mineral analysis of the sands was based on Krumbein and Pettijohn, (1938).

4.0 Results and Discussion

4.1 Petrographic Study

The result of modal composition analysis of the sands of the Nanka Formation is presented in Table 1 and Figures 3. Quartz is the dominant mineral in all the sand samples and constitutes 64 to 85% of the modal framework fraction. Both monocrystalline (Qm) and polycrystalline (Qp) quartz types are present, with the monocrystalline quartz grains dominating the polycrystalline quartz grains in the samples. Quartz grains are generally sub- angular to sub- rounded in shape, though few quartz grains are rounded and exhibit undulose extinction. Quartz grain abrasion and iron oxide coatings are also attributes exhibited by the sands. Quartz overgrowth exists (SE2) and quartz grain contacts are mostly point and long contacts, though floating quartz grain contact was also found in the modal framework. The sands are commonly medium to coarse grained and moderately well sorted to poorly sorted. Other modal constituents of the investigated sands include feldspars that range from 1 to 4% and consist of microcline and plagioclase feldspars with cross- hatching and polysynthetic twining characteristics respectively, rock fragments vary from 1 to 15%, matrix consists of clay and varies from 8- 15% and opaque fractions. Framework grains generally lack cement (except minor iron oxide; hematite which occur in some samples).

Table 1: Modal composition (%) of the sands of Nanka Formation

Sample no	Qm	Qp	QT	Feldspar	Rock fragment	Matrix	Iron oxide (cement)	Opaque
SD2	45	20	65	1	2	15	15	2
SD3	54	10	64	4	8	14	7	3
SE1	65	7	72	1	13	15	-	-
SE2	61	15	76	2	3	14	5	-
SR1	50	20	70	1	10	13	3	3
SW1	55	15	70	1	12	8	5	4
SL1	51	33	84	2	1	11	-	2
SL2	66	19	85	2	1	12	-	-
ST1	75	7	82	1	4	10	2	1

Qm= monocrystalline quartz, Qp= polycrystalline quartz and QT= total quartz

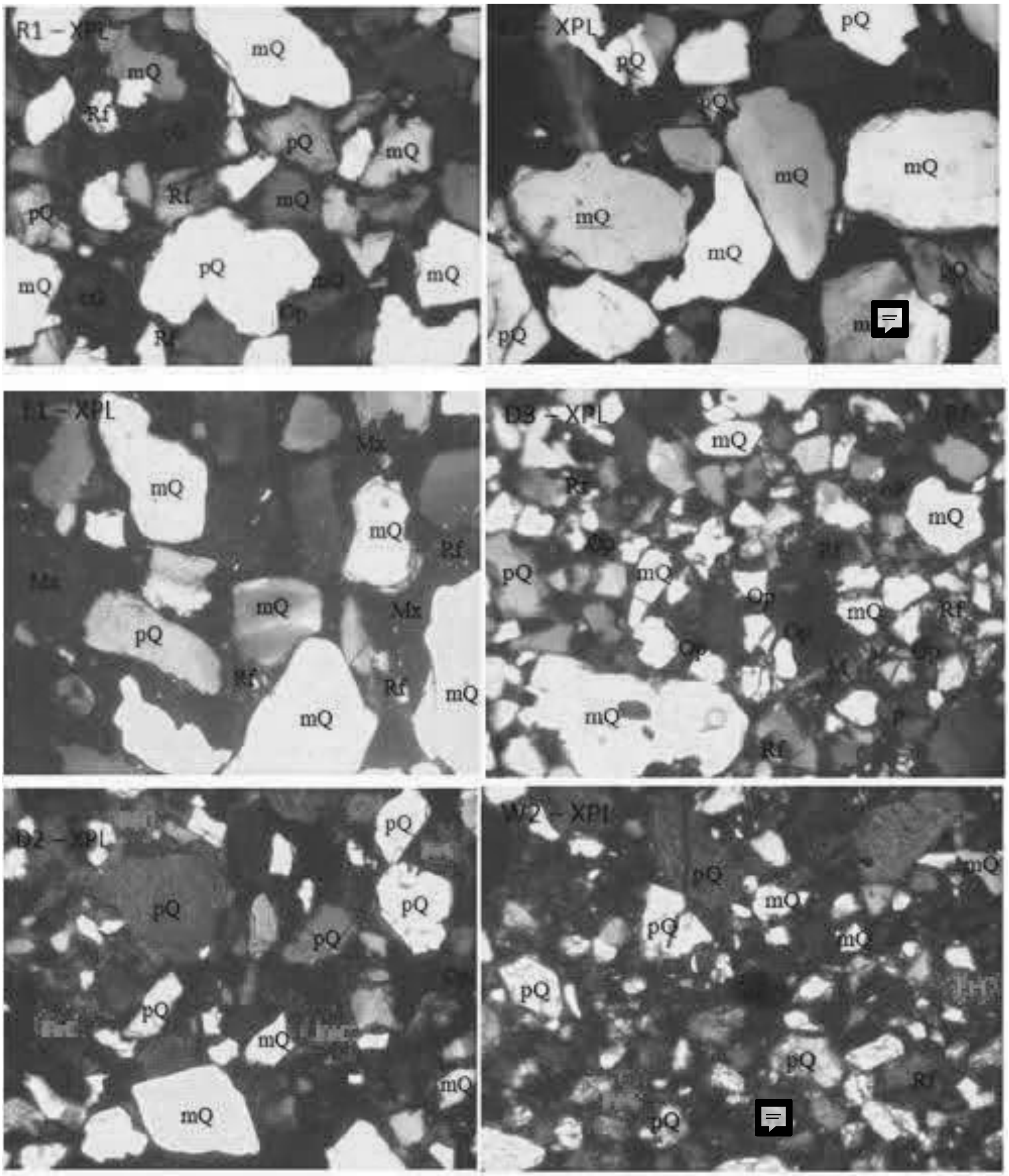


Fig. 3: Photomicrographs of the Petrographic sections of the sands

The modal composition of the investigated sands was re-calculated based on the percentages of the three major components; quartz, feldspar and rock fragment or lithic component (QFR or QFL and QmFLt) (Table 2). The QFL is an important tool in the determination of sandstone type and maturity (Folk, 1974; Pettijohn *et al.,* 1987) whereas both QFL and QFLt are useful in the discrimination of sandstone provenance and tectonic settings (e.g Dickinson and Suczek, 1979; Dickinson *et al.,* 1983).

Table 2: Recalculated modal composition (%) of the sands of the Nanka Formation

Sample no	QFL (%)			QmFLt (%)		
	Q	F	RF or L	Qm	F	Lt
SD2	96	1	3	94	2	4
SD3	84	5	11	82	6	12
SE1	84	1	15	83	1	16
SE2	94	2	4	92	3	5
SR1	86.5	1.2	12.3	82	2	16
SW1	84.3	1.2	14.5	81	1	18
SL1	97	2	1	94	4	2
SL2	97	2	1	96	3	1
ST1	94	1	5	94	1	5

Q= quartz, F= feldspar, Rf or L= rock fragment or lithic, Lt= total lithic components

4.1.2 Classification of the sand based on modal composition

The investigated sands were classified based on the QFR ternary plot of Pettijohn *et al.,* (1987). The sands plot within the fields of quartz arenites and sublitharenites (Fig. 4). Arenites are quartz rich sands in which matrix percentage is below 5%. Quartz percentage in quartz arenites are over 95% whereas quartz percentage in sublitharenites falls between 75 and 95%. Sublitharenites contain more rock fragments than feldspars. The very low percentage of feldspars and high clay contents observed in the investigated sands suggest weathering of feldspars under humid condition. Low percentage of rock fragment in the sands can be attributed to weathering and long distance transport. The angular shapes and poor sorting exhibited by some of the sands are in support of long distance transport, during which some of the coarse grained quartz were fractured and broken down to smaller angular fractions due to abrasion. Many of the coarse grained quartz in the sands are better rounded than finer ones.

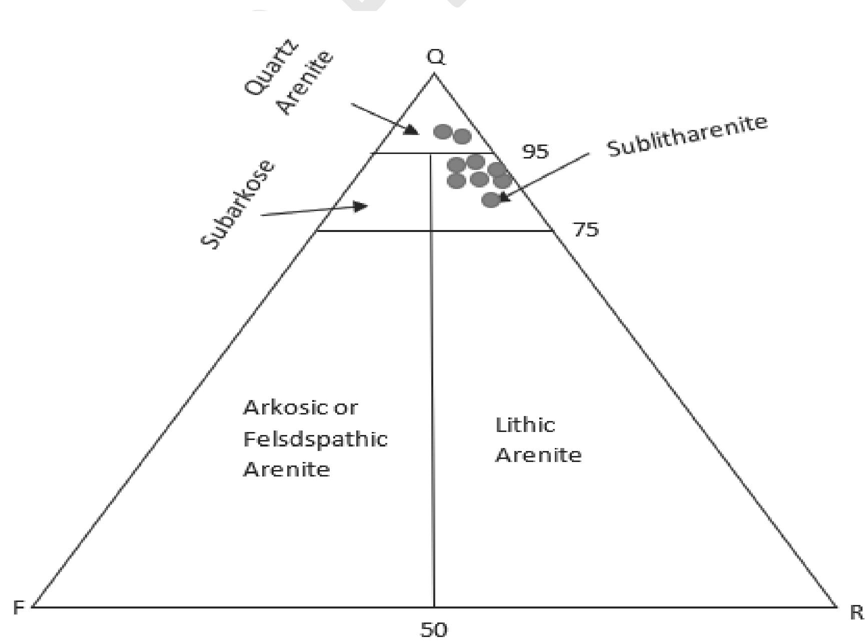


Fig. 4: Ternary plot of Nanka Sands based on modal composition

4.1.3 Maturity of the Sands

The textural maturity of clastic particles such as sands is judged based on its clay contents, degree of sorting and grain rounding (due to abrasion during transport) (Pettijohn, 1975; Nichol, 1999). Quartz arenites are known for low matrix contents, good sorting and with rounded grains while sublitharenites are moderately to moderately well sorted with sub-angular to sub- rounded grain shapes. The sands of Nanka Formation can be classified as texturally sub-mature to mature.

Mineralogical maturity on the other hand was evaluated based on Nwajide and Hoque (1985). The sands of Nanka Formation are submature to supermature. The quartz arenites are mineralogically supermature due to very high quartz contents of over 95%, with feldspar and rock fragments accounting for the remaining percentage whereas sublitharenites are mineralogically submature.

4.1.4 Diagenesis

Diagenesis is the sum total of physical, chemical and biological processes that occur in sediments and sedimentary rocks from immediately after deposition through to the metamorphic realm (Montañez and Crossey, 2018). Diagenetic processes which were observed in the petrographic sections of the investigated sands include precipitation of authegenic quartz overgrowth, framework that lack silica or calcite cement except the precipitation of minor iron oxide cement in some of the samples and hematite coatings on some quartz grains. Alteration of feldspar to clay which accounts for high clay contents of the sands. Quartz grain contacts, which varies from floating grains to point and long. Sutured contacts are rare. Stage of diagenesis and degree of formation of pressure solution can be evaluated based on grain to grain contacts and degree of cementation by quartz overgrowth (Pettijohn *et al.,* 1987). The floating, point to long grain contacts exhibited by the investigated sands coupled with absence of cement in the framework grains indicate minor to no pressure solution. Liberation of silica from feldspar degradation and subsequent clay reactions may have aided in the nucleation and growth of quartz overgrowths (Worden and Morad, 2009) found in the investigated sands. According to Bullard and White (2002), hematite is thought to be associated with early diagenetic clay mineral grain coating, which probably was transformed from various Fe- hydroxides and Fe- oxides. Mechanical compaction may have begun during shallow burial, which resulted to the formation of point and long grain contacts. Absence of sutured grains and pressure solution coupled with oxidation of Fe to hematite are suggestive of early stage diagenesis (Eodiagenesis).

4.2 Heavy Mineral Analysis

Ultra- stable non opaque (zircon, tourmaline and rutile) and opaque (hematite and ilmenite) heavy mineral assemblages were recovered from the sands (Fig. 5). Zircon is dominant (75- 86%) heavy mineral, followed by rutile (8- 15%), tourmaline (4- 10%) and opaques (0- 5%). There is general absence of unstable heavy minerals. Zircon is colourless under plane polarized light (ppl) but produced spectrum of interference colours that range from pale pink, pale green and light yellow (typical of fourth order except for yellow that belongs to third order) under cross polarized light (xpl). Zircon grains are commonly prismatic and sub-rounded to rounded in shape. Rutile occur as small rounded grains that are reddish brown in both ppl and xpl whereas tourmaline is of colourless variety (elbaite), prismatic and sub-rounded in shape. The ZTR (zircon, tourmaline, rutile) index calculation for the sands was based on Hubert (1962) and stated as follows;

ZTR index= $(z + t + r)/\sum$ non- opaque x 100 -- (1)

The ZTR index of the sand samples is 100%

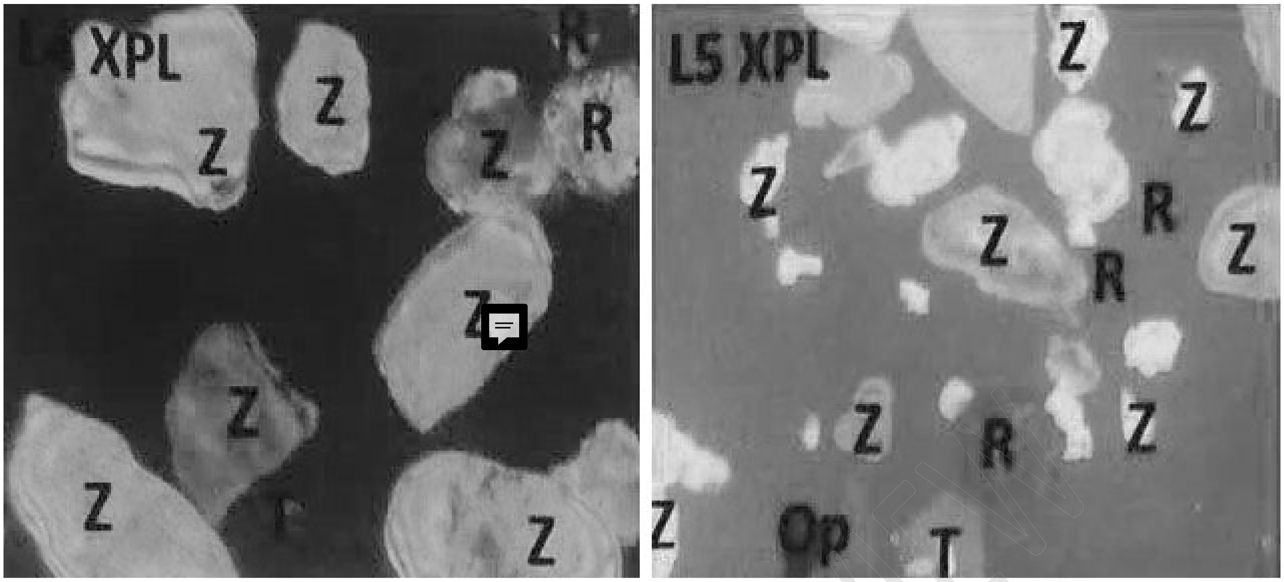


Fig. 5: Photomicrographs of heavy mineral assemblages from Nanka sands

4.3 Provenance and Tectonic Setting

The word provenance in sedimentary petrology encompass all factors related to the production of sediment with specific reference to the composition of the parent rocks as well as the physiography and climate of the source area from which sediment is derived (Weltje and Eynatten, 2004). The ultimate goal of provenance studies is to deduce the characteristics of source area from measurements of compositional and textural properties of sediments, supplemented by information from other lines of evidence (Pettijohn *et al.,* 1987). The sands of the Nanka Formation plot into the fields of Craton interior and recycled orogen and in the quartzose recycled in the QFL and QmFLt ternary plots respectively, of Dickenson *et al.,* (1983) (Figs. 6a & b). The quartz arenites plot within the craton interior and the sublitharenites in the fields of recycled orogen and quartzose recycled. Sandstones that plot in the field of craton interior are mature sandstones derived from relatively low- lying granitoid and gneissic sources, supplemented by recycled sands from associated platform or passive margin (Dickinson *et al.,* 1983). Alkali feldspars are essential minerals in alkali and acid igneous rocks such as granites and in high grade gneisses (Gribble, 1988). Microcline and oligoclase are the k- feldspar and plagioclase feldspar respectively, which occur in the investigated sands. Presence of these feldspar types suggests derivation from metamorphic and acid igneous rocks respectively. Sediments sources within recycled orogen are dominantly sedimentary with subordinate volcanic rocks derived from tectonic settings where stratified rocks are deformed, uplifted and eroded (Dickinson, 1985; Dickinson and Suczek, 1979). High Qm/Qp ratios in mature quartzose sands indicate that monocrystalline quartz has greater potential for survival in the sedimentary cycle than polycrystalline lithic fragments (Dickinson, 1985), thus high Qm/Qp exhibited by sands of the Nanka Formation may probably suggests sediment recycle or long-distance transport.

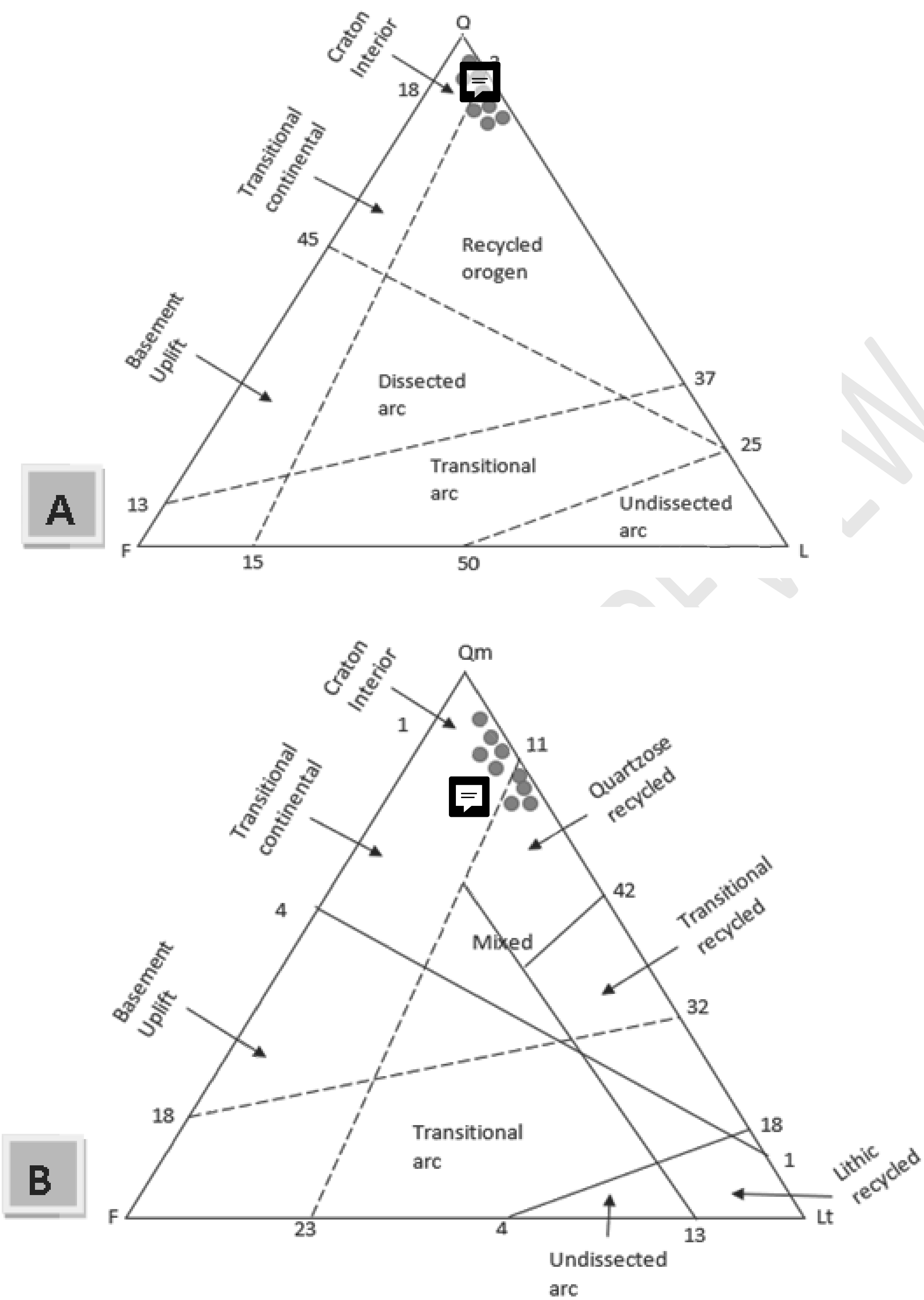


Fig. 6a: The QFL ternary plot of sands of the Nanka Formation (b): The QFLt ternary plot for Nanka sands

Heavy minerals such as zircon, rutile and tourmaline in sandstones are sourced from plutonic igneous (granites) and metamorphic (gneisses) rocks. These heavy minerals due to their superior hardness (zircon=

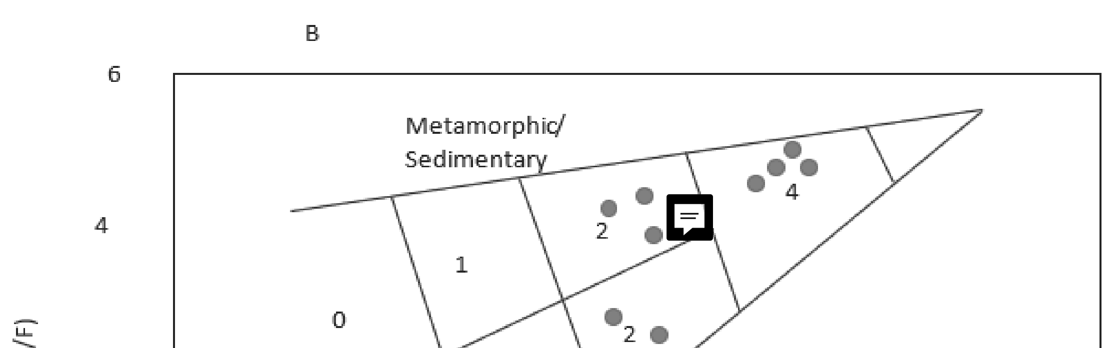
7.5, tourmaline= 7.0- 7.5 and rutile= 6.0- 6.5) are resistant to chemical weathering, thus can survive multiple recycling like quartz. The degree of rounding of he[redacted] mineral grains is an indicator of sediment transport history. The concentration of only ultra- stable non opaque minerals in the sands of the Nanka Formation coupled with the sub- rounded to rounded nature of their grains suggest long distant transport from one basin to another, thus sediment recycling (sedimentary source). This agrees with the ZTR index of over 95%, which according to Hubert (1962) is an indication of sediment recycle or a sedimentary source.

The plutonic and metamo[redacted]ic rocks of the Oban Massif (Basement) and older sedimentary rocks of the Benue Trough and Anambra Basin are considered as parents to the sediments of the Nanka Formation.

4.3.1 Paleo- climate and Relief

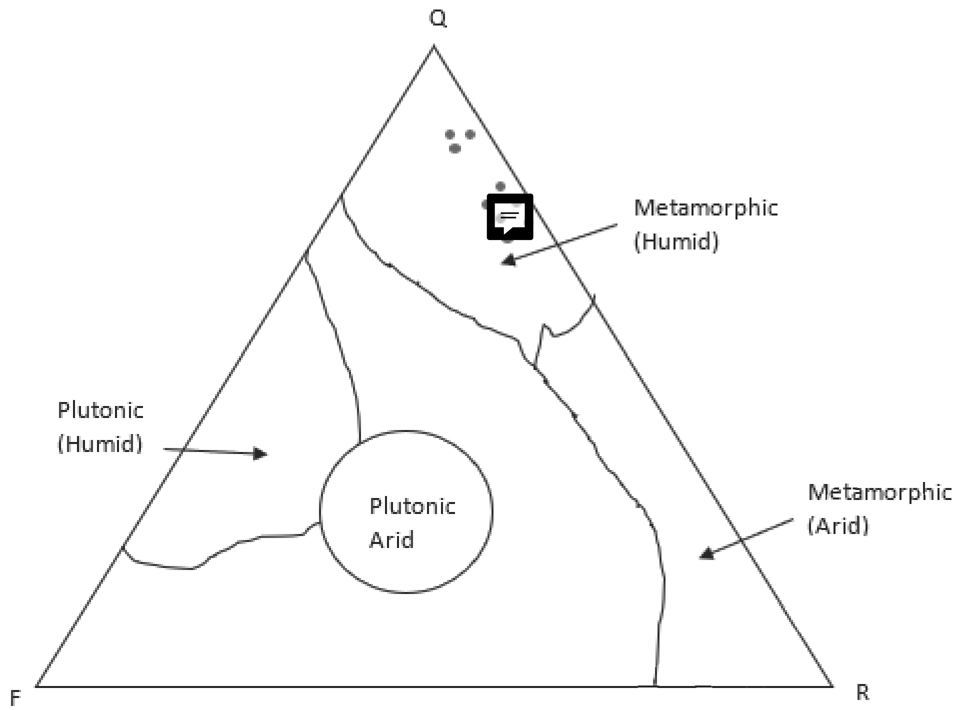
Sandstone composition is influenced by climate and relief. The paleo- climate and relief were evaluated in this study using the semi- quantitative approach of Weltje (1994). His semi- quantitative approach was based on modern fluvial sands with known source rock lithologies and different physiographic conditions. He calculated a semi- quantitative weathering index (wi) from the formula c*r; where c is the rate of weathering (climate) and r is the residence time of the sediment in the weathering environment (relief). The [redacted]- ratio plot (Q/F vs Q/Rf) defines a clear relationship between sandstone composition, weathering index and source rock lithology. The sands of the Nanka Formation plot into fields of wi= 4 and 2; indicating metamorphic, plutonic and sedimentary sources in a low relief and under semi- humid to humid (tropical) climate (Fig. 7).

The effect of climate on the composition of the sands of Nanka Formation was also evaluated using the plot of Suttner *et al.,* (1981). The sands plot into the field of metamorphic (humid) (Fig. 8). This also indicates metamorphic parentage and humid paleo- climatic condition of the source area. The plot only considers metamorphic and plutonic rock sources as well as arid and humid climatic conditions.



Semi Quantitative Weathering Index (W= Cir) (Weltje, 1994)			Relief (r): High Mountain	Moderate Hill	Low Plains
			0	1	2
Climate (C)	Semi-Arid Mediterranean	0	0	0	0
	Temperate	1	0	1	2
	Tropical Humid	2	0	2	4

Fig. 7: Log- ratio plot of the sands of Nanka Formation based on Weltje (1994). Fields labeled 1- 4 are referred to as the semi- quantitative weathering indices defined on the bases of climate and relief



Fig, 8: Effect of climate on the composition of sands of the Nanka Formation based on Suttner *et al.,* (1981).

5. Conclusion

The sands of the Nanka Formation are quartz arenites and sublitharenites that are matrix rich but lack cement. Plutonic and metamorphic rocks Basement (Oban Massif) and sedimentary rocks of the Benue Trough and Anambra Basin are suggested as their parents. The paleo- climate and relief of the source area were semi- humid to humid and low plain respectively.

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