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The Geshere syenite-peralkaline granite pluton: a key to understanding the anorogenic Nigerian Younger Granites and analogues elsewhere

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Abstract

The Geshere complex, one of the few intrusive centers among the Nigerian Younger Granites that has not yet been characterized, contains an association of syenite and peralkaline granite. The suite shows a classic sequence of rocks related by fractional crystallization of a parental magma, leading to the pseudoternary minimum in the granite system. The syenite is hypersolvus and contains a ferro-richteritic amphibole as the dominant femic mineral, whereas the most evolved granite is subsolvus and contains annite as the dominant femic mineral. Textural evidence points to the crystallization of these minerals from an interstitial femic melt present at the solidus of these rocks, in which magnesium is a trace constituent. Such a late melt appears because of the low thermal stability of these extremely Fe-enriched minerals and the massive removal of alkali feldspar. Calcite inclusions in the primary amphibole and annite, locally defining an emulsion texture, are considered to represent globules of a carbonate melt present at the source.

Key words: syenite; peralkaline granite; anorogenic magmatism; Nigerian Younger Granites; ferro-richterite; annite; calcite globules; Geshere; Nigeria.

Introduction

The Younger Granite province of Nigeria is recognized as a classic example of the anorogenic (A-type) granite-syenite-gabbro association. Of the fifty-two intrusive complexes that make up this province, the Geshere pluton is still virtually unknown, yet it may well hold important clues concerning the petrogenesis of the entire association. The emplacement of the A-type suites in this province, in the Jurassic, was roughly coeval with the opening of the Atlantic Ocean. They were emplaced in a largely Pan-African basement complex also containing gneissic rocks of Archean age (Fitches et al., 1985; Bowden et al., 1987). The 400 Myr hiatus between the Pan-African cycle of orogenic igneous activity and the emplacement of the epizonal complexes known collectively as the Nigerian Younger Granites (NYG) shows clearly that the generation of the relevant magmas had nothing directly to do with an orogeny.

Our objectives in this paper are to provide the first map of the Geshere pluton, and to describe the mineralogy and textures of representative samples. We focus on the mineralogy of amphibole and mica, and on evidence that there possibly was a carbonate melt present in the felsic magma that produced the Geshere suite.

Background information

Memoir number 1 of the Geological Society of London, by R.R.E. Jacobson, W.N. McLeod and R. Black, published in 1958, firmly established the Nigerian Younger Granites as classic examples of anorogenic igneous activity. Since then, the major complexes have been well mapped and dissected, but there remain some plutonic complexes that are poorly known. Among these is the Geshere pluton (Figure 1), also known under the name Kerku in older compilations. The pluton contains dominantly syenite and peralkaline granite. These rock types are well represented in other complexes, but it is fair to say that many questions remain concerning the petrogenesis of the association. The complexes are epizonal manifestations of anorogenic magmatism, and several contain ignimbritic units. Basic rocks are recurrent but minor members of these complexes, and some complexes show evidence of the mingling of felsic and more mafic magmas. Further north along the same belt, in Niger, the complexes are deeper and older (Paleozoic), and differ in containing more gabbro and anorthosite, but ignimbrites are not common there. Much more is known about such deeper manifestations of anorogenic magmatism. The working hypothesis of Emslie (1978) has been amply tested and confirmed in recent investigations of so-called AMCG (anorthosite-mangerite-charnockite-granite) suites: the syenites and granites are formed by crystallization of crustal melts that contain cryptic (i.e., invisible) contamination by a mantle-derived source, and anorthosites and gabbros are formed by crystallization of mantle-derived melts that contain cryptic contamination by crustal material. The Nigerian complexes are the high-level equivalents of AMCG suites. As such, and building on evidence gained from mesozonal and catazonal complexes elsewhere, one can expect that felsic magmas formed at the expense of the Pan-African and Archean basement in Nigeria will be found to contain isotopic evidence of a minor component of mantle-derived material.

The Geshere Complex

This report is based on the mapping and sampling of the complex (Figure 2) by the first author. The pluton is composite, and consists of a northern zoned body with syenite in the rim and arfvedsonite-bearing granite in the core. In the southern body, biotite granite largely predominates over quartz syenite. We have focused on fifteen representative samples in our petrographic descriptions and detailed characterization of bulk composition by X-ray fluorescence (Table 1). Normative compositions are plotted in terms of the system Qtz-Ab-Or in Figure 3. A full description of the mineralogy and geochemistry of those samples is deferred to a later contribution.

The Geshere rocks plotted in Figure 3 define a characteristic trend indicative of fractional crystallization of a syenitic parental magma located close to the join Ab-Or. The trend conforms fully to the path first defined experimentally by Tuttle and Bowen (1958). Once formed, presumably by anatexis of a suitable lithology in the basement, the parental magma starts its ascension and becomes saturated in alkali feldspar, a disordered and homogeneous sanidine solid-solution (e.g., Martin, 1988). Its progressive removal in massive amounts, most likely from a magma in motion in which the feldspar can coat the walls of conduits, and be removed that way

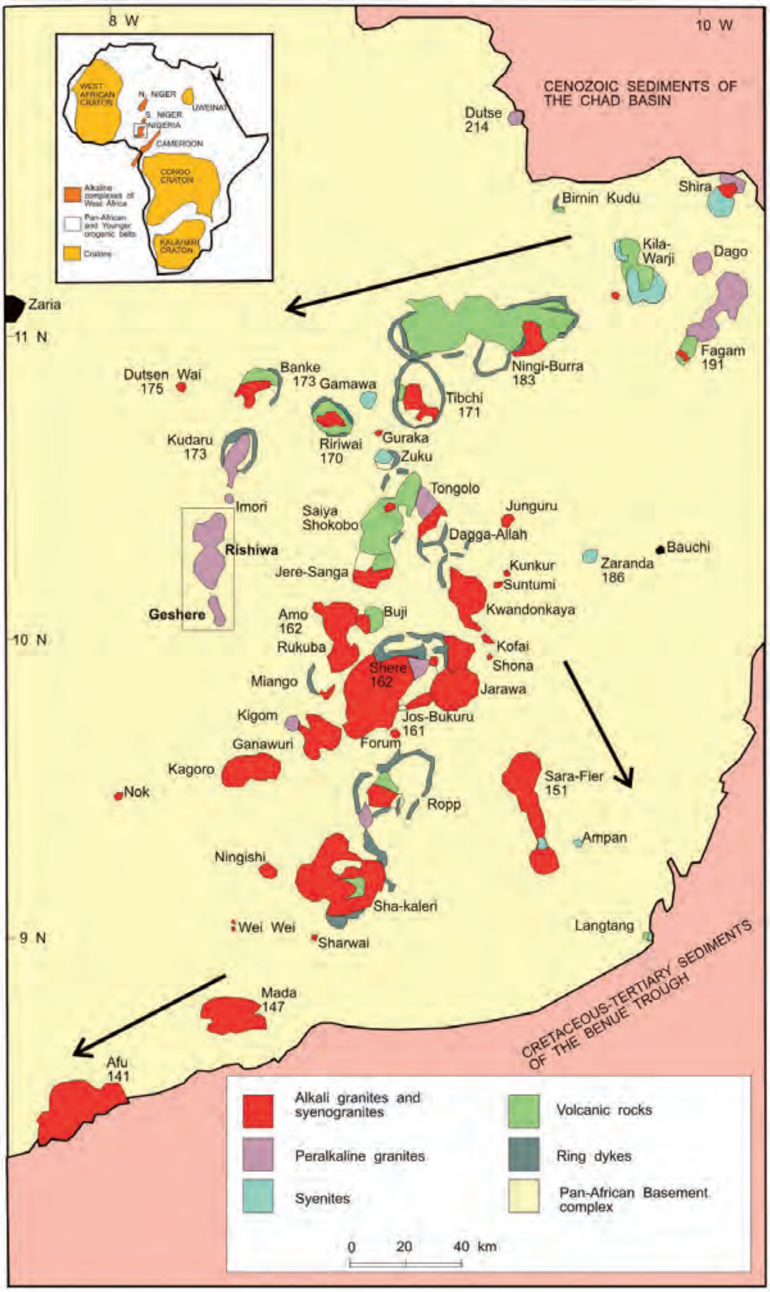


Figure 1. Simplified geological map of the Nigerian Younger Granite (NYG) complexes (after Kinnaird, 1985) showing the location of the Geshere complex; arrows indicate the direction of migration of ages of Mesozoic magmatic centers. Inset is a map of Africa (after Bowden et al., 1987), with location of the NYG province.

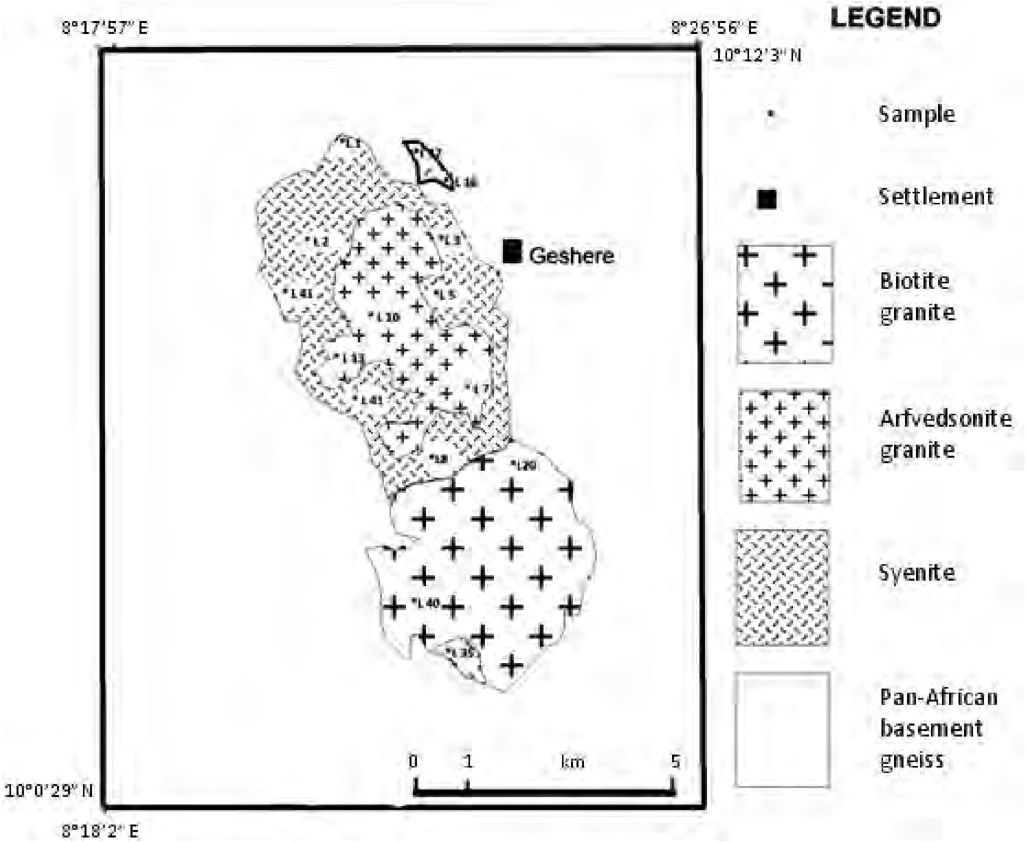


Figure 2. Map of the Geshere complex, showing the location of fifteen representative samples.

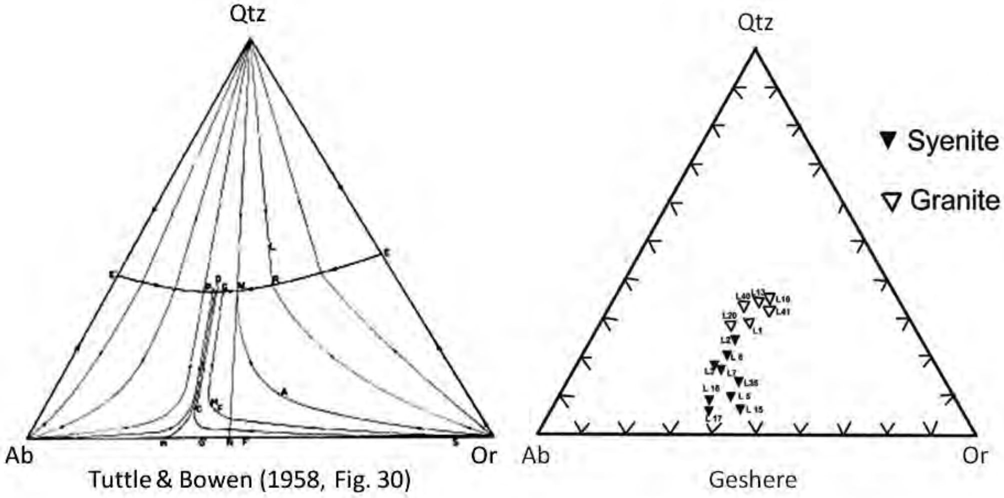
(gravitational settling will be incredibly slow in such a viscous magma), causes a progressive enrichment in the magmatic component Qtz, up to the point where the pseudoternary minimum in the haplogranite system is reached, in the central part of the diagram (Figure 3). The Geshere rocks illustrate well the progressive nature of this fractionation process, as both parts of the complex contain quartz syenite ($5 < Qtz < 20\%$) and quartz-poor granite ($20 < Qtz < 25\%$). Note that the less evolved rocks are of hypersolvus character (Tuttle and Bowen, 1958), i.e., they contained a single magmatic alkali feldspar, which subsequently exsolved. In contrast, the more evolved rocks contain coexisting primary albite and K-feldspar, which indicates a subsolvus texture. The juxtaposition of hypersolvus and subsolvus variants in the same complex can be expected to occur by progressive increase in the activity of H_2O as a direct result of the removal of the anhydrous fractionating phases (sanidine solid-solution and quartz). The rocks crystallized at a shallow level, to judge from the presence of globular quartz forming an intergrowth with the alkali feldspar, i.e., a coarse granophyric texture.

The exact nature of the alkali feldspar (composition, degree of Al-Si order) in the

Table 1. Bulk composition of selected samples of the Geshere complex, Nigeria.

	L16	L17	L5	L15	L8	L2	L35	L41	L1	L7	L20	L3	L13	L10	L40
SiO_2 wt.%	57.85	59.90	65.19	64.71	66.17	66.35	66.83	70.24	69.99	72.83	72.03	68.46	72.30	72.26	72.40
TiO_2	1.32	1.04	0.46	0.47	0.61	0.58	0.34	0.23	0.29	0.20	0.24	0.30	0.26	0.27	0.28
Al_2O_3	15.47	15.50	15.03	15.15	14.44	14.42	14.70	14.19	14.41	13.65	11.43	15.42	14.04	14.02	13.96
Fe_2O_3	2.16	3.24	1.42	1.49	2.02	1.75	1.88	0.96	0.71	0.70	1.24	2.87	0.13	0.38	0.27
FeO	6.22	4.81	4.50	4.48	3.83	3.90	2.82	2.31	2.59	1.63	4.25	0.30	1.95	1.75	1.91
MnO	0.17	0.17	0.19	0.17	0.20	0.24	0.12	0.07	0.07	0.04	0.17	0.03	0.03	0.03	0.03
MgO	1.26	0.76	0.01	0.06	0.02	0.02	0.09	0.02	0.11	0.02	0.02	0.06	0.29	0.30	0.30
CaO	3.67	2.66	1.34	1.78	0.73	0.62	1.32	0.54	1.13	0.27	0.56	0.16	1.18	1.08	1.00
Na_2O	5.72	5.37	5.99	5.45	5.30	5.30	4.95	5.46	4.60	4.92	4.36	3.20	3.32	3.23	3.05
K_2O	4.13	4.81	5.37	5.56	5.31	5.29	5.37	5.41	5.35	5.26	4.41	5.94	5.46	5.60	5.88
P_2O_5	0.59	0.28	0.04	0.08	0.04	0.04	0.06	0.02	0.04	0.01	0.03	0.03	0.07	0.09	0.09
LOI	0.41	0.68	0.12	0.18	0.61	0.66	1.01	0.31	0.26	0.32	0.29	2.87	0.89	0.82	0.83
Total	99.90	99.95	100.21	100.21	99.83	99.71	99.89	100.08	99.95	100.07	99.57	99.74	100.20	100.09	100.28
D.I.	72.8	77.5	84.9	85.8	88.2	88.3	87.7	91.0	89.6	94.9	86.8	89.0	88.3	88.8	89.1
Qtz	0	3.6	5.7	6.8	12.1	12.3	14.1	16.2	19.1	22.9	26.5	26.8	27.9	28.4	28.5

The analyses were done with X-ray-fluorescence spectroscopy at McGill University on fused beads prepared from ignited samples. The amount of normative quartz can be used to give these rocks a label: 0 < Qtz < 5%: syenite, 5 < Qtz < 20%: quartz syenite, 20 < Qtz < 28%: granite. The samples are ordered from left to right according to the amount of quartz in the norm.



Tuttle & Bowen (1958, Fig. 30)

Geshere

Figure 3. Plot of whole-rock compositions in terms of normative quartz-albite-orthoclase. The most primitive rocks plot on the Ab-Or join, at the minimum on that binary join. The magma compositions migrate toward the pseudoternary minimum in a central position of the triangle, much as predicted according to the experimentally established phase-relations in the quaternary system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O at one kbar, projected onto the anhydrous base (Tuttle and Bowen, 1958, Fig. 30).

Geshere rocks has not yet been established. Petrographically, there are increasing signs of grid-twinned microcline as the granite minimum is approached, but no such signs in the syenite. On the basis of findings in other complexes among the Nigerian Younger Granites, the degree of Al–Si order in the K-feldspar is likely stuck metastably in the transition orthoclase to microcline. Sakoma and Martin (in press) have found a mixture of orthoclase + intermediate (i.e., incompletely ordered) microcline in the Kwandonkaya metaluminous NYG system (Figure 1), and expressed the view that this disequilibrium situation probably is quite representative of NYG complexes. Note that the ordering reaction in K-feldspar occurs below 500°C, involves H_2O, and takes a very long time to reach completion. Unlike Kwandonkaya, Geshere shows mildly peralkaline tendencies (see below), such that the enhanced alkalinity of the aqueous fluid likely explains the success of the ordering reaction in the most evolved rocks, which do locally contain well-ordered microcline and a subsolvus mineralogy (Martin, 1988).

The Mafic Minerals of the Geshere Rocks

The mafic minerals crystallizing from the syenitic and granitic magmas at Geshere did not exert any role in controlling the path of fractionation. Petrographic evidence clearly shows that the majority of the mafic fraction formed at or near the solidus, as crystallization was just about complete. As reviewed above, a sanidine solid-solution was the main fractionating phase, and quartz appeared only upon reaching the pseudoternary minimum. Both minerals reject iron, not quantitatively in the case of the alkali feldspar, but the statement stands as a first approximation. Ferro-richterite is the dominant mafic mineral in the syenitic rocks; with increasing fractionation, annite becomes dominant. Sparse grains of iron-rich clinopyroxenes are enclosed in the amphibole, and fayalite is suspected to have been present, but is now converted to a low-temperature pseudomorphic assemblage.

Ferro-richerite, ideally $Na(CaNa)Fe^{2+}{}_5Si_8O_{22}(OH)_2$

In the syenitic rocks, a ferro-richteritic amphibole is the dominant mafic mineral. It accounts for only up to 15-20 vol.% of the rocks, but textural information clearly shows that it is the last mineral to crystallize from the melt. The amphibole crystals are invariably anhedral, completely molded around the feldspar grains that preceded it as the melt crystallized. In turn, the amphibole contains poikilitically the bulk of the accessory minerals, which thus preceded or crystallized simultaneously with the amphibole: perrierite-(Ce) or chevkinite-(Ce), ilmenite, magnetite, monazite, apatite with vestiges of britholite, zircon, sphalerite, bastnäsite and calcite. Figure 4 shows syenite sample L2, in which the alkali feldspar, now coarsely perthitic, contains crystals of zircon, anhedral calcite, and parts of tablets of ilmenite, but the bulk of the accessory phases are at least partly enclosed in the ferro-richteritic amphibole. The implication of this type of textural development in the syenitic magma is that ferro-richerite crystallized at the solidus or very close to it, and from a melt that had become femic and strongly depleted in Al, in fact rather close to the bulk composition of the amphibole.

The reason for this curious behavior is that the primary ferro-richterite is extremely iron-rich and contains virtually no Mg (Table 2), with mg# [100 Mg/(Mg + Fe_{tot} + Mn] commonly in the range 0.1 to 1.4. It is well known that in all mineral series, the Fe end-member invariably has a greatly reduced field of thermal stability compared to the Mg analogue (e.g., fayalite versus forsterite, annite versus phlogopite). At Geshere, the degree of iron enrichment clearly is unusually high. In exploratory experiments on the amphibole-bearing Quincy (Massachusetts)

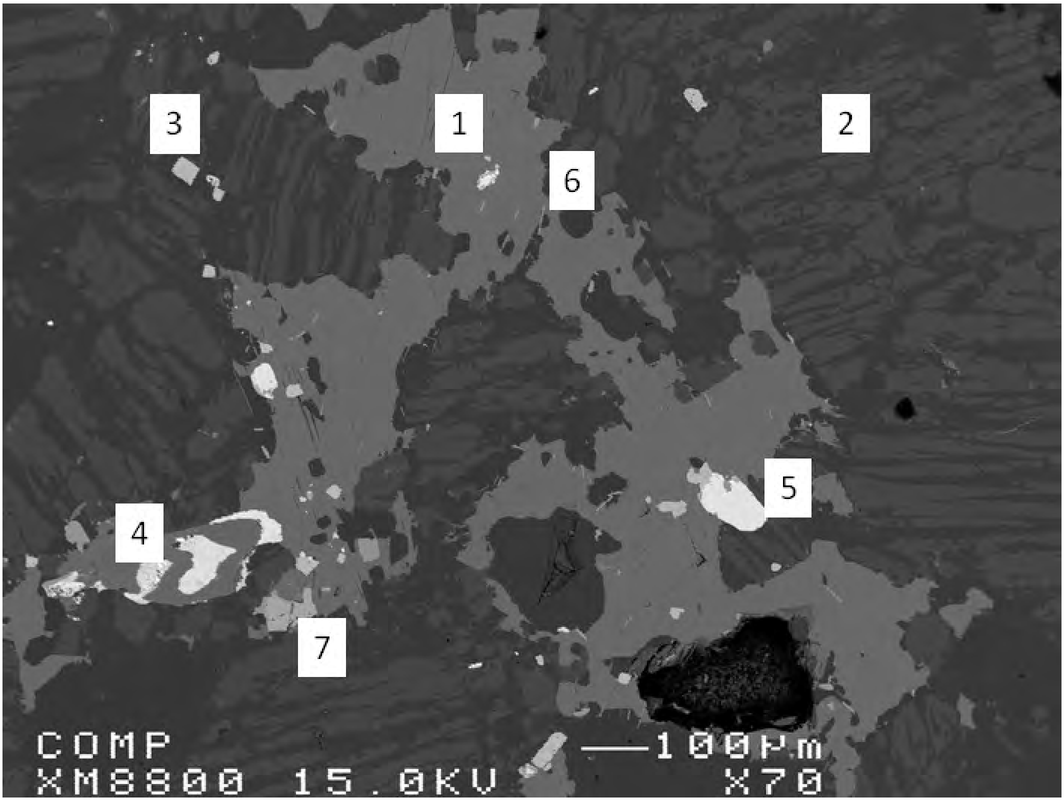


Figure 4. Extremely anhedral domain of homogeneous ferro-richterite, interstitially developed in quartz syenite L2. The amphibole hosts a large proportion of the accessory minerals in this rock. Numbered locations: 1 homogeneous ferro-richterite, 2 coarsened exsolution-induced texture in alkali feldspar (the rock is hypersolvus), 3 zircon (trapped in alkali feldspar, and thus early), 4 apatite with inclusion and rim of monazite, 5 perrierite (or chevkinite), astride the perthite-amphibole contact, 6 tiny needles (tablets) of ilmenite, partly astride the perthite-amphibole contact, 7 magnetite with ilmenite rim. The black patch above the scale is a hole.

A-type granite, Tuttle and Bowen (1958, p. 92) showed that the ferro-richteritic amphibole breaks down at 625 °C and is unstable at magmatic temperatures at 1 kbar. The amphibole thus crystallized at the solidus at “well above 650 °C”; Tuttle and Bowen (1958, Tables 11, 12) established the solidus of the Quincy granite at 720 °C at 1 kbar and 695 °C at 2 kbar [P(H_2O = P(total)]. The composition of the Quincy granite is very similar to bulk composition L40 at Geshere (Table 1).

It might be expected that the ferro-richteritic amphibole in the most primitive syenitic rock and in the most evolved granitic rock would differ significantly in the proportion of Fe, Mn and Ca. To a first approximation, however, the primary amphibole does not seem to vary much in composition. The primary amphibole in granite L7 is virtually indistinguishable from that in Geshere syenite L5 (Table 2). However, in the transition from syenite to granite, one sees a progressive decrease in the proportion of ferro-

Table 2. The composition of amphibole-group minerals in the Geshere pluton.

	L16	L5	L5	L2	L2	L2	L7	L7	L15
		low Na	high Na	low Mg	⇒	high Mg	low Na	high Na	
n	6	5	2	5	3	4	9	3	5
SiO_2 wt.%	46.23	47.46	48.05	46.23	46.50	44.27	48.89	49.80	47.70
TiO_2	1.74	1.21	0.55	1.38	0.59	1.22	1.64	0.56	1.48
Al_2O3	2.32	1.30	0.75	2.31	2.53	5.65	1.91	0.93	1.78
FeO	34.68	35.10	36.19	35.37	32.94	25.09	34.93	35.69	34.15
MnO	1.03	0.88	0.72	0.76	0.85	0.68	1.02	0.92	0.91
MgO	0.16	0.03	0.03	0.19	2.35	6.86	0.19	0.16	0.04
CaO	6.07	4.87	1.35	6.15	6.54	9.46	6.03	1.79	3.70
Na_2O	4.42	4.63	6.47	3.89	3.94	4.11	4.24	6.55	6.16
K_2O	1.20	1.05	0.46	1.07	1.10	0.31	1.15	0.76	1.48
F	0.49	0.35	0.13	0.35	0.79	1.55	0.45	0.20	0.57
Cl	b.d.l.	b.d.l.	b.d.l.	0.10	0.08	0.14	0.07	0.02	0.03
O=F, Cl	0.21	0.15	0.05	0.17	0.35	0.68	0.21	0.09	0.25
Total	100.12	98.96	97.72	99.89	100.12	100.21	102.28	100.07	99.60
Si *apfu*	7.476	7.708	7.782	7.466	7.399	6.881	7.682	7.878	7.722
^{IV}Al	0.442	0.249	0.143	0.440	0.474	1.035	0.318	0.122	0.278
^{VI}Al	0.000	0.000	0.000	0.000	0.000	0.000	0.036	0.051	0.062
Ti	0.212	0.148	0.067	0.168	0.071	0.143	0.194	0.067	0.180
Fe^{3+}	0.445	0.670	1.563	0.726	0.917	0.465	0.342	1.169	0.333
Fe^{2+}	4.245	4.098	3.338	4.051	3.467	2.796	4.248	3.552	4.291
Mn	0.141	0.121	0.099	0.104	0.115	0.090	0.136	0.123	0.125
Mg	0.039	0.007	0.007	0.046	0.557	1.590	0.045	0.038	0.010
Ca	1.052	0.847	0.234	1.064	1.115	1.576	1.015	0.303	0.642
Na	1.386	1.458	2.032	1.218	1.216	1.239	1.292	2.009	1.934
K	0.248	0.218	0.095	0.220	0.223	0.061	0.231	0.153	0.306
F	0.251	0.180	0.067	0.179	0.398	0.762	0.224	0.100	0.292
Cl	0.000	0.000	0.000	0.027	0.022	0.037	0.019	0.005	0.008
OH calc.	1.749	1.820	1.933	1.794	1.581	1.201	1.758	1.895	1.700
Diff. index (rock)	72.8	84.9		88.3			94.9	85.8	
mg# (amphibole)	1.4	0.1	0.1	0.5	6.5	21.0	0.5	0.4	0.1

The data were acquired with a JEOL-8900L electron microprobe at McGill University, operated at 15 kV, 20 nA, with a 5 µm beam. The raw data were corrected using the ZAF procedure. The counting time was 20 seconds for all elements except F, which was counted for 50 seconds. We employed the following standards: albite (Na), fluorite (F), vanadinite (Cl), orthoclase (K, Al), hematite (Fe), diopside (Si, Mg, Ca), TiO2 (Ti), spessartine (Mn), and chromite (Cr). The Differentiation Index is defined as the sum of normative Qtz + Ab + Or (Thornton and Tuttle, 1960). The mg# index is defined as 100 Mg/(Mg + Fe_{tot} + Mn). n: number of analytical datasets that are being averaged. The data were recalculated on the basis of 23 atoms of oxygen and OH + F + Cl = 2 apfu. The recalculations were carried out with Andy Tindle's set of programs (freeware).

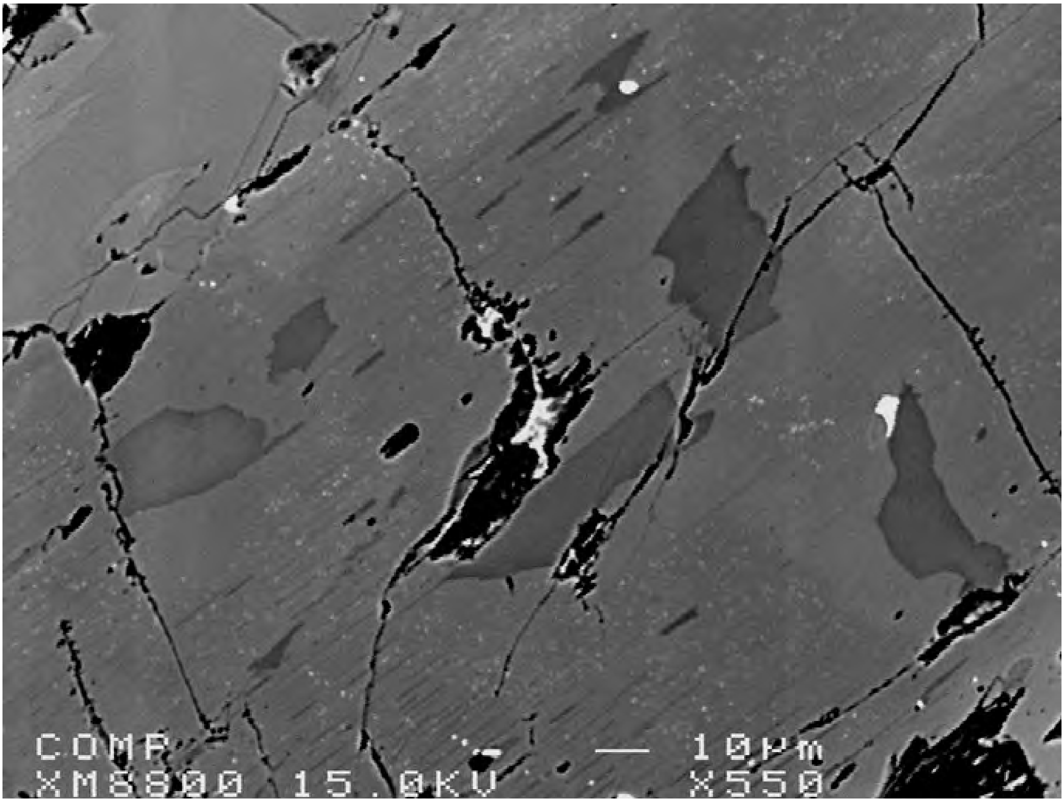


Figure 5. Wisps and shreds of a more magnesian ferro-richterite in the primary (extremely Mg-poor) ferro-richterite in quartz syenite L2. The anhedral fragments of the relict amphibole are considered to represent unmelted debris brought in from the source area. The new amphibole nucleated on these xenocrystic shreds, and the array of submicroscopic accessory phases appeared in ferro-richterite after an interval of crystallization of "clean" ferro-richterite.

richterite grains, and a progressive increase in the proportion of annite. There is evidence that a small amount of Fe^{3+} might occupy the *T* site to compensate for the paucity of Al in the growth medium.

The interest of ferro-richterite at Geshere is not limited to its lateness in crystallizing, but to the clear evidence of a relict more magnesian amphibole embedded in it. The ferro-richterite found in quartz syenite L2 contains anhedral islands and wisps of a more magnesian and F-rich variant of Ca-Na amphibole (mg# = 21.0) (Figure 5). This high-magnification image also shows the presence of myriads of submicroscopic specks that indicate the presence of tiny bright grains, most likely of the accessory minerals that have already been named. Interestingly, they seem to be absent in the vicinity of the shreds of the more magnesian amphibole, which suggests that they appeared after the ferro-richterite had begun to coat the relict shreddy amphibole. The anhedral and angular nature of these shreds suggests that they were perhaps members of a relatively refractory residue carried up with the syenitic magma as it left the source region.

The ferro-richterite must have crystallized quickly as the syenitic magma reached the upper crust. Its bulk composition contains both Fe^{2+} and Fe^{3+}, although no efforts is made in Table 2 to calculate a ratio of the two owing to the unknown amount of OH. The amphibole may well have undergone early adjustments in its Fe^{2+}: Fe^{3+} ratio, but if there were postmagmatic adjustments, this does not show in its appearance; the ferro-richterite seems completely pristine and unmodified. Another early mineral to appear, completely embedded in the amphibole, is considered to have been fayalite. Because it was unable to develop a defect structure that does contain Fe^{3+} (laihunite), in order to keep up with the inferred oxidation upon emplacement, it was completely destroyed, and transformed to an unanalyzable pseudomorphic mixture of hydrated products.

Sample L5 (Figure 6) is a quartz-poor granite in which the grain of ferro-richterite (mg# = 0.1) is partially rimmed by an arfvedsonitic amphibole (mg# = 0.1: Table 2). Keeping in mind the breakdown of the Quincy sodic amphibole documented by Tuttle and Bowen (1958), we attribute the development of the arfvedsonitic rim to subsolidus circulation of an alkaline aqueous fluid in open spaces. Such open spaces are expected to develop owing to 1) thermal contraction of the primary amphibole and other minerals, and 2) ordering and exsolution reactions, which both are associated with a negative ΔV of reaction.

Annite, ideally $KFe^{2+}AlSi_3O_{10}(OH)_2$

Like the amphibole, the mica is extremely iron-rich, with the amount of Mg generally inferior to the amount of Mn (Table 3). The annite crystallizing sparsely in a syenitic magma seems more or less of the same composition as the annite crystallizing in greater quantities from the granitic magma. Thus to a first approximation, the interstitial mafic melt crystallized variable proportions of the same dominant minerals, ferro-richterite and annite, the proportion of the potassic phase increasing as the magma makes its way to the granite minimum (Figure 3). Recalculated compositions (Table 3) reveal that some Fe^{3+} must occupy the *T* site, i.e., there is a tetraferriannite component that results from the deficiency of Al in the growth medium.

Whereas the ferro-richterite and the annite both contain anhedral patches of calcite, the annite in quartz syenite sample L35 shows a striking development of an emulsion texture of calcite spheres trapped in the annite as it grew (Figure 7). Although the cleavages in annite have opened up slightly during the subsolidus stage, with resulting oxidation to iron oxy-hydroxide and the local development of chamosite, the original emulsion texture is not affected. The presence of calcite spheres in annite is not due to postmagmatic circulation of an aqueous phase, and there is no sign of a replacement texture. We consider the texture primary, and a sign that the magma arrived in the upper crust with evidence of blobs of an immiscible carbonate melt, which became trapped in the last fraction to crystallize.

Clinopyroxene

We have come across scattered grains of clinopyroxene in or on the amphibole crystals. They are volumetrically minor, and the compositional data acquired (Table 4) indicate that not all crystallized from the femic melt. Syenite sample L16 contains sodian hedenbergite. The fact that its mg# is very low (0.4), suggests that like its amphibole host, it crystallized from the late femic melt. The same low-Mg sodian hedenbergite is present as anhedral grains in the amphibole in quartz syenite L2, but other grains included in the primary amphibole, also anhedral, are distincly more magnesian (mg# = 17.7). Like the shreds of more magnesian amphibole in the same sample of quartz syenite, these more magnesian grains of clinopyroxene may represent xenocrystic domains rafted in as

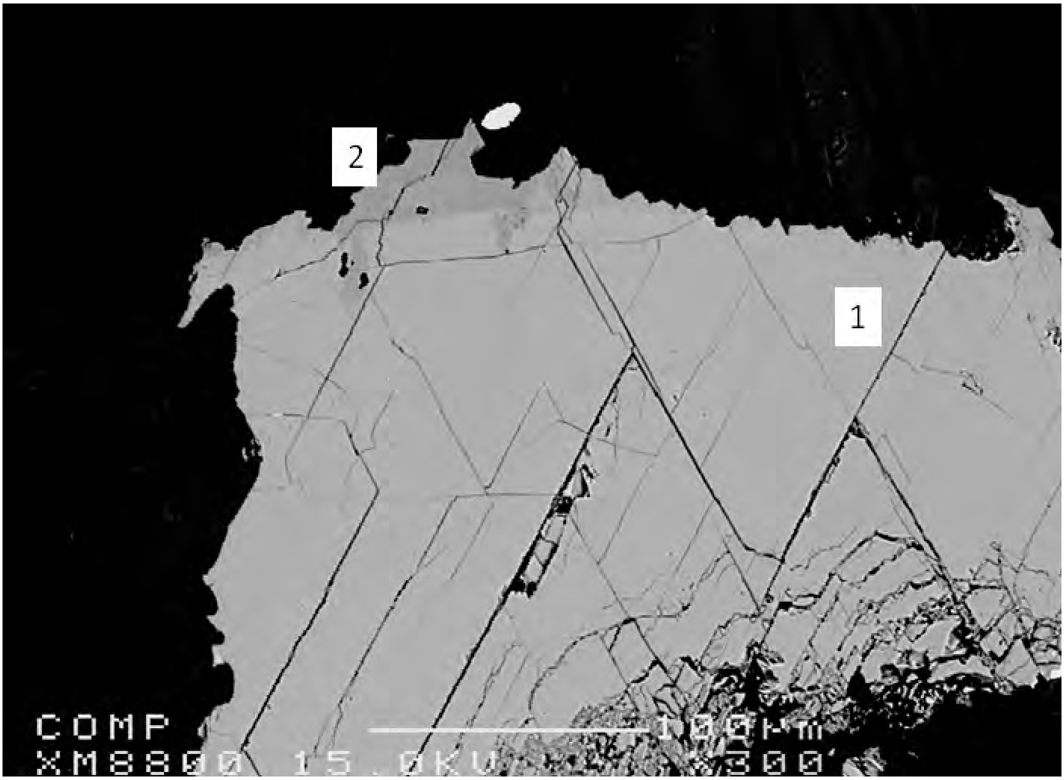


Figure 6. Homogeneous ferro-richterite in quartz syenite L5. Numbered locations: 1 ferro-richterite, 2 arfvedsonitic amphibole developed as an overgrowth at the perthite-amphibole contact where open space became available at a subsolidus stage.

solid debris from the source area, and still present at the ultimate stage of crystallization. Finally, quartz syenite sample L8 contains an overgrowth of aegirine-augite on ferro-richterite laden with calcite domains, and granite sample L15 contains an anhedral intercalation of aegirine associated with quartz in ferro-richterite, also laden with anhedral blobs of calcite.

Discussion

The big picture in Nigeria

Syenitic magmas are an important component of felsic anorogenic suites throughout the world. In uncomplicated situations like in Nigeria, where the cycle of Jurassic anorogenic activity postdates the previous orogeny by over 400 million years, the origin of the igneous activity is an important question to be resolved. Although we do not possess geochronological data of the type presented by Andersen et al. (2009), who was able to identify distinct source-rocks of A-type granites in southwestern Fennoscandia by recording Lu-Hf systematics of inherited domains in zircon crystals, we do agree with the general consensus that the Jurassic plutons arose by partial melting of the Pan-African crust, and possibly of the Archean component of the basement in some areas. But this basement is

Table 3. The composition of annite in the Geshere pluton.

	L16	L5	L35	L2	L10	L7
n	1	2	12	4	7	2
SiO_2 wt.%	35.90	34.73	35.61	35.38	36.08	37.63
TiO_2	3.19	0.02*	3.05	3.56	2.65	3.42
Al_2O_3	7.69	6.24	9.41	8.98	8.40	8.22
FeO	37.75	42.53	37.64	36.26	37.41	35.40
MnO	0.82	0.88	0.27	0.39	0.46	0.39
MgO	0.26	0.04	0.23	2.27	0.20	0.25
CaO	0.22	0.06	0.03	0.03	0.08	0.34
Na_2O	0.06	0.04	0.10	0.18	0.09	0.30
K_2O	8.70	8.36	8.82	8.88	8.52	8.07
F	0.02	0.07	0.65	0.85	0.40	0.10
Cl	0.22	0.44	0.15	0.25	0.26	0.25
H_2O calc.	3.44	3.19	3.20	3.13	3.25	3.46
O = F, Cl	0.06	0.13	0.31	0.41	0.23	0.10
Total	98.21	96.47	98.86	99.74	97.57	97.73
Si *apfu*	6.137	6.246	6.015	5.901	6.173	6.317
^{IV}Al	1.550	1.323	1.873	1.765	1.694	1.627
^{IV}Fe	0.313	0.431	0.112	0.334	0.133	0.058
Ti	0.410	0.003	0.387	0.447	0.341	0.432
Fe	5.084	5.968	5.209	4.724	5.220	4.912
Mn	0.119	0.134	0.039	0.055	0.067	0.055
Mg	0.066	0.011	0.058	0.564	0.051	0.063
Ca	0.040	0.012	0.005	0.005	0.015	0.061
Na	0.020	0.014	0.033	0.058	0.030	0.098
K	1.897	1.918	1.900	1.889	1.859	1.728
OH	3.925	3.826	3.610	3.481	3.708	3.876
F	0.011	0.040	0.347	0.448	0.216	0.053
Cl	0.064	0.134	0.043	0.071	0.075	0.071
Diff. index (rock)	72.8	84.9	87.7	88.3	88.8	94.9
mg# (annite)	0.7	0.1	0.6	5.8	0.5	0.7

The Differentiation Index is defined as the sum of normative Qtz + Ab + Or (Thornton and Tuttle, 1960). The mg# index is defined as 100 Mg/(Mg + Fe_{tot} + Mn). n: number of analytical datasets that are being averaged. See Table 2 for the details of the method of analysis. * The annite in sample L5 is anomalous, and may well be a secondary mica. The compositions were recalculated on the basis of twenty atoms of oxygen and OH + F + Cl = 4.000 apfu.

generally quartzofeldspathic, not syenitic. A syenitic partial melt is not an easy target melt to explain.

One model that has been proposed recently to explain the inception of a cycle of anorogenic magmatism leading to AMCG suites in Proterozoic terranes involves delamination and foundering of an overthickened lower crust into the upper mantle (McLelland et al., 2010). There results the diapiric rise of hot, fertile asthenospheric mantle, which in short order is juxtaposed against the cratonic crust. It is this scenario that, in Emslie's (1978) opinion, led to the juxtaposition of two kinds of melts, one a mafic magma generated from the asthenosphere in decompression mode, and one of syenitic to granitic character generated with the heat added from below to a deep crustal source. A proposal of progressive delamination of the lower crust in Nigeria accompanying regional attenuation is attractive, and could explain the generally southward progression of igneous centers (Figure 1). This model would seem to be more plausible than a hotspot model, evaluated by

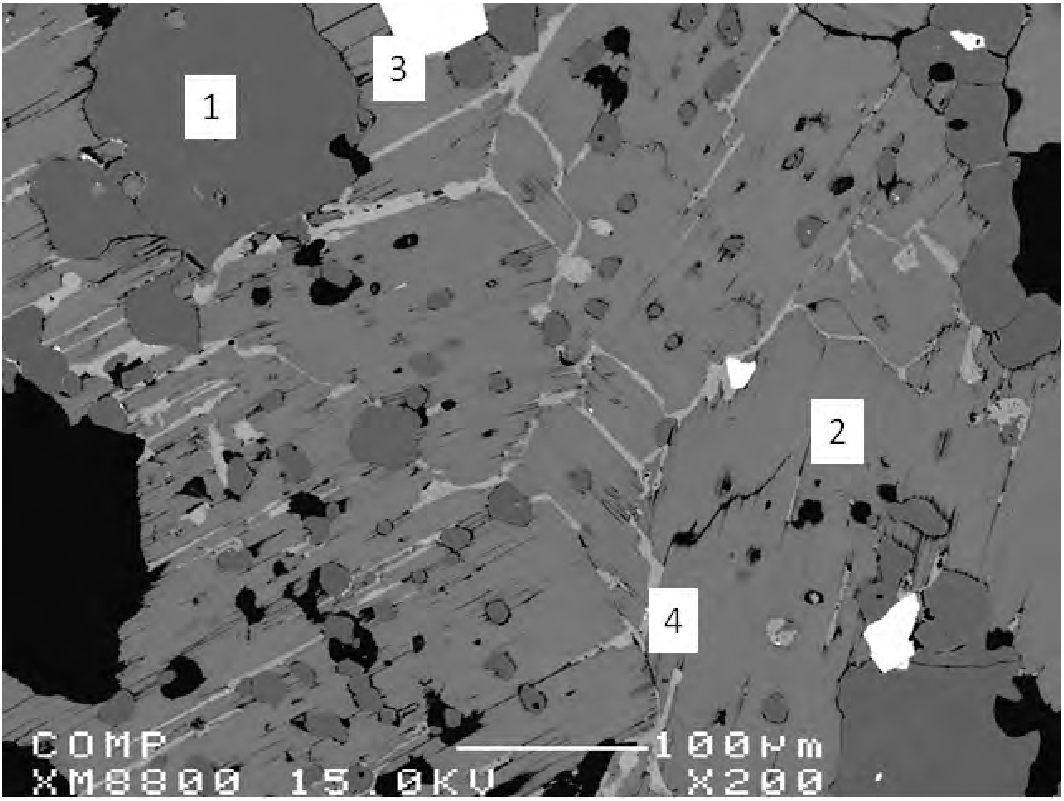


Figure 7. Emulsion texture developed in annite in quartz syenite L35. Numbered locations: 1 calcite, 2 annite host, 3 zircon, 4 iron oxy-hydroxide decoration (secondary) along the opened cleavage in annite. The texture is interpreted to indicate an emulsion of two melts, one the interstitial femic silicate melt developed near the solidus of L35, from which the annite crystallized, and a carbonate melt, presumably carried up as immiscible globules from the source area.

Table 4. The composition of clinopyroxene in the Geshere pluton.

	L16	L2	L2	L8	L15
		low Mg	high Mg		
n	5	1	2	4	2
SiO_2 wt.%	49.26	48.68	49.63	51.42	52.33
TiO_2	0.15	0.18	0.33	0.43	0.49
Al_2O_3	0.32	0.18	0.58	0.34	0.59
FeO	28.89	29.47	21.90	29.68	29.68
MnO	1.02	0.90	0.90	0.43	0.11
MgO	0.11	0.13	4.91	0.03	0.02
CaO	15.62	16.63	20.80	6.31	0.13
Na_2O	3.94	3.11	1.16	10.17	13.94
K_2O	0.04	0.02	0.04	0.02	0.03
Total	99.35	99.30	100.25	98.85	98.85
Si *apfu*	1.920	1.977	1.955	1.980	1.983
Ti	0.005	0.005	0.010	0.012	0.014
Al	0.016	0.009	0.027	0.015	0.026
Fe^{3+}	0.454	0.273	0.134	0.760	0.941
Fe^{2+}	0.549	0.728	0.587	0.196	0.000
Mn	0.036	0.031	0.030	0.014	0.004
Mg	0.007	0.008	0.288	0.002	0.001
Ca	0.695	0.724	0.878	0.260	0.005
Na	0.317	0.245	0.089	0.759	1.024
K	0.002	0.001	0.002	0.001	0.001
Diff. index (rock)	72.8		88.3	88.2	85.8
mg# (clinopyroxene)	0.4	0.4	17.7	0.1	0.1

The Differentiation Index is defined as the sum of normative Qtz + Ab + Or (Thornton and Tuttle, 1960). The mg# index is defined as 100 Mg/(Mg + Fe_{tot} + Mn). n: number of analytical datasets that are being averaged. See Table 2 for the details of the method of analysis. The recalculation of the chemical data is based on six atoms of oxygen and four cations per formula unit. The ferrous-iron-dominant pyroxenes in this suite seem to contain $^{IV}Fe^{3+}$ in view of the shortage of Al in the femic melt. Pyroxenes L8 and L15 contain major proportions of Fe^{3+}, i.e., the aegirine component.

Rahaman et al. (1984), among others.

Martin (2006) has proposed that it was not only heat that was added from the rising asthenospheric mantle source, but also hot H_2O-CO_2 mixed fluids capable of fertilizing the granulitic lower crust locally, preparing it for an episode of anorogenic crustal melting. The crust needs to be locally desilicated or, more likely, alkali-metasomatized (i.e., fenitized) in order to create a crust that will melt to give a syenitic bulk-composition. As Bonin (2008) correctly stated, no one has ever seen a migmatite in which the leucosome has the composition of a typical A-type granite or syenite. That is one reason for Martin's (2006) suggestion, not for partial melting, but rather close-to-complete melting of a suitably metasomatized precursor.

As the incoming fluid brings in CO_2 from the mantle one can expect efficient local carbonation of the reacting assemblage, and creation of charnockitic assemblages (Newton, 1992). Such carbonation reactions can account for the appearance of meionitic scapolite at the expense of plagioclase in deep-seated granulites. One can expect also that calcite will be a byproduct of these carbonation reactions of granulite-facies rocks. There is evidence that such a metasomatic overprint also occurred at the end of the Pan-African collisional event in Nigeria, leading to late granitic and syenitic rocks of A-type character having an age close to 580 Ma and a crustal signature (Ferré et al., 1998; cf. Oyawoye, 1965). The possibility of metasomatizing a basement rock that had already been metasomatized 400 Myr earlier offers an interesting potential explanation for the generation of strongly peralkaline suites present in some of the Nigerian Younger Granite complexes.

The situation at Geshere

The origin of A-type felsic parental melts is the topic of ongoing debate, and the Nigerian suites clearly have much to offer in terms of quality of exposure and accessiblity. More importantly, they offer a simple tectonic setting at the time of emplacement, and are devoid of near-coeval emplacement of orogenic magmas. Careful sampling of the Geshere plutonic suite has clearly shown a suite of interrelated syenites and peralkaline granites. The massive crystallization of sanidine solid-solution led to the progressive shift in the bulk composition of the parental magma toward the low-pressure granite minimum, as well established experimentally in the classic investigations of Tuttle and Bowen (1958). The pluton crystallized as a relatively shallow depth, possibly 3 or 4 km.

As magnesium is virtually a trace element in the parental melt, the ferromagnesian minerals that can crystallize from such a parental magma are extremely enriched in iron. For this reason, they appear very late in the crystallization sequence, and seem to have crystallized in situ from a femic or ultrafemic melt trapped in interstices among feldspar grains, and produced at each step of the way as the felsic magma made its way from the syenite "saddle" in the system Qtz-Ab-Or toward the granite minimum. (Note that the word *mafic* is etymologically incorrect, as there is virtually no magnesium in the melt). Both the ferro-richterite and the annite crystallized from the femic rest-liquid, as did some of the clinopyroxene and, we infer, fayalite. Importantly, the rest-liquid also produced the bulk of the accessory minerals that are now poikilitically enclosed in the ferro-richteritic amphibole and the annite.

We have discovered clear evidence of an emulsion of two liquids at some stage in the development of the Geshere pluton. We show that the femic rest-liquid contained vestiges of a carbonate melt. It is likely that at the time of final emplacement in the upper crust, the calcite blobs and spheres were solid, but their shape is strongly suggestive of an earlier stage deeper in the crust at which they were molten. We consider it unlikely that the calcite nucleated and grew in situ in a carbonate-bearing felsic melt, because it would then be expected to grow as rhombohedral crystals of calcite, not blobs and spheres (cf. Swanson, 1979).

There are postmagmatic phenomena affecting the amphiboles on a small scale, as documented earlier at the Tibchi ring-complex (Ike et al., 1984; 1985), northeast of Geshere (Figure 1). These have caused the destabilization of fayalite, and the local alteration of biotite, but the ferro-richterite and its hedenbergite inclusions seem to have survived the deuteric changes rather well.

Extensions to other localities of anorogenic magmatism

The incidence of calcite in felsic igneous rocks is usually ascribed to low-temperature alteration. Occurrences of an emulsion texture certainly seem very rare in such rocks, to judge from the literature available. There exist clear indications, however, that carbonate is a component of the felsic melts of AMCG suites. Consider for example the work of Frost and Touret (1989), who documented CO_2-dominant fluid inclusions in trapped in quartz on the Sybille monzosyenite, part of the Laramie anorthosite complex. Although no calcite was noted in the rock, we believe that it must be present if the orthomagmatic fluid phase is carbonate-dominant. Konnerup-Madsen (1977) documented CO_2-rich fluid inclusions in the relatively melanocratic and charnockitic facies of the Kleivan anorogenic granite, in the Farsund area of southwestern Norway, and H_2O-dominant fluid inclusions in the biotite-bearing facies. It would seem likely that signs of primary calcite should exist in the charnockitic and mangeritic (i.e., syenitic) members of that AMCG suite.

Conclusions

1) The Geshere plutonic suite consists of an anorogenic syenite and peralkaline granite that define a fractionation sequence.

2) Massive crystallization of alkali feldspar caused the magma to reach the granite pseudoternary minimum in the system Qtz-Ab-Or.

3) Because Mg is a trace element in this suite, the latest fraction of magma became femic, and it is from this disseminated, interstitial melt that a ferro-richteritic amphibole and annite cocrystallized, along with a large number of minute grains of accessory minerals.

4) There is evidence of incorporation of Fe^{3+} at the T site of the iron-rich minerals owing to the paucity of Al in the femic melt, a result of the earlier massive fractionation of the alkali feldspar.

5) Both dominant “ferromagnesian” phases contain anhedral inclusions of calcite, and annite in one case contains an emulsion-like cluster of calcite globules, likely inherited from globules of carbonate melt formed at the source, carried up in the parental felsic magma, and ultimately incorporated in the femic minerals that formed from the rest-liquid.

(6) The late appearance of a femic liquid and the evidence for a carbonate melt in the Geshere system are considered general attributes, not restricted to Geshere. Evidence for these features should be sought in other A-type complexes.

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