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

Petr Černý
Department of Geological Sciences
University of Manitoba
Winnipeg, Manitoba R3T 2N2

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 phases, 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 cognetic 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>
<thead>
<tr>
<th>Table 1</th>
<th>Composition of typical fertile granites.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Oasis Lake</td>
<td>2 - Lac du Bonnet</td>
</tr>
<tr>
<td>biotite granite</td>
<td>coarse-grained leucogranite</td>
</tr>
<tr>
<td>SiO₂ (wt%)</td>
<td>73.15</td>
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<tr>
<td>TiO₂</td>
<td>0.12</td>
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<tr>
<td>Al₂O₃</td>
<td>14.40</td>
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<tr>
<td>Fe₂O₃</td>
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<td>FeO</td>
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<td>CaO</td>
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<tr>
<td>K₂O</td>
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<tr>
<td>P₂O₅</td>
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<tr>
<td>CO₂</td>
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<tr>
<td>F⁻</td>
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<tr>
<td>-O=F²⁻</td>
<td>0.01</td>
</tr>
<tr>
<td>total</td>
<td>100.07</td>
</tr>
<tr>
<td>A/CNK **</td>
<td>1.16</td>
</tr>
<tr>
<td>A/NK **</td>
<td>1.31</td>
</tr>
<tr>
<td>Li (ppm)</td>
<td>71</td>
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<tr>
<td>Rb</td>
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<td>Cs</td>
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<td>78</td>
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<td>Hf</td>
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<td>Sn</td>
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<td>2737</td>
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<tr>
<td>Th/U</td>
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</table>

Notes
1 Peraluminous LCT granite grading from biotite through two-mica + garnet to muscovite + garnet + tourmaline types (from Černý and Brbin, 1982)
2 Metaluminous NYF fertile granite with biotite and extremely rare garnet (from Černý et al., 1987)
- not determined; nd, not detected
** A = molecular Al₂O₃; CNK = CaO + Na₂O + K₂O, and NK = Na₂O + K₂O
Pegmatite groups consist of tens to hundreds of cogenetic bodies, ranging from a few to about a hundred per km², and maintaining such densities of occurrence over areas of a few tens of km². 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-YF; 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; Meinitzer, 1977). 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 sub-horizontal 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 δ¹⁸O data shows two maxima at about +8.5‰ and +11.2‰ (Černý and Meinitzer, 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; δ¹⁸O 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, focused 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 subtype.

**Figure 1** Contrasting petrochemistry of the LCT and NYF fertile granites, on the examples of the Oasis 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 Oasis 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 non-systematic 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 NYP granite pegmatite families, pegmatites are largely confined to the interior or margins of the granites, are 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), Rossosvsky 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., Jahn 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](image1.png)

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

![Figure 3](image2.png)

**Figure 3** (right) Regional zoning of the Niau-Kulam pegmatite field, Afghanistan (modified from Rossosvsky and Chmyrev, 1977; Rossosvsky, 1981). Fertile granites (++) generate steeply dipping oligoclase + biotite + K-feldspar + muscovite pegmatites within gneisses (foliation pattern) and in an early porphyric granite (xxx); subhorizontal albiteized 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 rafted 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 (aluminium 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 F; 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 iuwogranite.

**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., Rossovskiy

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**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, Redont 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 Pecosaddie 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 Varutrask, Bikita, Harding, Londonderry and Tanco deposits (Figure 3. Cerny, 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-Hindu Kush province in Afghanistan; Rosovskiy et al., 1976a, Rosovskiy, 1981b).

Granite + pegmatite systems of post-orogenic to anorogenic tectonic affiliation are related to subvertical diatreme 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, mimicking the large-scale behaviour of their granitic hosts. Although vertical movement certainly 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-pa greenschist to) lower amphibolite facies (Beus et al., 1968). The A 21 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* (Cerny, 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 magmaticogenetic 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 hydrothermal 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 mini-ma. 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; Breakes 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; (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 analogues, (9) last, but not least, not a single case of "absorbed segregation" of highly fractionated pegmatite melts in *status* of metamorphic/anatectic nascent 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 exomorphous, 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 dupli-
cates of exterior pegmatites in metamorphic rocks 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, or 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 magmato-genic 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. The mechanism can be considered as 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, Ta, 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 underappreciated by researchers in the 1970s, but was re-instated recently as a poten factor: increased polymerization in silicic melts, changes in availability of complexing ligands, and extraction of some trace elements into liquid 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 litera-
stricted 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 anatetic hypotheses reviewed earlier can seriously compete with this model. On the contrary, several investigators who started their research seriously considering or advocating the anatetic mechanism largely abandoned it because of evidence to the contrary generated by their own research (J.W. Breaks, J.J. Norton, and the schools of J.J. Papke, G. Matheis and G. Morteau). Unless unambiguous geological evidence and experimental proof are provided for the anatetic or aqueous cases, the existence of metamorphogenic pegmatites of the rare-element class, convergent with those of proven magmatic 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 concentration 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 6; Černý, 1989c); the Proterozoic (Hudsonian) Enlajarvi field in Finland (Lahti, 1981); the Caledonian Leinster field in Ireland (Lucpe, 1981; McIvor and Kennan, 1983); and the Apline Nila-Kulam field in Afghanistan (Rossowsky, 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 Muntezer, 1982). (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) Tump-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 Turekian and Černý, 1982).

Li, Be, Ta, Nb

Increasing fractionation.
Volatlie enrichment.
Complexity of zoning.
Extent of replacements.
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 Quelitco belts in the Superior Province (Černý, 1980), 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 Zimbabwean and Kaapvaal cratons in Africa (Anhaeusser, 1976). The Proterozoic Central Svecofennian Subprovince in Scandinavia (Černý, 1991b), the Hercynian Appalachian Province (Jahn 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.

Age distribution. Worldwide pegmatite populations have formed in most tectono-magmatic 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 (2750-2550 Ma) provinces were quoted in the preceding section. Hudsonian (1800-1600 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) (65-20 Ma) orogenies 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 Nulaghanian-Karelian (2200-1900 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 nuciel 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). Geologic, 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, 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 neighboring 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 re-mobilized 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 Phanerozoic sequences of intermediate levels (hosting pegmatites of the muscovite class; Rosovsky 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 Fellingbro-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 Koresten 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 orogenetic 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

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**Figure 10** Distribution of rare-element pegmatite fields in the Superior Province (modified from Černý, 1990). Names denote only the volcano-plutonic (open) and metasomatic (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 (Rosovsky 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 (Mokoro 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, 1991a, 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 metasedimentary 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 compres- sional 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 anatectic, and commonly dissected into stacks of fault-bounded panels.

Aubuma-type metamorphism marked by relatively steep geothermal gradients is typical of rare-element pegmatite fields, and includes 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 dynamothermal metamorphic 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 Svecocfenian 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 (Beaks 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 struc-
tural controls alone. This is amply demonstrated by the Pikes Peak batholith, the Wausau pluton, the Grenivillan 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 crustal 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 paragenetic 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 metamudstone suites 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. Viezewuz and Holloway (1988) demonstrated that even fluid-absent melting of metapelites produces peraluminous melts. However, a number of fertile granites have been identified recently as derived from mixed basements 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 metatilaelite seem to be the sole source, leading to both I- and S-characteristics (Wright and Hazle, 1982; Harris et al., 1986; Černý, 1991a). These protoliths are surprisingly highly fractionated in mineral assemblages that participate in initial low-percentage melting (Černý, 1993c).

Thus, LCT systems may evolve relatively early in orogenic events, concentrating easily mobile components in dehydration anatexis of H2O-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 Hamer, 1981; Černý and Meintzer, 1988).

Intermediate to granitic plutons, which are commonly spatially associated with felsic granites of the LCT family, are not necessarily consanguineous with them. Recent studies invariably show separate derivation of the felsic 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 felsic granites as products of protracted igneous differentiation, starting from batholithic tonalites and diorites (e.g., Ginsburg et al., 1979).

The NYP suite. This family is typified by subaluminous to metaluminous granite compositions, relatively dry parent magma and relatively shallow emplacement. The NYP 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 NYP suites during regional dynamothermal metamorphism seems to be exceptional (Černý, 1991a). Most NYP 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 NYP 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 Weilin, 1987). A process combining anatexis of a depleted granulite source with juvenile igneous input was also considered (Anderson and Wïskström, 1985). However, accumulation of the NYP 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 NYP elements in purely magmatic mantle-derived suites can be expected only in peraluminous systems. Mantle-derived fluids enriched in NYP 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 NYP, A-type felsic 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 NYP + LCT suite. Several localities are known with a principally NYP granite + pegmatite system, but with strong LCT overtones (some of them quoted in table 4 of Part I). They show either a transition from NYP 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 NYP magma became contaminated by digestion of undepleted lithologies (Juve and Bergström, 1988). In view of the uncertainties about the origin of the NYP 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, NYP 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 NYP granite + pegmatite systems, and the specific nature of mixed NYP + 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](https://example.com/figure12.png)

Figure 12. Felsic 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 orogen, 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 antitornas, 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 Sitin, 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 homogenous 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., Gordyenko, 1971, 1976; Černý, 1975; Zagorsky et al., 1983; Zagorsky, 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; Gordyenko, 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 suites 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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