Pegmatite genesis: state of the art

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Abstract: No one universally accepted model of pegmatite genesis has yet emerged that satisfactorily explains all the diverse features of granitic pegmatites. Genesis from residual melts derived from the crystallization of granitic plutons is favoured by most researchers. Incompatible components, fluxes, volatiles and rare elements, are enriched in the residual melts. The presence of fluxes and volatiles, which lower the crystallization temperature, decrease nucleation rates, melt polymerization and viscosity, and increase diffusion rates and solubility, are considered to be critical to the development of large crystals. A number of new concepts have shed light on problems related to pegmatite genesis.

Cooling rates calculated from thermal cooling models demonstrate that shallow-level pegmatites cool radically more rapidly than previously believed. Rapid cooling rates for pegmatites represent a quantum shift from the widely held view that the large crystals found in pegmatites are the result of very slow rates of cooling and crystal growth.

Experimental and field evidence both suggest that undercooling and disequilibrium crystallization dominate pegmatite crystallization. London’s constitutional zone refining model of pegmatite evolution involves disequilibrium crystallization from an undercooled, flux-bearing granitic melt. The melt is not necessarily flux–rich and the model does not require the presence of an aqueous vapor phase.

Experimental studies of volatile- and flux-rich melts and fluid inclusion studies suggest that volatile-rich silicate melts may persist to temperatures well below 500 °C and even down to 350 °C.

Studies of melt inclusions and fluid inclusions have led some researchers to suggest that the role of immiscible fluids must be considered in any model regarding pegmatite genesis. Fluid saturation is thought to occur early in the crystallization history of pegmatites. Two types of melt inclusions along with primary fluid inclusions have been found coexisting in pegmatite minerals.

Advances by Petr Černý in pegmatite classification are in wide use and the fractionation trends of Nb, Ta and other HFSE and K, Rb, Cs, Li, Ga and Tl are now well understood.

How pegmatitic melts are produced, the types of source rocks involved and how melt generation relates to plate tectonic models are challenging areas for future investigations. Also, the roles of regional zoning, anatexis, and chemical quenching in pegmatite genesis are areas for future pegmatite research.

Key-words: pegmatite, pegmatite genesis, thermal modelling, chemical quench, classification, regional zoning.

Introduction

Pegmatites are intrusive igneous rocks with very coarse-to-gigantic-sized textures. What typifies the world’s most famous granitic pegmatites is a combination of gigantic crystal size and extreme enrichment of rare elements. However, pegmatites actually have the greatest range of grain sizes known in any rock type, from sub-millimeter to tens of meters. Pegmatic textures can develop in any intrusive igneous rock type from ultramafic, to granitic, to syenitic in composition. Most commonly, the term is used to refer to granitic pegmatites and is generally understood to refer to rock of overall granitic composition when it is used without a qualifying adjective (e.g. gabbroic pegmatite). Granitic pegmatites are composed predominantly of quartz and feldspars with accessory mica.

Although no universally accepted model of pegmatite genesis has yet emerged that satisfactorily explains all the diverse features of granitic pegmatites, genesis from residual melts derived from the crystallization of granitic plutons is favored by most researchers. Incompatible components, fluxes, volatiles and rare elements, concentrate in the residual melts. The presence of fluxes and volatiles, which lower the crystallization temperature, decrease nucleation rates, melt polymerization and viscosity, and increase diffusion rates and solubility, are considered to be critical to the development of large crystals and pegmatic textures.

Most pegmatites appear to form from a single intrusive magmatic event, but undergo a complex internal crystallization history that can result in a large range in grain sizes; consistent changes in mineral chemistry from wall zone to cores; increasing concentrations of fluxes, volatiles and rare elements and, in rare instances, the formation of...
pockets containing gem-quality crystals. Additionally, pegmatites appear to have crystallized from their margins toward their interiors, based on a variety of factors including geothermometry studies and comb-structure texture with wedge-shaped crystals oriented perpendicular to pegmatite margins.

Significant advances in understanding pegmatite genesis have been made over the last 40 years. In the 1970’s and 80’s the most widely accepted model of pegmatite genesis was that of Richard Jahns (Jahns, 1955, 1982; Jahns & Burnham, 1969) who promulgated the idea that pegmatites evolve from residual granitic melts comprised of coexisting water vapor and silicate melt. Jahns & Burnham (1969) and Jahns & Tuttle (1963) cited experimental evidence that pegmatites formed by equilibrium crystallization of coexisting granitic melt and hydrous fluid at or slightly below the hydrous granite liquidus. Jahns & Burnham (1969) also firmly established the concept that water acted as an incompatible phase that increases in the residual melt as crystallization progresses until a discrete water-rich vapor separated from the silicate-rich melt (Fig. 1 and 2). In the Jahns model it is the interaction of the melt and vapor phases that gives rise to pegmatitic textures and the transition of granite into pegmatite begins at the point of H₂O-fluid saturation. The presence of a discrete aqueous vapor phase is thus essential to pegmatite formation and was used to explain the large size of crystals in pegmatites. Although more recent experimental evidence by London (1992, 2005a) suggests that the presence of a hydrous vapor phase is not essential to the development of pegmatitic texture, the model presented by Jahns & Burnham (1969) was a landmark contribution to the understanding of pegmatite genesis.

Newer developments

Pegmatite classification

Modern pegmatite classification schemes are strongly influenced by the depth-zone classification of granitic rocks published by Buddington (1959), and the Ginsburg & Rodionov (1960) and Ginsburg et al. (1979) classification which categorized pegmatites according to their depth of emplacement and relationship to metamorphism and granitic plutons. Černý’s (1991) revision of that classification scheme (Table 1–3) is the most widely used classification of pegmatites today. Černý’s (1991) pegmatite classification, which is a combination of emplacement depth, metamorphic grade and minor element content, (Fig. 3) has provided significant insight into the origin of pegmatitic melts and their relative degrees of fractionation. This classification has been widely accepted and is in general use today.
Table 2. The four classes of granitic pegmatites showing minor elements, metamorphic environment, relation to granite, structural features and examples (after Černý, 1991).

<table>
<thead>
<tr>
<th>Class</th>
<th>Typical Minor Elements</th>
<th>Metamorphic Environment</th>
<th>Relation to Granite</th>
<th>Structural Features</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abyssal</td>
<td>U, Th, Zr, Nb, Ti, Y, REE, Mo</td>
<td>(upper amphibolite to) low- to high-P granulite facies</td>
<td>none (segregations of anatectic leucosome)</td>
<td>conformable to mobilized cross-cutting veins</td>
<td>Rae and Hearne Provinces, Sask. (Tremblay, 1978); Aldan and Anabar Shields, Siberia (Bushev &amp; Koplus, 1980); Eastern Baltic Shield (Kalita, 1965)</td>
</tr>
<tr>
<td></td>
<td>poor (to moderate) mineralization</td>
<td>~ 4–9 kbar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscovite</td>
<td>Li, Be, Y, REE, Ti, U, Th, Nb &gt; Ta</td>
<td>high-P, Barrovian amphibolite facies (kyanite-sillimanite)</td>
<td>none (anatectic bodies to marginal and exterior)</td>
<td>quasi-conformable to cross-cutting</td>
<td>White Sea region, USSR (Gorlov, 1975); Appalachian Province (Jahns et al., 1952); Rajahstan, India (Shmakin, 1976)</td>
</tr>
<tr>
<td></td>
<td>poor (to moderate) mineralization, micas and ceramic minerals</td>
<td>~ 5–8 kbar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ 650–580 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCT</td>
<td>Li, Rb, Cs, Be, Ga, Nb &lt; &gt; Ta, Sn, Hf, B, P, F</td>
<td>low-P, Abukuma amphibolite to upper greenschist facies (andalusite-sillimanite)</td>
<td>interior to marginal to exterior</td>
<td>quasi-conformable to cross-cutting</td>
<td>Yellowknife field, NWT (Meintzer, 1987); Black Hills, South Dakota (Shearer et al., 1987); Cat Lake-Winnipeg River field, Manitoba (Černý et al., 1981)</td>
</tr>
<tr>
<td></td>
<td>poor to abundant mineralization, gemstock industrial minerals</td>
<td>~ 2–4 kbar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>~ 650–500 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rare - Element</td>
<td>Y, REE, Ti, U, Th, Zr, Nb &gt; Ta, F</td>
<td>variable</td>
<td>interior to marginal</td>
<td>interior pods, conformable to cross-cutting exterior bodies</td>
<td>Llano Co., Texas (Landes, 1932); South Platte district, Colorado (Simmons et al., 1987); Western Keivy, Kola, USSR (Beus, 1960)</td>
</tr>
<tr>
<td></td>
<td>poor to abundant mineralization, ceramic minerals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NYF</td>
<td>Be, Y, REE, Ti, U, Th, Zr, Nb &gt; Ta, F</td>
<td>shallow to sub-volcanic</td>
<td>interior to marginal</td>
<td>interior pods and cross-cutting dikes</td>
<td>Pikes Peak, Colorado (Foond, 1982); Sawtooth batholith, Idaho (Boggs, 1986); Korosten pluton, Ukraine (Lazarenko et al., 1973)</td>
</tr>
<tr>
<td></td>
<td>poor mineralization, gemstock</td>
<td>~ 1–2 kbar</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Relationships between Černý’s (1991) pegmatite classes, families, types and subtypes, showing the types and subtypes related to LCT and NYF families.

<table>
<thead>
<tr>
<th>Class</th>
<th>Family</th>
<th>Type</th>
<th>Subtype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abyssal</td>
<td>LCT</td>
<td>BERYL</td>
<td>beryl-columbite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>beryl-columbite-phosphate</td>
</tr>
<tr>
<td>Muscovite</td>
<td>LCT</td>
<td>COMPLEX</td>
<td>spodumene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(rare element)</td>
<td>petalite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>lepidolite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>amblygonite</td>
</tr>
<tr>
<td>Rare-Element</td>
<td>NYF</td>
<td>ALBITE-SPODUMENE</td>
<td>allanite-monazite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ALBITE</td>
<td>gadolinite</td>
</tr>
<tr>
<td>Miarolitic</td>
<td>NYF</td>
<td>RARE-EARTH</td>
<td></td>
</tr>
</tbody>
</table>

This classification has four main categories or classes. These are Abyssal (high grade, high to low pressure), Muscovite (high pressure, lower temperature), Rare-Element (low temperature and pressure), and Miarolitic (shallow level). The Rare-Element Classes are subdivided based on composition into LCT and NYF families: LCT for Lithium, Cesium, and Tantalum enrichment and NYF for Niobium, Yttrium, and Fluorine enrichment (Table 3). The Rare-Element Class is further subdivided into types and subtypes according to the mineralogical or geochemical characteristics. Almost all recent pegmatite descriptions classify pegmatites according to LCT- and NYF–families, types and subtypes. The classification has provided insight into the origin of the melts and relative degrees of fractionation. Virtually all recent pegmatite descriptions classify pegmatites according to LCT- and NYF-types and subtypes. Another important contribution of the classification is the petrogenetic component of the classification, which shows the association of LCT pegmatites with mainly orogenic plutons, and NYF pegmatites with mainly anorogenic plutons (Table 4). Furthermore, this classification has proved to be quite successfully, especially in Canada, as an exploration tool for locating rare element pegmatites with economic potential.

Recently, Černý & Ercit (2005) published a new revision of the Černý (1991) classification. They propose a number of changes that address NYF pegmatite classification and a petrogenetic classification of pegmatites derived from plutons. New categories of NYF and LCT subclasses are introduced and the geochemical signatures are expanded. The modified petrogenetic classification is a “family system” of classifying granitic pegmatites of plutonic derivation (Table 5).

**Geochemical fractionation**

In the last two decades, studies mainly by Černý and colleagues have documented the geochemical behavior of numerous minor- and trace-element systems in pegmatitic
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Table 4. Petrogenetic affiliations (after Černý, 1991), showing geochemical signature, orogenic affiliation, granite bulk composition, source lithologies and granite type (I, S, A).

| Orogenic Types | LCT          | Li, Cs, Ta |
|               |              | Synorogenic to late Orogenic |
|               |              | Peraluminous parent granites: undepleted upper to middle crust |
| S and I types  |              | Nb > Ta, Y, F, REE, Ti, Sc, Zr, U, Th |
|               |              | Mainly Anorogenic |
| Anorogenic     | NYF Types    | Sub - to - Metaluminous, Peralkaline |
| Mixed Cross-bred | LCT & NYF   | Metaluminous to Peraluminous |
|                |              | Mixed protoliths or assimilation |

Table 5. The family system of petrologic classification of granitic pegmatites of plutonic derivation. For the complete classification refer to Černý & Ercit (2005).

<table>
<thead>
<tr>
<th>Family Pegmatite subclass</th>
<th>Geometric signature</th>
<th>Pegmatite bulk composition</th>
<th>Associated granites</th>
<th>Granite bulk composition*</th>
<th>Source lithologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCT REL-Li</td>
<td>Li, Rb, Cs, Be, Sn, Ga, Ta&gt;Nb, (B, P, F)</td>
<td>Peraluminous to subaluminous</td>
<td>Synorogenic to late-orogenic (to anorogenic) largely heterogeneous</td>
<td>Peraluminous S, I or mixed S+I types</td>
<td>Undepleted upper- to middle-crust basement gneisses</td>
</tr>
<tr>
<td>MI-Li</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Basement gneisses</td>
</tr>
<tr>
<td>NNYF MI-REE</td>
<td>Nb&gt;Ta, Ti, Y, Sc, REE, Zr, U, Th, F</td>
<td>Subaluminous to metaluminous (to subaluminous)</td>
<td>Syn-, late, post- to mainly anorogenic quasi-homogeneous</td>
<td>Peraluminous to subaluminous and metaluminous A and I types</td>
<td>Depleted middle to lower crustal granulites, or juvenile granitoids</td>
</tr>
<tr>
<td>Mixed Cross-bred LCT</td>
<td>Mixed</td>
<td>Metaluminous to moderately peraluminous</td>
<td>Postorogenic to anorogenic; heterogeneous</td>
<td>Subaluminous to slightly peraluminous</td>
<td>Mixed protoliths or assimilation of supracrustals by NYF granites</td>
</tr>
<tr>
<td>&amp; NYF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Peraluminous, A/CNK > 1; subaluminous, A/CNK ~ 1; metaluminous, A/CNK < 1 at A/NK > 1; subalkaline, A/NK ~ 1; peralkaline, A/NK < 1, where A = Al_2O_3, CNK = CaO + Na_2O + K_2O, and NK = Na_2O + K_2O (all in molecular values; Černý 1991).

The fractionation patterns of Nb, Ta and other HFS elements in numerous pegmatite systems have been well documented, especially in LCT pegmatites (Černý, 1989a, 2005; Breaks et al., 2005). The fractionation patterns of K, Rb, Cs, Li, Ga and Tl in feldspars, micas, beryl and other minerals have also been described by Černý (2005). The enrichment trends of alkali elements in feldspars and micas have proven valuable in understanding pegmatite petrogenesis and the internal fractionation of pegmatites. These relationships and trends have also proven to be especially helpful in geochemical exploration for pegmatites (Breaks et al., 2005; Trueman & Černý, 1982). Examples of some of the more significant trends documented by Černý for the columbite group minerals, feldspars, beryl and micas are shown in Fig. 4–8. In general, in columbite group minerals Mn/Fe and Ta/Nb increase with fractionation, but patterns are strongly related to the composition of the pegmatite and fluorine also plays an important role in the shape of the trends for Nb and Ta (Fig. 4 and 5). Rb and Cs increase with fractionation in feldspars, micas and other minerals. The trends are apparent in minerals between groups of pegmatites and within individual pegmatites from margins toward cores, with the most fractionated portions of pegmatites containing the greatest enrichments. In complex pegmatites with replacement units, enrichments generally reach their highest levels in minerals within the replacement units. Linnen (1998, 2005) has shown experimentally that manganotantalite is more soluble in granitic melts than manganocolumbite and that the addition of Li and F enhances the solubility of manganotantalite in the melts, which helps explain the tendency of Ta-rich phases to occur in the most highly fractionated assemblages (Linnen & Cuney, 2005).

Exomorphic reactions

Exomorphic haloes of Be (emerald), B (tourmaline) and Li (holmquistite) are well established examples of wallrock
alteration associated with pegmatites in a number of locations (Simmons, 2007a). In addition, LCT pegmatites have been shown to have exomorphic haloes of alkali enrichment in the surrounding wallrocks. Li, Rb, and Cs enrichments have been shown to be associated with rare element pegmatites and soil geochemistry has been successfully used to locate buried rare element pegmatites (Galeschuk & Vanstone, 2005).

Temperatures of formation

The proposed temperatures of the final stages of pegmatite crystallization have declined over the last few decades. The Jahns model suggested that pegmatites crystallize at or near the hydrous minimum melt temperatures of about 600 °C (Jahns & Burnham, 1969). Based on stable isotopic studies, Taylor et al. (1979) proposed temperatures of emplacement of pegmatite melts at about 700 °C to final temperatures of 525 °C in the pockets in San Diego County, California pegmatites.

Two-feldspar thermometry using reintegrated perthite compositions from the intermediate zones of pegmatites in the South Platte, Colorado NYF district gave temperatures of 550–500 °C (Simmons et al., 1987). Two-feldspar thermometry of feldspars showing no evidence of exsolution from the Little Three pegmatite, California (Morgan & London, 1999) gave temperatures of ~400–435 °C near the margins to 350–390 °C near the pegmatite pocket zone and a sharp decrease to 240–275 °C in the pockets where K-feldspar is perthitic (Fig. 9). Nabelek et al. (1992a,b) reported equilibrium temperatures of about 350 °C for coexisting quartz and K-feldspar in the cores of several Black Hills, South Dakota, pegmatites. Sirbescu & Nabelek (2003a,b) suggest that the Li-bearing Tin Mountain pegmatite, Black Hills, South Dakota, crystallized from fluid-rich, compositionally complex melts at ~400–350 °C with the low crystallization temperatures resulting from the combined fluxing effects of Li, B, P, H₂O and carbonate anions. Their determinations are based on microthermometric data on primary fluid inclusions cogenetic with crystallized-melt inclusions.

Volatiles and fluxes in pegmatite melts

London’s experimental work has shown that water saturation, as proposed by Jahns & Burnham (1969) is neither necessary nor likely in the early crystallization of pegmatites (London, 1992, 2005a and references therein). His experiments have shown that other fluxes such as B, F, P and Li in addition to H₂O play a critical role in the formation of rare element pegmatites.

The presence of these fluxes alter the melt by appreciably lowering the crystallization temperature, decreasing nucleation rates, decreasing melt polymerization, decreasing viscosity, increasing diffusion rates, and increasing solubility (London, 1992, 2005a; Simmons et al., 2003). The fluxes act as network modifiers that prevent or hinder the formation of nuclei and increase the diffusion rates of ions to the few nuclei that do survive and begin to grow. Thus, network modifiers act to prevent nuclei formation and at the same time increase the effectiveness of diffusion. These two effects combine to facilitate ion migration over greater distances and promote the growth of the few nuclei that do manage to form, resulting in fewer, much larger crystals.

Fluid and melt inclusions

Melt inclusions (MI), small blebs of melt that are trapped in crystallizing minerals at magmatic temperatures and pressures that become essentially solid at surface temperatures, may record parental melt compositions at the time of host mineral growth (Roedder, 1979, 1984; Lowenstern, 1995) and they may monitor the chemical changes of the residual liquid during magma evolution (Pettke, 2006). Fluid inclusions (FI) entrap fluid that remains in large part fluid at surface temperatures (Roedder, 1984). Recent studies pertaining to FI and MI are extensive (e.g. Lowenstern, 1995, 2003; Sobolev, 1996; Peretyazhko et al., 2000; Hauri et al., 2002; Bodnar & Student, 2006). Many additional references pertaining to igneous systems can be found in Roedder (1984, 2003), Samson et al. (2003) and Kontak et al. (2004). Challenges involved in interpreting MI from felsic plutons are discussed in detail by Webster & Thomas (2006). Thomas et al. (2003, 2006a) looks specifically at MI in felsic aplite and pegmatite systems. Sirbescu & Nabelek (2003a and b) focus on FI in pegmatites.

The study of FI and their characterization as either primary or secondary is not always straightforward and can lead to very different interpretations of the same pegmatite. For example, London (1985, 1986) describes FI from petalite, eucryptite, spodumene, and coexisting quartz from the Tanco Pegmatite, Bernic Lake, Manitoba. Spodumene occurs both as fine-grained intergrowths with quartz resulting from the breakdown of petalite (SQUI) and as coarse-grained crystals embedded in massive quartz. Both types of spodumene and quartz trapped an abundance of FI that were uniform within each host mineral phase but very different between them. FI hosted by spodumene typically contained a low-salinity aqueous liquid plus vapor (at 25 °C) and a consistent assemblage of daughter minerals including albite, cookeite, pollucite-analcime solid solution, quartz, an unidentified carbonate and lithium tetraborate, Li₂B₄O₇, described as the new mineral species diomignite by London et al. (1987). The minimum possible entrapment temperature determined from this mineral assemblage was 470 °C (London, 1985). The identity of diomignite, described as an abundant and widely distributed highly birefringent phase in crystal-rich FI in spodumene, was established by several analytical techniques (no definitive chemical analysis was performed) and confirmed by identical Gandolfi X-ray diffraction patterns for diomignite and synthetic Li₂B₄O₇ (London et al., 1987). The FI in quartz are described as being quite distinct from those in spodumene in that the inclusions contained only liquid and vapor phases at 25 °C, had few crystalline solids, were comparatively CO₂-rich and the aqueous component was comparatively saline (London, 1985). Accord-
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Fig. 4. Fractionation trends of Ta/(Ta+Nb) vs. Mn/(Mn+Fe) of columbite group minerals in pegmatites: A-Greer Lake field, Canada; B-Black Hills, South Dakota and Himalaya pegmatite, California; C-Yellowknife field, NWT, Canada; Altai field, China; Cross Lake field, Manitoba (after Černý et al., 1986).

Fig. 5. Tantalum and Manganese enrichment trends in fluorine-rich and fluorine-poor pegmatites (after Černý, 1989b).

Fig. 6. K/Rb vs. Cs weight percent of blocky K-feldspar in pegmatites of the Winnipeg River district, southeastern Manitoba, Canada (after Černý, 1989b).

Fig. 7. Na/Li vs. Cs weight percent for late beryl from granite pegmatites: A- barren and beryl-type pegmatites; B- beryl-columbite and beryl-columbite-phosphate pegmatites; C- albite-spodumene and complex pegmatites; D- Li, Cs, Ta-rich complex pegmatites-spodumene, petalite, amblygonite and lepidolite subtypes (modified from Černý, 2002).

According to London (1985) the two very different types of liquids trapped by spodumene (a dense, hydrous, alkali borosilicate fluid) and quartz (an aqueous fluid with low solute concentrations) of the intergrowths could not have coexisted coincident with the breakdown of petalite and thus were generated at different times during pegmatite evolution. The interpretation of the inclusion data by London (1985, 1986) is that the FI in quartz are secondary, whereas the FI in spodumene are representative of the primary liquid, a dense, hydrous, borosilicate fluid, which played an important role in the internal evolution of the Tanco pegmatite and the concentration and development of rare-metal ore units. The included solids in spodumene-hosted FI are interpreted as daughter minerals and the daughter minerals plus the aqueous fluid together represent the products of a single, homogeneous phase (hydrous borosilicate liquid). Spodumene-hosted FI data was combined with the experimentally calibrated phase relationships in the lithium aluminosilicate system (London, 1984) to define emplacement conditions, cooling histories and fluid evolution in the Tanco pegmatite.

Anderson et al. (2001) examined hundreds of crystal-rich FI in spodumene from three pegmatite localities including Bikita and Kamativi, Zimbabwe and Tanco, Bernic Lake, Manitoba by optical examination and laser Raman spectroscopy. They concluded that 96 % of the high...
birefringence grains in over 500 FI, including FI in a wafer of spodumene from the Tanco pegmatite reported to contain the type specimen of diomignite, are in fact zabuyelite (Li$_2$CO$_3$). No phase yielding the Raman spectrum of Li$_2$B$_4$O$_7$ (diomignite) was observed.

An estimate of the bulk composition of the fluid entrapped in spodumene at Tanco was obtained by averaging the composition of hundreds of coeval fluid inclusions, additionally, the composition of individual fluid inclusions was determined using a variety of analytical techniques including laser Raman spectroscopy, synchrotron X-ray fluorescence and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). Anderson et al. (2001) concluded that FI in both spodumene and quartz from intergrowths (SQUI) at Tanco trapped a low-salinity, alkali-rich, aqueous carbonic fluid. The FI in spodumene are believed to be secondary in origin and were trapped within healed fractures and cleavage planes. The solid phases, dominantly quartz and zabuyelite, represent reaction products between a host spodumene crystal and trapped low-density, aqueous carbonic fluid during the late stages of pegmatite evolution, and not an equilibrium assemblage that crystallized from a hydrous borosilicate melt as proposed by London (1985, 1986). Anderson et al. (2001) suggest the apparent absence of diomignite (even in the type specimen) and the failure to detect significant concentrations of boron in the inclusions have important implications regarding models for the internal evolution of rare-element pegmatites. Additionally, P-T estimates of entrapment for spodumene FI (475 °C and 2.75 kbar) at Tanco are no longer valid.

Fluid inclusions with daughter crystals of orthoboric acid, sassolite (H$_3$BO$_3$) were found and described for the first time by Smirnov et al. (1999). They suggest that difficulty in identifying sassolite, which must include Raman spectroscopic work, prevented previous identification. Peretyazhko et al. (2000) and Smirnov et al. (2005) report that boric acid solutions with daughter sassolite crystals were found in topaz, tourmaline, quartz, beryl, danburite and adularia from 31 miarolitic pegmatites from central and eastern Transbaikalia, the middle Urals, central and southwestern Pamirs, Afghanistan, Pakistan, Nepal, California, Elvis and Madagascar. The maximum H$_2$BO$_3$ content found in FI in pegmatites was 27 wt.%. However, boric acid solutions occurred in a wide range of physiochemical conditions and Peretyazhko et al. (2000) suggest that inclusions of boric acid solutions will be found worldwide in all tourmaline-bearing and some topaz-beryl miarolitic pegmatites. Thomas (2002) found sassolite as a daughter mineral phase in MI in pegmatites of the Ehrenfriedersdorf complex, Germany.

Due to the very small size of MI, an in-situ analytical technique is necessary to obtain compositional data. The study of MI has advanced tremendously with the advent of sophisticated and accurate analytical techniques enabling the study of volatile-rich phases in igneous rocks (see Thomas et al., 2005 for a discussion of MI analytical techniques). Thomas (2000, 2002) and Thomas et al. (2006a) utilized confocal laser Raman microprobe spectroscopy, which made possible the study of very small MI from a wide variety of pegmatite minerals including quartz, feldspar, topaz, tourmaline, beryl, garnet, and micas. Their work has resulted in the determination of H$_2$O concentrations of 0.5 to over 35 wt.% in glassy MI as small as 3 μm with an accuracy of ±0.2 wt.% H$_2$O.

Quartz crystals from the F-, B- and P-rich pegmatites of the Ehrenfriedersdorf tin-tungsten deposit, Erzgebirge, Germany, continuously trapped two different types of MI during cooling and growth, a H$_2$O-poor, P$_2$O$_5$-, F- and silicate-rich melt (Type A) and a H$_2$O- and B-rich, silicate-poor melt (Type B) (Thomas et al., 2000). The two types of MI are interpreted as coexisting melts that were trapped simultaneously on both sides of a two-melt solvus. Water concentration in the type A inclusions increases from 2.4 to 16.2 wt.% with increasing homogenization temperatures from 500 to 700 °C whereas water concentration in

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Fig. 8. K/Rb vs. Cs wt. % in micas across Tanco pegmatite. Dashed boundaries are approximately between muscovite (ms), lithian muscovite (Li-ms) and lepidolite (lpd) zones (after Černý, 2005).

Fig. 9. Two-feldspar temperatures for the Little Three pegmatite-aplite dike, California with respect to height above the base of the footwall aplite (after Morgan & London, 1999).
the type B inclusions decreases from 43.8 to 27.8 wt.% over the same temperature range. Complete miscibility is attained at the critical point of 712 °C and 21.5 wt.% H₂O at 1 kbar. Thomas et al. (2000) conclude that at the critical point conditions detailed above, a P-, B-, and F-bearing silicate melt may dissolve unlimited quantities of H₂O and that upon cooling, the silicate melt will separate into two melts each of which has very different physical properties that will readily separate from one another and fractionate incompatible elements differently.

Veksler & Thomas (2002) conducted experiments with a synthetic peraluminous pegmatite (H₂O-saturated, 0.1–0.2 GPa) spiked with 5 wt.% each of P₂O₅, B₂O₃ and F, 1 wt.% each Rb₂O and Cs₂O and 0.5 wt.% Li₂O, to simulate the most enriched compositions found in natural MI in pegmatite quartz (Thomas et al., 2000). Aluminosilicate melt, low-density hydrous fluid, and hydrosaline melt strongly enriched in Na₂AlF₆ and H₂BO₃ components, were observed coexisting in all experimental charges.

Thomas et al. (2006a) and Veksler & Thomas (2002) suggest that evidence for the stable coexistence of three immiscible phases – aluminosilicate melt (consisting of SiO₂, Al₂O₃, FeO, K₂O, Na₂O, Li₂O and other, less abundant oxides), hydrosaline melt (borates, phosphates, fluorides and chlorides of alkaline and alkaline earth elements), and lower salinity aqueous fluid (volatile, primarily H₂O and CO₂) both experimentally and in MI and FI from pegmatite minerals should be considered an important factor contributing to the internal differentiation of pegmatite bodies.

**Rapid cooling rates and disequilibrium crystallization**

Pegmatites by definition have crystals that average 2 cm or more in diameter. In actuality, many pegmatites display an enormous range in crystal size from mm-size crystals up to large crystals that are 10’s of meters in length. It has often been assumed (particularly in introductory level geology textbooks) that crystal size in igneous rocks is a direct indicator of crystal growth rates and magmatic cooling history, i.e., small crystals grow quickly from a rapidly cooling magma producing fine-grained (aphanitic) textures, whereas large crystals grow more slowly from a slowly cooling magma, producing coarse-grained (phaneritic) textures. Clearly this paradigm does not hold in many pegmatites, particularly when looking at genetically related coarse-grained pegmatites and fine-grained aplites in pegmatite-aplite dikes, without invoking great variability in the cooling history within an individual pegmatite body (i.e., rapid followed by slow cooling and crystallization).

Pegmatites display striking variability in terms of size of the pegmatite itself, from thin sheet-like dikes with diameters in terms of < 1 m to 20 m or so, to ellipsoidal or teardrop shaped pegmatites, many of which show pronounced large-scale zonation and often display well-developed quartz cores. The country rock into which pegmatites are emplaced also varies widely from brittle, relatively cold, country rock to hotter migmatitic terranes. In most dikes or sills, variations in grain size are small (2 to 3 orders of magnitude), and grain size generally increases uniformly from dike margin to center (Cashman, 1990). In contrast, most sheet-like pegmatite-aplite dikes display changes in crystal size from < 0.1 mm in aplites, to > 10 cm (or indeed meter size) for crystals in the hanging wall, core zone, and pockets. In addition, the grain size does not always increase consistently from the margins to the core. Pegmatite-aplite dikes typically have a fine-grained footwall, coarse-grained hanging wall, and a core zone with miarolitic cavities. Footwall aplites can be layered or non-layered, layered aplites can alternate with pegmatite, and aplites can occur in an irregular distribution throughout the footwall. Clearly, changes in grain size of ~ 5 or more orders of magnitude, and an irregular distribution of grain size with respect to the dike margins and centers, indicate that crystallization history parameters such as nucleation and growth rates are not consistent during the crystallization history of many pegmatites.

Another striking feature of pegmatites is the textural heterogeneity they display with respect to crystal morphologies. The experimental studies of Swanson & Fenn (1986, 1992), MacLellan & Trembath (1991) and Fenn (1977, 1986) on quartz and feldspar crystallization in granitic melts demonstrated that skeletal and graphic morphologies reflect rapid crystal growth from a highly undercooled melt. The experimental work of Lofgren (1974, 1980) demonstrated that crystal morphology varied from euhedral to skeletal to radial with increasing degree of liquidus undercooling. London (1992) found that mineral zoning patterns, sharp changes in grain size, mineral textures, and oriented fabrics that typify pegmatites could all be replicated experimentally from undercooling vapor-undersaturated Macusani glass and that at progressively larger liquidus undercooling of a hydrous silicate melt, crystal orientations changed from random to increasingly anisotropic, oriented (comb structure) fabrics.

Thus the textural relationships of minerals in pegmatites reflect the degree of pegmatite undercooling, nucleation rate and growth rate. Strong undercooling is required to explain the textural characteristic of many pegmatites, including skeletal and dendritic crystal morphologies, elongated, and sometimes wedge-shaped crystals, and the development of comb structure along the contacts between pegmatite and country rock. More elongate crystal forms (needle like, skeletal, branching, wedge-shaped) are favored by rapid rates of cooling, larger degrees of undercooling, higher growth rates and fewer nucleation sites, whereas tabular to equant forms are favored by slower cooling rates, smaller degrees of undercooling, lower growth rates, and abundant nucleation sites.

Yet even with textural evidence that seems to clearly indicate rapid crystal growth rates, it wasn’t until the cooling histories were quantitatively evaluated for the Harding pegmatite, New Mexico (Chakoumakos & Lumphkin, 1990); the George Ashley, Mission, Stewart and Himalaya dikes, San Diego County, California (Webber et al., 1997, 1999); and the Little Three dike, Ramona, California (Morgan & London, 1999) that it became clear that these pegmatites cooled rapidly (in days to months, not in thousands to millions of years as previously believed) thus constraining crystal growth rates to the cooling history of the peg-
mattites. Based in part on textural relationships, it is now thought that many shallow-level pegmatites cooled extremely rapidly.

**Thermal model**

Many pegmatites can be likened to sheet-like structures. As such, the cooling history of these dikes can be modeled with well established conductive cooling models for thin sheets. In considering cooling models, a number of parameters must be evaluated, including the width of the dike (which can easily be measured), the emplacement temperature of the pegmatitic magma (which can be determined from phase equilibria) and the temperature of the country rock (which can be constrained using estimated depths of emplacement and reasonable geothermal gradients for the study area, observations of any reactions or lack of reactions between the country rock and magma, etc.). Pegmatites of the Pala and Mesa Grande Pegmatite Districts, San Diego County (SDC), California are typically thin, sheet-like, composite pegmatite-aplite dikes. Aplitic portions of many SDC dikes display pronounced mineralogical layering referred to as “line rock,” characterized by fine-grained, garnet-rich bands alternating with albite- and quartz-rich bands (Fig. 10). Thermal modeling was conducted on four dikes in SDC including the 1 m thick Himalaya dike, the 2 m thick Mission dike, the 8 m thick George Ashley dike, and the 25 m thick Stewart dike. Calculations were based on conductive cooling equations accounting for latent heat of crystallization, emplacement temperature of 650 °C into 150 °C country rock. Half-width of the dike is plotted with the dike center at 0. The position of the contact between the country rock and the dike is shown. The interval where layered aplite (line rock) occurs within the dike is between the 2 heavy lines (Webber et al., 1997).

All calculations, growth rates for large pegmatitic minerals such as the 10 cm long Himalaya hanging wall, comb-structure tourmaline crystals may have been on the order of 10^{-5} cm/s (Fig. 12). The cooling times presented in Table 6 indicate that the dikes cooled and crystallized rapidly, with variable nucleation rates but high overall crystal-growth rates. Initial high nucleation rates coincident with emplacement and strong undercooling can account for the millimeter-size aplite grains. Lower nucleation rates coupled with high growth rates can explain the decimeter-size minerals in the hanging walls, cores, and miarolitic cavities of the pegmatites. The presence of tourmaline and/or lepidolite throughout these dikes suggests that high melt concentrations of incompatible (or fluxing) components such as B, F, and Li (+ H2O), aided in the development of large pegmatitic crystals that grew rapidly in the short times suggested by the conductive cooling models.

In order to evaluate the effect on cooling times with variations in country rock temperatures and pegmatite emplacement temperatures, Webber et al. (2005) modified the initial cooling parameters used for the SDC pegmatites including the Himalaya, George Ashley and Stewart, and added the Animikie Red Ace (ARA) pegmatite, Wisconsin – a thin dike emplaced into hotter country rock (Falster et al., 1997, 2005). The results presented in Table 6 illustrate that even though modifying the initial parameters increases cooling times, the results are still rapid.

Even the very large, 100 m thick Tanco pegmatite appears to have cooled quite rapidly. Černý (2005) recently suggested that the Tanco pegmatite very likely solidified quite rapidly, “in decades to a maximum of a few hundreds of years”. In order to quantitatively evaluate this, Webber & Simmons (2007), using the cooling model outlined above and the parameters reported by Černý (2005) (thickness of 100 m; emplacement temperature of 700 °C; emplacement depth of 10 km; and country rock temperatures of 25 °C to 300 °C calculated that the Tanco pegmatite cooled to ~ 450 °C in ~ 700–1000 years.
Table 6. Calculated conductive cooling times for three pegmatites in San Diego County, California and the Animikie Red Ace pegmatite, Wisconsin. Pegmatite emplacement temperature and country rock temperature was varied in the conductive cooling equations to observe the effect on cooling times.

<table>
<thead>
<tr>
<th>Pegmatite</th>
<th>Width</th>
<th>Emplacement Temp °C</th>
<th>Country Rock Temp °C</th>
<th>Cools To Temp °C</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Himalaya, SDC, CA</td>
<td>1 m</td>
<td>650 °C</td>
<td>150 °C</td>
<td>550 °C</td>
<td>5 days</td>
</tr>
<tr>
<td>Himalaya, SDC, CA</td>
<td>1 m</td>
<td>600 °C</td>
<td>150 °C</td>
<td>400 °C</td>
<td>20 days</td>
</tr>
<tr>
<td>Himalaya, SDC, CA</td>
<td>1 m</td>
<td>650 °C</td>
<td>300 °C</td>
<td>400 °C</td>
<td>50 days</td>
</tr>
<tr>
<td>George Ashley, SDC, CA</td>
<td>8 m</td>
<td>650 °C</td>
<td>150 °C</td>
<td>550 °C</td>
<td>340 days</td>
</tr>
<tr>
<td>George Ashley, SDC, CA</td>
<td>8 m</td>
<td>650 °C</td>
<td>150 °C</td>
<td>400 °C</td>
<td>3 yrs</td>
</tr>
<tr>
<td>George Ashley, SDC, CA</td>
<td>8 m</td>
<td>600 °C</td>
<td>300 °C</td>
<td>400 °C</td>
<td>10 yrs</td>
</tr>
<tr>
<td>Stewart, SDC, CA</td>
<td>25 m</td>
<td>650 °C</td>
<td>150 °C</td>
<td>550 °C</td>
<td>9 yrs</td>
</tr>
<tr>
<td>Stewart, SDC, CA</td>
<td>25 m</td>
<td>650 °C</td>
<td>150 °C</td>
<td>400 °C</td>
<td>30 yrs</td>
</tr>
<tr>
<td>Stewart, SDC, CA</td>
<td>25 m</td>
<td>600 °C</td>
<td>300 °C</td>
<td>400 °C</td>
<td>75 yrs</td>
</tr>
<tr>
<td>Animikie Red Ace, WI</td>
<td>1 m</td>
<td>600 °C</td>
<td>400 °C</td>
<td>500 °C</td>
<td>20 days</td>
</tr>
<tr>
<td>Animikie Red Ace, WI</td>
<td>1 m</td>
<td>600 °C</td>
<td>400 °C</td>
<td>450 °C</td>
<td>50 days</td>
</tr>
</tbody>
</table>

Fig. 12. Photograph of the upper Himalaya dike exposed in the Himalaya Mine. Large wedge-shaped schorl crystals, some over 10 cm in length, can be seen growing out in a comb structure from the pegmatite hanging wall-country rock contact. The dike has a width of ~ 1 m.

Chemical quenching

Metastable undercooled melts can also be produced by the removal of a fluxing component by a crystallizing phase, instead of by rapid thermal cooling. The remaining melt is then undercooled since it is no longer fluxed by the removed component. This process is referred to as a chemical quench.

Pegmatites hosted in deeper seated metamorphic terranes also occasionally show comb structures and wedge-shaped crystals which are indicative of rapid crystallization, although it is clear that, thermally, they must cool more slowly than shallow-level pegmatites. The mechanism for rapid crystallization of deeper seated pegmatitic melts, which cool more slowly, may be a chemical quench. This process involves removal of a fluxing component, such as B or F, from a melt by a crystallizing phase which then initiates rapid crystallization, since the melt is no longer fluxed by that component. For example, crystallization of tourmaline or fluorine-bearing phases can result in melt that is suddenly undercooled even though the surrounding rocks and the melt itself remain at about the same temperature.

The Ipé pegmatite in Minas Gerais, Brazil, (Fig. 13) which has a well-developed comb structure of extremely
The large Ipé pegmatite, Minas Gerais, Brazil shows a spectacular tourmaline comb structure. Some of the wedge-shaped schorl crystals exceed 2 m in length. Large and rapid undercooling initiates heterogeneous nucleation along the hanging wall contact. This produces radially flaring crystals, with their fast-growth axes pointed toward the melt that are able to sustain growth as the crystallization front advances. The result is highly oriented comb-structure tourmaline.

Skeletal and elongated schorl crystals oriented perpendicular to the pegmatite-country-rock contact, is an example of a large deeper seated pegmatite that is inferred to have crystallized rapidly as a result of chemical quenching (Simmons et al., 2003).

**Constitutional zone refining**

Rapid crystallization from a strongly undercooled melt produces a boundary layer of excluded phases ahead of the crystallizing front. A constitutional zone refining model of pegmatite formation proposed by Morgan & London (1999) and London (2005a,b) involves disequilibrium crystallization from a flux-bearing granitic melt that is undercooled by about 100–300 °C. The melt is not necessarily flux rich and the presence or absence of an aqueous vapor phase is not required (London, 2005a).

A lag time between cooling and the initiation of crystallization produces a supersaturated melt. When nucleation and crystallization commence, excluded fluxes and volatiles accumulate in a boundary layer ahead of the crystallizing front (London, 2005). The solidus of the boundary layer is lowered by the fluxes and, as crystallization continues, this boundary layer liquid becomes progressively enriched in fluxes, water and other incompatible elements relative to the bulk melt composition (Fig. 14). Boundary layers advancing from the wall zones inward may merge, especially in thin dikes. In the final stages of crystallization an aqueous vapor phase may evolve, giving rise to the formation of miarolitic cavities and evolved suites of pegmatitic minerals (London, 2005a).

**Origin of line rock**

In the past, numerous theories have been advanced to explain the origin of line rock, fine-grained layered aplite, in composite pegmatites-aplite dikes. These dikes are typically thin, low-angle to subhorizontal, sheet-like dikes with aplitic portions mainly in the foot wall that display pronounced mineralogical layering characterized by fine-grained, garnet- or tourmaline-rich bands alternating with albite- and quartz-rich bands. The contrast in crystal size between the coarse-grained pegmatite and fine-grained aplite has been the subject of numerous investigations. Jahns & Tuttle (1963) suggested that aplite layering could be explained by the periodic loss of water vapor, a viable mechanism for quenching by relief of pressure (shifts of the alkali feldspar-quartz field boundary with changes of vapor pressure related to epizonal degassing). London (1992) proposed that significant undercooling could also produce layering and he was able to experimentally produce rhythmic layering of quartz and alkali feldspar in experiments with no fluctuations in pressure (London, 2005a). Kleck (1996) proposed gravitational crystal settling as an explanation for the George Ashley line rock. Webber et al. (1997, 1999) proposed a mechanism of diffusion controlled oscillatory nucleation and crystallization from a strongly undercooled melt for the formation of line rock in San Diego Co., CA pegmatite-aplite dikes. They suggested that
the initiation of line rock formation could be caused by a number of “triggers”, including a thermal, chemical or pressure quench. Morgan & London (1999) proposed constitutitional zone refining for the Little Three pegmatite, California. Frindt & Haapala (2004) proposed that diffusion-controlled oscillatory nucleation and rapid growth from undercooled melt, coupled with changes in vapor pressure could explain the layered aplites and undercooling textures from the Gross Spitzkoppe stock, Namibia.

We believe that aplitic line rock forms by oscillatory nucleation and crystallization that can be initiated by a high degrees of undercooling alone or by an external forcing factor such as pressure reduction produced by dike dilatancy (fracture propagation). Any event that results in strong undercooling has the potential to initiate line-rock formation. Emplacement of melt into relatively cool country rocks (thermal quench), or a “chemical quench” resulting for example from crystallization of tourmaline that effectively removes boron from the melt (Rockhold et al., 1987), or dike rupture or dike dilatancy (pressure quench), can all increase the degree of melt undercooling and act as a trigger to destabilize the crystallization dynamics of the pegmatite system. Such events can initiate rapid heterogeneous nucleation and oscillatory crystal growth, the development of a layer of excluded components in front of the crystallization front, and the formation of line rock.

Areas for future research

Classification and origin of pegmatitic melts

A number of new modification to Černý’s (1991) classification, which was based on a combination of depth of emplacement, metamorphic grade and minor element content have been proposed over the last few years (Zagorsky, et al., 1999; Wise, 1999; Pezzotta, 2001; see Simmons, 2005 for an overview). Many pegmatites fall nicely into Černý’s categories, but during the last decade various investigations have revealed pegmatites that don’t fit well into these categories. Most notably pegmatites of the NYF affiliation have required a more detailed classification as more studies revealed a greater diversity of NYF pegmatites. One problem is the classification of some pegmatites as NYF that contain little or no yttrium or others that contain little or no niobium. Many pegmatites from Madagascar described by Pezzotta (2001) that are hyperenriched in Cs don’t fall into these categories. Additionally, a number of pegmatites show “mixed” NYF and LCT characteristics and the origin of these are not addressed in the classification. Černý’s classification also fails to address the possibility of pegmatites forming by direct anatexis. Moreover, attempts to relate pegmatite types or subtypes to magma genesis or tectonic regimes, as has been attempted in granite classifications, are not satisfactory (Simmons, 2005, 2007a,b).

Wise (1999) introduced a new expanded classification of NYF pegmatites. His classification relates pegmatites with NYF geochemistry to A-type granite plutons. He related these pegmatites to post-tectonic to anorogenic plutons formed in continental or oceanic rift zones. His classification has three main categories based on aluminum saturation of the parent granite, peralkaline, metaluminous, and peraluminous. Within each group, pegmatite types are distinguished by mineralogical and geochemical characteristics. This classification is comprised of 6 types and 9 subtypes. His classification relates NYF pegmatite mineralogy to variations in the alkalinity of the parental granitic melts.

Černý & Ercit (2005) introduced a revised petrogenetic classification in which three families are distinguished: “an NYF family with progressive accumulation of Nb, Y and F (besides Be, REE, Sc, Ti, Zr, Th and U), fractionalized from subaluminous to metaluminous A- and I-granites that are generated by a variety of processes involving depleted crust and/or mantle contribution; a peraluminous LCT family marked by prominent accumulation of Li, Cs and Ta (besides Rb, Be, Sn, B, P and F) derived mainly from S-granites, less commonly from I-granites; and a mixed NYF + LCT family of diverse origins (e.g., NYF plutons contaminated by digestion of undepleted supracrustals).” Ercit’s (2005) report on REE-enriched granitic pegmatites elaborates on the Černý & Ercit (2005) classification. He reports that Černý rejects the use of the term “LCT” and “NYF” in a purely geochemical sense for individual pegmatites as opposed to granite-pegmatite suites (families). LCT, NYF and Mixed are families of granitic pegmatite suites.

In examining more than 500 pegmatite descriptions, Ercit (2005) found a low degree of correlation between accessory mineralogy and depth of emplacement for NYF pegmatites. He proposed that NYF pegmatites belong to the Abyssal, Muscovite-Rare-Element class, as well as the Rare-Element and Miarolitic classes. He also subdivided the abyssal class into two subdivisions: the LREE-enriched and the HREE-enriched types. The Rare Element Class consists of the Rare Earth type and the Allanite-Monazite, Euxenite and Gadolinite subtypes. This paper discusses numerous details and problems of the systems of REE-enriched pegmatites. Clearly much future research will be devoted to REE-enriched pegmatites.

Martin & De Vito (2005) contend that the depth zone classification cannot account for the two main geochemical categories of pegmatites: LCT and NYF. They propose that the tectonic setting determines the nature of the parent magma and the derivative rare-element enriched magmas. Thus, LCT pegmatites are generated in compressional tectonic settings (orogenic suites) and NYF from extensional tectonic settings (anorogenic suites). Mixed NYF and LCT are proposed to be the result of contamination, either at the magmatic or postmagmatic stage, in which the evolved NYF rocks get “soaked” with a fluid bringing in not only Li and B, but also Ca and Mg from the host rock, such that part of the pegmatite body may contain dravitic, elbaitic and liddicoattic tourmaline, danburite, and other exotic species such as microlite, fersmite, londonite and pezzottaite. They propose that some of the exotic Madagascan pegmatites with a hybrid or “mixed” NYF / LCT character may be caused by remelting of just-formed NYF pegmatites by such metasomatic fluids. They also propose that pegmatites may form by anatexis from both crustal and
mantle rocks, which may have been previously metasomatically altered.

It is clear that a trend toward a petrogenetic classification is emerging. We feel that a petrogenetic classification that can relate pegmatites to tectonic regimes and the related magma generating processes is ultimately essential in order to advance our understanding of pegmatite genesis within the larger-scale earth processes. This is an area for much needed future research.

Chemical quenching in deeper seated pegmatites

Some pegmatites that formed in deeper seated metamorphic terranes may show skeletal and comb textures indicative of rapid crystallization even though it is clear that they must cool more slowly than shallow level pegmatites. As discussed above, the mechanism for rapid crystallization of deeper seated pegmaticitic melts, which cool more slowly, may be the removal of a fluxing component, such as boron or fluorine, from the melt by a crystallizing phase. Chemical quenching can initiate rapid crystallization since the melt is no longer fluxed by that component. Crystallization of tourmaline or fluorine-bearing phases can result in melt that is suddenly undercooled even though the surrounding rocks and the melt itself remain at about the same temperature. Comb structures and tapered crystals, seen in numerous pegmatites, may have resulted from rapid crystallization initiated by a chemical quench. Evaluating the role of this process is another area for future research.

Regional zoning

The mechanism of regional zonation described by Černy (1991) for orogenic LCT pegmatites is a problematic process that needs more research. Regional zoning does not appear to occur in NYF pegmatite fields. The typical LCT pegmatite zoning pattern is concentric around an inferred parental pluton with the least fractionated pegmatites adjacent to the parental pluton, and the most fractionated pegmatites distal to the parental pluton. How pegmatites can be derived from a source pluton by periodic escape of pegmaticitic melt such that the earlier proximal pegmatites are the simpler less fractionated pegmatites, and the later, more distal pegmatites are the most fractionated and complex, remains to be satisfactorily explained. We see several problems. If less fractionated pegmaticitic melts escape early from a fractionating pluton as proposed by Černy (1991), it would seem that those melts would remove constituents that should remain in the pegmaticitic melt in order to achieve the high levels of concentration necessary for the formation of the more highly “evolved” pegmatites. How do Li, Cs, Ta, etc. remain in the pluton to be released later? Further, how can they travel outward from the pluton and leave no trace of their passage?

London (2005a) has suggested that a zoned magma chamber might give rise to different batches of pegmaticitic melts, with the more evolved melts related to the upper parts of the magma chamber, as has been described from studies of rhyolitic ash-flow tuffs such as the Bishop Tuff (Hildreth, 1979). The more fractionated melts at the top of the zoned magma chamber could then move farther into the surrounding country rocks than melts derived from the lower portions of the zoned magma chamber. However, this would seem to require rather highly zoned plutons which have not been documented. The zoning proposed in plutons as evidenced by ash-flow tuffs is not nearly as extreme as would seem necessary to produce the most fractionated LCT melts. Furthermore, the best examples of highly fractionated rhyolites such as the topaz and red beryl rhyolites in Utah, are from anorogenic settings and not orogenic. Also, given the evidence for rapid crystallization of pegmaticitic melts, how is it possible for even the most fluxed melts to travel large distances from the pluton into progressively cooler country rock? High over pressures and very rapid injection velocities may be the answer, but there is little data supporting either concept.

We suggest that perhaps in some cases the pegmaticitic melts farthest from the pluton are not derived from the pluton by protracted fractional crystallization but are very low degree partial melts generated in the thermal halo of the pluton. In other cases the pegmaticitic melts may form in migmatitic terranes with no associated pluton. Roda et al. (1999) in a study of pegmatites in the Fregeneda area, Salamanca Spain, proposed that pegmatites surrounding the Lumbrales granite, showing a typical regional zoning pattern from proximal barren pegmatites to distal enriched pegmatites, were formed by three different paths of fractional crystallization of melts generated by partial melting of quartzo-feldspathic rocks and were not derived by fractional crystallization of the granite. More research needs to be done on the possible causes of regional zoning.

Anatexis

Pegmatites are generally acknowledged to form by a process of fractional crystallization of a granitic composition melt. In many cases the connection of pegmatites with a parent pluton is obvious from spatial relationships, age determinations and chemical characteristics. However, it also has been proposed that it may be possible to form a pegmaticitic melt of the same composition as that formed by protracted fractional crystallization by direct anatexis of rocks with the appropriate composition.

Simmons et al. (1995, 1996) proposed that in general low-degree partial melts produced around plutons in orogenic environments could form pegmaticitic melts and that some pegmatites in western Maine could form by direct anatexis. Metasedimentary rocks containing evaporite sequences may provide a source of fluxing components such as boron and lithium and other incompatible elements. Basically the argument is that in collisional tectonic environments if a sedimentary sequence (including volcanics) contains fluxing components and incompatible elements that ultimately end up in a granitic melt (pluton) which can subsequently fractionally crystallize to form a pegmaticitic melt, then those same fluxing components and incompatible el-
ments will be preferentially partitioned into a low-degree partial melt that can directly form a pegmatite.

Other researchers have also proposed anatexis as a mechanism for forming pegmatic melts. Based on oxygen isotope systematics, Nabelek et al. (1992a, b) proposed that the granite-pegmatite couplets in the Black Hills were derived from partial melting. Falster et al. (1997, 2005) proposed that the Animikie Red Ace and related pegmatites in Florence County, Wisconsin could have formed directly by partial melting of the surrounding metasedimentary and metavolcanic country rocks, possibly aided by evaporation within the metasedimentary package. Roda et al. (1999) in a study of pegmatites in the Fregeneda area, Salamanca Spain proposed that the regionally zoned pegmatites around the Lumbrakes granite were anatetic in origin. Experimental research on forming pegmatites by direct anatexis is another area of possible future research.

Isotopic ages versus conductive cooling models

There are some glaring discrepancies between the cooling times implied by $^{39}$Ar/$^{40}$Ar zoned mica ages (Snee & Foord, 1991; Snee et al., 2006) versus the conductive cooling models. Snee et al. (2006) report that muscovite cores of several zoned mica samples from the Little Three Pegmatite, San Diego County, California, were up to 1.3 million years older than their corresponding rims of similar composition based on $^{40}$Ar/$^{39}$Ar ages. This is clearly at odds with conductive cooling models for the Little Three Pegmatite (Morgan & London, 1999) as well as other San Diego County pegmatites (Webber et al., 1997, 1999). Snee et al. (2006) suggest that the discrepancies may be explained by either differential cooling rates, or different argon closure temperatures, or different times of crystallization resulting from a complex multi-event pegmatite emplacement process. Smith et al. (2005) showed that incorporation of Li, F, Rb and Cs in the mica structure resulted in lower argon closure temperatures in lepidolite. Research to help clarify this age discrepancy would be very useful.

Role of immiscibility in pegmatite genesis

The MI and FI studies of minerals in pegmatites detailed by Thomas et al. (2000, 2005, 2006b) and Webster et al. (1997) suggest that pegmatite-forming melts are low viscosity, H$_2$O-rich, high diffusivity, alkaline-rich aluminosilicate melts, with the ability to easily transport trace and other elements leading to the extreme enrichment of pegmatites in elements such as P, F and B. Additionally, melt-melt immiscibility occurs early in the crystallization history of pegmatite magmas.

The relative roles of immiscibility, fractional crystallization and boundary layer crystallization with respect to pegmatite genesis, as well as an understanding of the percentage and composition of pegmatic fluids, are topics for further research. As pegmatologists we enjoy finding the mineralogical and chemical oddities, but in the end, any model for pegmatite genesis must reconcile the fact that at the outcrop scale the majority of pegmatites are granitic in composition and mineralogically simple.

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