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The genesis of granitic pegmatites – recent controversies

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Introduction

Granitic pegmatites, very coarse-grained (>2 cm) rocks of magmatic origin and granitic composition, are probably the least understood rocks in terms of genesis. Mainly four features make the understanding of the origin and formation of pegmatites challenging: (1) the very coarse but also highly variable crystal size, (2) the heterogeneous distribution (zoning) of minerals within pegmatite bodies, (3) the common occurrence of massive, monophase quartz cores in the centre of pegmatites, and (4) the extreme enrichment in incompatible elements (high-field-strength and large ion lithophile elements) including Rb, Cs, Ta, Nb, Be, Li and rare earth elements (REE) in some pegmatites or pegmatite zones. These elements can have enrichment factors of greater than 100,000 in rare element pegmatites compared to the average composition of the continental crust (e.g. Linnen *et al.* 2012).

Over more than a century pegmatites have sparked controversy, and numerous models have been proposed to explain the origin and evolution of this fascinating rock type. The classical model of pegmatite formation implies that the bulk of pegmatite bodies encountered worldwide represent residual melts derived by simple progressive fractionation of a large-volume intrusion (pluton) of felsic magma (Cameron *et al.* 1949, Jahns 1953, Černý 1991, London 2008). That is definitely true for the majority of intra-plutonic miarolitic pegmatites, pegmatite dykes and stockscheider-type pegmatites. The model is able to explain up to a certain degree the enrichment of incompatible elements, fluxes, and volatiles in the pegmatite-forming residual melts via simple, progressive fractionation out of a large-volume pluton. The presence of fluxes and volatiles, which lower the crystallization temperature, decrease the nucleation rates, melt polymerization and viscosity, and increase diffusion rates and solubility, are generally considered to be critical to the development of large crystals and pegmatite textures (e.g. Simmons & Webber 2008). However, the evolution of the residual melts that generates the pegmatite-forming melt out from granite plutons, the transportation of that melt from the crystal mush to the point of emplacement, and its post-emplacement evolution, must involve a more complex and interdependent series of processes beside simple fractionation in order to explain the partially extreme enrichment of the pegmatite melt constitutes and the strong chemical and mineralogical zoning of pegmatite bodies (e.g. Thomas & Davidson 2016). In the following the two most recent and controversial models of pegmatite formation are introduced and discussed.

Current models

Model 1: Pegmatite melts are initially supercritical fluids that involve into co-existing silicate-rich and volatile-rich melts and aqueous fluids

Thomas & Davidson (2012, 2016) suggested that the formation of pegmatites is characterized by the interaction of a sequence of very different processes: (1) the initial formation of a supercritical fluid due to high availability of H₂O, (2) interaction of this fluid with the surrounding, (3) generation of silicate-dominated (A-type melt) and volatile-rich (B-type melt) immiscible melts out of the supercritical fluid, (4) pneumatolytic and hydrothermal activities, including crystallization and recrystallization, and (5) possibly transitions to the sol–gel state relevant for the formation of often huge monomineralic quartz cores. According to Thomas & Davidson (2012, 2016) the formation of granitic pegmatites generally begins in the supercritical fluid stage at high temperatures. In such melts/fluids, near the critical region the solubility of common pegmatite-forming elements, including F, P, B, Be, Cl, Rb, Cs, Sn, Nb, and Ta, are extremely high compared to granite systems. These supercritical fluids also have volatile concentrations (principally H₂O) typically between 20 and 33.3 wt.% and thus are intermediate between silicate melts and hydrothermal fluids. These supercritical melts/fluids form naturally during the extended fractionation of felsic magmas. Measured maximum solubility for incompatible elements can be in the wt.% range, and calculated viscosities are <5 Pa·s due to their de-polymerizing constituents. The depolymerized stage results in much higher ion diffusion rates which would explain a number of the specific features of pegmatites. With such extreme properties these melt/fluids make an ideal medium for sequestering, concentrating, and transporting incompatible elements (including volatiles) from felsic magmas. These fluids also provide excellent conditions for Ostwald ripening that is important for the formation of giant crystals in pegmatites. And the high H₂O content surpasses the nucleation rate supporting the growth of large crystals. If the supercritical stage drops below its critical conditions three phases can coexist: a silicate-dominated melt (A-type melt), a volatile-rich melt (B-type melt) and an aqueous fluid (C-fluid). The type-C fluid forms directly from the supercritical stage after dropping below critical conditions. The coexistence of these three very different phases permit a three stage fractionation and separation of some trace elements, allowing very high degree enrichment in the post-critical stage.

The model by Thomas & Davidson (2012, 2016) is based on the general assumption that pegmatite melts represent residual melts resulting from the fractionation of large-volume granite plutons and thus, providing an initially high water content in the melt (>10 wt.% H₂O). The processes deduced from different granite pegmatites worldwide can, however, work independently from a granite system. Crucial is only the temperature, the availability of water and access alkalis ± other volatile components like boron, fluorine, phosphorus, and sulphate with a strong tendency to go into the water-rich phase. Therefore it is no wonder that there are evidences of an increasing number of pegmatites even those which are extremely enriched in incompatible elements formed via direct anatexis of meta-igneous or -sedimentary rocks (e.g. Romer & Smeds 1996, Simmons *et al.* 1996, Falster *et al.* 1997, 2005, Roda *et al.* 1999, Müller *et al.* 2015) or are generated by transmagmatic fluids directly. Simmons *et al.* (1996) proposed that rare-element-enriched pegmatite melts could form by low-degree partial melting of metasedimentary rocks containing evaporate sequences providing a source of fluxing components such B and Li and other incompatible elements and most importantly H₂O. However, it is debatable if low-degree partial melting is able to produce the amount of H₂O and melt network formers needed to form a supercritical pegmatite-forming fluid independently of large-volume granite plutons.

Model 2: Constitutional zone refining as driving process of pegmatite crystallisation

Constitutional zone refining is a process known from metallurgy by which a metal alloy is refined when its crystallization leads to the accumulation of fluxing components in a narrow zone of melt that

forms at the front of crystallizing components. The flux-enriched boundary layer sequesters and concentrates impurities that would otherwise contaminate the metal, and hence the composition of the boundary-layer liquid begins to deviate from that of the bulk alloy. The flux- and trace element-enriched boundary layer at the crystallization front grows in width and in the concentration of excluded components with progressing crystallization. London (2009) suggested that the model of constitutional zone refining can explain the suggestive enrichment of fluxes, volatiles and incompatible elements with progressing pegmatite crystallisation. London's argument is that compared to the classical concept of pegmatite melt formation via fractional crystallization the modal of constitutional zone refining produces a higher final concentration of incompatible components in a smaller volume of rock than fractional crystallization does (Morgan & London 1999). Furthermore, by applying the model the pre-enrichment of volatiles and fluxes is not required to explain some of the pegmatite textures. However, the model can, for example, not explain the formation of massive quartz cores and the extreme high diffusion rates parallel to the boundary layer necessary to form large isolated rare element minerals (e.g. beryl) which can be separated from each other by several meters.

London (2009) proposed that the outer zones of pegmatite bodies, which contain most of the fine-grained, graphic, and highly anisotropic fabrics of pegmatites, are dominated by the effects of undercooling (in the range of c. $\Delta T = 200^\circ\text{C}$) on the crystallization response of the granitic liquid. The inner zones of pegmatites, which carry the exceedingly coarse-grained and blocky textures, result from the buildup of fluxing components in a boundary layer of liquid that advances into the pegmatite along the crystal growth front. Grain size increases dramatically due to more rapid diffusion through the low-viscosity, flux-enriched boundary-layer liquid (Bartels *et al.* 2011), and graphic intergrowths segregate into monophase crystals. However, the undercooling model is in contrast to the conditions under which, for example, the intra-plutonic miarolitic pegmatites of the Erongo massif in Namibia and Strzegom massif in Poland were formed. In those cases the pegmatite melt and the granitic host had evidently similar temperatures at the initial crystallization stage.

Concluding remark

As outlined above the genesis of granite pegmatites remains controversially. The narrow field relationships of pegmatites to granites may tempt us to infer that the first are directly related to the granites, but we suggest that the connection is not so direct and, thus, a rethinking is necessary.

References

- Bartels, A., Vetere, F., Holtz, F., Behrens, H. & Linnen, R.L. (2011): Viscosity of flux-rich pegmatitic melts. *Contributions to Mineralogy and Petrology* **162**, 51-60.
- Cameron, E.N., Jahns, R.H., McNair, A.H. & Page, L.R. (1949): *Internal structure of granitic pegmatites*. Economic Geology Monograph 2, 115 p.
- Černý, P. (1991): Rare-element granitic pegmatites. Part I: Anatomy and internal evolution of pegmatite deposits. Part 2: Regional to global environments and petrogenesis. *Geoscience Canada* **18**, 49–81.
- Falster, A.U., Simmons, W.B. & Webber, K.L. (1997): The origin of evolved LCT-type granitic

pegmatites in the Hoskin Lake granite-pegmatite field, Florence Co., Wisconsin. *IAVCEI General Assembly, Program with Abstracts*, January 1997, Puerto Vallarta, Mexico, p. 118.

- Falster, A.U., Simmons, W.B. & Webber, K.L. (2005): Origin of the pegmatites in the Hoskin Lake pegmatite field, Florence Co., Wisconsin. Crystallization processes in granitic pegmatites. International Meeting, Elba Island, Italy, MSA web site, http://www.minsocam.org/MSA/Special/Pig/PIG_articles/Elba%20Abstracts%207%20Falster.pdf
- Jahns, R.H. (1953): The genesis of pegmatites. I. Occurrence and origin of giant crystals. *American Mineralogist* **38**, 563-598.
- Linnen, R.L., van Lichtervelde & M., Černý, P. (2012): Granitic pegmatites as sources of strategic metals. *Elements* **8**, 275-280.
- London, D. (2008): *Pegmatites*. Canadian Mineralogist Special Publication 10, 347 p.
- London, D. (2009): The origin of primary textures in granitic pegmatites. *Canadian Mineralogist* **47**, 697-724.
- Morgan, G.B. VI & London, D. (1999): Crystallization of the Little Three layered pegmatite-aplite dike, Ramona District, California. *Contributions to Mineralogy and Petrology* **136**, 310-330.
- Müller, A., Ihlen, P.M., Snook, B., Larsen, R., Flem, B., Bingen, B. & Williamson, B.J. (2015): The chemistry of quartz in granitic pegmatites of southern Norway: petrogenetic and economic implications. *Economic Geology* **110**, 137-157.
- Roda, E., Pesquera, A., Velasco, F. & Fontan, F. (1999): The granitic pegmatites of the Fregeneda area (Salamanca, Spain): characteristics and petrogenesis. *Mineralogical Magazine* **63**, 535-556.
- Romer, R.L. & Smeds, S.-A. (1996): U-Pb columbite ages of pegmatites from Sveconorwegian terranes in southwestern Sweden. *Precambrian Research* **76**, 15-30.
- Simmons, W.B. & Webber, K.L. (2008): Pegmatite genesis: state of the art. *European Journal of Mineralogy* **20**, 421-438.
- Simmons, W. B., Foord, E. E. & Falster, A. U. (1996): Anatectic origin of granitic pegmatites, Western Maine, USA. *GAC-MAC Annual meeting - Abstracts with Programs*, University of Manitoba, Winnipeg, May 27-29, 1996, ISBN 0-919216-61-7.
- Thomas, R. & Davidson, P. (2012): Evidence of a water-rich silica gel state during the formation of a simple pegmatite. *Mineralogical Magazine* **76**, 2785–2801.
- Thomas, R. & Davidson, P. (2016): Revisiting complete miscibility between silicate melts and hydrous fluids, and the extreme enrichment of some elements in the supercritical state — Consequences for the formation of pegmatites and ore deposits. *Ore Geology Reviews* **72**, 1088–1101.