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THE KIGOM PERALKALINE GRANITE PLUTON OF THE NIGERIAN YOUNGER GRANITE SUITE

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ABSTRACT

The Kigom granites in central Nigeria are alkali amphibole bearing and peralkaline in nature. They are hypersolvus in character and contain mesoperthite in which the albite (Or_{1-2}) and microcline are present in approximately equal proportions. The albite is fully ordered while K-rich feldspar is dominantly microcline. The extreme compositions of these feldspars suggests effective crystallization and ordering by hydrothermal fluids at lower than 300°C. Geochemical data suggest that the fluid involved in the metasomatism was peralkaline in composition and resulted in the enrichment of Nb, Y, and Th, in microgranite, and of Rb, Zn, Li, Sn, and F in the amphibole-bearing units suggesting that the granites underwent long duration of rock-fluid interaction in a peralkaline environment.

Keywords Kigom, Peralkaline granite, Mesoperthite, Arfvedsonite, Riebeckite,

INTRODUCTION

The Nigerian Younger granite suite consists of several northerly trending granite complexes intruded during the Jurassic. The granite complexes form part of a chain of intrusions, extending from the Republic of Niger to the margin of the Benue trough (Fig. 1). This chain is structurally controlled by the existing Pan-African trend within the basement, and continues southwards to Southern Africa along the zone of inferred initial crustal separation of the African and South American continents (Jacobson *et al.*, 1958; Turner, 1976; Bowden and Jones 1978). The complexes occur as ring dykes, circular or elliptical, varying in diameter from 2 to 25 km. The southward progression is shown in both their age variation and dominant rock type. The granites range in age from 200 Ma for the northern complexes to 140 Ma for the southern complexes (van Breemen and Bowden, 1973; Bowden *et al.*, 1976; Bowden, 1982). Alkaline members are more developed in the central portion of the province. In several of the complexes that have been mapped (Jacobson *et al.*, 1958; Turner, 1976; Bowden, 1982), peralkaline granite occurs mainly as a marginal facies of a complex and its emplacement is intimately related to ring fracturing and the outpouring of attendant ignimbrite flows and sheet-like intrusions. However, the Kigom complex (KYGC) lacks the attendant volcanic rocks and ring fractures do not seem to have been important during or after its emplacement.

The KYGC is located in the Jos area of central Nigeria. It is a small (6 km across), well-exposed pluton located 40 km southwest of Jos (Naraguta sheet 168, 1:100,000), in the central part of the belt of the Younger granite intrusives (Omada and Martin, 1995). In this paper, we present basic information on the petrography, feldspar mineralogy, and bulk composition of the rocks of the KYGC.

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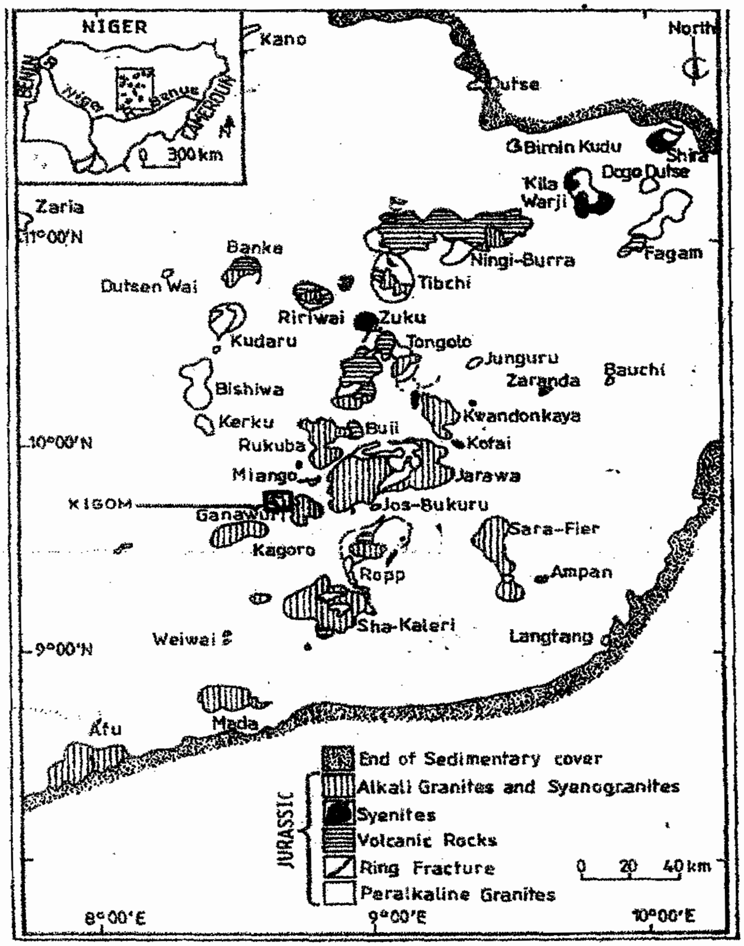

Figure 1. The Geology and distribution of the Nigerian Younger Granite complexes (modified after Bowden, 1976). Box shows study area.

II Geological setting and field mapping

Field mapping shows that the complex is composed of four units (Fig. 2). These are:

1) fayalite-bearing aegirine microgranite (FAG),
2) riebeckite granite (RG),
3) arfvedsonite granite (AFG) and
4) riebeckite-aegirine granite (RAG) which has locally a biotite-bearing variety (RABG). The AFG and RG form rugged topography and the RG shows compositional gradations to RAG-RABG (Omada and Martin, 1995). All the four units are completely free from enclaves and no cross-cutting contact relationships have been found among the amphibole-bearing units. Many dykes and pegmatites with northwest and north strikes intruded the RAG, AFG and the country rock (Fig. 2). Geological mapping reveals that the intrusive has sub-vertical contact with the

gneissic country rock exposed in the northern, western and southern sides. Similarly, the contact between the complex and the Ganawuri complex in the south east is sub-vertical.

Mineralization in the Younger Granite complexes is largely Sn, accompanied by Nb-Ta, Zn and W, and these are found in the peraluminuous members, especially biotite granite (e.g., Jacobson *et al.*, 1958; Bowden and Jones, 1978; Ike, 1979; Olade, 1980; Badejoko, 1988; Imeokparia, 1985). In contrast, the KYGC is the only complex to contain Mo mineralization (Omada and Martin, 1995) which is associated exclusively with the riebeckite granite along the northern contact. The petrography and geochemistry of the molybdenite mineralization at Kigom was presented by Omada and Martin (1995) and Omada (2000). The study of the zone of mineralization is now being extended to other parts of the Kigom complex.

III. Sample selection and analytical methods

A total of 75 rock samples was collected from the Kigom complex. After a petrographic study (Table 1), representative samples were selected for bulk chemical analysis and feldspar mineralogical study. The samples were analyzed for the major and minor

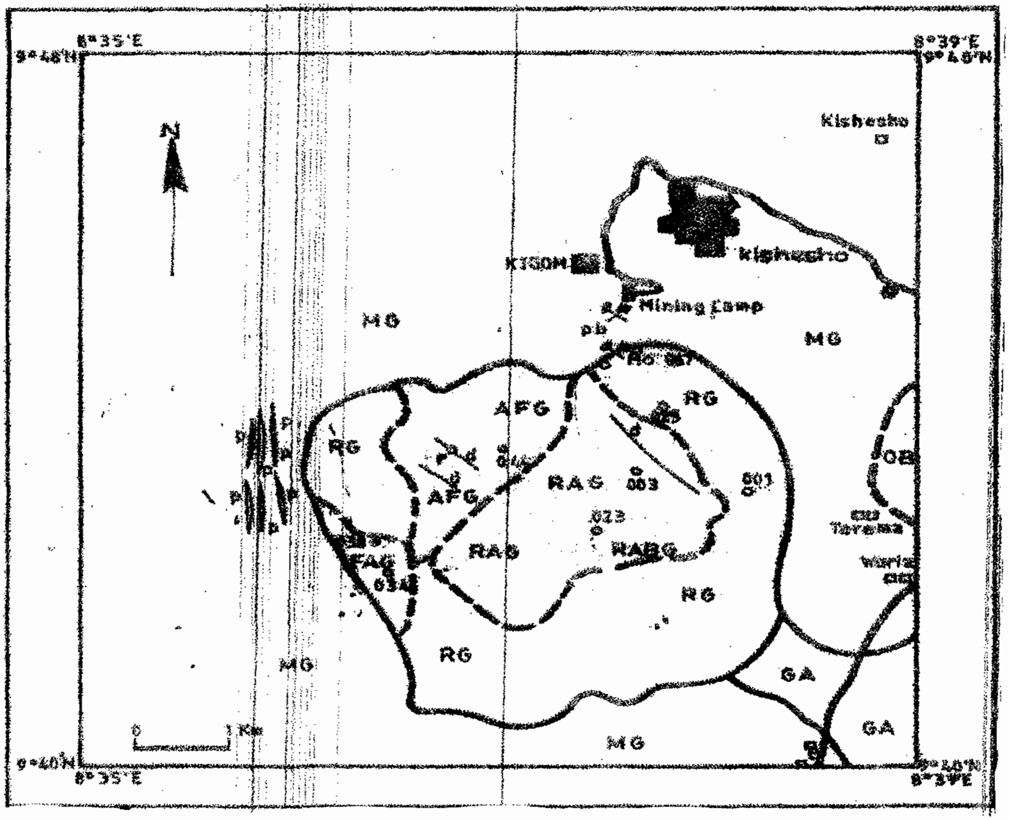

Figure. 2. The Geology of the Kigom Younger Granite Complex (KYGC). FAG, fayalite bearing aegirine microgranite; AFG, arfvedsonite granite; RG, riebeckite granite; RAG, riebeckite aegirine granite; RABG, riebeckite aegirine biotite granite; P, Pegmatite Dyke; GA, the neighbouring Ganawuri Granite Complex; MG – Migmatite; ob, older basalt. representative samples locations are shown.

elements by XRF, supplemented by ammonium metavanadate titration for FeO and an ion-selective electrode technique for F (as described by Jenkins and van Gelder, 1968) in the Geochemistry Laboratory, Department of Geological Sciences, McGill University. The abundance of Mo, W, Be, Li, Sn, and Ag were determined using ICP Spectography as described by Thompson and Walsh (1983) at the ACME Laboratories, Vancouver. Detection limit for major elements: 0.01%, Cu and Zn: 10ppm, Pb: 4ppm, other trace elements: 2ppm. The results of the analyses are shown in Table 2.

The alkali feldspar making up the bulk of these rocks was characterized by powder X-ray diffraction. Indexed and corrected diffraction-maxima were used as input to a cell-refinement program (Appleman and Evans 1973). The unit-cell parameters of 7 representative samples were used to estimate the composition and degree of Al-Si order of the two feldspars making up the perthitic

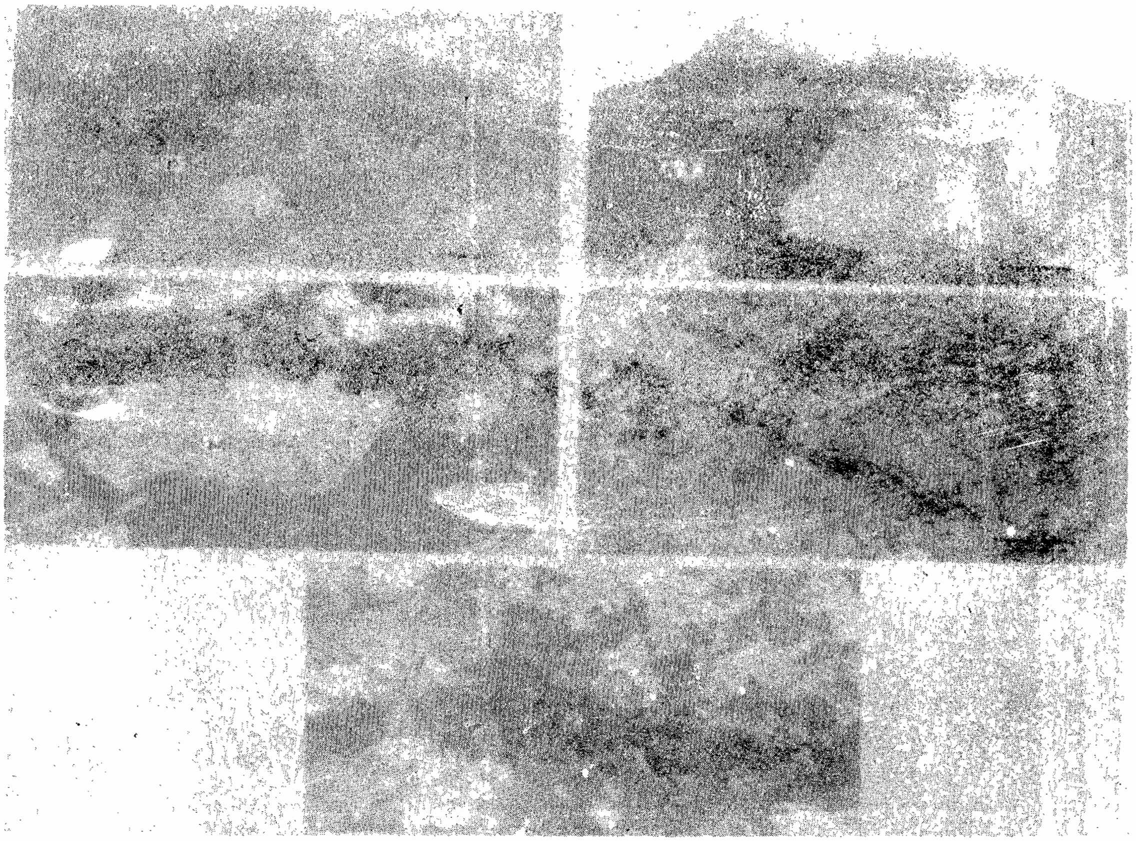

Figure 3. Photomicrographs of the units of the KYGC in Crossed Polarised Light. 1: mesoperthite (P), quartz (Q) and haematite (H) in FAG, 2:mesoperthite (P) at contact with arfvedsonite (Af) in AFG, 3: mesoperthite (M) with development of cross-hatchedtwining in RG, 4: riebeckite (R) in RAGaltered in part to aegirine (Ae) and biotite (B), 5: euhedral crystal of zircon(Z) in RG. Scale bar represents 0.6cm in all cases

Table 1 Mineral assemblage and textural developments of the Kigom complex.

FAG	AFG	RG	RAG-RABG	Stage of cystallization
Quartz large euhedral crystals associated with fayalite, also present as subhedral crystals in groundmass (31% by volume)	**Quartz** large euhedral crystals graphic intergrowth with perthite. Also present as subhedral crystals in groundmass and as inclusions (25% by volume)	**Quartz** large euhedral poikilitic crystals having inclusions of perthite, intergrowth with perthite. Also present as subhedral crystals in groundmass. (27% by volume)	**Quartz** large euhedral poikilitic crystals having inclusions of perthite, intergrowth with perthite. Also present as subhedral crystals in groundmass. (29% by volume)	
Mesoperthite Amazonitic, exsolved. (55%, by volume)	**Mesoperthite** poikilitic, exsolved, altered along margins at contacts with arfvedsonite. (60%, by volume)	**Mesoperthite** poikilitic, exsolved, altered along margins at contacts with riebeckite. (60%, by volume)	**Mesoperthite** Poikilitic, exsolved, altered along margins and along twin planes to biotite (58%, by volume)	**Magmatic**
	Arfvedsonite oikocrystic (14%, by volume)	**Riebeckite** oikocrystic (13%, by volume)	**Riebeckite** Oikocrystic (9%, by volume)	
Fayalite Euhedral crystals, altered at margins and along cleavages to hematite (6%, by volume)	**Magnetite** (accessory)	**Magnetite** (accessory)	**Magnetite** (accessory)	
	Zircon euhedral (accessory)	**Zircon** euhedral (accessory)	**Zircon** Euhedral (accessory)	
	Thorite (accessory)	**Thorite** (accessory)	**Thorite** (accessory)	
	Fluorite (accessory)	**Fluorite** (accessory)	**Fluorite** (accessory)	
	Astrophyllite (1%, by volume)	**Astrophyllite** (<1%, by volume)	**Astrophyllite** (<1%, by volume)	
	Biotite (accessory)	**Biotite** (accessory)	**Biotite** (3%, by volume)	**Hydrothermal**
Aegirine (5%, by volume)			**Aegirine** (1%)	
Haematite (2%, by volume)				

Table 2 Bulk composition of the major rock units of the Kigom complex

Oxides wt%	1	2	3	4	5	6
SiO_2	76.93	75.64	76.14	75.46	73.81	73.16
TiO_2	0.11	0.07	0.08	0.08	0.26	0.27
Al_2O_3	11.28	11.82	11.87	11.61	12.40	12.07
Fe_2O_3	0.85	1.41	1.03	1.82	1.24	1.86
FeO	0.35	1.21	1.23	1.38	1.58	1.99
MnO	0.01	0.01	0.01	0.02	0.06	0.07
MgO	tr.	tr.	tr.	tr.	0.20	tr.
CaO	0.01	0.05	tr.	0.01	0.75	0.50
Na_2O	4.06	4.76	4.51	4.70	4.07	4.57
K_2O	4.31	4.22	4.31	4.20	4.65	4.79
P_2O_5	0.01	0.01	0.01	0.01	0.04	0.02
L.O.I	0.72	0.28	0.27	0.29	-	0.20
Total	98.64	99.48	99.46	99.58	99.06	99.50
CIPW norm wt%						
Q	36.93	32.02	33.32	32.41	30.47	27.65
Or	25.45	25.18	25.70	25.08	27.69	28.63
Ab	34.01	37.68	37.41	36.73	34.72	35.84
Ac	0.29	2.65	0.98	3.06		2.90
Hy	0.00	0.62	0.60	0.69	0.60	0.58
Mt	0.84	0.74	1.02	1.14	1.82	1.28
Il	0.21	0.13	0.15	0.15	0.50	0.52
Trace elements (ppm)						
Nb	208	110	118	79	37	
Zr	530	483	457	588	528	
Y	52	64	35	21	75	
Sr	4	2	1	2	48	
Rb	176	274	299	290	169	
Pb	8	22	12	17	24	
Th	34	21	34	27	23	
U	4	5	5	4	5	
Cu	33	99	125	85	2	
Zn	79	327	285	402	120	
Mo	1	1	2	1	-	
W	4	4	2	4	-	
Li	48	78	137	111	-	
F	560	900	960	1220	-	
Sn	1	6	7	10	-	
Ag	3	0.2	0.1	0.2	-	
Be	4	4	7	7	-	
Ba	4	3	1	1	-	
Ni	1	9	10	10	-	
Cr	28	27	33	30	-	
Ratios						
Rb/Sr	44	137	299	145	3.50	
Rb/Ba	44	97	299	290	0.50	
Zr/Y	10.2	7.50	13	28	7.00	
Zr/Ti	0.8	1.20	1	1.27	0.35	
Na + K/Al	1.01	1.05	1.02	1.06	0.95	

1 FAG (sample no 034); 2 AFG (sample no 044); 3 RG (sample no 025) 4 RABG in RAG (sample no 023); **5 typical A-type granite of Whalen** ***et al,*** **(1987); 6 arfvedsonite granite of the Sha-Kaleri complex (trace element data not determined) (Jacobson** ***et al.,*** 1958).

intergrowth in these samples (Table 3). Other details of analytical techniques are provided as footnotes to the tables.

IV. Petrography

Table 1 summarizes the petrographic features of the representative samples of the KYGC. Alkali amphibole (arfvedsonite and riebeckite), aegirine and astrophyllite are present in many of the samples reflecting the dominant peralkaline character. The suite is leucrocratic and mildly porphyritic. Quartz and fayalite are well preserved in FAG. Fayalite ($FeSiO_4$) occurs as pods associated with euhedral crystals of quartz, the pods range from 3 to 15 cm across and increase in size towards the contact with country rock. The fayalite has been altered to haematite along cracks and at margins. The pods occur isolated and have chilled margins with the other minerals, suggesting that they represent the early magmatic materials.

Arfvedsonite, riebeckite, quartz, zircon, and mesoperthite show textures characteristic of primary magmatic minerals variously modified by later hydrothermal fluids. Over much of the area mapped as AFG and RG, arfvedsonite and riebeckite are oikocrystic containing quartz and feldspar suggesting crystallization close to solidus conditions. Arfvedsonite in the AFG occurs as prismatic crystals with blunt terminations against quartz and perthite (Fig. 3) and commonly has inclusions of primary quartz. Riebeckite, in the RG and RAG, is present as large oikocrystic crystals that enclose crystals of mesoperthite, quartz, and zircon. At the contact with riebeckite, mesoperthite becomes turbid due to alteration. In the RAG-RABG, riebeckite crystals are replaced along cleavage planes and at margins by fine and oriented aegirine and biotite crystals, respectively. Albite is present interstitially. Astrophyllite occurs along cleavage planes of arfvedsonite, riebeckite and mesoperthite. Aegirine in the Kigom complex is generally greenish and occurs as fine crystals in FAG and as late-stage mineral in RAG-RABG. Red-brown biotite occurs at margins and along cleavage planes of perthite and the sodic amphibole in RAG-RABG. Euhedral crystals of zircon, thorite and fluorite are common accessory minerals.

V Feldspar mineralogy

All the granite rocks contain only mesoperthite as feldspar. The Kigom granites thus are hypersolvus according to Tuttle and Bowen (1958). The albite is very close to the end member (1-2% Or at most) and fully ordered (Table 3). The K-rich feldspar is microcline and low sanidine is absent. The degrees of order of the microcline are close to 1.00. The composition of microcline is in most cases more potassic than 98% Or. The FAG is the only unit in the Kigom complex proper to still contain orthoclase. It is present in minor proportions only in sample 034 coexisting with microcline that falls short of complete Al-Si order. In sample 038, there was no conversion of orthoclase to microcline. The other three samples of the KYGC contain a range of degrees of Al-Si order and compositions. The path of crystallization of the feldspar is thus orthoclase to microcline as crystallization proceeded from late magmatic to hydrothermal.

VI Geochemistry

The suite is characterized by a restricted range in SiO_3, content, (75-77%), high abundances of Na_2O and K_2O, and a relatively low content of Al_2O_3 (11.2-11.87%). MgO and CaO are trace amounts in the suite (Table 2). According to Tuttle and Bowen (1958), the major-element proportions correspond to the "magma residua system" or "the granite system".

All the samples are peralkaline with an agpaitic index in the range 1.01-1.06 (Table 2). This degree of departure from the plane of the haplogranitic system is minimal. The Fe_2O_3/FeO ratio of the granites follows the same pattern

3 (a) Unit cell parameters and indicators of compositions and degrees of Al-Si order in K-feldspar and albite

Sample	a	b	c	α	β	γ	V	#	A*	b*	c*	α*	β*	γ*
034	8.5783	12.9621	7.2180	90.568	115.942	87.860	721.20	36	0.129723	0.077204	0.154071	90.409	64.061	92.103
	0.0020	0.0021	0.0015	0.025	0.017	0.018	0.19		0.000031	0.000012	0.000033	0.024	0.017	0.017
(FAG)	8.1385	12.7892	7.1612	94.266	116.633	87.682	664.41	53	0.137463	0.078411	0.156528	86.389	63.457	90.456
	0.0007	0.0010	0.0007	0.011	0.009	0.008	0.08		0.000015	0.000006	0.000017	0.011	0.009	0.008
038	8.5967	12.9751	7.1949	90.000	115.933	90.00	721.74	35	0.129348	0.077071	0.154549	90.000	64.066	90.000
	0.0041	0.0033	0.0022	0.000	0.048	0.00	0.51		0.000100	0.000019	0.000066	0.000	0.048	0.000
(FAG)	8.1399	12.7903	7.1594	94.237	116.592	87.76	664.69	59	0.137387	0.078401	0.156511	86.384	63.493	90.391
	0.0007	0.0013	0.0007	0.012	0.009	0.01	0.08		0.000015	0.000008	0.000016	0.012	0.009	0.009
044	8.5822	12.9682	7.2236	90.602	115.946	87.659	722.30	37	0.129686	0.077179	0.153958	90.470	64.057	92.311
	0.0017	0.0014	0.0010	0.016	0.013	0.013	0.14		0.000026	0.000008	0.000021	0.015	0.012	0.012
(AFG)	8.1402	12.7876	7.1631	94.261	116.600	87.682	664.84	73	0.137394	0.078420	0.156440	86.394	63.490	90.461
	0.0007	0.0011	0.0008	0.011	0.010	0.008	0.09		0.000016	0.000007	0.000020	0.011	0.010	0.008
025	8.5752	12.9669	7.2212	90.645	115.974	87.616	721.20	44	0.129620	0.077188	0.154046	90.444	64.030	92.337
	0.0015	0.0014	0.0011	0.015	0.017	0.015	0.15		0.000025	0.000008	0.000029	0.015	0.017	0.015
(RB)	8.1397	12.7898	7.1615	94.283	116.637	87.661	664.54	54	0.137446	0.078409	0.156527	86.380	63.455	90.471
	0.0007	0.0010	0.0007	0.011	0.010	0.008	0.09		0.000017	0.000006	0.000021	0.011	0.010	0.008
003	8.5864	12.9625	7.2193	90.644	115.950	87.717	721.92	42	0.129620	0.077209	0.154052	90.395	64.055	90.483
	0.0016	0.0020	0.0014	0.021	0.015	0.018	0.17		0.000025	0.000012	0.000031	0.021	0.015	0.008
(RAG)	8.1371	12.7880	7.1594	94.269	116.643	87.657	664.02	64	0.137498	0.078418	0.156578	86.399	63.449	92.185
	0.0007	0.0010	0.0007	0.010	0.008	0.008	0.08		0.000016	0.000006	0.000016	0.010	0.008	0.018
AD	8.5857	12.9714	7.216	90.609	115.958	87.960	722.08	66	0.129617	0.077142	0.154136	90.315	64.047	91.971
	0.0014	0.0027	0.001	0.020	0.015	0.018	0.07		0.000028	0.000016	0.000028	0.022	0.014	0.019
	8.1369	12.7885	7.160	94.248	116.614	87.673	664.25	75	0.137467	0.078413	0.156525	86.413	63.477	90.477
	0.0007	0.0011	0.001	0.010	0.009	0.008	0.08		0.000015	0.000006	0.000015	0.010	0.009	0.008
PT	8.5835	12.9829	7.202	90.000	116.039	90.000	721.12	18	0.129664	0.077024	0.154536	90.000	63.961	90.000
	0.0013	0.0017	0.001	0.000	0.015	0.000	0.14		0.000023	0.000010	0.000022	0.000	0.015	0.000
	8.1412	12.7886	7.155	94.163	116.609	87.826	664.24	27	0.137384	0.078403	0.156630	86.432	63.472	90.348
	0.0011	0.0020	0.001	0.026	0.017	0.015	0.015		0.000027	0.000012	0.000031	0.027	0.017	0.017

The cell dimensions of the K-rich feldspar are listed before those of the coexisting sodic plagioclase. # number of peaks used in the least-square refinement [program of Appleman & Evans (1973), as adapted by R. G. Garvey]. Units a*, b*, c*, in A, and V (unit-cell volume) in A^3, interaxial angle in direct and reciprocal space in degrees.

Table 3(b) Unit cell parameters of representative samples of the Kigom pluton.

K-rich feldspar					Na-rich feldspar			
S/No	**Description**	**N_{or}**	**t_1O**	**–**	**An**	**N_{or}**	**t_1O**	**_131**
034	FAG	96.0	0.95	0.91	0	1.0	1.00	1.099
038	FAG	96.7	0.39	0	0	1.5	0.98	1.120
044	AFG	99.2	1.00	1.01	0	1.8	1.01	1.096
025	RG	96.0	1.00	1.01	0	1.2	1.01	1.097
03	RAG	98.0	0.98	0.95	0	0.3	1.01	1.088
PT	AFG	97.7	0.90	0.82	0	0.8	1.00	1.084
PT	PT	95.0	0.40	0	1	0.7	0.96	1.118

Composition N_{or} is expressed in mol % Or and was calculated using the equations of Kroll & Ribbe (1983) relating unit-cell volume to N_{or} for feldspar composition that are structurally ordered [i.e. that belong to the low microcline ($t_1O \geq 0.092$) - low albite series] or structurally intermediate. The degree of Al-Si order, expressed by t_10 was computed using the equations of Blasi (1977). The error in N_{or} and t_10 is believed to be ± 0.015 in most cases. The obliquity of a microcline is equal to 12.5 (d_{131} - d_{131}); both and t_10 should have a value of 1.00 for fully ordered microcline. The _131 indicator of a plagioclase is the calculated angular separation of the 131 and 131 diffraction maxima, in $^{0}2\theta$ (Cukα radiation); it should be close to 1.10^{0} in end-member ordered albite.

as that of the agpaitic index resulting in the presence of up to 3.06% normative acmite in the RABG (Table 2). The units of the Kigom have normative Q+Or+Ab>92% in which Ab>Q>Or.

The units of the KYGC are enriched in Rb and the HFSE, and are strongly depleted in Ba and Sr. Among the units of the KYGC, the FAG is the most enriched in Nb while the RAG-RABG is the most enriched in F and Zn. This indicates that the rock-fluid interaction increased in intensity towards the RAG-RABG.

VII. Discussion and conclusion

Among the mafic minerals of granitic rocks of the KYGC, fayalite ($FeSiO_4$) was the first to crystallize from the initial melt. Some of the accessory minerals like zircon and thorite are among the early magmatic minerals in the complex. Thereafter, the melt witnessed the introduction of peralkaline magmatic fluids, which led to the crystallization of mesoperthite, arfvedsonite, and riebeckite. The astrophyllite, aegirine, and biotite associated with the arfvedsonite and riebeckite invariably formed late at the subsolidus hydrothermal stage as products of peralkaline metasomatism. All samples thus consist of magmatic minerals and variably hydrothermally altered minerals.

The feldspar mineralogy indicates that the metasomatism involved the local removal of Na consumed in the late growth of riebeckite. The ability of the K-feldspars to attain the maximum degree of ordering may be due to the presence of aqueous fluid beyond the monoclinic-triclinic inversion temperature of (450°C) which allowed for long duration of rock-fluid interaction (e.g., Smith, 1976). The feldspar compositions and ordering states are also consistent with those expected for efficient recrystallization in the presence of a peralkaline fluid well within the field of stability of microcline at temperature below 450°C. The compositions of feldspars in the AFG, RG, RAG, RABG indicate temperatures even lower than 300°C (e.g. Brown and Parsons, 1989). Arfvedsonite and riebeckite from some other complexes in Nigeria which are chemically riebeckite-arfvedsonite, are usually found in thoroughly recrystallized granites (Bowden and Turner, 1974; Badejoko, 1988). This suggests that the KYGC is also a recrystallized member of the Younger granites of Nigeria. The enrichment of the Kigom rocks in elements like Zr (>457 ppm), Y (>21 ppm), and Th (>21ppm) coupled with very high Rb/Sr, Rb/Ba, Zr/Y, Zr/Ti and F/Zr ratios is typical of such recrystallized rocks and peralkaline suites (e.g., Whalen *et al*, 1987; Bowden, 1982). The bulk composition of the granites at Kigom suggests that: (a) the crystallizing silicic (>75 wt% SiO_2) magma differentiated early, low *solidus* temperatures prevailed in the late-magmatic crystallization and excess alkali was available in the hydrothermal fluid (e.g., Ludington *et al*., 1979; Hildreth, 1979), (b) the interaction between the crystallizing melt and the later aqueous fluid increased steadily from the FAG, AFG, to the RG and RAG-RABG members which had the greatest intensity and longest duration of rock-fluid interaction, and (c) that the enrichment of HFSE and other trace elements in the KYGC granites, initially disseminated within the melt, was enhanced by the increasing F-content in the hydrothermal fluid during the period of rock-fluid interaction (e.g., Haapala, 1985).

The KYGC provides evidence for crystallization from magma later invaded by aqueous fluid. It is a good example of a Younger granite complex which is exposed as a single mass and in which rock-fluid interaction is dominant and lasted for a long period of time. The KYGC may in fact be a 'late granite' that represents one of the recrystallized phases of the Younger granite complexes of Nigeria in the Jurassic period. KYGC has intrusive contact with the neighbouring Ganawuri Younger granite complex which is contemporaneous with the Jos-Bukuru complex dated 160 Ma (van Breeman and Bowden, 1973; Bowden *et al*., 1976).

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