Universidade de Évora - Escola de Ciências e Tecnologia

Mestrado em Geologia

Dissertação

Point Pattern Analysis of Mineral Occurrences in Nigeria. Insights For Ore Deposits Genesis.

OBINNA JOSEPH ONYEALISI

Orientador(es) | Pedro Miguel Nogueira
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A dissertação foi objeto de apreciação e discussão pública pelo seguinte júri nomeado pelo Diretor da Escola de Ciências e Tecnologia:

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ANÁLISE DE PADRÕES DE PONTOS DAS OCORRÊNCIAS MINERAIS NA NIGÉRIA. PERCEPÇÕES SOBRE A GÊNESE DOS DEPÓSITOS DE MINÉRIO

RESUMO

A distribuição espacial das ocorrências minerais desempenha um papel fundamental na compreensão da gênese dos depósitos minerais e no aprimoramento das estratégias de prospeção mineral. Este estudo emprega uma abordagem geoespacial integrada utilizando QGIS, R-Studio e técnicas avançadas de análise espacial para investigar a disposição espacial das ocorrências minerais na Nigéria e sua importância geológica. A estrutura analítica inclui análise de distribuição de pontos, análise da função K, análise de Fry e análise de densidade de pontos, cada uma fornecendo percepções únicas sobre os controles geológicos subjacentes à mineralização.

Os resultados da análise de distribuição de pontos revelam que as ocorrências minerais na Nigéria não seguem um padrão espacial aleatório, mas exibem fortes tendências de agrupamento, sugerindo uma estreita associação com controles geológicos e estruturais. A análise da função K corrobora ainda mais essa observação, confirmando agrupamentos estatisticamente significativos em múltiplas escalas espaciais, o que está alinhado com a presença de características estruturais-chave, como zonas de falha, zonas de cisalhamento e limites litológicos que influenciam a deposição de minério.

Além disso, a análise de Fry destaca tendências direcionais distintas na mineralização, com alinhamentos espaciais correspondentes a grandes sistemas regionais de falhas, lineamentos e outras descontinuidades estruturais. Isso sugere que a mineralização segue caminhos influenciados tectonicamente, reforçando ainda mais o papel da deformação estrutural na formação de depósitos minerais. Adicionalmente, a análise de densidade de pontos identifica zonas de alta concentração mineral, reforçando a importância de ambientes geológicos específicos no controle da deposição mineral.

Estes resultados indicam, no seu conjunto, que a mineralização na Nigéria é maioritariamente controlada por estruturas, com os depósitos minerais a formarem-se preferencialmente ao longo de feições tectónicas que funcionaram como condutas para sistemas hidrotermais mineralizantes. O estudo fornece informações valiosas sobre os processos de formação de minério, apoiando a hipótese de que a atividade hidrotermal, a deformação estrutural e as variações litológicas foram fatores determinantes na deposição mineral. Esta investigação não só aprofunda a compreensão dos padrões de mineralização na Nigéria, como também oferece uma estrutura metodológica sólida para futuras iniciativas de exploração mineral, facilitando a identificação de novas áreas com potencial, com base em critérios estruturais e espaciais.

ABSTRACT

The spatial distribution of mineral occurrences plays a fundamental role in understanding ore deposit genesis and refining mineral exploration strategies. This study employs an integrated geospatial approach using QGIS, R-Studio, and advanced spatial analysis techniques to investigate the spatial arrangement of mineral occurrences in Nigeria and their geological significance. The analytical framework includes point distribution analysis, K-function analysis, Fry analysis, and point density analysis, each providing unique insights into the underlying geological controls on mineralization.

The results of point distribution analysis reveal that mineral occurrences in Nigeria do not follow a random spatial pattern but exhibit strong clustering tendencies, suggesting a close association with geological and structural controls. K-function analysis further substantiates this observation, confirming statistically significant clustering at multiple spatial scales, which aligns with the presence of key structural features such as fault zones, shear zones, and lithological boundaries that influence ore deposition.

Moreover, Fry analysis highlights distinct directional trends in mineralization, with spatial alignments corresponding to major regional fault systems, lineaments, and other structural discontinuities**.** This suggests that mineralization follows tectonically influenced pathways, further supporting the role of structural deformation in ore formation. Additionally, point density analysis identifies zones of high mineral concentration, reinforcing the importance of specific geological environments in controlling mineral deposition.

These findings collectively indicate that mineralization in Nigeria is predominantly and stratigraphy, with ore deposits preferentially forming along tectonic features that acted as fluid conduits for mineralizing hydrothermal systems. The study provides valuable insights into the ore-forming processes, supporting the hypothesis that hydrothermal activity**,** structural deformation, and lithological variations were key factors in mineral deposition. This research not only enhances our understanding of mineralization patterns in Nigeria but also offers a robust methodological framework for future mineral exploration efforts, facilitating the identification of new prospective areas based on structural and spatial criteria.

Keywords: Point Pattern Analysis, Geographical information system, Nigeria Geological Survey Agency, Complete spatial randomness.

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CONTENTS

1 INTRODUCTION

Nigeria is endowed with vast mineral resources distributed across different geological terrains and domains ranging from metallic and non-metallic minerals to energy resources such as oil and uranium. These mineral occurrences reflect the complex geodynamic evolution of the Nigerian basement and sedimentary basins, making the country an important area for mineral exploration and, as such economic and social development. However, despite the wealth of mineral deposits, their spatial distribution, clustering tendencies, and relationship with geological structures and litho tectono-stratigraphic and magmatic units remain insufficiently analysed in a quantitative manner. Understanding these spatial patterns is crucial for advancing mineral exploration strategies and refining models of ore deposit genesis.

Point pattern analysis (PPA) is a powerful spatial statistical technique used to evaluate the distribution, clustering, and randomness of geological features, such as mineral occurrences. This method provides insights into the spatial relationships between mineral deposits and underlying geological controls, including fault zones, lithological boundaries, and magmatic intrusions. By employing advanced geospatial tools, such as Geographic Information Systems (GIS) and spatial statistical models, researchers can detect patterns that may indicate genetic processes responsible for ore formation. The application of point pattern analysis to mineral occurrences in Nigeria offers a novel approach to understanding the fundamental factors influencing ore deposit localization.

Given Nigeria's diverse metallogenic provinces, such as the Pan-African basement complex, the Mesozoic Benue Trough, and the Cretaceous to Tertiary sedimentary basins. This study seeks to determine whether specific spatial trends exist and how they correlate with known geological structures or geological units. Insights gained from such analysis can improve predictive mineral exploration models, reduce exploration risks, and contribute to more efficient resource management and exploration. In the subsequent chapters, this thesis presents a review of relevant literature on Nigeria geological and geo-tectonic setting, describes the methodology employed for spatial analysis, discusses the results and their implications, and concludes with recommendations for future research and mineral exploration strategies in Nigeria.

1.1. Geographical setting

Nigeria is a West African country located between longitudes 3° and 14°E and latitudes 4° and 14°N (see figure 1.1). It covers a land area of approximately 923,768 km^2. Nigeria shares borders with Niger and Chad to the north, Benin to the west, and Cameroon to the east. Its southern border is formed by the Atlantic Ocean, giving it a coastline of around 800km. This extensive coastline positions Nigeria as a potential maritime power. Nigeria boasts abundant arable land, making it suitable for agriculture, industry, and commerce. Despite being entirely within the tropics, the country experiences a diverse climate, ranging from tropical along the coast to subtropical inland. Nigeria has two distinct seasons, the rainy season from April to October and the dry season from November to March. Coastal areas in the south can reach maximum temperatures of 37°C, while minimum temperatures can dip to 10°C. The climate becomes drier further north, with temperature extremes ranging from 40°C to 50°C.

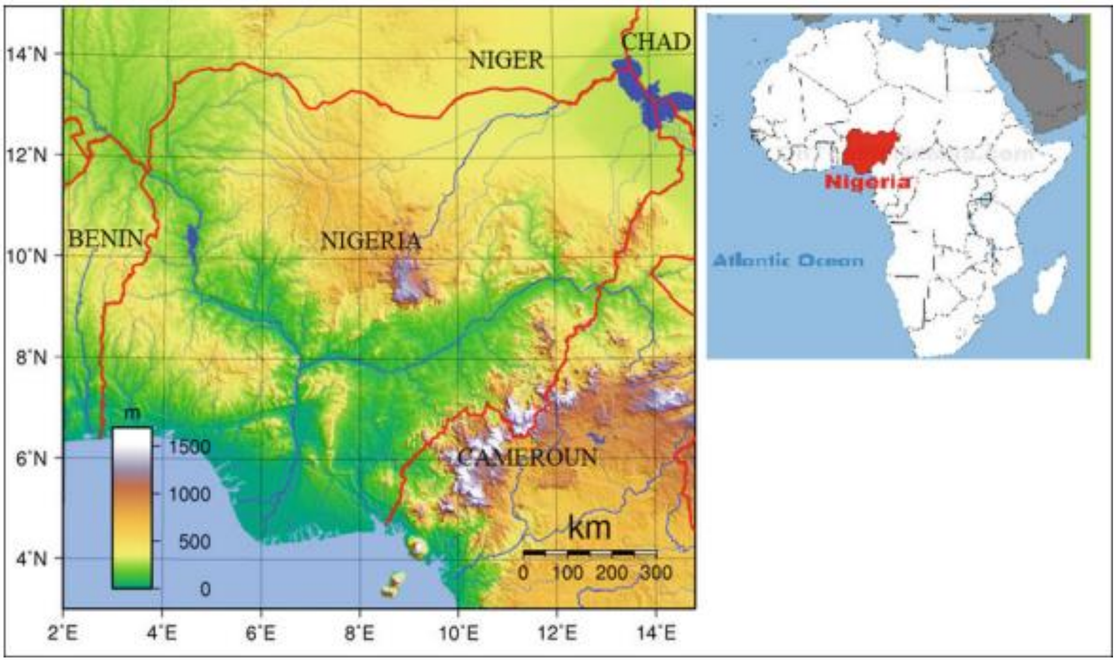

Figure 1.1. The location of Nigeria and its neighbouring West African nations, displaying Nigeria's topography Source: (http://en.wikipedia.org/)

1.2. State of the Problem

Mineral exploration in Nigeria has traditionally relied on conventional geological mapping and geochemical surveys, often implying a high exploration cost and uncertainties in targeting mineralized zones. Despite the country's rich mineral endowment, the spatial distribution of mineral occurrences remains poorly understood, limiting the efficiency of exploration strategies. One major challenge is the lack of a systematic approach to analysing the spatial arrangement of mineral deposits and their relationships with key geological structures such as faults, lithological boundaries, and geological units or magmatic intrusions. Understanding these spatial patterns is crucial, as mineral deposits are often not randomly distributed but influenced by underlying geological controls.

Additionally, existing exploration models in Nigeria have yet to fully integrate advanced spatial analysis techniques, such as point pattern analysis, which can provide quantitative insights into clustering, dispersion, and randomness in mineral occurrences. Without such an approach, critical information that could enhance the prediction of ore deposit locations and improve exploration success rates remains underutilized.

This study addresses these gaps by employing point pattern analysis to evaluate the spatial distribution of mineral occurrences in Nigeria. By integrating geospatial datasets with statistical and geostatistical methods, this research aims to enhance the understanding of ore deposit genesis and contribute to more effective mineral exploration strategies.

1.3. Objectives

This study aims to analyse the spatial distribution of mineral occurrences in Nigeria using point pattern analysis techniques (point pattern analysis, Ripley's K-function, point density analysis, Fry method) to determine clustering, dispersion, and randomness. It also seeks to assess the relationship between mineral occurrences and key geological features, such as faults, lithological contacts, and magmatic intrusions. By identifying spatial patterns, the research aims to provide insights into ore deposit genesis and their implications for mineral exploration. Additionally, it contributes to improved exploration models by integrating point pattern analysis with geospatial datasets.

2. GEOLOGICAL BACKGROUND

Africa is the world's second-largest continent, spans a geographical area of roughly 30 million km square. Renowned for its vast mineral wealth, the continent holds the world's richest deposits of metallic ores and gemstones, accounting for approximately 30% of global mineral reserves (Sharaky, 2014). This wealth is largely due to Africa's favourable geological setting and multiple tectonic events during the Precambrian Era, which are known to have formed many of the world’s largest mineral deposits. Africa ranks first and second globally for reserves of platinum, gold, diamonds, manganese, chromite, cobalt, vanadium, zirconium, and phosphate rocks, alongside significant resources of bauxite, industrial minerals, gemstones, and rare earth elements (Taylor et al., 2005). In addition to its mineral abundance, Africa possesses substantial fossil fuel reserves. Key oil- and gas-producing countries include Nigeria, Angola, Gabon, and Algeria, while Nigeria is also home to tar sand and bitumen deposits, South Africa and Mozambique has significant coal reserves. Over the past century, mineral exploration in Africa, conducted by both colonial and indigenous governments, is estimated to have generated around $10 trillion in value.

For many African countries, mineral wealth serves as a primary economic driver, contributing significantly to gross domestic product GDP and government revenues. For example, mining contributes as much as 45% of government revenue in Botswana, 26% in the Democratic Republic of Congo, 23% in Guinea, 22% in Mauritania, 20% in South Africa, 16% in Namibia, 14% in Zambia, and 10% in Ghana (Adu & Dramani, 2008). However, more than 90% of Sub-Saharan Africa’s mineral production is exported with minimal value addition, encompassing commodities like gold, diamonds, uranium, platinum, chromium, nickel, bauxite, phosphate, copper, tantalum, vanadium, and cobalt. Gold and diamonds are the most lucrative exports due to their high market value.

Nigeria is Africa’s most populous country and its nominally largest economy, derives most of its mineral wealth from oil and gas extraction. It lacks significant large-scale mining operations or world-class metallic mineral resources. By contrast, South Africa, with a slightly smaller economy, has a well-established mining sector. This industry accounts for about 10% of South Africa’s GDP, employs over 450,000 people, and makes the nation a leading global exporter of precious minerals like platinum, gold, and diamonds. Conversely, Nigeria’s mining sector is virtually non-existent, contributing only 0.5% to GDP, with metals accounting for just 0.001% and other minerals about 0.02% (Olade, 2019).

2.1 Geology of Africa

The African continent is predominantly characterized by a geologically stable landmass, with over 75% of its surface comprising Precambrian basement rocks. These are overlain by younger Phanerozoic sedimentary and volcanic cover rocks. Geologically, the continent can be categorized into three primary tectonic domains: (a) Stable Cratons, formed during the Archean to Early Proterozoic era; (b) Mobile Belts, developed in the Mid to Late Proterozoic era; and (c) Phanerozoic cover rocks. Four major cratons, large ancient rock masses that have remained stable for approximately 1.6 billion years since the Eburnean Orogeny, are particularly significant (Petter, 1991). These cratons include the Kalahari Craton, Congo Craton, West African Craton, and Saharan Metacraton (see figure 2.1).

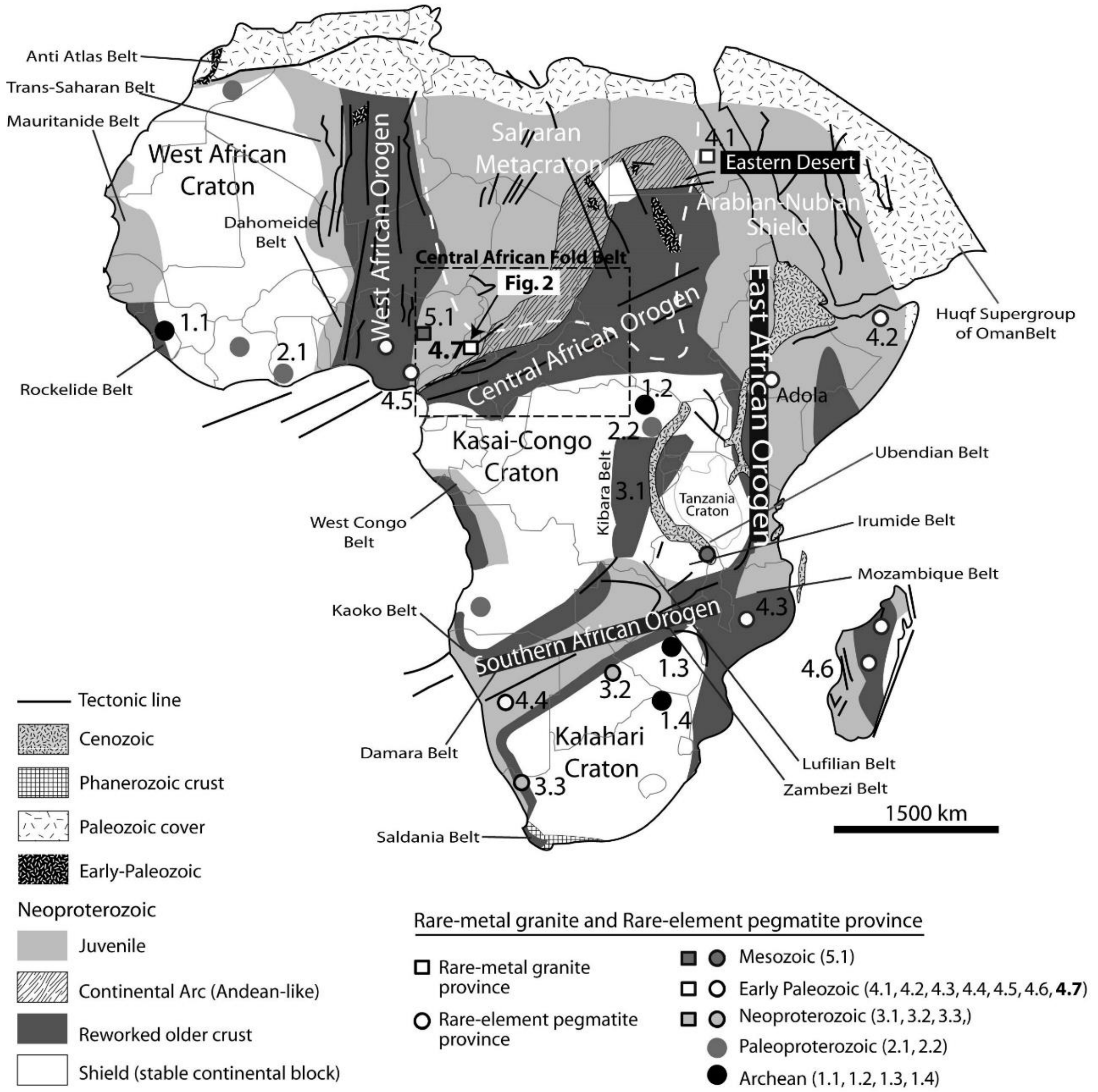

Figure 2.1. Cratons and pan African mobile belts in Africa. 1.1 Man Shield. 1.2 Congo Craton. 1.3 Zimbabwe Craton. 1.4 Kaapvaal Craton. 2.1 Birimian Province. 2.2 Kibalian in North-Eastern of Democratic Republic of Congo (DRC). 3.1 Kibara Belt. 3.2 Kamativi Schist Belt. 3.3 Orange River Belt. 4.1 Eastern Desert. 4.2 Adola Belt. 4.3 Alto Ligonha Province. 4.4 Damara Belt. 4.5 Older Granites (Nigeria). 4.6 Madagascar. 4.7 Mayo Salah in northern Cameroon domain of Central African Fold Belt. 5.1 Younger Granites (Nigeria). Modified by (Kröner, et al, 2004)

Each Craton is composed of ancient Archean (3.8-2.5 billion years old) nuclei, often referred to as "shields," surrounded or amalgamated by younger Early Proterozoic (2.5-1.6 billion years old) mobile orogenic belts. These cratons formed through a gradual process of continental growth or accretion, where new crustal and sub-crustal material was added/accreted to older blocks.

During the NeoProterozoic, the southern part of the Kalahari Craton was covered by a thick sequence of supra-cratonic clastic sediments, including the Witwatersrand and Ventersdorp Transvaal basins. These basins host the extensive paleoplacer Witwatersrand gold and uranium deposits in South Africa. The Damara Mobile Belt of Pan African ages, located in Namibia and South Africa, separates the Kalahari Craton from the Congo Craton. During the early Proterozoic, the southern part of the Kalahari Craton was covered by a thick sequence of supra-cratonic clastic sediments, including the Witwatersrand and Ventersdorp Transvaal basins. These basins host the extensive paleoplacer Witwatersrand gold and uranium deposits in South Africa. The Damara Mobile Belt of Pan African ages (fig 2.1) located in Namibia and South Africa, separates the Kalahari Craton from the Congo Craton.

In the Neoproterozoic, the southern section of the Kalahari Craton became overlain by thick sedimentary layers, forming supra-cratonic basins like the Witwatersrand and Ventersdorp-Transvaal. These regions are notable for hosting the ancient Witwatersrand deposits of gold and uranium found in South Africa. The Kalahari Craton is separated from the Congo Craton by the Damara Mobile Belt an orogenic zone of Pan-African age that stretches across Namibia and parts of South Africa.

The Congo-Tanzania Craton comprises a fusion of the larger Congo Craton and the smaller Tanzania Craton, forming the geological basement of much of central Africa. This craton includes five Archean blocks joined together by orogenic belts from the Paleoproterozoic period. It is bordered and interrupted by Mesoproterozoic structures such as the Kibaran and Irumide Belts. Late Proterozoic tectonic activity along its southern edge led to rifting events that shaped features like the Lufilian Arc and the Zambezi Belt. These episodes were accompanied by volcanic activity and the deposition of sedimentary sequences forming the Katanga Supergroup across modern-day Zambia and the Democratic Republic of Congo an area rich in copper and cobalt resources. The craton is encircled by various Pan-African belts, including the West Congo Belt between Angola and Gabon, the Central African Belt between Congo, Cameroon, and Chad, and the Mozambique Belt to the east.

The West African Craton (see Figure 2.2) spans much of western and north-western Africa. It consists of an Archean nucleus, represented by the Rgueïbat Shield, joined by the Paleoproterozoic Birimian Orogenic Belt. This belt comprises thick sequences of metavolcanic and metasedimentary rocks. To the east, the craton is bordered by Mid-Proterozoic sediments, including the gold-bearing Tarkwaian conglomerates and quartzites, which are believed to be eroded remnants of the Birimian Orogenic Belt. The Dahomeyan-Ahagger Mobile Belt, also known as the Trans-Saharan Orogeny (Kroner & Stern, 2014), is located east of Ghana, extending into Togo, Nigeria, and further north into Niger and Algeria (see Figure 2.2). This belt represents zones of reactivation and deformation of ancient gneiss, granite, and metasedimentary rocks that were reworked during the Pan-African Orogeny.

The Birimian rocks are a significant source of orogenic gold and manganese deposits found in Ghana, Mali, and Burkina Faso. Other notable mineral resources in the region include bauxite and lateritic iron deposits in Guinea, rutile and iron ore in Sierra Leone, and tin and tantalite in Nigeria, the latter being associated with Pan-African granitic pegmatites.

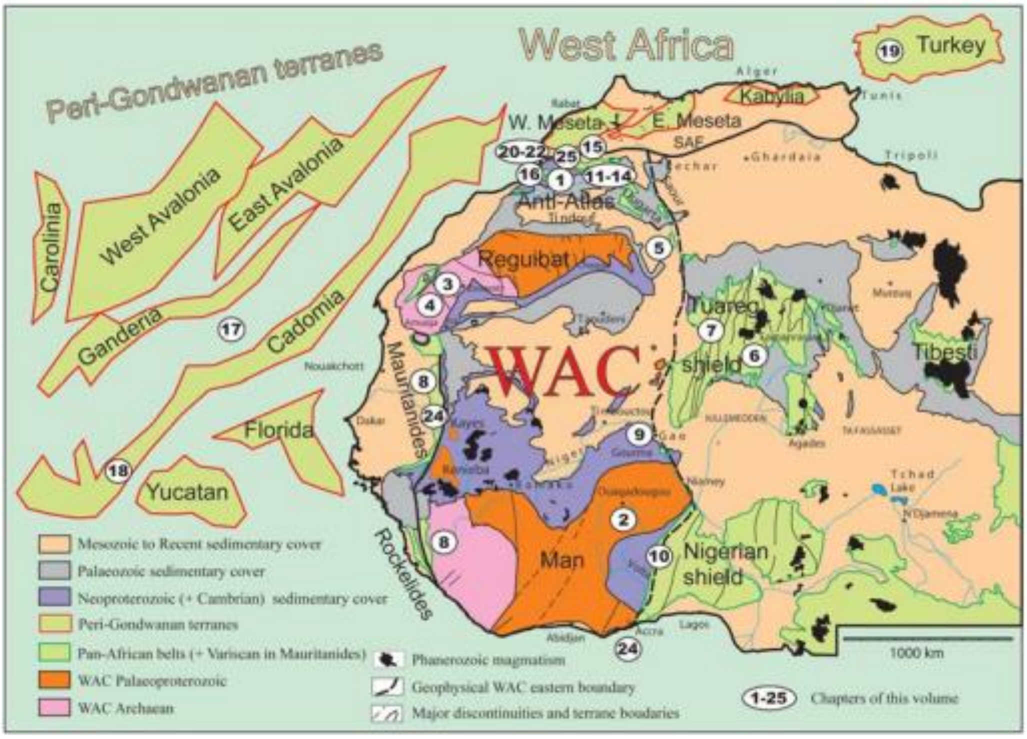

Figure 2.2 Geological map of West Africa showing the orogenic belts. from Fabre (2005) and Lie´geois et al. (2005)

Following the Precambrian Era, Africa's stable platform underwent significant geological events during the Phanerozoic, including the formation of localized fold belts. Notable examples include the Cape Fold Belt in South Africa, the Anti-Atlas Belt in Morocco, and the Mauritanide Belt along the north-eastern borders of the West African Craton. During the Phanerozoic, large-scale regional uplifts and epirogenic basins formed, accompanied by the deposition of the Karoo system, consisting of sediments and volcanic rocks, which served as cover rocks in areas such as South Africa, Namibia, and East Africa in the Middle Phanerozoic. The breakup of Gondwana in the Early Mesozoic led to the creation of several inland sedimentary basins and the accumulation of marine and continental sedimentary sequences across north-western Africa. In the Cenozoic Era, sedimentary deposition continued in some inland basins, and structural deformation occurred. During the Tertiary, widespread erosion surfaces developed across western Africa, leading to deep tropical weathering and the formation of lateritic bauxite deposits (Wright, 1985).

2.2 Geotectonic Framework of Nigeria

Nigeria's geotectonic setting is a part of the Precambrian geology of Africa, particularly West Africa. The region's geological framework comprises stable cratons, unchanged for 1.5 Ga, and mobile belts affected by the Late Proterozoic Pan-African Orogeny (Wright, 1985). Nigeria is situated within the Pan-African mobile belt, bounded by the West African and Congo Cratons to the south and the Tuareg shield to the north (Black et al., 1979; Black, 1980). This mobile belt resulted from a plate collision between the passive continental margin of the West African Craton and the active Pharusian belt (Tuareg shield), approximately 600 million years ago (Burke and Dewey, 1972; Caby et al., 1981; Dada, 2006). The Pan-African mobile belt in Nigeria is distinct from the West African Craton, separated by Infra-Cambrian to lower Palaeozoic sediments and the Togo belt's intensely thrust-faulted rocks (Wright, 1985). The region's geological setting exhibits a "basin and swell" pattern, characterized by Pan-African rocks forming the Togo-Benin-Nigeria swell, also known as the Benin-Nigeria shield (Wright, 1985).

Nigeria geological setting consists of Precambrian basement rocks. Notably, the Jos Plateau area features Mesozoic calc-alkaline ring complexes (Younger Granites) that intruded these basement rocks. The basement rocks themselves are the result of multiple orogenic cycles, involving deformation, metamorphism, and magmatism. These cycles correspond to at least four major episodes:

- Liberian (c. 2500 Ma)
- Eburnian (c. 1850 ± 250 Ma)
- Kibarian (c. 1100 ± 100 Ma)
- Pan-African (c. 550 ± Ma)

Nigeria's Precambrian rocks underwent multiple cycles of transformation, with the first three cycles (the Liberian, Eburnian and Kibarian) characterized by intense deformation, folding, and regional metamorphism, followed by extensive migmatization (Abaa, 1983). In contrast, the fourth cycle, the Pan-African Orogeny (c. 550 ± Ma), involved regional metamorphism, migmatization, granitization, and gneissification, resulting in syntectonic granites and homogeneous gneisses. The structural orientation of Nigeria's Precambrian rocks generally aligns with the following directions N-S, NNE-SSW and NNW-SSE. These alignments are attributed to the Pan-African Orogeny, the most recent significant geological event shaping the region's Precambrian rocks.

The late stages of the Pan-African Orogeny in Nigeria were characterized by the emplacement of granites and granodiorites, accompanied by contact metamorphism, during the final stages of deformation. This period also saw faulting and fracturing as significant tectonic activities associated with the edification of the orogeny (Gandu et al., 1986; Olayinka, 1992). The Precambrian Basement Complex of Nigeria is unconformably overlain by sedimentary formations ranging from the Mesozoic to Cenozoic periods (Obaje, 2009). These sedimentary covers include the Cretaceous Bida Basin, Benue Trough, and Anambra Basin, which connect with the Cenozoic to Quaternary sedimentary deposits of the Niger Delta. Further northeast, the Upper Benue Trough transitions into the Bornu Basin, dominated by Quaternary sediments. Additional basins such as the Dahomey Basin and the Calabar Flank, which span the southern coastline, also converge with the Niger Delta on its western and eastern edges, respectively (Wright, 1985; Petters, 2004).

2.3 Geological Setting of Nigeria

Nigeria's geology consists of three primary litho-petrological units: the Basement Complex, Younger Granites, and Sedimentary Basins (Figure 2.3). The Precambrian Basement Complex includes the Migmatite-Gneiss Complex, Schist Belts, and Older Granites. In contrast, the Younger Granites, dating to the Jurassic period, are a series of magmatic ring complexes mainly found around Jos and other parts of north-central Nigeria, distinct in structure and petrology from the Older Granites.

The sedimentary basins (see Figure 2.3), spanning Cretaceous to Tertiary periods, encompass the Niger Delta, Anambra Basin, Lower, Middle, and Upper Benue Trough, Chad Basin, Sokoto Basin, Mid-Niger (Bida-Nupe) Basin, and Dahomey Basin. These geological formations host a wide variety of economically significant mineral resources, including gold, iron ore, cassiterite, columbite, wolframite, pyrochlore, monazite, coal, limestone, clays, barites, and lead-zinc, distributed across Nigeria's 36 states and the Federal Capital Territory. Oil and gas are primarily concentrated in the Niger Delta Basin, with additional reserves potential in other sedimentary basins such as the Anambra Basin, Benue Trough, Chad Basin, Sokoto Basin, Bida Basin, and Dahomey Basin.

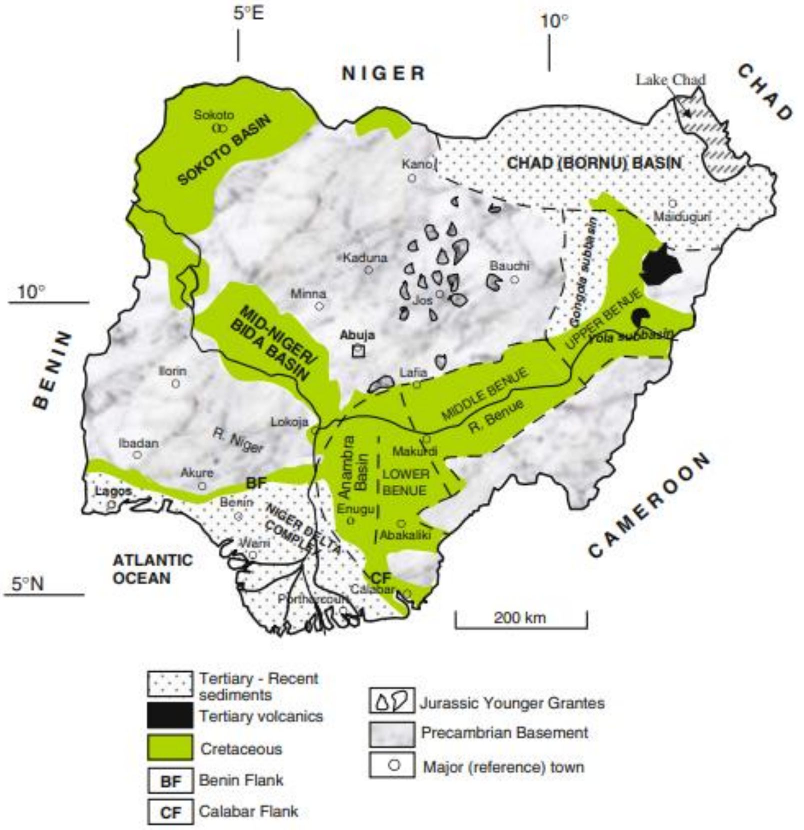

Figure 2.3. Geological map of Nigeria showing the major geological components, Basement Complex, Younger Granite and Sedimentary Basin. Adapted from (Obaje, N.G. 2009)

2.3.1 The Basement Complex

The Basement Complex is one of the three primary litho-petrological units that constitute Nigeria's geology. It forms part of the Pan-African Mobile Belt and is situated between the West African and Congo Cratons, south of the Tuareg Shield (Black, 1980). This complex is intruded by Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments. The Basement Complex was significantly impacted by the 600 Ma Pan-African orogeny, which reactivated the region due to the plate collision between the passive margin of the West African Craton and the active Pharusian Continental Margin (Burke and Dewey, 1972; Dada, 2006). The rocks of the Basement Complex are the result of at least four major orogenic cycles involving deformation, metamorphism, and remobilization. These cycles correspond to the Liberian (2,700 Ma), Eburnean (2,000 Ma), Kibaran (1,100 Ma), and Pan-African (600 Ma) events. The first three cycles were marked by intense deformation and isoclinal folding, accompanied by regional metamorphism and extensive migmatization. During the Pan-African orogeny, regional metamorphism, migmatization, granitization, and gneissification occurred, producing syntectonic granites and homogeneous gneisses (Abaa, 1983). The later stages of this orogeny involved the emplacement of granites and granodiorites alongside contact metamorphism, culminating in faulting and fracturing (Gandu et al., 1986; Olayinka, 1992). Within the Nigerian Basement Complex, four distinct petro-lithological units can be identified:

- The Migmatite – Gneiss Complex (MGC)
- The Schist Belt (Metasedimentary and Metavolcanic rocks)
- The Older Granites (Pan African granitoids)

- Undeformed Acid and Basic Dykes

2.3.1.1 The Migmatite – Gneiss Complex

The Migmatite–Gneiss Complex, often regarded as the Basement Complex *sensu stricto* (Rahaman, 1988; Dada, 2006), is the most extensive unit within the Nigerian basement. This complex comprises a heterogeneous assemblage of migmatites, orthogneisses, paragneisses, and metamorphosed basic and ultrabasic rocks. Petrographic studies reveal that Pan-African tectonothermal events led to the partial melting and recrystallization of many of its constituent minerals, resulting in medium- to upper-amphibolite facies metamorphism. The age of the Migmatite–Gneiss Complex ranges from Pan-African to Eburnean, and the "Migmatite-Gneiss-Quartzite Complex" constitutes approximately 60% of the Nigerian basement's surface area (Rahaman and Ocan, 1978). The rocks of this complex record three significant geological events (Rahaman and Lancelot, 1984):

- Around 2,500 Ma, crust-forming processes began, including the formation of banded grey gneisses, such as those in Ibadan, originating from the mantle, and crustal growth through sedimentation and orogeny.
- The Eburnean orogeny occurred at approximately 2,000 ± 200 Ma, producing granite gneisses, such as the Ibadan-type granite gneisses.
- Ages ranging from 900 to 450 Ma correspond to the Pan-African orogeny, which structurally reworked older rocks, reset geochronological systems, and generated new lithological units, including granite gneisses and migmatites.

A striking similarity exists between these events and the development of the Birimian rocks in the West African Craton. However, while Birimian rocks are associated with gold, manganese, and iron mineral deposits, their equivalents in Nigeria appear to be sparsely mineralized. The extent of Eburnean and older rocks in Nigeria remains uncertain, but geochemical evidence confirms their presence south of latitude 9°N (Rahaman and Lancelot, 1984). In contrast, lithologically similar rocks in north-eastern and south-eastern Nigeria have yielded only Pan-African ages (Tubosun, 1983). The Migmatite–Gneiss Complex is widely distributed across Nigeria, occurring in regions such as Abuja, Keffi, Akwanga, Bauchi, Kaduna, Kano, Funtua, Okene, Egbe, and Ajaokuta in northern Nigeria; Ibadan, Ile-Ife, Akure, and Ikere in western Nigeria; and Obudu and the Oban Massif in eastern Nigeria.

2.3.1.2 The Schist Belt (Metasedimentary and Metavolcanic rocks)

The Schist Belts of Nigeria are low-grade, metasediment-dominated formations that trend predominantly N–S and are most prominent in the western part of the country. These Upper Proterozoic supracrustal rocks are infolded into the migmatite-gneiss-quartzite complex and exhibit a wide range of lithologies, including coarse- to fine-grained clastic sediments, pelitic schists, phyllites, banded iron formations, carbonate rocks (calcite and dolomitic marbles), and mafic metavolcanics such as amphibolites. Some belts may also contain fragments of ocean floor material derived from small back-arc basins (Rahaman, 1976; Grant, 1978). Debates exist regarding their formation. While Rahaman (1976) and Grant (1978) suggest the presence of multiple depositional basins, Oyawoye (1972) and McCurry (1976) argue for a single supracrustal cover. Olade and Elueze (1979), on the other hand, propose that the belts are fault-controlled rift structures. Structural and lithological studies by Grant (1978), Holt (1982), and Turner (1983) imply different sedimentary ages, whereas Ajibade et al. (1979) contend that all belts share identical deformational histories. The relationship between the Schist Belts and the basement rocks has also been examined. Truswell and Cope (1963) viewed the contacts as conformable metamorphic fronts, but Ajibade et al. (1979) identified structural breaks in these relationships. Geochronological studies remain inconclusive; however, the ages of cross-cutting Older Granites set a lower age limit of approximately 750 Ma. A metamorphic Rb/Sr age of 1,040 ± 25 Ma was reported for the Maru Belt phyllites (Ogezi, 1977). Generally, these rocks are considered Upper Proterozoic.

The geochemistry of the amphibolite complexes within the Schist Belts has been a subject of debate. Klemm et al. (1984) suggested that the Ilesha Belt may represent an Archaean greenstone belt, while Olade and Elueze (1979), Ogezi (1977), and Ajibade (1980) emphasized an ensialic origin for the belts. Conversely, Ajayi (1980), Rahaman (1981), and Egbuniwe (1982) pointed out the presence of oceanic materials with tholeiitic affinities. The Schist Belts are confined to an approximately 300 km wide NNE-trending zone. To the west lies the gneissic and migmatitic Dahomeyan terrain (Burke and Dewey, 1972), while to the east, no Schist Belts are found for about 700 km until the Pan-African granite-migmatite terrain in Cameroon, where Upper Proterozoic schist belts occur north of the Congo Craton. Detailed studies have been conducted on the Schist Belts in areas such as Maru, Anka, Zuru, Kazaure, Kusheriki, Zungeru, Kushaka, Iseyin-Oyan, Iwo, and Ilesha. These belts are commonly associated with gold mineralization.

2.3.1.3 The Older Granites (Pan African Granitoids)

The term "Older Granite" was introduced by Falconer (1911) to differentiate the deep-seated, often concordant or semi-concordant granites of the Basement Complex from the high-level, highly discordant tin-bearing granites of Northern Nigeria. The Older Granites are considered pre-, syn-, and post-tectonic intrusions that cut across both the migmatite-gneiss-quartzite complex and the schist belts. These rocks vary widely in age and composition, representing a prolonged magmatic cycle (750–450 Ma) associated with the Pan-African orogeny. Their composition ranges from tonalites and diorites to granodiorites, true granites, and syenites, with charnockites forming a significant group of high-level intrusions produced through anatexis (Rahaman, 1981). Although the suite generally lacks direct mineralization, thermal effects may have contributed to remobilizing mineralizing fluids.

The Older Granites are a prominent manifestation of the Pan-African orogeny and account for significant crustal material additions, reaching up to 70% in some areas (Rahaman, 1988). However, efforts to classify these granites based on their emplacement timing within the orogeny are only locally valid. Contact relationships among various members of the suite indicate the coexistence of multiple magmas. Compositionally, the granites fall within the calc-alkaline field on the AFM diagram, are rich in alkalis, and are often slightly corundum normative.

Dada (2006) advocated for the term "Pan-African Granitoids" to replace "Older Granites," as it better reflects the rocks' age and encompasses the diverse petrologic groups formed during the same period. The granitoids associated with the schist belts in northwestern and southwestern Nigeria include biotite granites, biotite-muscovite granites, syenites, charnockites, serpentinites, and anorthosites. Rahaman (1988) rejected earlier classifications of the Older Granites based on texture, mineralogical composition, and relative emplacement timing. Instead, he proposed a classification framework primarily based on their textural characteristics.

- Migmatitic granite;
- Granite gneiss;
- Early pegmatites and fine-grained granite;
- Homogeneous to coarse porphyritic granite;
- Slightly deformed pegmatite aplites and vein quartz; and
- Undeformed pegmatites, two-mica granites and vein quartz.

In northern Nigeria, the prevalence of Pan-African granites increases eastward. West of Zaria, these granites are primarily isolated intrusions (McCurry, 1973). In contrast, in the region between Rahama and the Mesozoic-Cenozoic sedimentary cover, the granites and related rocks envelop remnants of migmatites. McCurry (1973), focusing on the area west of Zaria, classified the granites into two main groups based on their field relationships:

- **Syntectonic Granites**: These are elongate, batholithic sheets that are partially concordant with surrounding rocks and display foliation.
- **Late-Tectonic Granites**: These are poorly foliated, discordant bodies enriched with mafic xenoliths and characterized by a lower proportion of K-feldspar.

The late-tectonic granites are interpreted as products of widespread mobilization and reactivation of older basement rocks during the Pan-African orogeny. The Older Granites are intricately associated with the Migmatite–Gneiss Complex and the Schist Belts, into which they have intruded. Consequently, they are present wherever rocks of the Migmatite–Gneiss Complex or the Schist Belts occur. Prominent occurrences of Older Granites include areas around Wusasa (Zaria), Abuja, Bauchi, Akwanga, Ado-Ekiti, and Obudu.

In the Bauchi area and parts of southwestern Nigeria, the Older Granites often exhibit a dark greenish-grey colour and include significant amounts of olivine (fayalite) and pyroxene alongside quartz, feldspars, and micas. Due to this unique composition, these granites are locally referred to as Bauchite (in Bauchi) and Oyawoyite (named after Professor Oyawoye, who first mapped them) in southwestern Nigeria. For consistency in terminology, both Bauchites and Oyawoyites are grouped as the charnockitic rocks (charnockites) of the Basement Complex.

2.3.2 The Younger Granite

The Mesozoic Younger Granite ring complexes of Nigeria are part of a broader region of alkaline, anorogenic magmatism. This magmatic province spans a 200 km-wide and 1,600 km-long zone from northern Niger to south-central Nigeria. Rb/Sr whole-rock dating reveals a north-to-south age progression, with the northernmost Adrar Bous complex in Niger being Ordovician and the southernmost Afu complex in Nigeria being Late Jurassic (Bowden et al., 1976). Aeromagnetic anomalies suggest that NE–SW-oriented buried lineaments, likely representing incipient rifts, controlled the spatial distribution of these complexes (Ajakaiye, 1983).

The Younger Granites have been extensively studied in Nigeria, both for their geological significance and for their economic importance, as they were identified in the early 1900s as the source of rich alluvial cassiterite deposits around the Jos Plateau. Field mapping of the complexes shows a consistent magmatic progression from volcanism to plutonism, with the emplacement of predominantly granitic melts at shallow crustal levels. These rocks are overwhelmingly acidic, with over 95% classified as rhyolites, quartz-syenites, or granites, while basic rocks constitute less than 5%. Their compositions range from strongly alkaline to peralkaline, with some being aluminous to peraluminous.

Nigeria hosts over 50 Younger Granite complexes, varying in size from less than 2 km to more than 25 km in diameter (Kinnaird, 1981). Together, these complexes cover an area of approximately 7,500 km², with most ranging from 100 to 250 km² in circular or elliptical forms. Examples include overlapping centres like Ningi-Burra and individual centres like Ririwai. These complexes typically began as volcanic chains, with initial explosive eruptions depositing ash-fall tuffs and agglomerates. Ignimbrites dominate the volcanic sequences, accompanied by minor rhyolitic and basic flows. Volcanic feeder intrusions, though minor, are crucial during the caldera-forming stage, linking subvolcanic roots to the overlying volcanic deposits. Fayalite-hedenbergite quartz porphyry with ignimbritic textures is also common. The Younger Granites are discordant, high-level intrusions formed through piecemeal stopping during the collapse of central blocks. Early stages involved the intrusion of significant volumes of acidic lavas, tuffs, and ignimbrites, much of which has been partially preserved due to subsidence along ring faults. These rhyolitic rocks often directly overlie the metamorphic basement, indicating that the complexes were emplaced in uplifted regions undergoing erosion.

Granitic ring dykes dominate most Younger Granite complexes, varying in diameter from less than 5 km to over 30 km. Their shapes range from polygonal to circular, crescentic, and more irregular forms, occasionally appearing as simple stocks or bosses. Some complexes exhibit a broadly concentric pattern, suggesting localized activity, while others show overlapping rings, indicating that the centre of magmatic activity shifted over time. In the southern complexes, erosion has exposed granite extensively, while in others, the absence of volcanic rocks is likely due to erosion rather than a lack of eruptions. The emplacement of these ring dykes is thought to have involved mechanisms of underground cauldron subsidence.

The granitoid suite is overwhelmingly granitic, making up more than 95% of the area, with intermediate and basic rocks constituting less than 5%. Several distinctive types of granite are identified within these complexes:

- Peralkaline granites and related syenites (with alkali or calcic amphibole) plot close to Q-A join in the Streckeisen Q-A-P plot;
- Peraluminous biotite alkali feldspar granites and biotite syeno-granites plot close to the boundary between the two fields on the Streckeisen diagram;
- Metaluminous fayalite and hornblende-bearing granites and porphyries with amphiboles or biotite plot in the granite field.

The granites of the Younger Granites series predominantly occur as ring complexes. These granites include varieties such as soda pyroxenes and amphiboles, biotite, and fayalite granites, along with syenites and trachytes. Minor rock types include gabbros and dolerites. Rhyolites, tuffs, and ignimbrites are seldom preserved. The centers of intrusion typically overlap, with a general southward shift in emplacement. Additionally, northeast-trending alignments of complexes are evident, potentially reflecting deep-seated zones of weakness within the basement, although no clear surface correlations with regional tectonic features have been identified (Black and Girod, 1970). The Younger Granites are of significant geological and economic interest due to their well-defined structures, mid-plate anorogenic characteristics, and associations with cassiterite, wolframite, scheelite, and zinc mineralization. These complexes have sustained a notable alluvial tin mining industry in the region.

Fifteen complexes have been isotopically dated, revealing a discernible age progression from the north to the south: 213 ± 7 Ma at Dutse, 186 ± 15 Ma at Zaranda, and 183 ± 7 Ma at Ningi-Burra, to younger ages in the south, such as 151 ± 4 Ma at Pankshin, 145 ± 4 Ma at Mada, and 141 ± 2 Ma at Afu. This trend, along with the presence of similar alkali granite ring complexes in southern Niger and northern Air that are Carboniferous, Devonian, and Ordovician in age, supports a sequential age progression spanning approximately 500 Ma across a distance of over 2,000 km (Bowden et al., 1976). Further isotopic studies (Rahaman et al., 1984; Bowden and Kinnaird, 1984) corroborate this progression. Among African ring complex provinces, the Younger Granites of Nigeria are the most extensively studied. While their geological features, such as ring structures and petrogenetic evolution, are comparable to those of other provinces, their economic significance surpasses most, except for the carbonatite complex of Phalabora (Kinnaird, 1984; Bowden and Kinnaird, 1984).

2.3.3 The Sedimentary Basins of Nigeria

Nigeria is rich in geological history, particularly in terms of its sedimentary basins (see figure 2.4), which are of great importance for natural resource exploration, including oil, gas, metallic and non-metallic minerals. Two key sedimentary basins in Nigeria, the Benue Trough and the Niger Delta Basin, have distinct geological characteristics and play critical roles in the country's economy and geology.

2.3.3.1 The Benue Trough

The Benue Trough of Nigeria is a prominent Cretaceous rift basin located in central West Africa. It stretches approximately 800 km in an NNE–SSW orientation, with a width of about 150 km. Its southern boundary is marked by the northern edge of the Niger Delta Basin, while its northern extent is defined by the southern margin of the Chad Basin. The trough is filled with up to 6,000 m of Cretaceous–Tertiary sediments, with pre-mid-Santonian sediments exhibiting folding, faulting, and uplift in various areas. The mid-Santonian tectonic event caused compressional folding throughout the Benue Trough, resulting in the formation of numerous anticlines and synclines (Benkhelil, 1989). Notable structural features include:

- **Lower Benue Trough**: Abakaliki anticlinorium and Afikpo syncline.
- **Middle Benue Trough**: Giza anticline and Obi syncline.
- **Upper Benue Trough**: Lamurde anticline and Dadiya syncline.

After the mid-Santonian tectonism and associated magmatic activity, the depositional axis of the Benue Trough shifted westward, leading to the subsidence of the Anambra Basin (Figure 2.4).

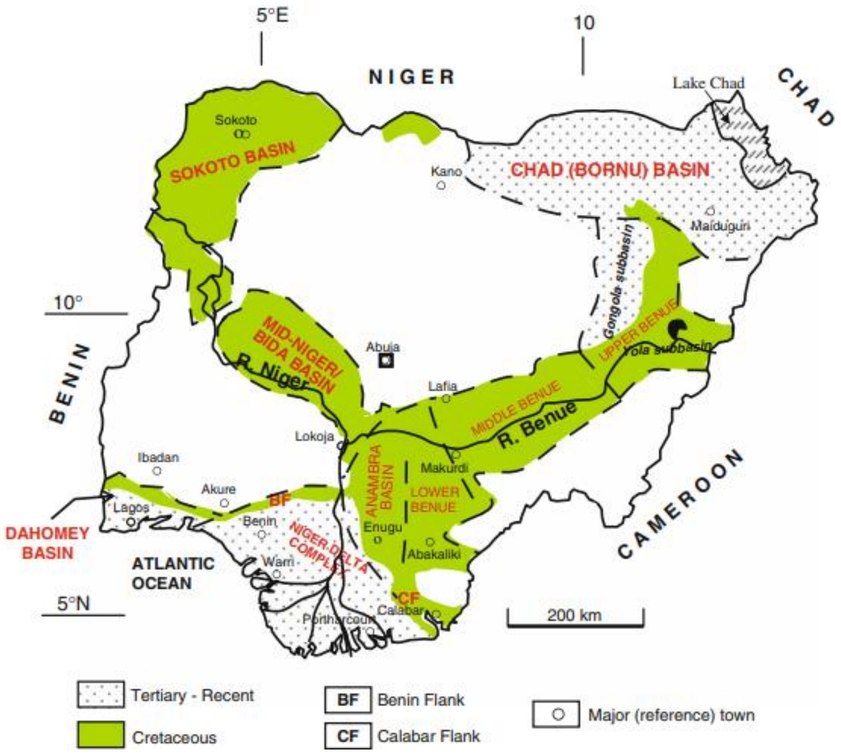

Figure 2.4. Highlighted in red the sedimentary Basin of Nigeria. Adapted from (Obaje, N.G. 2009).

The Anambra Basin is considered a component of the Lower Benue Trough and contains post-deformational sediments dating from the Campanian-Maastrichtian to Eocene periods. Its inclusion within the Benue Trough is logical due to its development as a related structure after the compressional stage of the mid-Santonian tectonic episode (Akande and Erdtmann, 1998). The Benue Trough is conventionally subdivided into three segments: the Lower, Middle, and Upper Benue Trough. These divisions are not demarcated by clear boundaries but are instead characterized by the major localities (towns/settlements) that serve as the depocenters for each segment, as documented in various studies (e.g., Petters, 1982; Nwajide, 1990; Idowu and Ekweozor, 1993; Obaje et al., 1999).

- **Lower Benue Trough**: Depocenters are primarily around Nkalagu and Abakaliki, which are central to this segment's geological structure.
- **Anambra Basin**: Though post-deformational, its main depocenters are Enugu, Awka, and Okigwe.
- **Middle Benue Trough**: This section extends from Makurdi through Yandev and Lafia, forming another significant sedimentary region.

The division highlights the spatial distribution of geological features and sedimentary deposits across the Benue Trough.

2.3.3.2 Niger Delta Basin

The Niger Delta Basin (see figure 2.5) is located in the southern part of Nigeria margin of the Gulf of Guinea, the basin’s evolution and stratigraphy is well studied by (Kulke,1995). The evolution is closely associated with the Formation of the Benue trough in Nigeria during the incipient separation of the continental crust of South America and Africa, in the late Jurassic (Burke, 1972) after the separation of the continental plate of South America and Africa, the opening of the Atlantic Ocean in turn gave rise to a marine incursion as marked by marine sedimentation in the Benue Trough and the Anambra Basin. During the lower cretaceous in Nigeria as the influx of Niger River clastic form the adjacent highland increase in the early Tertiary, then Niger Delta formed at the point where Benue Trough adjoined the Atlantic Ocean (Doust and Omatsola, 1990). The Niger Delta consists of a sedimentary sequence over 12km thick and represents a pro-gradational package (Short and Stauble, 1967). The sedimentary sequence consists of three lithostratigraphic units (see figure 2.6) (i) Akata (ii) Agbada (iii) Benin.

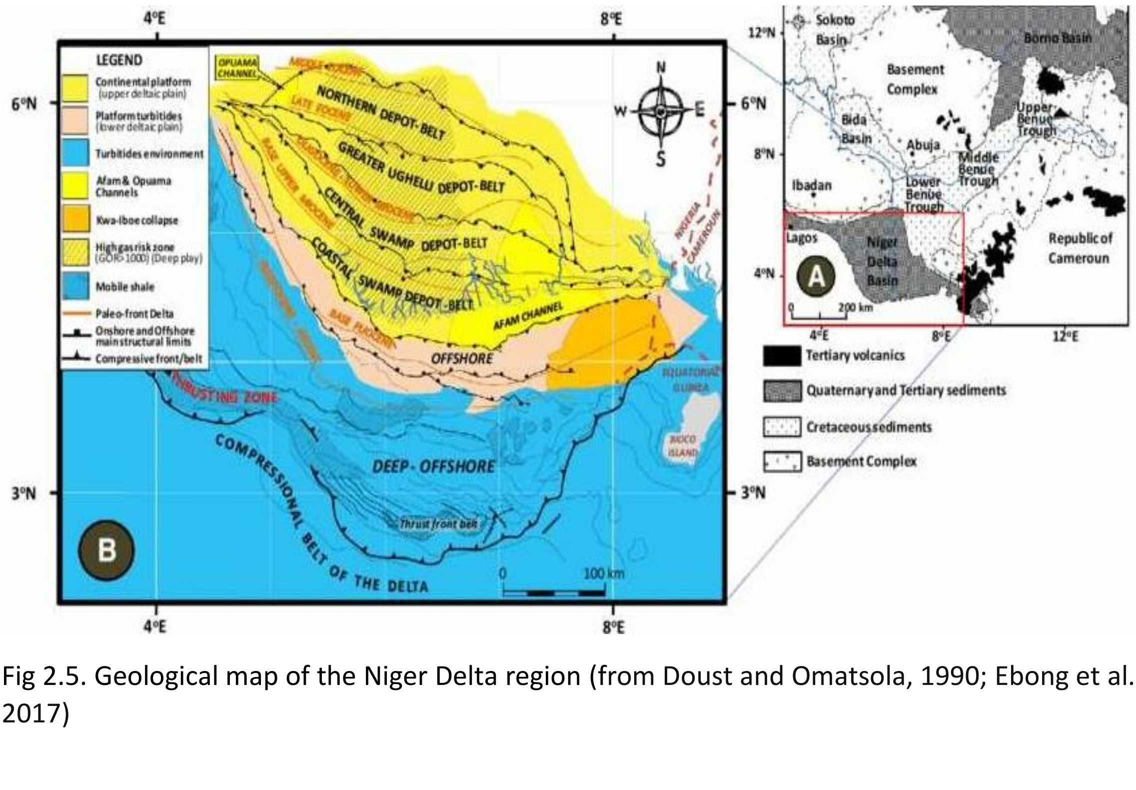

Fig 2.5. Geological map of the Niger Delta region (from Doust and Omatsola, 1990; Ebong et al. 2017)

The Akata is situated at the base of the Delta and have marine origin and composed of thick shale sequence (potential source rock of oil deposits) turbidite sand and small amount of clay and silt. The process started in the Palaeocene to Recent, the Akata Formation formed during low stands when terrestrial organic matters and clays were transported to deep water area characterized by low energy conditions and oxygen deficiency, the Formation underlies the entire Delta and is typically over pressured. Turbidity currents likely deposited deep sea fan sands with in upper Akata Formation during the development of the Delta.

The Agbada Formation overlies the Akata, it is the major petroleum bearing unit, it began in the Eocene and continued until Palaeocene the information consists of paralic silica-clastics over 3700 meters thick and represents the actual Deltaic portion of the sequence. The clastic accumulated in Delta-front, Delta-topset and fluvio Deltaic environment in the lowest Agbada Formation shale and sandstone beds were deposited in equal proportion and the upper portion is mostly sand with only minor shale interbeds.

The Benin Formation overlies the Agbada, it is a continental Late Eocene to Recent deposit of alluvial and upper coastal plain sand that are up to 200m thick. Petroleum in the Niger Delta is produced from sandstones and unconsolidated sands predominantly in the Agbada Formation, the characteristic of the reservoirs in the Agbada Formation are controlled by depositional environment and depth of burial.

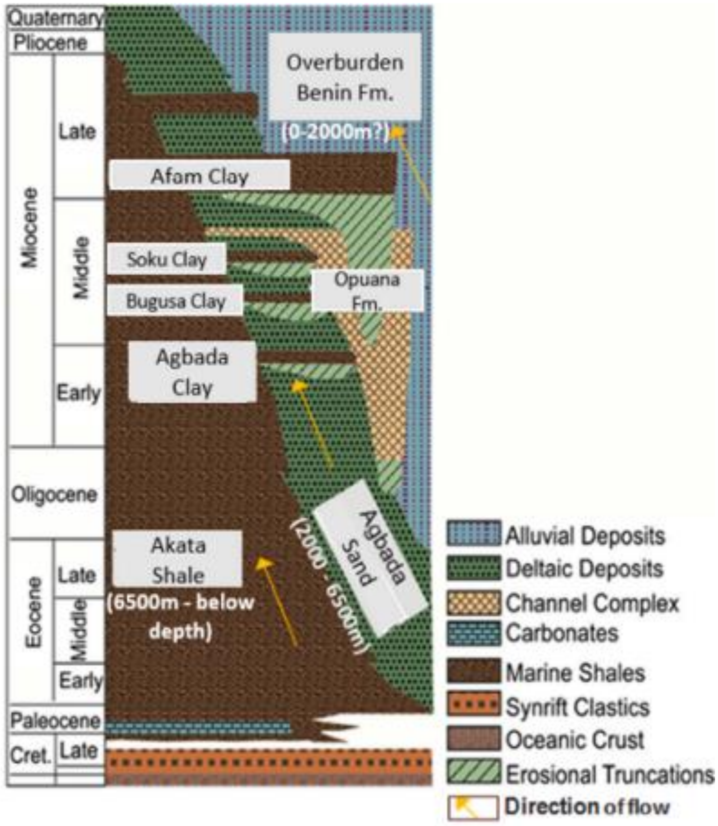

Fig 2.6 lithostratigraphic sessions in the Niger Delta Basin modified after (Folorunsho et al., 2015)

2.4 Mineral Resources of Nigeria

Nigeria has often been described as a country endowed with abundant mineral resources, including but not limited to precious, ferrous and base metals, some energy minerals and a variety of industrial (non-metallic) minerals and rocks (see figure 2.7).

According to the Nigeria Geological Survey Agency, over 40 different types of economic minerals have been reported from approximately 500 locations spread widely across the country (see Figure 2.7). Among these diverse mineral resources, the major most significant and economically important ones will be discussed. However, it is obvious from mineral production statistics that most of these minerals are non-metallic, and over 75% of the occurrences can justifiably be described as” mineral showings” with little or no economic potential or value (Olade, 2019a).

The currently known economic minerals in Nigeria belong to three main categories as follows and classified by the metallogenic domain (see figure 2.8) (Olade, 1981):

Metallic minerals: gold, tin, niobium-tantalum, lead-zinc, manganese, iron ore, copper, tungsten, nickel, and chromium:

Industrial Minerals: oil and gas, barite, gypsum, talc, salt, bentonite, clays, kaolin, zircon, mica, tourmaline, beryl, glass sand, gemstones.

Solid Energy minerals: coal, tar sand and bitumen.

Industrial rocks: limestone, marble, granite, dolerite, sand, shale and laterite.

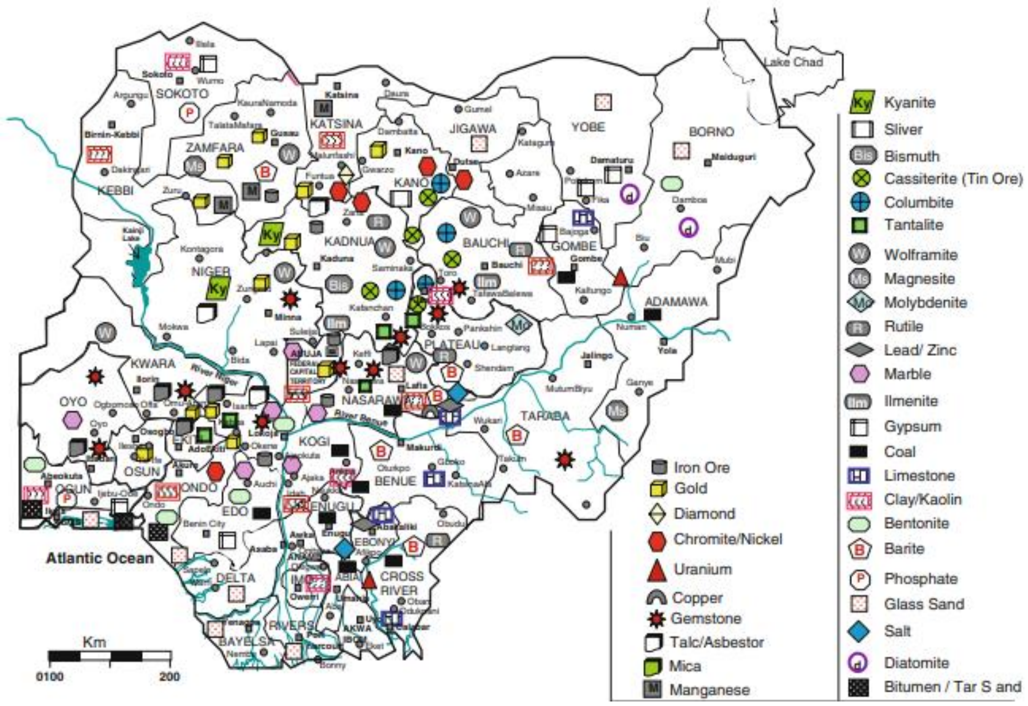

Figure 2.7. Map of Nigeria showing Mineral Resources distribution across states. Adapted from (Obaje, N.G. 2009)

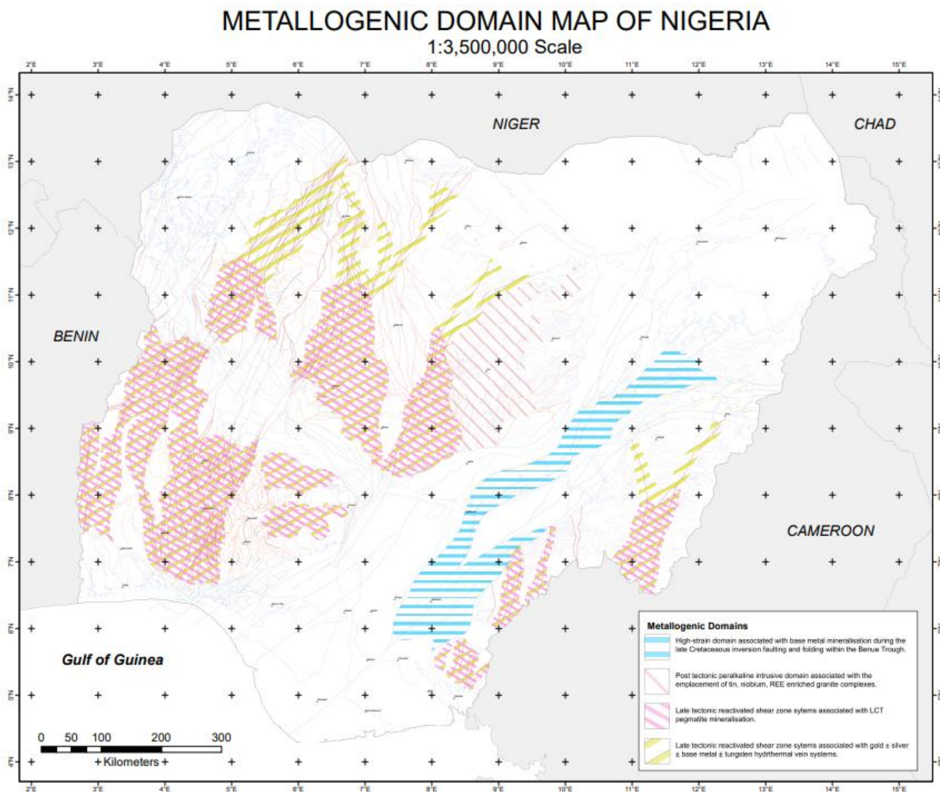

Figure 2.8. Metallogenic domain map of Nigeria. Adapted from (NGSA, mineralization map of Nigeria, 2023)

2.4.1. Metallic Minerals

2.4.1.1. Gold

Gold mining reached its peak in the year 1935–1941 but since 1950 has been generally limited to very small-scale alluvial workings. In recent years the defunct Nigerian Mining Corporation did some extensive exploration work and planned a production from alluvials in the Ilesha area. Typically, gold bearing quartz veins carry some sulphides, galena and pyrite being the most common. The veins are very often conformable with the general N–S to NNE–SSW structural grain of the basement and occur in a variety of geologic settings which suggests that there was more than one period of mineralization. Regionally it was observed by Woakes and Bafor (1983) that primary gold deposits are associated with some schist belts (e.g. Ilesha, Maru, Anka, Kushaka) but not with others (e.g. Wonaka, Karaukarau, Iseyin-Ogun River), and that they are often spatially related to amphibolites and regional NE–SW to N–S fault or shear zones, with no specific relationship to the Older Granites or BIF. In the Ilesha (Elueze, 1981) and Egbe (Garba, 1985) areas, gold occurs in the amphibolites in amounts above the average primary gold content for similar rocks and is sufficient to provide the source of some of the alluvial deposits. The alluvial deposits throughout the goldfields are found not only in the present river channel deposits but also in older buried placers which in places have been eroded by the modern drainage system and are the source of modern placers. Russ (1957) also reported small quantities of gold in the basal conglomerates of the Cretaceous Nupe Sandstone in several localities fringing the Mid-Niger Basin. No similar deposits have been reported from the Benue Trough where the Cretaceous and later sediments are derived from basement areas with only very minor schist occurrences.

2.4.1.2. Iron Ore

Iron ore is used as raw material in the production of steel which is the most widely used construction and engineering material. Nigeria has for over 50 years tried to develop a national iron and steel industry based in Ajaokuta, using local raw materials (Olade, 2020). There are several deposits of low-grade iron ores in Nigeria. They are of three geological types; ferruginous quartzites (metamorphosed), ferruginous schists (metamorphic) and oolitic ironstones (sedimentary) (Olade, 2019b).

Major deposits are found in the Okene and Lokoja areas of Kogi State (Itakpe and Agbaja) respectively. The Agbaja Kogi mine located about 15 miles west of Okene is producing relatively higher-grade magnetite ore (>45% Fe) from sedimentary and lateritic ironstones. Indicated reserves are 200 million tons. For the proposed iron and steel production, the Precambrian ferruginous quartzites contain more than 500 million tons of proven reserves from several deposits located in the Okene area including Itakpe, Ajabonoko, Cnokochoko etc. Grades are low, ranging between 32 and 40% Fe, but can be upgraded to up to 65% Fe by beneficiation for direct feed into steel processing plants at Ajaokuta and Aladja complexes.

2.4.1.3. Lead-Zinc

Lead and zinc ores are commonly found together as fissure-filling veins within the Cretaceous sediments of the Benue Trough (Obaje, 2019). Numerous small deposits are located along a belt stretching from south of Abakaliki in Ebonyi State in the southeast to Gombe State in the northeast. The mineralization in Nigeria's lead-zinc deposits is primarily composed of siderite, sphalerite, galena, and barytes, with minor amounts of gold and silver. This mineralization type is characteristic of fracture-filling assemblages. Lead-zinc mineralization dominates, with only small quantities of barytes, notably in the more argillaceous sediments of the Albian Asu River Formation within the Abakaliki and Zurak provinces. Over 30 lodes of lead-zinc, totaling around 7,000 meters, have been documented in Nigeria's lead-zinc fields. Drilling results have revealed that this mineralization extends up to 100 meters deep. In the Abakaliki region, mineralization is associated with calcareous shales and shaly limestones. Two distinct rock types are identified within the lead-zinc fields: galena-rich and sphalerite-rich rocks (Obaje, 2019.

In the Ameri and Nyeba deposits, the Nigerian Lead-Zinc Mining Company (1956) provided a conservative estimate of 693,000 tonnes of lead-zinc ore, with concentrations of 9.0% lead and 7.0% zinc. The Abakaliki field remains Nigeria's most significant lead-zinc deposit, serving as a crucial source of these minerals for local and national industries. This mineralization, with its deep fracture-filling characteristics and significant reserves, underscores the strategic importance of the Abakaliki and Zurak provinces in Nigeria's mining sector, highlighting their role in supporting the nation's lead-zinc production capabilities.

2.4.1.4. Tin-Tantalum-Niobium Pegmatites

The production of tin remains the most economically significant solid mineral output in Nigeria, far surpassing the monetary value of other mineral resources. Tantalum, niobium, and other associated metals are often recovered as by-products during tin mining. Approximately 95% of the estimated 650,000 tonnes of cassiterite (tin) produced in the country originates from alluvial deposits linked to the Mesozoic Younger Granites, while the remaining 5% is sourced from pegmatites. These pegmatites form a distinct ENE–WSW trending belt extending from the central Jos Plateau to the Ife-Ilesha area. In addition to cassiterite, some pegmatites yield gem-quality corundum, which is actively mined on the Jos Plateau (Jacobson & Webb, 1946; Wright, 1970).

Jacobson and Webb (1946) were among the first to observe that the pegmatites predate the Younger Granites, associating them with the Pan-African Older Granite suite located nearby. However, subsequent research by Matheis and Vachette (1983) distinguishes between barren and tin-bearing pegmatites, noting that the tin-bearing ones are approximately 100 million years younger than both granites and barren pegmatites. They also highlight a close relationship between tin-bearing pegmatites and schist belts in the Ilesha and Egbe regions, suggesting that metamorphic processes played a critical role. Conversely, Kinnaird (1984) links these mineralized pegmatites to late or post-Pan-African orogenic granites.

The pegmatite belt represents a unique metallogenetic feature in the basement, crossing the schist belt structures despite the predominantly N-S orientation of most pegmatites. The mineralized pegmatite zone parallels the ENE–WSW alignment of Younger Granite intrusions and the Cretaceous Benue Trough. These pegmatites consist primarily of quartz, potash feldspar, albite, and muscovite, with less frequent occurrences of biotite and accessory minerals like tourmaline, cassiterite, and columbo-tantalite. The pegmatites, forming dykes and flat-lying sheets up to 2 km in length, have been mined extensively in both their weathered primary forms and the secondary alluvial deposits derived from them (Matheis & Vachette, 1983; Kinnaird, 1984).

2.4.1.5. Manganese

Manganese deposits are found at Tudun Kudu, located within the Karaukarau schist belt to the west of Zaria in northwestern Nigeria. Detailed mineralogical investigations by Muecke and Okujeni (1984) support the theory that these deposits formed through epigenetic processes. Various researchers have characterized the manganese occurrences in this region differently. Wright and McCurry (1970) described them as “conformable beds of quartzite,” while Moneme et al. (1982) referred to them as “manganiferous quartzites interlayered with phyllites.” Muecke and Okujeni (1984) observed them as “veins aligned with phyllite foliation and showing distinct boundaries.”

These manganese deposits are restricted to just two of Nigeria’s schist belts: the Maru belt, which also hosts banded iron formations (BIF), gold, and amphibolite rocks; and the Karaukarau belt, which is characterized by detrital quartzites but lacks BIF, has no significant gold presence, and contains only minimal amphibolites. Manganese plays a critical role in steel production, primarily serving to eliminate oxygen and sulfur impurities during the smelting process.

2.4.1.6. Ni-Sulphide and base-metal deposit

Several researchers (e.g., Bafor, 1981; Elueze, 1981) have identified various sulphide minerals, such as pyrite, pyrrhotite, pentlandite, bornite, and chalcocite, occurring in small quantities within the gabbro intrusives and metavolcanics of the schist belts. The Nigerian basement geology is known to have the potential for Ni-Cu-sulphide minerals, particularly in magmatic synvolcanic formations, such as komatiites and tholeiites.

Klemm et al. (1984) characterized the Ilesha schist belt as displaying field and geochemical features that align with Archaean granite greenstone terrains, which contrasts with other viewpoints that categorize it as part of an Upper Proterozoic sequence (Rahaman and Lancelot, 1984). Klemm et al. (1984) further identified komatiites, also known as metapyroxenites, within the amphibolite complex.

Significant Ni-sulphide deposits in Archaean terrains in regions such as Australia, Canada, and Zimbabwe are typically associated with the base of komatiite flows. Additionally, within other schist belts, the tholeiitic volcanics of Maru, Kushaka, and other Nigerian schist regions may be analogous to deposits like the Pechanga deposit in the USSR and Lynn Lake in Canada, where minor amounts of sulphides have also been documented.

The dominance of clastic sediments over tholeiitic volcanics in the Nigerian schist belts, coupled with a possible rift subsidence environment (Olade and Elueze, 1979), suggests a favourable geological setting for the presence of either Besshi-Kieslager Cu-Zn-type or exhalative Pb-Zn sedimentary deposits. These Nigerian schist belts share similarities with the Pan-African Damara Belt in Namibia (Martin, 1978), where the Matchless Amphibolite Belt contains Besshi-Kieslager type copper deposits, such as the Otjihase deposit (Goldberg, 1976).

These copper deposits occur near large volcanic masses, within sequences of clastic sediments, and are often accompanied by small exhalative iron formations and zones of chloritic alteration. The Nigerian schist belts also exhibit such features, and a more focused exploration for Cu/Zn deposits, based on these geological indicators, appears to be a promising area for further research (Martin, 1978; Olade and Elueze, 1979).

2.4.1.7. Uranium

The potential for uranium mineralization in Nigeria gained prominence following discoveries in neighbouring Niger Republic and secondary uranium minerals in Cameroon. Recent investigations have increasingly suggested the presence of uranium ore in specific regions of Nigeria. Initial evidence emerged from airborne radiometric surveys conducted by International Resources Inc., USA, which highlighted radioactive anomalies primarily in the continental-paralic Cenomanian-Turonian deposits, such as the Bima, Keana, Makurdi, and Ezeaku Formations, as well as the adjacent Basement and Younger Granite rocks.

Uranium deposits in Nigeria may occur in peneconcordant or discordant settings, meaning that uranium could have been eroded from source rocks, transported, and concentrated in areas like old river channels, fractures, and voids within fluviatile arkosic sandstones or basal micaceous sandstones of the host formations. Fossil organic materials, such as plant debris, serve as potential agents for uranium precipitation. Additionally, uranium could be enriched through secondary processes, originating from underlying igneous or Basement rocks, especially along fracture zones in arenaceous formations.

In the Nigerian Younger Granite rocks, uranium coexists with niobium and thorium, notably alongside pyrochlore. Pyrochlore acts as a constant accessory mineral in the albite-riebeckite granite of the Younger Granite complex, which contains approximately 10–12 ppm uranium (Bowden, 1982). Although the connection between the Younger Granite rocks and the uranium occurrences in the Cretaceous sediments of the Benue Trough remains unclear, paleogeographic studies and bedding analysis indicate that the Cretaceous sediments' detrital materials largely originated from the nearby Basement and Younger Granite formations (Bowden, 1982).

Therefore, Nigeria's uranium mineralization reflects a combination of geological processes, including transportation, concentration, secondary enrichment, and precipitation facilitated by organic matter, which have resulted in the observed uranium anomalies across multiple regions (Bowden, 1982; radiometric surveys by International Resources Inc., USA).

2.4.1.8. Chromite, nickel, Talc and Asbestos

Significant occurrences of chromite and asbestos in Nigeria are located within the north-western schist belts of Sokoto State, characterized by a serpentinite belt extending approximately 150 km from Ribah through Tungan Kudaku, Maikwonaga, and Sado. At Tungan Kudaku, the serpentinite is intersected by an unaltered diorite showing deformation only at its edges, indicative of a late Pan-African age. Another serpentinite occurrence at Mallam Tanko, about 100 km east of the Sokoto alignment, consists of an 8 km-long series of N-S-oriented small bodies embedded in gneisses, representing the southern extension of the Wonaka schist belt. While serpentinites have also been reported in the Federal Capital Territory, these occurrences remain unmapped (Shibayan, 1985; Elueze, 1982). The Sokoto and Mallam Tanko serpentinites are primarily intrusive formations, measuring up to 15 km in length and 1 km in width. They contain chromite deposits, occurring in small pods (up to 0.5 m in size), layered structures, spotted textures, and as fine disseminations. Analyses suggest Cr_2O_3 concentrations ranging from 40 to 60% (Shibayan, 1985). Anthophyllite asbestos is common, appearing in microscopic forms and larger veins, with some derived soils showing nickel enrichment (Ogezi, 1977). Additionally, talc deposits, sometimes associated with magnesite, have been reported in close relation to these serpentinites (Elueze, 1982).

2.4.2. Industrial Mineral

2.4.2.1 Tar Sand / Bitumen

Bitumen and tar sands are found within the Quaternary Coastal Plain Sands of the Benin Formation, distributed across the coastal areas of southwestern Nigeria. Extensive geological and geophysical investigations by (Ogunsola and Williams, 1988) have revealed significant deposits of tar sands in Nigeria, capable of producing over 31 billion barrels of heavy oil. The properties of the extracted heavy oils from these tar sands are comparable to those of previously imported varieties. Tar sands in Nigeria consist of sand, bitumen (heavy oil), mineral-rich clay, and water in proportions of approximately 84%, 12%, 2%, and 4%, respectively (Fasasi et al., 2003). This bitumen, a highly viscous and complex mixture of hydrocarbons and heterocyclic compounds, is believed to form through processes like thermal alteration, microbial degradation, water-washing, gas de-asphalting, or even radioactive bombardment (Fasasi et al., 2003). The bituminous sands are predominantly found along an east-west belt covering about 120 km by 6 km, extending across Lagos, Ogun, Ondo, and Edo States in southwestern Nigeria (Ogunsola and Williams, 1988). These tar sands are vital raw materials for producing unconventional petroleum products, such as lubricating greases, oils, waxes, bitumen, and asphalt, especially for industrial needs like those of the Kaduna Refinery.

2.4.2.2. Coal

Aside from a few isolated reports of lignite and low-grade sub-bituminous coal occurrences in the Sokoto Basin (Kogbe, 1976) and the Mid-Niger Basin, Nigeria's significant coal deposits are primarily located within the Benue Trough. Economically viable coal reserves have been identified in areas such as Enugu, Okaba, Ogboyaga, Orukpa, Lafia-Obi, Gombe, and Chikila. These coalfields are categorized into two main types based on their geologic age: Turonian-Coniacian and Campanian-Maastrichtian coals.

2.4.2.3. Limestone, Phosphate and Gypsum

Limestone, phosphate, and gypsum are key minerals found in Nigeria's sedimentary basins, often occurring in association. Limestone deposition, typically formed in shallow coastal marine environments, has occurred multiple times throughout the basins' geological history, primarily during periods of transgressive and regressive cycles. The Middle Albian transgression, ending in the Cenomanian, resulted in limestone deposits forming the Odukpani Formation at the Calabar flank in south-eastern Nigeria. This formation includes two significant limestone beds, approximately 25 m and 65 m thick, which supply raw materials for the Calabar Cement Factory. A later Cenomanian-Turonian transgression produced extensive limestone deposits stretching from south-eastern to north-eastern Nigeria. Key formations include:

- Ezeaku Formation (Lower and Middle Benue Trough): This encompasses deposits at Nkalagu, Igumale, Makurdi, Gboko (Yandev), and Akahana-Jangerigeri.
- Pindiga, Jessu, and Dukul Formations (Northeast Nigeria): Deposits occur in Kanawa, Deba Habe, Jalingo, and Ashaka.

Limestones in the Gboko (Yandev) area can be correlated with those of the Jangerigeri region, sharing similar ages and depositional environments. Recent discoveries of limestone near Awe, Nasarawa State, have sparked proposals for cement production. Most Nigerian limestones are high-quality, with over 80% calcium carbonate ($CaCO_3$). For instance, the main limestone bed at Yandev measures up to 35 m thick, with an estimated reserve of 68 million tonnes. Nearly all deposits are utilized in cement manufacturing.

Phosphate occurs in economic quantities in the Dukamaje Formation (Sokoto Basin) at Wurno and the Kalambaina Formation (Sokoto Basin) at Dange and Shuni. Additional deposits have been identified in the Ewekoro Formation (Dahomey Basin) in southwestern Nigeria. Limited studies have explored phosphatic beds in the Pindiga Formation (Upper Benue Trough) near Gombe. Carter et al. (1963) initially reported phosphate rock in this formation, while Offodile (1976) identified about 34 m of phosphatic clays and limestones interbedded with gypsum at the Pindiga type section. These deposits, overlain by Gombe sandstones, require further investigation to assess their quality and lateral extent.

Gypsum is often associated with phosphates, occurring in the Dukamaje Formation (Wurno) and the Dange Formation (Dange). Additional occurrences are reported at Nafada and Potiskum (Upper Benue Trough) and Gboko (Middle Benue Trough). While gypsum quantities are insufficient for export, they adequately meet the demands of local cement factories in these areas.

2.4.2.4. Marbles

Marble in Nigeria is found within the migmatite-gneiss-schist-quartzite complex as remnants of sedimentary carbonate rocks. These rocks date back to the Upper Proterozoic schist belts and typically show a lack of carbonates. Several marble deposits are being actively exploited for cement production (e.g., Ukpilla, Obajana**)** and decorative stone applications (e.g., Jakura, Kwakuti, Igbetti). Additionally, some ground rock is being produced for industrial use. These marble deposits are mainly confined to the western regions of southern and central Nigeria. Significant marble deposits are located in areas such as the Muro Hills and Ugya, situated in the Toto Local Government Area of Nasarawa State. Although these deposits are mined locally and sparingly, their substantial size offers investment potential in cement manufacturing (Elueze, 1982)

2.4.2.5. Talc

Talc deposits in Nigeria, although not yet fully commercially exploited**,** are found in multiple regions across the country. Some of these deposits have high-grade potential, although many contain coloured varieties of talc. These occurrences are mainly associated with amphibolites within the schist belts (Elueze, 1982). With further exploration, these talc deposits could support commercial mining activities due to talc's significant industrial applications and economic importance**.**

2.4.2.6. Sillimanite

Sillimanite has been identified in several schist formations in Nigeria, occurring as isolated high-grade metamorphic islands. These high-grade areas are embedded within the larger, low-grade facies schist belts of western Nigeria (McCurry, 1976; Rahaman, 1976). The occurrence of sillimanite highlights the presence of metamorphic zones with higher-grade mineral assemblages, which could have significant economic and industrial relevance.

2.4.2.7. Graphite

Graphite is found south of Jalingo in Taraba State**,** located in the basement rocks of Northeastern Nigeria**.** Several extensive but low-grade graphite deposits have been reported in this region. Additionally, in the Kushaka schist belt (Ajibade, 1980) and the Maru schist belt (Egbuniwe, 1982), graphitic slates and graphitic phyllites have been observed, showcasing Nigeria's potential as a source of graphite within basement rock formations.

2.5 Tectonic Evolution of Nigeria Mineral Resources

The map exposed in (figure 2.9) illustrates the exposed basement domains of Nigeria, dividing the country's geological structure into three major provinces: the Western Domain, Central Domain, and Eastern Domain, with a Transitional Domain acting as a boundary zone between the Western and Central Domains. These domains reflect distinct geological and structural attributes influenced by different tectonic events and crustal developments.

The Western Domain, covering much of the northwestern and southwestern regions, consists predominantly of ancient basement rocks shaped by earlier tectonic and metamorphic processes. This domain is associated with older geological formations, including Precambrian rocks, which have undergone extensive deformation and metamorphism.

The Central Domain lies east of the Western Domain and is marked by more recent tectonic events, including rifting and basin formation processes. This area includes significant geological features such as the Benue Trough and is characterized by sedimentary deposits and tectonic reactivation, contributing to its mineral potential.

Separating the Western and Central Domains, the Transitional Domain represents a structurally complex zone where characteristics of both domains overlap. It reflects the effects of tectonic interactions between the older basement complex of the Western Domain and the younger tectonic activities of the Central Domain.

The Eastern Domain, located in the southeastern part of Nigeria, shares similarities with the Central Domain in terms of sedimentary cover and tectonic evolution but is distinguished by its unique structural history and mineralization patterns. This domain also contains significant sedimentary basins and is an important region for hydrocarbon and mineral exploration.

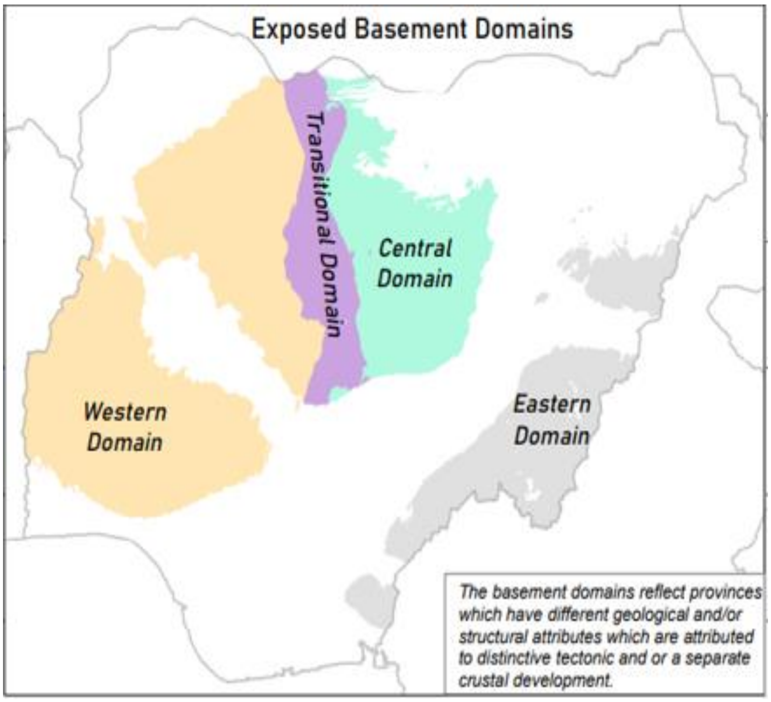

Figure 2.9. Exposed basement domains map of Nigeria. Adapted from (NGSA. Mineralization map of Nigeria, 2023)

The (figure 2.10) presents a comprehensive overview of Nigeria's geological framework, illustrating the interplay between tectonic evolution, lithological domains, and mineralization across the Western, Central, and Eastern Domains. The tectonic evolution timeline on the left captures key geological events from around 600 million years ago to the present, highlighting significant tectonic processes such as rifting, volcanic activity, and deformation events that shaped the country's geology. Rift-related volcanics, represented by pink patterns, indicate periods of volcanic activity associated with rifting, while compressional deformation and extensional exhumation mark phases of tectonic compression and extension. Major geological features like the Benue Trough in the Central Domain and the Sokoto Basin in the Eastern Domain formed during these significant tectonic episodes, particularly during rifting and basin formation.

The lithological domains are divided into younger granites, older granites, volcano-sedimentary belts, rift basins, schist belts, and cover sequences. The younger granites, predominantly found in the central domain (Jos Plateau), represent post-collisional granitic intrusions, whereas the older granites are part of the pre-existing basement complex. The volcano-sedimentary belts and rift basins are crucial for mineral deposits, shaped by complex volcanic and sedimentary processes, while the cover sequences reflect sedimentary basins like the Sokoto and Chad Basins formed through later sedimentary deposition.

Mineralization patterns across Nigeria are also highlighted showing various mineral systems associated with different geological settings. Strata bound deposits such as phosphate and channel iron deposits are primarily found in sedimentary basins like the Benue Trough and Sokoto Basin. Sediment-hosted mineral systems, including Pb-Zn-Cu-Ba deposits, are concentrated in fault-hosted basins, particularly within the Benue Trough. Rare-metal pegmatites, typically linked to granitic intrusions, are prominent in the central domain. Vein-type mineralization systems, comprising Au, Cu, Pb, Zn, and Ag, are associated with reactivated fault and shear zones that underwent tectonic events in later geological periods. Ultramafic and orthomagmatic systems, which include Cr, Ni, Co, and PGE mineralization, are connected to deep mantle-derived magmatic activity, while banded iron formation deposits in the Western Domain are linked to ancient tectonic events associated with back-arc basin systems.

The structural and geological controls depicted in the image emphasize how tectonic shear zone structures and their geodynamic evolution influence the distribution of mineral deposits across Nigeria. The Benue Trough stands out for hosting diverse mineral deposits due to its rift-related tectonic history and sedimentary fill, while the Western Domain shows a high potential for banded iron formations tied to older Archean-Proterozoic tectonic events

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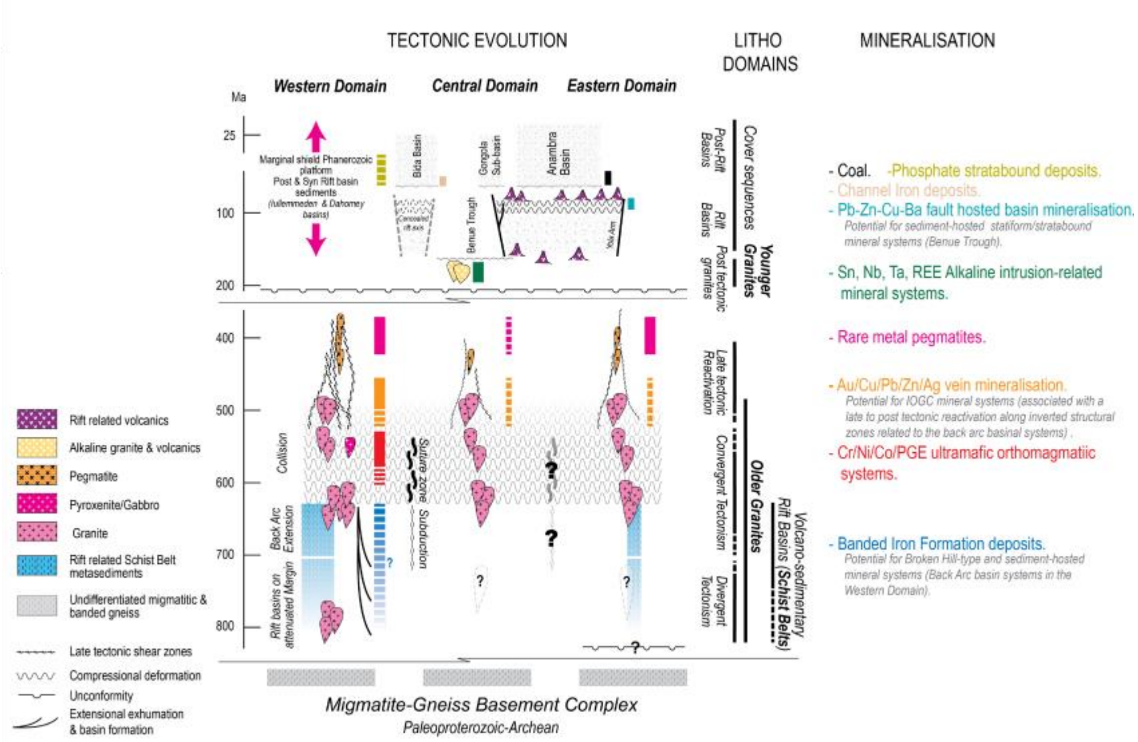

Figure 2.9. Nigeria's tectonic evolution and its relationship to mineral resources. Adapted from (NGSA. Mineralization map of Nigeria, 2023)

3. Methodology

3.1 Data Collection and Preparation

The mineralization map of Nigeria, scaled at 1:2,000,000, was obtained from the Nigeria Geological Survey Agency (NGSA) database. This map provides a comprehensive representation of the spatial distribution of various mineral commodities across the study area, along with key geological features such as faults, shear zones, and different basement granitic rock types. To facilitate visualization and analysis, the map was processed using QGIS software, which allowed for the extraction and interpretation of relevant spatial data. From the mineralization map, the locations of fourteen specific mineral deposit types were selected for further analysis. A dataset was created to mark their exact positions using point features in QGIS. Additionally, significant geological features, including basement granitic rocks, shear zones, and fault distributions, were also identified and digitized on the map. To enhance data organization and facilitate spatial analysis, separate shapefiles were created for the fourteen mineral commodities, basement granitic rocks, and geological structures, specifically shear zones and faults.

The shapefiles containing the mineral deposit locations were then imported into R-Studio for advanced spatial analysis. Various spatial analytical techniques were applied, including point distribution analysis, Fry analysis, density analysis, and K-function analysis. These analyses were executed through custom scripts developed in R, ensuring accurate and reproducible results. Several R packages, such as sf for handling spatial data, ggplot2 for data visualization, leaflet for interactive mapping, and spatstat for spatial point pattern analysis, were employed to process and interpret the spatial relationships within the dataset. By integrating GIS-based data extraction with R-based spatial analysis, a comprehensive understanding of the spatial distribution patterns of mineral deposits in relation to geological structures was achieved. This workflow provided valuable insights into the clustering tendencies, spatial interactions, mineral genesis, and geological controls influencing mineral occurrences within the study area.

3.2 Spatial Analysis Techniques

3.2.1 Point Pattern Analysis

Points in a two-dimensional space exhibit spatial associations that can be categorized as clustered, random, or regular (Boot and Getis, 1988; Diggle, 1983; see Figure 3.1):

- **Random pattern**: This occurs when points are distributed randomly across space, indicating a lack of interaction between them. Such points are typically the result of independent processes.
- **Clustered pattern**: In this pattern, points are closer to each other compared to a random distribution. It suggests that related processes have caused the localization of groups of objects in specific areas.
- **Regular pattern**: Points are more widely spaced than in a random pattern, suggesting dispersion influenced by processes that drive objects away from each other, leading to their arrangement in specific localities.

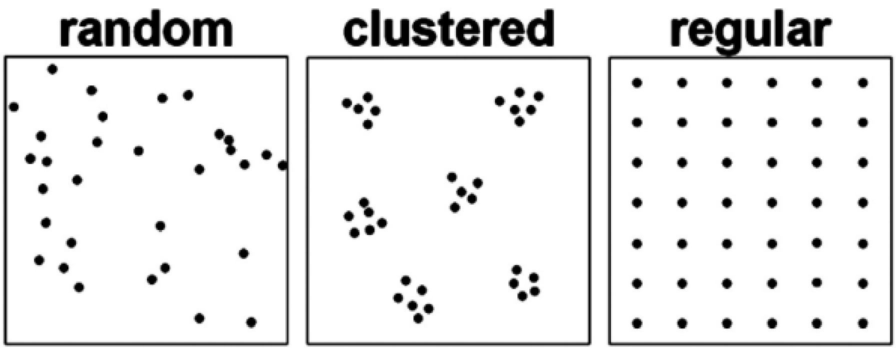

Figure 3.1. Basic types of point pattern. Random, clustered, regular

Mineral deposits are typically non-random in nature, as their formation is governed by specific geological processes (Carranza, 2009). These deposits are often localized due to mineralization-related geological events, which can result in either centralizing or dispersing patterns (Carranza et al., 2008).

Point pattern analysis is used to assess the spatial distribution of known mineral occurrences by comparing them with the spatial distribution of an equal number of randomly distributed points in the same area (Lisitsin, 2015). This comparison, particularly the distances between known mineral occurrences and randomly distributed non-mineralized points, helps determine the spatial pattern of the mineral occurrences. In this study, point pattern analysis will be conducted for the selected mineral deposits in Nigeria, with their specific point occurrences provided in Table 3.1.

For n points, the distance from each of the points to the other points is measured. This distance is denoted as 1st order, 2nd order, 3rd order or (n-1)th order neighbour distance. The 1st- order is the distance between each point and its nearest neighbour point. Thus, n points will have n-1 means of ordered neighbour distances, with the 1storder means, being the mean of nearest neighbour distances among points (Carranza, 2009; Parsa et al., 2017).

Table 3.1. List of selected mineral commodities in Nigeria and their number of point occurrences

No.	Minerals	Point occurrences
1	Gold	776
2	Iron	88
3	Copper	34
4	Base-Metal	78
5	Lithium-Tantalum	74
6	Manganese	31
7	Tungsten	29
8	Beryllium	134
9	Barium	128
10	Oil gas	32
11	Coal	143
12	Limestone-Marble	117
13	Talc	35
14	Phosphate	29

The spatial distribution of known mineral occurrences can be interpreted based on the comparison of their ordered neighbour distances with those of randomly distributed points:

- **Clustered Pattern**: Known mineral occurrences are considered clustered if their ordered neighbour distance means are consistently lower than those of random points.
- **Regular Pattern**: Known mineral occurrences are interpreted as regularly distributed if their ordered neighbour distance means are consistently higher than those of random points.
- **Random Pattern**: If the ordered neighbour distance means of known mineral occurrences and random points are similar, the spatial distribution is considered random, indicating no significant geological control on the distribution (Carranza, 2009).

3.2.2 K-Function Analysis

The k-function analysis in geology is a statistical tool used to analyse the spatial distribution of geological features such as, mineral deposits, faults and fractures, folds, volcanic vents, hydrothermal veins. The k-function from 'spatstat' packages create a set of variables in response to the desired analysis. These variables are plotted as lines are used to interpret results. The Kiso, 'Ktrans', 'Kbord', and 'Kpois', lines in the plot of the K-function in 'spatstat' are reference lines that represent the expected value of the k-function for different model point patterns.

'**Kiso'**: the line represents the expected value of the k-function for an isotropic point pattern, where points are randomly distributed in all directions, the 'kiso' line is a straight line with slope π, which represents the expected number of points in a circle of radius r.

‘Ktran’: the line represents the expected value of the k-function for a translational point pattern, where points are randomly distributed along a line or curve.

‘Kbord’: the line represents the expected value of the k-function for a point pattern that is confined to a region with boundary.

‘Kpois’: the line represents the expected value of the k-function for a Poisson point process, where the points are randomly distributed in space with a constant intensity.

As so, the K-function from the `spatstat’ package emerges as the quintessential tool for unravelling the complexities inherent in spatial point pattern. The function calculates an estimate of the so-called k-function, which quantifies the spatial dependence of points in a point pattern.

k-function is defined as the expected number of points, in a pattern, that are within a specified distance ‘’r’’ of a randomly chosen point in the pattern. In other word, the k-function measures the spatial clustering of points in a pattern, as a function of the distance ‘’r’’.

if the plot is randomly distributed, the k-function will be equal to $\pi \times r^2$ which is the area of a circle with radius ‘’r’’. if points are clustered, the k-function will be smaller than $\pi \times r^2$ for small value ‘’r’’, and if points are dispersed, the k-function will be smaller than $\pi \times r^2$ for small value of ‘’r’. The kest() function calculates an estimate of the k-function for a given point pattern by dividing the point pattern into a grid of cells and counting the number of points in each cell, that are within a distance ‘’r’’ of the randomly chosen points in the pattern.

To interpret the obtained result, it is necessary to examine the plot of the of the k-function estimate. A plot of the k-function shows how the expected number of points within a distance ‘’r’’ changes as it increases. If the plot is close to $\pi \times r^2$, then the point pattern in the pattern is randomly distributed, and if the plot is above $\pi \times r^2$ then the points are clustered. If the plot is below $\pi \times r^2$, then the points are dispersed.

3.2.3 Point Density Analysis

An alternative method for analysing point patterns involves calculating the intensity or density of points within a specific area by dividing the total number of points by the domain's area. This estimate can be represented visually as a heatmap or contour plot, highlighting regions with high or low point density. The density analysis visually represents the spatial intensity of a particular mineral deposits in the study area. It uses a gradient of colours to convey variations in mineral density, where blue represents areas with low density, pink indicates moderate density, and yellow marks regions with the highest density intensity. This plot serves as a valuable tool for understanding the spatial distribution and clustering of mineralization across the study area.

3.2.4 Fry analysis

Fry analysis is a geometrical technic used to analyse spatial autocorrelation of points objects of a kind (Fry, 1979). Fry analysis was originally developed for evaluation of strain in rocks expressed as patterns of object that appears to be randomly distributed (Fry, 1979; Hana and Fry, 1779). Fry analysis is performed through the construction of an autocorrelation diagram called the fry plot, (see figure 3.2) the diagram can be constructed manually or computationally with the following procedures (Fry, 1979).

- One of the points in the original distribution is placed at the centre of the diagram preserving the distance and orientation of all other points

- The position of every point of the original distribution are marked in the new diagram (i.e., fry plot)
- A second point in the original pattern is placed at the diagram centre and the position of the remaining points are registered. This procedure is repeated until every point in the original distribution is used as the centre of the diagram.

For Fry analysis to be efficient the object of interest (i) must be well dispersed so they can be represented as points in a homogeneously deformed Metrix (ii) Allow for numerically relevant sampling (dozen to hundreds of objects) (iii) have relatively regular or clustered pre-strain distribution. The third condition is critical because the fry diagram of a set of objects with random distribution does not present relevant result.

Twenty years after the development of Fry analysis as a tool for the study of rock deformation, it has been successfully applied to study the spatial distributions of various types of mineral deposits both regional and local scale (Vearncombe and Vearncombe, 1999; Stubley, 2004; Blenkinsop and Kadzviti, 2006; Kreuzer, et al.,2007; Carranza, 2008, 2009). Among others, when applied to the investigation of mineral deposits Fry analysis provides insight into directional controls on mineralization by using each spatial relationship between deposits (Vearncombe and Vearncombe, 1999). At regional scale Fry analysis highlights pattern of directions and spacing associated with structures that control mineralization. At local scale, it can be applied to determine direction of orebodies based on the distribution of positive drill hole intersections. thus, representing an alternative of directional variography (Vearncombe and Vearncombe, 1999). This alternative use of Fry analysis has been applied by several authors to study the spatial distributions of mineral deposits of Au, Cu, Pb, and other elements (Stubley, 2004; Kreuzer et al., 2007; Austin and Blenkinsop, 2009; Carranza, 2009; Carranza and Sadeghi, 2014).

The typical result of these studies is for the (i) identification of subtle preferential orientations in the distribution of mineral deposits which are hardly perceived from their original map locations (Vearncombe and Vearncombe, 1999; Lisitsin, 2015). (ii) recognition of structural trends of mineral occurrence at different spatial scale (Austin and Blenkinsop, 2009; Carranza, 2008, 2009). (iii) recognition of preferred corridors for mineralization (Vearncombe and Vearncombe, 2002; Carranza and Sadeghi, 2010), these results will be integrated and used to describe structural control on mineralization.

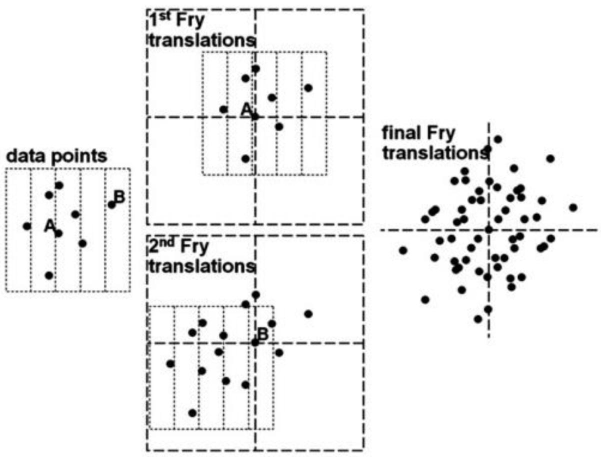

Fig 3.2 Schematic procedure of creating fry plots for a set of points

4. Results

4.1 Gold Point Pattern Analysis

The point distribution of gold minerals in Nigeria (figure 4.1a) shows strong association with Precambrian Basement Complexes consisting of schist, gneisses, granites and quartz veins. The spatial distribution suggests clustering along NE - SW trending shear zones, consisting of a regional tectonic framework. The points show significant clustering in certain regions, these clusters likely represent areas of higher gold occurrences or mineralization. The distribution highlights the high potentials for gold exploration in areas such as Zamfara, Osun and Niger state, where both geological and geomorphological conditions favour mineralization. Some points are sparsely distributed, possibly indicating isolated occurrences or less mineralization, while a small number of points appear further to the southeast suggesting minor or secondary deposits. It can be said that the clustering may align with major tectonic or lithological structures such as shear zone, fractured and mineral belts.

4.1.1 Gold K-Function Analysis

The observed K - function (figure 4.1b) visualizes the (Kiso, Ktrands, Kbord) generally lie above (kpois) indicating significant clustering of gold mineral points compared to a random distribution. The gap between K(r) and Kpois (r) increases with a distance (r) suggesting that clustering is more pronounced at larger scales. At a smaller distance (r close to o), clustering is pronounced as seen in the convergence of the curves and as r increases, the clustering becomes more evidence indicating spatial dependence and potential geological control (shear zone, fault, mineral belts).

The clustering observed in the K-function indicates that Nigeria gold occurrences are not randomly distributed but rather controlled by geological factors such as structural feature's fault, shear zones or lithological units (schist belts).

The increasing clustering at larger scale suggests that exploration efforts should focus on broader regional patterns, particularly within known mineral belts or along the idea that gold deposits in Nigeria are influenced by regional control such as vein-hosted deposits along shear zone.

4.1.2 Gold Density Analysis

The plot reveals a prominent yellow zone, indicating regions of maximum gold deposit density. This area represents a hotspot for gold mineralization and is likely to correspond to locations with high geological potential for gold exploration and mining activities. Based on known metallogenic provinces in Nigeria, the high-density zone aligns with the north western region, encompassing states like Zamfara, Kebbi, Niger, and parts of Kaduna. These areas are historically known for their significant gold occurrences and have attracted both artisanal and commercial mining operations.

Surrounding this high-density zone is a pinkish area, signifying regions of moderate gold density this region correlates with the western domain consisting of states like Osun, Niger, Oyo, Ondo, and Kwara State. These transitional zones suggest the presence of gold occurrences, though not as concentrated as in the core yellow zone. While they may not represent primary targets for large-scale mining, they still hold economic potential, particularly for small- to medium-scale exploration and mining ventures. In contrast, the blue regions on the map indicate areas with little to no gold mineralization. These areas may lack the necessary geological structures, such as faults and shear zone or favourable host rocks, required for the formation of significant gold deposits. While they may not be priorities for gold exploration, they could still be of interest for other types of mineral resources.

From a regional perspective, the high-density gold zones are typically associated with the Pan-African Basement Complex and the Birnin-Kebbi Schist-Belt, both well-known for hosting gold deposits, as seen in the mineral map of Nigeria. The density plot suggests a spatial clustering of gold occurrences, likely influenced by geological structures such as shear zones, fractures, and lithological contacts. These structural features play a crucial role in the genesis and localization of gold deposits, further reinforcing their significance in exploration targeting.

4.1.3 Gold Fry Analysis

Fry analysis of Nigeria's gold deposits (figure 4.1d) highlights a significant clustering trend along the NE-SW fault system within the schist belt. The plot reveals a distinct cluster of higher-grade samples, indicating a concentrated zone of significant gold mineralization. This area likely represents the core of the deposit, where gold is most abundant. In contrast, a long tail extending to the left suggests the presence of numerous low-grade samples, which may correspond to the halo or peripheral zone of the deposit, where gold mineralization is less concentrated. The Fry plot analysis of gold mineralization reveals three distinct alignment trends. The primary structural trend is oriented in a Northeast direction at N32E, indicating a dominant geological control on the spatial distribution of gold deposits. In addition to this main trend, two secondary alignments are observed, with one following a N20E orientation and the other aligning at N40E. These variations in trend directions suggest multiple structural influences, possibly related to faulting, shear zones, or regional tectonic forces that have contributed to the spatial arrangement of gold deposits in the study area.

Exploration efforts should prioritize the high-grade concentration zone identified in the plot to maximize the chances of encountering economically viable mineralization. Selective mining techniques may be necessary to effectively target the higher-grade minerals while managing the lower-grade zones efficiently.

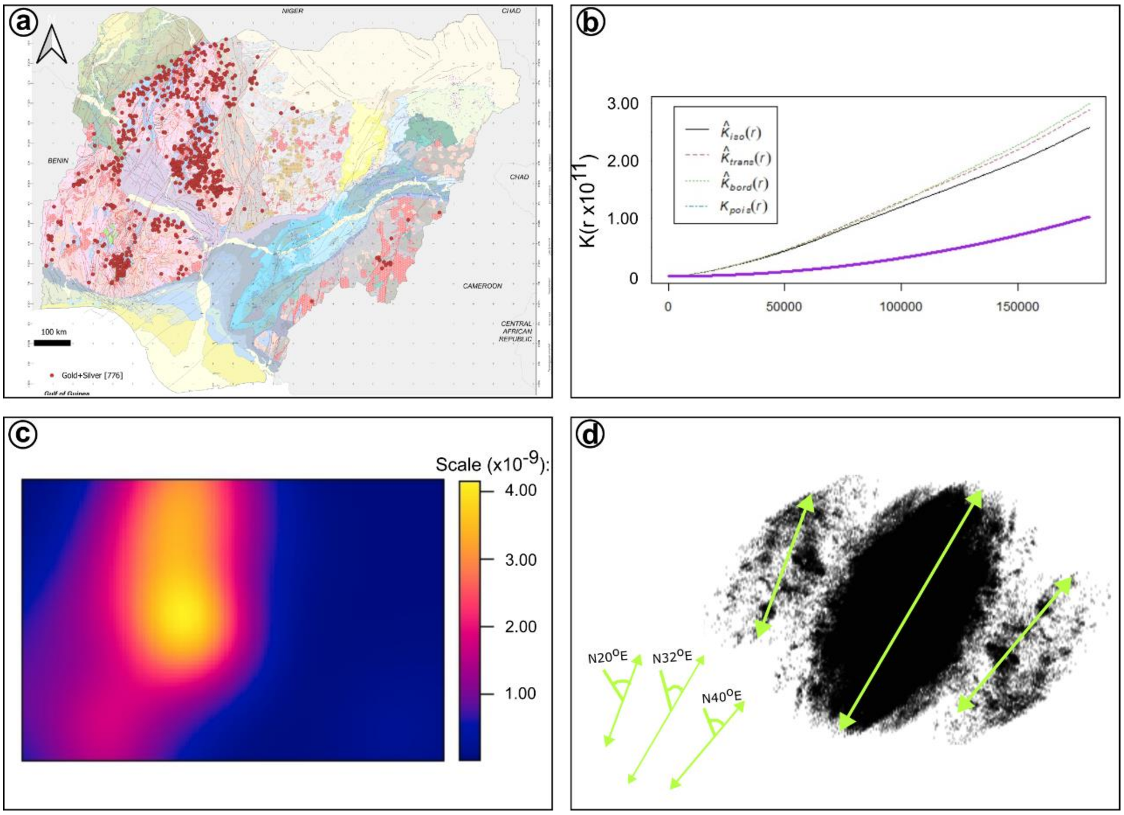

Figure 4.1. a) point distribution of gold mineral deposits in the study area. b) K-function for gold deposits with the purple Kpois line lying below the other curves, indicating clustering. c) density plot for gold deposit with the most prominent or high-density areas with bright yellow colours, the pinkish areas signifying regions of moderate gold density and the blue regions on the map indicate areas with little to no gold mineralization. d)Fry plot image shows a significant clustering trend alignment along the N32^{0}E, N20^{0}E and N40^{0}E.

4.2 Coal Point Pattern Analysis

Nigeria Coal deposits are predominantly found in major coal-bearing regions such as the Anambra Basin, Benue trough and the Enugu coal field, the point distribution of coal deposit in Nigeria (figure 4.2a) shows heavy clustering within the Anambra Basin and parts of the Benue trough indicating a strong localization in these areas, the Enugu coal field shows a dense concentration of deposits. The Deposit are aligned with in the NE trending geological structures in the Benue Trough indicating the influence of folds and faults on coal formation. The clustering of these local deposits correlates with sedimentary Basins formed during the cretaceous and tertiary periods. Coal deposits are predominantly associated with deltaic and fluvial sedimentation. These are known features of swamps and lagoons.

This Analysis identifies the Anambra Basin and Southern parts of the Benue Trough as high priority area for coal exploration due to their dense clustering and alignment with geological structures exploration efforts should focus on detailed structural mapping and geophysical survey to uncover additional resources in these regions.

4.2.1 Coal K-Function

The K-function plot (figure 4.2b) shows all observed k(r) lines (kiso, Ktrans, kbord) are significantly above (kpois). Indicating strong clustering of coal deposit in Nigeria. The K-function Analysis reveals significant clustering of coal deposits in Nigeria, particularly at large scale. This clustering such as the localization of coal deposits within specific sedimentary Basins (Anambra

Benue Trough) and features like faults or folds the result suggest that coal formation is clustered and influenced by underlying geological processes

4.2.2 Coal Density Analysis

The plot (figure 4.2c) uses a gradient colour scheme ranging from blue (low density) and yellow (high density) to represent the concentration of Coal deposit areas with yellow or red hue indicate regions of high coal deposit density. The highest density region is concentrated in the lower-left quadrant of the plot. as indicated by the prominent yellow-red area and this suggest a localized cluster of coal deposit in a specific part of the study area. This indicates that the intensity of coal deposits in the densest regions is significantly higher than in surrounding areas.

The high-density region indicates a significant clustering of coal deposits in a particular geographical area around the known coal-bearing basins such as Anambra basin and parts of the Benue trough. The clustering could be as a result of favourable geological conditions like sedimentary environments and tectonic influence. The blue areas represent region with sparse or no coal deposits, possibly due to the absence of suitable geological conditions for coal formation.

The Nigerian coal mineral density plot (fig 4.2c) suggests that significant clustering of coal deposits occur within the Anambra basin and parts of the Benue Trough, emphasizing the need to focus exploration and resources management strategies in these areas.

4.2.3 Coal Fry Analysis

The coal fry plot (figure 4.2d) shows that the coal minerals exhibit a clustered distribution with a dominant northeast-southwest trend, the plot indicates that coal deposits in Nigeria are not evenly distributed instead, they appear to be clustered in certain areas within the Anambra basin and Benue Trough. This suggest that coal deposits in Nigeria are likely to have been influenced by stratigraphic factors that favours coal formation.

The Fry plot analysis of coal mineralization reveals two distinct alignment trends. The primary trend is oriented at N45^{0}E degrees, which corresponds closely with the structural framework of the Anambra Basin and Benue Trough, indicating a strong stratigraphic control on coal deposition within these regions. Additionally, a secondary trend is observed at N10^{0}E degrees, specifically within the Gongola Sub-basin, suggesting localized structural influences that may have played a role in coal accumulation in this area. These alignments reflect the tectonic and depositional history that governed coal formation in the study region.

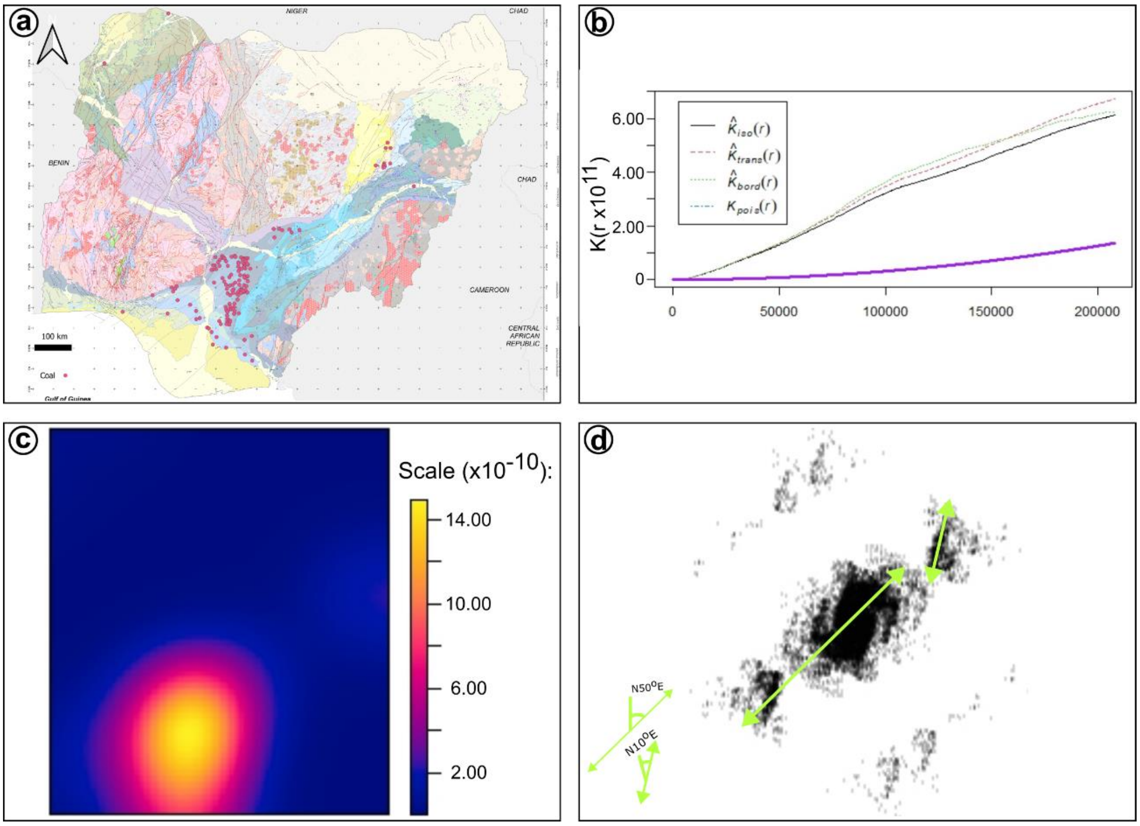

Figure 4.2 a) point distribution of Coal mineral deposits in the study area. b) K-function for coal deposits in the study area, the plot highlights all observed k(r) lines (kiso, Ktrans, kbord) are significantly above (kpois), Indicating strong clustering of coal deposit in Nigeria. c) density plot for coal deposit with the high-density areas with bright yellow colours, the pinkish areas signifying regions of moderate coal density and the blue regions on the map indicate areas with little to no coal mineralization. d) Fry plot image of coal mineral deposits, exhibits a clustered distribution with a dominant trend alignment of NE-SW.

4.3 Beryllium Point Pattern Analysis

The point distribution of beryllium mineral in Nigeria (figure 4.3a) is closely tied to the Basement Complex and structural trend such as NE-SW and N-S orientation high density clusters in the central region of the plot likely correspond to areas like the Jos-Plateau or part of the Benue Trough.

The Nigeria Basement Complex contains abundant pegmatite, granite and schist which are the primary host of beryllium materials such as beryl. These pegmatites are often aligned with regional tectonic structures, the pegmatite belts in the Basement Complex often align in N-S or NE-SW oriented influence by regional tectonic activities.

The Benue Trough is a Cretaceous rift basin known for its complex tectonic structures. It hosts several mineral deposits, including beryllium often associated with pegmatitic and granitic intrusion in localized areas.

The densely packed point in the central region suggests areas of significant mineralization, these clusters are likely associated with favourable geological conditions such as pegmatites or granitic terrain, which are known host for beryllium minerals. The isolated or sparsely distributed points indicate regions with scattered or smaller scale occurrences of beryllium minerals, these could correspond to secondary deposits or less favourable geological environment. The Jos-Plateau and parts of the Benue trough areas are high-priority zones for exploration.

4.3.1 Beryllium K-function Analysis

Observations of the K-function plot (figure 4.3b) shows that (Kiso, Ktrans, Kbord) are consistently above the purple line (Kpois) this indicate that the beryllium deposits exhibit significant clustering at all analysed spatial scales. The clustering implies that the deposits are not randomly distributed and are influenced by specific geological or structured control.

At smaller distances (Lower r), the K-function value rise steeply, reflecting strong clustering of deposits within close proximity. At larger deposits (higher r) the K-function value continues to increase but the slope decreases slightly, indicating weaker clustering at broader spatial scale. This suggests that clustering is more prominent at local scale, possibly influenced by specific geological units or structures.

The isotropic Kiso(r) translational Ktrans(r) and border-corrected Kbord(r) functions shows similar trend indicating that the correction for edge effect do not significantly alter the result this reinforces confidence in the reliability of the clustering.

The clustering suggests that beryllium deposits are likely controlled by geological structures such as faults, factures of lithological boundaries.

Regions exhibiting strong clustering (at smaller scale) should be prioritized for detailed exploration activities. The clustering pattern suggests that deposits might follow specific structural trends or lithological zones, such as pegmatite belt in Nigeria’s Basement Complex or granitic intrusions in the Younger Granite province.

4.3.2 Beryllium Density Analysis

The density plot (figure 4.3c) highlights a spatial clustering of beryllium mineral in Nigeria with distinct zone of high density. The plot shows distinct clusters of high density in certain regions, with bright yellow spots signifying concentration areas of beryllium mineralization. Surrounding the high-density clusters are transitional area (red/purple) where the density decreases gradually.

Two or more significant high-density zones can be observed, separated by regions of lower density (Blue area). This indicates that beryllium mineralization is localized and not evenly distributed across the study area.

The high-density areas (yellow zones) likely correspond to favourable geological settings such as regions with abundant pegmatites, granitic intrusions, or structurally controlled deposits. These clusters may align with known geological province such as the younger granite province or the Nigeria basement complex. The yellow and red zones should be prioritized for exploration as they represent areas of significant mineral occurrences.

4.3.3 Beryllium Fry Analysis

The fry plot (fig 4.3d) exhibits dense clusters in the central area, with a gradual reduction in point density towards the edges, this indicates that beryllium mineral deposits are not randomly distributed but tend to form spatial clusters some elongation or directional patterns can be observes in the point distribution suggesting a spatial trend or structural control in the mineralization process in more sparse point at the edges indicates areas with lower concentration or outliers in the spatial patterns.

The plot suggests a preferred orientation or trend in the mineralization process possibly following geological features such as, fault lines, fracture zone, pegmatitic or granitic intrusions, the elongation or clustered points align with regional structural trends such as the NE-SW orientations common in Nigerian geology.

The Fry plot analysis of beryllium mineralization reveals two dominant alignment trends. The primary trend is oriented at N56°E, indicating a major structural control on the spatial distribution of beryllium deposits. A secondary trend is observed at N40°E, suggesting an additional structural influence that may be associated with faulting, shear zones, or lithological boundaries. These trends reflect the geological forces that have influenced the emplacement and concentration of beryllium mineralization in the study area.

The clustering and alignment are likely controlled by the presence of pegmatite, younger granite intrusion, or other lithologies associated with beryllium mineralization.

The cluster correspond to the Nigeria Basement Complex, particularly areas with pegmatite-hosted mineralization, likely region includes the Jos plateau (younger granite province). The particular belt (zones enriched in pegmatites and rare metal observation from the plot show that exploration activities should prioritized around the activities should be prioritized around the Jos-plateau, region of the Basement Complex of Nigeria due to its high-density cluster

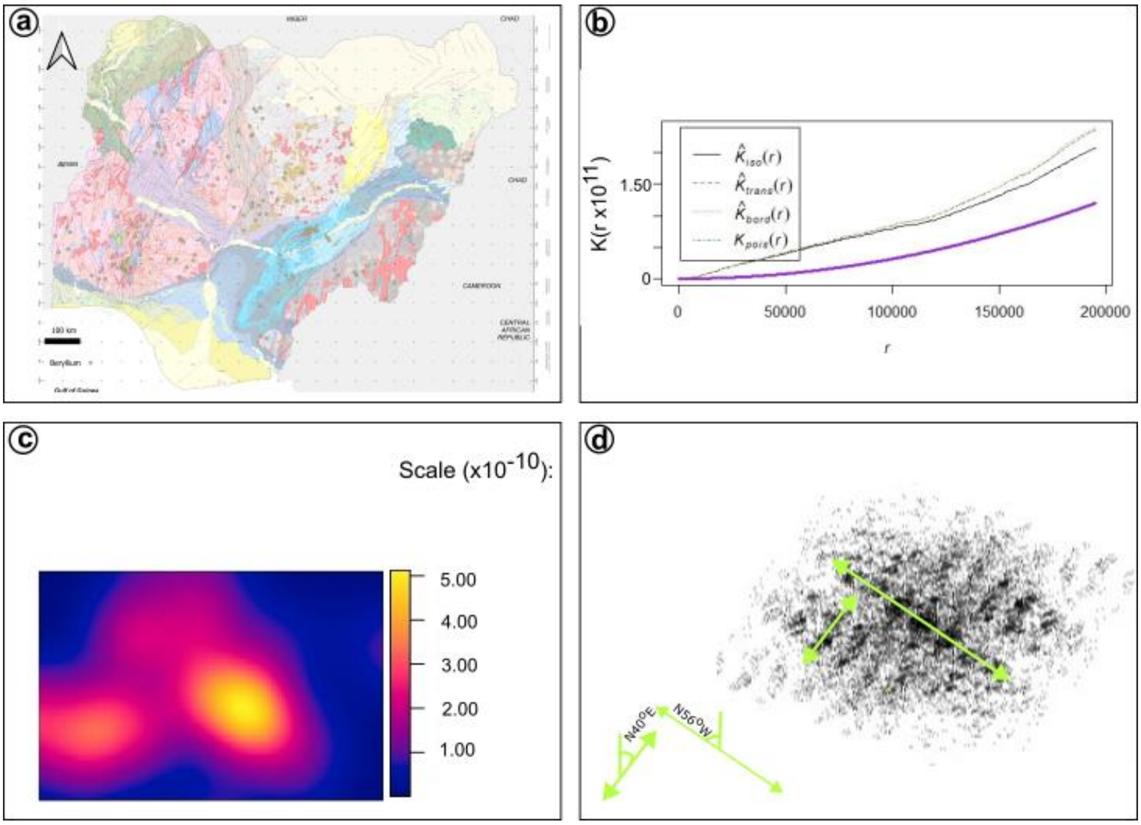

Figure 4.3 a) point distribution of beryllium mineral deposits in the Nigeria. b) Kiso, Ktrans, Kbord are consistently above the purple line (Kpois) this indicates that the beryllium deposits exhibit significant clustering. c) density plot highlights a spatial clustering of beryllium mineral in Nigeria, with the high-density areas with bright yellow colours, the pinkish areas signifying regions of moderate coal density and the blue regions on the map indicate areas with little to no coal mineralization. d) fry plot of beryllium mineral deposits, visualizes a dense cluster around the central area and other occasional clustering distribution with a regional structural trend of NE-SW or NW-SE orientations.

4.4 Barium Point Pattern Analysis

The Nigerian barium mineral point distribution (fig4.4a) are not uniformly distributed but appears to form distinct clusters in the Benue Trough area, a prominent cluster of points is visible in the central portion, indicating a higher concentration of barium mineral occurrences in that region. A linear alignment of points is observed within the central clusters, suggesting a structural control, such as fault or lithological boundaries on barium mineralization. In other parts of the plot, the points are more dispersed indicating region with lower barium mineral dusting.

The observed clustering and linear trend likely align with faults lines fractures or other structural features, barium mineralization may be associated with specific host rocks, such as sedimentary units or hydrothermal veins, which are structurally controlled.

The clustered areas could correspond to known geological belts or provinces in Nigeria such as Benue Trough, a region rich in barite deposit sedimentary Basins where barium mineral is known to form through hydrothermal or sedimentary processes. The central clustered point falls around the Benue Trough and environ, exploration activities and further studies should be prioritized on these areas.

4.4.1 Barium K-Function Analysis

The plot (figure 4.4b) compares different estimates of K-function against a reference poisson model to identify spatial trends. The isotropic estimate of the k-function Kiso(r) (black line) increases with distance r indicating that clustering occurs at multiple scales. The translation-correction Ktrans (r) is slightly higher than the Kiso(r), suggesting moderate clustering. The border correction k-function Kbord(r) align closely with the isotropic estimate, confirming consistent spatial clustering results. The observed K-function estimates are significantly above this line indicating non-random distribution and clustering. At smaller distances (low r values), the observed K-function rises steeply compared to Kpois(r), demonstrating strong clustering at a lower scale. At larger distance (higher value), the curve maintains a gap above Kpois(r) indicating clustering persists over broader scales.

The significant deviation from Kpois(r) confirms that barium mineral deposits are not evenly distributed but are spatially clustered.

The cluster pattern may result from the spatial distribution of host rocks, structural features like faults or hydrothermal processes that favours the deposition of barium minerals. The Benue trough of Nigeria is known to host the barite mineral deposit. The persistence of clustering at multiple scale implies both local control and regional influence (Tectonic Settings). Exploration activities should be focused on Benue trough areas exhibiting strong clustering.

4.4.2 Barium Density Analysis

The density plot (fig 4.4c) reveals that barium mineral deposits in Nigeria are not uniformly distributed across Nigeria. There are distinct regions with higher densities of deposits compared to others. The most prominent features are a cluster of high-density regions (yellow colour) in the central and eastern parts (Benue Trough) of the country. This suggests a concentration of Barium deposits in these areas.

The density graduation decreases Central and Southeastern hotspot towards the Northern and western parts of Nigeria, this indicates a decreasing likelihood of finding Barium deposits as on moves away from the high-density zones. The spatial distribution of Basin deposits might be influenced by underlying geological factors such as rock types tectonic activities and mineral forming processes.

4.4.3 Barium Fry Analysis

The Dots in the plot seem to cluster in certain direction, suggesting a possible alignment of the barium occurrence. This alignment could be influenced by geological factors such as faults, fractures or mineral veins. There appear to be a general trend of the alignment from the central to Southern part of the country, indicating a possible direction of mineral formation or deposition. The plot (figure 4.4d) reveals several hotspots of Barium occurrences particularly in the central and South-eastern region of Nigeria. These areas likely have favourable geological conditions from barium mineralization. The distribution is not uniform with higher densities in certain areas and lower densities in others. This suggest that the geological factors controlling barium mineralization are not evenly distributed across the country.

The plot reveals two primary trend alignments, reflecting the spatial distribution of mineral deposits in the study area. The first trend is oriented at N20°E, which corresponds to the mineralization within the Middle and Lower Benue Trough, indicating a structural control associated with the basin's geological evolution. The second trend, aligned at N65°W, is closely related to deposits found within the Basement Complex, suggesting an influence of basement-related structural features such as faults and shear zones on the localization of these deposits. These alignments highlight the distinct geological settings that govern mineral distribution in the region.

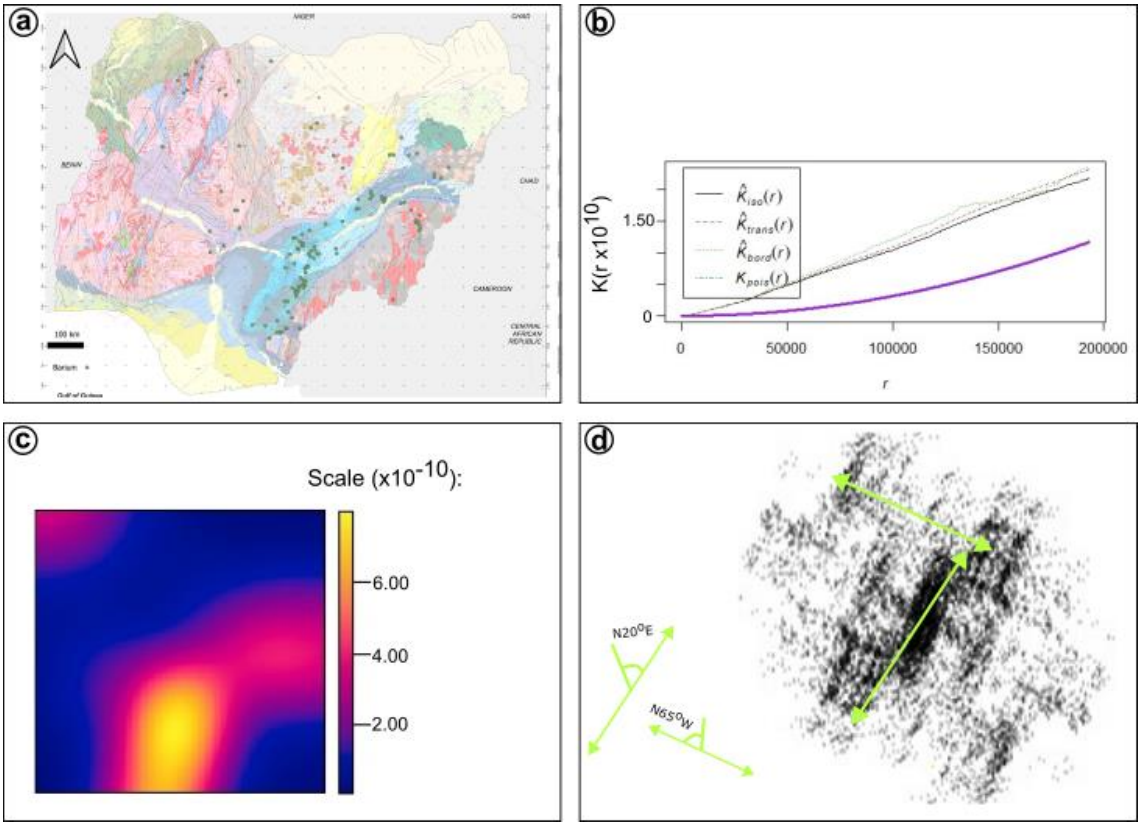

Figure 4.4 a) point distribution of barium mineral deposits in the Nigeria. b) K-function estimates Kiso, Ktrans, Kbord are significantly above the Kpois purple line indicating non-random distribution and clustering. c) density plot highlights a spatial clustering of barium mineral in Nigeria, with the high-density areas with bright yellow colours, the pinkish areas signifying regions of moderate coal density and the blue regions on the map indicate areas with little to no mineralization. d) Fry plot of reveals several hotspots of Barium occurrences particularly in the central and South-eastern region of Nigeria, aligned at N34^{0}E and N65^{0}W.

4.5 Limestone and Marble Point Pattern Analysis

The spatial distribution of limestone mineral deposits in Nigeria reflects the geological processes and sedimentary environments responsible for their formation. Limestone is a sedimentary rock primarily composed of calcium carbonate ($CaCo_3$) and is typically associated with marine environment, carbonate platform or shallow water depositional settings.

Limestone deposits in Nigeria are predominantly found in the sedimentary basin such as Benue Trough notably in areas like Gboko (Benue state) and Yandev. Sokoto Basin significantly deposits are located in areas like Kalanbaina and Wurno. Dahomey Basin found near Ewekoro and Shagamu. Chad Basin, limited but notable occurrences. The point distribution of limestone deposits (figure 4.5a) in Nigeria is linked to Marine transgression that deposited limestone during various geological periods the proximity to tectonic structures that influenced the deposition and preservation of carbonate sediments.

Limestone deposits often follow stratigraphic layer and are aligned with the paleo coastline of ancient seas. Some deposits may appear as isolated clusters, reflecting localized depositional environment or post–depositional erosion. Higher density of deposits is observed in region with significant carbonate sedimentation history such as the middle Benue Trough and South Western Dahomey Basin. However limestone and marble are not differentiated o the mineral map of Nigeria.

4.5.1 Limestone and Marble K-function Analysis

At small distances (r) the observed k-function line Kiso, Ktrans and Kbord. deviate from the kpois purple line, indicating a higher level of clustering at short ranges. The increasing value of K (r) with r suggest that clustering becomes more pronounced as the distance increases, up to a certain scale. The observed k-function lie above Kpois (r) throughout the range, confirming the presence of spatial clustering in Limestone mineral deposit rather than a random distribution.

The K-function Analysis (figure 4.5b) reveal significant clustering of limestone deposits, likely reflecting underlying geological control such as stratigraphy, sedimentary basin, and tectonic features. Clustering occurs over both small and large spatial scales possibly linked to localized depositional features. Clustering aligns with known limestone rich region in Nigeria such as the Benue Trough Sokoto Basin and Dahomey Basin. These areas host extensive limestone deposits due to favourable depositional conditions.

4.5.2 Limestone and Marble Density Analysis

The plot (fig4.5c) is a heat map style density plot representing the spatial intensity of limestone mineral deposits in Nigeria. The colour scale ranges from blue (low density) to yellow (high density) with intermediated level shown in shades of purple and pink. Bright yellow areas represent the highest concentration of limestone deposits suggesting focal points of significant geological interest.

The pink and purple zones indicate intermediate concentration likely corresponding to secondary limestone deposits or transitional geological zones. The blue regions demote sparse or absent limestone deposits possibly due to unfavourable depositional conditions.

The density plot reveals clustering of deposit in specific regions, indicating area of high geological activities conducive to limestone formation. The density gradient reflects variations in sedimentary environment, tectonic setting or historical depositional processes.

The limestone mineral density plot in Nigeria aligns with known basins in Nigeria, such as Benue Trough, Sokoto basin and Chad Basin, which are favourable for carbonate deposition. The clustering suggests localized factors influencing limestone accumulation such as paleoenvironments (e.g Carbonate platforms) or proximity to structural highs. High density regions are prime target for exploration and mining activities, the moderate density zones may require additional exploration to asses economic viability.

4.5.3 Limestone and Marble Fry Analysis

The fry plot for limestone-Marble mineral deposits in Nigeria (fig 4.5d) consists of numerous black points scattered around a central origin, creating a dense core and more dispersed peripheral regions. The Clustering of points near the centre of the plot indicates that limestone is spatially aggregated in specific areas, suggesting strong clustering behaviours. A peripheral spread can be observed outward from the dense core, implying that while clustering dominates some deposits are distributed over a broader range. The elongated shape of the cluster suggests Anisotropy, Possibly the plot suggest that limestone-marble deposits are not randomly distributed but influenced by geological factors like sedimentary environment (limestone) or tectonic activities (marble).

The Clustering on the central part of the plot corresponds with the Benue Trough basin of Nigeria due to the favourable carbonate-rich environment. The directional elongation of points aligns with known structural trends such as the orientation of the Benue Trough, Sokoto Trough, Chad basin but also includes parts the Basement complex that host Marble. Geological structure like anticline, syncline or fault might play a role on guiding the distribution of limestone minerals in Nigeria. The clustering could be also linked to carbon platforms systems or paleo environmental conditions that favoured limestone deposition during specific geological periods.

The Fry plot of limestone-marble deposits reveals two primary trend alignments, reflecting the structural control on their spatial distribution. The first trend, oriented at N40°E, corresponds to the deposits found within the Benue Trough and Anambra Basin, indicating a strong correlation with the limestone sedimentary environments and tectonic settings of these basins. The second trend, aligned at N78°W, is associated with deposits within the metasedimentary regions that host marble, suggesting an influence of metamorphic processes and basement-related structural features on the distribution of marble deposits. These alignments provide insights into the geological controls governing the occurrence of limestone and marble in the region.

The high-density regions around the Benue Trough, highlighted in the fry plot are primarily targets for limestone exploration whereas peripheral points around the Sokoto Basin, Chad basin and Basement Complex, with smaller scattered deposits requires further investigation.

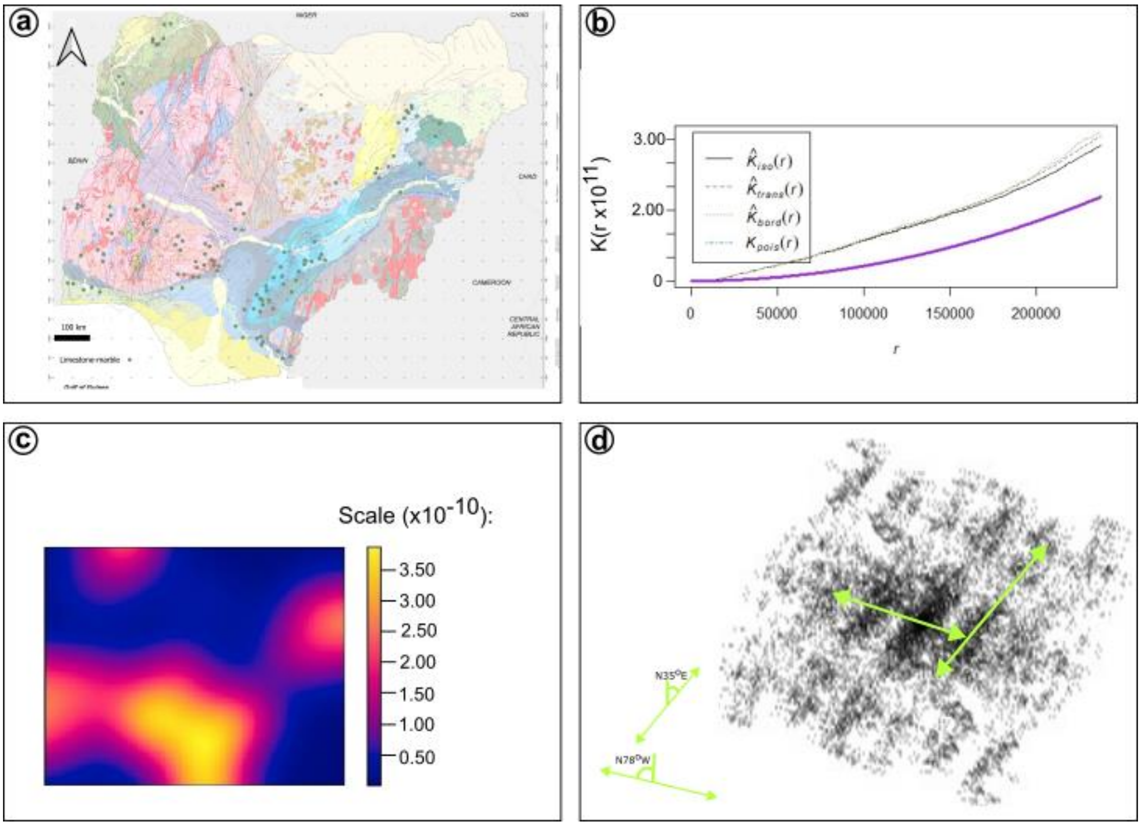

Figure 4.5 a) point distribution of limestone-marble mineral deposits in Nigeria. b) K-function estimates Kiso, Ktrans, Kbord are all significantly above the Kpois purple line indicating non-random distribution and spatial clustering. c) density plot highlights a spatial clustering of limestone-marble mineral in Nigeria, with the high-density areas having bright yellow colours, the pinkish areas signifying regions of moderate limestone-marble density and the blue regions on the map indicate areas with little to no mineralization. d) Fry plot of limestone-marble deposits displays a directional elongation of points with known structural trends such as the orientation of the Benue Trough, Sokoto Trough, Chad basin and part of the Basement Complex that host marble.

4.6 Iron Point Pattern Analysis

The point distribution of iron deposits across Nigeria (figure 4.6a) often shows a clustered pattern with a tendency to occur in specific geological regions. Iron deposits are strongly associated with Precambrian Basement Complex, meta-sedimentary belts and region influenced by tectonic activities.

The central and Northern Nigeria host significant iron mineralization, identified in regions such as Itakpe, Ajabanoko, and Agbaja. These regions lie within the lokoja-Okene axis and are part of the Precambrian terrain with rich hematite and magnetite ores. Iron rich lateritic deposits also occur within the sedimentary formation in the Benue Trough and chat basin, often formed through secondary processes like weathering and sedimentation. Minor deposits maybe found in regions of low tectonic activities or in isolated sedimentary basins.

The clustering of iron mineral deposits suggests they are controlled by geological features such as faults, folds, and lithological variations. The occurrence of iron in specific regions implies a non-random spatial trend, heavily influenced by geological history and structural frameworks, Areas with dense clustering of points aligns within the Precambrian basement complex of Nigeria, these regions represent prime locations for exploration and mining peripheral and isolated point may indicate smaller, less economical significant deposits that require further validation.

4.6.1 Iron K-function Analysis

The empirical K-functions (Kiso, Ktrans, Kbord) lie above the theoretical Poisson function (Kpois), indicating that the iron mineral occurrences exhibit clustering rather than a random distribution. The greater the deviation of the empirical K-function from Kpois(r), the stronger the clustering effect. This pattern suggests that geological or structural controls influence the distribution of iron deposits. Clustering may result from tectonic and structural controls, where deposits are concentrated along fault lines, shear zones, or mineralized belts. Geochemical factors could also play a role, with specific geological formations or lithological units hosting multiple iron occurrences. Additionally, mineralization processes such as hydrothermal activity, sedimentary deposition, or magmatic events may contribute to localized clustering.

4.6.2 Iron Density Analysis

The density plot illustrates the spatial distribution of iron mineral deposits in Nigeria, with colours indicating varying concentrations. High-density regions, represented by yellow and pink areas, suggest significant iron deposit clusters. These areas correspond to mineral-rich regions such as Kogi, Itakpe, parts of Kwara, Benue, Nasarawa, Zamfara, and Kaduna States, where iron ore formations are well-documented. In contrast, low-density regions, shown in deep blue, indicate sparse occurrences and may correspond to areas lacking favourable geological conditions for iron mineralization, such as parts of the Southwestern, South-eastern, and North-eastern zones. The clustering of high-density areas suggests that specific geological formations, including banded iron formations (BIFs) and Basement Complex rocks, play a key role in ore distribution. This spatial pattern highlights potential exploration hotspots, emphasizing the need for further geochemical and geophysical surveys to assess the full extent of iron ore mineralization.

4.6.3 Iron Fry Analysis

The Fry plot (see figure 4.6d) reveals a strong directional alignment of iron mineral deposits in Nigeria, indicating that they are not randomly distributed but follow a structural trend. The elongated, dense cluster at the center, with points extending outward in a preferred direction, suggests that the deposits are influenced by geological structures such as faults, shear zones, or lithological boundaries. The anisotropic clustering pattern implies that mineralization is controlled by major geological features rather than occurring uniformly. This trend aligns with known metallogenic belts in Nigeria, particularly in regions such as Kogi, Kwara, Nasarawa, and Benue States, where significant iron ore deposits are located. The observed spatial orientation suggests a connection to fault-controlled deposits, including those within the Itakpe iron ore belt, which is influenced by basement fractures. The Fry plot analysis reveals three dominant trend alignments, indicating the spatial distribution patterns of the deposits. The primary alignment, observed at N60°E, corresponds to the major deposits located within the north-central region, suggesting a strong geological control in this direction. The second alignment, oriented at N10°W, is associated with deposits within the Basement Complex, where occurrences are more limited and scattered. These trends highlight the structural influences on the mineralization and provide insights into the regional geological framework controlling the deposit distribution. These findings highlight the role of tectonic activities and structural deformation in the distribution of iron deposits, emphasizing the need for further geological and geophysical studies to refine the understanding of their formation and spatial characteristics.

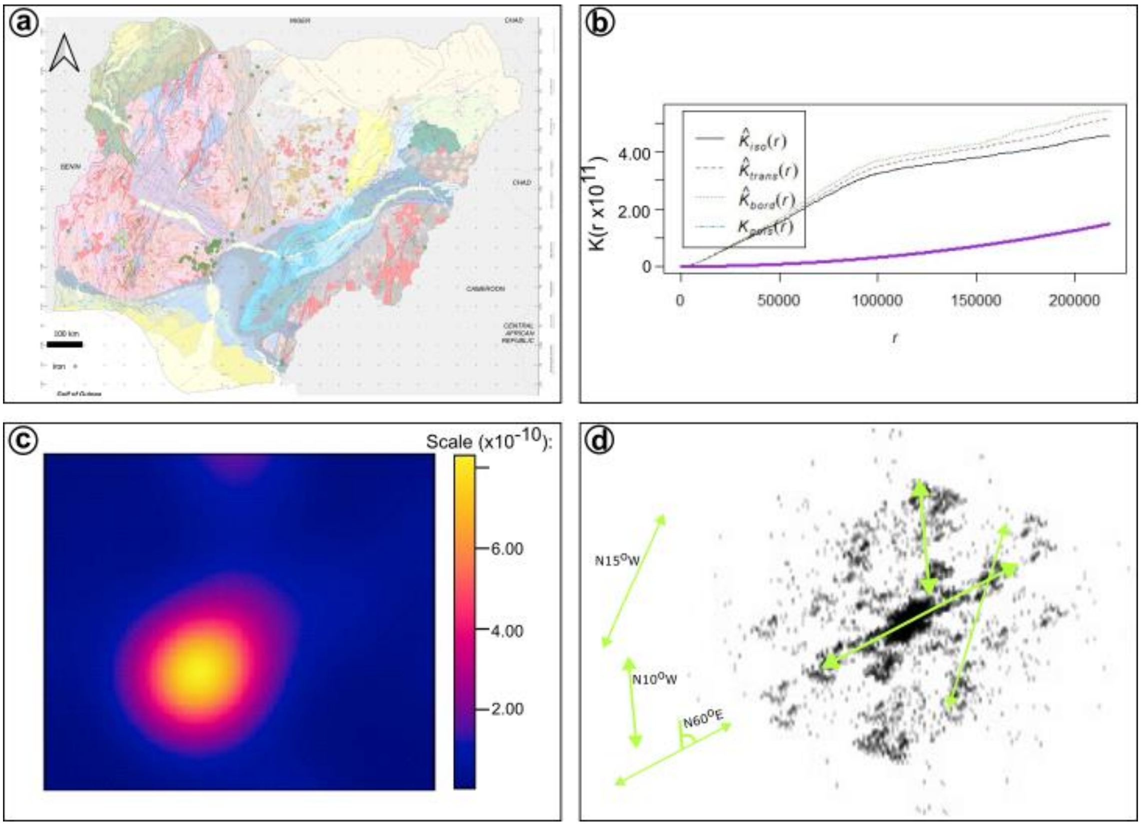

Figure 4.6 a) point distribution of iron mineral deposits in Nigeria. b) K-function estimates Kiso, Ktrans, Kbord are all significantly above the Kpois purple line indicating non-random and spatial clustering. c) density plot highlights a spatial clustering of iron mineral in Nigeria, with in the central and northcentral areas are high-density region with bright yellow colours, the pinkish areas signifying regions of moderate coal density and the blue regions on the map indicate areas with little to no mineralization. d) Fry plot shows an elongated, dense cluster at the centre, with points extending outward in a preferred direction, suggests that the deposits are influenced by geological structures such as faults, shear zones, or lithological boundaries

4.7 Base-Metal point Distribution

The point distribution of base-metal mineral deposits in Nigeria (figure 4.7a) shows a scattered pattern with occasional clustering in specific regions of geological significance. These deposits are typically associated with area of metamorphic terrains, intrusive igneous rock and sedimentary basins. The Benue trough is particularly rich in base metals such as lead-zinc and copper, the deposits are distributed along faults and fractures within sedimentary sequence of the Trough.

The younger granite complex in the central Nigeria (e.g Jos) base metal like tin and tungsten are often found in association with granitic intrusions and pegmatite. The southwestern Nigeria is notable for deposits of lead-zinc often associated with the Precambrian basement complex rocks and their contact zone.

The Northern part of Nigeria is known for its occurrences of base metal like copper and nickel in both igneous and sedimentary formation. The deposits are influenced by tectonic events such as faulting and folding, which created favourable conditions for mineralization. Hydrothermal processes and replacement mechanism have played significant roles in the distribution and formation of base metal deposits. Clustering of deposits is often observed near major fault lines in structurally controlled regions. The spatial distribution is non-random and reflects the geological history of Nigeria including episodes of rusting, magmatism and sedimentation.

4.7.1 Base metal K-function Analysis

The solid black curve Kiso and the other empirical curves ktrans, kbord (see figure 4.7b) lies above the theoretical CSR curve kpois. Indicating significant spatial clustering of base metal disposition. The difference between the empirical k-function and the CSR model increases with r, suggesting that clustering becomes more pronounced at Larger spatial scale. The curve appears smooth reflecting a well fitted analysis of spatial distribution.

4.7.2 Base Metal Density Analysis

The central region of the plot (see figure 4.7c) aligns with the high-density hotspots which is part of the Younger Granite Complex and the mineral rich zones of Jos Plateau, known for tin and lead-zinc mineralization. The Benue Trough pattern likely reflects the influence of tectonic activity which has enriched this area with lead, zinc and copper deposits.

The southwestern Basement complex aligns with the moderate density of base metal distribution in Nigeria, found in the contact zone of Precambrian rocks.

The density gradient transition from low (dark blue to high yellow) reflecting the uneven geological control on mineral deposition. Areas with diffuse density patterns may correspond to regions with less exploration of sparse deposits. The density plot highlight regions of interest for the future exploration activities falls within the younger granite complex, central part of Nigeria, precisely within Jos plateau Benue trough and part of Kogi State.

4.7.3 Base-metal Fry Analysis

The fry plot data for base-metal mineral deposition in Nigeria (see figure 4.7d) shows a spatial distribution pattern that can be interpreted as follow. The central darkened area indicates a strong clustering of mineral deposits suggesting localized enrichment rather than a completely random spread, this implies that mineralization is controlled by specific geological factors such as faults, fractures ore lithological contacts. If there is an elongation or liner alignment of points in the fry plots, it suggests a preferred structural direction. The fry plot (fig) appears to be a radial or weakly elongated distribution, implying that base metal deposits may be associated with multiple structural controls, such as shear zone, fold belts, or intrusive contact rather than a single directional fault system.

The Fry plot analysis reveals two primary trend alignments, reflecting the spatial distribution of deposits. The first alignment at N38°E corresponds to deposits located within the Benue Trough, indicating a structural and stratigraphic control influenced by the Trough's geological framework. The second alignment is the most significant observed at N56°W is associated with deposits found within the Basement Complex of the north-central and northwestern regions, suggesting a different tectonic influence on mineralization. These observed trends highlight the role of structural geology in the localization of deposits within the study area. The clustering seen in the fry plot (fig) corresponds to the known mineral belts, Benue through (Pb-Zn deposits in Abakaliki, Ishiagu, and Zurak). The Central Nigeria (Bauchi, Jos and Nasarawa with Tin, Lead and Zinc deposits), the Northwest Nigeria (Zamfara, Kebbi, with associated Copper, Lead and Zinc veins).

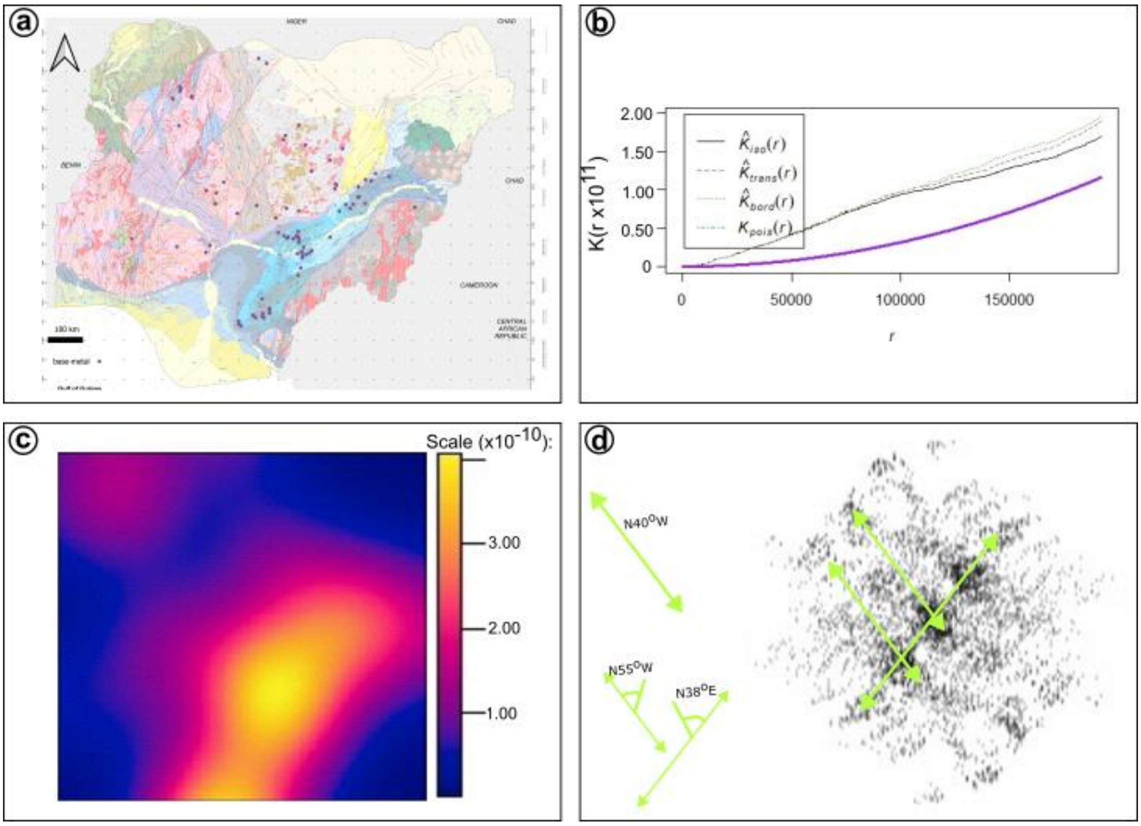

Figure 4.7a. point distribution of base-metal mineral deposits in Nigeria. b) The plot shows the solid black curve Kiso and the other empirical curves ktrans, kbord, lie above the theoretical CSR curve kpois. Indicating significant spatial clustering of base metal disposition. c) density plot highlights a spatial clustering of base-metal in Nigeria, with in the central areas are high-density region with bright yellow colours, the pinkish areas signifying regions of moderate density and the blue regions on the map indicate areas with little to no mineralization. d) Fry plot image shows dominant NE-SW, NW-SE trend.

4.8 Lithium-Tantalum Point Pattern Analysis

The spatial distribution of Lithium and Tantalum mineral deposits in Nigeria (see figure 4.8a) follows specific geological control, primarily, linked to pegmatite belts and structural trend within the country. Lithium and tantalum deposits in Nigeria are not randomly distributed but rather exhibit a clustered pattern along known pegmatite fields. These clustered alignment with Precambrian Basement Complex rocks particularly within the Pan-African orogenic belt that host Lithium-bearing pegmatite.

The clustering suggests that pegmatite intrusions, which host these minerals are controlled by regional tectonic setting and crustal fractures. Most of the Lithium and tantalum pegmatites in Nigeria align in a Northeast-Southwest (NE-SW) direction, following the regional trend of the Nigeria Basement Complex. The deposits are mainly found in central Nigeria (Nasarawa, Kogi, Kwara, and Oyo State) and extends towards the western part (Ekiti, Osun, and Osun and Ogun State), many Lithium-Tantalum deposits occur in the same zones as tin and columbite mineralization, particularly in Plateau, Bauchi and parts of Kaduna.

lithium and Tantalite are hosted in rare-metal pegmatites which are controlled by fractures and shear zones. Pegmatite intrudes along faults and fractures which mean their spatial distribution follow tectonic activities. Pegmatites rich in Lithium and Tantalum often occur near granitic intrusions forming a belt-like distribution. Deposits align with metamorphic terrain such as the Kibaran-age pegmatite in Northern Nigeria.

4.8.1 Lithium-tantalum K-function

The Kiso, Ktrans and Kbord, curves are significantly above the Kpois Poisson distribution (see figure 4.8a), this indicates strong clustering in the spatial distribution of Lithium-tantalum deposits. If the curves were following the purple line, it would suggest a random spatial pattern and if the curves were below the purple line it would suggest dispersion (even spacing between deposits). The clustering suggest that lithium-tantalum mineral deposits are controlled by geological factors such as, pegmatite belt, Distribution, structural controls, magmatic association. The Analysis confirms that Lithium tantalum deposits in Nigeria occur in clusters, so Exploration should focus on known pegmatite belts and corridors. Region like Nasarawa, Kwara, Kogi, Oyo, and Ekiti state host lithium-rich pegmatite are high priority targets.

4.8.2 Lithium-Tantalum Density Analysis

The density distribution of lithium-tantalum mineral deposits in Nigeria (see figure 4.8c) reflects areas with high and low intensity Density. These can be linked to geological regions across the country known for hosting rare-metal pegmatites and granitic intrusion. The high-density regions are characterized by significant clusters and concentrations of lithium-tantalum deposits as indicated by the yellow and orange regions in the density plot. The high-intensity regions fall within the South-Western and North-Central Nigeria (Ogun State, Oyo State and Osun State) are parts of the South West Basement Complex knowing to host rare metals pegmatites associated with Lithium and tantalum Mineralization. North-Central, falls with states such as Nasarawa, Kogi and Niger are within the Younger Granite province and the Benue Trough. These regions have granitic intrusion that are conducive to Lithium tantalum deposits.

Low-intensity density areas are represented by the blue and pink colour regions on the density plot. They show scattered or space occurrences of lithium and tantalum deposits. The Low-intensity Density Regions falls within the Northern, South-eastern and Southern Nigeria. Kano and Kaduna State have Low-density Lithium-tantalum deposits, reflecting Limited pegmatite activities or less mineralized zones. Ebonyi State and part of Abia State within Abakiliki fold belt exhibit low-intensity density, likely due to the tectonic settings not being favourable for pegmatite intrusion. Region in Edo and Delta State show lower densities potentially reflecting limited geological conditions for lithium and tantalum enrichment.

High-intensity areas such as the South Western Basement Complex and Parts of North-Central Nigeria should be prioritized for detailed exploration and mining while the low intensity areas, particularly in the North and South-east, may require further geological survey to identify additional pegmatite belt or potential deposits.

4.8.3 Lithium-Tantalum Fry Analysis

The fry plot for Lithium-tantalum mineral in Nigeria (see figure 4.8d) provides insights into the spatial alignment and clustering of the deposits, the fry plot reveals a dense central cluster, which represents a significant concentration of Lithium-tantalum deposits in a particular region. Peripheral points appear more dispensed, suggesting lower concentrations or isolated occurrences of deposits. The central alignment and tight clustering suggest these deposits are structurally controlled by regional geological features such as fault zones, pegmatite intrusions or granite provinces. The plot shows a clear radial symmetry in the central region, with denser alignments possibly aligned linear structures or fault systems. These trends are indicative of the underlying tectonic and geological sittings that favour the formation of rare-metal pegmatite.

The central clustering corresponds to areas in South Western Nigeria and North-Central Nigeria, particularly in the Basement complex and the younger granite province, (e.g. Oyo, Osun, Ekiti and Ogun State) and towards the North Central parts with States like Kogi, Nasarawa and Niger. The clustering also matches the trend alignment N42^{0}E (see figure 4.8d). Dispersed points around the main cluster aligns with N38^{0}w, suggest occurrences in Northern and Southern Nigeria, possibly associated with isolated pegmatite systems or less mineralized zones. High-density clusters around the North-Central and South Western region should be the focus to detailed geological mapping and mineral exploration, particularly in pegmatite rich zones.

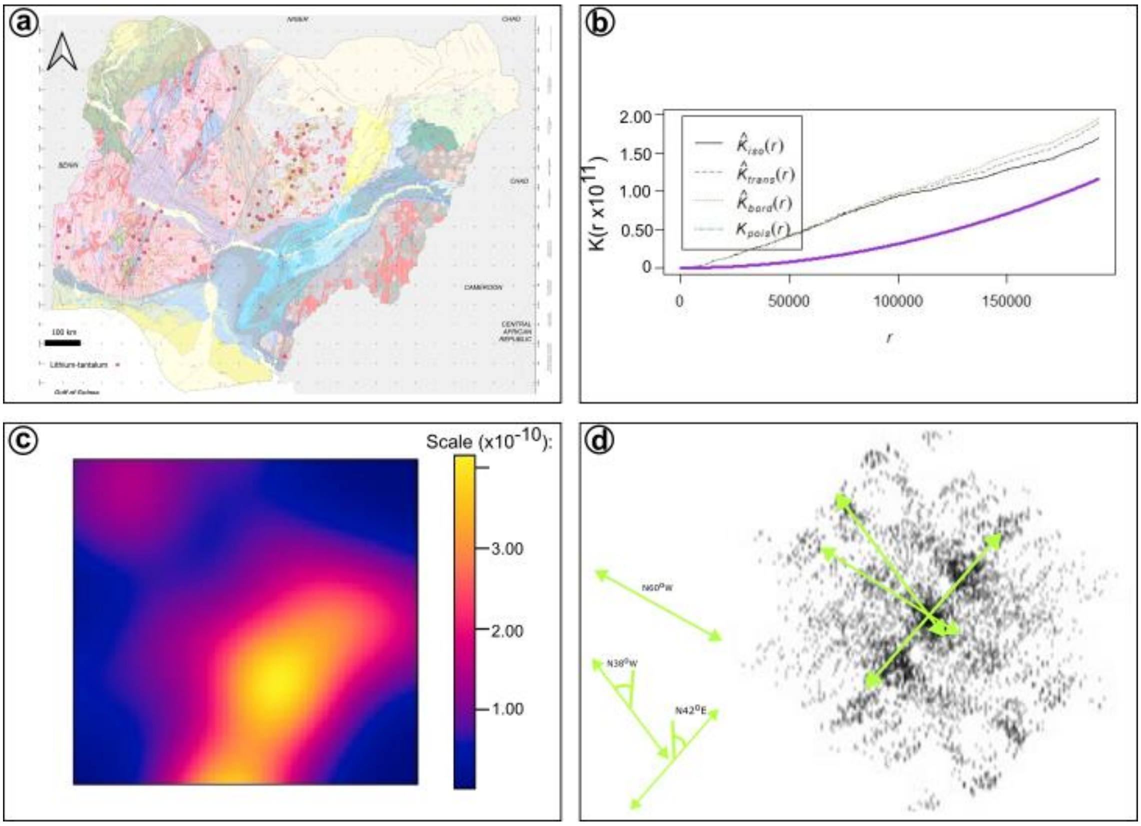

Figure 4.8 a) point distribution of Lithium-Tantalum mineral deposits in Nigeria. b) The image displays Kiso, Ktrans and Kbord, curves are significantly above the Kpois Poisson distribution, this indicates strong clustering in the spatial distribution of Lithium-tantalum deposits. c) density plot of Lithium-Tantalum with high-density intensity region around the Basement Complex, South-Western and North-Central Nigeria (Ogun State, Oyo State and Osun State). d) The fry plot image shows a clear radial symmetry in the central region, with a trend of N42^{0}E and N38^{0}W.

4.9 Talc Point Pattern Analysis

Talc mineral point distribution (see figure 4.9a) exhibit localized clustering in specific geological zone. These clustering is typically influenced by areas with ultramafic rocks such as serpentines, which are primary sources of talc formation. These clusters might be prominent in the regions with significant metamorphic activity or proximity to major shear zones. The distribution of talc deposits may align with tectonic trends especially near fault zones or in areas with hydrothermal alteration. Regions with associated metamorphic or igneous rocks, particularly in the Basement Complex, are likely to dominate the point distribution map. South Western Nigeria with state such as Osun, Oyo, Ogun and Ekiti often host talc deposits due to the presence of metamorphic rocks and shear zones. Northern Nigeria states such as Kogi, Niger may also feature talc deposit particularly in areas associated with ultramafic and metamorphic rocks. Talc distribution is controlled by the availability of precursor rocks (such as serpentines) and metamorphic conditions conducive to its formation.

4.9.1 Talc K-Function Analysis

The interpretation of the K-function plot for talc mineral deposits (see fig 4.9b) estimates (kiso, Ktrans and kbord) lie above the complete spatial randomness line (Kpois). This indicates that talc mineral deposits in Nigeria are spatially clustered rather than randomly distributed. The increasing gap between the empirical k-functions and CSR line at larger distance suggest that clustering occurs over a wide range of spatial scale.

4.9.2 Talc Density Analysis

The density plot of talc mineral deposits in Nigeria (see figure4.9c) reveals a non-uniform distribution, with distinct high-density clusters indicating areas of significant mineralization. The most prominent zones of high density, shown in yellow and bright pink, are concentrated in the southwestern and central parts of the study area, corresponding to known talc deposits in states such as Ogun, Oyo, Osun, and Kogi. These occurrences are primarily associated with metamorphic rock formations, including schists and dolomitic marbles. Additional high-density spots in the northern region suggest smaller, localized deposits, potentially within Niger and Kaduna States, where talc-bearing rocks have also been reported. The variation in density highlights the influence of geological factors such as regional metamorphism, faulting, and hydrothermal activity, which control talc formation and distribution. Areas with low density, represented by dark blue regions, indicate sparse or absent talc occurrences, potentially due to limited exploration or unfavourable geological conditions. The clustering pattern suggests that talc mineralization is structurally controlled, likely linked to major lithological units within the Precambrian basement complex. These insights have important economic implications, as high-density zones could serve as potential exploration targets for further resource assessment. Given talc’s industrial applications in cosmetics, pharmaceuticals, and ceramics, understanding its spatial distribution can support more effective mining strategies and resource management in Nigeria.

4.9.3 Talc Fry Analysis

The fry plot (see figure 4.9d) exhibits a linear alignment of points, indicating a predominant directional trend in the spatial distribution of talc deposits. This linearity suggests that the deposits are controlled by specific geological features such as faults, shear zones or fracture systems. The plot reveals an elongated clustering along a specific axis, which aligns with a structural or tectonic orientation in the region.

The Fry plot analysis of talc deposits reveals two primary trend alignments. The first trend at N54°W suggests a structural control associated with tectonic features influencing talc mineralization. The second trend at N58°E is the most significant, indicates another directional alignment, potentially corresponding to fault and shear zones or lithological boundaries that govern the distribution of talc deposits.

The distribution observed in the fry plot correlates with geological provinces rich in ultramafic and metamorphic rocks such as the Basement Complex regions of Nigeria. Areas such as Ogun, Osun, Kogi and Niger State are prominent locations for talc mineralization and are likely aligned with the observed spatial pattern, The observed linear trends suggest that talc formation is associated with regions experiencing significant tectonic stress, where ultramafic rocks underwent alteration and metamorphism. Exploration strategies should focus along these linear trends to identify additional deposits.

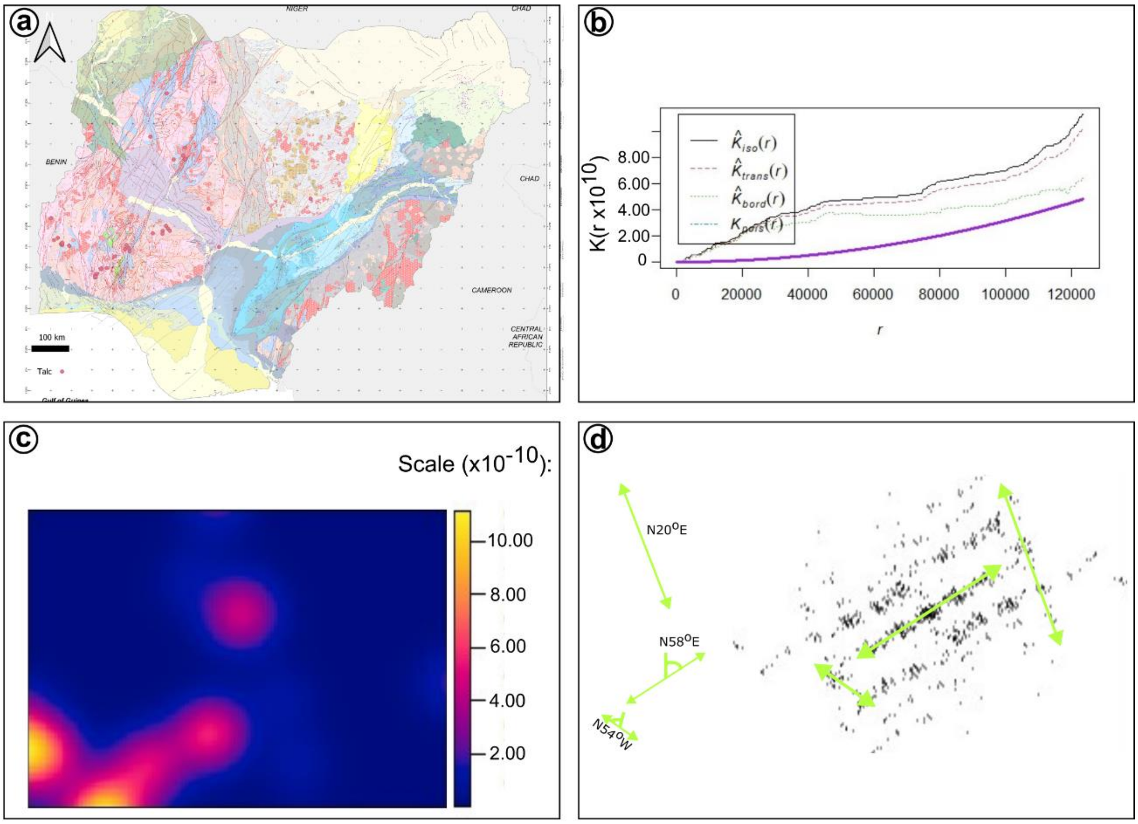

Figure 4.9a. point distribution of Talc mineral deposits in Nigeria. b) Kiso, Ktrans and Kbord, curves are significantly above the Kpois Poisson distribution, this indicates that talc mineral deposits in Nigeria are spatially clustered rather than randomly distributed. c) density plot of zones with high-density, shown in yellow and bright pink, are concentrated in the southwestern and central parts of the study area. d) Fry plot image visualizes two main trend alignments of points at N54°W and N58°E, indicating a predominant directional trend in the spatial distribution of talc deposits.

4.11.3 Manganese Fry Analysis

The fry plot (figure 4.11a) visualizes the clustering, trends and directional alignment of manganese Mineral deposits in Nigeria. The presence of dense point near the centre suggest that manganese deposits are not randomly distributed but rather form clusters. This clustering implies a localised mineralization process likely controlled by geological structures such as faults or folds. The distribution appears elongated along a diagonal trend alignment of N68^{0}E and N65^{0}W suggesting a preferred orientation of manganese deposits. This alignment could be indicative of mineralization along a fault line, shear zone or lithological boundaries. The spatial pattern corresponds to known mineral belts or geological formation that host manganese, a significant manganese bearing region influenced by tectonic processes. Central and northern Nigeria, Basement complex area with metamorphic and sediment hosted manganese mineralization. The western Nigeria, possible occurrences with in meta sedimentary sequences. Since the deposits exhibits alignment exploration should focus on regions with similar faulting pattern and geological location

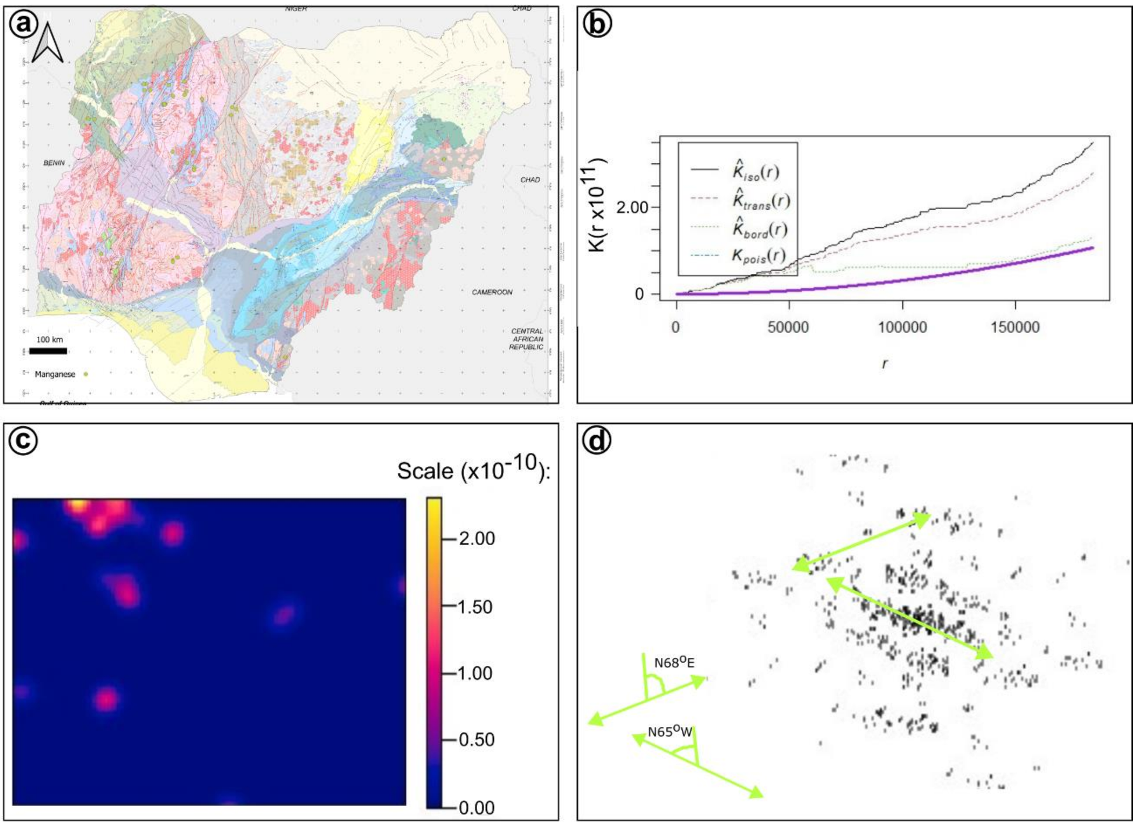

Figure 4.11 a) point distribution of manganese mineral deposits in Nigeria. b) kiso and Ktrans lie significantly above the purple Poisson line (Kpois). This suggest strong clustering meaning manganese deposits in Nigeria are not randomly distributed but occurs in clusters. c) most prominent zones of high-density, located at the (top left section) within the Basement Complex (Kaduna and Kebbi state). d) Fry plot image displays an elongated distribution along a diagonal trend of N68^{0}E and N65^{0}W suggesting a preferred orientation of manganese deposits.

4.10 Copper Point Pattern Analysis

The spatial distribution of copper deposits in Nigeria (figure 4.10a) is influence by geological formation, tectonic structures and mineralization processes. Copper deposits in Nigeria tend to occur in clusters than being evenly distributed. This clustering is often due to the presence of favourable host rocks such as schists, granites and sedimentary formation rich in sulphide minerals. Copper deposits are prominently found along major mineral belts particularly in regions associated with past volcanic and hydrothermal activities. Some region exhibits higher densities of copper deposits suggesting rich ore zones that could be economically viable for mining.

Copper mineralization in Nigeria is primarily concentrated in the Benue Trough, the Jos-Plateau, North-Central Nigeria, and the Ilesha Schist Belt in the southwest. In the Benue Trough, spanning North-Central and Eastern Nigeria, copper-bearing sulphide deposits are commonly associated with lead-zinc mineralization. Major occurrences are found in areas like Abakiliki and Gombe. The Jos-Plateau and North-Central Nigeria host copper deposits linked to granitic intrusions and pegmatites, often occurring alongside tin and tungsten mineralization. In Southwestern Nigeria, the Ilesha Schist Belt contains copper deposits within metamorphic and sedimentary sequences, where occurrences are frequently associated with gold mineralization and quartz veins. The clustering of copper deposits in these specific regions highlights strong geological controls, including hydrothermal activity, faulting, and sedimentary processes. The Benue Trough and the

Schist Belt represent promising zones for further copper exploration due to their structural and mineralogical characteristics.

4.10.1 Copper K-Function

The plot (see figure 4.10a) represents the spatial point pattern analysis of copper mineral deposits in Nigeria using Ripley's K-function. The empirical K-function kiso(r), Ktrans(r) and Kbord(r) lies significant above the complete spatial randomness line Kpois(r). This suggest that copper deposits in Nigeria are spatially clustered meaning they tend to occur in localized groups rather than being randomly distributed. The widening gap between empirical curve and the CSR baseline at greater distance suggest that clustering is not just local but extends over large spatial scales.

The slight variation in the Kiso, Ktrans and Kbord lines indicates spatial heterogeneity, meaning copper deposit may be influenced by multiple geological controls, such as rock types, faults or mineral belts. The clustering of copper deposits suggests localized mineralization zones, potentially associated with faults systems, hydrothermal processes or specific formations.

4.10.2 Copper Density Analysis

This density plot (see figure4.10c) provides a spatial visual of the distribution of copper mineral deposits across Nigeria. The copper deposits are not uniformly distributed but appear as isolated across the study area. The hotspots (yellow regions) represent areas higher copper concentration suggesting geologically favourable mineralization zones. Most of the study area remains dark blue, indicating low or no significant copper deposits in those regions.

The copper deposits in Nigeria exhibit a northwest-southeast trend, suggesting alignment along major geological structures such as faults, fractures, or mineral belts. These deposits are primarily associated with the Benue Trough, Schist Belt, and Basement Complex terrains, with identified hotspots aligning with known copper-bearing locations. In the Benue Trough, particularly in Central-Eastern Nigeria, copper mineralization is linked to volcanic-sedimentary formations. The Jos Plateau in North-Central Nigeria, known for hosting various mineral resources, possibly contains copper deposits as well. The Schist Belts of Western Nigeria are recognized as important zones for base metals, making them significant for further copper exploration.

4.10.3 Copper Fry Analysis

The fry plot (figure 4.10d) shows a clear directional alignment with points forming an elongated diagonal cluster across the plot. This suggests that copper deposits in Nigeria are not randomly distributed but instead follow a structured geological trend. The North-west and South-west (NW-SE) orientation of the plotted points suggest that copper mineralization is strongly controlled by regional geological structure such as fault, fractures, shear zones and mineralized belts. This pattern is consistent with known mineralization zones in Nigeria particularly in areas associated with the Benue Trough, Schist belts and Basement Complex.

The alignment observed in the Fry plot suggests that copper deposits in Nigeria are concentrated along specific geological belts, the Benue Trough in Central-Eastern Nigeria is known for base metal mineralization associated with volcanic and sedimentary formations. The Schist Belt in Western Nigeria serves as a significant host for various mineral deposits, influenced by metamorphic and structural settings. Additionally, the Jos Plateau and North-Central Nigeria present potential for copper mineralization, particularly in pegmatitic and granitic terrains, highlighting key zones for further exploration.

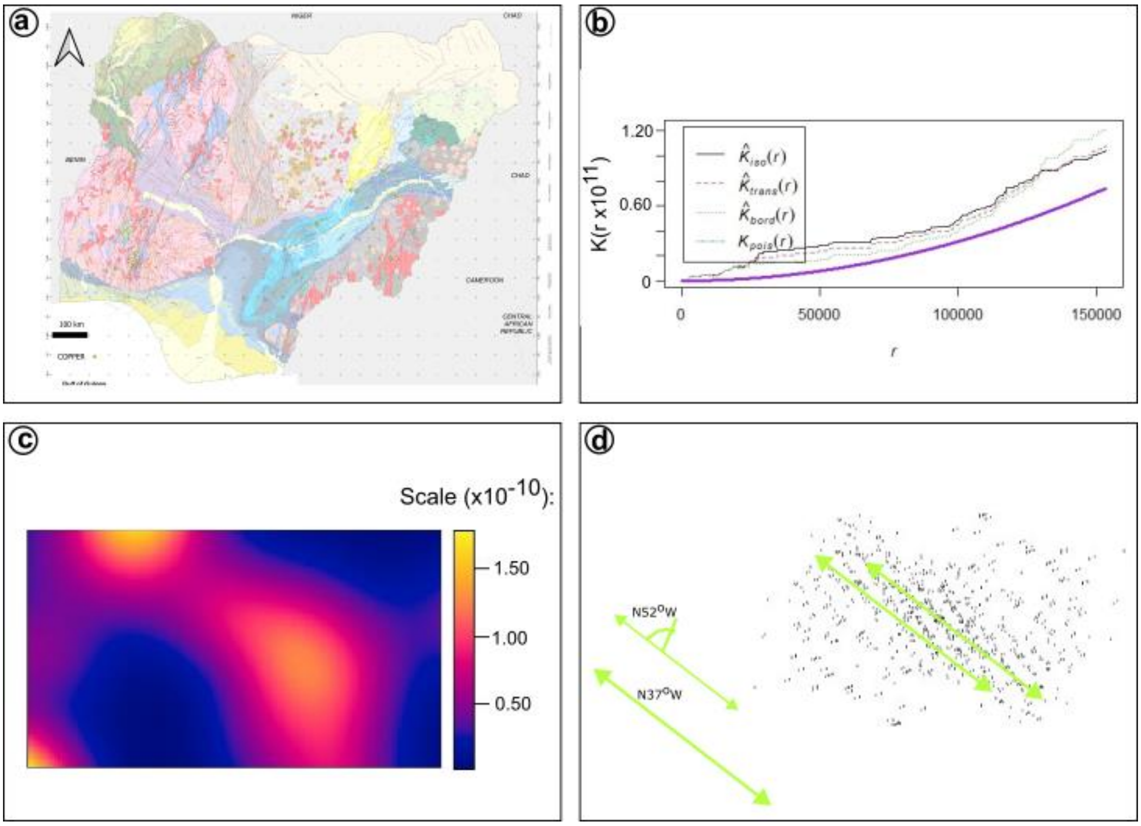

Figure 4.10a. point distribution of copper mineral deposits in Nigeria. b) K-function Kiso, Ktrans and Kbord lies significant above the complete spatial randomness line Kpois. This suggest that copper deposits in Nigeria are spatially clustered. c) most prominent zones of high-density, shown in yellow and bright pink, are concentrated around the Benue Trough in Central-Eastern region of the study area. d) Fry plot image follows a structured geological trend of N52^{0}W orientation and shows a clear directional alignment with points forming an elongated diagonal cluster.

4.11 Manganese Point Pattern Analysis

The point distribution of Manganese mineral deposits in Nigeria (see figure 4.11a) are not randomly scattered but tend to form clusters along specific geological belts, they are commonly found in sedimentary basins, Faulted zones and weathered rocks, particularly in areas with favourable geochemical conditions. The distribution of manganese deposits in Nigeria aligns with major tectonic structures, following either a north-south or northeast-southwest trend, depending on the influence of faults, shear zones, and stratigraphic layers. Predominantly, manganese deposits are found in the Benue Trough (North-Central and Eastern Nigeria), which hosts sedimentary manganese formations. The Nsukka Formation in Southeast Nigeria is known for its manganese-bearing rocks, while Kaduna, Kebbi, and Zamfara States in Northwestern Nigeria contain deposits associated with metamorphic and ferruginous formations. The Basement Complex hosts minor manganese concentrations, primarily due to weathering and hydrothermal alterations.

4.11.1 Manganese K-Function Analysis

The kiso and Ktrans lies significantly above the purple Poisson purple line Kpois (see figure 4.11b). This suggest strong clustering meaning manganese deposits in Nigeria are not randomly distributed but occurs in clusters. The deviation from the Poisson model increases with distance confirming persistent clustering at larger spatial scales. The continuous increase in K-value with distance indicate that clustering remains dominant over large distance. The higher K-value suggest regional scale clustering like following geological structures such as fault lines mineralized belt or sedimentary basins.

The clustering suggest that manganese deposits are concentrated in specific geological belts or faulted zones rather being scattered randomly. The clustering aligns with known metamorphic zones, sedimentary formation and Basement Complexes rich in manganese deposit. Mining efforts should focus on regions where clustering is evident as these areas are likely to contain economically viable manganese concentration.

4.11.2 Manganese Density Analysis

The density plot (fig 4.11c) visually represents the spatial concentration of manganese mineral deposits in Nigeria. The plot reveals non-uniform clustering of manganese deposits around the Benue Trough (central Nigeria) known to host sedimentary manganese Mineralization. Certain Regions (top left section) shows high intensity clustering suggesting areas with higher probability of economic manganese concentration around the Basement Complex (Kaduna and Kebbi state). Other areas within the southwestern Nigeria remain sparsely distributed or absent confirming localized mineralization. The clusters follow a structural trend possible aligning with geological formations, fault lines or mineral belts. The orientation of the clusters suggest association with major manganese bearing formations likely found in sedimentary basins or metamorphic belts. The density plot suggest that exploration should focus on the high-density clusters to maximize resource potentials, the bright region (yellow-red) indicates the most promising exploration sites.

4.12 Oil Gas Point Pattern Analysis

Oil and gas deposits in Nigeria are not randomly distributed but are concentrated in specific geological formations influenced by tectonic and sedimentary processes. The deposits exhibit high clustered distribution in the Niger Delta Basin (figure 4.12a), linear alignment along sedimentary basins, indicating structural controls sparse occurrences in inland basins such as Benue Trough and Chad Basin. Oil and gas deposits in Nigeria are primarily concentrated in four major regions, the Niger Delta Basin in South-South Nigeria is the largest oil and gas-producing region, characterized by highly clustered deposits due to its thick sedimentary sequences rich in hydrocarbons. The Anambra Basin in Southeast Nigeria exhibits a semi-clustered pattern with localized gas accumulations. The Benue Trough in North-Central Nigeria contains scattered occurrences, mainly in its southern section. The Chad Basin in North-eastern Nigeria has a sparse distribution of oil and gas deposits, with ongoing exploration efforts revealing promising discoveries and potential for further findings.

4.12.1 Oil and Gas K-Function Analysis

The empirical K-function (Kiso, Ktrans, Kbord) are significantly above the theoretical Poisson function (Kpois) purple line (see figure 4.12b), suggesting that oil and gas deposits in Nigeria are highly clustered rather than randomly distributed. This means that oil and gas occurrences are spatially dependent, likely influenced by geological structures such as sedimentary Basins, fault line and deltaic formations.

The Kiso(r) K-function line, shows a strong upward trend, confirming intense clustering at various distance(r). The Ktrans(r) follows closely indicating that clustering persists even after transformations. The green border corrected K-function Kbord(r) is lower than the isotropic K-function but still above the Poisson expectation implying that the clustering pattern is not solely due to boundary effects.

Clustering aligns with known oil and gas basin such as the Niger delta basin, where petroleum accumulation is concentrated. The distribution of petroleum deposits in Nigeria does not follow a random pattern, indicating that exploration should focus on established petroleum provinces and their extensions rather than expecting even distribution. Structural geology plays a crucial role, as clustering often aligns with fault lines, sedimentary formations, and deltaic regions that control hydrocarbon accumulation. The Niger Delta Basin exhibits high clustering, particularly in oil-rich zones such as Rivers, Bayelsa, Delta, and Akwa Ibom. Moderate clustering is observed in the Anambra Basin and Benue Trough, where emerging oil fields contribute to localized accumulations. In contrast, the Chad Basin shows a sparse and dispersed distribution, likely due to the early stage of petroleum exploration in the region.

4.12.2 Oil and Gas Density Analysis

The density plot (see figure 4.12c) provides a spatial representation of oil and gas deposit distribution in Nigeria. The colour gradient, ranging from blue to yellow, indicates varying densities, with yellow representing high-density zones and blue indicating low-density or absence of deposits.

High-density areas, shown in yellow and pink, correspond to significant oil and gas accumulations, likely aligning with known petroleum basins. Moderate-density regions, depicted in pink, may indicate emerging fields, prospective areas, or zones with less-known reserves. Low-density or absent zones, represented in dark blue, have little to no known oil or gas deposits, often corresponding to basement rock regions or areas with insufficient petroleum formation conditions.

The highly dense region aligns with the Niger Delta Basin, Nigeria’s most productive petroleum region. Other potential clusters may correspond to the Anambra Basin, Dahomey Basin, and the Chad Basin. The plot suggests a south-south to south-western alignment, consistent with the Niger Delta depositional system and fault-controlled oil accumulation. Some density regions extending inland could represent new exploration zones or secondary basins, such as the Benue Trough and Anambra Basin. The northern regions appear mostly blue, indicating minimal oil and gas presence. This aligns with geological expectations, as northern Nigeria primarily consists of basement rock formations, except for the Chad Basin, which has limited petroleum discoveries.

4.12.3 Oil and Gas Fry Analysis

The given fry plot oil and gas deposits in Nigeria (figure 4.12d) reveal important spatial trends and alignment. The data points form a diagonal structure, indicating a preferred spatial alignment of oil and gas deposits in Nigeria. The Elongated clustering along a central axis suggest that the distribution of oil and gas follows a linear geological trend. This aligns with fault-controlled petroleum systems, where hydrocarbons accumulate along major structural trend, controlled by the stratigraphic succession.

The Northwest to Northeast orientation observed in the plot is consistent with the Niger delta basin’s geological trend. The clustering reveals a primary depositional controlled tectonic and sedimentary processes that shaped oil and gas reservoirs. This orientation aligns with the strong clustering trend confirms that oil and gas deposits in Nigeria are not randomly distributed but instead follow major sedimentary basin alignment. The south-south and south-western regions, particularly the Niger Delta remain the dominant hydrocarbon zones. Some minor clusters towards the Northeast could be linked to the Chad Basin.

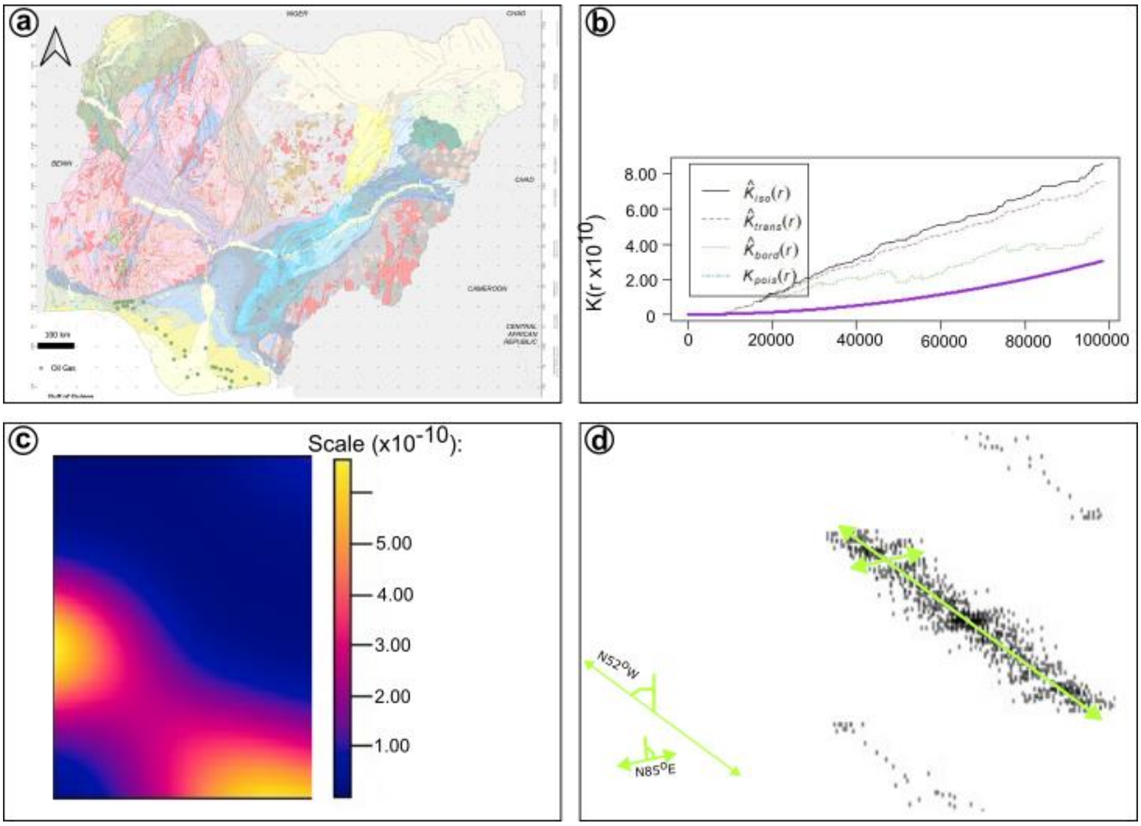

Figure 4.12a. point distribution of oil gas mineral deposits in Nigeria. b) K-function (Kiso, Ktrans, Kbord) are significantly above the theoretical Poisson function (Kpois) purple line, suggesting that oil and gas deposits in Nigeria are highly clustered. c) most prominent zones of high-density intensity with yellow colour, located around the Niger Delta Basin and Anambra Basin. d) Fry plot visualizes a trend alignment of N52^{0}W and N85^{0}E orientation and points appears to form a diagonal Structure indicating a preferred spatial alignment.

4.13 Phosphate Point Pattern Analysis

The point distribution of phosphate mineral deposits in Nigeria (see figure 4.13a) can be explained through their spatial patterns and the geological factors influencing their occurrences. These deposits exhibit a clustered distribution in regions with favourable geological formations, such as sedimentary basins or areas with specific rock types like phosphorites or marine sediments. Localized occurrences tend to appear in specific regions where geochemical conditions have allowed phosphate minerals to precipitate and accumulate over geological time. Phosphate deposits in Nigeria are primarily associated with sedimentary basins, notably the Sokoto Basin and the Benue Trough, which provide suitable environments for the formation of phosphate-rich sediments. Ancient marine transgressions and regressions play a crucial role in influencing these deposits, as phosphate commonly forms in shallow marine settings characterized by high biological productivity. Significant phosphate deposits are found in Sokoto State, particularly around the Sokoto Basin. Areas within or near this basin, including parts of Kebbi and Zamfara states, also host phosphate deposits. In addition, regions within the Benue Trough, such as Benue and Cross River states, are known for their sedimentary phosphate formations.

4.13.1 Phosphate K-Function Analysis

The provided plot (see fig 4.13b) illustrates the K-function analysis for phosphate mineral deposits in Nigeria, highlighting various spatial interaction models of the deposits over increasing distances. The Kiso(r) curve lies above the Kpois curve for most distances, indicating that phosphate deposits exhibit a clustered distribution rather than a random one, particularly at shorter to medium distances. If Kiso(r) were to align with Kpois, it would suggest a random spatial distribution. The steep slope of Kiso(r) at shorter distances implies stronger clustering at smaller spatial scales. As the distance increases, Kiso(r) continues to diverge from Kpois(r), indicating that clustering persists over a broader range of distances. The Ktrans curve presents a slightly different trend compared to Kiso, as it accounts for boundary effects within the dataset. The Kbord(r), represented by a dotted green line, displays irregular variations, which may reflect local heterogeneity or the presence of outliers in the data.

4.13.2 Phosphate Density Plot Analysis

The image (see figure 4.13c) presents a phosphate density plot that visually represents the spatial distribution and intensity of phosphate mineral deposits in Nigeria. High-density zones are highlighted by bright yellow areas, indicating regions with the highest concentration of phosphate deposits. These zones correspond to known phosphate-rich regions such as the Sokoto Basin, a significant area for phosphate mineralization, and the Benue Trough, a geological region recognized for its sedimentary deposits, including phosphate. In contrast, low-density zones are shown as dark blue areas, representing regions with sparse or no significant phosphate deposits. These areas may lack the geological conditions necessary for phosphate formation, such as specific rock types or appropriate depositional environments. The density plot reveals that phosphate deposits are not evenly distributed across Nigeria but instead exhibit spatial clustering influenced by geological formations, sedimentary basins, and historical deposition patterns. High-density zones identified on the plot represent priority targets for phosphate exploration and mining activities, as they offer economically viable concentrations of phosphate minerals.

4.13.3 Phosphate Fry Analysis

The fry plot for phosphate mineral deposits in Nigeria (see figure 4.13d) provides insights into the spatial distribution, alignment and clustering trends of phosphate deposit in Nigeria. the points are evenly distributed, forming clusters elongated patterns in certain areas. A significant concentration of points appears in the central and diagonal regions of the plot, indicative of strong spatial clustering. The points show a noticeable trend of alignment along certain directions, particularly in a diagonal (top-left to bottom-right) and horizontal pattern. This suggests that the phosphate mineral deposits are influenced by geological structures, such as faults or stratigraphic layers that control their alignment. Clustering of points reflect areas where phosphate deposits are densely located, which could correspond to regions of favourable geological conditions. The gaps between the clusters indicate regions with little to no phosphate mineralization, possibly due to unfavourable depositional environments. The diagonal and horizontal alignment of points suggests that the phosphate deposits are closely associated with linear geological features like fractures bedding planes or paleo channels. The clustering pattern may indicate depositional environments such as sedimentary basins where Phosphate minerals tend to accumulate in specific stratigraphic units along specific structural control.

The regions displaying clustering in the Fry plot correspond to phosphate-rich stratigraphic level in Nigeria. The Sokoto Basin is known for its phosphate-rich sedimentary deposits, and the clusters observed in the plot likely align with this region. The Benue Trough, a significant geological feature with phosphate potential, shows clustering patterns that may be associated with its faulted and folded zones, which are favourable for mineral accumulation. The Chad Basin also presents phosphate prospects, with some of the scattered clusters in the plot potentially corresponding to this region. Exploration efforts should prioritize areas exhibiting clustering and follow the alignment trends indicated by the Fry plot. These regions are the most promising for hosting economically viable phosphate mineralization and represent key targets for further investigation and resource development.

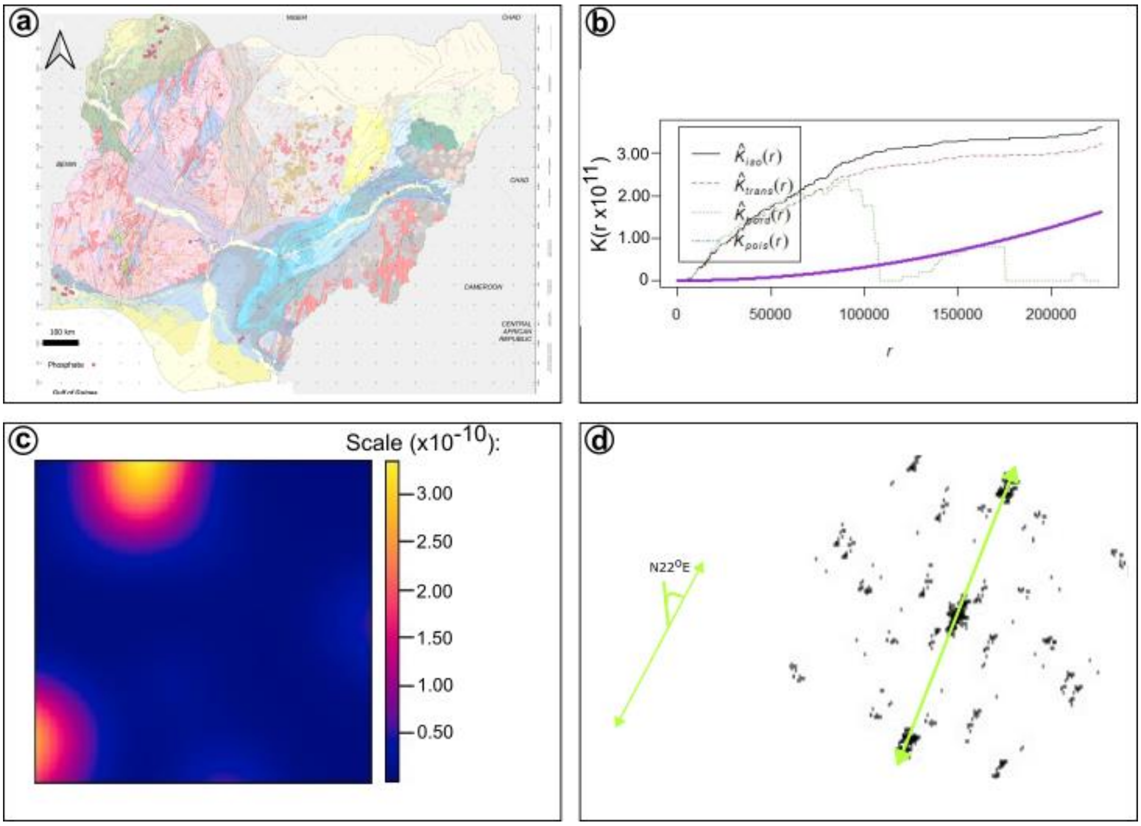

Figure 4.13 a) point distribution of phosphate mineral deposits in Nigeria. b) Kiso curve lies above the Kpois curve for most distances, indicating that phosphate deposits exhibit a clustered distribution rather than a random one. c) most prominent zones of high-density intensity with yellow colour, located around the Sokoto Basin and Benue Trough region. d) Fry plot image visualizes a significant concentration of points in the Sokoto Basin and Benue Trough regions of the plot, indicative of strong spatial clustering. The points show a trend alignment of N22^{0}E along certain directions, particularly in a diagonal (top-left to bottom-right).

4.14 Tungsten Point Pattern Analysis

The point of distribution of tungsten mineral deposits in Nigeria (see figure 4.14a) provides insights into the spatial patterns, patterns, alignment, clustering and regional locations of tungsten occurrences. Tungsten deposits tend to form clusters in areas with favourable geological conditions. The clusters may indicate regions with known tungsten bearing geological formations such as granitic intrusion or hydrothermal vein systems. Tungsten deposits may show alignment along specific geological structures, such as fault lines, shear zones, or igneous contracts. If points are distributed linearly, it suggests control by tectonic processes or mineralization zones. Tungsten deposits are rarely uniformly distributed, instead, they occur in specific mineral belts or zones with concentrated occurrences. Random or scattered points may represent isolated occurrence while dense clusters are likely tied to significant mineralized zones. tungsten is associated with granitic rocks and pegmatite regions like Kano, Kaduna, and part the Jos Plateau are key areas where tungsten bearing minerals such as wolframite are found. Tungsten deposits in Nigeria are often linked to regions within land tantalum mineralization since they share similar geological controls particularly in pegmatite and granitic environments. Alignment along fault zones or structural belts indicates potential pathways for mineralizing fluids and should be targeted for exploration.

4.14.1 Tungsten K-Function Analysis

The plot (see figure 4.14b) gives different estimation of the k-function for tungsten mineral deposit in Nigeria. The Empirical K-functions (Kiso, Ktrans, Kbord) are all above the Poisson Expectation curve kpois, this suggest that the tungsten deposits are more clustered than would be expected under complete spatial Randomness. The isotropic correction Kiso (solid black line) is the highest among the estimations, indicating a strong clustering pattern. The border correction (Kbord) (dotted green line) is slightly lower which may reflect edge effect in the data set.

4.14.2 Tungsten Density Analysis

The tungsten density plot (see figure 4.14c) visually represents the spatial distribution and intensity of tungsten mineral deposits in Nigeria. The colour gradient indicates the density of deposits, with bright yellow regions representing areas of highest density, transitioning through red and pink to dark blue regions, which signify the lowest density.

The bright yellow zones in the plot highlight regions with the highest concentration of tungsten deposits. These clusters suggest areas with favourable geological conditions for tungsten mineralization, potentially corresponding to known mineral-rich regions in Nigeria, such as parts of the Jos Plateau or Central Nigeria Basement Complex, which are historically known for hosting tungsten-bearing minerals like wolframite.

The dark blue areas indicate regions with sparse or no significant tungsten deposits. These areas likely lack the geological structures or mineralization conditions necessary for tungsten formation, such as specific rock types or tectonic settings.

The distribution pattern in the plot suggests that tungsten mineral deposits in Nigeria are not uniformly distributed but instead show distinct clustering. This spatial clustering could be influenced by geological factors such as fault lines, tectonic activity, or historical magmatic processes. The high-density zones represent priority areas for exploration and mining activities, as they are more likely to yield economically viable concentrations of tungsten. Further analysis of geological maps and field studies would help correlate these clusters with specific geological formations, refining exploration efforts for tungsten mineralization in Nigeria.

4.14.3 Tungsten Fry Analysis

The fry plot (see figure 4.14d) provides insights in spatial point pattern analysis to detect the presence of preferred orientations or alignments in the spatial distributions of tungsten mineral deposits. The plot shows that a high-density concentration of points around the centre suggesting a strong spatial clustering of tungsten deposits. The Elongated spread of points indicates preferential alignment of the deposits, suggesting a structural or geological control. If the fry plot displays an elliptical or linear elongation, it may imply fault-controlled vein-hosted mineralization. The Fry plot analysis of tungsten deposits reveals a single dominant trend alignment at N56°W, indicating a strong structural control on the spatial distribution of these deposits. This alignment suggests that tungsten mineralization is influenced by regional tectonic features such as faults, shear zones, or lithological boundaries. The observed trend provides insights into the geological processes that have contributed to the localization of tungsten within the study area. A non-random distribution suggests that tungsten mineralization in Nigeria follows tectonic or lithological controls. Exploration efforts should target the main orientation trends revealed by the plot.

The high-density concentration of points around the centre correlate with the North-central Nigeria, key states with significant tungsten occurrence includes Nasarawa, Kaduna, Plateau and part of Bauchi. These are part of the Nigeria younger granite province, which is associated with pegmatite-hosted tungsten. The Low-density concentration of tungsten Deposit on the fry plot correlate with the southwestern region indicate that future exploration should focus on high-density region along these structural trends.

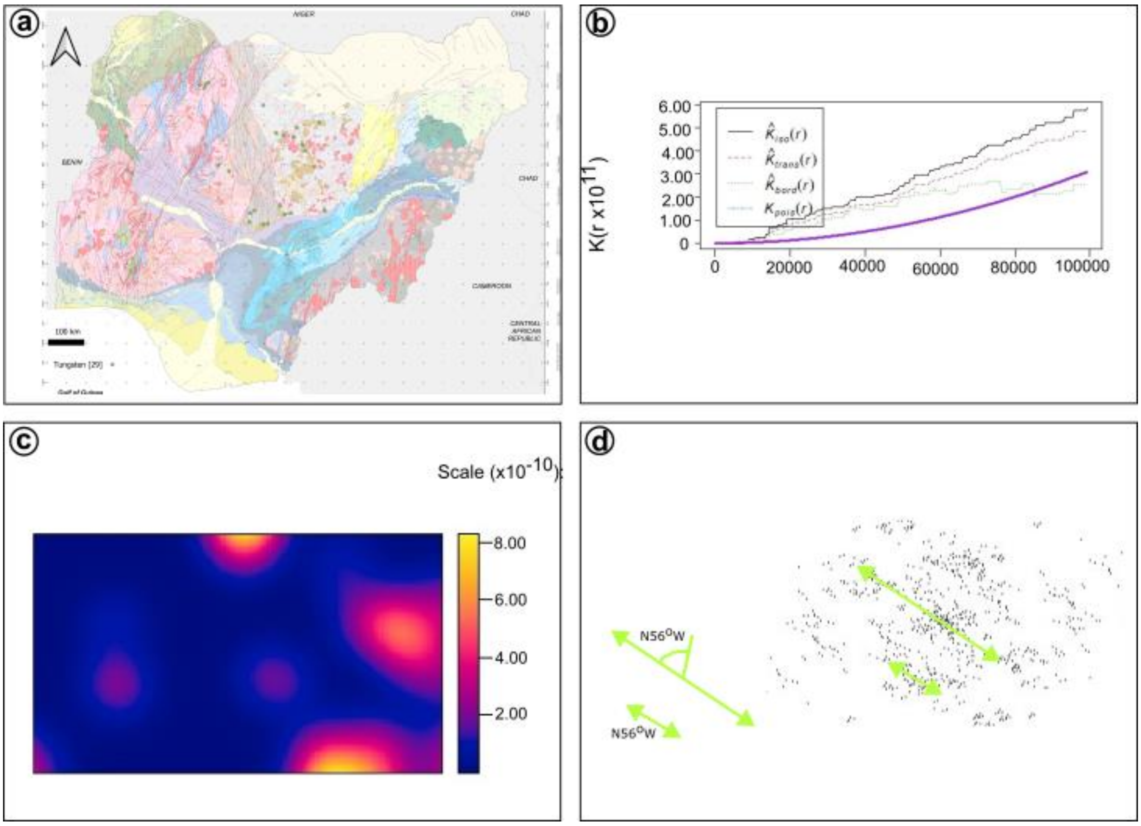

Figure 4.14 a) point distribution of tungsten mineral deposits in Nigeria. b) K-functions Kiso, Ktrans, Kbord are all above the Poisson Expectation curve kpois, suggest that the tungsten deposits are more clustered than would be expected under complete spatial randomness. the border correction (Kbord) dotted green line is slightly lower which may reflect edge effect in the data set. d) Fry plot image visualizes a spatial trend of tungsten deposits in Nigeria to follows a trend alignment of N56°W with an Elongated spread of points.

5. DISCUSSION

5.1 A Synthesis of the results

5.1.1. Gold-Silver Deposits Genesis

Gold mineralization in Nigeria exhibits the highest point occurrence among various mineral deposits, as depicted in the geological map (see figure A.1, in annex). This widespread distribution is largely controlled by shear zones, faults, and magmatic intrusions, which provided pathways for hydrothermal fluids responsible for gold deposition. Gold mineralization in Nigeria is primarily associated with the Precambrian Basement Complex (PBC) particularly within the schist belts. The genesis of gold mineralization in Nigeria is closely linked to structural features and specific rock types, as illustrated in the geological map (see figure A.1, in annex). Gold-silver occurrences are predominantly concentrated in the western and northwestern regions in the Basement Complex, where shear zones and faults provide essential pathways for hydrothermal fluids transporting gold. These structural features, including extensional and compressional faults, played a crucial role in creating open spaces and traps for gold deposition.

Gold mineralization is strongly associated with late to syntectonic granites and syntectonic granite within the (PBC). Deposits are primarily concentrated within two distinct lithological units on the map. The Paleoproterozoic banded gneiss (PBG) lithology consists of undifferentiated gneiss, banded gneiss, local peraluminous gneiss, and schist, while the Paleoproterozoic migmatite gneiss (PMG) lithology comprises undifferentiated migmatitic gneiss, with ages ranging from the Archean to the Paleoproterozoic. Additionally, syntectonic gabbro-granite intrusive complexes show some correlation with gold occurrences, suggesting their involvement in remobilizing and enriching gold deposits along shear zones. The presence of undifferentiated felsic to alkaline volcanic suites indicates a possible connection to ancient magmatic and hydrothermal activity. The dense clustering observed in the results of the Fry plot analysis for gold indicates that favourable geological structures, such as shear zones, faults, and late to syntectonic granites, play a significant role in gold mineralization. This suggests that exploration efforts should be focused on fault lines within these clusters, as they are likely to host gold deposits due to their structural controls on mineralization.

5.1.2. Coal Deposits Genesis

The coal deposits in Nigeria, represented by the pink dots on the map (see figure A.2) are predominantly concentrated in the southeastern and south-central regions of the country. These deposits are closely associated with sedimentary basins, particularly the Anambra Basin, the Benue Trough, and other regions characterized by extensive sedimentary sequences. The spatial distribution suggests that coal mineralization is largely confined to these sedimentary environments, where conditions for organic matter accumulation and preservation were favourable. The distribution of coal deposits in Nigeria, as depicted on the map (see figure A.2) aligns with specific lithological units from the Late Cretaceous period. These include the CUC lithology of the Nsukka Formation, which consists of sandstone, coal, and mudstone; the CAC lithology of the Ajali Formation, characterized by shale, sandstone, and coal; and the CNL lithology of the Nkporo Group. These formations collectively define the geological settings in which coal deposits are found across the country.

The geological genesis of coal in Nigeria is primarily linked to sedimentary processes during the Cretaceous period. Coal formation occurs in deltaic, fluvial, and swamp environments where organic material, such as plant debris, accumulates under anoxic conditions. Over time, burial and compaction of these organic materials, coupled with geothermal heat and pressure, led to the formation of coal seams. The spatial distribution of coal suggests a strong association with stratigraphic features, sedimentation patterns and subsidence rates. The presence of concealed faults and shear zones could also be significant during sedimentation processes. The trend alignment observed in the Fry plot analysis of coal deposit confirms that coal mineralization is primarily influenced by favourable sedimentary conditions that facilitate coal formation, along with structural controls within a localized region. Therefore, exploration and mining activities should be concentrated along the main trend alignments identified in the Fry analysis, as these areas are most likely to host significant coal deposits.

5.1.3. Beryllium Deposits Genesis

The Beryllium mineral deposits in Nigeria (see figure A.3) are primarily concentrated in the central, north-central of the Basement Complex and the Benue Trough region. Benue Trough is a Cretaceous rift basin known for its complex tectonic structures, it hosts several mineral deposits, including beryllium. The deposits within the central and north-central areas are closely associated with syntectonic granites and undifferentiated alkaline granites. These deposits are often located near major fault lines and shear zones, indicating structural control in their formation. The presence of gabbro-granite intrusive complexes in some areas suggests that magmatic differentiation processes may have contributed to Beryllium enrichment.

The strong correlation between Beryllium deposits and syntectonic granites suggests a primary magmatic origin. Pegmatites derived from granitic intrusions are known to host Beryllium-bearing minerals like beryl and phenakite. Additionally, the gabbro-granite intrusive complex could have played a role in mineralization through fractionation processes. The alignment of deposits along shear zones and faults highlights the role of post-magmatic hydrothermal processes in concentrating Beryllium. Early extensional shear zones and rift-related faults provided fluid pathways for mineralization, enabling Beryllium to be leached from granitic sources and re-deposited in structurally favourable locations.

Overall, the Beryllium mineralization in Nigeria, namely those emplaced in the basement, is primarily magmatic, with significant tectonic and hydrothermal influences that controlled its distribution and concentration. The combination of granitic intrusions, structural deformation, and fluid movement played a critical role in forming these economically significant deposits. The Fry plot analysis for beryllium provides clear evidence that mineralization processes within the Central, North-Central, and Benue Trough regions are strongly influenced by favourable geological structures. These structural controls play a key role in the formation of beryllium deposits. Therefore, exploration activities should be directed along the identified trend alignments to maximize the chances of discovering significant beryllium mineralization.

5.1.4. Barium Deposits Genesis

The distribution of barium mineral deposits in Nigeria, as seen in the geological map (see figure A.4) reveals a strong correlation with specific geological formations (Benue Trough). Geologically, some barium deposits appear closely associated with syntectonic granites and gabbro-granite intrusive complexes within the basement complex, which may have served as sources for mineralizing fluids. Additionally, some occurrences are located near undifferentiated felsic to alkaline volcanic suites, suggesting a possible magmatic or hydrothermal origin. The influence of tectonic activity is further evident as many of these deposits are found within regions containing concealed faults and shear zones. The presence of early and late shear zones in proximity to barium mineralization points to multiple mineralization events over geological time.

Regionally, the deposits are unevenly distributed, with noticeable clusters in the north-central and southeastern parts of Nigeria. These areas correspond to regions of intense deformation and magmatic activity, reinforcing the idea that tectonic reactivation played a crucial role in concentrating barium-rich fluids. The overall geological setting suggests that barium mineralization in Nigeria is primarily hydrothermal, with fluids migrating along fault and shear zones. Some deposits may also have formed through magmatic differentiation associated with syntectonic granites, while others could be linked to volcanic exhalative processes in felsic to alkaline volcanic terrains. The Fry analysis of barium deposits suggests that mineralization processes in the North-Central and South-East regions are strongly influenced by geological structures that control barium deposition. Therefore, exploration efforts should be concentrated along the trend alignments identified in the analysis, as these areas are most favourable for barium mineralization.

5.1.5. Limestone and Marble Deposits Genesis

The distribution of limestone-marble mineral deposits in Nigeria, as shown in the geological map (see figure A.5), is closely associated with specific lithological units and tectonic structures. The deposits are primarily concentrated in regions underlain by sedimentary and metamorphic rock formations within the Benue Trough and Basement Complex, indicating a strong link to geological processes such as sedimentation, regional metamorphism, and magmatic intrusion. Some marble deposits are particularly associated with syntectonic granites and gabbro-granite intrusive complexes, suggesting that magmatic activities may have influenced their formation through contact metamorphism. Regionally, the deposits are distributed across central and southeastern Nigeria, with noticeable clusters along tectonic boundaries. Additionally, the limestone deposits occur within sedimentary basins, indicating their origin from marine carbonate deposition before subsequent metamorphism. The genesis of limestone-marble deposits in Nigeria is largely sedimentary and metamorphic respectively as shown in the point distribution. Limestone forms through the accumulation of carbonate sediments in ancient marine environments.

5.1.6. Iron Deposits Genesis

The distribution of iron mineral deposits in Nigeria, as depicted in the geological map (see figure A.6), indicates a strong relationship with specific lithological units and tectonic structures. Iron deposits are widely distributed across central, western, and southeastern Nigeria, where Precambrian basement rocks, particularly banded iron formations (BIF). BIF occur primarily within the Precambrian basement rocks, particularly in the schist belts and meta-sedimentary sequences. These formations are characterized by alternating layers of iron-rich minerals such as hematite and magnetite, along with silica-rich minerals like quartz, which were deposited under ancient marine conditions. The most significant occurrence is the Itakpe iron ore deposit in Kogi State, which serves as Nigeria's primary source of iron ore and is part of the Proterozoic Metasedimentary Belt. It consists mainly of magnetite, hematite, and quartz. Another notable deposit is the Agbaja iron ore in the Lokoja area, also in Kogi State, which, although not a classic BIF, contains high-phosphorus iron ore. The schist belts in the Turen-Kogi-Igarra region, spanning Kogi and Edo States, contain BIF occurrences associated with quartzite and ferruginous rocks. Additional occurrences have been reported in the Gwoza-Biu-Maiduguri Belt of Borno State, within the meta-sedimentary sequences of northeastern Nigeria. The Obajana and Okene areas in Kogi State also contain iron-rich formations similar to those in Itakpe, with economic significance.

These BIF formed during the Precambrian period, particularly in the Paleoproterozoic era, under anoxic marine conditions and were later influenced by tectonic and metamorphic events, including the Pan-African Orogeny. Their economic importance lies in their role as a significant source of iron ore, essential for steel production, with the Itakpe mine remaining the largest and most developed deposit supporting both local and potential international industries. The dense clustering observed in a specific region of the Fry plot analysis for iron deposits suggests that mineralization processes are strongly influenced by favourable deformation processes and stratigraphic controlled. This indicates that structural factors play a crucial role in the localization of iron ore. Therefore, exploration activities should be focused on the trend alignments identified in the Fry analysis, as these areas are most likely to host significant iron mineralization.

5.1.7. Base-Metal Deposits Genesis

The distribution of base-metal mineral deposits in Nigeria (see figure A.7) is strongly influenced by depositional environment within the Benue trough. These deposits are primarily concentrated within southeastern Nigeria. Some of these deposits may have also formed through sedimentary exhalative processes in volcanic and sedimentary environments in the Benue Trough.

5.1.8. Lithium - Tantalum Deposits Genesis

The distribution of lithium-tantalum mineral deposits in Nigeria, as shown in the map (see figure A.8), is primarily concentrated in the Basement Complex, central and western parts of the country. These deposits are closely associated with syntectonic granites, gabbro-granite intrusive complexes, and undifferentiated alkaline granites, suggesting a strong genetic link to magmatic and hydrothermal processes. The alignment of these deposits along major fault zones and shear structures highlights the structural control on mineralization, with key faults and shear zones serving as conduits for mineralizing fluids. The geological genesis of lithium-tantalum mineralization in Nigeria is largely linked to the emplacement of rare-metal granites and pegmatitic intrusions. These pegmatites, which are rich in lithium-bearing minerals such as spodumene and lepidolite, as well as tantalum-rich minerals like columbite-tantalite, are typically associated with late-stage magmatic differentiation. The crystallization of lithium-tantalum pegmatites occurred in structurally favourable zones, where extensional shear zones and faults facilitated the intrusion and emplacement of these mineralized bodies.

Mineralization of lithium and tantalum in Nigeria is controlled by a combination of magmatic and hydrothermal processes. The initial concentration of these elements occurred through magmatic differentiation, where residual fluids enriched in lithium, tantalum, and other rare metals crystallized in pegmatites. Subsequent hydrothermal alteration and remobilization further enhanced the grade and distribution of these minerals. The association of these deposits with extensional shear zones, post-rift faults, and concealed thrust shear zones indicates that tectonic reworking played a significant role in redistributing and concentrating lithium-tantalum mineralization. Overall, the lithium-tantalum deposits of Nigeria are structurally controlled and genetically linked to evolved granitic intrusions and pegmatitic systems. The interplay of magmatic processes, structural deformation, and hydrothermal activity has resulted in the formation of significant lithium-tantalum resources, making Nigeria an important location for rare-metal mineralization in West Africa.

The mineral deposits are primarily located within two distinct lithological units on the map. The PBG lithology comprises undifferentiated gneiss, banded gneiss, local peraluminous gneiss, and schist, while the PMG lithology consists of undifferentiated migmatitic gneiss, both lithologies are dated Archean Paloeproterozoic. Result from the Fry analysis of the lithium-tantalum deposit indicate a significant degree of deposit clustering within these lithologies. This suggests a strong spatial correlation between the deposits and these rock units. Based on this clustering pattern, future exploration efforts should be concentrated along the main trend alignment identified in the Fry analysis, as it represents the most prospective zone for further mineralization.

5.1.9. Talc Deposits Genesis

The distribution of talc mineral deposits in Nigeria, as depicted in the map (see figure A.9), is widespread but concentrated primarily in the central and western regions of the country. Talc deposits are predominantly hosted within two major lithological units on the map, in the Precambrian Basement Complex. The PBG lithology comprises undifferentiated gneiss, banded gneiss, local peraluminous gneiss, and schist, while the PMG lithology consists of undifferentiated migmatitic gneiss, both lithologies are dated Archean-Paleoproterozoic. These deposits are closely associated with major shear zones, fault systems, and specific geological formations, particularly areas characterized by the presence of syntectonic granites and gabbro-granite intrusive complexes. The spatial alignment of talc occurrences with key structural features suggests a strong structural control on their formation, with major fault zones and shear zones acting as pathways for mineralizing fluids.

The geological genesis of talc deposits in Nigeria is mainly linked to the hydrothermal alteration of ultramafic and mafic rocks, particularly in regions affected by intense tectonic activity. Talc is primarily formed through the metamorphic transformation of magnesium-rich rocks, such as serpentinites, dolomites, and tremolite schists, under the influence of hydrothermal fluids. These alteration processes occur in tectonically active zones where fluids rich in silica, carbon dioxide, and magnesium interact with host rocks, resulting in the replacement of primary minerals by talc. The association of talc deposits with major faults, shear zones, and granitic intrusions further supports a metamorphic-hydrothermal origin. Mineralization of talc in Nigeria is predominantly controlled by metasomatic and hydrothermal processes, which are facilitated by regional deformation and magmatic activity. The interaction between hydrothermal fluids and ultramafic rocks in structurally deformed zones leads to the recrystallization of talc, often accompanied by accessory minerals such as chlorite, tremolite, and magnesite. The presence of talc along early extensional shear zones, concealed faults, and low-angle thrust shear zones indicates that structural reworking played a crucial role in the localization and concentration of talc mineralization.

The Fry analysis of talc deposits reveals a significant clustering of occurrences within these lithologies, indicating a strong spatial relationship between the deposits and these rock units. To maximize exploration success, future activities should be strategically focused along the main trend alignment identified in the Fry analysis, as it represents the most promising zone for further mineralization. Overall, the talc deposits of Nigeria seem to be structurally controlled and genetically linked to the metamorphism of magnesium-rich protoliths under hydrothermal conditions. The combination of tectonic deformation, hydrothermal alteration, and metasomatic replacement processes possibly associated to shear zones has resulted in the formation of significant talc occurrences, making Nigeria an important source of high-quality talc mineralization in West Africa.

5.1.10. Copper Deposits Genesis

The distribution of copper mineral deposits in Nigeria, as represented in the map (see figure A.10), shows that occurrences are mainly concentrated in the central and northern parts of the country. The deposits appear to align with major fault zones and shear structures, suggesting a strong structural control on their emplacement. These deposits are closely associated with regions containing syntectonic granite, gabbro-granite intrusive complexes, and undifferentiated felsic to alkaline volcanic suites. The geological genesis of copper mineralization in Nigeria is primarily linked to magmatic and hydrothermal processes. Copper deposits are commonly found in areas with extensive igneous activity, particularly in regions with syntectonic granitic intrusions. These intrusions likely provided the heat necessary to drive hydrothermal circulation, leading to the deposition of copper-bearing minerals in structurally favourable zones such as faults and fractures. Additionally, some of the copper mineralization may be associated with volcanogenic massive sulphide systems, where copper-bearing sulphide minerals precipitate from hydrothermal fluids in volcanic environments.

The mineral deposits are primarily concentrated within three distinct lithological units on the map. The PBG lithology consists of undifferentiated gneiss, banded gneiss, local peraluminous gneiss, and schist, while the PMG lithology comprises undifferentiated migmatitic gneiss within the Basement Complex, with ages ranging from the Archean to the Paleoproterozoic. The third lithological unit is hosted within the Benue Trough, specifically in the CAP1, CAP2, and CAP3 lithologies, which consist of carbonaceous shale, mudstone, shaly limestone, and coal seams, all dated to the Late Cretaceous period. These lithological units provide the primary geological framework for mineralization in the region, influencing deposit distribution and exploration potential. Tectonic structures, including early extensional shear zones, thrust faults, and late-stage shear zones, played a significant role in controlling the localization of copper mineralization. These structural features created conduits for hydrothermal fluids, allowing for the precipitation of copper minerals in fractured and altered host rocks. The presence of copper deposits along major fault zones further supports the idea that mineralization is structurally controlled and related to fluid migration during regional deformation events.

5.1.11. Manganese Deposits Genesis

The distribution of manganese mineral deposits in Nigeria, as shown in the map (see figure A.11), indicates a widespread but structurally controlled occurrence. The deposits are primarily concentrated in the central and northeastern regions, aligning closely with major fault zones and shear structures. These deposits are associated with a variety of geological formations, including syntectonic granites, gabbro-granite intrusive complexes, and undifferentiated felsic to alkaline volcanic suites, suggesting a strong link between manganese mineralization and tectonic-magmatic processes. Manganese deposits are primarily located within the lithological units on the map. The PBG lithology comprises undifferentiated gneiss, banded gneiss, local peraluminous gneiss, and schist, while the PMG lithology consists of undifferentiated migmatitic gneiss, both within the basement complex with ages ranging from the Archean-Paleoproterozoic. The third lithological unit is hosted within the Gundumi Formation, specifically in the CIG1 lithology, which consists of feldspathic sandstone, undifferentiated sandstone, claystone, limestone, and conglomerate, all dated to the Late Cretaceous. Additionally, a few deposits are found within the NS lithology, which comprises undifferentiated volcano-sedimentary supracrustal units aged from the Early to Mid-Neoproterozoic.

The genesis of manganese mineralization in Nigeria is primarily associated with sedimentary and hydrothermal processes, as well as magmatic influences in structurally deformed regions. Manganese deposits commonly occur in sedimentary basins where chemical precipitation from seawater or lacustrine environments leads to the formation of manganese-rich layers. Additionally, hydrothermal activity along faulted and fractured zones has contributed to manganese enrichment through fluid circulation and subsequent precipitation. The role of tectonism in manganese mineralization is evident from its spatial association with fault zones, early extensional shear zones, and thrust faults. These structural features facilitated fluid movement and mineral deposition, leading to the concentration of manganese ore in favourable host rocks. Some manganese occurrences are also linked to volcanic-associated deposits, where hydrothermal fluids leached manganese from surrounding rocks and re-deposited it in structural traps. The results from the Fry analysis of manganese deposits confirm a significant clustering of occurrences within these lithologies, indicating a strong spatial correlation between the deposits and the geological units. To maximize exploration success, future activities should be strategically focused along the main trend alignment identified in the Fry analysis, as it represents the most prospective zone for further mineralization.

5.1.12. Oil-Gas Deposits Genesis

The distribution of oil and gas deposits in Nigeria is largely influenced by stratigraphic factors, particularly the presence of sedimentary basins and fault-controlled traps. The oil and gas deposits marked as green dots on the map (see figure A.12) are primarily concentrated in the southern region, especially in the Niger Delta Basin, where fault zones and rift-related structures have played a crucial role in hydrocarbon migration and accumulation. The post-rift and early rift faults (represented in different shades of blue and pink) indicate areas of structural traps that facilitate the concentration of hydrocarbons. Oil and gas deposits are primarily found within the QCM and QAL lithologies of the Niger Delta Basin, which consist of recent alluvial sediments and longitudinal desert dune sands, both dated to the Quaternary period. These lithological units serve as key reservoir rocks, influencing the distribution and accumulation of hydrocarbon resources in the region. The results from the Fry analysis of oil and gas deposits confirm a significant clustering of hydrocarbon reservoir rocks within these lithologies, indicating a strong spatial relationship between the deposits and the geological units. To optimize exploration success, future activities should be strategically focused along the main trend alignment identified in the Fry analysis, as it represents the most prospective zone for hydrocarbon accumulation.

Geologically, the oil and gas deposits are confined to sedimentary basins, whereas the northern and central regions**,** dominated by igneous and metamorphic rocks, lack significant hydrocarbon potential. In contrast, the Niger Delta Basin, characterized by a deltaic depositional environment rich in organic material, has provided suitable conditions for hydrocarbon formation.

The rift and basin evolution of Nigeria also contributed to the current distribution of oil and gas resources. The fault-concealed and rift-related structures suggest that extensional tectonic processes played a major role in the development of sedimentary basins that later served as hydrocarbon reservoirs. The early extensional shear zones facilitated the formation of these basins, allowing for the accumulation of organic-rich sediments over millions of years, which later transformed into oil and gas under heat and pressure. Among the sedimentary basins, the Niger Delta Basin is the most prolific, accounting for the vast majority of Nigeria's oil and gas production. Other basins, such as the Benue Trough and Chad Basin**,** hold some potential for hydrocarbons but remain underdeveloped compared to the Niger Delta. The presence of faults and has played a crucial role in forming and trapping hydrocarbons within these basins.

5.1.13. Phosphate Deposits Genesis

The geological genesis and spatial distribution of phosphate deposits in Nigeria seem to be influenced by lithological associations. Phosphate occurrences, represented as red dots on the geological map (see figure A.13), are scattered. Phosphate mineralization in Nigeria can be attributed to both sedimentary and magmatic processes, in the sedimentary environment phosphate deposits are primarily found within the TGW1 and TGW2 lithologies of the Sokoto Basin, which consist of laterite, sandstone, clay, and undifferentiated sand and clay, respectively, with ages ranging from the Paleogene to Neogene. Additionally, the QCS lithology of the Anambra Basin and Benue Trough comprises fine- to coarse-grained sand with minor lignite, dated to Neogene–Quaternary and Cretaceous respectively. These lithological units play a crucial role in controlling the distribution and occurrence of mineral deposits within the region. These deposits formed through chemical precipitation in marine settings, often influenced by upwelling currents that brought phosphate-rich waters to the surface. In contrast, phosphate mineralization in the crystalline Basement Complex suggests an association with igneous and metamorphic processes. The presence of phosphate-bearing alkaline granites, gabbro-granite complexes, and felsic volcanic suites indicates magmatic differentiation and possible hydrothermal alteration as key processes in phosphate formation.

The distribution of phosphate deposits in Nigeria highlights the strong influence of stratigraphy on the mineralization. The highest phosphate potential exists in structurally complex regions such as the Sokoto Basin in the northwest, the Benue Trough in central Nigeria, and the Cross River Basin in the southeast. These areas, characterized by sedimentary succession basins should be prioritized for further exploration.

5.1.14. Tungsten Deposits Genesis

The genesis and spatial distribution of tungsten mineral deposits in Nigeria, as represented by green dots on the map (see figure A.14), are closely associated with specific lithological units. Tungsten occurrences are mainly concentrated within regions dominated by syntectonic granites, gabbro-granite intrusive complexes, and undifferentiated alkaline granites. Tungsten mineral deposits are primarily located within the lithological units on the map. The PBG lithology comprises undifferentiated gneiss, banded gneiss, local peraluminous gneiss, and schist, while the PMG lithology consists of undifferentiated migmatitic gneiss, both within the Basement Complex with ages ranging from the Archean to the Paleoproterozoic. These lithologies suggest that the tungsten mineralization is genetically linked to magmatic processes, particularly those associated with granitic intrusions and hydrothermal activity. Tungsten is typically found in pegmatitic and hydrothermal veins, often within or adjacent to granitic intrusions, where fluids rich in tungsten, tin, and other rare metals migrate through fractures and faults.

The spatial distribution of tungsten deposits in Nigeria aligns strongly with major fault zones and shear zones. These structural features likely played a critical role in providing pathways for hydrothermal fluid circulation, which facilitated the transport and deposition of tungsten-bearing minerals such as scheelite and wolframite. Many of the tungsten occurrences are found within the Pan-African orogenic belt, a region known for its extensive deformation, metamorphism, and intrusion of granitic bodies. The interaction between these magmatic intrusions and regional structures created favourable conditions for tungsten mineralization. The presence of tungsten deposits near shear zones and faults suggests a strong structural control on their formation. Shear zones act as fluid conduits, allowing mineralizing fluids to concentrate within fractures and faults, leading to the precipitation of tungsten minerals. The map shows that tungsten deposits are particularly associated with early extensional shear zones and concealed faults, which likely provided secondary structural traps for mineral deposition. Additionally, regions with late-stage deformation and magmatic activity would have facilitated remobilization and enrichment of tungsten minerals within the existing rock formations.

5.2. Generalization of the results

5.2.1. Result summary

The analysis indicates that mineral occurrences are not randomly distributed but instead align with major geological structures such as fault zones, shear zones, geological units and lithological boundaries. This suggests a strong correlation between mineralization, stratigraphy, magmatic and tectonic features, reinforcing the role of structural geology in ore formation. The spatial clustering of minerals highlights regional concentrations, with gold, base metals, and copper predominantly found in the northwest and southwest regions, aligning with known metallogenic belts associated with Precambrian basement rocks and shear zones. Beryllium, barium, and iron are widespread in the northeast and northwest, reflecting their association with Pan-African orogenic structures and pegmatite-hosted mineralization. Lithium-tantalum and phosphate deposits exhibit strong presence in the northeast and northwest, while manganese and talc cluster in the northwest and southwest, suggesting control by lithological contacts magmatic processes and metamorphic processes. The concentration of oil and gas coal and phosphate corresponds with sedimentary basin development, while tungsten occurrences in the northwest align with granitic intrusions and shear zones.

Directional trends identified in the Fry analysis suggest that mineralization follows key tectonic features such as the Benue Trough as seen in (Table 5.1) which influences hydrocarbon and phosphate deposits, the Kibaran and Pan-African shear zones, which are closely associated with gold, base metals, and lithium-tantalum occurrences, and the Younger Granite Complexes, which play a role in the distribution of beryllium and tungsten. These alignments confirm that Nigeria's mineralization patterns are structurally controlled, emphasizing the genetic link between ore deposition and the region's tectonic evolution. The implications for mineral exploration are significant, as the clustering patterns revealed by Fry analysis help identify priority zones for prospecting. The concentration of deposits in structurally complex regions suggests that future exploration efforts should focus on high-density mineral zones, particularly where intersecting fault systems enhance ore-forming processes. By integrating structural analysis into exploration strategies, geologists can improve predictive models and enhance the discovery of new mineral deposits, reinforcing the importance of tectonic features in the genesis of Nigeria's ore deposits.

Table 5.1. Results from Fry analysis trend alignment projection for Nigeria commodities.

No.	Minerals	NE	NW	SW	SE
1	Gold	32			
2	Coal	50			
3	Beryllium	40	56		
4	Barium	20	65		
5	Limestone-Marble	35	78		
6	Iron	60	15		
7	Base-metal	38	55		
8	Lithium-tantalum	42	38		
9	Talc	58	20		
10	Copper	52			
11	Manganese	68	65		
12	Oil gas	52	85		
13	Phosphate	22			
14	Tungsten	56			

5.2.2. Mineral deposit types summary

The recognized mineral deposit types in Nigeria have been classified according to a structured mineral systems approach. The mineral deposit domain map (Figure 2.8) illustrates the spatial distribution of these deposits within specific mineral deposit categories. These classifications are framed based on the influence of structural and tectonic settings, which controlled the fluid and magma systems responsible for mineralization.

This classification system reflects the development of major metallic deposit types in Nigeria. It categorizes mineralization by metal and fluid sources, as well as fluid/magma associations (See table 5.2) covering key deposit types such as Au, Li, Pb-Zn-Cu-Ba, and Sn-Nb-Ta. Additionally, it considers emplacement conditions, geological age, and tectonic settings.

Table 5.2 Mineral Deposit Types Summary

Mineralization Provenance	Magmatic			**Hydrothermal-magmatic**		
Mineralization System	Rare metal granitic mineral systems		Orthomagmatic mafic/ultramafic related mineral systems	IOCG mineral systems	Au-Ag±Te-base metal veins	Volcanic associated massive sulphides
Fluid/Magma System	Felsic magma		Ultramafic to mafic magma	Post-orogenic magmatic fluids mixed with surface waters	Fluids from felsic-hosted granites	Moderate temperature volcanic exhalative fluids
Deposit Type	LCT-Be-Ca-Ta-Sn pegmatite	Peralkaline Ta-Zr-Nb-REE granites and pegmatite	Intrusive related Ni-Cu-PGE deposits	Cu, Au, Fe, REE magmatic and hydrothermal deposits	Low temperature, high salinity epithermal Au-Ag-Te-Zn-Pb-Cu	Massive sulphide hosted Zn-Pb-Ag-Au-Cu
Age	Early Palaeozoic	Jurassic	Middle to Late Palaeozoic	Late Neoproterozoic to Early Palaeozoic	Late Neoproterozoic to Early Palaeozoic	Middle Neoproterozoic
Geological and Tectonic Association	Rare metal granitic mineral systems are associated with late to post-orog. felsic magm., which has formed reduced peral. pegmatite-hosted deposits in the basement terrains of the Western Domain and the Eastern Domain.	Peralkaline and S-type granites are the most tectonically peraluminous intrusive systems in the Central Domain.	Crystallization of Ni-Cu-PGE mineralizing magmas led to the accumulation of economic concentrations.	The geodynamic setting for potential IOCG deposits is subduction-related.	Late reactivated fault systems in the basement gneiss of the Western Domain.	Basin-associated faulting and volcanism during back-arc rifting through the Western Domain.

Mineralization Provenance	Hydrothermal - metamorphic.A*u*	Hydrothermal basalt fluids	
Mineralization System	Orogenic Au	Pt-Zn-Cu-Ba fault hosted mineralization	Sedimentary exhalative systems
Fluid/Magma System	Moderate temperature, CO2-bearing metamorphic fluids in compressional to transpressional settings	Low temperature, high salinity oxidized basalt-derived fluids	Low temperature oxidized basin-derived ~20% poor fluids
Deposit Type	Structurally controlled low sulphide Au + Ag	Sandstone/shale hosted fault-controlled Pb-Zn-Cu-Ba deposits	Stratabound siliciclastic hosted Zn, Pb, Ag
Age	Late Neoproterozoic to Early Palaeozoic	Late Ordovician	Late Cretaceous
Geological and Tectonic Association	Late reactivated fault systems within the meta-arc belts of the Western Domain.	Syn-pressional reactivation and inversion of fault-controlled basinal brines.	Deposits within the ex-craton sedimentary fill.

Mineralization Provenance	Sedimentary Deposits				Surficial Deposits
Mineralization System	Chemical precipitate deposits		Clastic Deposits	Residual deposits	Miscellaneous non-metallic commodities
Fluid/Magma System	Deposits formed by precipitation from evaporitic brines in restricted arid shallow inland marine and deep marine euxinic environments		Clastic	Deposits formed by regolith and/or aggressive meteoric processes	Organic-based deposits
Deposit Type	Alpotna-type banded iron formation	Phosphates and evaporites	Laterite, placer, and other surficial deposits	Ionic REE clay deposits	Coal
Age	Middle Neoproterozoic to Early Palaeozoic	Cambrian and Early Cretaceous	Late Cretaceous - Cenozoic		Late Cretaceous - Cenozoic

Geological and Tectonic Association	Deposits within the ex-craton sedimentary fill.	Basin-scale phosphate-bearing strata in the Western Domain.	Concentrated through weathering and erosion.	Associated with regolith systems.	Associated with organic-rich strata within the Benue Trough.

5.3. CONCLUSIONS

This study employed spatial analytical techniques, including point distribution analysis**,** K-function analysis, Fry analysis, and point density analysis, to investigate the spatial patterns of mineral occurrences in Nigeria. The goal was to derive insights into ore deposit genesis by evaluating the spatial relationships and clustering tendencies of mineral deposits across various geological settings. The findings of the point distribution analysis revealed that mineral occurrences in Nigeria are not randomly distributed but exhibit distinct spatial clustering influenced by geological structures, lithological variations, and tectonic controls. This suggests that mineralization processes are highly dependent on pre-existing geological conditions and structural frameworks. The K-function analysis further confirmed that mineral deposits tend to cluster at varying spatial scales, indicating that mineralization is not a purely independent process but is significantly influenced by geological and tectonic control. The clustering tendency at different distances provides evidence of regional-scale mineralization controls, such as fault zones, shear zones, and other structural discontinuities. The application of Fry analysis offered deeper insights into the directional alignment of mineral occurrences, suggesting that structural and stratigraphy controls, play a crucial role in ore deposit formation. The analysis identified prominent structural trends associated with mineralization, reinforcing the idea that structural deformation is a key driver in some ore genesis. The point density analysis revealed regions of high mineral concentration, highlighting potential mineral-rich zones that may warrant further exploration. These high-density zones often coincide with major geological formations and tectonic boundaries, reinforcing the importance of spatially-driven exploration strategies.

The spatial analyses collectively indicate that several mineralization in Nigeria is structurally controlled and strongly influenced by tectonic activity. The clustering of mineral deposits along fault systems and geological boundaries suggest that ore-forming fluids were channelled through structurally prepared zones, leading to the deposition of economically significant minerals. This supports the hydrothermal model of mineralization where structural conduits act as pathways for mineralizing fluids. Furthermore, the findings underscore the necessity of integrating spatial analytical techniques with geological and geophysical data to enhance mineral exploration strategies. The identified clustering patterns and structural alignments provide valuable guidance for future exploration programs, particularly in targeting prospective mineral belts.

5.3.1. Recommendations

1. **Targeted Mineral Exploration:** Future exploration efforts should prioritize regions with high mineral density and structural alignment, as identified by this study.
2. **Integration with Geophysical Data:** Combining spatial analysis with geophysical surveys could refine exploration models and enhance predictive capabilities.
3. **Further Statistical and Machine Learning Approaches:** Advanced geostatistical and machine learning models could be applied to refine spatial predictions of mineral occurrences.
4. **Field Validation:** Ground-truthing of identified mineral clusters should be carried out to validate the spatial analysis results and refine exploration targets.

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ANNEX

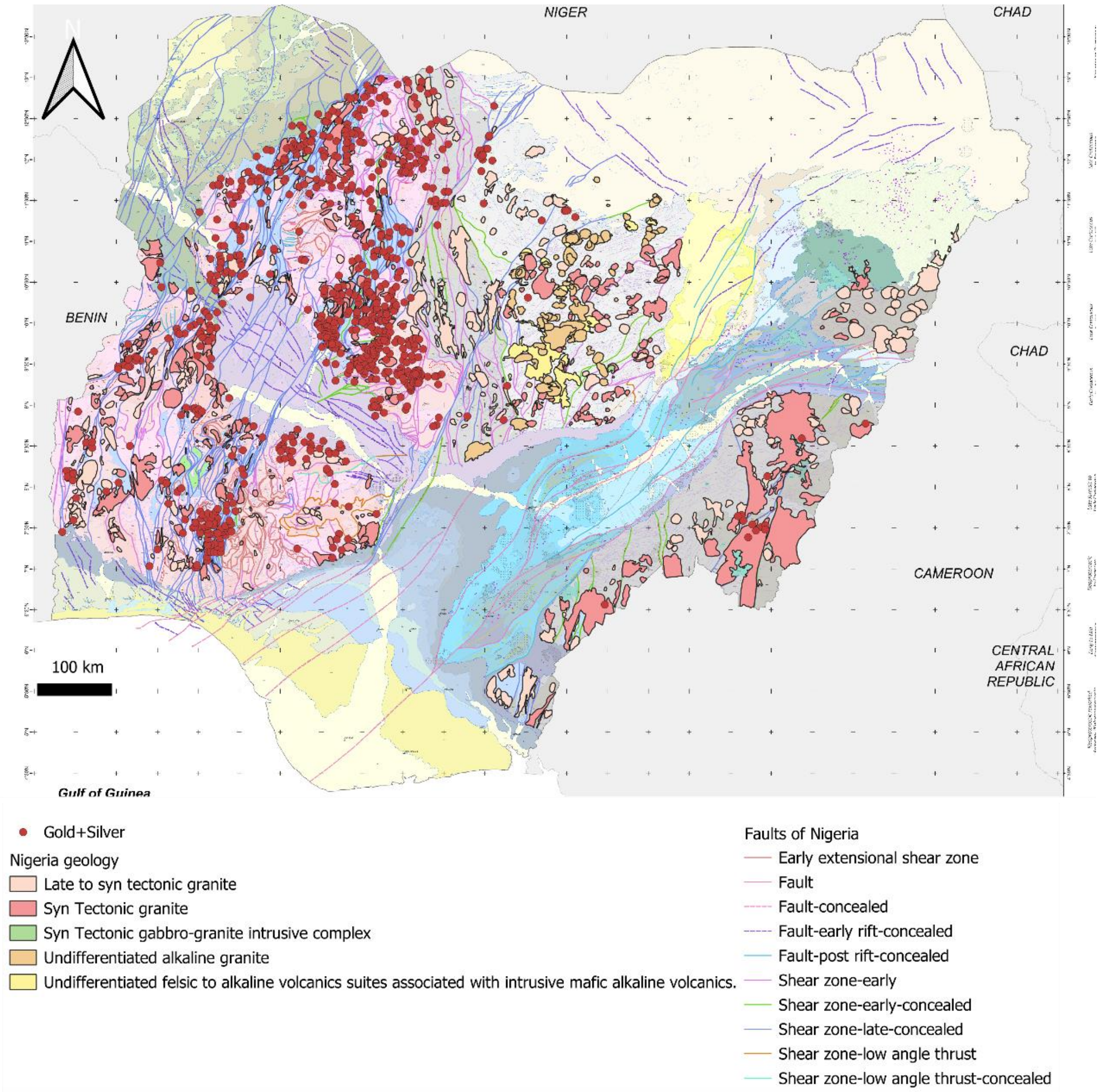

Figure A.1 Map of Nigeria displaying the locations of gold-silver deposit occurrences with associated geological structures

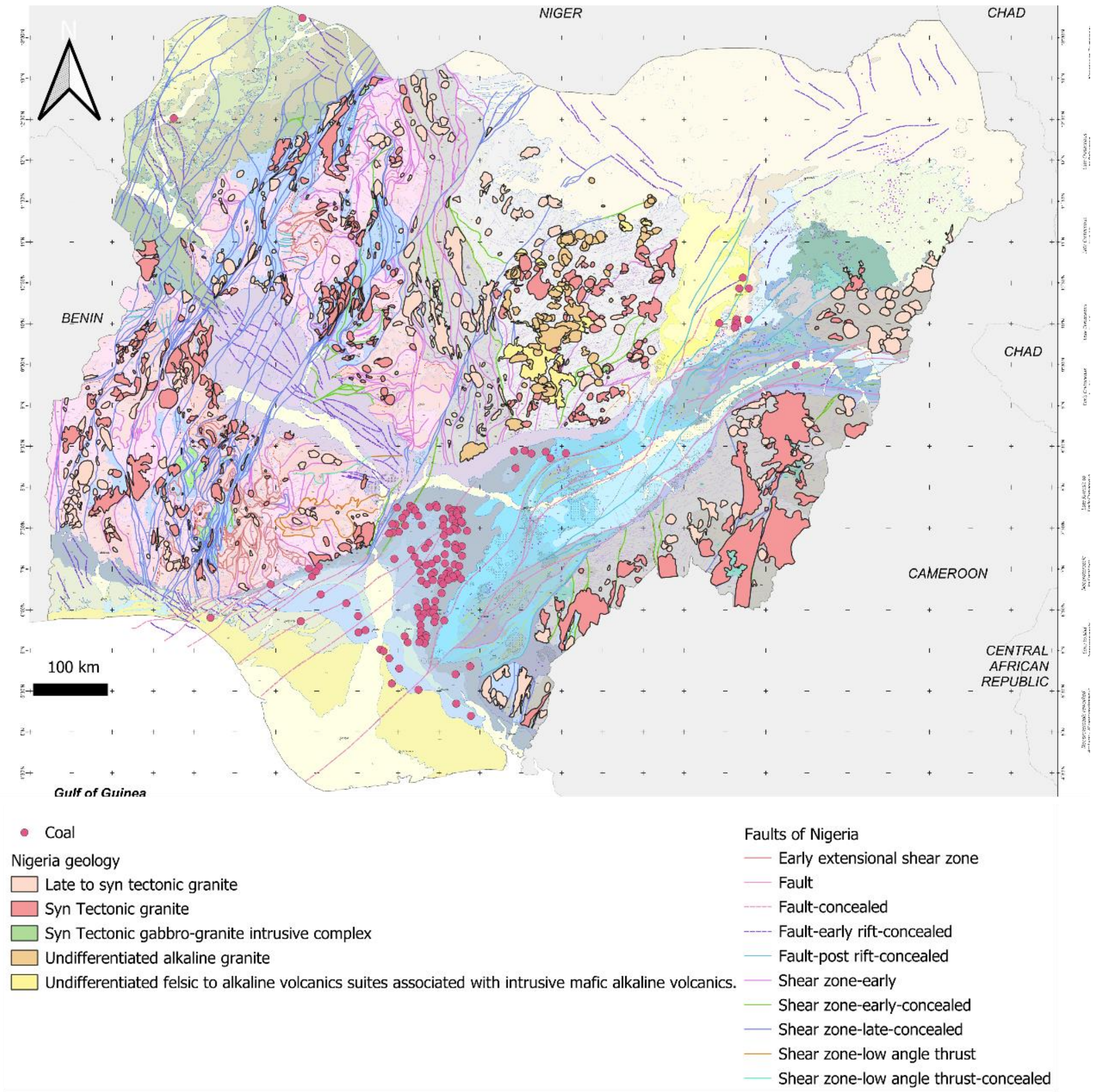

Figure A.2 Map of Nigeria displaying the genesis of coal deposit occurrences within associated sedimentary region and structures in some localized areas.

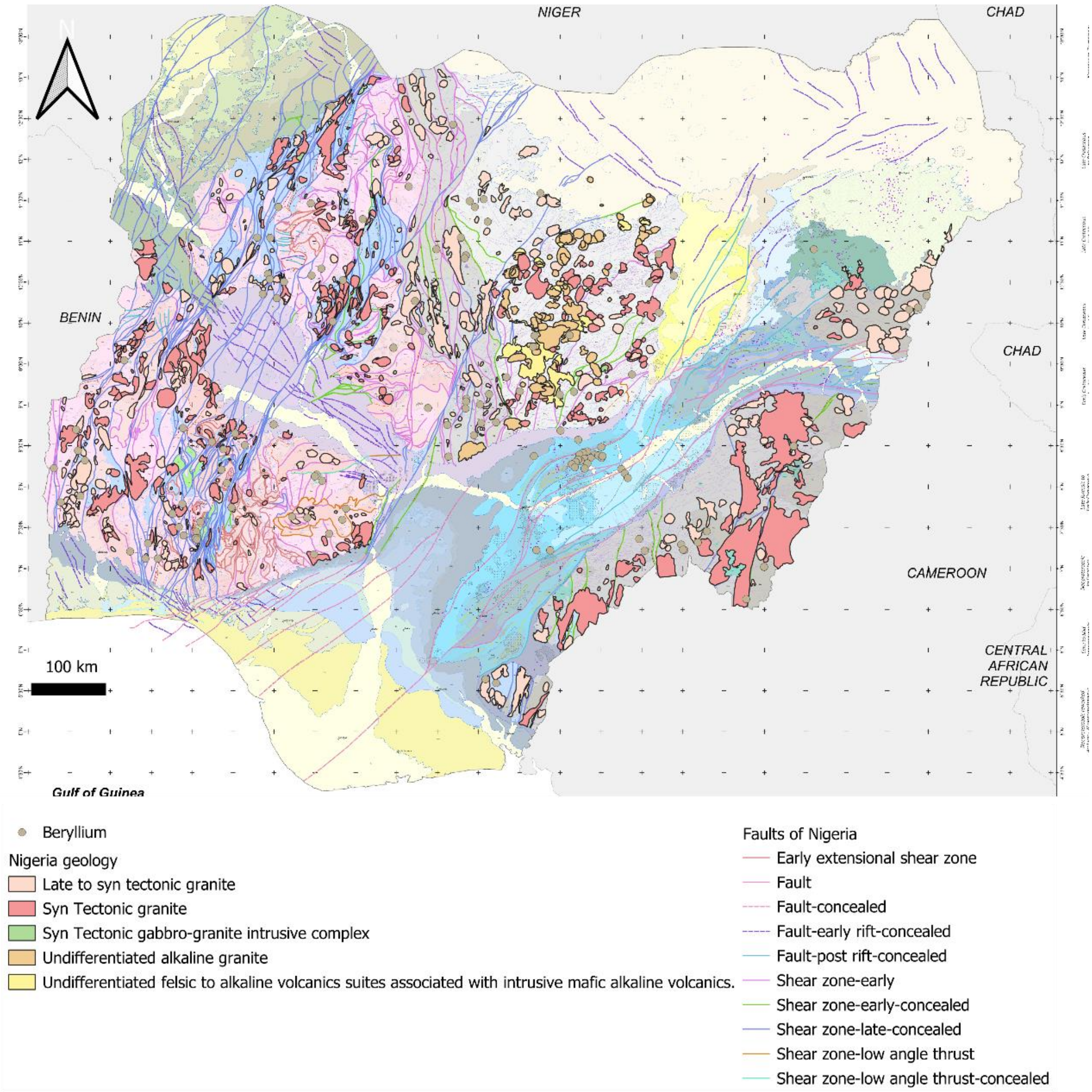

Figure A.3. Map of Nigeria displaying the genesis of beryllium deposit occurrences with associated geological structures.

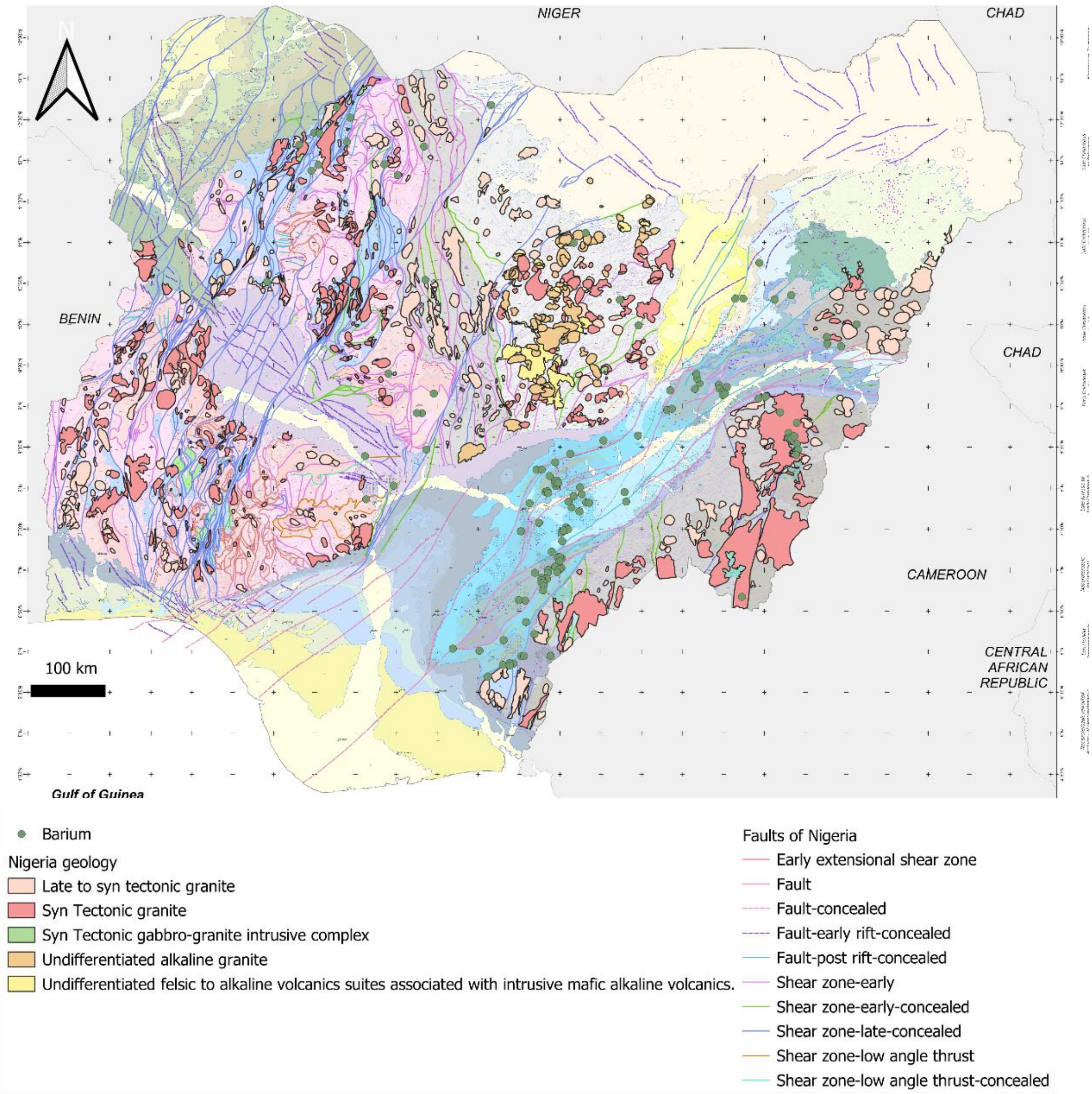

Figure A.4. Map of Nigeria displaying the genesis of barium deposit occurrences with associated geological structures.

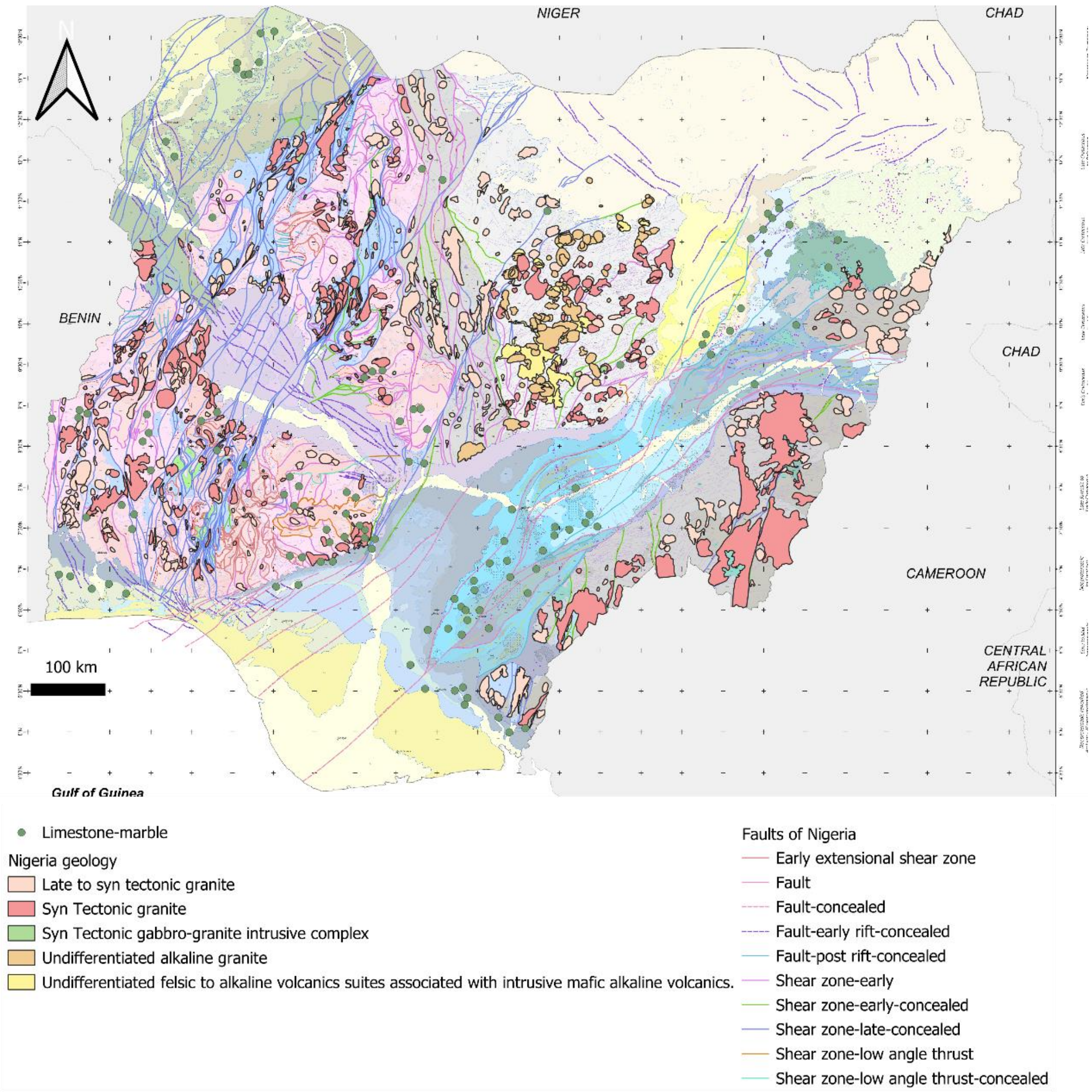

Figure A.5. Map of Nigeria displaying the genesis of limestone-marble deposit occurrences with associated geological structures.

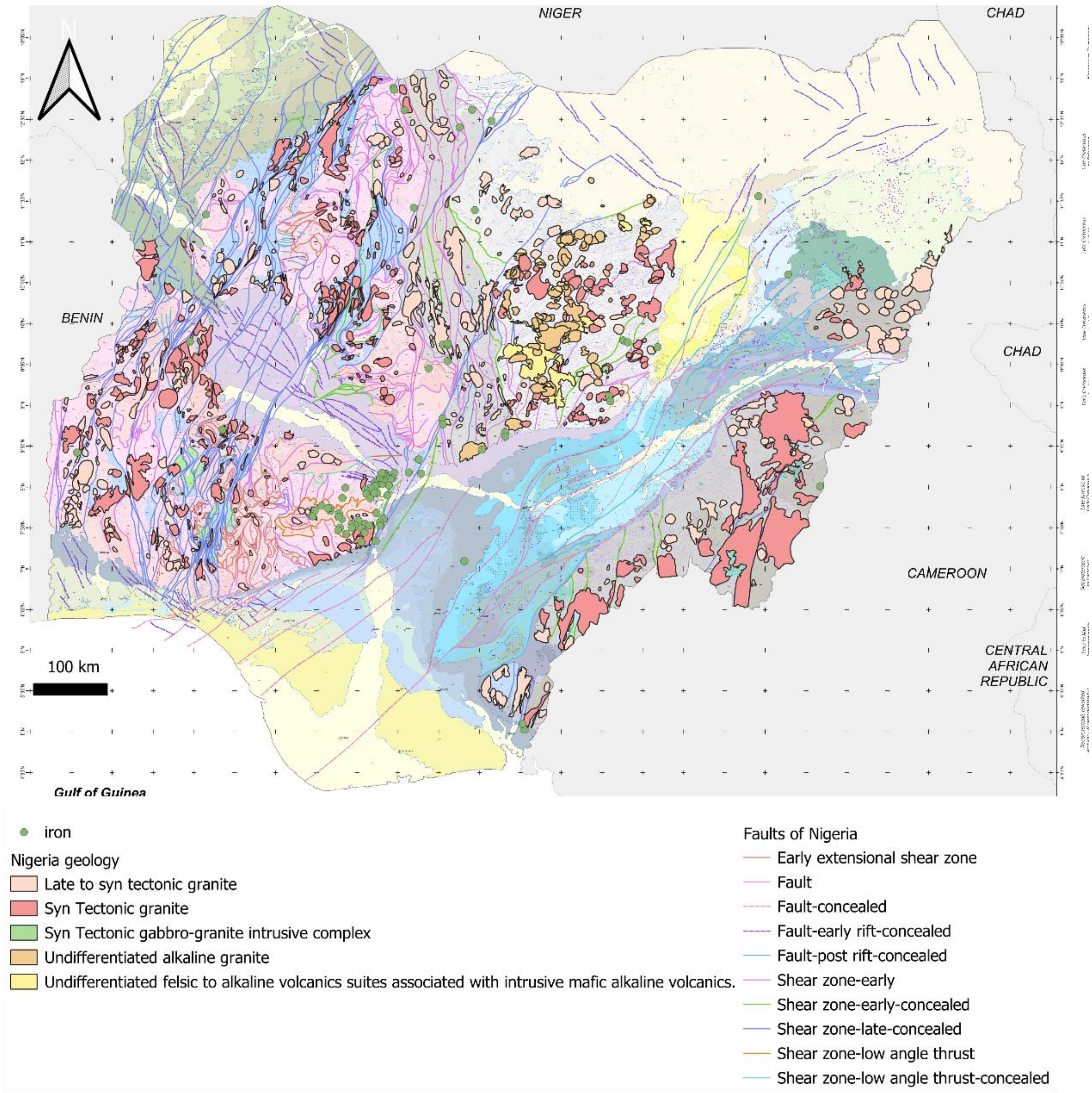

Figure A.6. Map of Nigeria displaying the genesis of iron deposit occurrences with associated geological structures.

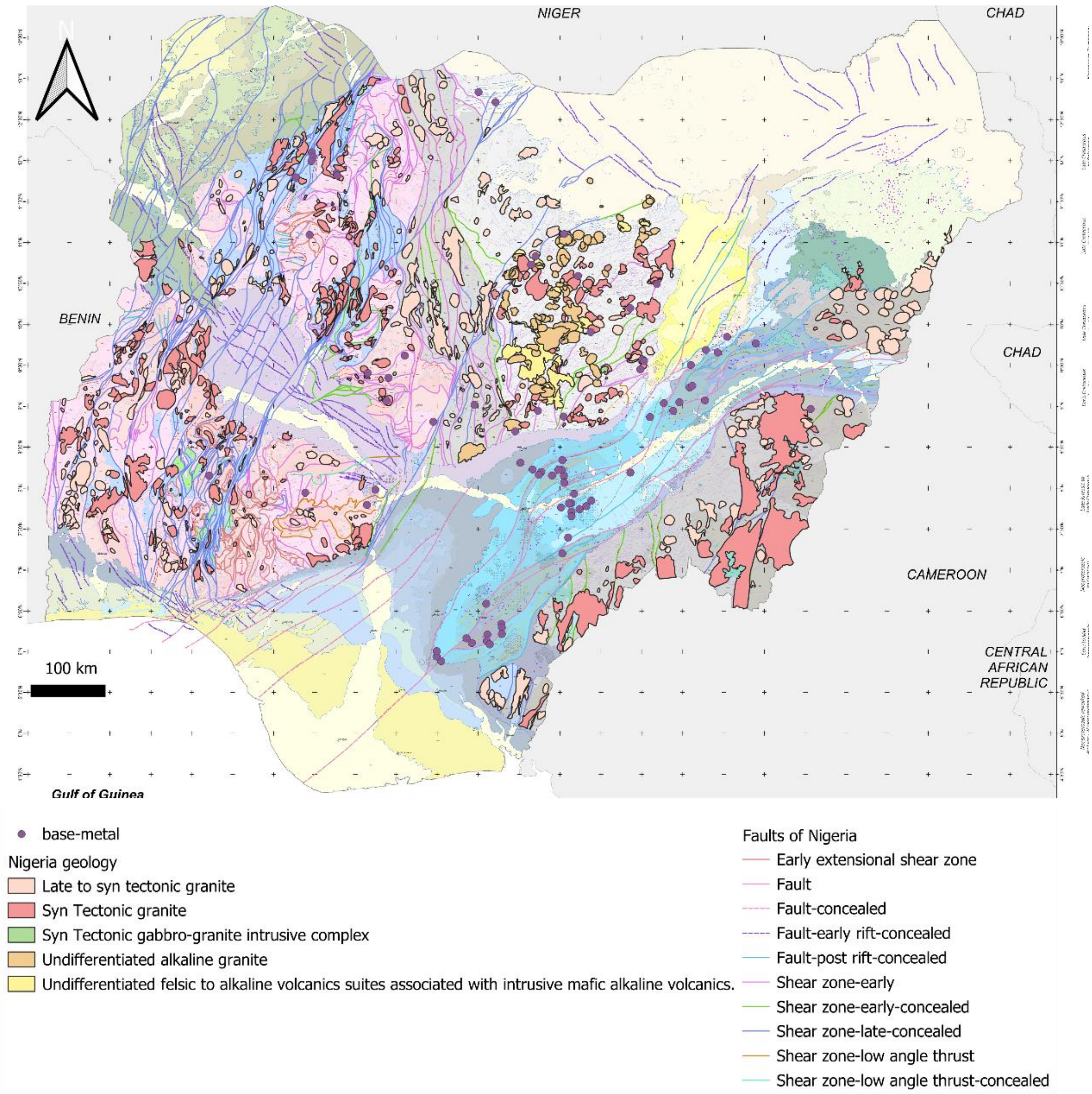

Figure A.7. Map of Nigeria displaying the genesis of base-metal deposit occurrences with associated geological structure in the study area.

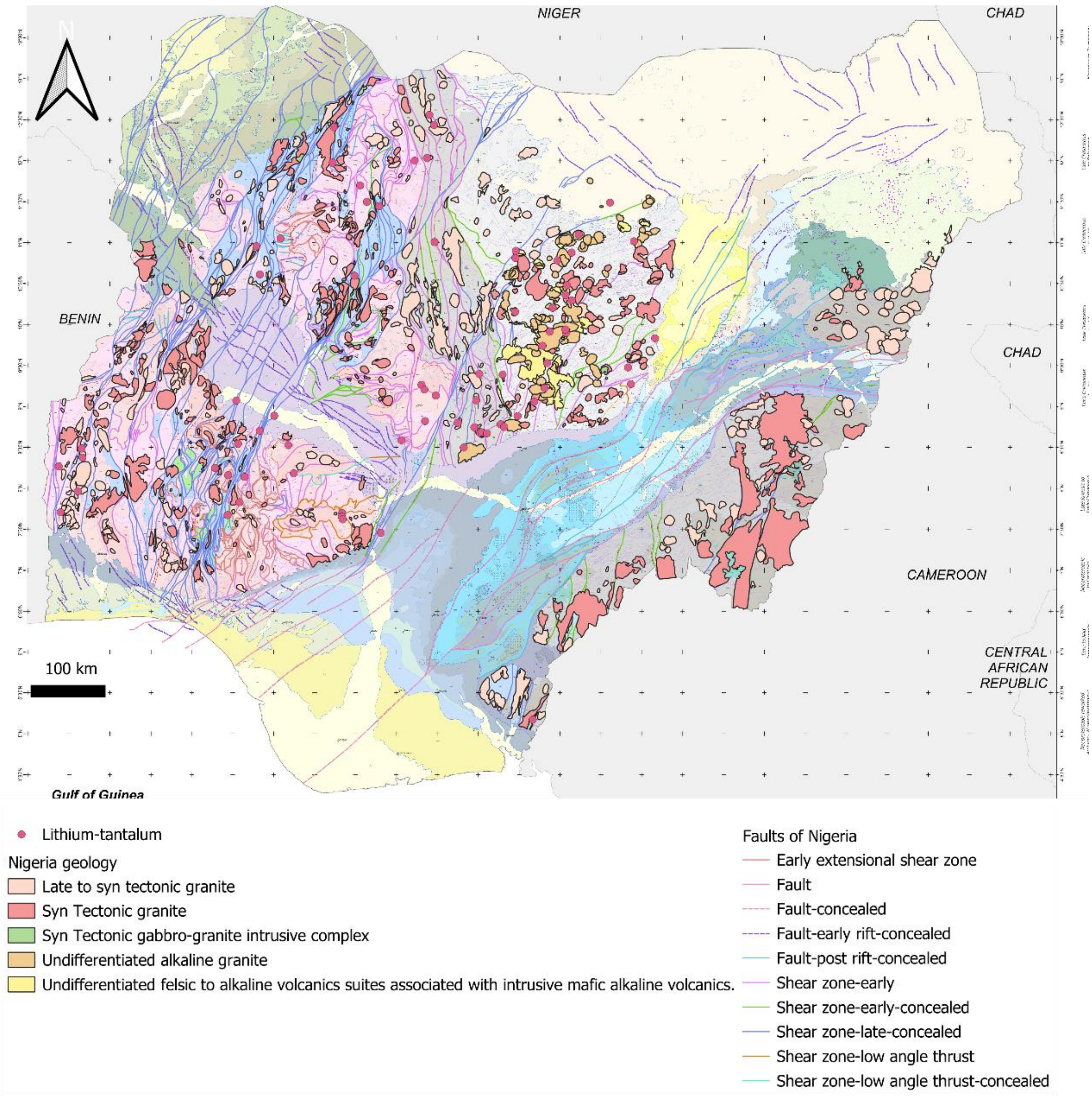

Figure A.8 Map of Nigeria displaying the genesis of Lithium-tantalum deposit occurrences with associated geological structure in the study area.

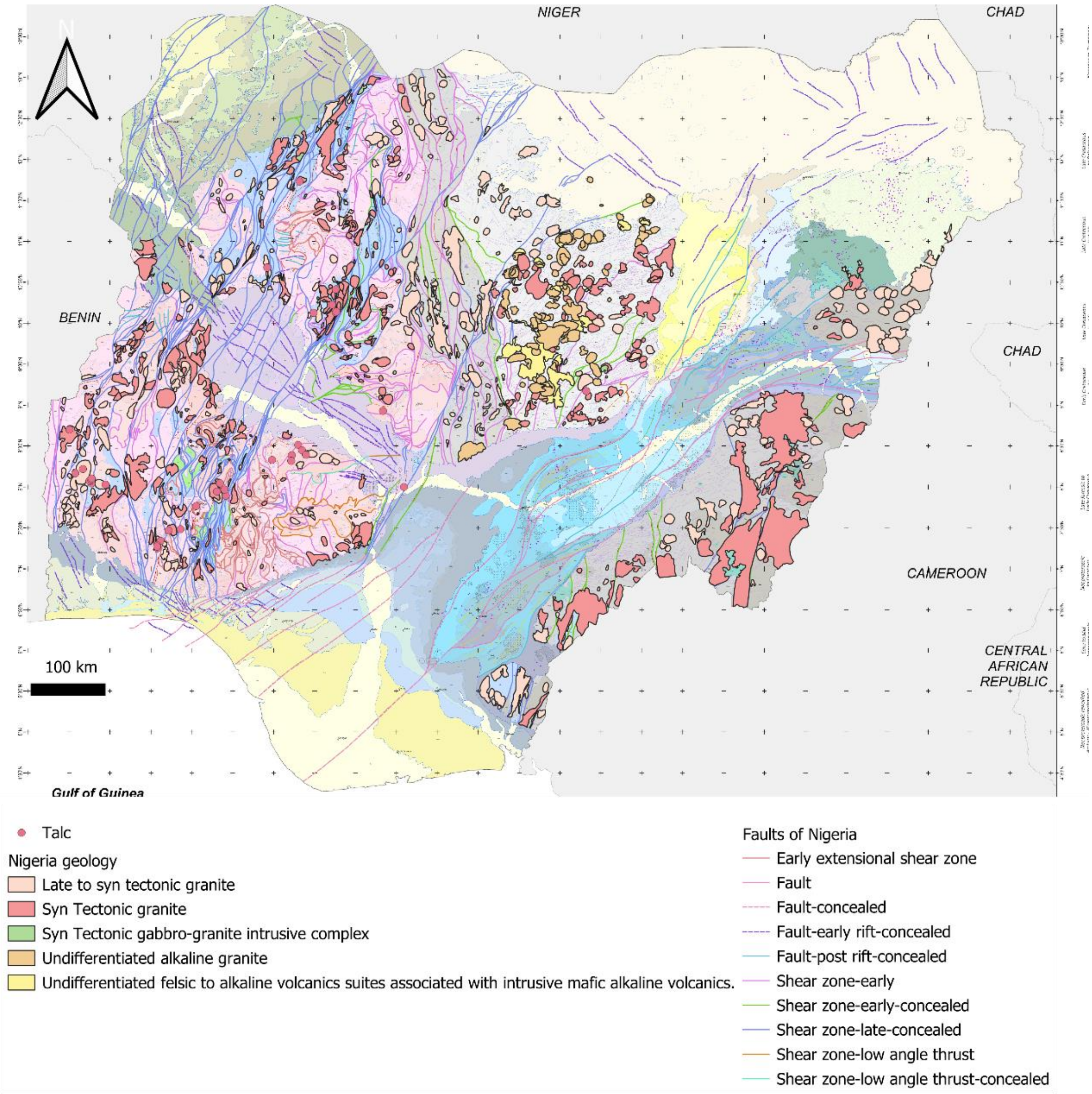

Figure A.9 Map of Nigeria displaying the genesis of talc deposit occurrences with associated geological structure in the study area.

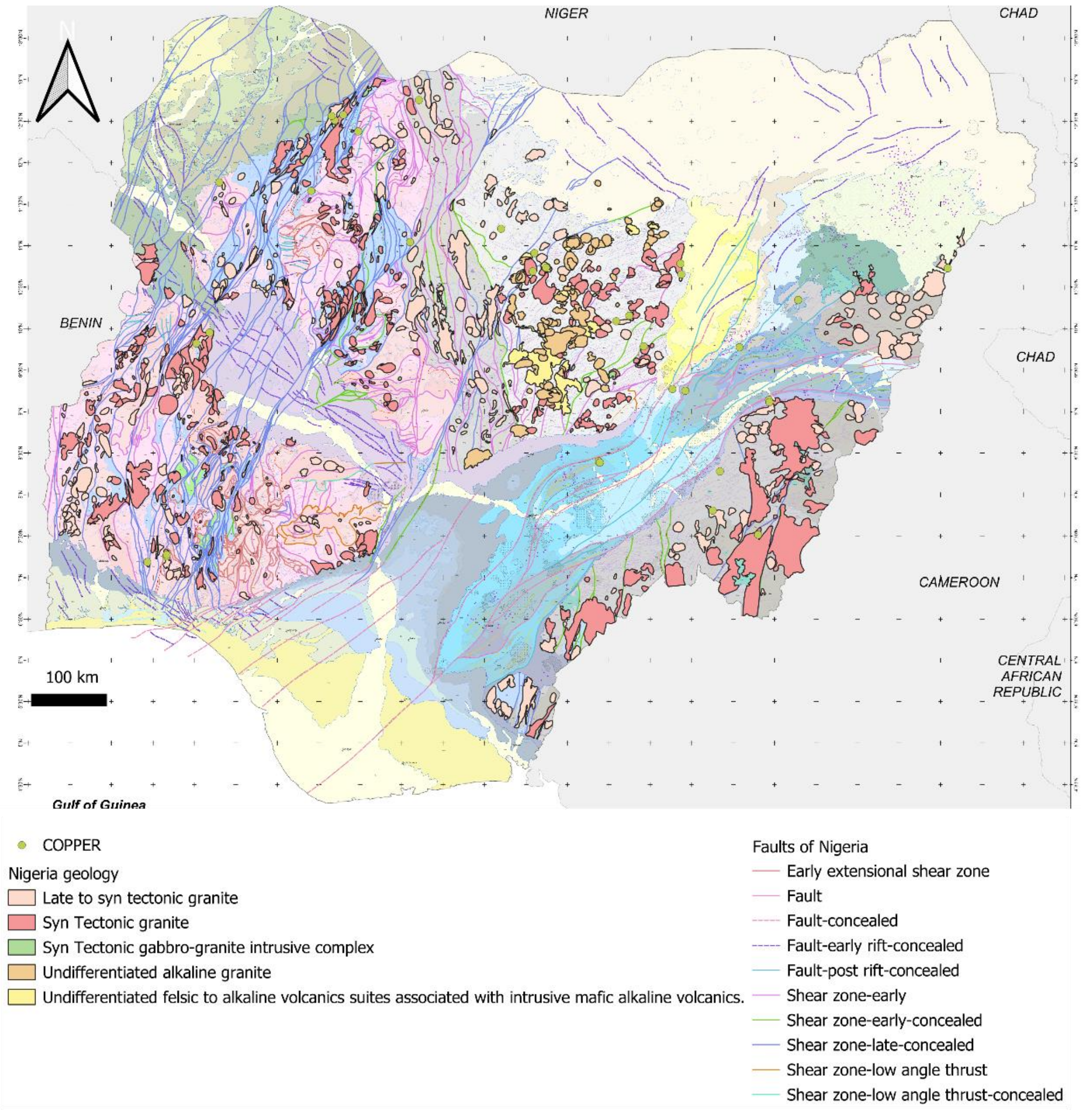

Figure A.10 Map of Nigeria displaying the genesis of copper deposit occurrences with associated geological structure in the study area.

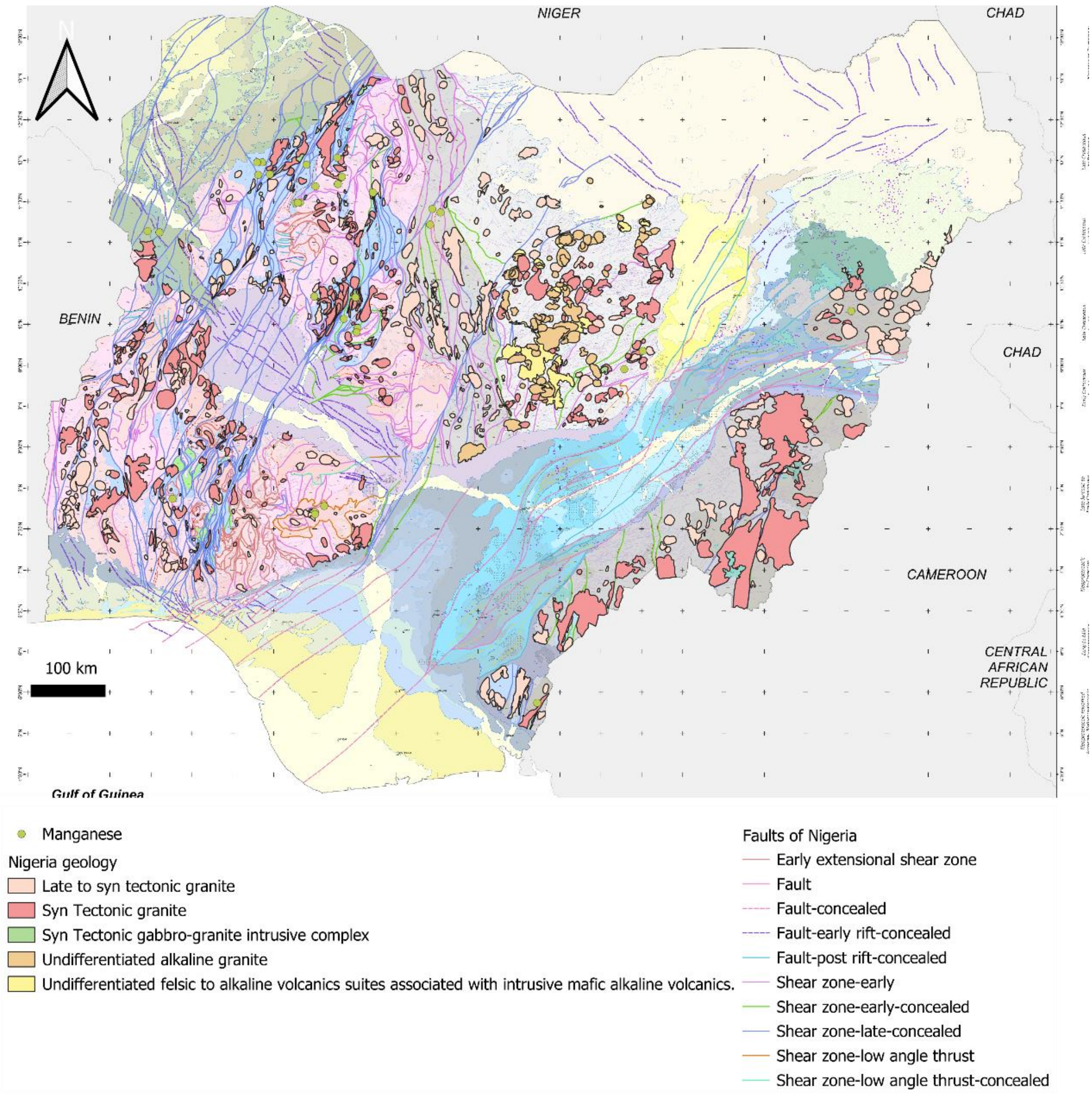

Figure A.11 Map of Nigeria displaying the genesis of manganese deposit occurrences with associated geological structure in the study area.

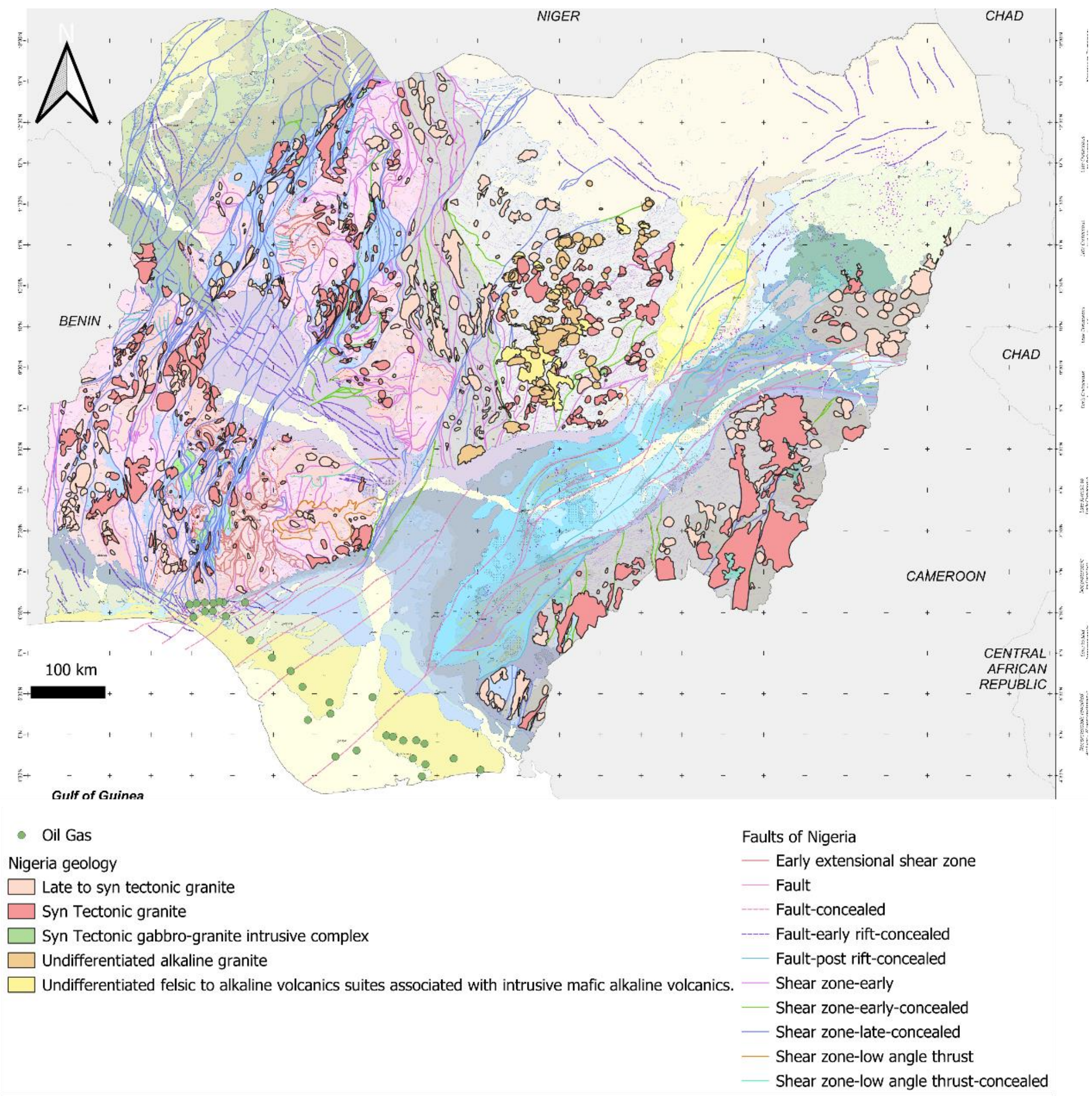

Figure A.12 Map of Nigeria displaying the genesis of oil-gas deposit occurrences with associated geological structure in the study area.

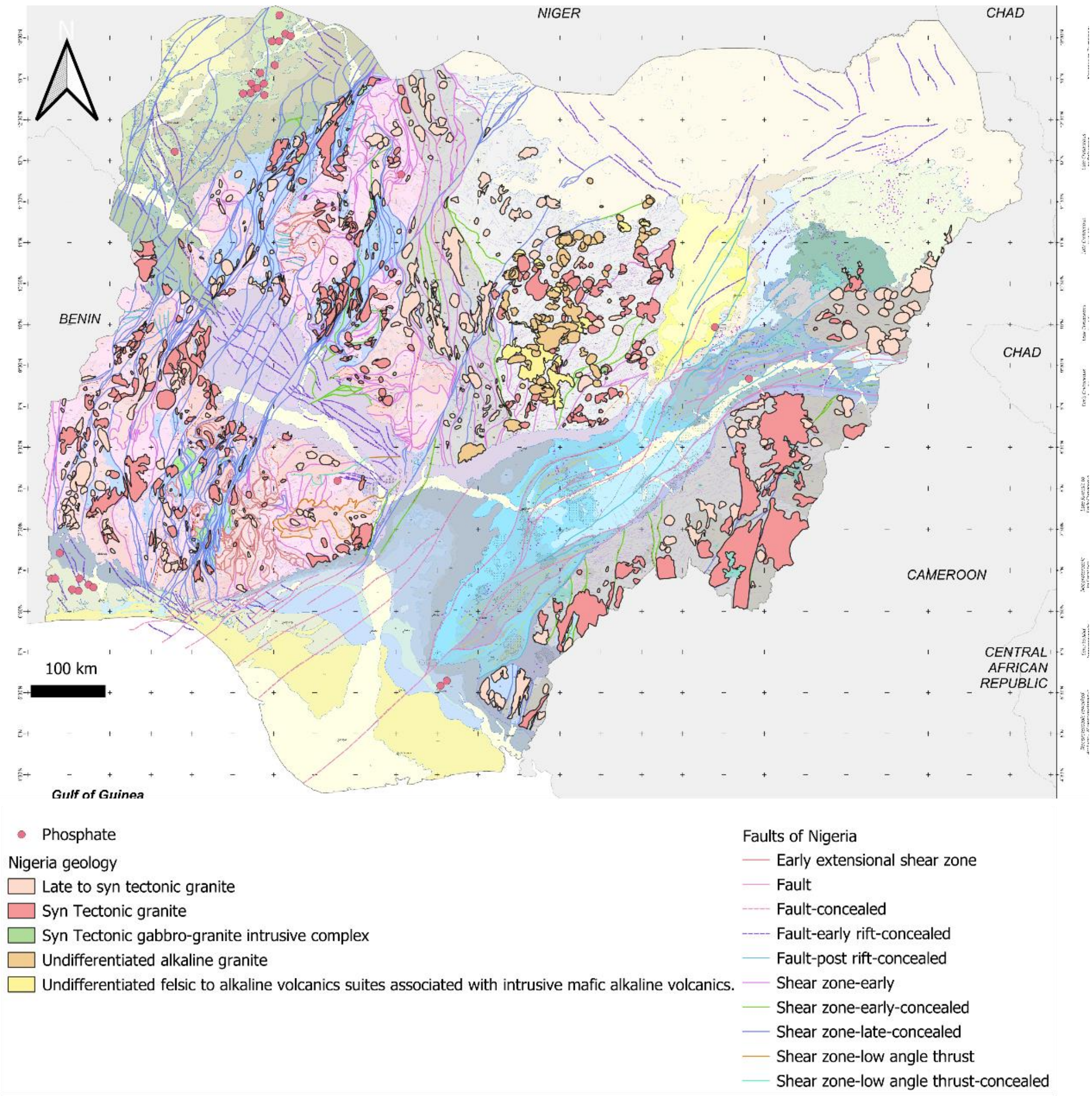

Figure A.13 Map of Nigeria displaying the genesis of phosphate deposit occurrences with associated geological structure in the study area.

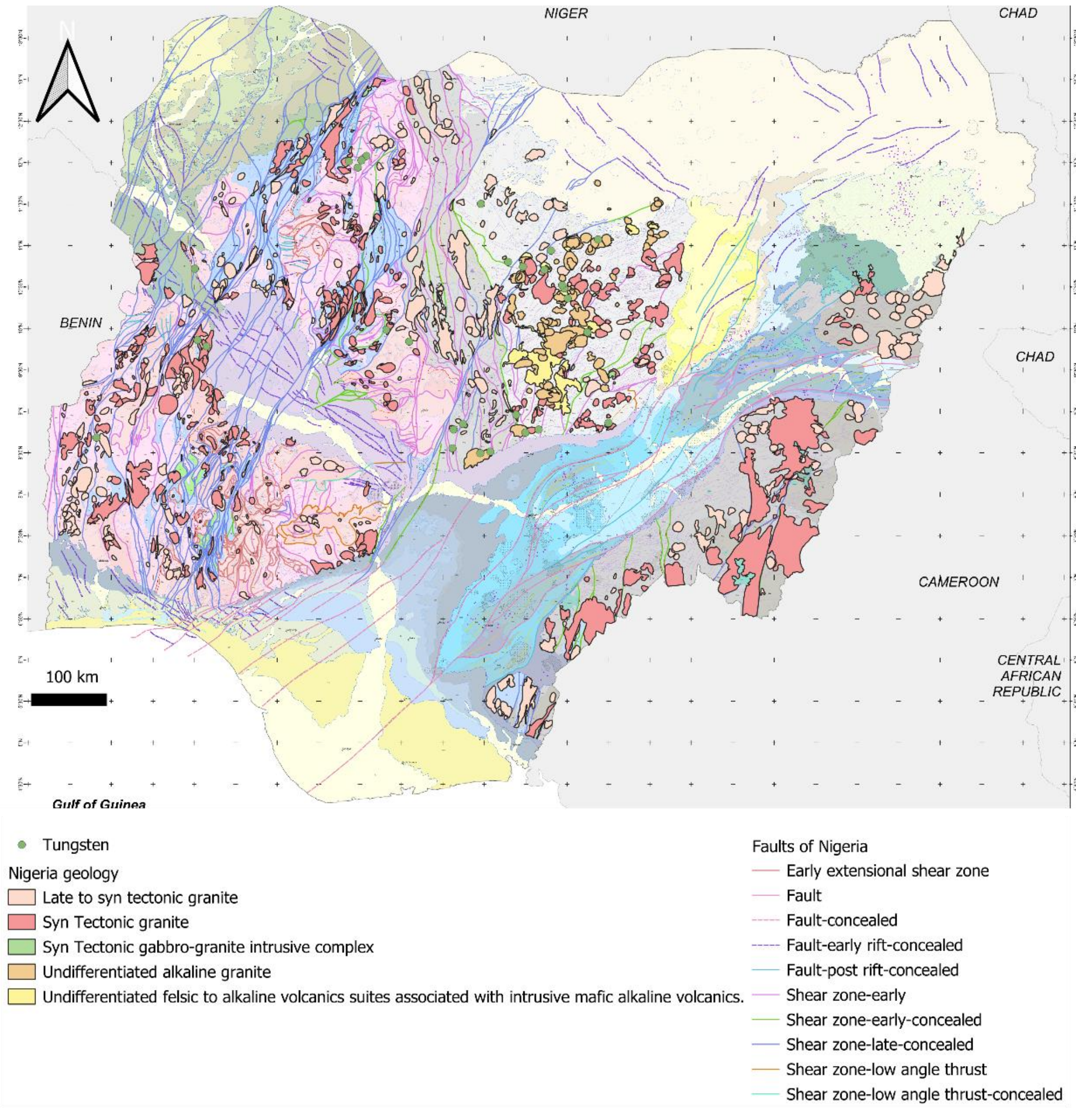

Figure A.14 Map of Nigeria displaying the genesis of tungsten deposit occurrences with associated geological structure in the study area.