Crystallization Dynamics

KAREN L. WEBBER AND WM. B. SIMMONS[1]

[1]University of New Orleans, Department of Earth and Environmental Sciences, New Orleans, LA, USA 70148

ABSTRACT

Pegmatites are chemically, mineralogically, and texturally heterogeneous on many scales from microscopic to hand sample to outcrop. The paradigm that relates crystal size in igneous rocks to crystal growth rates and magmatic cooling history is unsatisfactory in explaining the variability in crystal size in pegmatites. Rapid crystallization of pegmatites, regardless of resulting crystal size and the development of a flux-rich, chemically variable boundary layer, coupled in some cases with rapid overall cooling of the pegmatitic body can explain many of the heterogeneous features in pegmatites.

Keywords: *pegmatite; aplite; line rock; layering.*

INTRODUCTION

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 sized crystals up to ginormously large crystals that are 10's of meters in length. Many introductory-level geology textbooks state that crystal size in igneous rocks is a direct indicator of crystal growth rates and magmatic cooling history, e.g small crystals grow quickly from a quickly 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 variablity in the cooling history within an individual pegmatite body (e.g. rapid followed by slow cooling and crystallization).

PEGMATITE HETEROGENEITIES

Pegmatites display striking variability in terms of size of the pegmatite itself, from thin sheet like dikes with diameters in terms of <1 meter to 20 meters 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 (2–3 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. However, individual dikes display a wide range in grain size. Footwall aplites can be layered or nonlayered, 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 parameters such as nucleation and growth rates are not consistent during the crystallization history of many pegmatites.

Another striking feature of pegmatites is the textual heterogeneity they display with respect to crystal morphologies. The experimental studies of Swanson and Fenn (1986), MacLellan and Trembath (1991), and Fenn (1986) on quartz crystallization in granitic melts demonstrated that skeletal and graphic quartz morphologies reflect rapid crystal growth from a highly undercooled melt. The experimental work of Lofgren (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 undercoolings of a hydrous silicate melt, crystal orientations changed from random to increasingly anisotropic oriented (comb structure) fabrics.

FIGURE 1. The large Ipe pegmatite, Minas Gerais, Brazil shows a spectacular tourmaline comb structure. Some of the wedge-shaped schorl crystals exceed 2 meters in length. Fine-scale layering has developed around the large country rock screen. 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

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, large degrees of undercooling, high growth rates and fewer nucleation sites, whereas tabular to equant forms are favored by slower cooling rates, small degrees of undercooling, low growth rates, and abundant nucleation sites.

PEGMATITE COOLING HISTORY

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 and Lumpkin, 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 and London, 1999) that it became clear that these pegmatites cooled rapidly (days to months) thus constraining crystal growth rates to the cooling history of the pegmatites.

However, the assumption that crystal growth begins at the time of emplacement will yield minimum growth rates, as the experimental work of Swanson (1977), Fenn (1977), and London (1992) all demonstrate that there is a considerable nucleation lag time between when a haplogranitic melt has cooled through the liquidus and when crystallization actually begins.

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, California are typically thin, sheet-like composite pegmatite-aplite dikes. Aplitic portions of many dikes display pronounced mineralogical layering referred to as “line rock,” characterized by fine-grained, garnet-rich bands alternating with albite- and quartz-rich bands.

Thermal modeling was performed for four dikes in San Diego County 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.

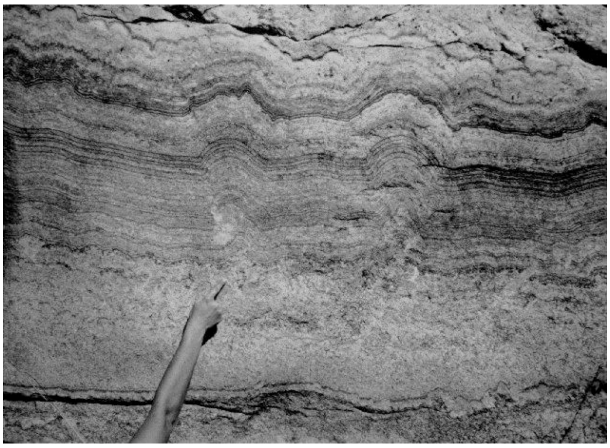

FIGURE 2. Layering in the George Ashley aplite ("line rock). The dark layers are enriched in garnet, and the light layers in albite and quartz. K-spar megacrysts are in the center of some of the nested loops.

Calculations were based on conductive cooling equations accounting for latent heat of crystallization, a melt emplacement temperature of 650 °C into 150 °C fractured, gabbroic country rock at a depth of 5 km, and an estimated 3 wt% initial H_2O content in the melt. Cooling time to <550 °C at the center of each dike was determined (Webber *et al.*, 1997, 1999).

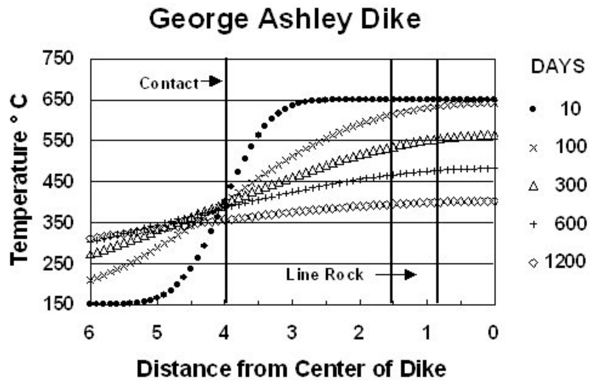

FIGURE 3. Cooling curve for the George Ashley dike calculated with latent heat of crystallization. Half-width of the dike is plotted with the dike center at 0. The position of the contact between the country rock and the dike is shown. The interval where layered aplite (line rock) occurs within the dike is between the 2 heavy lines (Webber et al., 1999).

Based on these calculations, growth rates for large pegmatitic minerals such as the 10 cm long Himalaya hanging wall tourmaline crystals may have been on the order of 10^{-5} cm/s. These results 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 although the melts were initially H_2O-undersaturated, high melt concentrations of incompatible (or fluxing) components such as B, F, and Li ($\pm H_2O$), aided in the development of large pegmatitic crystals that grew rapidly in the short times suggested by the conductive cooling models.

FIGURE 4. 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 ~ 1m.

We believe that aplite "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 propogation). 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. Thus, the textures that characterize San Diego County pegmatite-aplite dikes are consistent with rapid growth rates for most of the cooling history of the dike. Nucleation rates were higher during crystallization of the relatively volatile-poor, fine-grained aplitic footwall than they were during crystallization of the more volatile-enriched, coarser-grained hanging wall.

For this paper, we modified the cooling parameters for the San Diego County California pegmatites including the Himalaya (Him); George Ashley (GA); and Stewart (Stew), and added the Animikie Red Ace (ARA) pegmatite, Wisconsin, USA, in order to evaluate the effect on cooling times with hotter country rock, lower pegmatite emplacement temperatures and lower "solidification" temperatures. The results presented in Table 1 illustrate that while cooling times do of course increase as the emplacement temperature decreases and country rock temperature increases, the results are still rapid (days to 75 years) and consistent with the abundant textural evidence.

TABLE 1. Calculated Conductive Cooling Times for Selected Pegmatites at Various Temperatures.

Pegm	Width	Emplace-ment Temp ˚C	Country Rk Temp ˚C	Cools To Temp ˚C	Time
Him	1 m	650 ˚C	150 ˚C	550 ˚C	5 days
Him	1 m	650 ˚C	150 ˚C	400 ˚C	20 days
Him	1 m	600 ˚C	300 ˚C	400 ˚C	50 days
GA	8 m	650 ˚C	150 ˚C	550 ˚C	340 days
GA	8 m	650 ˚C	150 ˚C	400 ˚C	3 yrs
GA	8 m	600 ˚C	300 ˚C	400 ˚C	10 yrs
Stew	25 m	650 ˚C	150 ˚C	550 ˚C	9 yrs
Stew	25 m	650 ˚C	150 ˚C	400 ˚C	30 yrs
Stew	25 m	600 ˚C	300 ˚C	400 ˚C	75 yrs
ARA	1 m	600 ˚C	400 ˚C	500 ˚C	20 days
ARA	1 m	600 ˚C	400 ˚C	450 ˚C	50 days

REFERENCES CITED

Cashman, K.V. (1990) Textural constraints on the kinetics of crystallization of igneous rocks. Mineralogical Society of America Reviews in Mineralogy, 24, 259–314

Chakoumakos, B.C. and Lumpkin, G.R. (1990) Pressure-temperature constraints on the crystallization of the Harding pegmatite, Taos County, New Mexico. Canadian Mineralogist, 28, 287-298.

Fenn, P.M. (1977) The Nucleation and growth of alkali feldspars from hydrous melts. The Canadian Mineralogist, 15, 135–161.

Fenn, P.M. (1986) On the origin of graphic granite. American Mineralogist, 71, 325-330.

Lofgren, G. (1980) Experimental studies on the dynamic crystallization of silicate melts. In R.B. Hargraves, Ed., Physics of Magmatic Processes, p. 487–551. Princeton University Press, New Jersey

London, D. (1992) The application of experimental petrology to the genesis and crystallization of granitic pegmatites. The Canadian Mineralogist, 30, 499–540.

MacLellan, H.E. and Trembath, L.T. (1991) The role of quartz crystallization in the development and preservation of igneous texture in granitic rocks: Experimental evidence at 1 kbar. American Mineralogist, 76, 1291–1305

Morgan, G.B., VI, and London, D (1999) Crystallization of the Little Three layered pegmatite-aplite dike, Ramona District, California. Contributions to Mineralogy and Petrology, 136, 310-330.

Rockhold, J.R., Nabelek, P.I., & Glascock, M.D. (1987) Origin of rhythmic layering in the Calamity Peak satellite pluton of the Harney Peak Granite, South Dakota: The role of boron. Geochemica et Cosmochimica Acta, 51, 487–496.

Swanson, S.E. (1977) Relation of nucleation and crystal-growth rate to the development of granitic textures. American Mineralogist, 62, 966–978.

Swanson, S.E. and Fenn, P.M. (1986) Quartz crystallization in igneous rocks. American Mineralogist, 71, 331–342

Webber, K.L., Falster, A.U., Simmons, Wm. B., & Foord, E.E. (1997) The role of diffusion-controlled oscillatory nucleation in the formation of line rock in pegmatite-aplite dikes. Journal of Petrology, 38, 1777–1791.

Webber, K.L., Simmons, Wm. B., Falster, A.U & Foord, E.E. (1999) Cooling rates and crystallization dynamics of shallow level pegmatite-aplite dikes, San Diego County, California. American Mineralogist, 84, 708-717.