The Geochemistry and Petrogenesis of the Kofayi Younger Granite Complex, Central Nigeria

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Abstract
The Kofayi Younger Granite Complex is one of the fifty three (53) anorogenic granite suite in Nigeria which intruded the Precambrian Basement Complex. The complex is found to comprise of felsic rocks like; biotite-granites, biotite micro granites, hornblende and biotite granites. The complex is also found to be associated with mafic rocks like diorites which, at some portions have formed hybrid rocks. The geochemistry of sixteen (16) representative rock samples was carried out on the energy dispersive x-ray fluorescence (EDXRF) for twelve (12) major and thirty seven (37) trace and REE elements. Agpaitic index and alumina saturation index suggest that the rocks are peraluminous. The widely used SiO_2 vs K_2O classify most of the granite samples as high K rocks while the mafic diorites are calc-alkaline. Discrimination diagrams for tectonic interpretation of granitic rocks ((Na_2+K_2O)/CaO vs Zr+Nb+Ce+Y and Nb vs Y, suggest that all the samples are WPG, as well as A-type granites. The enrichment of high field strength (HFS) elements in the investigated granites confirms their A-type identity and exclude them from other granitic types. Spidergraph show negative Sr anomaly suggesting the feldspar fractionated nature of the granitoids where plagioclase played an important role in the evolution of the A-type magmatism. The magma that gave rise to the granitoids most likely came from the lithospheric mantle.The enrichment of Zr and Nb in the rocks indicate Nb-Sn-W mineralization. The northern part of the Complex contains Pb>15 which confirms that it are tin-bearing or productive granitoid suite.

Keywords - *A-type, Anorogenic, Granite, Kofayi, Mineralization.*

INTRODUCTION

The Younger Granite Ring Complexes are located in the southern part of a 200 km wide zone, along the 9^{th} meridian and extending 1,250 km from Andrar Bous in northern Niger to Afu in the margin of the Benue Trough in Nigeria. The form and general pattern of the ring centres may have been controlled by pre-existing lines of weakness in the Pan African basement (Kinnaird et al, 1985) (Fig. 1). The Kofayi Younger Granite Complexes is one of the fifty three anorogenic Younger Granite Complexes in the Nigerian Precambrian Basement Complex (Macleod et al, 1971). The granite suite is located approximately forty five (48) kilometres north east of Jos, the Plateau State capital. Kofayi Complex constitute a significant window to the detailed understanding of the magmatic evolutionary trends and metallogenic characteristics of the Nigerian Younger Granites as a whole. This is because of the prominent occurrence of mafic rocks which may represent the more primitive magma in the Younger Granite Province. The complex is found associated with gabbroic and doleritic enclaves, peralkaline and peraluminous igneous rocks (Figure 1). Details on the field geology and mineralogy of the Kofayi Complex has been discussed by the authors elsewhere (Aga and Haruna, 2019)

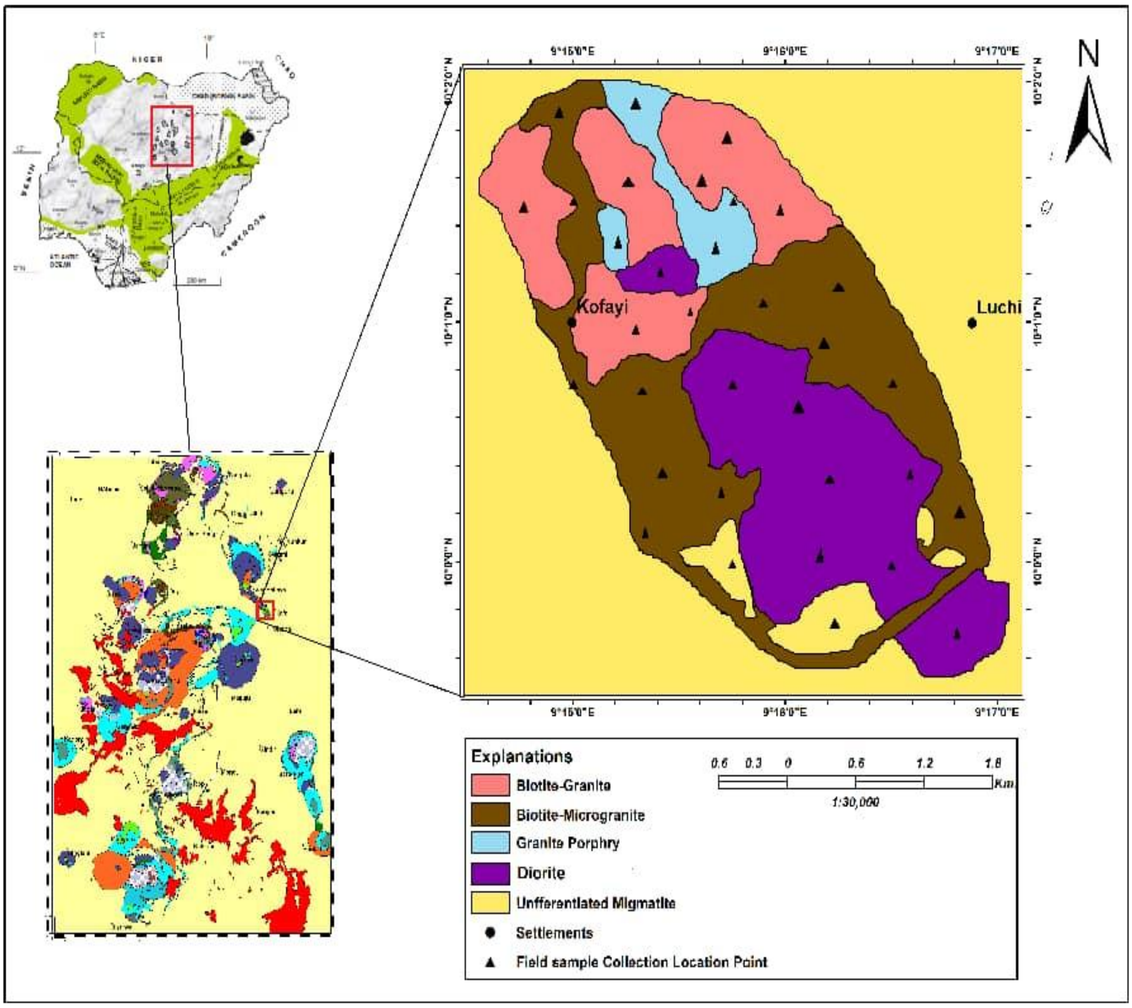


Fig.1: Top = Geological Map of Nigeria Showing the Location of the Younger Granite Ring Complexes (After Obaje, 2009); Left = Map of Younger Granites Ring Complexes of Nigeria (Modified After Kinnard et` al, 1985); Centre = Geological Map of Kofayi Younger Granite Complex

Anorogenic, A-type granites are characterized by high SiO_2, Na_2O+K_2O, Fe/Mg, Ga/Al, Rb, Nb, Zr, Ta, Y, Cs, Ga, U, Th, REE (except Eu) and low abundances of MgO, CaO, Mg, Ba, Sr, P, Ti, Ni, Cr, Co, V (Collins et al,1982 and Whalen et al, 1987). Many models have been proposed to the origin of A-type granitoids. These models can be grouped into two broadly speaking due to the challenge of linking the various petrological and geochemical properties of granitic rocks to the sources, processes and tectonic settings that produced them.

One popular approach was first proposed by Chappell and White (1974) and emphasizes the sources of granitic rocks as a key factor that controls their characteristics. This approach originally classified granites into two types: I-type (from igneous source rocks) and S-type (from sedimentary source rocks). Such a classification is intrinsically independent of tectonic processes. This scheme has been further developed into the I-S-A-M-H classification scheme in which "A" indicates anorogenic (Loiselle and Wones, 1979), "M" represents "mantle-derived", and "H" denotes "hybrid" types (Castro et al., 1991). Although this classification scheme is useful, the different types may overlap. For instance, S-type granite can also be classified as A-type granite, and highly felsic I-type granites generally have an A-type affinity.

Another approach is to analyze tectonic environments using trace element discrimination diagrams, such as those proposed by Pearce et al. (1984). This is the main approach adopted in this study because the fields on the discriminant diagrams reflect source regions and crystallization histories. The purpose of this paper is to provide a geochemical data on the Kofayi A-type granite and associated mineralization, so as to infer their petrogenesis and tectonic setting.

GEOCHEMISTRY

The rock chemistry of sixteen (16) representative samples was carried out on the energy dispersive x-ray fluorescence (EDXRF) for twelve (12) major and thirty seven (37) trace and REE elements. The sample preparation and analysis were carried out at the Geochemistry laboratory of the Nigerian Geological Survey Agency in Kaduna. The samples analyzed comprise of four (4) diorites samples, one (1) granodiorite and eleven (11) granites of varying textural compositions. The detailed geology and petrography of the samples is described elsewhere (Aga and Haruna, 2019). The discrimination and correlation diagram are plotted to characterize each granite type and to discuss the petrogenesis and mineralization of the granites from the study area.

Major, Trace and REE Element Classification

The result of the chemical analyses are given in the tables 1, 2a and 2b below. The granite exhibit restricted distribution of SiO_2 (71.01 - 75.06; av. 73.35) and Al_2O_3 (12.64 - 13.6; av. 13.05) which is also high when compared to the diorites (50 - 52.24; av. 56.35) and (10.3 - 11.26; av.10.78) respectively. The inverse relationship exist with respect to MgO (0.93 - 9.10 Av; 5.015) and CaO (4.23 – 9.90; av. 7.07) in the diorites and comparatively lower in the granites (0.01 – 0.61; av.0.30) and (0.65 – 3.25; av. 1.95) respectively. The average values of Na_2O and K_2O for the diorites are 0.25 and 1.50 which are comparatively lower to the granites: 0.81 and 3.44 respectively. The whole samples analyzed are peraluminous. Agpaitic Index (AI= molecular portion of Na_2O+K_2O/Al_2O_3) and alumina saturation index (A/CNK = molecular $Al_2O_3/Na_2O + K_2O + CaO$) ratio < 1 peraluminous (corundum and anorthite normative; AI >1) (Fig. 2). The Na_2O-Al_2O_3-K_2O triangular diagram plot most of the samples within the peraluminous region (Fig. 3). Further, the widely used SiO_2 vs K_2O diagram classify most of the granites as high-K rocks. Meanwhile, the diorite and granodiorite belong to the calc-alkaline series (Fig. 4).

Tectonic setting and Petrogenesis

The geochemical nature of the studied A-type granites are critically tested using the standard common schemes as well as the adopted three-tiered geochemical classification scheme of granites rocks. As the extreme Fe*O enrichment relative to MgO (high FeO*/MgO) is a typical signature of A-type granitoids, all the present granite samples are grouped as A-type granite on the Fe* {FeO*/(FeO+MgO)} vs SiO_2, Na_2O+K_2O-CaO vs SiO_2 and (Na_2O+K_2O)/CaO vs Zr+Nb+Ce+Y diagrams (Figs. 5, 6 and).

Table 1: Major Element Concentration of Kofayi Younger Granite Complex

Sample ID	Location	Petrology	SiO_2	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	MnO	P_2O_5	Fe_2O_3	Al_2O_3	H_2O^+
AT4	Kofai	Granite	72.7	1.85	0.03	0.52	4.01	0.86	0.67	0.2	0.003	3.7	12.8	1.6
AT17	Kofai	Granite	74.61	1.06	0.03	0.48	4.86	0.43	0.74	0.061	0	1.5	13.43	1.68
AT18	Kofai	Granite	73.2	0.65	0.007	0.062	5.55	1	0.66	0.039	0	2.04	13	2.34
AT22	Kofai	Granodiorite	72.7	2.5	1.89	0	1.9	0.48	1.78	0.15	0	3.92	12	2.08
AT23	Kofai	Diorite	56.5	6.81	3.06	0.33	1.6	0.46	4.03	0.21	0.18	12.8	10.3	2.81
AT26	Kofai	Granite	73.43	0.3	0.04	0.003	5.09	1.06	0.5	0.024	0	3.46	13.01	2.24
AT29	Kofai	Diorite	54.4	9.9	1.02	0.77	0.98	0.07	1.94	0.26	0.06	12.3	10.3	4.58
AT44	Kofai	Granite	87.6	0.73	0.14	0.48	5	1.02	0.13	0.026	0	0.44	2.43	1.02
AT37	Kofai	Diorite	58.5	4.23	9.1	0.62	2.03	0.43	2.68	0.22	0	8.06	10.5	3.05
AT39	Kofai	Granite	74	1.07	0.5	0.072	5.12	1.04	0.48	0.081	0.003	1.16	13.06	2.06
AT51	Kofai	Granite	75.06	0.38	0.007	0.23	5.85	0.76	0.16	0.028	0	1.98	13	1.78
AT60	Kofai	Granite	71.01	2.04	0.5	0.17	4	0.34	1.39	0.096	0	3.038	12.86	2.86
AT62	Kofai	Granite	72.48	3.25	1	0.61	1.03	1.28	1.3	0.067	0.004	2.9	12.66	1.4
AT68	Kofai	Granite	75.2	0.33	0.005	0.3	6.29	0.53	0.2	0.039	0	1.05	13.46	1.4
AT71	Kofai	Diorite	54.2	7.62	0.93	0.73	1.09	0.63	2.77	0.23	0.04	16.09	11.26	3.08
AT 81	Kofai	Granite	73.06	3.18	0.34	0.13	4.65	0.81	0.83	0.11	0	4.18	12.64	2.07

Table 2a: Trace and REE Concentration of Kofayi Younger Granite Complex

Sample ID	Location	Petrology	V	Cr	Cu	Sr	Zr	Ba	Zn	Ce	Pb	Bi	Ga	As	Y	Ir	Au	Ni	Rb	Nb
AT4	Kofai	Granite	90	12	250	240	840	1700	210	91	880	<0.001	12	<0.001	17	3.3	0.22	<0.001	34	100
AT17	Kofai	Granite	4	<0.001	240	1150	1000	900	30	30	200	3.05	2	15	15	3.1	<0.001	<0.001	30	480
AT18	Kofai	Granite	4	<0.001	230	190	720	100	50	150	70	<0.001	7.4	7	39	3.1	0.014	<0.001	9.84	140
AT22	Kofai	Granodiorite	200	110	280	128	1700	500	250	85	130	<0.001	2	0.501	24	4.3	0.6	<0.001	25	110
AT23	Kofai	Diorite	650	30	400	246	1500	600	470	0.001	0.54	30	3	<0.001	52	11	<0.001	<0.001	30	0.001
AT26	Kofai	Granite	5	<0.001	250	0.001	7640	201	30	110	600	1.47	8.3	9	51	2.8	0.13	<0.001	56	600
AT29	Kofai	Diorite	780	310	360	1900	780	300	440	0.001	0.32	<0.001	<0.001	<0.001	33	<0.001	2	<0.001	22	4.2
AT44	Kofai	Granite	<0.001	<0.001	170	490	340	500	20	31	140	<0.001	1	5.3	3	20	<0.001	290	64.4	0.001
AT37	Kofai	Diorite	20	6.06	340	1870	1500	700	420	50	640	2.68	0.9	<0.001	32	20	1.7	<0.001	36	0.001
AT39	Kofai	Granite	7	7.1	230	0.001	140	101	120	89	1	<0.001	4	52	0.001	3.2	1.4	<0.001	40	300
AT51	Kofai	Granite	2	16	200	0.001	2440	650	330	14	170	<0.001	12	6.5	41	1.7	0.02	<0.001	80.9	52
AT60	Kofai	Granite	20	13	270	1010	790	2300	94	0.001	260	<0.001	7.2	0.9	22	2	<0.001	<0.001	58	84
AT62	Kofai	Granite	100	4.42	340	3070	1400	180	130	40	430	<0.001	20	24	2.7	7.7	<0.001	<0.001	39	0.001
AT68	Kofai	Granite	80	14	210	0.001	2070	1100	370	0.001	100	<0.001	130	7.7	37	2	0.72	<0.001	79.5	490
AT71	Kofai	Diorite	33	2	1160	2120	2400	2200	390	0.001	69	0.054	<0.001	<0.001	42	<0.001	<0.001	<0.001	24	560
AT 81	Kofai	Granite	40	8	440	3090	1600	2700	200	0.001	630	32	33	2	27	3	0.46	<0.001	12	0.001

Table 2b: Trace and REE Concentration of Kofayi Younger Granite Complex

Sample ID	Location	Petrology	Mo	Co	Cd	Ru	Eu	Re	Hg	Ag	Ta	W	Hf	Yb	In	Se	U	Th	Sb	Sn	Ge
AT4	Kofai	Granite	0.001	0.08	<0.001	1.6	220	30	<0.001	<0.001	48	1.03	2	30	4.1	40	0.002	0.05	<0.001	11.801	2.7
AT17	Kofai	Granite	<0.001	<0.001	<0.001	1.26	120	0.09	<0.001	<0.001	36	0.96	20	<0.001	1.9	0.32	0.033	0.001	0.86	4.501	<0.001
AT18	Kofai	Granite	0.11	<0.001	1.02	<0.001	120	0.001	<0.001	<0.001	64	13.3	16	<0.001	3	<0.001	0.001	<0.001	<0.001	2.31	0.004
AT22	Kofai	Granodiorite	<0.001	0.002	0.001	28	250	<0.001	1	<0.001	71	12	6.62	0.004	1.8	0.0003	<0.001	<0.001	<0.001	20.13	1.32
AT23	Kofai	Diorite	<0.001	0.0009	<0.001	430	33	<0.001	20	3.7	<0.001	<0.001	2.012	0.003	0.7	8	0.006	0.31	0.2	11.31	<0.001
AT26	Kofai	Granite	0.0007	<0.001	0.0003	<0.001	200	<0.001	0.881	<0.001	74	12.4	42	0.004	2.8	<0.001	<0.001	<0.001	<0.001	13.551	<0.001
AT29	Kofai	Diorite	<0.001	0.001	<0.001	<0.001	38	<0.001	20	0.051	0.45	0.15	21	0.002	0.3	22	<0.001	<0.001	3.1	5.32	<0.001
AT44	Kofai	Granite	<0.001	<0.001	<0.001	0.014	57	0.087	<0.001	2.044	<0.001	<0.001	3.48	<0.001	2.8	2.011	0.005	0.009	<0.001	1.801	0.001
AT37	Kofai	Diorite	<0.001	<0.001	0.005	<0.001	290	2	22	<0.001	<0.001	<0.001	<0.001	<0.001	60	<0.001	0.054	0.32	<0.001	<0.001	0.001
AT39	Kofai	Granite	<0.001	<0.001	0.003	28	14	<0.001	<0.001	0.62	25	3.06	<0.001	<0.001	2.7	<0.001	0.004	0.03	<0.001	5.3	<0.001
AT51	Kofai	Granite	<0.001	0.012	0.008	<0.001	120	25	0.055	<0.001	16	0.34	4.34	<0.001	2.2	<0.001	0.067	0.4	<0.001	12.11	0.22
AT60	Kofai	Granite	0.007	0.002	<0.001	0.022	1600	<0.001	0.002	<0.001	24	1.08	14.2	<0.001	2.7	0.002	<0.001	<0.001	0.004	4.011	<0.001
AT62	Kofai	Granite	0.002	0.004	<0.001	<0.001	180	28	<0.001	0.3	<0.001	<0.001	71	0.04	1.4	0.033	<0.001	<0.001	<0.001	50.17	<0.001
AT68	Kofai	Granite	<0.001	0.003	0.002	2.9	11	1	<0.001	<0.001	70	16	28	<0.001	2.5	0.005	0.0009	0.0052	3.2	6.61	<0.001
AT71	Kofai	Diorite	1.024	0.001	0.008	35	32	6	<0.001	<0.001	71	12	28	<0.001	0.7	6.4	<0.001	<0.001	1.9	2.04	1.202
AT 81	Kofai	Granite	<0.001	0.0021	0.008	8.3	14	<0.001	1.02	<0.001	<0.001	24	0.0001	0.0001	6.4	<0.001	<0.001	0.0002	5.11	1.202	

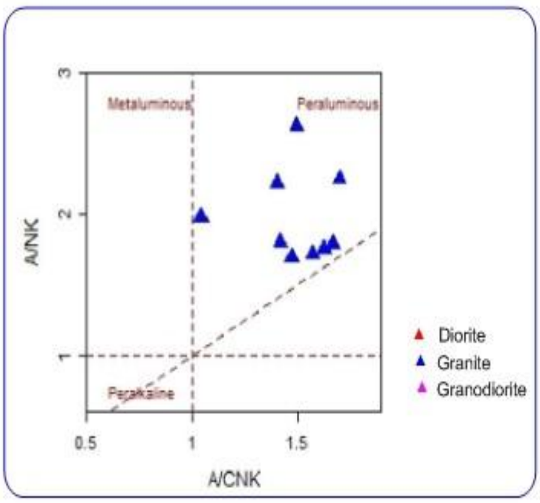


Fig. 2: ANK vs A/CNK diagram for rocks

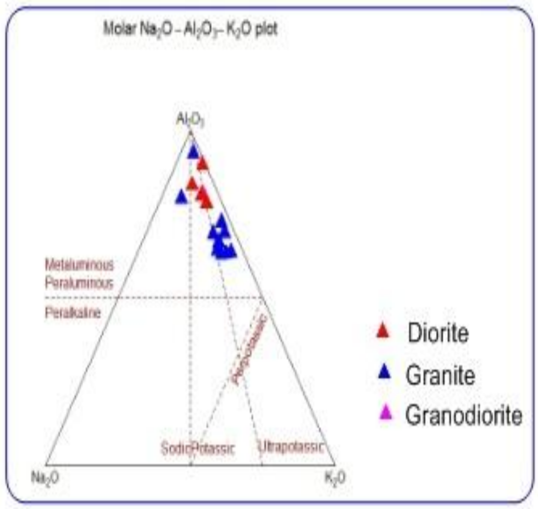
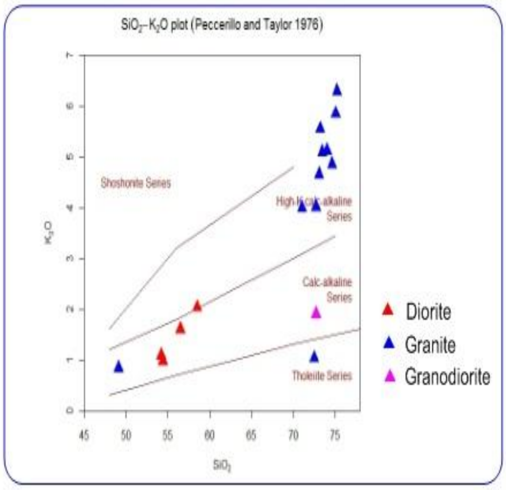


Fig. 3: Molar Na_2O-Al_2O_3-K_2O triangular diagram



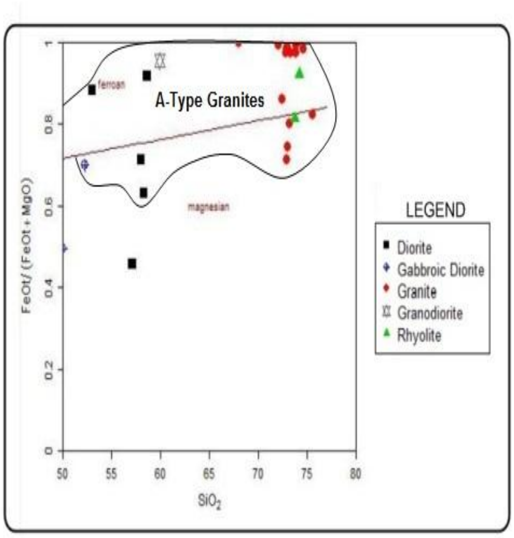
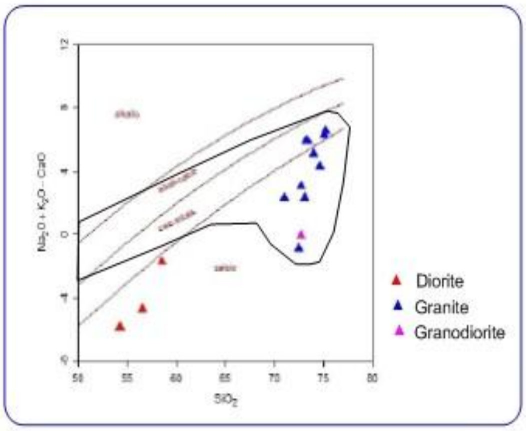


Fig. 4: $SiO2$ vs K_2O diagram with Field Fig. 5. Chemical Classification using FeO*/(FeO+MgO) vs SiO_2



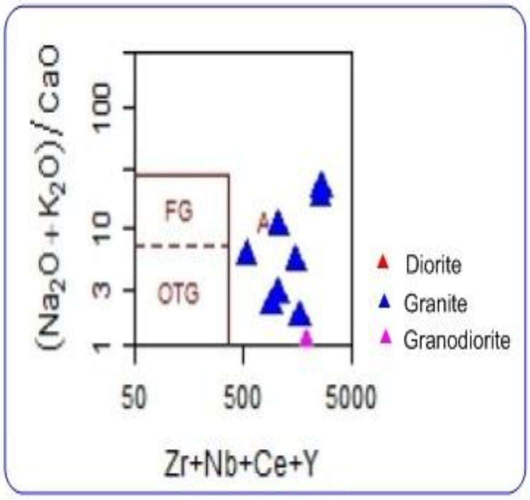
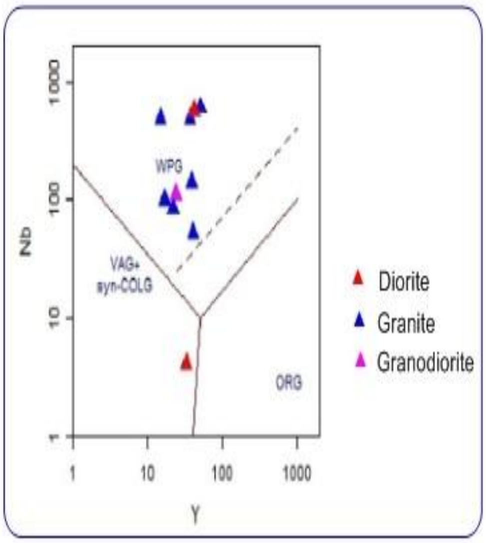


Fig. 6: Na_2O+K_2O-CaO vs SiO_2
Fig. 7: $(Na_2O+K_2O)/CaO$ vs Zr+Nb+Ce+Y



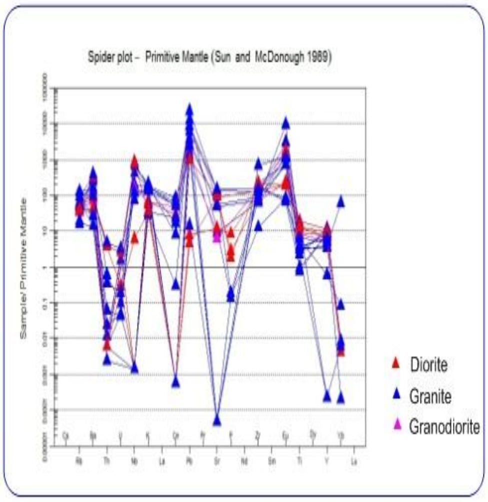


Fig. 8: Tectonic discrimination diagram Nb vs Y
Fig. 9: Spidergraph - REE Primitive Mantle

Use of the popular Pearce et al trace element discrimination diagram for tectonic interpretation of granites rocks (Y vs Nb), almost all the samples plotted as within plate granites (WPG), as delineated by Stern and Gottfried (Fig. 8). These diorites and gabbroic diorites are high in MgO, FeO*, CaO, Sr while the granitoids are high SiO_2, Na_2O, K_2O, Fe/Mg, Y and show both the LREE and HREE (Eby and Kochhar, 1990).

Spidergraphs show negative Sr, Th, Nb and Yb anomalies, indicating either the retention of plagioclase and accessory minerals in the source during partial melting or their separation during fractionation (Fig. 9). It also supported by their high Zr, Y and low Ti contents, characteristic of acid magmas generated within-plate tectonic environment. Enrichment in the high field strength (HFS) elements is a characteristic feature of alkaline A-type granites in general. The high enrichment of these elements in the investigated granites confirm their A-type identity and exclude them from other granite type on the $(Na_2O+K_2O)/CaO$ vs Zr+Nb+Ce+Y diagram (Fig. 7). All of the REE patterns have strong negative Eu anomalies and exhibit concave downward shapes of obvious positive slopes due to heavy REE enrichment relative to middle and light REE. The heavy REE are more greatly depleted suggesting absence of garnet in the source, since heavy REE are highly compatible in garnet (Wilson, 1989). This further indicate that, if mantle participation is assumed in the source material, a shallow mantle is preferred rather than deep one where spinal stability is favored rather than garnet (Ragland, 1989). The enrichment of Zr and Nb in the rocks indicate Nb-Sn-W mineralization. The northern parts of the Complex contains Pb>15 which confirms that they are tin-bearing or productive granitoid suites.

CONCLUSION

From the field relati**on**s and petrographic studies (Aga and Haruna, 2019) and the geochemistry of the A-type Kofayi Younger Granite Complex, the following petrogenetic model is likely. The mafic **magmas** most probably derived from the upper part of the lithospheric mantle were emplaced in a deep crustal magma chamber. During their ascent, these magmas may have undergone high fractionation and possibly minor contamination by crustal material. The second stage was characterized by fractionation of the mafic magmas in the magma chamber to produce the more felsic members of the suite with crustal assimilation not being significant at this stage.

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