Pegmatite Genesis: Recent Advances and Areas for Future Research

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Abstract

London's constitutional zone refining model of pegmatite evolution which involves disequilibrium crystallization from an undercooled, flux–bearing granitic melt is an important advance. The melt is not necessarily flux rich and the presence of an aqueous vapor phase is not required. Modelled cooling rates of rare element pegmatites are radically more rapid than previously believed. Advances by Petr Černý in pegmatite classification and the fractionation trends of Nb, Ta and other HFSE and K, Rb, Cs, Li, Ga and Tl are widely used. Regional zoning, anatexis and chemical quenching are areas for future pegmatite research

Key-words: (maximum 6)

Introduction

Significant advances in understanding pegmatite genesis have been made over the last 25 years. In the 1970s and 80s the most widely accepted model of pegmatite genesis was that proposed by Jahns and Burnham (1969) who proposed that pegmatites formed by equilibrium crystallization of coexisting granitic melt and hydrous fluid at or slightly below the hydrous granite liquidus.

Recent Developments

More recently, the detailed mineralogical and geochemical investigations of Petr Černý and the experimental studies of David London have led to a much improved understanding of the details of pegmatite genesis.

Černý's (1991) pegmatite classification scheme, which is a combination of emplacement depth, metamorphic grade and minor element content, is now widely used. Almost all recent pegmatite descriptions classify pegmatites according to his LCT– and NYF– families, types and subtypes. The classification provides insight into the origin of the melts and relative degrees of fractionation.

The fractionation patterns of Nb, Ta and other HFS elements in numerous pegmatite systems have been well documented, especially in LCT pegmatites (Černý, 1989). The fractionation patterns of K, Rb, Cs, Li, Ga and Tl in feldspars, micas and other minerals have also been described by Černý (2005) and the enrichment trends of alkali elements in feldspars and micas has proven useful in geochemical exploration for pegmatites (Trueman and Černý, 1982).

The role of fluxes in the crystallization of pegmatites has been demonstrated by London's experimental work which has shown that water saturation is neither necessary nor likely in the early crystallization of pegmatites (London, 2005). Other fluxes such as B, F, P and Li in addition to H_2O play a critical role in the formation of rare element pegmatites by lowering the crystallization temperature, decreasing nucleation rates, decreasing melt polymerization, decreasing viscosity, increasing diffusion rates, and increasing solubility (Simmons *et al.* 2003; London, 2005). 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, we have network modifiers acting to prevent nuclei formation and at the same time increasing 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.

Until recently, pegmatites were widely believed to be products of extremely slow cooling. Studies of the Harding pegmatite, New Mexico, by Chakoumakos and Lumpkin (1990), the Himalaya–San Diego pegmatite dike system, Mesa Grande, CA, by Webber *et al.* (1997, 1999) and the Little Three dike, Ramona, CA, by Morgan and London (1999) all show that these pegmatite bodies cooled to their solidus in days to months. Černý (2005) has recently suggested that the very large Tanco pegmatite also solidified quite rapidly, in decades to a few hundred years. These proposed cooling rates of rare element pegmatites are radically more rapid than previously believed and represent an extraordinary contradiction of the paradigm that large crystal size requires long cooling times.

London's constitutional zone refining model of pegmatite evolution 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, 2005). A lag time between cooling and the initiation of crystallization produces a supersaturated melt. When nucleation and crystallization commence, excluded fluxes accumulate in a boundary layer ahead of the crystallization 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. 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, 2005).

Our understanding of the origin of line rock, fine–grained layered aplite, in composite aplite–pegmatites has also advanced. These pegmatites 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, 1955, Jahns and Tuttle, 1963, Kleck, 1996). Until recently, the most widely accepted model was that of Jahns and Tuttle (1963) which involved the periodic loss of water vapor as a mechanism for quenching by relief of pressure. London 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, 2005). Webber *et al.*, (1997) quantitatively modeled the cooling history of the George Ashley and other San Diego Co., CA composite pegmatite–aplite dikes and found that the pegmatites cooled below their solidus extremely rapidly. They proposed a mechanism of diffusion controlled oscillatory nucleation and crystallization from a strongly undercooled melt for the formation of line rock in pegmatite–aplite dikes. They suggested that the initiation of line–rock formation could be caused by a number of "triggers", including thermal, chemical or pressure quench.

There is abundant textural evidence in both the aplitic and pegmatitic portions of the dikes to support rapid crystal growth rates. The experimental studies of Swanson and Fenn (1986) and Fenn (1986) on quartz crystallization in granitic melts demonstrate that skeletal and graphic quartz morphologies reflect rapid crystal growth from a highly undercooled melt. Many quartz grains in the George Ashley layered aplite have a skeletal morphology. Grains are elongated parallel to *c* and oriented perpendicular to the layering, and poikilitically include albite and garnet. Graphically intergrown K-feldspar and quartz is present in all San Diego County pegmatite-aplite dikes, principally in the hanging wall. Many of the K-feldspar grains are wedge-shaped and flare toward the core. Comb-structure tourmaline, indicative of rapid growth is present at the country rock-pegmatite contact of the Himalaya dike. Foord (1976) reports plumose and dendritic albite, as well as skeletal and elongated garnet in the hanging wall of the upper Himalaya dike.

AREAS FOR FUTURE RESEARCH

Classification and origins of pegmatic 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. Černý's (1991) classification has 4 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 **L**ithium, **C**esium, and **T**antalum enrichment and **NYF** for **N**iobium, **Y**ttrium, and **F**luorine enrichment. The Rare-Element Class is further subdivided into types and subtypes according to the mineralogical / geochemical characteristics. This scheme has been used in most modern pegmatite studies.

Many pegmatites fall nicely into these categories, but during the last decade various investigations have revealed pegmatites that don't fit 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 hyper-enriched in Cs don't fall into these categories. Additionally, a number of pegmatites show "mixed" NYF and LCT characteristic and these are not addressed in the classification. 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 et al. 2003).

Černý's (1991) classification also fails to address the possibility of pegmatites forming by direct anatexis. Consequently, over the last few years several new modifications of Černý's classification have been proposed.

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. The three groups are 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 and Ercit (2005) introduce a new 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), fractionated 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 Černy and 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 and 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 liddicoatitic tourmaline, danburite, and other exotic species such as microlite, fersmite, londonite and pezzottatite. They propose that some of the exotic Madagascar 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. 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 another area for much needed future research.

Regional zoning

The mechanism of regional zonation is a problematic process that needs more research. How pegmatites can be derived from a source pluton by periodic escape of pegmatitic melt such that the proximal pegmatites are the simpler less evolved pegmatites and the most distal pegmatites are the most fractionated and complex remains to be satisfactorily explained. There are two main problems. If pegmatites escape early from a fractionating pluton, it would seem that those melts would remove constituents that should remain in the pegmatitic melt to achieve high degrees of fractionation. How does the Li, Cs, Ta *etc*. remain in the pluton to be released later? Also given the evidence for rapid crystallization of pegmatitic melts, how is it possible for the most evolved melts to travel large distances from the pluton into progressively cooler country rock?

Anatexis

Pegmatites are generally acknowledged to form by a process of fractional crystallization of a granitic composition melt. It has, however, also been proposed that it may be possible to form a melt of the same composition 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 pegmatitic melts and that some pegmatites in western Maine could form by direct anatexis. Metasedimentary rock containing evaporite sequences may provide a source of fluxing components such as boron and lithium. Basically the argument is that if a sedimentary sequence contains the elements that ultimately end up in a granitic melt (pluton) that can subsequently fractionally crystallize to form a pegmatitic melt, then those same elements will be preferentially partitioned into a low–degree partial melt. Experimental research on forming pegmatites by direct anatexis is another area of possible future research.

The role of chemical quenching in deeper seated pegmatites

Pegmatites intruded into deeper seated metamorphic terrains may show textures indicative of rapid crystallization although it is clear that 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. The removal of a fluxing component, such as boron or fluorine, from the melt by a crystallizing phase can initiate 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. Undercooled melts crystallize rapidly once crystals begin to form. 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.

Isotopic ages versus conductive models

There are some glaring discrepancies between the cooling times determined by Ar–Ar mica ages and the conductive cooling histories. Research to help clarify the problems would be very useful.

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