

## MICROFACIES AND MINERALOGICAL ANALYSES OF THE LATE CRETACEOUS CARBONATE ROCKS FROM THE CENTRAL BENUE TROUGH, NIGERIA

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### ABSTRACT

The Cretaceous limestone facies from Yandev section in the central Benue Trough, Nigeria constitutes parts of the potential reservoirs and sources rocks for petroleum prospects in the basin. The central Benue Trough is the least studied basin among its contemporaries due to lack of subsurface data. Detailed mineralogical, facies analysis and diagenesis of these carbonate rocks in the basin have not received significant study. The aim of this study was to employ multifaceted methodology such as sedimentological, facies analysis petrographic and geochemical approaches which was lacking in previous research in the trough. The sedimentological analysis was done to evaluate fabrics grain sizes, and lithology types. For petrographic analysis, thin sections were prepared and examined under a petrographic microscope and categorized according to Dunham's classification. Geochemical analysis involved X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscope - energy dispersive X-ray spectroscopy (SEM-EDX) techniques to unveil mineralogical, oxide, and elemental compositions. The sedimentological results revealed light to dark grey medium to fine-grained limestone facies with intercalation of dark grey shales and siltstones. The XRD mineralogy data, revealed calcite (60.00 - 64.10%), quartz (14.30 - 51.00%), albite (12.30 - 19.00%), and chlorite (6.30 - 8.10%). Microfacies results revealed distinct sandy bioclastic wackstone and sparitic intraclastic packstone, as well as micritic intraclastic wackstone and sparitic bioclastic packstone. SEM images highlighted the intricate composition, including elongated structures, whites and dark spots suggesting varying conditions of deposition. Elemental analysis through EDX emphasized significant proportions of carbon, oxygen, sodium, potassium, calcium, silicon, aluminum, iron, and magnesium. Based on sedimentological, biofacies, lithofacies and geochemical evidence we infer that the carbonate sediments were mainly deposited in a shallow marine depositional environment (inner to outer neritic).

**Keywords:** Cretaceous, Central Benue Trough, Petrography, Facies analysis, Geochemical analysis.

### INTRODUCTION

The Benue Trough of Nigeria, is known for its significant occurrences of carbonate rocks, which have been extensively studied in existing literature as discussed by (Nwajide, 2013; Adekeye and Akande, 2002). Geological investigations have revealed the presence of various carbonate formations within the trough, including limestone and dolomite. These carbonates play a crucial role in understanding the geological history and evolution of the region (Nwajide, 2022).

The central Benue Trough is an integral part of the Benue Trough. The lithostratigraphic succession in the central Benue Trough comprises Eze-Aku Group and the Asu River Group (Nwajide, 2013, 2022). The subdivision of the stratigraphic

sequence within the Albian Asu River Group in the central Benue Trough is discussed in (Nwajide, 2022). The subdivision of the stratigraphic units of the Asu River Group starting from oldest to youngest are Bima, Uomba, Arufu, Gboko (Yandev limestone) and Awe Formations, respectively. The Gboko and Arufu Formations are dominantly limestone units, up to millions of tonnes (Adekeye and Akande, 2002; Nwajide, 2013). Other rock types within the Gboko and Arufu Formations includes dolomite, marl limestone, shale, sandy shale and sandstone. The central Benue is the least studied trough among its peers due to paucity of subsurface data.

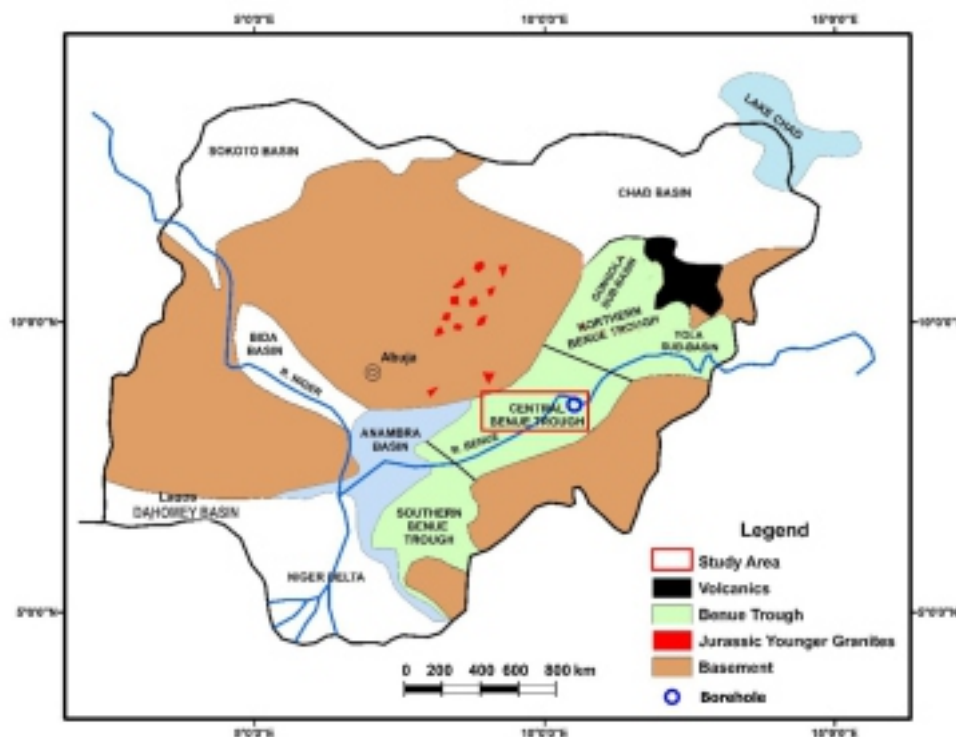
Few works on carbonate studies have been done on the central Benue Trough. Adekeye and

Akande (2002) investigated the carbonate depositional environment, concentrating on the Albian Asu River Group in the area of Yandev in the central Benue Trough. The sedimentary sequence was deposited in a shallow marine environment, according to the integration of lithologic, paleontological, and sedimentologic data (Adekeye and Akande, 2002; Dessauvage, 1968 and Fayose, 1976). Dessauvage (1968) investigated carbonate rocks in Odukpani within the Benue Trough using Foraminifera biostratigraphy. The foraminifera species recovered within the section were few and characterized by planktonic forms. The lack of benthic forms within the section may be as result of anaerobic bottom conditions (Dessauvage, 1968). Akori *et al.* (2022) carried out lithological and organic geochemical analyses on 17 outcrop samples from Gboko Formation in central Benue Trough. The lithologic data display mainly black limestone, bioclastic limestone, shale and muddy limestone facies. Their geochemical investigation revealed a type IV kerogen with a fair to poor source rock quality that are mainly gas prone. A total of 26 representative samples were used by Owonipa *et al.* (2016) from Gboko Formation outcrops in the central Benue Trough. The sedimentary strata were deposited in a shelf lagoonal, shallow marine environment determined from petrographic analysis and fossil evidence. Bolarinwa *et al.* (2013) studied the Tse-Kucha limestone-shale sequence in the Benue Trough. This series is a part of the Albian Asu River Group and was deposited during the Benue Trough's first marine transgressive cycle. The main mineral in the Tse-Kucha limestone, according to the petrographic analysis, is calcite. Akande *et al.* (1988) studied another significant area in the central Benue Trough of Nigeria. They noted that lead-zinc fluorite veins can be found at Arufu and Akwana in the lower Cretaceous (Albian) carbonate sequence of the central Benue Trough. The majority of published papers in the

aforementioned research area are outcrop-based.

Carbonate diagenesis at burial depth of an outcrop data is different from that of core log data. Outcrop data are exposed to subaerial weathering unlike the core log data. In addition, previous investigations in the study area used limited number of methodologies. According to the authors' knowledge, little to no work has adopted core samples including the integration of sedimentological, facies analysis, XRD, XRF, and SEM/EDX data in their study, based on prior research conducted within the central Benue Trough. Existing research has provided valuable insights into the lithology, and geochemistry of carbonate deposits in the central Benue Trough. However, a literature gap exists concerning detailed studies on the mineralogy, depositional environments, diagenetic processes, and paleoenvironmental implications of these carbonate formations. Further research is needed to address these gaps.

The carbonate rocks found in the Yandev well 3004 in the central Benue Trough are continuously and comparatively undisturbed recorded by the core samples used in this investigation area (Figure 1). Sedimentological and facies studies were conducted, incorporating the integration of SEM/EDX, XRD, and XRF techniques to comprehensively assess the textural, mineralogical, elemental, and diagenetic features of the carbonate samples. These techniques aid in the reconstruction of the past environment, identify sediment sources and mineralogical composition as well as the impact of diagenesis on carbonate reservoir quality in hydrocarbon exploration. Lastly, based on the aforementioned methods, this study aims to characterize sedimentological features, mineralogical compositions, and microfacies to infer the depositional environment of the carbonate sediments in the central Benue Trough, Nigeria.



**Figure 1:** Map of Nigeria showing major sedimentary basins and the study area (Modified after Abubakar, 2014 and Aigbadon *et al.*, 2023).

### GEOLOGICAL SETTING OF THE CENTRAL BENUE TROUGH AND SEDIMENTATION HISTORY

The Benue Trough also referred to as the West central African rift system is an intricate rift system whose origin can be traced to the Cretaceous period (Bolarinwa *et al.*, 2022). The Nigerian sector of the Benue Trough which occupies over 1000 km is subdivided into southern, central and northern Benue Troughs, respectively based on geological and geomorphological features (Nwajide, 2013; 2022). The Benue Trough is an intra-cratonic rift structure that presents a northeast-southwest trend and is situated between the northern edge of the Niger Delta and the southern edge of the Chad Basin (Zaborski, 1998; Likkason *et al.*, 2013; Nwajide, 2013). The southern Benue Trough, dangles southwest, and contains two main structural units namely: The N60°E trending Abakaliki Anticlinorium, flanked by the N30°E moving Anambra syncline, with the central Benue Trough possessing a nearly linear pattern in the region of the basin. According to Bolarinwa *et al.* (2013) and Likkason *et al.* (2013), the Asu River Group, a portion of the central Benue Trough (Figure 2 a, b) is characterized by

interbedded marine shaly limestone succession that was deposited during the sedimentation that occurred in the early Albian. The basin has also revealed an increase in carbonate thickness of over 20 m within the Awe Formation. Within the central Benue Trough, the Lafia Formation overlies all the other formation being the youngest (Obaje *et al.*, 1994).

Previous researchers have rendered vivid accounts of the lithostratigraphy of the central Benue Trough (Obaje *et al.*, 1994; Petters, 1982; Offodile and Reymont, 1976 and Offodile, 1976; Figure 2 a, b). The Asu River Group sediments believed to have been sourced during the marine transgression which marked the first depositional cycle in the central Benue region during the early Albian, is the oldest (Figure 2 a, b). For instance, Offodile and Reymont (1976) described the sediments as being rich in fossils such as ammonites and ostracods, respectively. More so, Petters (1982) and Ramanathan and Nair (1984) stated that a large number of calcareous and agglutinated foraminifera species and some ostracods are also found within the sedimentary succession. The Awe Formation, which was deposited during the regression that took place

during the late Albian to early Cenomanian is part of the Asu River Group in the central Benue Trough and reaches a thickness of approximately 200 m. According to Offodile (1976), the 100 m-thickness Awe Formation is made up of clay with an upwards coarsening sequence pattern, consisting of medium to coarse-grained calcareous sandstone, carbonaceous shales, gastropods, and pelecypods, suggesting a transitional environment. The Awe Formation is overlain by the Keana Formation comprising cross-bedded, coarse-grained, feldspathic sandstones that are primarily poorly sorted. Offodile (1976) states that the Keana Formation is non-fossiliferous and comprises conglomerates, shales bands, and limestones intercalations thought to have been deposited in a fluvial environment during the Cenomanian regression episode that affected the central Benue region. The Makurdi Formation is said to be the lateral equivalent of the Keana Formation in the central Benue Trough. The Eze-Aku Formation which unconformably overlies the Keana Formation signifies the commencement of the second depositional cycle that took place between the late Cenomanian to the early Turonian. The stratigraphy of the Eze-Aku Formation is characterized by shaley limestone layers, calcareous shales, and fine to medium-grained, micaceous and friable shales and sandstones, respectively (Offodile, 1976). Offodile and Reyment (1976), also opined that the Eze-Aku Formation is made up of fossils such as ammonites, bivalves, ostracods, and foraminifera, respectively. The Awgu Formation, which lies directly above the Eze-Aku Formation in the

central Benue sector, contains the basal marine deposits that mark the second Turonian-Coniacian depositional cycle. Shaley limestone, calcareous shale, bluish-grey to dark-black carbonaceous shales, siltstones, and coal seams are the sediments that occupy the Awgu Formation (Obaje *et al.*, 1994). The coal accumulation suggests that the depositional environment a swamp. According to Obaje *et al.* (1994), the Awgu Formation presents evidence of an abundance of palynomorph with alternating carbonaceous shales, coaly shales, and coals rich in spores, pollen, and dinoflagellates, respectively (Ariyo, 1987). The Campano-Maastrichtian Enugu Nkporo Formation in the southern Benue Trough is thought to be the lateral equivalent of the Lafia Formation, which thickens toward the southwest and is generally not fossiliferous. (Offodile, 1976).

The northern Benue Trough is separated into the Yola and Gongola arms, with each arm's stratigraphy being stated from oldest to youngest strata (Figure 2 a). In the Gongola arm of the basin, the Fika Shales and the lateral equivalents of the Gongola and Pindiga Formations lie directly on the Yolde Formation. They are distinguished by a mixture of coloured limestone units and dark carbonaceous shale. The Yola arm is made up of the Numanha Shale, Lamja Sandstones, Bima, Yolde, Dukul, Jessu, and Sukuliye Formations. The oldest formation, known as the Bima Formation, is made up of limestones, sandstone, siltstone, shale, and limestones intercalated with dark shaley units (Obaje *et al.*, 1994, 2009).

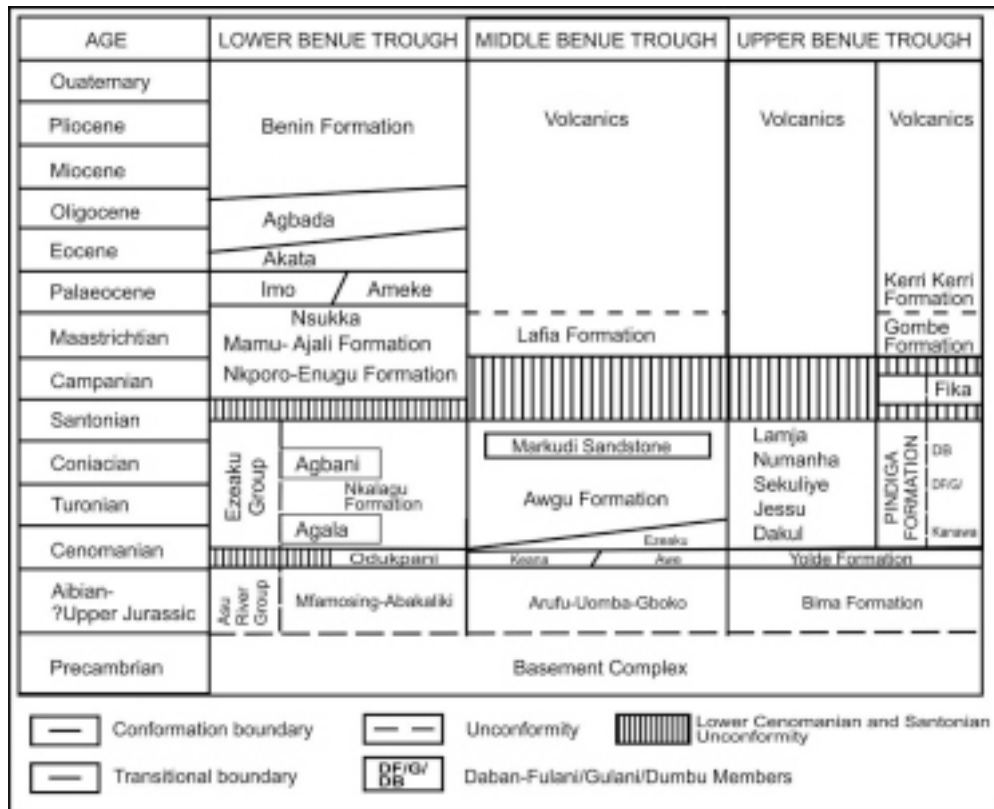


Figure 2a: Stratigraphy of the Benue Trough (Modified after Petters, 1982; Obaje *et al.*, 1994).

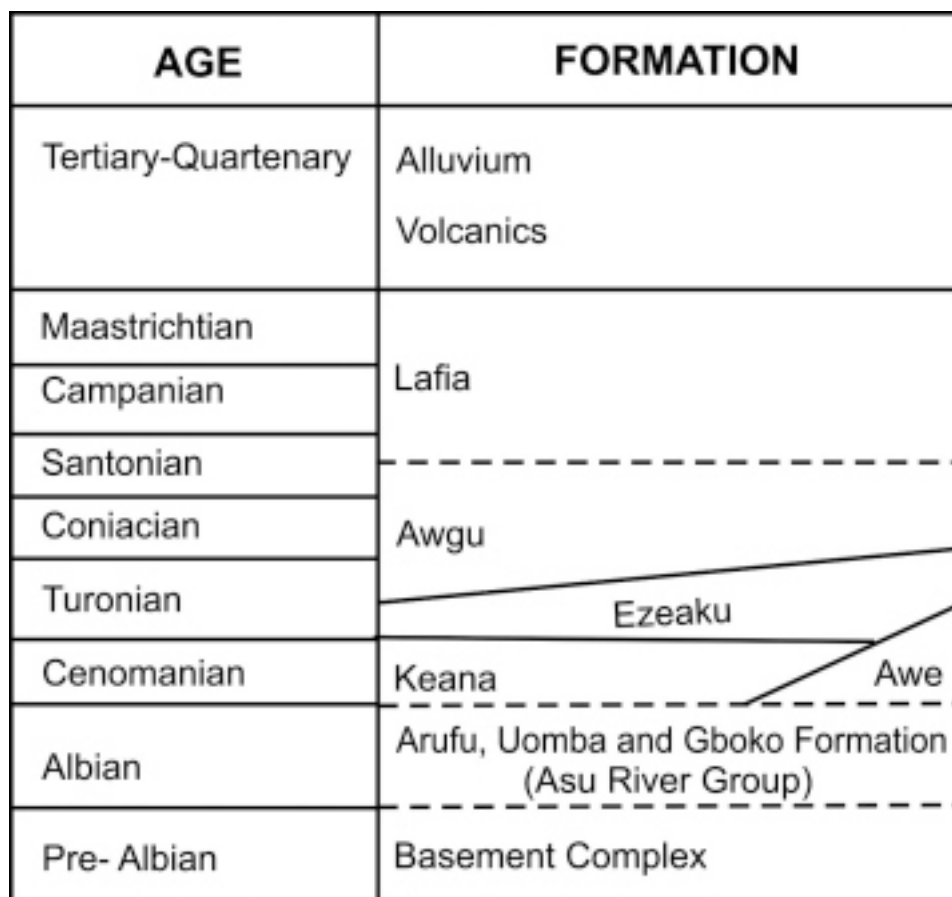


Figure 2b: Stratigraphic successions in the central Benue Trough, Nigeria (from Obaje *et al.*, 1994).



## MATERIALS AND METHODS

Ten core samples from the Asu River Group Formation were used for the current investigation (Figures 1 and 3). The core samples were provided by Nigerian Geological Survey Agency (NGSA), Kaduna, Nigeria. The core samples were collected within a stratigraphic span of 20 to 150 meters in borehole (GSN BH 3004). The spot sampling approach was used to collect the samples. The availability, quality and type of core sample determine the range of sampling intervals, which is 5 to 10 m. The sedimentary formations and lithofacies, colors, and textures of the core samples were identified visually. Sedimentological studies on the core sample were based on the works (Dunham, 1962; Ogbahon *et al.*, 2021). Thin section preparation and slides examination were carried out at the mineralogy laboratory of the Department of Geology, Federal University Lokoja. For petrographic analysis, the samples were fragmented into smaller pieces and then subjected to thin section preparation in the laboratory using standard methods (Ogbahon *et al.*, 2021; Aigbadon *et al.*, 2023). Subsequently, polished thin sections were examined using the Olympus BX41-P polarizing light petrographic microscope, with the aid of the appropriate references mentioned above. The photomicrographs of the petrographic characteristics (texture, structure, composition and degree of alteration) were captured. The 10 carbonate samples were categorized according to the Dunham (1962) classification method. Geochemical analyses were done at the geochemistry laboratory of the Nigerian Geological Survey Agency (NGSA), Kaduna State, Nigeria. The geochemical analyses include X-ray fluorescence (XRF), X-ray diffraction (XRD), and Electron Microscope (SEM) attached with an Energy Dispersive X-ray Spectrometer (EDX). These analyses were carried out on 10

carbonate samples to ascertain their mineralogical, oxide, and elemental makeup after Zhu *et al.* (2020), Ali *et al.* (2021), Ali *et al.* (2023) and Aigbadon *et al.* (2023). To determine the major elemental oxides as well as trace and rare elements within the carbonate samples, pressed powder pellets were prepared and examined using the Xenometrix (IF Genius) X-ray fluorescence spectrometer (Aigbadon *et al.*, 2023). The X-ray diffraction analysis was done by a Rigaku Mineflex 600 X-ray Diffractometer to determine the mineralogical composition of the samples. This technique involved subjecting 50 g of powder samples to X-ray radiation and measuring the resulting diffraction patterns. A Phenom-proX JOEL-JSM 7600F SEM-EDX was employed to examine the structural and elemental characteristics of the carbonate samples. SEM allowed for high-resolution imaging, and EDX provided elemental composition data. SEM-EDX analysis was done after the works of Zhu *et al.* (2020), Ali *et al.* (2021) and Ali *et al.* (2023).

## RESULTS AND DISCUSSION

### Lithological Description

The Asu River Group's core log shows that the stratigraphic layer is mostly made up of limestone, with interbedded shale, sandstones and siltstone beds gradually replacing the carbonate facies at the top of the section. Small light grey calcareous materials can be found locally in the fine-grained, massive to occasionally horizontally laminated shale. The shale ranges in color from light grey to dark grey. The drilled core's limestone facies ranges in color from milky white, light to dark grey with fine to medium-sized grains, and local shell that are occasionally wavy (Figure 3). The facies of the limestone are composed of tabular, cm-thick limestone layers that range in thickness from 0.25 to 0.5 m.

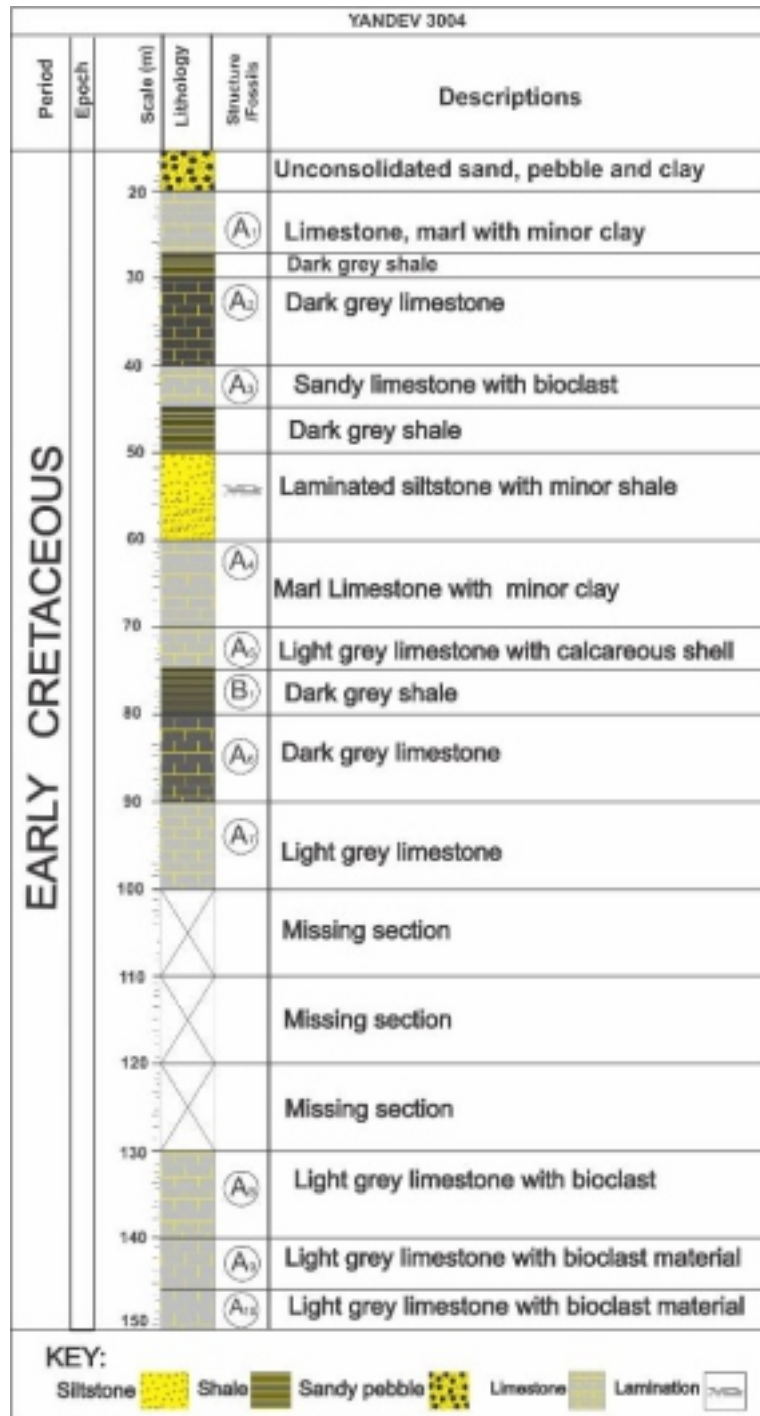
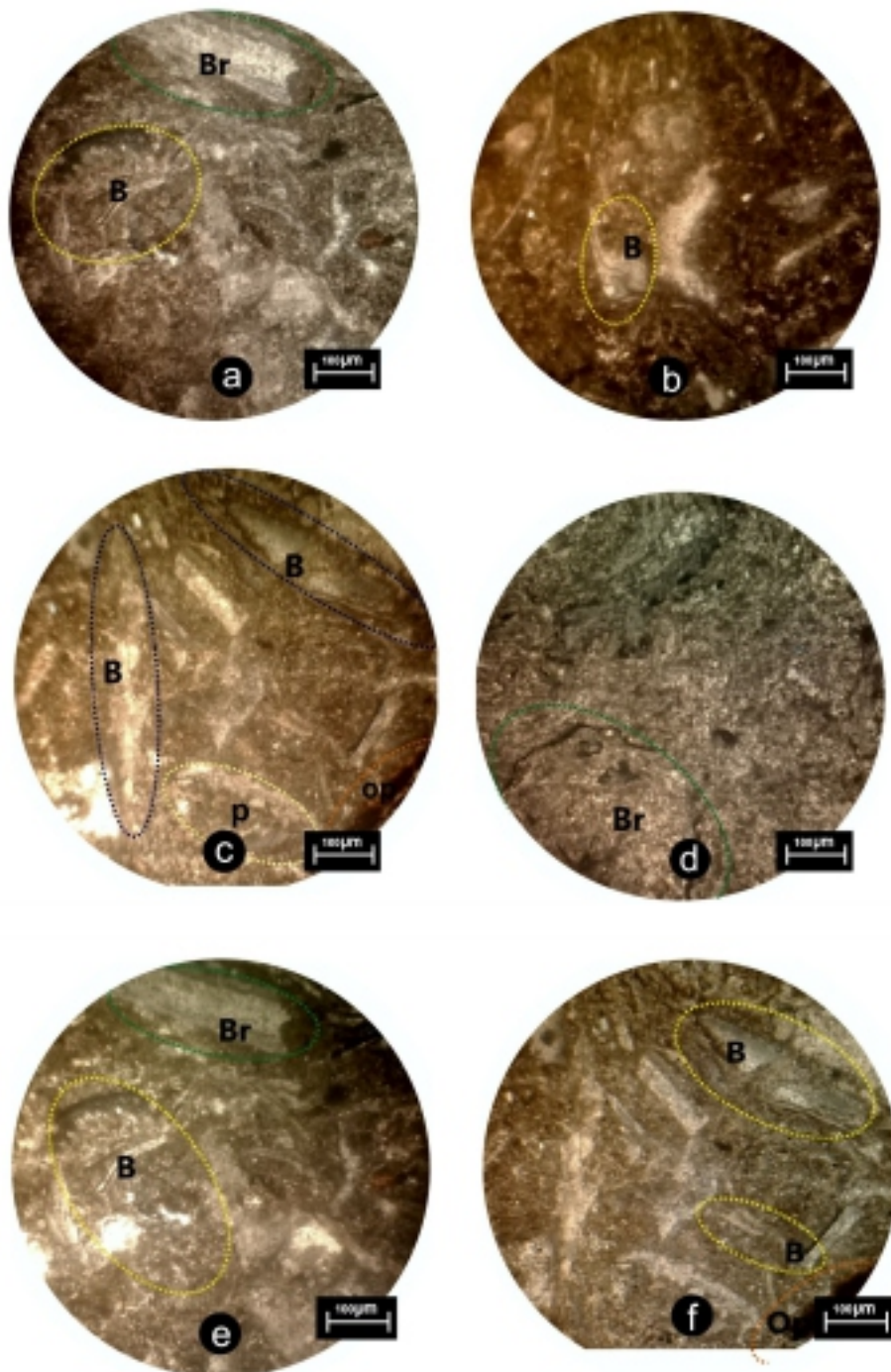


Figure 3: Showing sampled depth for core log 3004 in Yandev, central Benue Trough.

**Microfacies**

**Sandy bioclastic wackestone:** The observations made on photomicrographs in Figure 4 (a, d, e) show it has a sandy texture, with a micritic matrix embedded in it. It also shows the presence of fossils such as brachiopods and bivalves scattered within them. There is also the presence of quartz inclusions.

**Sparitic intraclastic packstone:** The photomicrographs in Figure 4 (b, c, f), show a significant presence of a sparry calcite cement (sparite) within the matrix of the studied samples in the borehole. It also revealed the presence of a considerable number of fossils such as brachiopods, bivalves, ostracods and pelecypods. It also shows small inclusions of quartz within its matrix.

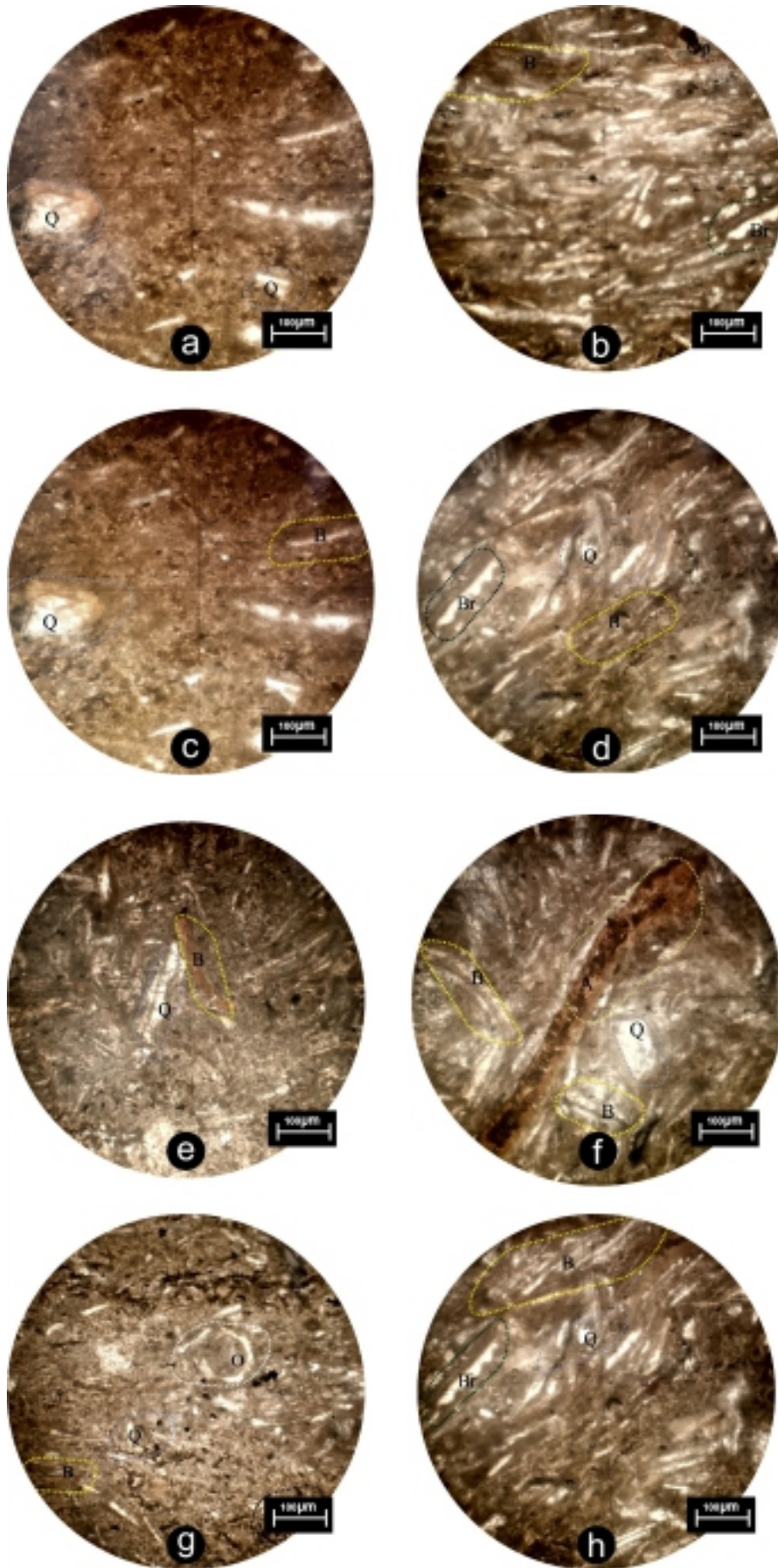


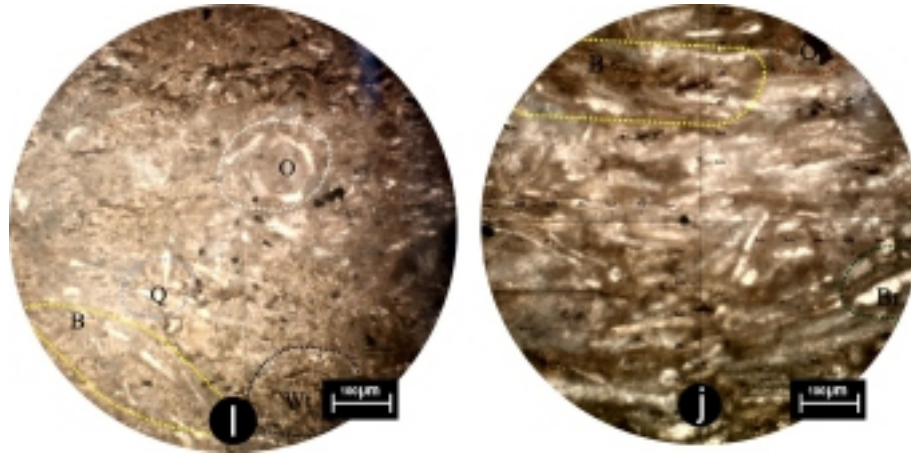
**Figure 4:** Photomicrograph showing the sandy bioclastic wackestone facies (a, d, e); and the sparitic intraclastic packstone (b, c, f). B – Bivalve, Br – Brachiopods, P – Pelecypod, O – Ostracod.

**Micritic intraclastic wackestone:** From the studied core section in borehole 3004, the photomicrographs in Figure 5 (a, c, e, g, i), indicate there is a significant presence of micrite within the sample. There is also the presence of quartz inclusions. Fossils such as brachiopods, bivalves, ostracods, algae and worm tubes can also be observed within the photomicrographs.

**Sparitic bioclastic packstone:** The photomicrographs in Figure 5 (b, d, f, g, j) revealed a significant amount of sparry calcite cement within the matrix of the studied samples. It also revealed the presence of a considerable number of fossils such as algae, brachiopods, bivalves and ostracods. It also shows very little inclusions of quartz within its matrix.







**Figure 5:** Photomicrographs showing the micritic intraclastic wackestone facies (a, c, e, g, i) and sparitic bioclastic packstone facies (b, d, f, g, j). A - Algae, B - Bivalve, Br - Brachiopods, P - Pelecypod, O - Ostracod, Q - Quartz, Wt - Worm tube.

### Mineralogy

Samples from Yandev (A-1 to A-10) in the central Benue Trough underwent a series of geochemical analyses to determine its mineralogy, yielding data

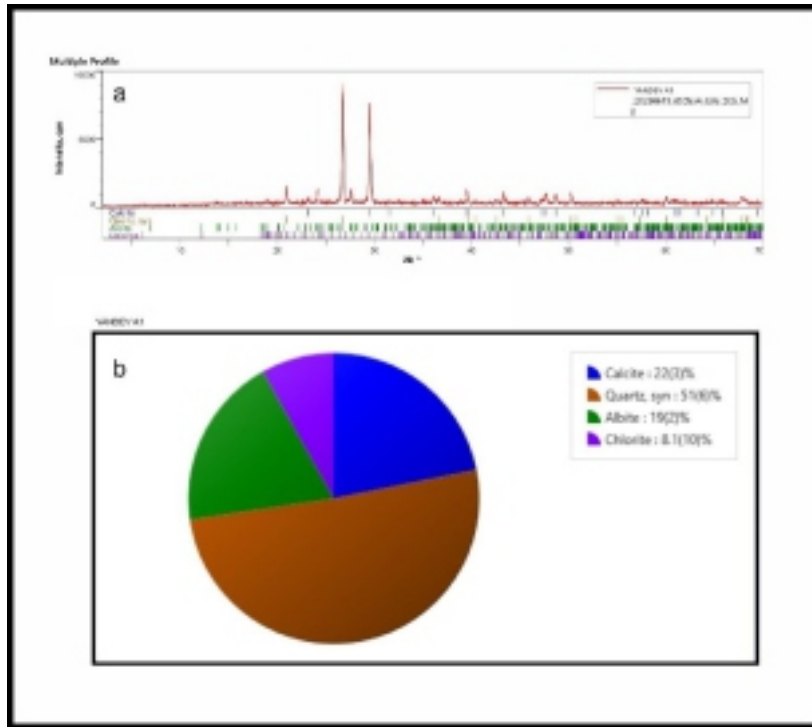
from X-ray diffractometer (XRD), X-ray fluorescence (XRF), and SEM-EDX techniques, the results of which are provided below (Figures 6, 7 and Table 1).

**Table 1:** Results for % XRD mineral composition of limestone from Yandev core log, central Benue Trough, Nigeria.

Sample No	Lithology	Quartz	Calcite	Albite	Chlorite	%Total
A-1	Limestone/Marl	19.00	60.10	12.30	7.90	99.30
A-2	Limestone	18.30	61.00	14.00	6.50	99.80
A-3	Quartz-Limestone	51.00	22.00	19.00	8.00	100.00
A-4	Limestone/Marl	18.00	60.10	15.20	6.30	99.90
A-5	Shelly Limestone	14.30	64.10	14.30	6.90	99.60
A-6	Limestone	15.00	62.10	13.40	9.00	99.50
A-7	Limestone	13.50	62.10	13.50	7.00	99.60
A-8	Limestone with bioclast	14.30	64.10	16.30	7.90	99.10
A-9	Limestone	17.00	60.00	16.30	6.70	100.00
A-10	Marly limestone	18.30	60.20	14.20	6.90	99.60

The XRD mineralogical result revealed that limestone facies ranges between 22.00-64.10% for calcite, Quartz (14.30-51.00%), Albite (12.30-

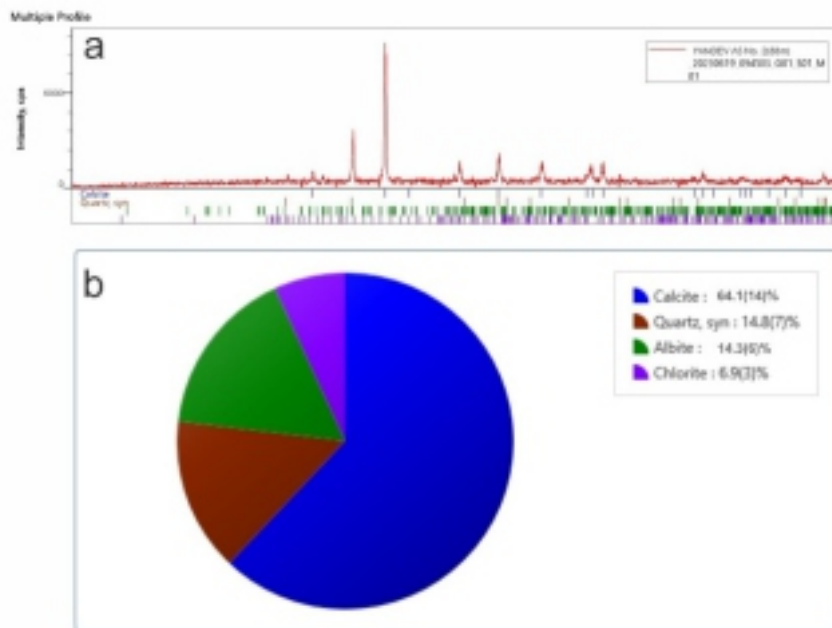
19.00%) and Chlorite (6.30-9.00%), respectively in the studied section (Table 1).



**Figure 6:** XRD Result of Sample A 3 of Yandev from the central Benue Trough.

In the XRD analysis of Sample A 3 from Yandev within the central Benue Trough (Figure 6, Table 1), the results revealed the average concentration of the following minerals indicated proportions: Calcite (22.00%), Quartz (51.00%), Albite

(19.00%) and Chlorite (8.10%). This suggests that quartz is the dominant mineral and the limestone is dominantly sandy material rich in silica materials. It can also be called Quartz-limestone.



**Figure 7:** XRD Result of Sample A 5 of Yandev from the central Benue Trough.

In the XRD analysis of Sample A 5 from Yandev within the central Benue Trough (Figure 7, Table 1), the results revealed that the concentration of the following minerals indicated proportions: Calcite (64.10%), Quartz (14.80%), Albite (14.30%) and Chlorite (6.90%), respectively. It suggests that sample A5 is rich in calcite.

### XRF data

In the central Benue Trough, XRF analyses of the samples have unveiled the presence of major and

minor elements expressed as oxides, as detailed in Table 2. From Yandev core log, the composition by weight percent consists of SiO<sub>2</sub> (28.09-48.00), MnO (0.014-0.09), Fe<sub>2</sub>O<sub>3</sub> (1.80-10.80), CaO (37.00-62.00), MgO (0.00-1.20), Al<sub>2</sub>O<sub>3</sub> (4.00-19.80), and K<sub>2</sub>O (0.01-2.00), P<sub>2</sub>O<sub>5</sub> (0.25-0.50), respectively. The XRF results further complement the XRD values that calcite and silica are the dominant mineral in limestone facies in the studied sections of core logs.

**Table 2:** Major elements composition (in wt. %) of limestone and shales from Yandev, central Benue Trough, Nigeria.

Sample No	Lithology	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	Cl	CaO	MgO	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	wt% Total
A-1	Limestone/Marl	30.22	4.48	4.00	0.015	1.40	58.00	0.00	0.02	0.03	0.45	98.62
A-2	Limestone	31.11	4.59	3.90	0.014	0.41	59.00	0.00	0.01	0.02	0.40	99.09
A-3	Quartz-Limestone	48.00	8.00	7.00	0.02	0.32	37.00	0.00	0.10	0.10	0.50	98.34
A-4	Limestone/Marl	32.10	4.28	3.59	0.03	0.45	59.00	0.00	0.12	0.23	0.25	99.95
A-5	Shelly Limestone	28.09	5.00	1.80	0.05	1.50	62.00	1.20	0.15	0.33	0.28	99.96
A-6	Limestone	29.29	4.00	3.99	0.06	0.60	60.80	0.00	0.16	0.35	0.30	99.52
A-7	Limestone	28.90	4.52	4.89	0.07	1.00	59.80	0.00	0.20	0.38	0.31	99.37
A-8	Limestone with bioclast	28.10	5.49	2.00	0.05	0.03	61.20	1.10	0.13	0.22	0.32	99.44
A-9	Limestone	29.22	5.35	3.20	0.05	1.00	60.20	0.01	0.23	0.30	0.42	99.97
A-10	Marly limestone	30.20	4.47	4.10	0.014	1.41	57.90	0.00	0.03	0.03	0.44	98.63
B1	Shale	47.20	19.80	10.80	0.09	0.90	19.00	0.00	2.00	0.01	0.01	99.00

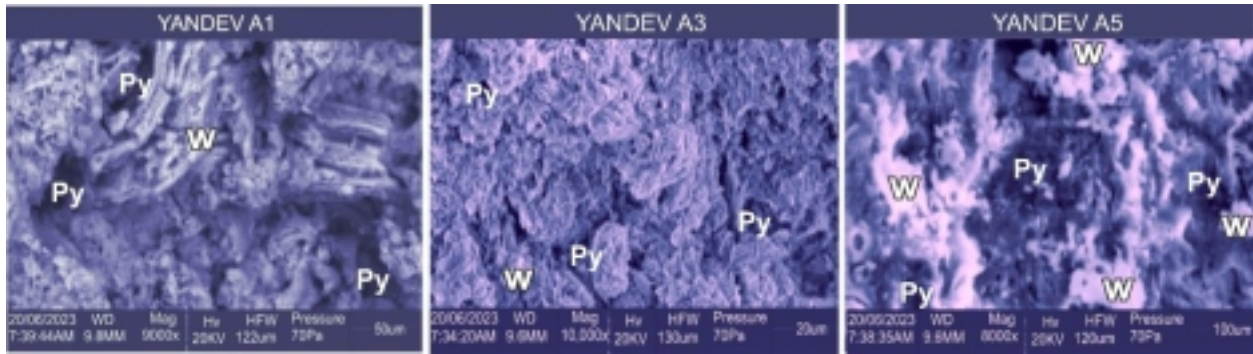
wt- weight percentage

### The SEM-EDX

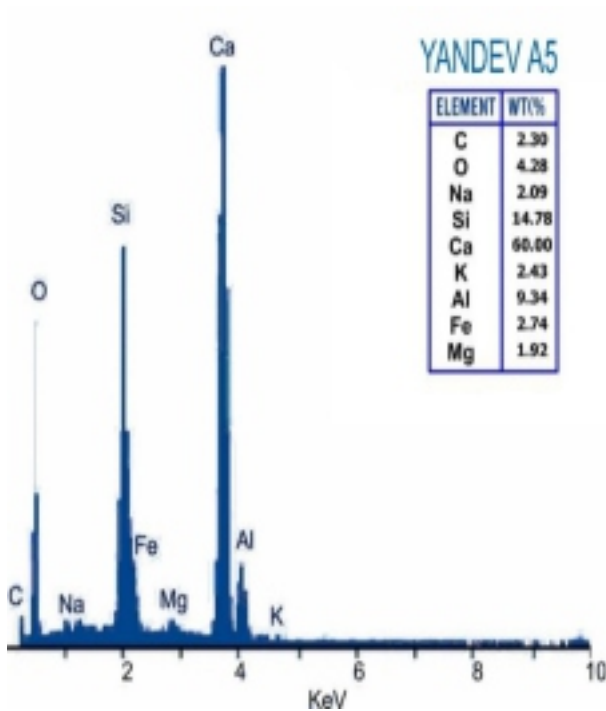
The SEM images from the Yandev core log display a surface characterized by a rough texture, with an indistinct crystal structure (Figure 8). Notably, elongated structures are evident, suggesting a potential alignment or anisotropic nature within the carbonate material. The dark spots (Py) observed in (YANDEV A1-A3) indicate the likely presence of dark minerals (i.e.; pyrite). The thick white spots (W) in YANDEV A1-A3 are likely represent areas of differing composition within the sample, possibly indicating the presence of minerals /materials rich in carbonates. The overall complexity of the composition is suggested by the coexistence of these features; rough texture, lack

of clear crystal structure, elongated structures, and the presence of dark spots; highlighting a diverse and intricate makeup of the observed material. Noteworthy are the presence of elongated structures, implying that certain elements or features within the material are arranged in an elongated pattern, possibly indicative of specific growth patterns or alignment. This diversity in composition, as evidenced by the combination of a rough texture, indistinct crystal structure, elongated structures, and the presence of dark spots, suggests a complex and heterogeneous nature of the carbonate rocks.

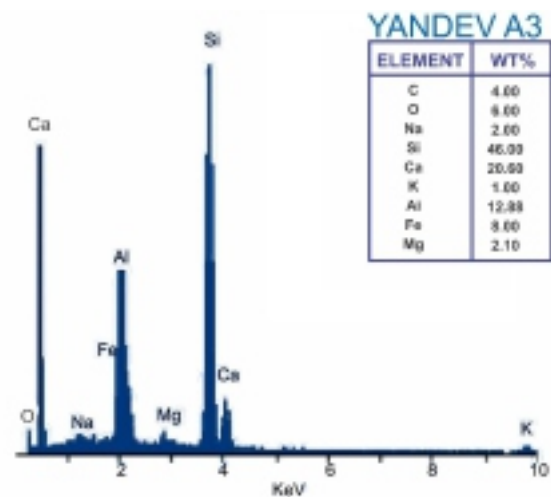




**Figure 8:** SEM images showing structures of samples from Yandev of the central Benue Trough. Py – Pyrite, W – sparry calcite cement.



**Figure 9:** EDX diffractogram showing elemental composition of sample A5 from Yandev area.



**Figure 10:** EDX diffractogram showing elemental composition of sample A3 from Yandev area.

The combination of the energy dispersive X-ray spectroscopy with scanning electron microscopy (SEM-EDX) on samples from Yandev core log has revealed the elemental composition of the major components (Figures 9 and 10), expressed in weight percentages as follows: Carbon (C) (2.30-4.00%), Oxygen (O) (4.28-6.00%), Sodium (Na) (2.00-2.09%), Potassium (K) (1.00-2.43%), with Calcium (Ca) (20.60-60.00%) being the dominant element. Other elements include Silicon (Si) (14.78-46.00%), Aluminum (Al) (9.34-12.88%), Iron (Fe) (2.74-8.00%) and Magnesium

(Mg) (1.92-2.10%), respectively. This detailed breakdown not only provides insights into the elemental makeup of the sample but also emphasizes the significance of Ca, K, Al, Mg and Si, showcasing the diverse and distinctive composition of the analyzed specimen from the Yandev area in central Benue Trough.

## DISCUSSION

The petrographic result provides a detailed insight into the microfacies variations within the Yandev area of central Benue Trough. This revealed that

the petrofacies are sandy bioclastic wackestone and sparitic intraclastic packstone, as well as micritic intraclastic wackestone and sparitic bioclastic packstone, which suggests varying depositional environments and sedimentary processes during the Cretaceous period in the central Benue Trough. The micritic intraclastic wackestone depicts a low energy in shallow marine settings. This supports the works of (Flügel, 1982; Ogbahan *et al.*, 2021). If the carbonate deposits originated in a shelf lagoonal environment, the sparitic bioclastic packstone and sparitic intraclastic packstone indicate that the deposits were created in a shoal and relatively high setting. This supports the research done by Wilson (1975), Nwajide (2013) and Ogbahan *et al.* (2021).

The XRD results revealed that sample A3 (Figure 6) contains majorly Calcite (22%) and Quartz (51%), indicating that the predominance of quartz as an indication that the quartz minerals were reworked and transported (allochthonous) from the neighboring basin to the carbonate deposits in the studied basin (Flügel, 1982). This is evidenced in Figure 3 and this supports that the limestone facies to be classified as sandy bioclastic wackestone in the studied samples (A3). Also, evidence from XRD result of A5 (Figure 7) revealed that Calcite (64%), Quartz (14.8%) both being dominant minerals. The result proves that calcite is the dominant mineral implying that limestone is calcite-rich (autochthonous). SEM images (Figure 8) provided a visual representation of the structural characteristics of the samples from Yandev. The rough texture, indistinct crystal structure, elongated structures, and dark and white spots suggest a heterogeneous composition (Ali *et al.*, 2023). The presence of elongated structures implies specific growth patterns or alignments, adding a layer of complexity to the understanding of the carbonate material. The SEM-EDX revealed C, O<sub>2</sub>, Na, K, Ca, Si, Al, Fe, and Mg were found for each sample. The presence of Mg (1.92-2.10%wt) and Fe (2.74-2.98%wt) revealed little presences of dolomitic limestone and siderites, respectively. The above distinctive compositions revealed by EDX show the diverse nature of the carbonate rocks.

These findings reflect a broader implication for understanding the geological evolution of the

central Benue Trough during the Cretaceous period. The dominance of Calcite and Quartz in the mineralogical composition aligns with typical carbonate rock characteristics and also points to specific diagenetic processes such as cementation and lithification, shaping the carbonate facies of Asu River Group. This corroborates the work of Nwajide (2013).

### **Microfacies Analysis**

The four microfacies analysis of the carbonate rock samples from Yandev in the central Benue Trough provides detailed insights into the internal characteristics of these formations, shedding light on the depositional conditions and the history of the rocks. The identified four distinct microfacies:

***Sandy bioclastic wackestone facies:*** The sandy texture suggests a sedimentary environment with fine to coarser grains. Its micritic matrix indicates the presence of fine-grained carbonate mud, pointing to a calm water environment for deposition. Sandy lithoclasts display a textural variation that may indicate the migration of sediments from high-energy settings over shoals to low-energy settings in the lagoonal settings, likely across a middle-shelf environment (Flügel, 1982). The presence of brachiopods and bivalves signifies a marine environment (Kiel and Peckmann, 2019). These fossils can provide insights into the paleoecology and paleoenvironment of the area. The quartz inclusions suggest contributions from a different source or a transitional environment (Kameda *et al.*, 2014).

***Sparitic intraclastic packstone facies:*** The significant presence of sparry calcite cement indicates diagenetic alteration (Xiong *et al.*, 2016), which can help in understanding the post-depositional processes affecting the rock. The presence of fossils within the matrix, including brachiopods, bivalves, ostracods, and pelecypods, suggests a diverse marine biota and enhances the potential for paleontological analysis and reconstruction of the ancient ecosystem (Kiel and Peckmann, 2019). Similar to the first microfacies, the presence of quartz inclusions also reflects the sediment source to be from transitional to marginal marine settings due to sea level changes and environmental changes (Garber *et al.*, 1987).

***Micritic intraclastic wackestone facies:*** The significant presence of micrite suggests fine-grained carbonate deposition in a low-energy environment (Dunham, 1962). The diverse fossils, including brachiopods, bivalves, ostracods, algae, and worm tubes with good amount of mud support the preservation of these diverse fossils. Lagoonal mud that has been deposited shoreward is reflected in the micritic intraclastic wackestone facies. Worm burrows and the presence of recrystallized micrite to drusy cement are typical indicators of a shallow intertidal environment with low energy (Wilson, 1975).

***Sparitic bioclastic packstone facies:*** Similar to the second microfacies, the sparry calcite cement is indicative of diagenetic processes affecting the rock over time. The matrix with a variety of fossils, including algae, brachiopods, bivalves, and ostracods, suggests a shoal and a relatively high environment with diverse fossil forms (Titus and Cameron, 1976), if the deposition developed in a restricted inner shelf lagoonal environment likely proximal to strandline. This corroborates the works of Wilson (1975), Dalrymple *et al.* (1992) and Nwajide (2013). The small amount of quartz inclusions could reflect environmental changes and the quartz materials are sourced outside the basin.

### Mineralogy

Based on the aforementioned mineral, calcite is the dominant mineral. The calcite often forms from the precipitation of calcium carbonate from water, and the presence of this abundant calcite suggests that these rocks likely originated from calcium-rich marine environments (Lerman and Mackenzie, 2018). The presence of other minerals like quartz, chlorite, and albite, though in smaller proportions, adds complexity to the mineralogical composition. These minerals can provide clues about the geological processes and environmental conditions that influenced the rock's formation. The presence of quartz suggests the influence of siliciclastic input, possibly indicating changes in the depositional environment over time (Kameda *et al.*, 2014).

The X-ray fluorescence (XRF) analysis further emphasized the significance of calcium, with a remarkably high concentration of calcium oxide

(CaO) at 64.10%. This suggests a substantial presence of calcium within the samples. Additionally, the SEM images display a rough texture with elongated structures, potentially indicative of carbonate rocks. The thick spots observed in the SEM images further suggest the likely presence of materials rich in carbonates (Ali *et al.*, 2023). The observed rough texture in the SEM images, lack of clear crystal structure, and the presence of elongated structures further suggest a heterogeneous nature of the carbonate rocks (Ali *et al.*, 2023). The EDX diffractograms (Figures. 9 and 10) provide a detailed breakdown of the elemental composition, with Si comprising (46.00% in Sample A3 and 14.87% in Sample A5). Calcium is a dominant element, constituting 64.00% in Sample A5 and 26.00% in Sample A3. The coexistence of silicon and calcium in substantial percentages strongly supports the interpretation that carbonate rocks, likely in the form of calcitic and sandy carbonate facies which are prevalent in the Yandev samples. The high concentration of calcite is significant, as it not only confirms the calcitic nature of the carbonate facies but also indicates their potential use in various applications (Xu *et al.*, 2023). Calcite is often associated with carbonate sedimentary rocks and can provide valuable information about the history and formation of these deposits. The results from the mineralogical analysis further enhance our understanding of the rock composition and properties of carbonate rocks in the Yandev area of central Benue Trough, Nigeria.

### CONCLUSION

The comprehensive analysis of Cretaceous carbonate rock samples in the central Benue Trough has provided a detailed understanding of the geological and mineralogical characteristics of the limestone facies of the Asu River Group in Yandev area. The study involves the integration of sedimentological, petrography and geochemical methods. The sedimentological reveal that the lithology from the core log showed that the studied stratigraphic unit comprises mainly fine to medium-grained limestone facies. The limestone facies ranges from light to dark grey colours. Other include siltstone, sandstone and dark grey laminated shale facies with periodic calcareous materials at intervals. Based on the sedimentological and petrography data the



limestone facies consist of siliciclastic lime mudstone, bioclastic wackstone as well as bioclastic packstone with skeletal grains of pelecypods, gastropods and mollusca. The carbonate rock, which is supported by lime mud, is rich in preserved gastropod and pelecypod shells. The lack of agglutinated benthic foraminifera and very few ostracods, with no planktonic foraminifera indicates that the environment is shallow marine and shelf lagoonal. The XRF, XRD, and SEM-EDX techniques, provided a comprehensive view of the mineralogical composition, showcasing the prevalence of mineral composition, along with major and minor elements expressed as oxides. SEM images added a visual dimension, emphasizing the heterogeneous nature of the samples with rough textures, elongated structures, and dark spots suggesting varying material compositions. The XRD and XRF results further confirmed the dominance of calcite and quartz in the mineralogical makeup of the samples. Moreover, geochemical analysis unveiled the mineralogical and elemental compositions, contributing to a comprehensive characterization of the carbonate sediments. Integration of sedimentological, biofacies, lithofacies, and geochemical evidence led to the conclusion that these carbonate sediments were predominantly deposited in a shallow marine environment, ranging from inner to outer neritic zones. Overall, this study significantly advances our knowledge of the Cretaceous limestone facies in the central Benue Trough, providing essential data for future exploration and development efforts in the region.

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#### CONFLICT OF INTEREST

The authors state that none of their known financial conflicts or interpersonal connections could have influenced the work that was published in this paper.

#### STATEMENT OF DATA AVAILABILITY

The authors obtained all of the data utilized in this study, and upon request, they are willing to make the data available.

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