Mineral Textures of the Auckland Volcanic Field: Insights into Ascent Processes

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Joshua L. Coker
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TITLE

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Mineral Insights into the Auckland Volcanics

ABSTRACT

The Auckland Volcanic Field, a prominent monogenetic basaltic field, is characterized by rapid magma ascent from source to surface, yielding a landscape of diverse volcanic morphologies. Despite being extensively studied, the fundamental processes governing this field remain largely enigmatic. This study aims to shed light on these mysteries by scrutinizing mineralogical textures and chemistry at a scale representative of the entire volcanic field.

To achieve this, we employed advanced techniques, including Scanning Electron Microscope (SEM) image analysis, Electron Microprobe chemical analysis, equilibrium testing, and thermobarometry. Through these methods, we scrutinized various minerals and identified compelling evidence suggesting fluctuations in magma ascent rates. Notably, we observed variable normal zoning rates in Olivine, oscillatory zoning in clinopyroxenes, and the presence of lamellae exsolution, surrounded by unexsolved crystallization of Fe-Ti oxides. These mineralogical features offer crucial insights into the dynamic processes taking place during the ascent of magma beneath the Auckland Volcanic Field.

The implications of these findings extend beyond geological curiosity. Understanding the changes in magma ascent rates carries significant implications for the forecasting and early detection of moving magma beneath Auckland. If magmas can be identified during slower ascent stages, this knowledge could serve as an essential precursor to the potentially hazardous rapid ascent phase. This insight is not only valuable for understanding the volcanic field's monogenetic nature but also for enhancing the safety and preparedness of the Auckland region in the face of volcanic activity.

In conclusion, our research unveils critical mineralogical evidence of variable ascent rates within the Auckland Volcanic Field, enriching our understanding of this complex geological system. Furthermore, the potential implications for volcanic hazard mitigation underscore the practical significance of this study, as it has the potential to improve volcanic forecasting systems and protect the well-being of the Auckland community.

KEYWORDS

Auckland Volcanic Field, Monogenetic Volcanism, Mineralogical Textures, Magma ascent rates, Scanning Electron Microscope, Equilibrium Testing, Volcanic Hazards

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1. INTRODUCTION

The Auckland Volcanic Field (AVF) is renowned for its enigmatic geological features and complex dynamics of volcanic activity. This field, characterised by monogenetic and heterogeneous volcanism, proves difficult but important to understand for geologists due to potential risks affecting the overlying city.

Traditionally, studies in this field have relied on petrographic and geochemical analyses, with a primary focus on whole rock compositions. While there has been extensive published research on the geochemistry of the AVF, there has been little work done on the mineralogy. Searle (1960, 1961) used optical microscopy to complete a broad mineralogical study targeting a number of eruptive centres, while others have looked more specifically at individual case studies on single volcanoes (Brenna et al., 2018; Smith et al., 2008). Common minerals within AVF lavas include olivine, clinopyroxene, iron oxides including titanium bearing magnetite, ilmenite, and haematite. However, as one would expect from lavas of different whole rock compositions, they are known to present additional accessory minerals.

Whole rock analyses have produced models of heterogeneity (different chemical compositions) generated by peridotites below the spinel-garnet transition zone, acting as the mantle sources for the AVF (McGee et al., 2015; McGee et al., 2013). Seismic models propose that the magma originates from small batch melting at depths of 70-90 kilometres below the Earth's surface (Horspool et al., 2006). Furthermore, studies investigating the entire AVF suggest the heterogeneity is a result of the interplay between potential sources of melt, and minor evolution upon ascent via mechanisms such as fractionation, assimilation, or crystallisation (Smith et al., 2008). These considerations are consistent across the AVF.

Volcanic fields are typically comprised of monogenetic volcanoes, where each volcano is thought to only erupt once. They physically manifest as cinder cones, tuff rings and cones, maars and spatter cones (Cañon-Tapia, 2016), they make comparatively small surface features compared to their polygenetic counterparts. These differences in surface expressions are a result of a range of eruptive styles ranging from phreatomagmatic to fire fountaining and lava flows. However monogenetic volcanism is more complex than the term implies, with potential for crustal storage and magmatic dynamics that go beyond rapid source to surface ascent (Kereszturi et al., 2014; Németh & Kereszturi, 2015). While Auckland is considered a monogenetic volcanic field, it has an outlier in Rangitoto, the youngest volcano in the region. This most recent eruptive centre is thought to have erupted twice with ~50 years between events. This may indicate a deviation from a monogenetic system or add to the enigmatic nature of monogenetic volcanism. To better identify these intricacies of subsurface plumbing, tools such as geothermobarometry and textural analyses must be implemented.

Geothermobarometry is a method which gives a glimpse of the journey some minerals prior to crystallisation. This includes fractionation, assimilation, and crystallization, as well as determining any plumbing that may shift theories from sensu stricto monogenetic volcanism. Equilibrium testing is used to establish whether a mineral has formed in equilibrium with the crystallised melt it has been found in. If minerals such as olivine or clinopyroxene are found to be in equilibrium, they can be used to attain pressure and temperatures that correlate to depth of initial mineral precipitation (Putirka, 2008).

While the primary focus centres on the minerals essential for geothermobarometry and the intriguing textures within these rocks, it is crucial to recognize the broader implications of understanding ascent processes. Volcanic forecasting and eruption modelling within the AVF are not merely academic pursuits; they hold the key to safeguarding communities and resources in the region. The ability to comprehend the intricacies of magma ascent and eruption dynamics is pivotal for risk assessment and management (Lindsay, 2010). As our understanding deepens, we move closer to improved forecasting models, enhanced preparedness, and more effective response strategies. By providing fresh insights into the magmatic processes at play in this volcanic field, this research contributes directly to the ongoing efforts to mitigate the potential impact of future eruptions. (Fearnley & Beaven, 2018)

In the pages that follow, we present a brief geological context, methodology, results, and discussion that aim to improve the understanding of Auckland’s volcanoes. Using the petrographic and geochemical intricacies of this volcanic field, we hope to challenge established assumptions, refine existing models, and ultimately deepen our comprehension of the processes resulting in the AVF. With this improved understanding of the volcanic field, this will better help decision makers with the safety and resilience of the communities living in harm’s way.

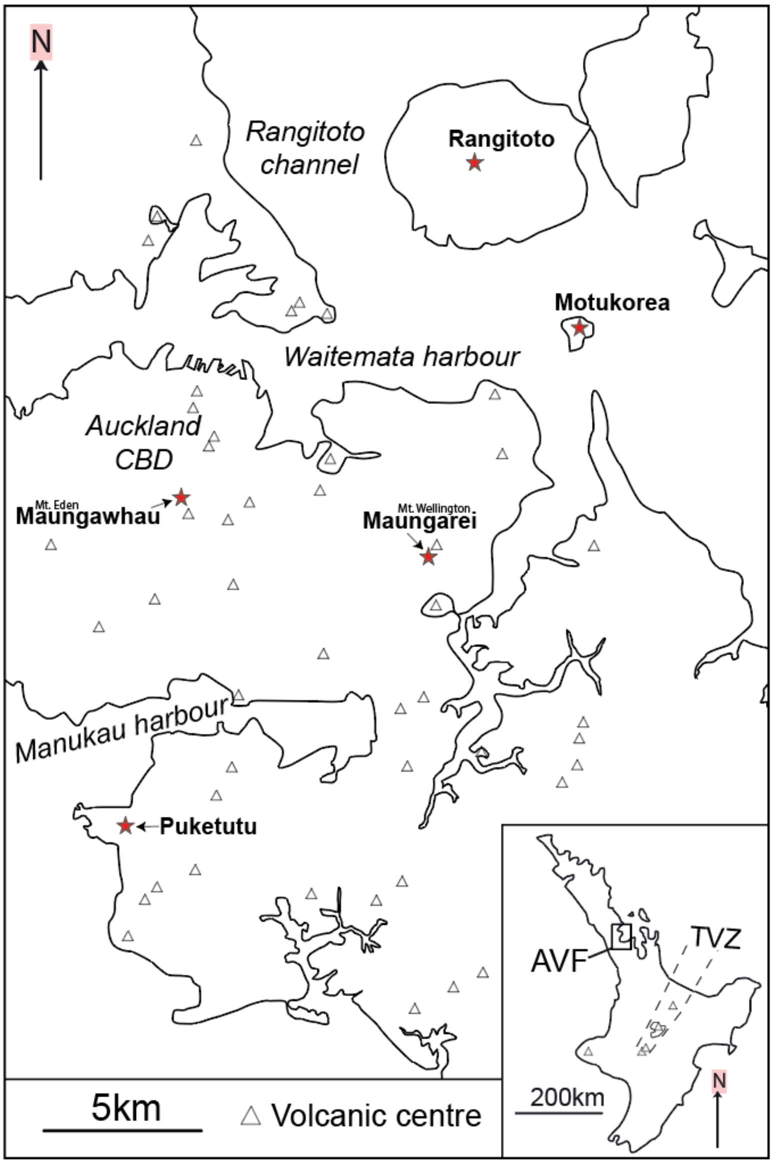

Figure 1: The Auckland Volcanic Field, comprised of 53 volcanoes, sits beneath a heavily urbanised area. Its distal relationship to the Taupo Volcanic Zone (inset, bottom right) is yet to be completely understood.

2. GEOLOGICAL SETTING

The AVF is situated in the North Island of New Zealand and acts as the youngest of a north-trending chain of volcanic fields (Okete, Ngatutura, South Auckland, AVF). There are also two fields further north (Puhipuhi-Whangarei and Kaikohe-Bay of Islands). All 6 fields are intraplate and fall along the Dun Mountain Ophiolite Belt, a terrane boundary considered a key component of the enigmatic system (Adamson, 2008). The AVF encompasses a region often defined by an elliptical area of ~30 x ~20 km. Comprising of 53 centres, it is one of the smallest and youngest fields on Earth (Hopkins et al., 2021).

The origins of the AVF can be traced back to approximately 193,000 years ago when volcanic activity in the region commenced and has continued into modern times, with the last being Rangitoto’s second eruption approximately 500 years BP (Needham et al., 2011). Unlike conventional volcanic settings associated with plate boundaries or subduction zones, the AVF's formation is enigmatic. It lies within the interior of the Australian Plate, far removed from tectonic plate boundaries, making it a distinctive and compelling area of study.

The AVF is composed primarily of alkalic to sub-alkalic basaltic volcanic rocks, typical of other monogenetic volcanic fields (McGee & Smith, 2016). These rocks have been instrumental in deciphering the geological history of the field. The underlying processes that govern the formation and evolution of the AVF are complex and multifaceted.

The five volcanoes chosen for this research, Puketutu (29.8 ± 4.4 ka), Mount Eden/Maungawhau (26.0 ± 0.6 ka), Motukorea (24.4 ± 0.6 ka), Mount Wellington/Maungarei (10 ± 0.4 ka), have been dated with tephrochronology and Rangitoto 2 (504 ± 10 yrs bp) with 14C (Hopkins et al., 2017; Needham et al., 2011). With time between corruptions generally considered to be decreasing (Leonard et al., 2017) excluding Rangitoto 2, the field is still considered active today.

The AVF boasts a diverse array of volcanic features, each volcano with its own unique characteristics. These five centres offer valuable insights as they represent different sizes, ages, and geochemical compositions. Whole rock geochemistry has been conducted on a large percentage of the AVF, with the entire field trending from subalkaline basalts to nephelinites on the total-alkali vs silica diagram (McGee et al., 2011; McGee et al., 2012). This is indicative of a primarily mafic field that as has not approached an intermediate composition, suggestive of limited involvement with the crustal environment.

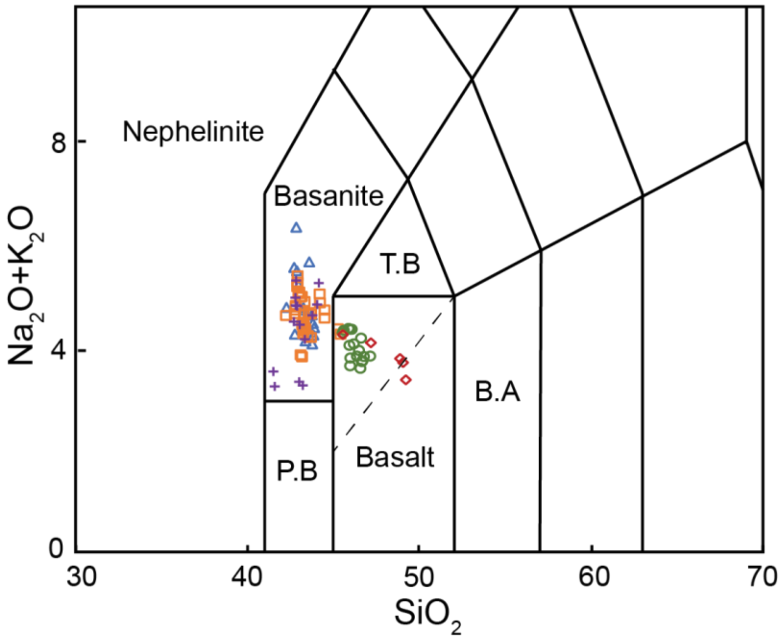

Figure 2: Ranging from basalts below the subalkali line (dashed), to primarily within the basanite field, the volcanoes chosen for this study are closely grouped with regards to total alkali vs SiO_2.

3. METHODS

The methodology employed in this research represents a systematic approach to investigate the petrographic and geochemical attributes of volcanic rocks from the AVF focussing on the mineralogy of lavas. The methodologies outlined below were designed to address the research objectives and facilitate a comprehensive understanding of the magma's ascent to the surface.

3.1 Sample Collection and Preparation

The volcanic rock samples utilized in this research were supplied by the Earth Sciences department of the University of Auckland. These samples (Appendix A) were selected due to their availability and prior work being done on them, mainly whole rock geochemistry, and to represent an important range in the field in terms of age and size. The samples were prepared as 30μm thick, 750 x 250mm polished thin sections for analysis.

3.2 Petrographic Analysis

Preliminary rock descriptions were made using transmitted light microscopy to identify mineral phases and key textures. This step was essential in selecting target features for subsequent imaging and establishing the mineral and rock history.

3.3 SEM Imaging

The SU7000 Scanning Electron Microscope (SEM) at Adelaide Microscopy, University of Adelaide, was used for imaging each sample. Specific features, such as contact boundaries between Olivine phenocrysts and other minerals, zoning patterns within olivines, clinopyroxenes, Fe-Ti oxides, plagioclase, spinel inclusions, melt/glass, and other anomalies were targeted for imaging. The SEM settings used were probe current 50 and accelerating voltage of 15 kV

3.4 Electron Microprobe Analysis

The Cameca SXFive Electron Microprobe was employed for major element quantitative analysis on aforementioned SEM target minerals. The target focus was on the same key minerals and textures as seen in SEM imaging.

Beam current 60-100 nA and 15 kV accelerating voltage was used for all targets/samples, with the spot size 2µm changing depending on what mineral was being targeted. With Cr-Spinel inclusions typically being 2-5µm in diameter, a 2µm spot size was used to collect the most accurate data accounting for proximal contamination and drift-over-time due to longer queues of target locations. This spot size was used for all minerals with the exception of plagioclase, where 5µm was used to compensate for element migration due to the beam. Dwell time was also adjusted per mineral to improve the accuracy of aluminium data collection. This accuracy was necessary for olivine thermometry; therefore, the prolonged dwell time was used specifically for olivine targets.

X-ray spectra were obtained using the EDS detector to enhance the accuracy of mineral identification as well as qualitative elemental abundances for textures only identifiable on the SEM.

3.5 Thermobar

Thermobar, a python script produced by Wieser et al. (2022), was used to test the equilibrium state of olivine and clinopyroxene cores to determine targets for thermobarometry modelling. The program acts as a step-by-step implementation of some of the most commonly used formulas to convert raw geochemical data into analytically presentable tables and figures.

3.5.1 EQUILIBRIUM TESTING

Prior to thermobarometric testing, equilibrium testing was conducted. This is used to establish whether a mineral formed in equilibrium with the melt, or are xenocrysts (a crystal not associated with the magmatic system) or antecrysts (associated with the same magmatic system, but a different magma).

Whole rock data was employed as a proxy for the initial melt composition, facilitating the determination of which olivines and clinopyroxenes were in equilibrium with the melt. This test is to quantify whether tested minerals formed within the melt they were found in. For consistency of olivine testing, Roeder and Emslie's (1970) distribution coefficient (K_D 0.3±0.03) was used as it establishes a single growth trend from equilibrium through crystal evolution without categorizing all olivine cores as xenocrysts as with the Matzen (2011) distribution coefficient (K_D 0.34±0.012). Olivine Sample equilibrium is test dependent, with Roeder & Emslie (1970) allowing for a higher Ol Fo% and broader range to be accepted, while Matzen (2011) is the opposite on both accounts. Consequently, whether or not an olivine is in equilibrium is subject to change depending on which equilibrium test is being used. Clinopyroxene equilibrium was also tested, using Putirka (2008) eq35 as presented by Neave (2017).

3.5.2 THERMOBAROMETRY

Putirka (2008), eq19 Olivine-Liquid thermometer is used to establish a temperature for initial formation of the olivine. From the list of potential equations provided by Thermobar, eq19 was chosen as it was not H_2O dependent and allowed the input of pressures to assess changes. Thermometry test pressure-inputs included 5 kbar (default), 13 kbar as in Chilean tests (Sánchez-Torres et al., 2022) and 20 kbar as in Australia's Newer Volcanic Province (Van Otterloo et al., 2014).

4. OBSERVATIONS AND RESULTS

4.1 Mineralogical and Textural features

The five volcanoes are all comprised of the same primary constituents – Olivine, Clinopyroxene, Fe-Ti Oxides, Plagioclase, and varied amounts of residual glass. However, the abundance, grain size, proportion etc. of these mineral phases make up the major differences between each sample. Each eruptive centre had noticeable normal zoning in the olivine phenocrysts. However, differences were present when considering zoning intensity and crystal size between samples. Additionally, chromium-spinel inclusions were present in a significant number of the olivine phenocrysts in all five samples.

Table 1: Key textures used to identify changes in ascent rates.

Volcano	Olivine Populations	Clinopyroxene Oscillatory Zoning	Fe-Ti Oxide Exsolution	Plagioclase Dominated Groundmass
Rangitoto	1[1]	No	No	Yes
Puketutu	2	Yes	Yes	No
Motukorea	2	Yes	Yes	No
Maungawhau/Mt Eden	2	Yes	Yes	Yes
Maungarei/Mt Wellington	2	Yes	Yes	No

[1] Continuous crystallization resulting in a wide variety of sizes and shapes.

4.1.1 RANGITOTO

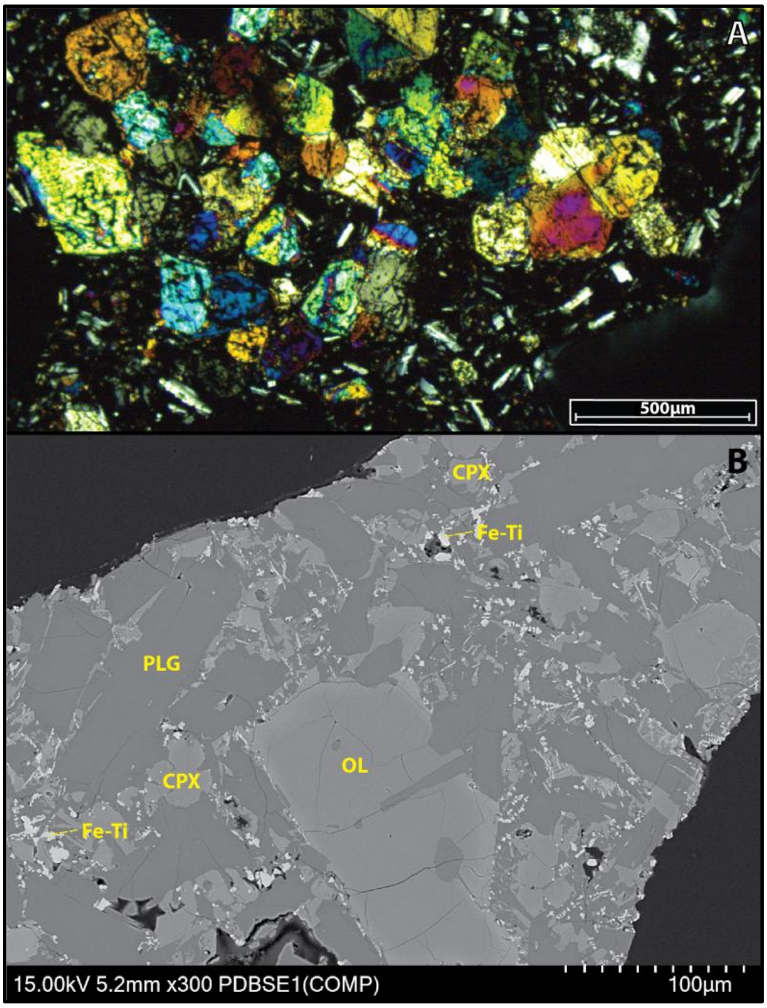

Figure 3: (A) Transmitted Light Microscope (XPL) image of a clinopyroxene glomerocryst within a plagioclase rich groundmass. (B) SEM image of Minimal zoning in olivines, supported by equally large tabular plagioclase feldspar in an Fe-Ti oxide & CPX rich groundmass.

Subhedral olivine phenocrysts are the largest mineral in the sample. These olivines exhibit subtle normal zoning, and potential small amounts of resorption along the rims. There is a second generation of olivines where the zoning is more subtle and a fraction of the size. These make up a percentage of the ground mass that is primarily clinopyroxene and plagioclase feldspar with micro crystalline Fe-Ti oxides. Rangitoto is one of two samples (the other being Puketutu) with the presence of clinopyroxene glomerocrysts.

Exclusively, Rangitoto has less olivine of phenocryst size but an abundance of much smaller, entirely Fe-rich olivine that acts as a constituent to the groundmass. These small olivines do not include Cr-Spinel inclusions. While the spinel is not constrained by the size of the olivine it resides in, and to a lesser extent is not constrained by the location within the zoning profile, they are not found within the groundmass-forming olivine of Rangitoto.

4.1.2 MOTUKOREA

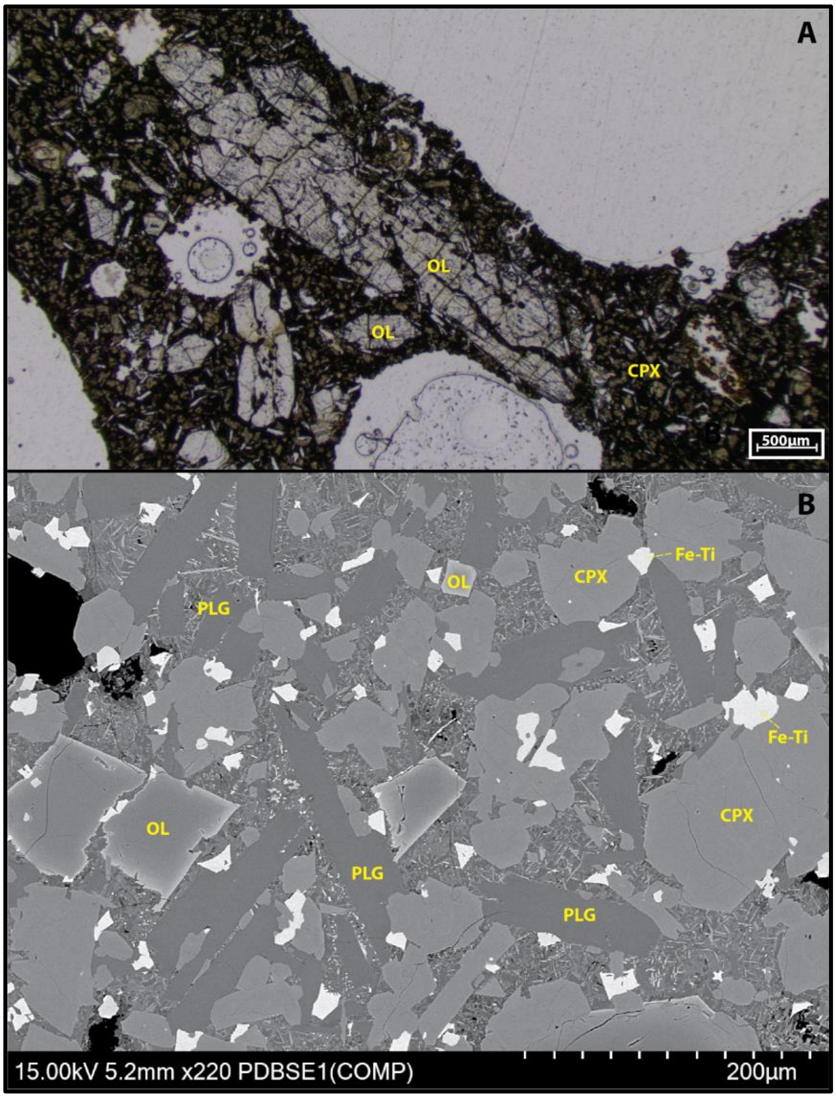

Figure4: (A) Evidence for embayed olivine phenocrysts, indicating disequilibrium and resorption. (B) Representation of the whole rock, revealing tabular plagioclase and olivine/clinopyroxene phenocrysts, as well as smaller constituents of olivines and clinopyroxenes.

Motukorea demonstrates two different populations of olivine with varying degrees of diffuse normal zoning. While the olivines themselves are not as large as other examples the iron rich rims demonstrate much stronger zoning intensities. The pyroxenes range from larger than the olivines to smaller than the smallest olivines and make up a portion of the ground mass. They exhibit the strongest examples of oscillatory zoning out of the five samples. The feldspar in this sample larger than most and almost phenocrystic in size with a tabular elongated shape however exhibit minimal if not no obvious zoning. The iron titanium oxides exhibit extreme lamellae exsolution in oxides that are on the larger end of the five samples.

4.1.3 MOUNT WELLINGTON

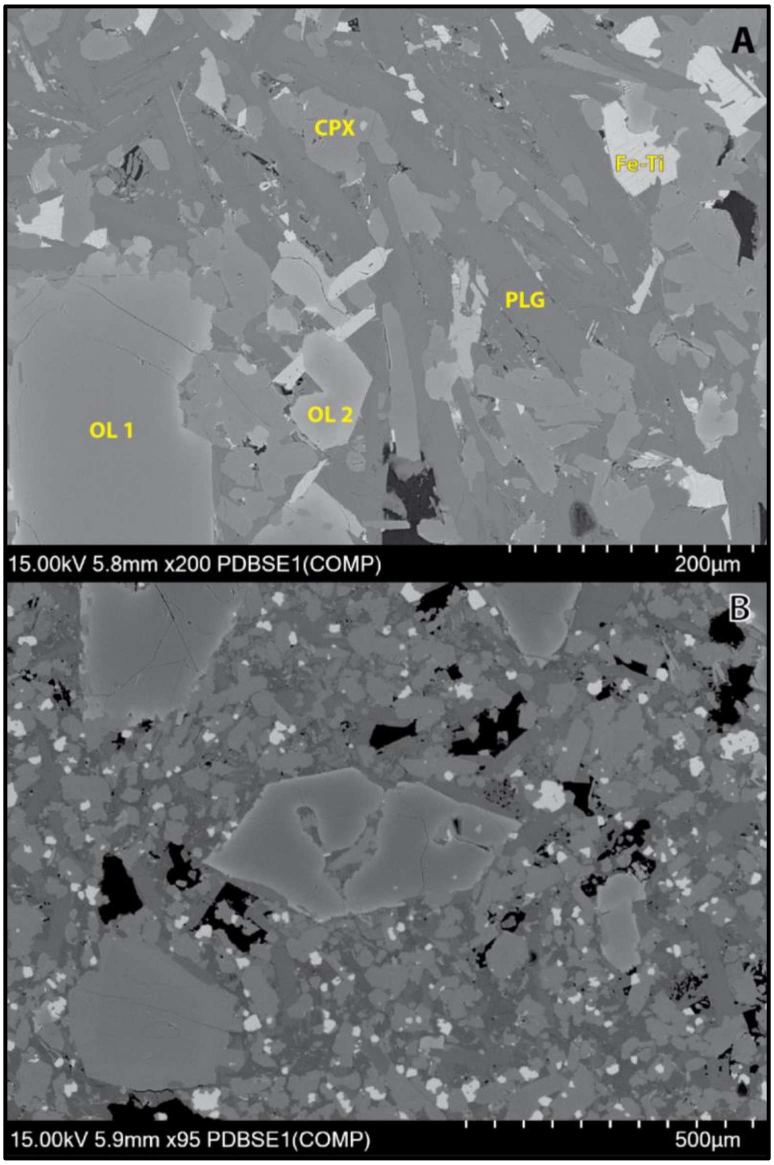

Figure 5: (A) Representative of the whole sample, there are two populations of olivine (OL1 & OL2) hosted in a groundmass of CPX, Fe-Ti Oxides and tabular plagioclase groundmass. (B) Evidence of embayed euhedral olivines with normal zoning, a feature common throughout most samples.

Mount Wellington also has at least two generations of olivine; one is sub to euhedral with embayments and resorption on the rims, and the other is anhedral and has a more iron rich core identified by more subtle zoning and a lighter interior. Clinopyroxene in mount Wellington exhibits some of the strongest demonstrations of oscillatory zoning in some of the largest CPX crystals. These clinopyroxene's also appear to have multiple generations as some pyroxenes rival even the olivines in size while others tend to be constituents of the ground mass. The ground mass appears to be primarily plagioclase feldspar as well as clinopyroxene and iron titanium oxides. Additionally, this thin section contained apatite. The presence of this accessory mineral is a sign there is more to be found in a comprehensive mineralogical study using advanced methods such as SEM analysis.

4.1.4 MOUNT EDEN

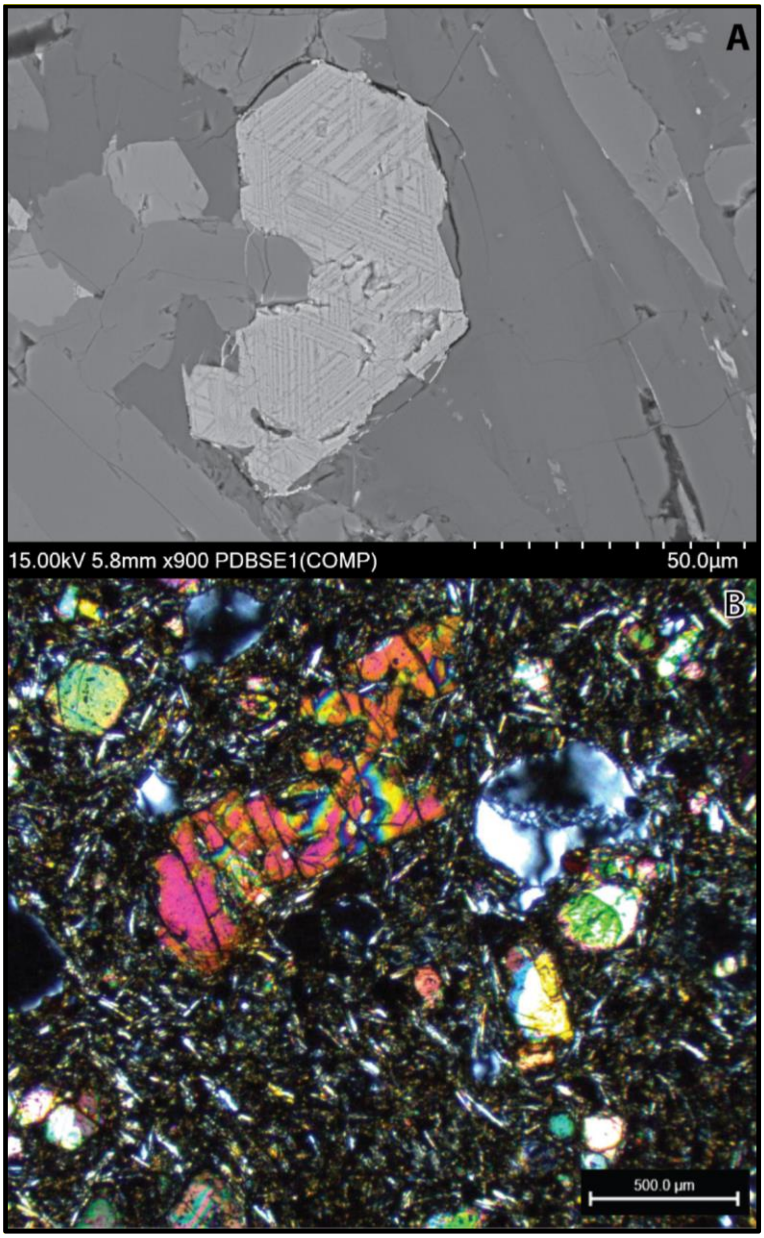

Figure 6: (A) Mt Eden shows clear evidence of lamellae exsolution within Fe-Ti Oxides, (B) Skeletal olivine with characteristic branching out of crystal structures due to rapid cooling.

Mount Eden has some of the largest olivines of the samples the largest of which have a significantly less diffuse zoning with a sharper iron boundary on the edges. There is also a second generation of olivine which has nucleated with a magnesium rich core and very little zoning. The iron oxides in Mount Eden also exhibit the same lamellae features as in the other centres (except Rangitoto). The clinopyroxene varies in size from hundreds of microns down to filling voids in the plagioclase rich groundmass.

4.1.5 PUKETUTU

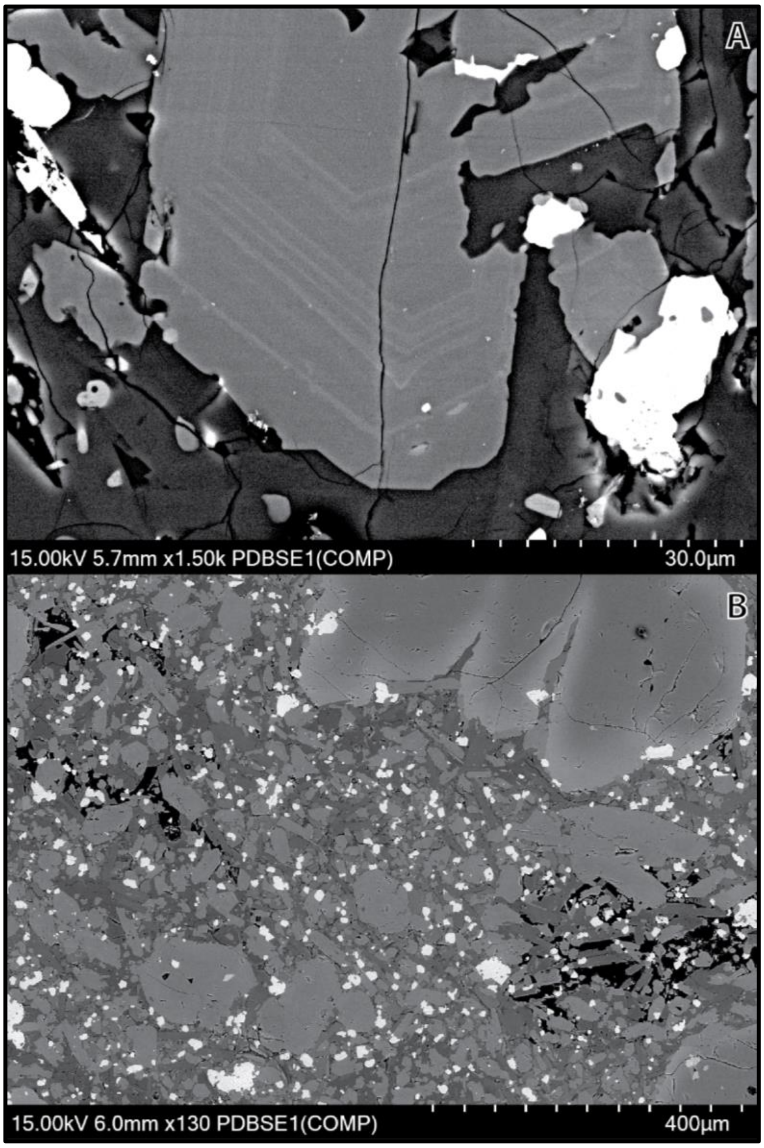

Figure 7: (A) Elemental oscillatory zoning in a small clinopyroxene, (B) Representative

Puketutu contains large olivine phenocrysts with normal zoning, that have undergone embayments. They range from euhedral to anhedral with no clear relationship with size. Additionally, the olivines contain spinel inclusions within both core and rims. These phenocrysts sit alongside subordinate clinopyroxene phenocrysts in a groundmass of

CPX, plagioclase, Fe-Ti oxides and glass. Clinopyroxene exhibits common oscillatory zoning, as well as the widest range of grain size.

4.2 Mineral Chemistry

4.2.1 OLIVINE

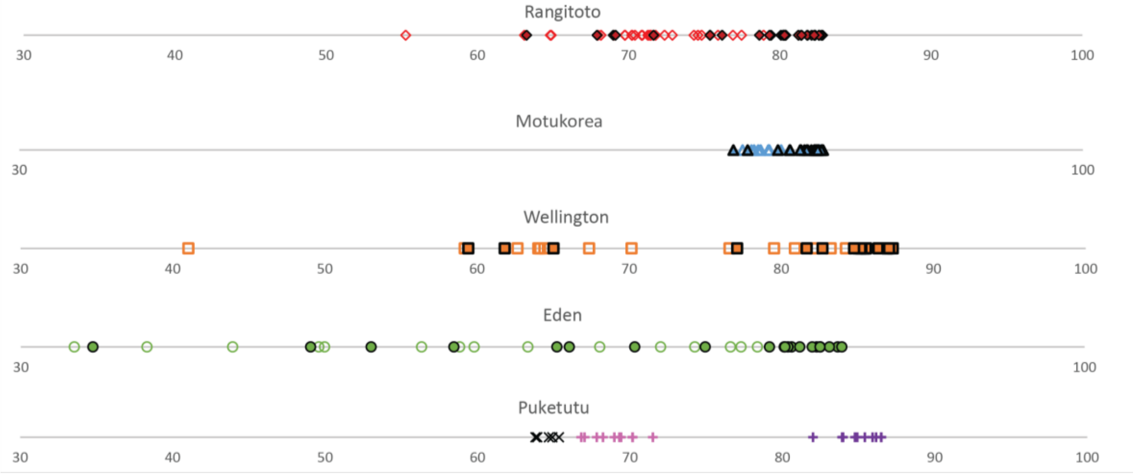

Figure 8: Olivine Forsterite content separated into cores and rims, indicating compositions of melt at the point of crystallisation. Solid black outlines and darker colours indicate cores with hollow coloured outlines showing rims. Black crosses in Puketutu are a separate generation with Fe-rich cores.

Olivines of the AVF have different starting compositions ($Fo_{84.7\pm2.7}$) and undergo different degrees of evolution (Figure 8). Rangitoto, Mount Wellington and Mount Eden all have a wide range of olivine compositions for both core and rim. Motukorea shows very little variance between all olivines, with little emphasis on cores (Fo_{77-83}) or rims (Fo_{78-83}). This makes it a curiosity, as there are visible zoning differences, but no variation in Fo%. Puketutu stands alone as the most significant core (Fo_{82-86}) to rim (Fo_{66-71}) comparison, while also having a separate generation of greater Fe cores (Fo_{64-65}).

4.2.2 CLINOPYROXENE

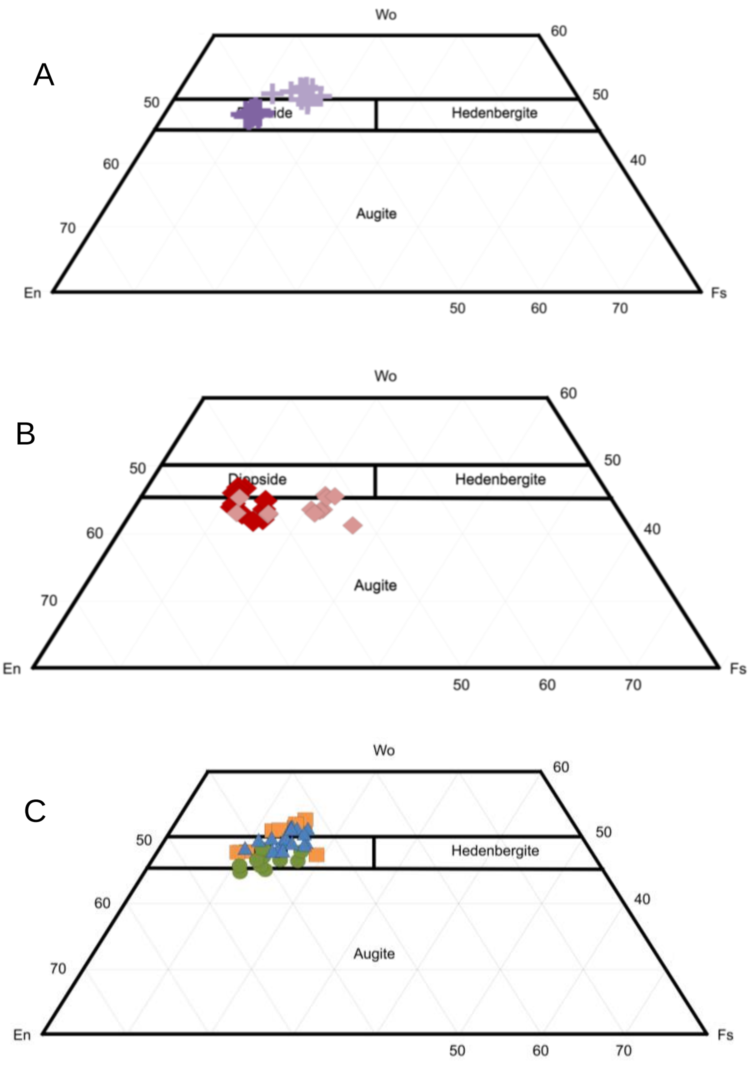

Figure 9: CPX characterized using trilinear analysis to determine the type of pyroxenes. (A) Puketutu indicating a diopside core with an evolution to Ca-rich rims within the Wo field. (B) Rangitoto also exhibiting composition zoning along the diopside-augite boundary with increasing Fe while maintaining Ca%. (C) The remainder of the clinopyroxenes did not exhibit identifiable zone groupings, however, do primarily plot within the diopside field.

The clinopyroxenes all tend to plot within or near the diopside field (Figure 9), as well as on the boundary of and into the wollastonite endmember field. Additionally, they display clear grouping in cases such as Puketutu, and Rangitoto. Mt Wellington, Puketutu and Motukorea all exhibit subtle, thin oscillatory zoning in clinopyroxene. This zoning was visually detectable on the SEM, but due to the size of the oscillations (approximately 2um wide) and subtlety, they could not be targeted on the microprobe for quantitative geochemical analysis. All clinopyroxenes contained in the target volcanoes are categorized by a more Ca rich composition than previously cited studies suggesting they are primarily Augite.

4.2.3 FELDSPAR

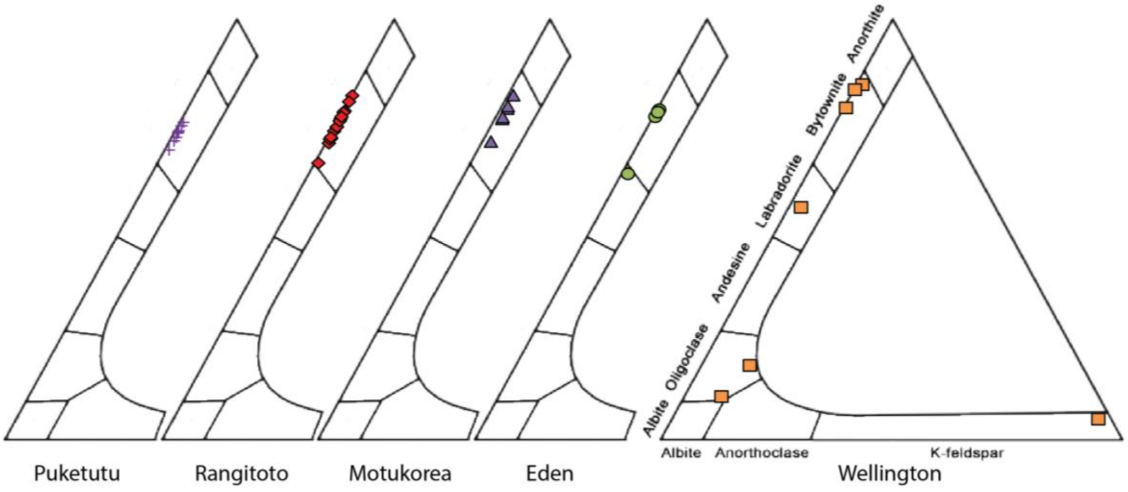

Figure 10: Feldspars of these samples consistently plot as Bytownite on an An-Ab-Or ternary diagram, with the exception of Mt Wellington. Mt Wellington shows significant outliers.

Feldspars from Puketutu, Rangitoto, Motukorea and Mt Eden all plot as Plagioclase Feldspar, categorized almost exclusively as Bytownite (Figure 10). Mt Wellington does not adhere to this trend, with values ranging from albite to orthoclase. It is unclear whether these are accurate geochemical targets, or accidental glass targets.

Plagioclase feldspar is primarily found in the groundmass for all five volcanoes; however, the abundance and prominence vary. Rangitoto and Mt Eden have plagioclase dominated groundmass while Mt Wellington and Motukorea have proportionally less. The latter are primarily clinopyroxene, but still have plagioclase present as a common groundmass mineral.

4.2.4 IRON-TITANIUM OXIDES

Fe-Ti Oxides are a major part of these volcanic rocks, as a common aspect of the groundmass within all five volcanic centres. They range in size and shape but are primarily <100µm and anhedral in shape. There are particularly small inclusions of Iron Titanium Oxides found within phenocrysts of Rangitoto – a feature not observed in any other samples.

Like the CPX, the oxides contain a texture that was too subtle to target on the microprobe, with lamellae Ti exsolution a common occurrence in Mt Eden, Motukorea and Puketutu. At <1-5um thick, targeting becomes difficult for a number of reasons when using the microprobe. Puketutu also has a second variant of exsolution. Rangitoto and Mt Wellington do not have apparent lamellae despite the similar abundance of oxides throughout. A particularly subtle feature when looking at these oxides is a thin non-exsolved rim.

4.3 Equilibrium Testing

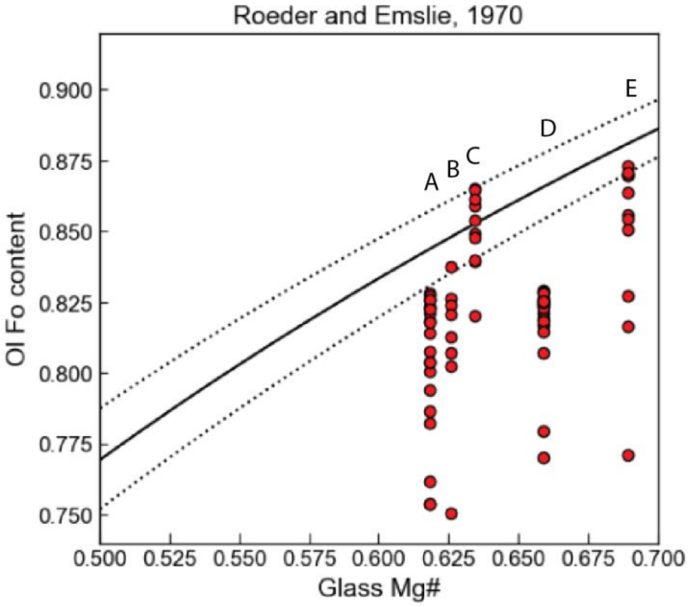

Figure 11: Rangitoto (A), Mt Eden (B), Puketutu (C), Motukorea (D) and Mt Wellington (E) olivine core targets for equilibrium tests. Points between the dotted lines are considered to be from the same melt that made the sample lava. Points below are considered more evolved than olivine formation should be based on the melt composition and are considered antecrysts.

Only three volcanoes indicate equilibrium olivine crystallisation (Mt Wellington, Mt Eden and Puketutu), with varying abundances (Figure 11). Rangitoto and Motukorea indicate the formation of their olivines are from prior magmatic batches by plotting below the K_D range.

Clinopyroxene equilibrium tests against Putirka (2008) eq35 all returned a result of disequilibrium. While this provides valuable insight into the processes resulting in magmatic evolution beneath the surface, the results have been discarded for the purposes of thermobarometry.

4.4 Thermometry

Only 3 volcanoes indicated the formation of olivine in equilibrium with our proxy melt. The thermometry results produced by the test used were pressure dependent, consequently producing a large variance. At 5 kbar (0.5GPa), Thermobar suggests olivine crystallisation temperatures ranging from 1316°C to almost 1360°C (Appendix A). Increases in pressure inputs resulted in increases in estimated temperatures by as much as 200°C. As these temperatures are considerably higher than they should be (based on the pressure used), compared to global monogenetic fields (Coote & Shane, 2018; Harder & Russell, 2006; Van Otterloo et al., 2014), and clinopyroxene formation PT was incalculable due to disequilibrium, thermobarometry results are not considered in the discussion.

5. DISCUSSION

The exploration of various textures, equilibrium indicators, and other characteristics that reflect variations in the speed of processes is a key aspect of our study. Although thermometry results were excluded from our analysis, the examination of equilibrium offers valuable insights.

Our study delved into the comprehensive investigation of five lava samples, focusing on petrography and mineral chemistry. Notably, we observed substantial similarities in textures across different centres, while the overall mineral compositions remained relatively consistent. To gain a deeper understanding of the connection between petrography and the history of magma ascent, it is important to contextualize these textures within potential cause models.

5.1 Mineral Textures

5.1.1 OLIVINE

In the context of our study, the presence of iron-rich rims within crystals can be attributed to the crystallization process during the course of an ascending melt's evolution. Variations in the intensity of gradient within these rims can be indicative of changes in the rate of ascent. This phenomenon is a consequence of the relationship between the speed of magma ascent and the subsequent cooling rate of minerals (Mollo et al., 2015). When magma ascends at a faster pace, minerals experience more rapid cooling, leading to the extraction of elemental constituents from the liquid. Consequently, this results in a narrower range of available elements for olivine to incorporate into its structure. It is integral to emphasize that our examination has revealed a notable contrast in olivine zoning patterns, characterized by slow and diffuse zoning. This is in stark contrast to instances of rapid olivine zoning, such as those observed in the case of Motukorea.

Skeletal olivines (Figure 6) and embayed olivines (Figure 5) play a crucial role in discerning the rates of magma ascent in volcanic and igneous rock systems. These distinct features offer valuable insights into the history of crystallization and cooling within magmatic systems. Skeletal olivines, characterized by their intricate, dendritic crystal shapes, are typically associated with rapid magma ascent (Jankovics et al., 2019). The formation of skeletal olivines is thought to result from a situation where crystal growth outpaces the diffusion of material from the surrounding magma (Ruprecht & Welsch, 2023). This can occur in scenarios of fast ascent when there is insufficient time for equilibrium to be reached between the crystal and the surrounding melt. As a result, the olivine crystals grow with extended arms or skeletal structures. Conversely, embayed olivines, characterized by their partially dissolved or corroded appearance, are indicative of slower magma ascent. Embayed features occur when olivine crystals partially dissolve or undergo resorption due to contact with the surrounding melt. This resorption is facilitated by the olivine crystal's limited ability to incorporate elements from the surrounding magma in a relatively sluggish ascent scenario. The embayed appearance arises from the dissolution of olivine at the crystal-magma interface, leading to irregular, recessed boundaries on the crystal. These observations align with established geological principles.

The rate of magma ascent is a key factor in determining the interactions between minerals and the surrounding melt. As magma ascends rapidly, minerals, like olivine, are 'frozen' into their crystal structure before complete equilibrium can be achieved, resulting in skeletal olivines. In contrast, slow magma ascent allows for a more thorough exchange of material between the crystals and the melt, leading to the formation of embayed olivines.

5.1.2 CLINOPYROXENE

Clinopyroxene shows evidence for both early and late crystallisation throughout the lavas, as they are present as both subordinate phenocrysts and a groundmass mineral (Figure 5). The larger of these phases often contains normal and oscillatory major element zoning. Consider these subtle compositionally different zones to be a result of a change in a part of the system that is resulting in minor changes in equilibrium states. One potential cause is the precipitation of these CPX along the walls of the plumbing (Smith et al., 2008). Oscillations in crystals such as CPX (Figure 7) can act like rings on a tree, revealing system conditions as the mineral grows (Ubide et al., 2021). As such, these textures may indicate prolonged exposure to changes in pressure, temperature and the melt it is present in.

5.1.3 IRON-TITANIUM OXIDES

The lamellae exsolution present in the oxides (Figure 6) of all samples except Rangitoto indicate a change in ascent rates. This cloth-like texture is thought to show slow-ascent, with likely titano-hematite and ilmenite as the exsolution. Turner et al. (2008) suggest the abundance of these exsolved oxides is the key indicator of the speed of ascent. Fast-ascending magmas may contain this texture; in each sample, at least a handful of Fe-Ti oxides will present lamellae exsolution. However, it is the overabundance of this texture that indicates a higher chance of a slower ascent, and it is a common texture within several samples (Turner et al., 2008).

In some examples, there is a ring of non-exsolved oxides surrounding the lamellae. A consistent white rim surrounding these minerals that contains no exsolution is an example of a change in a more rapid cooling event during mineral growth. The interior of the oxide has had enough time for the texture to form, whereas the outside has not been subject to the conditions or time to exsolve.

5.2 Equilibrium Testing & Thermobarometry

Equilibrium testing was initially completed to establish appropriate thermobarometric targets. Due to all clinopyroxenes being out of equilibrium, and consequently their Pressure-Temperature results being discarded, only the olivine temperatures remain. However, the amount of data available over the three volcanoes that provide equilibrium-positive results is limited and show variations difficult to contextualize. Instead, the abundance of minerals in disequilibrium provide another valuable insight into ~~the~~ processes involved in melt ascent. The existence of minerals out of equilibrium with the melt they've been found in, but not evidently xenocrysts, indicate slower ascent, stalling or storage until they are liberated into the latter melt.

5.3 Monogenetic Models

Explanations for changes in ascent noticeable in aforementioned features can be explained by two preestablished models regarding deep earth plumbing processes in monogenetic volcanoes; deep-seated fractionation, and complex dyke systems.

5.3.1 FRACTIONATION

During deep-seated fractionation, as magma rises through the Earth's mantle, it can become enriched in certain minerals, including clinopyroxenes with distinctive crystal structures and compositions. As the mantle-derived magma moves upward, it undergoes changes in pressure and temperature, which can cause certain minerals like clinopyroxenes to crystallize and settle out of the melt. One proposed model, suggested in a Crater Hill case study, proposes that clinopyroxenes precipitate along the walls of the magmatic plumbing system, leading to their removal from the initial melt (Smith et al., 2008). This process subsequently introduces these clinopyroxene crystals into a later iteration of the melt. Consequently, this mechanism contributes to the observed disequilibrium within the geochemical equilibrium tests conducted. It can also be used to explain the oscillatory zoning within these clinopyroxenes as they continue to be subject to longer crustal storages and changes in melt chemistry over time.

In tandem with our examination of zoning patterns in clinopyroxenes, the intricate lamellae exsolution patterns within iron oxides provide additional evidence to support the notion of deep-seated fractionation (DSF) as a pervasive process in magmatic systems. These exsolution patterns signify a transition from a slower ascent phase to a more rapid ascent phase, suggesting prolonged crustal storage for minerals beyond just clinopyroxenes. The presence of exsolved cores surrounded by unexsolved rims in iron oxides is a testament to the protracted periods of residence and mineral evolution within the magma. As the ascending melt finally experiences a late-stage rapid ascent, it leads to conditions that hinder further exsolution. This multi-mineral evidence underscores the significance of DSF in shaping the complex mineralogical compositions within magmatic systems and emphasizes the dynamic nature of magma ascent, which impacts a spectrum of minerals.

It is important to consider that the Smith et al. (2008) model does not contest the evidence that has supported preestablished rapid-ascent theories (i.e. Crustal contamination of the melt). This is because mineral precipitation along the plumbing channels provide insulation between ascending magmas and the country rock, preventing assimilation or incorporation of xenocrysts.

5.3.2 COMPLEX DYKES

A second model suggesting prolonged crustal storage without the incorporation of melt reservoirs is that of complex dyke systems resulting in slowing, stalling, and prolonged magma ascent (Brenna et al., 2011). The exploitation of the Dun Mountain Ophiolite Belt and its permeability, thought to extend from the base of the crust (Adamson, 2008) could accommodate lateral deviations in the plumbing where minerals accumulate and evolve separately from their source melt, before re-joining somewhere in the crust to remix before rapid ascent. These pathways could provide avenues for melt ascent where melt flows at the same speed, but a less direct ascent sees decreased impacts by pressure and temperature gradients.

5.4 Hazard Implications

Because the field is still considered active, there is a non-insignificant likelihood that there will be another eruption. Due to a lack of indication where the next eruption might occur within the AVF, it is difficult to predict where and what kinds of dangers will occur during said eruption. Seismology is a key way of detecting the magma moving through the crust on its way to the surface. Unfortunately, if the final stages of ascent are as rapid as some of this crystallisation suggests, warnings will be shorter than ideal and putting the people of Auckland at greater risk of danger. To avoid this issue in the future, it is important to understand the processes that cause the textures evident in these lavas and to associate these processes with means of detecting them. Seismographs already have difficulties collecting data under Auckland due to urbanisation, but the ability to detect earlier, slower stages of magma ascent and/or storage can be integral to improved alert systems.

6. CONCLUSION

Based on the extensive research conducted within the Auckland Volcanic Field, it is evident that the previously assumed simplicity of source-to-surface rapid ascent magmatism does not entirely capture the full complexity of the geological processes at play. The investigation into the mineral textures and associated attempts at thermobarometry have unveiled a more intricate narrative beneath the surface.

The employment of scanning electron microscopy (SEM) has been instrumental in this endeavour, particularly in identifying key mineral textures that challenge the initial hypothesis. Notably, the prevalence of oscillatory zoning in clinopyroxene and the presence of lamellae exsolution both suggest a slower and more multifaceted subsurface magmatic history. Moreover, microprobe geochemical testing has played a pivotal role in geothermobarometric modelling, aiding in the quantitative analysis of these textures observed via SEM.

While the thermobarometry results may not have yielded the expected outcomes, the equilibrium testing prior to thermobarometry has significantly reinforced the concept of a complex plumbing system. The disequilibrium exhibited by the majority of clinopyroxenes and olivines indicates a subsurface storage phase followed by ascent during a subsequent melt event. This delay in ascent is further substantiated by the presence of lamellae exsolution, which suggests a deceleration in the magmatic ascent process.

The diverse characteristics observed in olivines, from more diffuse to more abrupt zoning, and the varying features of embayed and skeletal olivines, reveal distinct ascent rates within the volcanic field. Oscillatory zoning implies extended interactions with fluctuating pressure and temperature conditions, adding further layers of complexity.

Collectively, these findings suggest a mosaic of variable ascent rates, potentially varying not only between different volcanoes within the field but also within the same volcanic structure. Future research in this area holds great promise, especially in employing diffusion rates and embayments to precisely determine ascent rates. Additionally, significant variance between mineral chemistries and morphologies Enhancing our understanding of these ascent rates will be pivotal in advancing volcanic forecasting, particularly in the context of monogenetic systems. This knowledge will contribute to improved hazard assessment and preparedness, ensuring the safety of communities in volcanic regions.

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APPENDIX A: GRAPHS, TABLES & DIAGRAMS

SAMPLE #	AVF #	VOLCANO
43375	AVF-568	MOTUKOREA
62410	AVF-924	MT. WELLINGTON
52329	RA-AN-75	RANGITOTO 2
59464	AVF-750	MT EDEN
62380	AVF-886	PUKETUTU
62381	AVF-887	PUKETUTU

Table A.1. Sample numbers and their associated volcanoes, catalogued by University of Auckland, New Zealand.

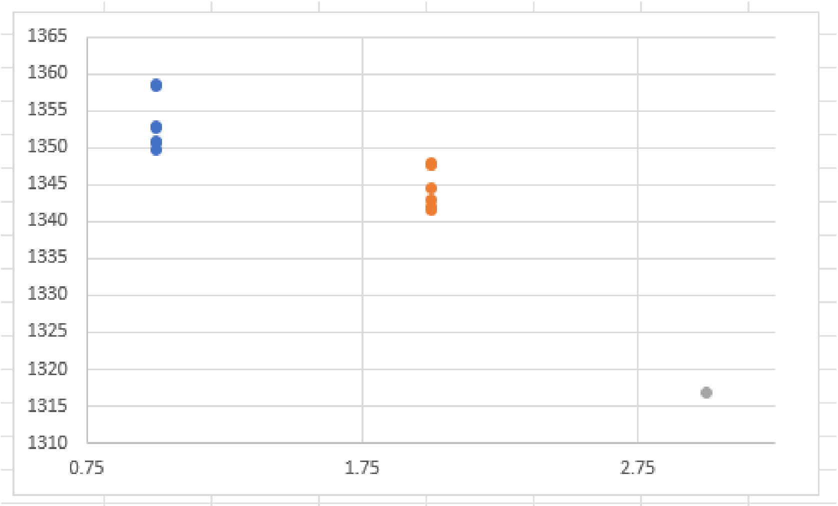

Table A.2. Results from thermometry testing by Putirka (2008) Ol-Liq test via Thermobar

APPENDIX B: SEM IMAGES

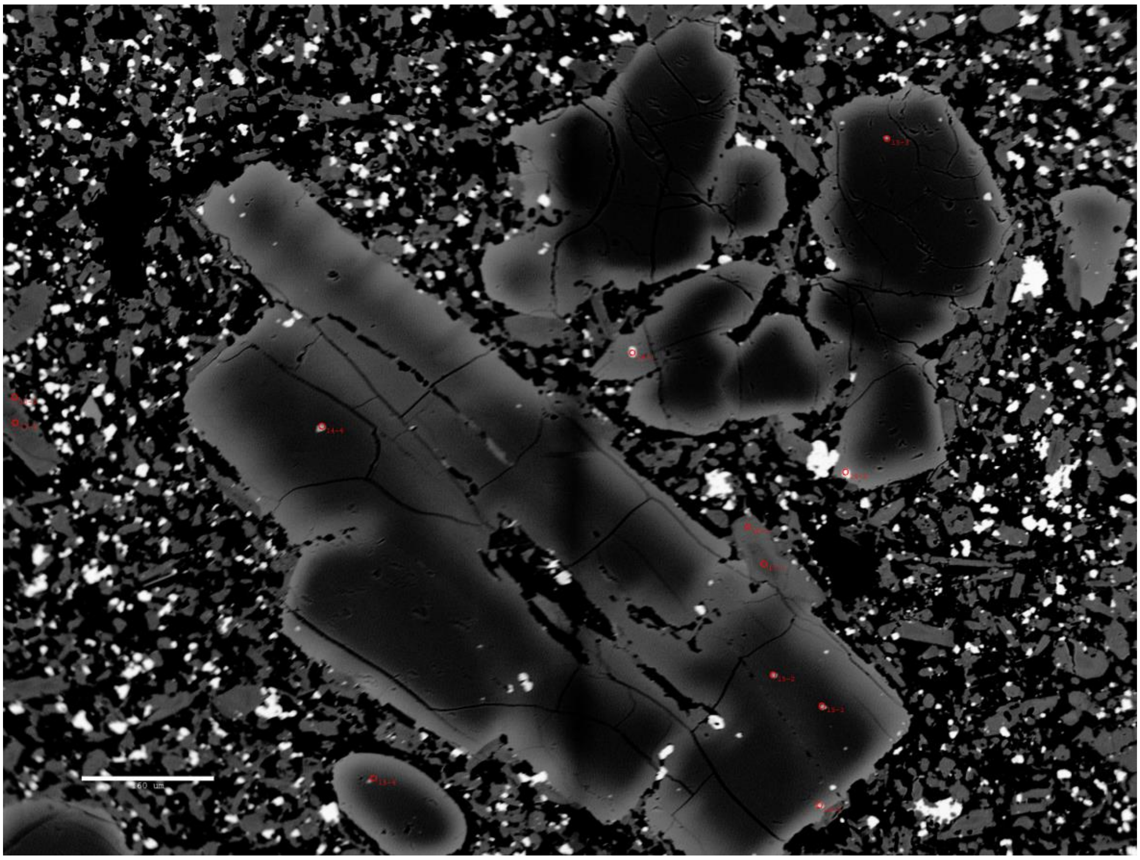

Table B.1. Puketutu olivine with probe targets for Cr-spinel, with contrast adjustment to extenuate elemental zoning