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Paleoenvironment, Paleoredox and Paleogeography of Mamu Shale Anambra Basin Southern Nigeria

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Abstract

The Shales in Okada and Usen within Mamu Formation, Anambra Basin were evaluated for Paleogeography, Paleoenvironment and Paleoredox conditions by examining the foraminifera, polymorph assemblages and the trace elements concentration accordingly. the application of trace element composition ratios: V/Cr, V/Ni, U/Th, Ni/Co, $V/(Ni+V)^2$, $V/(Sc)^3$ with the averages of $1x10^{-3}$, $8x10^{-4}$, $5.1x10^{-1}$, 1.31, $9x10^{-8}$ and $1x10^{-5}$ respectively. These paleo–redox index for both Usen and Okada Shales indicates oxic condition in the ancient environment. The foraminifera assemblages recovered are *Ammobaculites sp., Ammobaculites irregulariformis sp., Ammobaculites fisheri crespin sp., Textularia sp.* and *Textularia earlandi sp.* The forams recovered were of benthic arenaceous and calcareous foraminifera assemblages, typically of late Paleocene to early Eocene which coincides with marine incursion in the Anambra Basin. The presence of very few ammonites from the shale samples suggests some lithofacies control. The palymorphs assemblages recovered are *Triporites sp.*, *Triorites sp.*, *Hexacolpites sp.*, *Araucariacites australis sp.*, *Monoporites annulatus sp.*, *Pseudoschizaea sp.* and *Arecipites sp.* The presence of *Arecipites* in sedimentary rocks indicates the presence of palms in the local environment during the time the sediment was deposited. The recovered palymorphs indicates shales that were derived from terrestrial landscapes except *Pseudoschizaea sp.* that is found in wetlands and/or lacustrine environments. This suggested that the paleoecology at time the shale was deposited was predominantly land-based (terrestrial). The mixed terrestrial-marine environment and the oxic conditions would assist geologists to better assesses the potential for hydrocarbon accumulation and develop more effective exploration strategies.

Keywords: Foraminifera Assemblages, Paleoenvironment, Paleogeography, Paleo–Redox, Polymorphs

1.0 Introduction

Paleoenvironmental reconstruction involves deciphering the environmental conditions of past geological eras based on a comprehensive analysis of various sedimentary and stratigraphic records (Wogau *et al.,* 2019). This intricate process necessitates the integration of diverse techniques, including lithostratigraphy, biostratigraphy, sedimentology, and geochemistry, in order to construct an accurate portrayal of ancient landscapes and ecosystems (Li *et al.,* 2019).

Redox-sensitive trace element (TE) concentrations or ratios are among the most widely used indicators of redox conditions in modern and ancient sedimentary deposits (Akinyemi *et al.,* 2013). Paleo–redox environment refers to the study of ancient oxygenation and redox conditions that prevailed in Earth's oceans and sedimentary systems throughout geological history (Wang *et al.,* 2022; Al-Obaidi *et al.,* 2020). Investigating paleoredox environments requires a comprehensive analysis of sedimentary records, with a particular focus on geochemical proxies and mineralogical indicators that provide insights into the prevailing oxygen availability and redox state of ancient oceans (Madukwe, 2019; Khan *et al.,* 2022; Zou *et al.,* 2021).

Paleogeographic reconstructions rely on multiple lines of evidence, including sedimentary rocks, fossils, paleomagnetic data, and geological mapping. Fossils are also invaluable indicators for paleogeographic reconstructions. By studying the distribution and composition of fossil assemblages, paleontologists can determine the ancient biogeography and the connections between different regions. Index fossils, which have a restricted temporal and spatial range, aid in correlating rocks of similar ages and refining paleogeographic interpretations (Guoqi *et al.,* 2021).

Sedimentary rocks play a crucial role in paleogeographic analysis. Different types of sediments, such as sandstones, shales, and limestones, provide clues about the depositional environments in which they formed. The presence of marine fossils in sedimentary rocks suggests a past connection to the ocean, while the occurrence of river channels and floodplain deposits indicates terrestrial environments (Gama and Schwark, 2023).

By understanding the provenance and paleo-conditions of a sedimentary basin fill, as the Anambra basin, insights into its tectonic setting, maturity as well as other ancient conditions can be made. Although, extensive studies have been carried out to cut across provenance, paleoredox conditions, paleogeography, sedimentology, stratigraphy, Palynology, reservoir characterization and petroleum potential, (Peter et al., 2017; Mathew et al., 2019; Mengjiao et al., 2020; Tijani et al., 2010; Uzoegbu et al., 2013; Egboka and Emejulu, 2015; Okwara et al., 2020; Ogungbesan and Adedosu, 2021). However, this study is multidisciplinary research that provides an improved understanding of the Anambra Basin's geological history, giving an insight into the hydrocarbon potential of Mamu formation while contributing to the development of new methods and approaches for paleoenvironmental and paleoredox studies.

2.0 Materials and methods

2.1 Study Area

The study area of Usen and Okada lies between latitudes 6° 27' 23 N and 6° 36' 21 N and longitudes 5° 12'21 E and 5° 12'23 E respectively (Figure 2). The choice to study the shale outcrops of Okada and Usen was informed by the fact that they both belong to a common sedimentary formation and Basin. The geologic map and cross section of the study area (Figure 1) were generated using the GPS co-ordinates obtained from the field studies. The areas are covered in some parts with light vegetation while in other parts with zero vegetation and are very accessible. The study area is accessible through many roads (both major and minor roads), and footpaths; it can be accessed by the Okada-Benin-Lagos Express Way (Figure 1).

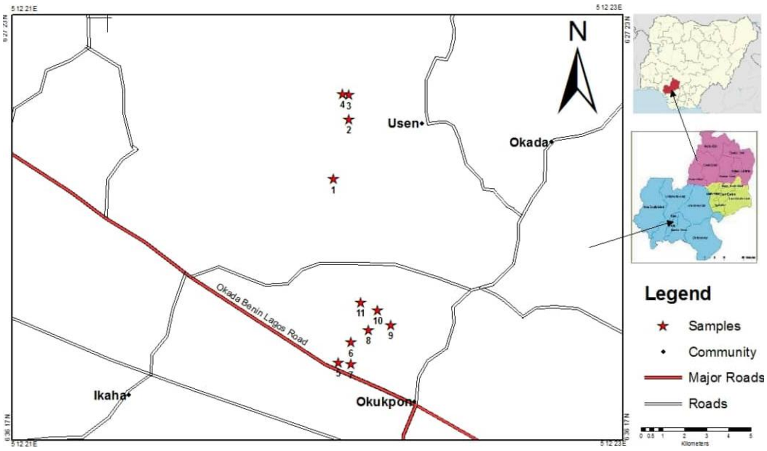

Figure 1: Location map of Usen, Okada and environs showing the sampled locations

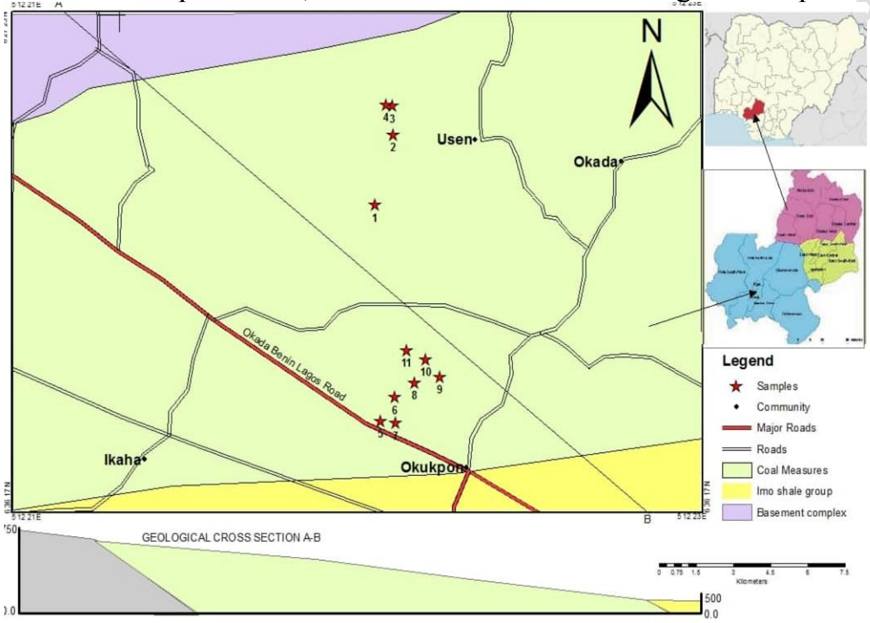

Figure 2: Geological map of Usen, Okada and environs showing the sampled locations

2.2 Geology of Anambra Basin

2.2.1 Tectonic History

Anambra Basin originated from the Benue arm of the triple rift valley system. Initially the Benue Trough, which was formed by rifting of the central trough was filled with sediments deposited by rivers and lakes. During the Late, Early to Middle Cretaceous, it subsided and then filled with ocean water. Large quantities of sediments accumulated in the bottom of the southern Abakiliki Rift in anoxic conditions (Nwajide, 2013). In the Upper Cretaceous, the Benue Trough probably formed the main link between the Gulf of Guinea and the Tethys Ocean (predecessor of the Mediterranean Sea) through the Chad and Iullemmeden Basins. After this period, the basin rose above sea level, and extensive coal forming swamps developed, especially in the Anambra Basin. The westward displacement of massive sediments in the Lower Benue Trough led to the formation of the Anambra Basin (Nwajide, 2013; Obaje, 2013, 2022).

The Anambra Basin is a NE–SW trending, roughly triangular shaped sedimentary depression covering an area of about 40,000 km^2 in the southern part of Nigeria (Figure 3a and b). It is bounded to the south by Tertiary Niger Delta, east by Abakaliki Anticlinorium, north by Basement Complex and west by Benin Hinge line. As one of the component basins of the Benue aulacogen, Anambra Basin reflects the features of the Lower Cretaceous break-up of the Gondwana supercontinent. During Albian-Santonian, the proto-Anambra basin was a platform only thinly draped by older sediments. The Santonian compressional uplift of the Abakaliki Benue trough with its resultant sediment folding and westward translation of depositional axis led to tectonic inversion that created the Anambra basin (Ogungbesan and Adedosu, 2019; Jaiyeola *et al.,* 2016).

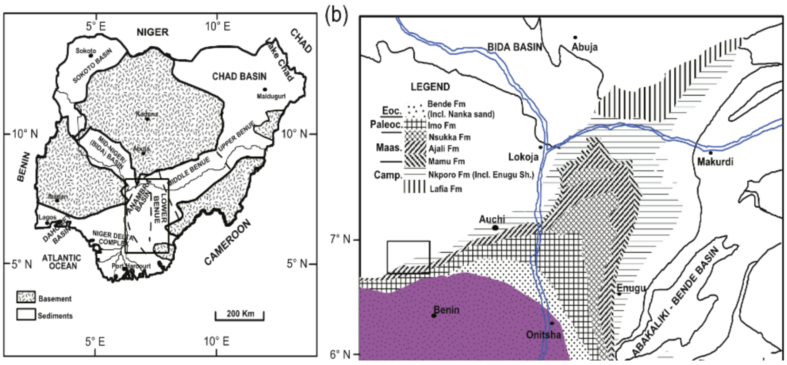

Figure 3: (a) Geological Map of Nigeria showing location of Anambra Basin and adjoining basins. (b) Geological Map of Anambra Basin (both modified after Ogungbesan and Adedosu, 2019).

2.2.2. Tectonic Framework and Associated Structures

The tectonic framework of the Anambra basin has been the subject of several studies in recent years. The Anambra basin is a Cretaceous-Tertiary sedimentary basin situated in southeastern Nigeria that is characterized by a complex tectonic framework resulting from multiple deformation events (Onuoha *et al.,* 2022; Ofoegbu and Onuoha, 2017; Ezeh *et al.,* 2020; Nwachukwu *et al.,* 2021). The basin is bounded by highlands to the east and west, the Benue trough to the north and the Niger delta basin to the south (Anakwuba *et al.,* 2021; Ejedawe *et al.,* 2016). The basin is believed to have formed as a result of rifting associated with the breakup of Gondwana during the Late Jurassic to Early Cretaceous. The rifting was followed by a period of thermal subsidence during the Late Cretaceous to Paleocene, which resulted in the deposition in the lower part of the fill. The basin experienced a major phase of compressional deformation during the Eocene to Oligocene, which resulted in the folding and faulting of the basin fill. The compressional deformation was followed by a period of extensional deformation during the Miocene to Pilocene, which resulted in the formation of horst and grabens along the basin margins (Ehrim *et al.,* 2020; Ibe *et al.,* 2021). The Nkporo syncline, a major structural element trend NW-SE and separates the basin into the northern and southern parts, while the Amasiri-Awkwa anticline which trends ENE-WSW divides the southern part of the basin into two sub-basins (Onuoha *et al.,* 2022; Ejedawe *et al.,* 2016; Nwachukwu *et al.,* 2021). Other significant structures of the basin include the Agwu anticline in the northern part of the basin and the Abakalili and Anambra River faults along the eastern and western margins. The major faults in the basin include the Abakaliki fault along the western margin. Other faults in the basin include the Oshiegbe, Ishiagu and Okposi faults (Ogbonna *et al.,* 2021; Ofoegbu and Onuoha, 2017).

The Abakaliki fault is a major NE-SW trending fault that separates the basin from the Abakaliki basin to the east. The fault is characterized by a series of horsts and grabens that formed as a result of normal faulting. The Oshiegbe fault is a NW-SE trending fault that runs parallel to the Abakaliki fault and shares similar characteristics. The Anambra River fault is a major NW-SE trending fault that divides the Anambra basin from the Niger Delta basin to the south. The fault is characterized by a series of horsts and grabens that formed as a result of faulting. The proper understanding of the tectonic framework of the Anambra basin is essential for the exploration and development of the basin's hydrocarbon and mineral resources (Ehrim *et al.,* 2020; Nwankwo *et al.,* 2020).

2.2.3 Stratigraphy of the Basin

The sedimentary depositional history of the Anambra Basin (Figure 4) has been presented in the light of a tripartite tectonic episode. The first phase: a Pre-Santonian (Albian ⁻ Santonian) event marked by pronounced subsidence in the Abakaliki domain of the Benue Trough, while the Anambra remained a platform with mud and shallow marine deposits. The second phase (Santonian to Early Paleocene, Danian) resulted in uplifting and folding of the Abakaliki- Benue Belt; while the Anambra platform subsided due to structural inversion. The detritus generated due to the tectonic uplift and erosion of the Abakaliki anticlinorium has been acclaimed to be the source of the Anambra lithic fills (Tijani *et al.,* 2010). The lithic fills of the Anambra basin comprise the Campanian-Lower Maastrichtian Nkporo/Enugu Shales (with its lateral equivalent, Owelli sandstone), the Maastrichtian Mamu Formation that is coal bearing, the Upper Maastrichtian Ajali sandstone Formation, the diachronous (Maastrichtian to Danian) Nsukka Formation, the Paleocene Imo Shale Formation, and the Paleocene to Early Oligocene Ameki Formation. The detailed descriptions of stratigraphic successions of the Anambra Basin are presented by several authors (Nwajide, 2013). The third phase of the sedimentary cycle initiated the southward progradation of the Niger Delta along the Anambra axis during the Late Eocene.

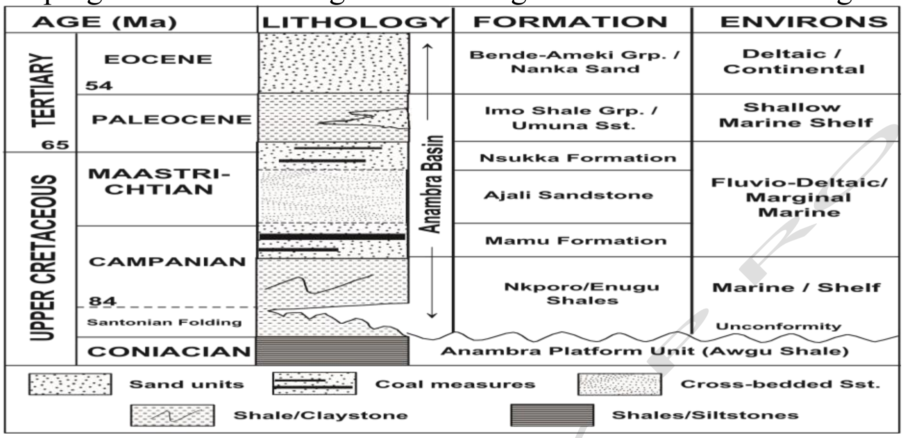

Figure 4: Stratigraphy of the Anambra Basin (after Ilevbare and Omodolor, 2020).

Nkporo Formation (Campanian – Maastrichtian)

Nkporo Formation consists of a sequence of bluish to dark grey shale and mudstone which is locally with sandy shales, thin sandstones, and shelly limestone beds. The shale facies grade laterally to sandstones of the Owelli and Afikpo Formations in the Anambra Basin (Nwajide, 2013).

Mamu Formation (Lower Maastrichtian)

The Mamu formation which is the focus of this work consists of alternating sandstone, sandy shales, and mudstones with interbedded coal seams. The formation is underlain by the Campanian Enugu/Nkporo shales (lateral equivalents) and Nsukka formation (Upper Maastrichtian) to Danian. five sedimentary units were recognized in the Mamu formation in the Enugu area where the thickest exposed section (approximately 80m) occurs. The basal units consist of shale or sandy shale, sandstone with occasional shale beds, carbonaceous shale, coal seams, and sandy shale (Simpsons, 1954; Reyment, 1965).

Ajali Formation

The Ajali sandstone overlies the Mamu Formation and it has a diachronous age from South to the North (middle – late Maastrichtian). In addition, it exhibits significant thickness variation from less than 300m to over 1000m at the centre of the basin. Depositional characteristics are uniform for most parts of the basin, and it is made up of textually mature sand facies i.e. mature quartz arenite intercalated with kaolinite beds.

Nsukka Formation

Nsukka Formation, which overlies the Ajali Sandstone, begins with coarse to medium grained sandstones and passes upward into well-bedded blue clays, fine-grained sandstones, and carbonaceous shales with thin bands of limestone (Reyment, 1965; Obi *et al.,* 2001).

Imo Formation

The Imo Formation consists of blue-grey clays and black shales with bands of calcareous sandstones, marls, and limestone. Ostracods and foraminifera biostratigraphy (Reyment, 1965), and microfauna recovered from the basal limestone unit, indicate a Paleocene age for the formation. The Imo Formation is the outcrop lithofacies equivalent of the Akata Formation in the subsurface Niger Delta, (Ahmed, 2022; Adegoke *et al.,* 1980; Arua, 1986).

Ameki Group

The Ameki Group consists basically of the Nanka Sand, Nsugbe formation, and Ameki formation which are laterally equivalents. The age of the formation has been considered to be either early Eocene or early to middle Eocene. The depositional environment has been interpreted as estuarine, lagoonal, and open marine based on the faunal content. Reyment (1965) interpreted an estuarine environment because of the presence of fish species of known estuarine affinity. Adegoke (1969) however, indicated that the fish were probably washed into the Ameki Sea from inland waters, and preferred an open marine depositional environment. Nwajide (1979) and Arua (1986) suggested environments that ranged from near shore (barrier ridge-lagoonal complex) to intertidal and subtidal zones of the shelf environments.

Ogwashi-Asaba Formation

The Ogwashi-Asaba Formation comprises of alternating coarse-grained sandstone, lignite seams, and light coloured clays of continental origin (Kogbe, 1976). Reyment (1965) suggested an Oligocene-Miocene age for the formation, while Jan du Chene *et al.,* (1978) reported middle Eocene age for the basal part from palynology. The Ameki Group and the Ogwashi- Asaba Formation are correlative with the Agbada Formation in the surface Niger Delta. Subsequently, Akande (1993, 1998) stated that there is increasing attention to the geochemistry of the southern Benue basins. Akande (2015) also reported that different methane precursors in the interbedded coal and shale lithologies suggest remarkable potential to contribute a mixture of hydrocarbons derived from marine and terrestrial organic matters.

3.0 Materials and Methods

Forty (40) outcrop samples were collected from Okada and Usen area in Edo State. The samples were also taken at an average interval of 0.50 m from the bottom of the outcrop to the top using the chip and grab method.

3.1 Foraminifera Assemblages and Palynomorph Analyses

About 40g of each sample was weighed on the beam balance and observed in small tray under the binocular microscope. Each of the weighed samples were crushed and soaked in hydrogen peroxide at room temperature for about 48 hours to disaggregate or dislodge the sediments from the fauna content present. After the time had elapsed, the hydrogen peroxide was decanted and the samples again soaked in detergent and then washed, at a time, under a jet of running water using the 63µm and 73µmsieve (Avong *et al.,* 2022). The residue of each sieve was properly washed with water, placed in well-labeled plastic container and left to dry. Fossils were then picked out from this dried sample at a magnification of 70x under the binocular microscope. The foraminifera species encountered were mounted temporarily with a gum on a micro-paleontological slide cavity and covered with a slip. These slides were numbered for identification by comparing with forms

Palynological sample preparation followed the standard procedures of using HF and HCl to remove the matrix (silicates and carbonates) and oxidized by adding concentrated nitric acid (Okeke, 2023; Evans and Sunday, 2018). The residues were sieved through 5μ size nylon sieve mesh and photomicrographs were taken using a light microscope equipped camera.

3.2 X-ray Fluorescence Spectrometry (XRF)

According to Gary, (2008), sample preparation trace elements, and instrumental neutron activation analysis were carried out using X-ray fluorescence spectrometry. Using an X-ray fluorescence (XRF) analyzer, the trace elements are (Ba, Sr, Cs, Rb, Ta, Nb, Sc, Y, Ni, Rb, Zr, Co, Ce, Se, Pb, Ga, V, Ti, La, Th and U) were identified.

4.0 Results and Discussions

The result has been presented using tables and figures for better understanding. The trace elements concentration for both Usen and Okada shale (ppm) are: Ba ranged 812-980 (~887); Cs ranged 8-14 (~11); Co ranged 12-43 (~26); Cr ranged 12-58 (~27); Nb ranged 12-35 (~20); Ni ranged 5-83 (~34); Sc ranged 8-110 (~56); Sr ranged 77-965 (~293); Rb ranged 10-191 (~115); Zr ranged 13-320 (~236); Ta ranged 0.48-0.72 (~0.62); Ce ranged 0.22-2.42 (~0.72); Se ranged 0.33-21.30 (~7.84); Pb was sited in just two locations (with one in each community) with value of 25 (~25); Nd ranged 0.20-0.92 (~0.49); Ga ranged 0.22-21.40 (~2.48); V had value of 0.01-0.02 (~0.03); Ti ranged 0.33-0.80 (~0.54); La ranged 0.20-0.24 (~0.22); Th ranged 0.20-0.70 (~0.43) and U ranged 0.20-0.30 (~0.22) (Tables 1a and 1b).

From the above data, it would be observed that all elements had appreciable increase across the samples except vanadium, lanthanum and uranium, which had less significant concentrations for both Okada and Usen shale.

According to Gao *et al*. (2020), Ni concentrations larger than 200 ppm and Co concentrations greater than 150 ppm are signs of mafic or ultramafic provenance. Co and Ni averaged 26 and 34 respectively indicating that the shale samples from Usen and Okada are most likely sourced from a felsic origin.

Table 1a: Trace Elements Concentration (ppm)

Sample Number	Ba	Cs	Co	Cu	Cr	Nb	Ni	Sc	Sr	Rb	Zr
OKA1	855	10	43	25	17	25	83	90	18	10	180
OKA2	930	10	43	25	17	25	83	90	18	10	180
OKA3	912	10	26	26	58	35	62	10	96	19	250
OKA4	812	10	26	26	58	35	62	10	96	19	250
OKA5	840	12	22	24	22	15	10	11	77	15	283
US1	945	12	22	24	22	15	10	11	77	15	283
US2	845	12	22	24	22	15	10	11	77	15	283
US3	920	14	21	28	19	12	5	8	12	14	320
US4	980	14	21	28	19	12	5	8	12	14	320
US5	835	8	12	22	12	15	10	10	15	18	13
Average	887	11	26	25	27	20	34	56	29	11	236

Table 1b: Trace Elements Concentration

Sample Number	Ta	Ce	Se	Pb	Nd	Ga	V	Ti	La	Th	U
OKA1	0.72	2.42	1.20	ND	0.20	0.22	0.02	0.33	0.22	0.60	0.20
OKA2	0.72	2.42	1.20	ND	0.20	0.22	0.02	0.33	0.22	0.60	0.20
OKA3	0.48	0.24	1.22	ND	0.37	0.30	0.02	0.80	0.20	0.20	0.20
OKA4	0.48	0.24	1.22	ND	0.37	0.30	0.02	0.80	0.20	0.20	0.20
OKA5	0.64	0.38	10.20	25	0.92	0.44	0.02	0.60	0.24	0.70	0.20
US1	0.64	0.38	10.20	ND	0.92	0.44	0.02	0.60	0.24	0.70	0.30
US2	0.64	0.38	10.20	ND	0.92	0.44	0.02	0.60	0.24	0.70	0.30
US3	0.63	0.25	21.30	ND	0.30	0.50	0.02	0.34	0.24	0.20	0.20
US4	0.63	0.25	21.30	25	0.30	0.50	0.02	0.34	0.24	0.20	0.20
US5	0.58	0.22	0.33	ND	0.40	21.40	0.01	0.66	0.20	0.20	0.22
AVERAGE	0.62	0.72	7.84	25	0.49	2.48	0.03	0.54	0.22	0.43	0.22

ND: Not detected

4.1 Paleo–redox Conditions of the Shale

Trace elements such as Cr, Co, Th, U, V, Mo, Ni, and Mn are redox sensitive and useful in the reconstruction of paleo-redox conditions of the depositional environment. Trace composition and elements ratio (Th/U, V/Cr, V/Sc, and U/Th) have been used for determining paleo-redox conditions (Jones and Manning, 1994; Matthew *et al.,* 2019; Mengjiao *et al.,* 2020). Despite the usefulness of the redox-sensitive trace elements emphasized the invaluable need for cautious use and in a relative sense. This is because of the problems associated with comparing their ratios directly to the threshold suggested in previous studies.

Table 2: Significant ratios of the trace elements of Okada and Usen shales

Sample Number	Ni/Co	V/Cr	U/Th	Cr/Ni	V/Ni	V/Sc	$V/(Ni+V)^2$	$V/(Sc)^3$
OKA1	1.93	0.001	0.33	0.20	0.0002	0.0002	$1x10^{-9}$	$3x10^{-8}$
OKA2	1.93	0.001	0.33	0.20	0.0002	0.0002	$1x10^{-9}$	$3x10^{-8}$
OKA3	2.38	0.0003	1.00	1.07	0.0003	0.002	$2x10^{-9}$	$2x10^{-5}$
OKA4	2.38	0.0003	1.00	1.07	0.0003	0.002	$2x10^{-9}$	$2x10^{-5}$
OKA5	0.45	0.0009	0.29	0.45	0.002	0.0002	$8x10^{-8}$	$2x10^{-8}$
US1	0.45	0.0009	0.43	0.45	0.002	0.0002	$8x10^{-8}$	$2x10^{-8}$
US2	0.45	0.0009	0.43	0.45	0.002	0.0002	$8x10^{-8}$	$2x10^{-8}$
US3	0.19	0.001	1.00	0.26	0.004	0.003	$3x10^{-7}$	$4x10^{-5}$
US4	0.24	0.001	0.83	0.26	0.004	0.003	$3x10^{-7}$	$4x10^{-5}$
US5	0.83	0.0008	1.10	0.83	0.001	0.001	$1x10^{-8}$	$2x10^{-5}$
Average	1.31	0.001	0.51	0.79	0.0008	0.0005	$9x10^{-8}$	$1x10^{-5}$

In the ratios of the trace elements in both communities (Table 2): Ni/Co ranged 0.19-2.38 with an average of 1.31; V/Cr ranged 0.0003-0.001 with an average of 0.001; U/Th ranged 0.29-1.10 with an average of 0.51; Cr/Ni ranged 0.20-1.07 with an average of 0.79; V/Ni ranged 0.0002-0.003 with an average of 0.0008; V/Sc ranged 0.0002-0.003 with an average of 0.0005; $V/(Ni+V)^2$ ranged $1x10^{-9}$ to $3x10^{-7}$ with an average of $9x10^{-8}$; $V/(Sc)^3$ ranged $2x10^{-8}$-$4x10^{-5}$ with an average of $1x10^{-5}$.

Table 3: Standards applied to trace elements ratios from previous work (Jones and Manning, 1994)

Element ratios	Oxic	Dysoxic	Suboxic to Anoxic	Euxinic
Ni/Co	< 5	5 to 7	> 7	
V/Cr	< 2	2 to 4.25	> 4.25	
U/Th	< 0.75	0.75 - 1.25	> 1.25	
V/(Ni+V)	< 0.46	0.46 - 0.60	0.54 - 0.82	> 0.84
V/(Sc)	< 9.1			

Jones and Manning (1994) applied the ratio of V/Cr to decipher paleo-redox conditions and stated that ratio values of <2, 2–4.25, and >4.25 represented oxic, dysoxic, and suboxic and anoxic conditions respectively. Similarly, the V/Cr ratio has been used as a paleo-oxygenation indicator in a number of studies. Values of V/Cr >2 are thought to represent anoxic depositional conditions, whereas values below 2 are indicative of more oxidizing conditions (Olajubaje *et al.,* 2018). The V/Cr ratios of the examined samples are far below 2 (~ 0.001) and therefore indicate the oxic depositional setting (Table 3). The ratio of U/Th was applied by Ejeh (2021), to distinguish between oxic (<1.25) and suboxic to anoxic (>1.25) settings. The U/Th ratios of the samples from Usen and Okada are <1.25 (~0.51), they are of oxic depositional setting (Table 3).

According to Olajubaje *et al.* (2018), the concentration of vanadium (V), and nickel (Ni) as well as their ratios provide a means of determining the degree of anoxic condition during deposition. Vanadium is usually enriched in comparison with Ni in anoxic marine environments. In this study, the

reverse is the case as nickel is more enriched than vanadium in the outcrop which implies an oxic setting was prevalent. In this investigation, V/Ni ranged 0.0002-0.003 with an average of 0.0008 indicating oxidizing conditions in the shale samples studied. Also, Ni/Co ratio above 5 indicates dysoxic to anoxic environment, whereas a ratio below 5 suggests an oxic environment (Jones and Manning, 1994; Olajubaje et al., 2018). The Ni/Co ratio of this study averages of 1.3 also indicates an oxic environment. Similarly, $V/(Ni+V)^2$ averages $9x10^{-8}$ being less than 0.46 and $V/(Sc)^3$ averages $1x10^{-5}$ < 9.1 standard also authenticate an oxic ancient condition for the shales, (Ilevbare and Omoruyi, 2020).

The application of trace element composition ratios: V/Cr, V/Ni, U/Th, Ni/Co, V/(Ni+V)2, V/(Sc)3 as proxies for paleo-redox conditions of the sediments obtained from the Usen and Okada shales all indicate paleo redox oxic conditions. This oxic condition aligns with the result from the foraminifera and palynomorph data since majority of the fossils recovered were Benthic and planktic forms, with abundance of Benthic forms which is an indicator of the oxygen level in the water while the presence of terrestrial palynomorph indicates proximity to land and potentially high oxygen levels.

4.2. Ancient Environment Reconstruction

Six locations were analyzed for foraminifera assemblages and a total of 24 species were recovered in order to reconstruct the ancient environment. In three locations (US26, OKA 34 and OKA 39) no forams were identified while in another three (OKA 36, US 32 and OKA 26), varying amounts of forams were collected and identified above (Table 4). A total of eleven, seven and six forams were collected in OKA 36, US 32 and OKA 35 respectively. The Okada shales appeared to have more fossils (total of seventeen in both locations) of forams than in Usen (total of six only in one location).

A total of ten fossils of *Ammobaculites sp*., five fossils each of *Ammobaculites irregulariformis* sp. and *Textularia sp.*, two (2) fossils of *Ammobaculites fisheri crespin sp.* and a fossil of *Textularia earlandi* sp. (Table 4). The *Ammobaculites sp*. being an in faunal deposit feeder is commonly found in long range habitat from marsh, estuaries, brackish to neritic, and bathyal environments. However, they can tolerate low oxygen levels. They are also described as test moderately inflated, planispirally involute in early part; raised chambers to slightly uncoil in the later part; sutures are flushed; hence, the chambers are somewhat indistinct in the coarsely agglutinated species. They occur commonly in the lower shale of the Dukamaje Formation and the shales of Mamu Formation (Olajubaje *et al.,* 2018).

A total of five (5) samples were collected of *Ammobaculites irregualriformis* (four in Okada and one in Usen) as seen in Table 4. *Ammobaculites irregulariformis* (Figure 5) is a species of foraminifera, which are single-celled organisms that typically live in marine environments. They possess hard calcareous shell that is composed of tiny chambers called tests, which they build themselves. They are also known for their irregularly shaped test reflecting their nomenclature, which can be quite variable in appearance. They are found in sedimentary rocks that were deposited during the Paleocene and Eocene epochs, which occurred between approximately 34 million years ago (Shevenell, 2021; Ilevbare and Omodolor, 2020).

A total of two (2) fossils were recovered for *Ammobaculites fisheri crespin* (two in Okada and none in Usen) from Table 4. *Ammobaculites fisheri* (figure 5) are commonly found in marine environments and are known for their elongated, cigar-shaped test that is tapered at both ends. It is typically found in sedimentary rocks that were deposited in the Paleocene and Eocene epochs, which occurred approximately 66 and 34 million years ago. *Ammobaculites crespin* (figure 5) belongs to the family *Ammobaculitidae.* It is known for its cylindrical or barrel-shaped test which is typically around 0.5mm in length. This species is found in shallow marine environments. *Ammobaculites crespin* is commonly found in sediments from the Cretaceous period, which occurred between approximately 145 and 66 million years ago. Although not common, they can be found in more recent sediments (Van der Boon, 2020; Singh, 2021).

A total of five samples were collected of *Textularia sp.* (two in Okada and three in Usen) as seen in Table 4 and Figure 4. *Textularia sp.* are single-celled organisms commonly found in the marine environment and can be found in a range of shallow to deep water. Their tests are typically elongated or cylindrical in shape, with a series of chambers arranged in a spiral or linear pattern. The fossilized remains of *Textularia sp.* can be found in sedimentary rocks dating back to the Jurassic period, which occurred approximately 201 and 145 million years ago, as well as in more recent sediments. Their presence can be used to infer water depth, temperature, quality and environmental health in marine settings. They can also be used to monitor the impacts of climate change and activities on the ocean (Hennissen, 2021).

Table 4: Foraminifera sp. recovered from the Okada and Usen Shale

	SAMPLE LOCATIONS						**TOTAL**
Foraminifera Species	**OKA 36**	**US 32**	**US26**	**OKA35**	**OKA39**	**US34**	
Ammobaculites sp.	5	2	-	3	-	-	10
Ammobaculites irregulariformis sp.	2	1	-	2	-	-	5
Ammobaculites fisheri crespin sp.	1	-	-	1	-	-	2
Textularia sp.	2	3	-	-	-	-	5
Textularia earlandi sp.	1	-	-	-	-	-	1
Total	11	7		6	-	-	24

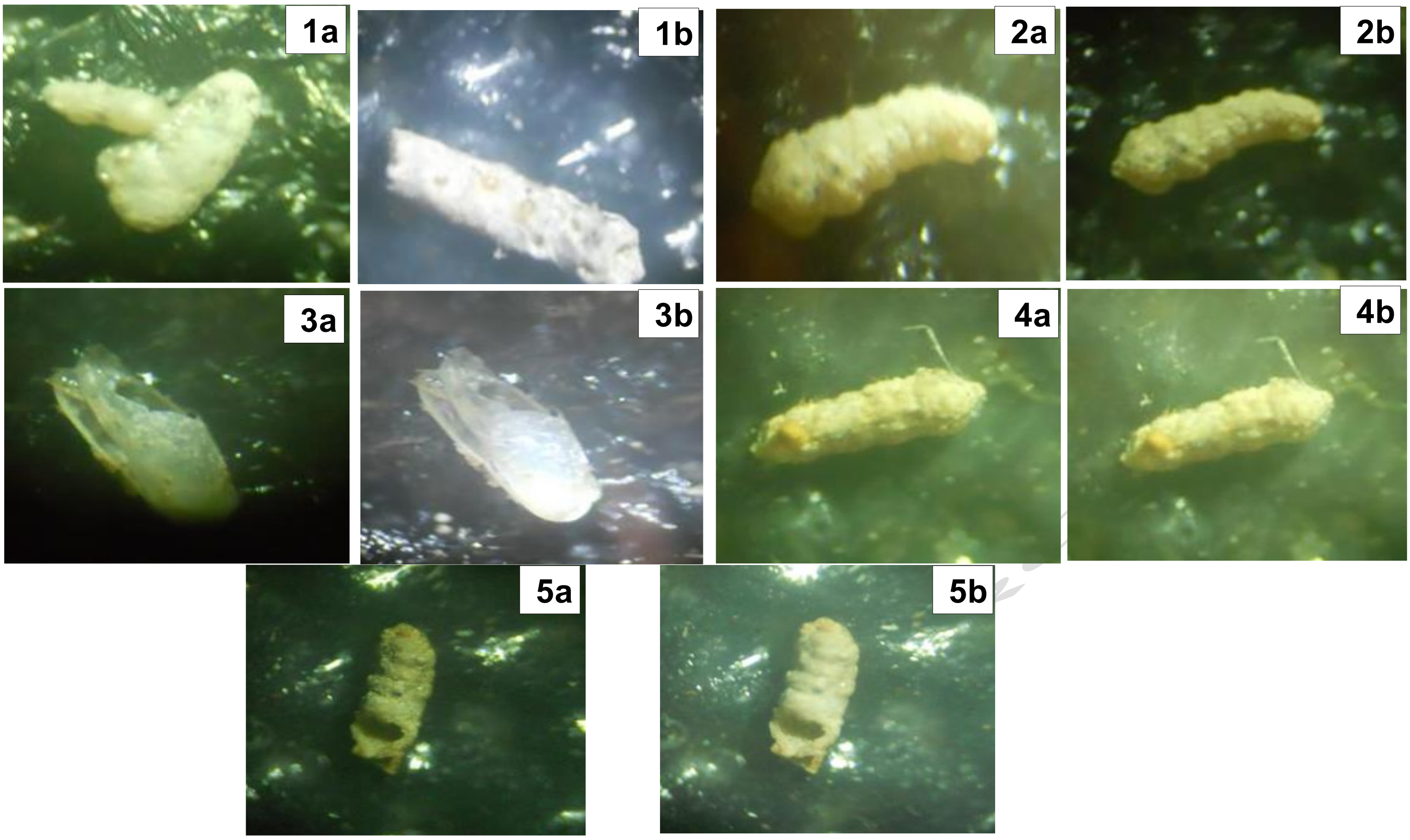

Figure 5: Foraminifera spp. of Okada and Usen Shale, Edo State *1a, b: Ammobaculites sp. 2a, b: Ammobaculites irregulariformis 3a, b: Ammobaculites fisheri crespin 4a, b: Textularia sp. 5a, b: Textularia earlandi*

Although forams recovered were very few benthic arenaceous and calcareous foraminifera assemblages were recovered, they are typically of late Paleocene to early Eocene which coincides with marine incursion in the Anambra Basin. The presence of very few ammonites from the shale samples suggests some lithofacies control. The anoxic environment in which the shale accumulates is unfavourable to benthonic fauna. While it is true that low occurrence of foraminifera may lead to underestimation of marine influence in the study area. However, using multiple proxies, such as sedimentology, geochemistry and palynology can help mitigate these biases and this study adopted these multiple proxies that comprises all of these proxies. In addition, a careful sampling and analysis that have been carried out has greatly minimized these biases.

4.3 Paleogeography

From a palynological point of view, the samples were poor. Three yielded some palynomorphs while three were barren. Seven different palynomorph types were recovered and identified (Table 5).

The samples were poor palynologically speaking. Three yielded some palynomorphs while three were barren. Seven palynomorph types were recovered and identified (Table 5). Seven species of palynomorphs were analysed in six locations. In three out of six locations, no palynomorph was taken. In the other three locations, paleo-organisms were scantily sited compared to the forams. A total of one, four and three palynomorphs were recovered in OKA24, OKA22 and US25 respectively; Usen location had the lowest uptake of palynomorphs (a total of three) than in Okada (a total of five) just as with the forams (Table 5). In all, eight palynomorphs were recovered from both Okada and Usen (Table 5).

Table 5: Palynomorphs recovered from Okada and Usen shale

Sample Number	Palynomorphs	OKA24	OKA22	US27	US25	US28	OKA2 1	TOTA L
1	*Araucariacites australis*		2					2
2	*Arecipites sp.*				1			1
3	*Hexacolpites sp.*				1			1
4	*Monoporites annulatus*		1					1
5	*Pseudoschizaea sp.*				1			1
6	*Triorites sp.*	1						1
7	*Triporites sp.*		1					1
	Total	**1**	**4**	**0**	**3**			**8**

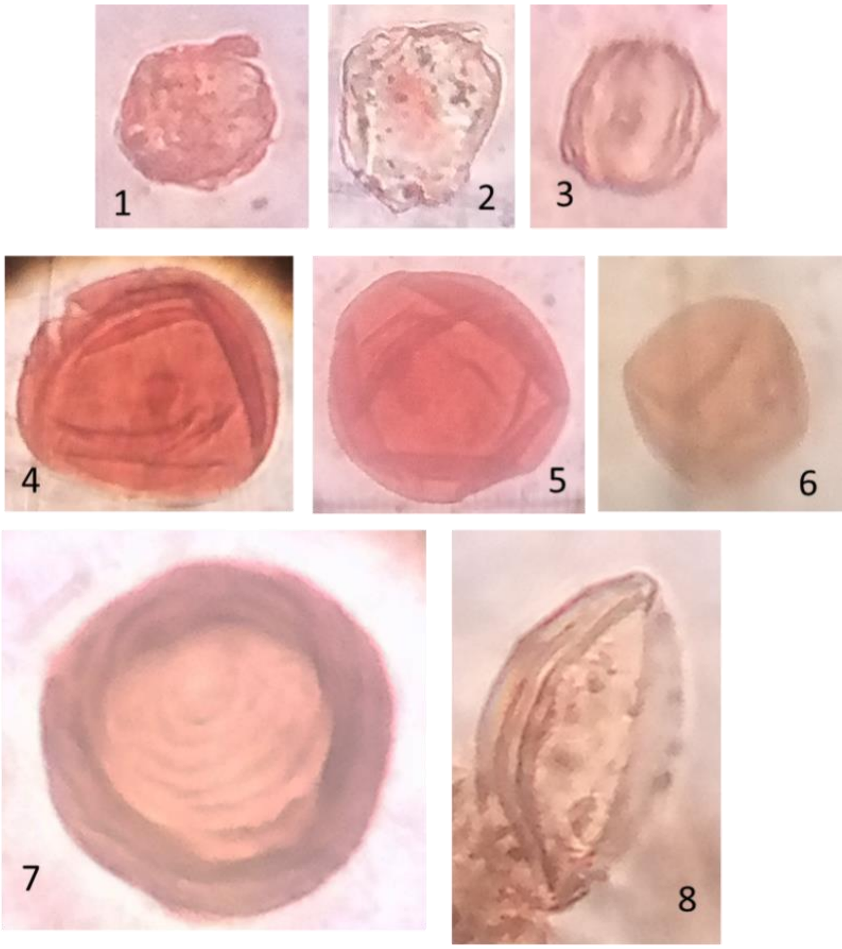

Figure 6: Palynomorphs recovered from the samples. 1. *Triporites sp.* 2. *Triorites sp.* 3. *Hexacolpites sp.* 4-5. *Araucariacites australis*, 6. *Monoporites annulatus*, 7. *Pseudoschizaea sp.* 8. *Arecipites sp.*

Araucariacites australis (Figure 6; 4-5) is a species of coniferous tree that belongs to the family *Araucariaceae.* It is known from fossilized remains that have been found in sediments from the Late Cretaceous period, which occurred between approximately 99 and 66 million years ago, in what, is now South America, particularly in Argentina and Chile and could reach heights of up to 40 meters. It has a straight trunk, and its branches are arranged in a spiral pattern around the stem. The leaves of *Araucariacites australis* are needle-like and arranged in clusters at the ends of the branches. The cones of this species are large and have scales with hooked tips that helps to protect the seeds inside (Figueiral, 2021; Collevatti, 2020).

Arecipites is a genus of fossil pollen that belongs to the family *Arecaceae,* which includes palm trees (Figure 6; 8). It is commonly found in sedimentary rocks that were deposited during the Cretaceous to Paleogene periods, which occurred between approximately 145 and 66 million years ago. The identification of *Arecipites sp.* in sedimentary deposits can provide important information about the past vegetation and climate of an area. For example, the presence of *Arecipites* in sedimentary rocks indicates the presence of palms in the local environment during the time the sediment was deposited (Obada, 2020; Figueiral, 2021).

Hexacolpites is a genus of fossil pollen that belongs to the family *Ephedraceae,* which includes plants commonly known as joint-firs. It is commonly found in sedimentary rocks that were deposited during the Cretaceous to Paleogene periods, which occurred between approximately 145 and 66 million years ago (Liu, 2021). Identification of *Hexacolpites sp.* in sedimentary deposits can provide important information about the past vegetation and climate of an area. *Hexacolpites* in sedimentary rocks indicates the presence of joint-firs in the local environment during the time the sediment was deposited (Wu, 2020; Xie, 2020).

Monoporites annulatus is a species of fossil coral that belongs to the family *Poritidae*. It is commonly found in sedimentary rocks that were deposited during the Paleogene period, which occurred between approximately 66 and 23 million years ago (Yang, 2020). *Monoporites annulatus* identification in sedimentary deposits can provide important information about the past marine environment and climate of an area. *Monoporites annulatus* indicates the presence of coral reefs in the local environment during the time the sediment was deposited in sedimentary rocks (Yang, 2021; Stilwell, 2020).

Pseudoschizaea is a genus of fossil plant that belongs to the order *Marattiales.* It is commonly found in sedimentary rocks that were deposited during the Carboniferous to Permian periods, which occurred between approximately 358 and 252 million years ago (Song, 2021). *Pseudoschizaea sp.* in sedimentary deposits can provide important information about the past vegetation and climate of an area. *Pseudoschizaea* in sedimentary rocks indicates the presence of ferns in the local environment during the time the sediment was deposited (Zhang, 2020). *Pseudoschizaea sp.* can serve as a proxy for paleoenvironmental conditions, providing insights into ancient ecosystems. It can complement other proxies such as sedimentology or foraminifera to provide a more comprehensive understanding of palaeoecological conditions and reconstruct ancient environment with greater accuracy.

Triorites is a genus of fossil pollen that belongs to the order *Bennettitales*. It is commonly found in sedimentary rocks that were deposited during the Mesozoic Era, which occurred between approximately 252 and 66 million years ago (Hagemann, 2021; Song, 2020). The identification of *Triorites sp.* in sedimentary deposits can provide important information about the past vegetation and climate of an area. The presence of *Triorites* in sedimentary rocks indicates the presence of cycad-like plants in the local environment during the time the sediment was deposited (Chen, 2020).

Triporites is a genus of fossil spores that belongs to the order *Lycopsida,* a group of ancient vascular plants that includes club mosses. It is commonly found in sedimentary rocks that were deposited during the Devonian to Permian periods, which occurred between approximately 419 and 252 million years ago (Kido, 2020; Xu, 2019). The identification of *Triporites sp.* in sedimentary deposits can provide important information about the past vegetation and climate of an area. The presence of *Triporites* in sedimentary rocks indicates the presence of lycopsid plants in the local environment during the time the sediment was deposited (Liu, 2019).

In the research carried out by Ayok *et al.,* (2020), most of the palynoflora assemblages were dominated by angiosperm pollen, followed by pteridophytic spores and dinoflagellages cysts. The pollen grains of similar interest documented was *Monoporites annulatus* and *Arecipites sp.* Also documented was the variability in distribution of the pollen grains similar with this study.

Contrary, however with this study and theirs, was the occurrence of the taxa such as *Monoporites annulatus* in high abundance (thirty-six in total at different depths) where just one sample of this species was sited in only one location. The palynomorphs of the Savannah ecology include *Monoporites annulatus* among others. They also observed *Monoporites annulatus* specie was consistent in the stratigraphic succession. The beach vegetation has *Arecipites sp.* as its palynomorphs. *Arecipites sp.* showed the most consistent occurrence.

All the samples recovered are derived from terrestrial landscapes except *Pseudoschizaea sp*. that is found in wetlands and/or lacustrine environments. This suggested that the paleoecology at time the shale was deposited was predominantly land-based (terrestrial). It is not practical to determine the age of the samples because of the paucity of palynomorphs. Those that were recovered have stratigraphic age ranges that are long, the reason they could not be used to accurately determine the age. In addition, marker forms with distinctly short age range were not recovered.

5.0 Conclusion

The following are the findings and/or conclusions from this study:

1. the trace element composition ratios: V/Cr, V/Ni, U/Th, Ni/Co, $V/(Ni+V)^{2}$, $V/(Sc)^{3}$ as proxies for paleo-redox conditions of the sediments obtained from the Usen and Okada communities all revealed oxic depositional setting.
2. the forams recovered were very few benthic arenaceous and calcareous foraminifera assemblages (marine ancient environment) were recovered, they are typically of late Paleocene to early Eocene which coincides with marine incursion in the Anambra Basin.
3. Palynomorph recovered are derived from terrestrial landscapes except *Pseudoschizaea sp*. that is found in wetlands and/or lacustrine environments, therefore suggesting a mixed environment of deposition for the Mamu Shale studied.

Future studies in this research area may have to compare the environmental proxies of this study with that of other formations in the Anambra basin or with other basins, which could provide valuable insights into the regional geologic history.

Conflict of Interest

There is no conflict of interest whatsoever linked to this research or among the authors.

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