https://dx.doi.org/10.4314/dujopas.v11i1c.34
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 11 No. 1c March 2025*

Geochemical Characterization and Mineralization Potential of Kaffo Albite Arfvedsonite Granites in the Riruwai Younger Granite Complex, Nigeria

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Abstract
This study presents geochemical analysis of the Kaffo albite arfvedsonite granites, a subset of the Riruwai Younger Granite Complex, Nigeria, to assess their mineralization potential and tectonic significance. Major and trace element compositions were analyzed using energy dispersive x-ray fluorescence (EDXRF), and Pearson correlation coefficients were calculated to establish elemental associations and identify mineralization patterns. The results highlight significant geochemical factors representing magmatic differentiation, crustal assimilation, and late-stage fluid processes. Strong negative correlations between SiO_2 and major oxides (CaO, MgO, Fe_2O_3) suggest fractional crystallization and crustal contamination, while positive correlations among Fe_2O_3, TiO_2, and trace metals (Cu, Zn, Pb) indicate possible ore mineralization associated with Fe-Ti oxides. The rare earth element (REE) distribution further suggests magmatic differentiation and hydrothermal influence, reinforcing the high potential for rare-metal mineralization, including Nb, Ta, Zr, and REEs. These findings enhance the understanding of the metallogenic evolution of the region and have significant implications for mineral exploration and mining.

Keywords: Petrogenesis, Geochemistry, Granite, Mineralization and Rare-earth-elements

INTRODUCTION
The study of granitic and alkaline rocks provides critical insights into magmatic evolution, mineralization potential, and tectonic settings. Albite-arfvedsonite granites are a distinct class of peralkaline igneous rocks commonly associated with rare metal mineralization, including elements such as Nb, Ta, Zr, Sn, and REEs (Ogunleye et al., 2006, Olasehinde & Ashsno 2021). The Kaffo Albite Arfvedsonite suite represents a significant geological formation within the Nigerian Younger Granite Province, a region known for its diverse magmatic history and

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metallogenic significance (Kinnaird, 1979, 1985). The Pearson correlation coefficient is a statistical tool used to measure the strength and direction of linear relationships between two variables. In geochemistry, it helps in understanding elemental associations and their implications for rock formation, alteration processes, and mineralization potential.

This study examines the Pearson correlation coefficients of major oxides and trace elements of the Kaffo Albite Arfvedsonite in the Riruwai Younger Granite Complex. By analyzing these correlations, we can infer magmatic differentiation trends, source characteristics, and potential ore-bearing mineral phases. Strong positive correlations suggest a common source, similar geochemical behavior, or co-precipitation during magmatic or hydrothermal processes. Negative correlations may indicate fractionation, substitution, or different petrogenetic pathways. Understanding these relationships is crucial for mineral exploration, as they highlight possible ore-related enrichment zones and the geotectonic environment of rock formation. This analysis provides insights into the geochemical controls on mineralization and the tectonic significance of the studied rocks. By comparing our results with other peralkaline granite occurrences worldwide, such as those in the East African Rift, the Massif Central (France), and the Ilímaussaq Complex (Greenland), we provide a broader geodynamic and metallogenic context for the Kaffo suite. This will help refine existing models of rare-metal enrichment in peralkaline granites and contribute to exploration strategies in similar geological settings. The implications of element intercorrelations and their alignment with mineralization trends will be discussed in relation to other documented studies on rift-related granitic systems.

The Geological Setting

The Riruwai Younger Granite Complex is one of the several Jurassic anorogenic intrusions in north-central Nigeria (Figure 1), forming part of the larger Younger Granites Province. This geological province is composed of high-level granitic intrusions that were emplaced within the Pan-African basement complex during the Mesozoic Era. The Riruwai Complex, like other Younger Granites, provides critical insights into the geodynamic processes that shaped the region during the breakup of Gondwana (Jacobson & MacLeod, 1977, Bowden et al., 1987).
The Younger Granites Province, including the Riruwai Complex, is closely linked to extensional tectonics associated with lithospheric thinning and mantle upwelling (Coulon et al., 1996). The Riruwai Complex (Figure 2) consists of multiple ring intrusions that exhibit a variety of rock types, reflecting a complex magmatic history (Bowden & Turner, 1974). These lithologies suggest a progression from mafic to felsic compositions, indicative of fractional crystallization and crustal assimilation processes that contributed to the final geochemical signatures of the granites. Structurally, the Riruwai Complex exhibits circular and elliptical ring structures, characteristic of forceful magmatic emplacement and subsequent caldera collapse. These features are consistent with the extensional tectonic environment that facilitated magma ascent and emplacement (Kinnaird, 1985).

The Riruwai Complex shares several geochemical and structural similarities with other Younger Granite complexes, such as Jos, Afu, and Bauchi (Bowden & Turner, 1974). However, it is distinguished by its unique peralkaline granites and significant rare-metal mineralization. The presence of high concentrations of elements such as tin (Sn), niobium (Nb), and tantalum (Ta) makes Riruwai economically significant compared to some other complexes that lack such mineralization and rare-earth elements (REEs) (Bowden et al., 1976; Jacobson & MacLeod, 1977, Kinnaird, 1985).

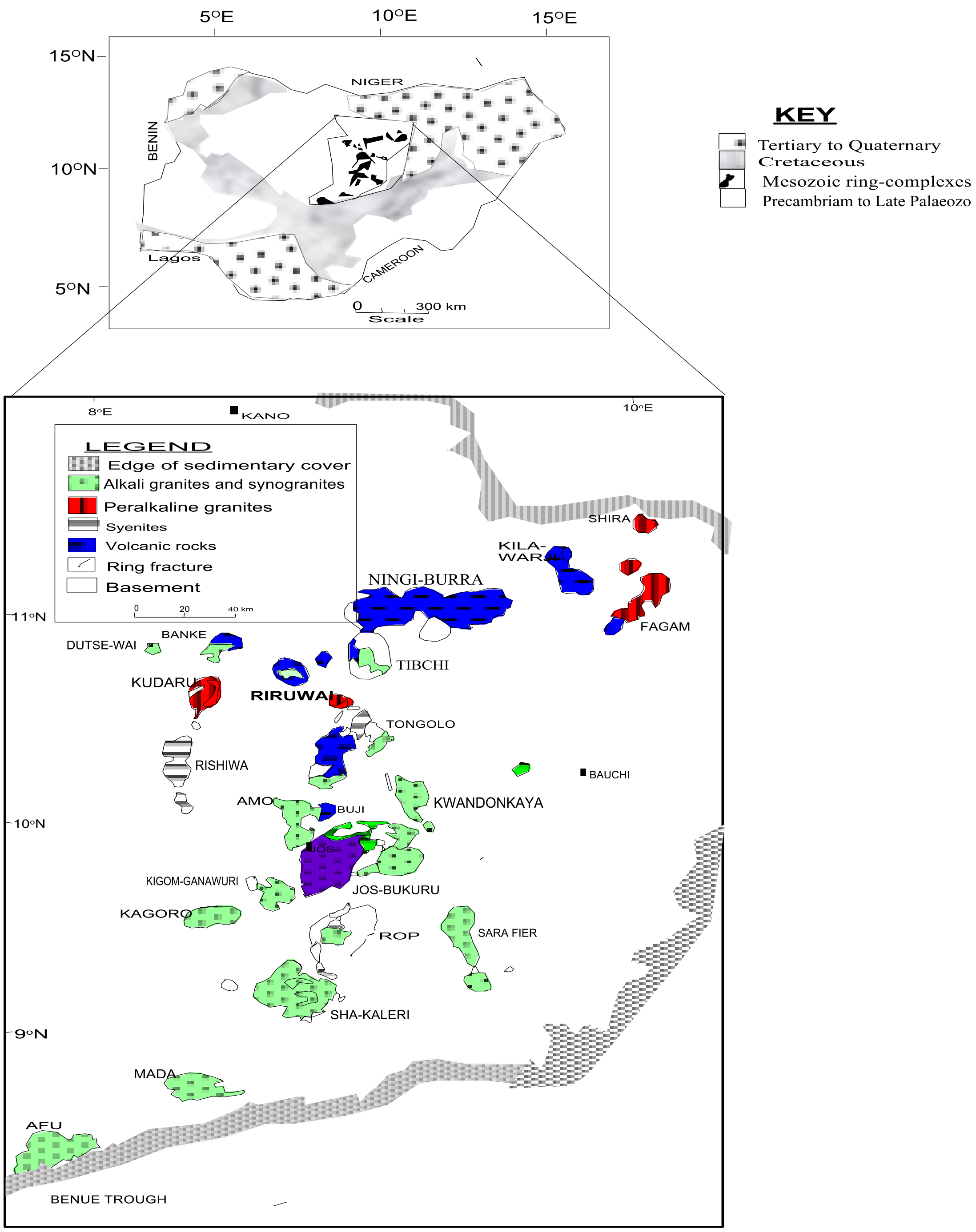

Figure 1 The Younger Granite Complexes of Nigeria Map. Modified after (Kinnaird, 1985; Ogunleye, et al. 2006)

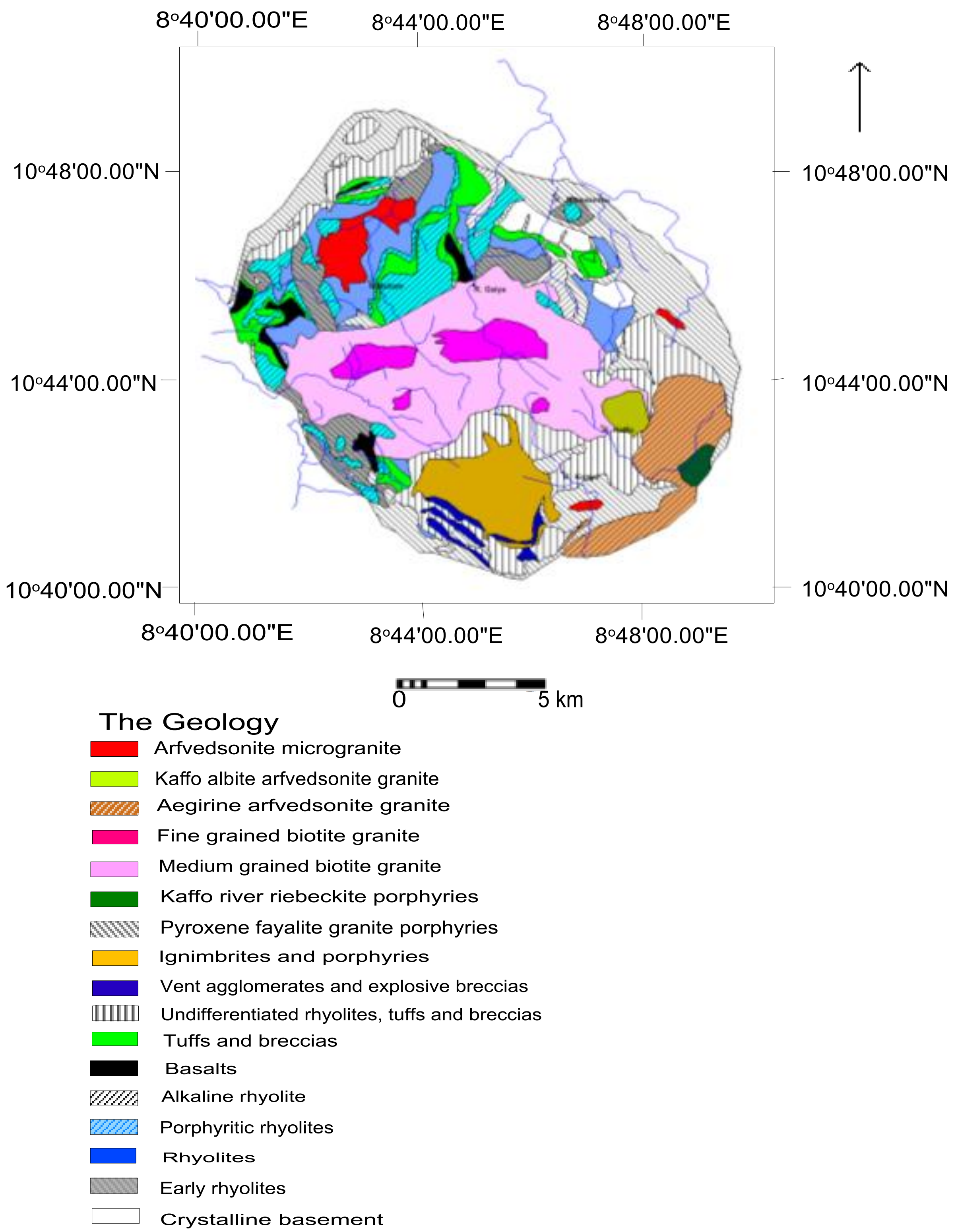

Figure 2 Geology Map of the Riruwai Complex. Modified after Ogunleye, et al. (2006)

METHODOLOGY

The methodology for analyzing the Pearson correlation coefficient and its implications for mineralization involves several key steps, including sample collection, geochemical analysis, data processing, and statistical evaluation. Rock samples were collected from the Riruwai Younger Granite Complex. Sampling focused on fresh, unweathered rock exposures to ensure the accuracy of geochemical data. Sampling and Analysis follows guide lines provided by Ashano (2009). Thirty-nine (39) samples were analyzed for major and trace elements which include SiO_2, CaO, Fe_2O_3, K_2O, Na_2O,TiO_2, MnO, P_2O_5, Al_2O_3, V, Cr, Cu, Sr,Zr,, Ba, Zn, Ce, Pb, Sn, Ga, Y, Ni,,Rb, Nb, La, Eu, Mo, Co, Ta, W, Hf, Pr, Lu, Gd, U, Th, and N of which three (3) albite arfvedsonite granites formed part of this study. The samples weighed from ~ 4 to ~ 5 kg. Samples were crushed, powdered, and homogenized before geochemical analysis. The major oxides and trace element compositions of the rock samples were determined using advanced analytical techniques. Energy Dispersive x-ray fluorescence (EDXRF) spectrometer of model "Minipal 4" was used for the analysis at the National Geoscience Research Laboratory (NGRL) Kaduna to quantify bulk chemical composition. The analysis had a precision that was better than 1% for the oxides over 10 wt% and 10% for the oxides below 10 wt%. The trace elements measurement also showed an error below 5%. The geochemical data were compiled, and descriptive statistics were generated to assess data distribution. Pearson correlation coefficients were calculated for all element pairs to determine relationships. The correlation values range from -1 to +1, where: +1 indicates a perfect positive correlation, -1 indicates a perfect negative correlation, 0 indicates no correlation and strong correlations between elements were interpreted in terms of magmatic differentiation, fractionation, and mineralization processes.

RESULT AND DISCUSSION

The result of the analysis of Kaffo Albite Arfvedsonit**e** (Table 1 and 2) highlights key element groupings that provide insights into its petrogenesis, tectonic setting, and mineralization. By comparing these findings with other peralkaline granitic systems worldwide, we can better understand the processes controlling rare metal enrichment.

Table 1 Major and trace element concentration of the kaffo albite arfvedsonite granite

Rock Type	Y41 Kaffo albite Arfvedsonite Granite 10°44′42.60″N 8°43′59.09″E	Y42 Kaffo Albite Arfvedsonite Granite 10°43′31.89″N 8°42′38.61″E	Y44 Kaffo Albite Arfvedsonite Granite 10°43′13.18″N 8°46′38.61″E
SiO_2	72.2	73.54	74.5
CaO	0.25	0.19	0.18
MgO	0.07	0.08	0.03
K_2O	4.34	3.75	3.74
Na_2O	5.66	5.84	5.06
TiO_2	0.11	0.12	0.08
MnO	0.06	0.05	0.04
P_2O_5	0.01	0.01	0.01
Fe_2O_3	2.41	2.36	2.33
Al_2O_3	12.24	12.31	11.86
LOI	1.68	1.34	1.84
Total	99.03	99.59	99.67
A/CNK	1.19	1.26	1.32
V	0.03	0.02	0.02
Cr	0.02	0.04	0.04
Cu	390	220	200
Sr	11	9.45	6.21
Zr	4300	5100	4620
Ba	20	40	26
Zn	1400	1250	1470
Ce	380	291	212
Pb	366	310	370
Sn	175	186	143
Ga	86	73	78
Y	410	419	394.4

Ni	245	184	194
Rb	1300	1181	1054
Nb	1446	1292	1560
La	143	134	126
Eu	2.7	2.2	2.1
Mo	11.5	12.3	9.1
Co	1.2	0.9	1.1
Ta	170	145.67	17.78
W	1	1	1
Hf	115.16	102.28	114.8
Pr	54.7	37.2	66.8
Lu	5.65	6.68	7.01
Gd	56.17	65.34	43.12
U	121	105	111
Th	201	199	232
Nd	112	91	222
REE	754.22	627.42	679.03
LREE/HREE,Y	1.80	1.46	1.67

Table 2 Pearson correlation of major and trace element concentration of the kaffo albite arfvedsonite granite

	SiO_2	CaO	MgO	K_2O	Na_2O	TiO_2	MnO	P_2O_5	Fe_2O_3	Al_2O_3	V	Cr	Cu	Sr	Zr	Ba	Zn	Ce	Pb	Sn	Ga	Y	Ni	Rb	Nb	La	Eu	Mo	Co	Ta	W	Hf	Pr	Lu	Gd	U	Th	Nd
SiO_2	1.00																																					
CaO	-0.96	1.00																																				
MgO	-0.69	0.45	1.00																																			
K2O	-0.92	0.99	0.34	1.00																																		
Na_2O	-0.67	0.42	1.00	0.31	1.00																																	
TiO_2	-0.65	0.40	1.00	0.29	1.00	1.00																																
MnO	-1.00	0.92	0.76	0.87	0.74	0.72	1.00																															
P_2O_5	0.10	-0.38	0.66	-0.49	0.68	0.69	0.00	1.00																														
Fe_2O_3	-1.00	0.97	0.66	0.93	0.63	0.61	0.99	-0.14	1.00																													
Al_2O_3	-0.72	0.49	1.00	0.38	1.00	1.00	0.79	0.62	0.69	1.00																												
V	-0.91	0.99	0.33	1.00	0.30	0.28	0.87	-0.50	0.93	0.37	1.00																											
Cr	0.91	-0.99	-0.33	-1.00	-0.30	-0.28	-0.87	0.50	-0.93	-0.37	-1.00	1.00																										
Cu	-0.95	1.00	0.42	1.00	0.39	0.37	0.91	-0.42	0.96	0.46	1.00	-1.00	1.00																									
Sr	-0.96	0.83	0.87	0.76	0.86	0.84	0.98	0.20	0.94	0.89	0.75	-0.75	0.81	1.00																								
Zr	0.48	-0.72	0.30	-0.79	0.33	0.35	-0.40	0.92	-0.52	0.26	-0.80	0.80	-0.74	-0.21	1.00																							
Ba	0.38	-0.64	0.41	-0.72	0.43	0.45	-0.29	0.96	-0.43	0.36	-0.73	0.73	-0.66	-0.10	0.99	1.00																						
Zn	0.22	0.07	-0.86	0.19	-0.87	-0.88	-0.31	-0.95	-0.17	-0.83	0.21	-0.21	0.11	-0.50	-0.75	-0.82	1.00																					
Ce	-1.00	0.94	0.73	0.89	0.71	0.70	1.00	-0.03	0.99	0.76	0.88	-0.88	0.92	0.97	-0.43	-0.33	-0.28	1.00																				
Pb	-0.04	0.33	-0.70	0.43	-0.72	-0.74	-0.06	-1.00	0.08	-0.67	0.45	-0.45	0.36	-0.26	-0.89	-0.94	0.97	-0.03	1.00																			
Sn	-0.65	0.40	1.00	0.29	1.00	1.00	0.72	0.70	0.61	1.00	0.27	-0.27	0.36	0.84	0.36	0.46	-0.89	0.69	-0.74	1.00																		
Ga	-0.68	0.87	-0.06	0.92	-0.09	-0.11	0.61	-0.79	0.72	-0.01	0.92	-0.92	0.88	0.44	-0.97	-0.94	0.56	0.64	0.76	-0.12	1.00																	
Y	-0.55	0.28	0.98	0.17	0.99	0.99	0.63	0.78	0.51	0.98	0.15	-0.15	0.25	0.77	0.47	0.56	-0.94	0.60	-0.82	0.99	-0.24	1.00																
Ni	-0.84	0.96	0.18	0.99	0.15	0.13	0.78	-0.63	0.86	0.22	0.99	-0.99	0.97	0.64	-0.89	-0.83	0.35	0.80	0.58	0.12	0.97	0.00	1.00															
Rb	-0.99	0.92	0.77	0.86	0.75	0.73	1.00	0.02	0.99	0.80	0.86	-0.86	0.90	0.98	-0.38	-0.27	-0.33	1.00	-0.08	0.73	0.60	0.64	0.77	1.00														
Nb	0.34	-0.05	-0.91	0.07	0.93	0.93	-0.42	-0.91	-0.29	-0.89	0.09	-0.09	-0.01	-0.60	-0.66	-0.74	0.99	-0.39	0.93	-0.94	0.46	-0.97	0.24	-0.44	1.00													
La	-1.00	0.94	0.73	0.89	0.71	0.70	1.00	-0.03	0.99	0.76	0.88	-0.88	0.92	0.97	-0.43	-0.33	-0.28	1.00	-0.03	0.69	0.64	0.60	0.80	1.00	-0.39	1.00												
Eu	-0.96	1.00	0.47	0.99	0.44	0.42	0.93	-0.36	0.98	0.51	0.99	-0.99	1.00	0.84	-0.70	-0.62	0.05	0.95	0.30	0.42	0.85	0.31	0.95	0.93	-0.07	0.95	1.00											
Mo	-0.65	0.40	1.00	0.29	1.00	1.00	0.72	0.69	0.61	1.00	0.28	-0.28	0.37	0.84	0.35	0.45	-0.88	0.70	-0.74	1.00	-0.11	0.99	0.13	0.73	-0.93	0.70	0.42	1.00										
Co	-0.42	0.66	-0.37	0.75	-0.40	-0.42	0.33	-0.95	0.46	-0.33	0.76	-0.76	0.69	0.13	-1.00	-1.00	0.80	0.36	0.92	-0.43	0.95	-0.53	0.85	0.31	0.72	0.36	0.65	-0.42	1.00									
Ta	-0.89	0.72	0.94	0.64	0.93	0.92	0.93	0.37	0.87	0.96	0.62	-0.62	0.70	0.99	-0.03	0.08	-0.64	0.92	-0.42	0.92	0.28	0.87	0.50	0.94	-0.73	0.92	0.74	0.92	-0.04	1.00								
W	0.42	-0.13	-0.95	-0.02	-0.96	-0.96	-0.50	-0.87	-0.37	-0.93	0.00	0.00	-0.10	-0.66	-0.60	-0.68	0.98	-0.47	0.89	-0.96	0.38	-0.99	0.15	-0.52	1.00	-0.47	-0.16	-0.96	0.66	-0.78	1.00							
Hf	-0.12	0.40	-0.64	0.51	-0.66	-0.68	0.03	-1.00	0.17	-0.60	0.52	-0.52	0.44	-0.18	-0.93	-0.96	0.94	0.06	1.00	-0.68	0.81	-0.76	0.65	0.01	0.90	0.06	0.38	-0.68	0.95	-0.34	0.85	1.00						
Pr	0.32	-0.03	-0.91	0.09	-0.92	-0.93	-0.41	-0.91	-0.27	-0.89	0.11	-0.11	0.01	-0.58	-0.68	-0.76	1.00	-0.38	0.94	-0.93	0.48	-0.97	0.26	-0.42	1.00	-0.38	-0.05	-0.93	0.73	-0.71	0.99	0.90	1.00					
Lu	0.98	-1.00	-0.54	-0.98	-0.51	-0.49	-0.96	0.29	-0.99	-0.58	-0.97	0.97	-0.99	-0.88	0.64	0.55	0.03	-0.97	-0.23	-0.49	-0.81	-0.38	-0.93	-0.95	0.15	-0.97	-1.00	-0.49	-0.58	-0.79	0.23	-0.31	0.13	1.00				
Gd	-0.51	0.23	0.97	0.12	0.98	0.98	0.58	0.81	0.46	0.96	0.10	-0.10	0.20	0.74	0.51	0.61	-0.95	0.56	-0.85	0.99	-0.29	1.00	-0.05	0.60	-0.98	0.56	0.25	0.98	-0.58	0.84	-1.00	-0.80	-0.98	-0.33	1.00			
U	-0.69	0.87	-0.05	0.92	-0.08	-0.10	0.62	-0.79	0.72	0.00	0.93	-0.93	0.89	0.45	-0.97	-0.93	0.55	0.65	0.75	-0.11	1.00	-0.23	0.97	0.60	0.45	0.65	0.86	-0.10	0.95	0.29	0.37	0.80	0.47	-0.82	-0.28	1.00		
Th	0.78	-0.57	-0.99	-0.47	-0.99	-0.98	-0.84	-0.55	-0.75	-1.00	-0.45	0.45	-0.54	-0.93	-0.17	-0.28	0.78	-0.82	0.60	-0.98	-0.08	-0.95	-0.31	-0.85	0.85	-0.82	-0.59	-0.98	0.24	-0.98	0.89	0.53	0.84	0.65	-0.93	-0.09	1.00	
Nd	0.72	-0.49	-1.00	-0.38	-1.00	-1.00	-0.78	-0.62	-0.69	-1.00	-0.37	0.37	-0.45	-0.89	-0.26	-0.37	0.84	-0.76	0.67	-1.00	0.02	-0.98	-0.22	-0.79	0.90	-0.76	-0.51	-1.00	0.33	-0.96	0.93	0.60	0.89	0.57	-0.96	0.01	1.00	1.00

Major Element Associations and Petrogenetic Implications

The Kaffo suite, a subset of the Riruwai Younger Granite Complex, exhibits a unique set of major element associations that provide valuable insights into its petrogenetic evolution. This The SiO_2 content in the Kaffo suite shows a strong negative correlation with CaO, K_2O, Fe_2O_3, MnO, and Rb, suggesting differentiation through fractional crystallization. This trend is typical of peralkaline granites, where the removal of mafic minerals leads to increased silica content. A similar trend is observed in the Ilímaussaq Complex, Greenland, where fractionation of Fe-Ti oxides and mafic minerals leads to enrichment of alkali elements and high field strength elements (Larsen & Sørensen, 1987, Sørensen & Larsen, 2001; Bailey et al 2006).

The high correlation of Na_2O with Al_2O_3 and K_2O in the Kaffo suite suggests feldspar fractionation, with albite playing a key role in the late-stage crystallization of the magma. This is consistent with the observations of Bowden and Turner (1974) in the Younger Granites of Nigeria, where differentiation trends are controlled by feldspar and amphibole fractionation. The Fe_2O_3 and MnO contents in the Kaffo suite are highly correlated, which is characteristic of arfvedsonite-bearing granites. The negative correlation of Fe_2O_3 and MnO with SiO_2 and positive correlation with CaO and K_2O suggests their crystallization from a Fe-rich melt before the final silica saturation. This is consistent with the petrogenetic model proposed for the Ilímaussaq Complex, where Fe-rich amphiboles control iron distribution.

The element associations in the Kaffo suite suggest a petrogenetic evolution characterized by differentiation through fractional crystallization, feldspar fractionation, and crystallization of Fe-rich amphiboles. These trends are consistent with those observed in similar peralkaline granitic complexes worldwide, such as the Ilímaussaq Complex and the Younger Granites of Nigeria. The study of the Kaffo suite provides valuable insights into the petrogenetic evolution of peralkaline granites and highlights the importance of major element associations in understanding the geological history of these complexes.

Trace Element Clustering and Rare-Metal Mineralization

Positive correlation with elements like Zr (0.48) and Hf (-0.12), which are typically enriched in highly fractionated granites. The geochemical data from the Kaffo suite reveals positive correlations between elements such as Zr, Hf, Nb, Ta, and Y, which are typically enriched in highly fractionated granites (René, 2014; Wu, et al, 2017). These correlations suggest that silica enrichment is linked to extensive magmatic differentiation, with depletion of major elements due to feldspar fractionation. This trend is consistent with the Kaffo suite, where differentiation through fractional crystallization leads to the formation of peralkaline granites. The clustering of Zr, Nb, Ta, and Y in the study indicates their geochemical coherence, reflecting their association with peralkaline magmatism (Xie, et al., 2024). This trend is similar to those observed in other peralkaline granite complexes worldwide, such as the Kymi Granite of Finland (Rämö & Haapala, 2005) and the Eastern Desert Granites of Egypt (Abdel-Rahman, 1987; El-Bialy & Omar, 2015; .Shahin, 2016). In these complexes, HFSE enrichment is linked to magma-fluid interactions in a rift-related setting, suggesting a similar petrogenetic evolution for the Kaffo suite. The strong positive correlation between Sn, Nb, Ta, and W suggests potential for rare-metal mineralization, similar to the Abu Khruq Complex (Egypt), where Nb-Ta mineralization occurs in association with arfvedsonite granites (Helba et al., 1997; Moghazi, et al, 1999). This correlation highlights the importance of considering the geochemical coherence of these elements in the context of rare-metal mineralization.

Peralkaline Magmatism and Late-Stage Magmatic Processes

The REE geochemistry of the Kaffo suite provides valuable insights into the petrogenetic evolution of the complex and the late-stage magmatic processes that controlled the distribution of these elements. The strong positive correlation between Ce, La, Nd, and Pr indicates REE enrichment, a common feature of peralkaline granites (Mohamed et al., 2015; Anenburg, 2020). This mirrors studies on other peralkaline complexes worldwide, such as the Thor Lake Peralkaline Complex (Canada) (Pinckston & Dorian, 2011) and the Amis Complex (Namibia) (Kogarko, 1990). The negative correlation of Eu with other REEs suggests Eu depletion due to feldspar fractionation, a signature of highly evolved peralkaline systems. This trend is consistent with the petrogenetic model proposed for the Kaffo suite, where differentiation through fractional crystallization leads to the formation of peralkaline granites.

The REEs also correlate negatively with elements like Th, U, and Hf, suggesting different modes of enrichment and mobility in late-stage magmatic processes. Nb and Ta show similar trends, indicating their common association with pegmatitic and hydrothermal processes. This suggests that the REEs and other incompatible elements were mobilized and concentrated in late-stage magmatic fluids, which is consistent with the formation of REE-bearing phases such as eudialyte and xenotime in peralkaline granitic environments. The high positive correlation between Ce, La, Nd, and Pr indicates that these elements were enriched together in the late-stage magmatic fluids, which is consistent with the formation of REE-rich minerals such as bastnäsite and monazite (Mohamed et al., 2015). The negative correlation of Eu with other REEs suggests that Eu was depleted due to feldspar fractionation, which is consistent with the formation of Eu-depleted minerals such as quartz and feldspar.

The Alkali and High Field Strength Elements Implications for Late-Stage Fluid Processes and Mineralization

Na_2O shows a strong positive correlation with Y (0.99), Sn (1.00), and Mo (1.00), implying an association with late-stage fluid processes, which often mobilize HFSEs in peralkaline systems. Rb and K_2O are highly correlated (0.86), indicating their control by potassic feldspar and mica. The strong Rb-Ta (-0.73) and Rb-Nb (-0.44) anti-correlation suggests that Ta-Nb mineralization occurs independently of K-feldspar fractionation and is likely related to late-stage fluid mobilization. The geochemical data from the Kaffo suite reveals several significant correlations and anti-correlations between alkali and high field strength elements (HFSEs), which provide valuable insights into the late-stage fluid processes and mineralization in the complex.

The strong positive correlation between Na_2O and Y, Sn, and Mo implies an association with late-stage fluid processes, which often mobilize HFSEs in peralkaline systems. This suggests that the Na_2O-rich fluids played a crucial role in the mobilization and concentration of these elements in the Kaffo suite. Similar associations have been observed in other peralkaline complexes worldwide, such as the Ilímaussaq Complex of Greenland (Hunt et al., 2014, Lindhuber, et al., 2015) and the Amis Complex of Namibia (Schmitt, et al., 2002). The high correlation between Rb and K_2O indicates their control by potassic feldspar and mica, which are common minerals in peralkaline granites. This suggests that the Rb and K_2O contents in the Kaffo suite were influenced by the crystallization of these minerals. The strong Rb-Ta and Rb-Nb anti-correlation suggests that Ta-Nb mineralization occurs independently of K-feldspar fractionation and is likely related to late-stage fluid mobilization. This implies that the Ta-Nb mineralization in the Kaffo suite was controlled by a separate fluid phase that was enriched in these elements. Similar anti-correlations have been observed in other peralkaline complexes worldwide, such as the Thor Lake Peralkaline Complex of Canada (Pinckston & Dorian, 2011) and the Eastern Desert Granites (Egypt) (Mohamed & El-Sayed, 2008; Zoheir, 2019).

Implications for Mineral Exploration

The correlation between Nb and Ta with Na_2O and Sn suggests a pegmatitic to hydrothermal enrichment mechanism, which is consistent with the formation of rare-metal deposits in peralkaline granites (Larsen & Sørensen 1987; Kogarko & Nielsen 2020). The positive correlation between Zr and Hf indicates potential for zircon and Hf-bearing accessory minerals, which are common in peralkaline granites. The negative correlation between U and Th with REEs implies that REE mineralization is largely decoupled from uranium-bearing phases, which is consistent with the formation of REE deposits in peralkaline granites. The

strong correlation between Sn and W suggests Sn-W mineralization linked to late-stage pegmatitic activity, which is a common feature of peralkaline granites.
The study suggests that the Kaffo suite shares geochemical affinities with other rift-related peralkaline granites known for rare-metal mineralization, such as the Mount Weld of Australia (Lottermoser, 1990; Zhukova, et al., 2021; Cook, et al., 2023) and Strange Lake of Canada deposits (McConnell & Batterson, 1987; Salvi & Williams-Jones, 2006; McClenaghan, et al., 2019). The strong Nb-Ta-Zr-Y association highlights the potential for economic deposits similar to those in Mount Weld and Strange Lake. This geochemical characterization provides a framework for exploration, suggesting that detailed mineralogical and fluid inclusion studies should be conducted to confirm ore potential. The Kaffo suite's geochemical characteristics are consistent with the formation of rare-metal deposits in peralkaline granites, including:

(a) Pegmatitic to hydrothermal enrichment mechanism, as indicated by the correlation between Nb and Ta with Na_2O and Sn.
(b) Potential for zircon and Hf-bearing accessory minerals, as indicated by the positive correlation between Zr and Hf.
(c) Decoupling of REE mineralization from uranium-bearing phases, as indicated by the negative correlation between U and Th with REEs.
(d) Sn-W mineralization linked to late-stage pegmatitic activity, as indicated by the strong correlation between Sn and W.

CONCLUSION

The Kaffo Albite Arfvedsonite suite reveals strong geochemical similarities with well-known peralkaline granite-related rare-metal deposits worldwide. The clustering of HFSEs, REEs, and Sn-W mineralization indicators suggests a high potential for economic deposits. The Pearson's correlation analysis of Albite-Arfvedsonite granite reveals a complex magmatic evolution with significant mineralization potential for Nb-Ta, Sn, Zr, and REEs. The data align with global studies on peralkaline granites and suggest that hydrothermal fluids played a key role in concentrating economic minerals. Further exploration and detailed mineralogical and fluid inclusion studies are recommended to confirm ore potential.

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