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The Shere Igneous Complex, Central Nigeria, geochemical constraints on the origin of peralkaline and associated granites

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Abstract

The Shere Igneous Complex comprises a sequence of metaluminous-peraluminous and peralkaline granites in the following order: (1) a central amphibole-fayalite granite, metaluminous in the core and peralkaline towards the margin; (2) a mildly peraluminous biotite granite in the east of the complex; (3) a peralkaline arfvedsonite-aegirine granite forming a peripheral ring around the central amphibole fayalite granite; (4) a peralkaline arfvedsonite-biotite granite forming a semi-circular body between (1) and (3); and (5) a peralkaline albite-arfvedsonite granite forming an outer semi-circular intrusion in the west of the complex.

The peralkaline and metaluminous/peraluminous granites show some overlap of agpaitic indices, but marked dissimilarities in trace element characteristics. The amphibole-fayalite granite has high contents of Ba, Sr, Zr and low contents of Rb, Th, Y and Li. The biotite granite is enriched in Rb, Y, Th, Li, F relative to the amphibole-fayalite granite and is presumably crystallized from a differentiated magma produced by fractional crystallization of the amphibole-fayalite granite magma.

The arfvedsonite-aegirine granite, the arfvedsonite-biotite granite and the albite-arfvedsonite granite are enriched in HFS elements and strongly depleted in Sr and Ba; these granites are presumably associated with a fluorine-bearing phase carrying high concentrations of HFS and other trace elements. This volatile phase has caused metasomatic alterations in surrounding rocks. The part of the arfvedsonite-biotite granite that is characterized by extreme levels of HFS elements is believed to have formed by metasomatic alteration of amphibole-fayalite granite along the contacts with arfvedsonite-biotite granite.

The granitic magmas were presumably formed by partial melting of anhydrous residual crust enriched in refractory ferromagnesian and accessory minerals during a previous cycle of anatexis. The high temperatures necessary for melting this granulitic crust were provided by the emplacement of mantle derived mafic magmas into the lower crust. The extensional tectonic setting allowed small batches of granite magma to rise without substantial mixing.

Introduction

The Shere Complex is a small ring structure between latitudes 9° 55′ and 10° 00′ N and longitudes 9° 00′ and 9° 07′ E in the northeast of the Jos-Bukuru Complex (Fig. 1). The Shere Complex was regarded as part of the Jos-Bukuru Complex by Jacobson et al. (1958) but Berridge (in Buchanan et al., 1971) considers it as a separate complex contemporaneous with the central granite cycle of the Jos-Bukuru Complex.

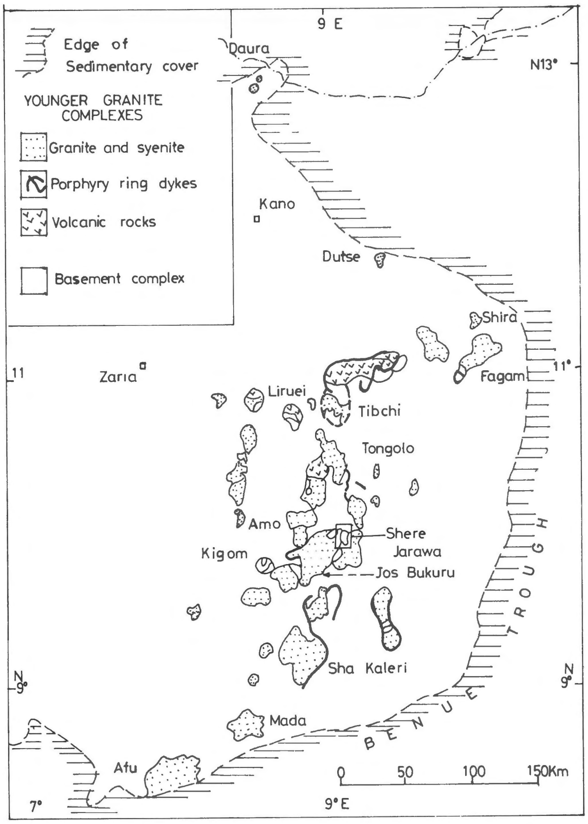

Fig. 1. Distribution and general geology of the Nigerian Ring Complexes, showing the location of the Shere Complex.

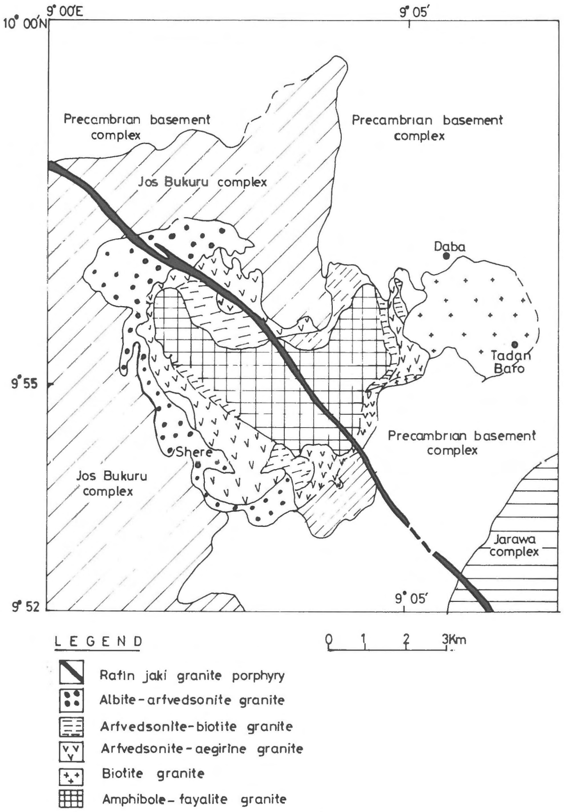

Fig. 2. Geological map of the Shere-Ring Complex, Central Nigeria (modified after Buchanan et al., 1971).

The Shere Complex is dominated by granites of peralkaline affinity (Fig. 2). Such rocks are of special geologic interest since they generally characterize subvolcanic structures formed during prerifting, epirogenic doming (Murthy & Venkataraman, 1964; Bowden, 1974)

Although the petrogenesis of the Nigerian alkaline granites has been widely discussed, a satisfactory evolutionary model is yet to evolve. One topical issue in this discussion has been the nature and source of the magma that gave rise to contrasting geochemical rock suites.

Peralkaline granites, although widely represented in the Nigerian Younger granite province do not occur in all granite intrusive complexes, suggesting that magma compositions were controlled by melting conditions and/or protolith compositions in restricted domains. Besides, where the peralkaline granites occur a genetic relationship with the other granitoids has not been established (Imeokparia, 1986). Furthermore different emplacement ages and isotopic ratios of the granitoid plutons do not suggest a simple model for the origin of the varied rock types.

This paper presents geochemical data on the Shere Complex and discusses its petrogenesis in relation to that of some other peralkaline granitoids in the world.

The Shere Complex

The Shere Complex is formed by a sequence of metaluminous/peraluminous and peralkaline granitoid intrusions, covering only about 44 km^2 (Fig. 2), which has been mapped in detail by Berridge (in Buchanan et al., 1971). Radiometric age determinations show that the granites were emplaced around 164 Ma ago (Van Breeman et al., 1975) into a Precambrian to early Paleozoic basement of gneisses and calc-alkaline older granites.

The core of the Shere Complex is formed by a coarse-grained amphibole fayalite granite containing orthoclase, microperthite, oligoclase and quartz phenocrysts in a quartz-oligoclase matrix. Aluminium-poor ferro-hastingsite (Borley, 1976) is the dominant mafic phase and sometimes has outgrowths of pale blue amphibole (arfvedsonite?). Other ferromagnesian minerals are biotite, fayalite and ferrohedinbergite partially altered to iron oxides. Accessory minerals include allanite, zircon and iron oxides.

The eastern flank of the Shere Complex consists of an approximately 8 km^2 biotite granite, which shows subhedral to euhedral perthite megacrysts (2–3 cm) in an equigranular medium grained matrix of quartz and subhedral feldspars (perthite and oligoclase). Biotite, the only mafic phase constitutes less than 5% of the rock. Accessory minerals are zircon, allanite, fluorite, sphene, ilmenite and magnetite.

An arfvedsonite-aegirine granite forms a heart-shaped ring around the central amphibole fayalite granite. The arfvedsonite aegirine is truncated in the west by a younger albite-arfvedsonite granite (Fig. 2). The granite contains phenocrysts of quartz and microcline microperthite in a matrix of albite, afvedsonite and aegirine. Accessories are fluorite, zircon pyroclore, astrophyllite and iron oxide.

The southwestern and northern parts of the Shere Complex are occupied by an arfvedsonite-biotite granite which partly encircles the central amphibole-fayalite granite (Fig. 2). The rock contains zoned cryptoperthite crystals in a matrix of arfvedsonite and biotite. As aegirine disappears, red brown biotite appears along with accessory iron oxide, zircon, pyrochlore and astrophyllite (Buchanan et al., 1971). North of the Shere hills, biotite is more abundant than arfvedsonite. Here the rock contains small clots of bleached biotite, hematite and fluorite. Thorite, zircon and xenotime occur as accessory minerals in the arfvedsonite poor zones.

Flanking the arfvedsonite-aegirine granite in the west is an irregular, semi-circular intrusion of albite-arfvedsonite granite. This granite shows well twinned laths of albite enclosed by microcline and quartz. Essential minerals are quartz, microcline perthite, albite, arfvedsonite, aegirine.

The country rocks around the Shere Complex consists of migmatitic granulitic gneisses and porphyritic two mica granites (Buchanan et al., 1971; McLeod et al., 1971).

The following sequence of intrusions in the Shere Complex is given by Buchanan et al. (1971):

1. Basement complex (of migmatites and order granites)
2. Amphibole (hastingsite) – fayalite granite
3. Biotite granite
4. Arfvedsonite-aegirine granite
5. Arfvedsonite-biotite granite
6. Albite-arfvedsonite granite
7. Rafin jaki basic dyke

Geochemistry

Chemical analysis of the granites of the Shere Complex are given in Table 1. On the basis of the agpaitic index, i.e. the atomic ratio of (Na + K/Al), the granites can be divided into peralkaline (Na + K/Al > 1) and metaluminous/peraluminous granites (Na + K/Al < 1). The peralkaline granites comprise the arfvedsonite-aegirine ± biotite granites and the albite-arfvedsonite granite. The biotite granite is mildly peralumious. The amphibole-fayalite granite is metaluminous in the core and peralkaline towards the margin. This classification is also shown in the $Al_2O_3 - CaO - (Na_2O + K_2O)$ diagram (Fig. 3a).

The covariation of Na_2O and K_2O in the Shere granite is given in Fig. 3b. In Fig. 3b the Shere granites plot in a different field as A-type granites of the Australian Lanchlan fold belt (Collins et al., 1982), but in the same field as Saudi Arabian peralkaline granites (Radain et al., 1981; Harris et al., 1986). The Nigerian granites are related to doming and failed rifts (Bowden, 1974) as distinct from the Australian A-type granites which are related to the terminal phase of an orogeny. Although the Shere peralkaline granites plot in the same field as the Saudi peralkaline granites, the low $^{87}Sr/^{86}Sr$ ratios

Table 1. Chemical composition of granites from Shere Complex; average and range in weight % oxides and ppm trace elements

Wt. % oxides	Amphibole-fayalite granite (3)	Granite contact zone (3)	Biotite granite (5)	Arfvedsonite-aegirine granite (5)	Arfvedsonite-biotite granite (5)	Albite-arfvedsonite granite (5)
	74.55	73.75	75.17	75.96	75.83	75.09
SiO_2	74.26–74.70		74.20–75.86	74.87–76.60	74.55–76.60	74.50–75.50
	0.18	0.22	0.09	0.10	0.11	0.11
TiO_2	0.12–0.22		0.07–0.11	0.07–0.13	0.10–0.12	–
	12.67	12.20	12.98	11.12	11.88	10.58
Al_2O_3	12.46–12.90		12.76–13.26	10.79–11.42	10.80–13.25	10.40–10.96
	1.00	1.90	0.52	1.40	1.50	2.59
Fe_2O_3	0.68–1.35		0.33–0.64	0.26–2.02	1.20–1.93	2.02–2.98
	1.03	0.92	0.89	1.13	1.00	1.04
FeO	0.78–1.26		0.68–1.05	0.78 1.98	0.44 1.69	0.83 1.54
	0.04	0.06	0.02	0.03	0.03	0.04
MnO	0.03–0.06		0.03–0.04	0.01–0.05	0.02–0.03	0.03–0.04
	0.17	0.08	0.08	0.07	0.11	0.06
MgO	0.15–0.19		0.05–0.12	0.03–0.09	0.05–0.20	0.03–0.08
	0.57	0.44	0.55	0.22	0.24	0.20
CaO	0.45–0.69		0.45–0.68	0.12–0.31	0.08–0.39	0.12–0.32
	4.56	4.52	4.03	5.01	4.54	5.01
Na_2O	4.44–4.63		3.84–4.30	4.23–5.52	4.44–4.60	4.58–5.66
	4.64	4.42	4.63	3.39	4.18	4.04
K_2O	4.18–4.90		4.35–4.96	3.76–4.81	4.04–4.40	3.50–4.46
	0.02	0.06	0.07	tr.	tr.	0.01
P_2O_5	0.02–0.03		0.01–0.02			–
Trace	Element (ppm)					
	18	136	80	135	119	337
Li	13–27		36–112	88–182	116–120	159–440
	213	496	464	369	283	850
Rb	160–260		320–610	260–470	265–320	550–1308
	480	68	137	30	63	25
Ba	300–800		98–200	12–45	55–68	15–35
	40	11	15	5	9	3
Sr	23–72		11–18	3–9	7–12	2–4
	520	970	194	846	490	2020
Zr	470–560		120–240	615–1103	410–540	1080–3073
	27	32	37	41	38	57
Ga	25–30		34–40	36–45	35–42	52–60
	84	212	132	381	218	762
Nb	75–100		75–218	330–430	215–225	460–1250
	115	240	140	341	220	524
Y	100–145		120–164	210–480	175–216	350–700
	1800	3800	2900	4200	4630	8200
F	1600–2100		2200–3400	3600–5400	4300–5000	6800–9600
	93	136	70	76	113	63
La	55–125		60–94	28–108	95–150	40–75
	201	367	125	136	218	220
Ce	160–228		104–145	70–215	195–245	189–260
	240	360	140	360	290	850
Zn	180–280		116–180	240–500	280–315	760–986
	440	360	96	490	357	702

Table 1. Continued

Wt. % oxides	Amphibole-fayalite granite (3)	Granite contact zone (3)	Biotite granite (5)	Arfvedsonite-aegirine granite (5)	Arfvedsonite-biotite granite (5)	Albite-arfvedsonite granite (5)
Mn	400–480		80–120	450–520	280–430	580–900
	10	15	14	32	22	47
Sn	8–12		8–22	18–50	18–25	30–70
	25	56	37	90	97	165
Th	17–30		19–54	57–160	90–110	126–220
	4	48	7	30	16	78
U	4–5		5–10	12–45	10–22	55–105
	18	36	26	71	75	185
	13–21		21–30	55–90	55–100	103–252

Number of samples in parenthesis.

All major elements except Na_2O, FeO and MgO were determined by X-ray fluoresence; Na_2O and MgO were determined by atomic absorption; FeO by redox titration; Ba, Rb, Sr, Zr, Ga, Nb, La, Ce, Sn, Th, U, Y were determined by X-ray fluoresence; while Li, Zn, Mn, and Pb were determined by atomic absorption and F by ion selective electrode.

of the Saudi granites contrast with the high ratios of the Nigerian granites (Van Breeman et al., 1975). The Saudi Arabian peralkaline granites are associated with ophiolites; in contrast, the Nigerian peralkaline granites occur in an intra-continental environment.

The peralkaline granites of the Shere Complex are clearly more sodic than the aluminous granites. Fig. 3b demonstrates that each granite shows inverse relationship between Na_2O and K_2O, possibly reflecting lower temperature feldspar fractionation.

In the AFM diagram the Shere granites plot with some overlap along the AF side close to the $Na_2O + K_2O$ apex (Fig. 4a) due to low MgO and moderate FeO contents. The trend towards Fe-enrichment in the peralkaline granites shown in Fig. 4a is typical of peralkaline rock suites the world over (Parsons, 1972; 1979; Barker et al., 1975; Radain et al., 1981; Collerson, 1982) and has been explained either by the dominance of Fe-complexing volatile species in the magma (Christiansen et al., 1983) or by involvement of residual magnetite in the melting process. In the normative

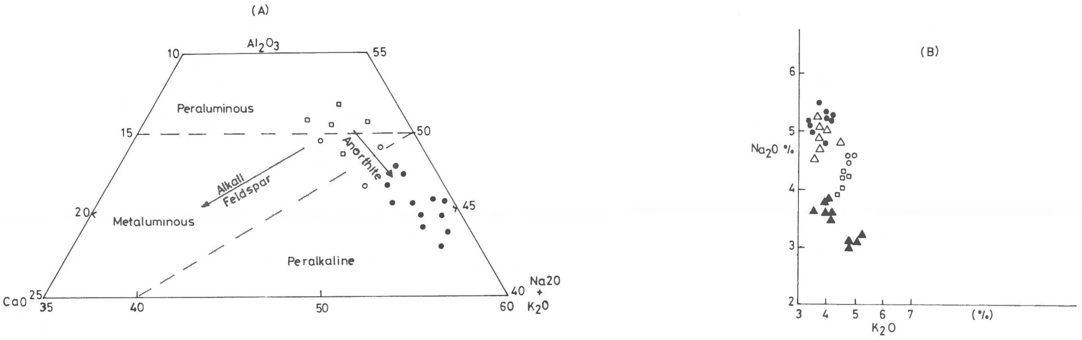

Fig. 3. (a) $Al_2O_3 - CaO - (Na_2O + K_2O)$ mole % plot for samples from the Shere Complex. Arrows indicate change in liquid composition from feldspar fractionation. Symbols: (●) peralkaline granites, (○) Fayalite-amphibole granite, (□) biotite granite (Diagram after Harris et al., 1986); (b) $Na_2O - K_2O$ relationships in rocks of Shere Complex. Symbols as in Fig. 3a. Also shown are fields of Australian A-type granites (▲) (Collins et al., 1982) and Jabel Sayid peralkaline granites (△) (Radain et al., 1981).

Q-Or-ab diagram (Fig. 4b) the analysed samples plot near the ternary minimum for water pressures of 1 to 3 kb (Bowen, 1945).

Trace elements

Trace element abundances for the Shere granites are also presented in Table 1.

The peralkaline granites carry relatively high levels of High Field Strength (HFS) elements such as Nb, Y, Th, U, Zr and relatively low levels of divalent elements such as Sr and Ba. A feature of particular interest is presented by the albite-arfvedsonite granite which shows a dramatic but variable enrichment in lithophile elements such as Li, Rb, F, Th, Nb, Y, Zr and Zn. This feature may be ascribed to roofward streaming of a vapour phase in which volatiles and metal complexes are concentrated (Harris, 1981). The Shere albite-arfvedsonite granite has trace elements (Nb, Y, Th, U, Zr, Rb, F), geochemical characteristics akin to the peralkaline Kaffo valley granite of Ririwai Complex (Kinnaird et al., 1985; Imeokparia, unpublished data), the molybdenium bearing peralkaline granite of the Kingdom Complex (Imeokparia, 1984) and also the proterozoic peralkaline granites of Saudi Arabia (Radain et al., 1981; Harris et al., 1986). The peralkaline arfvedsonite-biotite granite has very variable trace element contents possibly reflecting the variable mineralogy of the rock. The HFS elements vary in concentration between the values of the other peralkaline granites and those of the biotite granite. This is consistent with data of Bowden et al. (1976) for the arfvedsonite biotite granite of Amo Complex (see also Imeokparia, 1983).

The biotite granite is characterized by relatively high abundance of the trace elements Li, Rb, Th, F, Y and by relatively lower values of Zr, Ba, and Sr, compared to the amphibole-fayalite granite. However, compared with the peralkaline granites, the biotite granite has lower Li, Th, F, Y and Zr contents. Of five analysed samples two are metal-

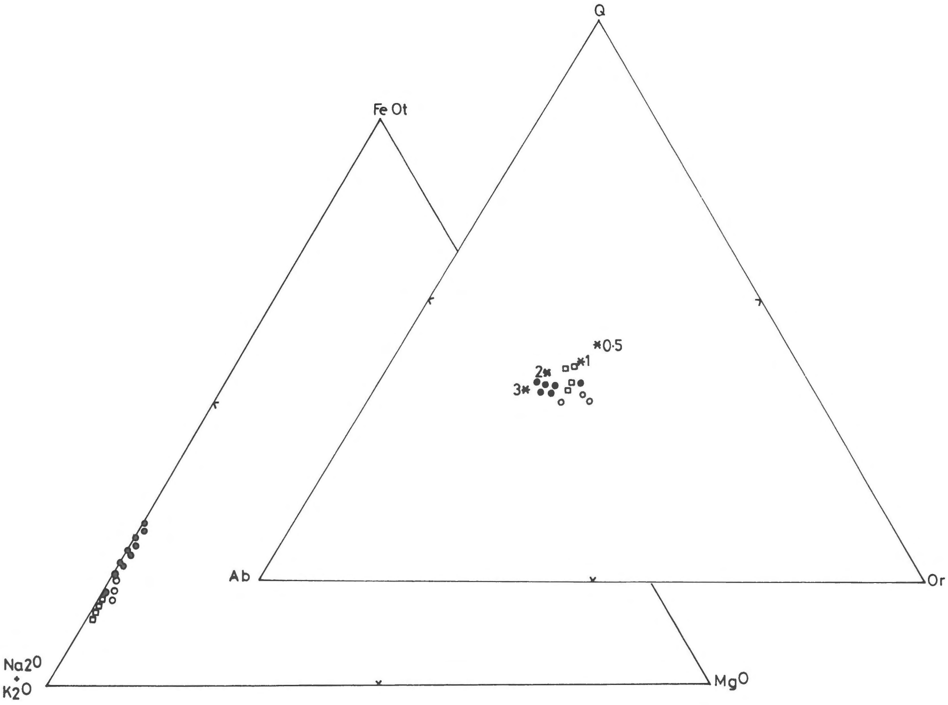

Fig. 4. (a) ($K_2O + Na_2O$) – FeO – MgO mole % plot for samples from the Shere Complex; Symbols as in Fig. 3a; (b) Q – Or – Ab normative plot for samples from the Shere Complex. Symbols as in Fig. 3a. Stars represent ternary minima at 0.5, 1.2 Kbar (Tuttle & Bowen, 1958).

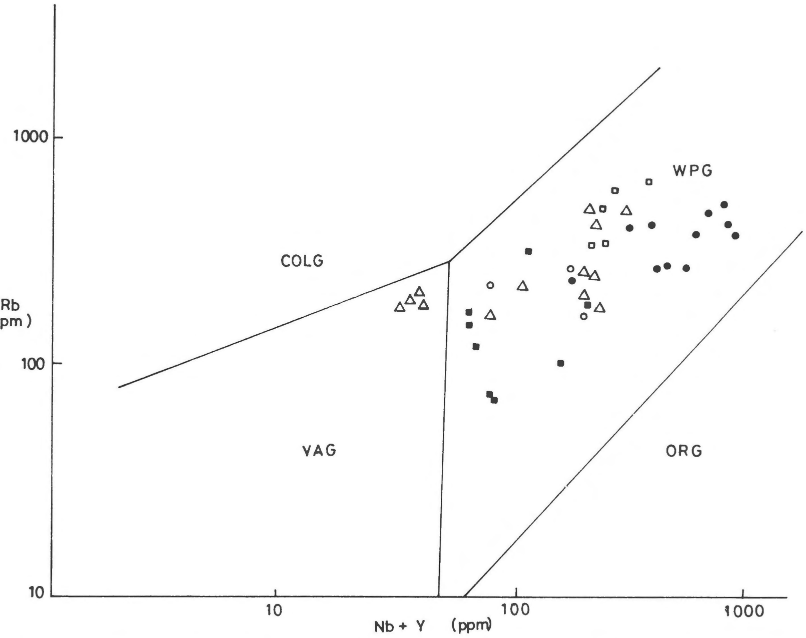

Fig. 5. Distribution of Shere granite data in Rb-(Nb + Y) discrimination diagrams of Pearce et al. (1984) Fields for Syn-Collision (COLG), volcanic arc (VAG), within-plate (WPG) and Ocean Ridge (ORG) granites are indicated. Symbols as in Fig. 3. Additional symbols: (CE) Topsails Igneous Complex Newfoundland (Whalen et al., 1987); (△) Jabel Sayid – Saudi Arabia (Harris et al., 1986).

uminous and three are mildly peraluminous, but the mineralogy and trace element geochemistry appear unrelated to alumina saturation. The amphibole-fayalite granite shows enrichment in divalent elements such as Sr and Ba relative to the other granites, but the values of Ga, Nb and U are comparable with those of the biotite granite.

The distinctive geochemistries of the peralkaline and metaluminous granites are reflected in their Y and Zr contents. If Y reflects the behaviour of the HREE in granites (Shannon, 1976), then the peralkaline granites are enriched in HREE relative to the other granites. Complexing by halogens particularly F has been invoked to explain this enrichment (Bailey & MacDonald, 1975; Harris, 1981). Mineyev et al. (1966) experimentally demonstrated the higher mobility of Y (as represented by HREE) relative to LREE (La and Ce) in fluorine- and sodium-rich acidic solutions across a temperature gradient.

Pearce et al. (1984) have proposed a tectonic classification of granites based on a Rb-(Nb + Y) discrimination diagram. Fig. 5 shows that the Shere peralkaline and metaluminous granites are clearly within-plate granites; plotting in the same field as peralkaline granites of for instance Saudi Arabia (Radain et al., 1981; Harris et al., 1986) and the Topsails igneous complex, Newfoundland (Taylor et al., 1980). The peralkaline granites of Saudi Arabia show an overlap from within-plate to volcanic arc granites. Whalen et al. (1987) have also found that some of the strongly peralkaline granites of the Nigeria Shira Complex are low in Y and Nb and plot within the volcanic arc field. A possible explanation for this aberration is that Y and Nb may have been selectively removed by a volatile phase. The samples exhibiting low Y and Nb are of peralkaline microgranite containing twice as much F as the other samples from the suite. The magma apparently co-existed with an F-oversaturated volatile phase which after precipitating fluorite left the magma, taking Nb and Y away from the crystallizing rock.

Discussion and Petrogenesis

Ajakaiye (1983) has indicated from geophysical evidence that incipient rifts have controlled the disposition of the Nigerian ring complexes. In such a tensional environment basic magma emplaced into the lower or intermediate crust may provide latent heat capable of melting the country rocks (Collerson, 1982). In this environment granites may be formed by:

i. fractional crystallization of the basic melt,
ii. partial melting of crustal rocks or
iii. interaction between crust and melts.

The Shere granitoids are not considered as fractionated silicic end members of mafic to felsic plutonic suites for the following reasons:

1. granitic rocks are dominant with only minor basic dykes cutting the granites;
2. all the granitoids have near-eutectic compositions in the ternary Q-Or-Ab diagram for 1–3 kbars PH_2O;
3. gravity evidence excludes large volumes of dense basic material underlying the granites (Ajakaiye, 1970);
4. the peralkaline granites have an initial $^{87}Sr/^{86}Sr$ ratio around 0.713 ± 0.01 indicating the involvement of crustal material (Van Breeman et al., 1975), the fayalite granite has an initial Sr-isotope ratio of 0.708 ± 0.03 indicating a crustal source with relative low $^{Rb}/Sr$ ratio typical of granulite facies metamorphic rocks (Collins et al., 1982);
5. the peralkaline rocks are enriched in an incongrous assemblage of trace elements (e.g. Zn along with Rb, Nb, Y and Zr) unlike that resulting from typical igneous enrichment trends; the peralkaline rocks have higher concentrations of LREE and steeper chrondrite normalized REE patterns (Alexiyev, 1970; Bowden et al., 1976).

The low Ca, Al, Mg contents of the Shere granites is apparently related to crustal melting processes and due either to retention of these elements in refractory minerals as calcic plagioclase and pyroxene or to originally low contents of these elements in the melt region (Long et al., 1986). The melt region may be characterized by phases like alkali feldspar plagioclase, quartz, pyroxene, biotite and amphibole i.e. by a mineralogy similar to that of granulites produced as residue after removal of a granitic melt fraction (Field et al., 1980; Nesbitt, 1980).

An important geochemical feature of the peralkaline rocks is given by the high Fe, Mn, Ti, Zn, Rb, Nb, Y, Zr, Th, F and Cl and low Al, Mg, Ca contents (Table 1). In this respect the Shere peralkaline granites are similar to peralkaline rocks of e.g. Ririwai (Bowden et al., 1976; Kinnaird et al., 1985). Amo and Buji complexes (Bowden et al., 1976; Imeokparia, 1983; 1986). The extreme enrichment in HFS elements (in particular Nb, Th, Y, Zr) suggests their migration in complexes with volatiles (Harris et al., 1986). Abundant fluorite and high fluorine content of amphiboles and biotites (Borley, 1976) in the Shere peralkaline granites suggest fluorine is an important complexing anion.

Extensive melting of dry crust, resulting in breakdown of hornblende and biotite, has been invoked for the petrogenesis of peralkaline granites (Collins et al., 1982; Clemens et al., 1986). However, such a process would result in Ca, and Al-rich melts (Harris et al., 1986), whereas the Shere peralkaline granites are depleted in these elements. This precludes close system anatexis and suggests influx of non-hydrous volatiles carrying HFS elements (Harris et al., 1986). Batchelor et al. (1985) have suggested that the Nigerian peralkaline granitoids can be generated by extensive fluid induced alteration or by a high degree of melting of leucosome-depleted basement gneisses. They argue that leucosome-depleted gneisses enriched in biotite and accessory minerals can provide high levels of rare elements in the peralkaline granites. Experimental work (Clemens et al., 1986) also favours the formation of A-type granites by partial melting at elevated temperature (830° C) of a source depleted in water by extraction of an I-type minimum melt magma. The anhydrous granulitic source is thought to be enriched in F- and Cl-bearing micas and amphiboles (Collins et al., 1982; Christiansen et al., 1983; Whalen et al., 1987). Anderson (1983) has suggested a tonalitic to granodioritic meta-igneous source as a viable alternative to a granulitic source.

The role of fluorine and chlorine in peralkaline magmas has been reviewed by Bailey & Mac Donald (1975), Harris (1981) and Christiansen et al. (1986). F and Cl distort the alumino-silicate framework, providing sites for the highly charged cations and stabilize complexes of highly charged large

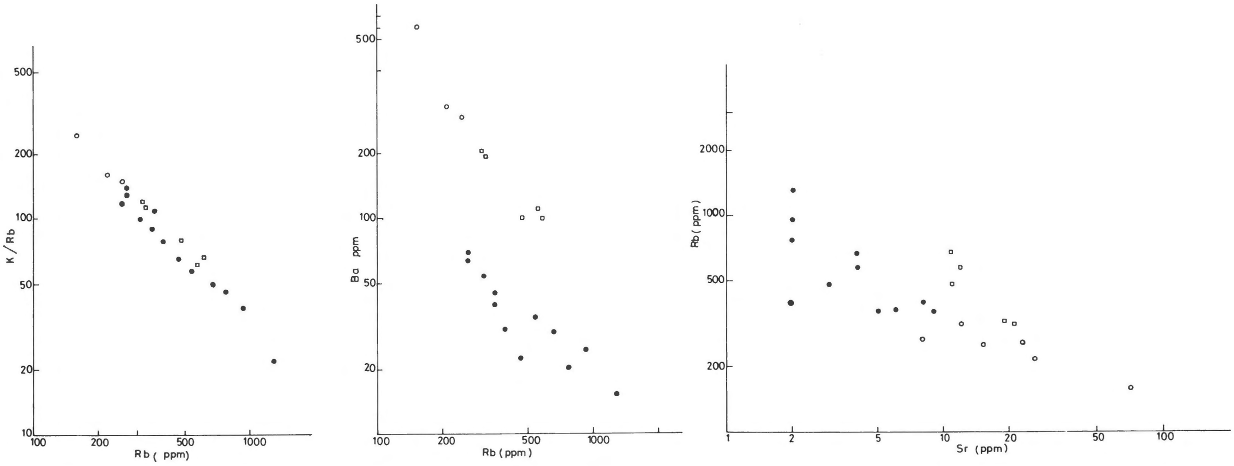

Fig. 6a–c. K/Rb-Rb; Ba-Rb, Rb-Sr relationships in the rocks of Shere Complex, Central Nigeria. Symbols as in Fig. 3a.

metal ions. For example, Na-Cl complexes in Cl-rich magmas may cause enhanced Ca-plagioclase fractionation (White, 1979) leading to production of peralkaline magmas (plagioclase effect of Bowen, 1945). Volatile escape may significantly change the F/Cl ratio and the fractionation path of the magma and these changes may result in the association of peralkaline and non-peralkaline granites within the same complex (Christiansen et al., 1986). Barker et al. (1975) have proposed an alternative reaction melting model in the petrogenesis of the Pikes Peak batholith: mantle derived mafic magma caused partial melting of granulite facies lower crust and contamination and differentiation of magmas produce peralkaline and non-peralkaline granite magmas.

It is difficult to imagine how Cl-rich peralkaline magmas could be derived from granulites without the introduction of Cl and other volatiles from a mantle source. The mobility of chlorine and a high concentration thereof in peralkaline magmas suggests that chlorine is introduced into the source regions of peralkaline magmas by mantle-derived metasomatic solutions prior to melting (Bailey, 1980; Boettcher & O'Neil 1980).

In accordance with the isotopic constraints, it is suggested that the formation of the Shere peralkaline granite magmas also requires a mantle source for the supply of volatiles and heat for the melting of granulitic crustal rocks. Anomalously high levels of HFS elements, chemical inhomogenity and metasomatic replacement textures along contacts of the Shere peralkaline granites provide evidence of metasomatic processes and element transport by a non-magmatic fluid phase. The arfvedsonite-aegirine granite is enriched in Y, Zr, U and Th along its contacts with the HFS element-rich albite-arfvedsonite granite and rock textures indicate hematite pseudomorphs after pyroxene and amphibole. The arfvedsonite biotite granite shows transitions from an outer arfvedsonite-rich to an inner biotite-rich zone, with biotite replaced by arfvedsonite and bleached biotite-hematite fluorite cloths indicating the role of a fluorine-rich volatile phase.

Batchelor et al. (1985) have indicated large negative Eu anomalies and large fluctuations in REE patterns and Zr/Hf ratios which may also be ascribed to preferential removal of divalent anions by the volatile phase. We suggest that part of the arfvedsonite-biotite granite is metasomatic in origin, resulting from the alteration of the amphibole-fayalite granite by fluorine-rich volatile phase derived from the peralkaline granite magmas. The replacement of biotite by arfvedsonite suggest a high oxygen fugacity in the volatile phase. Bowden et al. (1976) have suggested that the formation of astrophyllite in the arfvedsonite-biotite granite reflects a high concentration of volatile components with which HFS and other trace elements may form complexes.

The amphibole-fayalite granite (except in the contact zone) and the biotite granite do not show the trace element evidence for a significant role of halogen-rich volatiles. The biotite granite magma may be related to the amphibole-fayalite granite magma by potassium feldspar, amphibole and fayalite fractionation. This is suggested by the decrease of K/Rb ratio with increases in Rb (Fig. 6), the increase in $^{Rb}/Sr$ and the decrease in $^{Ba}/Rb$ ratios in the biotite granite relative to the amphibole-fayalite granite, and by the more aluminous character of the biotite granite.

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