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# Crystal size distribution analysis of plagioclase in experimentally decompressed hydrous rhyodacite magma

# Carrie R. Brugger \*, Julia E. Hammer

Department of Geology and Geophysics, University of Hawaii Manoa, 1680 East West Rd., Honolulu, HI 96822, USA

### A R T I C L E I N F O

# ABSTRACT

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Keywords: crystal size distribution plagioclase decompression experiments growth rate nucleation rate residence time of hydrous rhyodacite magma. Samples were annealed at 130 MPa, subjected to continuous decompression at either 2 MPa h<sup>-1</sup> or 0.5 MPa h<sup>-1</sup>, and then guenched along their respective decompression paths at ~20 MPa intervals. Samples display concave-up curved CSD plots which result from a combination of two crystal populations: those which formed during the anneal period and those which formed during decompression. The CSDs also display a decrease in crystal number density at 3–7 µm, a size range that is easily resolvable with the imaging strategy employed. The downturn at small sizes is presumably due to insufficient compensation for the intersection probability effect in converting 2D measurements to 3D size distributions. Crystal nucleation and growth rates derived from CSDs using standard assumptions are compared with values obtained using 2D measurements of bulk crystal populations (batch methods). CSD-calculated nucleation rates are substantially low relative to the batch values; in fact, CSD-derived volumetric nucleation rates may underestimate actual nucleation rates by up to two orders of magnitude. In contrast, growth rates from CSDs are consistently higher than batch rates. Although plagioclase growth rates are relatively constant during decompression at a given rate, the average growth rate in the rapidly decompressed series is approximately five times faster than the crystal growth rate in the slowly decompressed series. Because crystal growth rate depends on decompression rate, CSDs are incapable of revealing decompression timescales or magma ascent rates without independent knowledge of crystal growth rate.

This study presents crystal size distributions (CSD) of plagioclase forming during decompression experiments

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## 1. Introduction

Crystal size and number density are intricately linked to the rates of crystal growth and nucleation, which change in response to variations in magma temperature, vapor pressure, and melt composition. Thus, temporally-constrained studies of crystal textures provide insight into magma crystallization kinetics under changing thermobarometric conditions such as those imposed during magma transport, ascent, and eruption. The most commonly used quantitative measure of crystal textures is the crystal size distribution (CSD) technique, initially developed to study industrial crystallization in chemical engineering by Randolph and Larson (1971), and subsequently popularized for use in magmatic systems by Cashman and Marsh (1988) and Marsh (1988). Although it is possible to adopt any of a variety of models describing the time-, crystal size-, or even melt composition-dependence of crystal growth rate (e.g., Eberl et al., 2002; Jancic and Garside, 1976; Janse and deJong, 1976; Kile and Eberl, 2003; Marsh, 1998) in order to extract kinetic information from a CSD, the vast majority of practitioners (e.g., Armienti, 2008; Bindeman, 2003; Blundy and Cashman, 2008; Cashman, 1988, 1992; Cashman and McConnell, 2005; Hammer et al., 1999; Lentz and McSween, 2000; Piochi et al., 2005; Resmini, 2007; Salisbury et al., 2008) assume constant crystal growth rate. This simplifying assumption allows nucleation rate and characteristic crystal size to be extracted directly from the v-intercept and slope, respectively, of a plot of the natural log of the population density (n) versus crystal size (L). Additionally, when magma residence time ( $\tau$ ) is independently known, CSDs may be used to determine crystal growth rates (G). Volcanological applications of CSDs include determining crystal growth mechanisms (Kile and Eberl, 2003; Kile et al., 2000), magma cooling rates (Cashman, 1993; Garrido et al., 2001; Lentz and McSween, 2000), and the timing of magma mixing events (Higgins, 1996b). CSDs have also been used as evidence to support models of magmatic processes such as polybaric crystallization (Armienti et al., 1994), crystal settling (Bindeman, 2003), textural coarsening (Higgins, 1998, 1999; Higgins and Roberge, 2003), and mixing of distinct crystal populations in a batch of magma (Bindeman, 2003; Higgins, 1996b). Recent applications of CSDs have employed fixed growth rates to calculate magma ascent time and/or residence time in a magma chamber (Higgins, 1996a; Mangan, 1990; Noguchi et al., 2006; Piochi et al., 2005; Resmini and Marsh, 1995; Salisbury et al., 2008; Turner et al., 2003).

<sup>\*</sup> Corresponding author. Tel.: + 1 808 956 9544; fax: + 1 808 956 5512. *E-mail address*: brugger@hawaii.edu (C.R. Brugger).

Despite the widespread use of CSDs to answer fundamental questions about volcanic processes, few experimental studies constrain the link between textural measurements and known chemical, thermal, or barometric histories. Several recent experimental studies employing CSD analysis focus on textural development in cooling basalts. Zieg and Lofgren (2006) examine the textural evolution of olivine during continuous cooling of porphyritic olivine chondrules, and Pupier et al. (2008) use basaltic cooling experiments to constrain the effects of thermal history on plagioclase CSDs. However, we are unaware of any previous experimental studies of crystallization in silicic magmas that incorporate CSD analysis of crystal population evolution during ascent and decompression.

An important potential contribution of laboratory studies is the ability to constrain the crystallization time scale and thus explicitly determine rates of crystal nucleation and growth. Crystal growth rates have been determined experimentally in three ways: by measuring the largest 4-10 crystals observed in a charge and dividing by experimental duration (L<sub>max</sub>; Gardner et al., 1998; Hammer and Rutherford, 2002; Lesher et al., 1999; Marsh, 1998; Walker et al., 1976), by averaging 2D bulk population characteristics (batch method; Blundy and Cashman, 2008; Brugger and Hammer, 2010; Couch et al., 2003; Hammer and Rutherford, 2002; Larsen, 2005), and using in situ observations of growing crystals (Gonde et al., 2006; Means and Park, 1994; Schiavi et al., 2009). A potential concern surrounding this diversity of approaches is that growth rates obtained using these methods may not be suitable for adoption in volcanological studies, which, lacking explicit time information, employ CSD analysis-and myriad assumptions-to interpret magmatic processes. This study is the first attempt to make comparisons between batch calculations commonly used by experimentalists and the CSD calculations widely used in volcanological studies. Batch calculations of plagioclase nucleation and growth rates in experimental samples reported in a previous contribution (Brugger and Hammer, 2010) are compared with crystallization kinetics extracted from CSDs, analyzed in concert with broadly-applied assumptions. We also evaluate the efficacy of the CSD-based methodology in the specific case of magma ascent rate determination.

#### 2. Methods

#### 2.1. Decompression experiments

A complete description of experimental methods is provided in Brugger and Hammer (2010). In summary, the starting material for decompression experiments consisted of crystal-poor (~2 vol.%) rhyodacite pyroclasts from the 3430 years BP caldera-forming ignimbrite of Aniakchak Volcano in the Aleutian Arc. Charges were held at the magma reservoir equilibrium conditions (adopted from Larsen, 2006) of 880 °C and 130 MPa for 25–55 h prior to commence-

Tabl	le 1				
Run	table	and	batch	textural	characterization.

ment of decompression. All experiments were run water-saturated with oxygen fugacity held 0.5–1.0 log units above the nickel–nickel oxide solid buffering assemblage using short nickel filler rods and were quenched upon inversion of the vessel. Continuous decompression experiments were run at two different rates, 2 and 0.5 MPa/h. Six experiments were decompressed at each rate, quenched at progressively decreasing pressures: 109, 87, 68, 45, 26, and 5 MPa (Table 1). One sample (2 MPa/h quenched at 26 MPa) was lost in a polishing mishap and could not be included in the present study.

#### 2.2. Batch textural characterization

Back-scatter electron (BSE) images (Fig. 1) were collected from polished thin sections of experimental charges with a JEOL-5900LV scanning electron microscope (SEM) at University of Hawaii Manoa using an acceleration voltage of 15 kV. A total of 11-24 BSE images of each sample were obtained at magnifications of  $250 \times$  and  $750 \times$ . Plagioclase crystals were manually outlined in these images using Adobe Photoshop, and then converted to binary images (Fig. 1). The smallest digitized crystals were 3-5 pixels in width/length, corresponding to sub-micron sized crystals. Boundaries between touching crystals were assigned based on visual inspection of crystal shapes. Uncertainty introduced by this method is not considered significant due to the large number of crystals examined (n = 342-2688 per sample) and proportionately small number of touching crystals. Unless otherwise noted, measurement uncertainty is depicted in figures and tables using  $1\sigma$  variation obtained from multiple images, and thus represent sample heterogeneity rather than error associated with the technique. The long and short axes of bestfitting ellipses and the area of 2D crystals were ascertained with Image] freeware (NIH; http://rsbweb.nih.gov/ij/).

Plagioclase area fraction ( $\phi$ ) and area number density ( $N_A$ , mm<sup>-2</sup>) on a vesicle-free basis were determined by thresholding and counting crystals in each image (e.g. Hammer et al., 1999). Because the samples contain no discernible fabric, the area fraction of plagioclase is equivalent to the volume fraction (DeHoff and Rhines, 1968; Delesse, 1847). Number density and area fraction measurements were then used to calculate a characteristic crystal size,

$$S_N = \left(\Phi/N_A\right)^{1/2},\tag{1}$$

and volumetric number density,

$$N_V = N_A / S_N \tag{2}$$

(Blundy and Cashman, 2008; Cheng and Lemlich, 1983). Batch nucleation rates,

$$I = N_V / t, \tag{3}$$

Sample	Quench pressure	Decompression rate <sup>a</sup>	Anneal time (h)	Decompression time (h)	N <sub>A</sub> <sup>b</sup> (mm <sup>-2</sup> )	$\phi^{ m b}$	L <sub>max</sub> <sup>b</sup> (mm)
18-3	5	$2 \text{ MPa} \text{ h}^{-1}$	29	64.9	27,126 (6400)	0.256 (0.006)	0.15 (0.06)
18-2	45	$2 \text{ MPa } h^{-1}$	29	44.4	15,238 (7800)	0.148 (0.005)	0.11 (0.04)
18-1	68	$2 \text{ MPa } h^{-1}$	29	32.3	223 (118)	0.044 (0.002)	0.085 (0.009)
14-2	87	2 MPa h <sup>-1</sup>	26.4	22.4	991 (307)	0.055 (0.004)	0.082 (0.011)
14-1	109	2 MPa h <sup>-1</sup>	26.4	10.8	138 (16)	0.034 (0.001)	0.091 (0.007)
13-3	5	0.5 MPa h <sup>-1</sup>	55.7	279.30	7029 (593)	0.248 (0.006)	0.12 (0.05)
13-1	26	0.5 MPa h <sup>-1</sup>	55.7	230.95	15,262 (3924)	0.238 (0.007)	0.13 (0.05)
8-1	45	0.5 MPa h <sup>-1</sup>	24.9	197.68	8437 (2541)	0.141 (0.007)	0.097 (0.024)
21-1	68	0.5 MPa h <sup>-1</sup>	26.8	144.0	3349 (2100)	0.109 (0.004)	0.089 (0.009)
7-2	87	0.5 MPa h <sup>-1</sup>	42.0	99.9	12,706 (6100)	0.106 (0.005)	0.098 (0.017)
7-1	109	0.5 MPa h <sup>-1</sup>	42.0	48.5	13,513 (5564)	0.101 (0.004)	0.072 (0.011)
9-1	130	N/A	24.5	N/A	189 (13)	0.009 (0.003)	0.054 (0.022)

<sup>a</sup> The true decompression rate is slightly faster than the programmed rate shown here.

<sup>b</sup> One sigma error bars given in parentheses.



**Fig. 1.** Examples of BSE and binary images from the decompression experiments. Two dimensional width/length distributions for each sample are shown along with their best fit crystal habit as determined by CSDSlice (Morgan and Jerram, 2006). (a) Sample 7-2 decompressed at 0.5 MPa  $h^{-1}$  and quenched at 87 MPa. (b) Sample 13-3 decompressed at 0.5 MPa  $h^{-1}$  and quenched at 5 MPa h. (c) Sample 18-3 decompressed at 2 MPa  $h^{-1}$  and quenched at 5 MPa.

and growth rates,

$$G = S_N / t, \tag{4}$$

were calculated using time (t) equal to the decompression interval (e.g. Blundy and Cashman, 2008; Couch et al., 2003; Hammer and Rutherford, 2002; Larsen, 2005). All growth rates cited and calculated in this study involve total crystal length, and are thus double the advance rate of pinacoid faces. The batch methods described above are used extensively in microtextural studies of crystallization kinetics in experimental and natural systems (e.g. Blundy and Cashman, 2008; Couch et al., 2003; Genareu et al., 2010; Hammer and Rutherford, 2002; Hammer et al., 1999; Larsen, 2005; Szramek et al., 2006; Wong and Larsen, 2010). These equations are simple by design and easy to apply, which enables rapid characterization of first-order textural parameters and crystallization mechanisms. The strength of their application is in providing a means of comparison among samples in a suite. However, as far as we know, calculations of batch nucleation and growth rates have never been compared to values calculated using CSDs.

#### 2.3. Crystal size distributions

A limitation of grain sizes measured in thin sections is that the data represent 2D apparent crystal dimensions rather than 3D crystal shapes. Two primary problems with computing 3D values from 2D measurements are the cut-section effect, because a grain is rarely cut exactly through its center and thus one grain can produce different sized sections depending on its orientation, and the intersection probability effect, arising because a random 2D slice is more likely to intersect a large grain than a small one (Royet, 1991; Underwood, 1970). These problems and stereological solutions are discussed in detail by Higgins (2000), Peterson (1996), Sahagian and Proussevitch (1998), and Saltikov (1967).

The program CSDCorrections (Higgins, 2000) was developed to convert two dimensional intersection data to true three dimensional crystal size distributions by incorporating corrections for the intersection probability effect and cut-section effect. Users may upload length, width and area measurements for up to two data sets, which may be necessary if data are collected at two different scales on the same sample. If the volumetric abundance of the phase of interest is assessed independently, then the program can also correct the CSD to the known volume percent (Higgins, 2006). CSDCorrections version 1.39 was used in this study to convert 2D measurements of the long axis of the best-fitting ellipse to 3D crystal size distributions on a vesicle-free basis, and except where noted, the volumetric phase abundance correction was used. Logarithmic length intervals were used such that each bin is 1.6 times larger than the next smallest bin. Utilization of CSDCorrections requires estimation of the sample fabric, grain roundness and 3D crystal shapes. Samples were assumed to contain no fabric, which is considered valid because they were subjected to hydrostatic pressure and show no evidence of flow or crystal settling. Based on visual inspection of the samples, a roundness factor of 0.1 was chosen. The 3D shapes of crystals (Table 2) were determined using CSDSlice version 5 (Morgan and Jerram, 2006), which compares the distribution of 2D size measurements to a database of shape curves for random sections through 703 different crystal shapes. The program determines a best fit 3D crystal habit based on

**Table 2**Crystal size distribution results.

Sample	n <sup>a</sup>	Crystal shape		CSD minus overturn		Anneal cry	Anneal crystals only		dP/dt crystals only	
		Idb	$L_{\rm d}^{\rm b}$	Slope	Intercept	Slope	Intercept	Slope	Intercept	
18-3	2688	2.5	5	-41.7	15.3	-15.4	7.9	-188.5	20.2	0.25 (0.03)
18-2	1344	2.5	5	-45.6	15.7	-18.3	8.6	-184.1	19.5	0.17 (0.03)
18-1	831	1.8	8	-28.9	12.2	-28.9	12.2	N/A	N/A	0.10 (0.01)
14-2	717	3.6	10	-52.7	14.9	-52.7	14.9	N/A	N/A	0.11 (0.02)
14-1	342	1.5	3.8	-45.0	12.6	-45.0	12.6	N/A	N/A	0.06 (0.02)
13-3	1340	2.3	9	-21.0	14.0	-12.6	9.8	-63.2	16.7	0.31 (0.06)
13-1	2112	2.3	3.6	-51.8	16.1	-20.7	8.9	-197.6	19.7	0.19 (0.03)
8-1	836	2.8	4.5	-72.5	16.6	-31.6	10.5	-182.8	18.9	0.13 (0.02)
21-1	833	2.7	8	-47.2	15.4	-22.9	11.2	-87.8	16.6	0.12 (0.02)
7-2	1327	1.9	2.8	-88.6	16.9	-34.6	10.3	-249.5	19.6	0.13 (0.02)
7-1	1361	1.9	2.8	-113.6	16.9	-47.6	11.2	-360.5	20.8	0.10 (0.01)

<sup>a</sup>Number of crystals measured for CSD analyses.

<sup>b</sup>Crystal shape determined by CSDSlice (Morgan and Jerram, 2006). Short axis = 1 for all samples.

Volume fraction and one sigma error given by CSDCorrections (Higgins, 2000). Not corrected to known phase abundance.

regression calculations and fitting to the database (e.g. Fig. 1). The effects of shape selection on quantitative assessments of crystal volume fraction are considered below in Section 4.1.

Crystal size distributions are plotted as the number of crystals per unit length per unit volume  $(n(L); mm^{-4})$  as a function of crystal length (L; mm). Linear least-squares regression of  $\ln(n)$  vs. *L* was used to calculate slope and intercept values (Table 2); crystal growth rates (*G*) and nucleation rates (*I*) were calculated using

slope 
$$=$$
  $\frac{-1}{G\tau}$ , and (5)

intercept = I/G (6)

by assuming constant G (Armienti, 2008; Cashman, 1988; Marsh, 1988). Crystal volume fractions are calculated from the third moment of the crystal population distribution by incorporating a shape factor to account for the departure of grain shape from a cube (Cashman, 1990; Higgins, 2006; after Marsh, 1988) as

$$\phi = \sigma \sum n_V(L_j) L_j^3 W_j, \tag{7}$$

where  $W_j$  is the width of interval j,  $L_j$  is the length of crystals in interval j, and  $n_v(L_j)$  is the number density of crystals in the size interval. The shape factor,  $\sigma$ , is given by

$$\sigma = [1 - \Omega(1 - \pi/6)]I_d S_d / L_d^2, \tag{8}$$

where  $\Omega$  is the roundness factor, which varies from 0 for a rectangular parallelepipeds to 1 for a triaxial ellipsoid (Higgins, 2000),  $L_d$  is the long dimension,  $I_d$  is the intermediate dimension, and  $S_d$  is the short dimension.

For this study we use the most commonly applied assumptions and methods in recent textural studies of natural volcanic rocks (e.g. Field et al., 2009; Jerram et al., 2009; Magee et al., 2010; Mattsson, 2010; Moss et al., 2010; Noguchi et al., 2006; Piochi et al., 2005; Salisbury et al., 2008; Toothill et al., 2007). Firstly, crystal growth rates are assumed constant during the entire crystallization interval, thus Eqs. (5) and (6) can be used to calculate plagioclase nucleation and growth rates from the CSDs. Secondly, CSDSlice is used to convert 2D width to length ratios to 3D aspect ratios. Lastly, CSDCorrections is used to generate crystal size distribution plots from 2D crystal lengths. We do not evaluate the validity of these assumptions and methods; rather, our goal is to use the most commonly applied CSD-based methodology to calculate crystal nucleation and growth rates using the known decompression timescales and to make comparisons between these values and those calculated using batch methods.

## 3. Results

Nearly all of the experiments in this study produce concave-up curved CSD plots (Fig. 2). Samples 14-1, 14-2 and 18-1, which were decompressed at 2 MPa  $h^{-1}$  and quenched at 109, 87, and 68 MPa respectively, produce nearly straight crystal size distribution plots. The reason for this difference in shape is explained in the context of known crystallization histories of these samples (Brugger and Hammer, 2010; see Section 4.2 below). In addition, all the samples in this study display a CSD decrease at small crystal sizes (~3–7 µm; Fig. 2). In some cases, this overturn involves only one point and is slight (e.g. samples 14-2 and 18-3), but in other samples there is a larger decrease affecting several size bins (e.g. BJ3, 13-1, 8-1).

# 4. Discussion

#### 4.1. Effect of crystal shape on CSDs

Conversion of 2D crystal measurements into 3D crystal habits requires the assumption that all crystals in a particular sample have the same shape, a key condition that is nevertheless highly unlikely because a typical batch of magma contains crystals that formed at various degrees of undercooling (or effective undercooling), which is known to strongly affect crystal shapes (Hammer and Rutherford, 2002; Lofgren, 1974). To evaluate the effect of shape selection on the resulting CSD, we compare batch estimates of  $\phi$  with CSD-calculated values (Eq. (7), Fig. 3). As mentioned earlier, CSDCorrections can correct for the volumetric abundance of the phase of interest; however, for evaluative purposes the CSDs shown here are uncorrected. CSD-calculated volume fractions range from 82 to 232% of the values determined with batch methods, and in all cases, the two methods produce values within 2o. Batch and CSD-derived data are highly correlated: a line of slope equal to one fits the data with  $R^2 = 0.73$ . Thus, the crystal shapes ascertained by CSDSlice for the sample distributions and incorporated into the CSD calculations performed by CSDCorrections, adequately recover the known volume fraction of crystals.

#### 4.2. Interpretations of crystal size distribution shapes

The experimental samples have simple, known magmatic histories which are used to interpret crystal size distributions. All samples were annealed at the starting temperature and pressure for 24–55 h prior to decompression. During this anneal period, a small population of crystals nucleated and grew, as evidenced by experiments quenched immediately following the anneal period (sample 9-1, Table 1). Repeat experiments demonstrate constant crystallinity at the end of



**Fig. 2.** Crystal size distributions calculated using CSDCorrections (Higgins, 2000). The 2 MPa  $h^{-1}$  series is on the left, 0.5 MPa  $h^{-1}$  series is on the right. For each CSD, samples are divided into two sets of symbols; open symbols represent crystals that formed during the anneal period and closed symbols represent crystals that nucleated during decompression. Three samples (109, 87, and 68 MPa in the 2 MPa  $h^{-1}$  series) contain only anneal crystals (Brugger and Hammer, 2010), because these experiments were shorter than the delay associated with decompression-driven plagioclase nucleation. Sample numbers for all runs are given in the legend.

the anneal period irrespective of anneal times >24 h. Thus, with respect to crystal volume fraction, all samples reached a steady state prior to commencement of decompression. During decompression, this population of "anneal crystals" continued to grow as shown by the size increase of the largest crystals with progressive decompression (Table 1, Fig. 2). In addition, all experiments decompressed longer than 35 h contain "decompression crystals" which nucleated and grew after the anneal period. Lack of decompression crystals in the three samples (14-1, 14-2 and 18-1) decompressed for the shortest period of time reveals a lag time for nucleation of new plagioclase crystals (Brugger and Hammer, 2010).

A first-order feature of nearly all the CSDs obtained here is pronounced upward curvature (Fig. 2). The known experimental context indicates that this curvature is not a result of changes in the magma cooling rate, crystal aggregation, magma mixing, or textural



**Fig. 3.** Batch plagioclase volume fraction plotted against values calculated from crystal size distributions. Volume fraction is calculated without the volumetric phase abundance correction. The 2 MPa  $h^{-1}$  series are triangles, the 0.5 MPa  $h^{-1}$  series are circles. The solid line represents a 1:1 correlation.

coarsening, as has been suggested to explain curvature in the CSDs of many natural magmas (e.g. Armienti et al., 1994; Bindeman, 2003; Higgins, 1996a, 1998, 1999, 2002; Higgins and Roberge, 2003; Marsh, 1998; Marsh et al., 1991; Zieg and Marsh, 2002). Rather, this curvature is an artifact caused by the presence of two populations of crystals, those formed during the anneal period and those formed during decompression, associated with separate nucleation regimes. Consequently, we follow convention (e.g. Armienti et al., 1994; Cashman, 1988; Piochi et al., 2005; Salisbury et al., 2008) and divide our plots into two segments representing the two known crystal populations. Using the growth rate of the largest crystals ( $L_{max}$ ; see Section 4.3 below), the segment of the CSD corresponding to the anneal crystals is determined for each sample (Fig. 2). When this portion of the CSD is fitted to a separate least-squares regression line representing the anneal crystals, the remaining crystals form a fairly well-constrained straight line ( $R^2$  is always > 0.97) corresponding to the decompression crystals. The three samples lacking decompression crystals, 14-1, 14-2 and 18-1, contain only one population of crystals and are thus fit with only one regression line.

A population density decrease at small crystal sizes is a ubiquitous feature in all of the samples in this study (Fig. 2), and is also common in natural samples. An overturn at small sizes in natural rocks is typically interpreted as either a result of ripening (e.g. Congdon et al., 1993; Higgins, 1998; Higgins and Roberge, 2003; Shea et al., 2009; Waters and Boudreau, 1996), or inadequate spatial resolution (e.g. Cashman and Ferry, 1988; Hammer et al., 1999; Marsh, 1998; Resmini and Marsh, 1995). Neither of these explanations is satisfactory in this case. Ripening is typically associated with very low undercooling and extended time scales (Cabane et al., 2005; Higgins and Roberge, 2007; Voorhees, 1992). These samples were decompressed continuously and sustained relatively high effective undercooling (Brugger and Hammer, 2010), consistent with microtextures characterized by large crystal number densities and rapid growth (Fig. 1). Thus, it seems unlikely that crystallization was affected significantly by ripening, which redistributes mass from small to larger crystals to minimize crystal-melt interfacial area. Inadequate spatial resolution is also rejected to explain the downturn: at the highest magnification utilized, one micron is represented by 7 pixels and thus sub-micron crystals are well within detection limits. The fact that the overturn in size frequency occurs in each sample and is not propagated into larger bin sizes for samples undergoing progressive decompression suggests that this is not an authentic characteristic of the CSD. Rather, we infer

that it results from intersection probability effects, and if so, indicates that CSDCorrections does not boost small crystal sizes enough to compensate for this stereological problem.

#### 4.3. Calculations of nucleation and growth rates

CSD-based determination of 3D nucleation rates (*I*; Eq. (6)) fall significantly below rates calculated using the batch method (Eq. (3); Fig. 4). When the entire CSD is used to calculate nucleation rates (*I*), values are 1–2 orders of magnitude lower in all of the samples that contain decompression crystals. However, this is consistent with the largest crystals in each CSD having actually nucleated during the initial anneal period prior to commencement of decompression. Including these crystals in nucleation rate estimates would tend to artificially lower the calculated rates, because *I* is a function of CSD intercept and slope (Eqs. (5) and (6)). When nucleation rates are calculated using only the decompression-nucleated crystals (see Fig. 4 inset for example), estimates increase but are still 30–77% lower than nucleation rates calculated using the batch method.

Plagioclase growth rates are calculated for each sample using crystal size distributions (Eq. (5)), the batch method (Eq. (4)), and the  $L_{max}$  method (Fig. 5). The  $L_{max}$  method always produces the highest growth rates, which range from 2 to 32 times faster than rates calculated with the batch method. When the entire CSD is used, calculated growth rates fall somewhere between the  $L_{max}$  and batch methods. However, a large range of growth rates can be generated from one CSD plot by using different parts of the distribution. If the steepest portion of the CSD is used (arbitrarily defined by 3 points), calculated growth rates are quite low and similar to those obtained using the batch method. If however, large crystals from the shallowest part of the CSD are used, calculated growth rates are similar to those of the  $L_{max}$  method. The close agreement with bracketing growth rates suggests that image processing time may be saved by using the batch



**Fig. 4.** Nucleation rates calculated from CSDs are always less than nucleation rates determined by the batch method. Triangles represent nucleation rates calculated using the entire CSD (minus the overturn at small sizes) and squares represent calculations using only decompression crystals. Open symbols represent the 0.5 MPa h<sup>-1</sup> series and closed symbols represent the 2 MPa h<sup>-1</sup> series. Decompression time is used to determine nucleation rates in all samples except the three samples which contain no decompression crystals, anneal time is used instead for these three samples. Inset shows the CSD for sample 7-1 which has been divided into two populations of crystals, anneal crystals (circles) and decompression crystals (squares). The best fit linear regression lines (dashed) are shown for the entire CSD, and the two separate crystal populations.



Fig. 5. Calculated crystal growth rates; the top boundaries of shaded regions are calculated using the shallowest part of the CSD (as defined by 3 points at the largest bin sizes), while the bottom boundaries are calculated using the steepest part. The solid gray line inside the shaded region represents the calculated growth rate when the entire CSD is used. Crystal growth rates calculated using the  $L_{max}$  (squares) and batch (circles) methods are also shown. For each method, the time used to calculate growth rate is decompression time, which starts after the anneal period concludes. However, the largest crystals in each sample (those used in the  $L_{max}$  method) likely nucleated during the anneal period. Thus the  $L_{max}$  size at the end of the anneal period (sample 9-1) was subtracted from the  $L_{max}$  size of each experiment so that the size used in calculations represents only the growth during decompression. Error bars for the L<sub>max</sub> method reflect propagation of one sigma of the average length of the 5 largest crystals in each sample through the growth rate calculation. In contrast, the one sigma error bars for the batch method reflect sample heterogeneity as assessed from multiple BSE images. Thus, these error bars are not directly comparable because they represent different types of measurement uncertainty.

and  $L_{\text{max}}$  methods, which unlike CSD analysis do not require measuring hundreds of crystals.

Despite small variations in the  $L_{max}$  growth rates with progressive decompression, each series maintains a distinct and fairly constant growth rate (Fig. 6). The average growth rate in the 2 MPa h<sup>-1</sup> series is approximately five times higher than in the 0.5 MPa h<sup>-1</sup> series. The two series contain similarly sized crystals, despite representing crystallization time scales that differ by a factor of ~4 (Table 1). Thus, crystal sizes appear to correlate with pressure, and consequently the amount of decompression (P<sub>liquidus</sub>–P<sub>sample</sub>), rather than the time available for crystallization. Since growth rate is calculated using experiment duration, it appears that growth rates are dependent on decompression rate. Cashman (1993) reports an analogous result for crystals growing in cooling magma: faster cooling produces faster crystal growth. This correlation underscores a key result of this comparative analysis. The practice of using CSD-based methods to calculate magma ascent rates may be fundamentally flawed if crystal



**Fig. 6.** Plot of crystal length ( $L_{\max}$ ) versus decompression time for each series. The average crystal growth rate (*G*) is determined for each series from the slope of the best-fitting linear relationship between time and length. The shaded zone on the left represents the anneal period which is not included in calculations.

growth rates vary as a function of decompression rate, as shown here. The analyst's dilemma is that an accurate ascent rate estimate depends upon adoption of the appropriate crystal growth rate, and yet crystallization time (the product of magma ascent rate and ascent distance) must be known in order to select an appropriate crystal growth rate.

#### 4.4. Calculating magmatic timescales

In the majority of volcanological studies aimed at determining the timescales of magmatic processes, Eq. (5) is rearranged to solve for  $\tau$ , the slope of the population distribution is found from the CSD, and a value of crystal growth rate (*G*) is drawn from the literature. Cashman (1990) suggested that crystal growth rates under most magmatic cooling conditions are fairly uniform between  $10^{-9}$  and  $10^{-10}$  mm s<sup>-1</sup>, and these rates have been used in conjunction with CSDs to calculate residence times in many volcanic systems (e.g. Cigolini et al., 2008; Higgins, 1996a, 1996b; Higgins and Chandrasekharam, 2007; Higgins and Roberge, 2007; Jerram et al., 2003; Mangan, 1990; Pappalardo et al., 2007; Resmini and Marsh, 1995; Salisbury et al., 2008; Sen et al., 2006; Turner et al., 2003). However, subsequent studies have found that microlite growth rates may be as high as  $10^{-7}$  to  $10^{-6}$  mm s<sup>-1</sup> in ascending magmas where crystallization is driven by decompression and water exsolution (Couch et al., 2003; Gardner et al., 1998; Geschwind and Rutherford, 1995; Hammer et al., 1999). Thus plagioclase growth rates in magmatic systems vary over ~5 orders of magnitude. As noted above, computation of magma residence time requires accurate assessment of crystal growth rate. However, five orders of magnitude variation in possible crystal growth rate yields a five order of magnitude range in calculated residence time. So what considerations inform the selection of growth rate to use in CSD-based calculations of residence time?

In reviewing a large number of CSD studies, it appears that crystal growth rates are typically chosen based on contextual information. If crystals are thought to have formed as a result of slow cooling in a magma chamber, regardless of the magma's composition, then slower growth rates in the range of  $10^{-8}$  to  $10^{-10}$  mm s<sup>-1</sup> are used (e.g. Cigolini et al., 2008; Higgins, 1996a, 1996b; Pappalardo et al., 2007; Renzulli et al., 2009; Resmini and Marsh, 1995; Salisbury et al., 2008;

Turner et al., 2003). If crystals likely resulted from rapid decompression and water exsolution, these crystals are assigned rates between  $10^{-6}$  and  $10^{-8}$  mm s<sup>-1</sup> (e.g. Cigolini et al., 2008; Genareau et al., 2009; Mastrolorenzo and Pappalardo, 2006; McCanta et al., 2007; Noguchi et al., 2006; Piochi et al., 2005; Salisbury et al., 2008).

Using the range of crystal growth rates cited in the literature as potentially appropriate for ascent-driven growth of plagioclase, Eq. (5) is used in conjunction with CSD slopes to calculate an estimated "residence time," or decompression duration, for our samples (Fig. 7). Each of the three growth rates produces a broad, but exclusive field of residence times. As expected, calculated residence time depends on the selected growth rate. The fastest growth rate generates timescales ranging from 0.8 h to 4.5 h, the intermediate growth rate produces timescales of 8-45 h, and the slowest growth rate leads to magma residence times of 3-19 days. The actual range of timescales for all experiments containing decompression crystals is 1.8–11.6 days, and thus the slowest growth rate generates the most accurate time estimates. However, in studies of natural volcanic rocks the slowest crystal growth rate is selected in a minority of cases (e.g. Genareau et al., 2009; McCanta et al., 2007). The most commonly chosen growth rate for plagioclase in an ascending andesite or dacite is  $10^{-7}$  mm s<sup>-1</sup> (e.g. Mastrolorenzo and Pappalardo, 2006; Salisbury et al., 2008). Adoption of this value for interpretation of crystallization timescale in the experimental samples would underestimate the actual decompression interval by an order of magnitude.

Given the range of growth rates that have been deemed appropriate for syn-eruptive plagioclase microlite crystallization  $(10^{-6} \text{ to } 10^{-8} \text{ mm s}^{-1})$ , and the wide array of timescales (e.g. <5 h to nearly 19 days for just one sample) calculated from these rates, the choice of crystal growth rate is clearly of paramount importance for calculating an accurate magma crystallization timescale. We question the efficacy of calculating crystallization time using a growth rate value chosen solely on the inference



**Fig. 7.** Experimental decompression interval (known crystallization time) versus CSDcalculated "residence" time. Timescales are calculated using Eq. (5) and a range of growth rates previously associated with decompression-induced plagioclase growth:  $10^{-6}$  mm s<sup>-1</sup> (circles),  $10^{-7}$  mm s<sup>-1</sup> (squares), and  $10^{-8}$  mm s<sup>-1</sup> (triangles). The CSD slopes used in the calculations only correspond to the portions of the CSDs representing crystals formed during decompression. The 0.5 MPa h<sup>-1</sup> series is represented by open symbols, the 2 MPa h<sup>-1</sup> series is shown with closed symbols (only two points are shown because the other three samples did not contain decompression crystals). The 1:1 correlation line is shown for reference.

that the crystals in question grew during decompression. By assuming that a particular population of crystals has formed during magma ascent and picking a corresponding growth rate, the analyst has already constrained the timescale that will result. In other words, the resolution of calculated timescales is a function of the chosen growth rate rather than the microtexture.

#### 5. Conclusions

In the earliest CSD studies, crystal growth rates were calculated for systems in which independent knowledge of the crystallization timescales was available (e.g. Cashman, 1988; Cashman and Marsh, 1988). After publication of numerous studies involving crystallization in magma chambers, dikes, and lava lakes, Cashman (1990, 1993) concluded that plagioclase growth rates are not particularly sensitive to melt composition (except for extremely low melt viscosities; e.g. Peterson, 1990), and they are approximately constant at  $10^{-9}$  to  $10^{-10}$  mm s<sup>-1</sup> under most magmatic cooling conditions because most crystallization in shallow volcanic systems occurs at very small effective undercoolings. These conclusions led numerous subsequent authors to employ constant growth rates to calculate magmatic timescales, such as magma chamber residence times, timing of magma mixing events, and cooling rates of lava flows or shallow intrusions (e.g. Cigolini et al., 2008; Higgins, 1996a, 1996b; Higgins and Chandrasekharam, 2007; Higgins and Roberge, 2007; Jerram et al., 2003; Mangan, 1990; Pappalardo et al., 2007; Resmini and Marsh, 1995; Salisbury et al., 2008; Sen et al., 2006; Turner et al., 2003).

Degassing as a driving force for crystallization in H<sub>2</sub>O-saturated magmas gained wide acceptance toward the end of the 1990s (Gardner et al., 1998; Geschwind and Rutherford, 1995; Hammer et al., 1999; Lipman and Banks, 1987). While growth rates may in fact be limited to one order of magnitude variation in shallow volcanic systems where crystallization is driven by cooling (Cashman, 1990), the same does not appear to be true with decompression-induced crystallization. Rather, crystal growth rates during magma ascent can vary over three orders of magnitude and are highly dependent upon decompression rates (Couch et al., 2003; Gardner et al., 1998; Geschwind and Rutherford, 1995; Hammer et al., 1999). Thus, paradoxically, magma ascent rate and the crystallization timescale must be known before an appropriate growth rate can be chosen for CSD calculations. Consideration of the entire range of plausible decompression-induced crystal growth rates yields variation in the calculated timescales large enough to preclude meaningful volcanological interpretation. Thus, we conclude that crystal size distributions may be used in conjunction with slow crystal growth rates to constrain timescales of long-duration processes, such as magma chamber residence times or lava lake solidification duration, but they are not useful for determining magma ascent rates in the absence of an independent constraint on crystal growth rates.

Experimental studies linking crystal morphologies (e.g. euhedral, swallowtail, hopper and dendritic) with degree of undercooling and decompression rate may be more useful as calibration for estimating magma ascent rates in natural magmas than quantitative CSD-based methods performed in isolation from such textural information. When applied in conjunction with storage chamber depths, such comparisons can be used to calculate crystallization timescales. Moreover, even in systems where the magmatic timescales are known, CSDs may not provide the most efficient method for determining crystal growth rates. We report that CSD-calculated growth rates for the largest crystals in the sample are very similar to growth rates calculated using the  $L_{max}$  method. Taking measurements of only the largest crystals in a sample requires a small fraction of the time necessary to quantify the entire population and calculate the CSD. The  $L_{\text{max}}$  method is suggested as a practical means of obtaining crystal growth rates in instances where timescales are wellconstrained.

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#### References

Armienti, P., 2008. Decryption of igneous rock textures: crystal size distribution tools In: Minerals, Inclusions and Volcanic Processes. Rev. Mineral. Geochem. 69, 623–648.

- Armienti, P., Pareschi, M.T., Innocenti, F., Pompilio, M., 1994. Effects of magma storage and ascent on the kinetics of crystal growth: the case of the 1991–1993 Mt. Etna eruption. Contrib. Mineral. Petrol. 115, 402–414.
- Bindeman, I.N., 2003. Crystal sizes in evolving silicic magma chambers. Geology 31, 367–370.
- Blundy, J., Cashman, K., 2008. Petrologic reconstruction of magmatic system variables and processes In: Minerals, Inclusions and Volcanic Processes. Rev. Mineral. Geochem. 69, 179–239.
- Brugger, C.R., Hammer, J.E., 2010. Crystallization kinetics in continuous decompression experiments: implications for interpreting natural magma ascent processes. J. Petrol. 51, 1941–1965.
- Cabane, H., Laporte, D., Provost, A., 2005. An experimental study of Ostwald ripening of olivine and plagioclase in silicate melts: implications for the growth and size of crystals in magmas. Contrib. Mineral. Petrol. 150, 37–53.
- Cashman, K.V., 1988. Crystallization of Mount St. Helens 1980–1986 dacite: a quantitative textural approach. Bull. Volcanol. 50, 194–209.
- Cashman, K.V., 1990. Textural constraints on the kinetics of crystallization of igneous rocks. Rev. Mineral. 24, 259–314.
- Cashman, K.V., 1992. Groundmass crystallization of Mount St. Helens dacite, 1980– 1986: a tool for interpreting shallow magmatic processes. Contrib. Mineral. Petrol. 109, 431–449.
- Cashman, K.V., 1993. Relationship between plagioclase crystallization and cooling rate in basaltic melts. Contrib. Mineral. Petrol. 113, 126–142.
- Cashman, K.V., Ferry, J.M., 1988. Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallization. Contrib. Mineral. Petrol. 99, 401–415.
- Cashman, K.V., Marsh, B.D., 1988. Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallization II: Makaopuhi lava lake. Contrib. Mineral. Petrol. 99, 292–305.
- Cashman, K.V., McConnell, S.M., 2005. Multiple levels of magma storage during the 1980 summer eruptions of Mount St. Helens, WA. Bull. Volcanol. 68, 57–75.
- Cheng, H., Lemlich, R., 1983. Errors in measurement of bubble size distribution in foam. Ind. Eng. Chem. Fundam. 22, 105–109.
- Cigolini, C., Laiolo, M., Bertolino, S., 2008. Probing Stromboli Volcano from the mantle to paroxysmal eruptions. In: Annen, C., Zellmer, G.F. (Eds.), Dynamics of Crustal Magma Transfer. : Geological Society of London Special Publication, 304. Bath, UK, pp. 33–70.
- Congdon, R.D., Resmini, R.G., Marsh, B.D., 1993. Differentiation style in the Box Elder and Shonkin Sag Laccoliths; dependence on initial conditions. EOS Trans. AGU. 73, 336.
- Couch, S., Sparks, R.S.J., Carroll, M.R., 2003. The kinetics of degassing-induced crystallization at Soufriere Hills Volcano, Montserrat. J. Petrol. 44, 1477–1502.
- DeHoff, R.T., Rhines, F.N., 1968. Quantitative Microscopy. McGraw-Hill Book Co., New York.
- Delesse, M.A., 1847. Procedé mécanique pour déterminer la composition des roches. Comptes rendus de l'académie des sciences, 25, pp. 544–545. Paris.
- Eberl, D.D., Kile, D.E., Drits, V.A., 2002. On geological interpretations of crystal size distributions: constant vs. proportionate growth. Am. Mineral. 87, 1235–1241.
- Field, M., Gernon, T.M., Mock, A., Walters, A., Sparks, R.S.J., Jerram, D.A., 2009. Variations of olivine abundance and grain size in the Snap Lake kimberlite intrusion, Northwest Territories, Canada: a possible proxy for diamonds. Lithos 112, 23–35.
- Gardner, C.A., Cashman, K.V., Neal, C.A., 1998. Tephra fall deposits from the 1992 eruption of Crater Peak, Alaska: implications of clast textures for eruptive products. Bull. Volcanol. 59, 537–555.
- Garrido, C.J., Keleman, P.B., Hirth, G., 2001. Variation of cooling rate with depth in lower crust formed at an oceanic spreading ridge: plagioclase crystal size distributions in gabbros from the Oman ophiolite. Geochem. Geophys. Geosyst. 2 (10) 2000GC000136.
- Genareau, K., Clarke, A.B., Hervig, R.L., 2009. New insight into explosive volcanic eruptions: connecting crystal-scale chemical change with conduit-scale dynamics. Geology 37, 367–370.
- Genareu, K., Valentine, G.A., Moore, G., Hervig, R.L., 2010. Mechanisms for transition in eruptive style at a monogenetic scoria cone revealed by microtextural analyses (Lathrop Wells volcano, Nevada, U.S.A.). Bull. Volcanol. 72, 593–607.
- Geschwind, C.-H., Rutherford, M.J., 1995. Crystallization of microlites during magma ascent: the fluid mechanics of 1980–1986 eruptions at Mount St Helens. Bull. Volcanol. 57, 356–370.
- Gonde, C., Massare, D., Bureau, H., Martel, C., Pichavant, M., Clocchiatti, R., 2006. In situ study of magmatic processes: a new experimental approach. High Pressure Res. 26, 243–250.
- Hammer, J.E., Rutherford, M.J., 2002. An experimental study of the kinetics of decompression-induced crystallization in silicic melts. J. Geophys. Res. 197, 1–23.
- Hammer, J.E., Cashman, K.V., Hoblitt, R.P., Newman, S., 1999. Degassing and microlite crystallization during pre-climactic events of the 1991 eruption of Mt. Pinatubo, Philippines. Bull. Volcanol. 60, 355–380.

Higgins, M.D., 1996a. Crystal size distributions and other quantitative textural measurements in lavas and tuff from Egmont volcano (Mt. Taranaki), New Zealand. Bull. Volcanol. 58, 194–204.

- Higgins, M.D., 1996b. Magma dynamics beneath Kameni volcano, Thera, Greece, as revealed by crystal size and shape measurements. J. Volcanol. Geotherm. Res. 70, 37–48.
- Higgins, M.D., 1998. Origin of anorthosite by textural coarsening: quantitative measurements of a natural sequence of textural development. J. Petrol. 39, 1307–1323.
- Higgins, M.D., 1999. Origin of megacrysts in granitoids by textural coarsening: a crystal size distribution (CSD) study of microcline in the Cathedral Peak Granodiorite, Sierra Nevada, California. In: Castro, A., Fernandez, C., Vigneresse, J.L. (Eds.), Understanding Granites: Integrating New and Classical Techniques: Geological Society of London Special Publication, 168, pp. 207–219. London.
- Higgins, M.D., 2000. Measurement of crystal size distributions. Am. Mineral. 85 (9), 1105-1116.
- Higgins, M.D., 2002. A crystal size-distribution study of the Kiglapait layered mafic intrusion, Labrador, Canada: evidence for textural coarsening. Contrib. Mineral. Petrol. 144, 314–330.
- Higgins, M.D., 2006. Quantitative Textural Measurements in Igneous and Metamorphic Petrology. Cambridge University Press. Cambridge, UK.
- Petrology. Cambridge University Press, Cambridge, UK. Higgins, M.D., Chandrasekharam, D., 2007. Nature of sub-volcanic magma chambers, Deccan Province, India: evidence from quantitative textural analysis of plagioclase megacrysts in the Giant Plagioclase Basalts. J. Petrol. 48, 885–900.
- Higgins, M.D., Roberge, J., 2003. Crystal size distribution of plagioclase and amphibole from Soufrière Hills Volcano, Montserrat: evidence for dynamic crystallizationtextural coarsening cycles. J. Petrol. 44, 1401–1411.
- Higgins, M.D., Roberge, J., 2007. Three magmatic components in the 1973 eruption of Eldfell Volcano, Iceland: evidence from plagioclase crystal size distribution (CSD) and geochemistry. J. Volcanol. Geotherm. Res. 161, 247–260.
- Jancic, S., Garside, J., 1976. A new technique for accurate crystal size distribution analysis in an MSMPR crystallizer. In: Mullin, J.F. (Ed.), Industrial Crystallization. Plenum Press, New York, p. 472.
- Janse, E.H., deJong, E.J., 1976. The occurrence of growth dispersion and its consequences. In: Mullin, J.F. (Ed.), Industrial Crystallization. Plenum Press, New York, p. 472.
- Jerram, D.A., Cheadle, M.J., Philpotts, A.R., 2003. Quantifying the building blocks of igneous rocks: are clustered crystal frameworks the foundation? J. Petrol. 44, 2033–2051.
- Jerram, D.A., Mock, A., Davis, G.R., Field, M., Brown, R.J., 2009. 3D crystal size distributions: a case study on quantifying olivine populations in kimberlites. Lithos 112, 223–235.
- Kile, D.E., Eberl, D.D., 2003. On the origin of size-dependent and size-independent crystal growth; influence of advection and diffusion. Am. Mineral. 88, 1514–1521.
- Kile, D.E., Eberl, D.D., Hoch, A.R., Reddy, M.M., 2000. An assessment of calcite crystal growth mechanisms based on crystal size distributions. Geochim. Cosmochim. Acta 64, 2937–2950.
- Larsen, J.F., 2005. Experimental study of plagioclase rim growth around anorthite seed crystals in rhyodacitic melt. Am. Mineral. 90, 417–427.
- Larsen, J.F., 2006. Rhyodacite magma storage conditions prior to the 3430 y BP calderaforming eruption of Aniakchak volcano, Alaska. Contrib. Mineral. Petrol. 152, 523–540.
- Lentz, R.C.F., McSween, H.Y.J., 2000. Crystallization of the basaltic shergottites: insights from crystal size distribution (CSD) analysis of pyroxenes. Meteorit. Planet. Sci. 35 (5), 919–927.
- Lesher, C.E., Cashman, K.V., Mayfield, J.D., 1999. Kinetic controls on crystallization of Tertiary North Atlantic basalt and implications for the emplacement and cooling history of lava at Site 989, Southeast Greenland rifted margin. Proc. Ocean Drill. Program 163, 135–148.
- Lipman, P.W., Banks, N.G., 1987. Aa flow dynamics, Mauna Loa 1984. USGS Prof. Paper. 1350, 1527–1567.
- Lofgren, G.E., 1974. An experimental study of plagioclase crystal morphology: isothermal crystallization. Am. J. Sci. 274, 243–273.
- Magee, C., O'Driscoll, B., Chambers, A.D., 2010. Crystallization and textural evolution of a closed-system magma chamber: insights from a crystal size distribution study of the Lilloise layered intrusion, East Greenland. Geol. Mag. 147, 363–379.
- Mangan, M.T., 1990. Crystal size distribution systematics and the determination of magma storage times: the 1959 eruption of Kilauea Volcano, Hawaii. J. Volcanol. Geotherm. Res. 44, 295–302.
- Marsh, B.D., 1988. Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallization; I. Theory. Contrib. Mineral. Petrol. 99, 277–291.
- Marsh, B.D., 1998. On the interpretation of crystal size distributions in magmatic systems. J. Petrol. 39, 553–599.
- Marsh, B.D., Gunnarsson, B., Congdon, R., Carmody, R., 1991. Hawaiian basalt and Icelandic rhyolite: indicators of differentiation and partial melting. Geol. Rundsch. 80 (2), 481–510.
- Mastrolorenzo, G., Pappalardo, L., 2006. Magma degassing and crystallization processes during eruptions of high-risk Neapolitan-volcanoes: evidence of common equilibrium rising processes in alkaline magmas. Earth Planet. Sci. Lett. 250, 164–181.
- Mattsson, H.B., 2010. Textural variation in juvenile pyroclasts from an emergent, Surtseyan-type, volcanic eruption: the Capelas tuff cone, São Miguel (Azores). J. Volcanol. Geotherm. Res. 189, 81–91.
- McCanta, M.C., Rutherford, M.J., Hammer, J.E., 2007. Pre-eruptive and syn-eruptive conditions in the Black Butte, California dacite: insight into crystallization kinetics in a silicic magma system. J. Volcanol. Geotherm. Res. 160, 263–284.

- Means, W.D., Park, Y., 1994. New experimental approach to understanding igneous texture. Geology 23, 323–326.
- Morgan, D.J., Jerram, D.A., 2006. On estimating crystal shape for crystal size distribution analysis. J. Volcanol. Geotherm. Res. 154, 1–7.
- Moss, S., Russell, J.K., Scott Smith, B.H., Brett, R.C., 2010. Olivine crystal size distributions in kimberlite. Am. Mineral. 95, 527–536.
- Noguchi, S., Toramaru, A., Shimano, T., 2006. Crystallization of microlites and degassing during magma ascent: constraints on the fluid mechanical behavior of magma during the Tenjo eruption on Kozu Island, Japan. Bull. Volcanol. 68, 432–449.
- Pappalardo, L, Ottolini, L, Mastrolorenzo, G, 2007. The Campanian Ignimbrite (southern Italy) geochemical zoning: insight on the generation of a super-eruption from catastrophic differentiation and fast withdrawal. Contrib. Mineral. Petrol. 156, 1–16.
- Peterson, T.D., 1996. A refined technique for measuring crystal size distributions in thin section. Contrib. Mineral. Petrol. 124, 395–405.
- Piochi, M., Mastrolorenzo, G., Pappalardo, L., 2005. Magma ascent and eruptive processes from textural and compositional features of Monte Nuovo pyroclastic products, Campi Flegrei, Italy. Bull. Volcanol. 67, 663–678.
- Pupier, E., Duchene, S., Toplis, M.J., 2008. Experimental quantification of plagioclase crystal size distribution during cooling of basaltic liquid. Contrib. Mineral. Petrol. 155, 555–570.
- Randolph, A.D., Larson, M.A., 1971. Theory of Particulate Processes. Academic Press, New York.
- Renzulli, A., Del Moro, S., Menna, M., Landi, P., Piermattei, M., 2009. Transient processes in Stromboli's shallow basaltic system inferred from dolerite and magmatic breccia blocks erupted during the 5 April 2003 paroxysm. Bull. Volcanol. 71, 795–813.
- Resmini, R.G., 2007. Modeling of crystal size distributions (CSDs) in sills. J. Volcanol. Geotherm. Res. 161 (1-2), 118-130.
- Resmini, R.G., Marsh, B.D., 1995. Steady-state volcanism, paleoeffusion rates, and magma system volume inferred from plagioclase crystal size distributions in mafic lavas; Dome Mountain, Nevada. J. Volcanol. Geotherm. Res. 68 (4), 273–296.
- Royet, J.-P., 1991. Stereology: a method for analyzing images. Prog. Neurobiol. 37, 433-474
- Sahagian, D.L., Proussevitch, A.A., 1998. 3D particle size distributions from 2D observations; stereology for natural applications. J. Volcanol. Geotherm. Res. 84 (3–4), 173–196.
- Salisbury, M.J., Bohrson, W.A., Clynne, M.S., Ramos, F.C., Hoskin, P., 2008. Multiple plagioclase crystal populations identified by crystal size distribution and in situ chemical data: implications for timescales of magma chamber processes associated with the 1915 eruption of Lassen Peak, CA. J. Petrol. 49, 1755–1780.
- Saltikov, S.A., 1967. The determination of the size distribution of particles in an opaque material from a measurement of the size distributions of their sections. In: Elias, H. (Ed.), Proceedings of the Second International Congress for Stereology. Springer-Verlag, Berlin, pp. 163–173.
- Schiavi, F., Walte, N., Keppler, H., 2009. First in situ observation of crystallization processes in a basaltic-andesitic melt with the moissanite cell. Geology 37, 963–966.
- Sen, G., Borges, M., Marsh, B.D., 2006. A case for short duration of Deccan Trap eruption. EOS Trans. AGU. 87 (20). doi:10.1029/2006EO200001.
- Shea, T., Larsen, J.F., Gurioli, L., Hammer, J.E., Houghton, B.F., Cioni, R., 2009. Leucite crystals: surviving witnesses of magmatic processes preceding the 79 AD eruption at Vesuvius, Italy. Earth Planet. Sci. Lett. 281, 88–98.
- Szramek, L., Gardner, J.E., Larsen, J., 2006. Degassing and microlite crystallization of basaltic andesite magma erupting at Arenal Volcano, Costa Rica. J. Volcanol. Geotherm. Res. 157 (1-3), 182–201.
- Toothill, J., Williams, C.A., MacDonald, R., Turner, S.P., Rogers, N.W., Hawkesworth, C.J., Jerram, D.A., Ottley, C.J., Tindle, A.G., 2007. A complex petrogenesis for an arc magmatic suite, St Kitts, Lesser Antilles. J. Petrol. 48, 3–42.
- Turner, S., George, R., Jerram, D.A., Carpenter, N., Hawkesworth, C., 2003. Case studies of plagioclase growth and residence times in island arc lavas from Tonga and the Lesser Antilles, and a model to reconcile discordant age information. Earth Planet. Sci. Lett. 214, 279–294.
- Underwood, E.E., 1970. Quantitative Stereology. Addison-Wesley, Reading, Massachusetts.
- Voorhees, P.W., 1992. Ostwald ripening of two-phase mixtures. Annu. Rev. Mater. Sci. 22, 197–215.
- Walker, D., Kirkpatrick, R.J., Longhi, J., Hays, J.F., 1976. Crystallization history of lunar picritic basalt sample 12002: phase-equilibria and cooling-rate studies. Geol. Soc. Am. Bull. 87, 646–656.
- Waters, C., Boudreau, A.E., 1996. A reevaluation of crystal-size distributions in chromite cumulates. Am. Mineral. 81, 1452–1459.
- Wong, LJ., Larsen, J.F., 2010. The Middle Scoria sequence: a Holocene violent strombolian, subplinian and phreatomagmatic eruption of Okmok Volcano, Alaska. Bull. Volcanol. 72, 17–31.
- Zieg, M.J., Lofgren, G.E., 2006. An experimental investigation of texture evolution during continuous cooling. J. Volcanol. Geotherm. Res. 154, 74–88.
- Zieg, M.J., Marsh, B.D., 2002. Crystal size distributions and scaling laws in the quantification of igneous textures. J. Petrol. 43, 85–101.