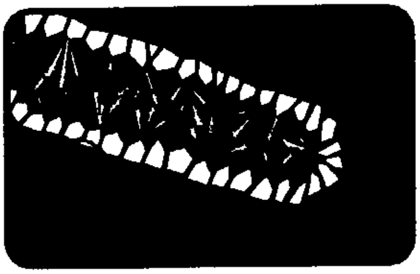

Rare-element Granitic Pegmatites. Part II: Regional to Global Environments and Petrogenesis

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INTRODUCTION

In Part I of this review of rare-element pegmatites, individual deposits were characterized in descriptive terms and subsequently interpreted as to the nature of their parent phase(s), course of crystallization, and origin of internal structural features (Černý, 1991c). Despite the broad diversity of paragenetic, geochemical and structural styles of rare-element pegmatites, it was concluded that they all have a common genetic feature: crystallization from a volatile-rich melt, enriched to different degrees in lithophile rare elements.

Part II examines populations of rare-element pegmatites on a regional scale, from cogenetic pegmatite groups through pegmatite fields and belts to pegmatite provinces. Structural setting, metamorphic milieu, relation to plutonic intrusions and the nature of associated granites are then utilized to derive a genetic interpretation best fitting the observed facts. This interpretation is, of course, also constrained by the parent medium, geochemical signature and internal evolution of individual pegmatites, as discussed in Part I. Paragenetic-geochemical and petrochemical classifications that were introduced in Part I also are frequently referred to, and are prerequisites for adequate understanding of Part II.

REGIONAL RELATIONSHIPS — PEGMATITE GROUPS

Rare-element pegmatites invariably occur in regional populations within well-defined areas. In order to understand the constitution of orogen-size and global distribution of pegmatite populations, an appreciation of the basic genetic unit, pegmatite groups, is necessary.

Table 1 **Composition of typical fertile granites.**

	1 – Osis Lake			2 – Lac du Bonnet	
	biotite granite	**coarse-grained leucogranite**	**pegmatitic leucogranite**	**leucogranite**	**pegmatitic leucogranite**
SiO_2 (wt%)	73.15	75.40	72.72	76.56	75.75
TiO_2	0.12	0.06	0.04	0.10	0.03
Al_2O_3	14.40	14.33	15.36	12.36	14.07
Fe_2O_3	0.46	0.72	0.61	1.07	0.36
FeO	1.05	0.28	0.68	0.56	0.15
MnO	0.03	0.08	0.06	0.03	0.01
MgO	0.48	0.13	0.06	0.10	0.09
CaO	0.76	0.72	0.29	0.56	0.68
Na_2O	3.12	4.09	4.44	3.65	4.20
K_2O	5.42	2.83	4.78	4.65	5.24
P_2O_5	0.15	0.16	0.49	0.02	0.00
CO_2	0.03	0.08	0.11	0.05	0.03
H_2O^+	0.88	0.67	0.46	0.36	0.22
F_2	0.02	0.04	0.02	0.01	0.02
$-O=F_2$	0.01	0.02	0.01	–	0.01
total	100.07	99.57	100.11	100.08	100.85
A/CNK **	1.16	1.29	1.18	1.02	1.12
A/NK **	1.31	1.46	1.23	1.02	1.12
Li (ppm)	71	63	10	28	–
Rb	187	137	343	216	244
Cs	15.4	8.4	8.4	2.9	–
Be	0.7	0.8	0.8	2.9	–
Sr	83	26	44	30	33
Ba	287	8	14	398	103
Ga	28	48	43	32	47
Y	nd	28	nd	51	19
U	30	23	3.5	9.9	2
Th	nd	6.7	nd	39	8
Zr	78	38	13	196	9
Hf	1.63	3.05	0.34	7.4	1.8
Sn	4.8	13	20	7.9	5
K/Rb	237	132	117	194	178
K/Ba	162	5402	7010	492	422
Ba/Rb	1.53	0.06	0.04	2.2	0.42
Rb/Sr	2.25	5.3	7.8	9.5	7.6
Mg/Li	39.7	11.5	31	25.6	–
Zr/Sn	16.3	2.9	0.7	22	2.1
Zr/Hf	47.8	12.4	5.8	27.5	12.8
Al/Ga	2737	1674	1890	2087	1586
Th/U	0.1	0.3	0.1	2.75	2.75

Notes

1 Peraluminous LCT granite grading from biotite through two-mica + garnet to muscovite + garnet + tourmaline types (from Černý and Brisbin, 1982)

2 Metaluminous NYF fertile granite with biotite and extremely rare garnet (from Černý *et al.*, 1987)

–, not determined; nd, not detected

** A = molecular Al_2O_3, CNK = CaO + Na_2O + K_2O, and NK = Na_2O + K_2O

Pegmatite groups consist of tens to hundreds of cogenetic bodies, ranging from a few to about a hundred per km^2, and maintaining such densities of occurrence over areas of a few tens of km^2. Pegmatite groups are commonly associated with plutonic granitic intrusions, and different pegmatite types tend to be systematically distributed within and/or around such plutons. In the case of syn- to late-orogenic suites, the granite + pegmatite systems are commonly confined to specific metamorphic grades of the enclosing rocks.

Associated Granites

The granites range from occasional synorogenic intrusions to predominantly late-orogenic and subordinate numbers of post-orogenic to anorogenic cases (Černý, 1991a). Even the synorogenic intrusions commonly postdate the peak of regional metamorphism. All of them are intruded along prominent fault or fracture systems, or into activated lithologic boundaries.

Granites of the NYF family (Nb-Y-F; see table 4 in Černý, 1991c), and those associated with simple LCT pegmatite types (Li-Cs-Ta; see table 4 in Černý, 1991c) are generally homogeneous in texture and composition. Equigranular to porphyritic, biotite or two-mica NYF plutons and those associated with albite-spodumene pegmatites are of this kind (Kuzmenko, 1976; Meintzer, 1987). However, LCT intrusions accompanied by complex pegmatites are commonly heterogeneous, grading from biotite-bearing at depth, through two-mica and muscovite + garnet facies, into caps of pegmatitic leucogranites. Banded sodic aplites and zoned potassic pegmatite pods are subordinate, but persistent, components. The pegmatite pods locally carry rare-element mineralization analogous to that of the associated pegmatites. Accessory garnet, tourmaline and/or cordierite are characteristic of the highly evolved leucocratic facies.

The LCT granites are silicic, peraluminous to hyperaluminous S to I types, low in Ca, Mg, Fe, Sr, Ba, Ti and Zr, but remarkably enriched in Rb, Be, Ga, Sn, Mn and Y (Figure 1 and Table 1); the contents of Li, Cs, Nb and Ta are also enhanced. Steep fractionation gradients are observed from the biotitic to the leucocratic pegmatitic facies. Rare-earth element (REE) abundances are low, mostly between 20× and 1× chondritic, with subhorizontal to heavy rare-earth element (HREE)-depleted patterns; extensive negative Eu anomalies and kinking of the patterns are common, but not an absolute rule. Overall REE abundances decrease, and Eu anomalies usually increase, with fractionation. Radiogenic and stable-isotope systematics are also disturbed at most localities; distribution of δ^{18}O data shows two maxima at about +8.5‰ and +11.2‰ (Černý and Meintzer, 1988).

In contrast, the NYF granites tend to be somewhat less silicic, largely subaluminous to metaluminous, A to A+I types with subordinate representation of peraluminous and subalkaline compositions. The granites are variably, but generally moderately, depleted in Ca, Mg and Sr; have high Fe/Mg, and are enriched in Nb, Ti, Zr, Y, Sc, REE, Th and U (Figure 1 and Table 1). Fractionation within the granites is usually mild. REE abundances are commonly HREE-depleted, with LREEs 350× to 100× chondritic, and undisturbed distribution patterns compatible with crystal/melt fractionation. Radiogenic and stable-isotope systematics also tend to be undisturbed; δ^{18}O data are centered around a single maximum of about +8.0‰ (Simmons *et al.*, 1987; Černý, 1991a).

Zoning of Pegmatite Groups

In the LCT pegmatite groups, regional zoning of different pegmatite types and subtypes is commonly observed, focussed around individual associated granites. Well-expressed concentric zoning is not a common feature, as the three-dimensional shape of any pegmatite group is strongly influenced by the distribution and attitude of potential pre-intrusion host structures (Figure 2), and by the level of erosional exposure (Figure 3). From observations by numerous researchers over the past four decades, the following spatial sequence of pegmatite categories can be outlined for zoned LCT groups, from the granite intrusion outward: (1) barren, (2) (rare-earth type), (3) beryl-columbite subtype, (4) beryl-columbite-phosphate sub-

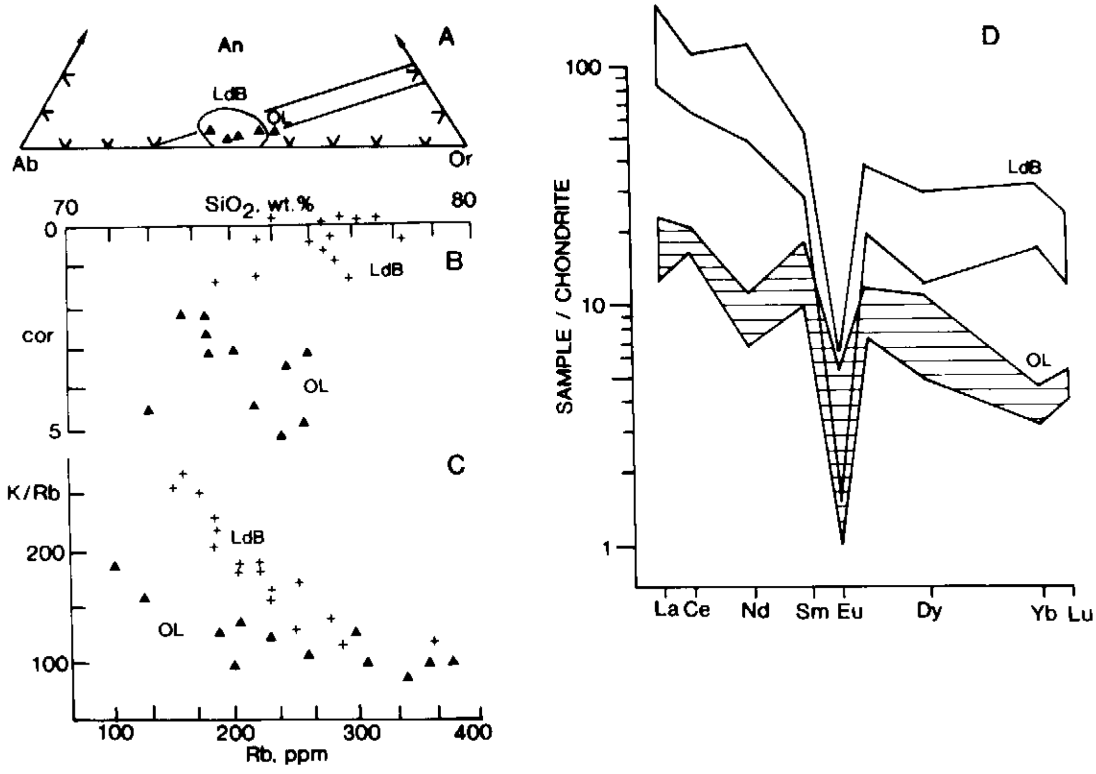


Figure 1 *Contrasting petrochemistry of the LCT and NYF fertile granites, on the examples of the Osis Lake peraluminous leucogranite and the Lac du Bonnet metaluminous leucogranite, respectively (after Černý et al., 1981). Note the low-Ca, Rb-enriched and REE-depleted character of the peraluminous LCT intrusion at Osis Lake, relative to the metaluminous NYF granite of Lac du Bonnet.*

type, (5) spodumene or petalite, ± amblygonite subtypes, (6) lepidolite subtype, (7) albite-spodumene type, and (8) albite type.

In this generalized sequence, assembled from segments documented from diverse terranes, the number of pegmatite bodies of a particular type/subtype usually decreases with increasing complexity and fractionation. The complex pegmatites typically constitute less than 2% of any given group and commonly occur in isolated segments or clusters within the necessarily discontinuous outer zones (Figure 4). Rare-earth pegmatites of zone (2) are commonly missing; the reasons for their locally typical appearances in the LCT suites are not clear. Another widespread variation is the nonsystematic representation of zones (5), (6) and (7). It is quite common that only one of the three zones is developed in a given group, with minimal percentage (if any) of the other categories.

As to the NYF granite-pegmatite families, pegmatites are largely confined to the interior or margins of the granites, are much more uniform within a given group, and regional zoning seems to be virtually absent (Figure 5).

Specific information and lists of references concerning regional zoning are available in Heinrich (1953), Beus (1960), Beus *et al.* (1968), Solodov (1971), Varlamoff (1972), Rossovskyi *et al.* (1976a,b), Černý *et al.* (1981), Černý (1982, 1989a,b), Meintzer (1987) and Norton and Redden (1990).

Granite-pegmatite Relationships

In the LCT granite + pegmatite systems, granites and associated pegmatite aureoles locally show physical continuity; gradation of textural, mineralogical and geochemical features is common, as are bulk compositional analogies and close geothermometric association.

Although not widespread, many cases of physical transition from plutonic LCT granites to highly evolved rare-element pegmatites have been documented (*e.g.*, Beus, 1948; Kuznetsov, 1977). Facial pods of highly fractionated pegmatites evolving within "ordinary" fine-grained or pegmatitic granites are common in many terranes (*e.g.*, Jahns and Wright, 1951; Haapala, 1966; Tatarinov, 1974; Černý *et al.*, 1981), and are invariably similar to or virtually identical with exterior pegmatites of the same group in structure and mineralogy.

Granites and surrounding pegmatite groups commonly share a general geochemical signature. Even if a continuous physical transition is not evident, fractionation from

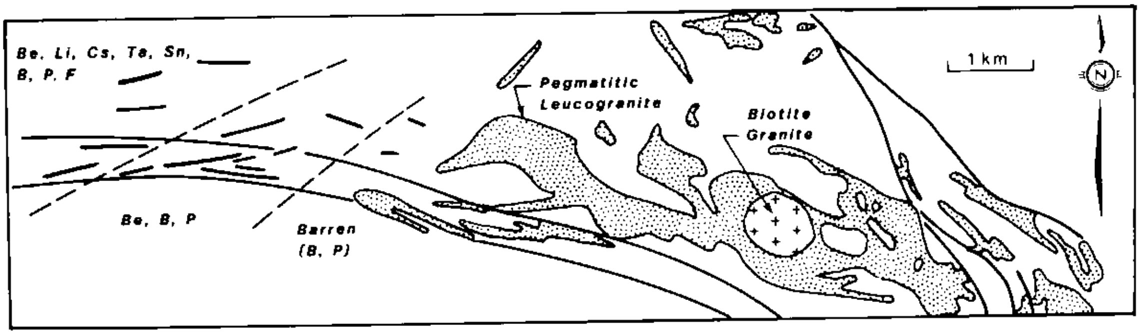
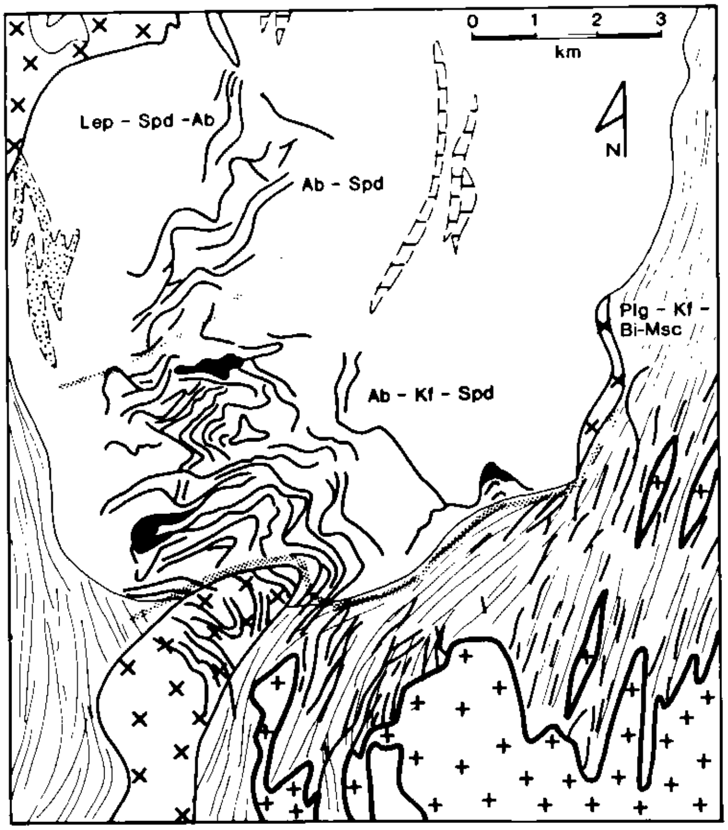


Figure 2 *The Osis Lake granite complex and the derived Rush Lake pegmatite group, southeastern Manitoba (after Černý and Brisbin, 1982). Solid lines denote faults coincidental with lithologic boundaries; dashed lines indicate approximate boundaries in regional zoning of pegmatites.*

Figure 3 ***(right)*** *Regional zoning of the Nilau-Kulam pegmatite field, Afghanistan (modified from Rossovskyi and Chmyrev, 1977; Rossovskyi, 1981a). Fertile granites (+++) generate steeply dipping oligoclase + biotite + K-feldspar + muscovite pegmatites within gneisses (foliation pattern) and in an early porphyritic granite (xxx); subhorizontal albitized microcline pegmatites with spodumene* ***(Ab-Kf)****, albite pegmatites* ***(Ab-Spd)*** *and lepidolite-spodumene-albite pegmatites* ***(Lep-Spd-Ab)*** *are located within a gabbro-diorite pluton (open) with rafts of schists and marble. Vertical elevation increases from the parent granite at 1700 m to the lepidolite-bearing pegmatites at 3700 m above sea level.*



granite into the progressively more evolved pegmatite types in the aureole is evident in geochemical surveys. More or less smooth, sequential or partly overlapping decrease in K/Rb, K/Cs, Sr/Rb, Nb/Ta, Zr/Hf, Ti/Sn and many other classic indicators of fractionation is typical (Černý *et al.*, 1981; Shearer *et al.*, 1985, 1987; Breaks, 1989). Geochemistry reveals close links even between mineralogically simple granites and highly evolved pegmatites; for example, micas of granites associated with Li-rich pegmatites commonly have high Li contents, indicative of a lithium-rich parent magma.

Bulk compositions of pegmatites of both LCT and NYF families are close to the associated granites in terms of their ASI (aluminum saturation index; estimated for the pegmatites from their mineralogy, in most cases). Within the limits of modification of some pegmatite bulk compositions by their high contents of Li, B, F and P, these compositions can be linked to the bulk chemistry of associated granites.

Temperature ranges of pegmatite crystallization discussed in Part I (Černý, 1991c) represent a downward extension from crystallization temperatures of a consolidating leucogranite.

Intrusive Relationships

Rare-element pegmatites associated with (syn- to) late-orogenic granites are generally intruded into the same structural environment as the associated granite, or into shallower levels of structures spatially and genetically related to it. In some settings, pegmatite-hosting structures could have been unlocked by preceding intrusion of associated granites. However, their final emplacement style is largely different, due to their smaller size, and considerably varied. Pegmatites form bulbous, lenticular and turnip-shaped bodies in plastic rocks (commonly in relatively deep-seated, high-grade lithologies), and a variety of flat-walled fracture fillings in brittle country rocks (usually in lower grade environments). Structural features indicative of forcible emplacement of pegmatite melts, such as deformation of wall-rock fabric along contacts and bridges of schistose host rocks, are widespread (Brisbin, 1986).

Fractionation and intensity of rare-element mineralization usually increase toward the topmost pegmatites (*e.g.*, Rossovskyi

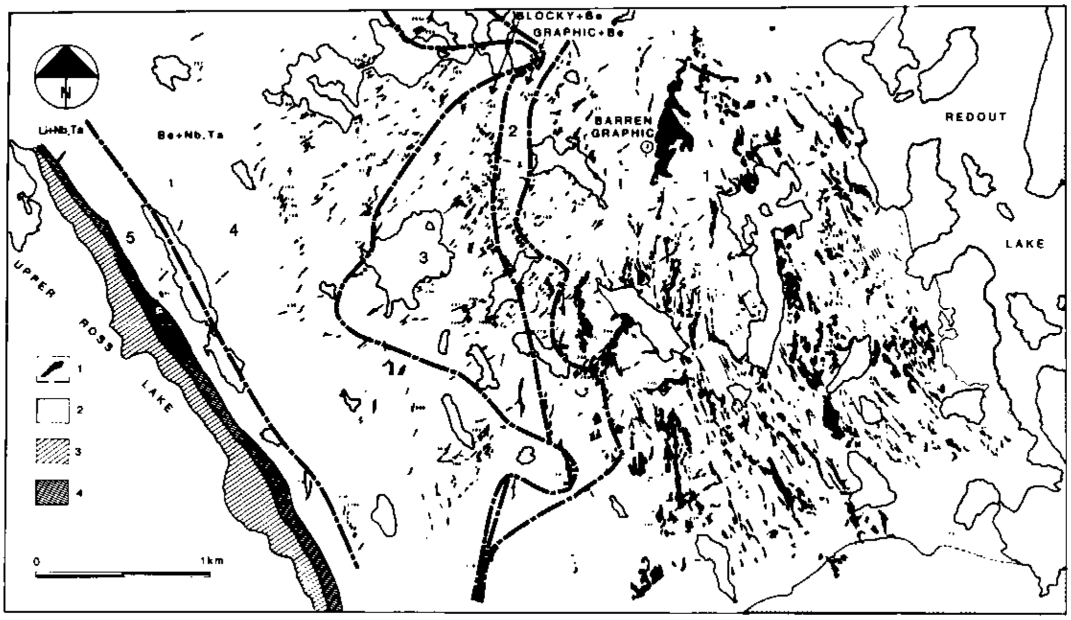


Figure 4 *The PEG group in the Yellowknife, NWT, pegmatite field (after Meintzer, 1987) showing westward regional zoning from the granitic source in the east;* ***1****, pegmatites;* ***2****, Redout granite;* ***3****, metasediments;* ***4****, metabasalt.*

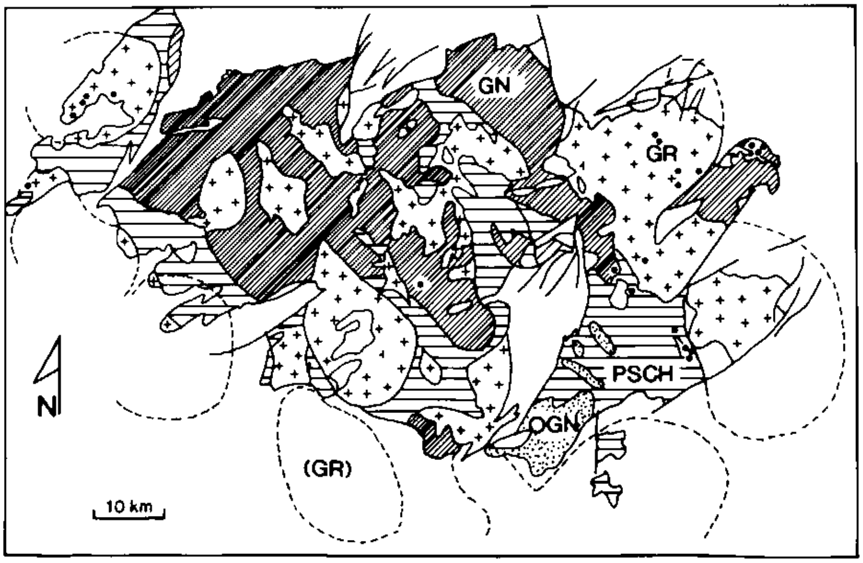


Figure 5 ***(left)*** *Pegmatite field of the Llano Uplift of central Texas (modified from Garrison* et al.*, 1979). Plug-shaped plutons and complex anastomosing bodies of post-tectonic granites* ***(GR)****, outcropping and geophysically contoured, penetrate the Packsaddle Schist* ***(PSCH)****, gneisses* ***(GN)*** *and orthogneiss. Pegmatites are marked by solid dots (after White, 1960 and Crook, 1977).*

and Shmakin, 1978). Among these, subhorizontal to shallow-dipping, fracture-filling pegmatites are on the average the best mineralized, *e.g.*, the Varuträsk, Bikita, Harding, Londonderry and Tanco deposits (Figure 3; Černý, 1991c, figure 5). Individual pegmatite fields displaying these relationships are numerous; some of the best examples come from terranes with deep vertical exposure (Figure 3; Pamir-Hindukush province in Afghanistan; Rossovskyi *et al.*, 1976a; Rossovskyi, 1981a,b).

Granite + pegmatite systems of post-orogenic to anorogenic tectonic affiliation are related to subvertical dilation structures, commonly in settings of, or resembling, incipient rifts. Pegmatites are located within the granites or along their margins, and they ascend largely by buoyancy of their low-density melts as bulbous plugs, imitating the large-scale behaviour of their granitic hosts. Although vertical movement definitely plays a role in their emplacement, the total distances are restricted and do not lead to three-dimensional separation of diverse types (*e.g.*, Simmons *et al.*, 1987).

Relationship to Metamorphic Grade

Rare-element pegmatites of late-orogenic LCT suites are typically found in low-pressure metamorphic sequences of the (upper-greenschist to) lower amphibolite facies (Beus *et al.*, 1968). The A 2.1 andalusite-cordierite-muscovite subfacies of Winkler (1967) is particularly characteristic, but not exclusive. Shifts to sillimanite-bearing subfacies are locally observed. In areas undisturbed by later tectonic events, the zoning tends to progress from associated granites and barren pegmatites in high-grade terrane toward the more fractionated pegmatites in lower-grade rocks.

In contrast, the metamorphic environment of post-orogenic and anorogenic pegmatites is variable, depending on the erosion level and ascent of the granite + pegmatite system. However, the setting tends to be uniform within consanguineous arrays of intrusions populating homogeneous terranes, such as those of the Grenville Province *sensu lato* (Černý, 1991a).

MODELS OF REGIONAL EVOLUTION

Once volatile-rich melts were recognized as the parent medium of individual rare-element pegmatites, the anatectic or igneous provenance of these melts became a crucial question. This question can be answered by interpreting the regional relationships described above, and related lines of evidence. The present state of our knowledge distinctly favours derivation by fractionation of igneous intrusions. However, let us examine first the direct-anatectic and related ideas, before demonstrating the compatibility of available observations with the magmatogenic concept.

Anatectic Concept and Related Hypotheses

Two principal concepts can be distinguished among the non-magmatic proposals: the heat-engine concept borrowed from hydrothermal genesis of sulphide ores, and the model of direct anatectic derivation.

The heat-engine hypotheses consider the quartzo-feldspathic pegmatites to be igneous, but the rare-element mineralization is assumed to be superimposed from hydrous solutions, which are set in motion by the thermal effects of associated granites. Rare elements leached from metamorphic host rock would be either deposited down the thermal gradient in already solidified pegmatites (Gaupp *et al.*, 1984), or mixed with pegmatite melts (Norton, 1981, for Li). These proposals encounter several serious objections: (1) the first hypothesis ignores the systematic and essentially simultaneous fractionation of all rare elements in both "primary magmatic" pegmatites and "late, externally introduced" accessory minerals of zoned pegmatite fields, which speaks against the involvement of two unrelated processes; (2) in the second case, flow of Li down a supposed concentration gradient, but up a steep thermal gradient, is next to impossible; (3) in the second case, no explanation is available for the provenance of other rare elements that mineralize pegmatites after the crystallization of spodumene or amblygonite; (4) in both cases, the lack of reaction of the laterally secreted fluid content with quartzo-feldspathic lithologies other than pegmatites (*e.g.*, barren granites hosting mineralized pegmatites in NYF systems) is not explained; (5) the nature of hydrothermal fluids supposedly leaching lithophile rare elements, as opposed to those that are known to mobilize base and precious metals alone, is not specified.

Anatectic proposals *sensu stricto* vary in detail, but all of them express the same idea. Most of them appeal to partial melting of "Li-enriched metasediments" which would presumably yield Li-rich magma at temperatures lower than those of haplogranite minima. This would explain the typical position of Li-rich pegmatites down the regional metamorphic gradient from the Li-poor and barren pegmatites and associated granites. Pegmatites are considered products of low-percentage partial melting at low temperatures, whereas the associated granites are assumed to be products of high-percentage melting, presumably generated later in the same progressive anatectic event (Norton, 1973; Zasedatelev, 1974, 1977; Stewart, 1978; Breaks *et al.*, 1978; Shmakin, 1983; Matheis, 1985). Again, all variants of the anatectic proposals run into considerable problems: (1) lithologies that may serve as protoliths extraordinarily enriched in rare elements (such as evaporites) are scarce in high-grade metamorphic terranes (and just about any Archean terranes), they do not cover the full spectrum of elements represented in different pegmatite types, and many of them (*e.g.*, evaporites) would be prone to devolatilization coupled with dispersion early in prograde metamorphism; (2) extremely low-percentage melting would be required to generate anatectic magmas even remotely similar to complex pegmatites, and would do so only if partition coefficients that work at >20% melting could be realistically extrapolated to about <3% melting; (3) in metamorphic rocks, lithophile rare elements, such as Li, Ta, Nb, Ti, Sc and Sn, are bound in mafic silicates and accessory oxide minerals, and at least biotite and hornblende (if not pyroxenes and refractory oxide minerals) would have to be broken down; at that stage, partial melts would be Ca-enriched and rare-element concentrations much below their abundances typical of pegmatites; (4) concentrations of rare elements encountered in complex pegmatites would require substantial removal of these elements from very large volumes of source rocks such as metapelites; (5) segregation of low-percentage melts (<3%) from enormous volumes of protolith into restricted spaces occupied by complex pegmatites would be mechanically difficult, and probably impossible; (6) passive flow of such melts down a pressure gradient into open space to be filled by pegmatite melt cannot be reconciled with the observed forcible mode of emplacement; (7) were such a segregation feasible, the melts passing through contrasting metamorphic lithologies would react with them, and lose most of their content of rare elements in the process; (8) localities examined in sufficient detail show systematics of radiogenic isotopes in pegmatites sharply discordant with those of the host rocks and their deep-seated analogs; (9) last, but not least, not a single case of "aborted segregation", of highly fractionated pegmatite melts in *statu* of metamorphic/anatectic *nascendi* has been observed; on the contrary, all partial melts show primitive geochemistry (such as abyssal- or muscovite-class pegmatite stringers), and dispersed rare-element distribution around pegmatites is proven to be exomorphic, as discussed in preceding chapters.

Igneous Differentiation

Observations cited in the description of pegmatite groups are in general agreement with the classic concept of rare-element pegmatites as igneous derivatives of fertile granitic intrusions, products of advanced fractionation of pluton-size batches of granitic magmas: (1) physical links are observed between mineralized pegmatites and their plutonic parents; (2) continuous textural, mineralogical and geochemical evolution is documented from the parent granites to associated pegmatites (analogous to that observed in highly fractionated rhyolite suites); (3) late-crystallizing pegmatite pods trapped within parent granites are locally exact duplicates of exterior pegmatites in metamorphic roofs of these granites; (4) bulk compositions of rare-element pegmatites correspond to the experimental minima in granitic systems modified by accumulation of Li, B, F and P, ± other "pegmatitic" lithophile elements; (5) temperatures of crystallization determined for rare-element pegmatites correspond to such modified granitic minima.

Different models for generating rare-element pegmatites by differentiation of "fertile" granites have been proposed, all claiming concentration of volatiles and rare elements in pools of residual melts during consolidation of plutonic granites. Pegmatites are then formed by tapping the pools of residual magma and intruding it into solidified parts of the parent granite and its metamorphic envelope. A credible magmatogenic model should therefore include discussion of processes yielding the observed extreme fractionation, and the mechanism of pegmatite separation, intrusion and zonal distribution.

Evolution of the parent granites. In texturally and mineralogically differentiated fertile granites of the LCT family, the bulk composition changes imperceptibly from one facies to another. However, the trace elements show very extensive fractionation: crystal-chemical compatibility, crystal/melt partitioning, complexing and fluid transport aided by thermogravitational convection-diffusion can be considered the main mechanisms, whereas transport in an exsolved aqueous fluid is apparently not involved.

Classic rules of crystal-chemical selection of compatible *versus* incompatible trace elements apply to crystallization of the fertile granites. It is this size-*cum*-valence selection alone that must relegate a substantial proportion of lithophile rare elements to residual melts (*e.g.*, Nb^{5+}, Ta^{5+}, Li^{+}, Cs^{+}). This mechanism also affects crystal/melt partitioning of closely related element pairs such as K and Rb.

The significance of crystal/melt fractionation was underrated by researchers in the 1970s, but it was re-instated recently as a potent factor: increased polymerization in silicic melts, changes in availability of complexing ligands, and extraction of some trace elements into liquidus accessory minerals (*e.g.*, LREEs into monazite) seem to be the main factors driving the partition coefficients to extreme values, surpassing any values known from less silicic rocks (Mittlefehldt and Miller, 1983; Mahood and Hildreth, 1983; Michael, 1983; Miller and Mittlefehldt, 1984).

Complexing had been extensively considered before the advent of London's experimental work, which questions the presence of separate aqueous fluids during the main stages of pegmatite consolidation. However, we do not know yet the form in which the rare metals survive until the breakdown of highly hydrous borosilicate melts that generate mineralized albitic units. The principal literature on complexes that may mask amphoteric rare elements (*e.g.*, Be^{2+}, Zr^{4+}, Nb^{5+}, Ti^{4+}) through orthomagmatic crystallization, and exert control over timing of cation release for incremental incorporation into solid phases, is discussed in Černý *et al.* (1985).

Fluid transport (*e.g.*, Shaw, 1968) may become significant in the advanced stages of evolution of the fertile granites. Extensively hydrated cations may essentially follow migration and accumulation of volatile components within homogeneous, highly hydrous, but still undersaturated, melts. This may be particularly significant for non-complexing cations.

Fluid transport can be very effectively promoted by thermogravimetric convection-diffusion (Shaw *et al.*, 1976; Hildreth, 1979, 1981; Crecraft *et al.*, 1979; Nash and Crecraft, 1981). This mechanism was not proved unambiguously for granitic plutons; experimental work casts some doubt on its feasibility within a geologically available time-frame (Lesher *et al.*, 1982), and the more recent concept of buoyant boundary layers has not been applied to granitic magmas. However, fertile intrusions are generally sufficiently voluminous and long-lived to accommodate at least a limited convective motion of magma, and the evolving melts may become relatively highly fluid because of gradual build-up of B, F, P and H_2O contents. Roofward enrichment of a high proportion of "pegmatitic" rare elements (such as Li, Rb, Cs, Tl, Be, Mn, Sc, Y, HREEs, Sn, U, Th, Mo, Nb, Ta and W) can be expected.

Transport of rare metals in an exsolved aqueous fluid was extensively advocated in earlier studies, but was just about eliminated by London's experiments on LCT pegmatite systems that are notoriously poor in Cl. Even if some supercritical fluid does co-exist with melt, as claimed by Thomas *et al.* (1988), lithophile rare elements would partition into the melt phase (London *et al.*, 1988) and the role of co-existing fluid would be insignificant. The low volume of aqueous fluid exsolved from metaluminous NYF pegmatites should reduce the role of such a transport even in these systems that may be locally Cl-rich.

The quantitative contributions of the individual factors enhancing fractionation in the fertile melts, and their continuation in the residual pegmatitic magmas, are not known at present. It is important, however, that the contributions of all individual mechanisms are qualitatively comparable, and their joint effect in an evolving melt must be cumulative.

Fertile granites of subaluminous to metaluminous A-type composition, and specifically those of the NYF family, are much more homogeneous than the peraluminous LCT intrusions. It is generally accepted that A-type melts are relatively dry and viscous, and that their main volatile component could be F($\pm CO_2$) rather than H_2O. Crystal/melt fractionation may be the main mechanism in their geochemical evolution, with the role of factors involving H_2O relatively suppressed.

Mechanism, sequence and zoning of pegmatite emplacement. Evidence of forcible intrusion was repeatedly recognized during early pegmatite research (reviewed by Chadwick, 1958). However, the notion of passive pegmatite emplacement into pre-existing voids (or openings generated by mechanisms independent of the pegmatite intrusion itself) is rather widespread in recent literature.

Pegmatite emplacement is actually subject to the same controls as any small-scale igneous intrusion: melt pressure, rheologic state of the host rock, lithostatic pressure, deviatoric stresses, and strength anisotropies in the host rocks. Brisbin (1986) successfully applied the general mechanism of igneous intrusion to the specific case of granitic pegmatites, documented by selected examples.

Residual pegmatitic melts may accumulate in essentially two ways. If filter pressing, fluid transport and/or gravitational convection-diffusion were the main mechanism generating the residual melt, it would accumulate in the uppermost cupolas of parent granitic intrusions (Figure 6A). If crystal-melt fractionation were dominant, promoted by the cooling effect of the metamorphic host rocks, the residual melt would concentrate in somewhat deeper central parts of fertile intrusions that solidified from contacts inward (Figure 6B). Buoyant rise of local segregations of pegmatite melts through incompletely solidified parent magma is rather uncommon (Figure 6C).

The internal pressure of the residual melt, in conjunction with tectonic disturbances in the outer solidified shell of the parent granite and its metamorphic roof, may tap the magma reservoir once or several times, giving rise to pegmatite aureoles generated by a single injection or by repeated pulses of the pegmatite melt. The degree of overall fractionation of a pegmatite group would depend not only on the initial geochemistry of the parent melt, but mainly on the degree of its evolution at the time of magma extraction. In cases of repetitive tapping, late pegmatite injections should be more fractionated; this is confirmed by field observations.

The distance of any pegmatite type from its source is proportional to the thermal stability of its particular melt composition (Figure 7). This is evidently the dominant reason for the regional zoning of pegmatite groups. Melts with the lowest liquidus temperatures should migrate farthest down the regional thermal gradient (which generally coincides with the pressure gradient). Most of the liquidus-depressing constituents also tend to reduce viscosity, and thereby considerably increase the overall mobility of the melt (*e.g.*, Manning and Pichavant, 1985).

The relatively dry conditions of the A-type, NYF-family magmas, and the apparently restricted degree of fractionation between the fertile granite magma and the pegmatite melt, could be the main reasons why the NYF suites show minimal spatial separation and so far no clearcut cases of regional zoning.

Concluding Remarks

The classic model of igneous derivation of rare-element pegmatites is the only one that has withstood the test of time, and become reinforced in the process. None of the multitude of aqueous and anatectic hypotheses reviewed earlier can seriously compete with this model. On the contrary, several investigators who started their research seriously considering or advocating the anatectic mechanism largely abandoned it because of evidence to the contrary generated by their own research (F.W. Breaks, J.J. Norton, and the schools of J.J. Papike, G. Matheis and G. Morteani). Unless unambiguous geological evidence and experimental proof are provided for the anatectic or aqueous cases, the existence of metamorphogenic pegmatites of the rare-element class, convergent with those of proven magmatogenic derivation, will remain purely speculative.

Internal evolution of the fertile granites and the mechanisms responsible for their steep fractionation should be examined in the future. Although generally anticipated and deemed acceptable, the diverse processes leading to the remarkable concentrations of lithophile rare-elements in residual pegmatitic magmas need experimental verification, and quantitative comparison with well-examined examples of highly fractionated fertile granites.

GLOBAL DISTRIBUTION

Pegmatite groups are the basic components of larger pegmatite populations that have common structural, igneous and geochemical links, related to specific periods of geological evolution. The observed wide variability in diverse attributes of these populations requires a simple classification, and characterization of their occurrences. Genetic concepts can then be developed from these data.

Pegmatite Fields, Belts and Provinces

A variety of terms has been used for categorizing pegmatite populations of variable scales (Kuzmenko, 1976; Ginsburg *et al.*, 1979; Černý *et al.*, 1981; Černý, 1989b). A satisfactory systematic and uniform terminology is not yet available. For the present purpose, a hierarchy of three categories above the group level is used.

Pegmatite fields are territories populated by pegmatite groups within a common geological and structural environment, usually less than 10,000 km² in extent. They are generated during a single tectonomagmatic stage of regional evolution, have the same type of granitoid sources, and are of about the same age. Typical examples include the Archean Cat Lake-Winnipeg River field in the Superior Province (Figure 8; Černý, 1989c); the Proterozoic (Hudsonian) Eräjärvi field in Finland (Lahti, 1981); the Caledonian Leinster field in Ireland (Luecke, 1981; McArdle and Kennan, 1989); and the Apline Nilau-Kulam field in Afghanistan (Rossovskyi, 1981a).

Pegmatite belts consist of pegmatite fields related to a large-scale linear structure such as a deep fault lineament, a mobilized cratonic margin, or a trough mobilized within a

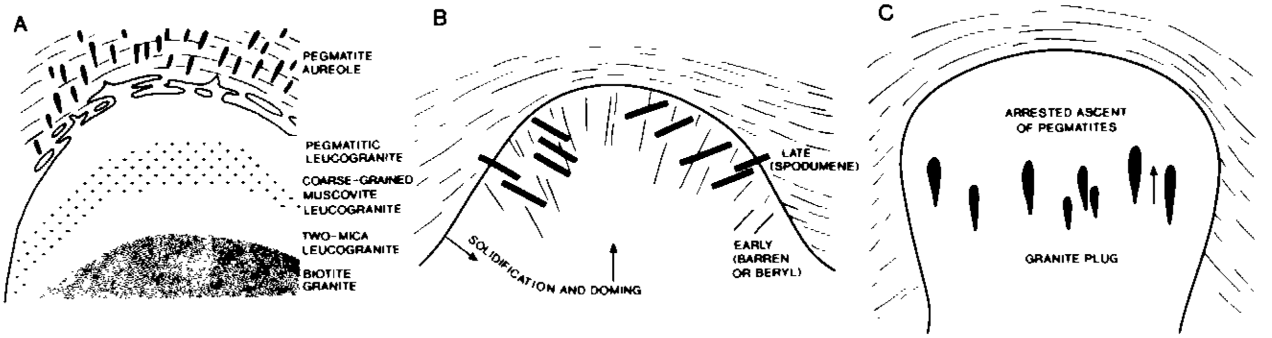
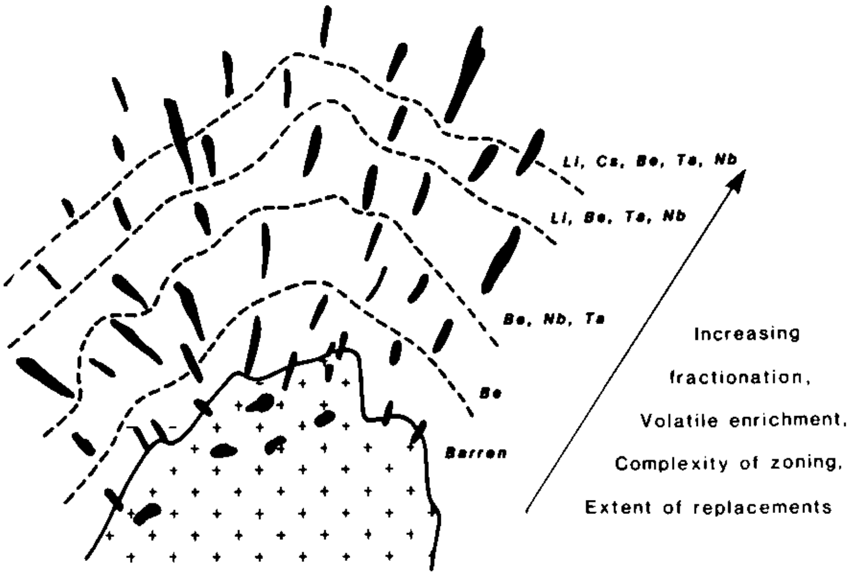


Figure 6 *Schematic representation of granite-pegmatite relationships.* (**A**) *Zoned outward-fractionated fertile granite with an aureole of exterior LCT pegmatites, typical of many fields of Kenoran and Hudsonian age (after Černý and Meintzer, 1988).* (**B**) *Interior to marginal LCT pegmatites in an inward-fractionated parent granite, located in fracture systems generated by upwarping of solidified upper crust of the intrusion (modified from Kuznetsov, 1977).* (**C**) *Turnip-shaped NYF pegmatites trapped during ascent through the parent granitoid mush (after Simmons* et al., *1987).*

Figure 7 ***(right)*** *Schematic representation of regional zoning in a cogenetic granite + pegmatite group (modified from Trueman and Černý, 1982).*



stable shield. Individual pegmatite fields may (but commonly do not) belong to different classes formed under different conditions; nevertheless, all are related to the geological history of one particular linear structure. The Archean English River and Quetico belts in the Superior Province (Černý, 1990), the Hercynian tin-spodumene belt in the Appalachian Province (Kesler, 1976), and the belts composing the western part of the Pamir-Hindukush Province (Figure 9; Rossovskyi and Chmyrev, 1977) are typical examples.

Pegmatite provinces constitute the sum of pegmatite fields and belts within a single metallogenic province, a large-scale geological unit with common fundamental features of geological evolution and mineralization style. Within a province, pegmatite fields and belts may (and commonly do) belong to different classes formed at different stages of crustal evolution, but each class displays repetitive properties throughout the province. The best-defined pegmatite provinces are those of Archean cratons such as the Superior or Slave provinces (Figure 10; Černý, 1990), the Pilbara and Yilgarn cratons in western Australia (Blockley, 1980), and the Zimbabwian and Kaapvaal cratons in Africa (Anhaeusser, 1976). The Proterozoic Central Svecofennian Subprovince in Scandinavia (Černý, 1991b), the Hercynian Appalachian Province (Jahns *et al.*, 1952), and the Alpine, rare-element class phase of the Pamir-Hindukush Province (Rossovskyi and Chmyrev, 1977) are typical representatives from younger terranes.

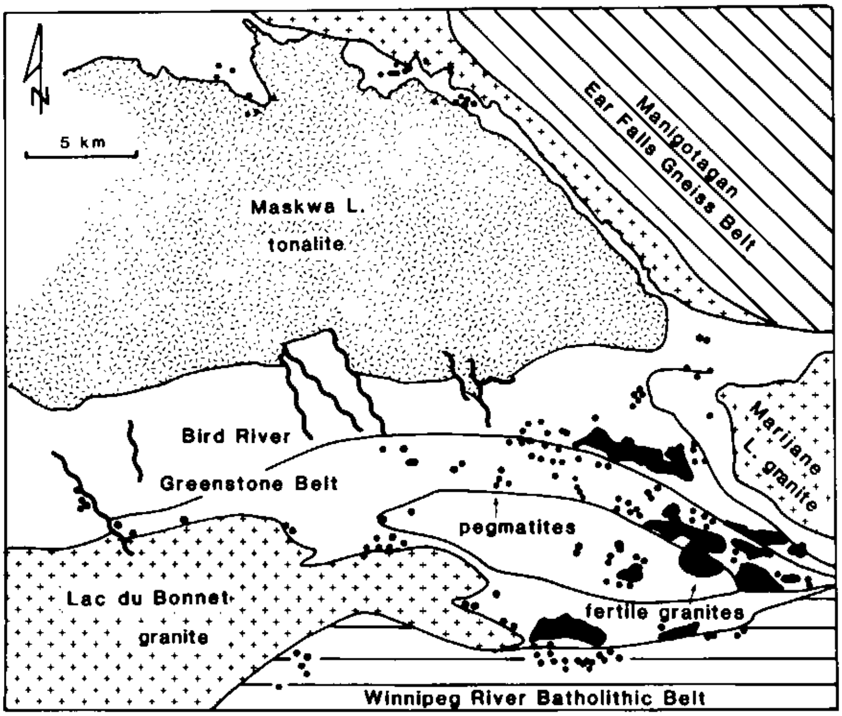


Figure 8 *Distribution of batholithic granitoids, fertile granites (black) and pegmatites in the Cat Lake-Winnipeg River pegmatite field (simplified from Černý et al., 1981); pegmatites indicated by dots are largely a symbolic representation of densely populated pegmatite groups.*

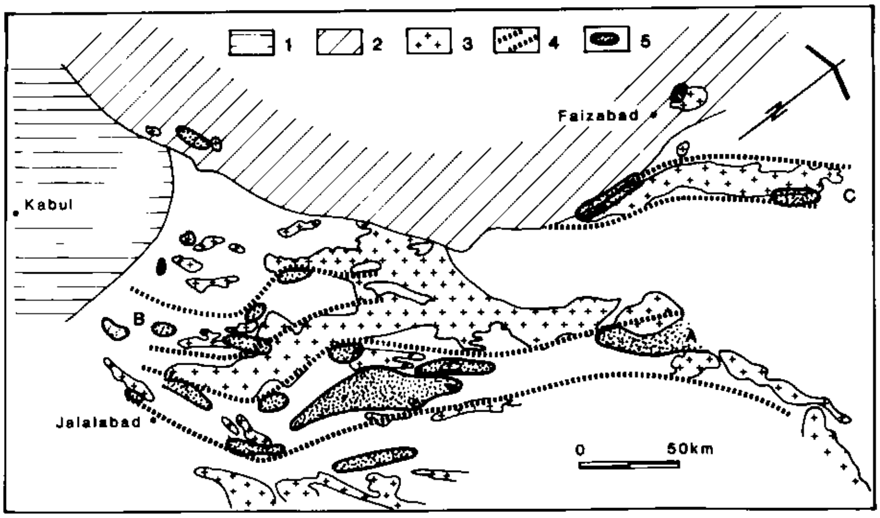


Figure 9 *Rare-element pegmatite fields and belts of eastern Afghanistan (modified from Rossovskyi and Chmyrev, 1977); 1, Baluchistan-Himalayan fold belt; 2, Hercynian fold belt of northern Pamir; 3, fertile granites of the Laghman complex; 4, boundaries of pegmatite belts (A, Nuristan; B, Hindukush; C, Badakhshan belts); 5, pegmatite fields.*

Age distribution. Worldwide pegmatite populations have formed in most tectonomagmatic cycles of geological history. Except in the oldest (>3000 Ma) orogens marked by abyssal-class populations, rare-element pegmatites were generated in more or less close conjunction with all orogenies. Kenoran (2,750-2,550 Ma) provinces were quoted in the preceding section. Hudsonian (1,800-1,600 Ma) populations reside in the "Churchill" Province, the Svecofennian orogen of Scandinavia, the South Siberian belt in the USSR, and in the Inner Mongolian Province of China. Hercynian (330-250 Ma) examples are the Appalachian Province in eastern North America, Moldanubicum in central Europe, and the Urals and Altai Province in the USSR. The Cimmerian (190-100 Ma) and Alpine (Laramide) (85-20 Ma) orogens contain the Transbaikalian pegmatites in the USSR, the aforementioned Pamir-Hindukush Province and the pegmatites of southern California, to name a few.

Rare-element pegmatite populations of other orogens, such as the Nullaghinian-Karelian (2,200-1,900 Ma), Pan-African (Riphean; 600-500 Ma) and Caledonian (480-350 Ma), are rather modest, in part because of their much more restricted extent. A modest depth of erosion is the main reason for limited exposure of geologically young granite + pegmatite suites. In contrast, the overall deep erosion of the Archean cratonic nuclei contributes to the relative abundance of rare-element pegmatites of Kenoran age.

Most rare-element pegmatite populations can be at least loosely related to one or another orogenic cycle, although most of them are late- to post-orogenic. Truly anorogenic suites seem to be scarce, but occasionally are linked to continental-scale anorogenic magmatism such as the 1400 Ma North American event (pegmatites of the Pikes Peak, Colorado and Wolf River, Wisconsin intrusive suites).

Geological, Lithologic and Metamorphic Environment, Structural and Tectonic Affiliation

Large-scale geological settings and structural controls of pegmatite populations have changed during crustal evolution. Nevertheless, several genetically significant features persisted throughout some three billion years, as far as synorogenic to post-orogenic granite + pegmatite systems are concerned.

In the Late Archean, Kenoran pegmatite fields were confined to two environments: greenstone belts and mobilized sedimentary troughs.

Linear greenstone belts separating batholithic tonalites and potassic granites are the most widespread hosts, typical of the volcano-plutonic subprovinces of Archean cratons. Parental granites are usually located along deep post-metamorphic faults, axial to the greenstone belts, and associated dislocations (Figure 8). Lithologic boundaries, particularly batholithic contacts, also are preferred loci.

Pegmatite fields tend to be particularly abundant along metamorphic and tectonic boundaries, or in the central parts of major sedimentary troughs which cross or border the volcano-plutonic terranes. These metasedimentary subprovinces host pegmatite fields again in axial faults of greenstone lithologies, but mainly in faults transecting paragneisses (Figure 10).

Hudsonian rare-element pegmatite fields are mostly confined to mobilized "geosynclinal" basins and troughs disposed locally along the margins of Archean cratons, or between their neighbouring pairs. For example, the Central Svecofennian Province of Finland and Sweden was generated during a Hudsonian orogeny in a sedimentary apron marginal to the Archean basement of the Baltic Shield. Fault systems, lithological boundaries and fault-related domal structures are typical locations of granite + pegmatite systems.

Phanerozoic pegmatite populations are confined to belts of fertile granites within more or less linear orogens of the Appalachian or Alpine type. These belts consist of metasedimentary sequences, or of segments of older crystalline terranes remobilized and penetrated by numerous granitoid plutons under both prograde and retrograde conditions. The Hercynian pegmatite provinces of central and western Europe represent this type. The Alpine orogen of the Afghan Hindukush also represents a classic example of these features, with a literally deep insight along extensive three-dimensional exposures (Figure 11). Fertile granites and derived rare-element pegmatites (80-25 Ma) intruded Permian to Triassic supracrustal rocks, but were generated largely from remobilized Archean basement (containing its own abyssal pegmatites) and Proterozoic sequences of intermediate levels (hosting pegmatites of the muscovite class; Rossovskyi *et al.*, 1976b).

Lithologic environments of rare-element pegmatite fields show considerable similarities, but also secular changes, throughout crustal evolution. Eugeosynclinal-like volcanic and sedimentary sequences are typical hosts in Archean greenstone belts (*e.g.*, Superior Province), sporadic in Proterozoic terranes (*e.g.*, southern Trans-Hudson Orogen in Manitoba), and rare in Phanerozoic terranes (Kings Mountain belt in the Appalachians). In contrast to this environment, which declines in abundance with decreasing age, metamorphosed terrigenous flysch-type turbidites devoid of volcanic components become the dominant hosts in younger orogens (*e.g.*, the Damara Province in Africa, and the Hindukush fields of Afghanistan).

Across the entire history of crustal evolution, truly synorogenic pegmatite populations are relatively scarce; on proper dating, most of them are turning out to be late- to post-orogenic (*cf.* Černý, 1991a). Pegmatites associated with the Fellingsbro-Stockholm granites of Sweden are one of the few reliably documented synorogenic cases. Most LCT populations are late- to post-orogenic (*e.g.*, the Yellowknife field, NWT or Manaslu aureole, Himalayas), and rarely are anorogenic (Quartz Creek field in Colorado). In contrast, mixed and NYF suites are mainly post-orogenic (Grenvillian pegmatites of central Texas, southeastern Ontario and Quebec, and southern Norway) to anorogenic (South Platte field, Colorado and Korosten batholith, Ukraine).

In contrast to the environment of closely orogen-related pegmatite populations, the anorogenic cases show strictly structural control. Relationship to long-lived rift systems is typical, and specifically to their aborted episodes. There is no link to orogenic events or lithological milieu; the metamorphic grade of the host rocks is variable with the depth of pre-intrusion uplift and erosion, and with the level of intrusive ascent.

Metamorphic environment is, however, rather constrained for syn- to late-orogenic granite + pegmatite systems. They are confined to regions of relatively steep geothermal gradients (*ca.* 40°-50°C/km). Abukuma-type facies series with andalusite-sillimanite assemblages in metapelites is the typical

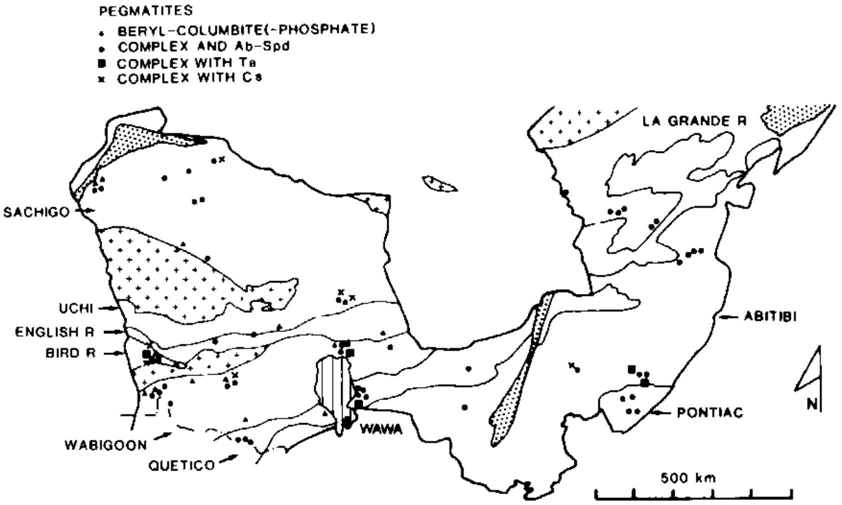


Figure 10 *Distribution of rare-element pegmatite fields in the Superior Province (modified from Černý, 1990). Names denote only the volcano-plutonic (open) and metasedimentary (dashed) subprovinces with identified pegmatite populations; the plutonic (crosses) and high-grade gneissic (dotted) subprovinces are barren. Symbols for different pegmatite types approximate their relative abundances in individual fields.*

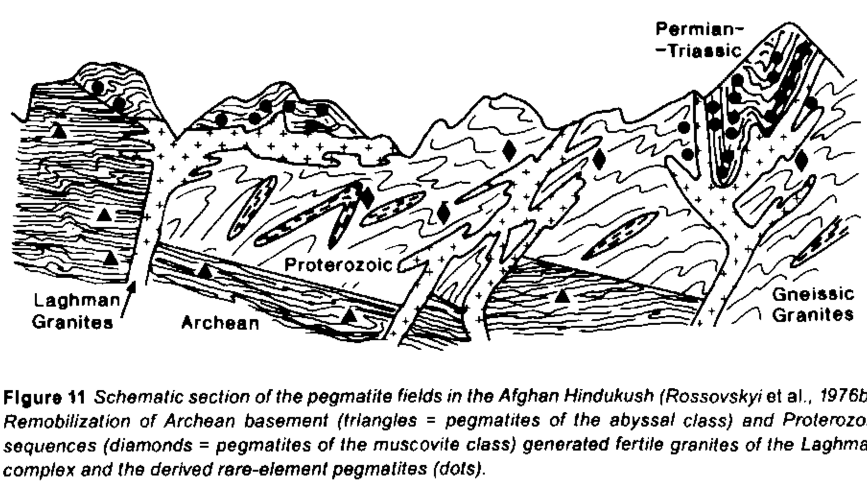


Figure 11 *Schematic section of the pegmatite fields in the Afghan Hindukush (Rossovskyi* et al., *1976b). Remobilization of Archean basement (triangles = pegmatites of the abyssal class) and Proterozoic sequences (diamonds = pegmatites of the muscovite class) generated fertile granites of the Laghman complex and the derived rare-element pegmatites (dots).*

host, mainly at the level of the lower-amphibolite, andalusite-cordierite-muscovite subfacies of Winkler (1967). Deviations into higher sillimanite facies are common, but extension down the gradient into upper greenschist subfacies is rare (Phuket, Thailand). Occurrences of rare-element pegmatites in kyanite-bearing host terranes are even more exceptional (Mtoko area in Zimbabwe, and possibly Greenbushes in Australia). However, detailed metamorphic relationships are not known at these localities, and the uncertainty in the aluminosilicate triple point comes close to the apparent upper pressure limit of rare-element pegmatite crystallization (4 kb; *cf.* Černý, 1991c, figure 1).

EVOLUTION OF PEGMATITE-GENERATING SYSTEMS

Once the igneous derivation of rare-element pegmatites is accepted, as outlined in "Models of Regional Evolution" above, deciphering the global distribution of this pegmatite class centres on the definition of conditions conducive to generating "fertile" granites. The crustal environment hosting rare-element pegmatite populations will be interpreted first, followed by evaluation of petrogenetic indicators of the granite + pegmatite suites.

Crustal Environment

This section focusses on the conditions that generate syn- to late-orogenic pegmatite fields, with a concluding note on anorogenic cases.

Host lithologies. In general, lithologies hosting syn- to late-orogenic rare-element pegmatites are of the same types throughout geologic history: shallow to deep, eugeosynclinal-like sediments with volcanics, turbidites and flysch, with the role of the volcanic component declining in importance with decreasing age. Four principal types of basins can be distinguished, in which these volcanic-sedimentary deposits accumulated: (1) back-arc, inter-arc, and continental arc sequences at active continental margins (*e.g.*, bimodal volcanic + sedimentary piles of continental magmatic arcs among the Archean greenstone belts), (2) forearc accretionary prisms and/or trench sediments (*e.g.*, the linear metasedimantary subprovinces of the Superior Province), (3) flysch accumulations along trailing continental margins (*e.g.*, western Siberia, Transbaikalia), and (4) large-scale troughs of ensialic rifts (*e.g.*, the Damara Province of southwestern Africa).

Depositional environments, closely linked to the character of their geotectonic position, are not easily recognized in some old terranes. However, the above generalization is valid, even though many individual cases are not unambiguously resolved.

Tectonic and metamorphic environment. In terranes with syn- to late-tectonic rare-element pegmatites of all age groups, the above sedimentary-volcanic sequences were subject to intensive orogenic compressional deformation and metamorphism. The synclinal character of the original strata may be partly preserved or enhanced, but, in many cases, it has been destroyed. The sedimentary volcanic piles become vertically extended, reaching from shallow levels of lower greenschist facies down to zones of anatexis, and commonly dissected into stacks of fault-bounded panels.

Abukuma-type metamorphism marked by relatively steep geothermal gradients is typical of rare-element pegmatite fields, and indicates either a relatively thin crust or high rate of heat flow, or both. With the exception of a minority of truly synorogenic cases, most of the late-orogenic granite + pegmatite systems postdate the peak of regional dynamothermal metamorphism; they are emplaced along stacked fault systems developed in an already consolidated, rigid metamorphic suite. Thus, the granites and pegmatites are actually divorced from the preceding metamorphism at the level of intrusion and, of course, from the niveau of anatectic generation of the parent fertile magma.

Geotectonic setting. Geological distribution, absolute age and the lithologic + tectonic + metamorphic environment of syn- to late-orogenic populations of rare-element pegmatites indicate their restriction to late-tectonic stages of compressive dynamometamorphic events in orogenic zones. Collision environments generating granite + pegmatite systems include continent-continent (the Himalayas *sensu lato*; Trans-Hudson Orogen; Hercynian component of the Appalachians), continent-island arc (central Svecofennian basin; Wawa Subprovince *versus* Superior craton), possibly island arc-island arc (within Superior Province, or Japan), and closures of ensialic rifts (Damara Province).

Fertile granites and pegmatites invade structures generated by slicing of the host rocks during continuing compression and thickening, after the peak of metamorphism. This is a common case in Archean greenstone belts: pegmatite groups are hosted by subparallel faults bounding complex mosaics of tectonic panels of dissected volcanic-sedimentary piles. Some pegmatites are even related to such large-scale features as the sheared and faulted provincial boundaries (Breaks *et al.*, 1978). The late character of the host structures is emphasized in cases of fault systems that are not co-planar with the strike of the host units. For example, the Phuket and Phangnga fields of lepidolite pegmatites are located within co-linear back-arc thrusts, but are hosted by a transform fault cutting across large-scale compression structures and lithologies (Garson *et al.*, 1969).

Anorogenic granite + pegmatite suites. In contrast to the syn- to late-orogenic cases, the relatively subordinate number of (post-to) anorogenic systems is subject to structural controls alone. This is amply demonstrated by the Pikes Peak batholith, the Wausau pluton, the Grenvillian systems in Ontario and Quebec, and the Korosten pluton in Ukraine: all of them are related to extensional regimes of different kinds, including incipient rifts, but their individual lithologic and metamorphic environments are quite different in each case. Relative to the syn- to late-orogenic systems, all localities of anorogenic suites show an even more striking divorce between the crust at the level of emplacement and that in which the magma must have been generated.

Petrogenesis of the Fertile Granites

The petrochemistry of the granite + pegmatite systems is the principal clue to determining their protoliths, in conjunction with the diverse protoliths available in different crustal settings. Consequently, the geochemical signatures of the LCT, NYF and mixed families of granites and their pegmatite aureoles must be considered separately.

The LCT suites. Among the chief attributes of this family are the peraluminous composition of its fertile granites, the hydrous nature of its parent magma, its S- to I-characteristics, and the many volatile components and mobile cations that act as liquidus-solidus depressants in melting and consolidation of magmas. Thus, it is conceivable that these elements will be extracted into the first melts derived from undepleted, progressively metamorphosed, wet or dry lithologies during synchronous dehydration and partial melting at middle-crustal levels.

Metapelites and metaturbidite sequences have been traditionally suspected to be the main or sole protoliths of the LCT suites because of their relative enrichment in LCT elements and an overall S character. Vielzeuf and Holloway (1988) demonstrated that even fluid-absent melting of metapelites produces peraluminous melts. However, a number of fertile granites has been identified recently as derived from mixed basement plus supracrustal protoliths, having intermediate homogenized chemistry and isotopic signature, or displaying diverse origins of individual plutons within a single field (Meintzer, 1987; Walker *et al.*, 1986; Černý, 1991a). In some cases, undepleted basement lithologies such as paragneisses and metatonalites seem to be the sole source, leading to both I- and S-characteristics (Wright and Haxel, 1982; Harris *et al.*, 1986; Černý, 1991a). These protoliths are surprisingly highly fractionated in mineral assemblages that participate in initial low-percentage melting (Černý, 1989c).

Thus, LCT systems may evolve relatively early in orogenic events, concentrating easily mobile components in dehydration anatexis of H_2O-undersaturated protoliths, which produces first-generation magmas during dynamothermal metamorphism. The post- to anorogenic LCT systems can also be interpreted as formed from the same kind of undepleted sources within a sagging thickened crust, subject to thermal doming and/or frictional heating and introduction of fluids along essentially post-metamorphic shears and faults (Strong and Hanmer, 1981; Černý and Meintzer, 1988).

Intermediate to granitic plutons, which are commonly spatially associated with fertile granites of the LCT family, are not necessarily consanguineous with them. Recent studies invariably show separate derivation of the fertile melts, unrelated to the magmatic differentiation of associated igneous suites (Černý *et al.*, 1987; Mackenzie *et al.*, 1988; Černý and Meintzer, 1988; Černý, 1991a). This is in conspicuous contrast to the traditional interpretation by Soviet petrologists, who view fertile granites as products of protracted igneous differentiation, starting from batholithic tonalites and diorites (*e.g.*, Ginsburg *et al.*, 1979).

The NYF suites. This family is typified by subaluminous to metaluminous granite compositions, relatively dry parent magma and relatively shallow emplacement. The NYF signature and isotopic data correspond to those of A-type granites. The preferred model is that of a second melting event in middle to lower crustal lithologies, dehydrated and generally depleted of most LCT elements during a preceding anatectic episode (Collins *et al.*, 1982; Whalen *et al.*, 1987; Černý, 1991a). Granulite grade metamorphism and previous depletion of protoliths explain the enrichment in F, liberated from F-based ferromagnesian metamorphic minerals stable at elevated pressures, and the rather dry nature of the high-ascending melts.

Breakdown of ferromagnesian minerals and refractory accessory phases (such as ilmenite, monazite, zircon and titanite) provides the typical HFSE (high field strength elements) assemblage and enrichment in REEs. Synorogenic anatexis of depleted granulites yielding NYF suites during regional dynamothermal metamorphism seems to be exceptional (Černý, 1991a). Most NYF melts are post- to anorogenic, generated by heat effects of mantle-derived gabbroic magmas on the depleted crust in extensional regimes.

Alternate scenarios include direct differentiation of the NYF systems from juvenile, mantle-derived magmas (Fowler and Doig, 1983; Wilson *et al.*, 1986) that are, however, typically tonalitic (M-granites of Whalen *et al.*, 1987). Another possibility is the anatexis of short-lived juvenile granitoids, isotopically indistinguishable from juvenile magmatic differentiates (Wilson, 1980; Anderson, 1983; Vocke and Welin, 1987). A process combining anatexis of a depleted granulite source with juvenile igneous input was also considered (Anderson and Wikström, 1989). However, accumulation of the NYF spectrum of minor elements in the granite + pegmatite systems poses some problems. Pre-enrichment in refractory minerals does not occur prior to melting of juvenile granitoids, and significant fractionation of NYF elements in purely magmatic mantle-derived suites can be expected only in peralkaline systems. Mantle-derived fluids enriched in NYF elements are invoked by many authors to overcome this obstacle, either as heating and fluxing agents in anatexis of lower crust, or as agents promoting separation of granitic melts from parent gabbroic magma.

Thus, we may conclude that the widely accepted model of anatexis of depleted granulite-grade lithologies seems to be the most probable process for generating the NYF-, A-type fertile granites. Further work is necessary to verify the viability of the other two proposals outlined above, and of the more or less mandatory fluid-borne enrichment in rare elements they require.

Mixed NYF + LCT suites. Several localities are known with a principally NYF granite + pegmatite system, but with strong LCT overtones (some of them quoted in table 4 of Part I). They show either a transition from NYF into LCT pegmatites across regional zoning, or combined signatures in virtually each pegmatite body of the given population. None of the known occurrences has been examined in sufficient detail to distinguish among three possible scenarios: the crust that provided the parent melts could have been only partially depleted (Whalen *et al.*, 1987); the anatexis affected a range of depleted plus undepleted protoliths (Whalen *et al.*, 1987); or a pristine NYF magma became contaminated by digestion of undepleted lithologies (Juve and Bergstøl, 1988). In view of the uncertainties about the origin of the NYF signature alone, any attempts to deal with genesis of particular localities of the mixed associations are premature at present.

Concluding Remarks

The variety of concepts presented in this chapter is not surprising when we consider the diversity of factors affecting the genesis of pegmatite populations: first, the LCT, NYF or mixed-signature pegmatites and their plutonic parents themselves; then, the variety of possible protoliths, diversity of anatectic processes at different crustal levels, and possible involvement of mantle-derived magmatism or fluids; and last, but not least, the spectrum of tectonic frameworks from synorogenic to anorogenic. All of this diversity is compounded by the fact that there is not a single pair among the above variables which exhibits an exclusive link or divorce (Figure 12). Although there is a strong statistical tendency toward high frequency of some combinations of compatible features, sweeping generalizations that would apply to large categories of rare-element pegmatites are rather scarce. Predictive models should therefore be applied prudently.

Among the main problems to be solved in the future are the provenance of the rare-element signature of NYF granite + pegmatite systems, and the specific nature of mixed NYF + LCT systems at their individual localities. Both questions have a multitude of potentially correct answers today, but none of them has been proved for any particular intrusive suite.

Another major task is systematic dating of granite + pegmatite systems and their lithologic and tectonic frameworks. The state of this aspect of pegmatite studies is deplorable (Černý, 1991a), but the complex behaviour of isotopic systems in pegmatites (*e.g.*, Clark, 1982) should not be a deterrent any more, given the contemporary sophistication of laboratory and interpretative approaches.

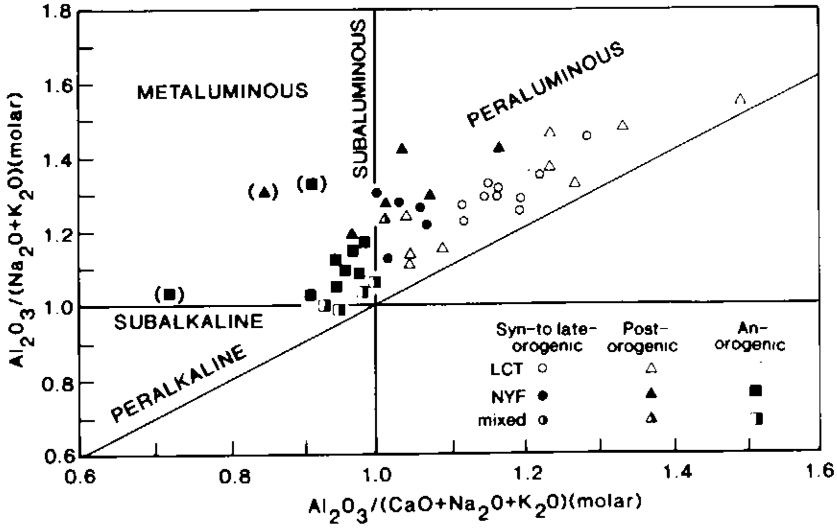


Figure 12 *Fertile granites in the alumina saturation (Shand index) diagram (modified after Maniar and Piccoli, 1980, from Černý, 1991a), coded by tectonic affiliation and geochemical signature.*

IMPLICATIONS FOR EXPLORATION

Constraints imposed by empirical observations and derived genetic models on the distribution of rare-element pegmatites define fundamental guidelines for prospecting and exploration. Because of the significant difference in assemblages of rare elements concentrated in the LCT and NYF pegmatites, these two families must be considered separately.

Exploration for LCT Pegmatites

Extensive concentrations of Li, Rb, Cs, Be, Ga, Sn, Nb and Ta are encountered in the LCT pegmatites of all major orogenies since, and including, the Kenoran event *sensu lato*; Late Archean and Early Proterozoic fields are possibly the most productive. Within the orogens, volcanic-sedimentary rocks (turbidites and flysch of trench, accretionary prism, forearc, inter-arc and back-arc sequences) are the main hosts, and the low-pressure, lower amphibolite facies is the dominant metamorphic environment, usually within steep regional metamorphic gradients (Beus *et al.*, 1968).

Deep large-scale fault systems, shears and faults bounding sliced panels of the above lithologies, cores of anticlinoria, and domal structures host the fertile granites. They can be identified by their silicic, peraluminous and highly fractionated composition, and their potential for differentiating mineralized pegmatites can be tested geochemically (Beus and Sitnin, 1968; Beus *et al.*, 1968; Trueman and Černý, 1982; Černý, 1989b).

The fertile granites, exposed or hidden, represent the foci of more or less zoned, concentric to unidirectional pegmatite groups. Changes in internal structure, patterns of metasomatism, mineral paragenesis and variations exhibited by typomorphic minerals of individual pegmatites within a group reveal the geometry of their regional zoning. Geochemical data for fractionation-sensitive minerals can reveal a cryptic zoning pattern, even if the above indicators fail in apparently homogeneous populations (Trueman and Černý, 1982; Černý, 1989b).

Individual pegmatite types within the rare-element class can be identified by their characteristic paragenesis, less so by internal structure. If poorly exposed, pegmatite types can be reliably estimated from geochemical signatures of their rock-forming minerals (*e.g.*, Gordiyenko, 1971, 1976; Černý, 1975; Zagorskyi *et al.*, 1983; Zagorskyi, 1983). Once recognized, the pegmatite type imposes constraints on the nature of potential mineralization.

Within individual pegmatites, the zoning of primary units, the distribution and nature of secondary assemblages, and geochemical indicators of fractionation guide the search for specific ores. Concentrations of some rare elements in rock-forming minerals may provide estimates of their quantitative accumulation in the entire pegmatite body. The Be, Sn, Nb and Ta contents of muscovite and the Cs content of lepidolite have proven useful in such evaluation (Beus, 1966; Heinrich, 1962; Gordiyenko, 1971, 1973; Gaupp *et al.*, 1984).

Dispersion haloes of rare alkalis and some other elements (such as Be, Sn and Cu) in country rocks aid in the search for hidden pegmatite deposits by relatively inexpensive regional surveys, once a prospective target area is outlined from outcropping pegmatites. Different techniques may estimate different pegmatite types and their approximate depth (Beus *et al.*, 1968; Ovchinnikov, 1976).

Exploration for NYF Pegmatites

Minor to moderate concentrations of Ti, Nb, Y, REE, Zr, U and Th are encountered in the NYF pegmatites that are generally dispersed over geological time. However, major suites are found in the Hudsonian granites of southern Sweden, in the 1400 Ma granites of North America, and among late Grenvillian intrusions of North America and Scandinavia.

Extensional regimes, including aborted rifts, host the dominantly post-orogenic to anorogenic fertile granites, with no particular preference for host rocks, their metamorphic grade or relative age difference. However, synorogenic and (significant) late-orogenic occurrences are also known. The granites are largely, but not exclusively, within the subaluminous-metaluminous range, and typically have the compositional attributes of A-granites.

The NYF pegmatites commonly reside within or close to their plutonic parents. Regional zoning has not been observed; individual groups commonly have uniform internal structure, mineralogy and geochemistry that may be distinctly different among diverse groups of a field. Border and wall zones and late metasomatic units in the interior usually host the main mineralization.

CONCLUDING NOTES

Pegmatite research has been in a state of flux lately, and we can expect significant improvements in our understanding of these deposits in the foreseeable future. These improvements will concern mainly the petrology of internal evolution of individual pegmatite bodies, the processes of origin and internal differentiation of the fertile granites, and the processes of generating fertile melts within the chemistry and dynamics of their source environment. Thus, improvements of the present genetic models can be expected.

A review of Canadian pegmatite populations is not included here, as it would excessively extend this presentation. However, significant pegmatite deposits are known in Canada only in the Shield, and interested readers will find a comprehensive review of these occurrences in Černý (1990).

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REFERENCES

Anderson, J.L., 1983, Proterozoic anorogenic granite plutonism of North America: Geological Society of America, Memoir, v. 61, p. 133-154.

Anderson, U.B. and Wikström, A., 1989, Mafic-felsic plutonic interaction in the Transscandinavian Igneous Belt, southern Sweden: Precambrian Granitoids Symposium, Helsinki, Program with Abstracts, p. 7-8.

Anhaeusser, C.R., 1976, Archean metallogeny in Southern Africa: Economic Geology, v. 71, p. 16-43.

Beus, A.A., 1948, Vertical zoning of pegmatites on the example of the pegmatite field Aksu Pushtiru (Turkestan Range): Doklady Academy of Sciences of the USSR, v. 60, p. 1235-1238.

Beus, A.A., 1960, Geochemistry of beryllium and the genetic types of beryllium deposits: Academy of Sciences of the USSR, Moscow, 329 p. [in Russian]

Beus, A.A., 1966, Distribution of tantalum and niobium in muscovites of granitic pegmatites: Geokhimiya, v. 1966, No. 10, p. 1216-1220. [in Russian]

Beus, A.A., *et al.*, 1968, Geochemical exploration for endogenic deposits of rare elements on the example of tantalum: Nedra Moscow, 264 p. [English Translation, G.S.C. Library, Ottawa]

Beus, A.A. and Sitnin, A.A., 1968, Geochemical features of the distribution of tantalum in granitoids: Geokhimiya, v. 1968, p. 579-585. [in Russian]

Blockley, J.G., 1980, The tin deposits of Western Australia, with special reference to the associated granites: Geological Survey of Western Australia, Mineral Resources Bulletin, v. 12, 184 p.

Breaks, F.W., 1989, Origin and evolution of peraluminous granite and rare-element pegmatites in the Dryden area, Superior Province of northwestern Ontario: Unpublished Ph.D. thesis, Carleton University, Ontario, 594 p.

Breaks, F.W., Bond, W.D. and Stone, D., 1978, Preliminary geological synthesis of the English River subprovince, northwestern Ontario and its bearing upon mineral exploration: Ontario Geological Survey, Miscellaneous Paper 72, 55 p.

Brisbin, W.C., 1986, Mechanism of pegmatite intrusion: American Mineralogist, v. 71, p. 644-651.

Černý, P., 1975, Alkali variations in pegmatitic beryl and their petrogenetic implications: Neues Jahrbuch für Mineralogie, v. 123, p. 198-212.

Černý, P., 1982, Petrogenesis of granitic pegmatites, *in* Černý, P., ed., Granitic Pegmatites in Science and Industry: Mineralogical Association of Canada, Short Course Handbook, v. 8, p. 405-461.

Černý, P., 1989a, Characteristics of pegmatite deposits of tantalum, *in* Möller, P., Černý, P. and Saupé, F., eds., Lanthanides, Tantalum and Niobium: Society for Geology Applied to Mineral Deposits, Special Publication 7, Springer-Verlag, p. 192-236.

Černý, P., 1989b, Exploration strategy and methods for pegmatite deposits of tantalum, *in* Möller, P., Černý, P. and Saupé, F., eds., Lanthanides, Tantalum and Niobium: Society for Geology Applied to Mineral Deposits, Special Publication 7, Springer-Verlag, p. 271-299.

Černý, P., 1989c, Contrasting geochemistry of two pegmatite fields in Manitoba: products of juvenile Aphebian crust and polycyclic Archean evolution: Precambrian Research, v. 45, p. 215- 234.

Černý, P., 1990, Distribution, affiliation and derivation of rare-element granitic pegmatites in the Canadian Shield: Geologische Rundschau, v. 79, p. 183-226.

Černý, P., 1991a, Fertile granites of Precambrian rare-element pegmatite fields: is geochemistry controlled by tectonic setting or source lithologies?: Precambrian Research, in press.

Černý, P., 1991b, Geochemical and petrogenetic features of mineralization in rare-element granitic pegmatites in the light of current research: Applied Geochemistry, in press.

Černý, P., 1991c, Rare-element granitic pegmatites, Part I. Anatomy and internal evolution of pegmatite deposits: Geoscience Canada, v. 18, p. 49-67.

Černý, P. and Brisbin, W.C., 1982, The Osis Lake pegmatitic granite, Winnipeg River district, southeastern Manitoba, *in* Černý, P., ed., Granitic Pegmatites in Science and Industry: Mineralogical Association of Canada, Short Course Handbook, v. 8, p. 545-555.

Černý, P., Fryer, B.J., Longstaffe, F.J. and Tammemagi, H.Y., 1987, The Archean Lac du Bonnet batholith, Manitoba: igneous history, metamorphic effects, and fluid overprinting: Geochimica et Cosmochimica Acta, v. 51, p. 421-438.

Černý, P. and Meintzer, R.E., 1988, Fertile granites in the Archean and Proterozoic fields of rare-element pegmatites: crustal environment, geochemistry and petrogenetic relationships, *in* Taylor, R.P. and Strong, D.F., eds., Recent Advances in the Geology of Granite-Related Mineral Deposits: Canadian Institute of Mining and Metallurgy, Special Volume 39, p. 170-207.

Černý, P., Meintzer, R.E. and Anderson, A.J., 1985, Extreme fractionation in rare-element granitic pegmatites: selected examples of data and mechanisms: Canadian Mineralogist, v. 23, p. 381-421.

Černý, P., Trueman, D.L., Ziehlke, D.V., Goad, B.E. and Paul, B.J., 1981, The Cat Lake-Winnipeg River and the Wekusko Lake pegmatite fields, Manitoba: Manitoba Department of Energy and Mines, Mineral Resources Division, Economic Geology Report ER80-1, 234 p.

Chadwick, R.A., 1958, Mechanism of pegmatite emplacement: Geological Society of America, Bulletin, v. 69, p. 803-836.

Clark, G.S., 1982, Rubidium-strontium isotope systematics of complex granitic pegmatites, *in* Černý, P., ed., Granitic Pegmatites in Science and Industry: Mineralogical Association of Canada, Short Course Handbook, v. 8, p. 347-372.

Collins, W.J., Beams, S.D., White, A.J.R. and Chappell, B.W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia: Contributions to Mineralogy and Petrology, v. 80, p. 189-200.

Crecraft, H.R., Nash, W.P. and Evans, S.H., Jr., 1979, Chemical evolution and development of compositional gradients in a silicic magma: Geological Society of America – Mineralogical Society of America, Annual Meeting, Abstracts with Program, San Diego, p. 452.

Crook, W.W., III, 1977, The geology, mineralogy, and geochemistry of the rare-earth pegmatites, Llano and Burnet Counties, Texas: Unpublished M.Sc. thesis, University of Michigan.

Day, W.C. and Weiblen, P.W., 1986, Origin of late-Archean granite: geochemical evidence from the Vermilion granitic complex of northern Minnesota: Contributions to Mineralogy and Petrology, v. 93, p. 283-296.

Fowler, A.D. and Doig, R., 1983, The age and origin of Grenville Province uraniferous granites and pegmatites: Canadian Journal of Earth Sciences, v. 20, p. 92-104.

Garrison, J.R., Long, L.E. and Richmann, D.L., 1979, Rb-Sr and K-Ar geochronologic and isotopic studies, Llano Uplift, central Texas: Contributions to Mineralogy and Petrology, v. 69, p. 361-374.

Garson, M.S., Bradshaw, N. and Rattawong, S., 1969, Lepidolite pegmatites in the Phangnga area of peninsular Thailand, *in* Fox, W., ed., 2nd Technical Conference on Tin, v. 1: International Tin Council and Department of Mines and Resources Thailand, p. 327-339.

Gaupp, R., Möller, P. and Morteani, G., 1984, Tantal-Pegmatite: Geologische, petrologische und geochemische Untersuchungen: Borntraeger, Berlin-Stuttgart, Monograph Series on Mineral Deposits No. 23, 124 p.

Ginsburg, A.I., Timofeyev, I.N. and Feldman, L.G., 1979, Principles of Geology of the Granitic Pegmatites: Nedra, Moscow, 296 p. [in Russian]

Gordiyenko, V.V., 1971, Concentration of Li, Rb, and Cs in potash feldspar and muscovite as criteria for assessing the rare metal mineralization in granite pegmatites: International Geology Review, v. 13, p. 134-142.

Gordiyenko, V.V., 1973, Cesium in lepidolite as indicator of the cesium content of granitic pegmatites: Doklady, Academy of Sciences of the USSR, v. 209, p. 193-196. [in Russian]

Gordiyenko, V.V., 1976, Diagrams for prognostic evaluation of rare-element mineralization in granitic pegmatites utilizing compositional variations in potassium feldspars: Doklady, Academy of Sciences of the USSR, v. 228, p. 442-444. [in Russian]

Haapala, I., 1966, On the granitic pegmatites in the Peräseinäjöki-Alavus area, South Pohjanmaa, Finland: Bulletin de la Commission Géologique de Finlande, v. 224, 98 p.

Harris, N.B.W., Pearce, J.A. and Tindle, A.G., 1986, Geochemical characteristics of collision-zone magmatism, *in* Coward, M.P. and Ries, A.C., eds., Collision Tectonics: Geological Society of London, Special Publication, No. 19, p. 67-81.

Heinrich, E.Wm., 1953, Zoning in pegmatite districts: American Mineralogist, v. 38, p. 68-87.

Heinrich, E.Wm., 1962, Geochemical prospecting of the beryl and columbite: Economic Geology, v. 57, p. 616-619.

Hildreth, W., 1979, The Bishop tuff: evidence for the origin of compositional zonation in silicic magma chambers: Geological Society of America, Special Paper 180, p. 43-75.

Hildreth, W., 1981, Gradients in silicic magma chambers: implications for lithospheric magmatism: Journal of Geophysical Research, v. 86, B11, p. 10153-10192.

Jahns, R.H., Griffitts, W.R. and Heinrich, E.Wm., 1952, Mica deposits of the Southeastern Piedmont: United States Geological Survey, Professional Paper 248-A, 102 p.

Jahns, R.H. and Wright, L.A., 1951, Gem- and lithium-bearing pegmatites of the Pala district, San Diego County, California: California Division of Mines, Special Report 7-A, 72 p.

Juve, G. and Bergstøl, S., 1988, Scandian ixiolite, pyrochlore and bazzite in granite pegmatite in Tørdal, Telemark, Norway. A contribution to the mineralogy and geochemistry of scandium and tin: Mineralogy and Petrology, v. 38, p. 229-243.

Kesler, T.L., 1976, Occurrences, development, and long-range outlook of lithium-pegmatite ore in the Carolinas: United States Geological Survey, Professional Paper 1005, p. 45-50.

Kuzmenko, M.V., 1976, ed., Rare-element granitic pegmatite fields (geochemical specialization and distribution): Nauka, Moscow, 332 p. [in Russian]

Kuznetsov, V.I., 1977, Formation of Pegmatites in Relation to the Tectonic Evolution and Consolidation of Granite Intrusions: Nedra, Moscow, 184 p. [in Russian]

Lahti, S., 1981, On the granitic pegmatites of the Eräjärvi area in Orivesi, southern Finland: Bulletin of the Geological Survey of Finland, v. 314, 82 p.

Lesher, C.E., Walker, D., Candela, P. and Hays, J.F., 1982, Soret fractionation of natural melts of intermediate to silicic composition: Geological Society of America – Mineralogical Society of America, Abstracts with Program, v. 14, 545 p.

London, D., Hervig, R.L. and Morgan, G.B., VI, 1988, Melt-vapor solubilities and element partitioning in peraluminous granite-pegmatite systems: Contributions to Mineralogy and Petrology, v. 99, p. 360-373.

Luecke, W., 1981, Lithium pegmatites in the Leinster granite (southeast Ireland): Chemical Geology, v. 34, p. 195-233.

Mackenzie, D.E., Glack, L.P. and Sun, Shen-Su, 1988, Origin of alkali-feldspar granites: an example from the Poimena granite, northeastern Tasmania, Australia: Geochimica et Cosmochimica Acta, v. 52, p. 2507-2524.

Mahood, G. and Hildreth, W., 1983, Large partition coefficients for trace elements in high-silica rhyolites: Geochimica et Cosmochimica Acta, v. 47, p. 11-30.

Maniar, P.D. and Piccoli, P.M., 1989, Tectonic discrimination of granitoids: Geological Society of America, Bulletin, v. 101, p. 635-643.

Manning, D.A.C. and Pichavant, M., 1985, Volatiles and their bearing on the behaviour of metals in granitic systems, *in* Taylor, R.P. and Strong, D.F., eds., Granite-Related Mineral Deposits: Canadian Institute of Mining and Metallurgy, Special Volume 39, p. 13-24.

Matheis, G., 1985, Geological setting of pegmatoid rare-metal mineralization: Fortschritte der Mineralogie, v. 63, Beiheft 1, Program with Abstracts, p. 150.

McArdle, P. and Kennan, P.S., 1989, Geological setting of tantalum mineralization in the Caledonides of SE Ireland, *in* Möller, P., Černý, P. and Saupé, F., eds., Lanthanides, Tantalum and Niobium: Society for Geology Applied to Mineral Deposit, Special Publication 7, Springer-Verlag, p. 257-260.

Meintzer, R.E., 1987, The mineralogy and geochemistry of the granitoid rocks and related pegmatites of the Yellowknife pegmatite field, Northwest Territories: Unpublished Ph.D. thesis, University of Manitoba, Winnipeg, 708 p.

Michael, P.J., 1983, Chemical differentiation of the Bishop tuff and other high-silica magmas through crystallization processes: Geology v. 11, p. 31-34.

Miller, C.F. and Mittlefehldt, D.W., 1984, Extreme fractionation in felsic magma chambers: a product of liquid-state diffusion or fractional crystallization?: Earth and Planetary Science Letters v. 68, p. 151-158.

Mittlefehldt, D.W. and Miller, C.F., 1983, Geochemistry of the Sweetwater Wash pluton, California: implications for "anomalous" trace element behavior during differentiation of felsic magmas: Geochimica et Cosmochimica Acta, v. 47, p. 109-124.

Nash, W.P. and Crecraft, M.R., 1981, Evolution of silicic magmas in the upper crust: an experimental analog: American Geophysical Union, Transactions, v. 62, p. 1075

Norton, J.J., 1973, Lithium, cesium, and rubidium – the rare alkali metals, *in* Brobst, D.A. and Pratt, W.P., United States Mineral Resources: United States Geological Survey, Professional Paper 820, p. 365-378.

Norton, J.J., 1981, Origin of lithium-rich pegmatitic magmas, southern Black Hills, South Dakota: Geological Society of America, Rocky Mtn. Section, 34th Annual Meeting, Rapid City, Program with Abstracts, p. 221.

Norton, J.J. and Redden, J.A., 1990, Relations of zoned pegmatites to other pegmatites, granite and metamorphic rocks in the southern Black Hills, south Dakota: American Mineralogist, v. 75, p. 631-655.

Ovchinnikov, L.N., 1976, ed., Lithogeochemical methods for prospecting rare-metal pegmatites: Academy of Sciences of the USSR, Moscow, 79 p. [in Russian]

Rossovskyi, L.N., 1981a, Zoning in rare-metal pegmatite fields (on the example of Hindukush): Izvestiya Akademii Nauk SSSR, seriya geologicheskaya, No. 5, p. 38-52. [in Russian]

Rossovskyi, L.N., 1981b, Rare-element pegmatites with precious stones and conditions of their formation: International Geological Review, v. 23, p. 1312-1320.

Rossovskyi, L.N. and Chmyrev, V.M., 1977, Distribution patterns of rare-metal pegmatites in the Hindu Kush (Afghanistan): International Geology Review, v. 19, p. 511-520.

Rossovskyi, L.N., Chmyrev, V.M. and Salakh, A.S., 1976a, Vertical range and zoning of spodumene pegmatite deposits in Afghanistan: Doklady, Academy of Sciences of the USSR, v. 227, p. 85-87. [translation by American Geological Institute]

Rossovskyi, L.M., Konovalenko, S.I. and Chmyrev, V.M., 1976b, Depth of formation of granitic pegmatites (as exemplified by the Hindukush): Izvestiya, Academy of Sciences of the USSR, seriya geologicheskaya, No. 10, p. 39-54. [in Russian]

Rossovskyi, L.N. and Shmakin, B.M., 1978, Unique example of vertical geochemical zoning in pegmatites of the Hindu Kush, Afghanistan: Doklady, Academy of Sciences of the USSR, Earth Sciences Section, v. 240, p. 204-206.

Shaw, D.M., 1968, A review of K-Rb fractionation trends by covariance analysis: Geochimica et Cosmochimica Acta, v. 32, p. 573-601.

Shaw, H.R., Smith, R.L. and Hildreth, W., 1976, Thermogravitational mechanisms for chemical variations in zoned magma chambers: Geological Society of America, Abstracts with Program, v. 8, p. 1102.

Shearer, C.R., Papike, J.J. and Laul, J.C., 1985, Mineral chemistry and geochemistry of the Harney Peak granite and associated pegmatites, *in* Rich, F.J. ed., Geology of the Black Hills, South Dakota and Wyoming, Second Edition, p. 241-260.

Shearer, C.K., Papike, J.J. and Laul, J.C., 1987, Mineralogical and chemical evolution of a rare-element granite-pegmatite system: Harney Peak granite, Black Hills, South Dakota: Geochimica et Cosmochimica Acta, v. 51, p. 473-486.

Shmakin, B.M., 1983, Geochemistry and origin of granitic pegmatites: Geochemistry International, v. 20, p. 1-8.

Simmons, Wm.B., Lee, M.T. and Brewster, R.H., 1987, Geochemistry and evolution of the South Platte granite-pegmatite system, Jefferson County, Colorado, Geochmica et Cosmochimica Acta, v. 51, p. 455-471.

Solodov, N.A., 1971, Scientific Principles of Perspective Evaluation of Rare-Element Pegmatites: Nauka, Moscow, 292 p. [in Russian]

Stewart, D.B., 1978, Petrogenesis of lithium-rich pegmatites: American Mineralogist, v. 63, p. 970-980.

Strong, D.F. and Hanmer, S.K., 1981, The leucogranites of southern Brittany: origin by faulting, frictional heating, fluid flux, and fractional melting: Canadian Mineralogist, v. 19, p. 163-176.

Tatarinov, A.V., 1974, Types of miarolitic pegmatites of the Borshtchovochnyi Kryazh: Zapisky Vsesoyuzhnogo Mineralogicheskogo Obshtchestva, v. 103, p. 52-67. [in Russian]

Thomas, A.V., Bray, C.J. and Spooner, E.T.C., 1988, A discussion of the Jahns-Burnham proposal for the formation of zoned granitic pegmatites using solid-liquid-vapour inclusions from the Tanco pegmatite, S.E. Manitoba, Canada: Royal Society of Edinburgh, Transactions, Earth Sciences, v. 79, p. 299-315.

Trueman, D.L. and Černý, P., 1982, Exploration for rare-element granitic pegmatites, *in* Černý, P., ed., Granitic Pegmatites in Science and Industry: Mineralogical Association of Canada, Short Course Handbook, v. 8, p. 463-494.

Varlamoff, N., 1972, Matériaux pour l'établissement des types et de la zonéographie des pegmatites granitiques à métaux rares de Madagascar: Academie Royale des Sciences d'Outre Mer, Sciences Naturales, Médicinales, N.S., v. 18-6, 72 p.

Vielzeuf, D. and Holloway, J.R., 1988, Experimental determination of the fluid-absent melting relations in the pelitic system: Contributions to Mineralogy and Petrology, v. 98, p. 257-276.

Vocke, R.D., Jr. and Welin, E., 1987, Origin of the Middle to Late Proterozoic granitoids of SW Sweden in light of their Nd and Sr isotope systematics: Proterozoic Geochemistry Symposium, Lund, Program with Abstracts, p. 90.

Walker, R.J., Hanson, G.N., Papike, J.J. and O'Neil, R.O., 1986, Nd, O and Sr isotopic constraints on the origin of Precambrian rocks, southern Black Hills, South Dakota: Geochimica et Cosmochimica Acta, v. 50, p. 2833-2846.

Whalen, J.B., Currie, K.L. and Chappell, B.W., 1987, A-type granites: geochemical characteristics, discrimination and petrogenesis: Contributions to Mineralogy and Petrology, v. 95, p. 407-419.

White, J.W., 1960, Topaz-bearing pegmatites and gem topaz in the Lano Uplift, Texas: Unpublished M.A. thesis, University of Texas, 120 p.

Wilson, M.R., 1980, Granite types in Sweden: Geologiska Föreningens i Stockholm Förhandlingar, v. 102, p. 167-176.

Wilson, M.R., Fallick, A.E., Hamilton, P.J. and Persson, L., 1986, Magma sources for some mid-Proterozoic granitoids in SE Sweden: geochemical and isotopic contraints: Geologiska Föreningens i Stockholm Förhandlingar, v. 108, p. 79-91.

Winkler, H.G.F., 1967, Petrogenesis of Metamorphic Rocks, Second Edition: Springer-Verlag, New York, 334 p.

Wright, J.E. and Haxel, G., 1982, A garnet-two mica granite, Coyote Mountains, southern Arizona: Geologic setting, uranium-lead isotopic systematics of zircon, and nature of the granite source region: Geological Society of America, Bulletin, v. 93, p. 1176-1188.

Zagorskyi, V.E., 1983, Rare-element composition of potassium feldspars as a criterion for appraisal of the specialization and arc potential of rare-element pegmatites: Doklady, Academii Nauk SSSR, v. 269, p. 715-718. [in Russian]

Zagorskyi, V.E., Galkina, T.N., Persikova, L.A., Petrov, L.L., Plotnikova, L.P. and Yaroshenko, S.K., 1983, Rare-element content of mica and K-feldspar as a criterium for evaluation of complex rare-element pegmatites: Mineralogicheskyi Zhurnal, v. 5, p. 38-46. [in Russian]

Zasedatelev, A.M., 1974, Possible accumulation of lithium in host rocks of lithium pegmatite veins during old sedimentation processes: Doklady, Akademii Nauk SSSR, Earth Science Section, v. 218, p. 196-198. [in Russian]

Zasedatelev, A.M., 1977, Quantitative model of metamorphic generation of rare-metal pegmatite with lithium mineralization: Doklady, Akademii Nauk SSSR, Earth Science Section, v. 236, p. 219-221. [in Russian]

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