Using crystal size distributions and qualitative textural analysis to deduce the crystallization histories of trachytic domes and dykes in the Akaroa Volcanic Complex, New Zealand

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ABSTRACT

Study of silicic domes and dykes located in predominantly basaltic volcanic complexes is crucial to the understanding of late-stage volcanic plumbing systems (Kobayashi et al., 2002; Bertolett, 2014; Gaddis, 2014; Maher, 2016). Crystal size distribution (CSD) analysis—when substantiated with qualitative petrographic observations and crystal damage assessment—can be used to construct models for the storage, ascent, and emplacement of such structures (Marsh, 1988; Zieg and Marsh, 2002; Mock and Jerram, 2005). Moreover, estimates of residence time for related feeder magmas can be calculated from CSD regression slopes (Resmini and Marsh, 1995). In the case of the Akaroa Volcanic Complex (AVC), an intraplate composite shield volcano active during the Miocene on New Zealand’s Banks Peninsula, CSDs and petrographic evidence for three different trachytic structures—Mount Sinclair dome, Panama Rock dyke, and Devil’s Gap Senior dome—show that late-stage trachyte magma faced at least two different paths of ascent after fractionating from a hawaiite reservoir at depths of 10-15 km (Hartung, 2011): (1) a direct and constant ascent, which is reflected in the linear CSD trends of Mount Sinclair dome and Panama Rock dyke, and (2) a stalled ascent, which is reflected in the downward inflections observed in Devil’s Gap Senior dome CSDs. The steeper regression slopes for Panama Rock dyke and Mount Sinclair dome—0.0236 and -0.0215, respectively—show that magma ascended at a relatively fast rate compared to Devil’s Gap Senior dome, which has an average CSD regression slope of -0.0127. The steeper regression slopes for Mount Sinclair dome and Panama Rock dyke also yield estimates of magma residence time over 4.5 times greater on average than those calculated for Devil’s Gap Senior dome—a disparity likely the result of Devil’s Gap Senior dome having crystallized from a larger body of magma. Furthermore, results from crystal damage assessments show that Devil’s Gap Senior dome likely breached the surface as an effusive lava dome, while Panama Rock dyke and Mount Sinclair dome solidified in the subsurface as shallow intrusives. The results presented here exemplify the complexity and variability involved in the emplacement of late-stage volcanic substructures. Moreover, the methodology used in this study can be easily adapted to future research on similar late-stage volcanic structures both in the AVC and abroad.

Keywords: Miocene; intraplate volcanism; stereological corrections; cryptodome; resorption

1. INTRODUCTION

Essential to the understanding of volcanic plumbing systems is the study of volcanic substructures—principally domes, shallow intrusions, and dykes—the textural properties of which offer crucial insights into the subsurface evolution of feeder magmas (Kobayashi et al., 2002; Bertolett, 2014; Gaddis, 2014; Maher, 2016). In the case of the Akaroa Volcanic Complex (AVC), an intraplate composite shield volcano active during the Miocene on New Zealand’s Banks Peninsula, a series of well-exposed trachytic domes and dykes hold the information necessary to develop a comprehensive model of the region’s larger volcanic system. However, previous studies (Maher, 2016; Gaddis, 2014; Johnson, 2012) have yet to explain definitively the formation of these trachytic structures. Two possible models pervade past research: (1) the “cap model,” which involves the plugging of previously active eruptive conduits by too-viscous-to-erupt trachytic magma (Johnson, 2012), and (2) the “gravity model,” which involves the lateral motion of trachytic magma due to an increase in gravitational stress on the magma chamber during a late stage of the eruptive cycle (Gaddis, 2014). The aim of this paper is to employ crystal size distributions (CSDs) and qualitative textural analysis to
determine the magmatic evolution and eruptivity of a number of the AVC’s trachytic substructures, including Mount Sinclair dome, Panama Rock dyke, and Devil’s Gap Senior dome. These findings will help to both place the trachytic substructures in their larger context within the AVC and better constrain a model for their formation.

Previous studies of the AVC’s trachytic units have focused primarily on structural characteristics, spatial distributions, qualitative textural properties, and bulk geochemistry (Gaddis, 2014; Bertolett, 2014; Eisenburg, 2013; Curtin, 2012). The geospatial work of Gaddis (2014) has revealed that domes are concentrated in close proximity to the AVC’s crater rim at elevations between 400 and 700 m. Moreover, there is at least one dome associated with each proposed volcanic vent in the region (Gaddis, 2014). While there is a lack of research comparing the geochemistry between domes, bulk geochemistry studies of the region as a whole have revealed a significant ‘Daly Gap’ between basaltic lava, the primary rock type in the AVC, and the trachytic substructures (Hartung, 2011). This gap is attributed to a two-stage fractionation process involving the extraction of a more evolved trachytic melt from mafic crystal mush (Hartung, 2011). Each trachytic unit has been proposed to represent the end of a magma batch’s eruptive cycle (Johnson, 2012), because trachyte magma extraction can occur only after accumulation of at least 50 vol. % crystals (Hartung, 2011). Despite past research, it is not yet known whether the majority of the extracted trachyte magma solidified below the surface as shallow intrusions or breached the surface as effusive lava domes. Moreover, few studies have set out to determine the magmatic histories of individual trachytic units within the AVC (Maher, 2016; Bertolett, 2014; Eisenberg, 2013; Curtin, 2012).

Only recently has work been done to quantify the textural properties of the AVC’s trachytic domes and dykes in order to determine their eruptivity. Maher (2016) used CSDs to determine magma residence time, crystallization rate, and relative eruptivity for three lobes of an eroded trachytic lava dome in Devil’s Gap Scenic Reserve, and, in doing so, developed a standard set of CSDs for eruptive trachyte to which future CSD studies could be compared. In this study, the CSDs of Devil’s Gap Senior dome, a structure known to be eruptive, are coupled with CSDs of Panama Rock dyke, a structure known to be non-eruptive, in the analysis of Mount Sinclair dome, a structure whose eruptivity is not yet known. Findings from this CSD analysis are further substantiated through investigation of the trachytic units’ qualitative textural properties. Furthermore, magma residence times for each of the three structures are calculated using CSD regression slopes and estimates of crystal growth rate. In addition to revealing a great deal about the crystallization histories of the individual units considered in this study, the research methods proposed here will serve as an easily adaptable framework for future research on trachytic domes and dykes—both in the AVC and in modern analogues abroad.

2. GEOLOGIC BACKGROUND

The volcanic complexes that make up Banks Peninsula are the most prominent volcanic landforms on the South Island of New Zealand (Figure 1). With a diameter of ~25 km and minimum volume of 1200 km³, the AVC is the largest of these volcanic features (Timm et al., 2009). The AVC was active from 9.41-8 Ma, near the end of active intraplate volcanism on Banks Peninsula (Gaddis, 2014). The alkali and hawaiite lavas that erupted effusively from the AVC were partially melted from a picritic source rock during lithospheric delamination (Timm et al., 2009). Fractionation of these same partial melts in two stages at mid- and upper-crustal levels led to the evolution of increasingly more felsic magma up to trachyte in composition. The over 7 million years of erosion that followed this period of active volcanism on Banks Peninsula has provided geologists a unique view into the internal plumbing networks that aided in the formation and mobilization of these rock types.

Recent research on the AVC has focused on locating and mapping eruptive centers. While early models depict the AVC as a single vent volcano (Dorsey, 1988), recent studies conducted by Hobbs
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(2012) and Gaddis (2014) suggest that nearly 10 eruptive centers fed the multitudinous lava flows that flank the AVC. Each eruptive center corresponds to a sector of the volcano, the borders of which have been loosely defined based on radial dike orientations, lava flow dip directions, and coastline morphology (Hobbs, 2012 and Gaddis, 2014). Eruptive centers are also marked by the presence of trachytic lava domes and dykes. The magmatic progression that led to the formation of these structures has been another subject of interest in recent studies of the AVC. Previous work by Gaddis (2014) suggests that primitive magma was initially erupted through vertical conduits, the formation of which was tectonically controlled. As continual eruptions built up the flanks of Akaroa and as vertical conduits began to solidify, an increase in edifice weight began to impart immense gravitational stress on the underlying magma chamber(s), which promoted a change from vertical to lateral magma flow. According to Gaddis, this gravitational stress was the primary control on trachytic dome and dyke emplacement during late stages of the AVC’s eruptive cycles.

This study concerns three of these trachytic structures: Devil’s Gap Senior dome, Panama Rock dyke, and Mount Sinclair dome (Figure 1). Devil’s Gap Senior (Figure 2B) is a large dome complex located near Peraki Valley in the southwestern quadrant of the AVC. According to geochemical and textural analyses conducted by Maher (2016), Devil’s Gap Senior comprises four effusive lava domes that filled the crater of an extinct scoria cone. Panama Rock dyke (Figure 2C)—located 3 km west of Le Bons Bay in the northeastern quadrant of the AVC—is believed to have fed a dome with a similar eruptive history. Like Devil’s Gap Senior, Panama Rock dome is situated within the crater of an extinct scoria cone (Curtin, 2012). However, unlike Devil’s Gap Senior, Panama rock dome was likely an endogenous cryptodome rather than an effusive lava dome (Curtin, 2012; Lewis and Hampton, 2015). The large (~4 m thick) dyke that fed this cryptodome is not believed to have been eruptive in any regard. While Devil’s Gap Senior and Panama Rock have each been subject to past research, Mount Sinclair dome (Figure 2A) in the northwestern quadrant of the AVC has yet to be studied in any substantial depth. The dome was discovered on a western flank of Mount Sinclair during detailed mapping of the AVC in February of 2016. Unfortunately, the poor exposure of Mount Sinclair dome makes it nearly impossible to make large-scale structural observations. Therefore, microscopic textural analysis is the key to unlocking the dome’s crystallization history.

3. METHODS

3.1. Overview of the CSD method

CSDs provide a quantitative measure of igneous textures and can reveal a host of information about the kinetics of magmatic crystallization, including estimates of cooling rate and magma residence time. The most surefire methods of measuring CSDs involve direct reconstruction of the 3D structure of a crystal population. Only then can the volume of each crystal be physically measured. There are a number of methods by which the 3D structure of crystals within a sample can be observed and measured. The most common method is serial sectioning, which takes several slices of the sample at regular spacing in order to show the habit of the crystals within 3D space. The slices can then be stitched together using 3D modelling software for ease of measurement. Mock and Jerram (2005) prefer this method to other direct and indirect methods of measuring CSDs due to its accuracy. However, serial sectioning has two major downfalls: (1) it is destructive (i.e. the sample is destroyed in the process) and (2) it is an incredibly laborious and time intensive process. Higgins (2002) claims that processing enough crystals for a statistically representative sample of the population is temporally impractical with serial sectioning. There are also a number of non-destructive methods to directly measure crystal dimensions in a 3D space. The two most widely used methods of this variety are X-ray tomography and confocal microscopy. While these methods are far less time-intensive than serial sectioning, they require a host of expensive equipment and have critical limitations that restrict their use to very specific scenarios (Jerram and Higgins, 2007). For example, since X-ray tomography cannot separate crystals based on differences in orientation and birefringence, it fails to distinguish
touching crystals of the same mineral. Therefore, this method can only be implemented in specific situations when crystals are known to be adequately separated.

To avoid the arduous process of serial sectioning and the many limitations of other direct methods of measuring CSDs, indirect methods can be used that convert measurements in the 2D cross-sectional space into 3D. The most common indirect method—and the method employed in this study—relies on an algorithm modified from the Saltikov correction method, a method primarily used in chemical engineering crystallography, by Higgins (2000). Conveniently, this algorithm is programmed into the stereological software CSD Corrections, which allows users automatically generate reliable CSDs simply by entering raw, 2D intersection data. 2D intersection measurements can be taken using photomicrographs of thin sections analysed with image processing software packages, such as ImageJ, CorelDRAW, and Adobe Photoshop. The most reliable crystal dimensions for an accurate portrayal of CSD are maximum length (i.e. the distance between the two furthest corners of the crystal) and box width (i.e. the length of the shortest side of the crystal) (Maher, 2016). While other dimensions can be used for CSD analysis—so long as the measured dimension is consistent across observations—maximum length and box width are preferred by most researchers because they tend to produce the distribution most closely described with a logarithmic-normal curve (Higgins, 2002). Therefore, maximum length and box width are the dimensions considered in this study.

3.1.1. CSD measurements and stereological corrections

Samples from two trachytic units were considered in this analysis: Mount Sinclair dome and Panama Rock dyke. CSDs for Devil’s Gap Senior were already produced in Maher (2016) and serve only for means of comparison. Thin sections for CSD analysis were chosen based on the degree of weathering and extent of damage to crystals as observed under petrographic microscope. In total, six samples were analysed—three each from Mount Sinclair dome and Panama Rock dyke. Three photomicrographs from each sample (a total of 18 photomicrographs) were taken at 100x magnification under crossed polarized light using a Leica DFC295 petrographic microscope. The images were rendered using Leica Application Suite version 3.4.1. Following the imaging process, photomicrographs were analysed in CorelDRAW X6. For ease of measurement, each crystal was overprinted with a polygon using a bézier tool (Figure 3A). In total, roughly two hundred crystals per sample (~1200 crystals overall) were chosen for measurement.

After setting the scale in CorelDRAW X6 to match that of the photomicrographs (0.66 x 0.49 mm), the box width and maximum length of each polygon were measured using a dimension tool. Each measurement was recorded in a Microsoft Excel spreadsheet, which was later exported into CSD Corrections version 1.53. Based on the settings used in Maher’s study of similar trachyte samples from Devil’s Gap Senior, crystal roundness and aspect ratio were set to zero and 1:10:10, respectively (Figure 3B). 3D CSDs were then calculated in two trials: once with maximum length measurements and once with box width measurements. Finally, each calculated CSD was plotted on a standard diagram in CSD Corrections.

3.2. Calculating magma residence times

Magma residence times can be calculated based on the linear regressions of CSDs using the equation

\[ \tau = -1 / m \cdot G \]  

(eq. 1)

where \( \tau \) is magma residence time, \( m \) is the CSD regression slope, and \( G \) is crystal growth rate (Resmini and Marsh, 1995). While the value of \( m \) is known, crystal growth rate must be estimated based on past experimental studies. Unfortunately, there are a host of factors—temperature, pressure, nucleation rate, magma composition, etc.—that can affect crystal growth and therefore precise values are hard to constrain (Resmini and Marsh, 1995). Thus, loose approximations of growth rate must be
used in calculations, rendering magma residence time as a purely comparative statistic. Resmini and Marsh (1995) suggest using $10^{-10}$ cm/s as an estimate of growth rate for common silicate minerals. However, due to the variability of crystal growth rates, residence time calculations using $G$-values of $10^{-11}$ and $10^{-9}$ cm/s are also reported.

3.3. Qualitative textural analysis

In order to validate findings from the CSD analysis, qualitative textural observations were made using a Leica DFC295 petrographic microscope. The mineralogy, structural characteristics, crystal content, crystal habits, and crystal forms observed in each sample were recorded in an Excel spreadsheet. Due to their implications to the eruptive histories of the trachytic units, special consideration was given to the amount of damage and resorption apparent in each crystal population. In order to standardize the extent of crystal damage, a rating system was established so as to provide a numerical statistic for comparison between samples. Numerical values for the extent of crystal damage ranged from 0 for perfectly euhedral crystals to 5 for crystals whose boundaries were barely visible due to resorption and/or physical abrasion. Observations were made under both crossed and plane polarized light, and at three different degrees of magnification: 40x, 100x, and 200x.

4. RESULTS

4.1. Crystal size distributions

3D corrected intersection measurements for Panama Rock dyke, Mount Sinclair dome, and Devil’s Gap Senior dome yield CSD curves showing the relationship between crystal dimensions over 4 – 6 bin sizes (x-axis) and the natural logarithm of the crystal population density for each size class (y-axis) (Figure 4). CSD Corrections automatically generates a negative log-linear regression for each CSD curve. For Panama Rock dyke and Mount Sinclair dome, maximum length input measurements produce CSD curves most closely described by negative log-linear regressions. In fact, regression fits for box width CSDs are so poor that they offer no intelligible insight into the cooling history of the sample population. Therefore, maximum length CSDs will serve as the primary basis upon which all interpretations will be made.

Maximum length CSD curves for Panama Rock dyke and Mount Sinclair dome show remarkable similarities (Figure 4). For one, the fitted regression slopes— -0.0236 and -0.0215 for Panama Rock dyke and Mount Sinclair dome, respectively—are nearly equivalent within a reasonable range of statistical significance. Moreover, the maximum length CSDs for Panama Rock dyke and Mount Sinclair dome both follow very linear trends with only slight downward inflections in the smallest bin size. However, according to Marsh (1988), such downward inflections are often the result of a measuring bias, because crystals in the smallest size class are hardest to identify in thin section and are also the most susceptible to physical abrasion and resorption in the magma chamber. Therefore, the population density of crystals in the smallest size class should be expected to stray downward from the generally linear trend of the CSD. While the distribution of crystal sizes for Panama Rock dyke and Mount Sinclair dome are nearly identical, crystals from Mount Sinclair dome are slightly larger on average. The average area of crystals, as measured directly from photomicrographs, is 1769.2 and 1706.8 μm$^2$ for Mount Sinclair dome and Panama Rock dyke, respectfully. Furthermore, the median 3D corrected crystal size class is 127 μm for Mount Sinclair dome compared to 103.55 for Panama Rock dyke. While this difference in average crystal size is substantial, the distribution of crystal sizes, in which there is no substantial difference between Panama Rock dyke and Mount Sinclair dome, is the more valuable statistic for deducing crystallization history.
While the CSDs for Panama Rock dyke and Mount Sinclair dome show no statistically significant differences in slope or shape, the slope and shape of the CSDs reported by Maher (2016) for Devil’s Gap Senior are indeed quite different (Figure 4C). At an average of -0.0127, the slopes of fitted linear regressions are considerably shallower for the four lobes of Devil’s Gap Senior. Furthermore, a number of the CSDs reported by Maher (2016) show a significant downward inflection around the 350 µm size class. Unlike the kinks observed in the smallest bin sizes of Mount Sinclair dome and Panama Rock dyke CSDs, these inflections cannot be attributed to measuring bias and therefore must relate to the crystallization history of the magma body. Additionally, the 3D corrected crystal sizes are markedly larger for Devil’s Gap Senior as compared to both Panama Rock dyke and Mount Sinclair dome. While the largest size class of the maximum length CSDs for Panama Rock dyke and Mount Sinclair dome is 319 µm, 800 µm is the largest size class of the maximum length CSDs reported for Devil’s Gap Senior dome (Maher, 2016). Finally, while maximum length measurements provided the closest fitting negative log-linear regressions for Panama Rock dyke and Mount Sinclair dome, the closest fitting regressions for Devil’s Gap Senior were calculated from box width measurements (Maher, 2016). However, this disparity may not be the result of greater variability in the 3D corrected maximum length measurements for Devil’s Gap Senior, but rather from the downward inflections observed in the CSDs.

4.2 Magma residence times

Table 2 presents residence time estimates calculated using eq. 1 for Panama Rock dyke, Mount Sinclair dome, and three lobes of Devil’s Gap Senior dome. Considering the values τ = 1.5 – 4 years reported by Resmini and Marsh (1995) for Dome Mountain, a similar late-stage volcanic structure in northwestern British Columbia, growth rate values of the order of magnitude represented by 10^-10 cm/s seem to yield the most realistic values of magma residence time. Assuming a growth rate of 10^-10 cm/s, the plutons from which Mount Sinclair dome and Panama Rock dyke solidified sustained liquid magma for between 1.3 and 1.5 years. The corresponding values for Devil’s Gap Senior are far longer at 4.4 – 7.7 years.

4.3. Petrography

Samples from each of the three trachyte structures considered in this study possess roughly the same mineral assemblage with subhedral to euhedral laths of alkali feldspar comprising the majority of both the groundmass and phenocrysts (75 – 90% of the whole rock; Table 1). Alkali feldspars commonly exhibit Carlsbad twinning, and some of the more tabular-shaped crystals also display perthite lamellae and subtle oscillatory zoning (Figure 5). Pyroxene crystals and opaque minerals are also abundant in each sample and comprise between 10 and 25% of the whole rock. Opaque minerals commonly form prismatic crystals and less commonly occur as interstitial crystal clusters. Pyroxene crystals, on the other hand, most commonly occur as light green to light brown (PPL) anhedral crystal clusters that fill gaps between the considerably larger alkali feldspars. A single euhedral pyroxene phenocryst was observed in sample JA2 from Panama Rock dyke. No glass was observed in any of the analysed thin sections.

In many respects, samples from each of the field sites have very similar broadscale textures. For example, every sample exhibits variable degrees of crystal alignment, and most samples are dotted with phenocrysts of alkali feldspar up to 3 mm in length that constitute <1 – 10% of the whole rock (Figure 5B/C). However, there are distinct textural differences on a microscopic scale between samples from the three different field sites—in addition to the differences in groundmass crystal sizes discussed above. In general, crystals from Panama Rock dyke and Mount Sinclair dome exhibit euhedral forms and sharp boundaries (Figure 5A/B). Crystals from Devil’s Gap Senior, on the other hand, are marked by high brittle fracture densities and abundant irregular resorption boundaries (Figure 5C). Using the classification scheme proposed in section 3.3, crystals from Panama Rock
dyke and Mount Sinclair dome have damage ratings between 0 and 2, which is significantly lower than ratings of 3 and above for crystals from Devil’s Gap Senior.

5. DISCUSSION

While it has been repeatedly suggested from geochemical and geophysical evidence that AVC’s trachyte originally formed through extraction from hawaiite crystal mush at depths of 10 – 15 km (Hartung, 2011; Johnson, 2012; Portner, 2013), the behaviour of this magma following extraction remains somewhat of a mystery. Recent studies have supported a model in which multiple batches of magma stall at shallow crustal levels before erupting (Johnson, 2012; Gerrits, 2014; Beckham et al., 2015). The textural evidence analysed here in large part supports that theory. However, CSD analysis—when substantiated with qualitative petrographic observations—allows us to go even further and deduce the magmatic histories of individual trachyte structures on a smaller-scale basis.

It is clear from textural evidence that each trachyte unit considered in this study—Panama Rock dyke, Mount Sinclair dome, and Devil’s Gap Senior dome—originated in a melt-rich reservoir, as the large (up to 3 mm long) alkali feldspar crystals observed in nearly every sample could only have formed early on when there was adequate melt space for sustained growth (Marsh, 1988; Maher, 2016). It is also clear that each magma body initially ascended through the crust gradually as represented by the linear trends in maximum length CSDs for large and medium crystal size classes. These CSD trends imply a constant rate of ascent and a near constant rate of cooling which, according to Marsh (1988), leads to a negative log-linear trend in the distribution of crystal sizes. Marsh (1988) also asserts that CSD slope is inversely related to the cooling rate (i.e. a more negative slope implies a faster cooling rate). Therefore, the relatively shallow slopes of the maximum length CSDs for Devil’s Gap Senior (-0.0127, on average) indicate a rather slow ascent relative to the Panama Rock and Mount Sinclair trachytes, which have respective CSD slopes of -0.0236 and -0.0215.

The key differentiating factor in the observed CSDs involves a downward inflection around the 350 μm size class. While many of the maximum length CSDs for Devil’s Gap Senior possess this feature, CSDs for Panama Rock dyke and Mount Sinclair dome do not. According to Marsh (1988), there are two possible explanations for downward inflections in the 3D corrected measurements: either (1) crystals in the smaller size classes faced widespread resorption and were therefore erased from the record, or (2) the magma body stalled beneath the surface, allowing the largest crystals to settle and new medium-sized crystals to nucleate and grow. In reality, petrographic and textural evidence points to a combination of these two processes as the likely culprit. Structural evidence, resorption in alkali feldspars, and brittle deformation suggest that Devil’s Gap Senior was, in fact, an eruptive lava dome complex (Maher, 2016). However, crystals in the medium to small size classes do not appear in to have been impacted enough by resorption and brittle deformation to have caused such a drastic inflection in the CSD. Moreover, an intermediate- to high-energy eruption would cause, if anything, an upward inflection in the smallest size classes of the CSD since the magma would crystallize small crystals rapidly upon contact with the relatively cold atmosphere (Marsh, 1988). Such an upward inflection is not, however, observed in any Devil’s Gap Senior CSDs. The lack of interstitial glass in Devil’s Gap Senior samples further refutes the possibility of an intermediate- to high-energy eruption. Therefore, it is likely that the downward inflection in the Devil’s Gap Senior CSD was indeed caused by subsurface magma storage at shallow crustal levels. After a period of stagnation, the magma then must have ascended further through the crust before breaching the surface in a series of effusive, low-energy eruptions. While these eruptions did cause some crystal deformation, they did not induce rapid enough cooling to significantly affect the CSD curve. Since crystals from Panama Rock dyke and Mount Sinclair dome do not show signs of significant deformation and exhibit linear CSD trends through all size classes, it can be inferred that their corresponding magma batches never erupted and instead solidified beneath the surface as shallow intrusions.
Results from residence time calculations seem to contradict the assertion that Devil’s Gap Senior dome was eruptive while Panama Rock dyke and Mount Sinclair dome were not, because one would expect purely plutonic magma bodies to sustain liquid magma for longer periods of time—the exact opposite of what was calculated. However, there are a host of other factors that influence residence time. One possible factor is the size of the body of magma. Had Devil’s Gap Senior formed from a larger pluton, then it would have taken a longer period of time for all of the melt in that pluton to crystallize. Much like the downward inflection observed in the CSD, the longer residence time for Devil’s Gap Senior may also be the result of a period of stagnation during ascent. If a stable magma body stalls at shallow levels and is periodically recharged, it may repeatedly erupt whilst continuing to sustain a voluminous melt phase over a relatively long residence time (Maher, 2016). Such a period of stagnation is the most probable explanation for the somewhat anomalous magma residence times obtained for Devil’s Gap Senior.

Figure 6 is a schematic diagram for the proposed sequence of trachytic dome and dyke emplacement in the AVC. Mount Sinclair dome and Panama Rock dyke are represented by structure “A,” a purely intrusive magma body that did not undergo a period of stagnation in the shallow crust. Devil’s Gap Senior dome is represented by structure “B,” an effusive lava dome that stalled for a period in the shallow crust before erupting.

6. CONCLUSIONS AND FUTURE RESEARCH

It is more than evident that CSDs have the potential to offer valuable insights into the magmatic evolution of small plutonic bodies. There are, however, numerous complicating factors that can affect CSDs—the volume of the magmatic body, resorption events, eruptions, magma mingling, the temperature of the country rock, etc.—and therefore they can be quite difficult to interpret. However, by analysing CSDs in conjunction with qualitative petrographic observations one can constrain the most probable sequence of events that led to the emplacement of the igneous structure in question. In the case of the Akaroa Volcanic Complex, CSDs—when substantiated with petrographic observations—show that trachyte domes and dykes formed as both effusive domes and shallow intrusions. CSDs for Panama Rock dyke and Mount Sinclair dome show that magma ascended gradually through the crust before solidifying at shallow crustal levels. CSDs for Devil’s Gap Senior, on the other hand, suggest that magma stalled beneath the surface before erupting effusively as a lava dome.

Future research may apply the methodology used here to other trachytic structures throughout the AVC in order to develop a more comprehensive model for their formation. Experimental studies of alkali feldspar growth rates should also be considered in order to provide for more accurate residence time calculations. Such studies would have to consider the effects of decompression, nucleation rate, magma mingling, host rock temperature, and the melt/crystals ratio on crystal growth rate. Future geochemical and geophysical work would be of tremendous help in the process of deducing storage depths for the AVC’s trachytic magmas. Future geochemical research on the AVC’s trachytic units may also aim to determine the relationship between major chemical oxide abundances and geographic location. This relationship is one of the keys to proving the sector model proposed by Hobbs (2012) and Gaddis (2014). Finally, future geochronological studies should seek to better constrain the age relationship between the AVC’s trachytic units and basalt lava flows. An understanding of this temporal relationship would assist in the ongoing effort to piece together an accurate sequence for the construction of the Akaroa volcanic Complex.
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FIGURES

**Figure 1** (1.5 column)

**Figure 2** (single column)
Figure 3 (single column)
Figure 4 (double column)
Figure 5 (single column)
TABLES

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<td>JA2</td>
<td>95% total: 90% Afs, 7% Px, 3% Op</td>
<td>5% total: 80% Afs, 20% Px (2 xls)</td>
<td>1</td>
</tr>
<tr>
<td>PR dyke</td>
<td>JA3</td>
<td>96% total: 80% Afs, 10% Px, 10% Op</td>
<td>4% total: 100% Afs</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1 (double column)
Table 2 (1.5 column)

<table>
<thead>
<tr>
<th>Unit</th>
<th>( G = 10^{-11} ) cm/sec</th>
<th>( G = 10^{-10} ) cm/sec</th>
<th>( G = 10^{-9} ) cm/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panama Rock Dyke</td>
<td>13.436</td>
<td>1.344</td>
<td>0.134</td>
</tr>
<tr>
<td>Mt. Sinclair Dome</td>
<td>14.749</td>
<td>1.475</td>
<td>0.147</td>
</tr>
<tr>
<td>DGS L1</td>
<td>48.045*</td>
<td>4.806*</td>
<td>0.480*</td>
</tr>
<tr>
<td>DGS L2</td>
<td>68.934*</td>
<td>6.896*</td>
<td>0.689*</td>
</tr>
<tr>
<td>DGS L4</td>
<td>77.341*</td>
<td>7.737*</td>
<td>0.773*</td>
</tr>
</tbody>
</table>

*Values taken from Maher (2016)

FIGURE CAPTIONS

**Figure 1**: Simplified geologic map of Banks Peninsula, New Zealand showing the location of the Akaroa Volcanic Complex in addition to the neighbouring Mount Herbert, Diamond Harbour, and Lyttelton volcanic groups. Black dots with corresponding labels show the locations of the three trachytic structures considered in this study: Devil’s Gap Senior dome, Mount Sinclair dome, and Panama Rock dyke. The inset map shows the location of Banks Peninsula on the East Coast of New Zealand’s South Island. (Image modified from Hampton, 2010)

**Figure 2**: Images of the three different field locations: (A) a dome-like structure on a western flank of Mount Sinclair. Use geologist for scale. (B) Devil’s Gap trachyte domes (Junior in front and Senior behind) located to the southwest of Akaroa Harbour. Use trees for scale. (C) Panama Rock dome and dyke. The dyke is labelled and outlined in black. Use trees for scale.

**Figure 3**: (A) Example of a photomicrograph of Mount Sinclair trachyte annotated using CorelDRAW X6 prior to CSD analysis. The length and width of each polygon overlay was measured using a dimension tool and then entered into CSD Corrections version 1.53. (B) Screenshot of the raw, 2D intersection measurements as inputted into CSD Corrections version 1.53. Note the values chosen for crystal aspect ratio, roundness, and measured area.

**Figure 4**: Ln(population density) versus maximum length CSD diagrams for Panama Rock dyke (A), Mount Sinclair dome (B), and Devil’s Gap Senior dome (C). Linear regressions are shown in red. The dashed black line connects the boundary points for each respective bin size. Note the inflection in the CSD for Devil’s Gap Senior dome at 350 \( \mu \)m. Also note the difference in scale between the CSDs for Devil’s Gap Senior dome and the other two trachyte units. The slight inflection in the smallest bin size, which is common to each of the diagrams, is likely due to measuring bias.

**Figure 5**: Photomicrographs at 40x magnification of sample JA2 from Panama Rock dyke (A), MTS015AM from Mount Sinclair dome (B), and DG1a from Devil’s Gap Senior dome. Note how the crystals are easier to identify in A and B. Also note the large phenocrysts of alkali feldspar in B and C, and observe how the lath-shaped groundmass crystals appear to flow around them. The yellow,
euhedral grain to the right of A is a pyroxene crystal. Refer to Table 1 for a more detailed mineralogical description of these samples.

Figure 6: Schematic diagram of the AVC’s internal plumbing system during the late stage of an eruptive cycle. The diagram shows the evolution of magma from its primitive source to its trachytic end composition. Trachyte is first fractionated near the brittle-ductile boundary at depths of 10-15 km. The trachyte then begins its ascent through the crust. “A” represents a trachyte batch that ascended gradually before solidifying in the subsurface as a shallow intrusion, much like Mount Sinclair dome and Panama Rock dyke. “B” represents a trachyte batch that stagnated at shallow levels before erupting as an effusive lava dome, much like Devil’s Gap Senior dome. The yellow band within the Akaroa volcanic edifice represents the zone of elevations in which trachyte units have been identified (Gaddis, 2014). All elevation and depth estimates were taken from Gaddis (2014) and Hartung (2011).

TABLE CAPTIONS

Table 1: Mineralogical descriptions of thin sections from the four lobes of Devil’s Gap Senior (DGS) dome, Mount Sinclair (MTS) dome, and Panama Rock (PR) dyke.

Table 2: Magma residence times for Panama Rock dyke, Mount Sinclair dome, and three separate lobes of Devil’s Gap Senior dome calculated from CSD regression slopes and three different estimates of crystal growth rate. Values calculated using the intermediate growth rate are highlighted in red as they are the most realistic given the geologic context and rock type.

Note: All formatting meets the submission requirements for the Journal of Volcanology and Geothermal Research