Rapid Conductive Cooling of Sheet-Like Pegmatites

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Pegmatites are characterized by large crystals (> 3 cm up to 10's of meters). It has often been assumed (particularly so in introductory level geology textbooks for instance) that crystal size is a direct indicator of growth rate and magma cooling rate, i.e. small crystals grow quickly from a quickly cooling magma, whereas large crystals grow slowly from a slowly cooling magma. However, this paradigm does not hold in many pegmatites. Pegmatites display striking variability in terms of size of the pegmatite itself, from thin sheet-like dikes with widths 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 pegmatite-aplite dikes.

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. It's important to note that undercooling can result from a temperature, pressure or chemical quench.

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. Thermal modeling was performed for 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, 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, results shown in Table 1). 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 (±H_2O), aided in the development of large pegmatitic crystals that grew rapidly in the short times suggested by the conductive cooling models.

We believe the aplite "line-rock" formed by oscillatory nucleation and crystallization, initiated by 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, loss of volatiles to the country rock, crystallization of tourmaline that effectively removes boron from the melt (Rockhold *et al.* 1987), and dike rupture or dike dilatancy, 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 SDC 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 SDC pegmatites and added the Animikie Red Ace pegmatite, Wisconsin, 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 cooling times do of course increase as the emplacement temperature decreases and country rock temperature increases. However, 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

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

References

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

Rockhold, J.R., Nabelek, P.I., and 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.

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