PETROGRAPHIC AND GEOCHEMICAL STUDY OF GRANITIC ROCKS IN THE IGARRA-UGBOGBO AREA OF EDO STATE, NIGERIA.

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DEDICATION

I dedicate this project specially to God Almighty. My supervisor, and Finally to my Wonderful parents and siblings. For their continuous support and prayers.

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I give thanks to the God Almighty who stood by me from the beginning of this program to the end.

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ABSTRACT

This project presents a detailed petrographic and geochemical study of granitic rocks in the Igarra-Ugbogbo area of Edo State Nigeria, within the Nigerian Basement Complex. In order to characterize the mineralogical composition, and interpret their petrogenesis and tectonic setting. To address the significant knowledge gaps in the understanding of this segment of the Pan-African orogenic belt using integrated field mapping with laboratory analysis, Five representative fresh samples (SJ01–SJ05) were collected and subjected to polarizing microscopy for petrographic study and X-ray fluorescence (XRF) spectrometry for whole rock major and trace element geochemistry. Petrographic analysis reveals that the granites are medium to coarse grained with a hypidiomorphic granular texture, indicating slow plutonic cooling. Modal composition is dominated by quartz (21-31%), plagioclase (31-35%), and microcline (20-26%), with biotite (7-10%) as the main mafic mineral. Minor hornblende, muscovite, and accessory zircon and opaque minerals are present. Textural features such as undulose extinction in quartz and sericitization of feldspars indicate post crystallization deformation and hydrothermal activity. Geochemical data classify the rocks as metaluminous to weakly peraluminous (ASI = 0.98-1.05), high-silica (69.23-71.44 wt. % SiO_2) granites with calc-alkaline affinity. They are enriched in Large Ion Lithophile Elements (LILE: e.g., Rb, Ba) and depleted in High-Field-Strength Elements (HFSE: e.g., Nb, Ta, Y), a signature characteristic of crustal-derived magmas. Trace element discrimination diagrams consistently plot the samples in the syn collision to post-collision granite fields. The integrated results lead to the conclusion that the Igarra granites are I-type granitoids formed primarily by partial melting of pre-existing crustal igneous rocks during the Pan-African Orogeny and their emplacement occurred in a post-collisional tectonic environment, accompanied by minor deformation and hydrothermal alteration. This study provides a crucial petrogenetic framework for the Igarra basement and contributes valuable data for understanding crustal evolution and mineral exploration potential in southwestern Nigeria.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The study of granitic rocks forms a cornerstone of igneous petrology, as these intrusions represent primary agents of continental crust formation and evolution. Within the Nigerian geological landscape, granites are particularly significant components of the Precambrian Basement Complex. Their widespread occurrence and varied characteristics offer a critical window into the tectonic processes that have shaped the region over geological time.

The Nigerian Basement Complex itself is a mosaic of ancient crystalline rocks that have undergone multiple episodes of deformation, metamorphism, and magmatic activity. This complex terrain provides the foundational geology upon which younger sedimentary basins were later deposited. Understanding the granitic components of this basement is therefore essential for reconstructing the complete geological history of not only Nigeria but also the broader West African region.

The Igarra area in Edo State presents a particularly compelling location for such a study. It is characterized by excellent exposures of basement rocks, including a diverse assemblage of schists, gneisses, migmatites, and several generations of granitic intrusions as presented in Figure 1.1. These granitic bodies were predominantly emplaced during the Pan-African Orogeny, a major tectonothermal event occurring around 600 million years ago. This orogeny was responsible for extensive reworking of the pre-existing crust, leading to the formation of the granitic suites seen across southwestern Nigeria.

Early geological work in the Igarra area, such as that by Odeyemi (1976), laid the groundwork by establishing the basic lithological and structural framework. This was followed by the seminal compilation of Kogbe (1989), which situated the Igarra terrain within the broader context of the Southwestern Nigerian Basement, noting its history of polyphase deformation and metamorphism.

These foundational studies correctly identified the presence of multiple granitic intrusions but often lacked the detailed, sample-specific analytical data needed for precise petrogenetic interpretation.

In more recent years, studies such as those by Udi (2023) have begun to address this gap, emphasizing how the granites of the Igarra area reflect a complex magmatic evolution intimately tied to regional tectonic forces. Furthermore, preliminary field observations in the Igarra-Ugbogbo corridor suggest there are significant variations in texture and mineralogy among the granitic outcrops. This study investigates these variations to determine if they indicate a more heterogeneous magmatic history than previously recognized. Despite these valuable contributions, a comprehensive characterization of many granitic bodies in the Igarra area remains lacking. This study seeks to build upon this existing knowledge base by conducting a detailed petrographic and geochemical investigation of selected granite samples from the Igarra-Ugbogbo area. The goal is to provide the necessary data to clarify their composition, classification, and geological history, thereby contributing to a more nuanced understanding of the Igarra Basement Complex.

1.2 Statement of the Problem

While the Igarra area has been the subject of numerous geological investigations, these studies have often focused on regional-scale mapping, structural analysis, or the economically appealing schist-marble sequences. Consequently, the granitic lithologies, despite their abundance and significance, have not received commensurate systematic and detailed analysis. This has resulted in several persistent knowledge gaps that this research aims to address.

A primary issue is the insufficient petrographic characterization of many granitic bodies. Without detailed modal analysis and textural examination, the mineralogical composition and crystallization history of these rocks cannot be accurately determined. This lack of fundamental data hinders their proper classification within standard petrological schemes and prevents meaningful correlation with other well-studied granite suites in Nigeria.

Furthermore, there is a notable deficiency in comprehensive geochemical data for the Igarra granites. While broad compositional ranges are sometimes mentioned, systematic major and trace element analyses are scarce. This gap impedes a confident assessment of their geochemical affinity, petrogenesis (including source characteristics and magmatic processes), and the tectonic setting in which they were emplaced. Key questions regarding whether they originated from crustal melting, mantle-derived magmas, or a hybrid source remain largely unanswered.

Field observations indicate visible variations in texture and mineral proportions among different granitic bodies in the Igarra-Ugbogbo area. These variations suggest potential differences in their emplacement mechanisms, cooling histories, or source materials. However, in the absence of supporting petrographic and geochemical data, these field observations cannot be robustly interpreted, and the implications for local magmatic evolution remain speculative.

Therefore, this study is designed to confront these problems directly through a focused investigation of selected granite samples. By integrating detailed thin-section petrography with high-quality X-ray fluorescence (XRF) geochemical data from five representative samples (SJ 01 to SJ 05), this research will provide the empirical foundation needed to resolve these outstanding questions and advance the understanding of the granitic component of the Igarra Basement Complex.

1.3 Aim and Objectives

Aim:

The primary aim of this research is to undertake a detailed analysis of the petrographic and geochemical characteristics of selected granite samples from the Igarra-Ugbogbo area, with the overarching goal of classifying these rocks and interpreting their petrogenesis and tectonic environment.

Objectives:

To achieve this aim, the study will pursue the following specific objectives:

1. To conduct a systematic field examination and collection of fresh, representative granite samples from well exposed outcrops in the study area, documenting their field relationships and macroscopic features.
2. To prepare high quality thin sections from the collected samples and conduct a thorough petrographic analysis to identify mineral constituents, determine their textural relationships, and document any post-magmatic alterations.
3. To perform a modal analysis to quantitatively estimate the mineral proportions within the granites, providing a basis for their accurate petrographic classification.
4. To determine the concentrations of both major element oxides and key trace elements in the granite samples using X-ray fluorescence (XRF) spectrometry.
5. To utilize the obtained petrographic and geochemical data to classify the granites according to standard international schemes, including the QAP (Quartz-Alkali Feldspar-Plagioclase) and TAS (Total Alkali-Silica) diagrams.
6. To synthesize all analytical results to develop a coherent model for the petrogenesis of the granites, inferring their magmatic source and the tectonic setting that governed their emplacement during the Pan-African Orogeny.

1.4 Significance of the Study

This research holds significance for several aspects of geological science, both academic and practical.

- **Contribution to Regional Geology:** The findings of this study will provide a valuable, data-rich addition to the existing knowledge of the Igarra Basement Complex. By delivering detailed petrographic and geochemical information on specific granite bodies, it will help to refine local geological models and contribute to a more complete understanding of crustal evolution in southwestern Nigeria during the Pan-African event.
- **Petrogenetic Insights:** The integration of modal mineralogy with whole-rock geochemistry will allow for a more robust interpretation of the petrogenetic processes involved in the formation of the Igarra granites. It will help clarify whether they are products of pure crustal melting, fractional crystallization of a more mafic parent magma, or complex crust-mantle interactions.
- **Tectonic Implications:** By applying geochemical discrimination diagrams, this study will provide evidence for the tectonic regime prevalent during the emplacement of these granites. This will contribute to the ongoing discourse regarding the nature of the Pan-African Orogeny in this part of Nigeria, helping to distinguish between syn-collisional, post-collisional, or other tectonic settings.
- **Resource and Educational Value:** The detailed characterization of these granites serves as a foundational dataset for academic reference, beneficial for future students and researchers. Furthermore, understanding the characteristics of basement granites is crucial for mineral exploration initiatives, as such rocks can host valuable mineral deposits. The results will also be pertinent for professionals in fields such as engineering geology and environmental planning where bedrock properties are a key consideration.
- **Economic Significance:** From an economic perspective, this research provides baseline geological information essential for mineral exploration activities in northern Edo State and surrounding regions. Granitic systems often host strategic metal deposits, and understanding their

petrogenetic characteristics guides exploration strategies for commodities such as tin, tantalum, tungsten, and rare earth elements. The identification of specific granite types and their alteration patterns can direct future mineral exploration efforts in this potentially prospective region.

1.5 Scope of the Study

This investigation is deliberately focused to ensure depth and precision. The geographical scope is confined to selected granite outcrops within the Igarra-Ugbogbo area of Edo State. The study is limited to five representative granite samples, designated SJ 01 to SJ 05, which were chosen based on their freshness and representativeness of the observed granitic varieties in the field.

The analytical scope encompasses three primary methodologies:

1. **Petrographic Analysis:** Involving the microscopic examination of thin sections to describe mineralogy and texture.
2. **Modal Analysis:** Employing point-counting techniques to quantify mineral abundances.
3. **Geochemical Analysis:** Using XRF spectrometry to determine the concentrations of major and trace elements.

It is important to note the boundaries of this study. The research does not include geochronological analysis (e.g., radiometric dating) to determine the absolute age of the granites. Nor does it involve advanced isotopic studies or a regional-scale geophysical survey. The interpretations are based on the petrographic and geochemical data obtained from the five specified samples, with the objective of providing a detailed and focused characterization rather than an exhaustive regional synthesis.

1.6 The Study Area

1.6.1 Location and Accessibility

The study area is situated around the town of Igarra and the adjoining Ugbogbo community, within the Akoko Edo Local Government Area of Edo State, Nigeria. The area is accessible via the major

Auchi-Igarra road, with a network of secondary lateritic roads and tracks providing access to specific outcrop locations, quarries, and stream sections where fresh rock exposures are optimal. The topography, characterized by low hills and rocky inselbergs, provides excellent natural exposures. Furthermore, anthropogenic activities such as quarrying and road construction have created additional, fresh exposures that are highly suitable for geological sampling. Accessibility is generally good, particularly during the dry season (November to March), when weather conditions are most favorable for fieldwork.

1.6.2 Climate and Vegetation

The Igarra area experiences a tropical climate, marked by two distinct seasons: a wet season that typically spans from April to October, and a dry season from November to March. The vegetation is primarily a mosaic of secondary forest, mixed shrubs, and grasslands, with significant areas converted to agricultural farmlands. This moderate vegetation cover allows for relatively clear observation of bedrock geology in many parts of the study area.

1.6.3 Drainage and Topography

The topography is moderately rugged, defined by a series of hills and ridges that reflect the underlying geology, with more resistant granitic and gneissic rocks forming topographical highs. The drainage pattern is largely dendritic and is controlled by structural features within the basement rocks, such as joints and foliation planes. A common and distinctive geomorphological feature of the area is the presence of granite domes, tors, and extensive boulder fields, which are the result of long-term spheroidal weathering and exfoliation processes typical of granitic terrains in tropical environments.

CHAPTER TWO

GEOLOGICAL SETTING AND LITERATURE REVIEW

2.1 Introduction

The granites exposed in the Igarra region are not isolated geological features but are products of a vast and complex history of crustal formation (Rahaman, 1976). To genuinely understand these rocks, one must appreciate the terrain that hosts them, the immense tectonic forces that shaped this terrain, and the protracted geological processes that generated the magmas from which they crystallized (Dada, 2006). This chapter provides a synthesized review of the essential context needed to analyze and interpret the Igarra granites. It examines the broader geological framework of Nigeria (Obaje, 2009) as presentd in Figure 2.1, delves into the evolution of the Basement Complex, explores the nature of granitic intrusions within it, and details the specific geology of the Igarra area (Odeyemi, 1976; Udi, 2023). Furthermore, it outlines the petrographic and geochemical principles fundamental to granite study and surveys previous research conducted in and around the study area.

2.2 Geological Setting of Nigeria

Nigeria's geology is fundamentally divided between ancient crystalline basement rocks and younger sedimentary basins, each representing distinct chapters in the geological evolution of West Africa (Obaje, 2009). The Precambrian Basement Complex, which forms the foundation for more than half of the country's territory, is of paramount importance. This complex is an integral part of the Trans-Saharan Pan-African Mobile Belt, a major zone of deformed and metamorphosed rocks situated between the stable West African Craton to the northwest and the Congo Craton to the southeast (Black, 1980).

This Basement Complex shows evidence of multiple cycles of crustal growth, deformation, and magmatic activity. These cycles peaked during the Pan-African Orogeny, a major tectonothermal event around 600 ± 50 million years ago that profoundly reworked the pre-existing crust (Rahaman, 1976). This orogeny was responsible for widespread metamorphism and the emplacement of vast volumes of granitoid intrusions across southwestern Nigeria (Dada, 2006). The granites of Igarra, which are the focus of this study, are part of this extensive suite of Pan-African intrusives, and their characteristics are a direct reflection of the conditions during this orogenic event (Udi, 2023).

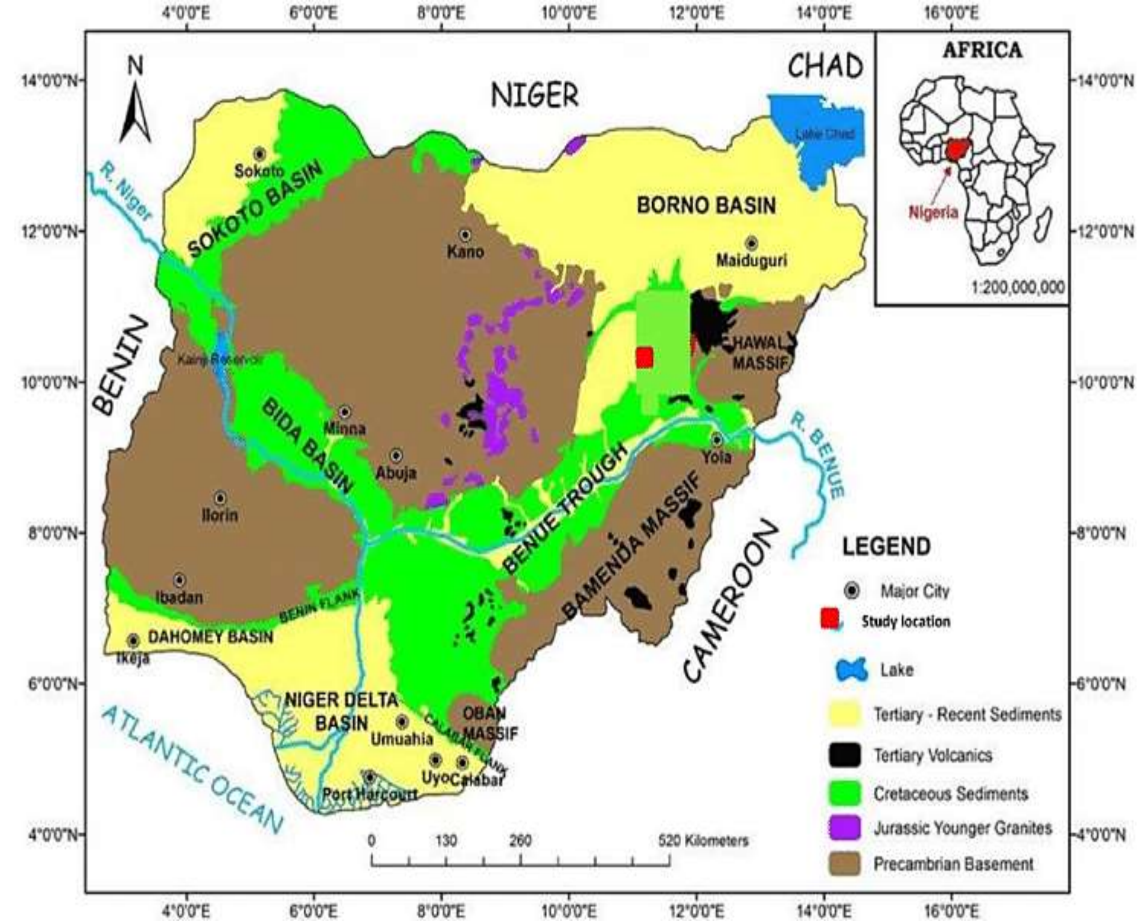

Figure 2.1: Simplified Geological Map of Nigeria showing the major Basement Complex terrains, younger sedimentary basins, and the general location of the study area (modified after Obaje, 2009)

2.3 Geology of the Nigerian Basement Complex

The Nigerian Basement Complex is universally recognized as a polycyclic terrain, meaning its constituent rocks have been formed, deformed, metamorphosed, and reworked multiple times throughout a long and complex geological history. The foundational compilation by Kogbe (1989) in "Geology of Nigeria" provides a traditional and widely used framework, dividing the Basement Complex into three major lithostratigraphic groups:

2.3.1 Migmatite–Gneiss Complex

This unit represents the oldest and most widespread component of the basement. It is a composite assemblage of high-grade metamorphic rocks that have experienced intense deformation and partial melting (Odeyemi, 1976). The complex typically includes:

i. **Banded Gneisses:** Characterized by alternating light and dark mineral layers, reflecting high-grade metamorphic differentiation.

ii. **Migmatites:** Mixed rocks that exhibit evidence of partial melting, featuring a paleosome (parent rock) and a neosome (newly crystallized melt).

iii. **Granite Gneisses:** Gneisses with a granitic composition, often showing protoclastic textures.

iv. **Charnockitic Gneisses:** Orthopyroxene-bearing granitic gneisses indicative of high temperature metamorphic conditions (Rahaman, 1976).

These rocks are generally interpreted as the deeply buried, reworked ancient crust that forms the basement upon which all younger rock successions were deposited or intruded (Grant, 1978).

2.3.2 The Schist Belts

These are Proterozoic metasedimentary and metavolcanic sequences that occur as elongated, NNE-SSW trending belts within the Migmatite-Gneiss Complex (Odeyemi, 1976). They comprise rocks such as schists, quartzites, phyllites, marbles, and amphibolites. The Igarra Schist Belt is a prominent example of this system (Udi, 2023). These belts are significant as they preserve evidence of ancient sedimentary and volcanic protoliths that were subsequently transformed during the Pan-African tectonic event (Kogbe, 1989). They record multiple phases of deformation and metamorphism, providing a history of the supracrustal environment before and during the orogeny.

2.3.3 The Pan-African Granitoids

This group represents the widespread granitic, granodioritic, and syenitic intrusions that were emplaced during the Pan-African Orogeny (Rahaman, 1976). They intrude both the Migmatite-Gneiss Complex and the Schist Belts, often cutting across the structural fabrics of the country rocks. Their mineralogy, geochemistry, and structural relationships provide a direct record of the history of crustal melting, magmatic differentiation, and the transition from compressional to extensional tectonic regimes during the waning stages of the orogenic event (Dada, 2006). The granites studied around Igarra are classified within this group of Pan-African granitoids (Udi, 2023).

2.4 Granitic Rocks in Nigeria

The Pan-African granitoid intrusions occur extensively throughout the Nigerian Basement Complex, manifesting as large batholiths, stocks, and smaller plutons. Their distribution and composition are highly variable, influenced by factors such as the depth of emplacement, the nature of the melt source, the water content of the magma, and the specific tectonic environment at the time of intrusion.

2.4.1 Classification and Types

Nigerian granites exhibit a diverse range of compositions and textures. Field and petrographic studies have identified several common types, including:

i. Biotite granites

ii. Granodiorites

iii. Syenogranites

iv. Porphyritic granites (containing large feldspar phenocrysts)

v. Hornblende granites

vi. Pegmatitic and aplitic derivatives (representing the final, fluid-rich stages of crystallization)

Field relationships often provide critical evidence for their intrusive nature, such as sharp contacts with country rocks, the presence of xenoliths (fragments of captured country rock), and late-stage cross-cutting pegmatitic veins.

2.4.2 Mineralogical Characteristics

The typical mineral assemblage of these granites forms the basis for their petrographic identification and classification. The essential minerals include:

a. **Quartz:** Anhedral to subhedral grains, often showing undulose extinction due to strain.

b. **Alkali Feldspar:** Predominantly microcline, easily identified by its distinctive cross-hatched or "tartan" twinning.

c. **Plagioclase Feldspar:** Typically showing albite or polysynthetic twinning, with compositions ranging from oligoclase to andesine.

d. **Biotite:** The most common mafic mineral, exhibiting strong pleochroism from brown to dark brown.

e. **Hornblende:** Present in some varieties, indicating a more hydrous and/or more mafic parent magma.

f. **Accessory Minerals:** These occur in minor but petrogenetically important amounts and include zircon, titanite (sphene), apatite, and opaque minerals (magnetite, ilmenite).

The relative proportions of quartz (Q), alkali feldspar (A), and plagioclase (P) are used in the standard QAP diagram for the modal classification of granitic rocks.

2.4.3 Geochemical Traits

Geochemically, the Pan-African granites of Nigeria consistently display signatures that reflect their origin through crustal melting processes. Common characteristics include:

i. High SiO_2 content, typically in the range of 65–75%, classifying them as felsic rocks.

ii. Moderate Al_2O_3 levels (12–16%).

iii. Low concentrations of MgO, CaO, and Fe_2O_3, indicating the fractionation of mafic minerals.

iv. Enrichment in Large-Ion Lithophile Elements (LILE) such as Rb, Ba, and Sr, which are incompatible and concentrate in the melt.

v. Depletion in High-Field-Strength Elements (HFSE) such as Nb, Ta, and Y, a pattern often associated with subduction-related processes or crustal melting.

These geochemical trends are consistent with petrogenetic models involving partial melting of pre-existing crustal rocks, accompanied by fractional crystallization, within a tectonic setting related to continental collision.

2.5 Geology of the Igarra Area

The Igarra region in Akoko Edo is renowned as one of the most geologically diverse parts of southwestern Nigeria. Its terrain exposes a wide array of rocks, including metasediments, gneisses, marbles, and extensive granitic intrusions, making it a natural laboratory for studying crustal evolution.

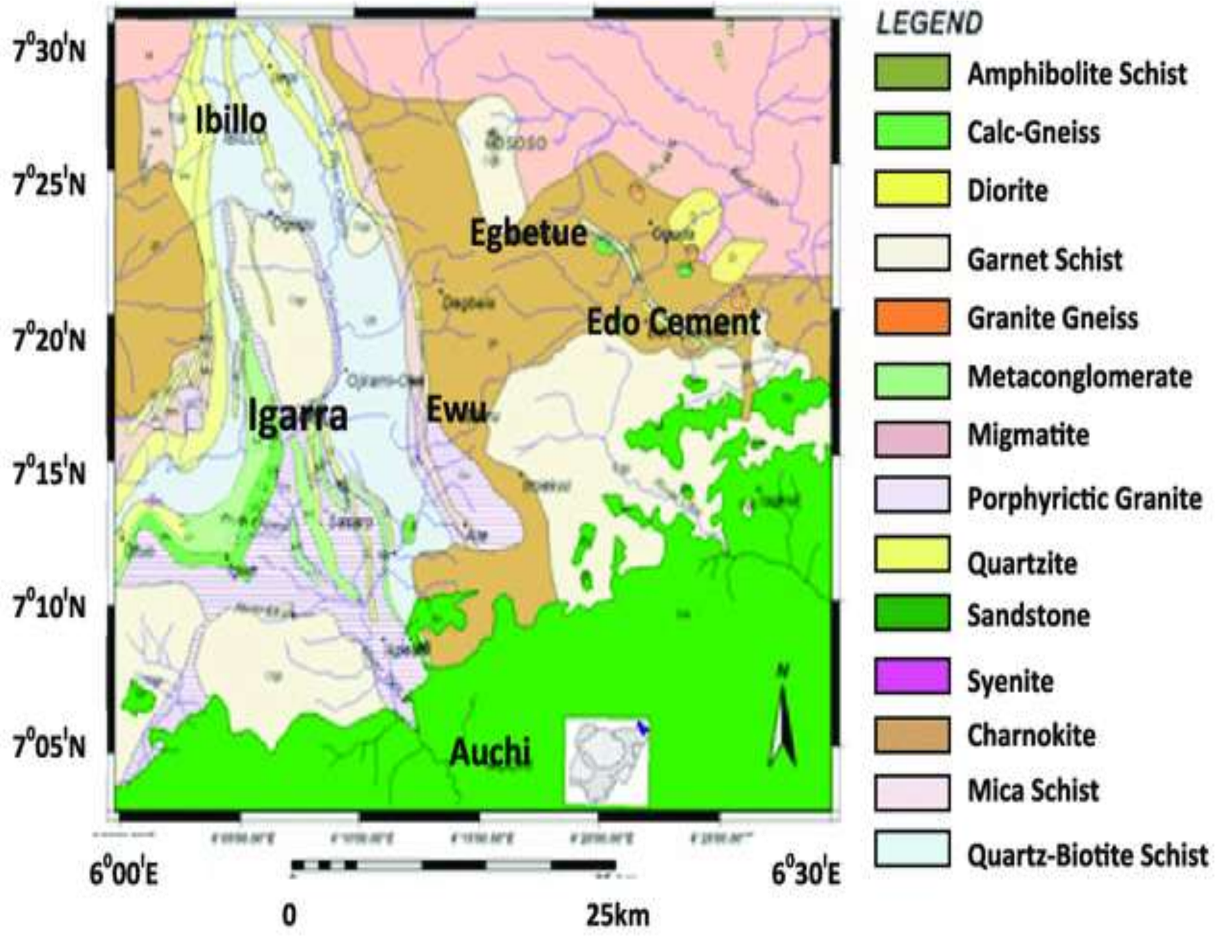

Figure 2.2: Geological map of Igarra in Edo State (modified after Anifowose et al 2006)

2.5.1 Regional Geological Framework

Based on the foundational work of Odeyemi (1976), the lithological units in the Igarra terrain can be summarized as comprising:

- Quartz-mica schists
- Calc-silicate rocks and marbles
- Quartzites
- Granite gneisses
- Granites and granodiorites (the subject of this study)
- Late-stage pegmatites and aplites

This assemblage records a history that begins with sedimentary deposition, progresses through regional metamorphism, and culminates in magmatic intrusion, representing a classic sequence of events in an orogenic belt.

2.5.2 Structural Geology and Tectonic Setting

The rocks around Igarra preserve a complex structural history indicative of multiple deformation events:

1. An early phase of folding and foliation development in the schist and marble units.
2. The development of NE-SW trending shear zones and mineral lineations, aligning with the regional structural grain of the Pan-African belt in Nigeria.
3. Late-stage brittle fracturing and jointing within the more competent granitic bodies.
4. The intrusion of pegmatites and aplitic veins along fractures and planes of weakness during the final stages of tectonic relaxation.

Udi (2023) correlated these structures with the compressional and subsequent extensional phases of the Pan-African Orogeny. In the field, the granites typically form low hills and prominent boulder exposures, often displaying exfoliation joints and other weathering features influenced by this regional structural fabric.

2.6 Petrographic Studies of Granitic Rocks

Petrography, the detailed description of rocks in thin section, is indispensable for understanding granitic rocks. The textures and mineral relationships revealed under the microscope provide critical insights into the conditions of crystallization, cooling history, and post-magmatic alterations.

2.6.1 Textures and Crystallization Features

Granitic rocks exhibit a range of textures that serve as indicators of their formation environment:

i. **Hypidiomorphic-granular:** This is the most common texture, where most crystals are subhedral (partly formed crystal faces). It is typical of slow cooling and crystallization at considerable depth within the crust (plutonic environment).

ii. **Porphyritic:** Characterized by larger crystals (phenocrysts) set in a finer-grained groundmass. This indicates a two-stage cooling history: slow cooling at depth allowing phenocryst growth, followed by more rapid cooling at shallower levels.

iii. **Graphic Intergrowth:** A intergrowth of quartz and feldspar that resembles cuneiform writing. It represents simultaneous crystallization of these two minerals from a water-rich residual melt.

iv. **Myrmekite:** An intergrowth of plagioclase and worm-like quartz, often found at the boundaries of K-feldspar grains and typically associated with deuteric (late-magmatic) alteration or deformation.

Evidence of post-crystallization processes is also common. Plagioclase often shows sericitization (alteration to fine-grained white mica), and biotite may be partially chloritized, both indicating the influence of hydrothermal fluids after the rock had largely solidified.

2.6.2 Mineral Relationships

Key mineral relationships provide further diagnostic information:

a. **Quartz** often displays undulose extinction, a wavy, non-uniform extinction under cross-polarized light, which is a clear indicator of mild solid-state deformation after crystallization.

b. **Microcline's** tartan twinning is a definitive identifier and confirms slow cooling, which allows for the necessary atomic ordering.

c. **Biotite's** pleochroism (brown to green) can indicate variations in its iron-magnesium ratio and oxidation state.

d. The presence of **hornblende** suggests the parent magma had a significant water content and a more mafic composition.

e. **Accessory minerals** like zircon and titanite are highly resistant and can preserve information about the early melt conditions even when the primary minerals have been altered. Collectively, these petrographic features are essential for determining the specific type of granite and reconstructing its crystallization and subsequent geological history.

2.7 Geochemical Classification of Granites

While petrography describes the mineralogical composition, geochemistry provides the quantitative chemical basis for a more rigorous classification and interpretation of granite origin.

2.7.1 Major Elements

The behavior of major element oxides during magmatic evolution reveals the processes of crystallization and differentiation:

- Increasing SiO_2 content correlates with a more evolved (differentiated) melt.
- Declining concentrations of Fe_2O_3, MgO, CaO, and TiO_2 mark the progressive removal of mafic minerals like biotite, hornblende, and Fe-Ti oxides through fractional crystallization.

- The ratio of K_2O to Na_2O helps distinguish between different granite types; for instance, syenogranites are typically richer in K_2O than granodiorites. These systematic variations are consistent with the trends observed in Pan-African granites throughout southwestern Nigeria.

2.7.2 Trace Elements

Trace elements, though present in low concentrations, are powerful petrogenetic indicators because they partition differently between melt and crystallizing minerals:

- Elements like Rb, Ba, and Sr are sensitive to feldspar fractionation.
- The concentrations and ratios of Nb, Ta, Y, and Zr are particularly useful for discriminating between different tectonic settings (e.g., volcanic arc, within-plate, collision).
- Rare Earth Elements (REEs) and their patterns (e.g., the presence and size of a negative Europium anomaly) reflect the degree of melt evolution and the role of specific fractionating minerals like feldspars.

Interpreting trace element ratios (e.g., Rb/Sr, Nb/Y) is a standard method for classifying granites and inferring whether they are derived predominantly from the crust, the mantle, or are hybrid in nature.

2.8 Petrogenesis of Granitic Rocks

The origin of granitic magmas can be attributed to several key geological processes operating in different tectonic environments.

2.8.1 Potential Melt Sources

- **Crustal Melting (Anatexis):** This is the most common mechanism for S-type and many I-type granites. The heating and/or decompression of pre-existing crustal rocks (either metasedimentary or meta-igneous) can cause them to partially melt.

- **Mantle–Crust Interactions:** Basaltic magma derived from the mantle can underplate the crust, transferring heat and triggering melting of the lower crust. This can produce hybrid magmas with mixed signatures.
- **Fractional Crystallization:** Advanced crystallization of a more mafic (e.g., basaltic or gabbroic) parent magma can leave behind a residual melt that is granitic in composition.

2.8.2 Role of the Pan-African Orogeny

The Pan-African Orogeny provided the ideal tectonic environment for extensive granite generation in Nigeria:

- Continental collision led to crustal thickening, which in turn caused heating and eventually partial melting of the deep crust.
- Increased heat flow from the mantle and radiogenic decay within the thickened crust promoted widespread anatexis.
- The resulting granitic magmas, being less dense and more mobile, ascended through the crust along zones of structural weakness.
- The transition to late-stage extensional tectonics allowed for the final emplacement of these magmas and the intrusion of pegmatites and aplites.

The granites in Igarra, through their textures, mineralogy, and chemical composition, are a direct record of these complex processes.

2.9 Tectonic Setting and Granite Emplacement

The Pan-African granites in the Igarra area were predominantly emplaced in a late- to post-tectonic environment. This specific setting is characterized by:

- A decline in the intense compressional stresses that dominated the peak of the orogeny.

- Crustal relaxation, uplift, and possible extensional collapse of the previously thickened orogenic wedge.
- The availability of fractures, faults, and shear zones that provided conduits for the ascent of magma.
- Final cooling and crystallization of the granites at shallow to moderate crustal depths. The cross-cutting relationships observed in the field, where granites intrude and therefore post-date the schists and marbles, provide clear field evidence for their younger age relative to the metasedimentary country rocks.

2.10 Review of Recent and Relevant Studies

The current study stands on the foundation laid by numerous previous researchers:

1. **Odeyemi (1976)** established the fundamental structural and lithological configuration of the Igarra schist and marble units, providing the first detailed geological map of the area.
2. **Kogbe's "Geology of Nigeria" (1989)** remains an essential reference, giving the indispensable regional context for understanding the Pan-African tectonic processes that shaped the Basement Complex.
3. **Agomuo's** work on the structural and petrological evolution of the nearby Ikpeshi area, which shares geological continuity with Igarra, offers valuable comparative insights.
4. **Udi (2023)** provided a more recent focus on the Pan-African orogeny and its specific impact on the basement rocks around Igarra, emphasizing structural controls.
5. **Olodokuma-Alonge and Akro (2025)** conducted petrographic and geochemical analyses specifically on granites within the Igarra-Ugbogbo zone, making their findings directly relevant and providing a contemporary dataset for comparison with the present study.

Collectively, these works provide a robust foundation upon which this current petrographic and geochemical investigation is built.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Field Description and Sample Collection Procedures

The fieldwork phase constituted the critical first step, providing the primary context and materials for all subsequent laboratory analyses. This stage involved a detailed geological assessment of granitic outcrops across the Igarra-Ugbogbo area, with careful attention to their spatial relationships with surrounding lithologies, textural variations, and the broader structural geology of the terrain.

3.1.1 Field Identification and Documentation

Prior to sampling, a reconnaissance survey was conducted to identify and map the distribution of major granitic bodies. Each accessible granite exposure was studied in detail, with observations systematically recorded in a field notebook. Key parameters documented included:

- **Macroscopic Characteristics:** Rock colour, overall grain size, and general appearance (e.g., massive, foliated, porphyritic).
- **Structural Features:** Jointing patterns, fracture density, exfoliation features, and any visible foliation or mineral alignment.
- **Contact Relationships:** The nature of contacts with adjacent country rocks (schists, gneisses, marbles), noting evidence of thermal metamorphism or assimilation.
- **Inclusions and Alteration:** Presence of xenoliths (fragments of country rock) and any signs of surface weathering or hydrothermal alteration.
- **Spatial Data:** Precise geographic coordinates for each sample location were recorded using a Garmin GPSMAP 64s global positioning system device, providing accuracy within 3 meters.

Photographic documentation of each outcrop and sample site was performed using a digital camera to provide a visual record for later reference.

3.1.2 Criteria for Sample Selection

To ensure the analytical results reflected primary magmatic characteristics and not secondary alteration, strict criteria were applied during sample selection:

- **Freshness:** Only unweathered, pristine samples were collected. The outer, weathered rind of outcrops was removed using a geological hammer to access fresh rock beneath.
- **Representativeness:** Samples were chosen to represent the dominant textural and compositional varieties observed within the granite bodies, ensuring the dataset captured the natural diversity present in the field.
- **Sample Integrity:** Blocks weighing approximately 3-5 kilograms were collected to provide ample material for thin section preparation, powdering for geochemical analysis, and archival storage.
- **Avoidance of Contamination:** Care was taken to avoid areas with visible veins, intense jointing, or obvious hydrothermal alteration to prevent analytical bias.

Five samples that best met these criteria were selected as the focus of this study and assigned the unique identifiers SJ 01 through SJ 05.

3.1.3 Techniques Used in Sample Extraction

Sample extraction was performed using standard geological tools, including a 2.5 pound crack hammer and a variety of cold chisels. For massive, unjointed outcrops, deeper cuts were made to extract corestones that showed minimal surface alteration. Each sample was immediately placed in a sturdy, labeled sample bag, with a duplicate label placed inside to prevent loss of identity. The samples were then transported to the laboratory for preparation.

3.2 Laboratory Sample Preparation

The laboratory phase involved preparing the field samples into forms suitable for microscopic and chemical analysis. This process required careful, contamination free techniques to preserve the original rock properties.

3.2.1 Cutting and Trimming of Samples

Upon arrival at the laboratory, each rock sample was cut using a Buehler® Isomet 1000 precision diamond saw. This process served two purposes: to create a flat, stable base for thin section preparation, and to obtain a representative chip for crushing and pulverization. Water was used as a coolant and lubricant during cutting to prevent thermal alteration of the samples and to suppress dust.

3.2.2 Thin Section Preparation

The production of high quality thin sections is paramount for accurate petrographic analysis. The procedure followed standard petrological protocols:

1. **Mounting:** A trimmed rock billet, approximately 30 mm x 45 mm in size, was affixed to a glass slide using a clear, high strength epoxy resin. The resin was allowed to cure for 24 hours to ensure a permanent bond.
2. **Grinding and Lapping:** The mounted sample was progressively ground to a thickness of about 80-100 microns using a series of silicon carbide abrasive powders (from coarse 120 grit to fine 600 grit) on a rotating lap wheel.
3. **Final Thinning and Polishing:** The section was then carefully hand-thinned to the standard thickness of 30 microns, at which point most rock-forming minerals become transparent and display their characteristic interference colours under cross-polarized light. A final polish with 0.3-micron aluminum oxide powder ensured a scratch-free surface for clear observation.

4. **Cover-slipping:** A thin glass cover slip was applied over the rock slice using Canada balsam as a mounting medium, creating a permanent, protected thin section ready for microscopic examination. Each finished section was labeled with its corresponding sample code (SJ 01-SJ 05).

3.2.3 Sample Pulverization for Geochemical Analysis

The remaining portions of each sample, distinct from those used for thin sections, were processed for geochemical analysis. The procedure was as follows:

- **Primary Crushing:** Rock chips were initially reduced to gravel-sized fragments (~<2 cm) using a hardened steel jaw crusher.
- **Pulverizing:** These fragments were then pulverized to a fine, homogeneous powder (<75 µm) in a tungsten carbide TEMA mill to minimize contamination and ensure a representative sample for XRF analysis.
- **Storage:** The resulting powders were stored in sealed, labeled plastic vials to protect them from moisture and atmospheric contamination prior to analysis.

3.3 Petrographic Examination

We carried out petrographic analysis to get a detailed look at the mineral makeup and texture of the granite samples. We examined the thin sections using a Leica DM750 P polarizing microscope, which lets you view samples in both plane-polarized light (PPL) and cross-polarized light (XPL). Switching between these two modes is crucial because it reveals different properties of the minerals, making identification much more accurate.

3.3.1 Mineral Identification Techniques

We identified minerals based on their unique optical properties, which is a standard method in optical mineralogy. Here’s a breakdown of what we looked for in each mode and why it was important for getting the results we’ll discuss later in Chapter Four:

- **Observations in Plane-Polarized Light (PPL):**
    - **Purpose:** We use PPL mainly to see how minerals absorb light. This tells us about their color and clarity.
    - **Colour and Pleochroism:** A mineral's plain color in PPL is a big clue. For example, when we rotated the stage and saw biotite change from light brown to dark brown, that confirmed its identity. This is the pleochroism we mention in the results for all our samples.
    - **Crystal Shape:** In PPL, it's easiest to see the crystal shapes, whether they are perfectly formed (euhedral), partly formed (subhedral), or irregular (anhedral). This is how we noted that the quartz grains were mostly anhedral to subhedral.
    - **Cleavage:** We also looked for cleavage planes, which are straight lines inside the grains where the mineral breaks. Seeing the perfect cleavage in biotite and muscovite was a key part of identifying them.
- **Observations in Cross-Polarized Light (XPL):**
    - **Purpose:** XPL is where we see what happens when light splits inside a crystal. This gives us interference colors and tells us about the mineral's internal structure.
    - **Birefringence and Interference Colours:** The bright colors you see in XPL are like a fingerprint. Quartz, for instance, typically shows up in dull grays and whites. Seeing this helped us pick out all the quartz grains in our samples.
    - **Extinction Angle:** This is the angle a crystal goes dark at when we rotate the stage. We specifically measured this on the plagioclase grains. By doing this, we could figure out that our plagioclase was mostly oligoclase to andesine, which we report in Section 4.2.1.
    - **Twinning:** XPL makes twinning patterns really stand out. The multiple parallel lines in plagioclase (polysynthetic twinning) and the cross-hatched "tartan" pattern in microcline are dead

giveaways. This was the main way we identified these feldspars and estimated their abundance for Table 4.1.

Undulose Extinction: When we saw quartz grains that didn't go dark all at once but had a wavy, shimmering extinction, we knew it was a sign of strain. This direct observation under XPL is what let us conclude that the rocks experienced some deformation after they formed, a point we discuss in both Sections 4.2.1 and 4.2.2.

3.4.3 Modal Composition

To supplement qualitative observations, a semi-quantitative estimation of the modal mineralogy (mineral percentages by volume) was performed using visual estimation charts. This provided a numerical basis for the petrographic classification of the granites, particularly for positioning the samples on the standard Quartz-Alkali Feldspar-Plagioclase (QAP) classification diagram (Streckeisen, 1976).

3.4 Geochemical Analysis of Major and Trace Elements

Geochemical analysis was performed at the RAOLAB Research and Diagnostic Laboratory. The major objective was to determine the concentrations of major element oxides and a suite of trace elements crucial for petrogenetic interpretation using wavelength-dispersive X-ray fluorescence (WD-XRF) spectrometry.

3.4.1 Analytical Setup and Calibration

A PANalytical Axios max WD-XRF spectrometer was used for the analysis. The instrument was calibrated using a suite of international certified reference materials (CRMs) of similar composition to granitic rocks to ensure analytical accuracy. Analytical conditions (voltage, current) were optimized for each element to achieve the best detection limits and precision.

3.4.2 Sample Preparation for XRF

Two types of pellets were prepared for each sample:

Fused Glass Beads for Major Elements: A homogeneous mixture of 0.6 g of sample powder and 6.0 g of lithium tetraborate flux (a 1:12 dilution) was fused in a platinum crucible at 1050°C to create a homogeneous glass bead. This method eliminates mineralogical effects and ensures accurate major element analysis.

Pressed Powder Pellets for Trace Elements: 10 g of sample powder was mixed with a few drops of polyvinyl alcohol (PVA) binder and pressed under 25-ton pressure in a hydraulic press to form a solid, stable pellet.

3.4.3 Oxides and Elements Measured

The analysis provided quantitative data for:

Major Oxides (reported in wt.%): SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, MnO, P_2O_5.

Loss on Ignition (LOI): Determined by heating a separate powder sample to 1000°C, this measures volatile content (e.g., H_2O, CO_2).

Trace Elements (reported in ppm): Ba, Rb, Sr, Y, Zr, Nb, Ga, Zn, Cu, Ni, V, Cr, and others as detailed in the results chapter.

3.5.4 Quality Assurance and Quality Control (QA/QC)

To ensure data reliability, a rigorous QA/QC protocol was implemented:

Replicate Analysis: Selected samples were prepared and analyzed in duplicate to monitor precision. The relative standard deviation for major elements was typically <1%.

Standard Analysis: Certified reference materials (e.g., G-2, Granite) were analyzed intermittently with the unknown samples to verify analytical accuracy. The results for the standards consistently fell within the certified ranges.

- **Blank Correction:** Routine analysis of a blank (the flux alone) was performed to correct for any background contribution from the flux or the preparation process.

3.5 Data Processing and Interpretation

The integration of petrographic and geochemical data formed the basis for all interpretations.

- **Petrographic Classification:** Modal mineral proportions were used to classify the samples on the International Union of Geological Sciences (IUGS) QAP diagram.
- **Geochemical Classification:** Major element data were plotted on the Total Alkali-Silica (TAS) diagram and used to calculate important petrogenetic indices such as the Aluminum Saturation Index (ASI).
- **Tectonic Discrimination:** Trace element concentrations and ratios (e.g., Rb vs. Y+Nb) were applied to established tectonic discrimination diagrams to infer the likely tectonic setting of magma emplacement.
- **Petrogenetic Modelling:** The combined dataset was interpreted to develop a coherent model for the origin and evolution of the Igarra granites, considering processes such as partial melting, fractional crystallization, and crustal contamination.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and interprets the petrographic and geochemical results from five granite samples (SJ01–SJ05) collected across the Igarra Ugbogbo area. It begins with mineralogical and textural observations from thin section petrography, followed by XRF derived geochemical data. The findings are evaluated within established geological models for Pan-African granites in southwestern Nigeria. Emphasis is placed on petrogenetic, tectonic, and evolutionary interpretations.

4.2 Petrographic Results

The petrographic study provides the most direct insight into the mineralogical framework, textural organization, and internal relationships among the constituent minerals of the Igarra granites. The modal compositions derived from detailed thin-section examination reveal well-crystallized plutonic textures and quantify the proportions of essential rock forming minerals. The modal concentrations of quartz, microcline, plagioclase, biotite, hornblende, muscovite, and opaque minerals are presented in Table 4.1.

Table 4.1: Modal Composition of Granite Samples (SJ01–SJ05) (Vol. %)

SAMPLE	QUARTZ	MICROCLINE	PLAGIOCLASE	BIOTITE	HORNBLEND	MUSCOVITE	OPAQUE
SJ 1	**30**	**20**	**33**	**10**	**4**	**3**	**-**
SJ2	**31**	**22**	**33**	**7**	**4**	**3**	**-**
SJ3	**21**	**20**	**35**	**8**	**2**	**4**	**-**
SJ 4	**29**	**26**	**35**	**7**	**2**	**5**	**-**
SJ 5	**30**	**21**	**35**	**7**	**3**	**4**	**-**

4.2.1 Mineralogical Composition

The modal analysis reveals a consistent mineralogical assemblage dominated by quartz, alkali feldspar (microcline), plagioclase, and biotite across all five samples. Quartz constitutes between 21–31% of the rock volume, forming anhedral to subhedral grains that frequently display undulose extinction under crossed polars. This optical phenomenon indicates that the granites experienced mild but pervasive deformation or crystal-plastic strain after their initial crystallization. Quartz typically occurs as interstitial patches filling spaces between earlier-formed feldspars, and in several samples, it forms interlocking mosaics with feldspar, a texture reflective of slow, uninterrupted cooling in a stable plutonic environment.

Microcline is consistently present in significant proportions (20–26%), readily identified by its characteristic cross-hatched "tartan" twinning. The crystals often exhibit perthitic exsolution textures and cloudy alteration patches, indicative of late-stage deuteric or hydrothermal activity. Its abundance, corroborated by moderate K_2O concentrations in the geochemical data, points to a melt that was enriched in potassium during the final stages of crystallization.

Plagioclase feldspar represents the highest single mineral proportion in most samples (31–35%), typically exhibiting well-developed albite and Carlsbad twinning. Based on maximum extinction angles measured on the universal stage, the plagioclase composition ranges from oligoclase to andesine (An_{25}–An_{40}). In several thin sections, particularly in samples SJ02 and SJ04, plagioclase cores show mild to moderate sericitization - a fine-grained alteration to white mica, suggesting the influence of hydrothermal fluids during or shortly after emplacement.

Biotite occurs in significant amounts (7–10%), manifesting as subhedral to euhedral brown pleochroic plates. In samples SJ01 and SJ03, portions of the biotite crystals appear partially chloritized along cleavage planes and crystal margins, a typical manifestation of late-stage alteration processes where ferromagnesian minerals react with circulating, low-temperature hydrous fluids. Hornblende is present but in consistently small quantities (2–4%), indicating that the parent magma had only a moderate mafic component. Its green to brown pleochroism and prismatic habit are characteristic. Muscovite appears in minor amounts (3–5%), and while present in low proportions, its occurrence as both primary and secondary phases alongside biotite suggests the granites possess a slightly peraluminous tendency. Opaque minerals, primarily magnetite and ilmenite, are present in trace amounts (<1%), typically as fine, anhedral grains disseminated throughout the rock matrix.

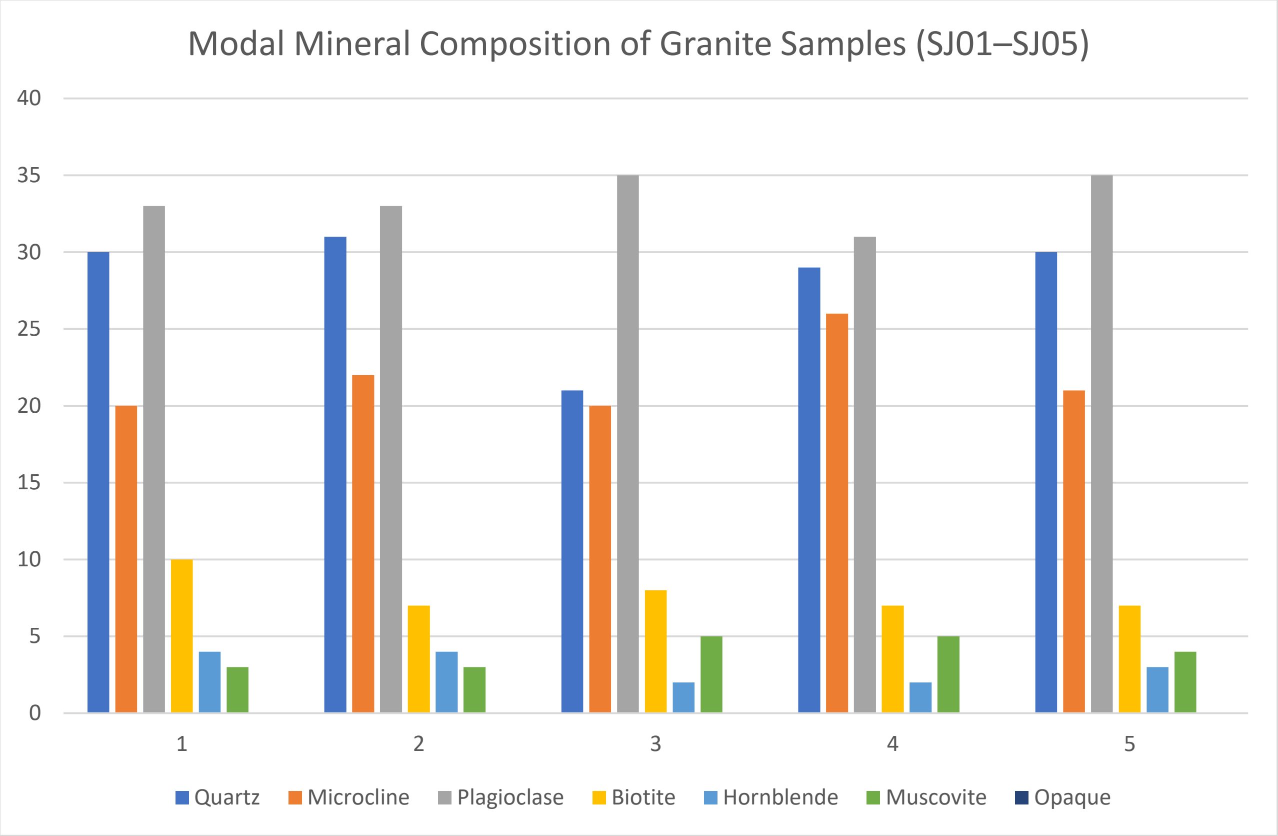

Fig 4.1; This is the modal composition of the analysed minerals.

4.2.2 Textural Characteristics

All samples display a dominant hypidiomorphic-granular texture, a hallmark of granites that solidified slowly within the crust, allowing for the partial development of crystal faces. In samples SJ01, SJ02, and SJ05, a weak preferred orientation of elongate minerals is observed, which correlates spatially with the undulose extinction in quartz. This suggests the rocks were subjected to mild but pervasive tectonic stress during or shortly after final crystallization.

In samples SJ03 and SJ04, the texture is slightly porphyritic, marked by the presence of larger microcline and plagioclase phenocrysts (up to 1.5 cm) set in a medium-grained groundmass. This signifies a two-stage crystallization history: an initial phase of slow cooling at greater depth allowing for phenocryst growth, followed by emplacement and more rapid cooling at a higher crustal level. Occasional graphic intergrowths of quartz and feldspar were noted in the groundmass of sample SJ05, representing the final crystallization from a silica-rich residual melt approaching eutectic composition.

4.2.3 Photomicrographs

The microscopic examination of the granite samples provided further clarity on the mineral relationships, textural patterns and optical properties observed during thin-section analysis. The photomicrographs presented in this section illustrate the key mineral constituents, their optical behavior in plane-polarized light (PPL) and cross-polarized light (XPL), and the textures that support field observations and modal analysis. Each sample exhibits a distinct interplay of quartz, feldspars, biotite and minor accessory minerals, yet collectively they reflect the felsic and holocrystalline nature of the Igarra granites.

Sample SJ 01

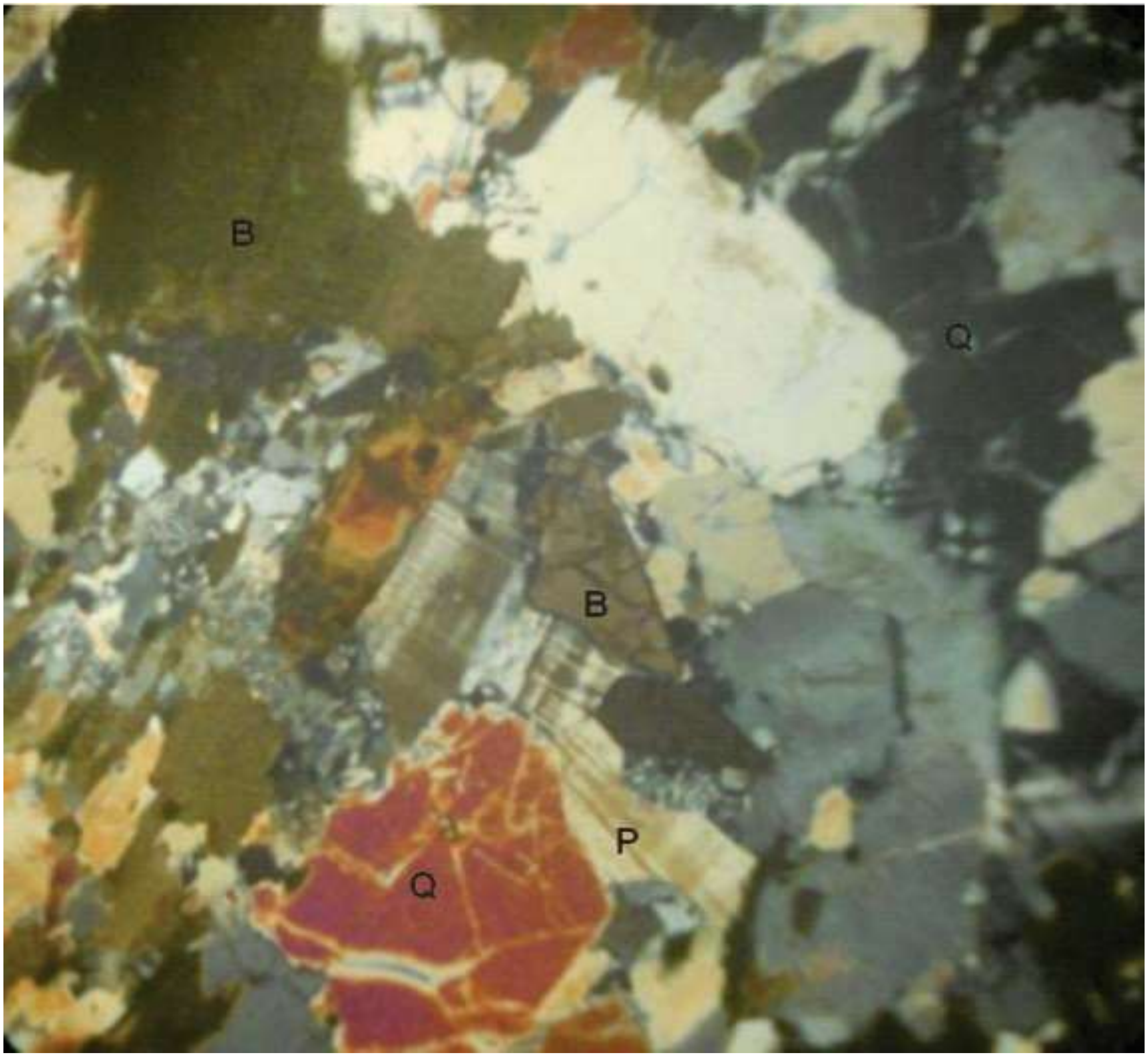

Figure 4.2: *Photomicrograph of Sample SJ01 in PPL showing anhedral to subhedral quartz grains occurring alongside microcline and plagioclase. Biotite displays weak pleochroism from light brown to dark brown, with occasional cleavage traces visible. The overall texture is granoblastic with slight interlocking of mineral boundaries.*

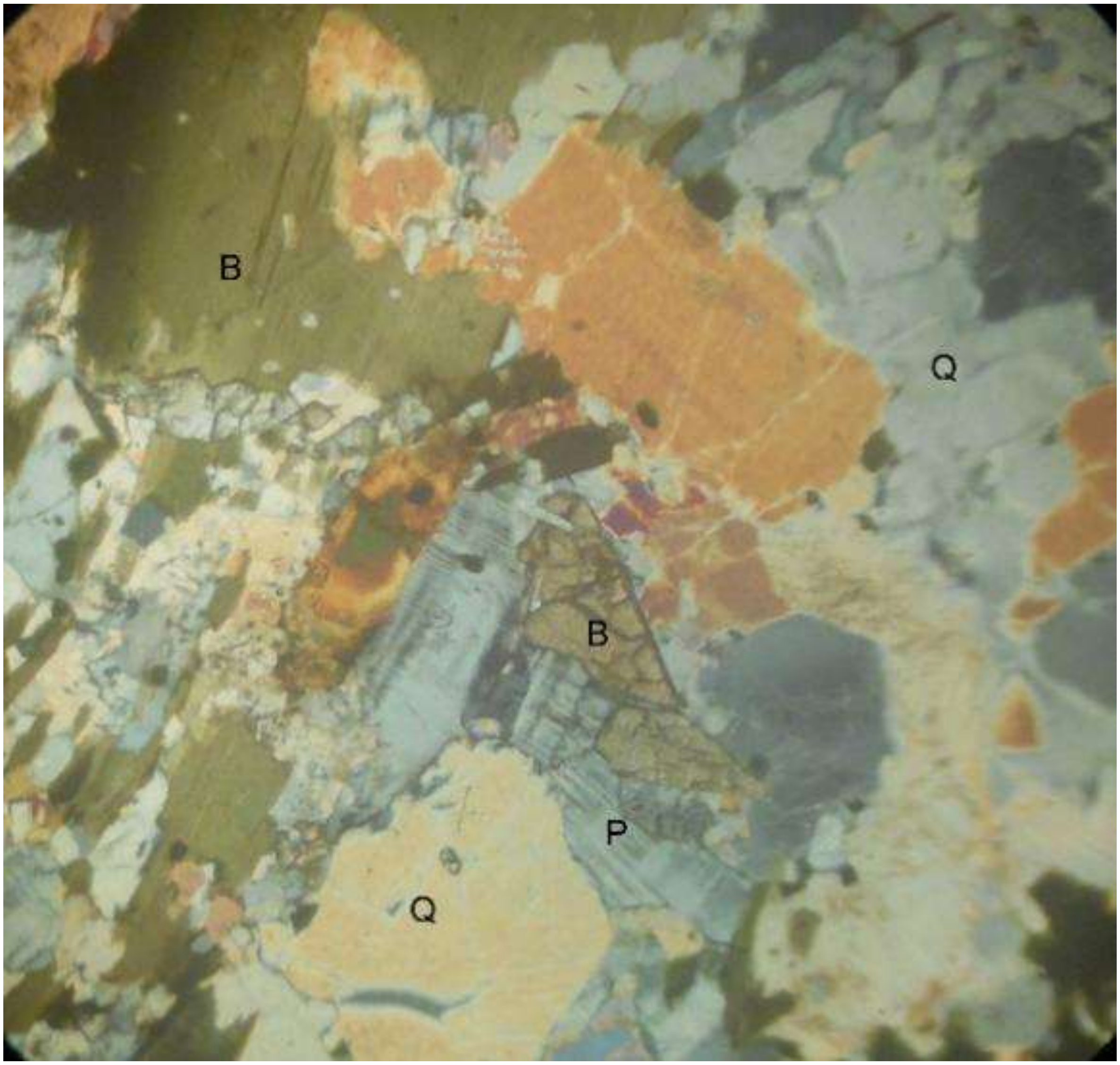

Figure 4.3: *Photomicrograph of Sample SJ01 in XPL highlighting quartz with characteristic undulose extinction, microcline showing distinct tartan twinning, and plagioclase exhibiting polysynthetic twinning. The feldspars form a slightly interlocking mosaic, supporting a hypidiomorphic-granular texture.*

Sample SJ 02

Figure 4.4: *Photomicrograph of Sample SJ02 in PPL showing abundant quartz and feldspars with biotite flakes distributed along grain boundaries. Biotite shows moderate pleochroism and occasional alteration along cleavage planes. Feldspars appear subhedral, with some showing cloudy extinction patterns due to incipient alteration.*

Figure 4.5: *Photomicrograph of Sample SJ02 in XPL displaying well-developed polysynthetic twinning in plagioclase and tartan twinning in microcline. Quartz grains exhibit smooth to slightly wavy extinction. The feldspar-quartz relationship is interlocking, consistent with typical granite textures.*

Sample SJ03

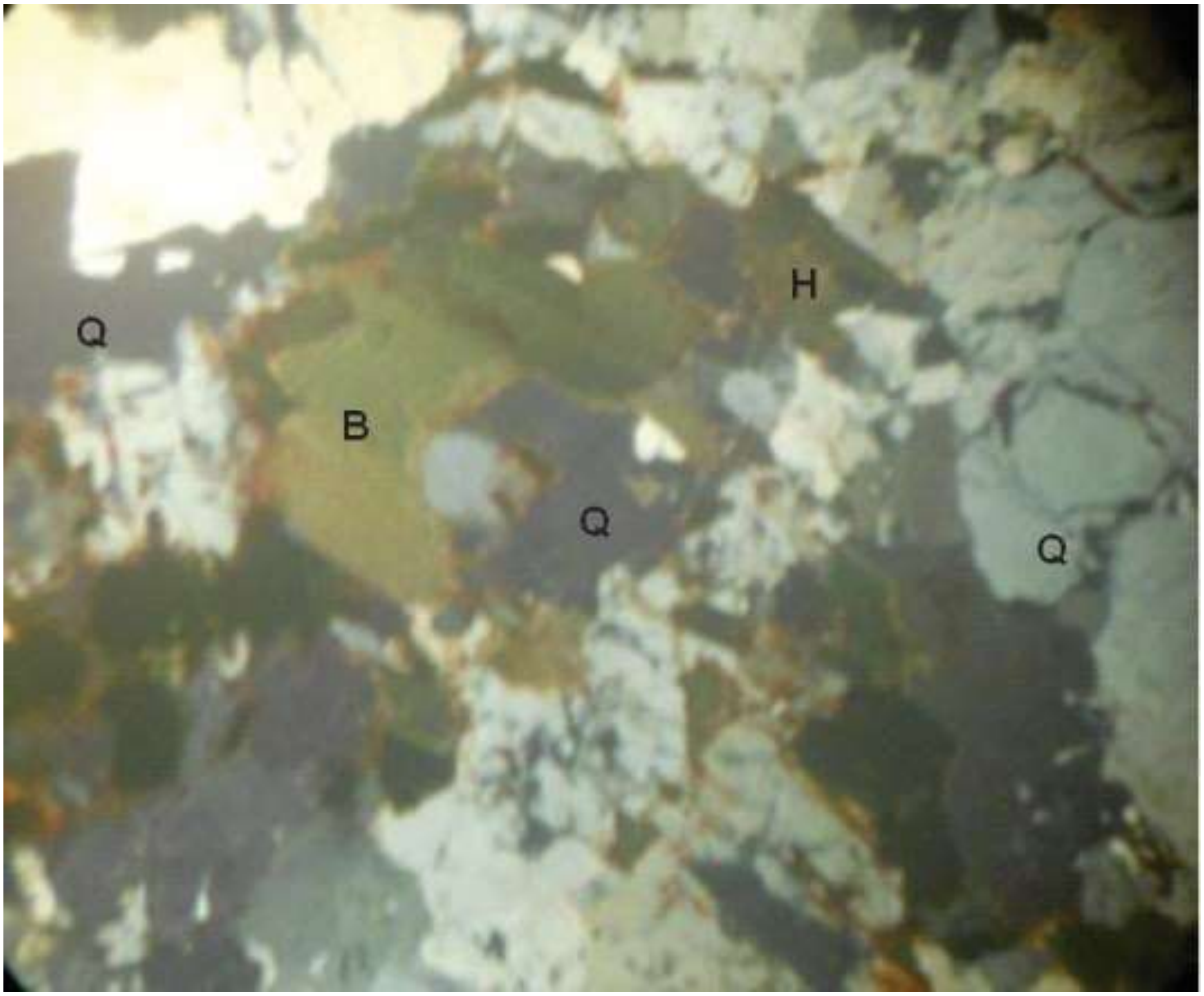

Figure 4.6: *Photomicrograph of Sample SJ03 in PPL showing relatively higher plagioclase content, with grains occurring as subhedral laths that form a significant portion of the groundmass. Quartz is present as irregular patches while muscovite flakes appear as clear, low-relief minerals with perfect basal cleavage. Minor biotite displays light pleochroism.*

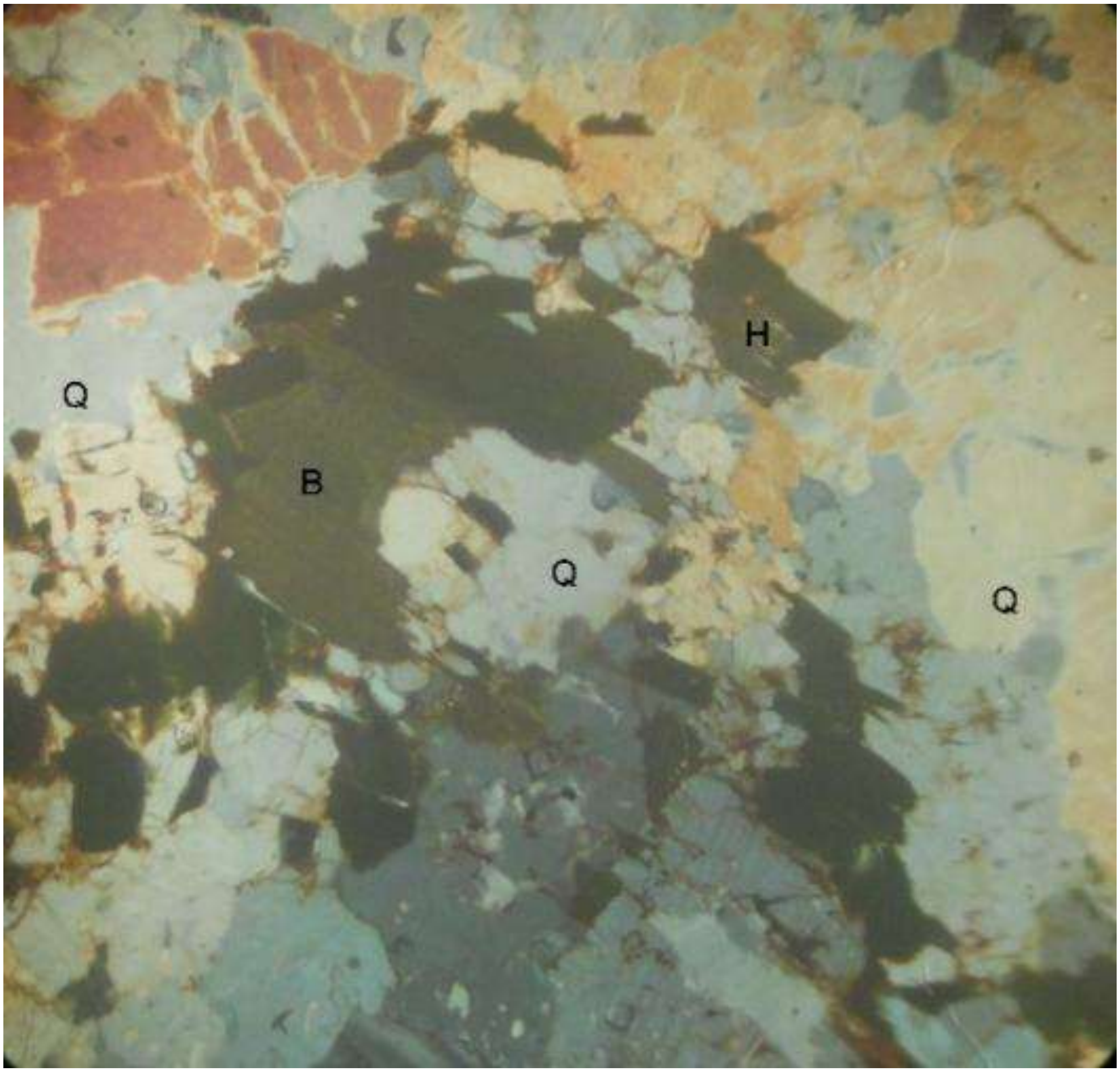

Figure 4.7: *Photomicrograph of Sample SJ03 in XPL illustrating bright interference colors in plagioclase, with distinct polysynthetic twinning. Quartz grains show undulose extinction, while muscovite exhibits straight extinction and second-order interference colors. The texture remains dominantly hypidiomorphic with closely packed grains.*

Sample SJ04

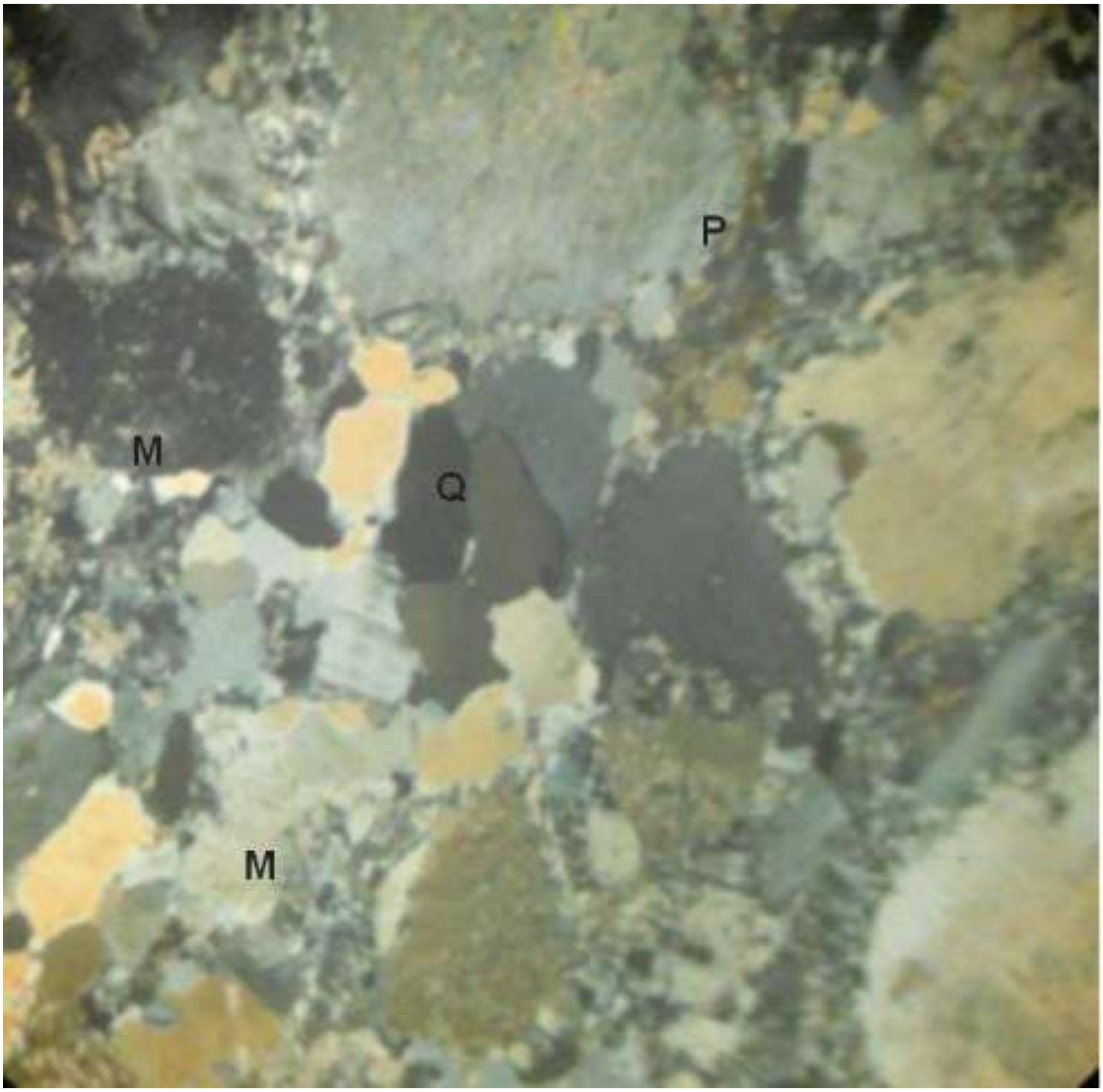

Figure 4.8: *Photomicrograph of Sample SJ04 in PPL showing a relatively higher microcline content compared to other samples. The feldspars appear subhedral with slight alteration rims. Quartz grains occur in irregular patches and biotite shows moderate pleochroism with faint alteration to chlorite along grain margins.*

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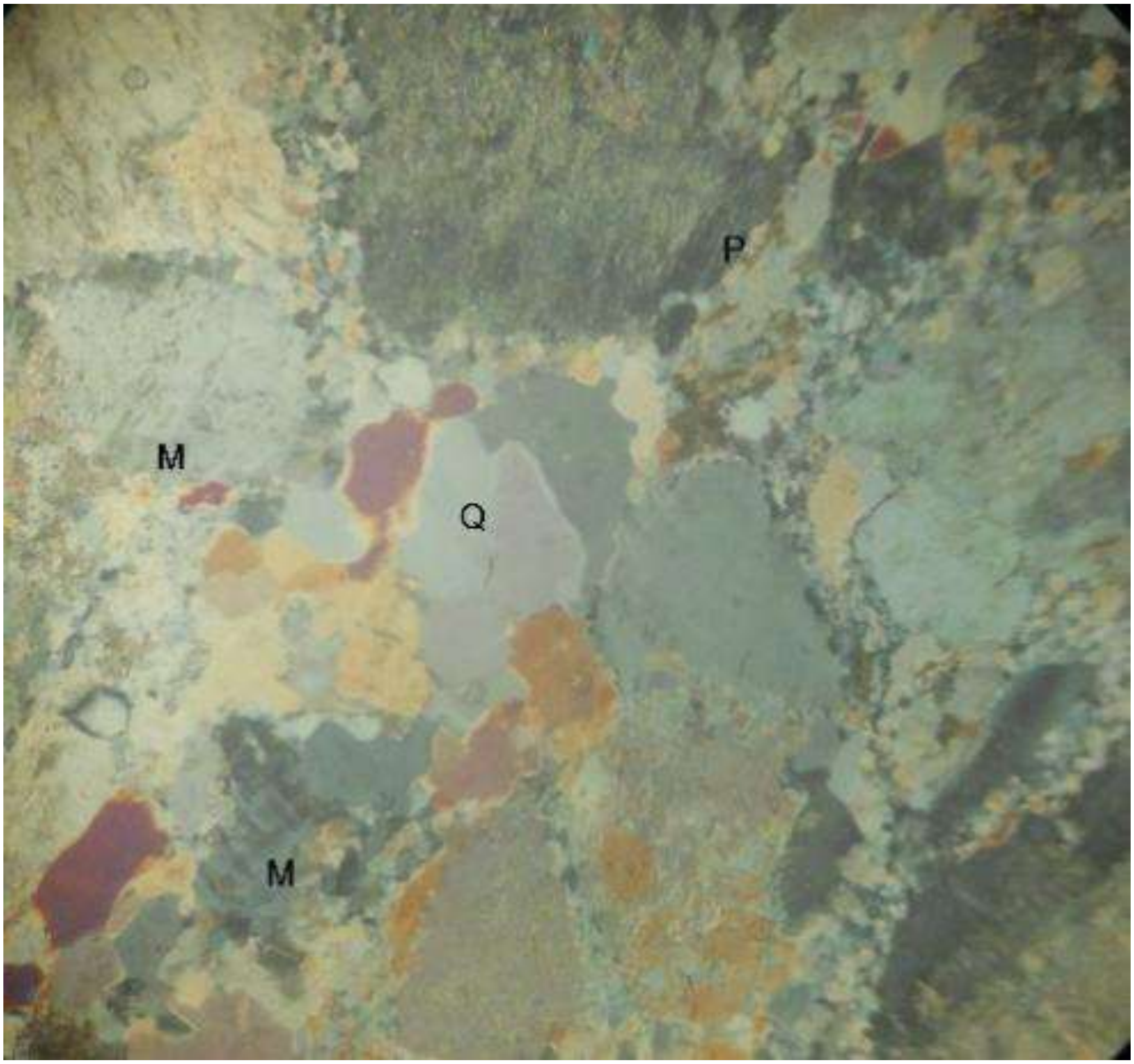

Figure 4.9: *Photomicrograph of Sample SJ04 in XPL showing well-developed tartan twinning in microcline and polysynthetic twinning in plagioclase. Quartz displays characteristic wavy extinction. Muscovite flakes, though minor, exhibit straight extinction and moderate birefringence*

Sample SJ05

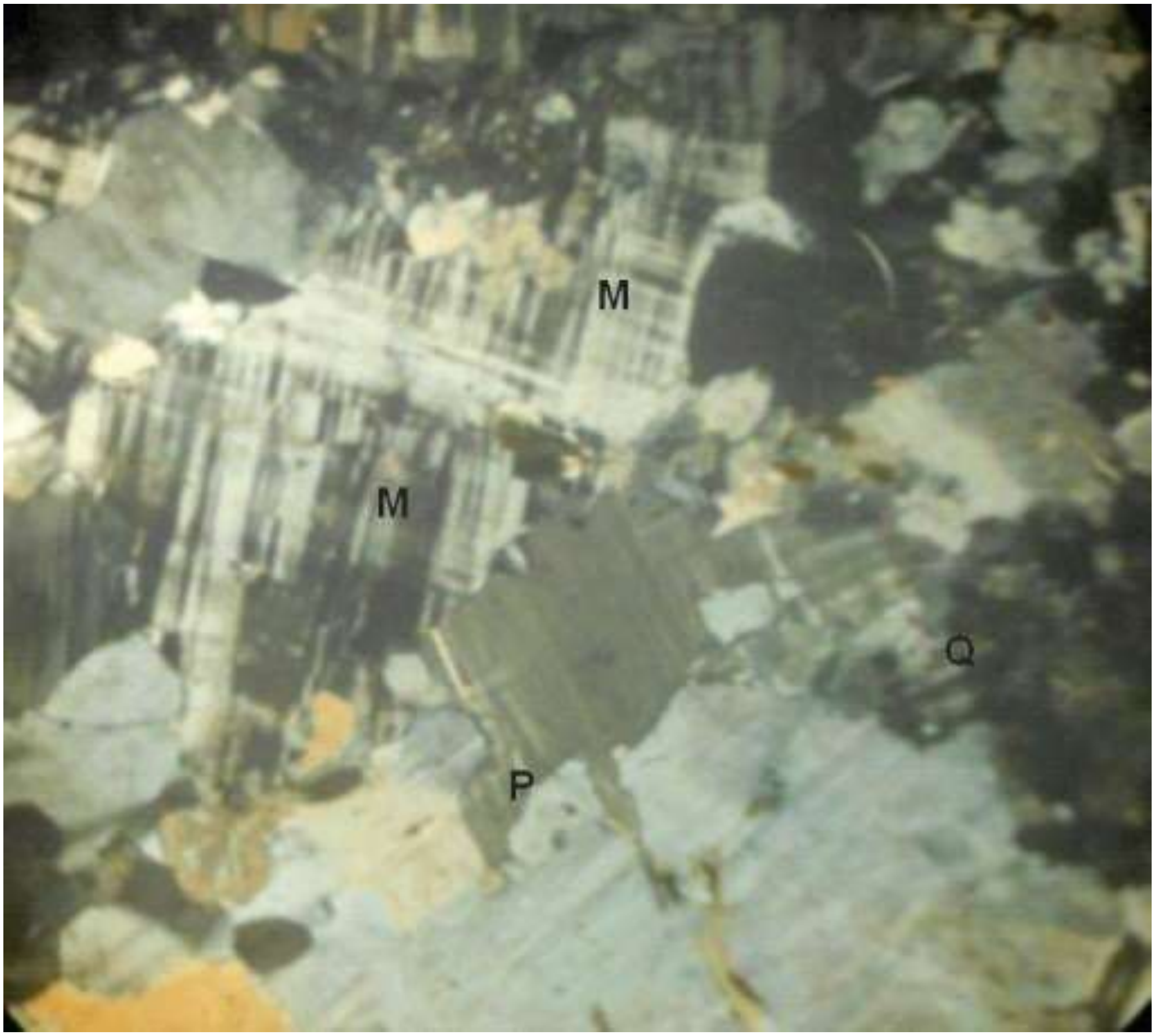

Figure 5.0: *Photomicrograph of Sample SJ05 in PPL revealing abundant plagioclase and quartz with moderate amounts of microcline. Biotite is present in small proportions and shows brown pleochroism. Muscovite appears as colorless flakes with perfect basal cleavage. The minerals form a fine to medium grained interlocking network.*

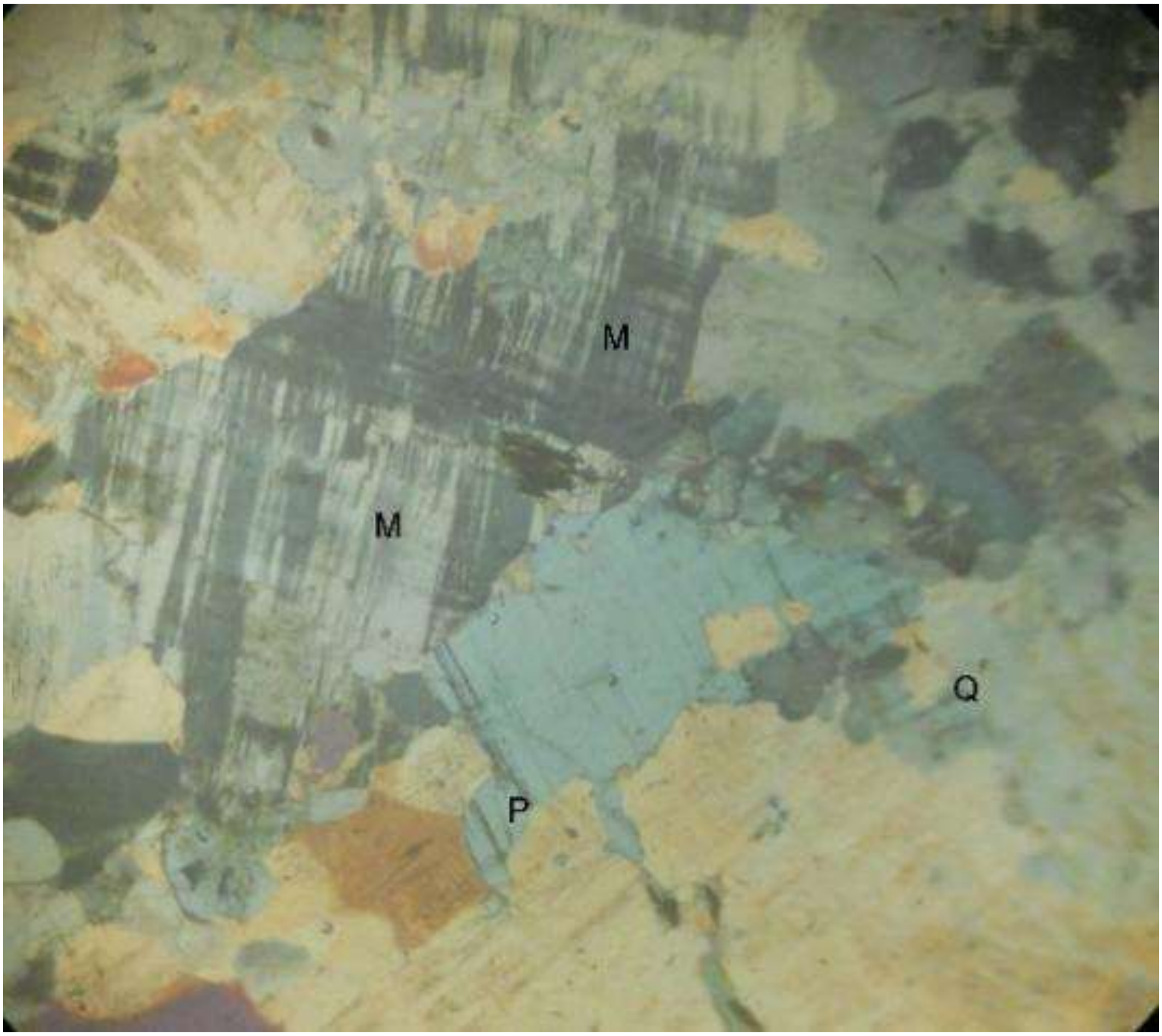

Figure 5.1: *Photomicrograph of Sample SJ05 in XPL highlighting bright interference colors in plagioclase, tartan twinning in microcline and undulose extinction in quartz. The overall texture is hypidiomorphic-granular, with a few grains showing slight sericitization along cleavage planes.*

4.3 Geochemical Composition

The geochemical results provide the quantitative basis for classifying the granites and interpreting their petrogenesis. The data are divided into two categories: (1) major-element oxides, which constitute the bulk chemical composition, and (2) trace elements, which offer more sensitive indicators of magma source, differentiation processes, and tectonic setting.

4.3.1 Major Element Chemistry

The major-element results (Table 4.2) reveal that the Igarra granites are chemically felsic and strongly siliceous. Silica (SiO_2) levels are consistently high across all samples, ranging from 69.23% to 71.44% (anhydrous basis), confirming a high degree of magmatic differentiation. Such elevated SiO_2 concentrations are typical of Pan-African granitoids within the Nigerian Basement Complex, which often result from extensive crustal melting and prolonged fractional crystallization.

Alumina (Al_2O_3) values are substantial, between 12.01% and 13.02%, reflecting adequate aluminum to support the feldspar-rich mineralogy observed petrographically. The low concentrations of Fe_2O_3(t) (3.16–4.50%), MgO (0.91–1.99%), and CaO (2.93–3.91%) are indicative of the early and efficient removal of mafic minerals (e.g., biotite, hornblende) from the melt through fractional crystallization. Potassium oxide (K_2O) values (2.70–2.84%) correlate well with the significant modal abundance of microcline, while sodium oxide (Na_2O) values (2.04–2.88%) align with the plagioclase content. The low TiO_2 values (0.56–0.89%) are consistent with the minimal modal abundance of Ti-bearing phases such as ilmenite or sphene.

The molecular $Al_2O_3/(CaO+Na_2O+K_2O)$ ratios, known as the Aluminum Saturation Index (ASI), range from 0.98 to 1.05. This places the samples on the boundary between metaluminous and weakly peraluminous compositions, a characteristic feature of I-type granites derived from igneous protoliths. The overall major-element chemistry, particularly the high silica and alkali contents, places all samples firmly within the granite field on the Total Alkali-Silica (TAS) classification diagram.

Table 4.2: Major Element Oxide Concentrations of Granite Samples (wt.%)

Oxides (wt.%)	**SJ 01**	**SJ 02**	**SJ 03**	**SJ 04**	**SJ 05**
SiO_2	69.23	70.01	71.44	69.92	70.12
Al_2O_3	12.99	13.02	12.01	12.18	12.16
Fe_2O_3	4.50	3.16	4.02	4.04	3.25
TiO_2	0.56	0.62	0.81	0.89	0.63
CaO	3.87	3.28	2.93	3.91	3.69
P_2O_5	0.83	0.70	0.59	0.89	0.92
K_2O	2.73	2.82	2.84	2.70	2.73
MnO	0.14	0.19	0.29	0.19	0.81
MgO	0.91	1.98	1.89	1.76	1.99
Na_2O	2.83	2.88	2.04	2.41	2.76
LOI	0.69	0.69	0.71	0.72	0.70

4.4 Trace Element Geochemistry

Trace elements provide powerful insights into magmatic processes because their concentrations are strongly fractionated by crystallization, partial melting, and crustal contamination. The trace-element data for key diagnostic elements are presented in Table 4.3.

4.4.1 Large-Ion Lithophile Elements (LILE): Ba, Rb, Sr, Cs

Barium and Strontium concentrations in the samples are moderately high (Ba: 449–523 ppm; Sr: 99–116 ppm), reflecting a melt in which feldspars were stable phases during a significant portion of the crystallization history. Their concentrations have not been depleted to very low levels, suggesting that feldspar fractionation occurred but did not proceed to exhaustion.

Rubidium values are elevated (120–209 ppm), with SJ04 having the highest concentration. As an incompatible element, Rb is concentrated in the melt during fractional crystallization, being excluded from the structures of early crystallizing plagioclase and mafic minerals. The high Rb values, particularly in the more silica-rich samples, support a model of extended fractional crystallization of the parent melt. Cesium values (10.64–21.83 ppm) show a slight enrichment, further supporting melt evolution and possible fluid interaction in the later stages of magmatism.

4.4.2 High-Field-Strength Elements (HFSE): Nb, Ta, Y, Th, U

The HFSE distribution is particularly informative for deciphering tectonic setting and source characteristics. The granites exhibit the following ranges:

- Nb: 12.40–20.16 ppm
- Ta: 4.32–8.12 ppm
- Y: 7.92–9.33 ppm
- Th: 3.50–8.12 ppm
- U: 1.31–5.44 ppm

The moderate enrichment of Nb and Ta, coupled with low Y concentrations, is typical of granitoids derived from crustal sources that have been influenced by tectonic thickening a characteristic of late to post collisional granites. The significant enrichment in the incompatible elements Thorium and Uranium suggests partial melting of crustal protoliths, particularly in tectonothermal regimes such as the Pan-African Orogeny, where the continental crust was heated and mobilised.

4.4.3 Transition and Ore-Related Elements: Cu, Pb, Sc

Copper values are low (6.03–8.98 ppm), as expected in highly evolved, felsic granites from which sulphide minerals have been largely excluded. Lead values are variable (3.17–10.52 ppm), consistent with the heterogeneous distribution of accessory minerals like zircon and feldspars that can incorporate Pb. Scandium concentrations remain low (5.32–9.12 ppm), which is consistent with minimal direct input from a mafic mantle source, as Sc is compatible in mafic minerals.

Table 4.3: Trace Element Concentrations of Granite Samples (ppm)

Element (ppm)	SJ 01	SJ 02	SJ 03	SJ 04	SJ 05
Ba	449.22	502.87	501.43	523.17	493.02
Rb	128.33	120.50	119.06	209.56	153.32
Y	8.63	7.92	9.33	8.12	8.77
Nb	15.32	12.40	20.16	19.13	18.19
Ta	4.32	6.12	6.42	8.12	6.78
Sr	102.03	112.09	99.68	116.03	109.06
Cs	12.42	10.64	18.01	21.06	21.83
La	32.10	37.12	30.12	32.17	37.92
Th	6.52	3.50	6.16	6.18	8.12
Sc	5.32	7.12	5.87	7.82	9.12
U	1.66	5.23	1.34	1.31	5.44
Cu	6.03	8.07	8.12	8.98	8.32
Pb	10.52	6.11	3.17	6.13	4.11

4.5 Discussion of Geochemical Evolution and Petrogenesis

The integrated petrographic and geochemical dataset allows for a robust interpretation of the evolution and origin of the Igarra granites. The combined major- and trace-element characteristics indicate that the granites underwent prolonged fractional crystallization, particularly involving the removal of plagioclase, biotite, and hornblende. This is evidenced by the strong negative correlations between SiO_2 and Fe_2O_3(t), MgO, and CaO on Harker variation diagrams, coupled with the increasing concentrations of incompatible elements like Rb.

The petrographic evidence of quartz with undulose extinction, the presence of both primary and secondary muscovite, and the overall weakly peraluminous geochemical signature (ASI ~1.0-1.05) strongly indicate that the granites were derived primarily through the partial melting of older, meta-igneous crustal sources. The elevated concentrations of Rb, Th, and U, relative to primitive mantle values, further support a predominantly crustal, rather than mantle-derived, source for the magmas. The depletion in Sr relative to Ba and the negative Eu anomalies (inferred from the low Sr and Eu contents) are classic indicators of feldspar fractionation during magma ascent and emplacement.

The tectonic discrimination using trace element ratios, such as the Rb vs (Y+Nb) plot, positions the Igarra granites firmly within the field of post-collisional granites. This is entirely consistent with the regional geological context of the Pan-African Orogeny in southwestern Nigeria, where the main phase of continental collision was followed by a period of crustal relaxation, extension, and widespread granite emplacement between 650--550 Ma.

The geochemical discrimination approach employed in this study is part of a robust methodological framework being applied to geological materials in Nigeria. Similar techniques have been successfully used for provenance studies of sedimentary units in Edo State (Omoruyi et al., 2022), highlighting the power of geochemistry to unravel complex geological histories across different rock types and terrains.

Overall, these results are consistent with the interpretation that the Igarra granites represent crustal anatexis products formed during the waning stages of the Pan-African Orogeny. They were generated by the partial melting of the lower crust, triggered by the thermal relaxation and decompression following continental collision. The magmas subsequently ascended, underwent fractional crystallization, and were emplaced at shallow to moderate crustal levels in a post-collisional tectonic setting. The mild solid-state deformation observed petrographically likely occurred during the final stages of this orogenic cycle.

CHAPTER FIVE:

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Findings

This research has undertaken a comprehensive investigation into the petrographic and geochemical characteristics of selected granite bodies in the Igarra-Ugbogbo area of Edo State, Nigeria. The study was designed to address significant gaps in the detailed characterization of these granitic rocks within the Nigerian Basement Complex. Through an integrated approach combining field geology, detailed petrography, modal analysis, and whole rock geochemistry, this research provides substantial new insights into the composition, classification, and petrogenesis of the Igarra granites.

The fieldwork component involved systematic examination and sampling of fresh granite exposures throughout the study area. Five representative samples (SJ01–SJ05) were collected from well exposed outcrops exhibiting minimal weathering and alteration. These samples were subjected to rigorous laboratory analysis, including thin-section petrography using polarizing microscopy and geochemical analysis via X-ray fluorescence spectrometry to determine both major and trace element concentrations.

The petrographic analysis revealed that the Igarra granites are typical plutonic rocks characterized by a hypidiomorphic granular texture, indicating slow cooling and crystallization at considerable depth within the crust. The mineral assemblage is dominated by essential felsic components: quartz (21-31%), microcline (20-26%), and plagioclase feldspar (31-35%), with biotite (7-10%) as the predominant mafic mineral. Minor constituents include hornblende (2-4%), muscovite (3-5%), and accessory phases such as zircon, apatite, and opaque minerals. Notably, several textural features provided evidence of post-crystallization processes, including undulose extinction in quartz indicating mild deformation, and sericitization of feldspars along with chloritization of biotite suggesting late-stage hydrothermal activity.

Geochemically, the granites are strongly siliceous, with SiO_2 contents ranging from 69.23 to 71.44 wt.%, classifying them as felsic rocks. The major element chemistry shows characteristic differentiatiation trends, with low concentrations of Fe_2O_3(t) (3.16-4.50%), MgO (0.91-1.99%), CaO (2.93-3.91%), and TiO_2 (0.56-0.89%), consistent with extensive fractional crystallization of mafic minerals. The total alkali content ($Na_2O + K_2O$) ranges from 4.88 to 5.70 wt.%, placing all samples firmly within the granite field on the TAS classification diagram. The Aluminum Saturation Index (ASI) values of 0.98-1.05 indicate metaluminous to weakly peraluminous compositions, characteristic of I-type granites.

Trace element geochemistry provided crucial insights into petrogenetic processes and tectonic setting. The granites show significant enrichment in large-ion lithophile elements (LILE) such as Rb (120-209 ppm), Ba (449-523 ppm), and Th (3.50-8.12 ppm), coupled with relative depletion in high-field-strength elements (HFSE) including Nb (12.40-20.16 ppm) and Y (7.92-9.33 ppm). These patterns, along with specific elemental ratios, are consistent with formation in a syn-collision to post-collision tectonic environment during the Pan-African Orogeny. The geochemical signatures strongly suggest derivation primarily through partial melting of pre-existing crustal rocks with possible minor mantle input.

5.2 Conclusion

Based on the combined petrographic and geochemical data, this study concludes that the Igarra-Ugbogbo granites are typical I-type granitoids of the Pan-African Older Granite suite. Their mineralogy and texture confirm crystallization at depth in a plutonic setting. Geochemically, they show clear signs of being derived from the crust, with high silica, low mafic elements, and a distinct enrichment in LILEs like Rb alongside a depletion in HFSEs like Nb and Ta. These features, along with tectonic discrimination diagrams, point to an origin through crustal melting in a syn- to post-collisional tectonic setting. Minor deformation and alteration are also noted, but the main story is one of crustal anatexis during the Pan-African event.

5.3 Recommendations for Future Research

Based on the findings and limitations of the current study, the following recommendations are proposed to build upon this research and address remaining questions:

1. **Comprehensive Geochemical Analysis Including Rare Earth Elements**

   While major and trace element data from XRF analysis provided significant insights, the determination of Rare Earth Element (REE) concentrations would substantially enhance understanding of melt evolution, source characteristics, and fractional crystallization pathways. Future studies should employ Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for a more complete geochemical characterization, particularly to better constrain source rock composition and differentiation processes through detailed REE modeling.

2. **Geochronological and Isotopic Studies**

   Establishing precise emplacement ages for the Igarra granites through radiometric dating methods is crucial for correlating these intrusions with specific phases of the Pan-African Orogeny. U-Pb zircon dating would provide the most reliable age constraints, while Rb-Sr or Sm-Nd isotopic systems could offer additional insights into source characteristics and crustal residence times. Such geochronological data would significantly improve regional tectonostratigraphic correlations within the Nigerian Basement Complex.

3. **Expanded Field Mapping and Structural Analysis**

   Broadening the field mapping to adjacent areas such as Ikpeshi, Ugboshi, Atte, and Okpe would help define the full spatial extent and variability of the granitic bodies. Detailed structural mapping focusing on the relationship between granite emplacement and regional deformation fabrics would clarify the timing of intrusion relative to tectonic events. Systematic structural analysis could also identify preferential emplacement controls and help reconstruct the regional stress fields during the Pan-African Orogeny.

4. **Advanced Petrogenetic Modeling**

   Quantitative petrogenetic modeling using specialized software such as GCDkit, IgPet, or MELTS would strengthen interpretations of the granites' origin and evolution. These tools enable testing of various petrogenetic scenarios including fractional crystallization, assimilation, and magma mixing through mass balance calculations and trace element modeling. Such an approach would provide more rigorous constraints on melt pathways and magmatic history.

5. **Comparative Studies with Other Nigerian Granites**

   A systematic comparison of the Igarra granites with well-studied granitic bodies from other parts of the Nigerian Basement Complex (e.g., Ife-Ilesha, Abuja, Kaduna, or southwestern Obudu) would help situate this study within a broader regional framework. Such comparative work would improve understanding of chemical variability and the principal controls on granite formation and evolution during the Pan-African Orogeny across different crustal domains.

6. **Mineralogical and Microanalytical Investigations**

   Detailed mineral chemistry studies using electron microprobe analysis (EMPA) of major rock-forming minerals (especially feldspars, biotite, and amphibole) would provide valuable information on crystallization conditions, including temperature, pressure, and oxygen fugacity.

Additionally, in-situ trace element analysis of zircon and other accessory minerals through Laser Ablation ICP-MS could reveal complex magmatic histories and provide more precise geochronological constraints.

7. **Geophysical and Subsurface Characterization**

   Geophysical surveys, including magnetic and electrical methods, could help delineate the three-dimensional geometry of the granite bodies and their relationships with surrounding rocks at depth. Such investigations would provide crucial information about the subsurface extent of the intrusions and their structural controls, which cannot be ascertained from surface mapping alone.

8. **Preservation and Geoconservation of Key Outcrops**

   Many excellent exposures in the study area face increasing threats from quarrying, weathering, and anthropogenic disturbance. It is recommended that local authorities and geological institutions consider developing protective measures for key outcrops to preserve them for ongoing academic research and potential geotourism development. Documenting and designating reference sections would ensure the long-term availability of these important geological sites for future scientific study.

Implementation of these recommendations would significantly advance the understanding of the Igarra granites and their place within the broader context of the Nigerian Basement Complex evolution, while providing valuable insights for both academic research and applied geological activities in the region.

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