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Lithological Characteristics, Petrographic and Ostracods Analyses of Carbonate Rocks in Parts of Sokoto Basin, Nigeria: Implications for Exploration Efforts and Petroleum Geology

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Abstract

This study investigates sedimentological characteristics of carbonate rocks from borehole data, in some segment of the Iullemmeden Basin, northwestern Nigeria, with a focus on hydrocarbon exploration potential. This study involved the use of lithological description, petrographic and microfossil analyses on carbonates rocks in parts of Sokoto Basin. The borehole 2051, which penetrates a 32.0-meter sedimentary sequence, reveals four lithostratigraphic units which are shale, limestone, silty mudstone and claystone. The Gamba Formation comprises dark laminated shale, brownish claystone containing silt material with thickness of about 4 m. The Kalambaina Formation is characterized by light to milky whitish bioclast-rich limestone with a thickness of 11.5 meters. The Gamba Formation comprises 4 meters of brownish claystones with silt and dark laminated shales at the top in the study section. Detailed microfacies analysis identified mudstone, lithoclastic wackestone, lithoclastic packstone, bioclastic wackestone, and peloidal bioclastic packstone, indicative of varied depositional environments from low-energy to more dynamic shallow marine conditions. Ostracod data from the studied Paleocene interval revealed twelve species: *Bairdia ilaroensis, Trachylebris teiskotensis, Cytherella sylvesterbradleyi*, *Cytherella* sp., *Paracosta cf. warensis*, *Buntonian beninensis*, *Cytherelloidea* sp., *Bairdia aegyptiaca*, *Paracosta kenfensis* and *Paracosta parakefensis*. These species reflect a diverse marine ecosystem with varying depths and ecological niches, indicating a stable, productive marine environment with periodic freshwater influxes. The findings suggest potential hydrocarbon systems within the basin, with the Dange Formation's rich in dark shales acting as potential source rocks and the Kalambaina Formation's bioclast-rich limestones serving as promising reservoir rocks. In conclusion, the integration of lithological descriptions, microfacies classifications, and paleoecological data provides insight to the basin's depositional history and its implications for hydrocarbon exploration.

Keywords: Ostracods, microfacies types, lithological description, Kalambaina and Dange Formations

1. Introduction

Carbonates sedimentary deposits found in the Sokoto Basin make it an area of great geological interest since most studies in Nigeria are basically on siliciclastic rocks where major hydrocarbon exploration and exploitation are carried-out. Though there are few other basins in Nigeria that also have carbonate rocks such as Dahomey basin (Ewekoro Limestone), Southern Benue Trough (Nkalagu, Gboko and Yandev) and Northern Benue Trough (Ashaka and Pindiga) as discussed in Nwajide (2013). This study location within the Sokoto Basin has

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drawn the interest of researchers looking into the region's geological history and hydrocarbon prospects because few works has published in the basin. The carbonate study is of economic interest because it can act as a source and reservoir rocks (Aigbadon *et al.*, 2024 a). Lithological and petrographic data in ostracod analysis of a basin can be used to obtain information regarding paleoenvironmental conditions and geological evolution of the basin over time.

Numerous studies have been conducted on the lithological features and microfossil analysis of sedimentary rocks in the Sokoto Basin as discussed in Aigbadon *et al.* (2024 b), Toyin and Adekeye (2019), Boboye *et al.*, (2018), Obaje *et al.* (2013), Adekeye and Akande (2006) and Okosun (1995), respectively. The sandstones, shales, and few limestone deposits are among the sedimentary formations in Dange and Kalambaina that make up the majority of the basin, according to Boboye *et al.* (2018). The Dange, Kalambaina and Gamba Formations serve as a record of the region's depositional history. According to Obaje *et al.* (2013), the Dange, Kalambaina and Gamba Formations lithological units frequently have distinct characteristics and textures that represent different depositional settings and processes. Petrographic study is required to understand the mineralogical composition, facies types and diagenetic history of sedimentary rocks in a sedimentary terrain (Aigbadon *et al.*, 2024 b, c). The Sokoto Basin has a range of mineral assemblages and microfacies, which are significant sources of information on the tectonic background and provenance of the basin, according to research done by Toyin and Adekeye (2019). Toyin *et al.* (2016) carried-out petrographic studies on carbonates rocks in parts of Sokoto Basin and the petrographic data provided an insight into the diagenetic changes and pore growth in these rocks, which affect reservoir quality and hydrocarbon potential in the basin. Ostracod assemblages have been used in studies by Petters (1978), Okosun (1999) and Youssef *et al.* (2017) to reconstruct paleoenvironments and paleoclimates within sedimentary basin, offering important constraints on historical climatic changes and depositional processes. And this is due to their widespread distribution in freshwater, marine and terrestrial habitats. Ostracods are important paleoenvironmental markers (Okosun, 1995). The integration of lithological characteristics, petrographic analysis, and ostracod studies, provides an in-depth study to the Sokoto Basin's geological evolution (Aigbadon *et al.*, 2024 b and Okosun, 1995). Though the biggest challenges in studying the Sokoto Basin is lack of acquiring subsurface and useful geological data compared to counter-part inland basin such as Niger-Delta, Nigeria where a lot of data is available for detailed investigations. The aim of this study is to review the existing work and update recent findings in the Sokoto Basin, Nigeria based on availability of ditch cutting carbonate samples from borehole (BH 2051). This will involve the use of sedimentological, thin section petrographic, facies analysis and ostracods studies to evaluate the region's depositional system, paleoenvironmental conditions and hydrocarbon exploration effort.

2. Geologic setting of the Sokoto Basin

The Sokoto Basin spreading over an area of over 700,000 km^2, is a circular intra-cratonic basin located in the south-central Saharan region of Africa (Fig. 1). It covers portions of northwest Nigeria, Niger Republic, Benin Republic, and Mali. Falconer (1911) provided a geological and geographical description of the Nigerian portion of the Sokoto Basin, also known as the Iullemmeden Basin, in the beginning of the 20th century. Obaje *et al.* (2013), Kogbe (1989), Petters (1979, 1978), Kogbe and Sowunmi (1975) are among the other notable research that were conducted in this basin. According to Nwajide (2013), the basin most likely began with rapid subsidence from its center portion in the late Jurassic (approximately 140 Ma). This was followed by a slow phase in the early Cretaceous-Turonian and then rapid again around 80 Ma. The basin's stratigraphic units begin with marine transgressions in the early Cretaceous which led to deposition of marine shale, mudstone, and limestone which were the main products of continuous deposition. This sediments deposition occurred within the Upper Cretaceous to the lower Paleogene under marine and estuarine conditions (Nwajide, 2013; Petters, 1978). While the Maastrichtian-Paleocene sedimentation was the product of two transgressive-regressive episodes brought about by the advancement and retreats of the Tethys sea, the "Continental Intercalaire" of Wright *et al.* (1985) depicts the basal sediments of the basin as primarily continental (Petters, 1979). The Sokoto Basin is mostly a plain that gently slopes upward from sea level, with an average elevation of between 250 and 400 meters, known as mesas which is prominent. This is the Dange Scarp which is the most noticeable structure in the basin (Obaje *et al.*, 2013; Petters,1979).

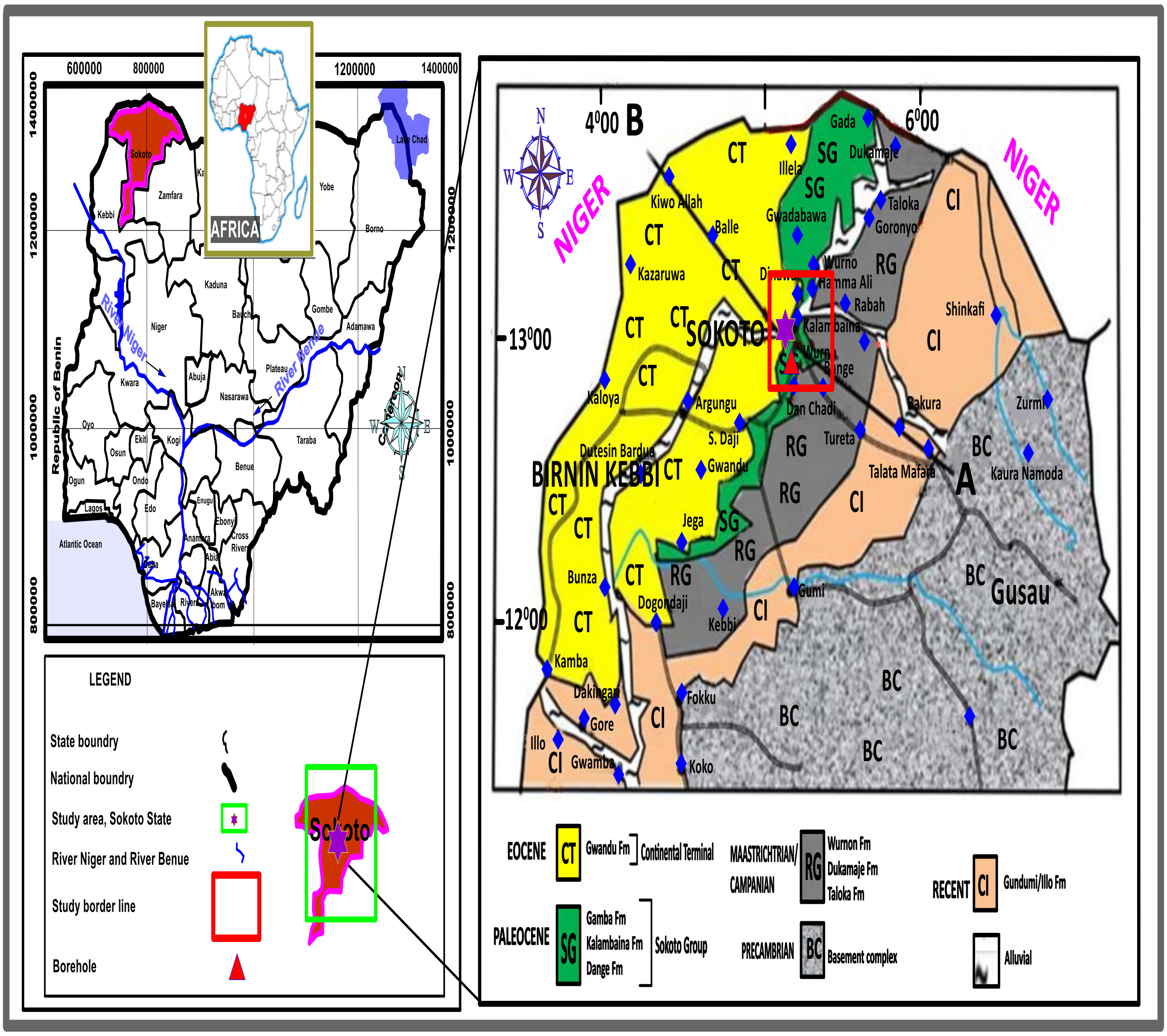

Fig. 1: Geological map of Sokoto Basin, Nigeria indicating study BH-2051 location (Akagbue *et al.*, 2023; Narimi *et al.*, 2019).

The underlying Precambrian rocks of the Sokoto Basin were covered in an uneven layer of sediments that accumulated over the course of four deposition episodes. The non-marine, pre-Maastrichtian Gundumi and Illo Formations are the earliest and first formations (Kogbe, 1991; Fig. 2). They are thought to be lateral counterparts and overlying the basement to the northeast and southwest of the basin, respectively (Kogbe, 1991). With the exception of some fossilized wood, the strata are continental in origin and devoid of body fossils (Kogbe, 1973). The Gundumi Formation is made up of lacustrine and fluviatile clay, grits, sandstone, and pebbles. In contrast, the Illo Formation, which is its lateral counterpart, is mostly made up of cross-bedded pebbly grits, sandstone, and pisolitic clay that is known to be rich in bauxite (Kogbe, 1991, 1989). The Maastrichtian Rima Group, which is made up of the Wurno, Dukamaje, and Taloka Formations, unconformably covers these formations (Kogbe, 1991; Fig. 2). The 60 m-thick Taloka deposit contain clayey material at the top and this grades into a 10 m thick layer of fissile, bluish-grey, gypsiferous shale, which includes marl from the Dukamaje Formation (Nwajide, 2013; Kogbe, 1989). Middle to Late Maastrichtian age is supported by the foraminiferal microfaunas of the Dukamaje deposit (Petters, 1978). Despite this, they pinch out in the southeast of the Iullemmeden Basin, northwest of Sokoto (Petters 1979, 1978). The Sokoto Group, which is virtually exclusively marine in origin, is deposited nonconformably overlaying the Rima Group (Petters, 1979; Fig. 2). The Dange, Kalambaina, and Gamba Formations are the three primary formations found in these Palaeocene deposits (Nwajide, 2013; Kogbe, 1991, 1989). The Kalambaina Formation, which sits on top of the Dange Formation, is composed mostly of milky to whittish fossiliferous limestone and a sparse interbedded of marl units (Toyin *et al.*, 2019; Kogbe, 1991). The Dange Formation is composed of indurated greenish shale and while the Gamba Formation shale which is yellowish to brown in colour is rich in fossiliferous material as discussed in Kogbe (1991). The continental deposits of the Gwandu Formation also known as Continental Terminal Group lie disconformably over the Upper Paleocene marine beds in the Sokoto Basin (Kogbe, 1991; Fig. 2). The Gwandu Formation contain lacustrine clays, cross-bedded sandstones, and siltstones and they outcrop as mesas and reaching a thickness of up to 300 m in the center of the basin (Nwajide, 2013; Kogbe, 1991).

Age	Formation	Group	Environment
Quaternary	Sandy drifts, lateites	–	–
	Unconformity		
Miocene to Upper Eocene(?)	Gwandu Formation	Continental Terminal	Continental
	Unconformity		
Middle Eocene	Primary oolitic ironstone		
to Paleocene Late	Gamba Formation Kalambaina Formation Dange Formation	Sokoto Group	marine
	Unconformity		
Maastrichtian to Campanian	Wurno Formation Dukamaje Formation Taloka Formation	Rima Group	Brackish water with brief marine intercalation
	Unconformity		
Earliest Cretaceous to Late Jurassic	Illo and Gundumi Formations	Continental intercalaire	Continental
	Major unconformity		
Precambrian		Basement complex	

Fig. 2: Lithostratigraphic succession in the Sokoto Basin (Kogbe, 1991)

3. Materials and Methods

For this study, 35 ditch cutting samples from BH 2051 near Dange village within the Sokoto Basin were acquired from the Nigerian geological survey agency. Six (6) representative carbonate rock samples were used for the thin section analysis. The rocks were trimmed to the desired sizes using a rock cutting machine. The trimmed pieces were immediately attached to a glass slide using an appropriate adhesive or epoxy, ensuring that the side to be cut is flat and clean. Next stage was to grind the mounted sample to a thickness of approximately 30 micrometers (0.03 mm) using a series of abrasives, beginning with coarse and progressing to finer grades. Following grinding, the surface was polished to remove scratches and achieve a smooth finish using finer polishing materials to enhance clarity. Immediately a thin cover glass was placed over the polished surface and secured with a mounting medium to preserve the thin section and facilitate smooth viewing under the microscope. The prepared thin section was placed on the microscope stage, starting with a low magnification objective to examine the rock's general texture and structure under plane polarized light (PPL) and crossed polarized light (XPL). Carbonate minerals and textural characteristics such as grain size, shape, cementation, and any fossil fragments were identified using a light microscope (Olympus BX 41-P).

For microfossil analysis, six (6) limestone and two (2) shale units from BH 2051 were collected. Dry samples (100g) of limestone were first soaked overnight in a bicarbonate (Na_2CO_3) solution, followed by the addition of hydrogen peroxide (H_2O_2) and deionized water. The residue was then washed through a series of sieves with mesh sizes of 630, 125, and 63 mm, and dried in an oven at 60°C for 24 hours. The processed samples were mounted on microslides and examined under an Olympus binocular microscope (BX 61-P). The ostracod assemblages were identified, described, and named according to the methodology outlined by Aigbadon and Igbinigie (2024 c), Adebambo *et al.* (2023), Youssef *et al.* (2017), Okosun (1999, 1995) and Reyment (1981).

4. Results and Discussion

4.1 Lithological Description of the BH 2051 in Sokoto Basin

The sedimentary sequence that borehole 2051 penetrates is made up of four rock types (shale, limestone, silty mudstone and claystone) that have been identified in the Sokoto Basin. Three separate lithostratigraphic units make up the borehole's succession, which has a total depth of 32.5 m (Fig. 3);

i. **The lower section**: This unit belongs to the Dange Formation. It has a thickness of 16.5 - 32 m (Fig. 3). The lithology at this depth consists primarily of light to dark grey shales, claystone with interbedded muddy siltstones in the borehole. These shales may vary in color due to differences in organic content or depositional environments. Additionally, compacted claystones are present, suggesting the deposition of claystone that has undergone compaction over time. Thin muddy siltstones are also observed, indicating intermittent deposition of fine-grained sediment with a slightly coarser grain size compared to the shales and claystone (Figs. 3 and 4). These lithologies suggest a relatively low-energy depositional environment conducive to the accumulation of fine-grained sedimentary materials.

ii. **The middle section:** This unit belongs to the Kalambaina Formation and has a thickness of 12.0 m (Fig. 3). Within this section, the lithology primarily consists of milky to whitish limestone. The presence of bioclasts suggests that these limestones contain fossil fragments or organic remains. The milky appearance indicates the presence of microcrystalline calcite or other mineral constituents (Fig. 5a, b). The lithology suggests deposition in a marine environment conducive to carbonate sedimentation, potentially indicating shallow marine conditions.

iii. **The upper section:** This unit belongs to the Gamba unit. It has a thickness of about 4 m (Figs. 3 and 4). The lithology at this upper section primarily consists of brownish claystone, and dark laminated shale. Within the claystone, there is the presence of silty material. Overlying the claystone is dark laminated shale, indicating the deposition of fine-grained sediment in a relatively low-energy environment. The presence of laminations suggests periodic changes in sedimentation rates or environmental conditions, leading to alternating layers of organic-rich and finer-grained sediments.

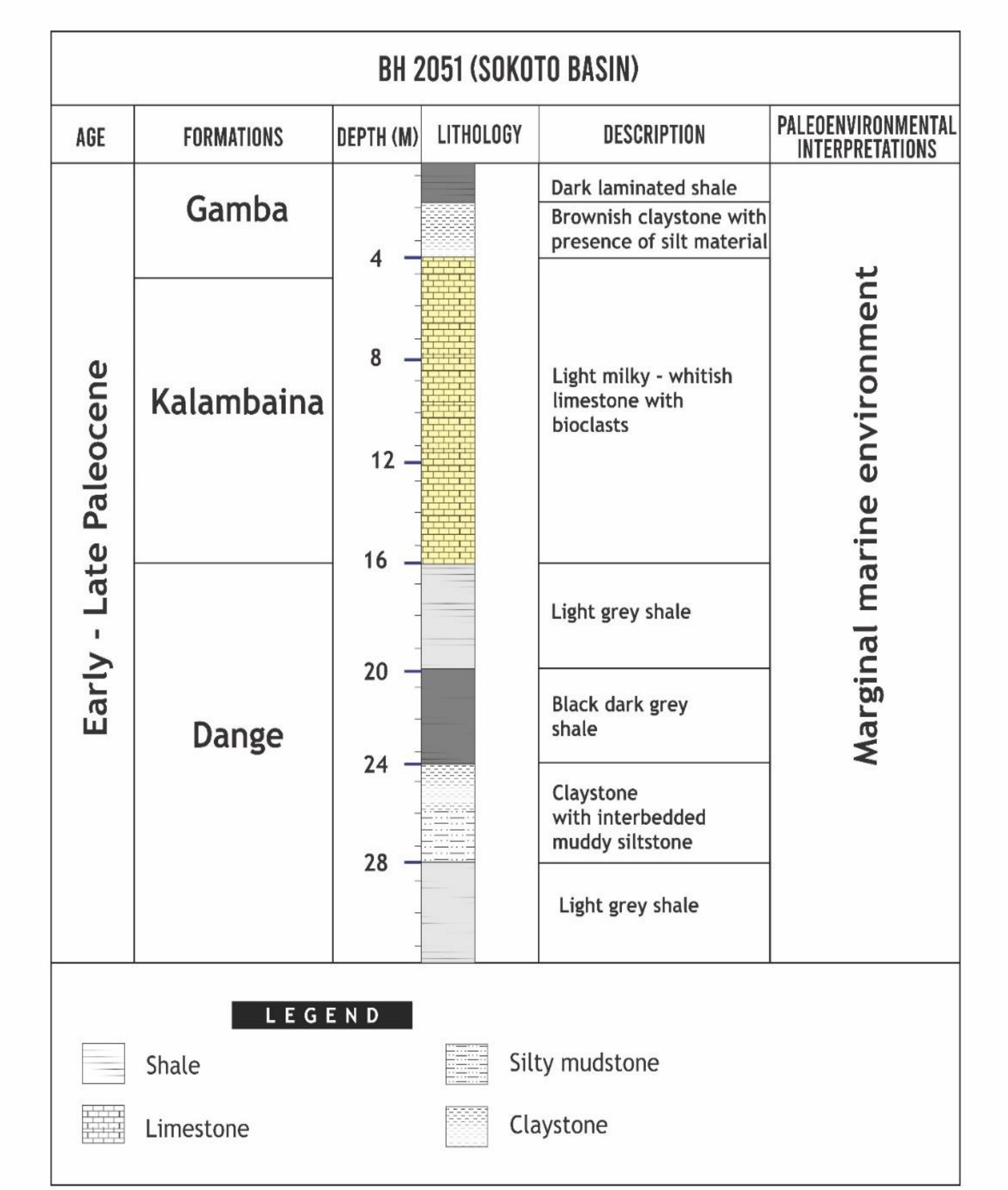

Fig. 3: Stratigraphic sequence scheme of BH 2051 within the Sokoto Basin (modified after Aigbadon *et al.*, 2024 d)

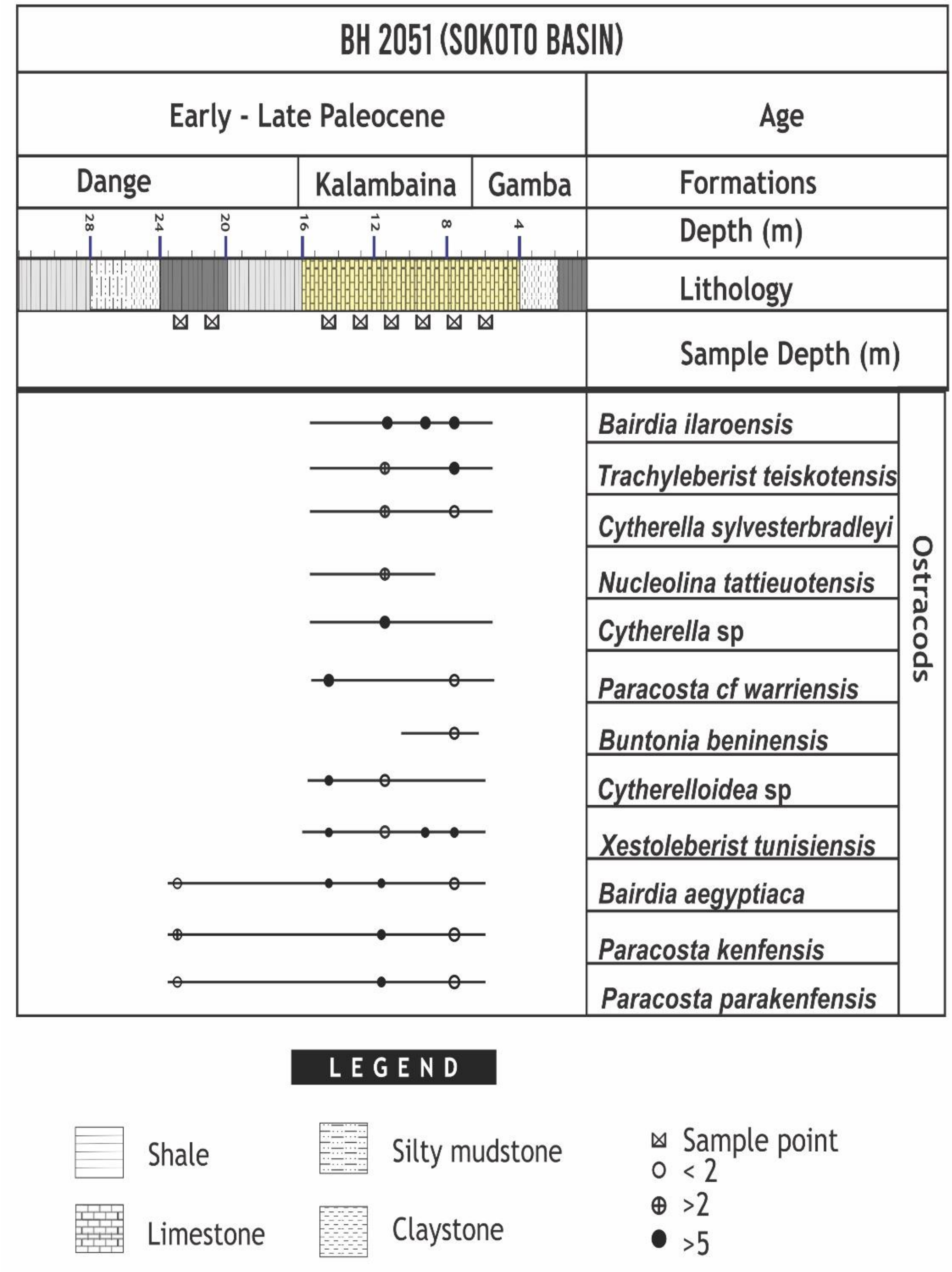

Fig. 4: Stratigraphic sequence of recovered ostracods assemblages within the BH 2051 in parts of the Sokoto Basin

Fig. 5: (a) The milky appearance of Kalambaina Limestone showing microcrystalline calcite with coarse grains. (b) Milky Kalambaina Limestone with microcrystalline calcite, other mineral constituents with fine grains..

4.2 Microfacies Classification

The determination of the microfacies and depositional environment of the carbonate samples, Dunham (1962) classification system was the classification scheme used. The identified microfacies were compared with the standard microfacies types (SMF), which combine Dunham's textural classifications with Flugel broad paleoecological insights. The identified carbonate microfacies are discussed below:

Mudstone: This microfacies is dominated by mud and contains less than 10% grains (Fig. 6 a and 6 b). The predominant non-skeletal grains are peloids, accompanied by bioclasts such as ostracods and opaque mineral inclusions within them.

Lithoclastic Wackestone: There is more than 10% grain content in this microfacies (Fig. 6 c). It is notable for having a large amount of sparry calcite cement. Bioclasts, like ostracods, are also visible in these microfacies.

Lithoclastic Packstone: This microfacies is characterized by a notable abundance of grains, constituting a significant portion of its composition (Fig. 6 d). Alongside, there is evident presence of sparry calcite cement. Moreover, peloids are abundant within this microfacies, and bioclasts such as algae are also observable.

Bioclastic Wackestone: Together with bioclasts like foraminifera, micrite is a characteristic of this microfacies (Fig. 6 e, g, h). Furthermore, peloids are included in this microfacies and add to its total composition. In addition, the presence of ostracods and algae, which contribute to the biological diversity within the microfacies.

Bioclastic Packstone: This microfacies is distinguished by a significant abundance of peloids (Fig. 6 f). It also contains bioclasts, including ostracods and bivalves. Additionally, the presence of sparry calcite cement is evident within this microfacies.

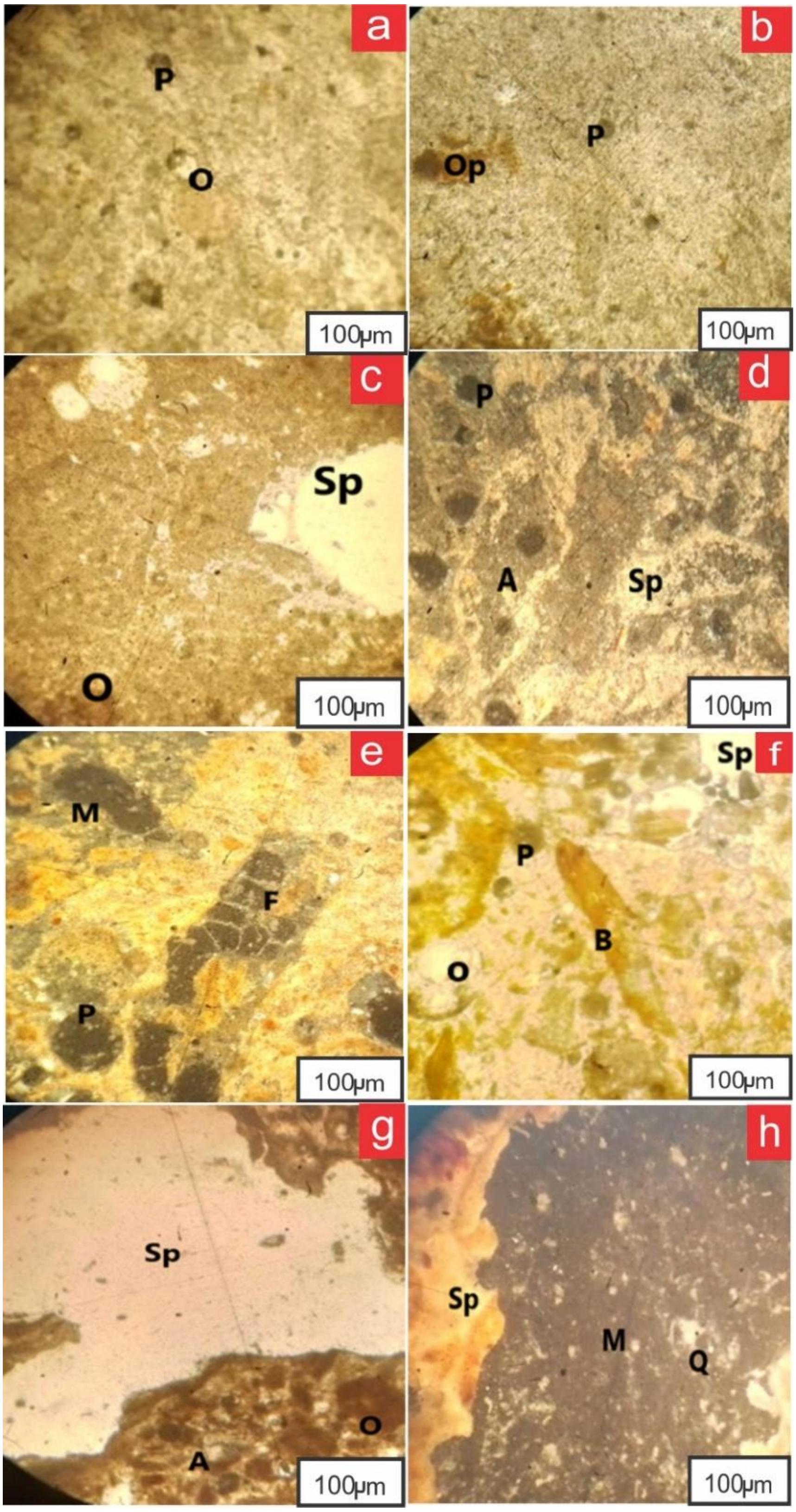

Fig. 6: Thin section of the carbonate samples studied; O - Ostracod, Sp - Sparite, A - Algae, Op - Opaque mineral, P - Peloid, M - Micrite, F - Foraminifera, B - Bivalve.

4.3 Ostracod species and paleoenvironment

The analyses of the 25 samples extracted from the Paleocene interval in BH 2051 yielded well-preserved ostracods and allowed us to recognize 10 species belonging to 6 genera and families. They include *Bairdia Ilaroensis, Bairdia aegyptiaca, Paracosta Kenfensis, paracosta parakefensis, Trachylebris teiskotensis, Cytherella sylversterbradleyi, Cytherella* sp, *Paracosta cf warensis*, *Buntonian beninensis* and *Cytherelloidea* sp. (Figs. 4, 7 b, c, f, i, j, k). The geological age of these ostracods is firmly placed in the Paleocene, which spans from approximately 66 to 56 million years ago (Okosun, 1995). Typically, marine habitats are home to *Bairdia Ilaroensis* species. Their existence indicates that during the Paleocene, the Sokoto Basin had marine conditions that were favorable for these ostracods (Youssef *et al.*, 2017). Marine habitats that are shallow are frequently linked to *Trachylebris teiskotensis*. This suggests a Paleocene shallow marine environment in the Sokoto Basin. *Cytherella* sp are known for their adaptability to various marine environments, indicating a stable marine ecosystem in the region during this (Okosun 1995). *Paracosta cf warensis* are indicative of shallow marine environments. This suggests that the Sokoto Basin may have experienced varying depths and possibly a more complex marine setting during the Paleocene (Nwajide, 2013; Okosun, 1995). *Buntonian beninensis* are typically found in marginal marine environments, such as lagoons and estuaries. This indicates that parts of the Sokoto Basin may have been influenced by such environments (Youssef *et al.*, 2017; Okosun, 1995). *Cytherella sp*., and *Cytherelloidea* sp (Fig. 7 a, e) are often found in marine to brackish environments. This further suggests that the Sokoto Basin had varied marine conditions, possibly with some areas influenced by brackish water (Reyment, 1981). The Paleocene ostracod fossils in BH 2051 of the Sokoto Basin are a varied and exceptionally well-preserved group. A rich and diversified marine ecosystem would have been sustained by the basin's varied marine conditions, as suggested by the species that have been identified.

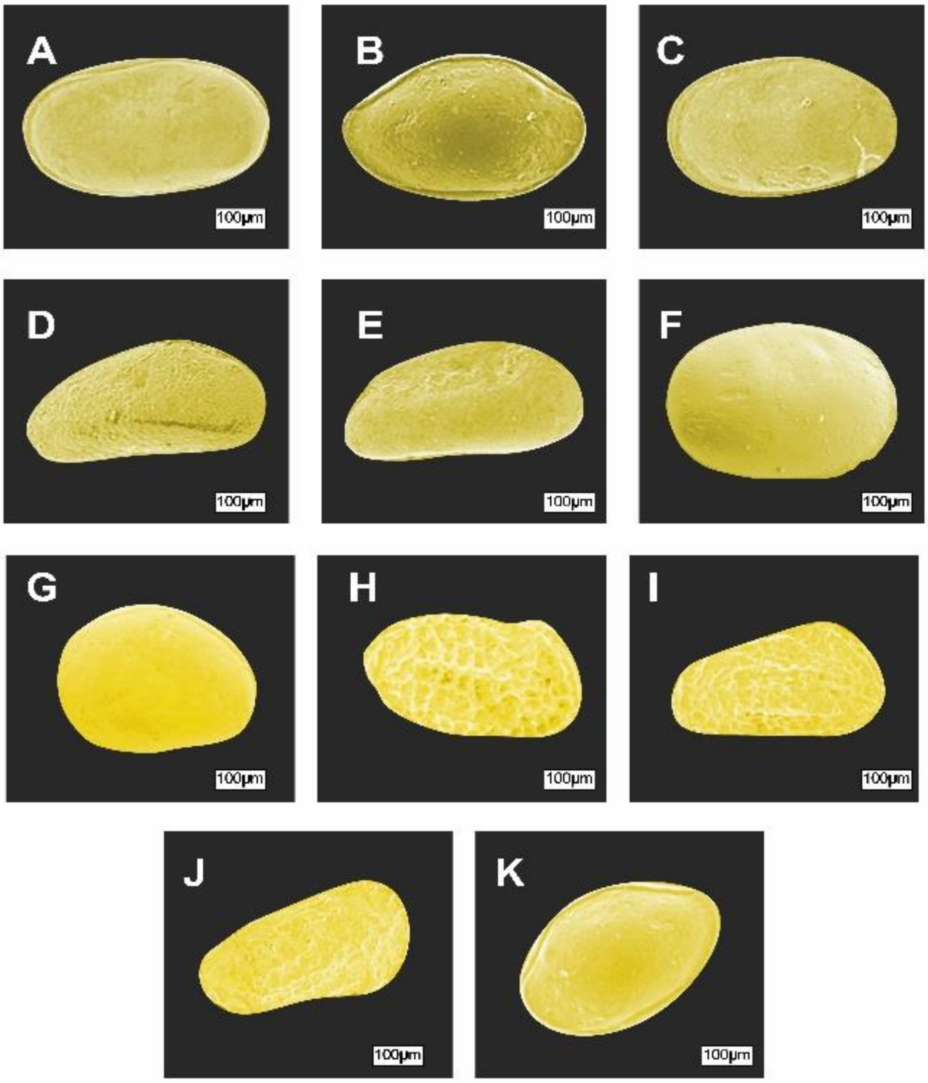

Fig. 7: Ostracods assemblages recovered within the studied borehole sections in the Sokoto Basin. a. *Cytherella sp*., b. *Bairdia ilaroensis*, c. *Trachylebris teiskotensis*, d. *Nucleolina tatteuolensis*, e. *Cytherelloidea* sp., f. *Cytherella slyvesterbradleyi*, g. *Xestoleberis tunisiensis*, h. *Paracosta Kenfensis*, i. *paracosta parakefensis*, j. *Buntonian beninensis*, k. *Bairdia aegyptiaca*.

4.4 Sedimentology

The BH 2051 penetrated the sedimentary sequence in the Sokoto Basin. The studied stratigraphy comprises three distinct lithostratigraphic units with a total depth of 32.5 meters as revealed by BH-2051 that penetrated the three formations. A low-energy depositional condition contributed to the formation of fine-grained sediments witnessed at the bottom unit of the borehole. This unit has a thickness of 16.5 meters and formed part of the Dange Formation. It is composed of thin muddy siltstones, compacted claystone, and light to dark grey shales. Additionally, compacted claystones are present, suggesting the deposition of clay-rich sediment that has undergone compaction over time and this corroborate works of Hajek and Straub (2017). These lithologies suggest a relatively low-energy depositional environment favourable to the accumulation of fine-grained sedimentary materials. Also, within the BH-2051, a 12-meter-thickness depth of the Kalambaina Formation, which is mainly made of bioclast-rich (bivalves, algae, ostracods and Foraminifera) milky to whitish limestone. The presence of foraminifera, bioclast-rich bivalves and algae, milky to whitish limestone further suggests active carbonate sedimentation in a shallow marine environment during deposition. This is in accordance with the published works of Toyin *et al.* (2015). The milky appearance may indicate the presence of microcrystalline calcite or other mineral constituents and this is in line with the work of Hashim and Kaczmarek (2021). Overall, the lithology suggests deposition in a marine environment favourable to carbonate sedimentation, potentially indicating shallow marine conditions. The topmost layer, which is 4.0 meters thick and a component of the Gamba Formation, is made up of dark laminated shales and brownish claystone with silt that show cyclical variations in sedimentation in a low-energy environment. Overlying the claystone is laminated shale, indicating the deposition of fine-grained sediment in a relatively low-energy environment. The presence of laminations suggests periodic changes in sedimentation rates or environmental conditions, leading to alternating layers of organic-rich and finer-grained sediments. This corroborate work of Al-Mufti and Arnott (2023). Overall, the lithologic description suggests deposition in a predominantly marine environment with occasional influxes of coarser sediment.

The different depositional conditions, ranging from low-energy environments to more dynamic, rich fossils (foraminifera, ostracods, bivalves and algae) settings was revealed by a detailed microfacies analysis. Detailed microfacies analysis further elucidates the sedimentological characteristics as mudstone microfacies, predominantly comprising mud with scant grains and bioclasts such as ostracods, suggest quiet water conditions (Toyin *et al.*, 2016). Lithoclastic Wackestone microfacies, distinguished by sparry calcite cement and an abundance of grains including ostracods, imply a slightly higher energy environment compared to mudstone deposition (Ahmad *et al.*, 2021).

Conversely, Lithoclastic Packstone microfacies, characterized by a notable grain abundance, sparry calcite cement, and peloids alongside bioclasts like algae, indicate a moderate energy environment supportive of increased sediment transport and deposition (Ahmad *et al.*, 2021). The discovery of well-preserved ostracods within the Paleocene interval underscores favorable conditions for preservation and offers insights into the paleoenvironmental dynamics of the area.

4.5 Paleoecology

The discovery and analysis of ostracod fossils in the Paleocene interval of the Sokoto Basin provide a window into the paleoecology of the region during this time. These fossils reveal a diverse and dynamic marine environment characterized by varying depths, ecological niches, and environmental conditions. The presence of ostracod species such as *Bairdia ilaroensis, Trachylebris teiskotensis*, *Cytherella sylversterbradleyi*, *Cytherella* sp, *Paracosta cf warensis,* *Bairdia aegyptiaca*, *Paracosta kefensis*, *Paracosta parakenfensis*, *Buntonian beninensis*, and *Cytherelloidea* sp., (Fig. 6 a, b, c, e, g - h), suggests that the Sokoto Basin during the Paleocene was a marine environment with significant ecological diversity. *Bairdia ilaroensis* and *Trachylebris teiskotensis* are indicative of shallow marine settings according to Reyment (1981). These species thrive in environments with moderate to high energy levels, suggesting that parts of the Sokoto Basin were characterized by relatively shallow waters with good circulation, possibly influenced by tides and waves (Mamman and Obaje, 2006). The identification of *Paracosta cf warensis* and *Paracosta parakenfensis*, species known to inhabit deeper marine environments, indicates that the basin also had areas of greater depth (Youssef *et al.*, 2017; Reyment, 1981). This implies a complex bathymetric profile with a range of ecological habitats. The co-existence of shallow and deep-water species suggests that the Sokoto Basin had a varied topography with slopes and basins, allowing for diverse marine habitats ranging from shallow coastal areas to deeper offshore environments as earlier proposed by Youssef *et al.* (2017).

The presence of *Cytherella sylversterbradleyi*, *Cytherella* sp., and *Cytherelloidea* sp. is significant as these genera are often found in marine to brackish environments (Okosun, 1999). Their adaptability to varying salinity levels indicates that parts of the Sokoto Basin might have experienced fluctuations in salinity, possibly due to freshwater influxes from rivers or seasonal changes (Okosun, 1995). This could point to estuarine or deltaic influences in certain areas of the basin, where the mixing of fresh and saltwater created brackish conditions favorable for these species (Adebambo *et al.*, 2023). Based on our findings the diversity of ostracod species in the Sokoto Basin during the Paleocene suggests a stable and productive marine ecosystem. The presence of species from different ecological niches indicates a well-balanced environment with various trophic levels and interactions. Such diversity also implies that the basin had a range of microhabitats, each supporting different communities of organisms. This ecological complexity has provided resilience against environmental changes, maintaining overall ecosystem stability. The varied marine environments suggest a warm and humid climate, conducive to maintaining high sea levels and diverse marine habitats. This is line with works of Youssef *et al.* (2017). The presence of brackish water species also indicates periodic freshwater influxes, possibly due to seasonal rains, which has further enriched the ecological diversity of the basin.

4.6 Implications for exploration efforts

The combined evidence from lithology, and carbonate microfacies and ostracod analysis of BH 2051 in the Sokoto Basin is promising for hydrocarbon exploration. The identified lithology in the borehole section offers clues about potential hydrocarbon reservoirs and source rocks. The dark grey shales and claystones of the Dange Formation (lower unit) could serve as potential source rocks rich in organic matter for hydrocarbon generation. The overlying Kalambaina Formation's limestone section (middle unit) indicates a shallow marine environment suitable for the formation of porous carbonate reservoirs. The microfacies analysis provides valuable insights into reservoir quality. Mudstone facies might act as impermeable caprocks, hindering hydrocarbon migration (Lucia, 2007). Conversely, wackestone and packstone facies, especially those containing bioclasts, often exhibit good porosity and permeability, making them potential reservoir rocks and this is in line with works of Toyin *et al.* (2015) and Worden *et al.* (2018). The presence of marine anoxic ostracods, particularly *Paracosta parakenfensis*, *Bairdia ilaroensis*, *Bairdia aegyptiaca*, *Cytherella sylvesterbradleyi* and *Buntonia beninensis*, supports a historical marine environment (Youssef *et al.*, 2017; Okosun, 1995; Reyment, 1981). Marine environments are often prospective for hydrocarbon exploration as they can host source rocks, reservoir rocks, and caprocks necessary for oil and gas accumulation. Overall, the combined data suggest a potential hydrocarbon system in the Sokoto Basin. The presence of marine ostracods, organic-rich lithology warrants further exploration efforts, including geochemical analyses and geophysical surveys, to delineate potential hydrocarbon accumulations.

5. Conclusion

The Sokoto Basin shows strong potential for hydrocarbon development due to its favorable sedimentary and geological framework. Analysis of BH 2051, which penetrates a 32.5-meter sedimentary sequence, reveals key lithostratigraphic units and microfacies types critical for potential hydrocarbon systems. These units, progressing from low-energy to dynamic shallow marine environments, include the Dange Formation shales and claystones, the Kalambaina Formation bioclast-rich limestones, and the Gamba Formation claystones and shales. The microfacies data reveals dominant microfacies types such as mudstone, lithoclastic wackestone, lithoclastic packstone, bioclastic wackestone, and peloidal bioclastic packstone in BH 2051 of the Sokoto Basin.

A dynamic Paleocene marine ecosystem and ecological niches within depths intervals of 2 to 32.5 m revealed *Bairdia ilaroensis, Trachylebris teiskotensis, Cytherella sylvesterbradleyi, Cytherella* sp., *Paracosta cf. warensis, Buntonian beninensis*, and *Cytherelloidea* sp., respectively as dominant ostracod species in the BH 2051. The presence of *Paracosta parakenfensis*, *Bairdia ilaroensis* and *Bairdia aegyptiaca*, revealed a marginal marine environment with fluvial interferences that impacted by sporadic inflows of freshwater. The dark-rich shales in the Dange Formation and the bioclast-rich limestone of the Kalambaina Formation are potential source and reservoir rocks which are pointer to potential hydrocarbon system in the Sokoto Basin.

Future exploration in the Sokoto Basin should include geochemical and geophysical surveys to validate its hydrocarbon potential. Integrating lithological, microfacies, and paleoecological data has provided insight to the depositional history and hydrocarbon prospects of the area.

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Authors Contribution

Both authors involved in the research design, laboratory analyses and physical examination of samples, drafting and proof reading of the manuscript.

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