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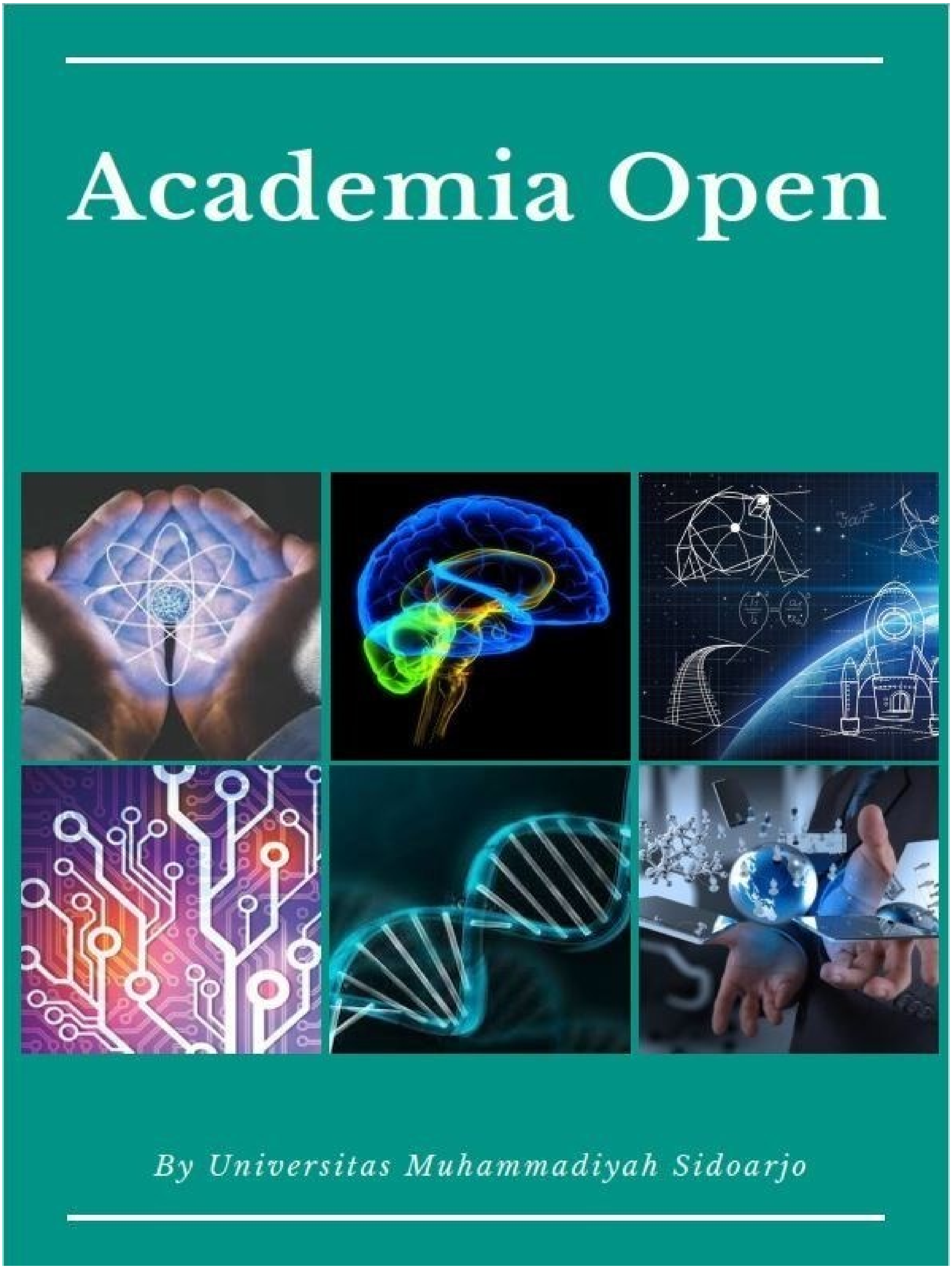

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Geochemical Signatures of Major Elements in Shintaku Granitic Rocks

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Abstract

General Background This study examines the geochemical behavior of granitic rocks in the Shintaku area, a region within the Nigerian Basement Complex where magmatic evolution remains debated due to limited integrated structural–geochemical data. **Specific Background** Earlier works suggest that Pan-African tectonism produced heterogeneous magmas in southwest Lokoja, yet the mechanisms generating the acidic and intermediate intrusive rocks in this locality are still insufficiently constrained. **Knowledge Gap** Despite numerous metamorphic studies, the petrogenesis and geochemical pathways of the granitic bodies in southeastern Lokoja have not been comprehensively analyzed using modern analytical techniques. **Aims** This research investigates magma sources, fractionation trends, and alumina saturation indices to reconstruct the magmatic evolution of the Shintaku granites. **Results** Major element compositions show enrichment in SiO_2, Al_2O_3, and alkalis, with smooth Harker trends implying fractional crystallization, while rough trends indicate partial melting and magma mixing. The coexistence of metaluminous and peraluminous signatures, along with subalkaline affinities, supports heterogeneous mantle–crust melt interaction. **Novelty** This study provides the first integrated petrographic and geochemical characterization of the Shintaku granites using XRF, SEM, and LA-ICP-MS datasets. **Implications** Findings refine the petrogenetic model of southeastern Lokoja and offer a stronger basis for assessing mineralization potential and regional tectonomagmatic evolution.

Highlight :

- Highlights major compositional variations that reflect the influence of magma fractionation.
- Emphasizes evidence of partial melting and magma mixing as drivers of magma heterogeneity.
- Confirms the S-type granitoid character linked to peraluminous supracrustal sources.

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Keywords : Granitic Rocks, Magmatic Fractionation, Fractional Crystallization, Partial Melting, Magma Mixing

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Introduction

The evolution of the Nigerian Basement Complex (NBC), as well as its mineral potential [42, 14, 15], has been the focus of geological studies in Nigeria for a decade. The scarcity of naturally verifiable data on the Earth's physicochemical conditions from the Precambrian [38] has posed a significant challenge, rendering the contributions to Precambrian geodynamic evolution of the Nigerian Basement Complex a subject of controversy among authors.

The understanding of the evolution of the Basement Complex of Nigeria has been controversial [35], although several authors have studied the geology [15, 34, 50, 56], geochemistry [2, 17, 20, 40, 54, 57], and structures [3, 11, 48, 50] within the Basement Complex. However, it has been postulated that the Nigerian Basement was affected by the Pan-African orogeny; however, the impact of the event remains subject to debate. While some authors [7, 15, 33] suggest that the Pan-African orogeny was regional, overprinted and obliterated all traces of older tectono-metamorphic events, others, including [1, 28, 39], insist that imprints of older tectonic events remain isotopically preserved within the Nigerian Basement Complex. Yet, [27] maintained that considering the ubiquity of the Pan-African reactivation across the Nigerian Basement, the age of the protolith within the basement remains debatable.

[50] identified structural geology and numerical modeling as two areas that have suffered apparent neglect in the study of the Nigerian Basement Complex, and considered many of the contributions in favor of isotope geology and geochemistry. [3], held the view that, due to the lack of structural data, most of the thermo-tectonic and orogeny events postulated for the basement complex are inferred from the correlation of available isotopic data with various dated events from different parts of Africa. Arguing in support, [47], related the seemingly poor comprehension and classification of the Nigerian Basement Complex to the over-reliance on isotopic data without a corresponding integration of other aspects of geosciences. Although [27] integrated structural and isotopic data to explain the evolution of the Basement Complex, [50] opined that more comprehensive data and efforts are required in this direction. [50], succinctly highlighted the lack of integrated, extensive structural and isotopic data as one of the missing links that caused the present poor understanding of the Complex. He recommended regional geoscientific studies using modern techniques to understand the geodynamic evolution of the Nigerian basement rocks, noting that quantitative models, structural analyses, and modern geochronological dating techniques are key to understanding the Precambrian Complex and its mineral potential for exploration and true diversification of the Nigerian mono-economy.

The contribution of [48] is useful in interpreting the Nigerian Basement Complex with respect to the geochemical evolution of the Pan-African magmatic rocks between Okene and Lokoja, the western flank of Lokoja, southwestern Nigeria. The research identified rocks as granitic and dioritic with calc-alkaline characteristics. He attributed the variations in trace elements to differentiation and fractional crystallization, suggesting that the diorites originated through the hybridization of basic magma with anatectic crustal materials to produce magma of intermediate composition, which can be compared to the S-type granites. The geochemical signatures of the major elements and their implication for the development of the granitic rocks in the Shintaku area of southeast Lokoja, Southwestern Basement Complex, Nigeria, is intended to complement the efforts of [48] on the adjoining area and contribute to the evolutionary studies of the area using modern analytical facilities like the XRF, LA-ICP-MS and SEM to obtain quality data on the granitic rocks [9]. Contributions to the petrology of the area southeast of Lokoja have been more on the metamorphic aspects than on the igneous. Major contributions in the area [6, 10, 11, 12, 18, 19, 21, 22, 23, 24, 51] have focused on aspects of metamorphic petrology and mineralogy. This study on the geochemical signatures of the major elements and their implication for the development of the granitic rocks around the Shintaku area of southeast Lokoja, Southwestern Basement Complex, Nigeria, is tailored towards bridging this gap and attempts to conduct evolutionary studies of the area using modern analytical facilities to obtain quality data on the granitic rocks. The result of this study will, in part, unravel the magmatic evolution of the intrusive rocks in the southeastern part of Lokoja, the southwest Nigerian Basement Complex. This will open discussions on the possible extent of mineralization in the area. It will lead to a robust mapping and characterization of the rocks in the area, providing invaluable insight into the tectonic evolutionary history of the basement complex. This will ultimately help in the search for mineral deposits and gemstones.

Goal of the Study and Overview of the Study Area

Motivation for this research arises from our interest in understanding the processes that formed the acidic and intermediate rocks that dominate southeastern Lokoja. In this effort, we investigate magma processes and fractionation and link them to the geologic environment. This will give us insight into the magmatic evolution of the area.

Lokoja Southeast is part of the Nigerian Basement Complex. It is bounded by longitudes 7°30΄E; 7°45΄E and latitudes 6°45΄N; 7°00΄N (Fig.1). The area is bordered in the north by the River Benue, in the west by the River Niger, and falls under the southeast quadrant of Topographical Map-Sheet 247 of the Nigerian Ministry of Lands and Surveys, and belongs to the Bassa LGA of Kogi State, Nigeria. A network of all-season roads connects the main parts of Lokoja, making the area accessible, while the rivers can be crossed by boats and ferries.

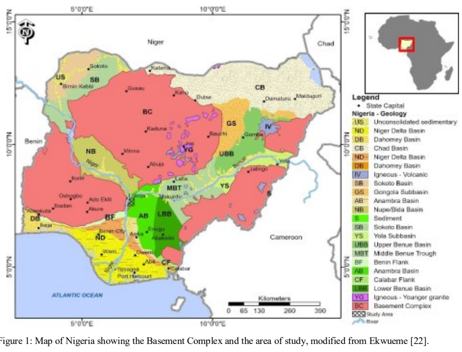

Figure 1: Map of Nigeria showing the Basement Complex and the area of study, modified from Ekwueme [22].

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The field investigations involved traversing the ridges and settlements, including Shintaku, Emi-Momo, Kpata, Echeu, Chite, Emi-Lafia, Akabe, Emi-Andrew, and Gboloko, within the study area in search of outcrops while equipped with the conventional field equipment (Fig. 2). Each outcrop, the position, the nature of exposed rock, and its field relationships were noted and documented. Representative samples were collected, and further geochemical investigations were conducted (Fig. 3). Contacts and other features of geologic interest in some places were also searched for and recorded. During the fieldwork exercise, adequate attention was also given to physiography, topography, and vegetation [4, 17].

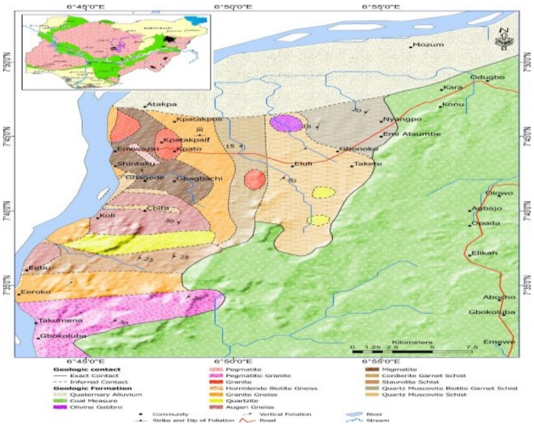

Figure 2: Geological map of the area southeast of Lokoja North-Central modified from Ekwueme [22].

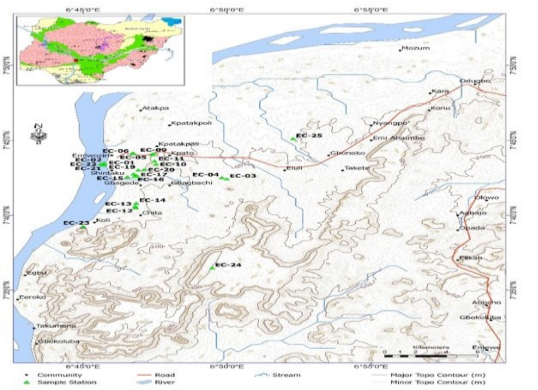

Figure 3: Sample location map of the rocks from the southeastern part of Lokoja, southwestern Nigerian Basement Complex.

Results

After careful examination of the field relationships between the rock outcrops, we sampled rocks with varying characteristics to obtain representative compositions. Twenty-five representative rock samples from the southeastern part of the Lokoja area were collected altogether. The sample location map is presented in Fig. 2 and indicates the location of the sample collection points. The collected samples were carefully labelled, documented, and packaged for further studies, such as petrological and geochemical investigations.

A. Petrography

The petrologic analysis was done using Scanning Electron Microprobe (SEM). Result of the modal investigation of rocks is presented in Table 1, Figure 4.

Table 1: Modal composition of granitic rocks in the southeast Lokoja area.

Sample	EC01	EC02	EC03	EC04	EC05	EC06	EC07	EC08	EC09	EC10	EC11	EC12	EC13	EC14	EC15	EC16	EC17	EC18	EC19	EC20	EC21	EC22	EC23	EC24	EC25
Qtz_Modal	30%	35%	37%	30%	35%	40%	35%	40%	32%	34%	40%	32%	35%	33%	30%	35%	30%	34%	35%	30%	28%	32%	35%	32%	35%
Plag_Modal	25%	20%	18%	24%	21%	18%	18%	15%	25%	16%	17%	20%	25%	20%	22%	24%	28%	20%	18%	17%	25%	21%	18%	22%	20%
K-Feld Modal	18%	15%	12%	15%	16%	17%	15%	11%	18%	18%	15%	15%	20%	18%	20%	15%	15%	17%	18%	13%	20%	16%	17%	18%	16%
Qt Norm	41%	50%	55%	43%	49%	53%	51%	60%	43%	50%	56%	48%	44%	46%	42%	47%	41%	48%	50%	50%	38%	46%	50%	44%	49%
Pl Norm	34%	29%	27%	35%	29%	24%	26%	23%	33%	24%	24%	30%	31%	28%	30%	32%	38%	28%	25%	28%	34%	30%	26%	31%	28%
KFsp Norm	25%	21%	18%	22%	22%	23%	23%	17%	24%	26%	21%	22%	25%	25%	28%	21%	21%	24%	25%	22%	28%	24%	24%	25%	23%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

EC-01 (SHT1)-EC-02(SHT2); EC-21(SHT3)-EC-22(SHT4) =Shintaku; EC-03 (EMLF1) - EC-04 (EMLF2)= Emilafia; EC-05 (EMWOZ1) – EC-06(EMWOZ2) = Emiwoziri; EC-07 (EMIMO) = Emimomo; EC-08 (KPAT1); EC-11(KPAT5) = Kpata; EC-12 (Chite1) – EC-14 (Chite5) = Chite; EC-15 (ECHEW1) – EC-20 (ECHEW6) = Echewu; EC-23 =Akabe; EC-24 = EmiAndi and EC-25 = Gboloko.

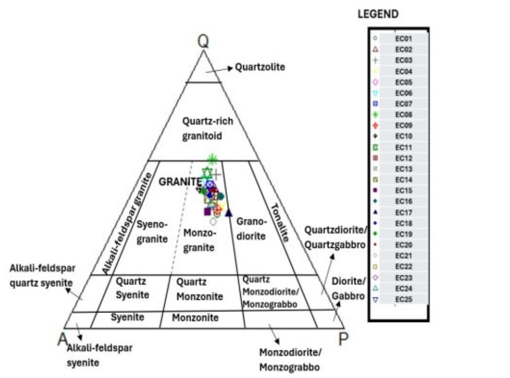

Figure 4: QAP diagram for the various southeast Lokoja plutons showing them as monzogranite, after Le Maitre *et al*. [41]

B. Geochemistry

Geochemical analysis of the sampled rocks was conducted using the X-ray Fluorescence Spectrometer (XRF) and Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) at the Department of Geosciences, Texas Tech University, Lubbock, Texas, United States of America.

Method

For the bulk rock compositional data, a single whole rock sample was analyzed in duplicate using the prepared disc of a 1:5 mixture of rock-to-fluxing agent (49.75% Li-metaborate, 49.75% Li-tetraborate, and 0.5% LiBr) along with 40µl of a Lil non-wetting agent. Major and minor elements analyses were conducted by sequential X-ray Fluorescence using a Thermo-Scientific ARL Perform X technique. The major, trace, and rare earth element compositions (wt%), CIPW-Norm, and the average composition of the analyzed rock samples are presented in Tables 2-4, respectively. The monzogranitic rocks in Table 2 have SiO_2 composition ranging from approximately 48 -79 wt% with a mean value of 66.6465 wt%, TiO_2 from 0.2 to 6 wt% with an average value of 1.4769 wt%, and Al_2O_3 composition ranging from 12 to 16 wt% with a mean value of 14 wt%. The standard deviation and variance values of the mentioned major oxides and those of Fe_2O_3, MnO, MgO, CaO, Na_2O, Na_2O, and P_2O_5 are summarized in Table 3, and interpreted in Figs. 5 and 6.

Table 2: Chemical compositions of the granitic rocks from the southeast Lokoja area

Oxides/Name	EC01	EC02	EC04	EC09	EC10	EC11	EC12	EC13	EC15A	EC15B	EC18A	EC18B	EC21A	EC21B	EC22	EC24	EC23	EC25	EC14
SiO_2	74.157	66.5299	65.9625	63.4715	59.0286	66.2899	64.2991	73.3821	73.9238	73.9519	70.0687	70.6654	48.0671	48.1511	57.2206	75.4444	67.7955	68.9145	78.9613
TiO_2	0.1557	0.5062	0.7207	0.9031	0.7726	0.3654	1.0589	0.2209	0.1465	0.1455	0.4666	0.4622	4.0759	4.0768	2.6309	0.0469	0.3903	0.3531	0.0592
$Al2O_3$	13.7554	15.0001	14.4294	14.2163	15.8263	15.6258	13.8238	13.5742	13.6109	13.5855	13.0856	13.0391	13.6165	13.7011	13.6312	13.2347	15.1198	14.8332	12.1077
$Fe2O_3$	1.4133	4.0993	5.4692	6.6963	9.2375	3.7868	7.423	2.1258	1.3837	1.4102	4.4135	4.4651	13.2115	13.1782	10.3739	0.2941	3.531	3.1191	0.4614
MnO	0.0225	0.0543	0.0539	0.0805	0.1559	0.03	0.082	0.0223	0.0138	0.0144	0.0483	0.0485	0.144	0.1445	0.1464	0.0077	0.0583	0.0481	0.0095
MgO	0.6062	2.4658	0.9539	1.2099	4.0546	0.6564	1.261	0.6348	0.6244	0.6266	0.7145	0.7202	4.4616	4.4398	2.6991	0.4621	2.357	2.0325	0.5177
CaO	0.7606	3.7502	2.3108	2.7945	2.2668	1.7135	2.9105	1.1818	0.8694	0.8696	1.6944	1.7094	7.3145	7.3292	4.4877	0.8684	2.8303	3.2574	0.6738
Na_2O	3.2617	4.1952	2.7605	2.441	3.4638	2.8148	2.4463	2.7216	2.5542	2.5523	1.9088	1.9479	2.6029	2.636	2.4249	2.8679	3.7077	3.7083	1.6022
K_2O	4.9938	2.1088	5.8515	5.3147	3.6152	6.9618	5.3408	5.3816	6.0405	6.0036	6.2303	6.2967	2.3026	2.3009	3.8801	5.4883	3.2562	2.9901	6.31
P_2O_5	0.0625	0.2009	0.1516	0.3474	0.2643	0.0746	0.4072	0.0763	0.0638	0.0646	0.1147	0.1176	2.4991	2.5154	1.2744	0.0239	0.1797	0.1478	0.0193
LOI	0.4703	0.5501	0.2746	0.4592	0.8729	0.3644	0.6074	0.3393	0.3848	0.3848	0.4548	0.4548	0.2475	0.2475	0.77	0.2975	0.8555	0.5474	0.2792
Total	99.659	99.4608	98.9386	97.9344	99.5585	98.6834	99.66	99.6607	99.6158	99.609	99.2002	99.9269	98.5432	98.7205	99.5392	99.0359	100.0813	99.9515	101.0013
Ab	45.33878	53.3308	33.66209	31.33515	47.33995	32.42917	31.03846	37.9493	35.07985	35.18686	26.3212	26.51574	30.62487	30.86711	31.22808	39.78386	48.52668	48.12353	25.02435
An	6.19925	27.95355	16.52239	21.03416	18.16541	11.57522	21.65285	9.662301	7.001313	7.029516	13.69993	13.64388	50.4613	50.32273	33.88694	7.063497	21.72029	24.78625	6.170697
Or	48.46197	18.71565	49.81552	47.63069	34.49463	55.99561	47.30869	52.3884	57.91884	57.78362	59.97888	59.84038	18.91383	18.81016	34.88498	53.15265	29.75303	27.09022	68.80495

Total Fe as Fe_2O_3; EC-01 (SHT1)-EC-02(SHT2); EC-21(SHT3)-EC-22(SHT4) =Shintaku; EC-03 (EMLF1) - EC-04 (EMLF2)= Emilafia; EC-05 (EMWOZ1) – EC-06(EMWOZ2) = Emiwoziri; EC-07 (EMIMO) = Emimomo; EC-08 (KPAT1) – EC-11(KPAT5) = Kpata; EC-12 (Chite1) – EC-14 (Chite5) = Chite; EC-15 (ECHEW1) – EC-20 (ECHEW6) = Echewu; EC-23 =Akabe; EC-24 = EmiAndi and EC-25 = Gboloko.

Table 3: Statistical descriptive summary of the major elements' distribution in monzogranitic rocks of the southeast Lokoja, Nigeria.

Descriptive Statistics

	N	Minimum	Maximum	Sum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
SiO2	19	48.07	78.96	1266.28	66.6465	1.96597	8.56945	73.436
TiO2	19	.15	5.92	28.06	1.4769	.41892	1.82605	3.334
Al2O3	19	12.11	15.83	265.82	13.9903	.21664	.94431	.892
Fe2O3	19	.29	13.21	96.09	5.0575	.91845	4.00343	16.027
MnO	19	.01	9.50	67.51	3.5532	.78242	3.41048	11.631

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MgO	19	.46	4.46	31.50	1.6578	.31692	1.38143	1.908
CaO	19	.67	7.33	49.59	2.6101	.45493	1.98301	3.932
Na_2O	19	1.60	4.20	52.62	2.7694	.15084	.65749	.432
K_2O	19	2.11	6.96	90.67	4.7720	.36014	1.56983	2.464
P2O5	19	.06	7.63	33.15	1.7446	.55926	2.43777	5.943
Lol	19	.25	.87	8.86	.4664	.04455	.19418	.038
Valid (listwise)	19							

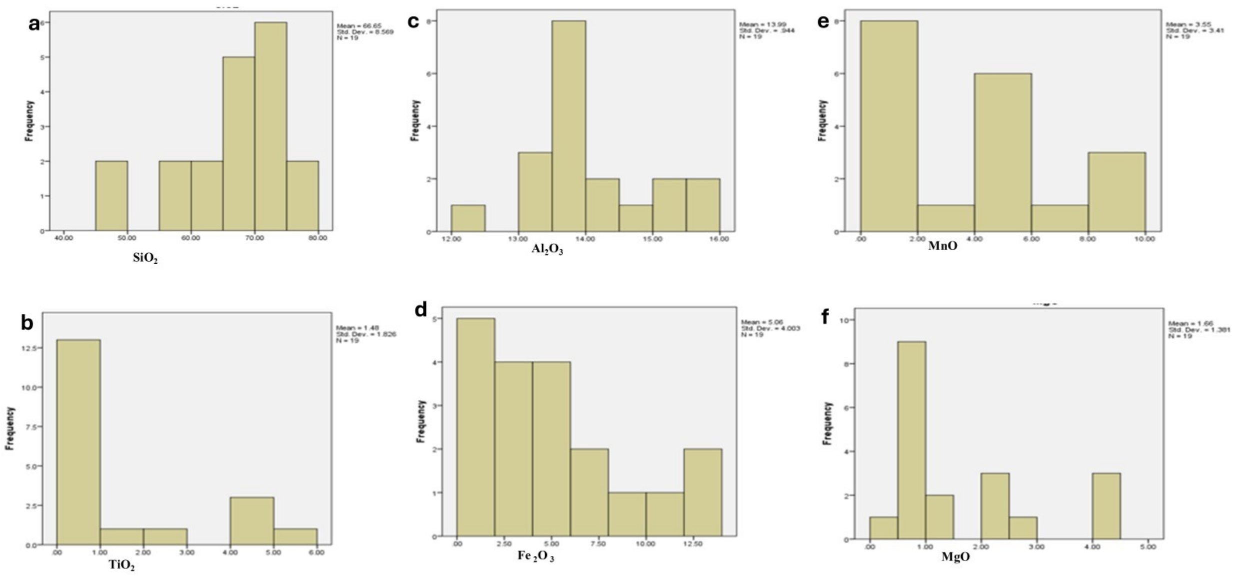

Figure 5: The histogram distributions of monzogranitic rocks in the southeast Lokoja area, (a) SiO_2, (b) TiO_2, (c) Al_2O_3, (d) Fe_2O_3, (e) MnO, (f) MgO

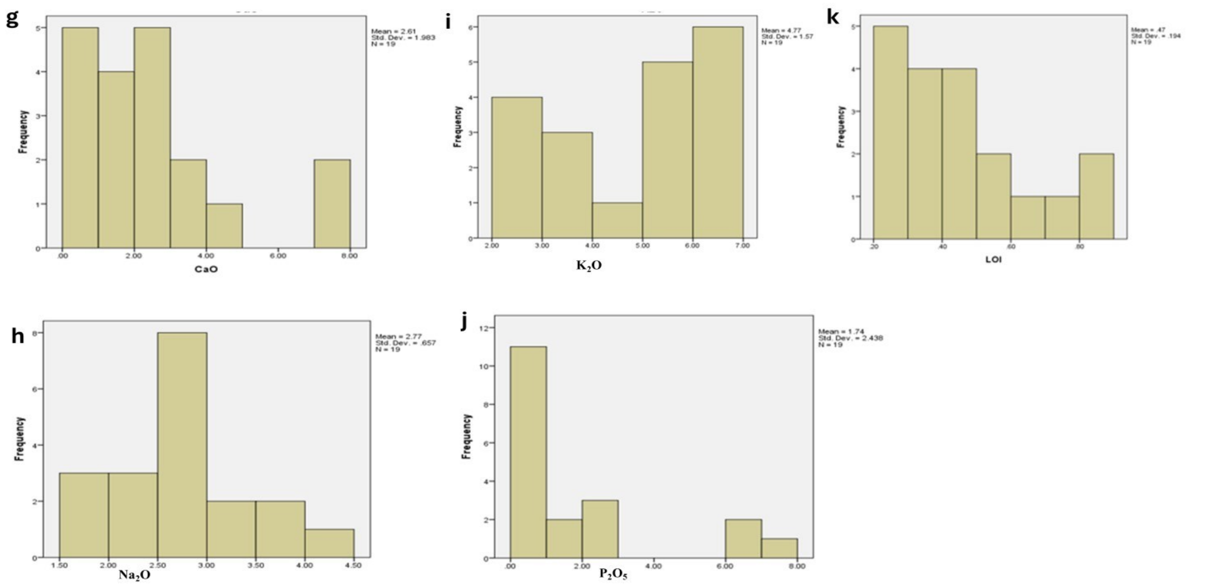

Figure 6: The histogram distributions of monzogranitic rocks in the southeast Lokoja area, (g) CaO, (h) NaO_2, (i) K_2O, (j) P_2O_5, and (k) LOI

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Table 4: Comparison of major elements from southeast Lokoja and similar rocks from Nigeria and other parts of the world.

Oxides	A	B	C	D	E	F	G	H	I	J	K	L	M
SiO2	66.6465	64.82	63.46	65.48	63.31	71.15	64.92	72.2	70.36	69.2	71.93	71.3	72.19
TiO2	1.4769	0.67	0.64	1.75	1.18	0.17	0.9	0.2	0.32	0.46	0.26	0.31	0.17
Al2O3	13.9903	15.08	19.87	17.94	15.12	4.45	15.82	13.7	14.42	14.86	14.58	14.32	14.82
Fe2O3	5.0575	5.39	2.94	4.9	7.25	0.59	4.65	1.85	3.61	3.11	2.2	2.85	1.33
MnO	3.5532	0.006	0.03	0.03	0.14	0.09	0.07	0.02	-	0.06	0.05	0.05	0.18
MgO	1.6578	1.35	1.61	3.18	1.56	0.25	1.98	0.38	0.09	0.6	0.66	0.71	0.41
CaO	2.6101	3.1	5.05	3.01	3.88	0.79	3.3	1.4	2.03	1.89	1.86	1.84	1.75
Na_2O	2.7694	4.55	3.48	4.07	2.93	3.01	3.56	3.53	3.35	3.64	3.57	3.68	3.94
K_2O	4.7720	0.44	5.37	1.07	4.09	6.17	3.29	5.09	5.38	5.17	4.02	5.07	3.68
P2O5	1.7446	0.16	-	-	0.47	0.11	0.33	0.08	-	0.16	0.08	0.12	0.01
Lol	.4664	0.60											
Total	104.7447												

A. Average composition of granitic rocks of southeast Lokoja (present work)

B. Average composition of granite-gneiss from the NE Obudu area, Bamenda massif [25].

C. Average composition of granite gneiss from Ushongo, Bamenda massif [16].

D. Average composition of granite gneiss from the Vandekyaa area, Bamenda massif [16].

E. Average composition of older granite from Jato Aka area, Bamenda massif [58]

F. Average composition of granite-gneiss from the southern Obudu area [18]

G. Average composition of granite-gneiss from Oban massif, SE Nigeria [20]

H. Average composition of granites from Kabba-Lokoja area, SW Nigeria [26]

I. Average composition of granite-gneiss from Jos Plateaux, northern Nigeria [59]

J. Average composition of older granite from Saminaka & Ririwai, northern Nigeria [49]

K. Average composition of granites and quartz monzonite from worldwide localities [36]

L. Average composition of 2485 granites [42]

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M. Average composition of metamorphosed granitic rocks of Idaho batholiths, USA [29]

C. Major element relationships:

Comparison with similar rocks from another region indicates that the SiO_2 content of the average composition of granitic rocks of the southeast Lokoja area is comparable to those of the northeast Obudu area, Bamenda massif [25], granite gneiss from Vandekyaa area, Bamenda Massif [16], granite gneiss from Oban Massif, SE Nigeria [20], and the older granite from Saminaka & Ririwai, northern Nigeria [49]. On the other hand, SiO_2 is lower than the average composition of granite-gneiss from southern Obudu area [18] granites from Kabba-Lokoja area SW Nigeria [26] granite-gneiss from Jos Plateau, northern Nigeria [59] granites and quartz monzonite from other localities other than the Nigerian Basement Complex [36] 2485 granites [42] and metamorphosed granitic rocks of Idaho batholiths, USA [29] and higher than the average composition of granite gneiss from Ushongo, Bamenda Massif [16] and the average composition of older granite from Jato Aka area, Bamenda Massif [58] (Table 4). Other major oxides are also compared in Table 4.

Analytical data for the major elements of the rocks are plotted on discrimination diagrams (Figs. 7 and 8), and Table 3 to reveal their geochemical characteristics. Magma's chemical composition is key to understanding processes and the origin of the rocks, as well as their tectonic setting. Plotting the rocks by their determined SiO_2 and $Na_2O + K_2O$ contents, Fig.7, interprets that the magma that formed the rocks is related by fractional crystallization from mafic magma that originated from the mantle to acidic magma in the crust. However, multiple magma sources can be linked to this suite, with the rocks plotted in the field of alkaline and subalkaline fields, suggesting possible partial melting of country rocks and magma mixing [13, 30, 37, 44]. The scenario can be linked to the interaction between mantle-crust melts, which produced more evolved acidic melts. The dominance of the subalkaline trend suggests a calc-alkaline magma origin, which is characteristic of subducted plates and post-orogenic tension, associated with the Nigerian Basement Complex [2, 50]. Based on the CIPW Normative feldspar composition of the acidic-intermediate plutonic rocks, Fig. 8 [46], rocks plot in the fields of granite, quartz-monzonite, and granodiorite, confirming possible magmatic differentiation. However, the CIPW normative of feldspar points to more predominant plagioclase-rocks, relative to acidic (granite) – intermediate (granodiorite). To further examine the magma fractionation and mineral differentiation pattern of the rock, major oxide compositions of granitic rocks from the southern Lokoja were plotted onto the Harker discrimination diagram (Fig. 9). [32] discriminated against granitic rocks into metaluminous (i.e., the I-type) and peraluminous (S-type) granites to reveal the processes that accompanied magma evolution. Magma crystallization trend can be traced based on mineral fractionation, a process in which ferromagnesian minerals crystallize, and their oxides are removed from the melt at the early stage (Figs. 9c, e, f, and g, [5]). K_2O increases with silica (9a), indicating magma enrichment with potassium during the late stage of crystallization to form more evolved magma. Na_2O, Al_2O_3, and CaO (Figs. 9b, d, and h) may suggest a continuous plagioclase fractionation from anorthite–albite–orthoclase following an ideal fractional crystallization trend, leading to more felsic lithospheric magma, and a decrease in P_2O_5 (9i) reveals the fraction of apatite in granitic rocks. The co-existence of metaluminous and peraluminous rocks is indicative of magma source heterogeneity, which is brought about by partial melting of metasedimentary rocks and magma mixing. This may pinpoint that granitic rocks in southern Lokoja are products of syn-late Pan-African tectonism [10, 46]. This can be related to calc-alkaline magmatism of post-convergent tectonism [52] and is assigned to the S-type granitoid produced from a supracrustal sedimentary source.

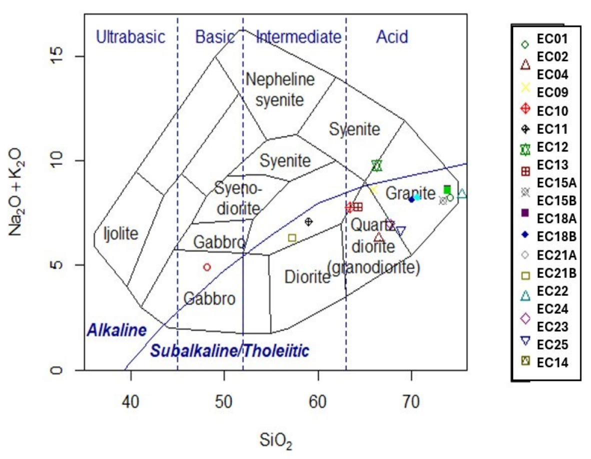

Figure 7: Total alkali versus silica (TAS) diagram, after Cox *et al.*[13]

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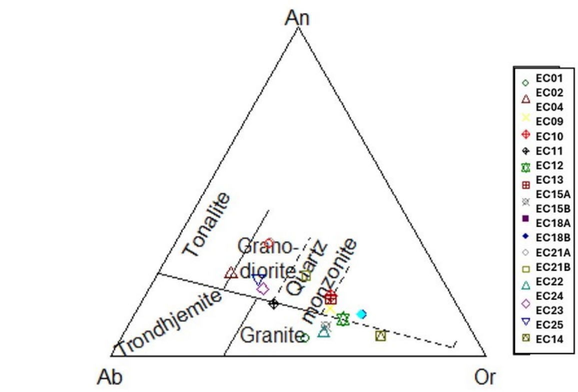

Figure 8: CIPW- Normative An-Ab-Or ternary diagram of the southeast Lokoja area, after O'Connor, [46].

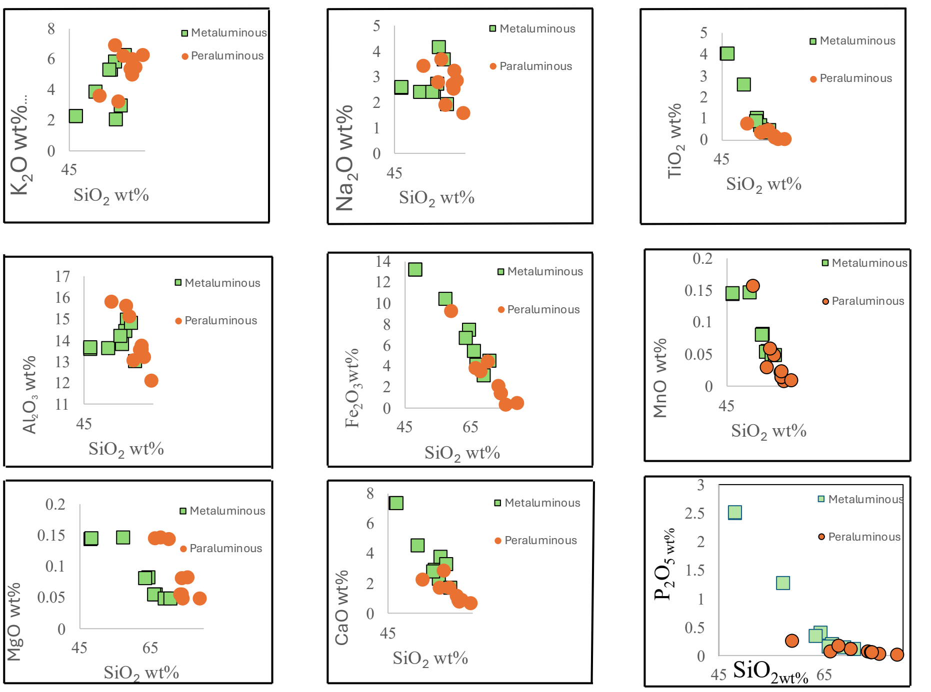

Figure 9: Harker variation diagrams (a - i) for granitic rocks from southeast Lokoja, after Harker [32].

D. The magma series and Alumina Saturation Index (ASI)- Magmatic difference constraint

To understand the mantle-crustal melt mingling and predict a possible petrogenic evolution of the magma, we studied the magma series and alumina saturation indices of the rocks. The igneous rocks are grouped based on the total molar alkali versus alumina content into peraluminous [Al_2O_3 > (CaO + Na_2O + K_2O)], or metaluminous [Al_2O_3 < (CaO + Na_2O + K_2O) but Al_2O_3 > (Na_2O+K_2O)] (Fig. 10,[54]. The bimodal composition of the rocks with a conspicuous overlap of the plot indicates progressive melt fractionation and partial melting of aluminous crustal rocks. A relationship between magma composition and pathways can be linked to the tectonomagmatic setting and the collision of the Nigerian Basement Complex during the Pan-African Orogeny, which resulted in granite plutonism [34, 45, 52]. Similarly, the granitic rocks plotted in the fields of metaluminous and paraluminous series onto the total alkali versus silica diagram (Fig. 11) [43, 37]. Plots of the metaluminous and peraluminous samples in the alkaline-subalkaline fields confirm magma heterogeneity within the system, which may be attributed to partial melting of the mantle-crust slabs, relative to the subalkaline magma type. The predominance of the plots in the subalkaline field reveals that the rocks belong to a calc-alkaline granite series, resulting in more evolved felsic, volatile-rich magma, which can be linked to an orogenic setting (31, 37].

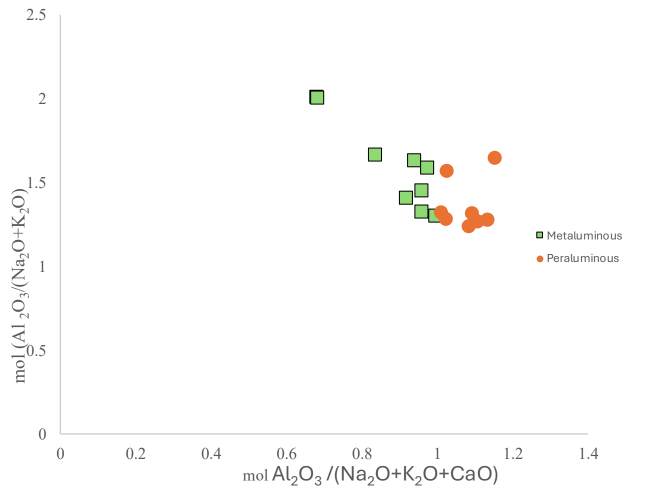

Figure 10: Alumina saturation index for the granitic rocks of southeast Lokoja, after Shand [54].

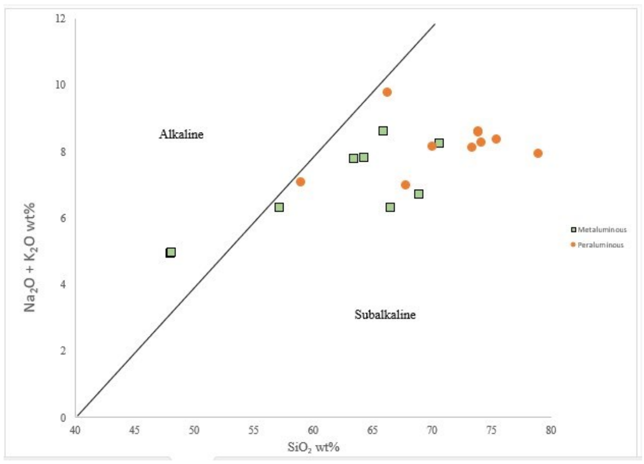

Figure 11: Alkali – Silica plot for the granitic rocks from the study area. The line in the middle represents the alkaline–subalkaline boundary of Irvine and Barager [37]

Discussions

The Harker diagrams reveal that rocks span a significant compositional range (from granitoids through granites to monzogranites or monzonites) and that there are both smooth and rough trends in the variation of each of the major oxides. The smooth trends in TiO_2, Fe_2O_3, MnO, CaO, and P_2O_5 (Fig. 9c, e, f, h, and i) strongly suggest that the magma that formed the rocks is genetically related and is influenced by a progressive magma fractionation from the mantle to the crust with a resultant light hue rock. Conversely, we have linked magma heterogeneity to the partial melting of mantle-crust material, and this is responsible for the rough trends observed in K_2O, Na_2O, Al_2O_3, and MgO (Fig. 9 (a, b, d, and g). The bulk rock geochemical data (Table 2) are essentially in line with the fractional crystallization outlined by [5]. The result is consistent with the observation that the decrease in MgO, Fe_2O_3, and CaO as Al_2O and SiO_2 increase coincides with the removal of the early-formed ferromagnesian minerals from the melt as crystallization progresses. The obvious rise in Na_2O and K_2O concentration confirms that, as ferromagnesian components and CaO are removed from the melt, any variables not absorbed into the crystallizing phase are preserved or concentrated in the subsequent liquid to make up the total components 100%. The remaining variables do not increase in value, but they comprise the proportion of the remaining melt. The increase in Na_2O and K_2O indicates that the albite component in the plagioclase that may have formed and settled earlier was low, and K-feldspar was depleted. The Al_2O_3 curve (Fig. 10) reveals an initial increase (especially in the metaluminous components) and then a decrease (in peraluminous components). Therefore, because CaO decreased continuously, clinopyroxene was absorbed earlier, with Ca removal, while plagioclase began to crystallize afterwards, absorbing both Ca and Al. The chemistry of the analyzed rocks suggests they are predominantly monzogranitic rocks, with relatively high SiO_2, Al_2O_3, and alkali ($Na_2O + K_2O$) contents. They, therefore, qualify for the S-type granites categories and are interpreted to have been formed from the partial melting of supracrustal sedimentary rocks. Silica and alumina enrichments are the clues for this, resulting in more felsic granitic rocks. S-type granites are oversaturated in aluminum with an ASI index greater than 1.1. where ASI = ($Al_2O_3 > CaO + Na_2O + K_2O$) in mol percent; [30,8, 60]. The color index of S-type granites can vary from melanocratic to leucocratic. Higher color indices correlate with higher plagioclase and alkali-feldspar ratios [55]. The most common high color index mineral in an S-type granite is biotite [8,53].

Mineralogically, the modal compositions of the S-type granites (8, 31] examined in this study have predominant alkali and plagioclase feldspars with quartz. Thus, they are silica oversaturated (Table 2) and do not contain feldspathoids. Their alkali feldspars are typically white in hand specimens, although color may change with advanced weathering.

Geochemically, major element characteristics of S-type granites include lower levels of sodium and calcium and elevated levels of silica. Iron and magnesium contents correlate with the color index in the rocks. Again, the S-type granites contain less magnesium than iron in the present investigation, unlike the opposite view held by [8]. With respect to aluminum, the S-type granites are more peraluminous than metaluminous or have a total alkali (+ calcium) to aluminum ratio of greater than one [8].

Conclusion

The results of our research have been summarized in petrography and geochemistry. We agree that the process that formed the acidic magma in Southeast Lokoja involves magma generation and ascent, and that the predominance of acidic rocks could have originated from two magmatic processes: (a) fractional crystallization, and (b) partial melting and magma mixing. The magmas could be related by fractional crystallization of mantle-derived parent magma, where ferromagnesian minerals crystallize at an early stage, and their oxides fractionate from the melt. This process can account for the formation of more evolved felsic minerals in the acidic rocks during the late stage of crystallization. The Harker diagrams show that the rocks span a significant compositional range from granitoids, granites, and monzogranites, which evidences fractionation from intermediate to felsic magmas. On the other hand, the felsic magma is evidenced to be produced by partial melting of peraluminous supracrustal sedimentary source, derived by intrusion of mantle-derived magma, followed by weathering at the Earth's surface, hence its classification as S-type granites. Otherwise, felsic magma was produced by remobilization and migration of the felsic magma due to the geothermal gradient.

The bulk chemistry shows enrichment in SiO_2, Al_2O_3, alkali ($Na_2O + K_2O$), and total Fe_2O_3. MgO and CaO are unevenly distributed, while the samples are depleted in Na_2O, K_2O, TiO_2, MnO, and P_2O_5, typical of the S-type granites.

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