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Carbonate Facies and Depositional Environment of the Kalambaina Formation, Sokoto Basin, Northwestern Nigeria

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Abstract
The Kalambaina Formation, part of the Paleocene Sokoto Group in the Iullemmeden Basin, represents a critical stratigraphic unit for understanding shallow marine sedimentation in northwest Nigeria. This study aims to characterize the lithologic, stratigraphic, and petrographic features of the formation to infer its depositional environment and economic significance. Field investigations were conducted across four key localities to document lithologic successions, while thin-section petrography was performed to identify microfacies and matrix composition. Results reveal a consistent vertical sequence of phosphatic shale overlain by fossiliferous limestone at all localities, suggesting a marine transgressive system. At Locality 1, the basal phosphatic shale transitions sharply into a 1.2m fossiliferous limestone, indicating a rapid environmental shift. Locality 2 shows a gradational boundary between a 3.5m shale unit and a 3m limestone, indicative of continuous transgression. Thin-section analysis classifies the limestone as biomicrite and wackestone adapting Folk and Dunham's classifications respectively. Micrite are micro crystalline carbonate having major or only rock component while wackestone are depositional textures that contains carbonate mud of greater than 10% grains. Fossil assemblages, including Elphidium Crispum and Endothyra, confirm deposition in low-energy intertidal to subtidal zones. The findings suggest that the Kalambaina Formation was deposited in a shallow marine carbonate platform influenced by periodic transgressive-regressive cycles. The phosphatic shales, with potential as hydrocarbon source rocks, and the porous fossiliferous limestones, indicative of reservoir potential, highlight the formation's economic importance. Comparisons with analogous systems in the Tarim Basin and Zagros Foreland Basin reinforce its role in regional sedimentary processes. This study provides new insights into the stratigraphic and paleoenvironmental evolution of the Kalambaina Formation, offering a framework for future hydrocarbon exploration and geological research in the Iullemmeden Basin.

Keywords: Kalambaina Formation, microfacies, wackestone, limestone, transgressive system tract

1.0 Introduction

Recent geological studies have focused a lot of interest on the Sokoto Basin, which is a subdivision of the Iullemmeden Basin in Northwestern Nigeria, because of its hydrocarbon potential and variety of lithostratigraphic units. Spanning several geological periods, this basin contains formations that are valuable for understanding sedimentary processes, depositional environments, and petroleum systems. Among these formations, the Kalambaina Formation stands out as a significant carbonate unit with implications for hydrocarbon reservoir potential and paleoclimate reconstructions. Outlining the distinctive features and depositional environments of the sedimentary units in the Sokoto Basin has been

the main goal of recent research. Yelwa et al. (2015) and Yelwa et al. (2022) conducted extensive research on the Maastrichtian deposits, utilizing field observations and petrographic analysis to reconstruct depositional environments. Similarly, Toyin et al. (2015) examined the microfacies distribution and diagenetic processes affecting the Kalambaina limestones, providing insights into their reservoir potential. Studies by Kogbe (1979); Kogbe (1981); Obaje et al. (2013) and Obaje al. (2019) have contributed significantly to the stratigraphic and petroleum system characterization of the Sokoto Basin, identifying it as a promising region for hydrocarbon exploration. The Kalambaina Formation was more recently recognized as a possible carbonate reservoir (Obaje et al. 2023), who emphasized the necessity of a thorough facies analysis to comprehend its depositional environment and resource potential.

Carbonate sediments, such as those in the Kalambaina Formation, are highly sensitive to environmental fluctuations and depositional processes. Their sedimentation is rapid under favorable conditions, driven by biological, chemical, and detrital mechanisms (Ham and Pray 1962). However, unfavorable conditions can halt carbonate deposition entirely. The textural characteristics of carbonate rocks, often dictated by the nature of skeletal grains, play a vital role in determining their diagenetic pathways and reservoir quality. Processes such as dissolution, cementation, recrystallization, and replacement can significantly alter the original fabric of these sediments, influencing their utility as reservoirs. Moreover, biofacies and lithofacies correlations highlight the role of organisms in shaping lithologic characteristics, with substrate conditions and water energy levels acting as critical controls on carbonate deposition.
The Kalambaina Formation, located within the Sokoto Basin, is predominantly a carbonate unit comprising marly limestones rich in fossil content. Its depositional environment has been interpreted as a shallow marine setting influenced by intertidal and supratidal processes during transgressive system tracts. These environments are associated with lagoonal settings and low-energy conditions, which favor the accumulation of fine-grained carbonate sediments. The presence of bioclastic wackestones and mudstones further underscores the restricted nature of the depositional environment (Dunham 1962; Folk 1962). Comparative studies using standard facies models, such as Wilson (1975) and Flugel (2004), have suggested that the Kalambaina Formation corresponds to specific standard microfacies types (SMF 16, 23), indicating lime mudstones and wackestones with bioclastic components.

Despite extensive research on the Sokoto Basin, gaps remain in understanding the precise depositional mechanisms and their implications for resource exploration. Previous studies have primarily focused on the lithostratigraphic and paleontological characteristics of the basin, with limited emphasis on the statistical validation of facies distribution or their relationship to regional tectonics and paleoenvironmental changes. Furthermore, while the Kalambaina Formation has been recognized as a potential hydrocarbon reservoir, the microfacies and sequence stratigraphy of this unit require further analysis to elucidate its reservoir quality and depositional history. Thereby conducting a thorough carbonate facies evaluation of the Kalambaina Formation in Kumshiyawa Village, Sokoto Basin, this study seeks to close these gaps. By integrating field observations, petrographic thin-section analysis, and established classification systems, we reconstruct the depositional settings and sequence tracts within this carbonate platform. With implications for paleoclimate reconstructions and hydrocarbon development, the findings advance our knowledge of the sedimentary and diagenetic processes that shaped the Kalambaina Formation.

1.1 Geological Setting

A noteworthy sedimentary province in Northwestern Nigeria is the Sokoto Basin, which is a section of the larger Iullemmeden Basin. A series of sedimentary strata that date from the Cretaceous to the Tertiary define this basin, and these Formations have been extensively studied in stratigraphic and paleontological research (Kogbe 1979; Obaje et al. 2013; Yelwa et al. 2015; Obaje et al. 2019). The stratigraphy of the Sokoto Basin reflects a complex depositional history shaped by marine transgressions, regressions, and fluvial processes, as illustrated in Figure 1. The pre-Maastrichtian Continental Intercalaire, comprising the Illo and Gundumi Formations, forms the basal unit of the stratigraphic succession in the Sokoto Basin. These formations are predominantly continental deposits, consisting of sandstones and minor clays, indicative of fluvial to deltaic environments (Obaje et al. 2019). The Taloka and Wurno Formations, which are composed of mudstones and friable sandstones, respectively, define the Maastrichtian Rima Group, which sits on top of this basal unit. Between the Taloka and Wurno Formations, the fossil-rich Dukamaje Formation, which is made up of calcareous and shaley deposits, lies unconformably, indicating a major marine transgression (Kogbe 1981; Adamu et al. 2020).

The Dange, Kalambaina, and Gamba Formations make up the Paleocene Sokoto Group, which comes after the Maastrichtian Rima Group. The Kalambaina Formation, the main subject of this study, is made up of calcareous limestone with a high fossil concentration, whereas the Dange and Gamba Formations are mostly made up of shales.

The Kalambaina Formation has been interpreted as a shallow marine carbonate platform deposited during a period of marine transgression (Yelwa et al. 2022; Obaje et al. 2023). Its lithology includes marls and bioclastic wackestones; plays role in understanding the reservoir quality and the environment of deposition in the region.

Above these units lies the Eocene Gwandu Formation, which constitutes the continental terminal deposits of the Sokoto Basin. This Formation is primarily composed of fluvial sandstones and clays, representing the final phase of sedimentation in the Sokoto basin (Kogbe 1979). The Sokoto Basin's stratigraphic units typically dip gently toward the northwest before gradually thickening in the Niger Republic, where they reach their greatest thickness (Obaje et al. 2019). Figure 1 depicts the stratigraphic succession in the Nigerian sector of the Iullemmeden Basin, highlighting the vertical arrangement and geological relationships among these Formations. The figure emphasizes the Kalambaina Formation's position within the stratigraphic sequence, underscoring its importance in understanding the basin's depositional history.

The Kalambaina Formation, the focus of this study, is predominantly composed of marly limestones interbedded with shales and is widely recognized for its fossiliferous content, including bivalves, gastropods, brachiopods, and echinoids. These fossils not only provide valuable insights into the depositional environment but also contribute to the formation's hydrocarbon reservoir potential. The limestone units of the Kalambaina Formation are typically yellowish to grey and exhibit varying degrees of fossil preservation and cementation. Petrographic analysis has revealed that calcite minerals ($CaCO_3$) dominate the composition, often accompanied by micrite, sparite, and bioclastic fragments. Geological mapping and previous studies indicate that the Kalambaina Formation represents a shallow marine depositional environment associated with transgressive system tracts. This setting is consistent with low-energy conditions, such as those found in lagoons or intertidal zones, where fine-grained carbonate sediments accumulate. The paleogeography of the Sokoto Basin during the Paleocene suggests a landward movement of the shoreline, which facilitated the deposition of carbonate and clastic sequences in a dynamic interplay of marine and terrestrial influences. Sokoto Basin's deposition patterns have been largely regulated by the tectonic structure of the Iullemmeden Basin.

The basin experienced periods of subsidence, creating accommodation space for the deposition of thick sedimentary sequences. Outcrops and exposed sections of the Goronyo–Taloka route have revealed some folded and inverted fault structures (Ibrahim et al. 2023). It is inferred that the strike-slip faults and basin inversions have influenced the main faults that control the Sokoto Basin (Ibrahim et al. 2023; Hamidu et al. 2023). Regional tectonics also influenced the distribution and preservation of carbonate facies, contributing to the development of potential hydrocarbon reservoirs within the basin. Therefore, folding and faulting, which have been observed in some parts of the Sokoto Basin, are indicators of post-depositional deformation and could have an impact on reservoir quality and the pathways of migration of hydrocarbons. In summary, the Sokoto Basin provides an excellent natural laboratory for studying sedimentary processes and carbonate facies. With its unique lithological and paleontological features, the Kalambaina Formation provides important new information about how depositional and diagenetic processes interact. Understanding these features is essential for reconstructing the basin's geological history and evaluating its hydrocarbon potential.

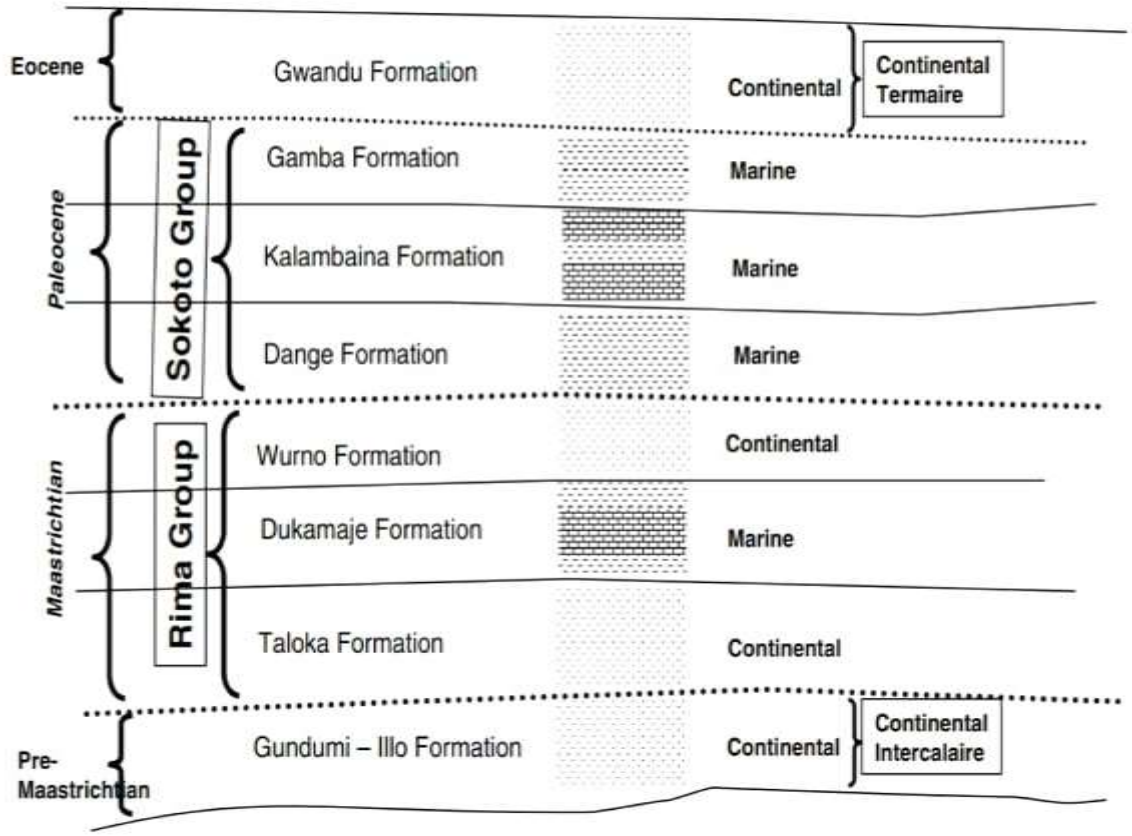


Fig. 1: Stratigraphic sequence in the Nigerian sector of the Iullemmeden Basin (Sokoto Basin). Modified from (Obaje et al. 2006)

1.2 Study Area

The study was carried out in Kumshiyawa Village and the surrounding area, which is located in Northwestern Nigeria's Sokoto Basin. The area under discussion is roughly 25 km² in size and is bordered by latitudes 13° 32′ 00″ N to 13° 36′ 26.7″ N and longitudes 5° 39′ 42.2″ E to 5° 42′ 22.7″ E. This area is a portion of the wider Iullemmeden Basin, which is distinguished by a series of Cretaceous to Tertiary sedimentary strata. Kalambaina Formation, the subject of the present study, is one of the stratigraphic and petroleum potentialities of the Sokoto Basin which had been emphasized in earlier studies (Kogbe 1979; Obaje et al. 2013; Obaje et al. 2019; Yelwa et al. 2022). A 1:25,000 scale topographic base map was used to create the study area map (Fig. 2). It illustrates the distribution of geological units and outcrop locations, forming the basis for detailed field observations.

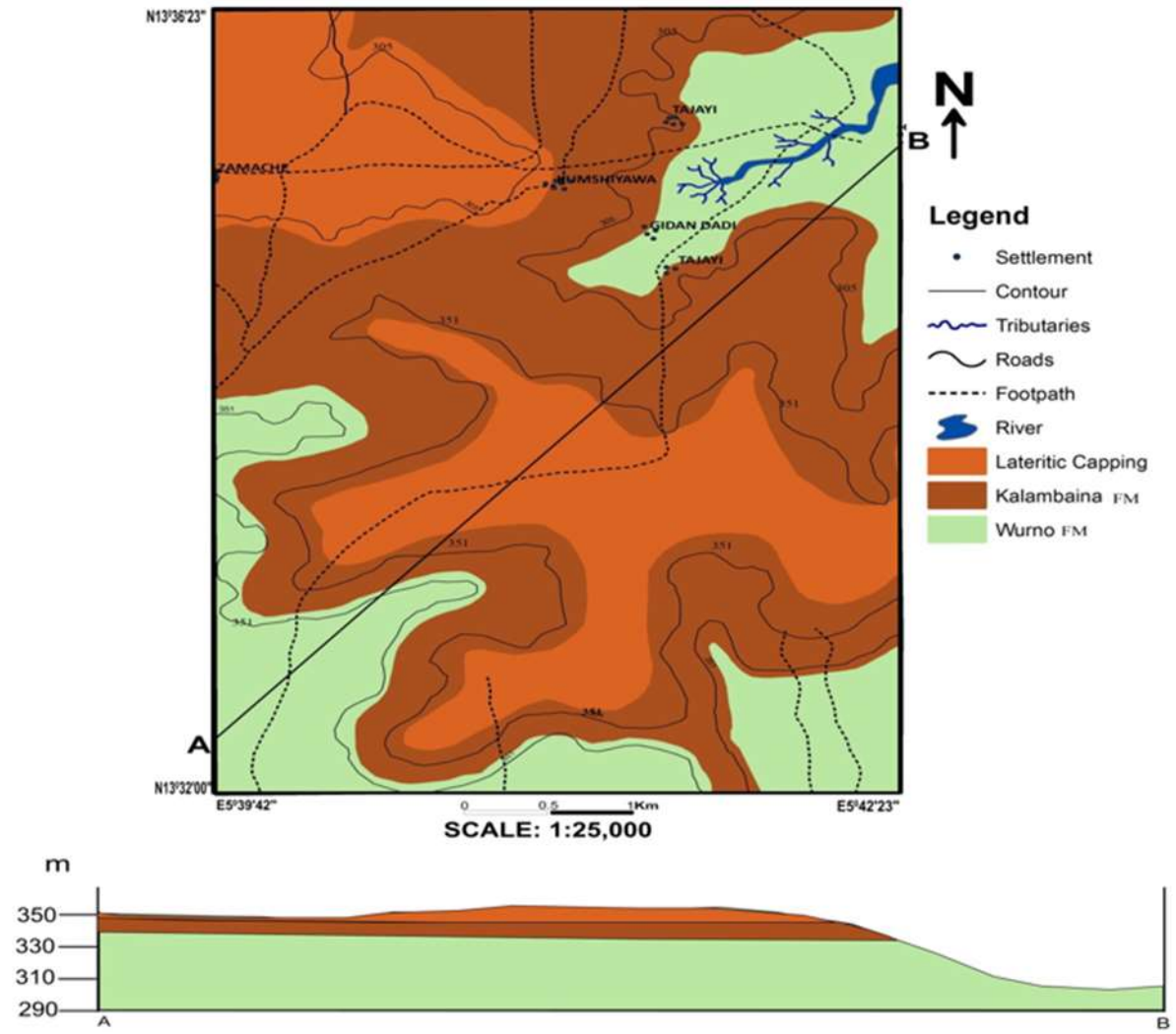


Fig. 2: Geological map of Kumshiyawa Village and environs, showing lithologic units and sampling locations (Part of Sheet 4 Sokoto SW).

2.0 Materials and methods

This section outlines the procedures and techniques adopted to analyze the lithologic, stratigraphic, and depositional characteristics of the Kalambaina Formation. The research integrates field investigations, sample collection, laboratory analyses, and data interpretation to re-establish the depositional environment and to figure out the geological vitality of the Kalambaina Formation.

A combination of qualitative and quantitative approaches ensures a comprehensive analysis of the study area. Each methodological step is detailed below to maintain transparency and reproducibility.

2.1 Fieldwork

Field investigations undertaken include detailed geological mapping, stratigraphic logging, and rock sampling at key outcrop locations. Observations included:

- Lithologic characteristics such as color, texture, grain size, and thickness.
- Sedimentary structures indicative of depositional processes.
- Fossil content and distribution, providing insights into paleoenvironmental conditions.
- Vertical and lateral stratigraphic relationships among lithologic units.

Stratigraphic logs were constructed to document vertical successions and identify key surfaces such as transgressive surfaces and unconformities (Adamu et al. 2020; Obaje et al. 2023; Zhu et al. 2023). Geospatial data were recorded

using handheld GPS devices to create a geological map, integrating field observations and lithostratigraphic relationships (Abubakar et al. 2023; Maju-Oyovwikowhe and Okudibie 2023).

2.1.1 Sample Collection

Fifteen (15) representative rock samples were collected from limestone and shale units to cover all lithologic variations. Sampling focused on:

- Fossiliferous zones to examine faunal content.
- Transitional contacts between lithologic units to capture depositional changes.
- Well-preserved outcrop sections to assess sedimentary textures and diagenetic features.

These samples were selected to assess the microfacies, cementation, and depositional characteristics of the Kalambaina Formation (Wilson 1975; Flugel 2004; Nikfard et al. 2023).

2.2 Laboratory Analysis

2.2.1 Thin-Section Preparation:

Rock samples were processed into thin sections following standard petrographic techniques to examine mineralogical and textural characteristics. The thin sections provided insights into matrix composition, grain types, and cementation features (Dunham 1962; Folk 1962; Zhu et al. 2023).

2.2.2 Petrographic Analysis:

Petrographic examinations were conducted using a polarizing microscope. Observations included:

- Identification of skeletal grains (e.g., bioclasts, peloids, intraclasts) and matrix types (micrite or sparite).
- Classification of textures as mud-supported or grain-supported.

Classification systems by Dunham (1962) and Folk (1962) were applied to categorize depositional textures, supported by quantitative point counting to validate microfacies distributions (Agustin et al. 2023; Maju-Oyovwikowhe and Owenvbiugie 2023).

2.2.3 Facies Analysis:

Microfacies data were correlated with standard facies models by Wilson (1975) and Flugel (2004) to infer depositional environments and system tracts. These analyses enabled the reconstruction of paleoenvironmental conditions and the depositional history of the Kalambaina Formation (Nikfard et al. 2023; Obaje et al. 2019).

3.0 Result and Discussion

The results and discussion section integrates field observations, petrographic analysis, and geological interpretations to elucidate the lithologic, stratigraphic, and depositional attributes of the Kalambaina Formation. These findings shed light on the microfacies, depositional settings, and hydrocarbon potential of the Sokoto Basin.

3.1 Results

3.1.1 Field and Lithological Description

Stratigraphic logs from field observations were correlated to identify vertical and lateral continuity of lithologic units (Fig. 3, Fig. 5, Fig. 6, and Fig. 7). Key surfaces such as transgressive surfaces and sequence boundaries were analyzed to infer sequence stratigraphic frameworks (Yelwa et al. 2022; Obaje et al. 2023; Zhu and Dong 2023).

3.1.1.1 Locality 1 (13° 32′ 25.1″ N, 05° 41′ 21″ E)

The first outcrop at 13° 32′ 25.1″ N and 05° 41′ 21″ E is composed of phosphatic fissile shale at the base. The shale, grey in color, is approximately 0.5 m thick but increases to about 1 m in the eastward direction. It becomes more fissile and includes intercalations of siltstone folded in a synformal pattern. The shale is fine-grained.

Overlying the shale is a whitish limestone layer, about 1.2 m thick. This limestone is highly fossiliferous, with fossils including bivalves, brachiopods, gastropods, and echinoids. The stratigraphic relationships observed at this location are illustrated in Fig. 3, while the exposure of the limestone-shale contact is shown in Fig. 4.

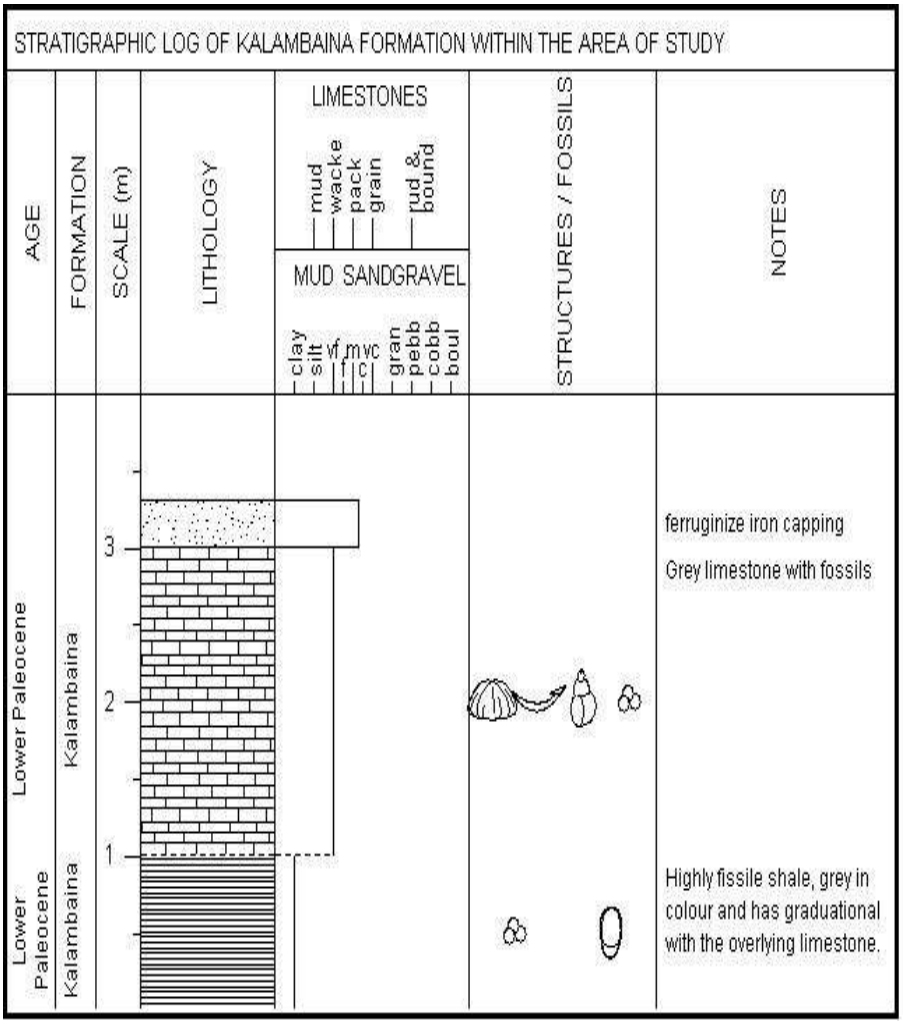


Fig. 3: Stratigraphic log of the Kalambaina Formation at Locality 1 (13° 32′ 25.1″ N, 05° 41′ 21″ E).



Fig. 4: Exposure of fossiliferous limestone overlying phosphatic shale with intercalated siltstone at Locality 1 (13° 32′ 25.1″ N, 05° 41′ 21″ E).

3.1.1.2 Locality 2 (13° 32′ 36″ N, 05° 41′ 22″ E)

The second outcrop at 13° 32′ 36″ N and 05° 41′ 22″ E comprises a shale layer 3.5 m thick, overlain by a limestone layer approximately 3m thick. The boundary between these lithologic units is gradational, indicating a transition from fine-grained siliciclastic deposition to carbonate sedimentation.

The topmost part of the limestone is capped by lateritic material. Fossils observed include bivalves, brachiopods, gastropods, and echinoids. These relationships are represented in Fig. 5.

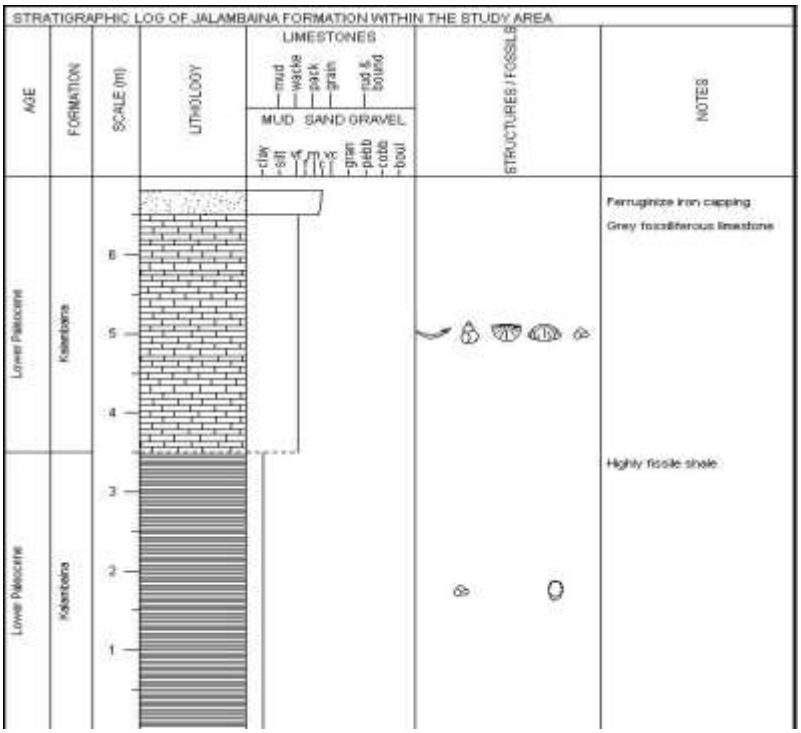


Fig. 5: Stratigraphic log of the Kalambaina Formation at Locality 2 (13° 32′ 36″ N, 05° 41′ 22″ E).

3.1.1.3 Locality 3 (13° 32′ 21.4″ N, 05° 40′ 38.7″ E)

The third location at 13° 32′ 21.4″ N and 05° 40′ 38.7″ E consists of 2m of fissile shale, overlain by 2 m of grey fossiliferous limestone. A ferruginized siltstone cap overlies the limestone, marking a sharp boundary.

The boundary between the shale and limestone is gradational, while the transition to the ferruginized siltstone cap is sharp. Fossils observed in the limestone include bivalves, brachiopods, gastropods, and echinoids. The stratigraphic log for this location is shown in Fig. 6.

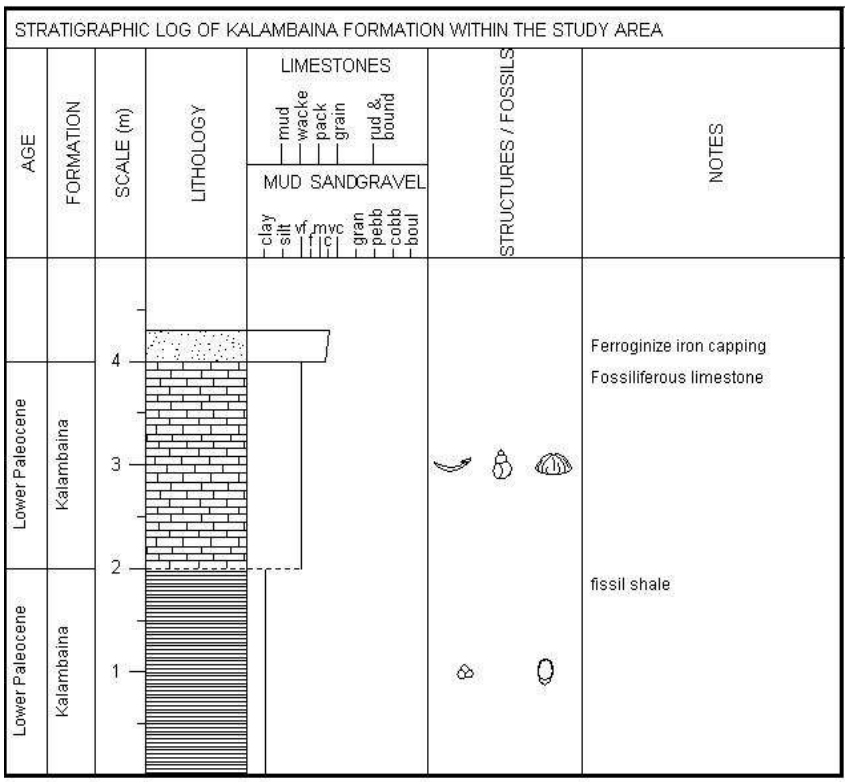


Fig. 6: Stratigraphic log of the Kalambaina Formation at Locality 3 (13° 32′ 21.4″ N, 05° 40′ 38.7″ E).

3.1.1.4 Locality 4 (13° 35′ 03.4″ N, 05° 41′ 59.3″ E)

The fourth location at 13° 35′ 03.4″ N and 05° 41′ 59.3″ E is composed of 2 m of ash-grey shale, overlain by 1 m of limestone. The topmost layer is 0.8 m of silty clay. The shale-limestone contact is sharp, whereas the limestone-silty clay transition is gradational. Fossils observed in the limestone include bivalves, brachiopods, gastropods, and echinoids. The stratigraphic sequence is represented in Fig. 7.

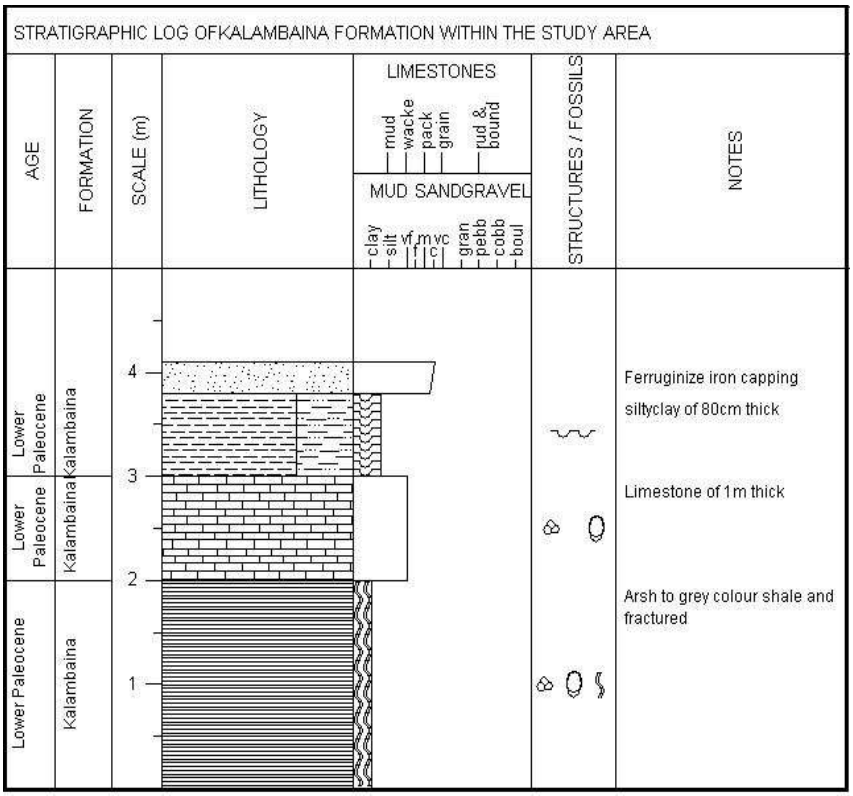


Fig. 7: Stratigraphic log of the Kalambaina Formation at Locality 4 (13° 35′ 03.4″ N, 05° 41′ 59.3″ E).

3.1.2 Geospatial Mapping

Data from field observations and GPS measurements were integrated into a GIS-based geological map (Fig. 2). This map visually represents the spatial distribution of lithostratigraphic units, facilitating a clearer understanding of the study area's geological architecture (Abubakar et al. 2023; Maju-Oyovwikowhe and Okudibie 2023).

3.1.3 Quantitative Petrography:

Point counting was performed on thin sections to determine the relative proportions of grains, matrix, and cement. This provided a quantitative basis for microfacies classification and depositional environment interpretations (Folk 1962; Flugel 2004; Adamu et al. 2020). The matrix of the Kalambaina Formation is primarily mud-supported, with a micritic composition and minimal grain content. The texture varies between mudstone and wackestone.

3.1.4 Fossil Content

Skeletal bioclasts observed include Elphidium Crispum and Endothyra, both of which suggest a low-energy depositional environment (Reyment 1980). These features are highlighted in thin-section images (Figs 8 and 9).

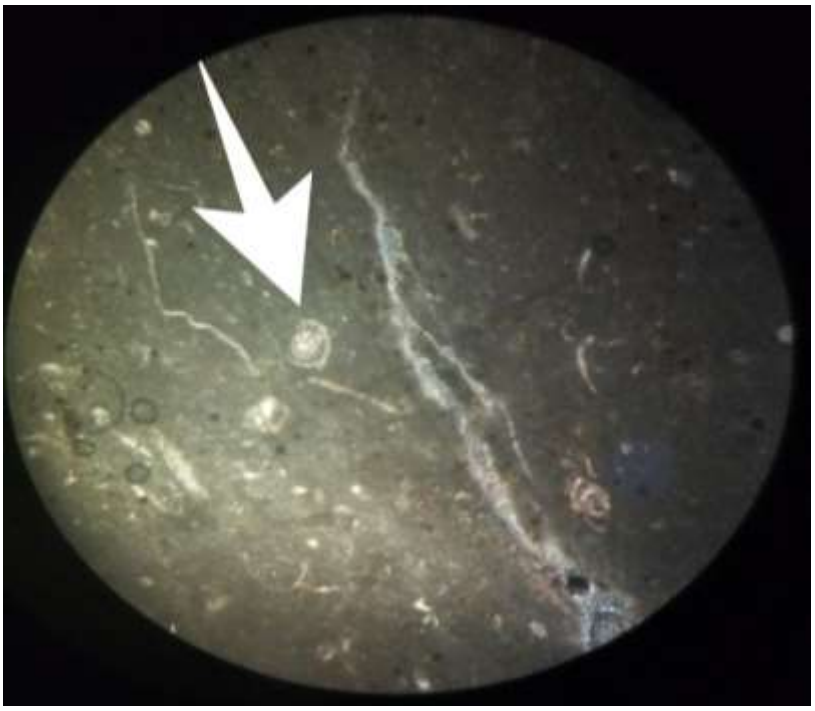


Fig. 8: Thin-section showing Elphidium Crispum species (Locality 1: 13° 32′ 25.1″ N, 05° 41′ 21″ E).

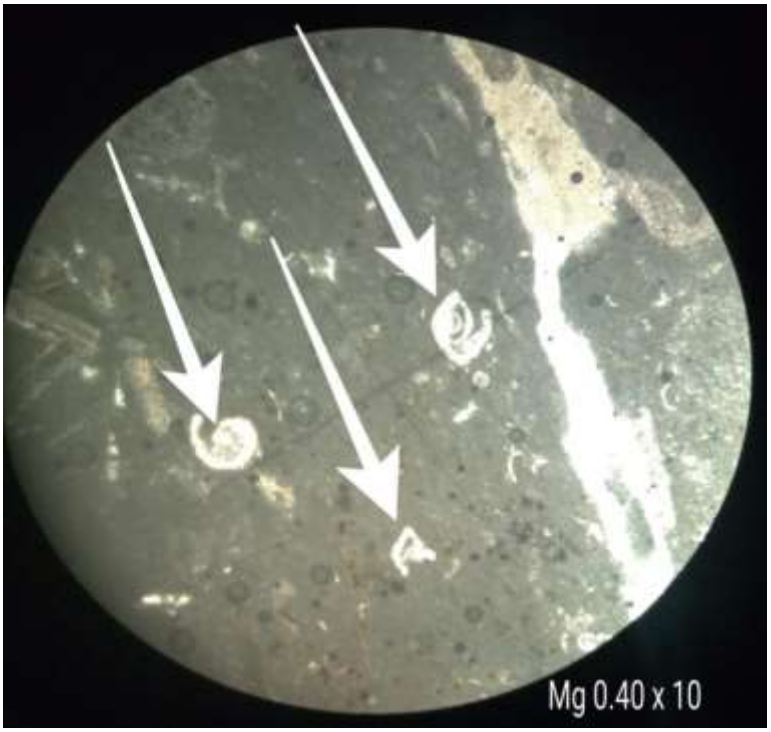


Fig. 9: Thin-section showing Endothyra species (Locality 1: 13° 32′ 25.1″ N, 05° 41′ 21″ E).

3.1.5 Grain Types

Grain types include bioclasts, peloids, and intraclasts, classifying the Kumshiyawa Kalambaina Formation as biomicrite. These features are depicted in the thin-section (Fig. 10).

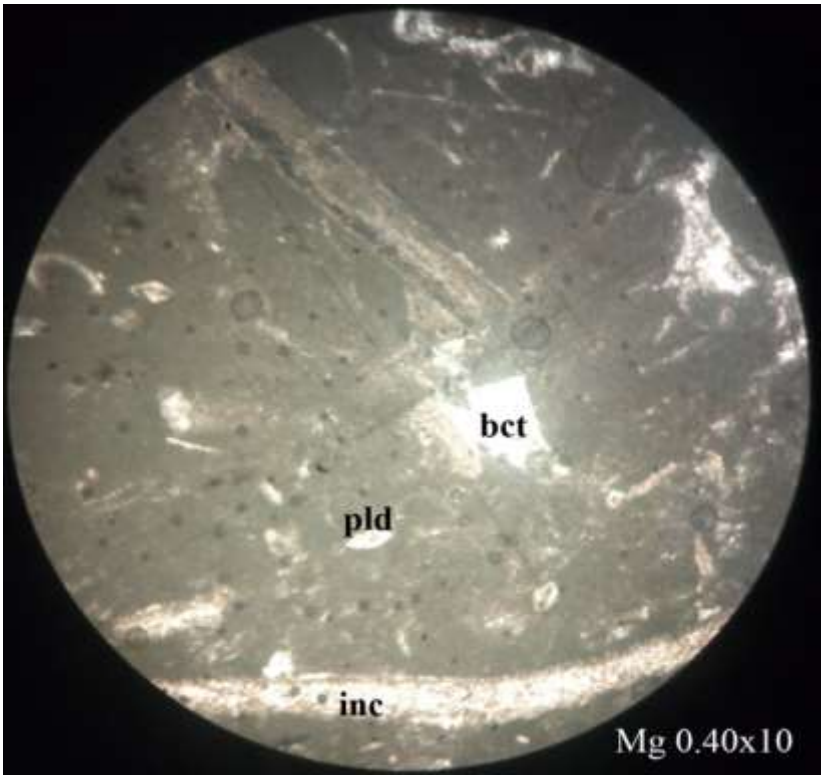


Fig. 10: Thin-section showing bioclasts (bct), peloids (pld), and intraclasts (inc) (Locality 2: 13° 32′ 36″ N, 05° 41′ 22″ E).

3.2 Discussion

3.2.1 Lithologic Units and Stratigraphic Logs

The stratigraphic logs from the study area (Figs 3-7) reveal a consistent vertical sequence of fossiliferous limestone overlying phosphatic shale at all localities. These observations strongly support the interpretation of a marine transgressive system, where shallow marine carbonate deposition progressively replaced deeper siliciclastic environments during shoreline migration. Key interpretations for each locality include:

3.2.1.1 Locality 1 (Figure 3)

The basal phosphatic shale (~0.5 m thick) transitions sharply into a 1.2 m thick fossiliferous limestone. This sharp contact reflects a rapid environmental shift, likely driven by rising sea levels and increased carbonate production. Similar sharp transitions are documented in transgressive systems within the Tarim Basin and Sokoto Basin (Obaje et al 2023; Zhu and Dong 2023).

3.2.1.2 Locality 2 (Figure 5)

The 3.5 m shale unit overlain by 3 m of limestone exhibits a gradational boundary, indicative of a continuous and gradual transgression. This type of boundary suggests low-energy environments evolving into carbonate-producing zones, a common feature in transgressive settings (Kogbe 1979; Flugel 2004).

3.2.1.3 Locality 3 (Figure 6)

The stratigraphic log highlights a fissile shale (2m), overlain by fossiliferous limestone (2m), and capped by ferruginized siltstone. The sharp boundary between limestone and siltstone suggests a depositional hiatus or a shift in sedimentary dynamics, potentially driven by localized tectonic events or regression. Local tectonic adjustments in the Iullemmeden Basin during the Paleocene could have caused such disruptions, as observed in other carbonate platforms under fluctuating sea levels (Wilson 1975; Yelwa et al. 2022)

3.2.1.4 Locality 4 (Figure 7)
The sequence of ash-grey shale (2 m), limestone (1 m), and silty clay (0.8m) suggests an initial rapid transgression, followed by sedimentary infilling of a lagoonal or restricted shallow marine environment. Fossil assemblages dominated by gastropods and echinoids reinforce this interpretation, paralleling findings in the Niger Delta (Adamu et al. 2020).

3.2.2 Microfacies Analysis
Using Dunham (1962) and Folk (1962) classification schemes, the limestone is identified as biomicrite (Folk) and wackestone (Dunham). Thin-section observations (Fig. 8-10) reveal the following key characteristics:

3.2.3 Matrix Composition
The limestone is predominantly micritic, with clay-sized materials and sparry calcite as cement. This suggests low-energy depositional conditions consistent with lagoonal or protected shallow marine environments.

3.2.4 Fossil Assemblages
Elphidium Crispum (Fig. 8) and Endothyra (Fig. 9) presence indicate low-energy intertidal to subtidal settings (Reyment 1980). Bioclasts, peloids, and intraclasts (Fig. 10) further confirm deposition in a carbonate platform environment under quiet water conditions.

3.2.5 Shale Microfeatures:
The phosphatic content of the basal shales, observed as nodules or fine disseminations, suggests periods of organic enrichment in anoxic to suboxic conditions. These features could indicate intervals of high organic productivity, making these shales potential hydrocarbon source rocks. When compared to (Wilson 1975 and Flugel 2004) standard facies models, these microfacies align with SMF 23 (non-laminated lime mud) and SMF 16 (bioclastic wackestone), characteristic of low-energy, shallow marine zones.

3.3 Depositional Environment
The overall depositional environment of the Kalambaina Formation corresponds to transgressive system tracts formed during shoreline migration. The observed sequence of shale transitioning into limestone reflects the interplay between siliciclastic and carbonate sedimentation during a marine transgression.

3.3.1 Intertidal and Subtidal Zones:
The predominance of bioclastic wackestone and sparry calcite matrix materials indicates deposition in intertidal to subtidal settings (Guiraud and Bosworth 1997). Reduced siliciclastic input and lower turbidity favored the proliferation of benthic foraminifera and other clear-water fauna, such as gastropods and echinoids.

3.3.1.1 Localized Tectonic Influence
The sharp contacts between limestone and ferruginized siltstone at Locality 3 suggest tectonic control during deposition. Such tectonism may have driven localized subsidence or uplift, temporarily interrupted deposition and led to sedimentary hiatuses.

3.4 Hydrocarbon Implications
The depositional and diagenetic characteristics of the Kalambaina Formation suggest significant hydrocarbon reservoir potential:

- Permeable Lower Facies:

The lower facies of the limestone, characterized by likely good porosity and a rich diversity of benthic foraminifera, provides a favorable reservoir. These characteristics are consistent with productive reservoirs in carbonate systems globally (Flugel 2004; Adamu et al. 2020).

- Organic-Rich Shales:

The phosphatic shales observed in the formation have potential as hydrocarbon source rocks. These shales, enriched in organic matter under low-energy, anoxic conditions, are comparable to other prolific source rocks found in transgressive systems (Obaje et al. 2023).

3.5 Mixed Siliciclastic-Carbonate Systems

The Kalambaina Formation exemplifies a mixed siliciclastic-carbonate system. The interplay between transgressive and regressive cycles has produced alternating shale and limestone layers, reflecting the dynamic depositional environment of the Iullemmeden Basin:

- Shale Deposition:

Phosphatic nodules within the shale suggest high organic productivity and potential source rock development under transgressive conditions.

- Carbonate Precipitation:

The overlying limestone reflects carbonate platform development during periods of reduced siliciclastic influx, consistent with transgressive phases globally. The Kalambaina Formation represents a shallow marine depositional environment shaped by transgressive-regressive cycles. Stratigraphic relationships, fossil assemblages, and petrographic features collectively reveal the interplay between siliciclastic and carbonate sedimentation (Nikfard et al. 2023). The study highlights the Kalambaina Formation's potential as a hydrocarbon reservoir, while the phosphatic shales provide further promise as source rocks. Following the tectonic influences, this study provides understanding of the formation's geological and economic significance.

4.0. Conclusion

The following are the main concluded points observed in the Kalambaina Formation in Kumshiyawa Village, Sokoto Basin: The lithologic units exhibit a consistent stratigraphic pattern of fossiliferous limestone overlying phosphatic shale, supporting the interpretation of a marine transgressive system. The presence of fossil assemblages, including Elphidium Crispum and Endothyra, aligns with observations of Paleocene epicontinental transgressions and their implications for low-energy, shallow marine conditions. Microfacies analysis for limestone indicates that the clay-sized materials (micrite) and calcite (calcium carbonate) serve as the main cementing agents binding the various microfacies together. Thus, the petrographic study shows that the Kalambaina Formation is dominated by micritic textures and classified as biomicrite and wackestone, indicative of intertidal to subtidal depositional environments. Also, the standard facies model corresponds to SMF 23, 16 which represent non-laminated lime mud, microsparite and some bioclasts wackestone texture. Based on the examination of hand samples and field notes, these thin sections are indicative of a shallow marine carbonate platform that reflects significant sea level fluctuations. The presence of bioclastic wackestone indicates deposition in a lagoonal environment, corresponding to the Transgressive System Tract.

These findings are consistent with broader tectonic and depositional trends in African basins, particularly the interplay between basin inversion and rifting, as documented by Guiraud and Bosworth (1997) and Fairhead and Binks (1991). The evidence of sharp contacts and transgressive system tracts in the Kalambaina Formation further underscores the influence of localized tectonic activity during the Paleocene, similar to patterns observed in other rift-related basins; including those in the Central African Republic, Niger, and Chad, where Genik (1992) highlighted the significance of structural rejuvenation and its effects on hydrocarbon systems. In conclusion, this research advances knowledge of the Kalambaina Formation's hydrocarbon potential, tectonic controls, and depositional history.

5.0 Recommendation

Future research should focus on detailed geochemical analysis, porosity and permeability assessments, and basin-wide stratigraphic correlations to further evaluate the Sokoto basin's resource potential and paleoclimatic significance.

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References

Abubakar, B., Danladi, J., & Nwosu, S. 2023. Stratigraphic and sedimentological study of the Gwandu Formation in the Sokoto Basin. Sedimentary Geology, 405, 106313.

Adamu, L. M., Obaje, N. G., Okafor, P. N., & Umar, U. M. 2020. Integrated geochemical and multivariate statistical examination of source rocks in the Sokoto and Anambra Basins, Nigeria: Implications for hydrocarbon prospectivity. Petroleum Science and Engineering, 4(2), 39–50.

Agustin, H., Retnaningdyah, C., Nugraha, F., & Priadi, B. 2023. Bioclastic limestone reservoirs in the Pre-Parigi Formation, Java, Indonesia: Insights from microfacies analysis. Geoscience Frontiers, 14(2), 54–73.

Dunham, R. J. 1962. Classification of carbonate rocks according to depositional texture. In W. E. Ham (Ed.), Classification of Carbonate Rocks (AAPG Memoir 1, pp. 108–121).

Fairhead, J.D., and Binks, R.M., 1991. Differential opening of the Central and South Atlantic Oceans and the opening of the Central African rift system. Tectonophysics 187, 191- 1215 203.

Flugel, E. 2004. Microfacies of Carbonate Rocks: Analysis, Interpretation and Application. Springer-Verlag.

Folk, R. L. (1962). Spectral subdivision of limestone types. In W. E. Ham (Ed.), Classification of Carbonate Rocks (AAPG Memoir 1, pp. 62–84).

Genik, G., 1992. Regional framework, structural and petroleum aspects of rift basins in Niger, Chad and the Central African Republic (CAR). Tectonophysics 213(1-2), 169-185.

Guiraud, R. and Bosworth, W. 1997. Senonian basin Inversion and rejuvenation of rifting in Africa and Arabia. Synthesis and Implications to Plate Tectonics. Tectonophysics, 282: 39 – 82.

Ham, W. E., & Pray, L. C. 1962. Modern concepts and classifications of carbonate rocks. In Classification of Carbonate Rocks (AAPG Memoir 1, pp. 2–19).

Hamidu, I., Hamza, H., Abdullahi, I. M., Adamu, I. H., Mohammed, D., Ayuba, S., Israel, T. and Yahaya, S.A. 2023. Lithostratigraphy of the Maastrichtian to Eocene successions of the Sokoto sector of Iullemmeden Basin (Sokoto Basin) Northwest Nigeria: A Review. Savanna Journal of Basic and Applied Sciences (December, 2023), 5(2): 111-142. P: ISSN 2705-3164 | E: ISSN 2695-2335

Ibrahim, H., Hamza, H., Adamu, I. H. and Mohammed, H. G. 2023. Tectonostratigraphy of the Nigerian Sector of Iullemmeden Basin (Sokoto Basin), Northwestern Nigeria. International Journal of Geoscience and Remote Sensing, 2(1): 107 DOI: https://doi.org/10.36266/IJGRS/107

Kogbe, C. A. 1979. Geology of the Southeastern (Sokoto) sector of the Iullemmeden Basin. Bulletin of the Department of Geology, Ahmadu Bello University, Zaria, 32, 142 pp.

Kogbe, C. A. 1981. Stratigraphy and tectonic history of the Iullemmeden Basin in West Africa. South African Journal of Geology, 94, 19–32.

Obaje, N. G., Aduku, M., & Yusuf, I. 2013. The Sokoto Basin of Northwestern Nigeria: A preliminary assessment of the hydrocarbon prospectivity. Petroleum Technology Development Journal, 3(2), 71–86.

Maju-Oyovwikowhe, G.E., and Okudibie, E.J. 2023. Geophysical and Hydrogeological Assessment and Characterization of Limestone Aquifers for Sustainable Groundwater Resource Management: A Case Study in Gada L.G.A. Sokoto State, Nigeria. Journal of Energy Technology and Environment, 5(2), 228-242.

Maju-Oyovwikowhe, G.E. and Owenvbiugie, E. M. 2023. Lithostratigraphic Characterization and Petroleum System Elements of the MI Well, Niger Delta Basin. Current Journal of Applied Science and Technology, 42(16), 67–83. https://doi.org/10.9734/cjast/2023/v42i164137

Nikfard, M., Tavakoli, V., & Sanei, H. 2023. Transgressive-regressive cycles in the Eocene Zagros Foreland Basin: Implications for mixed siliciclastic-carbonate systems. Marine and Petroleum Geology, 154, 105412.

Obaje, N. G., Lar, U. A., Nzegbuna, A. I., Moumouni, A., Chaanda, M. S., & Goki, N. G. 2006. Geology and mineral resources of Nasarawa State: An investor\u2019s guide. Nasara Scientifique (A publication of Nasarawa State University), 2(1), 1–34.

Obaje, N. G., Faruq, U. Z., Bomai, A., Moses, S. D., Ali, M., Adamu, S., Essien, A., Lamorde, U., Umar, U. M., Ozoji, T., Okonkwo, P., Adamu, L., & Idris-Nda, A. 2019. A short note on the petroleum potential of the Sokoto Basin in Northwestern Nigeria. Petroleum Science and Engineering, 4(1), 34–38.

Obaje, N. G., Bomai, A., Moses, S. D., Ali, M., Adamu, S., Essien, A., Lamorde, U., Umar, U. M., Ozoji, T., Okonkwo, P., Adamu, L., & Idris-Nda, A. 2023. Bio-chemo-petrographical characteristics of the Kalambaina Formation as a major potential carbonate reservoir in the Sokoto Basin of Northwestern Nigeria. In F. Lucci, D. M. Doronzo, J. Knight, A. Trav\u00e9, S. Grab, A. Kallel, & S. Panda (Eds.), Selected Studies in Geomorphology, Sedimentology, and Geochemistry (Advances in Science, Technology & Innovation, pp. 157–161). Springer. https://doi.org/10.1007/978-3-031-43744-1_32

Reyment, R.A., 1980. Biogeography of the saharan Cretaceous and Paleocene epicontinental transgressions. Cretac. Res. 1, 299–327.

Toyin, A., Sanni, Z., Bale, R. B., & Adekeye, O. A. 2015. Carbonate sedimentology and depositional environment of carbonate rocks of the Kalambaina Formation, penetrated by Illela Borehole, Sokoto Basin, NW Nigeria. Volume 51, Number 1, 47–55.

Wilson, J. L. 1975. Carbonate Facies in Geologic History. Springer-Verlag.

Yelwa, N. A., Abdullahi, I. M., Nabage, N. A., & Kasim, S. A. 2015. Petrography and paleoenvironmental interpretation of Taloka and Dukamaje formations, Southern Gadon Mata, Goronyo, Sokoto Basin-Nigeria. Journal of Environment and Earth Science, 5(2), 165–174. https://doi.org/10.33003/fjs-2022-0605-934.

Yelwa, N. A., Mohammed, D., Abdullahi, A. A., Shehu, J., Mutari, L., & Faruk, S. 2022. Petrographic studies of limestone in Dukamaje Formation at Gilbedi, Gada, Sokoto Basin, Nigeria. FUDMA Journal of Sciences, 6, 91–97. https://doi.org/10.33003/fjs-2022-0605-934.

Zhu, H., Zhao, W., & Dong, X. 2023. Sequence stratigraphy of transgressive carbonate platforms in the Cambrian Tarim Basin. Palaeogeography, Palaeoclimatology, Palaeoecology, 630, 35–50.