Viscosity and Crystal Size Distribution
Comparison Between Different Areas in the Cerro Bayo Cryptodome

Jämförelse av viskositet och kristallstorleksfördelning mellan olika platser i kupolen Cerro Bayo

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Abstract

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A clear understanding of magmatic plumbing systems is of importance for volcanic hazard monitoring and disaster prevention. If we understand how ancient volcanic structures formed and functioned, we can hopefully predict how active volcanoes will act.

Samples from the Cerro Bayo cryptodome, Argentina, were analysed using crystal size distribution (CSD) analysis to gather information of viscosity and crystal population in the now solidified magma that built the volcanic structure. The analyses have been done on large crystals, or phenocrysts, and smaller crystals, or microlites, in the rock matrix. Area measurements and CSD calculations have been done using Inkscape, ImageJ, CSDslice and CSDcorrections. The viscosity of the magma was estimated with the Einstein-Roscoe equation for particle fluid suspensions.

The phenocrysts have a clear concave upwards CSD curve, indicating two different crystal populations. Among the microlites it is only the plagioclase and feldspar/quartz that show a clear curved CSD, while the graphs for amphibole show a straight line indicating one population growth.

The phenocrysts are thought to have started to grow in the deeper magma system and during the later ascend been affected by a crystal coarsening event. The plagioclase and quartz/feldspar microlites are thought to have grown during the degassing stage in the conduit of the volcano while the amphibole microlites has only grown in the cryptodome.

Viscosity measurements show a viscosity contrast among samples. Sections of the cryptodome that are thought to have been emplaced at a later stage have a higher viscosity.

Keywords: cryptodome, viscosity, crystal size distribution, plumbing system, Cerro Bayo

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Sammanfattning

Jämförelse av viskositet och kristallstorleksfördelning mellan olika platser i kupolen Cerro Bayo
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Att kunna förstå hur magmatiska system och dess så kallade rörsystem fungerar är viktigt för att kunna undersöka dess risker och för att kunna förebygga förödande händelser. Om vi kan förstå hur de "fossiliserade" vulkaniska strukturerna byggdes upp så kan vi möjligtvis förutspå hur aktiva vulkaner kommer att agera.


Phenokristallerna har en tydlig konkav krökning av CSD kurvorna, vilket visar på två olika kristallpopulationer. För mikroliterna så visar plagioklas och fältspat/kvarts kurvorna en tydlig krökning medan amfibol visar en relativt rak linje vilket visar på endast en kristallpopulation.

Phenokristallerna tros ha börjat växa djupt ner i magmasystemet och under de senare delarna av stigningen blivit påverkade av tillströmning av ny magma vilket gjort att två populationer är synliga. Plagioklas och kvarts/fältspat mikroliterna tros ha växt under avgasningen av magma under dess stigning, medan amfibolmikroliterna tros ha växt endast i Cerro Bayo.

Beräkningarna av viskositeten visar en kontrast mellan de olika proverna där delar av magmakupolen som tros ha intruderat sist har högre viskositet.

Nyckelord: kupol, viskositet, kristallstorleksfördelning, magmatiska rörsystem, Cerro Bayo

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Introduction

Volcanic hazards have affected humans for our entire history, and many lives have been lost in sudden catastrophic events that have been hard to predict. The devastating consequences of a volcanic eruption have sometimes wiped out entire villages, and in present day they can cause millions in property damage (Luongo et al., 2003).

Volcanoes have helped shape the Earth, and for as long as humans have feared volcanoes, they have also fascinated us. Descriptions of volcanoes can be found in everything from art, songs, poems and movies. Often with its iconic cone shape and with perhaps one red huge spherical magma chamber beneath. Even though volcanoes have had such an impact on Earth history, there are still a lot of question marks about the underlying magmatic system.

By studying relict volcanic features, the crystal cargo of igneous crystalline rocks can give clues to what kind of processes the magma underwent before being solidified. If we can understand these processes, we can better predict the behaviour of active volcanoes today and hopefully even prevent large catastrophes (Burchardt, 2018).

How magma is moving in the mantle and crust is, among other things, dictated by the viscosity of the magma (Petford, 2009). Evidence of how the magmas moved are recorded in the crystal cargo and can be analysed in the crystals of igneous rocks.

Cryptodomes are a type of volcanic intrusion that grow by pushing away the overlying rock, which may cause collapse of the volcanic edifice and dangerous explosive eruptions (Lipman et al., 1981). An understanding of the build-up of these magmatic intrusions could help bring light to the risks associated with their growth.

The purpose of this study is to investigate if there is a viscosity difference between different parts of the Cerro Bayo cryptodome and link this to the processes occurring during growth and in the underlying magmatic plumbing system. A model for how the volcano might look like can be seen in figure 1.
Volcanic plumbing systems

In continental magmatic arcs, the magma is generated from a subduction zone by melting of hydrated mantle. The liquid melt will then migrate upwards thanks to the buoyancy contrast of melt and the solid surrounding rock (Cruden & Weinberg, 2018). Where melt accumulates is also dependent on tectonic stress, and the melt can even migrate downwards (Cruden & Weinberg, 2018).

Deformation is, however, crucial for upwards migration as it results in an escape path for the melt. It is a positive feedback as the heat from the melt weakens the surrounding rock leading to further deformation. The way melt escapes from the source can happen by both the slow establishment of channels or in one pulse from a larger deformation event, or something in between (Cruden & Weinberg, 2018).

So called MASH zones are areas above the source where Mixing, Assimilation, Storage and Homogenisation of the magma takes place (Hildreth & Moorbath, 1988). In this zone, the melt interacts with host rock, changing its chemical composition, and when large enough amounts of melt are in this zone it can begin further migration upwards (Cruden & Weinberg, 2018).

The mechanics of how larger amounts of melt migrate are still debated, but migration through buoyancy driven diapirism, dykes, magmatic stoping and ductile fractures are all suggested ways. When the buoyancy contrast between magma and host rock is no longer sufficient for further migration, it will arrest and develop a magmatic reservoir. Except from magma ascending through diaprism it is thought that reservoirs are filled by pulses of magma and intrude as sill-like structures diverting horizontally (Cruden & Weinberg, 2018).

In the lower to middle crust, plutons often have a tabular or wedge like shape, one or several conduits that feed the reservoir in pulses giving rise to mostly horizontal flow, and the lateral movement is dependent on the ductility of host rock. Space for magma is often made by roof uplift or floor compression. Plutons generally have a
thickness of 1 - 10 km and a filling time of about 1,000 – 10,000 years. Even if each magma pulse can occur in rapid succession, the pulses can be separated by long time gaps (Cruden & Weinberg, 2018).

In the middle to shallow crust magma is often transported through magma-filled fractures called dykes. The fractures can have been pre-existing due to tectonic deformation but can also have been created by the ascending magma itself (Kavanagh, 2018). Dykes cut layers and beds of strata and can ascend several kilometers, they are often thin and have lengths far larger than their thickness. Dykes do not tend to form as isolated events, but rather in swarms, and the same dyke can be used for multiple magma injections (Kavanagh, 2018). Dykes are the main feeder for volcanic eruptions, and they can both erupt as fissures like sheet-like structures, or they can change shape to a more cylindrical volcanic vent, however, not all dykes will erupt (Kavanagh, 2018).

Under volcanoes there is a network of sheet intrusions, these intrusions both build up the volcano and feed eruptions. There are three types of sheet intrusions in volcanic systems, radial dykes, cone sheets and dykes in volcanic rift zones, all of them have different geometry in regard to the centre of the volcano but can both emit magma for eruption or just inflate (Burchardt et al., 2018).

A conduit is a large cylindrical channel, that emits magma to the surface or other structures (Burchardt et al., 2018). Magma in volcanic plumbing systems can also be transported laterally through sills that cut in between layers of strata in host rock. Sills can also be used for storage, and grow to structures like laccoliths (Galland et al., 2018).

Laccolith, cryptodomes and lavadomes

Cryptodomes and laccoliths are names that have often been used interchangeably, describing a dome-shaped magmatic intrusion (Mattsson, 2018). Laccoliths were first described and named by Gilbert in 1877 who visualised doming of overburden strata due to a lens-like intrusion fed from a central pipe below a horizontal discontinuity (Roman-Berdiel et al., 1995). The flat basal surface of the laccoliths suggests that the intrusions have happened above a more resistant layer and the intrusions’ bell-shape have been attributed both to the status of overburden strata and ascending magma (Roman-Berdiel et al., 1995).

Laccoliths are most commonly intruded at shallow depth in the crust, above the crustal brittle-ductile transition zone (Corry, 1988). A correlation between size and intrusion depth has been observed, where increasing diameters are found at increasing depth (Roman-Berdiel et al., 1995).

The cause for the change in magma movement from vertical to horizontal has been discussed to be due to the magma reaching its neutral buoyancy level. However, this does not explain why the magma keeps inflating and doming the overlying strata or why intrusions from magma with similar densities are found at different depths. The change in magma movements is instead thought to be due to the magma hitting a stronger layer that act as a trap, and if the pressure from the
ascending magma is greater than the lithostatic overburden, it will start to dome instead of just continue to flow laterally (Westerman et al., 2004).

Laccoliths are thought to be filled in two stages, in the first stage the magma flows laterally almost to the total extent of the final structure, and in the second stage the magma intrusion thickens, inflating the intrusion (Westerman et al., 2004). Internal contacts have been observed in laccoliths indicating multiple sills stacked on top of each other. Faulting of host rock at the edges of intrusions is commonly observed and gives evidence for the emplacement history (Morgan et al., 2008).

Studies of cryptodomes are consistent with studies of laccoliths but they also show concentric brittle deformation (Goto & McPhie, 1998; Mattsson, 2018). Goto and McPhie (1998) described a cryptodome consisting of a massive core, banded rim and brecciated border toward the host rock. Radial columnar joints were found crossing both the massive core and the banded rim. The cryptodome was suggested to have been filled in one event and intruded a cold wet sediment resulting in fast crystallisation at the edge that acted as isolation and allowed the core to remain a high temperature. Stress from continues influx of magma resulted in brittle deformation at the more crystalline edge but as ductile deformation in the interior (Goto & McPhie, 1998). Similar results were obtained in a study of a cryptodome in Greece (Stewart & McPhie, 2003).

Lava domes are similar to cryptodomes, but lava is extruded from a vent at the surface. They can grow both through expansion due to internal influx of new magma, called endogenic dome growth, or by stacking discrete magma pulses that pierce through each other, called exogenic growth (Fink & Anderson, 2000). A lava dome can change its emplacement style while it is growing, and this is mainly controlled by the rate of magma supply (Hale & Wadge, 2008).

Flow bands and joints are two indicators of the internal flow of magma. Friction along the contact between ascending magma and host rock leads to the development of flow bands due to small-scale flow-velocity differences in the magma. Foliation patterns are also determined by emplacement history, for example onion-like foliation can be caused by endogenous growth (Fink & Anderson, 2000).

Laccoliths, cryptodomes and lava domes are all common features in volcanic complexes and their emplacement can potentially be hazardous. The biggest risk is pyroclastic flows caused by dome collapse. Even already solidified lava domes can pose a threat as they can still collapse and cause hot avalanches (Fink & Andersson, 2000).

Crystal cargo
The different types of crystals in a magma could provide crucial information about the ancient magmatic plumbing system.

Phenocrysts are larger crystals that have crystallised in the magma but were crystallised in another reservoir than where they are currently residing and are suspended in a fine groundmass. For this reason, the phenocrysts are in chemical
equilibrium with that magma. There might be some variations however, visible in their zoning, due to precipitation of other minerals (Jerram et al., 2018).

Antecrysts are recycled crystals that have formed in the current magmatic system, but perhaps from an earlier stage or an earlier crystallisation event. These crystals, although being hard to distinguish from the xenocrysts, which has been crystallised in a completely different magma, usually carry information about the system from an earlier stage and are highly interesting (Jerram et al., 2018).

The most common among eruptive products however are the microlites that usually only span between tens to hundreds of micrometres and form during the degassing stage of an erupting volcano (Jerram et al., 2018) (Muir et al., 2012).

Viscosity
Fluids in our everyday life have different tendencies to flow, and therefore have different viscosities. Ideally, viscosity is proportional to stress and strain rate, as in Newtonian fluids, but that is not always the case, e.g. in so called non-Newtonian fluids (Van der Pluijm & Marshak, 2004). Magma rheology deals with the flow of a multiphase system as it consists of both fluids, solids and gases. Effective viscosity of a magma is affected by multiple factors including thermal energy, particle size, viscosity of the melt, deformation rate and time (Petford, 2009). As it can be quite tricky to measure all these parameters, a commonly used method is to measure relative viscosity. This can be done by using the Einstein-Roscoe equation (1) (Deubelbeiss et al., 2010).

$$\mu_0^{agb} = \mu^{fluid}(1 - S\phi_s)^{-2.5}$$

Where $\mu_0^{agb}$ is the effective viscosity, $\mu^{fluid}$ is the melt viscosity, $S$ is a constant for inverse crystal packing density and $\phi_s$ is the crystal fraction. This equation therefore excludes a lot of the parameters and looks into a two-phase system, including the melted and solid part of the magma. It has been observed that the magma viscosity changes from Newtonian to non-Newtonian with increased crystal fraction (Deubelbeiss et al., 2010). This change happens when around 40 % of the magma consist of crystals (Petford, 2009). Crystal size and shape have non or small impact on effective viscosity, but as crystal shape determines the maximum packing it will indirectly affect the particle fraction (Deubelbeiss et al., 2010).

Geological background
The Chachahuén volcano
Many volcanic structures and systems can be observed in the western part of South America. This is due to the fact that the Nazca plate is subducting underneath the South American plate. This convergent zone has created a magmatic arc and with it, a back-arc basin called the Neuquén basin (Kay et al., 2006). The Neuquén basin is
a sedimentary basin that formed in the Mesozoic and have been uplifted due to the formation of the Andes.

Approximately 500 km east of the Chile trench, within the Neuquén basin lies the extinct volcanic complex known as Chachahuén. The late Miocene aged Chachahuén volcanic complex differs from the surrounding volcanoes that are a part of the Southern Volcanic Zone (SVZ) in that it is made up of mainly hornblende-bearing andesite with an arc-like chemical signature in contrast to the alkaline olivine basaltic flows that are present in the surrounding area and volcanoes (Kay et al., 2006).

The subducting Nazca plate has been undergoing a transient period of shallowing and steepening of the subduction angle. According to Kay et al., (2006), the Chachahuén volcano was formed as the plate subducted at a shallow angle between approximately 7.5 – 4.8 Ma. The volcano is now extinct and for the last 2.5 million years, there has been no slab influence on the back-arc (Kay et al., 2006).

Volcanic history of the Neuquén Basin

During the early Miocene, the Neuquén basin showed signs of an active volcanic arc forming with extensive eruptions. This period began with the break-up of the Farallón plate and the initial subduction of the Nazca plate beneath the South American plate. At this time, alkali olivine basalts were erupting in the back-arc region. In the late Early Miocene alkali olivine basalt eruptions became less common in favour of mafic andesites. This is interpreted as evidence that the subduction angle of the slab was starting to shallow (Kay et al., 2006).

Traces of subducted materials in the source of the magma comes from higher Lanthanum/Tantalum, Barium/Tantalum and Barium/Lanthanum ratios and the presence of hornblende in the mafic andesites is interpreted as the magma having more hydrous components. During the middle to late Miocene period, the basin experienced a magmatic hiatus from 16 Ma to 14 Ma. The hiatus was followed by more andesitic eruptions from ca 14 Ma to 10 Ma to then going back to a calmer time from ca 10 Ma to 7 Ma.

The late Miocene is characterised by the shallowest subduction angles of the slab, and this is also when the Chachahuén volcano was formed. High La/Ta and Ba/Ta ratios in the potassium-rich complex as well as clinopyroxene, amphibole, Fe-Ti oxide and titanite phenocrysts show evidence for a shallowly subducting slab and a hydrated arc-like magma respectively (Kay et al., 2006). The slab returned to a steeper position again during the last stage of Miocene which resulted in a more mafic character of the magma (Folguera & Ramos, 2011).

Stratigraphy of the volcano

The Chachahuén volcanic complex has produced a series of volcanic eruptions that have shaped the landscape for a significant amount of time (Kay et al., 2006). The area is however also characterised by the erosion of the volcano during its dormant stages. The following is a stratigraphic sequence of the complex:
I. The first volcanic activity in the area during Early Miocene is the eruption of the ca. 24 - 20 Ma alkali olivine basalts with an intra-plate like signature called the Matancilla flows.

II. After the Matancilla basalts the Chachahuén volcano produced the Vizcachas formation, between 7.9 - 7.0 Ma. The formation is composed of andesitic to dacitic ignimbrites and lava flows. An important feature to note is the presence of silicic vitrophyres located in the Cerro Bayo region.

III. The next stratigraphic unit is called the Early Chachahuén group, consisting of an older more silicic part, and a younger more mafic part. The younger part consists mostly of andesitic to dacitic domes and deposits of explosive eruptions. The older mafic part of the stratigraphic unit is made up of basaltic to mafic andesites. The age of this unit ranges from ca. 6.9 - 6.4 Ma.

IV. The late Chachahuén group is the name of the following stratigraphic unit. It consists of an older andesitic to dacitic group and a younger more mafic andesitic group. The age of this unit is approximately 6.4 to 5.3 Ma and includes many dykes and domes forming in the volcano.

V. The last stratigraphic unit becomes even more mafic and consists of more basaltic to basaltic andesite flows that are rich in clinopyroxenes. The age of this unit is approximately 5.3 to 4.9 Ma.

VI. The Quaternary has seen little volcanic activity and was restricted to basaltic eruptions spread over larger areas (Kay et al., 2006). This has resulted in large amounts of erosion and has led to many structures being exposed at the surface (Burchardt et al. under review).

The Cerro Bayo cryptodome
At present day, Cerro Bayo is exposed as a 0.3 km³ ovoid mountain, with a long axis striking NE-SW. The structure is 1300 m long, 1000 m wide and 350 m high, the basal surface of the intrusion is not exposed, and the roof has been eroded away (Burchardt et al., under review). The intrusion consists of porphyritic trachyandesite, and the groundmass in mainly made up of plagioclase and amphibole. There is no variation in lithology throughout the intrusions, and no internal chilled margins have been observed (Burchardt et al., under review).

Burchardt et al (under review) divided Cerro Bayo into several structural domains 1. Low-elevation outcrops, 2. Breccia domain, 3. Southern ridge, 4. Northern ridge, 5. Banana, 6. Northeast domain. Furthermore, they propose a three-stage emplacement history for the cryptodome. In stage 1, magma intruded as a sill followed by sill-inflation and doming of the host rock. Inflation of the sill caused shearing that resulted in concentric flow banding and fractured layers. In stage 2, inflation continued, and the intrusion took a mushroom-shape. Inflation happened mostly on the western part of Cerro Bayo and this was followed by brecciation of the rim of the intrusion and faulting of host rock. A viscosity increase due to crystallisation caused by degassing combined with intrusive deformation, rather than cooling, is suggested to be the reason for the brecciated rim. In stage 3, influx of magma was
concentrated as two lobes pushing through the already emplaced magma. The emplacement resulted in magmatic shear at the edges of the lobes but also brittle and ductile deformation of already emplaced magma.

The fact that no chilled margins or lithological boundaries have been found suggests that Cerro Bayo was intruded as one continuous event. This could either have happened as one single event or as small periodic influxes of magma, and therefore the structural domains are most likely due to strain-related change in magma rheology (Burchardt et al., under review).

Method

This project used two main methods to analyse the crystal size distribution of the crystal cargo in samples from Cerro Bayo. Both methods have analysed samples that were collected during a field campaign in 2016 by Steffi Burchardt and Octavio Palma. Thin sections CB14B and CB28 where scanned in plane polarized light and crossed polarized light to create digital images of the samples to make analyses of the large fractions of the crystal cargo, from now on referred to as phenocryst.

Samples CB10, CB14B, CB17, CB19, CB28, CB30, CB48 and CB50 were photographed with a scanning electron microscope to analyse the smaller fractions of the crystal cargo or microlites. The sample locations can be seen in figure 2.

Figure 2. Location of gathered samples on the Cerro Bayo cryptodome. The image is from Google Earth.

CSD

One of the most fundamental characteristics of igneous and metamorphic rock are their crystals, just from crystal size you can distinguish different rocks and crystallisation processes. These processes have been studied since 1805 when
James Hall reproduced basaltic textures in the lab, and since then many methods for understanding crystallisation have been tested (Cashman & Marsh, 1988). In 1971 chemical engineers Randolph and Larson proposed the theory of crystal size distribution (CSD) and Cashman and Marsh interpreted it in a geological context in 1988 (Cashman & Marsh, 1988). CSD is based on a population equation that looks at size and numbers of crystals as they nucleate and grow in a system and shows population density. A steady state crystal population balance can be described by equation (2):

\[ n = n^0 e^{-L(G\tau)} \]  

From this, population density, or \( \ln(n) \), can be plotted against length, \( L \), and give a CSD graph showing an interception point, \( \ln(n^0) \), yielding nucleation population density. The slope of the CSD curve is given by \( G\tau \), which is the average crystal growth rate and average crystal growth time (Cashman & Marsh, 1988).

The most intuitive way to measure crystal size in magmatic rocks would be by sieving, but this can only be done with some types of rock like carbonatites. X-ray tomography can be used for 3D measurements, but calculations of crystal sizes are mostly based on 2D measurements from crystal sizes in for example thin sections (Higgins, 2000). To get an accurate CSD analysis the volume of the crystals is needed, this requires transformation from 2D data to 3D data. This can be tricky, as the length seen in 2D does not need to represent the length in 3D. In 1961 Wager used following equation (3) to solve the problem (Higgins, 2000):

\[ n_V(L_{XY}) = n_A(L_{XY})^{1.5} \]  

In the equation, \( n_V(L_{XY}) \) stands for the numbers of crystals in a volume in a length interval between \( L_x \) and \( L_y \). \( n_A(L_{XY}) \) represent number of intersections in an area with an intersection length interval between \( l_x \) and \( l_y \). This is the simplest of calculations and does not give accurate results (Higgins, 2000).

Instead Higgins (2000) programmed a software called CSDcorrections to convert the 2D data to 3D. The software is built on modified equations that Saltikov made in 1967 and tries to calculate the true length from the intersection length. When using the software intersection length or width, crystal shape, overall dimension, degree of roundness, fabric, quality of fabric, orientation of section and area measured must be entered to get an accurate conversion (Higgins, 2000).

**Scanning electron microscope**

When analysing CSD for the groundmass of hypabyssal and volcanic rocks, images need to be taken of thin sections. The groundmass of a rock consists of a fine-grained matrix, in which larger phenocrystals are embedded. For the second method in this paper, the groundmass of thin sections from different places on the Cerro Bayo cryptodome were going to be examined and the viscosity approximated. Since
the groundmass microlites range from a scale of five to ten micrometres, a scanning electron microscope (SEM) was used to take the photos.

SEM produces images by firing an electron beam at an object and simultaneously projecting it on to a screen. The user can choose to extract topographic or chemical data from the beam. The method is highly used and very effective in mineralogy to analyse crystal morphology and chemical composition (Reed, 2005).

When the beam hits the sample, secondary electrons, back-scattered electrons and x-rays are produced and can be used to get information from the sample. For this project, the back-scattered electrons (BSE) were used to be able to get crystallographic data from the thin sections. Differences in composition can be acquired from the BSE, which will then be projected into a grey-scale image where highest density minerals will appear as the brightest grey-scale (Goldstein, 2017).

![Figure 3. Example of a SEM BSE image from a thin section.](image)

**Phenocryst CSD analysis**

The first method analysed plagioclase and amphibole phenocrysts, (this term is used even though no distinction to antecrysts have been made during the study) in thin sections CB14B and CB28. Both the plane polarized and crossed polarized images of thin sections were imported to the software Inkscape. The crystals were manually outlined in Inkscape. Outlines of the plagioclase crystals were done superimposed on the crossed polarized image and outlines of the amphibole crystals superimposed on the plane-polarized image. The plane-polarized image was also used as additional help outlining the plagioclase crystals, as some crystals could be extinct in the crossed-polarized light image and therefore hard to see.

The objective of manually outlining each crystal was to separate single crystals from clusters, as they would otherwise be considered as one large crystal in following steps. To get an accurate result it was crucial to be consistent in what was considered as a single crystal. For plagioclase, the following things were considered: 1. Colour change 2. Crystal boundaries 3. Symmetry. In cases where the crystal shape was hard to interpret from the image only, the thin section was observed under
the microscope where the extinction angle could be seen much more clearly. As clusters and twinning can make this somewhat difficult, a few examples follow to show how the choice was made (Fig. 4 & 5).

![Figure 4 and 5. Plagioclase phenocrysts and the layer superimposed with polygons representing the shape of the crystal.](image1)

Single amphibole phenocrysts were easier to distinguish as they were predominantly found as free-floating crystals. In cases where there were crystal clusters, the shape of the cluster was the main factor to determine what was a single crystal. See figure 6 and 7 for examples.

![Figure 6 and 7. Amphibole phenocrysts and the layer superimposed with polygons representing the shape of the crystal.](image2)

A 0.35 mm black line was added on the edges of the polygons to separate the outlines of crystals. When all the larger crystals had been outlined a polygon representing the width of the thin section was drawn and the two different polygon layers were exported as PNG files.

The files were opened in ImageJ where the polygon of the width of the thin section was used to make a scale bar. The image was cropped to take away as much excessive area as possible. The image was then converted to 16-bit grey scale and the threshold function was used to only mark the filled-in polygons; it was here the black line helped to separate the crystals. The despeckle tool was then used to remove noise from the image. The area, maximum length and minimum length of the polygons were then calculated, and two files containing this data were exported, one
text file that was later imported to excel and one CSD file that was imported to CSDcorrections (Higgins, 2000, 2002; Higgins & Chandrasekharam, 2007).

To make the conversion from 2D size data to 3D size data, CSDcorrections needed (except the CSD file created from imageJ) data of mean ratio of major and minor apparent length of the phenocrysts. This was calculated with CSDslice (Morgan & Jerram, 2006) from the text file imported to excel. All the data of major and minor apparent length, and the ratio that had been calculated in excel were imported into CSDslice and a population best fit was generated with average aspect ratio. This was then added to CSDcorrections, and roundness and fabric of the sample were estimated. CSDcorrections then generated a graph plotting mid-interval of a crystal-size bin against ln(n0), the graph was then fitted with regression lines to simulate the different populations. The intersection of the regression line was used to calculate n0, and the slope was used to calculate Gt.

Microlite CSD analysis
The second method used the same thin sections as the first in addition to other thin sections from the cryptodome. The localities of where the samples were taken from can be seen in figure 2. Since the groundmass was to be examined, a scanning electron microscope was used to get photos that could image the microscale (see figure 3 in previous section) instead of taking images in plane polarized light and cross polarized in a regular microscope.

Samples from the Cerro Bayo cryptodome were gathered by Octavio Palma and Steffi Burchardt as part of the Research Council of Norway project DIPS, granted to Olivier Galland, University of Oslo. The rock samples were processed into carbon coated thin sections and images were already taken using SEM BSE before the start of the project. Approximately 2-3 images were chosen from a variety of places in the Cerro Bayo cryptodome to get an overview of the mineralogy, and 38 images were chosen in total, the names of the localities can be seen in table 1. To only analyse the groundmass from the samples, the large phenocrysts visible in the photos from the SEM needed to be removed. This was done by using a software called InkScape.

The images were imported into the software one at a time and put as a layer. A second layer was created superimposed on the picture, and polygons were drawn overlying the large phenocrysts and put in white colour to make them distinguishable. When only the groundmass could be seen in the images with all the large crystals covered up, they were exported as a PNG file to make the new picture convert both layers as a single file. The now polygon-filled image was converted into a JPEG file to be able to be opened in the next software program used called ImageJ. To be able to calculate the shapes of the crystals from the SEM photos, a scale had to be set to every picture. This was done by using the scale function in ImageJ, which could vary from 100 µm to 10 µm.

After the scale was set, separation of the three mineral phases present in the samples could begin. This was done by carefully thresholding every grey-scale (dark grey, medium grey and light grey) and saving them one by one (see example in figures 8-10). The three different phases were identified as dark grey being alkali
feldspar or quartz, medium grey being plagioclase and light grey being amphibole. In some cases, the outlines of already removed phenocrysts could be visible as small pixels scattered randomly in the picture which were removed by despeckling. When the separation was done the image must be saved as a .tiff file, which was not done in this case by mistake. A .tiff file saves necessary information about the file such as the scale. This problem was solved by simply opening up the SEM pictures, copying the scale bar into the thresholded JPEG files, and then saving them again as tiff files. When this was done, information about the area, minor and major axial data of crystals could be calculated by ImageJ and saved as one text file and as one CSD file for each image.

The text file was opened up in an excel file were the minor and major axial data could be copied, and later opened up in a premade excel spreadsheet called CSDslice were the mean aspect ratio of the crystals was gathered. The mean aspect ratio of the crystals was needed to be put in CSDcorrections to estimate the shape of the crystals along with roundness of the crystals and their fabric. The roundness was set to 0 (block) based on CSDslice's approximation of prism-shaped crystals. When the aforementioned data was put into CSDcorrections, a graph with $\ln(n^o)$ against mid inter (size) along with volumetric data was plotted.

![Figure 8. Example of an SEM image.](image)

![Figure 9. Example of the same SEM image with the phenocryst removed.](image)

![Figure 10. Example of thresholded image.](image)

### Viscosity calculations

By using the volumetric percentage of crystals in the sample, the viscosity could be calculated with the Einstein-Roscoe equation (see equation 3). For sample CB14B and CB28 both crystal fractions from phenocryst and microlites were used, but only the plagioclase phase was used from the microlites. For remaining samples where only CSD analysis of microlites had been conducted, a mean value of particle fraction for the phenocryst in CB14B and CB28 was added. In the Einstein-Roscoe equation, melt viscosity ($\mu_{\text{fluid}}$) was set to $10^6$ Pa s, the melt viscosity of granite from Lesher and Spera (2015).
Result

Phenocrysts
The thin sections contain plagioclase and amphibole and minor quantities of other minerals and gas bubbles. The phenocryst cargo mainly consists of plagioclase, and they are found both as free-floating crystals and in clusters. They are often zoned or twinned and have a tabular shape, the minimum length measured in the samples was 0.039 mm and the maximum length was 4.865 mm. The amphiboles are fewer and mostly found as free-floating crystals with a prismatic or tabular shape. The minimum length measured in the samples of the amphibole phenocryst was 0.038 mm and the maximum length was 2.658 mm.

CB14B has a groundmass composed of small crystals, where it is somewhat hard to distinguish individual grains. The plagioclase crystals, seen as blue grey crystals in crossed polarized light (Fig. 11), are ranging in size from 0.04 - 4.87 mm and have weak fabric but are assumed to have a massive distribution. The amphibole crystals, seen clearly as black crystals in plane polarized light (Fig. 12), are ranging in size from 0.04 - 1.83 mm and are observed as dots in thin section view, and the thin section is therefore interpreted to be oriented perpendicular to the mineral lineation.

Figure 11. Crossed polarized image of CB14B.
Sample CB28 has a groundmass with elongated crystals and a greater portion of bubbles compared to CB14. The plagioclase phenocrysts are between 0.039 - 3.816 mm long and show sign of a weak fabric only. The amphibole crystals (Fig. 13) are aligned in parallel view trending from top left corner to lower right corner of the thin section and crystal sizes range between 0.038 - 2.658 mm.
Plagioclase
In sample CB14B 3,910 plagioclase crystals were mapped (Fig. 15), which made up 23.4 vol.% of the sample. Size data from ImageJ were input into CSDslice, which gave an average aspect ratio of 1.00:1.30:2.10 (short:intermediate:long).

CSD corrections generated a curve that could be fitted with two regression lines (Fig. 16). Nucleation density and characteristic length was calculated to 84.77 mm⁻⁴ and 0.212 mm for the first regression line and 0.76 mm⁻⁴ and 0.741 mm for the second.
Figure 16. CSD curve with regression lines for plagioclase in sample CB14B.

3840 plagioclase crystals were outlined in sample CB28 (Fig. 17) and they constituted about 21.4 vol.% of the sample. CSD slice yielded an average crystal aspect ratio of 1.00:1.40:4.50, and this was input into CSDcorrections.

Two regression lines were fitted to the CSD curve generated by CSDcorrectionss (Fig. 18), the first one giving a nucleation population density of 56.26 mm⁻⁴ and 0.31 mm characteristic length. From the second regression line, a nucleation population density of 0.63 mm⁻⁴ and characteristic length of 1.20 mm were calculated.
Figure 18. CSD curve with regression lines for plagioclase in sample CB28.

The CSD curves for plagioclase in samples CB14B and CB28 were both concave and could be fitted with two regression lines. However, a comparison between the two lines (Fig. 19) shows that plagioclase crystals in CB28 have a somewhat different shape and larger quantities of crystals in the size range 1 - 8 mm.

Figure 19. CSD curves for plagioclase crystals in sample CB28 and CB14B.
Amphibole
2998 amphibole crystals were mapped in sample CB14B, and they made up 5.9 vol.% of the sample. CSDslice gave an average aspect ratio of 1.0:1.25:1.80, which was used as crystal shape input for the CSDcorrections calculations.

![Figure 20. Outlined amphibole crystals in CB14B.](image)

The CSD curve generated was fitted with two regression lines (Fig. 21). Nucleation density of the first one was calculated to 181.27 mm\(^{-4}\) and characteristic length to 0.125 mm. The second regression line gave values of 2.08 mm\(^{-4}\) and 0.365 mm.

![Figure 21. CSD curve with regression lines for amphibole in sample CB14B.](image)
In sample CB28, we outlined 2733 amphibole crystals (Fig. 22) that constituted about 4.6 vol.% of the sample. The average aspect ratio calculated by CSDslice was 1.0:1.2:2.3, and this was used as input for crystal size in CSDcorrections.

The CSD curve generated for the amphibole crystals in CB28 was fitted with two regression lines (Fig. 23), the first one giving a nucleation population density of 157.59 mm\(^{-4}\) and a characteristic crystal length of 0.146 mm. From the second regression line, a nucleation population density of 0.19 mm\(^{-4}\) and characteristic length of 0.654 mm was calculated.
The CSD curves for amphibole in CB14B and CB28 were both concave and each could be fitted with two regression lines. The lines follow approximately the same pattern (Fig. 24) and have the same quantities for the different size intervals.

![CSD curves for amphibole crystals in sample CB28 and CB14B.](image)

**Figure 24.** CSD curves for amphibole crystals in sample CB28 and CB14B.

**Microlites**

The Cerro Bayo cryptodome is made up of porphyritic trachyandesite (Burchardt et al. Submitted). The crystals making up the rock are dominantly plagioclase and amphibole. Table 1 shows that plagioclase, referred at times here as medium grey, is the dominant crystal phase in all samples with a fractional volume ranging from 12 to 20 percent. Amphibole, the brightest of the grey-scales, is second with volumes ranging from 10 to 17 percent and third is the dark grey colour, interpreted to be quartz or feldspar, with the least quantity and volumes ranging from 8 to 12 percent. CSDslice estimated the majority of the samples to be of rectangular prism shape, with a few exceptions being acicular. The characteristic lengths (Gτ) follow the same principle with the exception of location CB48 were the quartz/feldspar crystals are longer than the amphibole on average. However, plagioclase crystals are the longest in all samples indicating faster growth rates for plagioclase than for the other phases.

The interpretations and calculations presented below are not based on all sample locations. This is because a few locations only had one thin section image available and for the purpose of this project, the interpretations are based on an average of multiple thin section images and the differences between locations. The following locations will be presented below: CB10, CB17, CB19, CB30, CB48, CB50.
Examples of thresholded images from location CB10:

*Figure 25 and 26. Thresholded image of plagioclase (left) and quartz or feldspar (right) from CB10.*

The large unfilled white spaces are phenocrysts removed from the images in Inkscape. The black areas represent crystals of each phase. The plagioclase phase has a volume of 23.11 %, while quartz or feldspar has a volume of 8.2 %, which is clearly visible in the microphotographs. The average volume of all samples can be seen in table 1. CSD graphs plotting Ln (population density) and crystal size per sample location and crystal phase. Calculated values for all plots are shown in table 1 and 2.
CSD plots for sample location CB10 and CB19:

Figure 27. CSD plots of all three mineral phases for CB10 and CB19.

Note the kinks on the curve for plagioclase at around -16 to -18 in sample location CB10. All graphs are curved with the amphibole graphs being the least curved.
CSD plots for sample locations CB30 and CB48

Figure 28. CSD plots of all three mineral phases for CB30 and CB48.

A distinct kink can be seen in the CSD for plagioclase in both sample locations. Both the quartz/feldspar graphs and the amphibole graphs do not have the same kink.
CSD plots for sample locations CB50 and CB17

**Figure 29. CSD plots of all three mineral phases for CB50 and CB17.**

The CSDs for amphibole have no kinks. The CSDs for plagioclase are somewhat curved, while the plots for quartz/feldspar has the largest curvature and a notable kink can be seen in sample location CB50.
<table>
<thead>
<tr>
<th>Sample location</th>
<th>Threshold</th>
<th>Average R² value</th>
<th>Average slope</th>
<th>Average intercept</th>
<th>Average Volume %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB10</td>
<td>Quartz/feldspar</td>
<td>0.943</td>
<td>-0.097</td>
<td>-11.03</td>
<td>10.44</td>
</tr>
<tr>
<td>CB10</td>
<td>Plagioclase</td>
<td>0.935</td>
<td>-0.068</td>
<td>-11.79</td>
<td>19.69</td>
</tr>
<tr>
<td>CB10</td>
<td>Amphibole</td>
<td>0.966</td>
<td>-0.074</td>
<td>-11.59</td>
<td>17.84</td>
</tr>
<tr>
<td>CB19</td>
<td>Quartz/feldspar</td>
<td>0.973</td>
<td>-0.099</td>
<td>-11.10</td>
<td>11.20</td>
</tr>
<tr>
<td>CB19</td>
<td>Plagioclase</td>
<td>0.914</td>
<td>-0.070</td>
<td>-12.04</td>
<td>18.33</td>
</tr>
<tr>
<td>CB19</td>
<td>Amphibole</td>
<td>0.986</td>
<td>-0.073</td>
<td>-11.20</td>
<td>12.30</td>
</tr>
<tr>
<td>CB30</td>
<td>Quartz/feldspar</td>
<td>0.949</td>
<td>-0.127</td>
<td>-10.38</td>
<td>11.26</td>
</tr>
<tr>
<td>CB30</td>
<td>Plagioclase</td>
<td>0.931</td>
<td>-0.071</td>
<td>-11.68</td>
<td>16.66</td>
</tr>
<tr>
<td>CB30</td>
<td>Amphibole</td>
<td>0.980</td>
<td>-0.095</td>
<td>-10.91</td>
<td>13.90</td>
</tr>
<tr>
<td>CB48</td>
<td>Quartz/feldspar</td>
<td>0.960</td>
<td>-0.092</td>
<td>-11.28</td>
<td>8.28</td>
</tr>
<tr>
<td>CB48</td>
<td>Plagioclase</td>
<td>0.931</td>
<td>-0.068</td>
<td>-12.03</td>
<td>18.46</td>
</tr>
<tr>
<td>CB48</td>
<td>Amphibole</td>
<td>0.981</td>
<td>-0.101</td>
<td>-10.91</td>
<td>13.33</td>
</tr>
<tr>
<td>CB50</td>
<td>Quartz/feldspar</td>
<td>0.900</td>
<td>-0.112</td>
<td>-11.19</td>
<td>5.84</td>
</tr>
<tr>
<td>CB50</td>
<td>Plagioclase</td>
<td>0.950</td>
<td>-0.087</td>
<td>-11.27</td>
<td>12.67</td>
</tr>
<tr>
<td>CB50</td>
<td>Amphibole</td>
<td>0.989</td>
<td>-0.084</td>
<td>-11.34</td>
<td>12.13</td>
</tr>
<tr>
<td>CB17</td>
<td>Quartz/feldspar</td>
<td>0.970</td>
<td>-0.117</td>
<td>-10.26</td>
<td>11.88</td>
</tr>
<tr>
<td>CB17</td>
<td>Plagioclase</td>
<td>0.963</td>
<td>-0.104</td>
<td>-10.33</td>
<td>16.64</td>
</tr>
<tr>
<td>CB17</td>
<td>Amphibole</td>
<td>0.990</td>
<td>-0.094</td>
<td>-10.61</td>
<td>14.95</td>
</tr>
</tbody>
</table>
Table 2. Average characteristic length (Gt), population density (n0) and aspect ratio for microlite sample locations.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Threshold</th>
<th>Gt (µm)</th>
<th>n° µm^-4</th>
<th>Average aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB10</td>
<td>Quartz/feldspar</td>
<td>10.26</td>
<td>1.615E-05</td>
<td>1:1.64:2.99</td>
</tr>
<tr>
<td>CB10</td>
<td>Plagioclase</td>
<td>14.63</td>
<td>7.572E-06</td>
<td>1:1.54:3.2</td>
</tr>
<tr>
<td>CB10</td>
<td>Amphibole</td>
<td>13.46</td>
<td>9.238E-06</td>
<td>1:1.67:3.0</td>
</tr>
<tr>
<td>CB19</td>
<td>Quartz/feldspar</td>
<td>10.10</td>
<td>1.511E-05</td>
<td>1:1.6:2.88</td>
</tr>
<tr>
<td>CB19</td>
<td>Plagioclase</td>
<td>14.31</td>
<td>5.903E-06</td>
<td>1:1.55:2.95</td>
</tr>
<tr>
<td>CB19</td>
<td>Amphibole</td>
<td>13.72</td>
<td>1.371E-05</td>
<td>1:1.5:3.4</td>
</tr>
<tr>
<td>CB30</td>
<td>Quartz/feldspar</td>
<td>7.85</td>
<td>3.105E-05</td>
<td>1:1.73:2.88</td>
</tr>
<tr>
<td>CB30</td>
<td>Plagioclase</td>
<td>14.04</td>
<td>8.504E-06</td>
<td>1:1.63:3.25</td>
</tr>
<tr>
<td>CB30</td>
<td>Amphibole</td>
<td>10.50</td>
<td>1.823E-05</td>
<td>1:1.58:3.05</td>
</tr>
<tr>
<td>CB48</td>
<td>Quartz/feldspar</td>
<td>10.84</td>
<td>1.267E-05</td>
<td>1:1.53:3.2</td>
</tr>
<tr>
<td>CB48</td>
<td>Plagioclase</td>
<td>14.66</td>
<td>5.963E-06</td>
<td>1:1.53:2.9</td>
</tr>
<tr>
<td>CB48</td>
<td>Amphibole</td>
<td>9.93</td>
<td>1.821E-05</td>
<td>1:1.63:2.77</td>
</tr>
<tr>
<td>CB50</td>
<td>Quartz/feldspar</td>
<td>8.96</td>
<td>1.379E-05</td>
<td>1:1.67:3.03</td>
</tr>
<tr>
<td>CB50</td>
<td>Plagioclase</td>
<td>11.53</td>
<td>1.279E-05</td>
<td>1:1.58:3.35</td>
</tr>
<tr>
<td>CB50</td>
<td>Amphibole</td>
<td>11.90</td>
<td>1.195E-05</td>
<td>1:1.72:3.28</td>
</tr>
<tr>
<td>CB17</td>
<td>Quartz/feldspar</td>
<td>8.56</td>
<td>3.518E-05</td>
<td>1:1.7:2.85</td>
</tr>
<tr>
<td>CB17</td>
<td>Plagioclase</td>
<td>9.59</td>
<td>3.280E-05</td>
<td>1:1.58:2.95</td>
</tr>
<tr>
<td>CB17</td>
<td>Amphibole</td>
<td>10.64</td>
<td>2.467E-05</td>
<td>1:1.75:3.35</td>
</tr>
</tbody>
</table>

Table 1 and table 2 show the calculated data for the six samples. The average R² value of all samples correspond to the curvature of the CSD in the previous section were the amphibole graphs have the highest R² value and accordingly had the straightest CSD, while the plagioclase CSD was the most curved.

Viscosity calculations

For sample CB14 and CB28, crystal fractionation data from both the phenocryst and microlite CSD analysis was used in the Einstein-Roscoe equation to give a value of 6.52 Pa s and 6.9 respectively. For remaining samples, where only microlite CSD analysis had been done, an average phenocryst crystal fraction of 27.65 % was used in the calculations. The data is compiled in table 3 and figure 30.

Table 3. Average crystal fraction and viscosity for all sample locations.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Crystal Fraction (%)</th>
<th>Viscosity (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB28</td>
<td>38%</td>
<td>6.52</td>
</tr>
<tr>
<td>CB50</td>
<td>44%</td>
<td>6.62</td>
</tr>
<tr>
<td>CB19</td>
<td>45%</td>
<td>6.66</td>
</tr>
<tr>
<td>CB48</td>
<td>46%</td>
<td>6.67</td>
</tr>
<tr>
<td>CB30</td>
<td>49%</td>
<td>6.74</td>
</tr>
<tr>
<td>CB17</td>
<td>50%</td>
<td>6.75</td>
</tr>
<tr>
<td>CB10</td>
<td>52%</td>
<td>6.79</td>
</tr>
<tr>
<td>CB14</td>
<td>57%</td>
<td>6.91</td>
</tr>
</tbody>
</table>
Figure 30. Mean phenocryst crystal fraction and microlite crystal fraction plotted against viscosity.

If the mean phenocryst crystallisation fraction is not added to the samples where phenocryst CSD have not been done, a modest kink in the graph can be seen.

Figure 31. Microlite and phenocryst crystal fraction for CB14 and CB28 and microlite fraction for the rest of samples.

Viscosity measurements using only crystal fractionation from microlite CSD analysis is compiled in table 4 and figure 32.
Table 4. Viscosity and crystal fraction calculated from microlite CSD data in different samples.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Crystal Fraction (%)</th>
<th>Viscosity (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB28</td>
<td>12%</td>
<td>6.14</td>
</tr>
<tr>
<td>CB50</td>
<td>16%</td>
<td>6.19</td>
</tr>
<tr>
<td>CB19</td>
<td>18%</td>
<td>6.21</td>
</tr>
<tr>
<td>CB48</td>
<td>18%</td>
<td>6.22</td>
</tr>
<tr>
<td>CB30</td>
<td>22%</td>
<td>6.26</td>
</tr>
<tr>
<td>CB17</td>
<td>22%</td>
<td>6.27</td>
</tr>
<tr>
<td>CB10</td>
<td>24%</td>
<td>6.30</td>
</tr>
<tr>
<td>CB14</td>
<td>27%</td>
<td>6.35</td>
</tr>
</tbody>
</table>

Figure 32. Viscosity plotted against crystal fraction calculated from microlite CSD.
Viscosity calculations for only phenocryst in sample CB14B and CB28 yields a viscosity of 6.33 Pa s and 6.38 Pa s (Fig. 33).

![Viscosity plotted against fractional crystallisation given from phenocryst CSD analysis in sample CB14B and CB28.](image)

**Figure 33.** Viscosity plotted against fractional crystallisation given from phenocryst CSD analysis in sample CB14B and CB28.

### Discussion

#### Error sources

Human bias can have affected the results as crystals were manually outlined. In the beginning the process of deciding what was a single phenocryst was difficult, but after a while of practice the separation of crystals became easier. The same goes for the thresholding of microlites. This can have led to a non-consistent mapping and therefore influenced the results of the CSD graphs. Regarding the thresholding of microlites, there where samples that did not have clear grey scales and therefore it was hard to distinguish the three different phases. Improper usage of software like CSDcorrections and excel spreadsheets could result in numbers being mixed up and the results being altered. As additional information about the crystal population were imported to CSDcorrections, incorrect estimates of fabric and roundness could yield inaccurate results.

If there have been errors or inconsistencies in the mapping and thresholding of the phenocrysts and microlites this would yield inaccurate crystal fractionations and furthermore inaccurate viscosity measurements. As this study focuses on the relative viscosity between samples, not much emphasis has been put on the calculations giving absolute values and this is therefore not considered as a source of error.

#### CSD phenocrysts

If a magma consists of one population of crystals, grown in an open steady state system with continuous crystallisation, the graph should represent a straight line (Marsh, 1988). This is not the case with the plagioclase and amphibole phenocryst
CSD of the analysed samples, which are curved concave upwards, and in some samples a distinct kink has been observed. In samples CB14B and CB28, two trend lines, both for plagioclase and amphibole, have been fitted to the lines indicating two different populations of crystals.

The maximum crystal sizes for plagioclase and amphibole measured from sample CB28 are larger than sample CB14B. For plagioclase there is also a larger number of crystals in the size interval 1 - 8 mm in sample CB28. However, the total crystal volume of phenocryst is larger in CB14. Observing the thin sections images, you can tell that there are a greater number of larger phenocrysts in sample CB28.

There are a number of proposed reasons for a curved CSD; for example, mixing, textural coarsening and abrupt changes in cooling rates (Higgins, 1996). Textural coarsening happens during temperature increase, followed by for example new magma influx, and when the temperature approaches the liquidus line. This affects the smaller crystals, which will dissolve, but not the larger crystals that will keep growing (Higgins & Roberge, 2003).

For amphibole phenocrysts, there is a clear pattern of the CSD curve shown in both CB14B and CB28. This suggest that they have experienced a similar or the same growth history. The plagioclase phenocrysts in these samples are instead somewhat different; the CSD curve for sample CB28 indicates a growth history favouring growth of larger crystals. This could for example happen if magma in CB28 was exposed to a temperature increase resulting in coarsening of crystals. Another suggested option was that plagioclase in CB28 shows some kind of fabric, and the fact that this was not included in CSDcorrections gives a misleading graph. The direction of fabric for amphibole differed from CB14B and CB28, which is probably due to the way the thin sections are cut. If plagioclase has some fabric this could affect how the crystals look in the samples. However, when data for plagioclase in both samples were put into CSDcorrections again with additional fabric of 0.2 the graph remained the same.

CSD microlites

From the CSD curves, characteristic length of a crystal population can be approximated from the slope, while nucleation population density can be interpreted from the intercept of the y-axis. If the plot has a curve, the curve is an indication that the different crystals in the sample have not grown linearly, meaning there has been a variation in growth rate (Marsh, 1988). This could be indicative that the crystals in the samples have grown in different locations or due to different processes that could affect the magma such as a sudden drop in temperature, degassing, crystal coarsening, magma mixing, or changed rate of magma influx (Marsh, 1988 & Riker et al. 2015). However, microlites form during the degassing of a magma, which could lead to multiple populations of microlite crystals (Hale & Wadge, 2008).

All CSDs for plagioclase are curved concave upwards and have the largest characteristic lengths along with the largest size intervals. While, for example, the amphibole CSDs are a lot more linear with the highest R^2-value, indicating a smooth
continuous growth rate. This shows that the amphibole crystals might not have been affected by an event that could affect their growth like those mentioned earlier. The CSDs for feldspar/quartz have the smallest characteristic lengths along with the least fractional volume in all sample locations. They are however curved which would indicate that they have experienced an event affecting their growth rate or alternatively their CSDs are controlled by plagioclase growth.

To summarize, the CSD results for the microlites indicate that the plagioclase crystals, that are the longest and take up the largest volume, have been affected by an event during their growth. This could mean that the plagioclase microlites started growing within the conduit but changed its growth rate when the magma reached Cerro Bayo. The amphibole CSDs show signs that the crystals have been growing continuously during a single crystallisation event in Cerro Bayo only, as is dictated by rather linearity, which is also a sign that they have not been affected by an event changing their crystallisation parameters, such as crystal coarsening or a change in growth rate. If an event occurred there must be at least two populations of microlites, which is not the case for the amphibole microlites. The feldspar/quartz crystals, like mentioned earlier, have a curved CSD, while at the same time the shortest lengths and volume. The phenocrysts consist of two populations, which is interpreted from the kink in their plots. The microlite quartz/feldspar and plagioclase also consists of two populations. Because the size intervals somewhat overlap, it is believed that there are overall three populations in the samples gathered from the Cerro Bayo cryptodome.

We propose that when the magma ascended, it degassed in the conduit leading to plagioclase and potentially quartz/feldspar growth. As the magma formed Cerro Bayo in the upper crust, the melt experienced a steady state crystallisation meaning growth parameters such as ascent rate and pressure, became somewhat constant. This could lead to the kinked CSDs, i.e. two populations, for the plagioclase and quartz/feldspar microlites, while the amphibole population plots are linear, i.e. single population.

Viscosity

There does not seem to be a correlation between the viscosity and the different CSDs. The CSDs for CB10 that have a higher viscosity look rather similar to the CSD for CB48 and CB50 that have a lower viscosity and even though CB17 and CB10 have a high viscosity, their characteristic length seem to differ a lot. The Einstein-Roscoe equation for viscosity is, however, flawed in that it does not take in many factors that play a large roll in viscosity measurements such as water and gas content, volatiles and others, so perhaps with a better overall measurement and the actual numbers for the viscosity, a greater understanding could be achieved (Petford, 2009).

The effective viscosities calculated for the samples are not the absolute values, as not all parameters have been measured. But as the main objective in this project was to find a viscosity difference between samples this has not been seen as a problem, as long as the other values have been constant. The viscosity measurements based
on the crystal fraction of amphibole and plagioclase phenocryst and plagioclase microlites show that CB14 has a much higher viscosity than CB28. This can be a bit contradicting looking only at the maximum crystals size for amphibole and plagioclase in the samples. Sample CB28 has the larger crystals, which intuitively would indicate a higher crystalline fraction and therefore should have higher viscosity. However, the quantities of larger crystals are very low and CB14 have a larger crystal volume in total.

The viscosity curve in figure 30 shows a relatively straight line, but there is a slight curvature towards the higher crystal fractions. This indicates that the magma that intruded Cerro Bayo acted as a Newtonian fluid but had begun transforming to a non-Newtonian fluid, but as the Einstein-Roscoe equation is used for calculating Newtonian fluids this might not be accurate. There are many methods to calculate effective viscosity and the Einstein-Roscoe equation has been discussed to give incorrect answers for non-Newtonian fluids (Petford, 2009). However, this is likely insignificant in this study as shortcomings of the calculations would affect the accuracy of the results, but the comparison would remain. Further, you can see a striking trend of the viscosity getting higher amongst samples, with higher viscosity correlating with higher crystal fraction.

As mentioned before, the Cerro Bayo cryptodome is believed to have grown in different stages and with different styles (Burchardt et al. under review). Visible in table 3, there is a viscosity difference between the different locations on the cryptodome. According to Riker (2015) the emplacement rate of magma controls the growth of crystals, where a slower extrusion rate allows for more crystals to nucleate and therefore a more viscous magma. The style of growth in cryptodomes is also constrained by the effusion rate (Nakada et al., 1995), and lobe growth is favoured by a slower extrusion rate as the magma have a higher viscosity and can penetrate already emplaced magma (Riker et al., 2015). This would mean that samples taken in the lower areas of Cerro Bayo, that is assumed to have grown by inflation, should have a lower viscosity than samples taken on the ridges that is suggested to have grown like two lobes that pierced through the structure. In most sample locations, this is true, with a few exceptions.

CB19 and CB28 came from the lower parts of the cryptodome and have a lower viscosity. CB10 and CB14 are a part of the southern ridge that is thought to have been emplaced in the later stages and accordingly, they have a higher viscosity. CB30 is fairly close to CB28, but has a higher viscosity, which is misleading. Both CB48 and CB50 is part of the northern ridge and would likely have a higher viscosity if they formed from lobe magma, which is not the case. CB17 also has a relatively high viscosity even though it is from the lower part of the cryptodome. However, for example CB17 is located in the structure domain called Banana. This is a complicated zone that has been interpreted to grow by magma influx, but it could perhaps be a small lobe that has pushed through already emplaced magma like the southern ridge which could explain the high viscosity of CB17. On the other hand, the northern ridge might have grown earlier by magma inflation and later on been pushed up, creating the ridge.
Plumbing system and emplacement
From the CSDs of both microlites and phenocrysts, we interpret that the largest plagioclase and amphibole phenocryst started to crystallise deep within the deep volcanic plumbing system. When the magma then moved upwards, the lower temperature caused crystallisation of more phenocrysts. During this ascent, the melt experienced processes such as temperature changes probably due to influx of hot new magma allowing crystal coarsening or changes in growth rate. This has been interpreted from the curved CSD of the phenocrysts.

The magma then continued its ascent up through the crust. Before the intrusion created the Cerro Bayo cryptodome, the magma experienced degassing, leading to the crystallisation of microlites, in this case plagioclase and quartz/feldspar. This is assumed from the kinks in the microlite quartz/feldspar and plagioclase.

When the magma finally intruded close to the surface and created the Cerro Bayo cryptodome, microlite of feldspar/quartz and plagioclase and phenocrysts of plagioclase and amphibole were in a melt and continued to crystallise while amphibole microlites started to crystallise.

Conclusions
The CSD analyses show that the crystal cargo in the magma that intruded the crust at Cerro Bayo consists of at least three crystal populations. Data indicates that the phenocrysts have grown in the deeper magma reservoir and conduits and then have been affected by a coarsening event. The plagioclase and quartz/feldspar microlites seems to have grown in the degassing stage in the conduit, while the amphibole microlites have only grown in the cryptodome as the magma reached a steady state crystallisation phase. The fact that there is a change of growth style indicate a changed rate of magma influx and crystallisation growth.

There is also a clear viscosity difference between different locations in the cryptodome. The data suggest that the southern ridge was emplaced in an exogenic like behaviour due to a slower intrusion rate. This would lead to the magma having more time to degas during the ascent and become more crystalline. The northern ridge and the lower part of the cryptodome have some contradictive viscosity values, which could indicate that the suggested emplacement history is not fully understood. For example, the structure domain Banana could also have been emplaced in an exogenic manner, but more data is needed to get a better understanding of the emplacement and how it is related to the magmatic pluming system and effusion rate.

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