

# A-type granites of crustal origin ultimately result from open-system fenitization-type reactions in an extensional environment

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## Abstract

The origin of A-type granites and rhyolites are ultimately relatable to mantle-derived melts and fluids in a zone undergoing extension. The basaltic magmas are accompanied by an alkaline fluid phase, dominantly  $\text{H}_2\text{O} + \text{CO}_2$ , which will induce alkali metasomatism of the granulitic crust above. The distinctive mineralogy and geochemistry are thus a direct result of the tectonic environment of formation. Metaluminous and peralkaline granites are magmatic compositions that typically contain evidence of crust and mantle in their genetic baggage, but peraluminous A-type granites may well be caused by efficient loss of alkalis during epizonal degassing. A-type granites and rhyolites are members of a vast family of rift-related magmas that include those of syenitic, nepheline syenitic and carbonatitic character. The fluid phase at work is alkaline. It can carry a host of trace elements in solution, in particular the high-field-strength elements and the rare earths. It can fenitize and fertilize a refractory lower crust, and prepare the precursor for near-complete melting. Some examples of A-type granitic magma do arise by efficient fractional crystallization of a mantle-derived basaltic magma, with or without accompanying assimilation, but many arise by partial or complete melting of an alkali-metasomatized crust.

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## 1. Introduction

The origin of A-type granites is still a source of confusion for most petrologists, mainly because so many compositional variants can be found. There are metaluminous A-type granites, in which the sum of Na and K is more or less balanced by Al, there are others that are decidedly alkaline, and still others are peraluminous. Bona fide A-type granites exist where no continental crust is present, and also in situations where nothing but continental crust has been involved as the source, and of course a wide variety of intermediate

cases in which both crust and mantle are involved. Furthermore, some examples are associated with coeval silica-undersaturated suites and carbonatites. Faced with this diversity, some petrologists have shunned the “A-type” label entirely, and have referred to bona fide examples of A-type granites by assorted other names.

Martin and De Vito (2005) have recently explored aspects of this situation insofar as it impacts on a separate debate, the origin of two variants of granitic pegmatite enriched in rare elements. They proposed that rare-element granitic pegmatites enriched in Nb, Y and F (so-called NYF pegmatites) are the end stage of fractionation of A-type granitic magma, related to crustal distension and mantle-derived contributions to

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the lower crust. In contrast, those granitic pegmatites enriched in Li, Cs and Ta (so-called LCT pegmatites) are the end stage of another lineage of granite formation, related to calc–alkaline or orogenic magmatism, in a context of crustal shortening through subduction or collision.

My purpose here is to review a few problematic characteristics of A-type granitic suites, largely derived from field-based observations. My goal is to accommodate these characteristics in a working hypothesis. Existing petrogenetic hypotheses include the following. (1) A-type granites and rhyolites arise by remelting of crustal rocks, in particular older granites or granulite-grade metasedimentary rocks that underwent an earlier melting event. (2) They arise by fractional crystallization of a mantle-derived mafic magma. Intermediate cases of (1) and (2) seem to abound through AFC-type processes. (3) As an alternative, they may be related to a front of open-system hydrothermal activity taking place above a rising plume of asthenospheric mantle, affecting the uppermost mantle in a state of extension, as well as the crust above it. This hypothesis accounts well, conceptually and qualitatively at least, for the controls on the development of peralkalinity in felsic igneous systems and for the enrichment of the lower crust in Nb, Y, F, and a host of other incompatible elements prior to crustal fusion.

## 2. Background information: the birth of the concept

Before the plate-tectonic revolution, the systematics of granitic magmatism were relatively simple. In his depth-zone classification of granitic rocks, [Buddington \(1959\)](#) considered one mode of generation of granitic magmas; the various textural and mineralogical manifestations of the resulting products of melting were classified as a function of depth of crystallization. His classification of plutons as being epizonal, mesozonal and catazonal is still found useful today. The plate-tectonic revolution ushered in a new era, however, in which granite formation had to be explained in two contrasting tectonic milieus, one of compression and crustal shortening, the other in terms of crustal relaxation and attenuation (e.g., [Martin and Piwinski, 1972](#)). Because the major batholiths of the world are related to areas characterized by crustal shortening, subduction and, ultimately, collision, attention has focused on these, especially after the introduction of the concept of I- and S-type granites ([Chappell and White, 1974](#)). There is now a consensus that although “end-member” I- and S-type granites do exist, the major calc–alkaline batholiths of the world crystallized from

magmas of hybrid genetic background, with the relative proportion of crust and mantle components decipherable only by the use of isotopic tracers.

In an innocuous abstract, [Loiselle and Wones \(1979\)](#) introduced a third member of the genetic alphabet. This abstract, one of the most highly quoted in the annals of igneous petrology, is unfortunately the only document written by the originators of the concept of an A-type granite; a follow-up paper never was published. This fact, and the premature death of David Wones in 1984, certainly contributed to the ongoing confusion in some circles concerning the attributes of A-type granites and related rhyolites. Interested readers will find a description of the main traits of A-type granites and rhyolites in [Whalen et al. \(1987\)](#) and [Eby \(1990, 1992\)](#).

## 3. Challenging aspects of A-type granites

There are several serious challenges facing the petrologist trying to propose a unifying working hypothesis that accounts for occurrences in oceanic *and* continental settings, and in the latter, that also accounts for occurrences showing signs of a source in the mantle in some instances, in the crust in some others, and a real mixture in the bulk of the cases. In what follows, I will list key characteristics of A-type granites that are admittedly difficult to explain.

### 3.1. Challenge 1: the juxtaposition of compositional variants of A-type granite

One puzzling aspect of A-type granites is that they come in various flavors, commonly in the same complex. Consider for example the Ririwai, Tibchi and Kwandonkaya plutons, in northern Nigeria, three examples among many in that classic belt of Jurassic anorogenic activity. These small plutons were emplaced in deformed Pan-African granites that are at least 350Ma older. After such a hiatus, the “Younger Granites” can clearly be qualified as anorogenic rather than late or post-orogenic; their emplacement in fact is coeval with the inception of opening of the Atlantic Ocean and with the White Mountain magma series in eastern North America. Field studies reveal ring-shaped units that contain virtually end-member fayalite+hedenbergite (metaluminous granite; e.g., [Ike et al., 1984, 1985](#)), units containing members of the arfvedsonite–ferroleakeite solid solution, cryolite and pyrochlore (peralkaline granite), and, typically near the core, annite granite that shows the late development of a Li-enriched white mica and greisen veins (peraluminous varieties;

e.g., Sakoma and Martin, 2004). Peralkaline (aegirine-bearing) ignimbritic units also have been described at Ririwai (Jacobson et al., 1958), showing that batches of evolved magma were of pantelleritic or comenditic composition. On the other hand, peraluminous ignimbrites are not encountered; rather, the peraluminous granites show clear evidence of vesiculation and superimposed hydrothermal effects. The peraluminous character is attributed to magma degassing and preferential loss of alkalis with respect to aluminum, as the latest, most H<sub>2</sub>O-enriched batches of evolved magma rose to the surface (Martin and Bowden, 1981; Sakoma and Martin, 2004).

If one restricts the study to the peralkaline variants only, it may be possible to propose a crystal-liquid “line of descent”, as was done by White et al. (2005) at the type locality of pantellerite, Pantelleria, Italy. That occurrence of A-type felsic magma formed a few thousand years ago in a transtensional environment in a region of overall compression, in the Sicily Channel of the Mediterranean Sea. The dominant fractionating phase in that case is an alkali feldspar of bulk composition Or<sub>35–36</sub>, and the parental magma is defined as being metaluminous, marginally peralkaline, and trachytic in character. Trachyte forms mappable units on the island. Temperatures were close to 1000 °C in the more primitive (trachytic) magmas, and below 700 °C in the most strongly peralkaline quartz-normative magmas. It seems likely that the closed-system fractionation of crystals from a slightly peralkaline trachytic melt (itself derived from a basaltic parent) applies to the Nigerian complexes, but peraluminous A-type granites, at least in epizonal complexes, seem to require an open-system origin.

### 3.2. Challenge 2: the “cleanliness” of the felsic magmas

Xenocrysts and xenoliths are widespread in orogenic granites; they are indicative of the importance of the assimilation of country rocks, which may involve melting, dissolution, ion-exchange reactions, thermally activated decomposition reactions, and redox reactions, not all necessarily indicative of an equilibrium situation (e.g., Clarke, in press). Other xenoliths are rafted in from the source area. In contrast, one is struck, in a pluton of A-type granite, by the relative “cleanliness” of the granite, i.e., the absence of country-rock xenoliths, crustal debris, and refractory “restitic” material. Xenoliths of the Pan-African granitic basement and host rocks are extremely rare in the Younger Granites of Nigeria, for example.

Two possible explanations come to mind. The composition and temperature of the melt, in particular its enrichment in fluorine (Baker and Vaillancourt, 1995), may have ensured a sufficiently low viscosity of the magma to permit efficient settling of such xenolithic debris. For magmas in the compositional interval between metaluminous A-type granite–syenite at a temperature of close to 900 °C, Giordano et al. (2004) have documented viscosities in the realm of 10<sup>7</sup>–10<sup>5</sup> Pas for magmas containing 2 wt.% dissolved H<sub>2</sub>O. Even lower viscosities can be envisaged for those magmas at Pantelleria, where temperatures are closer to 1000 °C (White et al., 2005), where some batches of rhyolitic magmas were richer in dissolved H<sub>2</sub>O, up to 4.3 wt.% H<sub>2</sub>O (Kovalenko et al., 1988) and, of course, where magmas were strongly peralkaline (relatively depolymerized) and halogenated. These are all additive factors that will allow efficient settling of stopped blocks and any entrained restitic debris in an A-type granitic magma, so that even where it has formed by anatectic reactions at the expense of the crust, as inferred by isotopic indicators, there are no obvious petrographic signs of this parentage.

But is it conceivable that an A-type granitic magma of anatectic origin forms by virtual complete melting of a source rock that corresponds closely to the target bulk-composition?

### 3.3. Challenge 3: the variable role of the basic magma

The extensional or transtensional setting that is the earmark of A-type granitic magmas is ultimately an expression of the rise of hot, asthenospheric mantle, with attendant decompression-induced melting. The resulting basaltic magma rises into the lower crust, underplates it, and undoubtedly raises its temperature regionally as a result. Isolated batches of basic magma find an easy access to the surface *via* the network of normal faults, and form independent map-units in the igneous complexes mentioned earlier. There is no doubt that efficient fractional crystallization of basaltic magma can ultimately give rise to trachytic, pantelleritic, comenditic, and metaluminous rhyolitic magmas, as in an oceanic setting at Pantelleria and in the Azores (Mungall and Martin, 1995), and along some continental rifts. In the anorthosite–mangerite–charnockite–A-type granite association exposed in Proterozoic terranes, there are cases where most of the association arose by fractional crystallization of a basaltic magma (e.g., Anderson et al., 2003). In most cases, the felsic rocks are dominantly crust-derived, with isotopic evidence of hybridization in both groups (e.g., Markl and Höhndorf,

2003). The basic magmas and “asthenospheric sources” provided the heat to cause the high-T H<sub>2</sub>O-undersaturated melting of the crust; later influx of H<sub>2</sub>O can lead to hydration of a hot mangeritic suite and to its remelting (Corfu, 2004).

In most ensialic A-type granite complexes, there is thus a strong bimodal population of rock types. Consider for example the Quaternary and Pliocene outpouring dominantly of ignimbritic rhyolitic magma in the Yellowstone Plateau volcanic field, in Wyoming, Idaho and Montana (Christiansen, 2001). Eruption began a mere 2Ma ago, and involved three cycles of basalt–rhyolite volcanism in which the two groups of volcanic products formed from distinct parental magmas. The region is still in a state of active distension. The emplacement of voluminous ocean–island-affinity tholeiitic basalt greatly enhanced the already high level of heat flow, and promoted the localized partial melting of mafic or intermediate granulites of the lower crust. Values of the ratio  $^{87}\text{Sr}/^{86}\text{Sr}$  for the basalts range from 0.7038 to 0.7089, with a recurrent value of  $0.7060 \pm 0.0005$ , and are consistent with contamination by crust. The voluminous rhyolitic ignimbrites (of the order of  $3700\text{ km}^3$ ) average  $0.7103 \pm 0.0015$ . They represent but a small part of the total volume of felsic magma emplaced high in the crust; the batholith-scale mass of A-type granitic material is still partly molten. Christiansen (2001) considered the value 0.7103 too low for the felsic magma simply to be remelted upper crust; similar arguments apply to the isotopic values of Nd and Pb. The lower-crust granulite xenoliths brought up in basaltic flows have generally higher values of  $^{87}\text{Sr}/^{86}\text{Sr}$ , in the range of 0.7125 to 0.727. Hildreth et al. (1991) concluded that the Nd, Pb and Sr isotopic data are most consistent with derivation from lower-crust rocks “that were extensively hybridized by basaltic magmas from the upper mantle”, and they did recognize a common overprint due to near-surface hydrothermal alteration. Fertilization of the crust prior to melting was not considered by these authors.

#### 3.4. Challenge 4: the production of a metaluminous to peralkaline melt from a peraluminous crust?

The ignimbritic rhyolites of Yellowstone are metaluminous, Fe-enriched and Mg-depleted, and locally are fayalite-bearing. Based on the major elements, they might be mistaken for products of fractional crystallization of a basaltic magma; the summary statements of the previous section show that this possibility cannot be entertained. How can one derive an A-type metaluminous granitic magma by the anatexis of a peraluminous

lower crust considered to be of intermediate to mafic composition? This is a major enigma that is at the root of the debates about the origin of A-type granites of crustal derivation. The situation is even more challenging if the product of anatexis is peralkaline instead of metaluminous.

The possibility of remelting after a period of low-temperature hydrothermal modifications at Yellowstone has been documented in a study of low- $\delta^{18}\text{O}$  rhyolites focused on quartz and zircon, both resistant to isotopic resetting (Bindemann and Valley, 2001). The rhyolites before and after remelting are chemically similar, but “tens of per cent of total oxygen” have exchanged with meteoric water, and the  $f(\text{O}_2)$  was raised slightly as a result. Rheomorphism would seem to be as straightforward in cases where alkalis are added, not only oxygen, and a common process much deeper in the crust.

Consider the case of the peralkaline rhyolites erupted near Lake Naivasha, in the vicinity of Nairobi, Kenya. Scaillet and Macdonald (2003) have shown experimentally that pantelleritic rhyolite can be produced by fractional crystallization of a comenditic magma of anatectic origin. But how does one produce such a comenditic starting point? One needs a quartzofeldspathic source containing an alkali-bearing clinopyroxene. The key finding concerns the need to keep the fugacity of oxygen low, in order to destabilize that clinopyroxene during the melting reaction. The authors mention the possibility of fluxing the quartzofeldspathic source by a fluorinated fluid phase to help achieve a peralkaline melt of anatectic origin. Bailey and Macdonald (1987) had proposed that the excess Na could be contributed externally as well, but Scaillet and Macdonald (2003) downplayed the need for any addition of Na.

As in the case of the Yellowstone Plateau, the Naivasha complex is bimodal. The basaltic magma assimilated variable amounts of Proterozoic amphibolite–facies crust, which raised the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  value to 0.7045–0.7055 (Davies and Macdonald, 1987). The comenditic rhyolites cannot have formed by fractional crystallization of that basaltic magma, based on their more radiogenic Sr, Nd and Pb isotopic values. Rather, the comenditic flows arose from small batches of melt of crustal origin; the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  values range widely, from 0.7055 to 0.7116 among individual flows. Halogens are considered to have played a fundamental role at the site of partial melting, allowing small-degree partial melts to form and accessory phases like zircon to destabilize. But what was the source of F and Cl? “One possibility is that intrusion of mafic magmas into the crust raised the local geothermal gradient, setting up a

hydrothermal system... which scavenged halogens from the surrounding crustal rocks. Alternatively, they may have been derived directly by mantle degassing” (Bailey, 1980). In view of the small volumes of comenditic rhyolite produced, Davies and Macdonald (1987) did not see the need to appeal to a mantle contribution of alkalis to locally transform a peraluminous crust into a peralkaline bulk composition.

### 3.5. Challenge 5: the juxtaposition with silica-undersaturated and carbonatitic magmas

Consider the Chilwa alkaline province, in southern Malawi, of Cretaceous age. What makes it unusual, but by no means unique, is the exceptional variety of rock types emplaced in this belt (Woolley, 1987; Eby et al., 1995). The largest plutons in the Chilwa Province (e.g., the Zomba–Malosa pluton) consist of syenite and peralkaline granite, and were emplaced at approximately 113 Ma; they turn out to be the youngest manifestations of a long-duration magmatic cycle. The smaller plutons consist of syenite, nepheline syenite and sodalite syenite, and are about 13 Ma older. Carbonatite and nephelinite started the cycle of activity, about 133 Ma ago. Is this sequence perhaps a manifestation of a general secular pattern of evolving partial melts in an ensialic rift?

The juxtaposition of such rock types can be found in the Mesozoic White Mountain magma series in New Hampshire and adjacent states, and in the Gaspé Peninsula in Quebec (Wallace et al., 1990). Mount Suswa, in south-central Kenya, located close to the SiO<sub>2</sub>-oversaturated complexes of southern Malawi, contains a peralkaline trachyte–phonolite association. The juxtaposition is also found in the Cretaceous Paraná–Etendeka province of Namibia, in a belt of Damaraland anorogenic centers of magmatism that formed upon breakup of western Gondwana (Trumbull et al., 2004). Along the latter belt, the Cape Cross complex is made up of A-type granite, nepheline syenite (135 Ma) and gabbro. The Paresis complex contains A-type rhyolite, comendite, quartz syenite, feldspathoidal syenite, and basic rocks. The Messum complex contains granite, quartz syenite, nepheline syenite, and gabbro. Within a single intrusive complex, the standard explanation of the juxtaposition involves the formation of SiO<sub>2</sub>-oversaturated batches of syenitic or A-type granitic magma at the expense of a critically undersaturated felsic magma by assimilation of crust coupled with fractional crystallization, whereas nepheline-normative syenitic melts crystallize without large amounts of contamination (Foland et al., 1993; Brotzu et al., 1997).

On a regional basis, rift-related igneous activity may thus involve juxtaposed A-type granitic magmas, nepheline-normative felsic magmas and carbonatitic magmas, such that the concept of a common parental magma advocated by Foland et al. (1993) would not seem generally applicable. Consider the Gardar Province of anorogenic magmatism in Greenland. One of the major silica-undersaturated complexes of the world, Ilímaussaq, emplaced 1.16 Ga ago, consists of a first phase of mildly alkaline augite syenite, a second phase of quartz syenite and alkali granite, and a third phase of agpaite nepheline syenites. Located 120 km to the west is the former Ivigtut cryolite deposit, located in the roof zone of a pipe of A-type granite emplaced 1.17 Ga ago (Goodenough et al., 2000). The Tugtutôq suite contains gabbro, nepheline syenite, quartz syenite and alkali granite; the Qassiarsuk suite contains trachyte and carbonatite (Upton et al., 2003), and carbonatite dykes cut the Igaliko nepheline syenite complex (Coulson et al., 2003). Rifting and the emplacement of associated anorogenic suites occurred during the interval 1350–1140 Ma in this belt.

Upton et al. (2003) contended that the principal pattern of magmatic evolution involves differentiation from a transitional alkali basalt to a phonolitic residuum, and that the generation of granitic magma is considered to involve “greater degrees of crustal assimilation” accompanying fractional crystallization. This general model has been tested within the Ilímaussaq Complex using Nd isotopic values by Stevenson et al. (1997). The granite and quartz syenite of the second phase have a  $\epsilon_{\text{Nd}}$  value lower than the augite syenite of the first phase (between  $-1.2$  and  $-2.4$  vs.  $\sim 0$ ). Interestingly, the agpaite rocks, formed from the most strongly alkaline and evolved magmas, have  $\epsilon_{\text{Nd}}$  values varying between 0 and  $-2$ , with the exception of one sample of poikilitic nepheline–sodalite syenite collected near the contact with supracrustal host-rocks ( $\epsilon_{\text{Nd}} = -3.9$ ). Faced with two competing hypotheses to explain the data, Stevenson et al. (1997) opted for assimilation of crustal material; however, appealing to assimilation of crust by a melt crystallizing a metaluminous assemblage (augite syenite) to give one crystallizing a strongly peralkaline assemblage seems an unlikely scenario, unless of course that crust has been alkali-metasomatized prior to intrusion of the complex. Macdonald and Upton (1993) had proposed a period of fertilization of the Gardar mantle source to cause enrichment in K, Ba, REE, C and halogens prior to melting, an option that holds considerably more promise to explain the hyperagpaite differentiates. More recently, Marks et al. (2004) have used isotopic indicators to point to

closed-system fractionation once the magmas arrive in the shallow crust, but it seems to me highly likely that open-system behavior is essential in the region of the source, in the upper mantle atop the asthenospheric plume, and in the crust above it, prior to intrusion.

### 3.6. Challenge 6: A-type granites apparently devoid of complex associations

Some A-type granites seem to be completely devoid of an association with rock types of mantle derivation, and thus may well be derived entirely at the expense of the crust. For example, the younger granites of Madagascar seem to be formed in an episode of distension soon after the Pan-African orogeny. [Nédélec et al. \(1995\)](#) have described regionally developed stratiform A-type granites in central Madagascar near Antananarivo, emplaced at a mid-crust depth in gneissic country-rocks 630 Ma ago, in a period of extension relatively soon after an important collision with western Gondwana before 650 Ma. The metamorphic basement in the area must have been regionally still hot as distension and influx of a fluid phase occurred. The area was later the locus of another episode of A-type granitic magmatism, of which the Carion pluton (532 Ma) is the best documented ([Meert et al., 2001a,b](#)). Although interpreted by the authors as a “late-synorogenic pluton”, mineralogical and geochemical details point to a typical A-type granite.

The central-south sector of Madagascar offers the best examples of “hybrid” granitic pegmatites in the world. These are NYF granitic pegmatites of possible anatectic origin that became contaminated during or soon after crystallization by a fluid medium enriched in Li, B, Ca and Mg, and possibly remelted in situ. [Martin and De Vito \(2005\)](#) reported high values of  $\delta^{18}\text{O}$  in the quartz (+15.9 to +16.3‰), alkali feldspar (14.1 to 15.2‰), and zoned tourmaline (+12.8 to +13.9‰) in the Anjanabonoina pegmatite, 55 km west of Antsirabe. One sample of country rock, part of the high-grade Itremo Sheet, gave a whole-rock value of +13.6‰. Such unusual hybrid pegmatites result from the 530-Ma cycle of activity ([Pezzotta, 2005](#)). The absence of nearby plutons of A-type granite and the high  $\delta^{18}\text{O}$  values are consistent with the possibility that the A-type magma is of purely anatectic origin, formed in the juvenile crust still in the process of cooling after the complicated collision+relaxation events that came before. At about the same time, huge amounts of anorogenic (syenitic to charnockitic) magmas were emplaced in a granulitic basement in Dronning Maud Land, Antarctica, on the other side of the Gondwana suture ([Markl and Piazzolo,](#)

1998). It seems clear that episodes of distension followed soon after orogeny on a regional basis.

Like in Madagascar, but in Mid-Proterozoic times, there was an important collision leading to the Grenville Orogeny in southeastern Ontario, southwestern Quebec, and in adjacent sectors of New York State. In the Grenville Province, a host of occurrences of NYF granitic pegmatite bearing geochemical characteristics of A-type granites formed during regional relaxation in the uplifted block of lower crust; in most cases, however, there is no pluton related to these pegmatites. [Ercit \(2005\)](#) has concluded that pegmatite-forming magma having the characteristic pattern of enrichment in incompatible trace elements of an A-type granite can arise not only by fractionation processes in a pluton but also by anatectic reactions of a suitable metamorphic source-rock in the deep crust.

## 4. The experimentalists' point of view

What kind of protolith can melt to give a magma composition having the major-element characteristics of A-type granites? [Patiño Douce \(1997\)](#) used a tonalite and a granodiorite from the calc-alkaline Sierra Nevada batholith for an investigation of melt generation at 950 °C at 4 and 8 kbar. The experiments were designed to evaluate dehydration melting; no H<sub>2</sub>O was added to the two rocks undergoing melting. The fugacity of oxygen was maintained within one log unit below the quartz–fayalite–magnetite buffer. Many characteristics of the average metaluminous A-type granite were indeed duplicated in the 950 °C, 4 kbar experiment in the two rocks, but not at 8 kbar. [Patiño Douce](#) found that incongruent melting of hornblende- and biotite-bearing H<sub>2</sub>O-poor granitic rocks at a shallow depth in the crust, with massive formation of plagioclase and orthopyroxene in the restite, could well explain the formation of metaluminous A-type granites. He proposed that the extensional environment of formation would favor the emplacement of mantle-derived basic magma necessary to insure the requisite source of heat in the upper crust.

Were the model of [Patiño Douce](#) of widespread applicability, one should find prominent xenoliths of dioritic or gabbroic rocks as the complementary fraction to the partial melting being proposed. Yet, as pointed out earlier, A-type granites are amazingly “clean”, devoid of refractory material. A shallow origin would presumably offer ideal circumstances to see such material entrained in the melt, as the rift environment allows the felsic melt to ascend from the source region without delay.

There is a contrasting and widely accepted view of the origin of A-type granites in the experimental

petrology literature; Collins et al. (1982), Clemens et al. (1986) and Whalen et al. (1987) have proposed that an A-type granitic melt arises by melting of relatively dry, granulitic meta-igneous restite previously depleted during an episode of partial melting. Enrichment of this restite in fluorine is considered important by some (Skjerlie and Johnston, 1993), but the resulting melts in this case tend to be more strongly aluminous (and topaz-bearing) than typical A-type granites.

Whereas the “residual source” model may well satisfy certain aspects of the major-element composition of an A-type granite, there are major flaws in any such proposal (Creaser et al., 1991). One certainly concerns the trace elements. Surely an early episode of anatexis would remove the most incompatible trace elements efficiently from the source, not only H<sub>2</sub>O. A second feature of the “residual source” model is the requirement that any such second melt be relatively anhydrous. This inference comes from laboratory studies, not from field evidence. Field evidence in favor of the contrary opinion is widespread, and the fact that a peralkaline granite contains the anhydrous assemblage quartz–microcline–albite–aegirine certainly does not imply that the magma was anhydrous!

At present, the experimental results available do not provide a convincing model to explain the generation of a voluminous amount of A-type metaluminous granitic magma according to a partial melting model in the deep crust. As for peralkaline compositions, Scaillet and Macdonald (2003) have shown that a pantelleritic melt can be produced at temperatures below 800 °C, at low  $f(\text{O}_2)$  and high  $f(\text{F}_2)$ , by extreme fractional crystallization of a high-SiO<sub>2</sub> comenditic magma by the suppression of the field of an alkali-bearing clinopyroxene or amphibole. The formation of a comenditic magma by anatexis of normal (peraluminous) crust raises problems addressed earlier.

## 5. A working hypothesis for the formation of A-type granite

### 5.1. The frustrations

When tackling the specific details of a petrogenetic model, authors of case studies of A-type granites and rhyolites commonly point to the deep crust, and to the uppermost mantle, or both, and state that a fertilized mantle has melted owing to decompression during its diapiric rise, and that the resulting magma has undergone fractional crystallization with or without simultaneous assimilation of the crust. If the basaltic magma has made it to an epizonal environment,

assimilation may occur near the Earth’s surface, as in the Ethiopian Rift (Peccerillo et al., 2003). In those cases, there is hope to characterize the likely crustal material being assimilated, and thus to quantify the extent of the assimilation and details of the process. In countless cases, however, the action is taking place in a catazonal environment, and no direct information is available on the nature of the assimilant, its mineralogy and its geochemical characteristics. In Namibia, for example, Trumbull et al. (2004) have documented the A-type granites in five prominent complexes sufficiently to conclude that although very similar, these occurrences must have involved two kinds of crustal assimilant. The major problem, as stated earlier, is that the granites in general are “clean”, devoid of telltale debris rafted in from the source area. In this way, they differ markedly from orogenic granites. Thus, any information on the crustal material involved in the formation of the granite or rhyolite is very sketchy and indirect. No one can say whether that crust is geochemically or mineralogically anomalous in any way. Schmitt et al. (2000) have shown that based on field and age relationships and Nd-isotopic composition, metaluminous and peralkaline granitic products in the Brandberg Complex, Namibia, had a common basaltic parent that assimilated deep crust in both cases. But how did they differ? Specification that batches of A-type granitic magma in Namibia arose by partial melting of dehydrated, and possibly melt-depleted (granulitic) lithologies in the lower crust would seem to predispose the partial melt to be moderately to strongly peraluminous. In Corsica, the formation of the metaluminous and peralkaline anorogenic suites in Late Permian times also involved a mafic magma, and the felsic rocks are characterized by a very large range of initial <sup>87</sup>Sr/<sup>86</sup>Sr (0.704–0.722) and  $\epsilon_{\text{Nd}}(t)$  values, +0.4 to –5.8 (Bonin, 2004). According to some, highly evolved peralkaline residual liquids could have been derived by fractional crystallization of a monzonitic derivative magma, with indications of a crustal component acquired as a result of post-magmatic readjustments in the isotopic systems rather than by a “Namibian-type” model involving partial melting of crust, but the point is still debated.

### 5.2. The model

Woolley (1987) published a most informative “cartoon” of a section across a rift zone (Fig. 1). The cartoon was drawn to illustrate relationships among the very diverse coeval products of anorogenic igneous activity in Malawi, but has broad applicability to magmatism in areas of extensional or transtensional

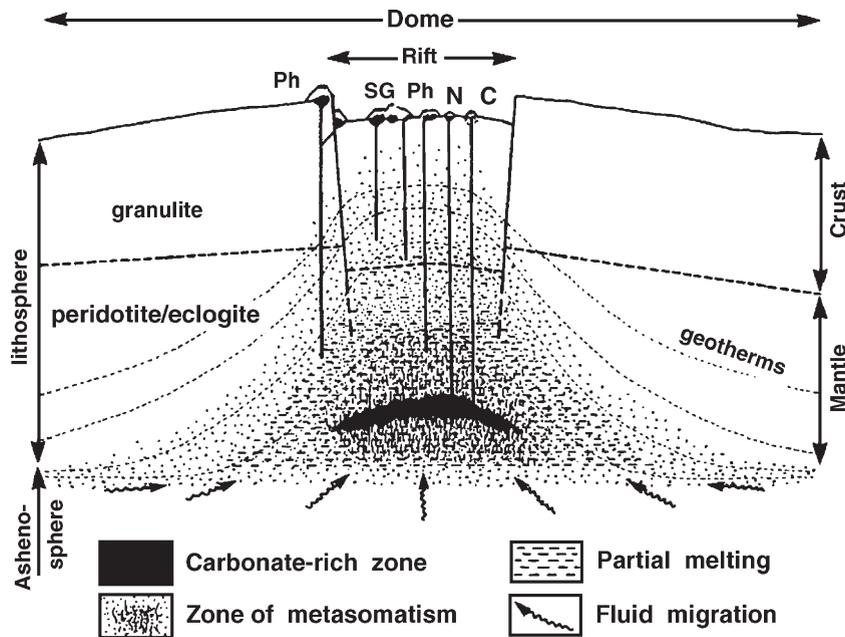


Fig. 1. Schematic cross-section of a zone of active rifting in a continental setting. The upward bulge in the asthenospheric mantle is accompanied by focused degassing. Here, the upward migration of fluid offers a very efficient mechanism of transfer of heat into the lower and middle crust. The degassing mantle emits both  $H_2O$  and  $CO_2$ , the proportion of which is of primordial importance in determining the nature of elements transported upward into the crust, and the nature of the melting reactions. Where the metasomatizing agent is dominantly  $H_2O$ , syenitic and granitic (SG) melts of A type will result. The metasomatic step leading up to partial melting has involved the preferential mobilization of alkalis over Al, which is reflected in an alkaline character of the partial melt. A phonolitic (Ph) melt could arise where the addition of alkalis is enhanced. Carbonatitic (C) and nephelinitic (N) melts will result in areas where  $CO_2$  was the main metasomatizing agent;  $SiO_2$  is not transported by a carbothermal fluid phase. The metasomatic step leading up to partial melting has caused a major enrichment in high field-strength elements, including the rare earths, and these patterns of enrichment are reflected in the magmas produced. Of course, all intermediate cases between the end-member situations are likely to be encountered, which explains the juxtaposition of silica-oversaturated and silica-undersaturated suites along belts of anorogenic igneous activity. The anomalously high temperatures at the base of the crust can promote efficient fertilization and refertilization of granulite-facies assemblages. Diagram courtesy of Alan R. Woolley (1987); reproduced with permission of the publisher.

environments. The crustal expression is directly a result of a regional thermal anomaly in the subjacent mantle. As Bailey (1980) and others have emphasized, rifts are loci of degassing of the Earth. Specifically, in response to a rising asthenospheric plume, a steady stream of fluid rises ahead of it and fertilizes the uppermost mantle in an open-system, “flow-through” style. The fluid phase is likely a supercritical mixed-volatile fluid containing dominantly  $H_2O$ ,  $CO_2$ , and  $CH_4$ , with F, Cl, and assorted other species. That such a fluid can transfer the high field-strength elements, the rare earths, and of course the alkalis seems clear from case studies of metasomatized lherzolite and harzburgite in a non-subduction-zone setting (e.g., Neumann et al., 2002; Zaccarini et al., 2004). As fully expected from the natural buoyancy and mobility of the fluid phase, the lower crust gets “soaked” from below by that very hot ( $\sim 1200^\circ C$ ) fluid. In fact, transfer of this fluid is directly responsible for the high values of heat flow in zones of active rifting. The fluid has the ability to metasomatize

rocks of the lower crust, and to refertilize them if they happen to have been depleted geochemically by previous episodes of melting, just as happens in the upper mantle. The disarmingly simple cartoon (Fig. 1) belies an amazingly complex array of transformations in which crustal rocks may become carbonated where the fluid is rich in  $CO_2$ , to the point where an anatexis reaction may involve the formation of batches of ensialic “pseudocarbonatite” (Mitchell, 2005). Where the fluid is more aqueous, I envisage the possibility that the lower crust can locally be transformed into an A-type granite composition by metasomatic means, then to be melted. This would not be a partial melting, but virtually a complete melting, thus accounting for the “cleanliness” of the resulting granite. It seems clear that the isotopic systems would be completely reset in such an environment, to a blend of recycled crustal signatures and a mantle contribution. McCulloch and Woodhead (1993) have shown how the lead isotope signature of the lower crust becomes homogenized regionally in such a

fluid-advection system, prior to the onset of anatectic reactions.

The major calc–alkaline batholiths of the world contain a mixture of mantle and crust components. In countless occurrences of A-type granite, there also is a mixture of mantle and crust components. If mantle and crust components are discernible in both, how does one account for the major-element differences between a calc–alkaline (I, S) granite and an anorogenic granite? The answer to this key question lies in the open-system fenitization-type reactions *prior to* melting of crust in anorogenic settings. The alkalis and silica are added to the crust in preference to aluminum. As in other contexts, aluminum invariably is relatively less mobile than alkalis and silica. I have successfully shown, in simple-minded polythermal experiments designed to evaluate the relative mobility of major elements from a mafic precursor in the presence of a supercritical aqueous fluid at pressures typical of the middle to deep crust (e.g., Martin, 1974), how it is possible to extract a felsic fraction from any igneous rock hydrothermally at a temperature of dissolution of 700°C (maximum temperature imposed by the equipment used). I have “synthesized” in this way felsic fractions resembling the bulk composition of peralkaline and metaluminous A-type granites, and was able to establish that the mobility can be expected to increase if temperatures of dissolution were higher.

Fenitization-type reactions at high temperatures are efficient at changing the bulk composition of any precursor. Preston et al. (2003) were able to completely transform a granodiorite into a nepheline syenite composition at 850°C and 1 kbar. Such an episode of fenitization as they described could transform and “predispose” a granodioritic precursor in the lower crust to melt almost completely to give a nepheline-normative syenitic melt by anatexis, for example. Fertilization of the crust in response to an incoming mantle-derived alkali-rich fluid could well occur under conditions below the quartz–fayalite–magnetite buffer or above it. In most instances, the A-type granitic melt is relatively reduced, but some instances of oxidized A-type granites are known (e.g., Dall’Agnol et al., 1999); this type of process could accommodate locally higher fugacities of oxygen, presumably buffered by the precursor assemblage.

One way to come to grips with what is going on in the lower crust during a period of rifting is to tackle with modern methods the unusual array of igneous and metamorphic rocks in areas where major uplifts have brought these rocks to the surface. The Bancroft area of southeastern Ontario, Canada, offers such a natural

laboratory, fully accessible, but still woefully understudied. In that area, there have been classic studies of nepheline syenite plutons that do not seem to be part of a fractionation sequence or an alkaline complex, “nephelinized” gneisses, corundum pegmatites, A-type granites, and pseudocarbonatites (e.g., Osborne, 1930; Gummer and Burr, 1946; Baragar, 1953; Gittins, 1961; Tilley and Gittins, 1961; Appleyard, 1967; Abdel-Rahman and Martin, 1987). As a testable hypothesis, these unusual rocks could be the product of metasomatic reactions involving a high-temperature alkaline fluid phase issued from the mantle, and able to transform locally pre-existing refractory rocks into nepheline- or quartz-normative bulk compositions that have the potential to melt. The corundum pegmatites (with corundum crystals up to a meter in length) could arise from a precursor in which aluminous phases are destabilized and locally desilicated by a high-temperature, high-pH fluid. The list of possible variants on the theme seems endless.

The transformation of granulites in the lower crust to fusible bulk compositions involves not only the major elements, of course, but a host of trace elements that generally are considered inert. However, with high temperatures, a high pH, and time, one can envisage regional anomalous buildups in high-field-strength elements, the rare earths, uranium and thorium, possibly ultimately reflected in ore deposits associated with the anorogenic complexes (Pirajno, 2004).

There has been broad acceptance of the concept of fertilization of sterile upper mantle; the model that I propose here merely extends the concept to the lower and middle crust directly above the newly fertilized upper mantle. Sterile crust can be metasomatized regionally, and can then melt to give anatectic A-type felsic magmas, either oversaturated or undersaturated in silica (Fig. 1), depending on the proportion of H<sub>2</sub>O and CO<sub>2</sub>. Only H<sub>2</sub>O can transport silica (Novgorodov, 1975). In the same area, basaltic melts can fractionate efficiently to give rise to A-type felsic magmas having a mantle signature. The stage is set to generate a complex array of felsic magmas containing both crust and mantle components. Where there is no continental crust, of course, the process will be greatly simplified.

The model proposed here explains many challenging aspects of A-type granites, and in particular the fertilization of granulitic crust to provide “ground preparation” for the formation of batches of A-type granitic magmas and associated other products. There are still many challenging questions, however. For example, why is it that bona fide A-type granitic melts are virtually unknown in the Archean?

## 6. Conclusions

- (1) There are serious challenges facing the petrologist attempting to explain the formation of A-type granites and related rhyolites of crustal derivation. One must explain (a) the juxtaposition of compositional variants of A-type granite, (b) the “cleanliness” of the rocks, (c) the variable role of a basic magma, (d) the production of metaluminous to peralkaline melts from a peraluminous crust, (e) the juxtaposition with silica-undersaturated and carbonatitic magmas, and (f) A-type granites apparently devoid of complex associations.
- (2) The origin of A-type granites and rhyolites is intimately tied in to the origin of nepheline syenite and carbonatite. All are manifestations of anorogenic magmatism, and are linked to processes going on in the upper mantle, and in the lower crust.
- (3) The working hypothesis rests on the fact that an area undergoing extension is a locus of mantle degassing. The mantle-derived fluid is alkali- and silica-bearing, and is able to transport a very wide array of elements, including the high field-strength elements, and a broad variety of anions are available to do the job.
- (4) Fentization-type reactions transform the refractory intermediate to mafic rocks of the lower crust to fertile assemblages that can melt (in cases completely) to give A-type granitic magmas of metaluminous or peralkaline character, or nepheline syenitic magmas, or carbonatitic magmas. Batches of peraluminous A-type granite may even result locally, but such granites also result from efficient near-surface degassing and preferential loss of alkalis.
- (5) The process is likely to homogenize geochemical and isotopic signatures completely and regionally.
- (6) Mass-transfer experiments and experimental fentization indicate the efficacy of this type of open-system process.
- (7) Cases of more shallow derivation of A-type felsic liquids by fractional crystallization of a basaltic parental magma, accompanied by minor amounts of assimilation, can be modeled successfully.
- (8) Owing to the remoteness and inaccessibility of the process in space and time, questions about the source of A-type granites in deep parts of ensialic rifts and zones of transtension, and about the starting point of fentization reactions prior to rheomorphism, will be extraordinarily challenging.

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