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Article

Geology occurrence and uses of limestone deposit in Kalambaina Formation Sokoto Basin, Northwestern Nigeria

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Abstract

Glamorous measures and mineralogical and geochemical studies were carried out on face soil samples in order to delineate vulnerability distribution and to find possible connections grounded on paleomagnetic counteraccusations in some parts of Kalambaina Area of Sokoto Northwestern Nigeria. Geomorphologically, this area is generally gentle, with sometimes irregular, limited by resistance laterites. Elevation generally decreases towards the northwest around the Nigeria- Niger Republic lessee with an average elevation of about 215 above mean ocean position. An aggregate of 90 samples was measured at arbitrary with DSM -10 vulnerability Kappa meter as well 20 core drilling samples were collected for further XRF geochemical analysis. Mass-specific vulnerability value ranges between 11.2 × 10 and 1.4 − 8.2 × 10 and glamorous remanence at 1 values range between 10 × 10 and 0.5 − 9.0 × 10 as well as 0.5 − 7.4 × 10. Chemical analysis by Xray luminescence analysis revealed the presence attention of colorful rudiments with their chance composition() and the chance composition of calcium carbonate content between> 40 and< 70,> 70 and< 80, core drilling depth and overload consistency of a limestone Subcaste and Overburden. Has also revealed low- and high-grade calcium carbonate content.

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Magnetic measurements; fluorescence analysis; paleomagnetic; Kalambaina; Sokoto

Introduction

The kalambaina limestone is located within the Sokoto basin, which is part of a large intracratonic lullemmedin basin the sediment is dominated by calcareous benthic, few arenaceous, and planktic foraminifera and the Kalambaina formation was chosen as an ideal area for study because it contains a rich and fairly diverse benthic foraminifera assemblages quantitative studies of the foraminifera species in this work provide the data for the paleoecological studies the species diversity, planktic/benthic ratio, and population composition are considered, the sediment of the sokoto basin constitute one tenth of the lullemmedin basin [1]. The lullemmedin basin is an extensive elongated sedimentary and structural basin, which trends NW direction from Nigeria in to the republic of Niger [2] the main feature in the sokoto sector is the ‘’Dange Scarp ‘’the regional dip is low with a WNW trend the sokoto basin has been affected by a series of marine transgressions during the Mesozoic and Tertiary, [3] resulting in deposition of a sequence of sediments these transgressions progressively affected a greater portion of the basin, resulting in overlap series

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towards the south the sediments of the basin overlie the basement complex the kalambaina formation which belong to the sokoto group, was deposited during the Paleocene [4]; the foramineferal paleoenvironment different types of characteristics benthic foraminifera have been used in the past for delineation of the paleoenvironments of the upper Paleocene sediment of the kalambaina formation Qualitative and Quantitative studies on fomineferal composition has been carried out . The fauna listed by previous workers represented a specific composition of about 20-25 species. This study permitted the identification of additional species totaling 33 species dominated by calcareous benthic the paleoecological interpretation the Sokoto basin in north western also known as lullemmedin basin is a cratonic sedimentary young Mesozoic-Cenozoic Basin in part of West Africa formed by marine transgression which was overlain by the Sokoto group of sediments. Using major and trace element analysis will help in bringing out a better understanding of the origin and the depositional environment of the limestone bed in the basin and also give a clue in future studies to find out more potentials of the basin. Major and Trace elements have been used to determine the origin and deposition of some basins in Nigeria such as Bida Basin, and Benue Through.

Scope and Methodology

A study to determine the suitability of the low-grade Kalambaina limestone deposit for glass-making has been carried out. Samples were collected from four different locations. The representative samples were analyzed and characterized to determine the chemical composition, mineral phase, and microstructural morphology using X-ray fluorescence (XRF), X-ray Diffraction (XRD), and Scanning Electron Microscopy (SEM) respectively. The results of the XRF showed that the deposit consists of 45.66 wt% CaO, 0.38 wt% MgO, 0.35 wt% Fe2O3, 0.22 wt% Al2O3, 1.13 wt% SiO2, 0.19 wt% TiO2 and the amount of material lost on ignition was 42.99% (LOI). Qualitative and quantitative XRD analyses revealed that calcite was the dominant mineral followed by quartz which occurred as the lesser phase. The percentages of calcite and quartz in the sample were 99.23 wt% and 0.77 wt% respectively. SEM/EDS analysis depicted the major elemental composition of the deposit and then the SEM-micrograph demonstrated the spherical calcite dust as a dominant phase. The composition of the limestone deposit compared favorably with the standard except for the high concentration of iron oxide (0.35 wt%) which is objectionable but the concentration of iron oxide is still tolerable for making green container glass (0.96 wt%). Notwithstanding, low-grade Kalambaina limestone can be upgraded through beneficiation to minimize the iron oxide concentration”[5].

The Geology of Sokoto Basin

The Sokoto Basin, situated in the southeastern region of the extensive Iullemmeden Basin, extends its geological influence across northwestern Nigeria, most of Niger Republic, Benin Republic, Mali , Algeria, and Libya [6]. Within Nigeria, it encompasses Zamfara, Sokoto, and Kebbi States [4], [6] Geologically, it is closely related to other sedimentary basins in Nigeria, forming part of the inland basins. These basins share historical connections with Cretaceous and tertiary subsequent rift basins in Central and West Africa, associated with the opening of the South Atlantic Ocean [7]. The geological studies of the Sokoto Basin have been extensively documented in the works [8], [7],[4], [6], [9], and [5.]The Sokoto Basin predominantly comprises gently undulating plains, with elevations averaging between 250 meters to 400 meters above sea level. These plains are occasionally interrupted below. Notably, the Dange

Scarp stands out as a prominent geological feature in the basin and is closely tied to its geology [10] Stratigraphically the Sokoto Basin exhibits a sequence starting from the Illo and Gundumi Formation at the base followed successively upwards by the Taloka, Dukamaje, Wurno, Dange, Kalambaina, Gamba, and Gwandu Formations. While the overall geological framework remains consistent with previous descriptions this study has identified previously unreported tectonic structures within the basin. The Sokoto Basin gradually thickens and gently dips towards the northwest, with its maximum thicknesses occurring near the border with Niger Republic [11]. Within the Continental Intercalary, there are lacustrine carbonaceous shales with the potential to serve as source rocks. However, the primary source rock of significance in the Sokoto Basin is the Dukamje Formation (Maastrichtian), which corresponds to the Nkporo Shale in the Anambra Basin and the Enagi and Patti Formation in the Mid-Niger (Bida) Basin [17], [18]. Additionally, various sandstone facies present in all formations, coupled with extensive carbonate deposits in the Kalambaina Formation, possess the potential to a reservoir rocks. Serving as regional seals are the Dange and Gamba shales, as well as the thick clays within the Gwandu Formation [6]. In the area, multiple folded and reversed fault structures have been identified particularly along the Goronyo-Taloka road, through the examination of outcrops and exposed sections [15].

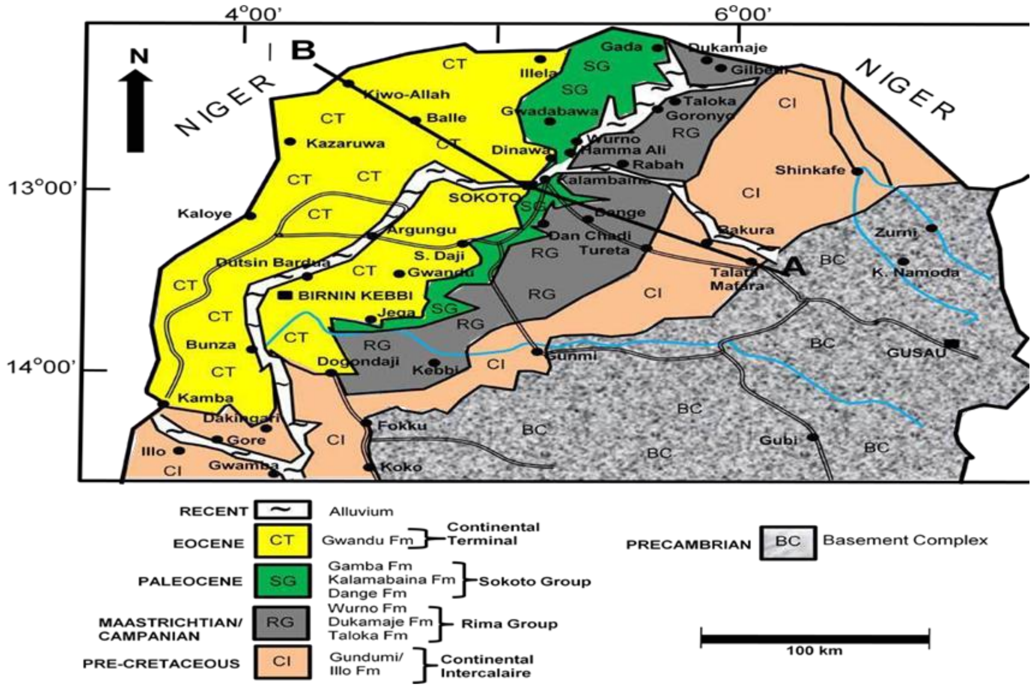

Figure 1. Geological Map of the Sokoto Basin (Nuhu George Obajeetal 2020).

Geological of Kalambaina

The Sokoto Basin in northwestern also known as Lullemmeden Basin, is a cratonic sedimentary young Mesozoic-Cenozoic basin in part of West Africa. Formed by marine transgression which was overlain by the Sokoto group of sediments. Using major and trace element analysis will help in bringing out a better understanding of the origin and the depositional environment of the limestone in the basin and also give a clue in future studies to find out more potentials of the basin Major and trace elements have been used to determine the origin and depositional environments of some basins in Nigeria such as Bida Basin and Benue Trough. The objective of this study is to ascertain the quantity, quality, and history of the limestone to see its economic value for industrial purposes The Kalambaina formation of the Sokoto basin consists of limestone, shale, clay, marl, and laterite as the major content of the topsoil signifying marine history The kalambaina formation is calcareous and very rich invertebrate Fossils. Some of these fossils found in Kalambaina formation are brachiopods, bivalves, mollusks, echinoderms, ammonite.

Figure 2. Fossil: cast of gastropod

Figure 3. Fossil: cast of ammonite

Figure 4. Fossil: cast of bivalve shell

Figure 5. Fossil: mold and cast of bivalve mollusc

Figure 6. Fossil: mold echinoderm

Figure 7. Fossil: mold of mollusks

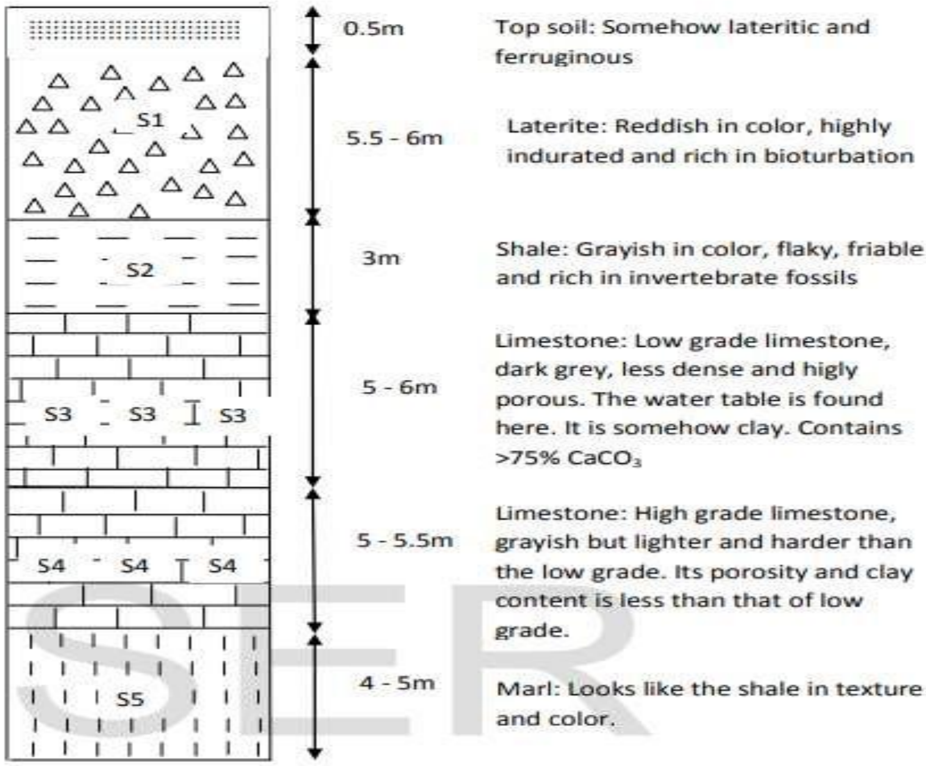

Figure 8. Soil Profile of a Type Section of Kalambaina Formation

Sokoto Sedimentary Environments and their Depositional History

The Maastrichtian Rima Group and the Palaeocene Sokoto Group of sediments outcrop in the Sokoto Basin in northwestern Nigeria, and form the southeastern sector of the Lullemmeden Basin. The latter is one of the young Mesozoic-Cenozoic inland cratonic sedimentary basins of West Africa. The Rima Group is deposited by Maastrichtian marine transgression and is overlain by sediments of the Sokoto Group. Several authors including 2, 4, 7, 9, 13, 20 studied the cretaceous and Palaeogene sediments of the Sokoto Basin. The sediments are observed to be dipping gently and thickening gradually towards the northwest, with a maximum thickness of over 1 000 meters near the frontier of the Niger Republic. These authors have suggested several geological successions. The previous work covers mainly the stratigraphy, sedimentology, paleontology, and geochemistry of the Basin. Ref.1 used the palaeontological aspect in the determination of the depositional environment. However major and trace elements have not been used in the determination of the origin and depositional environment of these sediments. Major and trace elements are of great importance in ascertaining the origin and depositional environment of sediments within a basin. This can be used in conjunction with other results like TOC, rock evaluation parameters, and petrographic study to determine the potential of basins as source rock for petroleum. Major and trace elements have been used to ascertain the origin and depositional environments in other basins in Nigeria, e.g., Benue Trough.1,5 The aim of this study is to investigate the provenance and environment of deposition of the upper Cretaceous to Palaeocene sediments of Sokoto Basin using major and trace elements. This involves the evaluation of elemental variations, sediments maturity, application of discriminant function for provenance, etc. The Iullemmenden Basin is entirely a cratonic basin created by tectonic pyrogenic movements or stretching and rifting of tectonically stabilized crust during the Palaeozoic. These movements became evident from the beginning of the Palaeozoic and continued until the Upper Cretaceous when the opening of the Goa Trench was achieved. These movements are responsible for the SW progradation of the sediments deposited within the basin.

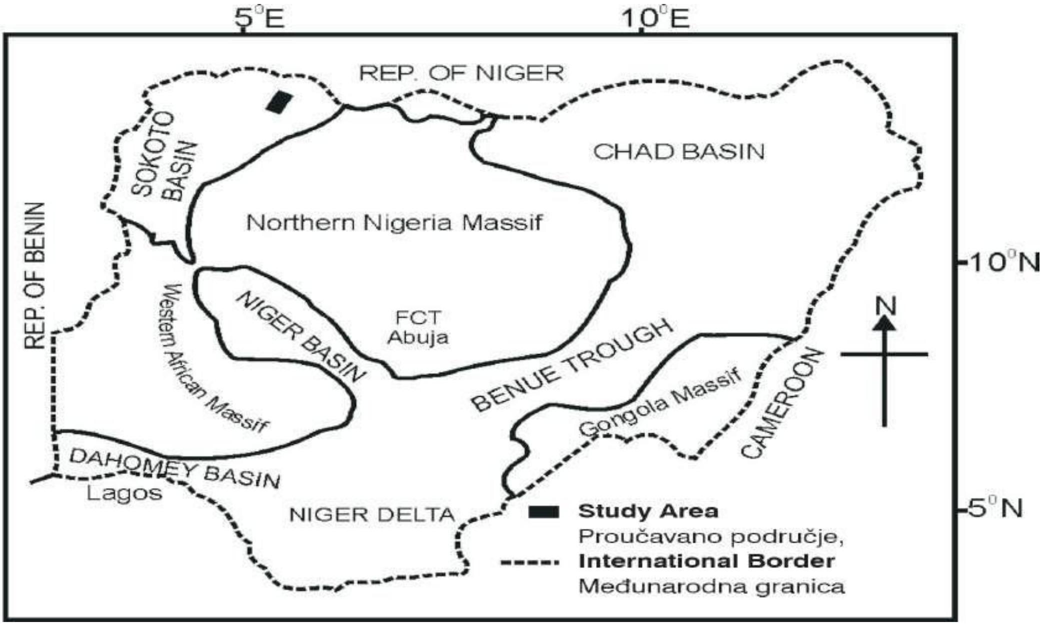

Figure 9. Geology map of Nigeria showing the study area

They become progressively younger as one moves towards the SW (Nigeria) from the north where it is referred to as the Sokoto Basin (Figure 1). In northwestern Nigeria, the sediments of the Iullemmeden Basin were deposited during three main phases of deposition which include the continental Mesozoic and Cenozoic phases, with an intervening marine Maastrichtian to Palaeocene phase. The sedimentary rocks of the Sokoto Basin have been classified into four main groups (Table 1). The pre-Maastrichtian (Lower

Cretaceous) sediments are of fluviatile and lacustrine origin. They belong to the Gundumi and Illo Formations which extend northwards into the Republic of Niger. The second phase in the depositional history of the northwestern Nigerian basin began during the Maastrichtian when the Rima Group was deposited unconformably on the Lower Cretaceous sediments as the Taloka, Dukamaje and Wurno Formations. The Taloka Formation also referred to as the lower sandstone and mudstone and lignite9, consists of interbedded grey to dark brown mudstone and light- coloured, medium to fine-grained sand with some thick bands of carbon carbonaceous shale or lignite.11 The Dukumaje Formation consists predominantly of shales with some limestone and mudstones. The shales contain numerous fragments of vertebrates and limb bones. A richly fossiliferous bone bed lies near the base. In refs.10, and 13 stated that the Dukamaje Formation is locally gypsiferous. The Wurno Formation consists of thin, friable, fine-grained sandstone intercalated with soft mudstone and siltstones.11 it is very similar to the Taloka Formation.

The Rima Group is overlain by the Sokoto Group belonging to the Upper Palaeocene age.16 The Sokoto Group consists of three formations (Table 1) namely Dange Formation (oldest), Kalambaina Formation, and Gamba Formation (youngest). The Dange Formation forms the base of the Sokoto Group of sediments. It consists of slightly indurated bluish-grey shale interbedded with thin layers of yellowish-brown limestone. The contact between the Wurno Formation (Maastrichtian) and Dange Formation (Palaeocene) can be seen at Dange village, characterized by a well-exposed erosional plane marking the top of the Wurno Formation. The contact marks the Cretaceous- Palaeogene boundary. The Kalambaina Formation (Table 1) overlies the Dange Formation. It consists of white, marine, clayey limestone and shale. The formation is rich in vertebrate fossils.11,21,25 The name Gamba Formation was proposed by.12 The formation consists of grey laminated shale overlying the calcareous Kalambaina Formation. The shales appear to be folded due to removal by a solution of the underlying limestone and the slumping of the overlying beds.

The Upper Palaeocene marine sediments of the Sokoto Group are overlain disconformably by a thick series of deposits consisting predominantly of red and mottled massive clays with sandstone intercalations. These sediments belong to the Gwandu Formation with its type section and type area (lat. locus typicus) in the Gwandu emirate of Nigeria.11 Ref.17 assigned a possible Eocene age to the Gwandu Formation based on palynological parameters.

Lithology and Mineral Composition of Limestone Deposits

The Kalambaina Formation in the Sokoto Basin of northwestern Nigeria consists primarily of white, highly fossiliferous limestone interbedded with marl. The limestone is composed of over 95% calcite, with trace amounts of recrystallized fossil fragments of planktonic foraminifera and mollusks, weakly deformed greenish glauconite grains, and traces of iron oxide minerals, quartz, and feldspar. Petrographic analysis indicates that the limestone exhibits characteristics typical of bioclastic wackestone and packstone microfacies, with less than 10% grains, classifying it as mudstone. Geochemical analyses show a range of SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, and MnO values. The limestone is underlain by dark grey shale of the Dange Formation. Shale interlayers are present in some limestone beds, while others are free of shale. The limestone is massive, with dry surface outcrops.

The Paleocene rocks of Kalambaina limestones and the underlying marine shales intersected by the Illela borehole belong to the Kalambaina and Dange Formation respectively. The Illela bore is situated in the NNW part of the Sokoto Basin bordering Northern Nigeria and the Niger Republic. The Sokoto Basin represents the south-eastern extension of the trans-saharan Paleocene transgression of the Tethys [15]. Lithostratigraphically, the sediments from the borehole comprise the lower marine shales, the interbedding limestones, and the upper continental intercalation of siltstones, mudstones, and ironstones. Carbonate sediments are particularly sensitive to environmental changes; their sedimentation is rapid but easily inhibited [16]. Temperature variations influence biogenic activities and affect sediment production; thus most carbonate production is strongly depth-dependent. Carbonate reservoirs are considered to be extremely challenging in terms of accurate recovery prediction because of their complexity and heterogeneity. When conditions are favorable for carbonate sedimentation, organic productivity is high; when unfavorable, it ceases. Carbonates form within the basin of deposition by biological, chemical, and detrital processes. The texture of carbonates is more dependent on the nature of the skeletal grains than on external influences. Carbonate minerals are susceptible to rapid dissolution, cementation, recrystallization, and replacement at ambient conditions in a variety of diagenetic environments [12] Biofacies and lithofacies often correlate, in other words, organisms produce typical lithofacies. Substrates control inhabiting organisms. Basin configuration and the energy level of water are other dominant controls on carbonate deposition. Organic productivity varies with depth and light (photic zone); upwelling and water agitation also influence organic productivity. Deep carbonate reservoirs commonly contain evaporate nodules [13].

The most abundant carbonate form, calcite is chemically unstable and is hence susceptible to change by transformation into other carbonate minerals such as siderite, dolomite, etc [14]. In this research work, an attempt has been made to classify the various facie types present in the carbonate rocks, deduction of their depositional environment and reservoir potentials, correlation of the depositional environment of both the carbonate rocks and shale units, and also to relate the area of study to other African basins paleobiogeographically.

Stratigraphy and Structure of the Kalambaina Formation

The Kalambaina Formation, part of the Sokoto Basin, is primarily composed of white, highly fossiliferous limestone and interbedded marls, deposited during the late Palaeocene. It overlies the Dange Formation, which consists of grey to dark grey shale. The formation is characterized by a gradual transition from marine to continental deposits, with limestone thickness varying across the basin. Stratigraphically, the Kalambaina Formation is situated within the Sokoto Group, which includes the Dange and Gamba Formations. The sediments dip gently northwest, becoming younger in that direction, and exhibit features such as caves and caverns due to dissolution processes. This formation is significant for its fossil content and potential as a reservoir rock in hydrocarbon exploration.

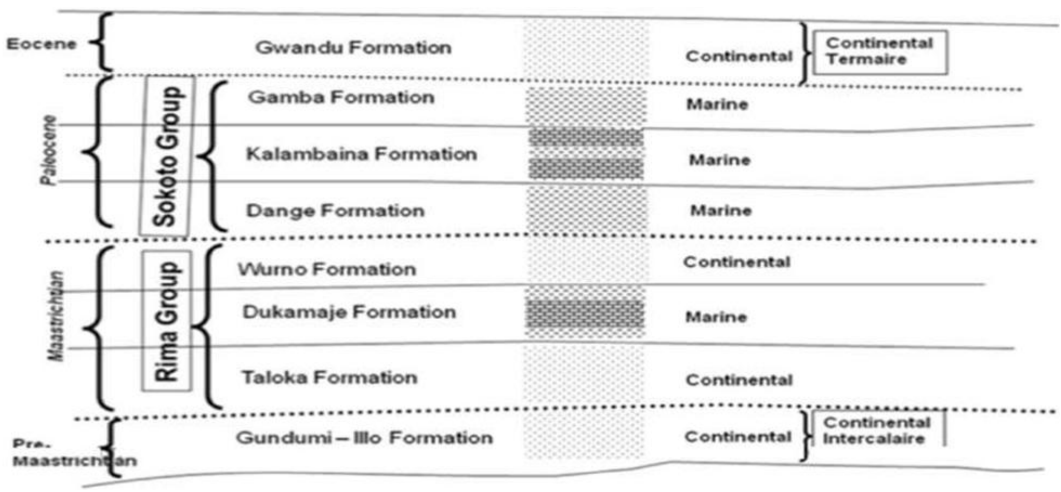

Figure 10. Stratigraphic successions in the Nigerian sector of the Iullemmeden Basin (Sokoto Basin) adopted from Obaje et al., 2004

Figure 11. Stratigraphic section of Kalambaina formation (Offodile, 2002)

Occurrences of Kalambaina Formation

The occurrence of the Kalambaina Formation in the Sokoto Basin is attributed to a complex geological history. The Sokoto Basin, located in northwestern Nigeria, is a sedimentary basin formed during the Pan-African orogeny, which occurred around 600 million years ago. The Kalambaina Formation is part of the sedimentary sequence within the Sokoto Basin. It is composed of various types of sedimentary rocks, including sandstones, shales, and mudstones. These rocks were deposited during the Permian period, approximately 298 to 252 million years ago. The deposition of the Kalambaina Formation was influenced by a combination of tectonic, climatic, and environmental factors. During the Permian period, the Sokoto Basin experienced a transition from a marine environment to a terrestrial setting, resulting in the accumulation of sediments such as sand and mud. The Kalambaina Formation is known for its economic significance due to the presence of hydrocarbon resources. Petroleum exploration activities have been conducted in the Sokoto Basin, targeting potential oil and gas reserves within the Kalambaina Formation. However, it is important to note that the commercial viability of these resources is still being evaluated and further exploration is required. The Kalambaina Formation in the Sokoto Basin is a result of geological processes that shaped the basin millions of years ago. The understanding of its geological characteristics and hydrocarbon potential is crucial for further exploration and development in the area. The formation of the Kalambaina Formation in the Sokoto Basin can beat tribute to several geological processes that have shaped the region over millions of years. These processes include:

1. Sedimentation: The deposition of sediments, such as sand, mud, and organic matter, played a crucial role in the formation of the Kalambaina Formation. Sedimentation occurs when eroded material is transported and settles in a particular area. In the case of the Sokoto Basin, sediments were sourced from surrounding land masses and carried by rivers, wind, or other geological agents before being deposited in the basin.

2. Tectonic Activity: Tectonic forces have significantly influenced the formation of the Kalambaina Formation. The Sokoto Basin is located within a region that has experienced various tectonic events throughout its history. These events include continental collisions, rifting, and faulting. The movement of tectonic plates, along with associated uplift and subsidence, contributed to the creation of the basin and the subsequent deposition of sediments.

3. Diagenesis: Diogenes refers to the physical and chemical changes that occur within sedimentary rocks after they are deposited. Over time, as these dements of the Kalambaina Formation were buried deeper within the Earth's crust, they underwent diagenetic processes such as compaction, cementation, and lithification. These processes helped transform loosely packed sediment into solid rock, consolidating the Kalambaina Formation.

4. Erosion and Weathering: The exposed rocks of the Kalambaina Formation have been subject to erosion and weathering processes over millions of years. External forces such as wind, water, and temperature fluctuation have gradually worn down the rocks, shaping the formation into its present-day features. Erosion and weathering play a significant role in exposing the underlying geological layers and making them accessible for study and exploration. It is important to note that the aforementioned processes are inter connected and often occur concurrently or sequentially over long periods of geologic time. The combination of sedimentation, tectonic activity, diagenesis, erosion, and weathering has contributed to the formation and subsequent geological characteristics of the Kalambaina Formation in the Sokoto Basin.

Limestone and Marble Formation. Limestone is formed either by direct crystallization from water (usually seawater) or by accumulation of shell and shell fragments. All limestone forms from the precipitation of calcium carbonate from water. Calcium carbonate leaves solutions in many ways and each way produces a different kind of limestone. All the different ways can be classified into two major groups: either with or without the aid of a living organism (that is, either by organic or inorganic processes). Most limestone is formed with the help of living organisms. Many marine organisms extract calcium carbonate from seawater to make shells or bones. Mussels, clams, oysters, and corals do this. So too do microscopic organisms such as foraminifera. When the organisms die their shells and bones settle to the seafloor and accumulate there. Wave action may break the shells and bones into smaller fragments, forming carbonate sand or mud. Over millions of years, these sediments of shells, sand, and mud may harden into limestone. Coquina is a type of limestone containing large fragments of shell and coral. Chalk is a type of limestone formed from the shells of microscopic animals. Limestone can also be formed without the aid of living organisms. If water containing calcium carbonate is evaporated, the calcium carbonate is left behind and will crystallize out of the solution. For example, at Mammoth Hot Springs in Yellowstone National Park, hot water containing calcium carbonate emerges from deep underground. As the hot water evaporates and cools, it can no longer hold all of the calcium carbonate dissolved in it and some of it crystallizes out, forming limestone terraces. The limestone formed from springs is called travertine. Calcium carbonate also precipitates in shallow tropical seas and lagoons where high temperatures cause seawater to evaporate. Such limestone is called oolite. Marble is a form of limestone transformed through the heat and pressure of metamorphism into a dense, variously colored, crystallized rock.

Physical and Chemical Properties. The principal component of limestone is the mineral calcite, but limestone frequently also contains the minerals dolomite [$CaMg(CO3)2$] and aragonite ($CaCO3$). Pure calcite, dolomite, and aragonite are clear or white.However, with impurities, they can take on a variety of colors. Consequently, limestone is commonly light-colored; usually, it is tan or gray. However, limestone has been found in almost every color. The color of limestone is due to impurities such as sand, clay, iron oxides and hydroxides, and organic materials. Colorful streaks in marble are the result of impurities such as quartz or dolomite in the original limestone, which result in the formation of minerals such as forsterite (or serpentine). If the limestone contains other materials such as sand and clay, the calcite will react with them to produce minerals such as tremolite, epidote, diopside, and grossular garnet. The strength of limestone and marble is the measure of its capacity to resist stresses and it depends on the rift, hardness of grains, state of aggregation and degree of cohesion and interlocking of grains, etc. The crushing strength of Nigerian limestone and marble varies between 8,000 and 27,000 psi (563 to 1,899 kg/cm2). The average specific gravity of Nigerian limestone and marble varies from 2.70 to 2.86. The surface of marble crumbles readily when exposed to a moist, acid atmosphere, but marble is durable in a dry atmosphere and when protected from rain. The purest form of marble is statuary marble, which is white with a visible crystalline structure. The distinctive luster of statuary marble is caused by light penetrating a short distance into the stone and then being reflected from the surfaces of inner crystals. When a drop of dilute hydrochloric acid is placed on a piece of limestone, the acid reacts with the calcite and forms bubbles of carbon dioxide. Calcite ($CaCO3$) of which marble is composed is highly susceptible to attack by acid agents. Marble is readily dissolved by acids, even very dilute acids. However, dolomite marble is much more resistant to acid attack than calcite marble.

How Limestones Mined

The mining of limestone typically occurs through surface quarrying or open-fit mining methods. This involves the removal of overburden material that overlies the limestone and extraction of limestone with the help of an excavation machine low grade and high-grade limestone, then crushing and processing it into a variety of products. Limestone is the raw material used in cement production and is due to underground geological formations called aquifer which holds and transmit water. Therefore, the extracted limestone that contains moisture was transferred by dump truck to an open space of dehydration which is called material handling. The limestone is classified based on: Low grade is due to white amorphous, soft, and less than 74% (65-75%) caco3) while high–grade = which is whitish, crystalline hard, shining, and 75% and above. The main 35% percentage of limestone constitutes some pounds like silica, alumina and ferric oxide, etc, which serve as correcting layers called bedrock (marl) and grayish clay which constitute a high percentage of correcting materials (CCNN). *(Nigeria–Limestone/Marble.pp.1–17.)*

Uses of Limestone

The limestone has a wide range of uses across various industries due to its characteristics. Here are some common uses of limestone:

1. Construction Materials: Limestone is a key component in the production of cement and concrete. It is used as an aggregate in concrete, abase material in road construction and as a building stone for construction projects.

2. Industrial Applications: Limestone is utilized in various industrial processes, such as in the production of steel, glass, and paper. It is used as a flux in steel making, as a raw material lass manufacturing, and in the production of paper and pulp.

3. Agricultural Ground Amendment: Limestone is often ground into a fine powder known as agricultural lime. It is used to improve soil quality by balancing pH levels and providing essential nutrients for crop growth.

4. Environmental Remediation: Limestone is used in environmental applications, including the treatment of acidic mine drainage and flue gas desulfurization in power plants to reduce air pollution. Given the potential presence of limestone in the Kalambaina Formation, it could serve as a valuable resource forth construction, industrial, agricultural, and environmental sectors.

Figure 12. The extraction of limestone.

Factors influencing the distribution of limestone deposits

The distribution of limestone deposits is influenced by several key factors:

Marine environments: Limestone predominantly forms in shallow marine environments where calcium carbonate-rich materials from marine organisms accumulate over extended periods.

Continental shelves: Many limestone deposits are found on continental shelves, where shallow water conditions favor the buildup of calcareous sediments.

Karst landscapes: Limestone terrain features like sinkholes, caves, and underground river systems develop due to the dissolution of limestone by acidic groundwater in karst landscapes.

Geological and environmental conditions: The global distribution of limestone is influenced by local geological and environmental factors. Notable limestone-rich areas include the United States, the United Kingdom, France, China, the Caribbean islands, India, and parts of the Middle East.

Porosity and permeability: Porosity, which is the volume of pores to the volume of bulk rock, determines the amount of fluid that can flow through the limestone and is a major factor affecting its distribution.

Diagenesis: Physical and chemical changes during diagenesis, such as compaction, cementation, and mineral alteration, play a crucial role in the formation and distribution of limestone deposits.

Results or Findings

The results of major and trace element analysis are tabulated and used in the interpretation of the environment of deposition and source of the sediments.

Elemental analytical results

Important oxides analyzed in the study include SiO2, MgO, Na2O, K2O SO3, TiO2, CaO, NO3, Al2O3, Fe2O3 and FeO. SiO2, CaO, Fe2O3, and Al2O3 account for between 80% concentration in the samples. The Maastrichtian samples are dominantly rich in SiO2. Al2O3 and Fe2O3 and these major elements account for between 91.28% to 99.58% of the samples.

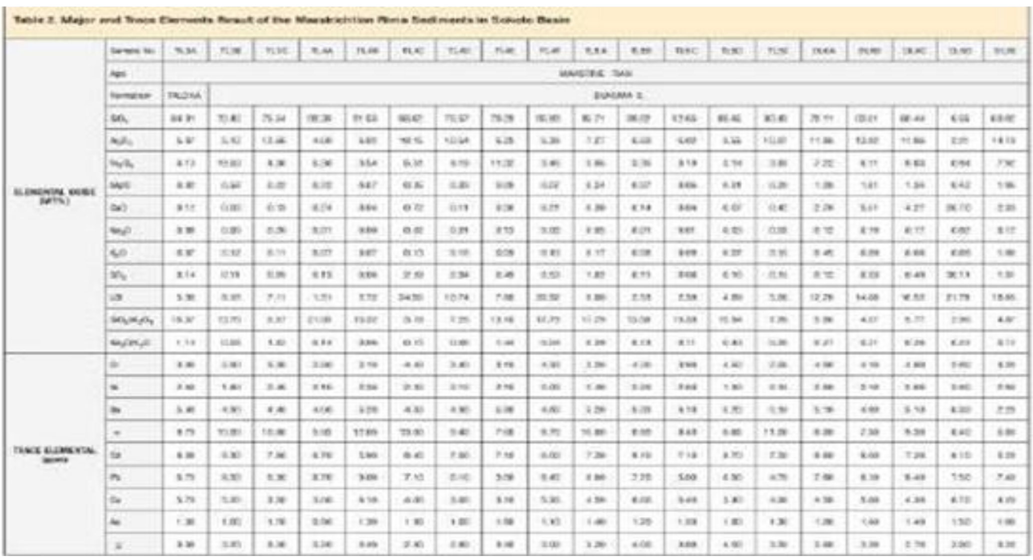

Table 2 shows the results of major and trace elemental analysis respectively for Taloka and Dukamaje Formations. The Taloka Formation has higher SiO2 values than the Dukamaje Formation, which is a reflection of differences in lithological components due to the differences in the environment of deposition. With the exception of Taloka lignite, the Dukamaje Formation, which contains a mud-shale suite has a little higher Al2O3 values than Taloka Formation. Figure 2 shows the composite log of Dukamaje and Taloka Formations. The siltstone at the top and mudstone at the base of the Taloka Formation yield the highest concentration of SiO2 values (99.38% and 95.89% respectively). There is a corresponding decrease in the Al2O3 values at these two levels which gives the formation a high SiO2/Al2O3 except for the Lignite samples (Figure 2). Generally, the ratio of SiO2/Al2O3 is high in all the samples from the Taloka Formation but low in samples from the Dukamaje Formation. That formation contains more CaO than the Taloka Formation because the former is made up of calcareous organic matter probably from the marine environment. Generally, the concentration of Fe2O3 in the Taloka Formation is high (average of 5.79%), which may be from the source rock, indicating the source rock contains some appreciable biotite and hornblende. It may also be an indication of oxidation conditions. The Taloka lignite and siltstone (TL4D) show more concentration of SO3 2 (2.57% and 2.04% respectively), which may be due to the mode formation of these beds which are deposited under anoxic conditions. Ref.21 described anoxia as probably a result of bottomwater stagnation due to the density stratification caused by a high input of terrigenous organic matter and poor circulation.

Table 3 shows the results of geochemical analysis obtained from samples of the Palaeocene sediments. SiO2, CaO, Fe2O3, and Al2O3 account for between 75% and 90% concentration in the samples. The SiO2 values ranges from 57.79 wt% to 59.98 wt% for shale samples in Gambia Formation, while this value ranges from 44.64 wt% to 62.28 wt% for samples from Dange Formation. The SiO2 value is low, ranging from 0.3 wt% to 0.5 wt%, for limestone from the Kalambaina Formation, while gypsum samples from the Dange Formation yield a value that ranges from 11.69 wt% to 25.07 wt%. These results are indication of low siliciclastic input for the limestone and gypsum samples. Al2O3 ranges from 10.01 wt% to 11.81wt% for the Gambia shales, 16.10 wt% to 21.81 wt% for Dange shales, 0.01 wt% to 0.02 wt% for limestone from the Kalambaina Formation, while it ranges from 5.41wt% to 18. 35 wt%, for gypsum samples from the Dange Formation. Clay samples from the Kalambaina Formation have Al2O3 values that range from 7.63 wt% to 30.30wt%. Alumina is a good maturity index. [20] regarded clay sediments as washed products of weathering and presumed that alumina, as the least mobile oxide, will tend to be in the most matured weathered residuum. The high alumina content in sediments from the Dange Formation shows that they are the most mature of the rock samples analyzed. F2O3 value ranges from 6.60 wt% to 7. 45 wt% for the Gamba shales, 5.12 wt% to 6.82 wt% for the Dange Shales, and 4.69 wt% to 6.28 wt% for gypsum sample in the Dange Formation while its value is low, ranging from 0.37 wt% to 0.38 wt% for the Kalambaina Limestone. Trace element contents were determined to assess possible relationships across stratigraphic profiles. Three groups of trace element associations can be identified from the Taloka Formation. The first group consists of Zn, Cd, Cr, and As, (Table 2) where they show the highest concentration in the Taloka lignite (TL4C). This may be due to low energy conditions during the deposition of the sediment, where processes of chemical transformation were greatly retarded. Leaching and weathering may be the factors that reduced the concentration of this group. The second group consists of Ba, Cu, and Hg (Table 2). They show a decrease in concentration in the Taloka Lignite (TL4C). The trends shown by both groups of trace elements across the profile (Figure 2) reveal probably by the difference in energy conditions during deposition and the environment of deposition across the stratigraphic profile. Ni falls into the third group, which shows no systematic variation with either lithology or depth, and the concentration is between 1.30 and 2.60 ppm. The Dukamaje Formation shows a decrease in the concentration of Ba, Cu, Cd, Zn, and Pb with depth. Sample No.DL6E shows the least concentration for the above trace elements, which may be due to leaching and diagenesis. The concentration of Ba is between 2.20 and 6.30 ppm while those of Zn and Pb are between 5.80 and 9.30 ppm, and 7.40 and 9.40 ppm, respectively. Cd concentration in the

Dukamaje samples analyzed is between 5.20 and 9.00 ppm and decreases with age (Table 2), thus supporting19 the hypothesis which states that Cd concentrations are greater in younger than older sediments. Gypsiferous shale (DL6D) shows an increase in the concentrations of Cu, Ba and Zn, and a decrease in the concentration of Cr, Hg and Pb, which may be due to the mode of deposition of the sediment.

Exploration Strategies and Methodologies used in the Sokoto Basin

The methodology of this study involves two phases. These are field studies for sample collection and laboratory analyses.

Field Study and Sample Collection

Rock outcrops in the area were studied across hills and pits and representative samples were collected for further laboratory analysis. For the Sokoto Group, 21 samples were collected from outcrops in two villages; Dange and Kalambaina via Sokoto. For the Rima Group, 19 samples representing two major formations namely; Taloka Formation (14 samples) and Dukamaje Formation (5 samples), were collected from three profiles. Spot sampling method was used in the field for sampling. Detailed composite lithologic descriptions of the samples were made.

Laboratory Analyses

This involves the determination of major and trace elements using x-ray fluorescence (abbr. XRF) and Atomic Absorption Spectrophotometric (abbr. AAS) methods. The X-ray fluorescence method was used to determine the concentration of a major element in order to infer the environment of deposition. The samples were pulverized for 60 seconds using Herzog Gyro-mill (Simatic C7- 621). Pellets were prepared from the pulverized sample; first by grinding 20 g of it with 0.4 g of stearic acid for 60 sec. Stearic acid is an organic binder that increases the mechanical stability of the sample. The 2 mm thick pellets were loaded into each sample holder of the x-ray machine (Phillips PW-1660) for analysis. This method operates on the principles of atomic physics and quantum chemistry. The specimens were exposed to the entire spectrum of photons consisting of primary radiation emitted from a standard X-ray tube which irradiated each specimen causing the element in it to emit secondary fluorescence with their characteristics of X-ray line spectra. The spectral line energies or wavelength of the emitted lines were used in the quantitative analysis of elements in the specimen. The intensities of the emitted lines were related to their elemental concentration.

Atomic Absorption Spectrometry (AAS)

This method is described in detail by 23 it is used for the determination of light elements with atomic numbers too low to be measured by XRF. Atomic absorption spectrophotometry is based on the observation that atoms of an element can absorb electromagnetic radiation. This occurs when the element is atomized and the wavelength of light absorbed is specific to each element. The rock samples collected were air-dried thoroughly. A representative rock sample of each was pulverized into fine powders of about 100 mesh size using a mortar and pestle. The mortar and pestle were washed and dried after grinding each sample so as to avoid contamination. The pulverized samples were carefully kept in small labeled test tubes to avoid misrepresentation. A wet method of digestion in nitric acid was used to determine TiO2 and the trace elements. In the wet digestion method, 0.5 g of powdered rock sample was weighed into a dry digestion tube, and 3 to 4 drops of distilled water were added to wet the sample. 5ml of hydrochloric acid (HCL) was added and the solution was stirred. 5ml of nitric/perchloric acid was prepared in the ratio of 3:2 and was added and stirred. The tube was left to stay overnight without heating. The samples were digested at a temperature of 120 °C in a hot water bath inside a fume cupboard. The solution was heated strongly until there was no fume coming out of the beaker. The samples were leached out with 5 ml of 6M hydrochloric acid (HCL) into a graduated test and were made up to 20 ml with distilled water. The content was shaken vigorously to avoid caking and the resulting solutions were referred to as the stock solution. All the test tubes were correctly labeled. The solutions were used directly to determine TiO2 and all the trace elements using AAS.

Depositional Environments

The result of the major elements analysis shows the Taloka Formation consisting predominantly of SiO2, Al2O3, and Fe2O3, which is an indication of high silt content. The SiO2/Al2O3 ratio also supports this. This means that the sediments are almost entirely fine-grained, usually mud, consisting of silt which is a characteristic pattern of distribution of tidal-flat sediments. Near the high water line and watershed, sediments are muddy and clayey. While near the low water line, the sediments are sandy. The reasons for this characteristic pattern of sedimentation of tidal flats are because of the energy and partly the transport mechanism. Near the low water line, the wave activity is strongest and active. It lasts longer as compared to higher parts of the intertidal zone; thus, the sand is enriched here. Lignite bed occurs at Taloka village, the type section for the Taloka Formation. The lignite yields the highest concentrations of SO3 which is an indication of the enriched presence of organic matter. Lignite occurrence is also of special environmental significance as it confirms the paralic nature of the depositional environments during the Maastrichtian in the Sokoto Basin.

The samples of the Dukamaje Formation consisting of laminated and non-laminated shales with thin bands of gypsum, represent the deeper marine sediments of the same sea. The major elemental interpretation shows these shales to have a low concentration of SiO2 and a high concentration of Al2O3, therefore the SiO2/Al2O3 ratio is low. This is an indication of low silt content which probably infers the marine environment. There is also a high concentration of CaO that suggests calcareous shale, from the marine environment.

Table 3. Major Elements Results of Paleocene Sokoto Sediment in Sokoto Basin

	Formation	Dange	Kalambina	Gamba						
	Age	Lower Paleocene			Middle Paleocene		Upper Paleocene			
	Lithology	Claystone	Shale	Gypsum	Shale	Limestone	Shale	Limestone	Marl	Clay
ELEMENTAL OXIDES (wt%)	SiO_2	37.56	61.47	25.07	59.98	0.30	57.79	0.50	17.51	60.16
	Al_2O_3	7.63	16.00	18.35	11.81	0.01	10.01	0.02	4.92	19.63
	FeO_3	2.48	7.31	8.28	6.60	0.38	7.45	0.37	1.55	5.19
	FeO	0.0014	0.0817	0.001	0.0017	0.0033	0.002	0.004	0.003	0.0013
	CaO	39.64	1.67	21.80	1.19	54.56	2.12	55.04	41.03	0.94
	MgO	1.80	1.96	1.52	6.81	0.34	7.63	0.37	2.22	1.15
	K_2O	0.17	1.13	0.66	0.43	0.05	0.43	0.05	0.22	1.12
	Na_2O	0.73	0.10	0.01	0.44	0.01	0.11	0.01	0.04	0.09
	SO_3	0.10	0.05	7.18	0.08	0.04	0.08	0.05	0.04	0.08
	TiO_2	0.004	0.0008	0.001	0.0005	0.003	0.001	0.00004	0.00004	0.00009
	NO_3	0.005	0.003	0.004	0.006	0.005	0.0014	0.005	0.004	0.004
	LOI	10.17	8.68	18.45	12.95	44.30	14.30	43.61	31.46	11.08
	Total	100.02	99.55	99.33	99.99	100.0	100.00	100.03	99.46	99.99
	SiO_2/Al_2O_3	4.92	3.84	1.37	5.07	30	5.8	2.5	3.6	3.1

The major elemental analysis of the gypsum reveals intertidal-lagoonal facies of transitional environment of deposition, probably in a lagoon cut off from the sea. As a result, evaporation caused the precipitation of gypsum, which is an example of sabkha. Clay and shale units with thin bands of muddy gypsum crystals were probably deposited in mud-rich sabkhas. Sediments of the mud-rich sabkhas were deposited in a belt parallel to the inner shelf and were better developed on the western side of the Sokoto Basin because of infiltration and evaporation of water in the lagoon, only mud was carried into it. However, the presence of dark phosphatic nodules, which is probably evidence of the replacement of gypsum by authigenic phosphate, suggests a shallow marine environment with access to the open sea at one side, where upwelling of phosphate as nodules, laminar or replacement of various forms of gypsum took place. Where such upwelling is common, particularly along the west coast of the continent, cold phosphate-rich water results and this leads to excessive phytoplankton bloom that poisons the water and causes mass mortality of fish; upon the death of the organism, more phosphate is contributed to the ocean floor via organic detritus. This is supported by the presence of a fossiliferous bed that has yielded fossil bones, including crocodilian skulls, and fish species, such as sharks and sawfish in the Sokoto Basin.

In other words, both Maastrichtian Formations are deposited in a transitional environment when the sea encroached the Sokoto Basin, during the Upper Maastrichtian, and the Taloka Formation represents the coastal plain sands and muds of the encroaching Maastrichtian Sea while the Dukumaje Formation represents a deeper marine facies of the same sea. For the Palaeocene sediments, the exceptionally high SiO_2, low Na_2O and K_2O content in the shale and gypsum sample is an indication of the deposition in shallow marine environment, where K_2O and Na_2O were in suspension and were later deposited further offshore.[1] The ratio of SiO_2/Al_2O_3 is low, lying between 3.1 wt% and 5.8 wt% for the Gamba and Kalambaina Formations and between 1.37 wt% and 3.87 wt% for the Dange Formation. The low value indicates lower silt content, suggesting therefore tendency toward marine conditions.[5] The clay and shale in the Dange Formation have a CaO value greater than 7.0 wt% which is indicative of a calcareous shale.[3] The high alumina content in sediments from the Dange Formation shows that they are the most mature of the rock samples analyzed. Alumina is a good maturity index. Ref. 22 regarded clay sediments as washed products of weathering and presumed that alumina, as the least mobile oxide, will tend to be in the most matured weathered residuum. The high values of Al_2O_3 (> 5.0 wt% on average) for the Dange and Gamba Formations is an indication of a reducing environment, while a low Fe_2O_3 for the Kalambaina Formation suggests an oxidizing depositional environment. The process of formation of iron in these sediments probably reduces iron from Fe^{3+} to $Fe^{2+} + e^-$ 6. This process takes place in a reducing environment. Skeletal fragments of mainly gastropods and ostracods show that the sediment was deposited in a shallow water environment, probably as subtidal-lagoonal facies. The presence of ooids shows these particles have been agitated and transported by a strong current, indicating a high kinetic energy in the deposition environment.

Conclusion

The Sokoto Basin in northwestern Nigeria is characterized by a diverse array of sedimentary deposits that lie atop Precambrian basement rocks, including gneisses, granites, phyllites, and quartzites. These sedimentary units, spanning the Upper Cretaceous, Palaeogene, and Quaternary systems, comprise materials such as clay, grits, mudstone, silt, silty sand, clay shale, lignite, limestone, gypsum, and alluvium. Rich in both vertebrate and invertebrate fossils, these units provide valuable geological and paleontological insights. The major elemental analysis of the Maastrichtian sediments, which form the Rima Group of the Sokoto Basin, highlights the following:

Taloka Formation (Lower Maastrichtian): Predominantly siltstones, chemically mature with a dominance of K-Feldspar and K-mica over albitic plagioclase, deposited under oxidizing conditions as indicated by high Fe2O3 concentrations. It also contains a lignitic bed deposited under reducing conditions.

Dukamaje Formation (Middle Maastrichtian): Composed of calcareous shale deposited in a marine environment with gypsum precipitates, showing stratigraphic variation in trace elements possibly due to differences in depositional environment, age, and lithological composition.

For the Palaeocene sediments, which include the Dange, Kalambaina, and Gamba Formations (Lower, Middle, and Upper Palaeocene, respectively), the elemental results suggest deposition in a reducing, shallow marine environment. These formations, part of the Sokoto Group, consist of shale, limestone, and gypsum.

Recommendations

Further Detailed Analysis: Conduct additional geochemical and petrographic studies to enhance understanding of the depositional environments and provenance of the sediments, focusing on minor and trace elements.

Paleoenvironmental Reconstruction: Utilize the fossil content and sedimentological data to reconstruct past environments, which can provide insights into the climatic and ecological conditions during the periods of deposition.

Exploration of Economic Minerals: Given the presence of gypsum, limestone, and lignite, evaluate the potential for economic exploitation of these resources within the basin.

Conservation of Fossil Sites: Implement measures to preserve fossiliferous sites within the basin, ensuring that valuable paleontological resources are protected for future scientific study.

Integration with Regional Geology: Compare the findings from the Sokoto Basin with adjacent sedimentary basins to develop a comprehensive regional geological model that can aid in broader geological and resource exploration efforts.

Declarations

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