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**MINERALOGICAL STUDY OF KALAMBAINA LIMESTONE AND ITS
INDUSTRIAL SIGNIFICANCE**

BY

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**A PROJECT SUBMITTED TO THE DEPARTMENT OF GEOLOGY, USMANU DAN
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SCIENCES, USMANU DANFODIYO UNIVERSITY SOKOTO, NIGERIA**

OCTOBER, 2025

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OCTOBER,2025

DECLARATION

I, ABDULSALAM SALISU, declare that this project work titled “MINERALOGICAL STUDY OF KALAMBAINA LIMESTONE AND ITS INDUSTRIAL SIGNIFICANCE” is my original work and has not been submitted in any way or form to any academic institution for the award of any degree. Information obtained from both published and unpublished sources has been duly acknowledged and referenced accordingly in the course of writing.

Salisu, Abdulsalam

Date

CERTIFICATION

This is to certify that this work titled “MINERALOGICAL STUDY OF KALAMBAINA LIMESTONE AND ITS INDUSTRIAL SIGNIFICANCE” was written by ABDULSALAM SALISU and submitted to the Department of Geology in partial fulfillment of the requirement for the award of Bachelor of Science (B.Sc.) Degree in Geology (Hons) at Usmanu Danfodiyo University, Sokoto.

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DEDICATION

This project is dedicated first and foremost to Almighty Allah (S.W.T.), the Most Gracious and the Most Merciful, for His guidance, protection, and countless blessings throughout my life and studies.

I also dedicate this work to the blessed memory of my late father, Malam Abdulsalam Adamu. May Allah forgive his shortcomings, grant him eternal rest, and reward him abundantly for the love, prayers, and sacrifices that shaped my path. *Amin.*

And to my beloved mother, Malama Adama Aliyu, whose love, patience, and unending prayers are the pillars of my strength — may Allah bless you with long life, good health, and peace of heart. *Amin*

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ABSTRACT

This study investigates the mineralogical composition, geochemical characteristics, and industrial potential of the Kalambaina Limestone within the Sokoto Basin, northwestern Nigeria. The research integrates field mapping, petrographic examination, and X-ray fluorescence (XRF) analysis to determine the quality and industrial suitability of the limestone. Field investigations revealed that the Kalambaina Formation consists predominantly of soft, whitish, fossiliferous limestone underlain by the Dange Formation and overlain by the Gwandu Formation, suggesting a Paleocene shallow marine depositional environment. Petrographic analysis of thin sections under plane- and cross-polarized light identified calcite as the dominant mineral, with minor dolomite, quartz, and clay minerals. The limestone displays a fine micritic matrix with patches of sparry calcite, indicating post-depositional recrystallization. XRF results show high CaO (76.60%) and low MgO (0.97%) contents, with minor oxides of SiO₂ (11.60%), Al₂O₃ (2.73%), and Fe₂O₃ (6.06%), confirming a chemically mature, high-calcium limestone. Trace element data, including elevated Sr and S values, reflect marine influence with limited terrigenous input. Integrating the petrographic and geochemical data indicates that the Kalambaina Limestone meets industrial-grade standards for cement and lime production, with additional potential for use in agriculture, metallurgy, and environmental management. The study concludes that the Kalambaina deposit is a high-quality, economically viable carbonate resource of national importance, and recommends further geotechnical and reserve quantification studies to enhance its sustainable utilization.

CHAPTER ONE

INTRODUCTION

1.0 Background of the study

Limestone is one of the most abundant and economically significant sedimentary rocks. It is composed primarily of calcium carbonate (CaCO_3), commonly in the form of the mineral calcite, and typically forms in shallow marine environments where biogenic debris—such as shells and skeletal fragments—accumulates alongside chemically precipitated carbonates (Dunham, 1962). Due to its chemical composition and physical characteristics, limestone has widespread industrial applications, including use in cement manufacturing, steel production, agriculture (as lime), glass making, water treatment, and various chemical processes (Obaje, 2009). However, the industrial utility of any limestone deposit is largely determined by its mineralogical composition, chemical purity, and physical properties such as porosity, grain size, and hardness.

This study focuses on the limestone deposits of the Kalambaina area, situated approximately 10 km southwest of Sokoto town in northwestern Nigeria. This region lies within the Sokoto Basin, a part of the extensive Iullemmeden Basin, which stretches across parts of Niger Republic and Nigeria. The Sokoto Basin is a broad sedimentary depression that developed during the Late Cretaceous to Tertiary periods and preserves a succession of both continental and marine deposits (Adeleye, 1971; Offodile, 1975). The accessibility of

Kalambaina by road and its proximity to Sokoto have made it a strategic location for quarrying and industrial limestone use, particularly in cement production.

The lithostratigraphy of the Sokoto Basin is well established, with several formations arranged in chronological succession. From oldest to youngest, these include the Illo and Gundumi Formations (Cretaceous continental sandstones), the Rima Group (comprising the Taloka, Dukamaje, and Wurno Formations), the Paleocene Kalambaina Formation, the Dange Formation, and the Eocene Gwandu Formation (Adeleye, 1971; Kogbe, 1976). The Kalambaina Formation, which forms the focus of this study, consists predominantly of soft, whitish to grey limestone, often interbedded with shale, marl, and occasional thin clay layers (Enu, 1987). This unit reflects variations in depositional energy and paleoenvironmental conditions during its formation.

Geological evidence indicates that the Kalambaina limestone was deposited in a shallow, low-energy marine shelf environment during a Paleocene marine transgression that inundated much of northwestern Nigeria (Kogbe, 1989). This setting promoted the accumulation of carbonate-rich sediments derived from marine organisms and chemical precipitation. Over time, post-depositional processes—such as compaction, cementation, recrystallization, and minor dolomitization—transformed these loose sediments into consolidated limestone (Obaje, 2009). In some areas, localized replacement of calcite by dolomite has occurred, further influencing the rock's geochemical behavior and industrial quality.

Mineralogically, the Kalambaina limestone is primarily composed of calcite, with varying amounts of dolomite, quartz, clay minerals (e.g., kaolinite, illite), and iron oxides or hydroxides such as hematite or goethite (Enu, 1987). These accessory minerals can affect

the color, reactivity, and overall quality of the limestone. For instance, quartz and clay minerals increase the silica and alumina content, which may reduce the limestone's suitability for cement production due to potential complications in kiln operations and clinker formation.

Economically, the Kalambaina limestone is of considerable significance. It serves as the main raw material for the Sokoto Cement Factory, one of Nigeria's earliest cement production plants, established in the 1960s and currently operated by BUA Cement Plc. The factory continues to play a vital role in Nigeria's construction sector, supplying materials for infrastructure development and housing. Beyond cement, Kalambaina limestone holds potential for diverse uses, including as a flux in steelmaking, a neutralizing agent in environmental management (acid mine drainage treatment), a filler in plastics and paints, and as lime in agriculture to improve acidic soils (Obaje, 2009). These varied applications make it a strategic mineral resource with both local and national economic relevance.

Despite the resource's importance, comprehensive mineralogical and geochemical investigations of the Kalambaina limestone remain sparse. Previous studies have primarily focused on regional stratigraphy, paleoenvironments, and lithology of the Sokoto Basin (Adeleye, 1971; Offodile, 1975; Kogbe, 1976), while only a few works have examined the limestone's detailed mineral composition, textural features, or industrial performance characteristics. This lack of detailed data presents a significant knowledge gap, particularly considering that even minor variations in mineral content can drastically influence the material's economic value and processing behavior.

For instance, limestone intended for cement manufacturing must meet specific requirements regarding silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and magnesium oxide (MgO) contents, as specified by standards such as the ASTM or Nigerian Industrial Standards (NIS). Similarly, high-purity limestone (over 95% CaCO_3) is sought after in industries such as pharmaceuticals, food processing, and chemical production. Therefore, a thorough mineralogical assessment is essential to evaluate the full industrial potential of the Kalambaina deposit.

In light of these considerations, the present study undertakes a detailed mineralogical and preliminary geochemical investigation of the Kalambaina limestone. Using thin section petrography to identify and describe the textures and mineral constituents, alongside X-ray fluorescence (XRF) analysis to determine the bulk chemical composition, this research aims to evaluate the limestone's industrial suitability. The integration of mineralogical and chemical data will provide insight into the quality, purity, and potential applications of the limestone. Ultimately, the study seeks to contribute to both academic knowledge and national development by informing the sustainable utilization of one of Nigeria's key limestone resources.

1.1 Study area description

The Kalambaina area lies to the south of Sokoto town in Sokoto State, northwestern Nigeria, within the Sokoto Basin, which is one of the major inland sedimentary basins of the country (Adeleye, 1971; Kogbe, 1976; Obaje, 2009). Geographically, the basin is located between latitudes $10^{\circ}30'\text{N}$ and $14^{\circ}00'\text{N}$ and longitudes $3^{\circ}30'\text{E}$ and $7^{\circ}00'\text{E}$, covering an area of about 59,570 km^2 (Adeleye, 1971; Kogbe, 1976; Fatoye & Gideon, 2013). The relief of the study area is generally low and gently undulating, with elevations ranging

between 250 and 400 metres above sea level (Offodile, 2002; Obaje, 2009). The land surface is dominated by broad plains, interrupted by occasional escarpments and low ridges, particularly where limestone beds of the Kalambaina Formation are exposed (Rahaman, 1988; Fatoye & Gideon, 2013). Such subdued relief provides favourable conditions for agriculture and accessibility to mineral deposits, while also reflecting the sedimentary character of the Sokoto Basin (Offodile, 2002; Igwe et al., 2018).

Drainage in the study area is controlled by the Sokoto–Rima River system, which flows generally northwestward before joining the Niger River (McCurry, 1976; Akpan et al., 2017). Smaller tributaries and seasonal streams (fadama) are also present, though they remain active only during the rainy season (Akanbi & Jibiri, 2020). The overall drainage pattern is dendritic to sub-dendritic, consistent with the soft sedimentary terrain (Offodile, 2002; Oteri & Atolagbe, 2003). In places, limestone outcrops influence the direction of drainage, diverting surface water and enhancing subsurface infiltration (McCurry, 1976; Igwe et al., 2018). Seasonal wetlands along valley bottoms play an important role in supporting dry-season farming (Nwankwoala, 2011).

Vegetation in Kalambaina belongs to the Sudan Savanna zone, marked by a mixture of grasses, shrubs, and scattered trees such as *Acacia albida*, *Azadirachta indica* (Neem), and *Adansonia digitata* (Baobab) (Areola et al., 2012; Noma et al., 2019). Natural vegetation has been heavily modified by human activities, with extensive areas cleared for farming and grazing. As a result, the vegetation cover is patchy, with more greenery concentrated along river valleys and cultivated lands, while limestone ridges and rocky exposures tend to remain sparsely vegetated (Adeleye, 1971; Noma et al., 2019).

The climate of the study area is tropical continental, controlled by the seasonal movement

of the Inter-Tropical Convergence Zone (ITCZ) (Olaniran, 2002). Two marked seasons dominate: the rainy season, which spans May to October and brings an annual rainfall of about 600–800 mm, and the dry season, which extends from November to April, characterised by high daytime temperatures—often above 38°C in March and April—and low humidity (Offodile, 2002; Nigerian Meteorological Agency, 2020). During the early dry months, the harmattan wind brings dry, dusty, and cool conditions, lowering night temperatures and reducing visibility (Olaniran, 2002; Adefolalu, 1986). Climatic conditions strongly influence agricultural practices, surface water availability, and weathering processes that affect the limestone exposures (Igwe et al., 2018).

Settlement in Kalambaina and its environs is largely rural, consisting of dispersed villages and hamlets clustered along rivers and fertile soils (Hamidu et al., 2017; Olofin, 1987). Traditional building styles dominate, with mud-walled houses and thatched or corrugated iron roofs, while Sokoto town, located nearby, serves as the main urban centre and hosts modern residential areas and industrial facilities. The presence of the Sokoto Cement Plant in Kalambaina has also encouraged industrial growth and employment opportunities, linking the rural setting to regional economic activities (Kogbe, 1976; National Bureau of Statistics, 2018).

Land use in the area reflects a combination of natural endowment and human adaptation. Agriculture is the primary occupation, with crops such as millet, sorghum, maize, cowpea, and groundnut cultivated during the rainy season, while irrigation farming is practiced along river valleys in the dry season (Akanbi & Jibiri, 2020; Noma et al., 2019). Livestock grazing is also widespread, especially cattle, goats, and sheep, which form an important part of the rural economy (Hamidu et al., 2017). Industrial land use is significant in

Kalambaina due to quarrying of limestone for cement and lime production (Obaje, 2009; Fatoye & Gideon, 2013). Expansion of Sokoto town has resulted in the conversion of farmlands to residential and commercial plots, gradually altering the land use structure (Hamidu et al., 2017; National Urban Development Policy, 2012).

1.2 Statement of the Problem

Limestone is one of the most widely used industrial raw materials, particularly in cement production, lime manufacture, agriculture, and construction (BGS, 2013). In Nigeria, the cement industry relies heavily on limestone deposits, yet variations in mineralogical composition often affect the quality and suitability of limestone for different industrial applications (Okogbue & Aghamelu, 2010).

The Kalambaina Formation, which forms part of the Sokoto Basin in northwestern Nigeria, is well known for its thick limestone deposits (Obaje, 2009). Previous studies on the Sokoto Basin have focused largely on its stratigraphic, paleontology, and general lithological descriptions (Jones, 1958; Adeleye, 1971; Akande *et al.*, 2010). However, there has been limited detailed mineralogical investigation of the Kalambaina limestone aimed specifically at determining its industrial potential.

This lack of mineralogical data presents a challenge for fully understanding the quality and suitability of the limestone for industries such as cement manufacturing, steel, and agriculture. In particular, the variability in calcium carbonate content, presence of impurities such as silica, alumina, and iron oxides, and textural characteristics can strongly influence its performance in industrial processes (Okogbue & Aghamelu, 2010; Nwajide, 2013).

Therefore, there is a need for a detailed mineralogical study of the Kalambaina limestone to provide baseline scientific data that will guide its industrial utilization. Such a study will not only bridge existing knowledge gaps but also contribute to resource optimization and sustainable economic development in the region.

1.3 Aim and Objectives of the Study

Aim

This study aims to evaluate the mineralogical composition and industrial potential of the Kalambaina limestone through integrated petrographic and geochemical analyses.

Objectives

The specific objectives are to

- i. Identify and describe the constituent minerals and textural features of the Kalambaina limestone using thin section petrography.
- ii. Determine the chemical composition of the limestone through X-ray Fluorescence (XRF) analysis.
- iii. Integrate petrographic and geochemical data to assess the quality and purity of the limestone
- iv. Compare the analytical results with established industrial standards to evaluate its suitability for cement manufacture and other applications.
- v. Highlight the economic significance of the limestone and recommend strategies for its sustainable utilization.

1.4 Scope of the Study

This study is confined to the mineralogical and chemical characterization of the Kalambaina limestone within the Sokoto Basin. The research focuses on hand specimens collected from selected outcrops of the Kalambaina Formation around Sokoto and its environs. Laboratory analyses are limited to thin section petrography, for mineralogical and textural identification, and X-ray Fluorescence (XRF), for chemical composition.

The study does not extend to detailed stratigraphic correlation, paleontological analysis, or geotechnical testing of the limestone. Similarly, industrial performance testing, such as clinker production trials, is outside the scope of this work. Instead, industrial suitability is assessed by comparing the petrographic and geochemical data with established standards for limestone utilization in cement, agriculture, and other related industries.

By defining these boundaries, the study remains focused on generating reliable mineralogical and chemical data to guide the assessment of the industrial potential of the Kalambaina limestone.

1.5 Significance of the Study

i. The Kalambaina limestone is one of the most important industrial raw materials in northwestern Nigeria, yet its mineralogical characteristics and chemical quality remain poorly documented. This study is significant for several reasons:

ii. **Academic Contribution:** It provides detailed petrographic and geochemical data on the Kalambaina limestone, filling a gap in the geological knowledge of the Sokoto Basin. The results will also serve as a useful reference for future geological and mineralogical research in the region.

iii. Industrial Relevance: By comparing the mineralogical and chemical composition of the limestone with established standards, the study offers practical insights into its suitability for cement manufacture, agriculture, and other industrial uses. This information is valuable for industries seeking reliable raw materials.

iv. Economic Value: The findings highlight the potential of the Kalambaina limestone as a resource that can support regional economic growth. Reliable mineralogical data can help reduce dependence on imported raw materials, promote local industries, and create employment opportunities.

v. Policy and Resource Management: The study provides baseline information that can assist policymakers and resource managers in developing strategies for sustainable exploitation and utilization of limestone resources in Nigeria.

CHAPTER TWO

LITERATURE REVIEW

2.0 Geological Setting of the Sokoto Basin

The Nigerian Sector of Iullemmeden Basin is located northwestern Nigeria and South-eastern Iullemmeden Basin, the sediments of the Nigerian Sector of Iullemmeden Basin we're accumulate during four main phases of deposition; the Pre-Maastrichtian, Maastrichtian, Paleocene and Post-Paleocene deposition. It consist of a gently undulating plain with average elevation varying from 250-450m above sea level occasionally

interrupted by low mesas. The origin of these basins is related to the opening of the South Atlantic and the accompanying rifting in many areas of Western and Central Africa. Dange scarp is the most prominent feature in the basin and is closely related to the geology of the area. The Pre-Cambrian basement is the foundation followed by the deposition of the Illo/Gundumi Formation known as Continental Intercalaire of West-Africa, Illo/Gundumi Formation are Pre-Maastrichtian deposits and unconformably overlain by the Maastrichtian Rima Group which are the Taloka, Dukamaje and Wurno Formations. After the deposition of Rima Group comes the deposition of Paleocene Sokoto Group which comprises the Dange, Kalambaina, and Gamba Formations, Sokoto Group is unconformably overlain the Post-Paleocene continental terminal which is the Gwandu Formation. These sediments deposition dip gently and thicken towards the northwest with maximum thickness of over 1200m near Niger republic border with Nigeria (Obaje, 2009).

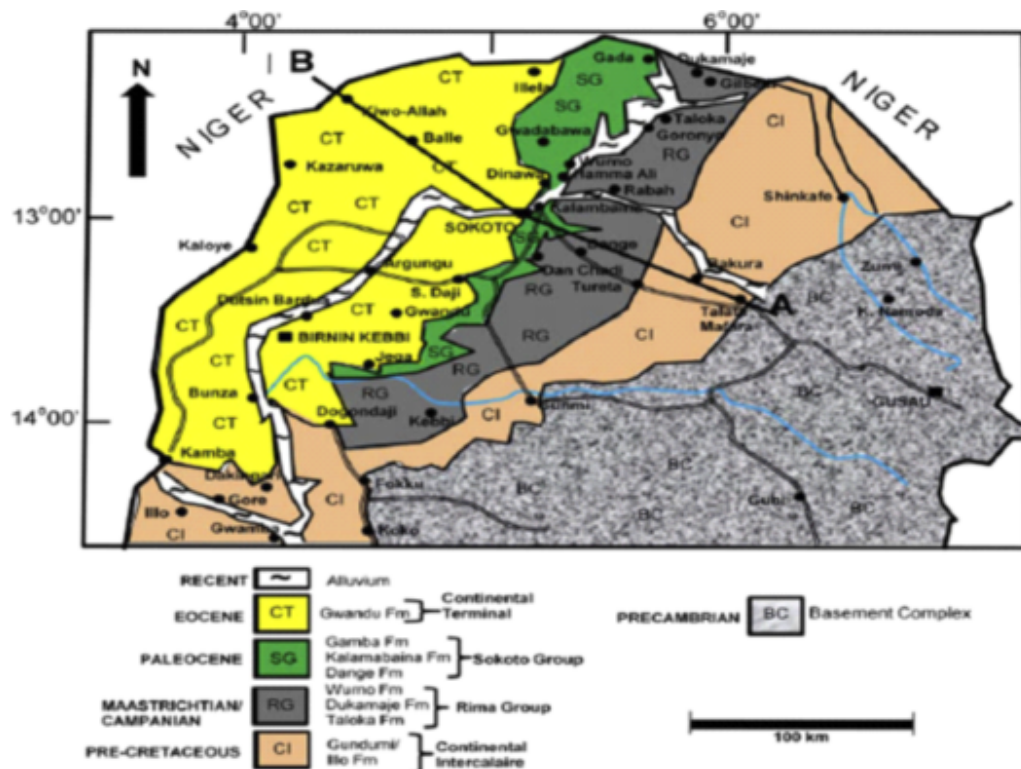


Figure 2: Geological map of the Nigerian Sector of Iullemmeden Basin (Obaje et al., 2004)

With respect to petroleum geology/petroleum system, some lacustrine carbonaceous shales within the Continental Intercalaire could constitute potential source rocks, while the sandstone facies are candidates for reservoir rocks. In the Rima Group, continental lacustrine shales in the Taloka and Wurno Formations and marine anoxic shales of the Dukamaje Formation constitute potential source rocks, while the Sandstone facies in all the Formations are potential reservoir rocks, within the Sokoto Group the Dange Formation could not have assumed maturity level to be a petroleum source rock but could constitute good seals in any stratigraphically lower plays and the Kalambaina carbonates are potential reservoirs while the Gamba shales may constitute regional seals (Furon, 1960). Obaje *et al*, (2020) suggest that potential petroleum systems exist in the Nigerian Sector of Iullemmeden Basin, however, show that organic matter in the source rocks are immature to sub-mature but may have attained the appropriate maturity at deeper depths to generate mainly gas and some oil.

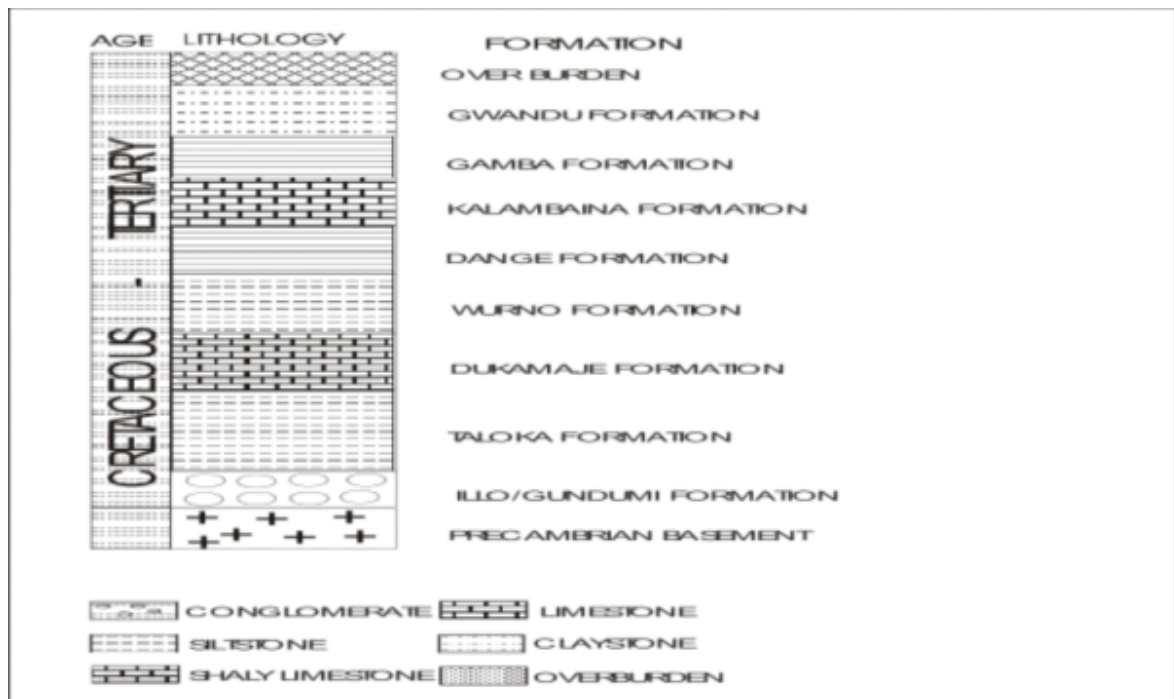


Figure 3: Stratigraphy of the Nigerian Sector of Iullemmeden Basin (Adelana et al., 2002)

2.1.1 Gundumi/Ilo Formation

The Gundumi and Ilo Formations are the oldest sedimentary units in the Sokoto Basin and rest unconformably on the Precambrian Basement. They consist mainly of coarse-grained sandstones, pebbly grits, and variegated clays deposited in fluvio-lacustrine settings (Offodile, 2002). Cross-bedding and conglomeratic bases suggest deposition under high-energy stream conditions, followed by calmer lacustrine phases.

Hydrogeologically, both formations are highly porous and permeable, forming productive aquifers (Anderson & Ogilbee, 1973). Groundwater flow through these sandy and gravelly beds contributes ions such as Ca^{2+} and HCO_3^- , which play roles in later carbonate precipitation and diagenetic alteration in the overlying Kalambaina Limestone. The Ilo Formation's sub-artesian aquifer also facilitates chemical exchanges that subtly influence

limestone purity and texture. Figure 4 and Figure 5 show lithologic profiles of the Gundumi and Illo Formations (Offodile, 2002).

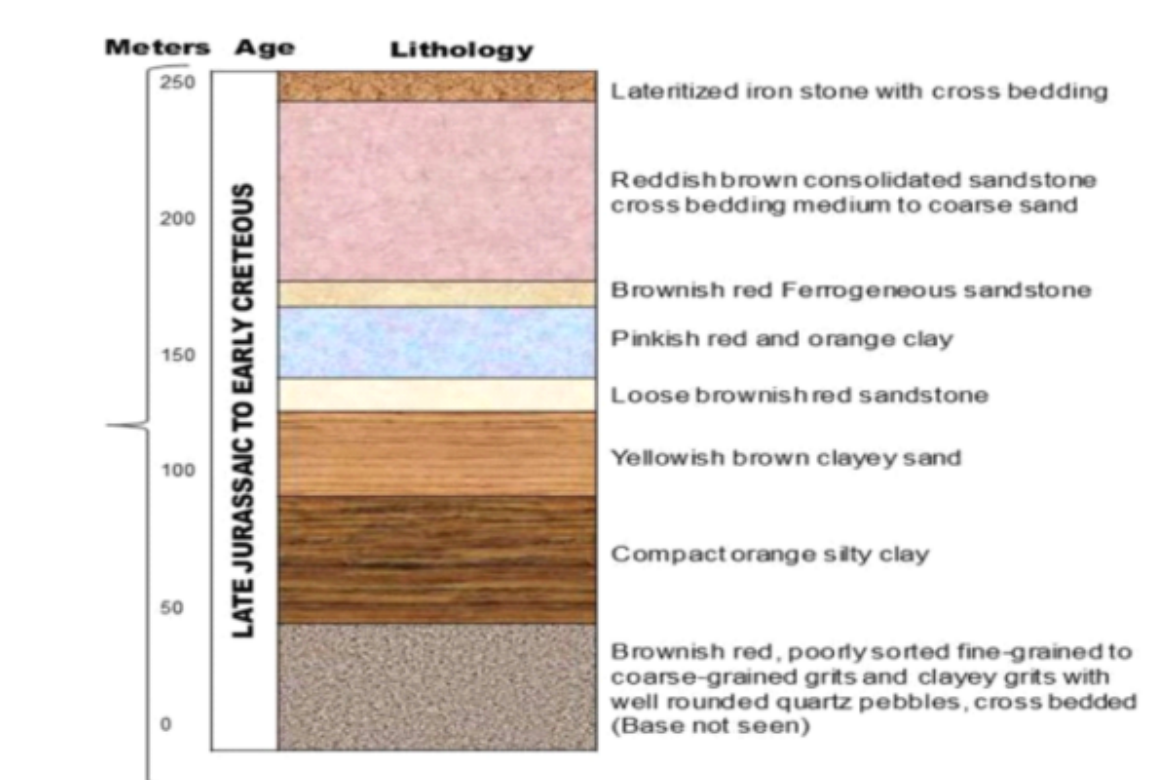


Figure 4: Borehole log of Gundumi Formation (Offodile, 2002)

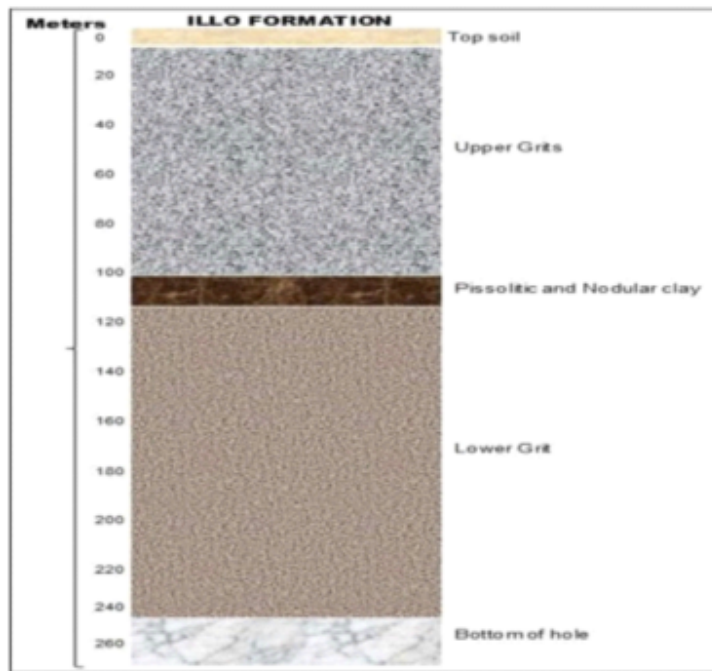


Figure 5: Borehole log of Illo Formation (Offodile, 2002)

2.1.2 Taloka Formation

The Taloka Formation overlies the Illo Formation and comprises fine-grained sandstones, siltstones, and carbonaceous shale bands, deposited under tidally influenced coastal conditions (Anderson & Ogilbee, 1973). Sedimentary structures such as flaser and wavy bedding indicate alternating energy regimes, typical of tidal flats and estuarine environments. The presence of carbonaceous layers points to occasional organic accumulation, suggesting periodic stagnation of water.

The Taloka Formation plays an important transitional role in the basin's evolution. Its fine-grained sediments form a semi-confining layer between older continental beds and younger marine deposits, including the carbonate-rich Kalambaina. These depositional and textural

characteristics reflect a gradual environmental shift from continental to shallow marine settings.

2.1.3 Dukamaje Formation

The Dukamaje Formation marks a widespread marine transgression during the Late Maastrichtian. It is composed mainly of gypsiferous shale, mudstone, and thin limestone interbeds rich in marine fossils and bone fragments (Kogbe, 1981). The alternating shale and limestone suggest deposition in a shallow, low-energy marine environment with periodic oxygen deficiency.

Mineralogically, the Dukamaje Formation introduces sulfate and carbonate minerals, notably gypsum and calcite, into the sedimentary system. These contribute to the basin's overall geochemical framework and influenced later limestone development. Hydrogeologically, its fine-grained lithology renders it an aquiclude, limiting vertical water flow but enhancing lateral migration between adjacent formations.

2.1.4 Wurno Formation

The Wurno Formation comprises pale, friable fine-grained sandstone interbedded with siltstone and mudstone, showing flaser and wavy bedding (Reineck & Singh, 1973). These sedimentary features indicate deposition in tidal-flat and deltaic environments under fluctuating hydrodynamic conditions.

The formation's sandy layers provide moderate aquifer potential in the basin's central region. Geochemically, the weathering of its feldspathic sandstones and minor iron-bearing minerals may have contributed trace elements such as Fe and Si into groundwater systems,

slightly influencing the diagenesis of overlying limestone formations. Figure 6 shows the borehole log of the Wurno Formation (Offodile, 2002)

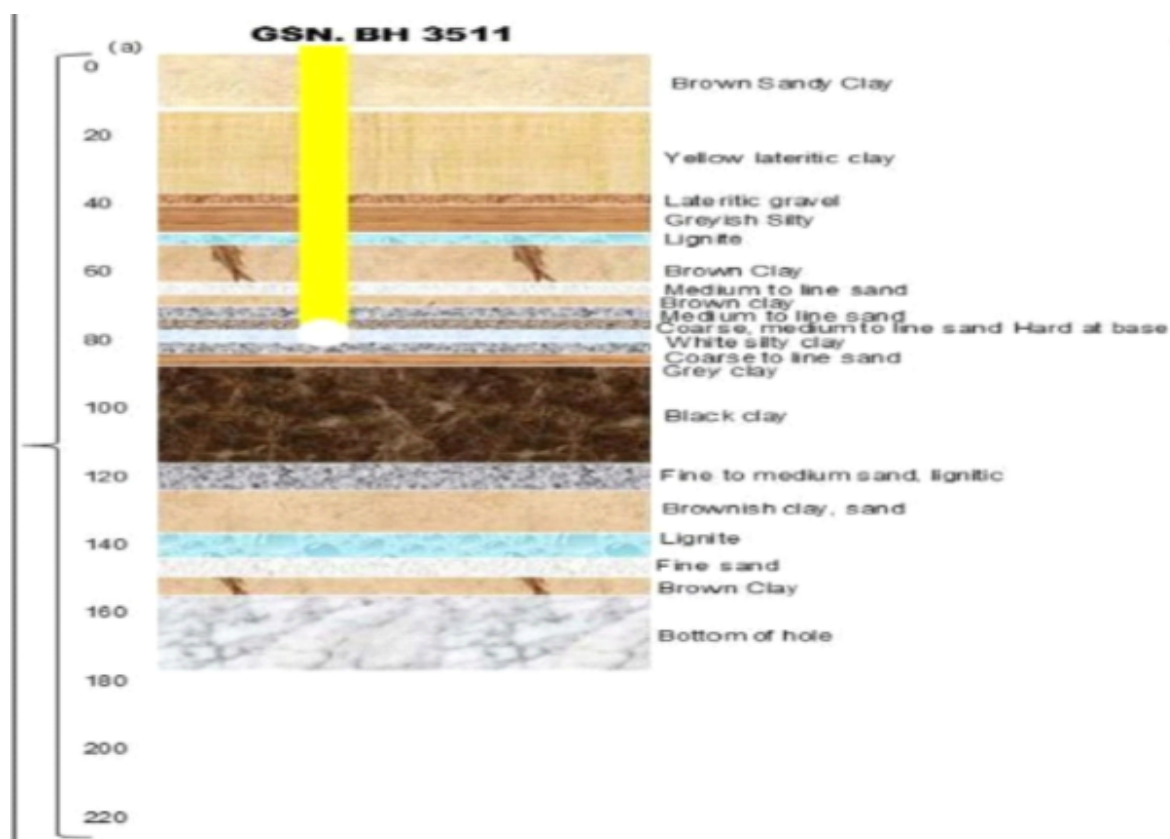


Figure 6: Borehole log of Wurno Formation (Offodile, 2002)

2.1.5 Dange Formation

The Dange Formation forms the base of the Paleocene sequence and consists of bluish-grey shale interbedded with thin bands of limestone and gypsum (Kogbe, 1981). Its fossiliferous and phosphatic nature indicates deposition in a shallow marine environment with occasional evaporitic influence.

This unit represents a chemical transition zone beneath the Kalambaina Formation. The upward diffusion of sulfate and phosphate ions from the Dange shales during early diagenesis likely affected the mineral balance of the Kalambaina limestone, influencing its calcite–clay proportions and industrial quality.

2.1.6 Kalambaina Formation

The Kalambaina Formation consists of marine white, clayey limestones and shales. The type section of the formation is at the quarry of the cement factory, near the village of Kalambaina, located about 6 km to the southwest of Sokoto town. The thickness of the formation is quite variable, because of the subsurface dissolution of the limestone. The maximum thickness in the boreholes is over 20 m, but usually only about 12 m of section is exposed in the quarry. Near the village of Dange, the Kalambaina Formation is reduced to about 5 m, but at Birnin Kebbi, further south, the formation is approximately 18 m thick. The formation is rich in invertebrate fossils, mainly echinoids, corals, nautiloids, lamellibranchs and gastropods. Foraminifera and ostracods have also been described from the formation by Reyment. (1965), Kogbe (1976) and Petters (1978). At the type locality, the type sections of the Kalambaina and Gamba Formations are well exposed. The profile consists of the Kalambaina Formation at the base, overlain conformably by the Gamba Formation, which in turn is succeeded by an oolitic ironstone unit. The Kalambaina Formation is generally marly with increasing clay content upwards. The formation is richly fossiliferous. About 16 km south of Sokoto, on the Sokoto-Gusau road, approximately 4 m of section is exposed in a road cutting; it consists mainly of weathered Kalambaina limestone capped by a thin layer of laterite. Here, the Gamba Formation has been stripped

off so that laterite has formed directly on the limestone. Figure 7 show lithologic profiles of the kalambaina Formations (Offodile, 2002).

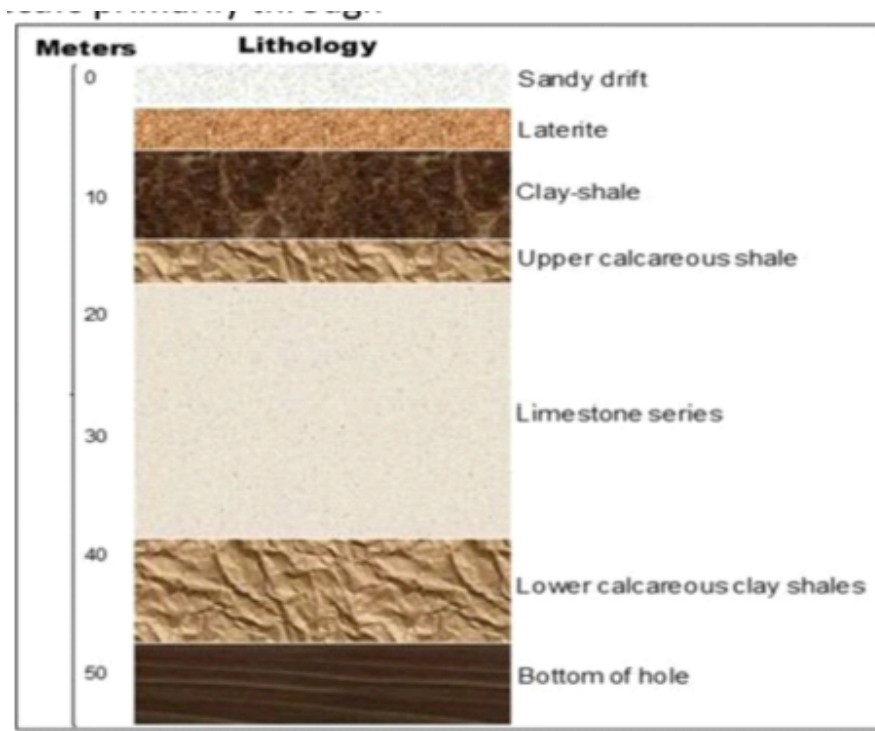


Figure 7: Borehole log of Kalambaina Formation (Offodile, 2002)

2.1.7 Gamba Formation

The Gamba Formation overlies the Kalambaina conformably and consists of grey laminated shale interbedded with thin phosphatic and ironstone bands (Obaje, 2009). It represents deposition in a quiet marine setting during the final stages of the Paleocene.

Although not economically significant itself, the Gamba Formation serves as a protective cap that limits surface alteration of the underlying Kalambaina Limestone. This has helped preserve the limestone's mineralogical purity and industrial quality..

2.1.8 Gwandu Formation

The Gwandu Formation (Continental Terminal) is the youngest sedimentary unit in the basin. It comprises poorly consolidated sands, silts, and clays of fluvial origin (Anderson & Ogilbee, 1973). The formation represents a continental depositional phase following the Paleocene marine regression.

Hydrogeologically, it forms the most productive artesian aquifer in the Sokoto Basin. Its recharge and discharge systems play a role in regional groundwater circulation, occasionally interacting with deeper carbonate beds. Such interactions can cause localized mineral alteration within the Kalambaina limestone through leaching and reprecipitation of calcium carbonate.

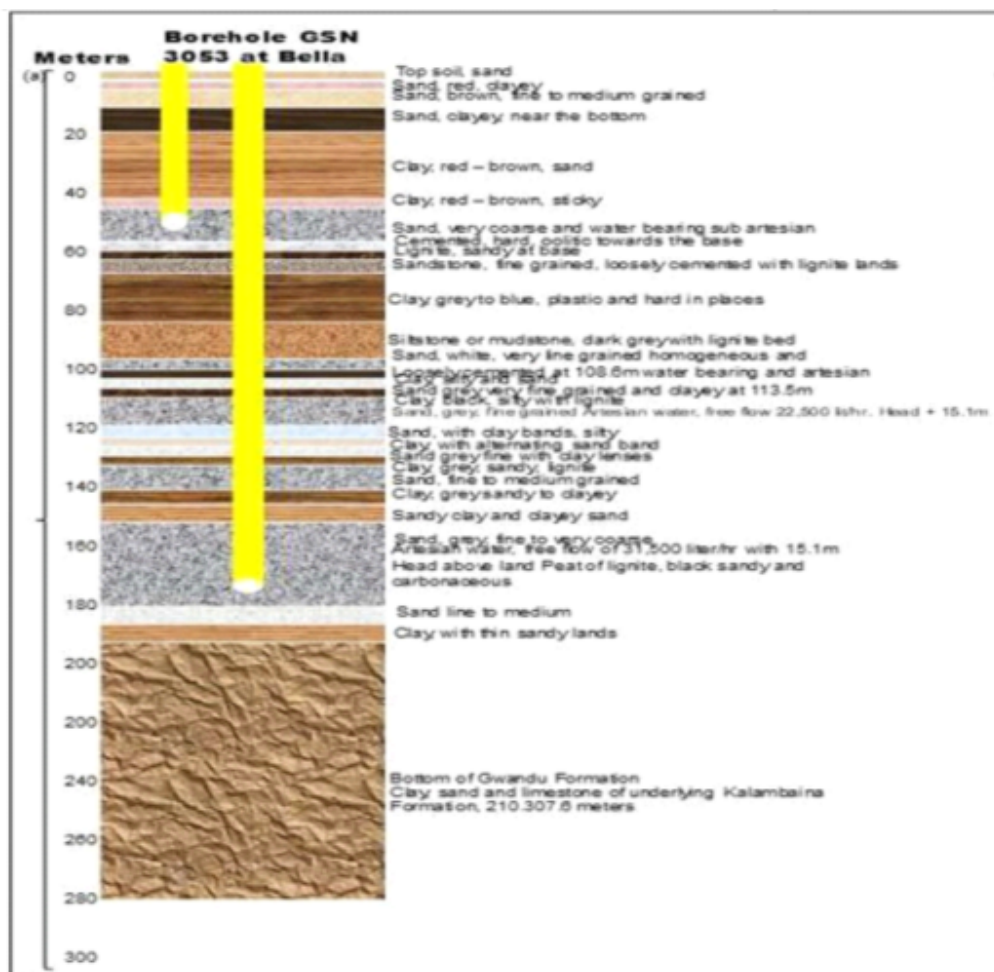


Figure 8: Borehole log of Gwandu Formation (Offodile, 2002)

2.2 Previous Studies on the Kalambaina Formation

The Kalambaina Formation is the principal carbonate unit of the Sokoto Basin and occupies a central place in both regional stratigraphy and local industry. Descriptions in classical and modern syntheses characterize the unit as a Paleocene, laterally extensive sequence of cream to whitish limestones, commonly fossiliferous and occasionally interbedded with thin marls and shales (Kogbe, 1981; Adeleye, 1971; Obaje, 2009). Field accounts emphasize its continuity across parts of the basin, its relative thickness compared with surrounding carbonate horizons, and its economic importance as a source of high-calcium feedstock for regional cement manufacture (Enu, 1987; Obaje, 2009). These broad features are well accepted, but careful reading of the literature shows important internal variations — in texture, fossil content and impurity loading — that directly control industrial suitability.

Early stratigraphic descriptions framed the Kalambaina as a shallow-shelf carbonate deposit formed during a Paleocene transgression; the frequent occurrence of benthic foraminifera, gastropods and bivalves in outcrop and quarry sections supports a nearshore to inner-shelf setting with episodes of higher energy that produced bioclastic grainstones and quieter periods that yielded micritic mudstone beds (Petters, 1978; Kogbe, 1981). Petrographic remarks in these works note a predominance of calcitic micrite and sparry calcite cements with sporadic dolomitic pockets, and report accessory quartz, clay minerals and iron oxides where siliciclastic influx increased — typically toward basin margins or along inferred

feeder channels (Kogbe, 1981; Obaje, 2009). Such accounts point to a platform that was broadly favorable to carbonate accumulation but sensitive to small changes in terrigenous input and local hydrodynamics; lateral facies changes from micritic, fossil-rich packages to more bioclastic or mixed carbonate-siliciclastic intervals are therefore common in mapped sections.

Diagenetic modification of the Kalambaina limestones is a recurrent theme in the literature and is highly relevant to both mineralogical description and industrial behavior. Recrystallization of micrite to sparite, development of neomorphic textures, partial dolomitization and the formation of stylolites are documented in petrographic notes and quarry reports (Kogbe, 1981; Obaje, 2009). These diagenetic processes concentrate insoluble residues along stylolite seams and can alter porosity and reactive surface area — factors that influence calcination behavior and the chemistry revealed by XRF. Where dolomitization is significant, the MgO content increases, with implications for thermal reactivity and lime quality. Likewise, stylolitization and pressure solution can locally concentrate silica and alumina residues, raising SiO₂ and Al₂O₃ values that may be deleterious for direct cement use without blending.

Despite the clear recognition of these lithologic and diagenetic features, few published studies provide systematic, quantitative mineralogical data for Kalambaina limestones. Most classic works (Adeleye, 1971; Kogbe, 1981; Petters, 1978) are descriptive and stratigraphic in focus; modern basin syntheses (Obaje, 2009) summarize lithofacies and economic use but do not substitute for spatially controlled thin-section petrography or quantitative geochemistry. A small number of more recent local reports and conference papers discuss quarry quality and general chemical characteristics (Enu, 1987; Aliyu, 2025),

yet they often rely on routine bulk assays or company reports rather than paired petrographic–geochemical datasets designed to explain the mineral hosts of key oxides. As a result, the literature contains qualitative consensus about the Kalambaina as a workable carbonate resource, but lacks the fine-scale, process-level data — thin section descriptions tied to XRF oxide budgets — that industry requires for raw-mix design, beneficiation decisions and spatial resource modelling.

From an industrial perspective, the Kalambaina Formation is attractive because of reported high carbonate content in many of its beds and because quarries are geographically close to cement plants, minimizing transport costs (Enu, 1987; Obaje, 2009). However, industrial studies elsewhere in Nigeria demonstrate that carbonate deposits that look uniform at outcrop may hide clay lenses, chert nodules or siliciclastic laminae that raise SiO_2 and Al_2O_3 contents above acceptable thresholds for direct clinker feed (Okogbue & Aghamelu, 2010; Taylor, 1997). The literature therefore recommends, but rarely shows in published detail for Kalambaina, a paired approach: systematic thin-section petrography to identify mineral hosts and textures, and XRF geochemistry to quantify oxide proportions and compare them with plant specifications. Without this integrated dataset the risk is either under-utilization of workable beds or costly processing of marginal rock that could have been avoided by targeted quarry planning.

2.3 Previous Studies on the Petrography and Geochemistry of Limestone

Petrographic and geochemical studies of limestone have long provided insight into its depositional environment, diagenetic evolution, and industrial suitability. Across Nigeria and beyond, researchers have analyzed various limestone formations to establish their mineral composition, texture, and economic potential.

Early works by Jones (1948) and Kogbe (1976) on the Sokoto Basin provided the first detailed petrographic descriptions of the Kalambaina and Dange Formations, identifying the predominance of micritic calcite and subordinate amounts of dolomite, quartz, and clay minerals. These studies revealed that the Kalambaina Limestone was deposited in a shallow, low-energy marine environment, typical of a carbonate platform system. Reyment (1965) and Petters (1978) further expanded this understanding by classifying the formation's microfacies, noting the presence of benthic foraminifera, ostracods, and echinoid fragments — all indicators of normal marine salinity and good oxygenation levels during deposition.

Subsequent petrographic examinations by Offodile (2002) emphasized the fine-grained, cryptocrystalline nature of the calcite and the presence of bioclasts cemented by sparry calcite. He linked these textural variations to minor post-depositional recrystallization and the influence of groundwater percolation from adjacent formations such as the Dange Shale and Gamba Formation. Similarly, Obaje (2009) highlighted that diagenetic alteration, including micritization and partial dolomitization, plays a key role in defining the chemical purity of limestones within the Sokoto Basin.

Geochemical analyses of Nigerian limestones have also been widely documented. Adeleye and Dessauvagie (1972) examined the chemical composition of Cretaceous–Tertiary carbonate rocks in northwestern Nigeria, noting that the Kalambaina Limestone contains an average of 85–96% CaCO_3 , 1–4% SiO_2 , and trace amounts of Fe_2O_3 , MgO , and Al_2O_3 . These results affirm the formation's high purity and suitability for cement and lime manufacturing. Enu (1980) and Akande (1989) both reported similar findings from other Nigerian carbonate units, reinforcing the general trend of high-calcium limestones across the Sokoto Basin.

More recent studies employing advanced techniques such as X-Ray Fluorescence (XRF) and Thin Section Petrography have provided a clearer understanding of the mineralogical and geochemical variability of the Kalambaina Limestone. Hamidu *et al.* (2022) used XRF to determine the major and trace oxide composition of limestones from Sokoto and Birnin Kebbi, confirming dominant CaO concentrations (above 50 wt%) and low silica impurities, consistent with industrial-grade limestone. Similarly, Wali *et al.* (2019) investigated the hydrogeochemical context of the Sokoto Basin and observed that groundwater interaction influences the leaching of minor elements like Mg, Fe, and Mn — a process that subtly modifies limestone mineralogy over time.

Globally, comparable petrographic and geochemical investigations have shown similar patterns. Studies by Flügel (2004) and Boggs (2009) demonstrated that texture, fossil content, and cement type are critical indicators of limestone depositional environments, while major oxides such as CaO, MgO, and SiO₂ determine industrial applicability. These principles align with findings in the Kalambaina region, where high calcite purity and minimal detrital contamination mark the limestone as economically valuable.

2.4 Industrial Significance of the Kalambaina Limestone

The Kalambaina Limestone holds remarkable industrial value, both as a raw material for cement production and as a versatile carbonate resource for various construction and chemical applications. Its significance arises from its abundance, accessibility, high purity, and favorable physical and chemical characteristics (Kogbe, 1981; Enu, 1987; Obaje, 2009).

Geologically, the Kalambaina Formation consists predominantly of soft to moderately hard, cream-colored limestones that are rich in calcite (CaCO₃) with relatively low levels of deleterious impurities such as silica (SiO₂), alumina (Al₂O₃), and iron oxides (Fe₂O₃). These

chemical characteristics make it an excellent raw material for the manufacture of ordinary Portland cement. Indeed, the limestone serves as the primary feedstock for the Sokoto Cement Plant and other local industries, which depend heavily on its proximity and quality for economic operations (Enu, 1987; Obaje, 2009). The reduced silica and magnesium contents reported by earlier workers (Adeleye, 1971; Kogbe, 1981) mean that the formation requires little beneficiation before use in clinker production.

Beyond cement manufacturing, the Kalambaina Limestone has wider industrial relevance. The high calcium carbonate purity makes it suitable for the production of lime (CaO) used in metallurgy, water treatment, and environmental control. Pulverized forms of the limestone are also used as fillers in paints, plastics, rubber, and paper industries, where whiteness, brightness, and fine grain size are key quality indicators (Enu, 1987). Furthermore, agricultural industries utilize ground limestone as an effective liming agent to neutralize acidic soils and enhance crop yield, owing to its high reactivity and slow release of calcium ions.

The soft to moderately hard nature of the Kalambaina rock allows for ease of quarrying and crushing, reducing energy costs and promoting large-scale mechanized extraction. This ease of exploitation, combined with its shallow overburden and widespread distribution in northwestern Nigeria, has attracted sustained industrial interest since the 1970s. Infrastructure projects in Sokoto and neighboring states frequently depend on aggregates derived from this limestone, particularly for road base materials and building stones (Enu, 1987; Obaje, 2009).

Chemically, the formation exhibits CaO contents often exceeding 50%, with MgO values generally below 2%, consistent with high-grade limestone classifications (Obaje, 2009). X-

ray fluorescence (XRF) data from previous studies reveal trace levels of silica, alumina, and iron, confirming its industrial suitability without extensive purification (Aliyu, 2025). Such high-calcium limestones are globally sought after for cement manufacture, soda ash production, and as fluxes in steel and glass industries (Taylor, 1997). The Kalambaina deposit therefore stands as one of Nigeria's most economically viable carbonate sources.

However, the industrial quality of Kalambaina Limestone is not entirely uniform across the basin. Localized variations in clay content, marl intercalations, and diagenetic dolomitization have been reported, particularly near facies boundaries (Kogbe, 1981; Petters, 1978). These heterogeneities necessitate careful mineralogical and geochemical characterization, using thin-section petrography and XRF analysis, to delineate zones of high industrial grade from marginal materials. Thus, while the formation remains a strategic industrial resource, its sustainable exploitation depends on scientific assessment and quality control.

In essence, the Kalambaina Limestone forms the industrial backbone of Sokoto's mineral economy. Its purity, abundance, and accessibility have supported cement production for decades and hold further potential for metallurgical, chemical, agricultural, and construction industries. Comprehensive mineralogical and geochemical studies will not only validate its quality but also guide efficient resource utilization, minimize waste, and promote regional economic development.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Geological Field Mapping and Materials Used

The geological fieldwork in the Kalambaina area of Sokoto was conducted to investigate the mineralogical characteristics of the Kalambaina Limestone and to obtain representative samples for laboratory analysis. The field mapping exercise was carried out mainly on foot using the traversing method, which involved systematic observation and documentation of rock exposures and outcrops at accessible locations across the study area. The area was easily accessible through a network of tarred and untarred roads, as well as several footpaths, which facilitated movement between observation and sampling points.

3.1 Field Methods

The field methods adopted for the mineralogical study of the Kalambaina Limestone were designed to obtain accurate geological information and representative samples for laboratory analysis. The fieldwork included geological mapping, sampling, and proper documentation of field observations.

3.1.1 Geological Mapping

The geological mapping was carried out mainly on foot using the traversing method. This involved systematic movement across accessible parts of the Kalambaina area to observe and record rock exposures, lithologic variations, and structural features. Each outcrop was

carefully examined to describe its color, texture, composition, and fossil content. The spatial distribution of the limestone was mapped to identify variations within the deposit.

A Global Positioning System (GPS) device was used to record the exact coordinates of each observation and sampling point. The dip and strike of the limestone beds were measured using a compass clinometer to determine the structural orientation of the rock layers. Field sketches were made in a notebook to illustrate the relationships between different rock units. Photographs were also taken to provide visual documentation of the study area and key geological features.

3.1.2 Sampling Techniques

Representative limestone samples were collected from different outcrops within the Kalambaina Formation. The sampling was done to ensure that the materials obtained captured both the lateral and vertical variations of the deposit. Samples were collected from fresh exposures to avoid weathered surfaces that might affect the mineral composition.

At each sampling location, solid pieces of limestone were broken off using a geological hammer to expose fresh surfaces. Both hand specimens and smaller fragments were collected for laboratory analysis. Each sample was properly labeled with details such as sample number, location coordinates, lithologic description, and date of collection. The labels were securely attached to the sample bags to maintain clear identification throughout the analysis process.

3.1.3 Equipment Used

The following equipment and materials were used during the field investigation:

- i. Geological hammer – for breaking rocks and collecting fresh samples.
- ii. Compass clinometer – for measuring dip and strike of bedding planes.
- iii. GPS device – for determining accurate coordinates of sampling and observation points.
- iv. Hand lens – for identifying minerals and textures in the field.
- v. Field notebook – for recording field data, sketches, and observations.
- vi. Camera – for taking photographs of outcrops and geological features.
- vii. Sample bags and labels – for safe storage and identification of samples.

3.3 laboratory methods

This section describes the various laboratory techniques and procedures used to analyze the collected samples from the field. It covers the preparation of samples, including cleaning, cutting, and making thin sections for microscopic examination. Additionally, it outlines the petrographic analysis performed to identify mineral composition and texture, as well as the use of advanced instrumental techniques like X-Ray Fluorescence (XRF) analysis to determine the chemical composition of the limestone samples. These laboratory methods are essential to provide detailed and accurate data that support the geological and industrial assessment of the Kalamaina limestone.

3.3.1 Laboratory Materials and Equipment

Laboratory analyses were performed using standard geological instruments, including a jaw crusher, mechanical grinder, sieves of various mesh sizes, and a drying oven for sample

preparation. A weighing balance ensured accurate measurements, while a polarizing microscope, epoxy resin, and glass slides were utilized for thin section preparation. The X-ray fluorescence (XRF) spectrometer was employed for elemental analysis, and additional materials such as a mortar and pestle, distilled water, and dilute hydrochloric acid were used for cleaning, grinding, and carbonate testing.

3.3.2 Sample Preparation

The collected limestone samples were carefully prepared for both petrographic and X-ray fluorescence (XRF) analyses. Each sample was first air-dried to remove surface moisture and then crushed using a jaw crusher to obtain smaller fragments. The crushed materials were subsequently pulverized using a mechanical grinder to produce a fine powder of less than 125 micrometres ($<125\text{ }\mu\text{m}$) particle size, suitable for XRF analysis. Meanwhile, larger rock chips were reserved for the preparation of thin sections used in petrographic examination. The powdered samples were sieved to ensure uniform particle size distribution, which is essential for obtaining accurate and reproducible geochemical results. After sieving, each prepared sample was properly labeled with its corresponding identification code and stored in airtight containers to prevent contamination and moisture absorption prior to laboratory analysis.

3.3.3 Thin Section Preparation:

Thin sections of the limestone samples were prepared for petrographic examination following standard geological laboratory procedures. A small slab was first cut from each representative sample using a rock-cutting machine, after which the cut surface was polished and affixed to a clean glass slide with epoxy resin. The mounted samples were

then ground on a lap wheel using progressively finer abrasives until a uniform thickness of approximately 30 microns was achieved, allowing light to pass through the mineral grains during microscopic analysis. The prepared surfaces were subsequently polished to a smooth finish and covered with a thin glass slip to protect the specimen. Each thin section was properly labeled with its corresponding sample identification code for easy reference during petrographic examination



Figure 3.X: Rock-cutting saw and polarizing microscope used in thin-section preparation and analysis.

3.3.4 Petrographic Analysis

The prepared thin sections were carefully examined under a polarizing microscope to identify and characterize the mineralogical composition and textural features of the limestone samples. Observations focused on determining the types and relative abundances of minerals such as calcite, dolomite, quartz, feldspar, and clay minerals, as well as assessing grain size, shape, and optical properties including birefringence, extinction angles,

and relief. The texture and fabric of the rocks—whether micritic, sparitic, crystalline, or fossiliferous—were also documented to understand the depositional characteristics of the formation. Additionally, diagenetic features such as recrystallization, dissolution, and the presence of stylolites were carefully noted. Representative photomicrographs were captured to illustrate significant mineral textures and structural features, and the petrographic data obtained were subsequently interpreted to infer mineral relationships and depositional environments within the Kalambaina Formation.

3.3.5 X-Ray Fluorescence (XRF) Analysis

X-Ray Fluorescence (XRF) analysis was carried out to determine the major oxide composition of the Kalambaina Limestone samples. For each analysis, approximately 10 grams of the powdered sample were pressed into pellets using a hydraulic press to ensure uniformity and compactness. The XRF spectrometer was then calibrated with certified reference standards to guarantee analytical accuracy. Each pellet was subsequently analyzed under fixed excitation conditions to quantify major oxides such as CaO, MgO, SiO₂, Al₂O₃, Fe₂O₃, Na₂O, K₂O, and SO₃. The oxide concentrations obtained from the instrument were processed and converted into equivalent mineral compositions based on standard geochemical relationships, for instance, CaO representing calcite and MgO representing dolomite. The results from the XRF analysis were employed to confirm the mineralogical composition previously identified through petrographic examination and to evaluate the chemical purity and industrial quality of the limestone samples.

3.4 Data Analysis and Interpretation

The petrographic and X-Ray Fluorescence (XRF) analyses were combined to determine the mineralogical and chemical composition of the Kalambaina Limestone. The XRF results were compared with standard compositions of calcite and dolomite to assess the limestone's chemical purity. Petrographic examination provided detailed information on mineral types, textures, crystal structures, and diagenetic features such as recrystallization and dissolution. These findings were integrated to understand the compositional variations and post-depositional changes within the limestone.

The combined geochemical and petrographic results revealed the depositional environment and processes that affected the limestone's quality and industrial potential. The results were further compared with previous geological and geochemical studies from the Sokoto Basin to ensure consistency and establish the relationship between the Kalambaina Formation and other carbonate units in northwestern Nigeria. This comparison improved understanding of the formation's geological history and confirmed its economic significance for industrial applications.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Geology of the Study Area

In the field, two major formations were observed: the Kalambaina Formation and the Gwandu Formation. The Gwandu Formation overlies the Kalambaina Formation and is subdivided into the Lower, Middle, and Upper Gwandu Members. The Kalambaina Formation is mainly composed of soft, whitish limestone, indicating a marine depositional environment, while the overlying Gwandu Formation consists mainly of sandstone and clay beds, suggesting continental deposition.

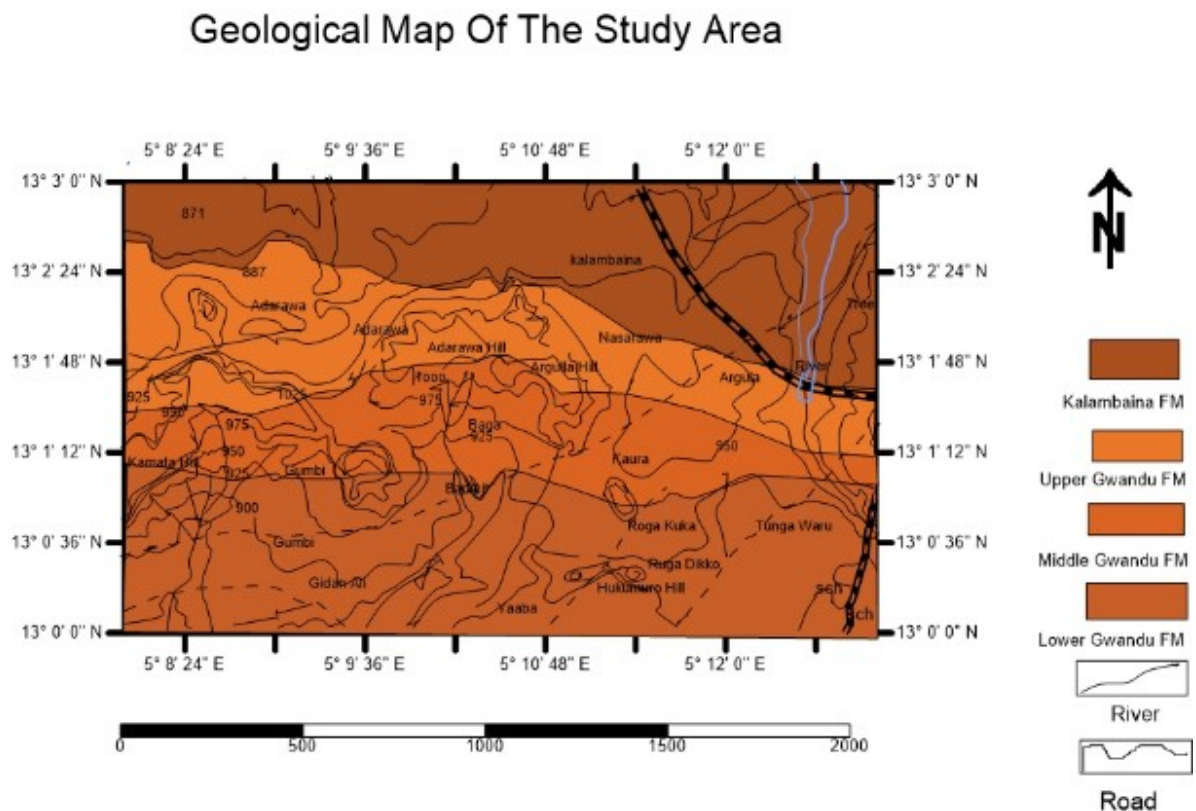


Figure : Geological Map of the study Area

4.1.1 Gwandu formqtion

i. Upper Gwandu formation

The Upper Gwandu Formation is the topmost unit of the Gwandu Formation, occurring above the Middle Gwandu Formation. It is predominantly composed of continental sandstones, which are generally coarse- to medium-grained, well-sorted, and often massive or cross-bedded, indicating deposition in fluvial or shallow deltaic environments. Minor interbeds of clay, silt, and occasional pebbly layers are also present, suggesting episodes of slower sedimentation or low-energy water flow. The formation is generally resistant to weathering and forms gentle ridges or low hills in the study area. Its composition and structure make it less suitable for cement production compared to the

underlying limestone, but it is an important reservoir rock and contributes to the overall stratigraphic framework of the Sokoto Basin.

ii. Middle Gwandu Formation

The Middle Gwandu Formation lies between the Lower and Upper Gwandu Formations. It is mainly composed of sandstones with occasional clay and silt interbeds, typically medium- to fine-grained and moderately well-sorted. Some beds show cross-bedding and ripple marks, indicating deposition in fluvial or shallow water environments with variable energy conditions. This unit is generally less resistant than the Upper Gwandu Formation and forms gentle slopes in the study area. Its composition suggests it acted as a transitional layer between the coarse Upper Gwandu sandstones and the finer Lower Gwandu sediments.

ii. Lower Gwandu Formation

The Lower Gwandu Formation is the basal unit of the Gwandu Formation, lying directly above the Kalambaina Limestone. It consists mainly of fine- to medium- grained sandstones with intercalations of clay and silt, indicating deposition in a low-energy fluvial or floodplain environment. The sandstones are generally moderately well-sorted and show faint bedding, ripple marks, and occasional small pebbly layers, suggesting episodic higher-energy events. This unit is relatively less resistant to erosion, forming gentle slopes or low-lying areas. The Lower Gwandu Formation marks the transition from the carbonate-dominated Kalambaina Limestone to the predominantly clastic Gwandu sandstones, completing the stratigraphic sequence of the study area.

4.1.1.1 Field Structures observed

i. **Bioturbation**

Bioturbation refers to the disturbance of sediments by living organisms, such as burrowing animals, worms, or plant roots. In the field, it is usually observed as irregular burrows, tunnels, or disrupted bedding in the limestone or sandstone. It indicates past biological activity and can provide information about the depositional environment, often suggesting a shallow marine or fluvial setting with active organisms.



Fig: showing bioturbation structure in Gwandu formation N 13 2 9.55, E 005 9 46.94 ELV
293m

ii. **Listric**

Fold

A listric fold is a type of fold where the axial surface is curved, typically flattening with depth. These folds are often associated with extensional tectonics or gravity-driven deformation. In the field, they appear as curved or spoon-shaped bending of strata and indicate localized stress and deformation within the rock layers.



Fig. Showing listric fold (spoon shape) structure of Gwandu formation in the study Area N

13 01 20.93, E 005 10 48.93, ELV 291m

Flower

Structure

Flower structures are vertical, upward- or downward-diverging fault-related features often seen in strike-slip fault zones. They consist of a series of faults radiating from a central zone, giving a “flower-like” appearance in cross-section. They indicate shearing and

deformation along strike-slip fault systems. The structures measured approximately



Fig : showing flower structure of Gwandu formation N 13 2 07, E 005 9 53.01,

ELV 280m

iii. Channel

Filling

Channel filling refers to sedimentary deposits that fill former channels, such as riverbeds or tidal channels. These deposits often differ in grain size, composition, or bedding from the surrounding rock and can be identified in the field as lens-shaped bodies of sandstone, conglomerate, or silt within finer sediments. They record past fluvial or shallow marine processes.



Fig : showing channel filling in Gwandu formation N 13 2 7.17, E 005 10 13.2, ELV

306m

iv. **Sigmoidal**

Fold

Sigmoidal folds are small, S-shaped or curved folds often found in layers affected by shear stress. They are indicative of ductile deformation and can show the sense of shear in the rock. In sandstone, they may appear as gentle, curved undulations in thin beds. They always have S or Z shape.



Fig : showing sigmoidal structure of Gwandu formation in the study Area N 13 01 25, E
005 10 49.75, ELV 290

v. **Cross-Bedding**

Cross-bedding consists of inclined layers within a horizontal bed, formed by the migration of ripples or dunes in water or wind. In the field, it is observed as angled laminae cutting across the main bedding plane. Cross-bedding indicates current direction, energy conditions, and depositional environment, commonly found in fluvial or shallow marine sandstones.

Inclined laminae measured

4.1.2 Kalambaina

Formation

The Kalambaina Formation, of Paleocene age, is predominantly composed of soft, whitish

to light grey fossiliferous limestone with minor marl and shale interbeds. The limestone is fine- to medium-grained, well-bedded, and often contains fossils such as gastropods, pelecypods, and foraminifera, indicating deposition in a shallow marine environment. The formation is relatively pure, with minor siliceous and clay impurities, and conformably overlies the Dange Formation (shale) while being overlain by the Lower Gwandu Formation. Structurally, the formation is tectonically stable, with gently horizontal bedding and minor joints and fractures. Its high calcite content and good bed thickness make it significant for cement production and other industrial applications.

4.2 Petrographic Analysis

The petrographic study of the Kalambaina limestone provides insights into its mineralogical composition and textural features. Thin sections were examined under plane-polarized light (PPL) and cross-polarized light (XPL).

4.2.1 Observation Under Plane-Polarized Light (PPL)

Under plane-polarized light, the limestone exhibits a fine- to medium-grained carbonate matrix dominated by micrite (microcrystalline calcite). The micritic matrix appears dull grey to light brown and constitutes the main component of the rock, suggesting deposition in a low-energy marine setting. Clear, transparent patches of sparry calcite are observed filling voids or replacing fossil fragments, indicating partial recrystallization during diagenesis. Fossil fragments of pelecypods, gastropods, and foraminifera are locally present and have been partly replaced by sparry calcite cement. Darker regions represent fine clay minerals or organic matter, while occasional detrital quartz grains are observed as isolated, clear inclusions within the carbonate matrix. Overall, the limestone under PPL is relatively

pure and well-cemented, with minor impurities that do not significantly affect its overall texture.

4.2.2 Observation Under Cross-Polarized Light (XPL)

Under cross-polarized light, the limestone displays moderate to strong birefringence typical of calcite minerals. Calcite crystals show interference colors ranging from pale yellow to orange, confirming their mineral identity. Sparry calcite grains exhibit distinct twinning and appear brighter under XPL, consistent with recrystallized calcite formed during diagenesis. The micritic matrix remains mostly dark or shows weak interference colors due to its fine grain size and uniform crystallographic orientation. Fossil chambers and voids filled with secondary calcite cement appear as bright patches with high interference colors, confirming post-depositional cementation. Clay and organic matter remain isotropic and appear as dark patches, while occasional quartz grains show high relief and undulatory extinction, typical of detrital origin. These microscopic features indicate that the limestone is dominantly composed of calcite with minor quartz and clay impurities, reflecting a relatively pure carbonate rock with slight diagenetic overprinting.

4.2.3 Textural and Mineralogical Interpretation

The textural relationship between micrite and sparite suggests that the limestone initially formed as a micritic mudstone or wackestone, which later underwent partial recrystallization to form sparry calcite. The presence of fossil fragments within the micritic matrix supports a biogenic origin and deposition in a shallow marine environment with low

to moderate energy conditions. The minor detrital quartz and clay inclusions indicate limited terrigenous input, possibly from nearby continental sources. Overall, the mineralogical and textural features reveal that the Kalambaina Limestone is a chemically mature, high-purity limestone dominated by calcite, consistent with the results of geochemical analysis.

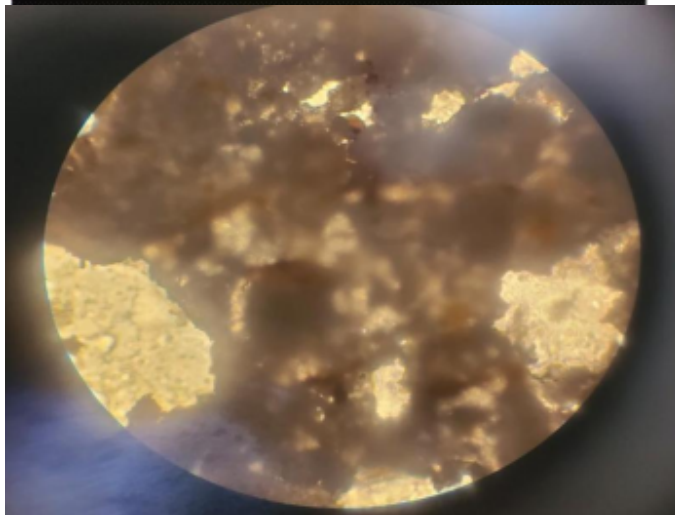
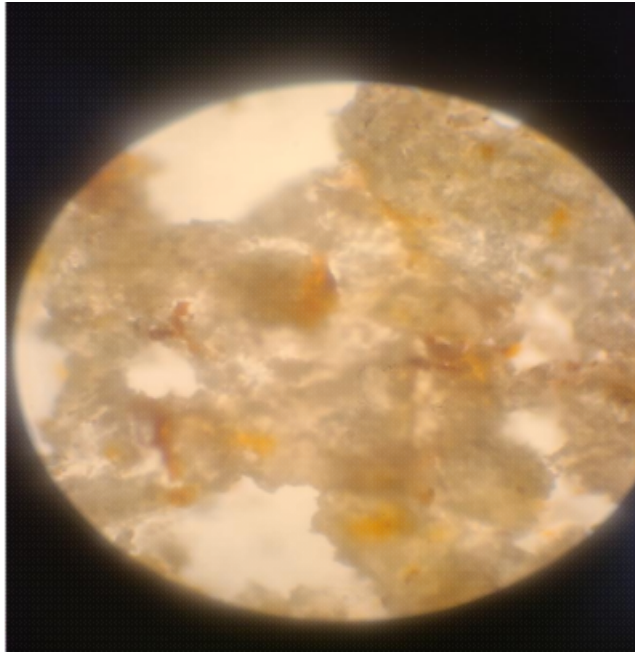
4.2.4 Summary of Petrographic Features

Feature	Observation (ppl)	Observation	interpretation
Matrix	Micritic (fine-grained calcite)	Low birefringence dark gray	Low-energy marine deposition
Sparry calcite	Clear patches replacing fossils and voids	Bright interference colors, twinning	Recrystallization (diagenesis)
Fossils	Fragments of gastropods, foraminifera	Bright interference in replaced areas	Biogenic origin, shallow marine
Quartz	Scattered clear detrital grains	High relief, undulatory extinction	Minor terrigenous input
Clay/organic matter	Dark patches	Isotropic (non-birefringent)	Minor impurities
Porosity	Low to moderate	Secondary calcite filling voids	Compaction and cementation

4.2.5 Implications for Industrial Use

The petrographic characteristics of the Kalambaina Limestone reveal that it is dominantly composed of calcite with minimal impurities, indicating high mineralogical purity. The compact texture, low porosity, and fine micritic matrix are favorable for industrial use, particularly in cement and lime production. The low content of silicate and clay minerals suggests minimal contamination during calcination, leading to efficient clinker formation

and high-quality industrial output. These petrographic features confirm that the Kalambaina Limestone meets the mineralogical requirements for use as a raw material in cement and lime manufacturing industries.



4.3 Geo chemical Analysis of limestone Using XRF

The chemical composition of the Kalambaina limestone was determined using X-ray fluorescence (XRF), providing quantitative data on major oxides and trace elements.

The results of the major oxide analysis are presented in **Table 4.1**. The limestone is dominated by CaO (76.60%), confirming its primarily calcitic composition. Low MgO content (0.97%) indicates only minor dolomite or magnesian calcite. SiO₂ (11.60%) and Al₂O₃ (2.73%) reflect minor quartz and clay impurities, while Fe₂O₃ (6.06%) suggests limited iron-bearing minerals. P₂O₅, TiO₂, and MnO occur in trace amounts, consistent with accessory minerals or minor organic input. Overall, the major oxide composition indicates a high-quality limestone suitable for industrial applications.

Table 4.1: Major Oxide Composition of Kalambaina Limestone (%) and Geological Interpretation

S/N	Major oxides	Conventration (%)	Geological interpretation
1	CaO	76.60	High value confirms calcitic composition (pure limestone)
2	SiO ₂	11.60	Indicates minor quartz or silicate impurities
3	Fe ₂ O ₃	6.06	May represent iron oxide impurities or substitution in calcite
4	Al ₂ O ₃	2.73	Suggests presence of clay minerals (kaolinite, illite)
5	MgO	0.97	Indicates minor dolomite or magnesian calcite
6	P ₂ O ₅	0.66	May result from organic or phosphatic remains
7	TiO ₂	0.21	Present as accessory mineral (rutile or anatase)

8	MnO	0.09	Trace element substituting in calcite lattice
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“The dominance of CaO (76.6%) confirms that the Kalambaina limestone is highly calcitic and chemically mature. Minor amounts of SiO₂, Al₂O₃, and Fe₂O₃ indicate the presence of small quantities of clay, quartz, and iron-bearing impurities. Trace oxides such as P₂O₅, TiO₂, and MnO likely represent accessory minerals or organic input, which do not significantly affect the limestone’s suitability for industrial applications such as cement and lime production.”

Table 4.2: Trace Element Composition of Kalambaina Limestone (ppm) and Geochemical Significance

S/N	Trace Elements(ppm)	Concentration	Geochemical significance
1	Sr	627	Indicates marine origin; substitutes for Ca in calcite
2	S	531	Suggests sulfate minerals (e.g., gypsum) or biogenic sulfur
3	Zr	136	Detrital input (zircon grains) from continental sources
4	Ba	64.9	Common in marine sediments; associated with barite or organic productivity
5	Cu	78.7	May occur in trace sulfides or adsorbed on organic matter
6	V	(128)	Indicates reducing depositional conditions
7	Zn	92.9	Linked to diagenetic processes or carbonate lattice substitution
8	Ni	40.5	Associated with clay minerals or organic matter
9	Rb	29.2	Suggests minor feldspar or mica impurities
10	Y	34.6	Trace REE indicator; reflects marine geochemical influence
11	Pb	18.4	Minor heavy metal inclusion; possibly galena traces
12	Cr	(104)	Suggests detrital or mafic rock contribution

“The high concentrations of Sr and S indicate deposition in a marine environment, with Sr substituting for Ca in calcite and S likely present as sulfate minerals. Trace elements such as Zr, Cr, and Rb suggest minor detrital input from continental sources, while V and Cu point to reducing to sub-oxic depositional conditions, possibly influenced by organic matter. Overall, the trace element data support a shallow marine to lagoonal depositional setting with slight terrigenous influence, consistent with the petrographic observations and major oxide composition of the limestone.”

4.4 Integration of Petrographic and Geochemical Data

The petrographic and geochemical analyses of the Kalambaina limestone provide complementary insights into its composition and quality. Thin section examination shows a predominance of micritic calcite with minor sparry calcite, suggesting partial recrystallization, while occasional darker patches indicate clay or organic impurities. These features reflect a relatively pure limestone with limited detrital content.

Geochemical analysis supports this observation, as high CaO content confirms a dominantly calcitic composition, while low MgO and minor SiO₂ and Al₂O₃ reflect minimal dolomite, quartz, and clay impurities. Trace elements such as Sr and S indicate deposition in a shallow marine environment, whereas Zr, Rb, Cr, and Ni suggest minor terrigenous input. V and Cu imply reducing depositional conditions influenced by organic matter.

Overall, the integration of petrographic and geochemical data confirms that the Kalambaina limestone is chemically mature, high in calcium, and of high quality. Its mineralogical purity and depositional characteristics make it suitable for industrial applications, particularly in cement and lime production.

4.5 Industrial Significance

The chemical and petrographic characteristics of the Kalambaina limestone indicate that it is highly suitable for industrial applications. The high calcium content, low magnesium concentration, and minimal clay or silicate impurities make it ideal for cement and lime production, as these factors ensure efficient calcination and high-quality clinker formation. The predominance of calcite, confirmed through thin section analysis and XRF results, further supports its suitability for industrial use.

Trace element analysis, showing elevated Sr and S levels, confirms a marine origin but does not significantly affect its industrial utility. Minor detrital contributions and the presence of iron-bearing minerals are within acceptable limits for cement manufacturing, while the overall chemical maturity of the limestone ensures consistent performance in industrial processes.

From an economic perspective, the Kalambaina limestone represents a valuable resource for the Sokoto Basin region. Sustainable extraction and utilization strategies, such as careful quarry planning, environmental impact monitoring, and quality control during processing, will maximize its industrial potential while minimizing environmental impacts. Its availability and quality make it a promising material for cement, lime, and other calcium-based industrial products, contributing to regional economic development.

The comparison of the major oxide composition of the Kalambaina Limestone with standard cement-grade limestone requirements (Table 4.3) shows that its chemical

parameters meet and, in most cases, exceed industrial standards. The high CaO (76.60%) and low MgO (0.97%) confirm its purity and suitability for cement and lime production.

Table 4.3: Comparison of Major Oxide Composition of Kalambaina Limestone with Standard Cement-Grade Limestone Requirements (ASTM C25)

S/N	Oxide component	Kalambaina limestone(%)	Standard requirement for cement Grade limestone	Interpretation
1	CaO	76.60	> 50.00	Exceeds standard; confirms high calcite purity
2	SiO ₂	11.60	< 20.00	Within limit; minor silicate impurities
3	Fe ₂ O ₃	6.06	< 6.00	Slightly high but acceptable; affects clinker color only
4	Al ₂ O ₃	2.73	< 6.00	Within limit; contributes alumina for clinker formation
5	MgO	0.97	< 5.00	Excellent; low dolomite content
6	P ₂ O ₅	0.66	< 1.00	Within acceptable range
7	TiO ₂	0.21	< 1.00	Within acceptable range
8	MnO	0.09	< 1.00	Trace level; no industrial effect

“In summary, the Kalambaina limestone meets or exceeds standard chemical requirements for cement-grade limestone, with high CaO, low MgO, and minimal impurities. These characteristics confirm its suitability for cement and lime production. Its abundance and accessibility in the Sokoto Basin also make it a promising material for industrial exploitation, supporting regional economic development.”

CHAPTER FIVE: SUMMARY, CONCLUSION, AND RECOMMENDATION

5.1

Summary

This study investigated the geology, petrography, geochemistry, and industrial potential of

the Kalambaina Limestone and the Gwandu Formation in the Sokoto Basin. Field observations identified two major formations: the Kalambaina Formation, dominated by soft, fossiliferous limestone, and the overlying Gwandu Formation, primarily composed of sandstones and clay beds. Structural features such as bioturbation, listric and sigmoidal folds, flower structures, channel fillings, and cross-bedding were documented, providing insight into the depositional and tectonic history of the area. Petrographic analysis confirmed that the Kalambaina Limestone is mainly micritic calcite with minor sparry calcite, clay, and quartz impurities, indicative of deposition in a low- to moderate-energy shallow marine environment. Geochemical analyses, including XRF, showed high CaO content (76.60%) and low MgO (0.97%), with minor trace elements, confirming the limestone's chemical maturity and industrial suitability. Integration of petrographic and geochemical data established the high purity and potential industrial applications of the Kalambaina Limestone, particularly in cement and lime production.

5.2

Conclusion

The study concludes that the Kalambaina Limestone is of high quality and industrially significant due to its high calcite content, low impurities, and favorable textural characteristics. The Gwandu Formation represents a transitional clastic sequence with fluvial and shallow deltaic depositional environments, providing important stratigraphic and reservoir information for the Sokoto Basin. Structural features observed in the field reflect localized deformation, consistent with the regional tectonic setting. Overall, the findings demonstrate that the Kalambaina Limestone meets the chemical and petrographic requirements for cement and lime production, while the Gwandu Formation contributes to the understanding of sedimentary processes and basin evolution.

5.3

Recommendation

Future studies should focus on detailed stratigraphic mapping and quantitative assessment of limestone reserves in the study area to optimize industrial extraction and resource management. High-resolution geological mapping, combined with remote sensing and GIS techniques, could improve the accuracy of reserve estimation and spatial distribution of the Kalambaina Limestone. Environmental impact assessments and the implementation of sustainable quarrying practices, including controlled blasting, dust suppression, and proper waste management, should be prioritized to minimize ecological disruption and preserve local biodiversity.

Further geochemical and mineralogical analyses of the limestone could explore its potential for alternative industrial applications beyond cement and lime, such as in ceramics, glass production, or as flux material in metallurgical processes. Detailed petrographic studies could also investigate microstructural variations that affect industrial performance.

Additionally, comprehensive hydrogeological and reservoir studies of the Gwandu Formation are recommended to better understand groundwater potential, subsurface fluid flow, and aquifer connectivity. Such studies could guide sustainable water resource management, inform agricultural planning, and support regional infrastructure development. Collaborative research involving geologists, environmental scientists, and industrial engineers could ensure that both resource utilization and environmental protection are optimized.

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