Lithos 152 (2012) 132–140

Contents lists available at SciVerse ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Punctuated anorogenic magmatism

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ARTICLE INFO

Article history:
Received 15 October 2011
Accepted 22 May 2012
Available online 27 May 2012

Keywords:
Punctuated anorogenic magmatism
A-type granite
Syenite
Post-collisional magmatism
Mineralization
Nigeria

ABSTRACT

The emplacement of anorogenic magmas, be they mantle-derived or crust-derived and silica-undersaturated or silica-oversaturated, marks a period of rifting or tectonic relaxation and apparent quiescence. In a given area, such magmatism commonly recurs episodically, and can yield even more strongly alkaline products than in the first cycle, in spite of the depletion that resulted from that episode of melting. Anorogenic magmatism is said to be punctuated where it recurs, in response to a triggering mechanism. The second cycle reflects an influx of heat and a fluid phase responsible for the fertilization of the depleted source-rock. In cases of an anorogenic stage after a major collision, the first cycle of magmatism, yielding an AMCG suite, arises by gravity-induced sinking of lithosphere and the diapiric rise of an asthenospheric mantle; renewed magmatism may involve localized and renewed detachment as late as 200 m.y. after the collision. Where the hiatus is much longer, as in Nigeria, we appeal to a propagating zipper-like zone of extension, possibly related to rotation of a crustal block. The economic ramifications of punctuated anorogenic magmatism are important; the second-generation magmas may well crystallize products that are mineralized in the high-field-strength elements and any other elements enriched in the source rocks. Such a model would account for the rich deposits of alluvial columbite, zircon and cassiterite associated with the Younger Granites of Nigeria.

1. Introduction

The emplacement of anorogenic magmas, be they mantle-derived or crust-derived and silica-undersaturated or silica-oversaturated, marks a period of tectonic relaxation and apparent quiescence. By definition, anorogenic magmas are those not associated with compressional forces, which lead to subduction and eventually to collision. It is in Africa that they are best displayed; as Bailey and Woolley (2005) pointed out, most of that continent has been free of orogenic magmatism for the last 550 m.y. Felsic rocks are present in 864 alkaline and carbonatitic complexes on African soil, and tholeiitic basalt is absent from all of them. It is an attribute of magma emplacement in such a context that it tends to be episodic, and repeated at a given location over long periods of time.

Initiation of a cycle of anorogenic magmatism may well follow closely an interval of crustal compression (e.g., subduction, collision), or it may mark a recurrence of igneous activity after a very long hiatus. It is not at all uncommon to find, in the younger cycle of magmatism, geochemically more evolved magmas, and rocks significantly more enriched in economically interesting elements than in the older rocks. In this review, we explore this theme of "punctuated anorogenic activity" from the point of view of geochemical enrichment potentially leading to mineralization. We attempt to answer an important question posed by many an explorationist searching for economically attractive deposits of the high-field-strength elements: why is one batch of magma inherently more promising than another in terms of its mineral potential?

2. The concept of "punctuated equilibrium", and an illustration in a case of recent rift-related mafic volcanism in Tanzania

It is in the area of the evolutionary sciences that punctuated equilibrium is very clearly displayed; evolutionary changes in some species come in spurts. By 1993, Gould and Eldredge (1993) could report that their concept of punctuated equilibrium, the opposite of gradualism, had achieved broad acceptance as a predominant pattern within the history of species. Already in 1985, however, the concept of punctuation had been applied to the field of sedimentary petrology: Morton (1985) proposed its use to signify instances of episodic diagenesis, "whereby sudden diagenesis is initiated by a change in pore-water chemistry", a pattern that he contrasted with the prevailing hypothesis of gradual transformations with progressive burial. It seems completely in keeping with the usage of Gould, Eldredge and Morton to apply the concept here to magmatic events. The concept of gradualism seems to apply perfectly to the progressive changes associated with the subduction factory (Tatsumi, 2005), at least during the lifetime of the orogenic belt. On the other hand, one can expect anorogenic igneous activity to start

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0024-4937/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.lithos.2012.05.020

suddenly after a short or a long period of apparent dormancy, in response to some triggering factor in the mantle environment.

In an overview of his career-long involvement in northern Tanzania, Dawson (2008) described a recent example of punctuated anorogenic magmatism along the Gregory Rift. The Older Extrusives, emplaced over the interval 8.1 to 1.2 m.y., consist dominantly of nephelinite or basalt, and include minor volumes of trachytic and phonolitic differentiates. The emplacement of the Younger Extrusives in the same geographic area follows a period of quiescence and major faulting. The younger lavas, produced in small batches, are much more explosively emplaced, and tend to be volatile-rich, dominantly ultrabasic, and highly enriched in the alkalis and high-field-strength elements. Natrocarbonatitic lavas, such as at Oldoinyo Lengai, form part of this second cycle of volcanism, and are associated with alkali-enriched nephelinites free of olivine and containing combeite, $Na_2Ca_2Si_3O_9$. Lavas of the second cycle vary widely in a plot of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$, some basic, felsic and carbonatitic lavas showing clear signs of involvement of crust (Dawson, 2008, Fig. 7–12). Morogan and Martin (1985) documented clear examples of the fenitization of crustal xenoliths at Oldoinyo Lengai, followed by melting of the alkali-metasomatized domains (glass is still present). The striking differences in products of volcanism in the second cycle of magmatism led J.B. Dawson to infer a surprisingly rapid and efficient refertilization of the upper mantle under northern Tanzania after the first cycle. It seems clear that 1) a mixed aqueous–carbonic fluid interacted with the mantle source to replenish it efficiently in alkalis and incompatible elements, and 2) the fluid phase continued its ascent into the Tanzanian crust, focused in the second-cycle volcanic cones like Oldoinyo Lengai, where it did induce fenitization of crustal blocks. What caused the rapid renewal and change in style of activity? As Bailey and Woolley (2005) pointed out, regional changes in the motion of plates may well be involved.

3. Punctuated anorogenic magmatism in the Chilwa Province of Malawi, East African Rift

The Chilwa Province of alkaline igneous rocks and carbonatites in Malawi and neighboring Mozambique displays three major cycles of igneous activity (Woolley, 1987). During the first cycle, between 138 and 132 m.y. ago (Eby et al., 1995, 2004), twenty intrusive complexes of carbonatite were emplaced, each associated with an extensive aureole of fenite. This was followed by renewed activity over the interval 129–123 m.y., dominated by syenite and nepheline syenite, locally with quartz syenite units. There are no obvious parental magmas. During the third cycle, over the interval 115–111 m.y. (Eby et al., 1995, 2004), peralkaline syenite, quartz syenite and A-type (i.e., ferroan) granite were emplaced. As in the previous cycle, basic rocks account for a fraction of 1% of the igneous suites (A.R. Woolley, pers. commun., 2012), and these basic rocks are not tholeiitic. The miarolitic pegmatites that appear at the end stage of the Zomba–Malosa complex are arguably the most spectacular example of the NYF category of rare-element-enriched granitic pegmatite in the world. They contain exceptional aegirine, arfvedsonite, barylite [$BaBe_2Si_2O_7$, i.e., Be in an Al-free mineralogical expression], zircon, bastnäsite-(Ce), parisite-(Ce), xenotime-(Y), caysichite, Y-rich milarite, hingganite-(Y), polycrase-(Y), Ce-rich pyrochlore, and niobophyllite–astrophyllite, among others (Guastoni et al., 2003, 2009; Martin and De Vito, 2005).

For cycle 1, Woolley (1987) proposed that a long period of focused metasomatism by a CO_2-bearing fluid led to domains of carbonated peridotite in the upper mantle; this peridotite melted to give an alkali-enriched carbonatitic magma directly, although the radiogenic isotopic values (Sr, Nd) of Simonetti and Bell (1994) also are consistent with separation of an immiscible carbonatitic fraction from a nephelinitic magma. On the other hand, their oxygen and carbon isotopic data indicate an open-system disturbance in the carbonatites of the Chilwa Island complex. The coeval silicate rocks of that complex indicate an interaction with fenitized granulitic basement.

In view of the virtual absence of basic rocks in cycle-2 complexes in Malawi, Woolley (1987) postulated that large volumes of phonolitic magma could be generated directly in the mantle at the expense of suitably transformed rocks. The fenitization–simulation experiments of Preston et al. (2003) and the field observations of contact fenitization of anorthosite by ferrocarbonatite (Drüppel et al., 2005), which both produced nepheline syenites, demonstrate the viability of the process. On a diagram of Yb/Ta versus Y/Nb, Eby et al. (2004) showed that phonolites showing a negative Eu anomaly plot in the OIB box, whereas other phonolites free of such an anomaly could have an origin tempered by a fluid-dominant process, possibly at high pressure.

For cycle 3, Woolley (1987) proposed that the fluids affecting the uppermost mantle continued their ascent into the lower crust, and caused K-feldspathization reactions and fenitization. Because there are again no basic antecedents in cycle 3, syenitic melt seems to have been generated by the virtually wholesale melting of fenitized and geochemically fertilized granulitic lower crust, which likely was then parental to the vast volumes of the Chilwa granites (Mlanje, Malosa, Zomba intrusive suites), all of the ferroan variety (Frost and Frost, 2011; Frost et al., 2001). Both the Mlanje massif and the Zomba–Malosa batholith contain metaluminous to peralkaline syenite, quartz syenite and granite; a 1-km aureole of feldspathization and fenitization of the enclosing of the Mozambique Belt granulites around Mlanje (Platt and Woolley, 1986) may well provide an example of the type of "ground preparation" that took place in the source area of the A-type felsic magma.

In these cases of punctuated rift-related magmatism, a possible triggering mechanism to initiate the youngest cycle of magmatism 20 million years after the first might be a secular change in the make-up of the fluid phase being added to the lower crust from below, from CO_2-dominant to H_2O-dominant. As carbonation reactions proceeded in the uppermost mantle, it seems likely that the supercritical fluid phase progressively became depleted in CO_2 and enriched in H_2O. The progressive transfer of an aqueous–carbonic fluid into the crust is considered the key in explaining the enrichment in high-field-strength elements and Be in syenites and A-type granites of crustal origin, and in the associated NYF-type (i.e., Nb-, Y- and F-enriched) granitic pegmatites (Martin, 2006; Martin and De Vito, 2005).

4. Punctuated anorogenic magmatism in the Gardar Province

Upton et al. (2003) reviewed the products of alkaline magmatism and their ages of emplacement in the Mesoproterozoic Gardar Province in southern Greenland. The area contains clear evidence of repeated episodes of extensional tectonics over the interval 1280–1140 m.y., related to the breakup of Pangea. Anorthositic xenoliths in several Gardar intrusive complexes imply the presence at depth of an extensive anorthositic–mangerite–charnockite–(ferroan) granite complex (AMCG; see below). There is a parallel with the events described in Malawi. The oldest dates mostly pertain to mantle-derived suites that contain "transitional" gabbro, nepheline syenite and carbonatite. The younger dates pertain largely to more evolved suites, which include agpaitic complexes. Ivigtut, at 1248 ± 25 m.y., is a relatively early manifestation of post-AMCG Gardar magmatism, but also the most strongly mineralized A-type granite (Blaxland, 1976). It also has the highest initial $^{87}Sr/^{86}Sr$ value, 0.7125. At face value, the Sr isotopes indicate a crustal origin, and could be consistent with an origin by melting of a metasomatized crust, possibly a metasomatized A-type granite of the subjacent AMCG suite. The same can be claimed for the Nunarssuit biotite granite [1162 ± 21 m.y., initial $^{87}Sr/^{86}Sr$ value 0.7068], whereas the Nunarssuit syenite [1154 ± 14 m.y., initial $^{87}Sr/^{86}Sr$ value 0.7043] is closer to a mantle value (Blaxland et al., 1978). Finally, the well-known Ilímaussaq complex contains agpaitic silica-oversaturated units that present a crustal signature [initial $^{87}Sr/^{86}Sr$ value 0.7096]; they contrast markedly with augite syenite and the silica-undersaturated units, which have a mantle signature (1.13 ± 0.05 Ga, initial $^{87}Sr/^{86}Sr$ value ~0.703, $\varepsilon_{Nd} \approx 0$: Blaxland et al., 1976; Paslick et al., 1993; Stevenson et al., 1997). The syenitic magma at Ilímaussaq, among the youngest manifestations of the 200 million-year interval of Gardar magmatism, is considered to have evolved by closed-system fractional crystallization, accompanied by efficient assimilation of wallrocks (Marks and Markl, 2001).

5. Punctuated anorogenic magmatism in the Grenville Province of eastern North America

Five major episodes of subduction, collision, and associated orogenic activity have shaped the Grenville Province in northeastern North America (Table 1). McLelland et al. (2010) have shown that each is followed by the emplacement of anorthosite–mangerite–charnockite–A-type granite (AMCG) suites in a post-collisional setting, when the crust was in a state of distension. Distension is interpreted to result from the diapiric rise of a fertile asthenospheric mantle following gravitational collapse and the ensuing detachment of the lower crust and sterile lithospheric keel. The changeover from an environment of active collision to a state of distension, diapiric ascent of fertile asthenosphere and anorogenic magmatism commonly takes about 10 to 20 million years in the AMCG complexes of the northeastern segment of the Grenville Province (McLelland et al., 2010, Fig. 7).

In the Okak Bay area of coastal Labrador, Emslie and Loveridge (1992) discovered an even older episode of "anorogenic or post-orogenic magmatism" in the Wheeler Mountains [2135 Ma, U–Pb zircon] than is mentioned in Table 1, also formed in an "extensional, asthenosphere-related event". They also documented a suite at 1775 Ma, and yet another at 1318 Ma in the area. Values of ε_{Nd} for all three suites are in the range −7.5 and −11.0, and the initial $^{87}Sr/^{86}Sr$ values exhibit a marked increase with decreasing age, from 0.7019 to 0.7090. The T_{DM} model ages of the samples analyzed extend only from 2.4 to 2.7 Ga in spite of the large range of crystallization, from 1.32 to 2.14 Ga. The data clearly imply that Archean crust played a significant role in the derivation of granitic magmas in all three suites. These findings have been amply confirmed in broader studies in AMCG suites in the area (Emslie et al., 1994; Hegner et al., 2010), and are the underpinnings of the "Emslie model" to account for the recurrent AMCG association of mantle-derived anorthositic rocks and coeval crust-derived mangerite, charnockite and A-type granites. The $\delta^{18}O$ values of zircon in the coeval granitic rocks and anorthosites clearly record "mutual" contamination, and in such a way that correlates with boundaries between crustal blocks (Peck et al., 2010).

Small ring-complexes of quartz syenite and peralkaline granite mineralized in the rare earths, yttrium and zirconium were emplaced in the Mistastin AMCG complex (1420 Ma), on the Quebec–Labrador border. One of these is the Misery pluton, dated at 1410 Ma (David and Dion, 2011), in which the mineralization is concentrated in late melanocratic units of "ferrosyenite" that truncate the annular intrusive units (Petrella, 2011). The Strange Lake pluton, in the same setting, has been dated at 1240 ± 2 Ma (U–Pb zircon age: Miller et al., 1997). This F-rich pluton contains the association hypersolvus granite–subsolvus granite–NYF granitic pegmatite, mineralized in Zr, Y, and the heavy rare-earth elements. It intrudes the Napeu Kainiut metaluminous granite, inferred to be coeval with the Mistastin AMCG complex. Several other examples of relatively late mineralized peralkaline plutons are known in Labrador: the Flowers River granite (1289 Ma), the Letitia Lake and the Red Wine intrusive suites (1330–1340 Ma: Miller et al., 1997).

Sokolov (2007) investigated a dike of granitic pegmatite well known locally as a source of amazonitic microcline at Saint-Ludger-de-Milot, in the Saguenay region of Quebec. The region constitutes the central part of the Grenvillian high-grade metamorphic terrane affected by the Shawinigan orogeny (Tables 1 and 2), and comprises highly deformed upper-amphibolite- to granulite-facies metasedimentary units. In this area, Higgins et al. (2002) recognized two pulses of late post-collisional magmatism, at 1080–1020 and at 1000–980 Ma, following the Ottawan orogeny. Those late events presumably reflect localized reactivated detachment and collapse in the mantle and renewed generation of felsic magmas in the crust. The Saint-Ludger-de-Milot pegmatite dike was emplaced in dolomitic marble less than 3 km from the undeformed Astra A-type granite, a pluton 10 km across, and concurrently with it (U–Pb on monazite, 1028 ± 3 Ma: Higgins et al., 2002). The Astra granite is intrusive in anorthosite, gabbro, mangerite and charnockite of the Lac Saint-Jean AMCG suite, dated at 1140–1160 Ma (Table 2 in McLelland et al., 2010). The enrichment of Pb in K-feldspar, resulting in the blue-green to green color characteristic of amazonitic microcline, is considered diagnostic of rare-element-enriched granitic pegmatites of NYF type (Wise, 1999).

Amazonitic microcline also is found in a prominent pegmatite dike on the largest island in the northern part of Lac Sairs, near the Kipawa alkaline complex, Témiscamingue County, western Quebec (Table 2). The region lies within the Grenville Front Tectonic Zone. The dike is emplaced in the Kikwissi gneiss, dated at 2717 + 15/−11 Ma. The gneiss is at the bottom of a stack of thrust slices; above it is the Lac

Table 1
Sequential development of the major orogenies and anorogenic AMCG Suites in the Grenville province of Northeastern North America.
Adapted from McLelland et al. (2010).

Orogeny	Interval (Ma)	AMCG suite	Interval (Ma)
Labradorian	1710–1620	Mealy Mountains	1650–1625
Pinwarian	1520–1460	Michikamau	1460
		Harp Lake	1450
		Mistastin	1420
Gardar faulting	1354–1311	Nain Complex	1353–1290
		Pentecôte	1350
Shawinigan	1200–1140	Adirondacks	1160–1140
		Morin	1153
		Lac St-Jean	1150
Ottawan	1090–1020	Magpie River	1060
		Lac Allard	1060
		CRUML Belt	1020–1040

CRUML: Château-Richer–Saint-Urbain–Mattawa–Labrieville belt of complexes.

Table 2
Summary of events leading to the generation of rare-element-enriched NYF-type pegmatites containing an amazonitic microcline.
Sources of these data are given in the text.

Saint-Ludger-de-Milot, Saguenay area, Quebec, Canada	
Grenville high-grade metamorphic terrane	
Collision, Shawinigan orogeny	1.20–1.14 Ga
Emplacement of Lac Saint-Jean AMCG suites	1.16–1.14 Ga
Collision, Ottawan orogeny	1.09–1.08 Ga
Renewed anorogenic plutonism, pegmatite dike	1.06–1.02 Ga
Renewed anorogenic plutonism	1.00–0.98 Ga
Lac Sairs, Kipawa region, western Quebec, Canada	
Kikwissi gneiss, a thrust slice of Archean (?)	2.72 Ga
Red Pine Chute A-type orthogneiss	1.39 Ga
Kipawa Zr- and REE-mineralized syenite complex	1.03 Ga
Lac Sairs NYF-type granitic pegmatite	
Morefield mine, Goochland terrane, Piedmont, Virginia, U.S.A.	
Grenville high-grade metamorphic suites	
Collision, granulite-facies metamorphism	
Emplacement of AMCG suite	1.04–1.02 Ga
Renewed anorogenic plutonism	0.60 Ga
Morefield NYF-type granitic pegmatite	0.28 Ga
Mount Ploskaya, Keivy Peninsula, Russia	
Volcanogenic succession, back-arc environment	2.83–2.87 Ga
Collision, granulite-facies metamorphism	
Emplacement of AMCG suites	2.68–2.66 Ga
Renewed collision (?), high-grade metamorphism	2.0–1.8 Ga
Alkali metasomatism, anatexis of modified crust	1.70–1.68 Ga
Emplacement of the NYF-type pegmatites	

AMCG: anorthosite–mangerite–charnockite–syenite suite.

McKillop sequence of gneiss, schist, and migmatite, then the Red Pine Chute orthogneiss, dated at 1389 ± 8 Ma (U–Pb on zircon: van Breemen and Currie, 2004). This orthogneiss is a strongly deformed A-type granite. The Kipawa syenite complex intrudes the Lac McKillop sequence; its emplacement is dated at 1033 ± 3 Ma. The undeformed Lac Sairs pegmatite dike has not yet been dated, but likely is coeval with the Kipawa complex or possibly even slightly younger, emplaced during the waning stages of the Grenville event. The appearance of amazonitic microcline and other lead-bearing accessory phases like "plumbomicrolite" signals a recurrence of anorogenic activity, where the youngest manifestation is geochemically more enriched than the precursor.

The Morefield pegmatite, in the Amelia pegmatite district, in Virginia, lies within an isolated block of multiply deformed and highly metamorphosed rocks of the Grenville-age Goochland terrane (Table 2). The oldest units of the terrane comprise the State Farm gneiss (~1023–1046 Ma: Owens and Tucker, 2003) and the Montpelier anorthosite (~1045 ± 10 Ma: Aleinikoff et al., 1996). Neoproterozoic A-type granitic rocks (ca. 600 Ma) intrude the State Farm charnockitic gneiss. Owens and Samson (2004) have reported ε_{Nd} values for these suites, from −0.4 to +1.3, and have suggested that the charnockitic gneiss and anorthosite define an AMCG suite. The Maidens Gneiss, which encloses all these units, is dated at ~1035 ± 5 Ma (Horton et al., 1995), but also gives local evidence of remobilization in the Devonian, on the basis of U–Pb data on zircon and monazite (Owens et al., 2004; Shirvell et al., 2004). The pegmatites of the Amelia district define an age of 280 ± 4 Ma (Rb–Sr method on muscovite and biotite: Deuser and Herzog, 1962). The lack of an obvious parental pluton and an extensional setting lead to a hypothesis that the Amelia pegmatites have been derived by crustal anatexis, like countless other NYF granitic pegmatites in the Grenville Province (T.S. Ercit, pers. commun., 2009). The unusual buildup in rare-earth minerals and the unusual aluminofluoride mineralization in the Morefield pegmatite (Kearns, 1993) suggest that the crust being melted itself had an A-type granite signature.

6. Punctuated anorogenic magmatism in the Kola Peninsula, Russia

The Mount Ploskaya area, west Keivy, in the Kola Peninsula of Russia, forms part of the northeast-trending Central Kola granulite terrane (Table 2). The oldest rocks comprise a volcanosedimentary succession deposited in an environment of extensional tectonics, probably a back-arc area of an active continental margin (Mints et al., 1996), around 2.87–2.83 Ga ago. The package of rocks was metamorphosed at amphibolite- to granulite-facies conditions during the collision of crustal blocks. The collision event was followed by the emplacement of voluminous gabbro-anorthosite intrusions (2.68–2.66 Ga: Bayanova et al., 1998) and spatially associated synchronous peralkaline granitic and syenitic bodies (Zozulya and Eby, 2008; Zozulya et al., 2001, 2005). The sheet-like plutons of gneissic A-type granite are mainly confined to the margins of the Keivy terrane (Zozulya et al., 2005). After a long period of quiescence, the area was subjected to another cycle of crustal shortening and high-grade metamorphism, at about 2.0–1.8 Ga. The post-collisional evolution of the region involved intensive alkali metasomatism of the Archean basement rocks and the overlying Proterozoic gneisses, as well as widespread development of NYF-type rare-element-enriched granitic pegmatites. The U–Pb zircon ages of the younger anorogenic pegmatites indicate 1682 ± 35 Ma, and the U–Pb xenotime and monazite ages yielded 1699 ± 5 Ma and 1673 ± 3 Ma, respectively (Bayanova, 2004). On a world scale, Mount Ploskaya stands out as the site of amazonitic microcline most strongly enriched in lead. The granitic pegmatite is unusual in displaying evidence of two generations of amazonitic microcline, one bluish green containing about 0.2 wt.% PbO and a younger generation of green microcline attaining 1.8 wt.% PbO. It is also a well-known repository of rare-earth- and yttrium-enriched minerals. What is considered significant is the absence of amazonitic microcline in the older anorogenic rocks, and the absence of a parental pluton in the case of the younger generation of rare-element-enriched NYF pegmatites, suggesting an origin by localized anatexis of suitably metasomatized older-generation A-type granites.

7. Punctuated anorogenic magmatism in Nigeria

We now turn, in our review, to a classic area of anorogenic magmatism in Mesozoic times, the Nigerian Younger Granites, which intrude a basement complex consisting of Older (largely Pan-African: Falconer, 1911) granites and their host rocks. There is even evidence of a cycle of alkaline felsic magmatism in southwestern Nigeria, in the Igbeti area, soon after the Eburnean event at about 1900 m.y. (Rahaman et al., 1983). These alkaline augen gneisses are associated spatially with porphyritic granite judged to belong to a calc-alkaline suite emplaced during the Pan-African orogeny, and dated 617 ± 37 Ma (Rb–Sr method), with an initial $^{87}Sr/^{86}Sr$ value of 0.7120 ± 0.0016. Egbuniwe et al. (1985) were among the first to recognize the presence of Pan-African syenites, some having alkaline tendencies. They documented the Kanoma and Sabon Gida plutons, southwest of Kano, both consisting of a quartz syenite rim and a granite core, both plutons being compositionally similar. The quartz syenite in both is mildly peralkaline. The Kanoma pluton was emplaced in the Maru Schist Belt, first deformed at 1.1 Ga, then again early during the Pan-African event (ca. 750 Ma). It has been dated by the Rb–Sr method at 514 ± 25 Ma, and the rocks have an initial $^{87}Sr/^{86}Sr$ value of 0.7101 (Egbuniwe et al., 1985). The initial ratio implies the dominance of a crustal component in the syenitic magma. The Sabon Gida pluton was emplaced along the boundary between the Maru Schist Belt and the Maiinchi calc-alkaline batholith (879 ± 65 Ma: Ogesi, 1977); it is considered coeval with the Kanoma pluton. Rahaman et al. (1991) focused on two bodies of potassic syenite, north of Ibadan in southwestern Nigeria, and locally associated with charnockites. The age of their emplacement is indistinguishable: 610 ± 7 Ma and 618 ± 4 Ma (U–Pb on zircon). A syenitic magma is considered diagnostic of an anorogenic suite, and the association with charnockite indicates an AMCG association, emplaced *after* the release of compressive forces (McLelland et al., 2010). The fact that one of the two plutons studied by Rahaman et al. (1991) is foliated does not justify an inference that the syenitic magma is orogenic, in our opinion.

Olarewaju (1987) described the petrography and composition of rapakivi granites and associated charnockites in southwestern Nigeria, in the Ado Ekiti–Akure area. Although anorthositic members of the AMCG association were not found, Olarewaju did recognize the association as being a largely undeformed, and therefore, a post-collisional manifestation of the Pan-African cycle of magmatism. These rocks yield an age of 631 ± 18 Ma, whereas in the nearby Idanre area, charnockite and granite yielded an age of 586 ± 5 Ma (U–Pb zircon: Tubosun et al., 1984). The suites are typically post-collisional, but the two distinct ages of emplacement in areas 50 km apart suggest the possibility of episodic anorogenic magmatism, as in the Grenville province.

The widespread fayalite-bearing "bauchite" in northwestern Nigeria is a variant of charnockite free of orthopyroxene but with prominent ferrohastingsite, and thus of a member of an AMCG post-collisional association. These fayalite-bearing granitic rocks in the basement were first described by Oyawoye (1962, 1965), and dated by van Breemen et al. (1977). A foliated granite from Panyam gave a zircon U–Pb of 605 ± 10 Ma, which is in agreement with a Rb–Sr whole-rock isochron age of 623 ± 23 Ma for a foliated granite; these are interpreted to be ages of emplacement. The high initial $^{87}Sr/^{86}Sr$ values, in the range 0.7065 to 0.7125, indicate a large component of crustal Sr in the magmas that formed this suite.

Ferré et al. (1998) have documented post-collisional monzogranite and syenogranite plutons from the Eastern terrane in Nigeria, part of the Trans-Saharan Pan-African orogen dominated by an Eburnean protolith. They sampled the Solli Hills, Rahama and Toro metaluminous plutons, characterized as being ferro-potassic and “trans-alkaline”, some with charnockitic tendencies. We judge these plutons to be of A type on the basis of 1) the geochemical and mineralogical data provided and 2) application of Eby's (1992) discriminants. Lead-evaporation ages on single-crystal zircon constrain the emplacement of the three plutons at approximately 580 Ma.

The above summary of geochronological findings is sufficient to make our point that anorogenic felsic magmas were produced on a large scale at the end of the Pan-African orogeny, and may have been followed locally by renewed contraction and high-grade metamorphism. There is even an indication of an earlier stage of peralkaline felsic magmatism at the end of the Paleoproterozoic Eburnean event. Once the synorogenic and post-collision magmatic activity associated with the Pan-African orogeny had died down, major uplift occurred, leading to the unroofing of the largely mesozonal plutons. In the eastern block of Nigeria, in the Bauchi area, Ferré et al. (2002) have assessed the rate of exhumation of the biotite–hornblende–fayalite-bearing plutons, emplaced at roughly 585 Ma, to be in the range 0.2–0.5 mm/year; during the early stage of uplift, a dextral shearing motion took over, which controlled the shape of the plutons. Note that we re-interpret these plutons as being generated after, not during, the major collision, as they geochemically and mineralogically conform to the profile of A-type granites. Thus they do not mark the timing of the orogeny itself.

After an interval of continued uplift, some event triggered a new cycle of magmatism, first in Niger at 455–435–407 Ma, in the Aïr block (Bowden et al., 1987), then in the Zinder–Gouré area of southern Niger (323–296–258 Ma: Rahaman et al., 1984; Turner and Webb, 1974), and into northern Nigeria, where there is a general progression of ages southward, from 213 Ma in the north (Dutse complex) to 141 Ma in the south (Afu complex), but not in a very consistent and “linear” way (Fig. 1; Rahaman et al., 1984). Beyond the Benue Trough, the trend continues into Cameroon (Ngako et al., 2006) with the emplacement of anorogenic magmas of Cenozoic age.

In northern Nigeria, there are over fifty high-level granite–syenite complexes (Jacobson et al., 1958). These commonly circular and elliptical intrusions have a diameter in the range 10–25 km (Fig. 1); many are ring complexes, some of them nested and not confocal, and they represent the roots of eroded volcanoes. In Nigeria, volcanic rocks commonly define map-units, especially in the northernmost complexes, and they are also prominent in complexes in Niger. Gabbroic and anorthositic members of the association are common in Niger; except for the occurrence of anorthosite xenoliths in a diabase dyke north of Jos (Wright, 1975), anorthosites are unknown in Nigeria, and basic intrusive rocks represent less than 1% of the total area of the Nigerian Younger Granite (NYG) province, so-named by Falconer (1911). Minor volumes of plagioclase-phyric basaltic lavas are present, and evidence of magma mixing has been noted in some complexes. The Younger Granite complexes are associated with a negative gravity anomaly (Ajakaiye and Burke, 1973).

Several distinct types of granite and related syenites have been defined by Jacobson et al. (1958): 1) peralkaline granites and related syenites, with syenite forming the ring dyke in some complexes (i.e., the rock is not a cumulate), 2) mildly peraluminous granites and syenogranites, and 3) metaluminous fayalite- and amphibole-bearing granites and related porphyries. The diversity of granites in the Nigerian anorogenic province is consistent with a variety of parental magmas, in some cases within the same complex. Consider the Ririwai complex (Fig. 1), a pluton about 15 km across in which uraniferous peralkaline arfvedsonite–cryolite–pyrochlore granite, comenditic ignimbrite, and a metaluminous to mildly peraluminous biotite granite mineralized with Zn and Sn are juxtaposed (Ogunleye et al., 2006).

In the Geshere syenite–peralkaline granite pluton (south of Rishiwa, Fig. 1), Magaji et al. (2011) have shown that the order of crystallization of the major minerals in these rocks is 1) alkali feldspar, 2) quartz, and 3) alkali–calcic amphibole ± annite. The magma, in other words, is becoming increasingly femic as the solidus is being approached; the femic minerals are on the solidus of the magma. The reason for this unorthodox pattern of behavior is the extreme degree of iron enrichment of the amphibole and annite. The primary Na–Ca amphibole contains Mg as a trace element, and its Mg# $[100Mg/(Mg+Fe_{tot}+Mn)]$ is in the range 0.1 to 1.4. The strikingly anhedral shape of the amphibole is not due to resorption or replacement, but rather to the shape of the intertices left available for it to occupy after quartz and the alkali feldspar had formed. We do not believe that the syenitic to granitic magmas at Geshere were unusual among NYG complexes. The ferro-richteritic amphibole does contain anhedral wisps of a more magnesian and more F-rich amphibole (Fig. 2; Mg# equal to 21), interpreted as shreds of the residuum assemblage. Furthermore, the coexisting annite contains spheres of calcite (Fig. 3), interpreted as droplets of carbonate carried up in the Geshere magma and incorporated in the last major mineral to crystallize. These features are consistent with the melting in the Jurassic of a carbonate-bearing quartzofeldspathic source-rock. We do not see any evidence via telltale xenoliths that banded iron-formations in the area contributed to the extreme degree of iron enrichment noted in the syenitic and granitic magmas, as proposed by Mücke (2003).

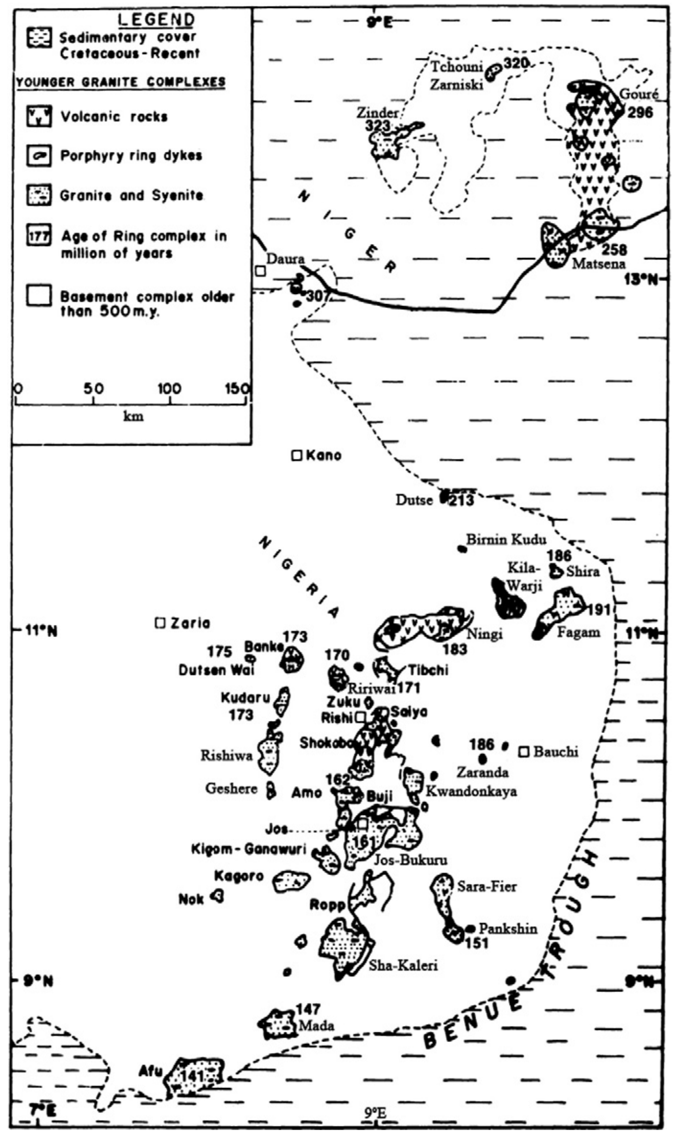

Fig. 1. The distribution of the Younger Granite complexes in southern Niger and in Nigeria, shown with radiometric ages, expressed in million years.
Modified after Rahaman et al. (1984).

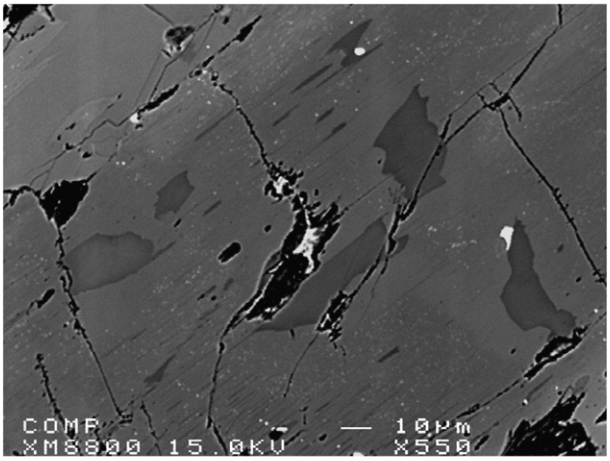

Fig. 2. Wisps and shreds of a more magnesian ferro-richterite in the primary (extremely Mg-poor) ferro-richterite in quartz syenite from the Geshere complex, in Nigeria. The anhedral fragments of the relict amphibole are considered to represent unmelted debris brought in from the source area. The new 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.
Reproduced from Magaji et al. (2011) with permission of the publisher.

One of the intrusive units mapped by Jacobson et al. (1958) in the Ririwai Complex is the Kaffo Valley peralkaline granite, unusual because of its strong peralkalinity, expressed in particular by the presence of magmatic cryolite. It has been prospected for uranium and the rare-earth elements (Ogunleye et al., 2006). This occurrence is not unique among NYG complexes. Comparable agpaitic rocks are unknown among the Pan-African rocks of A type.

Nigeria's tin fields are among the most important in the world. As Wright (1970) has summarized, the Older Granites feature a widespread development of pegmatite and aplite, with superimposed zones of intense albitization. The most important ore minerals are cassiterite and columbite-group minerals, which have become concentrated in alluvium during the unroofing of the older plutons. In a case study of an area of basement north of Jos, Pastor and Ogezi (1986) confirmed the presence of subeconomic concentrations of cassiterite in ten samples each of biotite gneiss, aplite and pegmatite. In the Younger Granites, cassiterite and columbite-group minerals again are dominant, and are manifested in several complexes and at succeeding stages of mineralization as the plutons cooled. We list in Table 3 all the examples of NYG mineralization listed by Pastor and Turaki (1985). Cases of disseminated cassiterite in biotite granite are commonly associated with areas of albitization. Cassiterite also is concentrated in roof-zone greisens, along with minerals of the "wolframite" series. Pastor and Turaki also recognized two episodes of lower-temperature veins, containing 1) quartz–sulfide–cassiterite and 2) quartz–cassiterite–"wolframite" (Table 3). Beryl and tourmaline-supergroup minerals, common in the Older Granites, are quite rare in the Younger Granites, presumably because the magma compositions are too strongly alkaline. Beryl in NYG complexes becomes important only in cupolas, where there has been important degassing (e.g., at Kwandonkaya), to make the rocks peraluminous; the magma itself is considered to have been metaluminous, not peraluminous (Sakoma and Martin, 2011).

As Wright (1970) has emphasized, economic mineralization in the NYG is "much more significant than in the basement". One must wonder why this should be, especially if the same ore minerals are involved. Elsewhere in the world, tin mineralization is commonly well developed in S-type orogenic granites. We believe that these are present in the basement, and that they have served as source rocks for the Mesozoic A-type granites. Stated in another way, it seems likely that both anorogenic and orogenic granites of Pan-African age were recycled during the Mesozoic cycle of anorogenic events. In this way, the syenitic and granitic magmas produced will inherit the anomalous level of Sn and Nb that account for Nigeria's impressive alluvial deposits. This inheritance provides a strong line of evidence in favor of a dominantly crustal origin of the NYG complexes. Tin is not closely identified with A-type felsic rocks elsewhere, but viewed in the context of the complex events that shaped the Nigerian basement, the presence of tin in metaluminous to peralkaline felsic rocks in Nigeria seems the culmination of a regional geochemical anomaly.

Dickin et al. (1991, Fig. 2) found a very wide range of ε_{Sr} compositions, from +9 (syenite in the Zaranda complex) to +251 and +429 (Kaffo Valley and the mineralized biotite granite, respectively, at Ririwai), but a rather restricted range in ε_{Nd}, from +0.9 (syenite in the Zaranda complex) to −2.7 and −5.6 (Kaffo Valley and the mineralized biotite granite, respectively, at Ririwai). According to the Pb isotope composition of the Amo, Jos, Pankshin, Ririwai and Zaranda complexes (one sample each, two for Ririwai) at 170 Ma, shown in

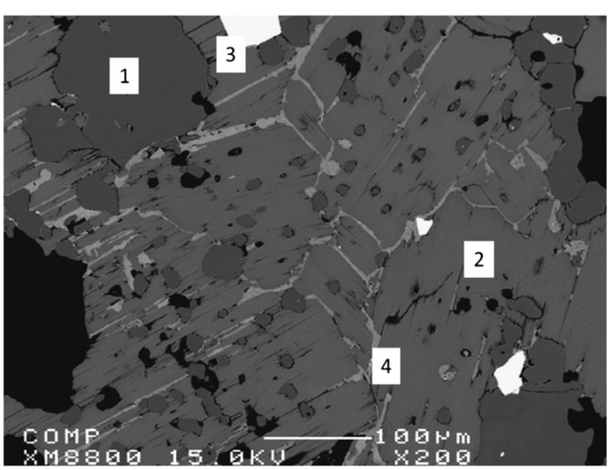

Fig. 3. Emulsion texture developed in annite in quartz syenite from the Geshere complex. Numbered locations: 1 calcite, 2 annite host, 3 zircon, and 4 iron oxy-hydroxide decoration (secondary) along the opened cleavage in annite. The texture is interpreted to indicate an emulsion of two melts, one the interstitial femic silicate melt that developed near the solidus and from which the annite crystallized, and a carbonate melt, presumably carried up as immiscible globules from the source area, which was incorporated in the last major mineral to form.
Reproduced from Magaji et al. (2011) with permission of the publisher.

Table 3
Economically important enrichments noted in the Nigerian younger granite complexes. This listing reproduces the four-part classification of Pastor and Turaki (1985), with their categories listed in the order from the highest-T mineralization (magmatic disseminations) to the lowest-temperature veins.

Magmatic disseminations	
Cassiterite ± magnetite ± ilmenite ± zircon	Ririwai, Fagam, Tibchi, Saiya-Shokobo
Columbite ± cassiterite ± ilmenite ± magnetite ± zircon	Jos-Bukuru, Ropp, Afu
Greisens	
Cassiterite ± molybdenite ± columbite ± wolframite	Banke, Ningi, Fagam, Tibchi, Ririwai, Saiya-Shokobo, Tongolo, Geshere[a], Kigom-Ganawuri, Jos-Bukuru, Ropp, Mada, Afu
Quartz–sulfide–cassiterite veins	
Sphalerite ± chalcopyrite ± galena ± arsenopyrite ± pyrite ± stannite	Ningi, Fagam, Tibchi, Ririwai, Saiya Shokobo, Tongolo, Zaranda, Ropp, Mada, Afu
Quartz–cassiterite–wolframite veins	
Cassiterite ± wolframite ± columbite	Ningi, Fagam, Tibchi, Ririwai, Saiya–Shokobo, Tongolo, Zaranda, Kwandonkaya, Kigom–Ganawuri, Ropp, Mada, Afu

Generation 4 cuts generation 1, 2 and 3; not all are represented in any given complex. For the location of these NYG complexes, see Fig. 1. In the above, note that columbite stands for minerals in the columbite–tantalite solid-solution series, and wolframite stands for minerals in the ferberite–hübnerite solid-solution series.
[a] The samples shown in Figs. 2 and 3 are from the Geshere complex.

their Fig. 3, the Pb in these NYG bodies is largely inherited from the basement, including, most likely, mixed Paleoproterozoic and Archean components. This is not a surprising discovery, as Pb is known to be among the most mobile of elements.

The ε_{Nd}–ε_{Sr} box defining the properties of the Precambrian basement beneath the Jos Plateau at 170 Ma ($\varepsilon_{Sr} > +100$, $\varepsilon_{Nd} < -8.3$: Dickin et al., 1991, Fig. 2) is based on data for three samples only, one each from the Panyam, Bauchi, and Rahama plutons. On the basis of the ε_{Nd} values representing the five NYG complexes sampled, Dickin et al. concluded that the NYG complexes are ultimately mantle-derived, with a minor component of crust, mostly added at the deuteric (subsolidus stage). At the same time, they assigned a crustal origin to the Panyam, Bauchi and Rahama anorogenic granites, of Neoproterozoic to Cambrian age. In other words, they believe that the Younger A-type syenites and granites are ultimately mantle-derived, whereas the Older A-type syenites and granites are crust-derived. Their reconstruction is not consistent with the hypothesis that the Younger Granites are largely derived by the reprocessing of the Older Granites. Our own preliminary data on the $\delta^{18}O$ of quartz from the Rishiwa and Geshere complexes, both of Jurassic age, range from 4.5 to 11.1‰ (SIMS analyses, University of Manitoba), and thus seem to indicate a mixture of protoliths in the source area, including hydrothermally affected crustal rocks. Quartz is taken as a proxy for the melt because it is unreactive in the subsolidus regime. In summary, much remains to be done in this classic suite of syenites and related A-type granites and NYF pegmatites to document the ultimate origin of the magmas, to quantify the relative roles of crust and mantle, and to identify the crustal blocks that have been involved (Archean, Eburnean, Pan-African), in addition to any underplated mantle-derived material. The work of Andersen et al. (2009) on the Lu–Hf isotope systematics of inherited domains in zircon in the Mesoproterozoic A-type granites of southwestern Fennoscandia can certainly serve as a model of what is possible to achieve in a basement containing distinctive crustal blocks.

8. Discussion

Igneous activity that is not a result of overall contraction, i.e., not of the type resulting from subduction and collision, is known to be episodic (Bailey and Woolley, 2005) and to involve repeated episodes of melting in the same general source-area in the upper mantle or crust (or both). The recurrence of activity involves source areas in the upper mantle or crust (or both), and leads to the inference that at every step in the progression, the starting point of each successive cycle may well be a product of a previous cycle of geochemical enrichments and depletions. Owing to punctuated anorogenic magmatism, renewed fertilization of domains in the source area contributes to a focused and secular enrichment of high-field-strength elements including Nb, Ta, U, Zn, Sn and Zr as an important step and mechanism in "mineral evolution" (Hazen et al., 2008, 2009) in the overall differentiation history of the Earth's crust.

Successive inputs of heat and fluids related to a rising asthenosphere are common features in the examples of rift-related anorogenic magmatism selected for consideration here. Dawson (2008) pointed out the surprising efficiency of the refertilization process in the depleted upper mantle leading to the second cycle of rift-related activity in northern Tanzania, responsible for an impressive production of small volumes of carbonatite, including natrocarbonatite, and explosive nephelinitic magmas. The findings of Morogan and Martin (1985) on crustal xenoliths at Oldoinyo Lengai point to the inescapable inference that the fluids causing refertilization in the mantle do rise into the crust and cause metasomatic adjustments involving the alkalis, the rare earths, and the high-field-strength elements. Woolley (1987) developed the hypothesis that some phonolitic magmas, as well as carbonatitic magmas, originate by anatectic reactions involving suitably metasomatized peridotites. In parallel, in such areas of active rifting, some batches of nephelinitic magma clearly do arise by differentiation in a closed-system fashion, and can, by efficient assimilation combined with fractional crystallization (AFC), produce derivative magmas that are silica-oversaturated, as seems to be the case in southern Greenland. However, such an AFC-based mechanism requires proximity of mantle-derived silica-undersaturated magma with batches of crust-derived silica-oversaturated magma or rafted crustal xenoliths. This would seem to rule it out in the case of batholith-scale bodies of syenite and A-type granite in areas devoid of a nephelinitic antecedent or a basic antecedent of any sort, as in the third cycle of magmatism in Malawi reviewed above. Woolley (1987) went on to develop the corollary concept that felsic magmas in rift-related areas like Malawi, in the East African Rift, can originate by near-wholesale melting of suitably metasomatized crustal rocks. He envisioned the "K-feldspathization" and fenitization of the lower crust by such rising fluids, followed by anatexis, a theme further developed by Martin (2006, 2012). We hasten to add that the association syenite–ferroan granite can also arise by fractional crystallization of a tholeiitic basaltic magma, as favored by Frost and Frost (2011), or of a mildly alkaline basaltic magma. In our opinion, petrogenetic diversity among ferroan granites has by now been duly recognized, and this diversity does not justify discarding the label "A-type".

Anorthosite–mangerite–charnockite–A-type granite (AMCG) suites are diagnostic products of the events that follow within 10 to 20 million years after a major collision. Circumstantial evidence is at hand to suggest that gravitational collapse and the ensuing detachment of the lower crust and sterile lithospheric keel constitute the necessary trigger to initiate a cycle of anorogenic activity (McLelland et al., 2010). The episodic nature of anorogenic magmatism in this setting, extending to 200 m.y. or more after collision, suggests that detachment recurs episodically, in the manner envisioned by Hoernle et al. (2006), who used the concept of gravity-induced lithosphere removal to explain the "diffuse" occurrences of intraplate centers of SiO_2-oversaturated and SiO_2-undersaturated volcanism in New Zealand in Cenozoic times.

Punctuated anorogenic activity requires an environmental change in the mantle, in the crust, or in both, that triggers a new cycle of magma generation. As emphasized by Bailey and Woolley (2005), the cause of reactivation may involve "long-distance" consequences of plate motions. What about cases like Nigeria, where the early anorogenic activity associated with the post-Pan-African collision is followed by a pulse a full 400 m.y. later, in Jurassic to Cretaceous time? At first glance, the occurrences of more or less coeval Jurassic anorogenic complexes on both sides of the Atlantic, in western Africa as well as in Brazil and in the White Mountains of New Hampshire (e.g., Eby, 1990), have led some to consider the opening of the Atlantic Ocean as the trigger for the new cycle of anorogenic activity. However, the long-lived and southward progression of igneous centers from Ordovician time in the Aïr Mountains of Niger to Cenozoic activity in Cameroon suggests instead a propagating zipper-like reactivation of a Pan-African or earlier suture, perhaps relating to a slight net counterclockwise rotation of northwestern Africa with respect to the eastern block of Nigeria, an event that may well have caused renewed and localized detachment of the lithosphere, to account for the formation of a new round of AMCG suites in Niger and of crustal melting in Nigeria.

9. Conclusions

1) Punctuated anorogenic magmatism is a common phenomenon in areas undergoing rifting and in terranes that have just experienced a major collision.
2) The concept of punctuation implies a change in an environmental factor affecting the source area, be it in the mantle or in the crust.
3) In this context, a fluid phase plays a key role in the geochemical enrichment of a source area prior to melting. Fertilization of a depleted source can be a very efficient process.

4) The enriched product of one cycle of activity can be the starting point for the next cycle, possibly hundreds of million years later.
5) Punctuated anorogenic magmatism can lead to fertilization of already fertile sources. This process ultimately contributes to a focused enrichment of high-field-strength elements and alkalis as an important mechanism in the differentiation history of the Earth's crust.
6) We review examples of punctuated anorogenic magmatism on the African continent, the Kola Peninsula of Russia, southern Greenland, and eastern North America.
7) In the Younger Granites of Nigeria, classic examples of the syenite–A-type granite association, the observed mineralization is considered to be inherited from both orogenic and anorogenic suites in the basement, enhanced by fertilization that preceded the anatectic reactions in Mesozoic times.

Acknowledgments

The research activities of all three authors have been covered by a Discovery Grant awarded to RFM by the Natural Sciences and Engineering Research Council of Canada. We are grateful to Drs. Robert B. Trumbull and Ronald B. Frost for comments and suggestions that led to improvements, and guest editor Gregor Markl for his forbearance, and for organizing the PERALK–CARB conference in Tübingen.

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