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Pan-African Granitoids Revisited: The Igarra Pluton as A Case Study for Crustal Recycling and Hybrid Magmatism in Orogenic Belts

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Abstract
The Igarra granitic pluton forms part of the Pan-African granitoid suite of the Nigerian Basement Complex and records important aspects of late Neoproterozoic crustal evolution within the Dahomeyide Belt. Petrographic observations reveal hypidiomorphic granular textures and locally developed syn-tectonic microstructures, indicating emplacement contemporaneous with regional deformation. Major-element geochemistry shows calc-alkaline affinity and predominantly metaluminous compositions, consistent with granitoids emplaced in convergent orogenic settings. Trace-element and rare earth element (REE) geochemistry provide key constraints on magma source and evolution. Chondrite-normalized REE patterns are characterized by strong enrichment of light rare earth elements relative to heavy rare earth elements, together with weak to moderate negative Eu anomalies. Primitive-mantle–normalized trace-element patterns show enrichment in incompatible elements and relative depletion in high-field-strength elements such as Ta. These geochemical signatures closely resemble those of Pan-African granitoids from the Ilesha, Idanre, Kabba–Lokoja–Igarra, and Egbe–Isanlu schist belts. The combined petrographic and geochemical characteristics indicate that the Igarra granite was derived predominantly from partial melting of continental crust during crustal thickening associated with the Pan-African orogeny, with magma evolution controlled by fractional crystallization. Although limited interaction with more mafic magmas during emplacement cannot be ruled out, the available data do not support a dominant juvenile mantle contribution. The Igarra pluton therefore represents a typical syn- to late-collisional Pan-African granitoid that documents significant crustal reworking during the assembly of the Nigerian Basement Complex.

Keywords
Dahomeyide orogen, Igarra granitic pluton, Syenogranite, Pan-African orogeny, Continental collision

1. Introduction

Granitoids have been known to be custodians of key information on crustal evolution that provides vital insights into the genesis of magma, tectonic regimes and the overall geodynamic history of orogenic belts (Yong-Fei et al., 2021). The Pan-African orogeny produced a widespread of syn/post-collisional granitoids (Fréville et al., 2024), but their petrogenesis, emplacement mechanisms, and tectonic significance remain as subjects of ongoing debate, especially in the Nigerian basement complex. The Igarra pluton occurs within the Precambrian basement of southwestern Nigeria, a part of the Dahomeyide Belt, which is a critical suture zone that marks the collision between the West African Craton and the Congo Craton during the Neoproterozoic (~600Ma)

(Villeneuve and Rossignol, 2023). The geochemical affinities, precise magma sources, and the tectonic setting of the Igarra pluton have remained poorly constrained despite the volume of previous studies done on the basement complex of Nigeria. And these constrains have limited the broader correlation with coeval magmatism across the Pan-African orogeny. The basement complex of Nigeria consists of an underlying gneissic granitoid, an unconformable metasedimentary cover, with which they are in-folded and subsequently intruding Pan-African (older) granites (Ominigbo, 2022). Based on variable combinations of limited geochemical, geochronological and structural data, the basement complex rocks of Nigeria have been allotted to the Archaean to Neoproterozoic age range, (Abdulmalik and Ahmed, 2024).

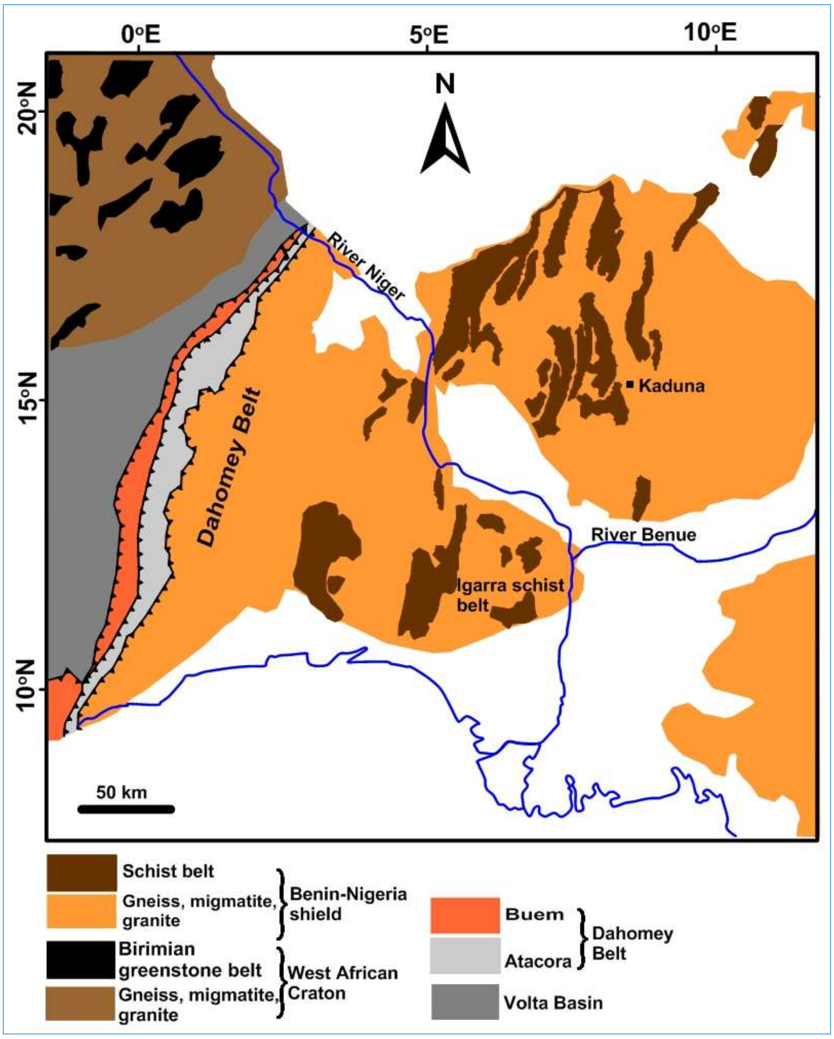

Fig. 1. Regional geology of the Benin-Nigeria Shield (modified after Turner, 1983). The Benin-Nigeria Shield is separated from the WAC by the Pan-African Dahomey Belt, which includes the Buem and Atacora structural units (Affaton et al., 1991). The Volta Basin is a passive margin that developed into a foreland basin (Carney et al., 2010)

This however does not suggest that all units are products of the same geotectonic process, but may represent different tectonic events separated in time, space and accompanying settings. The basement complex carries the imprint of the Neoproterozoic Pan-African Orogeny, whose effects are largely a reworking of older, polycyclic crust which has been given dates corresponding to the Liberian, (2.9 – 2.5 Ga), Eburnian (2.2 – 1.8 Ga) and Kibaran (1.3 – 0.9 Ga) orogenic events (Dada et al., 2024; Igonor et al., 2023). Apparently, however, imprints are not preponderant in every location as subsequent events tend to obliterate imprints of preceding events. Three tectonic models have been proposed for the schist belt including evolution by ensialic continental processes, evolution in an association with ocean floor island-arc and marginal basin settings, and evolution in a back-arc basin (Hofmann et al., 2025; Tijani, 2023; Salawu et al., 2021).

Studies on the Nigerian granitoids (Akinola et al., 2021; Okunola et al., 2023) have broadly classified them as either syn-collisional (I-type) or post-collisional (A-type), yet they are sparse of detailed petrographic and geochemical data on Igarra pluton. Some recent studies have underscored compositional heterogeneities in Pan-African granitoids that suggests complex interactions between mantle-derived melts and ancient crustal sources (Hamdja Ngoniri et al., 2021; Umaru et al., 2023; Kwékam et al., 2020).

However, a few vital questions remain: what is the actual petrogenetic evolution of the Igarra pluton – are they crustal melts products, mantle inputs or they are derived from hybrid sources? What tectonic setting do they represent – syn-collisional compression or post-collisional extension? And for a robust understanding, there is the need to know how they compare with other Pan-African granitoids – are there regional magma generation trends or they are localized anomalies?

This article, through an integrated petrographic and geochemical evaluation of the Igarra pluton, combines mineralogical analyses with the major and trace element geochemistry of whole-rock to; classify the granite type and the magma source, properly discriminate the tectonic setting using well known geochemical proxies, and finally evaluate the implications for the late-stage evolution of the Pan-African Orogeny. Aside from contributing to the crustal evolution models of the Dahomeyide Belt, this paper will also help broaden the understanding of similar magmatism of ancient orogens. This work also has significant relevance for the metallogenic studies in Nigeria considering the high economic potential for granitoid hosted mineralization (e.g., Sn-Nb-Ta pegmatites) in the region.

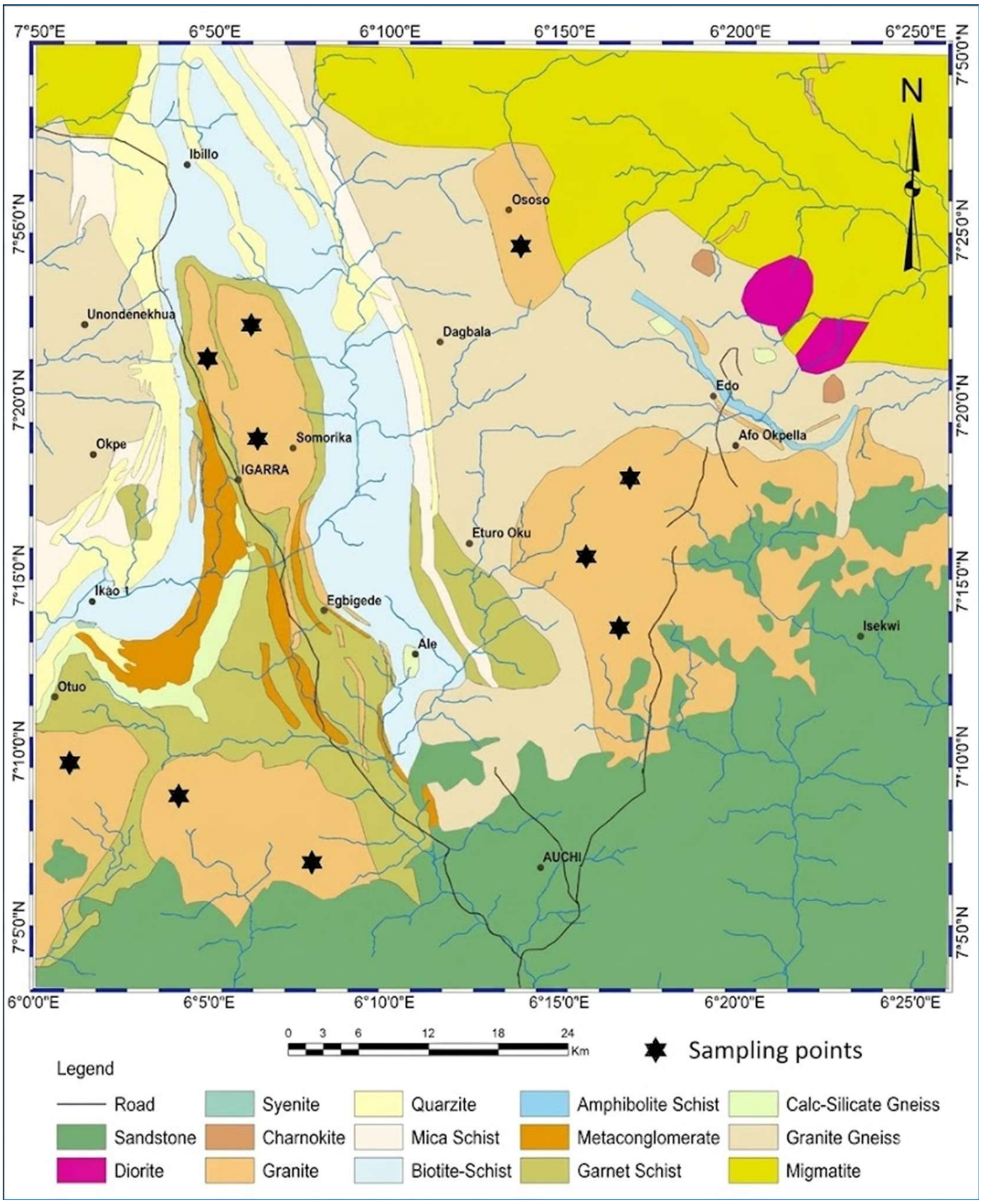

Fig. 2: Geological map of Igarra area (modified after Odeyemi, 1990)

2. Geologic Setting

Nigeria as a whole, lies within the Pan-African mobile belt, east and northwest of the West African and Congo cratons respectively (Fig. 1). The Igarra town, located in the Southwestern, Nigeria, is the type locality for the Igarra schist belt. The Igarra polluted, which occupy most part of the town and beyond, runs roughly northwest-southeast and constitutes a part of the basement complex rocks of the area. The regional descriptions of this area have been given variable nomenclature such as the Benin-Nigerian shield, the Pan African or Trans-Saharan mobile belt (Nweke et al., 2024; Kolawole et al., 2021). The basement complex rocks consist largely of gneissic granitoids, an unconformably overlying metasedimentary cover, with which they are in-folded, and subsequently intruding Pan-African granites. The Nigerian granitoids is restricted to two contrasting petrographic settings with a group associated with the Older Granites whereas the other member restricted to the Younger Granite series.

The Older Granites are characterized by significantly high concentrations of CaO, MgO and K_2O with K_2O typically exceeding Na_2O. On the other hand, the Younger Granites show broader compositional ranges, often with Na_2O/K_2O ratios (Kamaunji et al., 2020). As a result of episodicity and prolonged duration of geological events, different geological settings with diverse geochemical and mineralogical attributes have evolved in the Basement Complex of western Nigeria (Tijani, 2023). The Igarra plutons belong to the Neoproterozoic granitoids that intruded into the basement complex rocks. It is therefore imperative to investigate them on the basis of petrography and geochemistry with a view to establishing geotectonic evolution.

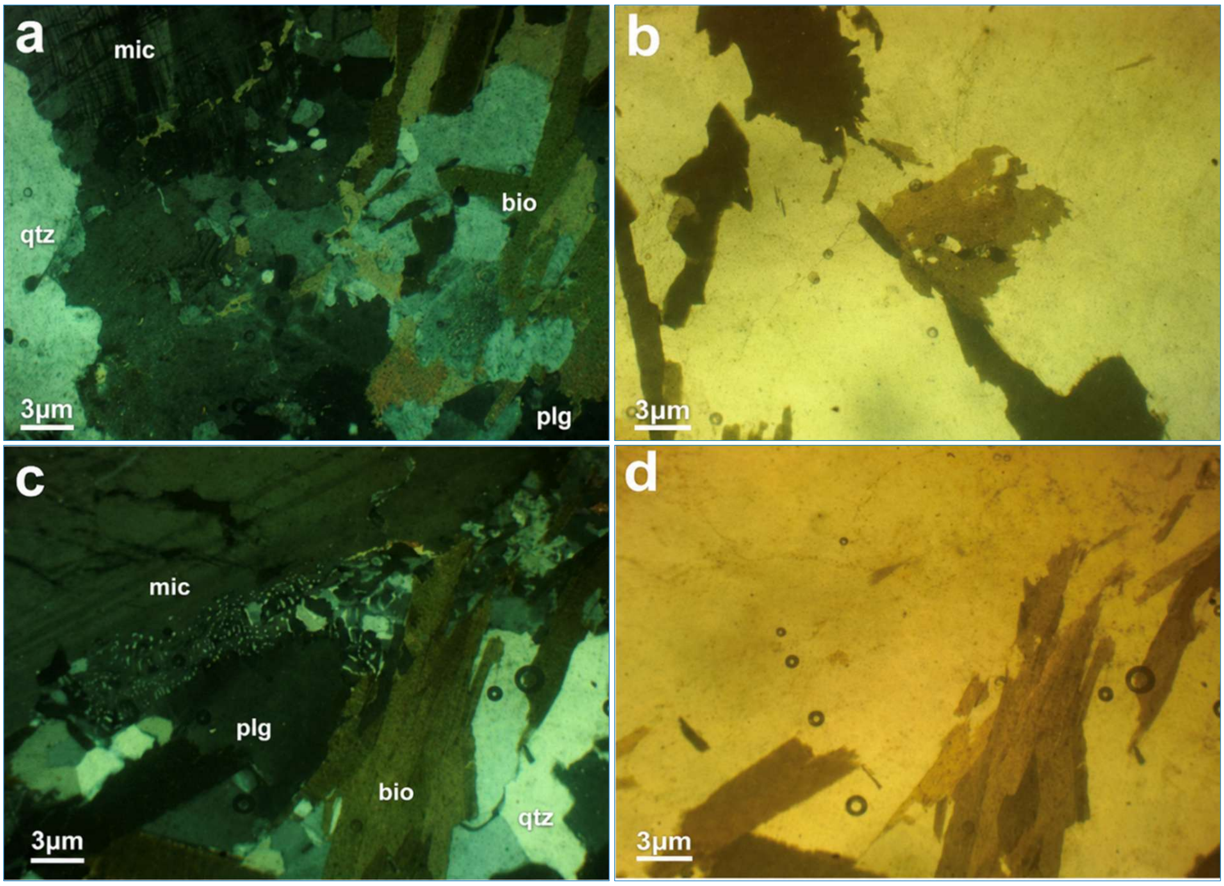

Fig. 3. Photomicrograph of Igarra granitic pluton: a and c = XPL, b and d PPl (bio = biotite, qtz = quartz, mic = microcline, plg = plagioclase)

Three major rock suits make up the basement geology of the Igarra area including the older migmatite-gneiss complex, the supracrustal metasedimentary cover and the subsequently intruding Pan African granitoids to which belongs the Igarra granitic pluton (Fig. 2). The older suite comprises amphibolite-grade quartz-feldspar (± hornblende) granitic gneisses and migmatite, whereas the metasedimentary suite comprises greenschist- to amphibolite-facies phyllite, greenstone and schist; the youngest suite comprises syn- to late-tectonic plutonic intrusions of granite-granodiorite with small masses of diorite, gabbro, syenite and related rocks (Ominigbo, 2022; Dada et al., 2024; Igonor et al 2023). The granitic rocks within Igarra area constitute an approximated area of 40 km^2 and roughly fall within longitudes 6°05' 5" E and 6°18" 0"E and latitudes 7° 05' 59"N and 7° 25' 57"N. Two distinct compressive stresses, NE – SW and E – W have been reported to have affected the Igarra area, with the relatively younger E –W event being more pervasive as structures related to it are more dominant within the basement (Udimwen, 2017). These dominant stress regimes apparently controlled the emplacement of the batholitic pluton.

3. Methodology

Detailed field mapping of the study area, using base maps, satellite images was carried out resulting in the collection of rock samples. Field observations were made on each outcrop including megascopic identification of minerals present in the rock outcrops, texture, degree and pattern of weathering, color of fresh rock surface, and measurement of strike and dip values. Samples were collected systematically, ensuring that they are spread to cover the extents of the pluton as much as possible. Thin sections were prepared in the laboratory and studied with the petrographic microscope. Photomicrographs were taken with digital camera and the modal content of the rocks analysed.

Geochemical sample preparation involved crushing and pulverizing to 425 microns. About eight grams (8g) of ten pulverized rock samples were analyzed at the Bureau Veritas laboratories, Vancouver, Canada. Partial digestion (using modified aqua ragia) and total digestion (using lithium metaborate ($LiBO_2/Li_2B_4O_7$) were deployed for trace and major element analyses respectively. For the partial digestion, 0.5 gram each of the pulverized samples was taken into graduated test tubes and 5ml of 1:1:1 mixture of HCl-HNO_3-H_2O (modified aqua ragia) was added to the samples. After mixing with the modified aqua ragia, the samples were heated in the oven at a regular temperature of 65^{0}C for twelve hours to extract metals from them. Later the contents were cooled and diluted to 20ml with ultra-distilled water. The samples were thereafter allowed to stay for a period of about 12 hours for settling of the suspended matter. Consequently, the supernatant liquid was transferred on to fresh test tubes and used for the analysis. For the total digestion, 0.2 g of each of the sample was mixed with a borate flux ($LiBO_2/Li_2B_4O_7$) inside a 95% Pt-5% Au crucible, heated to 1000 ºC with agitation until the flux melts to dissolve the sample. The hot melt was poured into diluted lithium metaborate/lithium tetraborate acid. The lithium metaborate dissolves acidic oxides such as SiO_2, Al_2O_3, SO_3, P_2O_5, TiO_2, and Fe_2O_3, while the lithium tetraborate dissolves basic oxides such as CaO, MgO and other oxides of the alkali metals and alkaline earth metals. Most oxides are best dissolved in a mixture of the two-lithium borate salt for spectrochemical analysis.

Table 1. CIPW norm result of granite

Minerals	Samples									
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
Q	23.7	24.3	23.7	23.2	22.8	21.4	22.2	21.9	23.0	22.9
Or	34.5	31.9	32.1	31.1	30.3	33.3	31.7	32.1	31.1	30.3
Ab	32.3	34.3	33.3	33.9	33.8	33.1	34.1	33.1	33.8	33.8
An	5.4	5.7	6.3	5.8	6.1	5.9	6.4	6.1	5.6	6.2
Di	0.5	0.8	0.4	0.0	0.0	0.02	0.0	0.6	0.1	0.0
Hy	1.9	1.8	2.2	1.9	2.1	2.2	2.1	2.0	1.8	2.1
Il	0.06	0.06	0.08	0.06	0.06	0.08	0.08	0.06	0.06	0.08
Hm	2.54	2.52	2.68	3.31	3.33	2.44	2.42	2.65	3.14	3.34
Tn	0.54	0.44	0.41	0.35	0.40	0.44	0.07	0.41	0.39	0.20
Ru	0.0	0.0	0.0	0.27	0.02	0.0	0.12	0.0	0.0	0.07
Ap	0.33	0.36	0.33	0.33	0.36	0.33	0.31	0.33	0.31	0.33
Py	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.4
SUM	101.81	102.22	101.54	100.26	99.31	99.25	99.54	99.29	99.34	99.72

Table 2. Major and minor elements (wt%) composition of Igarra granitic pluton

Samples	Elements											
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	LOI	SUM
G1	72.83	0.25	14.76	2.54	0.05	0.89	1.55	3.93	5.84	0.14	0.011	0.4	99.89
G2	72.56	0.21	14.59	2.52	0.05	0.86	1.69	4.05	5.39	0.15	0.013	0.2	99.99
G3	71.79	0.21	14.68	2.68	0.06	0.96	1.69	3.93	5.44	0.14	0.012	0.4	99.95
G4	70.43	0.2	14.44	3.31	0.05	0.77	1.46	4.01	5.27	0.14	0.01	0.4	99.93
G5	69.73	0.21	14.38	3.33	0.05	0.86	1.55	3.99	5.14	0.15	0.005	0.4	99.93
G6	69.73	0.22	14.71	2.44	0.06	0.9	1.51	3.91	5.64	0.14	0.009	0.4	99.89
G7	70.19	0.19	14.77	2.42	0.06	0.84	1.47	4.03	5.37	0.13	0.012	0.2	99.9
G8	69.75	0.2	14.53	2.65	0.05	0.93	1.68	3.91	5.43	0.14	0.011	0.4	99.95
G9	70.05	0.19	14.31	3.14	0.05	0.75	1.43	3.99	5.27	0.13	0.006	0.4	99.93
G10	69.73	0.19	14.39	3.34	0.06	0.83	1.5	3.98	5.13	0.14	0.005	0.4	99.93

4. Results

4.1. Geological Descriptions

The Igarra pluton is a pronounced and well-known intrusive body within the Pan-African basement complex of southwestern Nigeria, emplaced into the Igarra schist belt. It outcrops as a massive and poorly foliated exposure with several joint-controlled weathering patterns observable in many locations. Large, rounded boulders (but sometimes subangular) dominate the terrain, with occasional sheet-joints and exfoliations. These vary from pinkish gray to whitish gray in fresh exposures, and weathers to buff or reddish-brown due to iron oxidation.

At some points, sharp intrusive contacts with the surrounding metasedimentary rocks of the Igarra schist belt can be noticed. Very dark mafic enclaves ranging from 5-20 cm are locally present while xenoliths of schist and amphibolite occur near the margins.

Distinguished by texture and mineralogy, we have three main facies of the Igarra pluton. These are: the equigranular and hypidiomorphic coarse-grained biotite-rich granite dominant at the core of the pluton and prominent at the eastern flank of the area; at the transitional zones near the margins, we have the porphyritic granodiorite with k-feldspar megacrysts up to 3 cm in a medium grained matrix; along the pluton's margins and parallel to the shear zones is the mylonitic granite with protomylonitic to mylonitic features. The Igarra pluton is associated with the garnet-mica schists, quartzites and amphibolites of the Igarra schist belt along with Mafic Microgranular Enclaves (MMEs) and metasedimentary xenoliths. Observable structural features include weak magmatic foliations, ductile shearing along the mylonitized zones at the margins, and well pronounced brittle deformation causing late-stage joints and fractures which are mostly filled with quartz veins

4.2. Petrography and Mineralogical Descriptions

Representative photomicrographs of the samples studied are shown in Fig. 3. The Igarra granitic pluton is holocrystalline and medium- to coarse-grained, exhibiting predominantly hypidiomorphic granular textures. The principal mineral assemblage comprises quartz, K-feldspar, plagioclase, and biotite, with minor muscovite and accessory titanite, apatite, zircon, and opaque phases.

Quartz occurs as anhedral to subhedral interstitial grains, commonly exhibiting undulose extinction and locally sutured grain boundaries. Quartz is optically non-pleochroic and typically forms interlocking mosaics with feldspar. K-feldspar is present mainly as microcline and subordinate orthoclase. Microcline occurs as subhedral to euhedral grains characterized by well-developed cross-hatched (tartan) twinning under crossed polars. Perthitic textures are common, expressed as fine albite exsolution lamellae within K-feldspar, reflecting subsolidus unmixing during slow cooling. Orthoclase, where present, is typically untwinned or shows simple Carlsbad twinning and occurs as subhedral tabular grains. Plagioclase is predominantly albite-oligoclase in composition and occurs as subhedral grains exhibiting well-developed polysynthetic (albite) twinning. Plagioclase grains are locally enclosed within K-feldspar, producing poikilitic to interstitial relationships. Biotite is the dominant mafic mineral, occurring as subhedral platy crystals intergrown with quartz and feldspar. It exhibits strong pleochroism from pale brown to dark brown under plane-polarized light and commonly defines a weak preferred orientation in samples affected by marginal deformation. Minor chloritization along cleavage planes is locally observed. Accessory minerals include titanite, apatite, zircon, and opaque phases (ilmenite ± hematite), which occur as disseminated subhedral grains within the felsic matrix. Overall, the mineral assemblage and textural relationships are consistent with crystallization from a felsic, calc-alkaline magma, with localized evidence of post-emplacement strain along the pluton margins. In place of a modal analysis, a CPW norm was derived to give a more accurate mineral quantification (Table 1).

4.3. Geochemistry

4.3.1. Major Elements

The concentrations of the major oxide's composition of the Igarra granitic pluton are given in Table 2. The geochemical result show that the concentrations of the major oxides composition of the granite according to their decreasing order is $SiO_2 > Al_2O_3 > K_2O > Na_2O > Fe_2O_3 > CaO > MgO > TiO_2 > P_2O_5 > MnO > Cr_2O_3$. SiO_2 expectedly has the highest concentration in the rock. SiO_2 ranges from 69.73 – 72.83%, Al_2O_3 14.31 – 14.77%, Fe_2O_3 2.42 – 3.34%, MgO 0.75 – 0.96%, CaO 1.43 – 1.69%, Na_2O 3.93 – 4.05%, K_2O 5.13 – 5.84 %, TiO_2 0.19 – 0.25%, P_2O_5 0.13 – 0.15%, MnO 0.05 – 0.06% and Cr_2O_3 0.005 – 0.013.

Table 3. Average abundance of elements in the crust, ranges and average content of the elements in the analyzed (all values in ppm, Au and Ag in ppb; after Levinson (1974) and Rose et al. (1991))

Element	Average Crustal Abundance	Granitic rock	
		Average	Range
Mo	1.5	1.334	0.89-2.06
Cu	55	11.964	8.02-12.67
Pb	12.5	24.653	23-27.16
Zn	70	23.81	17.4-26.8
Ag	70	26	6-37
Ni	75	9.8	7.4-10.7
Co	25	3.56	2.7-3.9
Mn	1000	231.5	153-268
As	1.8	1.06	0.3-1.7
U	2.7	2.17	1.4-2.6
Au	4	0.184	0.1-0.22
Th	10	11.39	8.8-13.7
Sr	375	24.35	7.5-37.5
Cd	0.13	0.01	0.01
Sb	0.2	0.128	0.05-0.25
Bi	0.17	0.026	0.01-0.08
V	135	18	13-20
La	30	22.72	20-25.1
Cr	100	39.68	31.7-45.1
Ba	640	67.98	17.3-112.3
W	1.5	0.11	0.1-0.2
Sc	18	1.203	0.6-1.6
Tl	0.45	0.23	0.16-0.29
Ga	15	2.32	1.6-2.8
Zr	165	148.6	141-156
Y	33	13	10-17
Nb	20	13.2	10-17
B	10	16.3	8-21
Hg	0.08	3.6	3-4
Se	0.05	0.1	0.1
Te	0.005	0.02	0.02

Table 4. REE range and Chondrite normalized values for rocks from study area

Element	Measured range (ppm)	Chondrite value (ppm)*	Chondrite-normalized range
La	40 – 384	0.234	171 – 1641
Ce	85 – 2780	0.613	139 – 4535
Pr	10 – 287	0.092	109 – 3120
Nd	38 – 845	0.457	83 – 1849
Sm	7 – 85	0.153	46 – 556
Eu	2 – 6	0.058	34 – 103
Gd	6 – 38	0.199	30 – 191
Tb	1 – 4.5	0.036	28 – 125
Dy	5 – 21	0.249	20 – 84
Ho	1 – 3.4	0.056	18 – 61
Er	2 – 9.3	0.165	12 – 56
Tm	0.3 – 1.3	0.025	12 – 52
Yb	2.1 – 7.8	0.161	13 – 48
Lu	0.3 – 1.1	0.024	13 – 46
Ta	1 – 3.2	0.037	27 – 86

4.3.2. Trace Elements

Trace elements from this investigation were selected and grouped in order of range and average in relation their respective average crustal abundance (Table 3); this is intended to give an indication of any above-average enrichment that could be a pointer to mineralization potential of the pluton. Molybdenum (Mo) ranges from 0.89-2.06 with a mean of 1.334, while Copper in ranges from 8.02 to 12.67and a mean of 11.964 (Table 3). Lead (Pb), a primary mineral of galena has a concentration that varies from 23-27.16 with a mean of 24.653. The concentration of Zinc varies from 17.4 to 26.8 and a mean of 23.81 while the concentration of silver varies between 6 -37 with an average of 26. The concentration of Nickel on the other hand varies from 7.4 to 10.7 with a mean value of 9.8 while Co varies from 2.7 to 3.9 with a mean value of 3.56. Mn and As vary from 153-268 and 0.3 - 1.7 with a mean value of 231.5 and 1.06 respectively. Au, U and Th concentrations range between 0.1 - 0.22, 1.4 - 2.6 and 8.8 - 13.7 with mean values of 0.184, 2.7 and 11.39, respectively.

4.3.3. Rare Earth Element (REE) Geochemistry

The rare earth element (REE) concentrations of the Igarra granitic pluton display systematic and coherent fractionation patterns (Table 4). Light rare earth elements (LREEs) are strongly enriched, with La ranging from 40 to 384 ppm, Ce from 85 to 2780 ppm, and Nd from 38 to 845 ppm. In contrast, heavy rare earth elements (HREEs) show comparatively lower concentrations, with Yb ranging from 2.1 to 7.8 ppm and Lu from 0.3 to 1.1 ppm.

Middle REEs (Sm–Gd) occur at intermediate concentrations (Sm = 7–85 ppm; Gd = 6–38 ppm), defining a steeply fractionated REE pattern from La to Lu. Europium concentrations range from 2 to 6 ppm and are generally depleted relative to neighbouring Sm and Gd, indicating the presence of a negative Eu anomaly. Overall, the REE data are characterized by pronounced LREE enrichment, moderate HREE depletion, and weak to moderate negative Eu anomalies.

5. Discussions

5.1. Nomenclature

On the Total Alkali Silica (TAS) SiO_2 vs Na_2O + K_2O diagram of Cox et al. (1979), The Igarra pluton plots as granite which is a reflection of the largely acidic nature of the rock (Fig. 4a), while on the similar plot of Middlemost, (1994), the rock plots between the boundary line demarcating quartz monzonites and granite but are more inclined towards the latter (Fig. 4b). Also, when the major Oxides data were plotted in the R1-R2 diagram of De La Roche et al. (1980) the R2 is plotted along the Y –axis and is defined as R2=(Al+2Mg+6Ca), and R1 on X – axis as R1= 4Si-11(Na+K)-2(Fe+Ti), the Igarra pluton plots within the granite fields. (Fig. 4c). Furthermore, on the feldspar triangle diagram (Fig. 4d) showing Albite, Anorthite, Orthoclase compositions, according to O'Connor (1965), the Igarra pluton plots as granite and the mineral composition are abundant in albite and orthoclase and less of anorthite.

5.2. Rare Earth Element Constraints on Magma Evolution and Source

The REE geochemical characteristics of the Igarra granitic pluton provide important constraints on magma source and evolutionary processes. The chondrite-normalized REE patterns of the Igarra granite (Fig. 5) show strong enrichment of LREEs relative to HREEs, together with steeply fractionated REE patterns, that is typical of granitoids derived predominantly from partial melting of continental crust rather than from juvenile mantle melts.

Similar REE signatures have been widely reported for Pan-African granitoids across the Nigerian Basement Complex, including those from the Ilesha, Idanre, and Kabba–Lokoja–Igarra schist belts.

The depletion of HREEs (Yb–Lu) suggests that residual garnet and/or amphibole were stable in the source region during partial melting, implying melting at moderate to deep crustal levels. This interpretation is consistent with generation of granitoid magmas during crustal thickening associated with continental collision in the Pan-African orogeny.

The weak to moderate negative Eu anomalies observed in the Igarra granite indicate fractionation or retention of plagioclase during magma evolution. Such Eu behaviour is characteristic of calc-alkaline granitoids and reflects differentiation processes operating during magma ascent and emplacement rather than extensive feldspar accumulation from mantle-derived melts.

Consequently, the REE data supports a model in which the Igarra granitic pluton formed predominantly from crustal melts, with magma evolution controlled by fractional crystallization and residual mineral control in the source. While limited interaction with more mafic magmas cannot be ruled out, the REE patterns do not indicate a dominant juvenile mantle contribution.

The primitive-mantle-normalized trace-element spider diagram (Fig. 6) complements the chondrite-normalized REE patterns by highlighting the enrichment of incompatible elements and the relative depletion of high-field-strength elements such as Ta. Such signatures are widely regarded as characteristic of calc-alkaline granitoids associated with convergent orogenic settings and are common in Pan-African granitoids across the Nigerian Basement Complex.

The Ta depletion, together with strong LREE enrichment and HREE depletion, reflects source and evolutionary processes dominated by crustal melting and fractional crystallization rather than derivation from a purely juvenile mantle source. These trace-element characteristics are consistent with syn- to late-collisional granitoid magmatism during the Pan-African orogeny.

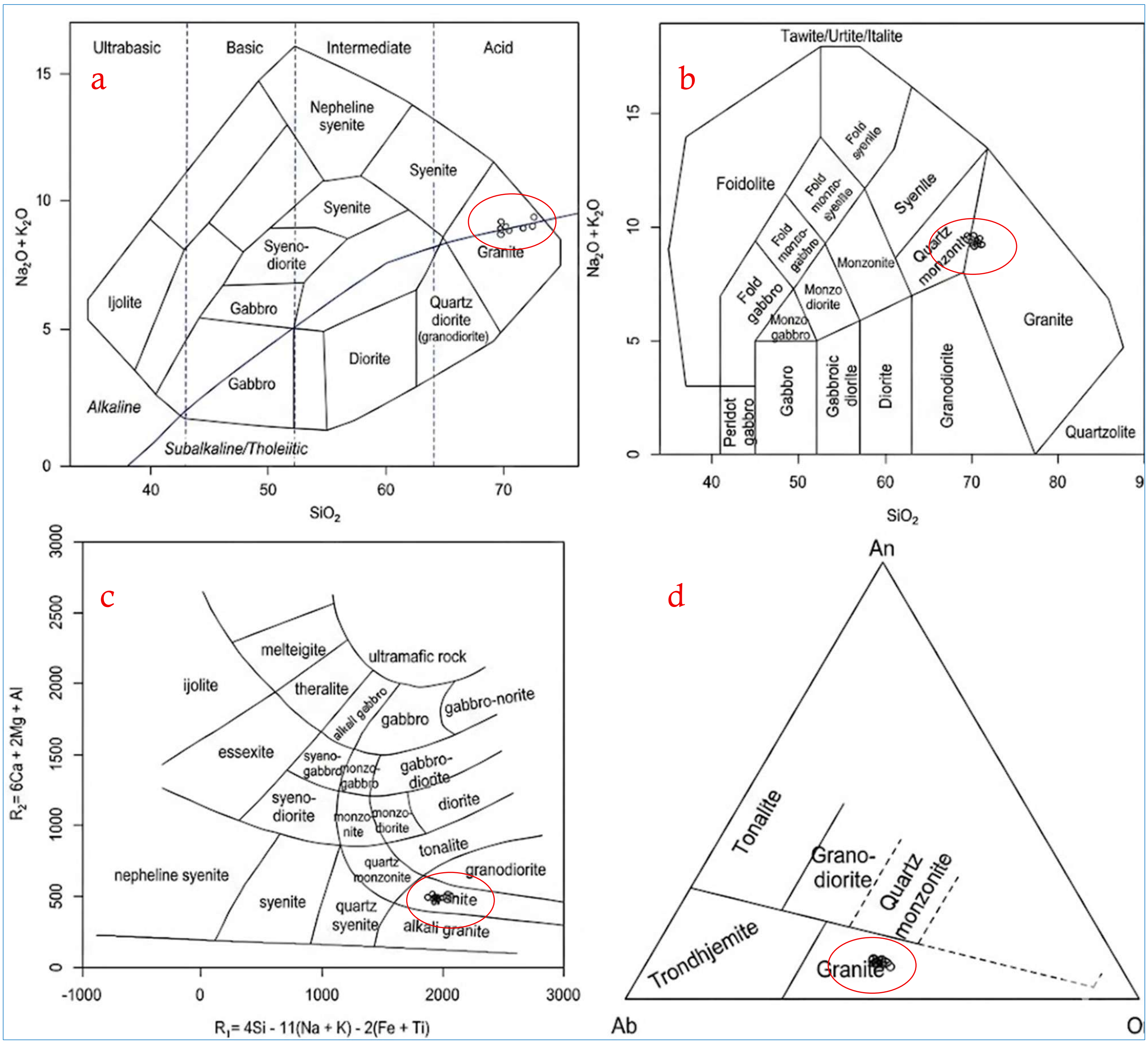

Fig. 4. (a) SiO_2 vs $Na_2O + K_2O$ (TAS) diagram (after Cox et. al., 1979) (b) Total Alkali Silica (TAS) diagram classification (after Middlemost, 1994) (c) R1-R2 diagram (after De La Roche et al., 1980) (d) the Feldspar triangle (after O'Connor 1965)

5.3. Geochemical Affinities

The A/CNK - A/NK (Al_2O_3/ (CaO+ Na_2O + K_2O) vs. Al_2O_3/ (Na_2O + K_2O)) plot of Shand (1943) shows that the rocks are mostly metaluminous in nature; they are however inclined towards the boundary lines with peralkaline and peraluminous (Fig. 7a). The B – A diagram (Debon and Le Fort, 1983) as outlined by Villaseca et. al. (1998), which is a measure of Dark minerals [B= Fe +Mg +Ti] and aluminous character [A= Al-(K+Na+2Ca) also indicates that the rocks are of metaluminous type (Fig. 7b). The compositional domain shown is metaluminous area A < 0 (Fig. 7b). The metaluminous character demonstrated by the B – A diagram for most of the samples reflects the presence of biotite (Brahmaiah et. al., 2017).

Generally, the rocks in the metaluminous domain are said to have been derived from magma of crustal origin (Brahmaiah et al., 2017). In the ASI vs SiO_2 (Frost and Frost, 2008) the Igarra granitic pluton plots as metaluminous, albeit they plot almost at the boundary line with peraluminous (Fig. 7c), while on the granite tectonic discrimination plot, the rock indicate magnesian affinity, (Fig. 7d) which according to Frost and Frost (2008), are usually associated with conditions of limited availability of H_2O and low oxygen fugacity. In the $Na_2O + K_2O - CaO$ vs SiO_2 diagram, the Igarra granitic pluton shows an alkali-calcic affinity (Fig. 8a), while the Al vs FSSI diagram shows that the granite are silica saturated (Fig. 8b). In the Fe_t vs SiO_2 (Miyashiro 1974) which presented dividing lines separating the rocks of the calc-alkaline and tholeiitic series, the Igarra granitic pluton plots as Calc-Alkaline series (Fig. 8c), an indication that the rock evolved from a magma of calc- alkaline affinity. The AFM plot of the granite (Irvine and Baragar 1971) also emphasizes the calc-alkaline affinity of this rock (Fig. 8d).

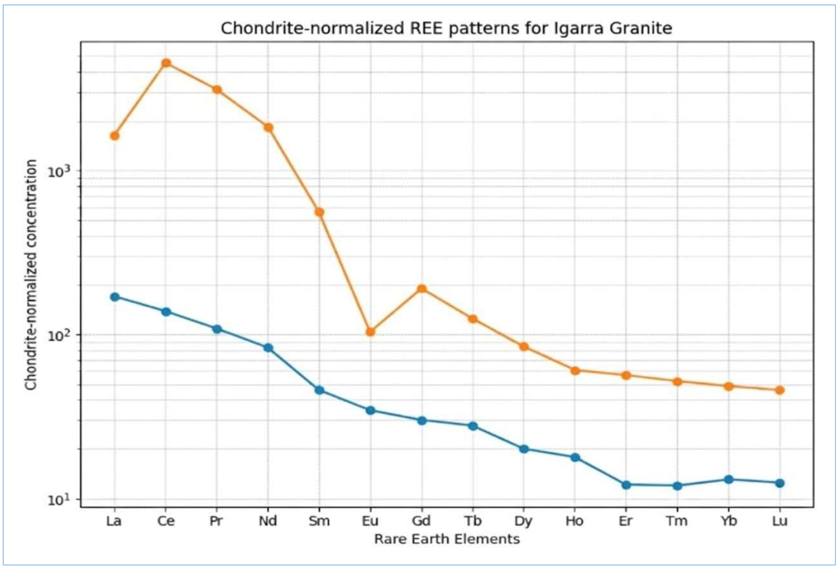

Fig. 5. Chondrite-normalized rare earth element (REE) patterns for the Igarra granitic pluton. Normalization values are from Boynton (1984). The granitoids show strong enrichment in light rare earth elements (LREEs), relative depletion in heavy rare earth elements (HREEs), and weak to moderate negative Eu anomalies, consistent with fractionated calc-alkaline granitoid magmas derived predominantly from continental crust

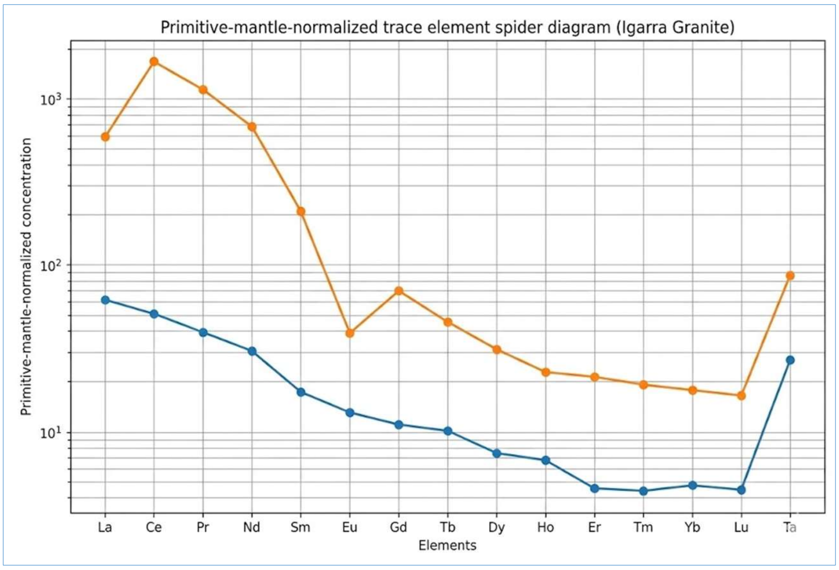

Fig. 6. Primitive-mantle–normalized trace element spider diagram for the Igarra granitic pluton (normalization values from McDonough & Sun, 1995). The granitoids show strong enrichment in incompatible elements (LREEs) relative to heavy rare earth elements, coupled with pronounced Ta depletion. This pattern is characteristic of calc-alkaline granitoids emplaced in convergent or syn-collisional tectonic settings and is consistent with dominant crustal melting during the Pan-African orogeny

Generally, all samples analyzed from the Igarra batholithic granite possesses some similar chemical characteristics. The generally low loss on ignition, (LOI) value range for these rocks (0.2 – 0.4) is suggestive of relative freshness and low alteration in the rocks From the SiO2 vs FeO/(FeO + MgO) plots, the Igarra granite plots at the boundary between Ferroan and magnesian affinity. Such rocks which are at the same time calc-alkaline granitoids are more likely to have formed from magmas derived from crustal melting or those that assimilated a large amount of crustal materials (Frost and Frost, 2011). The major and trace elements characteristics of granitoids associated with the Ilesha schist belt suggest that their emplacement is most probably in a continental environment with an associated extensional regime as well as a derivation from a magma with a significant crustal influence. This is inferred from their largely calc-alkaline, peraluminous and ferroan granitic affinity displayed by their major elements plots as well as their largely VAG+syn-COLG affinity of their trace elements plots.

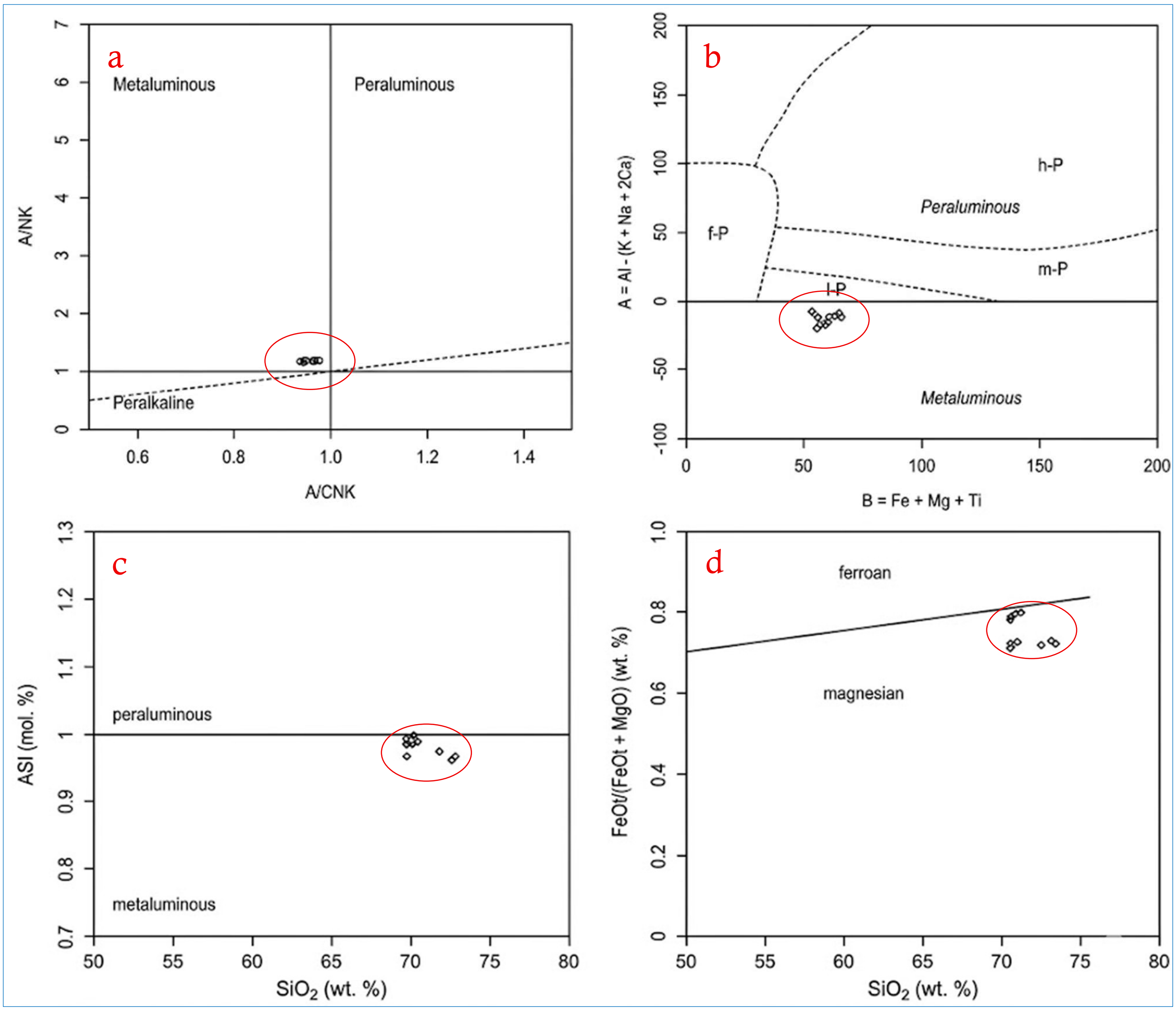

Fig. 7. (a) A/CNK vs A/NK plot (after Shand, 1943) (b) The B – A diagram (after Debon and Le Fort, 1983) (c) ASI vs SiO_2 (after Frost and Frost, 2008) (d) granite tectonic discrimination plot (after Frost and Frost, 2008)

5.4. Tectonic Settings

On the La/10 – Y/5 – Nb/8 (Cabanis and Lecolle, 1989), the Igarra granitic pluton plots in the late to post orogenic (compressive to diatensive) intra-continental domain (Fig. 9a). On the Nb versus Y diagram (Pearce et al., 1984) the Igarra granitic pluton plot largely in the fields of Volcanic Arc and Syn-collisional settings. (Fig. 9c) while on the Co-Th diagram it plots as high K-calc-alkaline and shoshonite series (Fig. 9d). Batchelor and Bowden (1985) distinguished granitic rocks into different tectonic setting using a main granitic rock assemblage diagram (Fig. 9b). R1 and R2 values can be recalculated according to the main oxide content of granites. All the samples are plotted in the syn- collision field. This may imply that the granite is derived from the upper crust, where separation and crystallization of minerals occur only in part of the rock, and melting occurs in most of the rock. Therefore, volcanic arc and syn-collision setting are the most probable tectonic setting for the Igarra granitic pluton.

In comparison with other Pan-African granitoids across Nigeria, the Igarra granite exhibits closely comparable geochemical, tectonic, and structural characteristics. Geochemically, it shares calc-alkaline affinity, predominantly metaluminous compositions, strong LREE enrichment, relative HREE depletion, weak to moderate negative Eu anomalies, and high-field-strength element depletion (e.g., Ta) that are typical of Pan-African granites from the Ilesha, Idanre, Kabba–Lokoja–Igarra, and Egbe–Isanlu schist belts (Oluyede and Klötzli, 2020; Okonkwo and Folorunso, 2013; Aliyu et al., 2021; Udi et al., 2023).

These signatures collectively indicate magma generation dominated by partial melting of continental crust and subsequent fractional crystallization rather than derivation from juvenile within-plate mantle sources. Tectonically, the Igarra granite fits a syn- to late-collisional emplacement model, consistent with granitoid magmatism associated with crustal thickening during the Pan-African orogeny.

Structurally (Udi et al., 2023; Aderogbin, 2025), microstructural features such as undulose extinction in quartz, bent plagioclase twins, and weak mineral preferred orientations mirror deformation patterns documented in other Nigerian Pan-African granitoids, supporting syn-tectonic emplacement and regional correlation within the Dahomeyide Belt. Together, these similarities indicate that the Igarra granite forms part of a widespread Pan-African granitoid suite recording significant crustal reworking during late Neoproterozoic continental collision in Nigeria. Together, these similarities indicate that the Igarra granite forms part of a widespread Pan-African granitoid suite recording significant crustal reworking during late Neoproterozoic continental collision in Nigeria.

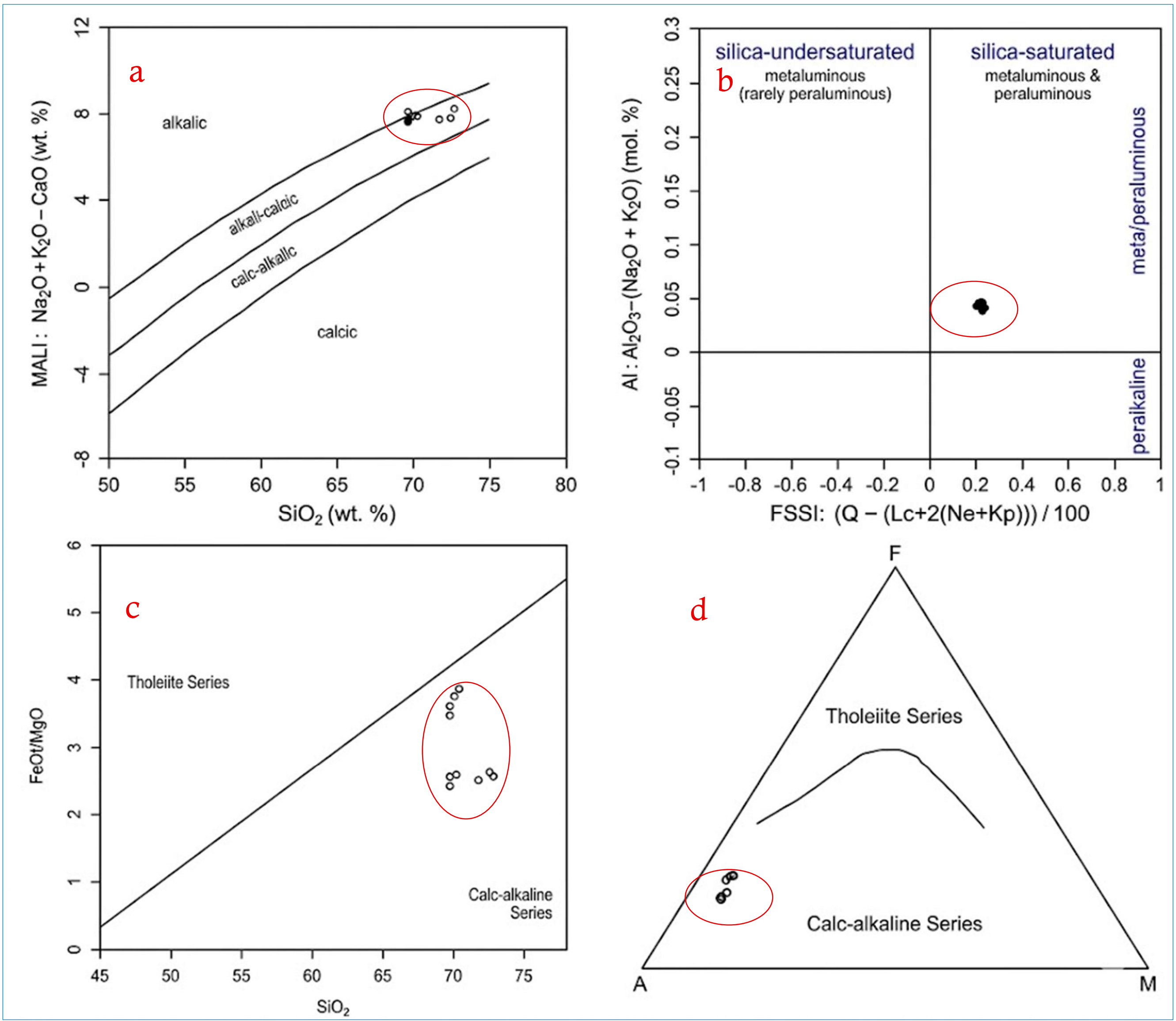

Fig. 8. (a) $Na_2O + K_2O - CaO$ vs SiO_2 diagram (after Frost and Frost, 2008) (b) AI vs FSSI diagram (after Frost and Frost, 2008) (c) Fe_t vs SiO_2 (Miyashiro, 1974) (d) AFM plot of the granite (Irvine and Baragar, 1971)

5.5. Structural Deformation and Regional Correlations

The Igarra granitic pluton appears to have undergone some deformation as evidenced by a weak foliation (Fig, 3); this is further corroborated by sutured grain boundaries of quartz and the mortar texture of the microcline. The petrographic footprint of Igarra batholith is indicative of a very minimal level of tectonic transformation. This also explains the absence of deformation or pronounced mineral alignment in the photomicrographs. Polygonal grains of quartz crystals with triple junctions and occasional cuspate grain boundaries in some of the thin section slides of the Igarra batholith are interpreted as an almost complete absence of deformation suffered by the rocks.

However, the presence of sutured grain boundaries in some of the thin section studied is interpretive of some level of strain on the rock. Also, bent polysynthetic twin lamellae of plagioclase as well as parallel alignment of long axes of biotite grains in certain directions and bent cleavage is indicative of minimal strain. The development of mylonitic fabrics along the pluton margins from structural studies, is believed to be indicative of syn-tectonic emplacement (Okpoli et al., 2022). These trends in the NNE-SSW direction, matching regional Pan-African shear zones and bears similarities with other Pan-African granitoids of syn-collisional emplacement in the Dahomeyide Belt like the Togo granite (Alayi et al., 2023) and the Nigerian younger granites (Bulus, 2021).

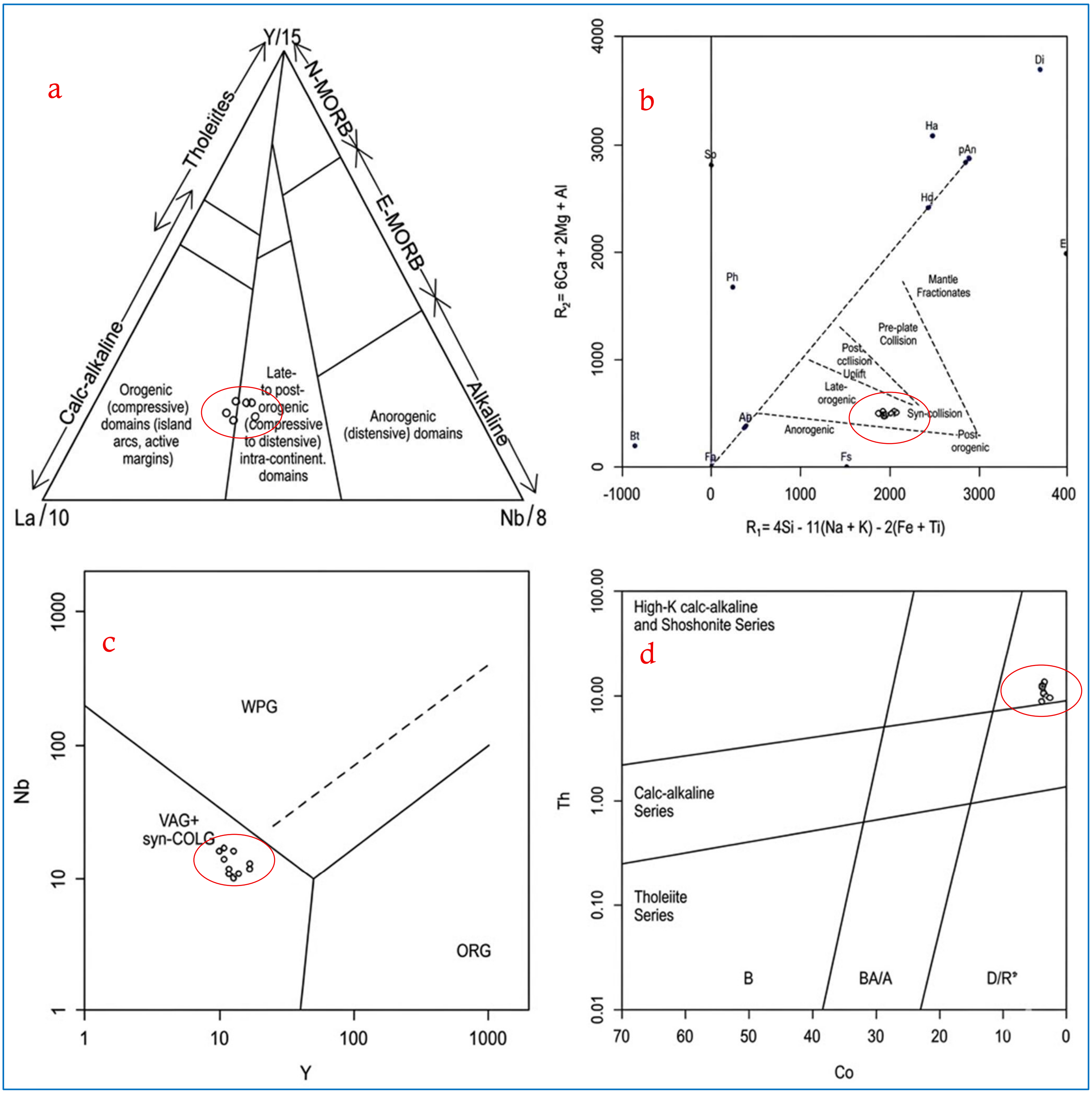

Fig. 9. Trace element plots for Igarra granitic pluton. (a) La/10 – Y/5 – Nb/8 (afterb Cabanis and Lecolle, 1989) (b) R1 vs R2 plot (after Batchelor and Bowden, 1985) (c) Nb versus Y diagram (after Pearce et al. 1984) (d) Co-Th diagram

The Pan-African orogeny produced widespread granitoids across Gondwana-forming terranes. And these include southwest Nigeria (Igarra pluton - IGP), Borborema Province in Brazil, The Arabian-Nubian shield (ANS) in Egypt, the Eastern Ghats Belt (EGB) in southern India, and the Maud Belt (MB) in East Antarctica. Granitoids from the Igarra region share similar collisional origin with granitoids from the Borborema Province of Brazil, but differ in crustal reworking as the Igarra pluton tends more towards hybrid mantle-crust sources. The ANS granitoids of Egypt, which are dominantly juvenile arc-related with very low crustal input, are quite unlike the crustal derived EGB granitoids of India and IGP of Nigeria. The granitoids of EGB and MB have been known to exhibit ultrahigh-temperature (UHT) metamorphism, which has not been observed in the IGP.

Though the IGP and granitoids of BP are both hybrid in origin (I-S transition), the BP rocks show more affinity for peraluminous s-type from metasediments. Due to post-collisional extension, A-type granitoids dominate the EGB and MB. The IGP and BP show evidence of syn-collisional shearing though migmatization is more pervasive in the BP.

6. Conclusions

The Igarra granitic pluton represents a typical Pan-African granitoid emplaced during the late Neoproterozoic evolution of the Nigerian Basement Complex. Petrographic characteristics, including hypidiomorphic granular textures and syn-tectonic microstructural features, indicate emplacement contemporaneous with regional deformation. Major-element geochemistry shows calc-alkaline affinity and predominantly metaluminous compositions, consistent with granitoids formed in convergent orogenic settings. Trace-element and rare earth element systematics provide further constraints on magma source and evolution. Chondrite-normalized REE patterns are characterized by strong enrichment of light rare earth elements relative to heavy rare earth elements, together with weak to moderate negative Eu anomalies. Primitive-mantle–normalized trace-element patterns display enrichment in incompatible elements and relative depletion in high-field-strength elements such as Ta. These geochemical features closely resemble those reported for Pan-African granitoids from the Ilesha, Idanre, Kabba–Lokoja–Igarra, and Egbe–Isanlu schist belts, and are widely interpreted as reflecting partial melting of continental crust under conditions of crustal thickening, with residual garnet and/or amphibole in the source and subsequent fractional crystallization. Holistically, the petrographic, geochemical, and trace-element characteristics of the Igarra granite support a dominantly crustal magma origin emplaced in a syn- to late-collisional tectonic setting during the Pan-African orogeny. While limited interaction with more mafic magmas during emplacement cannot be entirely excluded, the available data do not indicate a dominant juvenile mantle contribution. The Igarra pluton therefore constitutes part of the widespread crust-derived Pan-African granitoid suite that records significant crustal reworking during the assembly of the Dahomeyide Belt in southwestern Nigeria.

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Author Contributions

Emmanuel E. Igonor: conceptualization, writing – original draft, investigation and software. Sunday O. Daramola: visualization, methodology and validation. Isaac o. Ajigo: writing – review & editing. Sunday K. Abeiya: resources, supervision, visualization and validation. All authors commented on the various versions of the manuscript as the writing progressed. All authors read and approved of the final manuscript.

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Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Ethics Approval and Consent to Participate

This study did not involve human participants or animals, and therefore, ethical approval was not required. All fieldwork and sample collection were conducted in accordance with standard institutional and environmental guidelines. Not applicable, as this study did not involve human participants.

Consent to Publication

Informed consent was obtained from all individual participants. included in the study.

Competing Interests

The authors declare no competing. Interests.

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