THE PATTERNS OF ENRICHMENT IN FELSIC PEGMATITES ULTIMATELY DEPEND ON TECTONIC SETTING

ROBERT F. MARTIN[§]

Department of Earth and Planetary Sciences, McGill University, 3450 University Street, Montreal, Quebec H3A 2A7, Canada

CATERINA DE VITO[¶]

Dipartimento di Scienze della Terra, Università di Roma "La Sapienza", P.le Aldo Moro, 5, I–00185 Roma, Italia

ABSTRACT

The classification scheme of granitic pegmatites currently in vogue is largely an offshoot of the depth-zone classification of granitic rocks. We propose instead a focus on petrogenetic processes at work, and extend it to pegmatites in silica-saturated and -undersaturated systems. Small-scale bodies of pegmatites are encountered in metamorphic systems undergoing anatexis, as temperature is rising regionally. We include a newly recognized category of corundum-bearing anatectic felsic pegmatite formed in mantle peridotite earlier subjected to a metasomatic overprint by a mixed $H_2O + CO_2$ fluid. The bulk of the pegmatite bodies encountered are not obviously of anatectic origin, but are derived by fractionation of pluton-size batches of felsic magma. We consider LCT (Li–Cs–Ta-enriched) pegmatites to be members of orogenic (calc-alkaline suites) formed in a subduction setting; in contrast, NYF (Nb–Y–F-enriched) pegmatites, are affiliated with anorogenic suites, formed in an extensional setting, and really not fundamentally different in petrogenetic lineage from suites in silica-undersaturated systems, including carbonatites. Both LCT and NYF types involve magmas containing crust and mantle components, but in the case of anorogenic magmatism, a metasomatic ground-preparation by a mantle-derived $H_2O + CO_2$ fluid phase precedes large-scale melting, to assure a product having alkaline tendencies. A primary NYF–LCT signature may occur in shoshonitic suites. Finally, we discuss hybrid pegmatites in which an NYF pegmatitic system takes on a LCT-like overprint owing to contamination from local sources. The possibility of an LCT pegmatite also being affected by an LCT-type overprint, to form a "super-LCT pegmatite" is explored briefly. Proper documentation of the petrogenetic processes at work is essential in assessing the economic potential of pegmatite occurrences.

Keywords: granitic pegmatite, felsic pegmatite, classification, petrogenesis, LCT pegmatites, NYF pegmatites, hybrid pegmatites.

SOMMAIRE

Le système de classification des pegmatites granitiques actuellement en vogue est largement dérivé de la classification des granites selon la profondeur de leur mise en place. Nous proposons comme alternative une classification fondée sur les processus pétrogénétiques responsables, et nous incluons ici les pegmatites des systèmes saturés et sous-saturés en silice. Des venues pegmatitiques à petite échelle sont souvent formées en milieu anatectique, au cours d'une culmination métamorphique. Nous incluons une catégorie récemment décrite de pegmatites anatectiques à corindon, formées dans les massifs de lherzolite ayant subi une métasomatose mantellique préalable en présence d'une phase fluide à $H_2O + CO_2$. En revanche, la plupart des venues de pegmatite sont le produit du fractionnement d'un volume important de magma. Nous considérons les pegmatites LCT (enrichies en Li–Cs–Ta) comme membres de suites orogéniques (calco-alcalines), signalant un contexte de subduction ou de collision; par contre, nous attribuons aux pegmatites NYF (enrichies en Nb–Y–F) une affiliation aux suites anorogéniques, formées dans un contexte d'extension, et sans différence fondamentale du point de vue pétrogénétique avec les essaims pegmatitiques des complexes sous-saturés classiques, y inclus les complexes carbonatitiques. Les pegmatites de types LCT et NYF contiennent typiquement des composantes de croûte et de manteau, mais dans le cas d'un magmatisme anorogénique, il y a eu une étape de préparation métasomatique du socle en présence d'une phase fluide à $H_2O + CO_2$ avant de passer à l'étape de fusion, afin d'assurer un produit à tendance alcaline. Un signal NYF + LCT inhabituel peut se développer dans des suites shoshonitiques. Nous décrivons ensuite les pegmatites hybrides dans lesquelles un ensemble NYF change à la fin de l'intervalle de cristallisation à un assemblage de type LCT, témoignant d'une contamination locale du système. La possibilité existe qu'une pegmatite LCT puisse aussi être affectée par une telle surimposition tardive, pour donner une pegmatite qualifiée de "super-LCT". Une documentation des processus pétrogénétiques serait essentielle à une évaluation du potentiel économique des venues pegmatitiques.

Mots-clés: pegmatite granitique, pegmatite felsique, classification, pétrogenèse, pegmatite LCT, pegmatite NYF, pegmatite hybride.

[§] *E-mail address*: bobm@eps.mcgill.ca
[¶] *E-mail address*: cdevito@uniroma1.it

Introduction

The mineralogy, geochemistry and petrology of granitic pegmatites are very familiar themes to regular readers of *The Canadian Mineralogist*. It thus seems most appropriate, in this anniversary issue, to revisit these themes, so as to possibly shed new light on the mechanisms of acquisition of important compositional attributes of these evolved rocks. In particular, we are interested in exploring the interplay of petrological processes and tectonic environments that have shaped the bulk composition of pegmatites in various evolved systems, not only those that contain quartz, but also those whose composition is close to the join Ab – Or, as well as those that are clearly undersaturated with respect to silica (Martin 1999, Martin & De Vito 2004). We see clear benefits in considering pegmatites of all felsic systems in one unifying system as we revisit the theme "Magmatism and Tectonic Settings". In terms of petrogenesis, some examples of quartz-bearing pegmatites bear a very close kinship to occurrences of pegmatites in silica-undersaturated systems, as will become evident in this review. The existence and implications of this kinship have not been explored in other treatises on "pegmatology".

In terms of the widely accepted and "traditional" scheme of classification of granitic pegmatites (Černý 1991a, b, c, Černý & Ercit 2005), depth of formation is the dominant control on the formation of the multifarious classes, subclasses, types and subtypes recognized, as illustrated in the only figure of the companion paper (Černý & Ercit 2005). Note that a classification based on depth of crystallization as a primary criterion also is available for granites (Buddington 1959). Buddington's depth-related terms (*e.g.*, epizonal, mesozonal, catazonal) are still in use, but the consensus now is that his approach, based as it is strictly on depth of formation, has been supplanted by a "petrotectonic" basis of classification (*i.e.*, the so-called "genetic" alphabet, as applied to post-Archean granites of the world). Petrologists now recognize that felsic magmas arise in areas of compression in the crust (orogenic suites), as well as in areas undergoing extension (anorogenic suites). Thus to use Buddington's depth-indicator terminology, one should expect epizonal orogenic granites and epizonal anorogenic granites, mesozonal orogenic granites and mesozonal anorogenic granites, and so on. And by the same token, insofar as any of these granite plutons can be associated with cogenetic pegmatites, one should anticipate epizonal orogenic pegmatites, epizonal anorogenic pegmatites, *etc*. Depth is indeed important, but not as a primary criterion in a classification scheme.

The plutons referred to above may well result from a "regional" collection of very small volumes of melt that have arisen through localized anatexis. Such small volumes arise by dehydration-induced partial melting of a suitable source-rock as temperature rises (or as pressure is released) in a regional metamorphic context. In this essay, we first describe the attributes of pegmatites found associated with migmatitic terranes in the crust. Such pegmatites of anatectic origin are not directly related to a parental pluton, except perhaps circumstantially, owing to proximity to a heat source. We then mention examples of anatectic pegmatites formed in the mantle, or in hot mantle-derived rocks that are emplaced diapirically into the crust. These represent a rarely encountered and newly recognized category of anatectic pegmatites. Then we explore briefly pegmatites that are produced by protracted fractionation of large batches of relatively primitive felsic magma in a waning cycle of igneous activity. Such pegmatites have an igneous parent somewhere, visible at the current level of exposure or hidden "at depth". We list the general characteristics of each group in turn, and explain how petrogenetic processes and tectonic settings are intimately interconnected in the case of both anatectic and fractionated pegmatites.

Pegmatites Formed by Anatexis

Anatectic pegmatites formed in the crust

In a regional metamorphic context, quartzofeldspathic rocks that contain hydrous phases are expected to approach the temperature of "wet" melting at conditions of the middle amphibolite facies. A typical reaction might involve the breakdown of a hydrous phase like muscovite or biotite, or simply an adjustment in their composition, such that the proportion of OH (consumed as a reactant in the melting reaction) is reduced, and that of fluorine is correspondingly increased. It is known from experiments that increasing the proportion of F extends the field of stability of micas and amphiboles up-temperature, a phenomenon that forms the basis for one "popular" hypothesis to account for the origin of A-type granites (Collins *et al.* 1982; more about that theme later). In systems undergoing anatexis studied experimentally, it is generally difficult to discern the beginning of melting, because the reaction is very sluggish, especially so if the system is undersaturated with respect to H_2O. It may take weeks or months for the first melt to appear in suitable assemblages held isothermally and isobarically (Piwinskii & Martin 1970). But once within the field of melting, the amount of melt may relatively quickly exceed 40–50 vol.% within a few degrees of the solidus, depending of course on the proximity of the bulk composition to the minimum or eutectic. As a corollary, one can expect that the role of most accessory minerals in such anatectic reactions is completely overwhelmed by the vast amounts of quartz, K-feldspar and albite, and the minor amounts of the hydrous phase, that reacted to produce the melt. Thus one can expect such melts to be close to the quinary

system $Na_2O - K_2O - Al_2O_3 - SiO_2 - H_2O$, and to be largely devoid of unusual enrichments in rare elements, at least initially.

Investigators of migmatites in regional metamorphic terranes commonly encounter leucosomes with a pegmatitic texture. Quartz and K-feldspar in particular can reach very coarse grain-sizes, even tens of centimeters across, even though the extent of movement seems to have been very limited in general, to judge from the overall conformity of such domains of granitic pegmatite to the gneissosity of the enclosing metasedimentary package and the common presence of a melanosome developed along the outer contact. Such pegmatites are expected to be mineralogically very simple and devoid of any zonation from one wall to the other. While conforming to the dictates of phase equilibria in the granite system, their bulk composition is expected to reflect that of the metasedimentary package undergoing melting. In particular, the key presence of one or two micas, and possibly of other aluminous phases, as reactants in the anatectic reaction ensures that the melt will be mildly to decidedly peraluminous. If the metasedimentary package is younger than Archean (see below), one might well expect the leucosome to have a high value of $\delta^{18}O$, reflecting the role of low-temperature processes during the weathering of the source and during the diagenesis of the sedimentary precursor.

Where the leucosome is discordant and the melt phase can be shown to have migrated, crystals are expected to nucleate and grow on walls of channelways, and the melt phase can show signs of fractionation as it moves forward. A common assemblage reported in leucosome is quartz + sodic plagioclase + K-feldspar + muscovite + garnet + biotite ± apatite ± beryl ± tourmaline (Barr 1985); in light of the findings of Evensen & London (2002), the presence of beryl and tourmaline is a sign that the anatectic melts have moved and fractionated on the way. Sawyer (1987) has documented the progressive development of a negative europium anomaly as feldspar is removed; at the same time, the melt can be expected to become progressively enriched in dissolved H_2O owing to the growth of anhydrous minerals like quartz and feldspar on the walls. Relatively rapid coalescence of such small batches of anatectic melt can give rise to small leucogranitic plutons and dikes locally exhibiting a pegmatitic texture, and overall mineralogical homogeneity; these accumulations commonly show signs of modal homogeneity but isotopic heterogeneity. Such cryptic heterogeneity reflects distinctions in the isotopic characteristics of the source, and specifically of the component reactant phases in the metasedimentary protolith (Harris & Ayres 1998). The steep gradients documented in the ratio $^{87}Sr/^{86}Sr$ in the tourmaline-bearing Manaslu leucogranite in the Himalayan continent–continent collision zone (Deniel et al. 1987, Le Fort 1988) attest to rapid collection of many small batches of leucogranitic magma rising together from the source and mingling on the way. Small batches

of the more evolved magmas also can crystallize as zoned bodies of miarolitic granitic pegmatite showing limited development of LCT characteristics (see below) in this Himalayan environment of continental collision (Laurs et al. 1998).

A particularly interesting case of granitic pegmatites of anatectic origin is found in the ore sequence in the Broken Hill area, New South Wales, Australia. Here, the metasedimentary sequence has a volcanogenic origin, and contains galena and sphalerite, among other sulfides. The quartzofeldspathic package was progressively metamorphosed, and four major events are recognized (Wilson & Powell 2001, Nutman & Ehlers 1998), leading to the upper amphibolite to granulite facies on a regional scale (850°C, 5–7 kbar, according to Frost et al. 2005). Anatexis involved not only the breakdown of a hydrous phase, with the participation of the H_2O consumed in the melting reaction, but also the loss of other volatile species, and in particular at Broken Hill, H_2S. The peraluminous anatectic granitic melt thus took in the Pb and Zn originally present in the sulfides, and the sulfur was lost to a gas phase as melting proceeded. The amount of sulfur that can be dissolved in the anatectic liquid is known to be close to nil, such that the Pb and Zn ultimately had to be accommodated in the products of primary crystallization. The zinc is largely accommodated in gahnite, ideally $ZnAl_2O_4$, whereas the lead is largely accommodated in the K-feldspar, which is locally "bottle green" and amazonitic in the pegmatitic dikes that cut the ore zone. The K-feldspar contains up to 2 wt.% PbO (M. Sokolov, unpubl. data), and the Pb in the K-feldspar is isotopically identical to that in the ore (Stevenson & Martin 1986). The pegmatites locally have a graphic texture, but otherwise are unzoned and more or less in situ in the ore zone. There is a strong likelihood that the sulfide assemblage also was partly molten while the silicate melt was present. Frost et al. (2005) have estimated that the sulfide melt may have persisted in this metasedimentary package for a very long time after the anatectic silicate melt froze, although this point of view is contested by others (P. Spry and I. Plimer, pers. commun., 2005).

The graphic texture is known to form from melts that experience supersaturation in quartzofeldspathic components, usually as a result of rapid cooling, in the endocontact, for example (London 2005). In the Broken Hill case, the proposal of rapid cooling in the mesozonal environment of anatexis is most unlikely. Rather, the pegmatite-forming melt must have been forced to degas, perhaps owing to sudden uplift, forcing the rapid nucleation and growth of the skeletal growth-forms. The absence of exsolution and of appreciable Al–Si order in the amazonitic K-feldspar, which is orthoclase rather than microcline, indicate that the pegmatitic assemblage lost what orthomagmatic aqueous fluid it held before crossing into the field of microcline, at 450°C or so. As a result, the minerals of the pegmatites have aspects of a quenched system after crossing the solidus, in spite

of the mesozonal environment (see below). Retrograde effects (leading to the conversion of orthoclase to microcline and the "exsolution" of lead from the structure to form secondary galena) are present, but very much limited to grain boundaries (Stevenson & Martin 1986). The Broken Hill example of melting of an orebody is not unique. Frost *et al*. (2002) have listed 25 or so examples of suspected melting of the ore in such settings, and in many of these, amazonitic K-feldspar signals the presence of granitic pegmatites of anatectic origin generated in the ore zone.

Anatectic pegmatites also can be expected at greater depths, especially where the crust has been greatly thickened in the context of continent–continent collision. Grew *et al*. (2004) have documented the presence of unusual granitic pegmatites of anatectic origin in the Larsemann Hills area, Prydz Bay, in eastern Antarctica, considered to be near the site of an important collision of continental masses during the Pan-African orogeny. The pods and veinlets of boron-rich pegmatite do contain tourmaline, in a graphic intergrowth with quartz, but also prismatine, grandidierite, dumortierite and boralsilite, all considered to be primary. Fitzsimons (1996) has attributed the anatectic reaction to the dehydration of biotite in the metapelitic assemblages, and has inferred a depth of 25 to 30 km at a temperature close to 860°C. The pegmatites display an "extreme" degree of enrichment in boron, quite possibly because of the participation of tourmaline as a reactant in the anatectic reaction. Grew *et al*. (2004) attributed the diversity of primary borosilicate minerals in part to the minimal loss of boron to the granulite-facies wallrocks in this relatively H_2O-poor environment. An enrichment of the melt in boron may be of primordial importance in the development of a pegmatitic texture in such systems.

Anatectic pegmatites formed in the mantle

The western Pyrénées of France are the "type locality" of a newly recognized category of anatectic feldspathic pegmatite, found in peridotitic host-rocks. Of the 40 orogenic lherzolite massifs exposed along the North Pyrenean Zone, emplaced into the crust in a zone of transtension, two of them, Urdach and Espéchère, located in the western part of the belt, contain geochemically very unusual albitite dikes of pegmatitic texture (Monchoux *et al*. 2006). The unusual assemblage of magmatic minerals includes, in addition to albite, coarse corundum in some dikes, muscovite, zircon, thorite, strontian epidote, aeschynite-(Ce), betafite, ferrocolumbite, rutile, and a rich suite of other exotic accessory minerals enriched in the light rare-earth elements, niobium, tantalum, zirconium, strontium and barium. Potassium and rubidium, on the other hand, are highly depleted. Extremely high values of Zr/Hf (in the range 62 to 72) and $(La/Sm)_N$ (30 to 40) have been documented by Pin *et al*. (2006). The dikes are homogeneous, and up to 5 m across; there are no such dikes

beyond the outer contacts of the peridotite. Pin *et al*. (2001) concluded on isotopic grounds that these felsic pegmatites are not desilicated "normal" pegmatites of crustal origin, as had been proposed in the earlier literature. In fact, the corundum shows textural evidence of rapid growth (Monchoux *et al*. 2006), indicating perhaps that these batches of felsic melt crossed their solidus rather quickly, during diapiric rise of the lherzolite into the attenuated crust from the site of incipient melting roughly 100 million years ago.

It seems most unlikely that the Pyrenean peridotites, having harzburgitic tendencies, can melt to give a suite of felsic pegmatite dikes containing 62–64% SiO_2 and such extreme degrees of enrichment in the high-field-strength and light rare-earth elements. In fact, Pin *et al*. (2006) conclude that the depleted peridotite had to have been fertilized in a "ground-preparation" step of metasomatism prior to melting. The metasomatizing agent has the earmarks of a natrocarbonatite melt, or a related carbothermal gas phase, or both. It is clear that H_2O also was involved, however, because the dikes do contain hydrous phases that are primary.

This category of mantle-derived anatectic felsic pegmatite potentially holds the key to a major petrological puzzle: alkali basalts associated with the same zones of extensional tectonics as the peridotite bring up, in some instances, a suite of enigmatic megacrysts of anorthoclase, corundum, zircon, among others, whose source rock has never been encountered in the field. Because of their inherent economic importance, such megacrysts have been the subject of a voluminous literature [*e.g.*, Sutherland *et al*. (1998), and references therein]. The analogy between the mineral assemblages in the Pyrenean dikes and the megacryst suites is striking, and it is a principal thesis of Pin *et al*. (2006) that the alkali basaltic melts sample such dikes during their trajectory toward the surface. Thus, such pegmatites may turn out to be economically of great importance, although rarely exposed in the upper crust, and present only as dikes of rather small size at the present level of exposure.

They are rare, but they most likely are not unique! Mantle petrologists know well the Finero complex, in the Ivrea zone, along the Insubric Line in northern Italy. It has been the subject of many investigations owing to clear evidence of a wave of metasomatism affecting a peridotite initially having rather depleted characteristics. The fertilization led to the formation in the core zone of the complex of a major map-unit labeled *phlogopite peridotite*. Whether this metasomatism occurred in a subduction setting or in response to a rising diapir of asthenospheric origin has been the subject of animated debate among specialists. Interestingly, Stähle *et al*. (1990) have documented the presence of albite-dominant zircon syenite pegmatites that cut the phlogopite peridotite; these pegmatites are devoid of corundum, but do match the Pyrenean examples in their anomalous

buildups of key trace elements, though not to the same extent as at Urdach and Espéchères.

On the other hand, mineral collectors are aware that coarse corundum does occur in the Finero massif, in pegmatite dikes exposed in the Cannobina Valley, for example (A. Guastoni, pers. commun., 2004). Unfortunately, these dikes have never been investigated, but do seem to provide other examples of the mantle-derived category of anatectic pegmatite. Interestingly, the unusual discovery of zirconolite and a suite of exotic Zr–Th–U minerals containing Y, Hf, Pb, and LREE in chromitite in the fertilized peridotite at Finero led Zaccarini *et al.* (2004) to propose a metasomatic overprint of carbonatitic character. These authors thus bring a solid contribution to the ongoing debate, as carbonatitic activity is not a hallmark of a subduction-zone environment. Finero, like Urdach and Espéchères, thus most likely are sites of active metasomatism preceding and leading to incipient anatexis during diapiric emplacement of masses of peridotite into the crust in a local transtensional environment related to oblique collision. Corundum-bearing pegmatitic albitite dikes can thus be expected in areas of continent–continent collision, like in the Alps and the Pyrénées, where there was local attenuation of the crust and diapiric emplacement of fertilized lherzolite and harzburgite. Metasomatism clearly had to precede the anatectic reaction.

Pegmatites Formed by Fractionation of a Precursor Magma

As should be obvious from comments made above, almost all the voluminous work on felsic pegmatites has been done on examples whose existence can be linked to a parental body of relatively evolved magma sufficiently fluid and mobile to be undergoing fractional crystallization on the time-scale of its crystallization. Writing about the origin of rare-element-enriched granitic pegmatites, Černý (1991b) summarized the criteria that convinced him that they are "products of advanced fractionation of pluton-size batches of granitic magmas": 1) presence of physical links between pegmatite bodies and parental pluton, 2) continuity in textural, mineralogical and geochemical parameters, 3) identity of pegmatite bodies inside and beyond the outer contact of the pluton in a proximal position, 4) correspondence of bulk compositions to experimentally determined minima or eutectics in geochemically evolved systems, and 5) relevance of temperatures of crystallization to these experimental findings.

The simple-minded model of a pluton undergoing *in situ* crystallization from the walls in, from the bottom up and from the top down is certainly oversimplified. Yet many examples of dikes of granitic pegmatite have been documented cutting the parent granite itself, inside the endocontact. However, in view of the viscosity of the melt, fractionation, by which we mean the separation of a rest-liquid from crystals that it has produced,

likely does not occur *in situ*, like in a mafic magma; in fact, it must require movement of the magma and crystallization on the walls of a channelway, much as was demonstrated by Sawyer (1987) in cross-cutting leucosomes, mentioned in the previous section. In such a case, the crystals are "fed" by the magma flowing by, some reaching grain sizes worthy of the label "pegmatite".

Černý (1991b, Fig. 7) showed a pattern of outward zonation of pegmatite groups that is commonly developed in LCT suites (see below), from 1) relatively barren to 2) Be-enriched, to 3) Be-, Nb-, and Ta-enriched, to 4) Li-, Be-, Ta-, and Nb-enriched, to 5) Li-, Cs-, Be-, Ta-, and Nb-enriched groups. There are many examples in the literature to document the increasing degree of fractionation of pegmatite bodies outward from a parental pluton on a scale of kilometers. To London (2005), this question is the most intriguing aspect of research on granitic pegmatites, and still an unsolved puzzle. The progressively developed fractionation with increasing distance from the parental pluton seems to indicate that the dike system must remain open and connected over a very long time. However, Shearer *et al.* (1992) cautioned against jumping to the conclusion that the entire sequence illustrates progressive fractionation of a single batch of liquid; the lithium-enriched melts, in the portions of a pegmatite field furthest from a parental pluton, as an example, could emanate from a different source-area in a zoned parental pluton (or possibly from a different source-area having nothing to do with the parental pluton; see below).

What about the cases where a parental pluton is nowhere to be found? There are many instances in the world where a rare-element-enriched granitic pegmatite appears "out of nowhere", apparently devoid of a parental pluton. Geologists of course must work with what they have, but the temptation might be to infer that the pegmatite is simply of anatectic type, without a parental pluton in the petrogenetic picture.

In the case of the Cap de Creus granitic pegmatite, in northern Catalunya, in the Spanish foothills of the Pyrenées, Corbella & Melgarejo (1993) have identified four distincts episodes of dike emplacement in the lower Paleozoic, during the Hercynian orogeny, with the fourth one strongly sodic owing to Na metasomatism. In this instance, the parental pluton is not exposed, but the pattern of fractionation, as seen in the accessory minerals, and the progressive buildup of primary phosphates, most prominent in the third generation (Alfonso & Melgarejo 2000), favors the existence of an unseen fractionating system "below". Furthermore, the Cap de Creus suite is considered coeval with the Albera suite located on the French side of the border, where the parental pluton has been recognized (Malló *et al.* 1995). Thus caution definitely is needed before jumping to the conclusion that there is no parental pluton in one's study area, and that fractionation of crystals from a parental magma is not the main petrogenetic process at work.

FRACTIONATION-RELATED GRANITIC PEGMATITES AND TECTONIC SETTINGS

HAVE ALL GRANITIC SYSTEMS UNDERGOING FRACTIONATION ARRIVED AT AN EVOLVED STATE BY THE SAME PETROGENETIC PROCESSES? EVOLVED FELSIC PLUTONS ARISE IN TWO DISTINCT TECTONIC ASSOCIATIONS, WELL KNOWN TO IGNEOUS PETROLOGISTS, BUT REVIEWED HERE IN DETAIL FOR THE BENEFIT OF THOSE LESS FAMILIAR WITH THE RAMIFICATIONS OF THE PHRASE MADE FAMOUS BY READ (1957), "THERE ARE GRANITES AND GRANITES". WE CONTEND THAT PROCESSES DIFFER IN DETAIL IN EACH OF THE TWO ASSOCIATIONS, AND THAT TECTONIC SETTING AT THE TIME OF EMPLACEMENT IS THE KEY IN DETERMINING THE SEQUENCE OF PETROGENETIC PROCESSES THAT WILL UNFOLD.

OROGENIC OR CALC-ALKALINE MAGMATISM

The plutons

Felsic plutons of I- and S-type are emplaced in subduction-related settings, where crustal compression is dominant. There are countless variations on the theme, but basically H_2O, and the elements that it carries, become released as subduction proceeds, and "fertilize" the mantle wedge above a dipping zone of active subduction (Fig. 1). The "fertilization" involves the net addition to the mantle wedge of constituents released from the downgoing slab, and carried by the H_2O, which is being released in major amounts owing to dehydration-type metamorphic reactions affecting serpentine-, chlorite- and epidote-bearing assemblages. Chief among these constituents are the alkalis (especially Na), silica, chlorine, lithium, boron, and a host of other elements inherited from seawater, seafloor rocks and trench sediments. The partial melt that develops in the metasomatized mantle above the subduction zone is hydrous and basic to intermediate, possibly tonalitic or granodioritic, owing to the effect of H_2O on the field of stability of orthopyroxene. Such a mantle-derived partial melt rises into the crust directly above, underplates it, melts it, and there occurs a complicated sequence of magma mixing and mingling (Fig. 1). Each "end-member" in the mixture, labeled M and S by Castro *et al.* (1991), can also crystallize independently, and thus can give the isotopic values of the components of the mixture where the association is well exposed in orogenic belts. Granitic pegmatites in this association thus result from a magma that in general bears evidence of a mixture of sources (not necessarily only two!), and that itself has clearly undergone fractionation. The batch of evolved magma that crystallizes as pegmatites associated with such calc-alkaline magmas of I + S type will commonly bear a strong imprint of a crustal component (*i.e.*, a S-type source).

Oxygen isotopes provide one of the most reliable indicators of involvement of crustal rocks in an evolved granitic pegmatite. Thus if one finds high whole-rock values of $\delta^{18}O$, say +11‰, distinctly higher than a value

typical of the upper mantle, one is on safe grounds to infer that a metasedimentary sequence of rocks was present as source material for part of the system, and is thus a component of the mixed-source melt produced. But there is a secular dimension to the property, such that in the Archean, weathering reactions and low-temperature alteration had not progressed significantly to give a "non-mantle" signature to the sedimentary rocks. By measuring over a thousand grains of zircon to explore the importance of this effect (zircon being chosen because of its great resistance to change where the degree of metamictization is low), Valley (2003) found that one could expect a decodable "crustal" signature (a modest $8.0 < \delta^{18}O < 9.0‰$) only in S-type granites younger than 1.5 Ga. Rocks older than 1.5 Ga invariably give mantle-type values, which means that the Archean metasedimentary sequences are pristine and still possess their primordial characteristics. A corollary to the above discussion is that in general, vast tracts of peraluminous metasedimentary protoliths are not likely in Archean times, and as a result, the partial melts will tend to be metaluminous, rather than peraluminous, in spite of the important role of metasedimentary rocks at the source. Some igneous suites may even be confused for anorogenic suites (see below). Another corollary seems to follow: as the complement of major and trace elements has not been tapped earlier in an Archean episode of crustal melting and has not been affected by strong chemical weathering, the resulting pegmatites developed in Archean granitic suites may show unusual levels of enrichment in alkalis and economically important elements, *e.g.*, Li and Sn. The parental packages of such S-type crustal rocks seem in many cases to be "undergoing their first anatexis" (Černý 1992). The important findings of Valley (2003) indicate that the sources of Archean granites are indeed "different", as were plate-tectonic processes, at least in detail. Archean plate tectonics, just as Archean granites and Archean granitic pegmatites, should not be expected to conform to post-Archean examples in all aspects of their petrogenesis and in system of classification. Felsic suites identified as indicators of extensional tectonics also seem highly unusual in the Archean. Dall'Agnol *et al.* (2005) have shown that the oldest *bona fide* A-type granites on Earth are latest Archean in age.

The associated pegmatites are of LCT type

On the basis of the above discussion, the crustal component of an LCT-type rare-element-enriched pegmatite may or may not be strongly identifiable isotopically. Černý (1991b) defined the LCT-type pegmatites as those enriched in Li, Cs and Ta (giving the acronym), and also notably enriched in Rb, Be, Sn, B, P and F. Peraluminous bulk-compositions are dominant, at least in suites of Proterozoic age and younger. Note that the excess aluminum at the source allows phosphorus to be incorporated into the melt according
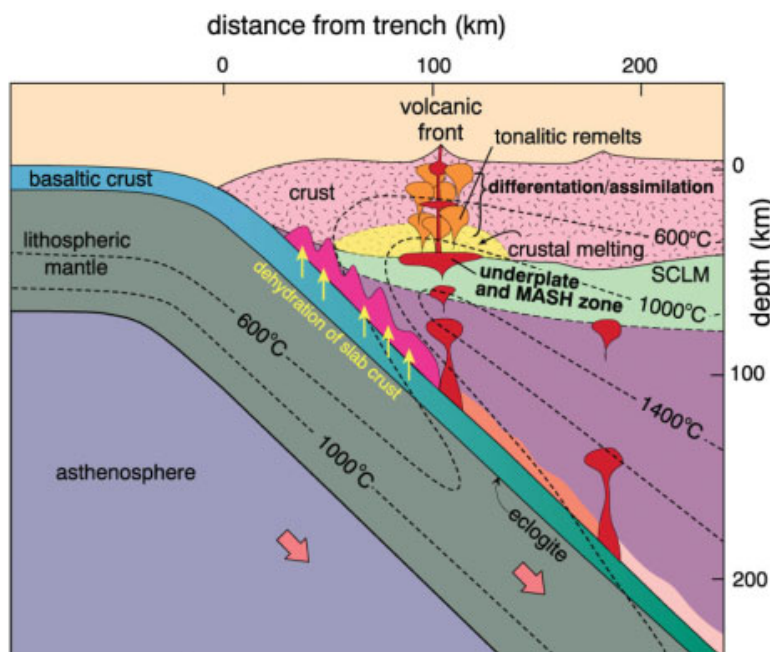
Fig. 1. Schematic cross-section of a zone of active subduction at a continental margin. As the slab of ocean-floor rocks and the veneer of trench sediments subduct, they will dehydrate. CO_2 is not important in this setting. The dehydration involves much more than H_2O, however. Sodium, chlorine, silica, lithium, and boron are among the constituents that are expected to rise and "fertilize" the subcontinental lithospheric mantle in the wedge directly above the subduction zone. The rising fluid phase also provides an efficient mode of transfer of heat into the crust, and the zone of melting and mixing of magmas propagates upward. Only a small part of the H_2O participates in melting reactions. The rest hydrates the crust on a regional scale and promotes metamorphic reactions. Batches of evolved calc-alkaline magmas likely get injected into metasedimentary host-rocks that have been "soaked" and sodium-metasomatized from below. Considered relevant to a discussion of fractionated pegmatites is the possibility that such batches of high-salinity fluid can be the medium of localized Na-metasomatism of the hot, recently formed pegmatitic suite. MASH: zone of melting, assimilation, storage and hybridization; SCLM: subcontinental lithospheric mantle. Diagram courtesy of John Winter (2001), and reproduced with permission.

to: 2 Si $\rightleftharpoons$ Al + P, and in fact many LCT pegmatites contain an important amount of P in the structure of their feldspars [*e.g.*, the pegmatites associated with the South Mountain batholith, Nova Scotia: Kontak *et al.* (1996), those of the Albuquerque batholith, in Spain: London *et al.* (1999), and those of the western Carpathians: Broska *et al.* (2004)]. In some LCT-type granitic pegmatites, there is also a rich development of primary and secondary phosphates that can monitor the temperature and $f(O_2)$ at the time of crystallization (Moore 1982, Fransolet *et al.* 2004, Whitmore & Lawrence 2004). The enrichment in boron and tin presumably reflects detrital components in the sedimentary precursor, and boron and lithium also may be part of an authigenic assemblage of clay minerals and chlorite, respectively, in the sedimentary precursor. Both B and Li are easily mobilized in subduction-zone settings, and are expected to rise with the H_2O carrier fluid into the mantle wedge (see below). Tin, P, Li and B eventually find their way into the melt phase, as can be ascertained by studies of melt inclusions trapped in quartz and other primary minerals (*e.g.*, Webster *et al.* 1997). In some orogenic granites containing evidence of an S-type affiliation, there are even hints of immiscibility of silicate and phosphate melts inside such melt inclusions, as illustrated by these authors.

At this stage in the characterization of fractionated granitic pegmatites and of their purported parental plutons, there are very few examples of quantitative tests of the parent – pegmatite linkage. In one such

example, Tomascak *et al.* (1998) used Sm–Nd isotope systematics to show that in the Topsham area of southwestern Maine, there are batches of granitic pegmatite of distinctly different and identifiable sources within a restricted area, some pegmatites of LCT type isotopically close to muscovite – biotite– garnet leucogranite occurring in well-defined plutons, whereas others are more similar isotopically to leucosomes in migmatitic metasedimentary material adjacent to those plutons. Yet these bodies of granitic pegmatite seem identical megascopically.

In almost all cases, the parentage issue remains untested, and the source characteristics unconstrained. In the case of LCT granitic pegmatites on the Island of Elba, in Italy, for example, there is superb exposure of pegmatite dikes in close association with the late stages of evolution of the Monte Capanne calc-alkaline pluton. The component parts of this very young and recently uplifted example of arc magmatism in the back-arc area of the Tyrrhenian Sea have been very well documented petrologically, mineralogically and isotopically (Dini *et al.* 2002a), and the classic LCT pegmatites have been very well characterized mineralogically (Orlandi & Scortecci 1985, Pezzotta 2000, Aurisicchio *et al.* 2002). The stage is now set to test the linkage. Which member of the Monte Capanne complex produced the leucogranitic magmas that crystallized as the thin, strikingly zoned dikes of miarolitic granitic pegmatite? Whereas the parental orogenic pluton has a clear isotopic signature of a mixed source (mantle + crust), is the same signature typical of the pegmatites? What about the ultimate source of the boron in the elbaite, and of the Li, Be, Sn, Ta in the more accessory minerals that made the Elban LCT pegmatites exposed near San Piero in Campo area so famous? Are these elements possibly contributed from the host metamorphic complex, which includes mafic and serpentinized ultramafic rocks? Similar questions can be asked of classic LCT pegmatites elsewhere, for example in Minas Gerais and in the Borborema belt in Brazil, and in the Pala District of southern California. The spatial association with calc-alkaline batholiths is striking, but the genetic fingerprinting of parent pluton and pegmatite remains for future investigators making use of robust isotopic systems.

Summary of petrogenetic processes

The parental mantle-derived magma, formed by partial melting in the mantle wedge in a tectonic environment of overall compression (Fig. 1), rises into the lower crust and presumably undergoes assimilation – fractional crystallization (AFC). The regional rise of the geotherms facilitates partial melting of regionally heated muscovite- and biotite-bearing metasedimentary sequences in the crust. This regional rise of geotherms is due to the hydrothermal plume rising from the subducting plate, which is responsible for the regional

metamorphic envelope that surrounds the batholiths (Miyashiro 1994). Magma mixing and magma mingling are both likely where contrasting magmas are juxtaposed. With progressive fractional crystallization of the magma, the composition of the product is more and more enriched in H_2O, B, P, F, and Li, all elements that are likely to have a marked influence on the rheology of the magma, and on its ability to fractionate efficiently. Note that the effects of the above constituents are likely to be additive, as they influence different sites in the structure of the melt. Extreme fractional crystallization of the melt can give rise to the inception of liquid immiscibility between the silicate magma and a phosphate liquid. The end-products are metaluminous to peraluminous granitic pegmatites whose particular pattern of geochemical enrichment is the cumulative reflection of all processes that have happened earlier in the petrogenetic lineage. It is clear that these have involved both crust and mantle source-materials to variable extents.

Of course, superimposed on the products of magmatic crystallization is the hydrothermal chapter of the story, where many of the magmatic products are recrystallized or replaced by minerals stable at a lower temperature, such that only relics and pseudomorphs may remain of what the magma once produced. The feldspar assemblage is particularly reactive; in granitic pegmatites of LCT parentage, as in those of NYF type (see below), the typical K-feldspar is now low microcline, and pseudomorphic after a primary monoclinic K-dominant feldspar that has in most cases been completely reprocessed compositionally and texturally (Martin 1988). What these processes do to the trace-element budgets of the bulk rock, in view of the volumetric importance of feldspar-group minerals, constitutes a fertile area of future study. Isotopic systems also are likely partially reset, which means that only the more robust systems (*e.g.*, Sm–Nd: Tomascak *et al.* 1998) can be expected to give unambiguous information about primary processes. Owing to its insoluble character relative to the feldspars, quartz will be relatively inert to these late modifications; the oxygen isotopic characteristics of the quartz thus may well be pristine. At issue here is the very definition of an igneous rock. The granitic pegmatite may be of igneous origin, but by and large, its mineralogy and geochemical signature are no longer igneous. *Caveat emptor!*

Anorogenic Suites

Igneous suites also are emplaced at times of tectonic quiescence, where the crust is in a state of lateral extension and attenuation. Such suites are considered anorogenic (*i.e.*, devoid of a link to an orogeny), whence the label "A-type" applied to a granite or rhyolite. Of course, the scale of the extension may be strictly local as opposed to regional; oblique collision of continental masses may give rise to localized and ephemeral cases

of "transtension", the environment in which diapirs of fertilized mantle-derived peridotite are considered to have risen into the crust, as discussed earlier. These cases of A-type granites in a belt undergoing overall compression may cause confusion, unless one focuses on the possibility of local extension and its consequences in the realm of igneous response.

It is clear that a tectonic regime in a given area may change rather suddenly from compression to tension, or *vice versa*. Consider the nature of recent magmatism in the Basin and Range Province of the western United States. Fitton *et al.* (1991) have documented a rapid change in the nature of the mantle source of basaltic volcanism in this area. First there were calc-alkaline magmas associated with a lithospheric mantle enriched by subduction-related fluids, then a sudden switch, within the space of three or four million years, to basalts generated in an upwelling mass of hotter, more fertile (and metasomatized) asthenosphere. The younger basalts are associated with A-type rhyolite in strongly bimodal suites. The thermal erosion of lithosphere by asthenosphere is of course not accomplished exactly at the same time throughout the Basin and Range Province; there may well result, in some areas and over a geologically brief interval, a confusing juxtaposition of coeval orogenic and anorogenic suites, involving distinct sources in the mantle. It seems clear that a tectonic setting can change (owing to plate geometry) in the span of three or four million years or so, but it is not reasonable to ask it to change while a batch of pegmatite-forming magma is in the process of crystallizing!

The anorogenic plutons

On the African continent, once the pericratonic Pan-African orogeny was over in Cambrian times, the orogenic suites gave way to anorogenic suites, in some instances soon after the compression gave way to a period of relaxation (Abdel-Rahman & Martin 1990); to this day, all igneous activity on the African continent is anorogenic, and characterized by bimodal suites, either silica-oversaturated or silica-undersaturated (Abdel-Rahman & El-Kibbi 2001).

Consider the Chilwa alkaline province, in southern Malawi, of Cretaceous age. What makes it unusual, but by no means unique in Africa and elsewhere, is the exceptional variety of rock types emplaced in this belt (Woolley 1987, 2001, 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, but 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 million years older. Carbonatite and nephelinite started the cycle of activity, about seven million years earlier. The juxtaposition of such rock types (Fig. 2) is rather common, and can be found in the White Mountain

magma series in New Hampshire and adjacent states, and the analogous rift-related Mesozoic suite on the other side of the Atlantic, in Niger and Nigeria. Bowden *et al.* (1987) have commented on the many parallels among A-type granitic magmas, silica-undersaturated magmas and carbonatitic magmas, in particular with respect to their hydrothermal overprints. Such a secular development of an intrusive sequence in the Chilwa Province and along similar zones of extensional tectonics may well signify the progressive heating and alkali metasomatism of the crust prior to its large-scale melting owing to underplating of the lower crust by basic magma coming in from the mantle (Fig. 2).

The associated granitic pegmatites are of NYF type

Within the above context, the label NYF is applied only to the silica-oversaturated suites. These are granitic pegmatites with Nb dominant over Ta, with an enrichment in Ti, Y, REE, Zr, Th, U, Sc and F (Černý 1992, Wise 1999). Thus they contrast strikingly in many ways with the LCT pegmatites described earlier. As an example, we may consider the bodies of NYF pegmatite that occur at Mount Malosa in Malawi, associated with the classic A-type granite mentioned earlier. These pegmatites are miarolitic, and 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, niobophyllite–astrophyllite, among others (Guastoni *et al.* 2003).

In addition to the spectacular NYF-type pegmatites of the Zomba–Malosa pluton, there are many others that are more familiar. The Pikes Peak batholith, emplaced 1.08 Ga ago in north-central Colorado, forms part of a well-documented anorthosite – gabbro – syenite – granite association (Barker *et al.* 1975, Smith *et al.* 1999), emplaced approximately 700 million years after the Yavapai orogeny, with which the nearby orogenic granites are associated. The mineralization associated with these NYF pegmatites involves fluorite and minerals enriched in the high-field-strength and rare-earth elements, for example members of the samarskite, fergusonite, monazite, xenotime, gadolinite, allanite, and bastnäsite groups, as well as yttrofluorite and aeschynite-(Y) (Simmons *et al.* 1987, Hanson *et al.* 1992). The fluids responsible for the hydrothermal mineralization in the Oregon No. 3 pegmatite, which shows some of the best mineralization among the pegmatite bodies in the South Platte District of the Pikes Peak batholith, are internally produced (Gagnon *et al.* 2004).

For some reason, perhaps because of lingering confusion as to what constitutes an anorogenic association and the associated NYF-type pegmatites mineralogically and geochemically, some interesting occurrences are remaining unnoticed in the literature. Part of the
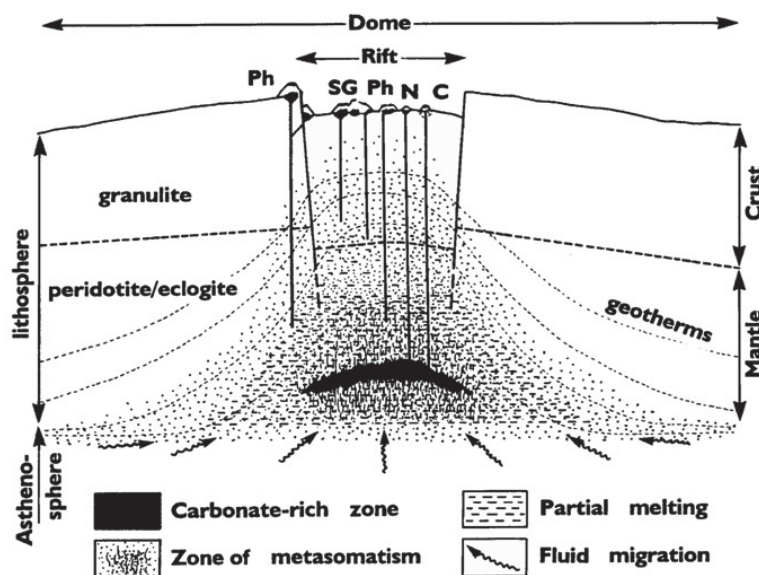
Fig. 2.   Schematic cross-section of a zone of active rifting in a continental setting. The upward bulge in the asthenospheric mantle is due to a focusing of mantle degassing and thermal expansion. Here, as in Figure 1, the upward migration of fluid offers a very efficient mechanism of transfer of heat 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 reaction. Where the metasomatizing agent is dominantly H_2O, granitic melts of A type will result. The metasomatic steps leading up to partial melting have involved the preferential mobilization of alkalis over Al, which is reflected an alkaline character of the partial melt. Carbonatitic and nephelinitic melts will result in areas where CO_2 is the dominant metasomatizing agent. Here, the metasomatic step leading up to partial melting has caused a major enrichment in high field-strength elements and the rare-earth elements, and these patterns of enrichment are reflected in the magmas produced. Of course, all intermediate cases between these two 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 promote granulite-facies assemblages, even though the environment is far from being anhydrous. Diagram courtesy of Alan Woolley (1987), and reproduced with permission of the publisher.

problem certainly stems from the fact that the original definition of what is an anorogenic granite is found in an abstract (Loiselle & Wones 1979), one of the most widely quoted in the petrological literature, in fact, and the full article was never written. Cases of confusion thus are common even in the recent literature.

Consider the classic granitic pegmatites associated with the Baveno granite, exposed near the shore of Lago Maggiore, in northern Italy. Boriani *et al.* (1995) documented two episodes of felsic magmatism in the area, one orogenic, dated at 466 Ma, and formed in a convergent plate-boundary situation in an accretionary terrane. The second episode is Permian in age (276 Ma), and gave the well-known metaluminous Baveno granites. The Baveno granite is locally fayalite- and

magnetite-bearing, and strongly LREE-enriched, and has a prominent negative Eu anomaly expected of a granite that may have fractionated from a mafic parent. In fact, the Baveno–Mottarone pluton seems closely related to the Appinite suite of mafic and intermediate stocks and dikes (Pinarelli *et al.* 2002). The Baveno granite has a $(^{87}Sr/^{86}Sr)_i$ in the range 0.708–0.710, which is diagnostic of a mixture of crust and mantle materials at the source. Many samples have sufficient Nb and Y to place them squarely in the field of within-plate granites. In spite of these indicators, Boriani *et al.* (1995) concluded that the Baveno granite is "calc-alkaline to weakly peraluminous" and post-orogenic, formed in an extensional regime in cratonized crust. In our opinion, this granite is not calc-alkaline. To label it

post-orogenic is not wrong, but is misleading; after a lapse of 190 million years of quiescence, a more precise term might have been "anorogenic". The extensional regime inferred by these authors must be associated with important rift-related igneous activity, possibly in a transtensional environment. The granite and the associated pegmatites bear the imprint of such a tectonic environment.

The pegmatites hosted by the Baveno granite are miarolitic, and are clearly of NYF type (Aurisicchio *et al.* 1999). The species bavenite, bazzite, cascandite, jervisite and scandiobabingtonite all have their type locality in those miarolitic cavities (Pezzotta & Guastoni 2003, Gramaccioli 2003). The patterns of enrichment are clearly those expected of an NYF-type pegmatite, contaminated at the hydrothermal stage by fluids in equilibrium with adjacent more mafic rock-types, the mineral constituents of which have become destabilized; calcium and scandium are contributed by the host rocks, and Be, in bavenite [$Ca_4Be_2Al_2Si_9O_{26}(OH)_2$] and bazzite [$Be_3(Sc,Al)_2Si_6O_{18}$], by the evolved, fractionated pegmatite-forming magma.

Analogues in saturated and silica-undersaturated anorogenic suites

The world's largest alkaline complex, Khibina, in the Kola Peninsula of Russia, of Devonian age, consists of a concentric array of arcuate map-units, mostly consisting agpaitic nepheline syenite. Carbonatite is a minor component at the present level of exposure. Pegmatites are found in all intrusive units, as are coarse-grained rocks of demonstrably hydrothermal origin (Yakovenchuk *et al.* 2005). In fact, pegmatite bodies commonly overlap or grade into hydrothermal assemblages, so that pegmatite *sensu stricto* and hydrothermal assemblages are not readily distinguishable (Pekov & Podlesnyi 2004). Prominent minerals include K-feldspar, nepheline, aegirine, eudialyte-group minerals, titanite, aenigmatite, apatite, villiaumite and sodalite as primary minerals, with analcime, natrolite, shortite and thermonatrite as lower-temperature products deposited hydrothermally. Typically, the hyperagpaitic minerals (*i.e.*, in which alkalis are greatly in excess of aluminum) are pseudomorphic after earlier-formed minerals, *e.g.*, zirsinalite after eudialyte, nacaphite after apatite. Interestingly, some of the late-stage pseudomorphs are Ca- and Sr-rich, and involve zeolites associated with calcite. These late minerals are possibly indicators of the hydrothermal influx of material from the enclosing rocks.

The hyperagpaitic assemblages represent the ultimate stage of fractionation in these pegmatitic systems, and as such are marked by strongly peralkaline, Al-poor or Al-free phases, some of which are soluble in water. Alkaline titanosilicates and zirconosilicates are among the characteristic minerals. Khomyakov (1994, 1995) has pioneered the investigation of these minerals and

has explored their implications. Among the phases found in the most strongly agpaitic assemblages are barytolamprophyllite, chkalovite, kazakovite, lomonosovite, olympite, pautovite, phosinaite-(Ce), rasvumite, steenstrupine-(Ce), villiaumite, vitusite-(Ce), vuonnemite, and zirsinalite. A sample listing of the formulas of these unfamiliar species (Table 1) indicates which elements are the ultimate expression of the processes of enrichment that began in the upper mantle, but at Khibina are greatly amplified by the accumulated affects of fractional crystallization in a near-surface environment. Note that they correspond to the same suite of incompatible trace elements that characterize the NYF pegmatites: the rare-earth elements, Nb, Ti, Zr, Th, Be, Li, Cs, Mn, and F. This geochemical coincidence supports our contention that NYF pegmatites and hyperagpaitic silica-undersaturated pegmatites are both examples of fractionated anorogenic magmas, not differing fundamentally in relevant processes, but perhaps only in extent, or in the nature of the fluid phase. Phosphorus consitutes one major difference between them, however. Whereas the NYF suites are all but devoid of phosphates, strongly alkaline (*i.e.*, strongly subaluminous) magmas clearly are able to accommodate phosphate groups in a way that does not involve a coupled substitution with Al. One possible scheme might well be $Na^+ + Si^{4+} \rightarrow \square + P^{5+}$.

Summary of petrogenetic processes in felsic anorogenic suites

The genesis of A-type granites thus can be discussed only as a subset of the grand theme of extension-related igneous activity. Whether the ultimate product of magmatic fractionation will be granite, syenite, nepheline syenite or carbonatite (Fig. 2) does not

TABLE 1. SELECTED ACCESSORY MINERALS FOUND IN
STRONGLY PERALKALINE SILICA-UNDERSATURATED
ANOROGENIC SUITES

barytolamprophyllite	K	$(Na,K)_2(Ba,Ca,Sr)_2(Ti,Fe)_3(SiO_4)_4(O,OH)_2$
chkalovite	L	$Na_2BeSi_2O_6$
kazakovite	L	$Na_6MnTiSi_6O_{18}$
lomonosovite	L	$Na_5Ti_2O_2(Si_2O_7)(PO_4)$
olympite	K	$LiNa_5(PO_4)_2$
pautovite	L	$CsFe_2S_3$
phosinaite-(Ce)	L	$Na_{13}Ca_2Ce[Si_4O_{12}](PO_4)$
rasvumite	K	KFe_2S_3
steenstrupine-(Ce)	I	$Na_{14}Ce_6Mn^{2+}Mn^{3+}Fe^{2+}{}_2(Zr,Th)(Si_6O_{18})_2(PO_4)_7 \cdot 3H_2O$
vitusite-(Ce)	L, I	$Na_3(Ce,La,Nd)(PO_4)_2$
villiaumite	Los	NaF
vuonnemite	K	$Na_{11}TiNb_2(Si_2O_7)_2(PO_4)_2O_3(F,OH)$
zirsinalite	K	$Na_6(Ca,Mn)ZrSi_6O_{18}$

The type locality of these "primary" accessory minerals is either in the Khibina (K) or Lovozero (L) complex, Kola Peninsula, Russia, or the Ilímaussaq (I) complex, South Greenland, except for villiaumite, discovered in the Los complex, Guinea. The pattern of enrichment is that found to be characteristic of NYF granitic pegmatites.

imply a fundamentally different process, but rather the extent to which that process has taken place, and the composition of the fluid phase responsible. Everything starts in the mantle, and is associated with a focusing of volatiles (Woolley 1987) ahead of a rising plume of fertile mantle peridotite (asthenophere). These volatiles metasomatize the uppermost mantle, in a way explored earlier in the case of localized anatectic phenomena associated with rising diapirs of fertilized harzburgite and lherzolite. As in that case, the fluid phase generally contains both H_2O and CO_2, and is alkaline. It can carry a host of trace elements in solution, in particular the high-field-strength elements and the light rare-earths, and continues from the mantle upward through the bulged-up crust, which is in a state of attenuation, extension and thermal anomaly (Fig. 2). In this way, there is regionally developed a pre-anatexis stage of metasomatic activity, which Abdel-Rahman & Martin (1988) called metasomatic "ground preparation". Only with such open-system alkali metasomatism can normal crustal rocks, which are metaluminous to peraluminous, become peralkaline in bulk composition. For example, Preston *et al.* (2003) have shown, in their experimental investigations of fenitizing fluids, how it is possible to hydrothermally convert a normal granodiorite into an aegirine-bearing silica-undersaturated assemblage. The reactions affecting the lower to middle crust are regionally developed fenitization-type reactions that can lead to rheomorphism (Martin 2006).

Some batches of A-type magma will arise by efficient fractional crystallization of a mantle-derived mafic magma, and will be identical to the mafic parent isotopically. Other batches of A-type magma can arise by rheomorphism of alkali-metasomatized crust, or by mixing of such a batch of magma with like magmas produced by fractionation, such that the product is isotopically a very complex mixture of mantle and crustal sources. If alkali metasomatism of a source involves mostly H_2O, and is mild, the magma will be granitic, and rocks having the earmarks of a typical A-type granite (Eby 1992, Whalen *et al.* 1987) will result. The metasomatic process is highly selective, and contributes directly to the A-type signature by ensuring greater hydrothermal influx of alkalis and silica than aluminum, which is much less mobile hydrothermally in these deep environments, just as it is in shallower, more familiar settings. A more intense and focused metasomatism, possibly involving both H_2O and CO_2, will give rise to crustal rocks that have become decidedly nepheline-normative (*e.g.*, Preston *et al.* 2003), and more enriched in the high-field-strength elements and fluorine, such that rheomorphism of more strongly fenitized crustal rocks could conceivably give rise to a nepheline-normative syenitic magma of truly anatectic origin, in parallel with that which would be expected to form by fractional crystallization of a mantle-derived mafic magma. Because of fluidity considerations, such evolved magmas would be expected to mix and frac-

tionate efficiently. Where carbonation of the precursor had occurred, a batch of coeval carbonatitic melt may ensue, as illustrated in the "cartoon" (Fig. 2).

Competing hypotheses about A-type granites

Unlike the silica-undersaturated expressions of anorogenic magmatism, there is still a lot of confusion about the origin of silica-oversaturated examples, the A-type granites, as pointed out earlier. Three general points of view are prevalent in the literature.

1) A-type granites simply do not exist (Creasey *et al.* 1991, Clarke 1992); they contain, after all, crust and mantle components, just like any subduction-related suites, and thus their origin should be evaluated in terms of a subduction model, where metasomatism also is important. This is definitely considered a minority view!

2) A-type granites are nothing more than the product of second-stage regional anatexis in the middle to lower crust, which earlier became "dehydrated and generally depleted of most LCT elements during a preceding anatectic episode" (Černý 1991b, p. 78). This hypothesis is quite popular with experimentalists, who first proposed it (*cf.* Collins *et al.* 1982), but it fails to explain very basic field relationships and the pattern of enrichment in HFSE and the rare-earth elements. Černý (1992) favored this view. The corollary to the "second melting" hypothesis is that anorogenic granites are relatively anhydrous, as one might expect if H_2O derived by dehydration reactions is consumed in a first-generation product of crustal melting. We contend that such genetic "baggage" must not be included as part of the definition of an A-type granite. We do not believe that the "residue melting" hypothesis has general validity, especially if one considers an A-type granite as a member of a vast family of rift-related magmas that include those of syenitic, nepheline syenitic and carbonatitic character. Field investigators of A-type granites have not noticed that their intrusive rocks have crystallized from magmas that are any less hydrous than in those leading to orogenic granites. Furthermore, the fact that a peralkaline granite contains an anhydrous mineral like aegirine says absolutely nothing about the H_2O content of the granitic magma that produced it.

3) A-type granites are ultimately linked to mantle-derived melts and fluids. The basaltic melt may fractionate to an A-type derivative magma, and the accompanying fluid leads to alkali-metasomatized crustal rocks during a period of extension. The distinctive mineralogy and geochemistry are thus a direct result of the extensional tectonic environment of formation. Metaluminous and mildly peraluminous variants, such as the topaz- and zinnwaldite-bearing Zapot pegmatite, in Nevada (Foord *et al.* 1999), are likely caused either by efficient loss of alkalis by degassing during epizonal emplacement (Martin & Bowden 1981), or by "dilution" of peralkaline melts by mixing locally with less strongly

alkaline or subalkaline (*i.e.*, alkali-deficient) batches of partial melt of crustal origin. We strongly favor the third point of view about the origin of A-type granites.

Early on in his development of the LCT–NYF classification, in the late 1980s, Černý (1992) reported that he did favor a working hypothesis that plutons of anorogenic granite do give rise to NYF-type pegmatites, *i.e.*, the hypothesis that is favored here. "However, this concept did not survive examination of 20 cases, for which differences in timing between the waning stages of orogenies and intrusion of fertile granites could be established within acceptable limits". Numerous LCT suites were found to be "post-orogenic to anorogenic" (up to 400 Ma after the orogeny), whereas some NYF suites were found to be late orogenic (0 to 40 Ma after the orogeny). One can reply that LCT and NYF suites, as well as the orogenic and anorogenic suites to which they are respectively linked, are not defined on the basis of timing of intrusion, but rather on strictly geochemical and mineralogical grounds. As we noted earlier, there is nothing to prevent a rift-related suite from being emplaced immediately after (or even during, in a case of "transtension"!) a protracted period of orogeny, and to have absolutely nothing to do with that orogeny. In the Basin and Range Province, as we saw, the mantle source has clearly changed character in a rather short time about 20 million years ago. On the other hand, there can be no "flip-flopping" of tectonic settings, certainly not as a batch of felsic magma is crystallizing!

Černý & Kjellmann (1999) summarized their views by stating that "the link between the geochemical signatures of the two families and their tectonic affiliation was found to be rather tenuous, and tectonic setting was discarded from the classification criteria." In our view, the tests suggesting the tenuous relationship should be repeated with *bona fide* representatives, and certainly representatives younger than Archean in age, in view of the widely accepted realization that Archean granitic magmatism follows different rules, probably because the nature of the crust, its thickness, and its temperature were different. Also, extensional tectonics in the Archean does not seem to have given rise to the rift-related felsic suites that typify post-Archean zones of rifting. Tectonic setting is indeed of primordial importance in explaining the dichotomy between NYF and LCT pegmatites, in our view, because it controls processes of magma generation.

Can Granitic Pegmatites of NYF Affinity Be Part of an Orogenic Suite?

The Himalayas constitute the best-known area of active continent–continent collision. This collision marks the final stage of a very long episode of subduction of oceanic crust. Sodium, Li, B, Cl and H_2O are removed early from a subducting plate (see caption to Fig. 1), and participate in metasomatic enrichment of the lithospheric mantle above. Potassium, on the other hand, is generally considered to remain sequestered in phlogopite and dragged down much deeper in the subducting plate. Once the ultimate upper stability of phlogopite is reached, however, K is mobilized and can in turn be added to the lithospheric mantle above the subducting plate, close to a depth of 200 km (Fig. 1). At such a depth, there is a possibility that asthenospheric mantle also is involved, especially where part of the lithospheric mantle has been stripped off (Williams *et al*. 2004). The melting reactions result in isolated small batches of high-K basic magma parental to shoshonitic suites emplaced "behind" the volcanic front (Fig. 1) or, in the case of the Himalayas, "behind" the suture zone, well into Tibet. The Neogene shoshonitic suites of Tibet are calc-alkaline, but at the same time anomalously enriched in K, Rb, Ba, and the light rare-earth elements. Williams *et al*. (2004) ruled out low-pressure fractional crystallization as the reason why these incompatible elements are enriched, because the most K-rich samples are also the most magnesian members of the association. Interestingly, such areas are associated with minor extension, with the rifts reported to be orthogonal to the direction of collision.

Whereas there are no reports of NYF pegmatites in Tibet, it seems likely that the Tibetan environment of localized deep metasomatism of a sterile subcontinental lithospheric mantle could generate small batches of partial melt having alkaline tendencies. As such, the basic and intermediate melts produced in this setting could give rise to derivative melts that are granitic or syenitic, but differing from the typical A-type granite and syenite in being enriched in both Ca and K. Evolved plutonic rocks fitting this profile have been referred to as durbachite, and have been documented in older collision-related belts. The Central Bohemian Plutonic Complex, in the Czech Republic, of Paleozoic age, is a case in point. The ultrapotassic plutons belong to a shoshonitic association developed at a convergent plate margin 340–350 million years ago (Žák *et al*. 2005).

The granitic pegmatites associated with the Třebíč durbachite massif have been described by Čech *et al*. (1999) as being of NYF type. The simpler bodies contain an allanite-group mineral as the main accessory, whereas the more evolved bodies contain an amazonitic K-feldspar, schorl, dravite, ilmenite, titanite, Nb–Ta–Ti–REE oxides, niobian rutile, zircon and beryl. They thus differ somewhat from classic NYF suites in containing primary minerals that are richer in Ca, the light REE, and Ta (with respect to Nb), a reflection of their calc-alkaline affinity and the role of the specific type of metasomatism of the mantle source of their parental magmas. Locally, at Kracovice (Novák *et al*. 1999), the NYF-type pegmatite contains Li-bearing micas, unique trends in tourmaline, and F-rich hambergite; the association is highly atypical of an NYF suite, and yet differs from that expected in a normal LCT suite. These assemblages are F-, Fe- and Mn-rich, and in part, indicate a high alkalinity and yet high levels of B and

Li in the melt. Novák *et al*. (1999) noted the transitional aspects between NYF and LCT pegmatites, but in general, a closer affinity to the NYF clan.

To Novák *et al*. (1999), "it seems probable that fractionation in both NYF and LCT pegmatites may tend to converge and produce mineralogically similar, but not identical, dikes showing combined NYF and LCT geochemical signatures." We prefer to consider these unusual pegmatites as a culmination of their very complex petrogenetic background. The subducted plate first received Li, B and Na early in its history, then was subjected to a different pattern of metasomatism once it had arrived at a greater depth, where phlogopite was nearing its upper stability limit; only later was the locally enriched mantle subjected to melting. In their tectonic reconstructions, Žák *et al*. (2005) reviewed the evolution of this Carboniferous orogenic belt of convergent plates, and Holub *et al*. (1997) stressed late large-scale extension in this area. Faced with this "composite" tectonic setting leading to shoshonitic suites, it should not be a surprise that the unusual granitic pegmatites also give a composite signal. Such a composite signal is here considered a result of processes at the source, and distinct from the case of "hybrid pegmatites", to which we now turn.

Hybrid NYF + LCT Pegmatites

As soon as the NYF–LCT classification appeared in the literature, there appeared reports of mixed NYF + LCT suites, "with a principally NYF granite + pegmatite system, but with strong LCT overtones" (Černý 1991b, p. 78). Hypotheses were mentioned, but could not then be evaluated in view of the paucity of data at the time. The situation has improved slightly; we describe here the curious association of minerals and present a summary of new data bearing on an extreme example of the juxtaposition.

The minerals found juxtaposed in a hybrid pegmatite

There probably does not exist a better natural laboratory for the study of hybrid NYF + LCT pegmatites than south-central Madagascar. We shall focus on Anjanabonoina, located about 55 km west-southwest of Antsirabe, in Antananarivo Province, a complex center of aplite–pegmatite emplacement already singled out as being unusual by Lacroix (1922), who considered it representative of a "sodalithic" class of pegmatites. It subsequently became known as the type locality of the tourmaline-group mineral liddicoatite, whose end-member formula is $Ca(Li,Al)_3Al_6(BO_3)_3Si_6O_{18}(O,OH,F)_4$. Another mineral that is a hallmark of such "hybrid" pegmatites is danburite, $CaB_2Si_2O_8$; at Anjanabonoina, it attains up to 20 vol.% of the pocket assemblage in places. In both minerals, calcium, an element that normally is expected to be removed early from the crystallizing pegmatite-forming melt, *i.e.*, at the wall zone,

is intimately associated in major amounts at the pocket stage with Li and B, two elements that are the hallmarks of an evolved LCT system. Yet the early stages of crystallization, at least in parts of the Anjanabonoina suite, are diagnostic of an NYF, not an LCT signature: pyrochlore, betafite, fersmite, zircon, amazonitic microcline, and native bismuth, which Brown (1999) included as a mineral typical of NYF pegmatites. Pocket assemblages more indicative of an LCT association at Anjanabonoina include spodumene, lepidolite, spessartine, beryl, fluorapatite, Li–Al tourmaline, and even dravite. The host rocks at Anajanbonoina consist of quartzite, marble and schist of the Itremo Group. De Vito *et al*. (2006) provide more details concerning the pegmatite body, the host rocks, and the curious associations of minerals, and focus on pyrochlore-group minerals and fersmite.

The Sakavalana granitic pegmatite, in Fianarantsoa Province, provides another example of a NYF–LCT hybrid. That pegmatite occurrence, emplaced in impure marble of the Vohimena Formation, has attracted attention lately as the type locality of pezzottaite, $Cs(Be_2Li)Al_2Si_6O_{18}$, a spectacular new beryl-group mineral formed in a pocket environment (Hawthorne *et al*. 2004). Here, we see the presence in the same mineral of the elements Li and Cs, the "L + C" of the LCT association, but in the presence of danburite, zircon, spessartine, amazonitic microcline and Nb–Ta oxides. Thus the enigmatic juxtaposition of NYF and LCT associations and calcium buildup is not limited to Anjanaboboina, and of course not limited to Madagascar.

Tindle *et al*. (2005) documented an occurrence of liddicoatite in the McCombe LCT-type granitic pegmatite, of Archean age, in northwestern Ontario. All the evidence in that case points to contamination of the McCombe pegmatite-forming magma by Ca- and Mg-rich host-rocks. Taken at face value, their findings show that a straightforward LCT pegmatite (*i.e.*, without the complications due to the presence of an NYF magma at an early stage) also can show the results of contamination while the pegmatite is forming, leading to the late buildup of Ca. Their views contrast with those of Novák *et al*. (1999) and Teertstra *et al*. (1999), who contended that the liddicoatite in their LCT-type pegmatites formed from an uncontaminated magma of most unusual bulk-composition, able to sequester calcium until the final stages of crystallization. Such an opinion is not supported by the experimental work done so far.

Coming back to Anjanaboboina, De Vito *et al*. (2006) have documented two generations of minerals of the pyrochlore and columbite (fersmite) groups in that part of the pegmatite referred to as Sarodivotra. The first generation crystallized from the melt, and those crystals are cut by fractures that contain an abundance of Ti- and Nb-dominant phases and very late Ta-dominant minerals, presumably hydrothermally deposited. The primary compositions are characteristic of a low degree of fractionation (*i.e.*, high Nb:Ta ratio). Similarly, there are two generations of fersmite, both with Nb dominant.

Coexisting with these oxide minerals are amazonitic microcline and euhedral, unzoned crystals of zircon. The morphology of the zircon, in particular the preferential development of the pyramidal form {101} and a single order of the prismatic form {h00}, is indicative of a magma having an alkaline character (Pupin 1980). The zircon is enriched in the heavy rare-earth elements and displays a strongly negative anomaly in europium content. The average Zr/Hf value of the zircon crystals analyzed is approximately 23.5, whereas the Hf content ranges between 1.45 and 2.5 wt.% (De Vito 2002). In the compilation of Wang *et al*. (2000), these are characteristics of zircon from an A-type granite.

Isotopic data on the assemblages at Anjanabonoina

Coexisting with the pyrochlore and zircon are quartz, amazonitic microcline and dravite. The ratio of ^{18}O to ^{16}O has been established for these minerals by mass spectrometry (Geochron Laboratories, Cambridge, Massachusetts); the results reported here, quoted in the usual δ notation, and will be reported in full elsewhere. The quartz shows $\delta^{18}O$ values ranging from +15.9 to +16.3‰. As the $\delta^{18}O$ value of quartz, like that of zircon referred to earlier, cannot be significantly reset hydrothermally, for example in the pocket environment, such a high value is a property of the granitic magma. It indicates an A-type magma probably consisting entirely of a crustal component, presumably suitably metasomatized prior to melting in order to ensure its mildly alkaline tendency (*cf*. Martin 2006). Similarly, the amazonitic microcline perthite shows values in the range 14.1 to 15.2‰. Where hydrothermally altered to kaolinite, among other products, the feldspar is even heavier isotopically, in the range 18.2–18.4‰, as expected of hydrothermal interaction at a very low temperature. The values obtained on the tourmaline (dravite–schorl to elbaite–liddicoatite) are in the range 12.8–13.9‰. The wallrock to the pegmatite, containing the assemblage quartz, feldspars, micas, amphibole, and hydroxylapatite, gives, on average, a value of 13.6‰. Thus the wallrock, from the point of view of the $^{18}O/^{16}O$ value, may be roughly representative of the source rock from which the A-type magma was generated. The δD values of tourmaline and wallrock are in the range –95 to –99‰.

The isotopes of boron in tourmaline and danburite also reveal clues about the unusual geochemical environment of a hybrid NYF–LCT system (De Vito *et al.* 2002, Dini *et al*. 2002b). Because the pegmatitic system in the Sarodivotra segment at Anjanabonoina has a mild alkaline tendency, boron can be expected to adopt two coordinations, ^{IV}B, as in danburite, and ^{III}B, as in tourmaline-group minerals. In view of the coexistence with danburite, however, it would not be too surprising to find ^{IV}B substituting for Si to a minor extent in the coexisting tourmaline-group minerals, as has been found recently in another context (*e.g*., Schreyer *et al*. 2002).

A high proportion of ^{IV}B in the system is expected to be favored by a high pH of the fluid phase (or high agpaitic index of a melt) and by high temperature (*e.g*., Schindler & Hawthorne 2001, Liebscher *et al*. 2004). The proportion of the two types of B-bearing complexes in the melt and later, in the fluid phase, will govern the proportion of danburite and tourmaline that will form; each mineral will then partition the isotopes of boron as a function of temperature, with ^{10}B apparently distinctly preferred in the tetrahedrally coordinated sites. In a given pocket, for example, the preferential early removal of ^{10}B in danburite could well explain fluctuations in $\delta^{11}B$ from pocket to pocket, in the range 6.0–7.0‰, but the extreme value encountered in tourmaline of one pocket, +14‰, must imply a locally greater alkalinity, and consequent removal of up to 40% of the initial boron *via* danburite. If one accepts that negative $\delta^{11}B$ values are typical of the upper mantle (Leeman *et al*. 2004), the high values encountered in the Anjanabonoina system could well be a strong indication of a metasedimentary source-rock of the pegmatite-forming magma.

A tangent: reflections about the mobility of lithium and boron

The recent literature on subduction-related metasomatism establishes without doubt the great mobility of lithium and boron during prograde metamorphism in a downgoing slab of sediments and of meta-igneous rocks that had equilibrated on the seafloor. The mobilization of B seems to begin at a shallower depth and lower temperature than that of Li, and Na and Cl presumably are being released in major quantities as subduction proceeds as well. Paquin & Altherr (2002) and Paquin *et al*. (2004) have shown that the Alpe Arami garnet peridotite, in the Swiss Alps, underwent a metasomatic overprint after the peak of Alpine metamorphism, interpreted to have occurred in a supra-subduction-zone setting. There was a substantial net addition of Li, presumably released from chlorite-group minerals; on the other hand, the addition of B, presumably released from clay minerals, was very limited; most of the boron remained within the percolating fluid, as did almost all the Be (Paquin *et al*. 2004). The evidence for metasomatic addition of these light elements comes from ion-microprobe traverses across grains of garnet, orthopyroxene, clinopyroxene and olivine. A comparable metasomatic enrichment seems to affect the hydrated peridotite source of arc lavas in the mantle wedge directly above any subduction zone, as revealed by lithium isotopic compositions of those lavas (*e.g*., Chan *et al*. 1999). Zack *et al*. (2003) found clear evidence that ^7Li is removed preferentially over ^6Li in the subducted slab, the strong isotopic fractionation reflecting the important difference in masses of the two isotopes (~15%). And by the time the slab has reached 200 km, B/Be and B/Nb in the dehydrated residue are down to ~5 to 12% of their initial values (Brenan *et al*. 1998).

Possible scenarios

In our opinion, the above discussion bears directly on the theme of hybrid NYF–LCT pegmatites, and perhaps has even broader ramifications. The fact that the NYF granitic pegmatite in the Sarodivotra suite at Anjanabonoina formed at the expense of an alkali-metasomatized crust suggests that this part of Madagascar experienced an episode of rifting and anorogenic igneous activity relatively soon after the termination of the Pan-African orogeny. This inference is based on an absence of deformation features in the pegmatite bodies sampled in south-central Madagascar. To Pezzotta (2005), the NYF-pegmatite-forming melts in the region were derived from anorogenic plutons of syenitic to granitic composition emplaced in the interval 570–540 Ma in a geologically young sedimentary sequence "experiencing its first significant thermal metamorphism", up to the lower amphibolite facies. He inferred that the regionally developed thermal regime was relatively hot, which would be the case if the fertile sedimentary sequence were being underplated by mantle-derived magma. As these NYF magmas were crystallizing, in some cases rather far from the parental pluton, Pezzotta visualized the circulation of "abundant boron-rich fluids of LCT geochemical affinity, liberated by the sedimentary sequence experiencing metamorphism". This led to thorough contamination of the pegmatite-forming magma "with boron-rich, LCT fluids of metamorphic origin, expulsed by the metasedimentary sequence". We consider Pezzotta's (2005) reconstruction very plausible.

The mantle-derived alkali-bearing fluids released from the sites of crystallization of anorogenic suites in catazonal and mesozonal environments (Fig. 2) can be expected to be reactive with respect to the hot, fertile Pan-African crust, newly formed in an accretionary wedge in a subduction or collision environment in Neoproterozoic to Cambrian time. In one plausible scenario, one can imagine the destabilization of metamorphic minerals hosting Li and B, which become mobilized hydrothermally in a zone where bodies of NYF granitic pegmatite are in the process of crystallizing from an anorogenic granitic melt. At the pocket stage, the two fluids mix, one of NYF provenance and one issued from the local crust, bringing in Li, B, Ca, and Mg among other elements. There results a real blending of geochemical trends, but strictly at the pocket stage, such that the minerals depositing from the mixed fluid will contain interesting juxtapositions of NYF-derived elements and elements usually considered characteristic of an LCT pegmatite, like Li and B, or elements usually considered characteristic of the wall-rocks, like Ca and Mg. Béhierite, $(Ta,Nb)BO_4$, found in the Manjaka granitic pegmatite, and schiavinatoite, $(Nb,Ta)BO_4$, found at Antsongombato, both NYF–LCT hybrids in central Madagascar, would seem to provide perfect examples. The Nb and Ta are largely of NYF

derivation, as is the indication of peralkalinity (presence of ^{IV}B); the late enrichment of boron is considered a signal of the influx of an externally derived fluid.

Where the incoming Li-, B-, Ca-, and Mg-bearing fluid phase is available in the vicinity of a pegmatite-forming melt *while* it is crystallizing, one can easily foresee high-temperature reactions involving replacement and pseudomorphism of the hot, newly formed NYF-related *rocks* by that external fluid, causing regeneration of a melt by *in situ* refusion of the products of that replacement and pseudomorphism. The possibilities seem numerous, and can only be tested with an extended database at Anjanabonoina and other examples of NYF–LCT hybrids in Madagascar.

What about the possibility of an LCT pegmatite being contaminated by an NYF overprint?

The mechanisms of explaining NYF–LCT hybrids described above rest on the great mobility of the elements causing the overprint. In sedimentary and greenschist-grade metamorphic protoliths, lithium and boron evidently are structurally incorporated in low-temperature minerals that do not have a large field of stability. Furthermore, they will become unstable in contact with an alkaline fluid. Their ultimate breakdown during prograde metamorphic recrystallization will be the opportune time to get these elements into solution. Lithium, in particular, with its low field-strength, would seem to be particularly mobile, as a chloride or carbonate complex, for example. In most crustal environments, boron seems to be mobilized mainly as ^{III}B in the uncharged aqueous species $B(OH)_3$ (Liebscher *et al.* 2004). The Ca and Mg are mainly contributed from the immediate host-rocks, dolomitic marble and assorted quartzofeldspathic assemblages of the Itremo Group.

The possibility of an LCT–NYF sequential development seems remote, simply because of the impossibility of mobilizing Nb, Ta, Y, and other high-field-strength elements in any fluid phase likely to be available in a situation and at a temperature at which a typical LCT granitic pegmatite is crystallizing.

What about the possibility of an LCT pegmatite being contaminated by a LCT-type overprint?

As a new twist on the theme, what about an LCT–LCT sequential development? We are taught that a parental calc-alkaline pluton may spawn a radially disposed array of swarms of pegmatite dikes in which the degree of fractionation increases with distance from the pluton. What now about the possibility that the Li-, B- and Na-carrying aqueous fluid is already in convective circulation in the metasedimentary sequence injected by granitic dikes emanating from a central pluton? We can foresee a situation where a newly formed granitic pegmatite (*i.e.*, a hot rock) gets "soaked" with such a hot fluid, becomes metasomatized, and the transformed

bulk-composition acquires a lowered solidus because of the fluxing influence of the added Li, B, and Na. There can result a new "super-enriched" melt of LCT affinity, the LCT overprint eventually being completely erased by the superimposed fusion and the normal pattern of crystallization of the second-generation melt.

This interpretation and the formation of "super-LCT suites" may well explain the situation in the Greenbushes granitic pegmatite, in southwestern Australia, the site of one of the world's major producers of Sn, Ta and Li. The pegmatite was emplaced along the contact of mafic amphibolites, ultramafic rocks, and laminated metasedimentary rocks (Fig. 3). Uranium–Pb dating of zircon gave 2.53 Ga as the age of emplacement (Solomon & Groves 1994). It is a 3-km-long body 40 to 250 m wide, and extending to a depth of 400 m (Partington *et al.* 1995). Close to the contact, a K-enriched zone is developed, whereas toward the center, a Na-enriched zone prevails. The presence of such Na- and K-dominant zones implies considerable fluid-mediated readjustment and movement of alkalis, possibly in a temperature gradient favoring ion exchange. The Ta–Sn mineralization is concentrated in the Na-enriched (albitized) zone (Partington 1990), which suggests that these elements were mobilized hydrothermally along with the sodium during metasomatism.

The Li-enriched pegmatite is the latest to be emplaced (Fig. 3), and the map pattern shows that it is external to the sodic pegmatite and the potassic pegmatite (Partington *et al.* 1995, Bettenay *et al.* 1998), not at all internally disposed with respect to them, as might be expected in the context of a normal pattern of fractional crystallization. Is it possible that the Li-enriched pegmatite represents an LCT-type pegmatite that remelted following a wave of metasomatism? This hypothesis can only be evaluated with a detailed textural and mineralogical investigation designed to test the hypothesis.

We have shown earlier that albitite pegmatites can be primary, but in so many other examples of Na-dominant granitic pegmatite, the sodium enrichment seems distinctly postmagmatic. Consider for example the latest generation of pegmatite dikes in the Cap de Creus suite, in Catalunya, Spain, which is devoid of K-feldspar, but characterized by secondary muscovite, and distinctly enriched in Ta (Corbella & Melgarejo 1993). Part of the Greenbushes pegmatite suite clearly offers another example, as do the Ta- and Sn-mineralized pegmatites of the Wodgina district, in Western Australia (Sweetapple & Collins 2002). The main Ta-mineralized suites are the Wodgina and Mount Cassiterite pegmatites, which are classified as of the albite and albite–spodumene types, respectively, by Černý & Ercit (2005). The economic importance of such a "wave" of Na-metasomatism and "reprocessing" of granitic pegmatite is great, as the ion-exchange reaction leads to an important increase in porosity and permeability. In spite of the economic importance of an LCT fluid-dominated overprint on an LCT-type pegmatite, it is surprising that so few data exist on the textural and mineralogical modifications in the affected rocks.

The Benefits of a Petrogenetic Classification

In reviewing the existing schemes of classification, Simmons *et al.* (2003) pointed out that none is ideal, as none addresses all the pertinent characteristics. "Absent is a genetic connection with the magma-generation process and the tectonic regime". In this paper, we have tried to provide these connections, but of course, in so doing, we have undoubtedly raised new questions. We contend that LCT and NYF granitic pegmatites both arise as a result of fractional crystallization, but that this process acts on magmas that have come about by very different mechanisms (Figs. 1, 2). We have stressed how these mechanisms are directly tied in to the tectonic environment at the time of magma generation, either in the mantle or in the crust. Orogenic suites are well understood by all. Anorogenic suites are not recognized at all by some, still poorly understood by others, and clearly quite a diverse lot. Only by recognizing that anorogenic igneous suites involve a stage of metasomatism in the crust and in the subjacent mantle prior to melting is it possible to explain their formation and their composition. The associated NYF pegmatites, as representatives of the end stage of a very complex chain of events, can be expected also to be a rather variable lot, depending in part on the ratio of H_2O and CO_2 at the "ground-preparation" stage, and on the intensity of the metasomatic transformations which, in the extreme cases, can lead to efficient desilication of the precursor assemblage, especially if the fluid phase is in equilibrium with a carbonatitic melt. The many economically important aspects of felsic pegmatites can best be understood by keeping these petrogenetic processes in focus.

Conclusions

1. Felsic pegmatites are of two broad types, those of anatectic origin, and those that have formed by fractional crystallization of a more primitive felsic magma in a pluton-size body. It seems clear that coalescence of many batches of anatectic melt can ultimately give a pluton-size mass of magma. To a large extent, therefore, the distinction between anatectic pegmatites and fractionated pegmatites is one of scale.

2. Anatectic pegmatites may arise from crustal rocks and mantle rocks, suitably modified by preparatory metasomatic modifications in many instances.

3. Evolved felsic magmas issued from a plutonic mass undergoing fractional crystallization are found in two distinct tectonic settings, one associated with
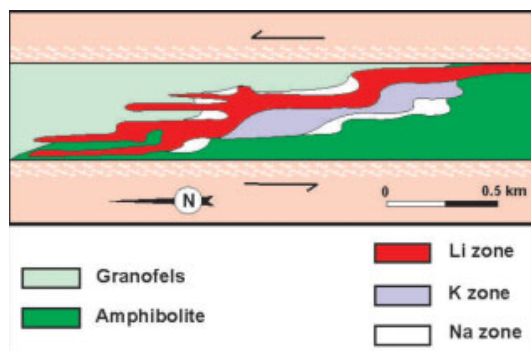
FIG. 3. Schematic disposition of three units of the Green-
bushes granitic pegmatite, in southwestern Australia,
emplaced along a contact between mafic amphibolites
and ultramafic rocks, in laminated metasedimentary rocks
(shown in pink). Note the relative timing of emplacement
of the K-enriched, Na-enriched, and Li-enriched units of
the pegmatite body. Adapted from Bettenay *et al.* (1988).

crustal shortening, subduction and collision (orogenic
magmas), the other associated with crustal attenuation
and rifting (anorogenic magmas).

4. LCT granitic pegmatites form part of the orogenic
association, and represent the culmination of protracted
crystallization of a magma typically formed in part at
the expense of metasedimentary materials. NYF granitic
pegmatites form part of the anorogenic association, and
may represent the culmination of protracted fractional
crystallization of a basaltic magma. Other NYF pegma-
tites may form at the expense of metasedimentary mate-
rials that had been earlier metasomatized in response
to an alkaline ($H_2O + CO_2$) fluid emanating from the
mantle. Mixed signatures (crust + mantle) are common,
presumably as a result of magma mixing.

5. Where the metasomatic "ground-preparation"
is more intense, the felsic pegmatites are syenitic or
nepheline syenitic, and may well be associated with
carbonatitic manifestations.

6. Parental magmas of shoshonitic suites, formed
"behind" the magmatic front or suture zone in zones of
subduction or collision, develop from a metasomatized
lithospheric mantle that has a "mixed" signature. As a
result, the granitic pegmatites are unusual in their juxta-
position of primary NYF- and LCT-type minerals.

7. Hybrid granitic pegmatites are NYF pegmatites in
which the late-stage alkaline orthomagmatic fluid helps
to induce important destabilization-type reactions in the
enclosing metasedimentary wallrocks, releasing lithium
and boron, in particular. Thus the magmatic NYF
assemblage gets overprinted by an LCT assemblage at
a hydrothermal stage. Owing to solubility constraints,
the converse situation, in which an LCT magmatic
assemblage gets overprinted by an NYF signature,
should not be expected.

8. One might well expect, in view of point 7,
cases of an LCT magmatic assemblage with an exter-
nally derived LCT-type hydrothermal overprint. The
commonly developed zones of late albitization and late
addition of lithium can best be viewed as being external
contributions from the enclosing rocks. In such "super-
LCT" suites, a proper understanding of the nature and
provenance of the overprinting material clearly has
economic implications.

9. In terms of accumulated and overlapping
processes, pegmatites developed in felsic systems are
inherently very complex. Depth of crystallization in
the crust is important, but not as a first-order variable.
The tectonic environment determines the petrogenetic
processes at work.

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