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**Controls on the architecture and dynamics
of the Campi Flegrei magmatic system in
the last 15 kyr**

Thesis Dissertation for Doctor of Philosophy
School of Natural Sciences
Discipline of Geology

by

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2025

Declaration

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A handwritten signature in black ink, appearing to read 'f amstutz', is written over a horizontal line.

Fay Amstutz

Summary

This thesis aimed to investigate controls on the architecture and dynamics of the Campi Flegrei magmatic system in the last 15 kyr, using a combination of modelling and geochemical analysis. An introduction outlining the motivation for investigating eruptions at long-lived caldera systems and Campi Flegrei as a case study is presented in **Chapter 1**. In addition, the specific knowledge gaps addressed in this thesis, and the aims and objectives of the study, are outlined. The results are presented in three core chapters (Chapters 2–4):

In **Chapter 2**, we investigated controls on the major element variation between eruptions in the last 15 kyr at Campi Flegrei, modelling this using Rhyolite-MELTS thermodynamic models. We used models of fractional crystallisation and assimilation-fractional crystallisation to constrain storage conditions and assimilation processes and determine how these varied for eruptions across the caldera.

In **Chapter 3**, the main objective was to further constrain assimilation, identified as an important process in magma evolution at Campi Flegrei in the previous chapter. We used stable and radiogenic isotopic analysis of eruptions to investigate how assimilation processes varied across the caldera. Comparison with the isotopic composition of potential crustal contaminants and modelling of the observed isotopic variation allowed us to constrain the composition of the assimilant and extent of interaction.

In **Chapter 4**, we investigated the record of magma evolution preserved within individual crystals, using clinopyroxenes from Minopoli 2 and Astroni 6 eruptions which we identified as isotopic end-members in the previous chapter. We combined analysis of crystal textures, trace element mapping, in-situ Sr isotope analysis and thermobarometry to construct a detailed picture of the sub-volcanic plumbing system.

A summary of the findings of this thesis and their implications for Campi Flegrei and more broadly are summarised in **Chapter 5**, as well as a discussion of some potential avenues for future research.

Abstract

Controls on the architecture and dynamics of the Campi Flegrei magmatic system in the last 15 kyr

Fay Amstutz

Caldera-forming volcanoes typically remain restless over long time periods following major collapse events; this continued activity provides a unique hazard as subsequent vents are disseminated across a wide area within the pre-existing collapse structure. One such volcano is Campi Flegrei (Naples, southern Italy), considered one of the most hazardous volcanoes on Earth having produced >70 eruptions in the past 15 kyr, and currently showing significant signs of unrest within a densely populated part of Europe. Post-15 ka eruptions span a range of eruptive styles (effusive lava domes to Plinian events) and compositions (shoshonite to trachyte-phonolite), which broadly correlate with the spatial and structural location of vents within the large caldera. These compositional and eruptive differences suggest an intrinsic link between their volcano-tectonic setting and processes operating within the sub-volcanic magmatic system. This thesis uses a combination of geochemical analysis and modelling to investigate controls on the architecture and dynamics of the Campi Flegrei magmatic system in the last 15 kyr.

We first investigated the major element variation between eruptions in the last 15 kyr, using Rhyolite-MELTS thermodynamic modelling. We tested models of fractional crystallisation of a single parental magma, which allowed us to constrain the most likely storage conditions but could not fully reproduce the observed major element variation. However, models of assimilation-fractional crystallisation improved the measured fit between modelled and observed compositions across the caldera. The assimilant composition which produced the best-fit model varied across the caldera. Compositions of eruptions from the caldera rim were best reproduced by models where small amounts of Palaeozoic metamorphic basement was added, whereas erupted compositions from the centre and west of the caldera were best reproduced by adding syenite to the models.

Characterising the oxygen, strontium, neodymium and lead isotopic composition of mineral and glass separates from post-15 ka Campi Flegrei eruptions, alongside basement rocks which may have contaminated the magmas, permitted further investigation of assimilation processes, and whether interaction between magma and country rock varies across the caldera. We found significant variation in isotopic composition between eruptions, which we attribute to assimilation of crustal material. Comparison with the isotopic composition of the basement rocks suggests small amounts of Palaeozoic metamorphic basement contaminated eruptions from northern/eastern caldera rim faults, whereas more extensive interaction with syenitic restite affected the isotopic composition of eruptions from the centre and west of the caldera, in agreement with our thermodynamic modelling of major element variation.

Processes occurring before volcanic eruptions are also preserved in crystals formed within the sub-volcanic plumbing system. We combined imaging of crystal textures, trace element mapping, in-situ Sr isotope analysis and thermobarometry in clinopyroxenes from Minopoli 2 and Astroni 6 eruptions of Campi Flegrei, to investigate magma evolution at the crystal scale. This revealed a magmatic history of fractional crystallisation, assimilation, magma recharge and mixing before eruption, within a complex sub-volcanic plumbing system. Comparison between eruptions suggests these processes operate with different frequencies, likely linked to the contrasting volcano-tectonic settings of each vent.

The results of this thesis provide new insights on processes operating in the sub-volcanic magmatic system beneath Campi Flegrei prior to an eruption and demonstrate an important link between these processes and the spatial and structural location of vents within the caldera.

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List of abbreviations

AFC	assimilation fractional crystallisation
ATA	assimilation during turbulent ascent
BSE	back scattered electron
CI	Campanian Ignimbrite
EC-AFC	energy constrained-assimilation fractional crystallisation
EPMA	Electron Probe Microanalysis
FC	fractional crystallisation
ka	kilo annum
kyr	kilo years
LA-ICP-MS	Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry
NYT	Neapolitan Yellow Tuff
SEM	scanning electron microscope
XRF	X-ray fluorescence

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1. Introduction

1.1 Thesis context

This thesis aims to investigate controls on the architecture and dynamics of magmatic systems at long-lived calderas, using the case study of Campi Flegrei, Italy. Processes operating within crustal magma systems control the composition, style and timing of volcanic eruptions at Earth's surface, making detailed understanding of these processes important for hazard forecasting at active volcanic systems.

1.1.1 Magma evolution at long-lived restless calderas

Caldera-forming volcanoes have been recognised worldwide, in all volcanic environments on Earth. These volcanoes have the potential to produce huge eruptions but such events are rare (Mason *et al.*, 2004). More commonly, they remain active over long time periods, producing smaller eruptions of varying style, size and composition following caldera collapse (Cole *et al.*, 2005). These long-lived, restless systems pose significant hazards especially when close to densely populated locations (Orsi *et al.*, 2004).

Post-collapse eruptions often span a wide range of styles and erupted magma compositions. As magma composition controls magma rheology and chemical properties (e.g. viscosity, volatile solubility) which impact the style of eruption (Cassidy *et al.*, 2018), investigations into the controls on magma evolution are crucial. Compositional variations in erupted products are controlled by complex processes operating within the sub-volcanic crustal magma system, including magma differentiation, mixing and mingling of magmas and assimilation of surrounding country rock (e.g. Anderson, 1976; DePaolo, 1981) in addition to mantle heterogeneity (Pearce and Peate, 1995; Annen *et al.*, 2015).

Post-caldera eruptions also typically occur in different spatial locations across the caldera system, including along caldera ring faults and regional lineaments (Acocella *et al.*,

1999). Some studies have begun to link the structural setting of eruption vents across a caldera to crustal processing. For example, Saxby et al. (2016) demonstrated a link between regional fault patterns and location of magma storage at Ilopango caldera (El Salvador) on the basis of gravity surveys, whereas Carracedo et al. (2007) noted compositional variation of eruptions in different locations across Tenerife (Canary Islands). However, the relationship between volcano-tectonic structures and sub-volcanic processes is poorly understood; it is unclear if structural controls impact magma system dynamics.

1.1.2 Petrological investigation into magma storage

Petrological investigations into the products of past eruptions are critical in understanding controls on magma composition and reconstructing magmatic processes prior to eruption. These approaches also inform the interpretation of monitoring data of current unrest, where techniques such as analysis of seismicity, deformation and gravity changes are often interpreted in the context of processes constrained from the petrological investigation of past eruptions (Blundy and Cashman, 2008; Jerram *et al.*, 2018). A number of petrologic methods are frequently employed to constrain magma evolution, each of which is suited for answering different questions surrounding sub-volcanic processes. The techniques used in this study are outlined briefly below.

1.1.2.1 Thermodynamic modelling

Thermodynamic modelling of magma evolution calculates the stable phase assemblages and compositional changes that occur as magma cools and crystallises. These models are typically based on minimisation of free energy, with the thermodynamic properties of each phase calibrated from experiments (Gualda *et al.*, 2012). Through systematically varying model crystallisation conditions (pressure, oxygen fugacity, initial melt major or volatile element composition) and comparing with the abundance and composition of phases observed in natural erupted products, modelling can constrain magma storage conditions. Various tools have been developed to facilitate thermodynamic modelling, including

Petrolog (Danyushevsky and Plechov, 2011), MAGEMin (Riel *et al.*, 2022) and the MELTS family of models (Ghiorso and Sack, 1995). In silicic systems, the Rhyolite-MELTS software is most commonly applied; it differs to its predecessor MELTS in the stability fields of quartz and sanidine, making it appropriate for modelling phase relations in hydrous silicic systems (Gualda *et al.*, 2012). The most recent version of Rhyolite-MELTS (v.1.2.) has a coupled H₂O-CO₂ fluid saturation model and the most comprehensive calibration dataset to date (Ghiorso and Gualda, 2015). It has been used to model phase equilibria and constrain magma storage conditions in diverse volcanic systems (e.g. Peach Spring - Pamukcu *et al.*, 2015; Aluto - Gleeson *et al.*, 2017; Villarrica - Boschetty *et al.*, 2022).

1.1.2.2 Isotopic analysis

Investigation into the isotopic composition of volcanic rocks offers insights into mantle source characteristics and fingerprints crustal assimilation (DePaolo, 1981; Hart *et al.*, 1986; Eiler, 2001). Radiogenic isotopes such as Sr, Nd, and Pb provide insights into the source characteristics of magmas as well as the involvement of crustal components, due to the distinct signatures in mantle versus crust derived material (DePaolo, 1981; Hart *et al.*, 1986). The isotopic composition of mantle-derived basalts is well-constrained and deviations from this can indicate the involvement of more differentiated, crust-derived material. Stable isotopes such as O are also sensitive to assimilation; the isotopic composition of the mantle falls within a narrow range ($\delta^{18}\text{O}=5\text{--}6\text{‰}$; Eiler, 2001) and is negligibly affected by crystallisation whereas crustal rocks span a wide range of $\delta^{18}\text{O}$ up to $\sim 30\text{‰}$ (Bindeman, 2008). They are particularly sensitive to interaction with water, due to the large fractionation factor between water and rock (Zhao and Zheng, 2003), so are especially useful in detecting assimilation of hydrothermally altered material (Cerling *et al.*, 1985). Comparison of the isotopic composition of volcanic rocks with potential crustal contaminants allows the nature of the contaminant and extent of contamination to be constrained, using isotope mixing models. These models historically considered binary mixing between end-member

compositions (Langmuir *et al.*, 1978) or assimilation coupled to evolution of the melt by fractional crystallisation (DePaolo, 1981). More recent models have built on this by incorporating consideration of the energy conservation involved in assimilation processes (Spera and Bohrson, 2001) and coupling isotopic changes to major element evolution of the melt (Bohrson *et al.*, 2020).

1.1.2.3 Insights from the crystal cargo of eruptions

Evidence of crustal processing is recorded within the crystal cargo of eruptions, and various techniques are used to reconstruct pre-eruptive history. The textures observed in crystals provide evidence of open-system processes such as magma mixing and recharge (Streck, 2008) and mapping of major and trace element compositional changes across minerals can record the evolution of magma during crystallisation (Ubide *et al.*, 2015). The measured compositions can be used to estimate the pressure and temperature under which the mineral formed using thermobarometry (Putirka, 2008), providing insight into the structure of the sub-volcanic magma system and tracking changes in magma storage conditions. Measurements of elemental diffusion gradients in zoned minerals are also used in diffusion chronometry to estimate the timescales of magmatic processes prior to eruption, placing temporal constraints on processes such as final recharge (Costa *et al.*, 2020). The isotopic composition of individual minerals can also be measured, providing constraints on crustal assimilation modifying the composition of the melt from which they grew. These measurements can be performed on whole minerals processed in bulk or on microdrilled sections of individual crystals (Knesel *et al.*, 1999) or using laser ablation to measure isotopic ratios in-situ (Francalanci *et al.*, 2012). Whilst combining in-situ isotopic measurements with high-resolution mapping of crystal textures and trace element variation would be a powerful tool to investigate magma evolution, this has so far not been explored.

1.1.3 The Campi Flegrei volcanic system

Campi Flegrei volcano, southern Italy, provides an ideal case study to investigate controls on the architecture and dynamics of the magmatic system of a long-lived caldera. Campi Flegrei is the largest structure in the Phlegraean Volcanic District, which also includes the Ischia and Procida volcanoes and submarine vents in the Bay of Naples (Orsi *et al.*, 1996). It is defined by a nested caldera structure ~13 km in diameter and formed as a result of multiple caldera-forming eruptions (Vitale and Isaia, 2014; Natale *et al.*, 2022a). Campi Flegrei is located close to the city of Naples with ~1.5 million people living within the caldera and ~3.5 million immediately impacted by an eruption (Orsi *et al.*, 2004).

1.1.3.1 Tectonic setting

Volcanism at the central Italian volcanoes is attributed to back arc extension and the opening of the Tyrrhenian Sea, related to rollback of the subducting Ionian oceanic plate (Faccenna *et al.*, 2007; Peccerillo and Frezzotti, 2015). Since the Pliocene, large-scale tectonic deformation in the Phlegraean area has given rise to two main regional fault systems, trending NE-SW and NW-SE (Fig. 1.1; Acocella, 2010; Vitale and Isaia, 2014). The NW-SE Apennine faults are associated with Tyrrhenian back-arc opening from the middle Tortonian to the present (Vitale and Ciarcia, 2013), whereas the NE-SW anti-Apennine structures are interpreted as either transfer faults connecting NW-SE planes or normal faults related to the Pliocene-Quaternary opening of the Marsili basin south of the Phlegraean district (Vitale and Isaia, 2014). Extensional deformation along these lineaments has formed a disconnected graben structure that transects Campi Flegrei (Orsi *et al.*, 1999). Both the distribution of Campi Flegrei vents (Bevilacqua *et al.*, 2015) and orientation of caldera collapse scarps (Orsi *et al.*, 1996; Di Vito *et al.*, 1999; Vitale and Isaia, 2014; Natale *et al.*, 2022a) have been influenced by these structures. Campi Flegrei also experiences bradyseismic, volcano-induced uplift which has caused additional fracturing and the reactivation of regional faults (Orsi *et al.*, 1996; Di Vito *et al.*, 1999; Orsi *et al.*, 1999).

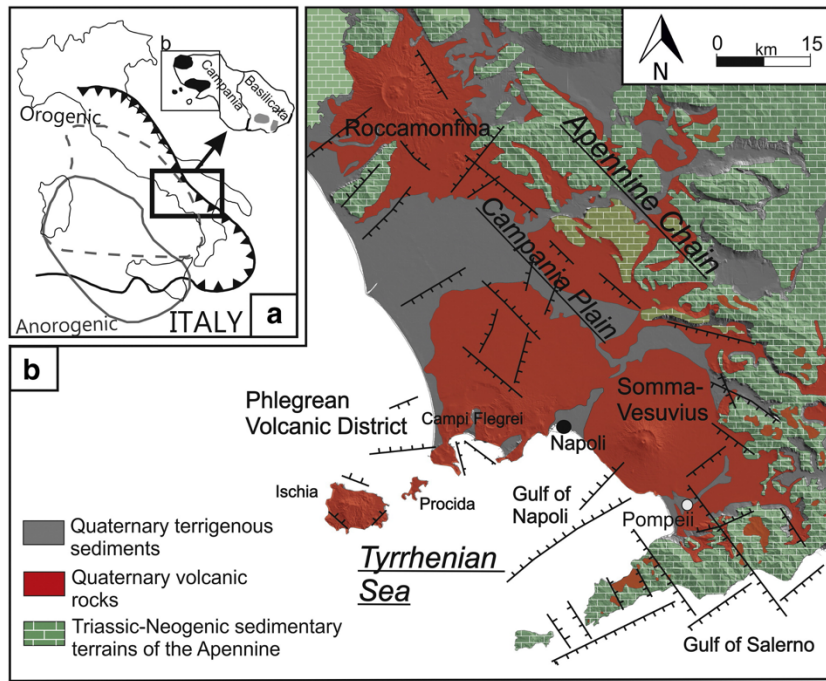


Figure 1.1: Geological map of the Phlegraean Volcanic District, showing regional-scale geology and major tectonic structures, adapted from Mazzeo *et al.* (2014). (a) Map of Italy showing the position of the Apennine thrust front, square indicates area enlarged in (b) and lines indicate Cenozoic anorogenic and orogenic magmatism in the central-western Mediterranean area. (b) Schematic map of the Phlegraean Volcanic District and surrounding area, showing major tectonic structures and the regional-scale geology.

1.1.3.2 Pre-15 ka history

The beginning of volcanism at Campi Flegrei is not well defined as proximal older deposits are rarely exposed and largely destroyed or buried by later eruptions, but distal deposits have been dated to >300 ka (De Vivo *et al.*, 2001; Rolandi *et al.*, 2003; Di Vito *et al.*, 2008; Fernandez *et al.*, 2024). These early eruptions occurred over a wide area within the Campanian region (Orsi *et al.*, 1996) and included both lava domes and explosive eruptions (Pappalardo *et al.*, 1999). At ~39 ka (Giaccio *et al.*, 2017) the Campanian Ignimbrite (CI) occurred, this was the largest eruption in the history of Campi Flegrei and produced part of the current caldera depression. The Masseira del Monte Tuff at ~29 ka (Albert *et al.*, 2019) and the Neapolitan Yellow Tuff (NYT) at ~15 ka (Deino *et al.*, 2004) produced further caldera collapses which formed the current structure at Campi Flegrei. Eruptions between the CI and NYT have not been widely studied, but multiple explosive events occurred during this period (Orsi *et al.*, 1996).

1.1.3.3 Post-15 ka eruptions

Campi Flegrei has experienced intense activity within the NYT caldera in the last 15 kyr, with >70 eruptions coupled with ground deformation (Table 1.1; Di Vito *et al.*, 1999; Isaia *et al.*, 2009; Natale *et al.*, 2022b). These can be broadly divided into three epochs of intense activity (mean eruption frequency 50–70 yrs), separated by periods of quiescence (~1.0–3.6 ka; Di Vito *et al.*, 1999): Epoch 1 produced ~30 magmatic and phreatomagmatic eruptions between ~15 and 10.6 ka; Epoch 2 produced 8 low magnitude eruptions between ~9.6 and 9.1 ka; and Epoch 3 produced 28 eruptions between ~5.5 to 3.5 ka. These eruptions display a range in eruptive style and magnitude from effusive lava domes, through small explosive events to the Plinian Agnano-Monte Spina eruption (Di Vito *et al.*, 1999; Smith *et al.*, 2011; de Vita *et al.*, 1999). The most recent Campi Flegrei eruption was at Monte Nuovo in 1538 CE, which is post-Epoch 3 and considered separate due to the long repose period between this event and the last eruption of Epoch 3 (>3 kyr, Piochi *et al.*, 2005; Smith *et al.*, 2011).

Vent locations for post-15 ka eruptions span across the NYT caldera (Bevilacqua *et al.*, 2015), with eruptions immediately following the NYT often exploiting caldera rim faults (including those formed or reactivated during the caldera collapse), and later eruptions migrating towards the interior of the caldera (Di Vito *et al.*, 1999; Vitale and Isaia, 2014; Bevilacqua *et al.*, 2015).

Melts of the post-15 ka Campi Flegrei eruptions range from shoshonite to phonolite in composition (Smith *et al.*, 2011). Magmas do not form a continual compositional trend between eruptive periods, but the most mafic shoshonitic products are from Epoch 1 with later eruptions extending to more evolved phonolite to trachyte compositions (Smith *et al.*, 2011). While the primary mantle melts feeding these eruptions are thought to be relatively constant (Mazzeo *et al.*, 2014), variations in erupted composition have been correlated with vent location across the caldera system (D'Antonio *et al.*, 1999b; Di Renzo *et al.*, 2011; Smith *et al.*, 2011): eruptions which occur along caldera rim faults are more primitive whilst

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Eruption	Age	Emplacement style	Volcano-tectonic group	Samples studied		
				Ch.2	Ch.3	Ch.4
Monte Nuovo	1538 AD	pdc & scoria fall in upper seq.	Western	x	x	
<i>Epoch 3: Volcanism between ~5.5 and 3.5 ka</i>						
Nisida	3213-4188	pdc	Northern/eastern	x	x	
Fossa Lupara	3978-4192	pumice & scoria fall interbedded with pdc	Northern/eastern			
Astroni 7		pdc & ash fall	Central	x		
Astroni 6		mainly pdc; basal subplinian pumice fall; upper scoria fall	Central	x	x	x
Astroni 5		mainly pdc & minor pumice fall in basal seq.	Central	x		
Astroni 4		mainly pdc interbedded with pumice fall	Central	x		
Astroni 3	4098-4297	mainly pdc interbedded with pumice fallot	Central	x		
Astroni 2		pdc, minor ash fall	Central			
Astroni 1	4153-4345	pdc & ash fall	Central	x		
Averno 2		mid-basal seq. mainly pumice fall; upper seq. mainly pdc	Western	x	x	
Solfatara	4181-4386	pdc; upper seq. mainly coarse fall & breccia	Central	x	x	
Accademia		strombolian scoria fallot & lava dome	Central			
Olibano tephra		coarse breccia & yellow ash	Central			
Paleoastroni 3		ash & pumice fall; minor pdc	Central	x		
Mt Olibano		lava dome	Central			
San Maria delle Grazie	4382-4509	mid-basal pdc; upper scoria fall	Central			
Agnano-Monte Spina	4482-4625	pdc & plinian-subplinian fall; proximal pdc; small caldera	Central	x	x	
Paleoastroni 2	4712-4757	subplinian fall & minor pdc	Central	x	x	

Paleoastroni 1	4745-4834	alt. ash & pumice fall	Central	x	
Monte Sant'Angelo	4832-5010	alt. pumice fall & pdc; upper seq. mostly pdc	Central	x	
Pignatiello 2		mainly pdc	Central	x	
Agnano 3		mainly pdc; some pumice fall at base	Central	x	x
Capo Miseno	3259-4886	mainly pdc; minor coarse pumice & scoria lenses	Western	x	x
Cigliano		mainly pdc; some pumice fall at base	Central	x	x
Averno 1	5064-5431	ash fall & minor pdc	Western	x	
Agnano 2		ash fall & minor pdc	Central	x	
Agnano 1	5266-5628	alt. ash & pumice fall	Central	x	
<i>Epoch 2: Volcanism between ~9.6 and 9.1 ka</i>					
St Martino	9026-9370	basal seq. pumice fall; upper seq. mainly pdc	Northern/eastern	x	x
Sartania 2		mainly pumice fall interbedded with pdc	Central	x	
Pigna San Nicola	9201-9533	mainly pumice fall interbedded with pdc	Central	x	
Costa San Domenico		mainly pdc & minor pumice fall	Central		
Sartania 1	9500-9654	mainly pdc	Central	x	x
Fondi di Baia	9525-9695	mainly pdc	Western	x	x
<i>Epoch 1: Volcanism between ~15 and 10.6 ka</i>					
Porto Miseno	10347-12860	mainly pdc	Western		
Bacoli	11511-14154	mainly pdc	Western	x	x
Casale Pisani 3		pumice fall	Central	x	
	10516-10755	ash fall	Northern/eastern	x	
Pignatiello 1		ash & pumice fall	Central		
Montagna Spaccata		scoria & minor ash fall	Northern/eastern	x	
Concola		scoria fall layers	Northern/eastern		
Fondo Riccio		scoria fall layers	Northern/eastern		x

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Pisani 2		scoria & minor ash fall	Northern/eastern	x		
Pisani 1		coarse scoria & minor ash fall	Northern/eastern	x	x	
Soccavo 5		ash fall	Northern/eastern	x		
Minopoli 2		coarse scoria & minor ash fall	Northern/eastern	x	x	x
Paleo San Martino		coarse scoria & minor ash fall	Northern/eastern	x		
Soccavo 4		basal seq. pumice fall; upper seq. mainly pdc	Northern/eastern	x	x	
Soccavo 3		mainly pdc	Northern/eastern	x		
Soccavo 2		mainly pdc	Northern/eastern	x		
Paleopisani 2		alt. pumice & ash fall	Northern/eastern	x		
Paleopisani 1		basal seq. pdc; upper seq. scoria fall	Northern/eastern	x		
Pomici Principali	11915-12158	alt. pumice & ash fall with pdc	Central	x	x	
Gaiola		pumice and minor ash fall layers	Northern/eastern	x		
Soccavo 1		pdc interbedded with pumice lenses; upper massive ash	Northern/eastern	x		
Paradiso		minor pdc interbedded with pumice fall	Northern/eastern	x		
Minopoli 1		coarse scoria fall	Northern/eastern	x	x	
Archiaverno	12555-12721	mainly pdc	Western			
Torre Cappella		mainly pdc interbedded with pumice lenses	Western			
La Pigna 2		alt. ash & pumice fall	Northern/eastern			
La Pigna 1	12749-13110	mainly pdc interbedded with pumice fall	Northern/eastern	x		
La Pietra		mainly pdc interbedded with pumice lenses	Central			
Santa Teresa		mainly pdc interbedded with pumice lenses	Central			
Gauro	12721-15511	mainly pdc	Northern/eastern	x	x	

Mofete	mainly pdc interbedded with pumice lenses	Western
Bellavista	mainly pdc interbedded with pumice lenses	Western

Table 1.1: Summary of post-NYT Campi Flegrei eruption stratigraphy, including age (where constrained), epoch of activity and emplacement style, adapted from Smith *et al.* (2011) and Bevilacqua *et al.* (2015). Volcano-tectonic group refers to the three groups defined in Chapter 2. The eruptions studied in each of the three research chapters of this thesis are also indicated.

those in the central caldera are more evolved and often indistinguishable on the basis of major element chemistry (Civetta *et al.*, 1991; Smith *et al.*, 2011). However, the causes of this compositional variation remain poorly constrained, and the possible control of the volcano-tectonic setting of individual vents has not been explored.

The crustal architecture beneath Campi Flegrei is currently characterised by a transcrustal magma system identified in magnetotelluric inversions (Isaia *et al.*, 2025), with a main storage zone at ~7.5 km evident in tomographic surveys (Zollo *et al.*, 2008; Bianco *et al.*, 2022), and recent unrest principally driven by shallower magma and/or fluid migration at 2–4 km (De Siena *et al.*, 2010; Calò and Tramelli, 2018; Giacomuzzi *et al.*, 2024). A similar crustal structure appears to have persisted over much of the past 15 kyr as evidenced by mineral thermobarometry (Astbury *et al.*, 2018; Giordano and Caricchi, 2022) and volatile constraints (Mangiacapra *et al.*, 2008; Arienzo *et al.*, 2010, 2016; Vetere *et al.*, 2011; Fourmentraux *et al.*, 2012; Stock *et al.*, 2016, 2018; Voloschina *et al.*, 2018; Balcone-Boissard *et al.*, 2024) which generally attest to eruptions being fed by magmas predominantly derived from >7–8 km depth but with shallower (possibly ephemeral) sills ~3–4 km. Further insights into the sub-volcanic plumbing system, for example variations in magma storage and processing across the larger caldera system, would provide important information for the interpretation of unrest in different parts of the caldera.

Modelling of pre-eruptive processes such as assimilation requires understanding of the potential lithologies magmas might encounter during crustal ascent. At Campi Flegrei,

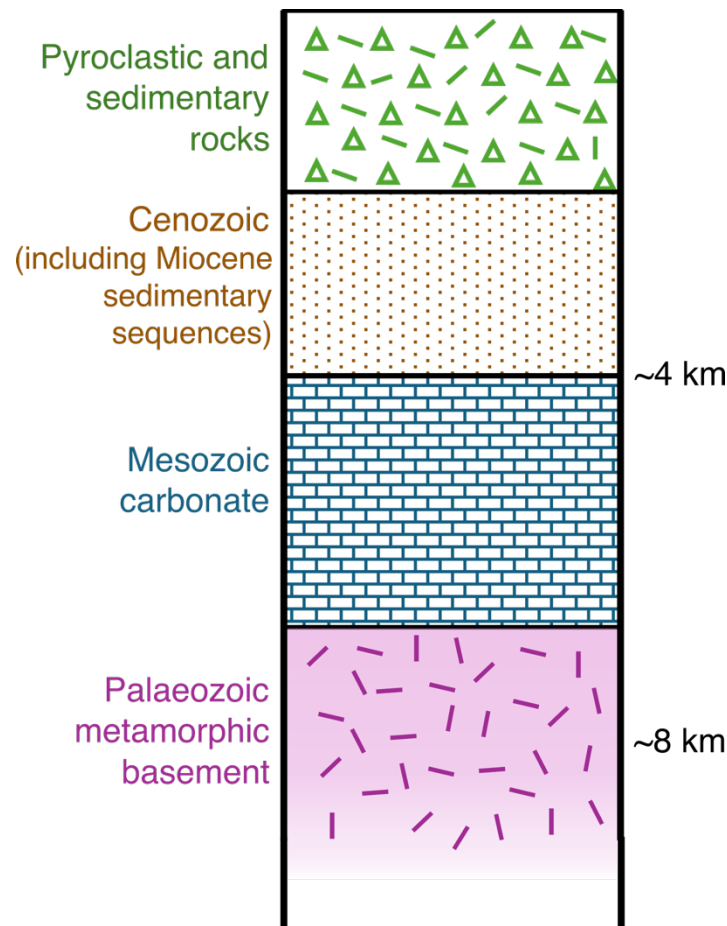


Figure 1.2: Summary sketch log of the lithology of the crust underlying Campi Flegrei. Lithologies $\lesssim 4$ km depth are constrained from borehole data (Rosi and Sbrana, 1987; D’Antonio, 2011; Piochi *et al.*, 2014) and at >4 km from homogenous density in tomographic and gravity data (Battaglia *et al.*, 2008; Berrino *et al.*, 2008). Syenitic cumulate residue from past eruptions is also suggested to form part of the basement lithology >4 km depth, and is observed in erupted xenoliths (Fedele *et al.*, 2006; Fowler *et al.*, 2007; D’Antonio *et al.*, 2011; Gebauer *et al.*, 2014). Not to scale.

geophysical and heat flow data indicate a Moho depth of <25 km (Ferrucci *et al.*, 1989; Pontevivo and Panza, 2006; Nunziata, 2010). Borehole records show that the upper ~ 4 km of the crust consist of buried pyroclastic deposits interbedded with Upper Miocene sedimentary sequences (Fig. 1.2; Rosi and Sbrana, 1987; D’Antonio, 2011; Piochi *et al.*, 2014). Below this level, tomographic and gravity surveys reveal basement rocks characterized by a homogenous density (Battaglia *et al.*, 2008; Berrino *et al.*, 2008). However, the nature of these basement rocks remains debated due to similarities in physical properties. Various interpretations suggest they could be Meso-Cenozoic carbonates (Judenherc and Zollo, 2004; Battaglia *et al.*, 2008; Zollo *et al.*, 2008), Palaeozoic metamorphic rocks (previously termed Hercynian basement; Pappalardo *et al.*, 2002), or

syenitic cumulate residue from past eruptions (Fowler *et al.*, 2007; D’Antonio, 2011). Additional information about the basement composition comes from erupted xenoliths, particularly within the lithic-rich Breccia Museo unit of the CI, which includes plutonic syenite clasts (Fedele *et al.*, 2006; Gebauer *et al.*, 2014) and hydrothermally altered lithics from shallow lavas beneath the caldera (Di Vito *et al.*, 1999). Pappalardo *et al.* (2002) also described two distinct xenolith types within Minopoli 1 eruption deposits; although detailed analysis was limited by their small size, they were interpreted as originating from Upper Miocene arenaceous sediments and the Palaeozoic metamorphic basement.

1.1.3.4 Current unrest

Campi Flegrei is currently showing significant signs of unrest, making it one of the most hazardous volcanoes on Earth (Orsi *et al.*, 2004). The area experiences persistent earthquakes, ground uplift and fumarolic emissions centred around Solfatara-Pisciarelli (Cardellini *et al.*, 2017; De Martino *et al.*, 2021; Tramelli *et al.*, 2022), with periods of intense activity (seismic crises) in 1950-52, 1970-72, 1982-84 and 2012-13 (Del Gaudio *et al.*, 2010; Tramelli *et al.*, 2022). After more than 20 years of subsidence, Campi Flegrei has undergone continual uplift since 2005 totalling ~1.2 m (Bevilacqua *et al.*, 2024) together with an increase in seismicity and degassing (De Martino *et al.*, 2014; Chiodini *et al.*, 2015b; D’Auria *et al.*, 2015; Cardellini *et al.*, 2017; Giudicepietro *et al.*, 2025). Uplift has accelerated since 2018, reaching rates of ~2 cm/month in 2024, resulting in frequent earthquakes including several of magnitude >4 (Iervolino *et al.*, 2024; Ricciolino *et al.*, 2024).

The intense urbanisation of both the active portion of the caldera (~350,000 people live within this area) and its surroundings (~1.5 million live within the caldera), alongside its history of explosive eruptions and current unrest, means the volcanic risk at Campi Flegrei is very high (Orsi *et al.*, 2004). A better understanding of the processes controlling magma evolution is therefore critical at Campi Flegrei. A detailed picture of the sub-volcanic

magmatic system, and processes which influence erupted compositions in different parts of the caldera, has important implications for hazard forecasting and the interpretation of monitoring data. As other long lived caldera systems also show correlations between structural setting and magma evolution, insights from this work could be applied to other restless calderas worldwide.

1.2 Aims and objectives of this thesis

The overall aim of this thesis is to investigate magmatic evolution at Campi Flegrei in the last 15 kyr, focusing on the link between the volcano-tectonic setting of eruption vents and processes operating prior to eruption to construct a detailed picture of the Campi Flegrei magmatic system. I use a combination of modelling and geochemical analysis to constrain these processes, interrogating information preserved in the major and isotopic composition of erupted products, as well as at the crystal scale. This aim was achieved through several research objectives:

- 1) To use thermodynamic modelling of major element variation in glass products from Campi Flegrei eruptions to constrain magma storage conditions and the controls on the liquid line of descent, during both fractional crystallisation and assimilation-fractional crystallisation.
- 2) To use radiogenic and stable isotope analysis of erupted glass and potential crustal contaminants to investigate crustal assimilation, quantifying the amount of assimilation and composition of assimilant in a selection of post-15 ka Campi Flegrei eruptions.
- 3) To investigate the crystal cargo of eruption deposits, using a range of analytical techniques to reconstruct the pre-eruptive history recorded in the crystals and build a picture of the sub-volcanic magma system. This includes thermobarometry, major and trace element analysis and in-situ Sr isotope measurements.

1.3 Outline of thesis

Following this introduction to the background of the study and the study area, Campi Flegrei, and the main research aims and objectives of this thesis (Chapter 1), the core research chapters (2 – 4) are comprised of three papers submitted to or in preparation to be submitted to international peer-reviewed journals. I am the first author of the three manuscripts, the work of which was undertaken and produced during my PhD at Trinity College Dublin. As the first author of these manuscripts I was responsible (unless stated otherwise) for sample collection and preparation, experimental design and data collection, data analysis and modelling, interpretation, and all stages of manuscript preparation. The contributions from each co-author for the core chapters are outlined at the beginning of each chapter. Chapter 2 investigates the controls on the major element compositional evolution of Campi Flegrei, identifying the importance of assimilation. Chapter 3 aims to verify these findings using the isotopic composition of erupted products. Chapter 4 focuses in on the record of magma evolution preserved within individual clinopyroxene crystals. Collectively, these chapters construct a detailed picture of the Campi Flegrei sub-volcanic magmatic system and constrain processes operating prior to eruption. The thesis is closed with a synthesis (Chapter 5), where the major findings of this research are summarised and recommendations for future studies are made.

2. Volcano-tectonic controls on magmatic evolution at Campi Flegrei, Italy: insights from thermodynamic modelling

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Coauthor contributions: Michael J. Stock: conceptualisation, supervision, sample collection, methodology, manuscript review and editing. Victoria C. Smith: conceptualisation, supervision, sample collection, EPMA analysis, manuscript review and editing. Roberto Isaia: conceptualisation, sample collection, supervision, manuscript review and editing. Stefano Vitale: sample collection, manuscript review and editing. Elliot J. Carter: sample prep and XRF training, manuscript review and editing. Jacopo Natale: sample collection, manuscript review and editing.

Lay Abstract

Campi Flegrei (near Naples, southern Italy) is one of the most dangerous volcanoes on Earth. In the last 15,000 years it has erupted more than 70 times and it continues to show signs of unrest today, especially concerning because of its location in a densely populated area. These recent eruptions vary depending on where within the caldera they occurred. Eruptions from the margins of the caldera are generally smaller, whereas those from the centre of the caldera have generated large, explosive events. The chemical composition of the eruptions also varies depending on where the eruption vent was. This suggests that processes operating beneath the volcano vary spatially. We investigated this by comparing the chemical composition of volcanic glass from these recent eruptions to simulations which model the change in composition as magma cools and crystallises. We ran 1800 models, varying in each model the conditions under which magma may be stored, for example the pressure. We found that magma storage conditions in models that best matched the erupted compositions varied depending on where the eruption occurs. For example, magma erupted from vents in the centre of the caldera likely contained more water than eruptions from vents at the margins of the caldera. In addition, we used these models to simulate magma interacting with different rocks in the crust under Campi Flegrei. We found that the type of rock the magma has interacted with (melted and incorporated into the magma) is different for eruptions in the centre and at the margins of the caldera. Linking the eruption chemistry to the spatial location of eruption vents can help provide new insights into how future eruptions at the volcano might behave.

Abstract

Campi Flegrei caldera (Naples, southern Italy) is one of the most hazardous volcanoes on Earth, having produced >70 eruptions in the past 15 kyr, and currently showing significant signs of unrest within a densely populated part of Europe. Post-15 ka eruptions span a range

of eruptive styles and compositions, which broadly correlate with the spatial and structural location of vents within the large caldera: eruptions from vents along northern and eastern caldera rim faults are typically small and extend to mafic compositions; eruptions from vents in the central and eastern side of the caldera extend to evolved compositions and have produced Plinian columns; and vents along regional faults (also activated by caldera collapse) in the western caldera have produced sub-Plinian eruptions which are often relatively Na₂O-rich and K₂O-depleted. These compositional and eruptive differences suggest an intrinsic link between their volcano-tectonic setting and structure and/or processes operating within the sub-volcanic magmatic system. To investigate this, we compare post-15 ka erupted glass major element compositions to liquid lines of descent produced using the Rhyolite-MELTS thermodynamic model. To constrain magma storage conditions at Campi Flegrei, we systematically vary the crystallisation conditions in 1800 models before employing a new statistical approach to assess the quality of fit between natural glass compositions and model outputs. In simple (uncontaminated) fractional crystallisation models, we find that glass compositions in each volcano-tectonic setting are best reproduced by similar storage conditions: pressure of 110–160 MPa, liquidus oxygen fugacity of 0–1 log unit above the quartz-fayalite-magnetite buffer, and a liquidus H₂O concentration of 2 wt% for northern, eastern and western caldera eruptions and 3 wt% for central caldera eruptions. However, the addition of an assimilant further improves the fit between predicted and observed major element compositions, with the amount and type of assimilant varying between volcano-tectonic settings. Best-fit models for vents along northern and eastern caldera rim faults include small (5–10%) amounts of Palaeozoic metamorphic basement, whereas those for vents in the centre of the caldera or along the western regional faults include larger quantities (~30%) of assimilated syenitic restite. The Fondi di Baia eruption is compositionally anomalous, and its evolution may reflect minor limestone or hydrothermal calcite contamination. Our results demonstrate a novel link

between the spatial and structural location of vents within the Campi Flegrei caldera and the physicochemical processes operating within its magmatic system, providing important information for the assessment of future hazard scenarios.

2.1 Introduction

Caldera-forming volcanoes occur worldwide and are frequently associated with long-lived magmatic systems, which produce eruptions of varying size, style, and composition through time (Cole *et al.*, 2005). Following collapse, post-caldera eruptions typically occur in different spatial locations across the volcanic system, including along caldera ring faults and regional lineaments (Lipman, 1984); vent locations are often directly related to local volcano-tectonic structures, with magma ascent exploiting pre-existing planes of weakness (Robertson *et al.*, 2016; Németh *et al.*, 2017; Pérez-Orozco *et al.*, 2021). Compositional variations in erupted products are controlled by complex processes operating within the sub-volcanic crustal magma system, in addition to mantle heterogeneity (Pearce and Peate, 1995; Annen *et al.*, 2015), with the major element variations controlling magma rheology and chemical properties (e.g., viscosity and volatile solubility) which in turn impact the timing and style of eruptions (Cassidy *et al.*, 2018). However, the relationship between volcano-tectonic structures and sub-volcanic processes is poorly understood; it remains unclear whether structural controls can impact the dynamics of magmatic systems and compositions of erupted melts. Addressing this has important implications for hazard assessment and the interpretation of monitoring data where unrest in different parts of a large active caldera system might reflect different crustal processes and result in different volcanic eruption styles or compositions.

Campi Flegrei volcano (southern Italy) has produced >70 eruptions since the last major caldera collapse at 15 ka (the Neapolitan Yellow Tuff [NYT] eruption; Smith *et al.*, 2011). While the primary mantle melts feeding these post-15 ka eruptions are thought to be

relatively constant with respect to the major element composition (Mazzeo *et al.*, 2014), the distribution of vents is closely associated with regional structures (Peccerillo and Frezzotti, 2015; Peccerillo, 2017) and subtle variations in erupted compositions have been identified across the caldera system (D'Antonio *et al.*, 1999; Di Renzo *et al.*, 2011; Smith *et al.*, 2011). Hence, Campi Flegrei presents an ideal location to explore whether the volcano-tectonic setting of an eruption impacts processes operating within the sub-volcanic system. Additionally, the region around Campi Flegrei is densely populated (~1.5 million people living within the caldera, and more than ~3.5 million likely to be immediately impacted by an eruption) and the system is currently showing significant signs of unrest, making it one of the most hazardous volcanoes on Earth (Orsi *et al.*, 2004; Bevilacqua *et al.*, 2017). Constraining the magmatic processes which influence erupted compositions in different parts of the caldera system has important implications for hazard forecasting and the interpretation of volcano monitoring data.

Magma storage conditions can be determined in different volcanic environments using a variety of petrological methods. These include: thermobarometry, using the pressure-sensitivity of exchange reactions of chemical components between various mineral assemblages (Putirka, 2008); comparisons between the chemistry of erupted products and those from experiments conducted under controlled conditions (Blundy and Cashman, 2008); and saturation depths calculated from the volatile contents of melt inclusions (Anderson *et al.*, 1989). The influence of assimilation on magmatic evolution can also be investigated, for example by comparison of the isotopic composition of the magma and potential crustal contaminants (James, 1981). Previous studies have attempted to link storage conditions to volcano-tectonic setting across a caldera system, for example Saxby *et al.* (2016) demonstrated a link between regional fault patterns and location of magma storage at Ilopango caldera (El Salvador) on the basis of gravity surveys, whereas Carracedo *et al.* (2007) noted compositional variation of eruptions in different locations across Tenerife

(Canary Islands). However, these techniques generally only allow assessment of magma storage conditions over discrete ranges in the evolution of the sub-volcanic system (i.e. within the crystallisation interval of the phase used in barometry) and typically provide information on one intrinsic variable (such as pressure for barometry or extent of assimilation for isotope mixing models). In this study, we use thermodynamic modelling to assess the range of variables which control magma storage conditions through the entire liquid line of descent, finding combinations of variables which are consistent with erupted compositions.

The Rhyolite-MELTS thermodynamic modelling software calculates the stable phase assemblage in a magmatic system under given conditions and can be applied to determine the evolving phase assemblage and phase compositions during fractional crystallisation (FC) or assimilation-fractional crystallisation (AFC, Gualda *et al.*, 2012; Ghiorso and Gualda, 2015). Through systematically varying model crystallisation conditions (i.e. pressure, oxygen fugacity, initial melt major or volatile element composition) and comparing with the abundance and composition of phases in natural erupted materials, previous studies have successfully used Rhyolite-MELTS (or its predecessor MELTS, which differs in the stability fields of quartz and sanidine, Ghiorso and Sack, 1995) outputs to constrain magma storage conditions in diverse volcanic systems (e.g. Peach Spring - Pamukcu *et al.*, 2015; Aluto - Gleeson *et al.*, 2017; individual Campi Flegrei eruptions - Fowler *et al.*, 2007; Fowler and Spera, 2010; Cannatelli, 2012). In general, these studies have identified the most probable set of magma storage conditions by visually identifying the modelled liquid line of descent which best fits erupted melt compositions. However, Gleeson *et al.* (2017) proposed a statistical method to quantify the fit between natural and predicted compositions, more accurately identifying the best set of model parameters where liquid lines of descent are similar or deviate from natural compositions over a limited ($\sim 30^\circ\text{C}$) crystallisation interval.

Here, we use Rhyolite-MELTS to model isobaric FC and AFC of a near-primitive Campi Flegrei liquid under different storage conditions, comparing the predicted phase assemblages and liquid lines of descent with erupted products from vents in different volcano-tectonic settings within the caldera. This extends previous work constraining magma storage for individual Campi Flegrei eruptions using MELTS modelling (e.g. Campanian Ignimbrite - Fowler *et al.*, 2007, Fowler and Spera, 2010; Minopoli 1 and Fondo Riccio - Cannatelli, 2012), investigating eruptions in the last 15 kyr for which there is published glass major element compositional data ($n=48$). By systematically varying the model pressure (P), liquidus fO_2 (L_{fO_2}), liquidus H_2O content (L_{H_2O}) and amount/type of assimilated material across the range of potential parameter space, we are able to constrain the conditions and processes operating during pre-eruptive magma storage, exploring the hypothesis that volcano-tectonic setting impacts magmatic evolution. As different combinations of storage conditions can produce model outputs which appear similar to a first order, we apply a novel statistical approach to assess the correlation between modelled liquid lines of descent and measured glass major element compositions. Our best-fit models (i.e. closest correlation between modelled liquid line of descent and natural glasses) are for magma storage conditions which agree well with previous estimates and show only minor variations between different volcano-tectonic settings. However, we find that the addition of assimilants ubiquitously improves the model fit, but that the type and amount of assimilant varies between eruptions from vents in different parts of the Campi Flegrei caldera, indicating spatial variations in the nature of magma-country rock interaction.

2.2 Geological setting

Campi Flegrei is the largest centre in the Phlegraean Volcanic District, an area of volcanism in southern Italy (near Naples; Orsi *et al.*, 1996), formed as a result of back arc extension and the opening the Tyrrhenian Sea, related to rollback of the subducting Ionian plate (Faccenna *et al.*, 2007; Peccerillo and Frezzotti, 2015). Large-scale tectonic deformation in

the Phlegraean area has given rise to two main regional fault systems, trending NE-SW and NW-SE (Acocella, 2010; Vitale and Isaia, 2014), which have influenced both the distribution of vents (Bevilacqua *et al.*, 2015) and orientation of Campi Flegrei caldera collapse scarps (Orsi *et al.*, 1996; Di Vito *et al.*, 1999; Vitale and Isaia, 2014; Natale *et al.*, 2022a).

The oldest volcanism at Campi Flegrei is dated to >300 ka (De Vivo *et al.*, 2001; Rolandi *et al.*, 2003; Di Vito *et al.*, 2008; Fernandez *et al.*, 2024), with the eruptive history punctuated by at least three major caldera collapse events: the ~40 ka Campanian Ignimbrite (CI, Giaccio *et al.*, 2017), the ~29 ka Masseira del Monte Tuff (Albert *et al.*, 2019) and the ~15 ka NYT (Deino *et al.*, 2004). These eruptions have produced a nested caldera structure (~13 km diameter), with collapse scarps juxtaposed against the regional tectonic lineaments (Vitale and Isaia, 2014; Natale *et al.*, 2022a). In the past 15 kyr, Campi Flegrei has produced >70 eruptions from vents located within the NYT caldera (Di Vito *et al.*, 1999; Smith *et al.*, 2011), coupled with ground deformation (Isaia *et al.*, 2019; Natale *et al.*, 2022b). These can be broadly divided into three epochs of intense activity (mean eruption frequency 50–70 yrs), separated by periods of quiescence (~1–3.6 ka; Di Vito *et al.*, 1999): Epoch 1 produced ~30 magmatic and phreatomagmatic eruptions between ~15 and 10.6 ka; Epoch 2 produced 8 low magnitude eruptions between ~9.6 and 9.1 ka; and Epoch 3 produced 28 eruptions between ~5.5 to 3.5 ka. These eruptions display a range in eruptive style and magnitude from effusive lava domes, through small explosive events to the Plinian Agnano-Monte Spina eruption (Di Vito *et al.*, 1999; Smith *et al.*, 2011; de Vita *et al.*, 1999). The most recent Campi Flegrei eruption was at Monte Nuovo in 1538 CE, which is post-Epoch 3 and considered separate due to the long repose period between this event and the last eruption of Epoch 3 (>3 kyr, Piochi *et al.*, 2005; Smith *et al.*, 2011).

Vent locations for post-15 ka eruptions span the NYT caldera (Fig. 2.1) and can be broadly divided into three distinct volcano-tectonic settings: 1) those along caldera rim faults in the northern and eastern sectors of the caldera, which were either formed or reactivated

during the NYT collapse and strike obliquely to the regional lineaments (“northern/eastern caldera eruptions”); 2) those in the west of the caldera aligned with caldera rim faults and regional tectonic fault systems characterised by a different orientation pattern of faults and fractures compared to those in the eastern sector (“western caldera eruptions”; Vitale and Isaia, 2014); and 3) those within the central caldera which are not located along major pre-existing planes of crustal weakness (“central caldera eruptions”; Fig. 2.1: Di Vito *et al.*, 1999; Isaia *et al.*, 2009; Bevilacqua *et al.*, 2015; Natale *et al.*, 2022b). Differences in the frequency and composition of eruptions as well as structural differences in fault patterns between the east and west of the caldera has led other authors to make similar divisions (Vilardo *et al.*, 2010; Vitale and Isaia, 2014; Bevilacqua *et al.*, 2016, 2017). In general, earlier eruptions were fed by magmas which exploited the caldera rim faults (including regional fault systems reactivated during caldera collapse), with later eruptions migrating towards the caldera interior (particularly in the northeastern sector; Di Vito *et al.*, 1999; Isaia *et al.*, 2009) or regional tectonic faults in the western caldera (Di Vito *et al.*, 1999; Vilardo *et al.*, 2010; Vitale and Isaia, 2014).

Throughout its history, Campi Flegrei has consistently produced alkali magmas (Vineberg *et al.*, 2023), with melts of the post-15 ka eruptions ranging from shoshonite to phonolite in composition (Smith *et al.*, 2011). Magmas do not form a continual compositional trend between eruptive periods, but the most mafic shoshonitic products are from Epoch 1 with later eruptions extending to more evolved phonolite to trachyte compositions (Smith *et al.*, 2011). Several previous studies have noted a correlation between

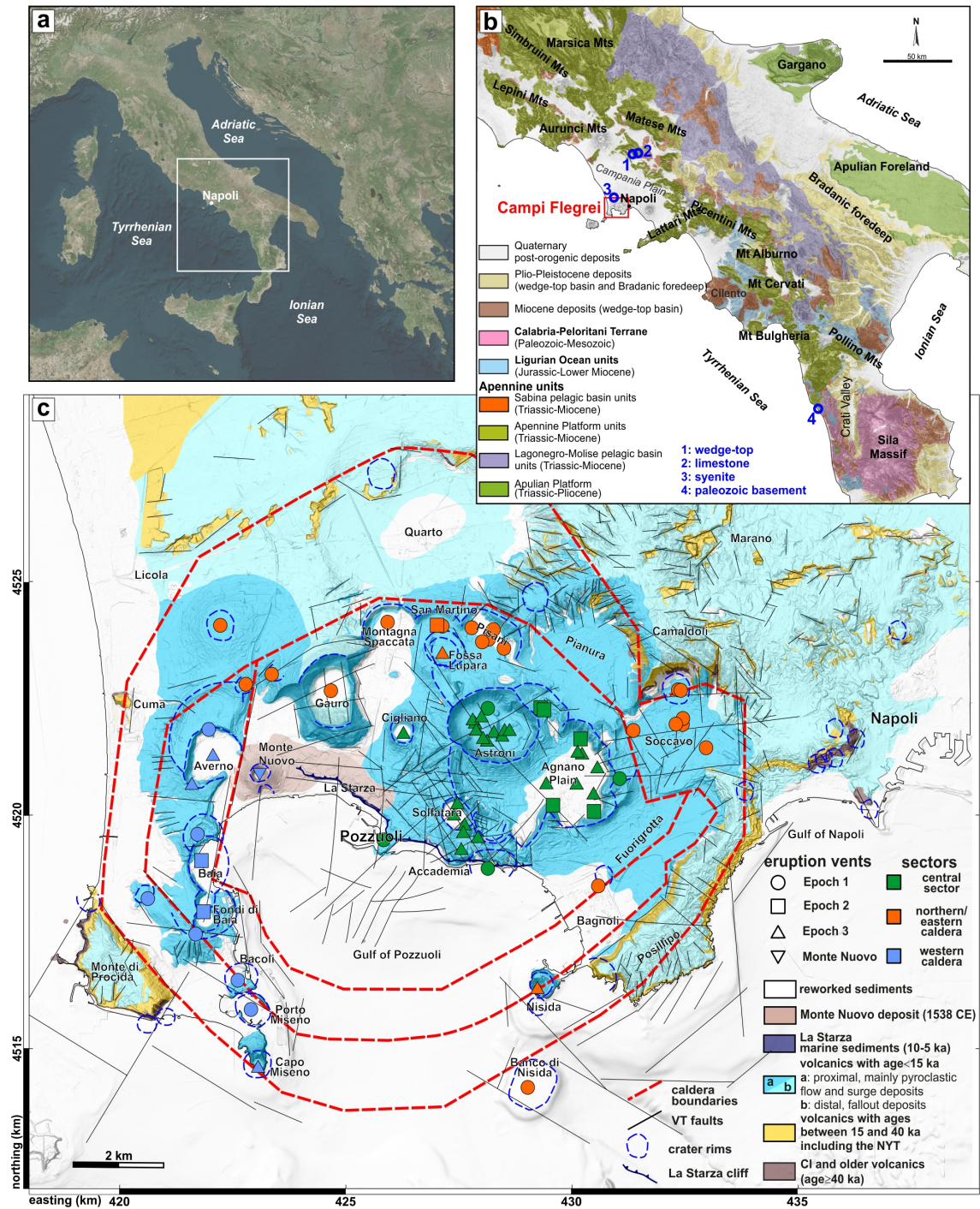


Figure 2.1: Maps showing Campi Flegrei and vent locations of eruptions in the last 15 kyr. (a) Map of Italy showing the location of Campi Flegrei, square indicates area enlarged in (b) to show sampling locations of the basement rocks (b) Simplified geological map of southern Apennines showing distribution of tectonic units (Ciarcia and Vitale, 2025) and the locations the basement rocks were sampled: 1. Syn-orogenic wedge-top flysch, sample 23-FMR-003; 2. Limestone, sample 23-FMR-001; 3. Syenite, sample 23-FMR-014; 4. Palaeozoic gneiss, sample 23-FMR-017. (c) Simplified geological map of Campi Flegrei showing locations of the vents in the last 15 kyr, from Smith et al. (2011). Colours refer to the tectonic setting of the vents: orange are eruptions that occurred along the northern/eastern caldera rim faults; purple are eruptions with vents along regional and rim faults on the western side of the caldera; and in green are the eruptions from vents in the central eastern side of the caldera. Map also shows the distribution of pyroclastic deposits (Natale et al., 2024b, 2024a) and caldera and crater rims (Vitale and Isaia, 2014; Natale et al., 2022a). Vent ages refer to epochs defined in Smith et al. (2011).

the volcano-tectonic setting of eruption vents and the composition of erupted products (D'Antonio *et al.*, 1999; Di Renzo *et al.*, 2011; Smith *et al.*, 2011). In general, northern/eastern caldera eruptions are the most primitive, occurring from NYT caldera rim faults (Civetta *et al.*, 1991) with more evolved Epoch 2 and Epoch 3 eruptions from the north-eastern caldera floor, and their products are indistinguishable on the basis of major element chemistry (Smith *et al.*, 2011). Eruptions from vents in the west of the caldera have been noted as the most compositionally diverse; for example, the Baia-Fondi di Baia deposits are highly evolved with distinct trace element concentrations relative to other post-15 ka eruptions (Smith *et al.*, 2011; Voloschina *et al.*, 2018).

Previous studies generally agree on the architecture of the Campi Flegrei sub-volcanic system being characterised by a main magma storage zone at ~7–8 km depth, with shallow (possibly ephemeral) sills at around 3–4 km depth (e.g. Stock *et al.*, 2018; Petrelli *et al.*, 2023). Seismic tomography and magnetotelluric investigations have imaged a main region of magma storage at ~7.5 km (Zollo *et al.*, 2008; Bianco *et al.*, 2022; Isaia *et al.*, 2025) and small shallow reservoirs between 2–4 km (De Siena *et al.*, 2010; Calò and Tramelli, 2018; Giacomuzzi *et al.*, 2024). This agrees with pressures obtained from the volatile contents of melt inclusions, which give saturation depths of ~2 to ~9 km for multiple eruptions in the last 15 kyr (Mangiacapra *et al.*, 2008; Arienzo *et al.*, 2010, 2016; Vetere *et al.*, 2011; Fourmentraux *et al.*, 2012; Voloschina *et al.*, 2018). Thermobarometry estimates of crystallisation depth suggest a main region of magma storage around 8 km (Astbury *et al.*, 2018; Giordano and Caricchi, 2022), with slightly shallower estimates of ~3–6 km from chlorine geobarometry (Balcone-Boissard *et al.*, 2024). Previous phase equilibria investigations at Campi Flegrei found observed compositions best reproduced by crystallisation depths of 6–12 km for the CI and two post-15 ka eruptions (Minopoli 1 and Fondo Riccio; Bohrsen *et al.*, 2006; Fowler *et al.*, 2007; Cannatelli, 2012). Measurements in melt inclusions from various eruptions agree on H₂O contents of 0.8–6% (Webster *et al.*,

2003; Cannatelli *et al.*, 2007; Mangiacapra *et al.*, 2008; Arienzo *et al.*, 2010, 2016; Fourmentraux *et al.*, 2012; Stock *et al.*, 2018), in agreement with estimates from K-feldspar-liquid hygrometry (Forni *et al.*, 2018a) and phase equilibria investigations (Fowler *et al.*, 2007; Cannatelli, 2012). Forni *et al.* (2018a) used oxygen barometry to constrain the oxygen fugacity (fO_2) for CI magmas to one log unit above the QFM buffer (QFM+1), similar to results of phase equilibria studies of the CI (Bohrson *et al.*, 2006; Fowler *et al.*, 2007), and Minopoli and Fondo Riccio eruptions (Cannatelli, 2012), where fO_2 between QFM and QFM+1 best reproduces the composition and phase assemblage of natural samples.

2.2.1 Lithology of the crust underlying Campi Flegrei

Modelling AFC processes requires understanding potential lithologies magmas might encounter during crustal ascent beneath Campi Flegrei. Geophysical and heat flow constraints on the structure of the Campanian crust generally suggest a Moho depth of <25km (Ferrucci *et al.*, 1989; Pontevivo and Panza, 2006; Nunziata, 2010). At ≤ 4 km depth, borehole data indicate that the shallow crust is composed of buried pyroclastic sequences, intercalated with Upper Miocene sedimentary sequences (Rosi and Sbrana, 1987; D'Antonio, 2011; Piochi *et al.*, 2014). At ≥ 4 km basement rocks are identified through their homogenous density in tomographic and gravity data (Battaglia *et al.*, 2008; Berrino *et al.*, 2008). However, due to similarities in their physical properties, the nature of the basement rocks beneath Campi Flegrei remains debated, with studies variously attributing it as Mesozoic carbonates (Judenherc and Zollo, 2004; Battaglia *et al.*, 2008; Zollo *et al.*, 2008), Palaeozoic metamorphic basement (previously termed Hercynian basement, e.g. Pappalardo *et al.*, 2002), or syenitic cumulate residue from past eruptions (Fowler *et al.*, 2007; D'Antonio, 2011). Insights into the basement lithology are provided by erupted xenoliths, particularly the lithic-rich Breccia Museo unit of the CI (Fedele *et al.*, 2008) which contains plutonic syenite clasts (Fedele *et al.*, 2006; Gebauer *et al.*, 2014) in addition to hydrothermally altered lithic fragments from shallow lavas beneath the caldera (Di Vito *et*

al., 1999). Additionally, Pappalardo *et al.* (2002) identified two different xenolith types within deposits from the Minopoli 1 eruption; although the small clast size hampered detailed characterisation, these are suggested as deriving from Upper Miocene arenaceous sediments and the Palaeozoic metamorphic basement. Studies of isotopic variation in Campi Flegrei erupted products also provide information on potential crustal contamination sources: radiogenic and stable isotopic variation in magmas erupted in the last 60 kyr is attributed to interaction of the magmas with small amounts of both metamorphic Palaeozoic basement (~1-12% assimilation) and arenaceous sediments (<10% assimilation; Pappalardo *et al.*, 2002; D'Antonio *et al.*, 2007; Arienzo *et al.*, 2011; Di Renzo *et al.*, 2011, Iovine *et al.*, 2018). Despite the suggestion that assimilation plays a role in controlling the compositional evolution of Campi Flegrei magmas, this is yet to be empirically verified and the composition of the assimilant and extent of contamination are poorly defined.

2.3 Analytical Methods

2.3.1 Sampling and sample preparation

To define the starting composition for our Rhyolite-MELTS models, we analysed melt inclusions in samples of tephra from the three most mafic post-15 ka Campi Flegrei eruptions: Minopoli 1, Minopoli 2 and Fondo Riccio (Smith *et al.*, 2011). Samples CF9 (Minopoli 2) and CF13 (Minopoli 1) were sampled by Smith *et al.* (2011) and sample CF410 (Fondo Riccio) was collected during fieldwork for this project in March 2022 (UTM 423047E, 4523062N). Samples were crushed and sieved, with clinopyroxene phenocrysts handpicked from the 250–500 µm size fraction.

Potential basement lithologies which might have contaminated Campi Flegrei magmas were sampled during fieldwork in May 2023. Sampling locations are given in Figure 2.1b and Table A1.4. These include: an upper Jurassic–lower Cretaceous limestone (sample 23-FMR-001, unit Gcb of Vitale and Ciarcia, 2018, no.2 on Fig. 2.1b); Upper

Miocene syn-orogenic wedge-top deposits (previously termed flysch, e.g. Fowler *et al.*, 2007; sample 23-FMR-003, unit CVTg of Vitale and Ciarcia, 2018, no.1 on Fig. 2.1b); Palaeozoic gneiss (sample 23-FMR-017, Sila unit of Graessner and Schenk, 2001; Filice *et al.*, 2015, no.4 on Fig. 2.1b); and a syenitic xenolith from the Breccia Museo (sample 23-FMR-014, no.3 on Fig. 2.1b). These whole rocks were crushed in a tungsten carbide jaw crusher before being ground in an agate TEMA mill.

2.3.2 Electron probe microanalysis (EPMA)

Clinopyroxene phenocrysts from mafic Campi Flegrei eruptions were picked from tephra samples, mounted in epoxy, ground and polished for analysis. Crystals and melt inclusions were analysed using a JEOL JXA 8200 wavelength-dispersive electron microprobe in the Research Laboratory for Archaeology and the History of Art, University of Oxford, UK. All analyses were conducted with a 15 kV accelerating voltage and a 6 nA beam current and 10 μm beam diameter were used to analyse the melt inclusions, while a 25 nA current and 3 μm beam were used to analyse the host crystals. On-peak count times were 12s (for Na), 30s (for Si, Al, K, Ca, Ti, Fe) and 50s (for Mg, P, Cl, Mn). Appropriate natural and synthetic standards were used for calibration (listed in Table A1.1), and the MPI-DING reference glasses (Jochum *et al.*, 2006) were analysed as secondary standards to check the accuracy and reproducibility of results, compared to the preferred values (detailed in Table A1.2). Accuracy was typically better than 2% with precision typically $<\pm 0.5\%$ RSD for Si and $\sim\pm 3\%$ for most other major elements except for Na ($\sim\pm 11\%$) and low abundance elements Ti ($\pm 6\%$) and Mn ($\pm 16\%$). All Fe is assumed to occur as FeO (FeO(t)). All EPMA analyses are included in the Table A1.5; from this survey of melt inclusions and their host crystals we selected the starting composition for our Rhyolite-MELTS models.

2.3.3 X-Ray Fluorescence (XRF) analysis

The crustal samples were prepared as fused glass beads and pressed powder pellets for whole-rock major (>1 wt%) and trace (<1 wt%) element analysis, respectively. Analyses were performed using the Zetium Wavelength Dispersive (WD) XRF in the Earth Surface Research Lab, Trinity College Dublin, following the methods described in Carter *et al.* (2024). From measurements of secondary standards analysed alongside the samples, accuracy is <2% for major and 5-10% for trace elements, and precision (in terms of relative standard deviation, standard deviation/mean) is generally <1% for major elements and <2% for trace elements (full details of secondary standard reproducibility in Table A1.3). Data are included in Table A1.4.

2.4 Literature Data

Matrix glass data from post-15 ka Campi Flegrei eruptions were compiled from the literature for comparison with Rhyolite-MELTS outputs. While bulk-rock and melt inclusion analyses might record liquid compositions, these can be affected by crystal accumulation/fractionation (e.g. Passmore *et al.*, 2012; Higgins and Stock, 2024) and post-entrapment processes (Lowenstern, 1995; Cannatelli *et al.*, 2016) and we exclude them from our analyses, instead preferring to limit the risk of misinterpretation by like-for-like directly comparing the last liquid remaining in the magmatic system before eruption. We investigate the processes affecting major element variability between eruptions, which does not preclude other processes, such as volatile fluxing and magma mixing, that have been reported for post-15 ka erupted products (e.g. Di Renzo *et al.*, 2011; Arienzo *et al.*, 2016). The compositions of natural glasses erupted from Campi Flegrei in the past 15 kyr were compiled from the GEOROC database (Sarbas, 2008); this yielded glass analyses from 48 eruptions and ~1900 analyses in total (Di Girolamo *et al.*, 1984; de Vita *et al.*, 1999; Brocchini *et al.*, 2001; Romano *et al.*, 2003; Piochi *et al.*, 2008; Smith *et al.*, 2011; Fourmentraux *et al.*, 2012;

Tomlinson *et al.*, 2012; Arienzo *et al.*, 2016; Stock *et al.*, 2018). Of these, 1036 matrix glass analyses are from 6 western caldera eruptions, 620 are from 20 northern/eastern caldera eruptions and 255 are from 22 central caldera eruptions. No glass data is currently available for other post-15 ka eruptions (~20 eruptions in total; Smith *et al.*, 2011). There was no systematic difference in glass compositions between studies. Due to the number of glass compositions in our dataset, the uncertainty of the EPMA measurements collapse in, assuming a normal distribution. Therefore, any misfit between models and the data is probably not an artefact of EPMA uncertainty.

2.5 Rhyolite-MELTS thermodynamic modelling

We modelled the stable phase assemblages and major element compositional evolution of the liquid phase in Campi Flegrei during FC and AFC using the Rhyolite-MELTS thermodynamic modelling software, which calculates the stable phase assemblage in a system under a given set of conditions based on minimisation of free energy, with the thermodynamic properties of each phase calibrated from experiments (Gualda *et al.*, 2012). We used Rhyolite-MELTS v.1.2. which has a coupled H₂O-CO₂ fluid saturation model and the most comprehensive calibration dataset to date (Ghiorso and Gualda, 2015). The models were run using the alphaMELTS2 front-end (Smith and Asimow, 2005), with a Python-based script designed to batch run simulations over a range of potential storage conditions (see Gainsforth *et al.*, 2015; Antoshechkina and Ghiorso, 2018; Gleeson *et al.*, 2023). We model fractional crystallisation as opposed to equilibrium crystallisation, following previous thermodynamic modelling (Fowler *et al.*, 2007, Cannatelli, 2012) and empirical major element geochemical studies (Civetta *et al.*, 1991) which suggest that this process best describes the relationship between the compositions of Campi Flegrei erupted products.

Despite previous studies identifying isotopic heterogeneity in Campi Flegrei erupted compositions (e.g. D'Antonio *et al.*, 2007; Arienzo *et al.*, 2010; Di Renzo *et al.*, 2011) and

2. VOLCANO-TECTONIC CONTROLS ON MAGMA EVOLUTION AT CAMPI FLEGREI

Sample	SiO ₂ (wt%)	Na ₂ O (wt%)	P ₂ O ₅ (wt%)	K ₂ O (wt%)	FeO (wt%)	Al ₂ O ₃ (wt%)	MgO (wt%)	CaO (wt%)	MnO (wt%)	TiO ₂ (wt%)
CF410_ cpx12_ MI18	51.07	2.14	0.54	4.70	6.75	14.82	6.23	11.62	0.16	0.95

Table 2.1: Chemical composition of Fondo Riccio melt inclusion used as the starting composition in our rhyolite-MELTS models. All measured melt inclusion compositions are given in Table A1.5.

suggesting separate end-member magma batches, these are not reflected in variations in major element chemistry, where eruptions can be related by crystallisation to a single parental magma (Civetta *et al.*, 1991; Smith *et al.*, 2011). We therefore model crystallisation of a single parental magma, using the most primitive melt inclusion that we measured in mafic post-15 ka eruptions as the starting composition in our models (CF410_cpx12_MI18;

Table 2.1). This clinopyroxene-hosted inclusion from Fondo Riccio has the highest MgO (6.23 wt%) and CaO (11.62 wt%) concentrations in our dataset and low incompatible element concentrations (Na₂O+K₂O 6.84 wt%), and is in equilibrium with its host crystal based on their $K_D(\text{Fe-Mg})^{\text{cpx-liq}}$ of 0.31 ± 0.07 (i.e. within the equilibrium range of 0.28 ± 0.08 from Putirka, 2008). Masotta *et al.* (2013) identified that melt alkali content can affect these calculations, but their revised model converges with the $K_D(\text{Fe-Mg})^{\text{cpx-liq}}$ range given in Putirka (2008) for $K_D > 0.2$, so we prefer to use this as it does not require prior knowledge of crystallisation temperature, although the narrow range likely reflects the majority of published experiments involving mafic systems with the actual equilibrium range potentially being larger (Di Fiore *et al.*, 2021). The selected melt inclusion is glassy, implying post-entrapment crystallisation (PEC) has not been extensive (Fig. A1.1) and a correction for PEC did not significantly alter our model outputs (Fig. A1.2). Although previous authors have reported more mafic melt inclusions (Webster *et al.*, 2003; Cannatelli *et al.*, 2007), they require extensive correction for post-entrapment crystallisation which can compromise their major element composition (Danyushevsky *et al.*, 2002; Kress and Ghiorso, 2004) so we prefer to use our own direct measurements.

2.5.1 Fractional crystallisation models

We initiated our FC models at the calculated liquidus and ended at a melt fraction of ~ 0.05 (5%; models fail closer to the solidus, likely due to extreme incompatible element enrichment in the melt phase), with a temperature step of 1°C . The proportions and compositions of all stable phases are recorded at each temperature step, with crystals removed from the bulk composition between steps. No constraints were placed on the phases Rhyolite-MELTS could stabilise; predicted phases were compared to those observed in natural samples. Model parameters ($L_{f\text{O}_2}$, P , $L_{\text{H}_2\text{O}}$) are defined for each model and, to constrain the conditions of Campi Flegrei magma storage, we varied these parameters across the range of possible conditions previously identified in the literature (Table 2.2). We varied $L_{f\text{O}_2}$ by fixing it above the liquidus and then allowing $f\text{O}_2$ to vary unbuffered below the liquidus. In our FC models, we tested a matrix of parameter space so that each intensive variable was tested against the full range of the remaining two, totalling 1720 individual simulations. To reduce the modelled parameter space, we follow previous studies in only considering isobaric crystallisation (Fowler *et al.*, 2007; Cannatelli, 2012; Rooney *et al.*, 2012; Stock *et al.*, 2016; Gleeson *et al.*, 2017). While previous authors have suggested that the Campi Flegrei sub-volcanic system could have magmas stored at multiple depths (e.g. Astbury *et al.*, 2018; Giordano and Caricchi, 2022), we find the liquid lines of descent

Intensive parameter	Range tested	Intervals	References
Pressure (MPa)	50 to 500	50	Arienzo <i>et al.</i> , 2016; Bohrsen <i>et al.</i> , 2006; Cannatelli, 2007; Fowler <i>et al.</i> , 2007; Zollo <i>et al.</i> , 2008.
Initial water content (wt%)	0.5, 1 to 6	1	Arienzo <i>et al.</i> , 2016; Forni <i>et al.</i> , 2018a; Mangiacapra <i>et al.</i> , 2008; Stock <i>et al.</i> , 2016.
Oxygen fugacity (log units relative to the Quartz-Fayalite-Magnetite buffer)	-2 to +3	1	Cannatelli <i>et al.</i> , 2012; Fowler <i>et al.</i> , 2007; Stock <i>et al.</i> , 2016.

Table 2.2: Magma storage conditions investigated in Rhyolite-MELTS models and the ranges over which they were varied. The ranges chosen were constrained based on previous studies of Campi Flegrei.

produced in our Rhyolite-MELTS models are not sensitive to polybaric crystallisation in the mid- to upper-crust within a reasonable pressure range (Fig. A1.3) and so consider only a simple isobaric scenario.

2.5.2 Assimilation models

Following Fowler *et al.* (2007), we model AFC taking the best-fit intensive parameters for each volcano-tectonic setting based on the results obtained from FC simulations (see *Statistical determination of best-fit storage conditions*, below) before adding a contaminant to Rhyolite-MELTS models at a fixed temperature, using the bulk compositions measured from samples of the basement lithology (Table A1.4; sample 23-FMR-001 = limestone; sample 23-FMR-003 = wedge-top deposits; sample 23-FMR-14A = syenite; sample 23-FMR-017 = Palaeozoic metamorphic basement). In each AFC model, we systematically varied the type and amount of assimilation, holding all other model parameters constant and producing 80 additional models. While we acknowledge that this is a simplification, simultaneously changing the type of assimilant, temperature interval over which contamination occurs, conditions of magma storage (P , L_{O_2} , $L_{\text{H}_2\text{O}}$) and adding mixtures of different assimilants creates an unmanageably large parameter space. Instead, our approach assumes that the intrinsic conditions of magma storage exert a first-order control on the liquid line of descent and that small amounts of assimilation of a dominant assimilant composition have a second-order impact. Rhyolite-MELTS can simulate assimilation under either isenthalpic or isothermal conditions (Ghiorso and Kelemen, 1987) which can constrain different aspects of assimilation. To investigate the effect of different assimilant compositions on the liquid line of descent in a long-lived magmatic system, we follow Fowler *et al.* (2007) in running AFC models isothermally, whereby the initial temperature of the assimilant is the same as the melt. Each model was run as a closed system FC simulation from the liquidus to 1100°C before the assimilant was added and chemically equilibrated with the new system. The melt then evolved once again down to low melt fractions, reducing

temperature by 1°C and extracting crystals at each step, as in FC models. The amount of assimilated was varied between $M_a/M_m = 0.01\text{--}0.3$ in 0.05 increments, where M_a/M_m is the ratio of assimilated to melt (equivalent to 1–30% contamination).

2.5.3 Statistical determination of best-fit storage conditions

Most previous studies which have determined magmatic processes/storage conditions by correlating the compositions of natural erupted materials with Rhyolite-MELTS outputs have qualitatively identified the best-fit model run conditions “by eye” (e.g. Fowler *et al.*, 2007; Fowler and Spera, 2010; Cannatelli, 2012). This approach was advanced by Gleeson *et al.* (2017), who employed a statistical method based on least-squares analysis to quantitatively determine the best-fit model conditions, comparing the residuals between compositional evolution of the modelled melt phase and whole-rock samples from Aluto volcano (Ethiopia). We build on this work, implementing an improved statistical assessment to determine the correlation between each of our 1800 (1720 FC and 80 AFC) Rhyolite-MELTS models and natural matrix glasses from Campi Flegrei. Rather than comparing models against our full literature dataset, we separate post-15 ka Campi Flegrei glasses into three groups, based on the volcano-tectonic setting of their eruption vents (i.e. western caldera eruptions, northern/eastern caldera eruptions, central caldera eruptions) to identify changes in magma storage conditions and/or processes across the caldera.

Our statistical procedure for identifying best-fit models is as follows: for each oxide output by Rhyolite-MELTS (except P_2O_5 which is in too low concentration), we calculated the root mean square error (RMSE) between the modelled liquid line of descent and natural Campi Flegrei matrix glasses following Willmott (1981):

$$RMSE_A = \sqrt{\frac{\sum_i^n (y_{i,A} - \hat{y}_{i,A})^2}{n}} \quad (\text{eq. 1})$$

where $RMSE_A$ is the root mean square error for oxide A , n is the number of natural samples whose composition we are comparing against Rhyolite-MELTS outputs; $y_{i,A}$ is the concentration of major oxide A in natural sample i at a given MgO concentration; and $\hat{y}_{i,A}$ is the concentration major oxide A predicted by Rhyolite-MELTS for the same MgO concentration. In this approach, MgO is an index of fractionation, decreasing along the liquid line of descent as it is incorporated into phases such as olivine, clinopyroxene and spinel group minerals.

The RMSE is in units of the variable y (in our case, wt%) and, as the concentration of major oxides varies considerably in natural volcanic glasses (e.g. ~1 wt% TiO₂ to >50% SiO₂ in our samples), the magnitude of RMSE varies accordingly. As a result, we normalised each RMSE value to the average concentration of the major oxide in our natural Campi Flegrei matrix glasses:

$$RMSE_{norm,A} = \frac{RMSE_A}{\bar{X}_A} \quad (\text{eq. 2})$$

where $RMSE_{norm,A}$ is the normalised root mean square error for oxide A and $\bar{X}_A$ is mean concentration of oxide A in all of our natural Campi Flegrei glasses.

The $RMSE_{norm}$ values for each major oxide were then summed to give a single, total RMSE ($RMSE_{total}$) for each model:

$$RMSE_{total} = \sum RMSE_{norm} \quad (\text{eq.3})$$

By identifying our Rhyolite-MELTS model which produces the lowest $RMSE_{total}$, we constrained the input conditions which best reproduce the liquid line of descent recorded by natural Campi Flegrei erupted products and thus mirror the most likely conditions of sub-volcanic magma storage. We have provided a sample Python code to calculate the RMSE of Rhyolite-MELTS models at doi:10.5281/zenodo.14900107. Our approach builds on the work of Gleeson *et al.* (2017) by comparing Rhyolite-MELTS outputs to natural data throughout the entire crystallisation sequence from the most mafic to evolved samples,

assessing which combination of intensive parameters best reproduces the observed liquid line of descent.

Our statistical measure of the best-fit conditions was supplemented by comparison of the phase assemblages predicted by Rhyolite-MELTS and those observed in natural samples (see *Fractional crystallisation models*, below).

2.5.4 Potential limitations of Rhyolite-MELTS

Previous studies using MELTS to constrain magma storage conditions, including those for the petrogenesis of the CI, note a displacement of up to ~3 wt% between predicted melt K₂O and CaO concentrations and those measured in natural samples (Fowler *et al.*, 2007; Fowler and Spera, 2010). The CaO discrepancy is likely due to under-stabilisation of clinopyroxene (Fowler and Spera, 2010), whereas the K₂O discrepancy may be the result of MELTS over stabilising sanidine due to a paucity of experimental data available for calibrating the alkali feldspar–liquid equilibria (Gualda *et al.*, 2012). The calibration of Rhyolite-MELTS used in this study (v.1.2.) remedies this issue by adjusting the stability of quartz and the potassium end-member of alkali feldspar and hence is more suitable for the alkali Campi Flegrei magmas (Gualda *et al.*, 2012). Rooney *et al.* (2012) note that Rhyolite-MELTS also overpredicts melt P₂O₅ concentrations, which they attribute to inaccuracies in the apatite solubility model. However, due to the low P₂O₅ concentrations in all our natural Campi Flegrei samples (generally approaching the lower limit of detection), this element is not considered in our subsequent estimates of best-fit storage conditions.

Rhyolite-MELTS is inherently limited by a lack of hydrous phase-bearing experiments and thermodynamic models for hydrous mafic silicates, making it largely inappropriate for systems where hydrous minerals are major phases controlling the liquid line of descent (e.g. amphibole-rich rhyolites; Gualda *et al.*, 2012). However, in Campi Flegrei hydrous minerals (e.g. biotite, apatite) are ubiquitously minor phases (Isaia *et al.*,

2004; Smith *et al.*, 2011; Stock *et al.*, 2018), hence we expect inaccuracies in reproducing hydrous mineral stabilities will have minimal impact on our model outputs. Sanidine compositions calculated by Rhyolite-MELTS are also more sodic than observed in natural samples, with sanidine appearing on the liquidus at higher temperatures ($\sim 40^{\circ}\text{C}$) compared to thermometry and experiments on natural systems (Gualda *et al.*, 2012; Gardner *et al.*, 2014; Gleeson *et al.*, 2017). However, as sanidine generally appears at low melt fractions (Fowler *et al.*, 2007; Cannatelli, 2012), it is also unlikely to significantly impact our model results for the questions posed in this study.

Rhyolite-MELTS remains an extremely valuable tool for evaluating how reasonable different scenarios are (FC and AFC), despite model inaccuracies largely related to the availability of experimental data. It has been successfully applied to model phase equilibria across a range of volcanic systems (e.g. recently Knafelc *et al.*, 2020; Boschetty *et al.*, 2022; Fred *et al.*, 2022). By comparing the fit of models run over a wide range of starting conditions to the natural data from Campi Flegrei, we can place new constraints on processes operating in the sub-volcanic system.

2.6 Results

2.6.1 Compositional variation in post-15 ka Campi Flegrei glasses

Post-15 ka Campi Flegrei eruptions derived from vents in the three volcano-tectonic groups have distinct matrix glass compositions (although some overlap between compositions exists, Fig. 2.2, D'Antonio *et al.*, 1999; Di Renzo *et al.*, 2011; Smith *et al.*, 2011). The northern and eastern caldera eruptions are the most mafic (typically shoshonite-tephriphonolite) with the highest MgO, FeO and CaO concentrations and the lowest SiO₂ content. The Minopoli 2 eruption forms a distinct high MgO group separate from other eruptions (Fig. 2.2). Western caldera eruptions extend to the most evolved compositions

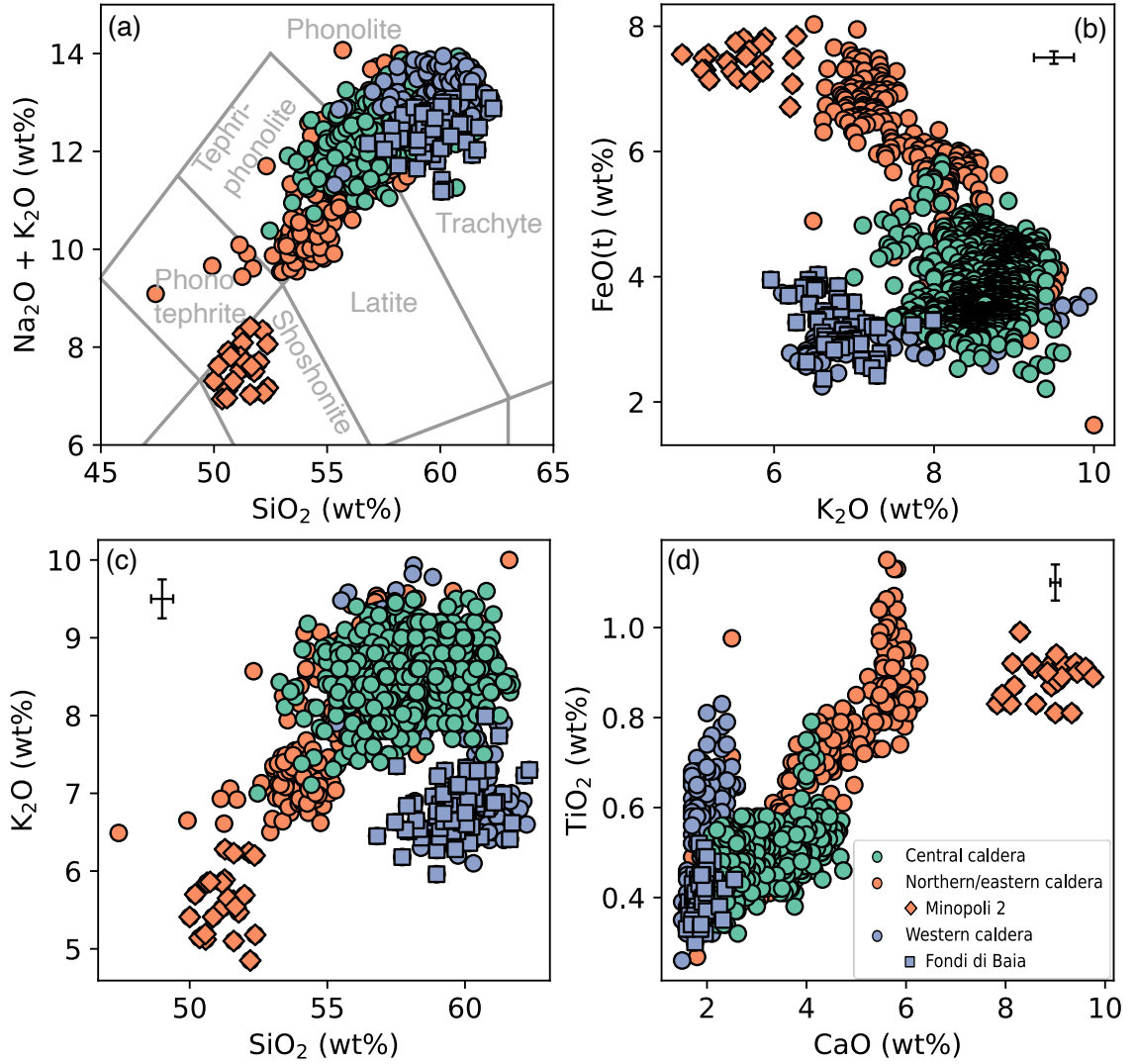


Figure 2.2: Major element variation diagrams of literature glass data for Campi Flegrei eruptions in the last 15 kyr. Points are coloured by tectonic group as illustrated in Figure 2.1. Error bars show representative 2 s.d. error from EPMA analysis from Smith et al. (2011). Glass data was compiled from GEOROC, see *Literature data* for references. Glass data from Minopoli 2 eruption, which forms a distinct high-MgO group, are shown with diamond markers and data from the Fondi di Baia eruption, which is discussed in the *Assimilation at Fondi di Baia* section, are shown with square markers.

(trachyte–phonolite), with low MgO, high SiO₂ and elevated Na₂O concentrations, forming a distinct low-K₂O, high-SiO₂ group (Fig. 2.2c). At very low MgO concentrations, western caldera eruptions also tend towards elevated TiO₂ and Na₂O and depleted K₂O. Central caldera eruptions are typically intermediate between the other two groups in terms of their extent of evolution, ranging from tephriphonolites to phonolites/trachytes. They have the highest K₂O concentrations and variable Al₂O₃.

2.6.2 Fractional crystallisation models

All our FC models show comparable geochemical trends with phases coming onto the liquidus in a similar order (Fig. 2.3). Depending on the intensive parameters, olivine or clinopyroxene are the liquidus phases (1100-1180°C) for all models, with clinopyroxene being the second phase to precipitate if not on the liquidus (Fig. A1.4). Spinel group minerals (predominantly magnetite; typically 1050-1120 °C) and plagioclase (typically 975-1050°C) precipitate next but their saturation temperatures depend strongly on the model pressure, L_{H_2O} and L_{fO_2} (see below). Small amounts of biotite (890-945°C), K-feldspar (sanidine; 805-890°C) and, in some models, leucite (800-950°C) come onto the liquidus at low temperatures. In a small number of models, olivine (~850°C), nepheline (720-735°C), garnet (705°C) or muscovite (~730°C) precipitate close to the solidus. Aside from these occasional near-solidus phases, the modelled phase assemblage mirrors that observed in post-15 ka Campi Flegrei eruptions (Stock et al., 2018).

Regarding the liquid line of descent, clinopyroxene-only crystallisation drives a decrease in MgO and CaO (from ~6 to 4.5 wt% and 11 to 9.5 wt% at *spinel-in* respectively), with other oxides (Al_2O_3 , K_2O , Na_2O , FeO, TiO_2) increasing in the residual liquid at high melt fractions, with FeO and TiO_2 beginning to decrease when spinel group minerals come onto the liquidus and the liquid evolves from shoshonite to latite. The onset of plagioclase crystallisation causes an inflection in Al_2O_3 with decreasing MgO as crystallisation continues, where Al_2O_3 becomes compatible in the crystallising assemblage and the liquid evolves from latite to tephriphonolite; plagioclase is initially Ca-rich, further driving the decrease in the liquid CaO concentration, but becomes increasingly sodic at lower temperatures, reducing the rate of Na_2O enrichment in the liquid. K-feldspar comes onto the liquidus when MgO has decreased to ~0.2 wt%; at this point K_2O becomes compatible in the crystallising assemblage and is depleted in the residual liquid, with the liquid evolving towards phonolite. This is accompanied by a sharp Na_2O enrichment in the liquid as the

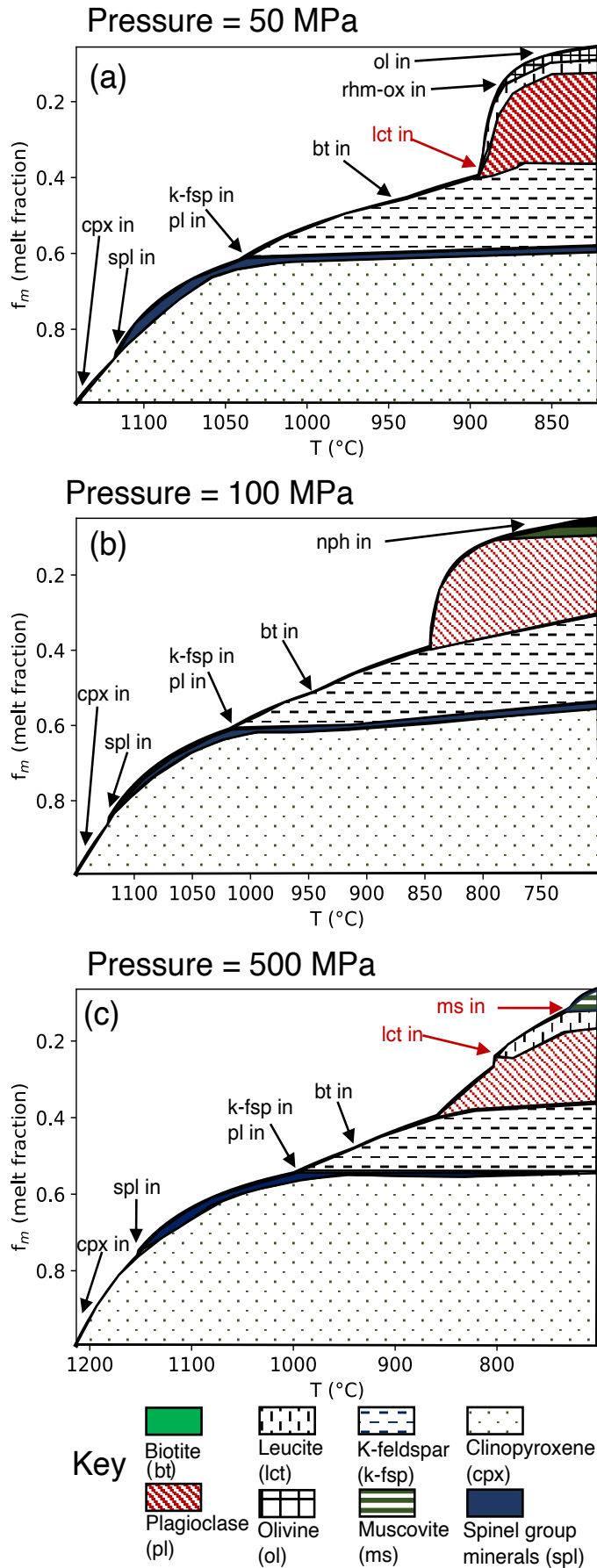


Figure 2.3: Phase proportions as a function of magma temperature for fractional crystallisation MELTS models at different pressures. Models are run at $L_{fO2} = \text{QFM}+1$ and $L_{H2O} = 2 \text{ wt\%}$. Phases highlighted in red are not observed in natural Campi Flegrei samples in the major crystallising assemblage. Phases not in key: nph, nepheline; rhm-ox, rhombohedral oxide

fraction of crystallising plagioclase decreases. Sharp compositional changes at very low MgO contents in both FC and AFC models (e.g. Fig. 2.4e) are likely a result of limitations modelling minor minerals which accommodate incompatible elements at low melt fractions (Gualda *et al.*, 2012). Although these trends hold generally for each of our simulations, the exact nature of the liquid line of descent depends on the liquidus temperature of each mineral phase and the proportions of crystallising solid, which vary as a function of the model intensive parameters.

2.6.2.1 Varying the initial H_2O content

Although varying L_{H_2O} does not have a significant effect on the type or order of minerals crystallising in our Rhyolite-MELTS models (Fig. A1.5), small differences in their solidus temperatures, modal proportions and compositions have significant effects on the liquid line of descent (Fig. 2.4). This is particularly the case for plagioclase, where crystal anorthite contents are highly sensitive to the H_2O content of their equilibrium melt (Lange *et al.*, 2009). At low L_{H_2O} (~0.5– 3 wt%), feldspar minerals stop crystallising at relatively high temperatures (~775–850°C), leading K_2O to behave incompatibly in the crystallising assemblage at low temperatures (below 800°C) and MgO contents. Conversely, at high L_{H_2O} (~4–6 wt%), feldspar continues to crystallise until the solidus and CaO behaves incompatibly in the melt at low temperatures (below ~810 °C). Reducing L_{H_2O} to <4% significantly reduces sanidine stability, resulting in very high melt Al_2O_3 contents (20–22 wt%; Fig. 2.4a). Prediction of sanidine compositions is a known limitation of Rhyolite-MELTS (Gualda *et al.*, 2012; Gardner *et al.*, 2014) which might explain these differences. Higher L_{H_2O} leads to a greater proportion of feldspar crystallising overall (~0.47 for 6 wt% L_{H_2O} compared to ~0.38 for 1 wt%, largely due to differences in the amount of sanidine predicted to crystallise). Initial melt H_2O content also has an impact on the predicted clinopyroxene composition which affects the melt TiO_2 content. At high L_{H_2O} (>3%), clinopyroxene has higher TiO_2 contents, especially at high temperatures, so crystallisation

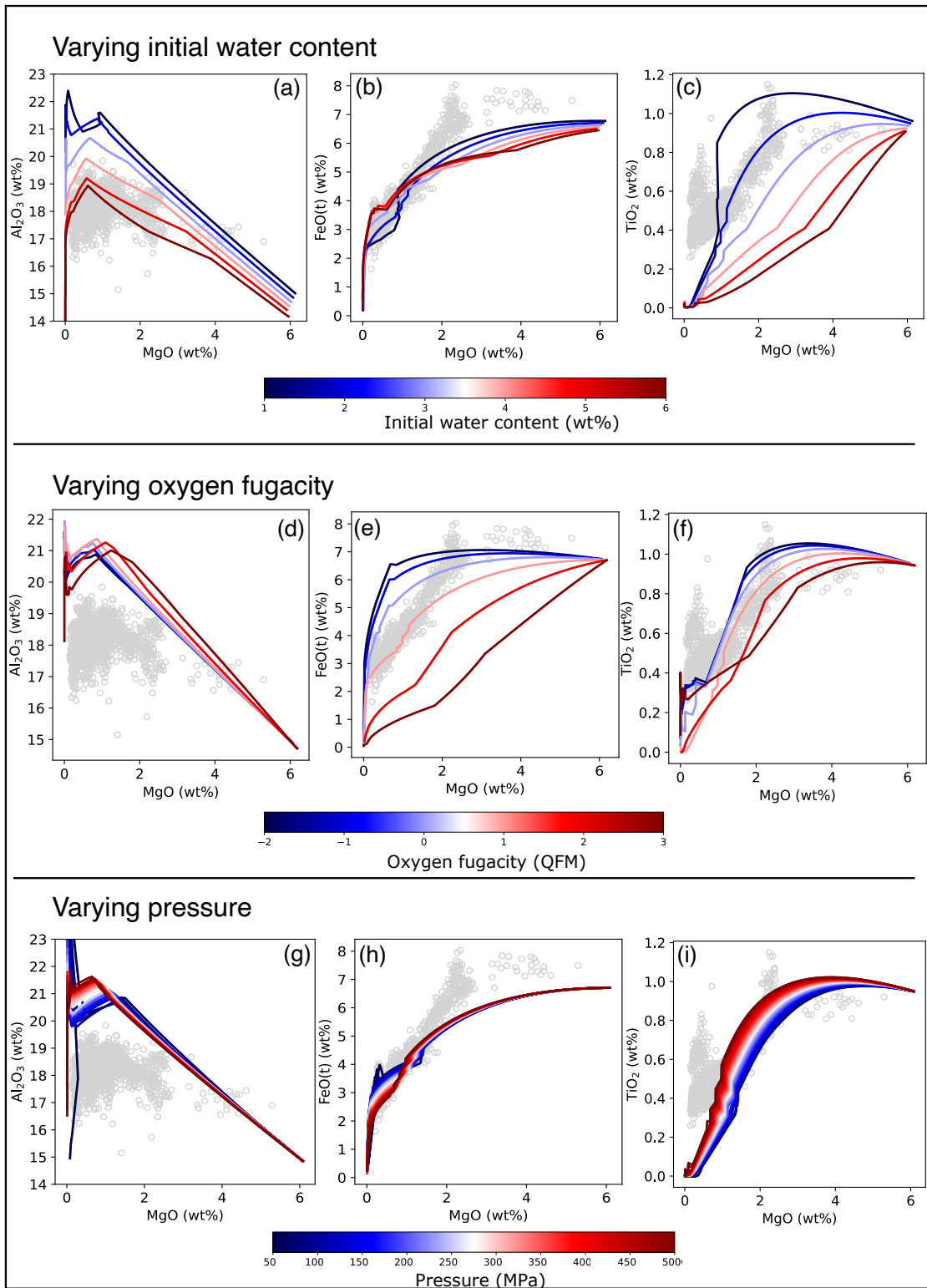


Figure 2.4: The effect of varying each intensive parameter on the resulting liquid line of descent predicted by Rhyolite-MELTS. The colour of the line represents the value of the intensive parameter being varied (where blue to red indicates the intensive parameter increasing from the lowest to highest value tested): $L_{\text{H}_2\text{O}}$ from 1 – 6 wt% in (a), (b), (c); $L_{f\text{O}_2}$ from -2 to +3 log units below/above the QFM buffer in (d), (e), (f); pressure from 50 to 500 MPa in (g), (h), (i). For (a)-(f), pressure was held constant at 160 MPa. For (d)-(i), $L_{\text{H}_2\text{O}}$ was 2 wt%. For (a)-(c) and (g)-(i), $L_{f\text{O}_2}$ was QFM+1. The grey points are all literature glass data for eruptions in the last 15 kyr. This figure represents a selection of all Rhyolite-MELTS models run; each intensive parameter was evaluated against the full range of the remaining two.

strongly drives down the melt TiO_2 content, whereas at lower $L_{\text{H}_2\text{O}}$ (<2%), clinopyroxene TiO_2 content is much lower until low temperatures, so the TiO_2 content remains elevated (Fig. 2.4c). Increasing $L_{\text{H}_2\text{O}}$ reduces the TiO_2 content of spinel group minerals, but the small quantities (~0.05) of spinel group minerals crystallised means the effect on melt TiO_2 content is minimal compared to clinopyroxene.

2.6.2.2 Varying oxygen fugacity

Increasing $L_{f_{\text{O}_2}}$ in our Rhyolite-MELTS models increases the stability of spinel group minerals which primarily impacts the SiO_2 and FeO concentrations of the residual melt during fractional crystallisation: under more oxidising conditions, where spinel group minerals stabilise at higher temperatures, melt SiO_2 concentrations begin to increase at higher temperatures and FeO contents are lower for any given MgO content (Fig. 2.4e). The earlier precipitation of spinel group minerals under more oxidising conditions is consistent with experimental studies (Toplis and Carroll, 1995; Feig *et al.*, 2010). Varying $L_{f_{\text{O}_2}}$ also effects the liquid line of descent for TiO_2 with generally lower melt TiO_2 concentrations in the more oxidised models, again because of the earlier spinel group minerals fractionation but also differences in the predicted clinopyroxene composition which initially contains more TiO_2 (Fig. 2.4f). However, at QFM+3, spinel minerals contain less TiO_2 than at QFM, so at lower $L_{f_{\text{O}_2}}$ there is a steeper reduction of TiO_2 in the melt after *spinel-in*.

2.6.2.3 Varying pressure

Changing pressure in our Rhyolite-MELTS models has minor impacts on the predicted phase assemblage. The major mineral phases observed in Campi Flegrei erupted products – clinopyroxene, plagioclase feldspar, alkali feldspar – are predicted to crystallise across all pressures (Fig. 2.3, Fig. A1.4). However, at high pressures (>200 MPa), Rhyolite-MELTS predicts minor muscovite and garnet crystallisation close to the solidus (Fig. 2.3c). Likewise, at low pressures (<70 MPa), leucite is predicted to crystallise in significant quantities (~7%, Fig. 2.3a). The liquid line of descent is not very sensitive to pressure; for

all major oxides there is generally <1 wt% difference in the predicted concentration of the oxide at equivalent MgO/temperature steps across the entire range of pressures (Fig. 2.4g-i). Small differences between models run at opposing ends of our pressure range observed at low temperature likely reflect the crystallisation of near-solidus muscovite, garnet and leucite.

2.6.3 Modelling assimilation – fractional crystallisation

The major and trace element compositions of basement rocks which represent potential Campi Flegrei assimilants are listed in Table A1.4. The addition of an assimilant to our Rhyolite-MELTS models produces similar geochemical trends for all volcano-tectonic groups, although these trends differ for each assimilant composition.

2.6.3.1 Assimilation of Palaeozoic metamorphic basement

The addition of Palaeozoic metamorphic basement assimilant to our Rhyolite-MELTS models significantly increases the predicted melt SiO₂ content and reduces the predicted Al₂O₃ content, relative to FC models run with the same set of intensive variables (Fig. A1.8, A1.12, A1.16); these effects increase with increasing quantities of the contaminant. Small quantities of Palaeozoic metamorphic contamination cause melt K₂O and Na₂O contents to increase at low temperatures and melt fractions, due to changes in the predicted phase assemblage: in models with $M_a/M_m = 0.1$ feldspar stops crystallising ~80° C higher temperature than for $M_a/M_m = 0.3$. For models with $M_a/M_m > 0.2$, Rhyolite-MELTS predicts crystallisation of quartz at low temperatures.

2.6.3.2 Assimilation of syn-orogenic wedge-top deposits

Addition of wedge-top deposits increases the predicted SiO₂ content of the melt in our Rhyolite-MELTS models compared to FC under equivalent storage conditions, especially at low temperatures and melt fractions (Fig. A1.7, A1.11, A1.15); at $M_a/M_m = 0.3$, the SiO₂ content of the residual melt is predicted to reach ~72 wt% at low temperatures. Addition of

wedge-top deposits also slightly increases the predicted melt CaO concentration and decreases the melt FeO, K₂O, Na₂O and Al₂O₃ at equivalent MgO content compared to FC models with the same intensive parameters, with the magnitude of these changes increasing with the amount of assimilated. For small amounts of wedge-top deposit assimilation, sanidine stops crystallising at higher temperatures, leading to K₂O incompatibility at low temperatures, whereas larger amounts of wedge-top deposit assimilation causes more Na-rich plagioclase to crystallise, lowering the Na₂O contents of the residual melt.

2.6.3.3 *Assimilation of limestone*

Addition of limestone in our Rhyolite-MELTS models has the most significant impact on the predicted CaO concentration (Fig. A1.6, A1.10, A1.14), causing it to increase relative to FC models run with the same intensive parameters. Conversely, the predicted liquid SiO₂ content is much lower relative to equivalent FC models at a given MgO concentration. These effects increase with greater amounts of limestone contamination, especially at $M_a/M_m > 0.01$ (Fig. A1.6, A1.10, A1.14). To a lesser extent, at equivalent melt MgO content, limestone assimilation causes slightly lower FeO and Al₂O₃ contents and slightly higher TiO₂ relative to equivalent FC models and with limestone addition at $M_a/M_m > 0.05$ Rhyolite-MELTS predicts minor garnet crystallisation at best-fitting intensive parameters for uncontaminated FC.

2.6.3.4 *Assimilation of syenite*

Where a syenite assimilated is added to our Rhyolite-MELTS models, melt SiO₂ contents are higher and Al₂O₃ contents are lower than in FC models run under equivalent conditions at the same melt MgO content, due to greater proportions of crystallising feldspar. For the other major oxides, adding syenite does not significantly change the liquid line of descent compared to equivalent FC models, saving a small reduction in K₂O content and increase in Na₂O, CaO and TiO₂ concentrations. In all cases, the predicted liquid lines of descent are similar irrespective of the quantity of contaminant (Fig. A1.9, A1.13, A1.17).

2.7 Discussion

2.7.1 Constraints on magma storage conditions

Contrasting major element compositions of matrix glasses erupted from vents in different volcano-tectonic settings allude to variations in the structure and/or processes operating within the sub-volcanic plumbing system in different parts of the Campi Flegrei caldera. Changing L_{H_2O} , L_{fO_2} and P in our models affects the predicted liquid line of descent (Fig. 2.4), which in turn controls how well the models match measured natural glass compositions from Campi Flegrei (Fig. 2.5). Our RMSE statistical test constrains the combination of intensive parameters which produce the best-fit between the liquid line of descent predicted by Rhyolite-MELTS FC models and that recorded by natural glass compositions (Table 2.3; Tables A1.6–A1.8).

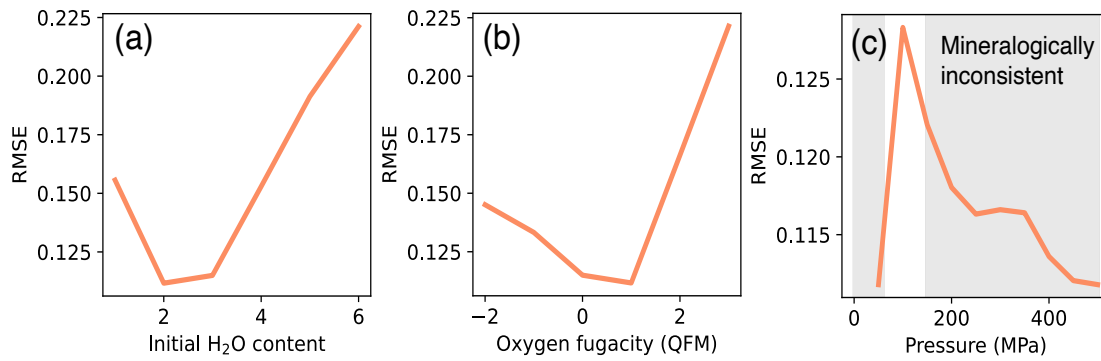
Best-fit	Northern/eastern caldera eruptions	Central caldera eruptions	Western caldera eruptions
Pressure (MPa)	110	140	160
Initial water content (wt%)	2	3	2
Oxygen fugacity (log units relative to the Quartz-Fayalite-Magnetite buffer)	1	0	0
Assimilant composition	Palaeozoic basement	Syenite	Syenite
Amount (% of total mass of magma)	10	30	30
Total amount FC (%)	54	58	66
Normalised RMSE (FC)	0.142	0.227	0.377
Normalised RMSE (AFC)	0.118	0.114	0.206

Table 1.3: Best-fit FC storage conditions and assimilant compositions and quantities for each tectonic setting as defined by the lowest RMSE between Rhyolite-MELTS models and the literature glass data. Total amount of FC refers to the amount required (as a crystallisation %) to reach the composition of the most evolved eruptions in each group.

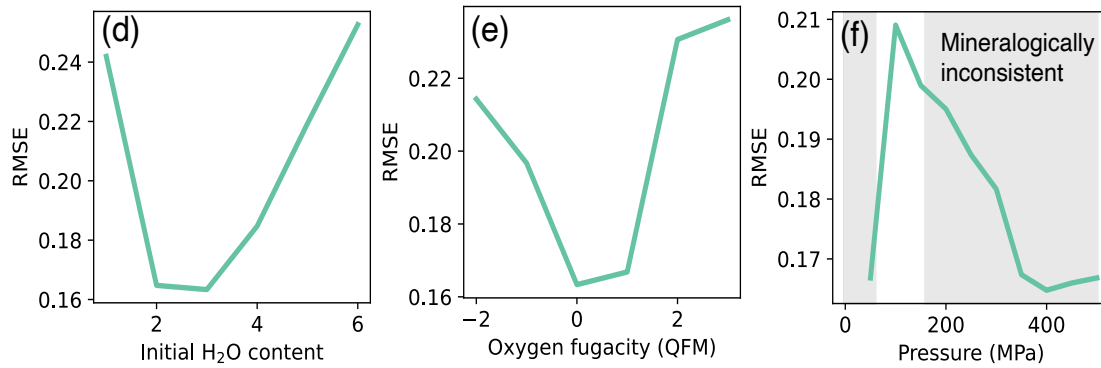
2.7.1.1 Liquidus H_2O concentration

Varying L_{H_2O} between 1–6 wt% markedly changes the stability of feldspar, with *feldspar-in* occurring at higher temperatures for lower H_2O contents, as observed in previous experimental (Eggler, 1972; Gaetani *et al.*, 1993; Sisson and Grove, 1993; Lange *et al.*,

Northern/eastern caldera eruptions



Central caldera eruptions



Western caldera eruptions

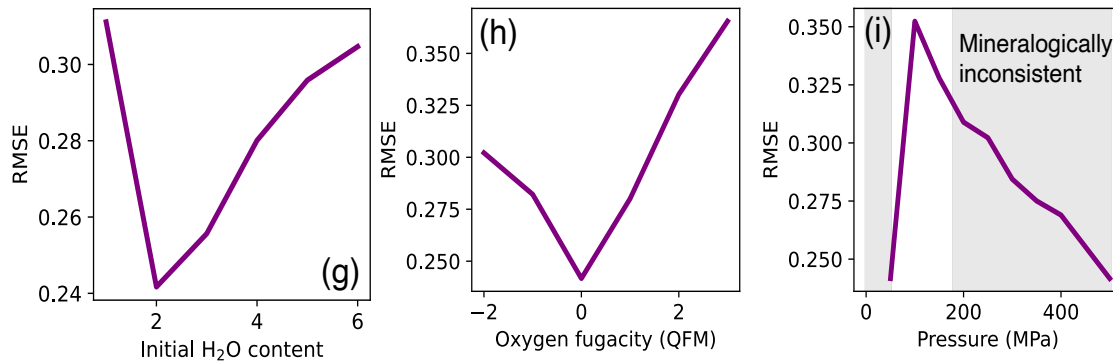


Figure 2.5: The effect of varying each intensive parameter on the RMSE of the resulting Rhyolite-MELTS model. For (a), (d) and (g), pressure and oxygen fugacity are held constant at the best-fit conditions for the tectonic group and the initial H₂O content is varied. For (b), (e) and (h) H₂O content and pressure are held constant and oxygen fugacity is varied. For (c), (f) and (i) H₂O content and oxygen fugacity are both held constant and pressure is varied. The grey shaded regions in (c),(f),(i) indicate pressures at which Rhyolite-MELTS predicts the crystallisation of phases which are not observed in natural Campi Flegrei rocks (muscovite, garnet, leucite).

2009), MELTS based studies (Fowler *et al.*, 2007; Cannatelli 2012) and observations of erupted plagioclase textures and compositions (e.g. at Stromboli - Landi *et al.*, 2004) . At the lower end of our L_{H_2O} range (0.5-2 wt%), our models predict an enrichment in the melt K_2O at low temperatures (i.e. incompatible behaviour) and consistently high melt TiO_2 contents, which are not observed in natural Campi Flegrei samples (Fig. 2.6). Similarly, at the top of our L_{H_2O} range (5-6 wt%), Rhyolite-MELTS predicts that the melt becomes enriched in CaO at low temperatures, with consistently low TiO_2 and high Al_2O_3 concentrations, which are also not observed. These constraints lead to higher RMSE for models with L_{H_2O} outside 2-3 wt% (Fig. 2.5a,d,g). For northern/eastern and western caldera eruptions, the natural glass compositions are best reproduced by crystallisation with 2 wt% L_{H_2O} , whereas the central caldera eruptions are best reproduced with a higher L_{H_2O} of 3 wt%.

The best-fit L_{H_2O} for each volcano-tectonic setting (2–3 wt%) are consistent with previous measurements of mafic melt inclusion H_2O concentrations (Webster *et al.*, 2003; Cannatelli *et al.*, 2007; Mangiacapra *et al.*, 2008; Stock *et al.*, 2018), those determined experimentally (Perinelli *et al.*, 2019) and L_{H_2O} values used in previous thermodynamic modelling of Campi Flegrei eruptions (Bohrson *et al.*, 2006; Fowler *et al.*, 2007; Cannatelli, 2012; Stock *et al.*, 2016). Forni *et al.* (2018a) assessed the H_2O contents of melts in equilibrium with late-crystallising K-feldspar were higher than those of near liquidus melts (i.e. prior significant crystallisation of anhydrous minerals), and also suggested that the H_2O content of Campi Flegrei magmas increased over the past 15 ka, from 0.5–3.5 wt% in the Epoch 1 Minopoli 1 and 2 eruptions to 3–6 wt% in the Epoch 3 Astroni and Monte Nuovo eruptions. However, their study only included a small number (12) of eruptions from the past 15 kyr and did not consider the possibility for a spatial, rather than temporal, correlation. As earlier eruptions generally occurred along the caldera rim and migrated towards the centre of the caldera over time (Smith *et al.*, 2011), their results are equally compatible with differences in L_{H_2O} between volcano-tectonic groups. Eruptions from vents on the caldera

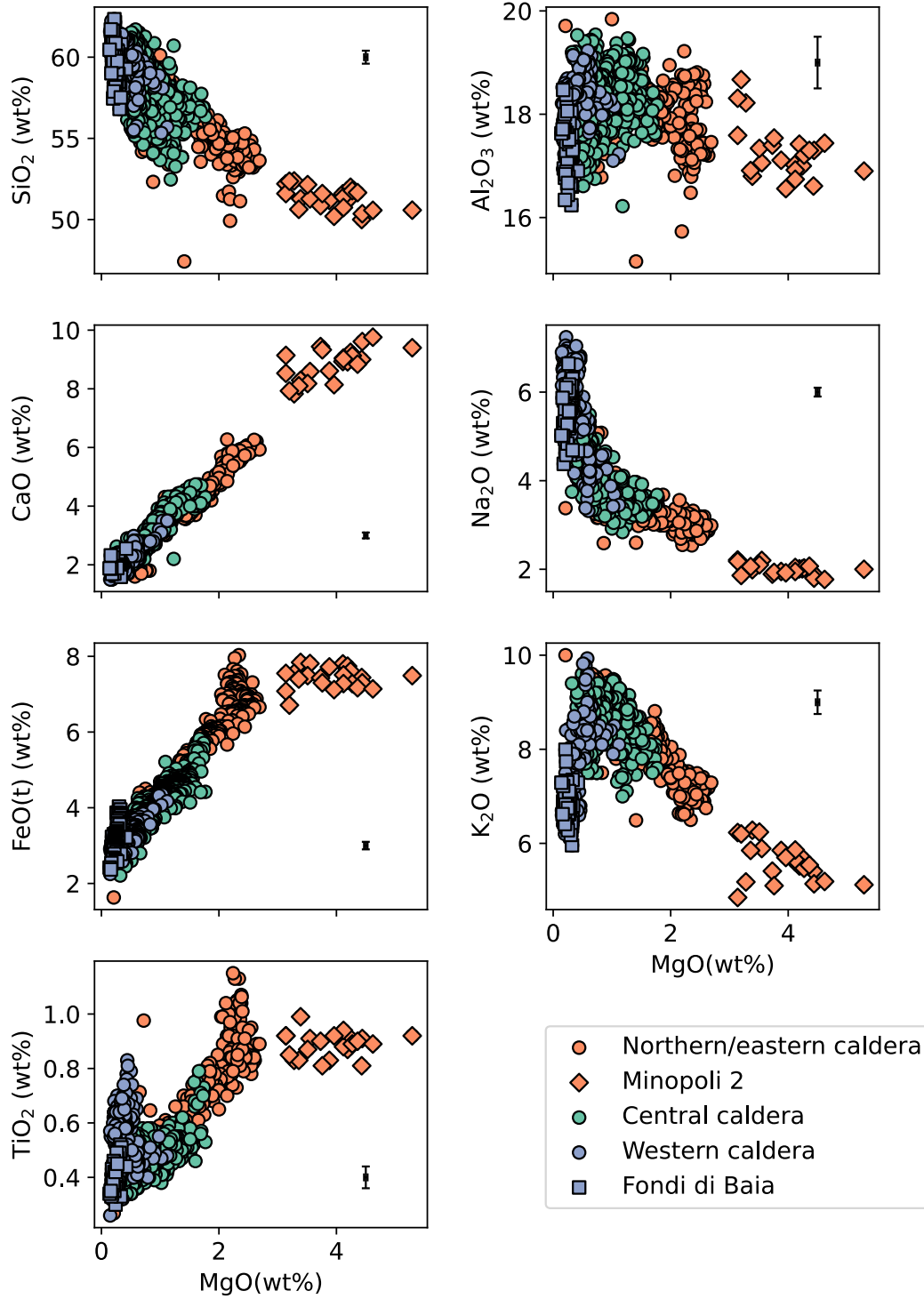


Figure 2.6: Harker diagrams of literature glass data for Campi Flegrei eruptions in the last 15 kyr. Points are coloured by tectonic group as illustrated in Figure 2.1. Error bars show representative 2 s.d. error from EPMA analysis from Smith *et al.* (2011). Glass data was compiled from GEOROC and studies are referenced in *Literature data*. Minopoli 2 eruption, which forms a distinct high-MgO group, are shown with diamond markers and data from the Fondi di Baia eruption, which is discussed in the *Assimilation at Fondi di Baia* section, are shown with square markers.

rim (e.g. Minopoli 1 and 2, Soccavo 4) were identified by Forni *et al.* (2018a) as having lower H₂O contents than eruptions in the central caldera (e.g. Astroni, Agnano-Monte

Spina). The eruption of Monte Nuovo, in the western caldera but with the highest H₂O content in the last 15 kyr, is the exception, which may be related to extensive fractionation at low temperatures.

The differences in best-fit L_{H_2O} between our volcano-tectonic groups could reflect changes in the H₂O content of near-primitive mantle melts feeding Campi Flegrei eruptions in different parts of the caldera system. However, despite their different structural setting, post-15 kyr Campi Flegrei eruptions are relatively closely spaced (e.g. ~1 km between some central and caldera rim vents) relative to a whole arc or ocean island scale, and L_{H_2O} variations would need to occur on significantly shorter length scales than any previously reported mantle heterogeneity (e.g. Kelemen *et al.*, 2003; Gibson *et al.*, 2012; Sims *et al.*, 2013). Consequently, we discount mantle heterogeneity as the potential source for variable L_{H_2O} across the caldera. Instead, we suggest that variations in L_{H_2O} between magmas in different volcano-tectonic settings result from interaction with hydrothermal water; such magma-fluid interaction has been suggested previously for Campi Flegrei eruptions on the basis of trace element and isotopic variation (Villemant, 1988; Civetta *et al.*, 1991). Although our approach cannot determine whether hydrothermal interaction and magma hydration genuinely occurred above the liquidus (i.e. as opposed to after some crystallisation), addition of water to the melt must have occurred at high enough temperatures and melt fractions to impact the crystallising phase assemblage. Campi Flegrei currently has a highly active hydrothermal system focused around Solfatara, in the central caldera (Troiano *et al.*, 2022) with geological evidence that this has persisted over the past 15 kyr (Isaia *et al.*, 2009). While the main hydrothermal aquifer beneath Campi Flegrei is currently within the shallow crust (2–3 km; Troiano *et al.*, 2022) above the main zone of magma storage (see below), the eruption of hydrothermally altered syenitic lithics (Fedele *et al.*, 2006; Gebauer *et al.*, 2014) suggests that fluids may be present at significantly greater

depths; this is supported by recent magnetotelluric imaging which shows a volatile-rich zone extending to ~8 km (Isaia *et al.*, 2025).

2.7.1.2 Oxygen fugacity

Varying L_{fO_2} between QFM-2 and QFM+3 has a significant effect on the predicted liquid line of descent, particularly for FeO and SiO₂ which are most impacted by changes in spinel stability (Fig. 2.4e). Under more oxidising conditions, spinel group minerals stabilise at higher temperatures resulting in lower FeO and higher SiO₂ concentrations in the residual melt, as observed in experimental studies (Hill and Roeder, 1974; Fisk and Bence, 1980). For $L_{fO_2} > \text{QFM}+1$, the predicted liquid line of descent for FeO significantly deviates from that measured in natural Campi Flegrei glasses, leading to higher RMSE for these models (Fig. 2.5b,e,h). For central and western caldera eruptions, the natural glass compositions are best reproduced by crystallisation with L_{fO_2} at the QFM buffer; northern/eastern caldera eruptions are best reproduced with L_{fO_2} QFM+1.

Our best-fit L_{fO_2} of QFM to QFM+1 suggests that the liquidus oxidation state of the magma is broadly similar across the caldera. Although we do not fix fO_2 to a buffering reaction below the liquidus in our models (as these reactions very rarely occur in nature; Anenburg and O'Neill, 2018), our best-fit L_{fO_2} range agrees well with previous thermodynamic modelling (Bohrson *et al.*, 2006; Fowler *et al.*, 2007; Cannatelli, 2012) and experimental studies (Fabbrizio and Carroll, 2008) which have consistently reproduced the phase assemblage of Campi Flegrei erupted products with fO_2 buffered between QFM and QFM+1.8 (close to Ni-NiO+1 at magmatic conditions, Frost, 1991). Our results are also consistent with fO_2 estimates for the Campanian Ignimbrite calculated by spinel-melt oxybarometry (QFM+1; Forni *et al.*, 2016).

2.7.1.3 Pressure

Varying pressure in the range 50–500 MPa has minimal effect on the liquid line of descent of all the major oxides (Fig. 2.4g-i), with the predicted concentrations of major oxides

varying by <1% at any given MgO concentration or temperature across the entire range of pressures (where other intrinsic variables are constant). Therefore, our RMSE statistical method is not an accurate discriminator of best-fit pressure. Eggler (1972) experimentally demonstrated that plagioclase stability is strongly sensitive to the equilibrium melt H₂O content but relatively insensitive to pressure, with melt-H₂O sensitivity also observed in erupted products at Stromboli by Landi *et al.* (2004). As plagioclase is a major crystallising phase in Campi Flegrei magmas (Isaia *et al.*, 2004; Piochi *et al.*, 2005; Stock *et al.*, 2018), this may partly explain the models' relative insensitivity to pressure variations. However, while the overall liquid line of descent predicted by Rhyolite-MELTS is relatively pressure insensitive, the mineral phase assemblage does vary close to the solidus and allows for some constraint on the most probable storage conditions. Our models predict that relatively late-stage muscovite and garnet will crystallise in Campi Flegrei magmas at pressures >200 MPa and that ~7% of leucite will precipitate at pressures <70 MPa (Fig. 2.3, Fig. A1.4). Muscovite and garnet have never been reported in any Campi Flegrei eruption products and leucite has only been observed rarely in low concentration (Isaia *et al.*, 2004; Smith *et al.*, 2011; Stock *et al.*, 2018); hence, these pressures likely represent unrealistic magma storage conditions. Despite our models run at intermediate pressures having the highest RMSE when comparing predicted liquid lines of descent to natural glasses (i.e. RMSEs decrease at both low and high pressures; Fig. 2.5c,f,i), this mineralogical disparity constrains storage pressures to the range 70–200 MPa. Within this range, the best-fit pressure for each volcano-tectonic group can be determined approximately by the lowest RMSE for SiO₂, which is the most sensitive to pressure variations. For northern/eastern caldera eruptions, the natural glass compositions are best reproduced by crystallisation at 110 MPa, for central caldera eruptions the best-fit pressure increases to 140 MPa and is highest for western caldera eruptions, at 160 MPa.

Given an average Campanian crustal density of 2.3 g cm⁻³ after Rosi and Sbrana (1987), our approximated crystallisation pressures correspond to magma storage depths in

the range ~5–7 km. This broadly agrees with previous phase equilibria investigations at Campi Flegrei, which visually identified that the compositions of natural samples were best reproduced by models run at pressures equivalent to 6–12 km (150–300 MPa; Bohrsen *et al.*, 2006; Fowler *et al.*, 2007; Cannatelli, 2012). Despite the inherent insensitivity of our method, our crystallisation depth estimate also agrees reasonably with independent petrological and geophysical constraints on the structure of the Campi Flegrei magmatic system, which predict the main magma storage region to be located at ~7–8 km (e.g. Zollo *et al.*, 2008; Stock *et al.*, 2018; Petrelli *et al.*, 2023; Isaia *et al.*, 2025). Critically, our depth estimates are not consistent with shallower crystallisation at 3–4 km, which corresponds with the depth of the current deformation source (Woo and Kilburn, 2010; Amoruso *et al.*, 2014; D’Auria *et al.*, 2015) and most recent seismicity (Scotto di Uccio *et al.*, 2024). This shallow unrest has previously been linked to fluid migration in the active hydrothermal system beneath Campi Flegrei (Troiano *et al.*, 2011; Chiodini *et al.*, 2012, 2015b) and may occur at the same depth as small/ephemeral sill intrusions (Stock *et al.* 2018). Rather, our data support the majority of magma storage and crystallisation occurring in the mid-lower crust.

2.7.2 Volcano-tectonic controls on assimilation

Rhyolite-MELTS FC models can produce best-fit liquid lines of descent which correlate reasonably with natural glass compositions for some major oxides (e.g CaO, FeO; Fig. 2.6; Fig. A1.18-A1.20) and there is good agreement between the modelled phase assemblages and those observed in Campi Flegrei erupted products. However, models fail to reproduce natural glass compositions for other major oxides under any set of intensive parameters. For example, modelled Al₂O₃ concentrations are consistently higher than in natural glasses, whereas SiO₂ concentrations are consistently lower (Fig. 2.7). While models are able to reproduce the K₂O composition of erupted glasses from northern/eastern and central caldera volcano-tectonic groups, the lower K₂O concentration of western caldera eruptions is not reproduced by any of our FC models (Fig. A1.20). These discrepancies suggest that

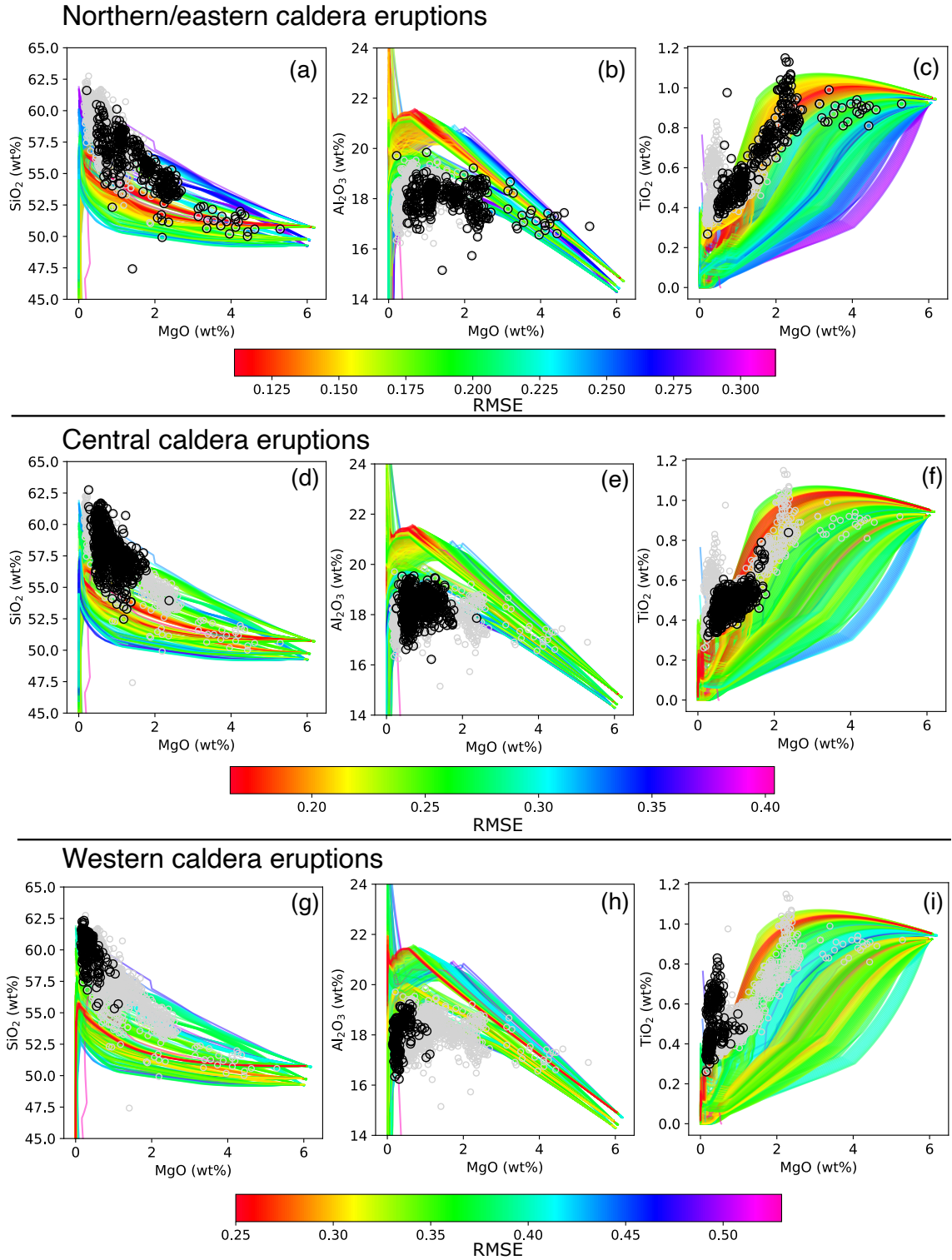


Figure 2.7: Results of all Rhyolite-MELTS models of fractional crystallisation. Grey points represent all literature glass data for eruptions in the last 15 kyr, black points are literature glass data for the tectonic group indicated. Each line represents the liquid line of descent predicted by Rhyolite-MELTS for a parental magma cooling and crystallising under a given pressure, initial H₂O content and oxygen fugacity. Each model is coloured according to the RMSE value indicating the goodness-of-fit between the model and natural data; red indicates a better fit, blue/purple indicates a worse fit. See *Statistical determination of best-fit storage conditions* for description of RMSE calculation, RMSE is an average of all major oxides. Plots of the other major oxides that are not shown in this figure are included in the Supplementary Material (SM) Fig. A1.18–A1.20.

assimilation may play a role in controlling the Campi Flegrei liquid line of descent, where addition of a contaminant could improve the fit between our model outputs and natural glass compositions.

Despite evidence for extensive limestone contamination at Vesuvius (~25 km east of Campi Flegrei; Del Moro *et al.*, 2001; Iacono Marziano *et al.*, 2008) and previous authors interpreting this as a potential contaminant of Campi Flegrei magmas (Iacono Marziano *et al.*, 2008; Pappalardo and Mastrolorenzo, 2012) addition of limestone does not significantly improve the fit between predicted and observed liquid lines of descent in post-15 ka volcano-tectonic groups relative to FC alone. This is reflected in limestone contamination producing only a very minor decreases in the RMSE between modelled and observed glass compositions; increasing quantities of a limestone assimilant lowers the melt SiO₂ concentration and increases CaO, forcing the predicted liquid line of descent for these elements away from the observed compositions of all volcano-tectonic groups (Fig. A1.6, A1.10, A1.14). At $M_a/M_m > 0.05$, limestone-contaminated models predict the crystallisation of garnet, which has never been observed in natural Campi Flegrei samples. Hence, in contrast with Vesuvius, our models clearly show that limestone is not a contaminant in Campi Flegrei (with the possible exception of the Fondi di Baia eruption, see below).

Syn-orogenic wedge-top deposits have previously been identified as a potential contaminant of Campi Flegrei magmas, based on their occurrence in the shallow crust within the Neapolitan area (D'Erasmus, 1931; Bernasconi *et al.*, 1981; Sollevanti, 1983). Where large amounts of wedge-top deposits ($M_a/M_m = 0.2-0.3$) are added to Rhyolite-MELTS AFC models, predicted liquid lines of descent have significantly higher SiO₂ and lower Na₂O, FeO and TiO₂ contents than are observed in natural Campi Flegrei glasses, increasing the RMSE relative to simple FC models (Fig. A1.7, A1.11, A1.15). Addition of small amounts of wedge-top deposits leads to K₂O enrichment in the melt at low temperatures as sanidine crystallisation is suppressed. While this mineralogical change is inconsistent with

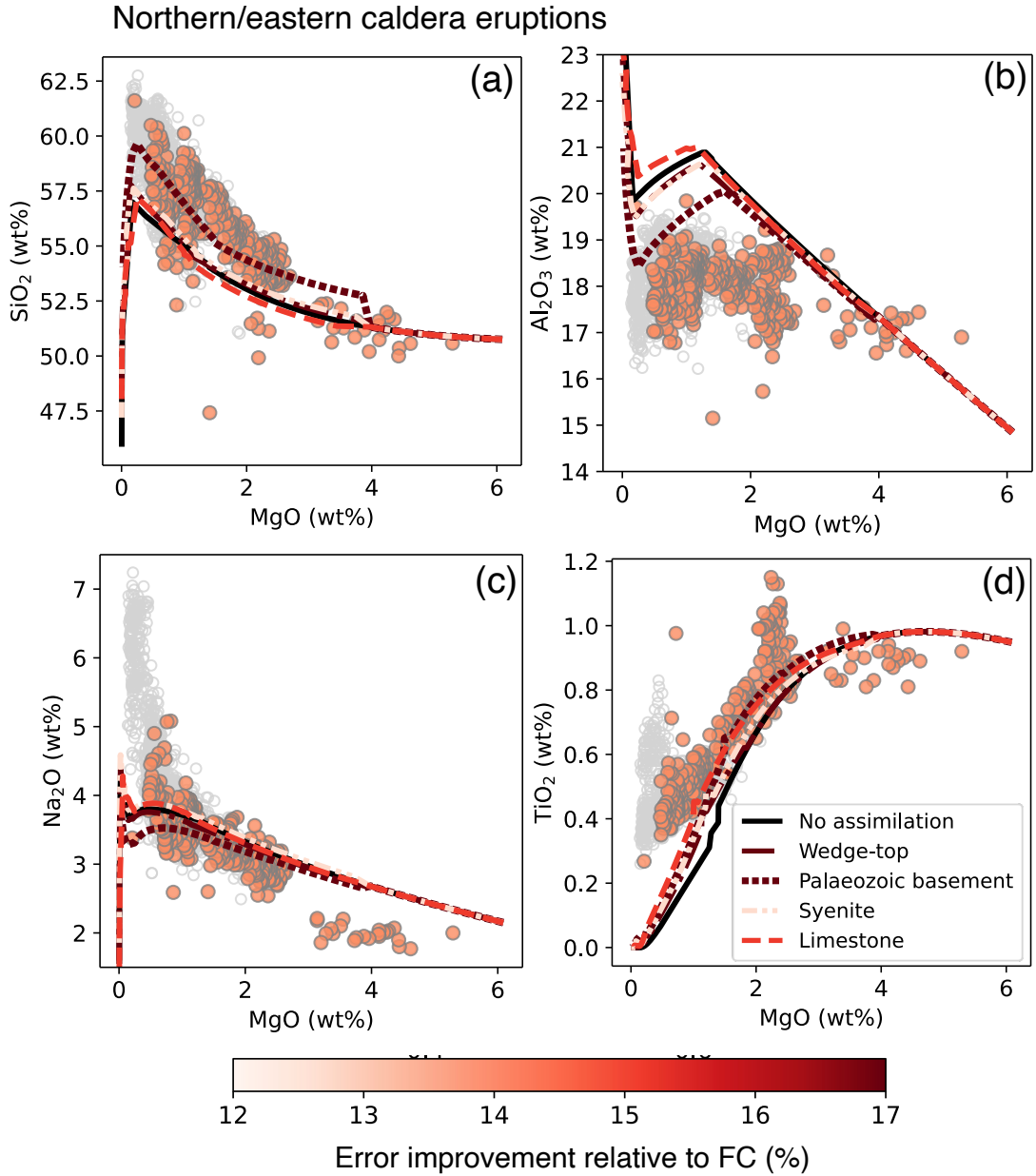


Figure 2.8: Results of Rhyolite-MELTS models of assimilation-fractional crystallisation for northern/eastern caldera group eruptions. Line styles indicate different assimilant compositions, the solid black line shows the best-fit FC model for northern/eastern caldera eruptions. For each assimilant composition, the amount of assimilant which led to the largest improvement in model fit compared to the FC-only model is plotted. The line colour refers to the percentage improvement of RMSE relative to the best-fit FC only model, pale red indicates less improvement to darker red which indicates the most improvement. Fit was calculated using normalised RMSE, as for FC models. Pale grey circles represent all literature glass data for eruptions in the last 15 kyr, orange filled circles represent literature glass data from northern/eastern caldera group eruptions. Assimilant was added en masse at 1100°C. Full results of AFC modelling for eastern caldera group eruptions are included in Fig. A1.6-A1.9

observations of natural samples (which all contain sanidine; Smith *et al.*, 2011) and negates this assimilation source, minor wedge-top deposits contamination lowers the predicted melt Al_2O_3 content compared to FC models which improves the overall fit between the observed

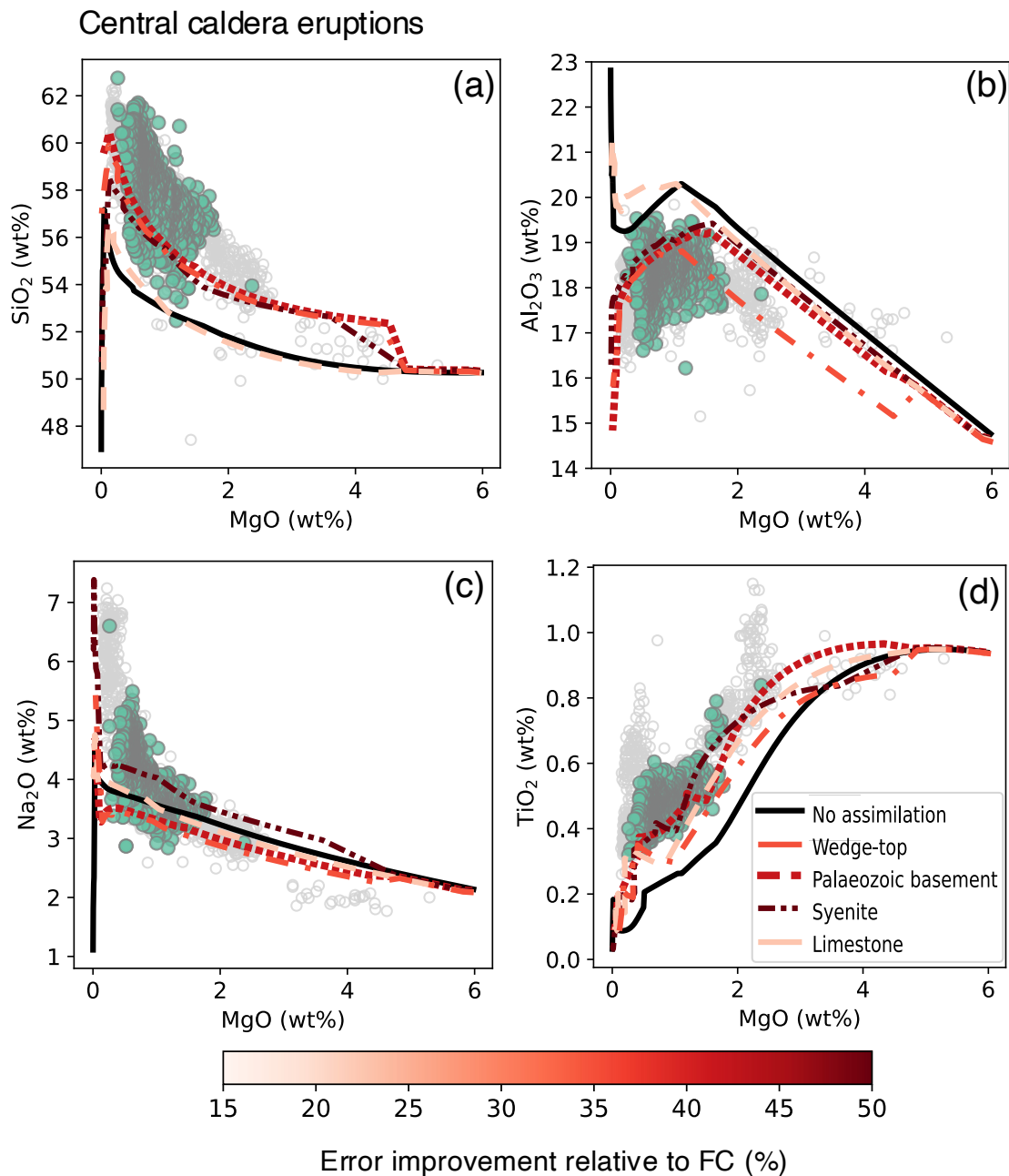


Figure 2.9: Results of Rhyolite-MELTS models of assimilation-fractional crystallisation for central caldera group eruptions. The colouring and line style of each Rhyolite-MELTS model is as described for Figure 2.7. Pale grey circles represent all literature glass data for eruptions in the last 15 kyr, green filled circles represent literature glass data from central caldera group eruptions. Full results of AFC modelling for central caldera group eruptions are included in Fig. A1.10-A1.13

and modelled liquid line of descent and reduces the RMSE in all volcano-tectonic groups, especially for very small amounts of contamination ($M_a/M_m = 0.05$; Fig. 2.8-2.10).

Long-lived volcanic systems are often thought to be underlain by large volumes of crystalline residue (mush), which fractionated during magmatic evolution but remained in

the crust as their accompanying liquids were evacuated during eruptions; in silicic systems, this crystalline restite has a syenitic or granitic composition (Bachmann and Huber, 2016; Cashman *et al.*, 2017; Edmonds *et al.*, 2019; Horn *et al.*, 2022). Campi Flegrei has been active for >300 kyr (De Vivo *et al.*, 2001; Rolandi *et al.*, 2003; Di Vito *et al.*, 2008)

and the presence of a sub-volcanic crystalline residue is attested by the presence of syenitic lithics, with previous thermodynamic studies suggesting that syenite assimilation impacted the composition of melts erupted during the Campanian Ignimbrite (Fowler *et al.*, 2007). In our models, assimilation of large proportions of syenite ($M_a/M_m = 0.3$) increases the SiO_2 content of the liquid and reduces the Al_2O_3 concentration (due to greater proportions of feldspar crystallising), improving the correlation between the modelled liquid line of descent and natural glass compositions. The RMSE, averaged across all major elements, is also reduced relative to simple FC models in all volcano-tectonic environments (Fig. A1.9, A1.13, A1.17). However, while predicted liquid lines of descent for syenite-contaminated magmas closely match the compositions of erupted glasses for central caldera and western caldera eruptions, modelled Na_2O concentrations markedly deviate from the observed concentrations at low temperatures for northern/eastern caldera eruptions, predicting much higher Na_2O concentrations than are observed.

Much of central Italy is underlain by Palaeozoic metamorphic basement, predominantly comprising low-grade to granulite-facies metamorphic rocks which formed during the Variscan orogeny (Caggianelli and Prosser, 2001). While the basement depth directly beneath Campi Flegrei remains poorly constrained geophysically and these Palaeozoic rocks have not been intersected in borehole records (AGIP, 1987), seismic datasets reveal relatively shallow basement (≥ 4 km; Battaglia *et al.*, 2008; Berrino *et al.*, 2008) beneath Campi Flegrei and these have been suggested as a potential source of isotopic contamination in Campi Flegrei magmas (Pappalardo *et al.*, 2002). Our models predict quartz saturation at relatively low temperatures with large amounts ($M_a/M_m > 0.2$) of

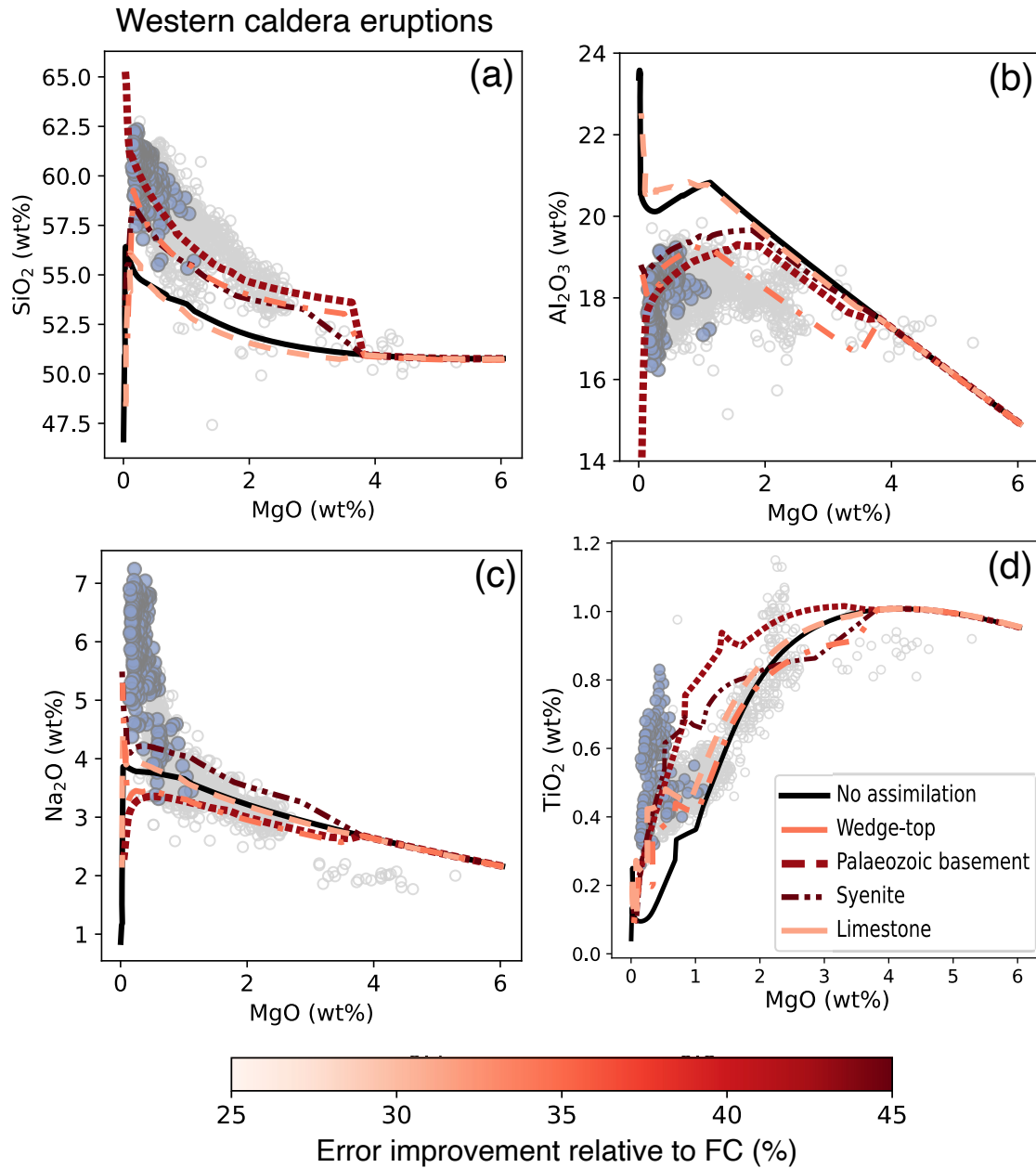


Figure 2.10: Results of Rhyolite-MELTS models of assimilation-fractional crystallisation for western caldera group eruptions. The colouring and line style of each Rhyolite-MELTS model is as described for Figure 2.7. Pale grey circles represent all literature glass data for eruptions in the last 15 kyr, purple filled circles represent literature glass data from western caldera group eruptions. Full results of AFC modelling for western caldera group eruptions are included in Fig. A1.14-A1.17

Palaeozoic metapelitic contamination and the absence of quartz in natural Campi Flegrei eruption products (Isaia *et al.*, 2004; Smith *et al.*, 2011) makes this an unlikely assimilation scenario. However, our models do not predict quartz saturation with smaller amounts of Palaeozoic metamorphic contamination ($M_a/M_m < 0.2$) but do produce higher melt SiO₂ contents and lower Al₂O₃ contents than simple fractional crystallisation, improving

calculated RMSEs for all volcano-tectonic environments (Fig. A1.8, A1.13, A1.17). While syenite contamination returns lower RMSEs for central and western caldera eruptions (of 0.11 and 0.21, representing 50% and 45% improvements respectively in the RMSE compared to FC alone), Palaeozoic metamorphic assimilation generates a lower RMSE overall for northern/eastern caldera eruptions (of 0.12, representing a 17% improvement on FC alone). These more mafic eruptions, from vents along the caldera rim faults, were generally earlier in the last 15 kyr, following the NYT eruption. This suggests earlier eruptions ascended from depth where they encountered the metamorphic basement before erupting along the caldera ring faults, whereas the later eruptions, in the central caldera, stalled in the crust and interacted with residual syenite before eruption.

A summary of best-fit AFC model outputs for each volcano-tectonic group (i.e. lowest RMSE) is shown in Fig. 2.8-2.10 and Tables A1.9-A1.11. In all volcano-tectonic settings, AFC models can produce liquid lines of descent which are closer to natural glass compositions than simple FC models. However, the nature of the assimilant source and extent of contamination in the best fitting model varies between each group. For northern/eastern caldera eruptions, the best-fit assimilation scenario is the addition of 0.05–0.1 M_a/M_o Palaeozoic metamorphic basement, which improves the fit of the model by ~17% compared to simple FC (Fig 2.8; Fig. A1.6–A1.9). This is consistent with AFC models of isotopic and trace element variations in selected post-15 ka eruptions, which suggest ~1–12% crustal assimilation of Palaeozoic metamorphic basement would explain the observed compositional variations (e.g. Pappalardo *et al.*, 2002; D’Antonio *et al.*, 2007; Iovine *et al.*, 2018). For central caldera eruptions, the best-fit assimilation scenario is addition 0.2-0.3 M_a/M_o syenitic material, which improves the model RMSE by ~49 % relative to FC models (Fig 2.9; Fig. A1.10–A1.13). This is the same for western caldera eruptions; the best-fit assimilation scenario is 0.25-0.3 M_a/M_o of syenite which produces a ~45% improvement compared to simple FC models (Fig 2.10, Fig. A1.14–A1.17). Hence, our results suggest

that post-15 kyr eruptions in different volcano-tectonic environments within the Campi Flegrei caldera not only underwent crystallisation under different intensive conditions but also interacted with different types of country rock material, consistent with the magnetotelluric imaging of Isaia *et al.* (2025) which suggests a transcrustal magmatic system in contact with basement rock at its margins. Eruptions along the caldera rim faults at the northern and eastern margins of the system were able to “see” and interact with Palaeozoic metamorphic basement at depth, prior to ascent and eruption, whereas eruptions from the centre of the caldera and along regional faults in the west of the caldera were stored within crystalline igneous material, left in the crust as a restitic residue during past eruptions.

2.7.2.1 Assimilation at Fondi di Baia

The eruption of Baia-Fondi di Baia at the beginning of Epoch 2 (~9.6 ka) was one of the most compositionally distinct events in the last 15 kyr, producing evolved melts from a vent located on a regional fault system on the west side of the caldera (Smith *et al.*, 2011; Pistolesi *et al.*, 2017; Vitale and Natale, 2023). While we have categorised it as a western caldera eruption based on its volcano-tectonic setting, the trace element compositions of Baia-Fondi di Baia glasses are distinct from all other post-15 ka Campi Flegrei eruptions, with low Ba and Sr concentrations and high Y, Nb, Nd and Th (Smith *et al.*, 2011). Previous studies have attributed this compositional deviation to mixing between distinct magma batches which had separate AFC evolutionary histories; while Sr-isotopes suggest some amount of limestone contamination, this was ruled out based on the absence of significantly elevated CaO concentrations, with authors instead invoking assimilation of residual magma from the CI (Voloschina *et al.*, 2018). However, our models suggest that, in contrast to other eruptions in the west of the caldera which are best reproduced by assimilation of crystalline restite, the addition of small amounts ($0.01 M_a/M_o$) of limestone to our best-fit FC model for western caldera eruptions accurately reproduces the major element compositions of Baia-Fondi di Baia glasses, with the fit between the modelled liquid line of descent and natural glass

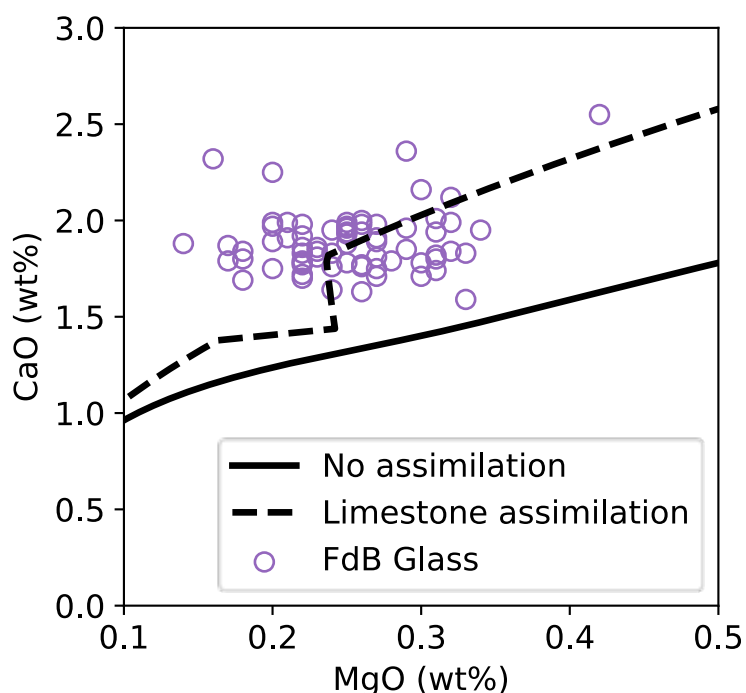


Figure 2.11: Rhyolite-MELTS model of limestone assimilation compared to Fondi di Baia glass data (purple circles; literature data). Solid black line is the result of the best-fit fractional crystallisation Rhyolite-MELTS model for the western caldera eruptions group. Dashed black line is the result of a Rhyolite-MELTS model run at the same pressure (160 MPa), L_{H_2O} (2 wt%) and L_{fO_2} conditions (at QFM buffer) with addition of 1% limestone.

compositions significantly improved for CaO, FeO and TiO_2 (other major oxides do not significantly change; Fig. 2.11, Fig. A1.21).

Although carbonate xenoliths have not previously been identified in Campi Flegrei eruption deposits (in contrast with Vesuvius; Fulignati *et al.*, 2000; Del Moro *et al.*, 2001; Gilg *et al.*, 2001), Meso-Cenozoic carbonates have been suggested as a possible lithology underlying the volcano at shallow levels (e.g. Brocchini *et al.*, 2001; Judenherc and Zollo, 2004; Battaglia *et al.*, 2008; Zollo *et al.*, 2008). Since Campi Flegrei caldera has been active for at least 300 kyr (De Vivo *et al.*, 2001), any carbonate would have been progressively removed during the previous eruptions, whereas the younger Vesuvius magmatic system has only been active for the last 39 kyr (Scandone *et al.*, 1991; Brocchini *et al.*, 2001) and is at an earlier stage in its development where an extensive shallow carbonate basement remains. It is possible that the tectonic setting of Baia-Fondi di Baia, on the west of the caldera and situated on regional faults, may have enabled interaction between the magma feeding the

eruption and more peripheral carbonate country rocks. Alternatively, hydrothermal calcite has been documented in both Campi Flegrei borehole samples (Chiodini *et al.*, 2015a) and lithic fragments, including tuffaceous lithics recovered from Baia deposits (Buono *et al.*, 2024). While we used an upper Jurassic–lower Cretaceous limestone as the assimilant in our models, sedimentary limestone and hydrothermal calcite would have comparable major element compositions, similarly impacting our modelled AFC liquid lines of descent; hence, we cannot discount this as an alternative Baia-Fondi di Baia assimilant source.

2.7.3 Volcano-tectonic controls on eruptive processes

Alongside compositional information, Rhyolite-MELTS outputs predicted physical properties for evolving magmas (e.g. density, viscosity) as well as information on the behaviour of magmatic volatiles; these properties vary between our best-fit models for each of our three volcano-tectonic groups (Fig. 2.12). H₂O behaves incompatibly, consistently increasing in concentration within the melt phase as the magma cools, but with a greater enrichment per unit temperature below the invariant point (temperature at which melt fraction drops and physical properties change over a short interval), likely due to enhanced crystallisation of anhydrous minerals (Fig. 2.12a). The volume fraction of exsolved H₂O coexisting with the magma increases dramatically around the invariant point for all tectonic settings, from ~10 vol% below to ~60 vol% above this temperature (Fig. 2.12b). This is consistent with other studies at Campi Flegrei (Fowler *et al.*, 2007; Cannatelli, 2012; Stock *et al.*, 2016) and elsewhere (e.g. Mount St. Helens, USA – Kent *et al.*, 2007; Calbuco, Chile – Arzilli *et al.*, 2019) which suggest that the dramatic increase in volatile content at low temperatures could trigger explosive eruptions. Stock *et al.* (2016) used the volatile content of apatite crystals and melt inclusions in Astroni 1 deposits to demonstrate the magma reservoir beneath Campi Flegrei remained volatile undersaturated until low temperatures, with volatile saturation likely triggering eruption on very short pre-eruptive timescales,

perhaps days to months. Forni *et al.* (2018a) suggest Monte Nuovo may also have been triggered by volatile saturation which occurred in the decades before the eruption.

H₂O saturation controls the viscosity and density evolution in our best-fit models (Fig. 2.12c, d). The large increase in melt H₂O content below the invariant point leads to a rapid drop in both viscosity and density across all tectonic settings, consistent with the results of Fowler *et al.* (2007) and Cannatelli (2012). The inflection in viscosity from an initial increase as magma cools and becomes more SiO₂ rich to a rapid decrease as dissolved melt H₂O concentration increases occurs at slightly higher temperatures and higher maximum viscosities for northern/eastern caldera eruptions (830°C) than western caldera or central caldera eruptions (815-820°C; Fig. 2.12a), reflecting small temperature differences in the invariant point. Our models show that, despite small differences in the temperatures at which viscosity and density change dramatically, the increase in volume fraction of exsolved H₂O

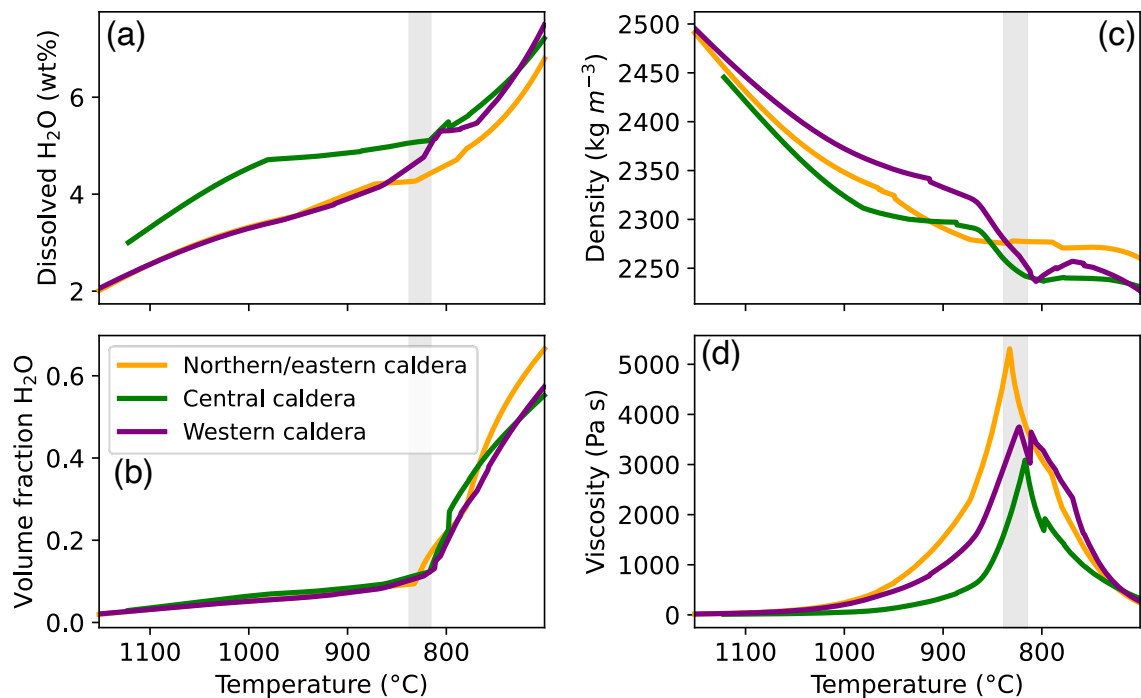


Figure 2.12: Variation of melt physical properties along the liquid line of descent as predicted by the best-fit Rhyolite-MELTS model for each tectonic group. Models were run at 110 MPa (northern/eastern caldera), 140 MPa (central caldera) and 160 MPa (western caldera), models run at the same pressures showed no significant differences in physical properties displayed here (a) T vs dissolved H₂O content, (b) T vs density of melt, (c) T vs volume fraction of exsolved H₂O, (d) T vs melt viscosity. The vertical grey bar in each plot indicates the temperature range over which melt fraction drops and physical properties change over a short temperature interval (invariant temperature range).

occurs late in magmatic evolution, at similar temperatures for all tectonic groups. While it remains possible that some eruptions were triggered externally (e.g. by recharge), our models validate the potential for eruption triggering by low temperature volatile saturation in all volcano-tectonic groups, despite differences in their pre-eruptive history (e.g. assimilation processes).

2.8 Conclusions

We have shown that Rhyolite-MELTS modelling can be used to evaluate a wide range of potential magma storage conditions, determining which (if any) can produce observed phase compositions by fractional crystallisation. Building on the statistical test proposed by Gleeson *et al.*, (2017) to quantitatively evaluate which model best reproduces natural samples, we show that magma storage before eruptions of Campi Flegrei in the last 15 kyr was most likely at pressures of 110 to 160 MPa (corresponding to depths of ~5-7 km), with a parental magma with L_{H_2O} of 2 – 3 wt% and an L_{fO_2} near the QFM buffer (QFM to QFM+1). Eruptions from vents in the centre of the caldera likely had higher melt H_2O contents (3 wt%) compared to those erupted at vents along caldera rim faults or regional faults in the west of the caldera (2 wt%), possibly due to interaction with crustal fluids.

We find that isobaric fractional crystallisation of a parental magma cannot fully reproduce the liquid line of descent recorded by natural samples under any realistic conditions. Instead, addition of a small amount of assimilant improves the fit of the models compared to observed compositions. For eruptions from vents along caldera ring faults in the east of the Campi Flegrei system, addition of 5–10 % of metamorphic Palaeozoic basement leads to the biggest improvement in model fit compared to FC alone. For vents in the centre of the caldera and along regional faults in the west, addition of 30% syenite is the best-fit assimilation scenario. Our results indicate that the magmatic evolution of an eruption, in terms of storage and assimilation, correlates with the volcano-tectonic setting of

its eruption vent. Central caldera eruptions likely evolved within the crystalline syenitic remnants of previous eruptions, whereas those on the periphery of the caldera system ascended from depth along faults in contact with the surrounding metamorphic basement. As assimilation influences the compositional evolution of the magmas, which in turn impacts the magma's physical properties and the eruptive style, the vent location (in terms of the volcano-tectonic setting) needs to be considered in hazard forecasting.

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3. Isotopic constraints on volcano-tectonically controlled assimilation at Campi Flegrei, Italy

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Lay abstract

In the last 15,000 years, Campi Flegrei (a large volcano near Naples, southern Italy) has produced more than 70 eruptions. The volcano is currently showing signs of unrest, and because it is in a densely populated area this makes it a significant hazard. These recent eruptions showed a range of styles (from small and effusive to large and explosive) and erupted material of different chemical compositions. The eruptions also occurred in different vent locations around the large Campi Flegrei caldera. We measured the isotopic composition of samples from some of these recent eruptions, as well as samples of rocks from the crust beneath the volcano. We investigated whether the interaction between magmas and surrounding rocks (assimilation) varied depending on where the eruption occurred within the caldera. We found that the eruptions had varied isotopic compositions, which correlated with the vent location of the eruption. Eruptions from the centre and west of the caldera have isotopic compositions that are explained by interacting with older volcanic material, related to previous eruptions at the volcano which remained within the crust. Eruptions from vents along the northern and eastern margin of the caldera have isotopic compositions that are consistent with interacting with old metamorphic basement rock which makes up part of the crust beneath the volcano. These differences reveal that the underground plumbing of Campi Flegrei is complex and varies spatially and helps to constrain processes occurring beneath the volcano before eruption.

Abstract

Campi Flegrei (southern Italy) has produced >70 eruptions in the last 15 kyr and is currently showing significant signs of unrest within a densely populated part of Europe. These eruptions span a wide range of eruptive styles and compositions and have erupted from different vent locations within a larger caldera system. Here, we characterised the oxygen, strontium, neodymium and lead isotopic composition of mineral and glass separates from

post-15 ka Campi Flegrei eruptions, alongside basement rocks which may have contaminated the magmas, to investigate whether interaction between magma and country rock varies across the caldera. Our data point to an important role of assimilation in the system, with differences between individual eruptions attesting to variation in the amount or type of assimilated material. These differences correlate with the vent location within the caldera; eruptions along northern/eastern caldera rim faults have isotopic compositions which deviate further from typical mantle source values than those erupted from the centre of the caldera or along western caldera rim faults. Comparison with the isotopic composition of the basement rocks suggests small amounts (<10%) of Palaeozoic metamorphic basement contaminated the eruptions from northern/eastern caldera rim faults, whereas more extensive (<30%) interaction with syenitic restite (i.e. pre-existing magma mush) affected the isotopic composition of eruptions from the centre and west of the caldera. Our results from vents located across the caldera provide new insights and further constraints on processes operating in the sub-volcanic magmatic system beneath Campi Flegrei prior to an eruption.

3.1 Introduction

Caldera-forming volcanoes typically remain restless over long time periods following major collapse events; this continued activity provides a unique hazard as subsequent vents are disseminated across a wide area within the pre-existing collapse structure, often spatially correlated with volcano-tectonic structures which may have formed or been reactivated during collapse (Cole et al., 2005). While previous studies have attempted to link the volcano-tectonic setting of vents to magma storage and compositional variation (e.g. Saxby et al., 2016), the relationship between volcano-tectonic setting and sub-volcanic processes remains poorly understood. A clearer understanding of the relationship between volcano-tectonic setting and the compositional evolution of post-caldera eruptions is critical for hazard forecasting.

Campi Flegrei (Naples, Italy; Fig. 3.1) is located in a densely populated part of Europe (~1.5 million people live within the caldera, ~3.5 million would be immediately impacted by an eruption) and is currently showing significant signs of unrest, making it one of the most hazardous volcanoes on Earth (Orsi et al., 2004). Since the last caldera-forming eruption at ~15 ka (Neapolitan Yellow Tuff eruption, hereafter NYT), Campi Flegrei has produced >70 eruptions (D'Antonio et al., 1999b) which were fed by relatively compositionally homogenous primary mantle melts (Mazzeo et al., 2014) but show variations in erupted magma composition across the caldera, presumably resulting from differences in crustal processing (D'Antonio et al., 1999a; Di Renzo et al., 2011; Smith et al., 2011). While some of the post-15 ka vents are closely associated with fault structures, others occur within the central caldera, away from major structural lineaments (Smith et al., 2011; Vitale and Isaia, 2014). Hence, post-15 ka Campi Flegrei eruptions present an ideal opportunity to investigate correlations between volcano-tectonic setting and the controls on magma evolution, with an improved understanding of these processes providing important insights for the interpretation of volcano monitoring data.

Previous studies have linked volcano-tectonic setting to magma processing across a caldera system; for example, at Ilopango caldera, El Salvador, where gravity surveys revealed a link between magma storage location and regional fault patterns (Saxby et al., 2016). At Campi Flegrei, assimilation of basement rocks has been suggested to influence magma evolution (Di Renzo et al., 2011; Pappalardo et al., 2002), with investigation into erupted glass major element chemistry suggesting this varies spatially (Amstutz et al., in press).

Further insight into magma processing prior to ascent and eruption is provided by the isotopic composition of volcanic rocks. Combined radiogenic and stable isotopes afford unique insights into the type and extent of crustal assimilation, which cannot usually be identified from one isotope system alone. The isotopic composition of primitive mantle-

derived basalts is well-constrained (Eiler, 2001; Hart et al., 1986) and deviations from this can indicate the involvement of more differentiated crust-derived components. Isotopic investigations are therefore instrumental in highlighting crustal assimilation processes, even where this does not leave a signature in major element compositions.

This study uses a combination of radiogenic (Sr, Nd, Pb) and stable (O) isotopes to investigate magma evolution at Campi Flegrei in the last 15 kyr, interrogating samples spanning the range of eruptive styles, compositions and vent locations. This extends previous work investigating isotopic variation within single eruptions at Campi Flegrei (e.g. Campanian Ignimbrite [CI] - Arienzo et al., 2009; NYT - Orsi et al., 1995; Baia-Fondi di Baia - Voloschina et al., 2018; Agnano-Monte Spina - Arienzo et al., 2010; de Vita et al., 1999; Astroni - Arienzo et al., 2015; Tonarini et al., 2009; Nisida - Arienzo et al., 2016) or broad variations across long time periods (e.g. 60 kyr of activity - Pappalardo et al., 2002) or geographic areas (e.g. the whole Phlegraean Volcanic District - D'Antonio et al., 2007; Iovine et al., 2018). These studies have identified significant variations in the isotopic composition of Campi Flegrei magmas, which are either attributed to mixing of isolated batches of magma before eruption (Arienzo et al., 2016, 2015; D'Antonio et al., 1999b; de Vita et al., 1999; Tonarini et al., 2009; Voloschina et al., 2018) or contamination through basement assimilation (Arienzo et al., 2009; D'Antonio et al., 2007; Di Renzo et al., 2011; Pappalardo et al., 2002). However, short-term spatio-temporal relationships between isotopically distinct magmas and processes responsible for generating them remain poorly constrained. We demonstrate that variability in the isotopic composition of post-15 ka Campi Flegrei eruptions is outside the range expected for fractional crystallisation of typical mantle-derived magmas and is instead the result of assimilation in the sub-volcanic magmatic system, with the type and amount of assimilation varying between different parts of the caldera where vents are located in different volcano-tectonic settings.

3.2 Geological setting

Campi Flegrei is the largest centre in the Campania Plain volcanic area which formed through back arc extension and opening of the Tyrrhenian Sea, related to rollback of the subducting Ionian plate (Rosenbaum and Lister, 2004). The oldest volcanism at Campi Flegrei has been dated to >300 ka (De Vivo et al., 2001) with at least four potential caldera-forming events (most recently at ~15 ka; NYT, Deino et al., 2004) producing a nested caldera structure ~13 km across (Natale et al., 2022a, 2024a; Vitale and Isaia, 2014). Volcanism since the NYT has been characterised by periods of intense activity separated by quiescence (Di Vito et al., 1999), broadly dividing the eruptions into three epochs: Epoch 1 produced ~30 eruptions from ~15 – 10.6 ka, Epoch 2 produced 8 eruptions from ~9.6 – 9.1 ka and Epoch 3 produced 28 eruptions from ~5.5 – 3.5 ka. The most recent eruption was at Monte Nuovo in 1538 CE and is considered separate to Epoch 3 (Piochi et al., 2005; Smith et al., 2011).

Melts produced at Campi Flegrei are ubiquitously alkali (Vineberg et al., 2023), with post-15 ka eruptions ranging from shoshonites to phonolites (Smith et al., 2011). Magma compositions do not follow a defined temporal or spatial trend over the last 15 kyr but, in general, the most primitive shoshonitic products erupted in Epoch 1 along NYT caldera rim faults in the northern and eastern caldera (Civetta et al., 1991; Smith et al., 2011) with later Epoch 2 and 3 eruptions extending to more evolved compositions and erupting from the central caldera floor or vents associated with volcano-tectonic faults in the western caldera (Smith et al., 2011; Vitale and Isaia, 2014).

The crustal architecture beneath Campi Flegrei is currently characterised by a transcrustal magma system as suggested in magnetotelluric imaging (Isaia et al., 2025), with a main storage zone at ~7.5 km evident in tomographic surveys (Bianco et al., 2022), and recent unrest principally driven by shallower magma and/or fluid migration at 2–4 km (De Siena et al., 2010). A similar crustal structure appears to have persisted over much of the

past 15 kyr with phase equilibria (Amstutz et al., in press), mineral thermobarometry (Giordano and Caricchi, 2022, and references therein) and volatile constraints (Arienzo et al., 2016, 2010; Stock et al., 2018, 2016; Voloschina et al., 2018) all generally attesting to eruptions being fed by magmas predominantly derived from >7–8 km depth but with shallower (possibly ephemeral) sills ~3–4 km.

Investigating assimilation at Campi Flegrei requires understanding the basement lithologies which ascending magmas might interact with. Previous studies have suggested four major assimilant lithologies beneath Campi Flegrei. First, isotopic studies on long-term (>60 kyr) magma variation at Campi Flegrei have suggested ascending melts are contaminated with Palaeozoic metamorphic basement (previously termed Hercynian basement, e.g. Pappalardo et al., 2002), and vesicular xenoliths found in the Minopoli 1 eruption have also been attributed to this lithology (Pappalardo et al., 2002). The southern Apennine structure suggests this basement should underlie the volcano at depth (Ciarcia and Vitale, 2025; Vitale and Ciarcia, 2018). Second, arenaceous sediments have been identified as likely contaminants based on isotopic variation in some eruptions (D’Antonio et al., 2007; Di Renzo et al., 2011; Pappalardo et al., 2002) and are also suggested as a second Minopoli 1 xenolith type by Pappalardo et al. (2002) based on similar mineralogy (quartz, tridymite and clinopyroxene), although small clast size made detailed characterisation difficult. These sediments may be derived from the shallow crust at <4 km depth, where borehole data indicate buried pyroclastic sequences covering Upper Miocene sedimentary sequences (D’Antonio, 2011; Piochi et al., 2014). Meso-Cenozoic carbonates and syenitic cumulate residue from past eruptions comprise the other two potential contaminants. Both lithologies have been suggested, along with the Palaeozoic metamorphic basement, as responsible for the homogenous density in tomographic and gravity data at depths >4 km beneath Campi Flegrei (D’Antonio, 2011; Judenherc and Zollo, 2004). Carbonate clasts are seldom found as lithics, unlike plutonic syenite xenoliths which have been identified in erupted products

such as the lithic-rich Breccia Museo unit of the Campanian Ignimbrite (Gebauer et al., 2014).

3.2.1 Previous isotopic constraints on Campi Flegrei magma compositions

Previous studies have identified isotopic compositional diversity in Campi Flegrei magmas, attributing this either to mantle source variations and/or assimilation of crustal materials. The isotopic compositions of the Campanian Ignimbrite eruption products have been attributed to two distinct magma batches which mixed prior to eruption (Arienzo et al., 2009). These comprised a less differentiated end-member with less radiogenic Sr- and Nd-isotopic composition, and a more evolved magma with more radiogenic isotopic composition, which likely evolved through combined crustal assimilation and crystal fractionation (Arienzo et al., 2009). In contrast, Sr-isotope variations through the NYT stratigraphy suggest that the eruption was fed by three compositionally distinct magma batches which were tapped simultaneously (Orsi et al., 1995). Studies of individual post-15 ka Campi Flegrei eruptions attribute their isotopic heterogeneity to distinct end-member melt components which fed isotopically diverse eruptions before residing in the system and mixing to form intermediate magmas which fed subsequent eruptions. The isotopic end-members have been identified as deriving from NYT residual melts, the magma feeding Minopoli 2 and more recently (in the last 5 kyr) the magma feeding Astroni 6 (Arienzo et al., 2016, 2015, 2010; D'Antonio et al., 1999b; Di Renzo et al., 2011). Prior to the Astroni 6 eruption, an additional component characterised by the magma feeding the Agnano-Monte Spina eruption may have fed earlier Astroni eruptions (Arienzo et al., 2015; Tonarini et al., 2009).

3.3 Methods

3.3.1 Sampling and sample preparation

We broadly divide post-15 ka eruptions into three volcano-tectonic groups following the categorisation of Amstutz et al. (in press), which is consistent with divisions made by other authors based on differences in fault patterns, eruption frequency, and compositions (Fig. 3.1c, Fig. 3.2, Bevilacqua et al., 2015; Natale et al., 2024b; Vitale and Isaia, 2014). The volcano-tectonic groups comprise: northern/eastern caldera rim eruptions with vents located along caldera rim faults which either formed or reactivated as a result of the NYT collapse (Natale et al., 2024b); eruptions from the western caldera, with vents aligned along volcano-tectonic faults with different orientation patterns of faults and fractures to those in the eastern sector (Vitale and Isaia, 2014); and eruptions from vents in the central caldera that are located on the caldera floor, often on the Agnano volcano-tectonic collapsed area (Bevilacqua et al., 2015; Di Vito et al., 1999; Isaia et al., 2009; Natale et al., 2022b).

Twenty-one tephra samples from eruptions in the last 15 kyr were selected for isotopic analysis, spanning the identified volcano-tectonic groups (Fig. 3.1c), erupted compositions (Fig. 3.2), and epochs of activity (Table 3.1). Samples were collected by R. Isaia and V. Smith in 2009-2010, documented in Smith et al. (2011), except for CF410 (Fondo Riccio; UTM 423047E, 4523062N) and CF424 (Agnano 3; UTM 430699E, 4521098N) which were collected during fieldwork for this study in March 2022. Samples were crushed in a tungsten carbide jaw crusher and sieved, with glass shards plus clinopyroxene, feldspar and biotite crystals handpicked from the 250–500 μm size fractions.

Samples of the four main lithologies that have previously been suggested to contaminate Campi Flegrei magmas were collected by Amstutz et al. (in press) who characterised their major element composition (Fig. 3.1b). These comprise: a Palaeozoic basement augen gneiss (Sila unit of Graessner and Schenk, 2001), an Upper Jurassic–Lower

Table 3.1: Sr-, Nd-, Pb- and O-isotopic composition of the matrix glass of analysed samples, with O-isotopic composition of selected mineral phases.

Sample	Eruption	Vent location	Epoch	Date	Analysed material	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\delta^{18}\text{O}$ (‰)
CF195	Monte Nuovo	Western (1)		1538 CE	Matrix glass	0.70763	0.512496	19.04	15.68	39.15	7.7
CF391	Nisida	Northern/eastern (2)	3	~3.2 - 4.2 ka	Matrix glass	0.70744	0.512478	19.02	15.68	39.13	8.1
CF78	Astroni 6	Central (3)	3		Matrix glass	0.70729	0.512493	19.04	15.68	39.15	6.8
CF78	Astroni 6				Clinopyroxene						6.8
CF78	Astroni 6				Feldspar						8.2
CF78	Astroni 6				Biotite						7.4
CF86	Averno 2	Western (4)	3		Matrix glass	0.70759	0.512476	19.03	15.68	39.14	12.8
CF86	Averno 2				Clinopyroxene						7.5
CF86	Averno 2				Feldspar						7.5
CF86	Averno 2				Biotite						7.6
CF415	Solfatara										
CF54	Agnano-Monte Spina	Central (5)	3		Matrix glass	0.70759	0.512477	19.03	15.68	39.13	14.0
CF62	Palaeoastroni 2	Central (6)	3	~4.5 ka	Matrix glass	0.70755	0.512466	19.03	15.68	39.14	7.2
CF424	Agnano 3	Central (7)	3	~4.7 ka	Matrix glass	0.70749	0.512449	19.04	15.68	39.14	6.0
CF92	Capo Miseno	Central (8)	3		Matrix glass	0.70744	0.512462	19.02	15.68	39.12	4.1
CF66	Cigliano	Western (9)	3	~3.2 - 4.9 ka	Matrix glass	0.70739	0.512477	19.02	15.68	39.12	5.3
CF99	St Martino	Central (10)	3		Matrix glass	0.70750	0.512473	19.03	15.68	39.14	3.9
CF100	Sartania 1	Northern/eastern (11)	2	~9.1 ka	Matrix glass	0.70758	0.512458	19.03	15.68	39.13	8.9
CF310	Baia-Fondi di Baia	Central (12)	2		Matrix glass	0.70762	0.512463	19.02	15.68	39.14	7.8
CF93	Bacoli	Western (13)	2	~9.6 ka	Matrix glass	0.70775	0.512460	19.03	15.68	39.14	8.4
CF410	Fondo Riccio	Western (14)	1	~11.5 - 14.1 ka	Matrix glass	0.70761	0.512478	19.02	15.68	39.13	6.5
CF410	Fondo Riccio	Northern/eastern (15)	1		Matrix glass	0.70778	0.512431	19.01	15.68	39.12	7.8
CF410	Fondo Riccio				Clinopyroxene						7.2
CF410	Fondo Riccio				Feldspar						8.3
CF410	Fondo Riccio				Biotite						7.7
CF25	Pisani 1	Northern/eastern (16)	1		Matrix glass	0.70766	0.512444	19.01	15.68	39.11	7.6
CF9	Minopoli 2	Northern/eastern (17)	1		Matrix glass	0.70843	0.512379	18.92	15.67	39.01	8.0
CF9	Minopoli 2				Clinopyroxene						6.9
CF9	Minopoli 2				Feldspar						8.7
CF9	Minopoli 2				Biotite						7.5
CF410	Soccavo 4	Northern/eastern (18)	1		Matrix glass	0.70740	0.512463	19.03	15.68	39.14	4.9
CF25	Pomici Principali	Central (19)	1	~12 ka	Matrix glass	0.70757	0.512479	19.02	15.68	39.15	6.7
CF13	Minopoli 1	Northern/eastern (20)	1		Matrix glass	0.70778	0.512429	18.98	15.68	39.08	7.7
CF94	Gauro	Northern/eastern (21)	1	~12.7 - 15.5 ka	Matrix glass	0.70752	0.512476	19.03	15.68	39.13	7.8

Eruptions are listed in stratigraphic order. Epoch and date of eruption refer to those defined in Smith et al. (2011). Vent location refers to the volcano-tectonic sector of the vents, as defined in Sampling and sample preparation, number in brackets refers to the location of the vent illustrated in Fig. 1. Sr, Nd and Pb concentrations for the samples are given in Table A2.3.

Table 3.2: Sr-, Nd-, Pb- and O-isotopic composition of samples of the potential basement lithology underlying Campi Flegrei

Sample	Basement lithology	Analysed material	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\delta^{18}\text{O}$ (‰)
23-FMR-003	Upper Miocene siliciclastic syn-orogenic wedge-top	whole-rock	0.72047	0.512154	18.58	15.67	38.69	12.3
23-FMR-017	Palaeozoic gneiss	whole-rock	0.71967	0.512101	18.85*	15.66	38.91*	8.5
23-FMR-14A	Breccia Museo syenite	whole-rock	0.70838	0.512438	19.09	15.68	39.15	13.2
23-FMR-001	Mesozoic limestone	whole-rock	0.70706	0.512288 [^]				22.4

Sr, Nd and Pb concentrations for these samples are given in Table A2.3. *Pb isotope values for the Palaeozoic gneiss from Pappalardo et al. (2002). [^]Limestone Nd isotope value from Cornacchia et al. (2018).

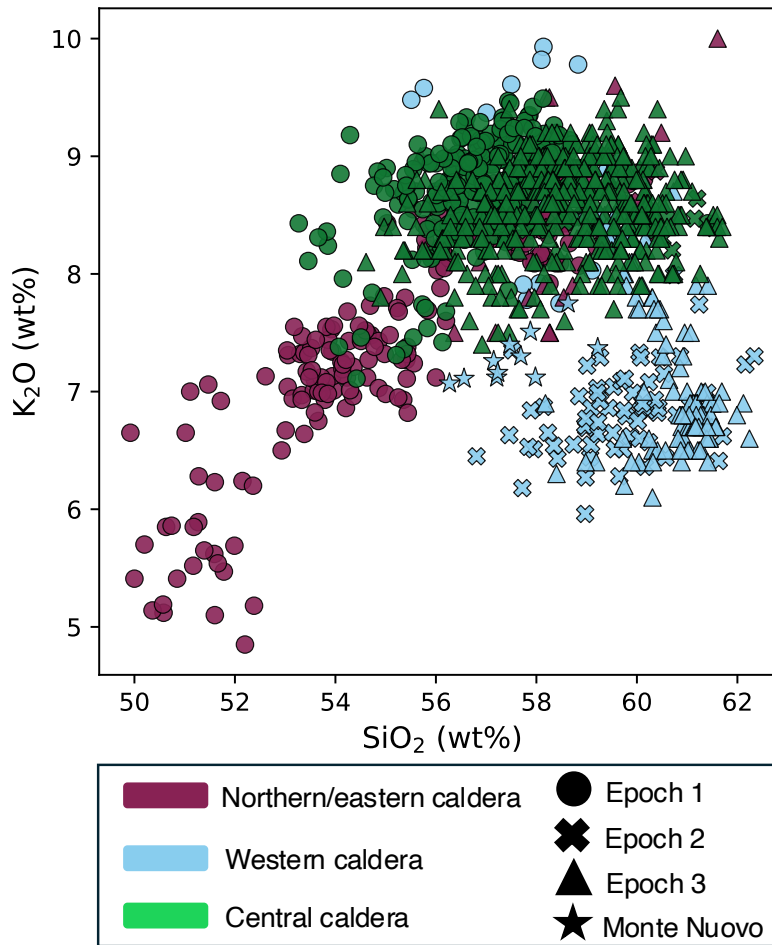


Figure 3.2: Variation of K_2O and SiO_2 in literature glass data for the studied eruptions, from Smith et al. (2011). Eruptions are coloured by sector and shaped by vent age as in Fig. 3.1.

Cretaceous limestone (unit Gcb of Vitale and Ciarcia, 2018), an upper Miocene siliciclastic syn-orogenic wedge-top basin deposit (unit CVTg of Vitale and Ciarcia, 2018), and a syenite xenolith from the Breccia Museo (representative of the sub-volcanic restite from past eruptions, no other cumulate material has been reported at Campi Flegrei). These whole rock samples were crushed in a tungsten carbide jaw crusher before being ground in an agate TEMA mill in the Department of Geology, Trinity College Dublin.

3.3.2 Radiogenic isotope analysis

Strontium-, Nd- and Pb-isotope ratios in glass separates from the selected eruptions and whole-rock crustal samples were determined in the National Centre for Isotope Geochemistry at UCD (NCIG). Samples were digested in HNO_3 and HF (1:4) at $\sim 150^\circ C$ in

closed PFA vessels. After processing to ensure complete digestions, an aliquot was analysed for trace elements using a Thermo Scientific iCAP Q-ICP-MS in standard mode, measuring ^{88}Sr , ^{146}Nd and ^{208}Pb for 20 main runs and 10 sweeps per run with a dwell time of 20 ms and 1 sample per peak using Aldrich TraceCert multi-element solutions for calibration. Strontium, Nd and Pb were then extracted from the remaining solution by ion-exchange chromatography, following methods described by Pin et al. (2014) and Walshaw et al. (2006). Strontium- and Nd- isotopic ratios were measured by thermal ionisation mass spectrometry using a Thermo Scientific Triton mass spectrometer in static mode on Faraday cups with amplifier rotation. The reported isotopic ratios were corrected for instrumental mass fractionation using the normalising ratios $^{86}\text{Sr}/^{88}\text{Sr} = 0.1134$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Measurements of SRM987 (National Institute of Standards and Technology, Gaithersburg, USA) and JNdi-1 (Tanaka et al., 2000) were performed alongside the unknowns (Table A2.1) and long-term reproducibility of SRM987 and JNdi-1 in the period 2015-2024 yields average values of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710266 \pm 0.000022$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.5120963 \pm 0.0000049$, respectively. The total blank was on the order ~ 6 ng for Sr and 1 ng for Nd during the period of measurement. The isotopic data were normalised to the accepted values of $^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$ for SRM987 and of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512115$ for JNdi-1.

Lead-isotope ratios were determined using a Thermo Scientific Neptune MC-ICP-MS in NCIG. The isotopic ratios were corrected for instrumental mass bias by addition of a thallium spike to the samples, using a $^{203}\text{Tl}/^{205}\text{Tl}$ value of 0.418922. SRM 981 was used as a standard and was measured before and after sample measurements, yielding ratios of $^{206}\text{Pb}/^{204}\text{Pb} = 16.935 \pm 0.001$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.489 \pm 0.001$ and $^{208}\text{Pb}/^{204}\text{Pb} = 36.693 \pm 0.003$.

Very low Nd and Pb concentrations in the limestone basement precluded analysis of these isotopes in our sample. Additionally, we note that our measured Pb-isotope values for the Palaeozoic gneissose basement differ significantly from literature values for similar lithologies, likely due to the presence of oxides which were not fully digested prior to Pb-

isotope analysis. As a result, in both cases we base our interpretation on reliable published values.

3.3.3 Stable isotope analysis

Analysis of $\delta^{18}\text{O}$ in whole-rock crustal samples and glass and clinopyroxene, feldspar and biotite mineral separates was carried out at Scottish Universities Environmental Research Centre by laser fluorination, following the method of Sharp (1990), modified for ClF_3 (Macaulay et al., 2000). Between 1–2 mg of glass or mineral separate was analysed. For mineral separates, overnight pre-fluorination was carried out to remove absorbed environmental water from the sample chamber and line. For glasses and whole-rock samples which are more reactive in ClF_3 , a 1 min pre-fluorination was used. Based on replicates of international and internal lab standards YP2, GP147 and UWG-2 standards (detailed in Table A2.2), the standard error for the measurements is less than 0.2‰, reported in standard notation as permil (‰) variations compared to V-SMOW.

3.4 Results

The Sr-, Nd-, Pb- and O- isotopic composition of the Campi Flegrei erupted glasses and potential crustal contaminants are shown in Tables 3.1 and 3.2, respectively, with the Sr, Nd and Pb concentrations in Table A2.3.

3.4.1 Post-15 ka Campi Flegrei glasses

The Sr- and Nd- isotopic variation in our Campi Flegrei glass separates is small, with $^{87}\text{Sr}/^{86}\text{Sr}$ varying 0.707292–0.708434 and $^{143}\text{Nd}/^{144}\text{Nd}$ varying 0.512379–0.512493. This is, nevertheless, outside of analytical uncertainty (standard error is typically ± 0.000005 for $^{87}\text{Sr}/^{86}\text{Sr}$ and ± 0.000003 for $^{143}\text{Nd}/^{144}\text{Nd}$, as shown in Fig. 3.3) and provides important information on magma evolution at the volcano. Minopoli 2, in the northern/eastern caldera rim eruptions group, has the most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and least radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ ratios

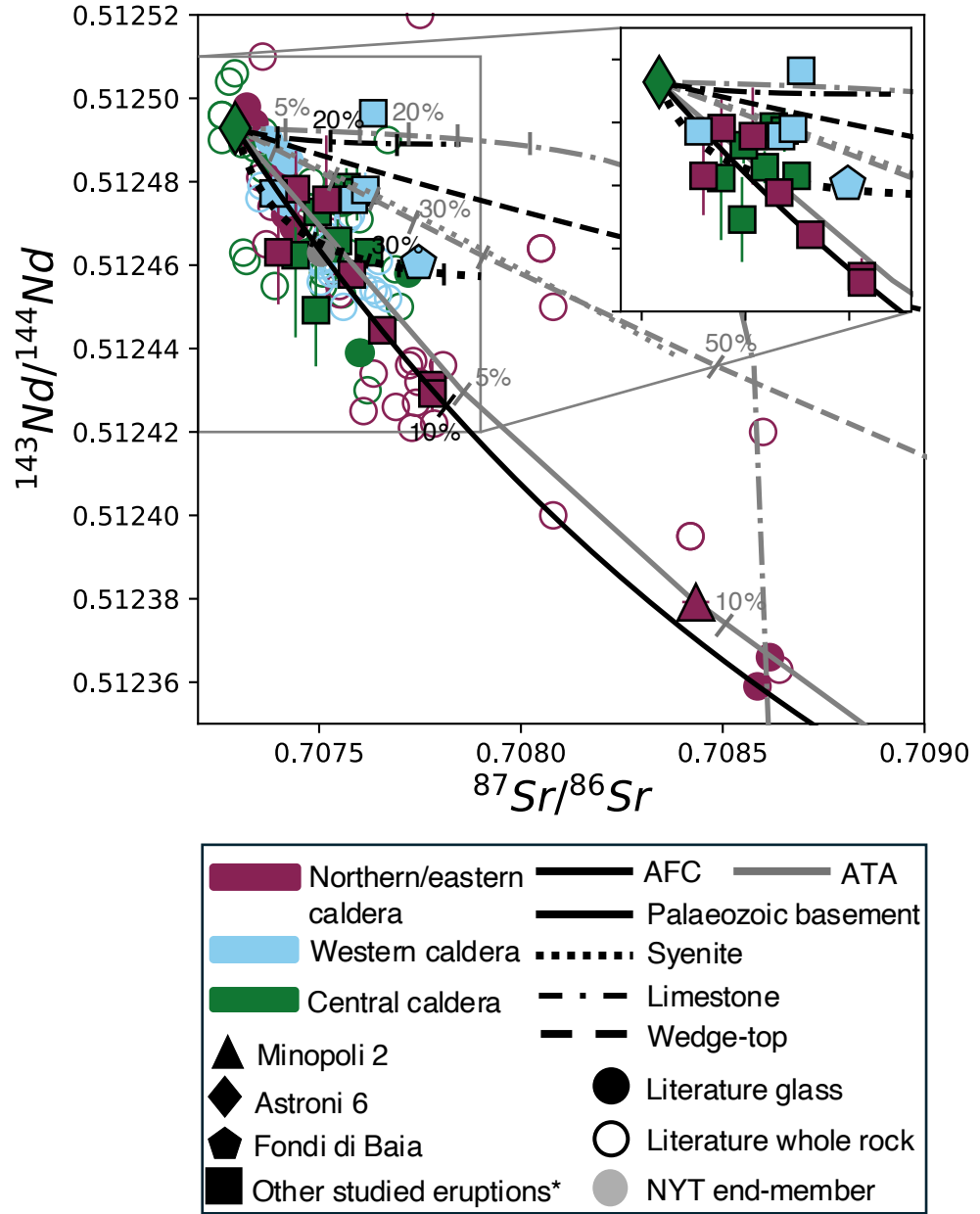


Figure 3.3: $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ binary diagrams for post-15 ka Campi Flegrei eruptions, with samples coloured by volcano tectonic setting. Error bars show ± 2 s.e. Whole-rock literature data are from Arienzo et al. (2010); Civetta et al. (1991); D'Antonio et al. (2007); Di Renzo et al. (2011); Di Vito et al. (2011); Pappalardo et al. (2002); Tonarini et al. (2009). Glass literature data are from Arienzo et al. (2010; 2016); Di Renzo et al. (2011); Di Vito et al. (2011). Average isotopic composition of the NYT end-member proposed in previous studies from Arienzo et al. (2010; 2016); Di Renzo et al. (2011). Grey lines show assimilation during turbulent ascent (ATA) models of assimilation of different crustal lithologies, using binary mixing models (Langmuir et al., 1978). Black lines show assimilation fractional crystallisation (AFC) models of assimilation of different crustal lithologies, modelled using the energy constrained-assimilation fractional crystallisation (EC-AFC) model of Spera and Bohrsen (2001). Line styles distinguish different crustal lithologies and are the same for AFC and ATA models. *Refers to eruptions listed in Table 3.1.

(0.708434 and 0.512379, respectively), whereas Astroni 6, in the central caldera group, has the least radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr} = 0.707292$) and most radiogenic Nd ($^{143}\text{Nd}/^{144}\text{Nd} = 0.512493$). Northern/eastern caldera rim eruptions generally define a trend between Astroni 6 and Minopoli 2, whereas central and western caldera eruptions form a cluster with $^{87}\text{Sr}/^{86}\text{Sr} < 0.707746$ and $^{143}\text{Nd}/^{144}\text{Nd} < 0.512449$.

Glass $^{206}\text{Pb}/^{204}\text{Pb}$ ratios vary between 18.916–19.043, $^{207}\text{Pb}/^{204}\text{Pb}$ ratios vary between 15.672–15.684, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios vary 39.013–39.152 (standard error typically ± 0.0004 for $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ and ± 0.0006 for $^{208}\text{Pb}/^{204}\text{Pb}$, smaller than the data points on Fig. 3.4). In most cases, the Pb isotope ratios of post-15 ka Campi Flegrei glasses cover a narrow range, except in Minopoli 2 which has distinctly low $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (39.013 and 18.916, respectively). Other northern/eastern caldera rim eruptions extend from the cluster of central and western caldera eruptions (with $^{208}\text{Pb}/^{204}\text{Pb} = 39.118$ – 39.152 and $^{206}\text{Pb}/^{204}\text{Pb} = 19.023$ – 19.043) towards the Minopoli 2 end-member (Fig. 3.4).

Glass $\delta^{18}\text{O}$ values range from 3.9–14.0‰ (standard error $< \pm 0.2\text{‰}$), with the lowest values derived from Cigliano eruption and the highest from Solfatara, both central caldera eruptions (Fig. 3.5). Except for Soccavo 4 (4.9‰), northern/eastern caldera rim eruptions cover a narrow $\delta^{18}\text{O}$ range (7.6–8.9‰), whereas central and western caldera eruptions show more variation. Mineral $\delta^{18}\text{O}$ values cover a narrower range, from 6.8‰ in Astroni 6 clinopyroxene to 8.7‰ in Minopoli 2 feldspar.

3.4.2 Potential crustal contaminants

Whole-rock samples representing the most likely crustal contaminants of Campi Flegrei magmas have a wide range of isotopic compositions, reflecting their lithological diversity. This aligns with previously published data for these crustal contaminants, which show a range of isotopic compositions (Fig. A2.1). The Miocene syn-orogenic wedge-top basin deposit and Palaeozoic gneiss have the most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and least radiogenic

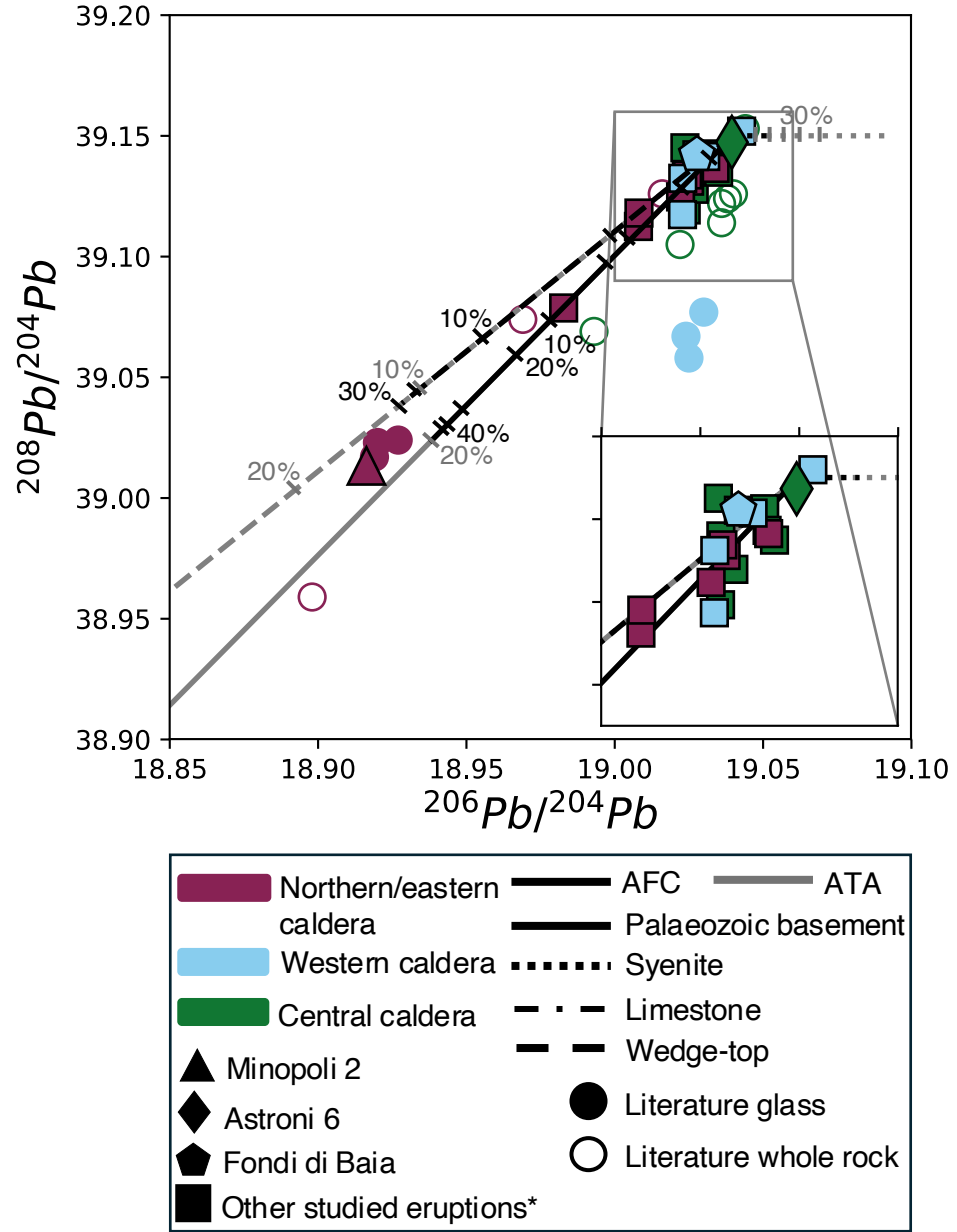


Figure 3.4: $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{208}\text{Pb}/^{204}\text{Pb}$ binary diagrams for post-15 ka Campi Flegrei eruptions, with samples coloured by volcano tectonic setting. Error of ± 2 s.e is within the symbol size. Whole-rock literature data are from Di Renzo et al (2011); Pappalardo et al. (2002); glass literature data from Di Renzo et al. (2011). Grey lines show ATA models of assimilation of different crustal lithologies, using binary mixing models (Langmuir et al., 1978). Black lines show AFC models of assimilation of different crustal lithologies, modelled using the EC-AFC model of Spera and Bohrsen (2001). Line styles distinguish different crustal lithologies and are the same for AFC and ATA models. *Refers to eruptions listed in Table 3.1.

$^{143}\text{Nd}/^{144}\text{Nd}$ ratios ($^{87}\text{Sr}/^{86}\text{Sr} = 0.720471$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512154$ for the wedge-top basin deposit; $^{87}\text{Sr}/^{86}\text{Sr} = 0.719670$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512101$ for the gneiss), with the similarity in their compositions likely reflecting a genetic relationship, whereby the younger wedge-top basin deposit is derived from erosion of the Palaeozoic metamorphic basement. Owing to issues with digestion during sample preparation, we take Pb-isotope values for the Palaeozoic gneiss from Pappalardo et al. (2002) who measured isotopic ratios in Campi Flegrei xenoliths believed to derive from the metamorphic basement ($^{206}\text{Pb}/^{204}\text{Pb} = 18.85$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.66$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.91$). The wedge-top basin deposit has slightly lower $^{206}\text{Pb}/^{204}\text{Pb}$ (18.578) and $^{208}\text{Pb}/^{204}\text{Pb}$ (38.691) and slightly higher $^{207}\text{Pb}/^{204}\text{Pb}$ (15.673) than the Palaeozoic basement. The $\delta^{18}\text{O}$ compositions of these potential contaminants differ, with the wedge-top basin deposit having a heavier $\delta^{18}\text{O}$ (12.3‰) than the gneiss (8.5‰).

The Breccia Museo syenite has a comparable radiogenic isotopic composition to our post-15 ka erupted glass analyses, with $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.708380 and 0.512438 and $^{206}\text{Pb}/^{204}\text{Pb} = 19.091$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.679$, and $^{208}\text{Pb}/^{204}\text{Pb} = 39.150$. However, the syenite $\delta^{18}\text{O}$ (13.2‰) is higher than that of most erupted glass samples. To model assimilation of hydrothermally altered syenite (see section 5.2.2) we distinguish between this unaltered syenite, and a hydrothermally altered syenite with low $\delta^{18}\text{O}$ (of 1.8‰, Gebauer et al., 2014).

The Mesozoic limestone has a significantly lower $^{87}\text{Sr}/^{86}\text{Sr}$ (0.707065) than erupted glass samples. As we were unable to measure carbonate Nd and Pb isotope compositions due to their low concentrations, we take these from Cornacchia et al. (2018), who measured $^{143}\text{Nd}/^{144}\text{Nd} = 0.512288$ in Miocene Apennine limestone successions. The basement limestone has the highest $\delta^{18}\text{O}$ value in any of our samples (22.4‰).

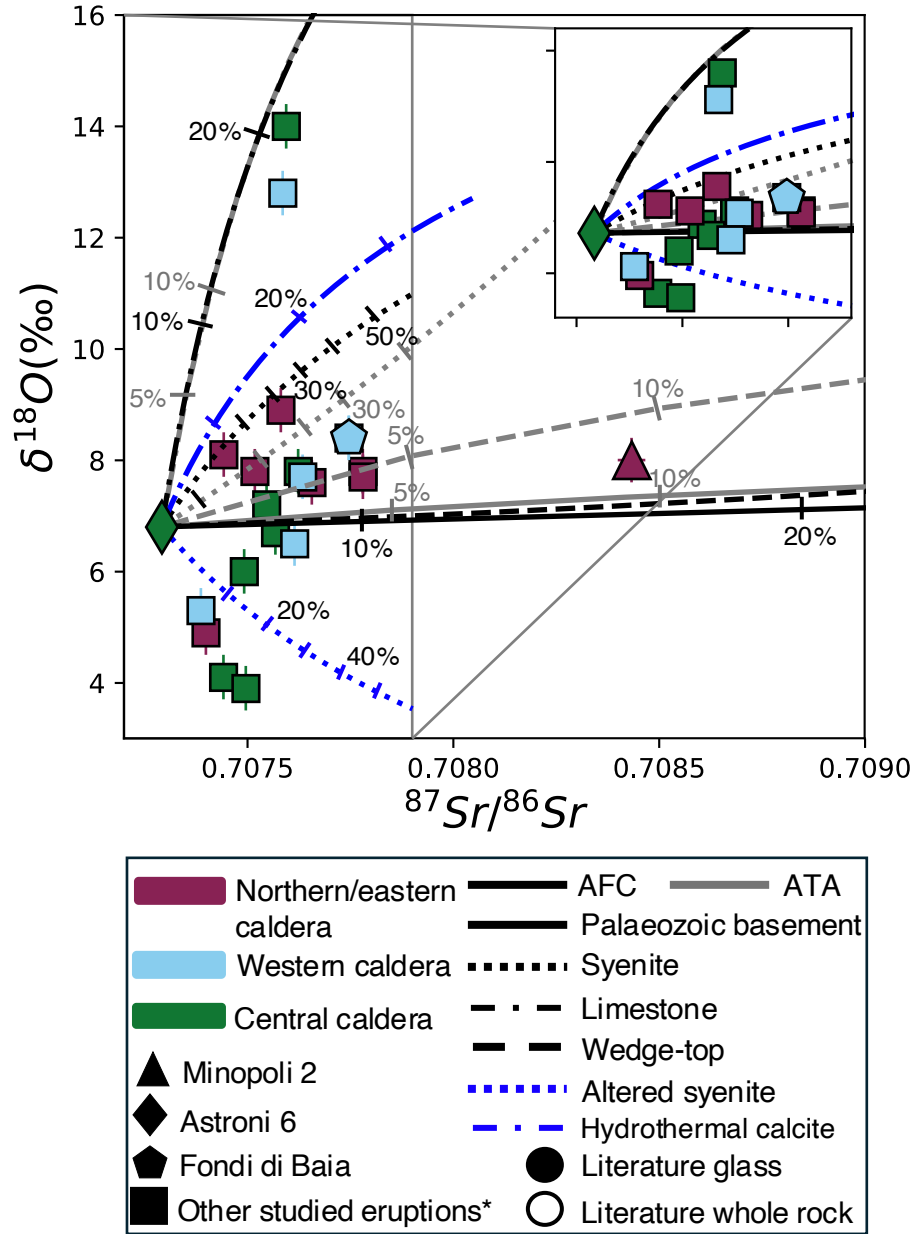


Figure 3.5: $^{87}\text{Sr}/^{86}\text{Sr}$ vs $\delta^{18}\text{O}$ binary diagrams for post-15 ka Campi Flegrei eruptions, with samples coloured by volcano tectonic setting. Error bars show ± 2 s.e. Grey lines show ATA models of assimilation of different crustal lithologies, using binary mixing models (Langmuir et al., 1978). Black lines show AFC models of assimilation of different crustal lithologies, modelled using the EC-AFC model of Spera and Bohrsen (2001). Line styles distinguish different crustal lithologies and are the same for AFC and ATA models. *Refers to eruptions listed in Table 3.1.

3.5 Discussion

3.5.1 Volcano-tectonic control on assimilation at Campi Flegrei

The radiogenic isotope composition of Campi Flegrei eruptions has varied significantly over the past 15 kyr. In general, our glass analyses follow one of two trends apparent in Figures 3.3 and 3.4: most of our glass analyses trend from a more mantle-like end-member with low $^{87}\text{Sr}/^{86}\text{Sr}$, high $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ towards a more crust-like end member with high $^{87}\text{Sr}/^{86}\text{Sr}$ but low $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$. The end-members are best represented by Astroni 6 and Minopoli 2 glasses, respectively (Figs. 3.3, 3.4). A minority of our glass analyses define a second trend between the more mantle-like Astroni 6 end-member and a third component with higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, towards the composition of glasses from the western caldera group Fondi di Baia eruption (Fig. 3.3).

Most published glass and whole-rock data for post-15 ka Campi Flegrei eruptions follow our data, plotting between the Astroni 6 and Minopoli 2 end-members, although a minority of older whole-rock data have more scattered $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ compositions (Figs 3.3, 3.4). This trend has been recognised in previous studies looking at individual Campi Flegrei eruptions in the last 15 kyr (Figs 3.3, A2.2, Arienzo et al., 2010, 2015, 2016; D'Antonio et al., 1999b; Di Renzo et al., 2011; Pappalardo et al., 2002; Tonarini et al., 2009; Voloschina et al., 2018). However, the isotopic variation measured within individual eruptions is less than observed across all post-15 ka eruptions (Fig. A2.2). This contrasts with pre-15 ka activity; isotopic compositions measured in NYT products vary significantly, including extending to more mantle-like values compared to post-NYT eruptions (Fig. A2.2). The NYT end-member identified in previous studies ($^{87}\text{Sr}/^{86}\text{Sr} = 0.707480\text{--}0.707530$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512458\text{--}0.512468$; Arienzo et al., 2016, 2010; Di Renzo et al., 2011) plots on the second trend identified in our data between the Astroni 6 and Fondi

di Baia glasses; its isotopic composition overlaps with glasses in the central and western caldera groups (Fig. 3.3).

Although previous studies have identified that Campi Flegrei isotopic heterogeneity records mixing between compositionally distinct end-member magmas, the origin of these end-member components remains largely unconstrained. The isotopic composition of the mantle beneath the Phlegraean Volcanic District is not well characterised, largely due to a scarcity of mafic rocks. However, the Solchiaro eruption on Procida (~22 ka; Alessio et al., 1976) produced high-Mg, K-basaltic lava lithics with near-primary geochemical features, providing an indication of the mantle composition. The lithics are less radiogenic ($^{87}\text{Sr}/^{86}\text{Sr} \sim 0.705$, $^{143}\text{Nd}/^{144}\text{Nd} \sim 0.5127$, $^{206}\text{Pb}/^{204}\text{Pb} \sim 19.1$, $^{207}\text{Pb}/^{204}\text{Pb} \sim 15.7$ and $^{208}\text{Pb}/^{204}\text{Pb} \sim 39.2$; D'Antonio et al., 2007, 1999b) than any Campi Flegrei eruptions in the last 15 kyr; this suggests that the post-NYT Campi Flegrei mantle source may be ubiquitously contaminated by subducted slab components, which have enriched primary melt compositions relative to typical mantle values (D'Antonio et al., 2007; Iovine et al., 2018; Mazzeo et al., 2014). While some authors have postulated that the isotopic end-members in Campi Flegrei erupted products result from heterogeneity in the mantle source (i.e. variable amounts of the enriched component; Iovine et al., 2018), the eruptions in our dataset are extremely closely spaced both temporally (centennial–millennial timescales) and spatially (~1 km between some caldera rim and central caldera vents with different isotopic signatures, Bevilacqua et al., 2015). Heterogeneous mantle sources from addition of subducted slab-derived components may occur over long timescales or on a whole-arc scale, but the variability in our dataset would require significant heterogeneity on both shorter timescales and distances than has previously been reported in arcs (Anderson, 2006) or even highly heterogeneous mantle plumes (Sims et al., 2013). Furthermore, Campi Flegrei melts necessarily ascend through thick continental crust, containing a complex vertically-extensive magma system (Giordano and Caricchi, 2022), which would act to homogenise signals of primary mantle heterogeneity

(cf. Shorttle et al., 2016). Hence, a primary mantle origin for the isotopic end-members in post-15 ka Campi Flegrei glasses seems unlikely.

Ascending magmas assimilating sub-volcanic rocks with heterogeneous isotopic compositions provides an alternative mechanism to alter the composition of the erupted products. Previous studies have suggested Campi Flegrei magmas may have been contaminated by a variety of crustal rocks, including metamorphic Palaeozoic basement, shallow volcanics, wedge-top basin sequences or arenaceous sediments (e.g. Amstutz et al., in press; Arienzo et al., 2011; D'Antonio et al., 2007; Di Renzo et al., 2011; Pappalardo et al., 2002). To test this, we modelled the effect of assimilating these different lithologies on the isotopic composition of Campi Flegrei magmas using the energy constrained-assimilation fractional crystallisation (EC-AFC) model of Spera and Bohrsen (2001). Despite having an evolved phonolitic major element composition (Smith et al., 2011), we chose the Astroni 6 sample as our starting composition as it has the least radiogenic Sr and most radiogenic Nd isotopic compositions and so best represents the primitive parental magma in terms of isotopic composition (assuming a primary arc magma enriched with subducted slab-derived components, Mazzeo et al., 2014). As the uncontaminated mantle isotopic composition is not well defined, it is possible the isotopic composition of Astroni 6 already reflects some country rock contamination, so the contamination proportions determined from EC-AFC modelling represent minimum estimates. The EC-AFC model is not coupled to major element changes (Spera and Bohrsen, 2001), so the evolved nature of Astroni 6 does not affect the modelled isotopic evolution. A complete set of modelling parameters are in Table A2.4 and model results are shown in Figs. 3.3–3.5. We also use binary mixing models between Astroni 6 and different crustal compositions to simulate the effect of assimilation that is decoupled from magma evolution (Figs. 3.3–3.5; contaminant parameters detailed in Table A2.5).

3.5.1.1 Assimilation in central and western caldera eruptions

Our Sr- and Nd-isotope EC-AFC models indicate that the cluster of central and western caldera eruptions, which define a trend between Astroni 6 and Fondi di Baia glasses, sit on the model trajectory between our most mantle-like compositions (defined by the Astroni 6 glass) and the basement syenite. The most contaminated sample (Fondi di Baia glass) is consistent with a magma that has assimilated up to 30% syenite (Fig. 3.3). This agrees with previous studies which identified syenite contamination in central and western caldera post-15 ka eruption products from major element variations (Amstutz et al., in press), and with magnetotelluric imaging which suggests the central caldera is underlain by a transcrustal mush comprising the crystalline remnants of past magma intrusions (Isaia et al., 2025; Fig. 3.6). The isotopic compositions of some central and western caldera eruptions sit between the modelled trajectories for assimilation of Palaeozoic metamorphic basement and syenite. This suggests mixing between batches of magma which have undergone different evolution and contamination, in agreement with previous studies which identify mixing of compositionally distinct magmas before eruption (Arienzo et al., 2016; 2015; Di Renzo et al., 2011; Tonarini et al., 2009; Voloschina et al., 2018). Our glasses follow the $^{87}\text{Sr}/^{86}\text{Sr}$ - $^{143}\text{Nd}/^{144}\text{Nd}$ mixing line between Astroni 6 and the proposed NYT isotopic end-member identified in previous studies (Arienzo et al., 2010; D'Antonio et al., 1999b; de Vita et al., 1999). However, they extend past the NYT end-member to more radiogenic Sr compositions, along the Astroni 6-syenite model trajectory, suggesting that the NYT end-member simply records syenite contamination.

A subset of recent eruptions from the western and central caldera group have similar $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ compositions but low Sr and high Nd concentrations, indicative of fractional crystallisation which does not affect these isotopic ratios whilst trace and major element contents vary as a result of cooling and crystallisation (e.g. SiO_2 increases from ~60 wt% in Astroni 6 to ~63% in Averno 2 which has the highest Nd concentration; Fig. 3.7a,

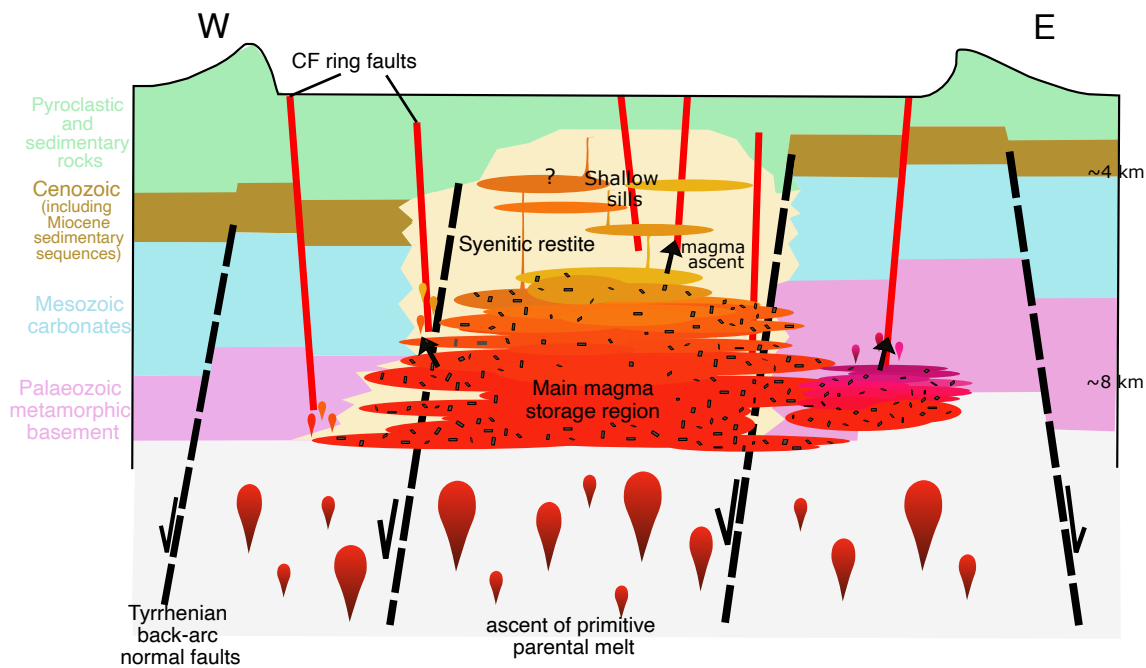


Figure 3.6: Summary schematic of Campi Flegrei sub-volcanic plumbing system based on isotopic variation in erupted products from the last 15 kyr. Black lines indicate normal faults related to regional tectonics, red lines indicate faults formed or reactivated during caldera collapse. The potential basement lithologies which ascending magmas may interact with are also sketched. The main regions of magma storage are indicated, with the magma colour related to assimilation: gradation from red to orange/yellow indicates progressive contamination with the syenitic restite (depicted in yellow); red to purple gradation indicates contamination with the Palaeozoic metamorphic basement (purple layer). Not to scale.

3.7b). These glass isotopic compositions are slightly more radiogenic than Astroni 6, suggesting some initial contamination of the parental magma with syenite before evolution through fractional crystallisation, perhaps in isolated magma batches.

Assimilation of syenite is less clear in EC-AFC models of Pb isotopes (Fig. 3.4) due to the syenite having low Pb concentrations (8 ppm) and a very similar Pb-isotope composition to post-15 ka erupted glasses.

3.5.1.2 Assimilation in northern/eastern caldera eruptions

Our EC-AFC models show that the dominant trend in northern/eastern caldera rim eruptions towards high $^{87}\text{Sr}/^{86}\text{Sr}$ but low $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ defines a model trajectory between the most mantle-like Astroni 6 end-member and the Palaeozoic metamorphic basement, with the Minopoli 2 glass consistent with ~10–15% gneiss contamination (Fig. 3.3). This is in agreement with previous studies which have suggested that Campi Flegrei magmas are contaminated by Palaeozoic metamorphic rocks based on

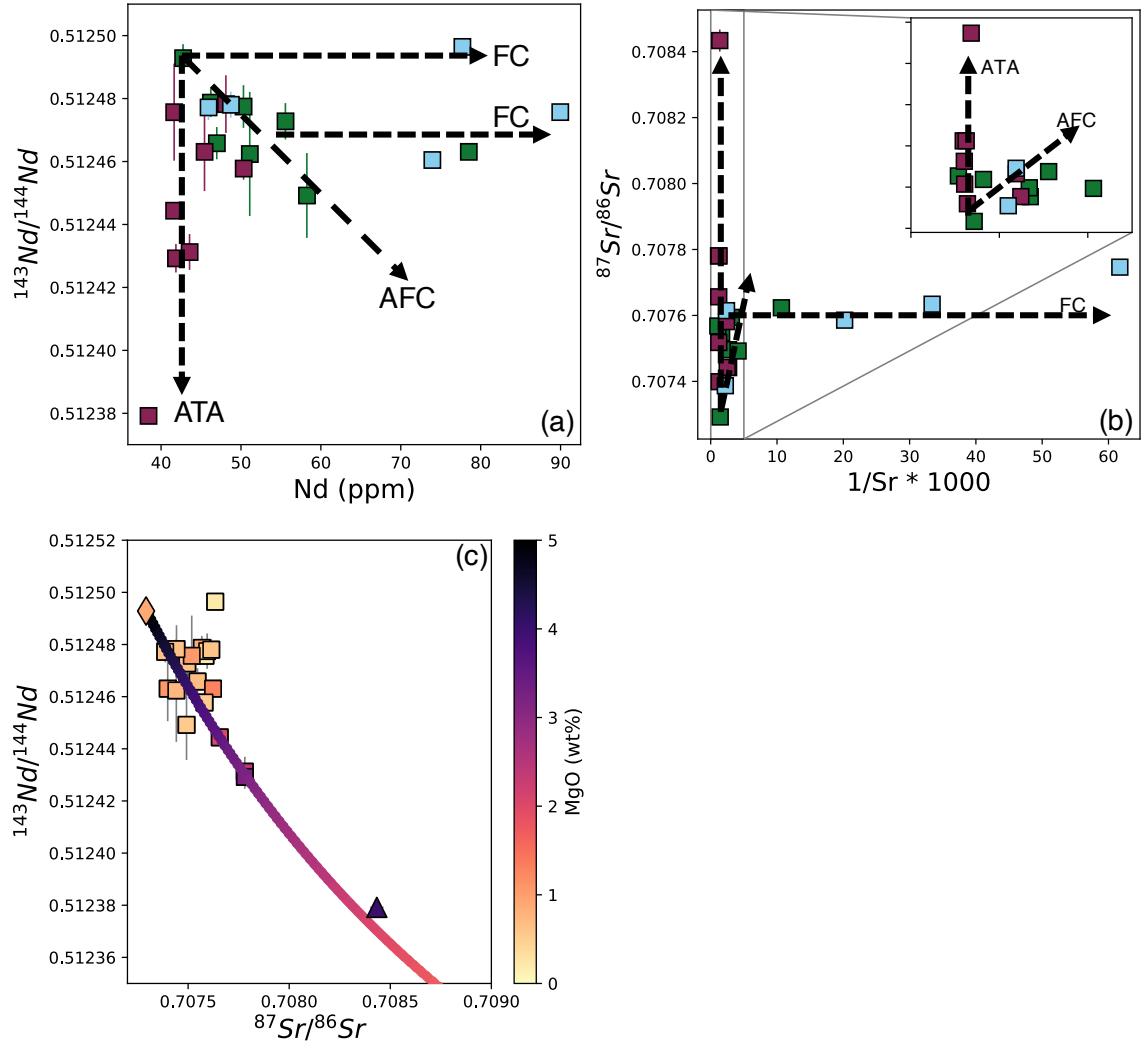


Figure 3.7: Comparison of the effects of AFC and ATA on the compositional evolution of erupted glass samples, which are coloured according to volcano-tectonic setting (a) Nd vs $^{143}\text{Nd}/^{144}\text{Nd}$ binary diagram with the expected changes from FC (from different initial isotopic compositions), AFC and ATA indicated by the arrows (b) $1/\text{Sr} \times 1000$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ binary diagram with the expected changes from FC, AFC and ATA indicated by the arrows (c) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ binary diagram showing sampled eruptions (square markers) and modelled AFC assimilation of Palaeozoic gneiss (line). Markers are coloured according to the MgO content of the eruption. Minopoli 2 is indicated by triangular marker and Astroni 6 by a diamond marker. The AFC model is coloured by the modelled melt MgO during AFC (model details in Table A2.7).

major element, trace element and isotopic evidence (Amstutz et al., in press; Arienzo et al., 2011; D'Antonio et al., 2007; Di Renzo et al., 2011; Pappalardo et al., 2002). Despite some heterogeneity in previously published isotopic compositions of the Palaeozoic metamorphic basement (Fig. A2.1; Pappalardo et al., 2002; Rottura et al., 1991), all measurements indicate the lithology has high $^{87}\text{Sr}/^{86}\text{Sr}$ but low $^{143}\text{Nd}/^{144}\text{Nd}$ consistent with the model trajectory and trend seen in the northern/eastern caldera rim eruptions. These eruptions generally occurred earlier (Fig. A2.3), suggesting that assimilation processes may have a temporal control. However, some early eruptions with vents located in the central and western caldera do not have isotopic compositions consistent with assimilation of Palaeozoic metamorphic basement. This indicates assimilation cannot be solely controlled by eruption timing and is more strongly influenced by vent location.

However, while EC-AFC models reproduce the radiogenic isotope trends seen in caldera rim eruptions, they are inconsistent with the sample major and trace element chemistry: these models inherently assume that the extent of fractional crystallisation and assimilation correlate, with magma MgO and compatible trace element (e.g. Sr) concentrations decreasing and incompatible trace element (e.g. Nd) concentrations increasing as a result of cooling/crystallisation while $^{87}\text{Sr}/^{86}\text{Sr}$ ratios increase and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios decrease through progressive incorporation of country rocks (Fig. 3.7a,b). While this holds for evolved eruptions in the central and western caldera, Minopoli 2 has the most crust-like Pb, Sr and Nd isotopic compositions but is also the most mafic post-15 ka Campi Flegrei eruption. Figure 3.7c illustrates how magma evolution (shown by decreasing MgO concentration) fails to reproduce the coupled major element and isotopic compositions of mafic caldera rim eruptions. At the point the modelled evolving magma reaches the isotopic composition measured in Minopoli 2, the MgO content modelled for the melt is much lower (~2.5 wt%) than measured in Minopoli 2 glasses (~4 wt%).

Given that the classic view of assimilation coupled to fractional crystallisation is incongruent with the contamination seen in these more mafic caldera rim samples, we suggest an alternative scenario whereby these eruptions experienced contamination during turbulent ascent of mafic magma (termed Assimilation during Turbulent Ascent – ATA; Huppert and Sparks, 1985). This process has been identified in tectonically diverse magmatic provinces globally, causing crustal assimilation over relatively short timescales and the most mafic magmas within a system to become the most contaminated. During ATA, magmas remain relatively unevolved (they do not cool and crystallise) and isotopic variations decouple from the elemental concentrations; major and trace element contents (e.g. MgO, Sr, Nd) remain near-constant but $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ can vary considerably.

The results of binary mixing models to simulate ATA show similar overall trends to our EC-AFC models but with a better agreement between observed elemental and isotopic variations in caldera rim eruptions; mafic glasses produced in these eruptions (e.g. Minopoli 2) are consistent with assimilation of Palaeozoic metamorphic basement during turbulent ascent (Fig. 3.3, 3.4). Hence, we suggest that magmas expelled in caldera rim eruptions ascended relatively quickly along pre-existing ring faults with little cooling or crystallisation but were in direct contact with the Palaeozoic metamorphic basement which was incorporated and assimilated (Fig. 3.6). The combination of the hot, mafic nature of these eruptions and their volcano-tectonic setting (i.e. pre-existing caldera ring fractures), resulted in ATA and the decoupling of assimilation from fractional crystallisation.

3.5.2 Oxygen isotopic records of hydrothermal and meteoric water interaction

The O isotope compositions of our glass samples are highly variable but consistent with the limited existing studies that have measured O isotope compositions of Campi Flegrei whole rocks and mineral separates (Iovine et al., 2018 and references therein). Central caldera eruptions generally show a greater diversity than those from the caldera rim (Fig. 3.5), and

most eruptions are isotopically heavier than typical mantle derived basalts which have $\delta^{18}\text{O}$ of $\sim 5.5\text{--}6\text{‰}$ (Eiler, 2001 and references therein).

To determine the source of this stable isotope variation, we first calculated the $\delta^{18}\text{O}$ increase of a mantle-derived magma evolving through fractional crystallisation using a forward-step mass balance model, following Bucholz et al. (2017). The temperature-crystallising assemblage and temperature-melt composition relationships are taken from the best-fitting post-15 ka Campi Flegrei Rhyolite-MELTS model of Amstutz et al. (in press) with initial $\delta^{18}\text{O}$ varied between $5\text{--}6\text{‰}$, exceeding the range of typical mantle derived basalts (Eiler, 2001). Most of our data fall outside the $\delta^{18}\text{O}$ range produced by fractional crystallisation, even at unreasonably low melt fractions (Fig. 3.8), supporting the radiogenic isotope results in suggesting that processes beyond simple fractional crystallisation are controlling the isotopic compositions of our glasses.

Next, we modelled $\delta^{18}\text{O}$ variation related to AFC and ATA, following the same methods as we used for radiogenic isotopes (described above; Fig. 3.5). While Sr, Nd and Pb isotope compositions of central and western caldera eruptions and northern/eastern caldera rim eruptions are consistent with assimilation of syenite and Palaeozoic metamorphic basement, respectively, O isotopes do not show clear agreement with these models. The $\delta^{18}\text{O}$ of glasses from central and western caldera eruptions are lower than those predicted for syenitic restite EC-AFC, whereas the $\delta^{18}\text{O}$ of northern/eastern caldera rim glasses are higher than predicted for Palaeozoic metamorphic basement ATA (Fig. 3.5). Hence, neither fractional crystallisation nor assimilation models can adequately reproduce the O isotope compositions of post-15 kyr Campi Flegrei glasses.

3.5.2.1 High $\delta^{18}\text{O}$ from low temperature alteration

Campi Flegrei glasses extend to $\delta^{18}\text{O}$ of 14‰ , significantly higher than would be expected from fractional crystallisation of typical mantle-derived magmas. One possible source for these high $\delta^{18}\text{O}$ values is limestone contamination. Carbonate assimilation is extensive at

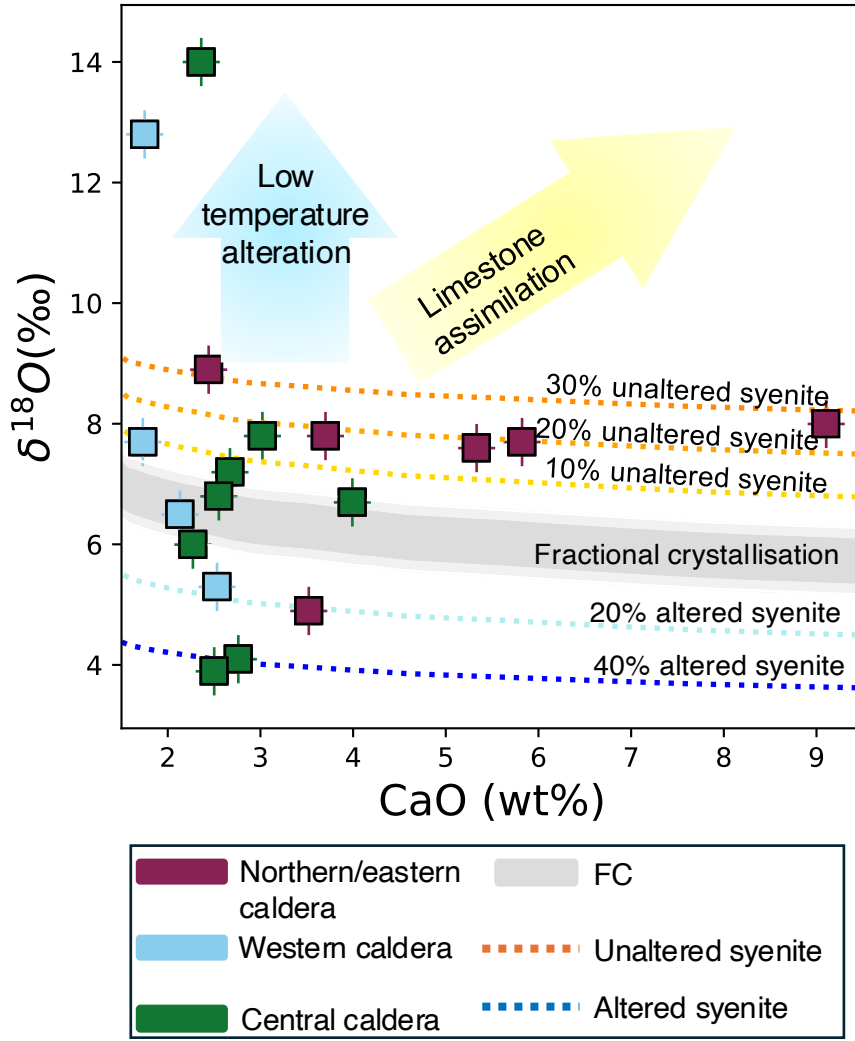


Figure 3.8: CaO (wt%) vs $\delta^{18}\text{O}$ variation in sampled Campi Flegrei glasses. CaO (wt%) values are from Smith et al. (2011) and samples are coloured according to volcano-tectonic setting. Arrows show the expected compositional change of low temperature alteration by meteoric water and assimilation of limestone. The grey bar shows the range of expected $\delta^{18}\text{O}$ values from a mantle-derived magma evolving by fractional crystallisation, following the method of Bucholz et al. (2017). Dashed lines show the expected $\delta^{18}\text{O}$ variation of a magma assimilating different proportions of unaltered syenite (orange lines) or hydrothermally altered syenite (blue lines) during fractional crystallisation.

nearby Vesuvius (Iacono Marziano et al., 2008) and Mesozoic limestones are thought to underlie Campi Flegrei (Judenherc and Zollo, 2004) with very high $\delta^{18}\text{O}$ compared to magmatic values (i.e. 22.4‰ versus ~5-6‰). Hydrothermal calcite ($\delta^{18}\text{O} \approx 14.9$) has also been documented in both lithic Campi Flegrei tuff fragments and borehole samples (Buono et al., 2024). Limestone and hydrothermal calcite AFC models (Fig. 3.5) show that our highest measured $\delta^{18}\text{O}$ values would be consistent with ~20% limestone addition. However, this extent of carbonate contamination is not consistent with our radiogenic isotope data (Fig. 3.3) or the major element compositions of glasses erupted in the past 15 kyr (Amstutz et al.,

in press), and would enrich melts in CaO (as observed at Vesuvius; Iacono Marziano et al., 2008) generating a correlation between $\delta^{18}\text{O}$ and CaO which is not recorded in our dataset (Fig. 3.8). Limestone xenoliths are also absent in Campi Flegrei erupted products, at odds with current assumptions based on tomographic data.

An alternative explanation for the high $\delta^{18}\text{O}$ values in some Campi Flegrei glasses is that they have undergone low-temperature alteration by meteoric water. Meteoric waters generally have low $\delta^{18}\text{O}$ values and Campi Flegrei hydrothermal waters have a $\delta^{18}\text{O}$ of approximately -5‰ (Valentino et al., 1999), but large fractionation factors between igneous rocks and water at low temperature lead to a significant increase in the $\delta^{18}\text{O}$ of altered glasses as the light oxygen isotope is exchanged for the heavy isotope (Cerling et al., 1985). This process can occur without changing the concentrations of other major and trace elements, such that even seemingly fresh glasses can have modified $\delta^{18}\text{O}$ values (Cerling et al., 1985). It is unlikely to affect the radiogenic isotope ratios due to the immobile nature of these elements in water (Jenner and Wyman, 1996), supported by comparison with unaltered mineral separates which display comparable radiogenic isotope compositions (e.g. Iovine et al., 2018). Hence, alteration by meteoric water provides a viable mechanism for decoupling $\delta^{18}\text{O}$ values from major elemental concentrations and radiogenic isotopes in our Campi Flegrei glasses.

While eruptions with the highest glass $\delta^{18}\text{O}$ values are most likely to have been affected by meteoric water alteration, others may also be impacted to a lesser extent. We investigate this by comparing the glass $\delta^{18}\text{O}$ values to those measured in mineral separates in select eruptions (Table 3.1) which are not affected by the low temperature alteration (Bindeman, 2008). The $\delta^{18}\text{O}$ values of the melt in isotopic equilibrium with the minerals ($\delta^{18}\text{O}_{\text{melt}}$) were calculated following the approach of Bindeman et al. (2004, Table A2.6). For Averno 2, $\delta^{18}\text{O}_{\text{melt}}$ calculated from feldspar and clinopyroxene crystals are 4.3–5.1‰ lower than $\delta^{18}\text{O}$ values measured in glass separates, providing further evidence that glass

compositions have been impacted by low temperature meteoric water alteration. However, $\delta^{18}\text{O}_{\text{melt}}$ of Fondo Riccio crystals are similar to glass $\delta^{18}\text{O}$, suggesting that meteoric water alteration isn't ubiquitous.

3.5.2.2 Eruptions with low $\delta^{18}\text{O}$ values

Several eruptions have $\delta^{18}\text{O}$ between 3.9–6‰, lower than expected for fractional crystallisation of a typical mantle-derived magma. Although uncommon, low $\delta^{18}\text{O}$ glasses have been observed in other volcanic deposits worldwide, especially in long-lived caldera systems (e.g. Troch et al., 2020), where they are typically attributed to assimilation of hydrothermally altered material by the magmas (Troch et al., 2020). As surface waters (meteoric or sea water) are the only geological reservoirs with $\delta^{18}\text{O}$ lower than typical MORB values (Bindeman, 2008), these low $\delta^{18}\text{O}$ eruptions must have inherited their isotopic composition from rocks that interacted with surface water. However, as large fractionation factors between water and igneous rocks at low temperatures means interaction raises the $\delta^{18}\text{O}$ in the altered rock (described above), these rock-water interactions must have taken place at high temperature, in active hydrothermal systems (Troch et al., 2020). We modelled this process at Campi Flegrei, using $\delta^{18}\text{O}$ from a hydrothermally altered syenite clast from the Breccia Museo to represent the low $\delta^{18}\text{O}$ material assimilated by ascending magmas ($\delta^{18}\text{O} = 1.8\text{‰}$, Gebauer et al., 2014) and find that eruptions with low $\delta^{18}\text{O}$, below typical MORB, are consistent with 20–40% assimilation of this material (Fig. 3.8). Eruptions with radiogenic isotope compositions consistent with syenite assimilation do not all have low $\delta^{18}\text{O}$, implying that the syenitic restite is variably hydrothermally altered.

Campi Flegrei currently has a well-developed and active hydrothermal system which is focused in the Solfatara-Pisciarelli area within the central caldera (De Siena et al., 2010; Troiano et al., 2014), and geological evidence suggests that this has persisted over much of the past 15 kyr (Isaia et al., 2009). Our low $\delta^{18}\text{O}$ glasses support this, recording the presence of a hydrothermally altered syenitic restite in the crust beneath the volcano, which was

assimilated by ascending magmas. As most eruptions with low $\delta^{18}\text{O}$ values are from the centre or west of the caldera, the hydrothermal system may have been focused in a similar geographic location in the past.

3.6 Conclusions

We have shown that post-15 ka Campi Flegrei eruptions have varied stable and radiogenic isotopic compositions, which correlate with the volcano-tectonic setting of the eruption vent and reveal a complex sub-volcanic plumbing system (Fig. 3.6). In general, eruptions from the northern/eastern caldera rim have more radiogenic Sr and less radiogenic Nd and Pb isotopic compositions to those in the centre of the caldera, or along regional faults in the west of the caldera. We suggest that this isotopic variation is outside the range expected for fractional crystallisation of a parent magma and that it is the result of assimilation of wall rock by the ascending magma, with assimilation processes differing spatially across the caldera.

Eruptions from the northern/eastern caldera rim assimilate small amounts (~10%) of Palaeozoic metamorphic basement, likely during turbulent ascent along caldera rim faults which expose the magma to the surrounding basement. In contrast, eruptions from the centre of the caldera show evidence of interaction with syenitic restite (up to 30%), representing the crystalline crustal residue from cooled magma feeding past eruptions. Central caldera magmas likely evolve by AFC within this mush, which is variably hydrothermally altered by a long-lived hydrothermal system. Magmas evolving in this region incorporate this syenitic restite and appear more isolated from the surrounding basement than eruptions from the caldera rims. It seems likely that there was some mixing between batches of magmas which have undergone different evolution and contamination, in agreement with previous studies (e.g. Arienzo et al., 2016, 2015, 2010; Di Renzo et al., 2011; Tonarini et al., 2009; Voloschina et al., 2018).

However, this study identifies the composition of the contaminant of the different end-member magmas and highlights the importance of the volcano-tectonic setting of individual eruption vents in controlling the magmatic evolution. Our results indicate that at long-lived caldera systems such as Campi Flegrei, magmatic evolution is strongly influenced by the volcano-tectonic setting of eruption vents, making vent location an important consideration in hazard forecasting.

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4. Complex magmatic histories of assimilation-fractional crystallisation recorded in single crystals: insights from Campi Flegrei clinopyroxenes

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Lay abstract

Crystals formed beneath volcanoes can hold chemical fingerprints that provide information on the processes occurring before a volcanic eruption. In this study, we looked at crystals of the mineral clinopyroxene from two past eruptions at Campi Flegrei, a large and restless

volcano near Naples, southern Italy. We chose two eruptions, Minopoli 2 and Astroni 6, which were very different in terms of the style of eruption, composition of material erupted and location of the eruption vent within the Campi Flegrei caldera. We examined the clinopyroxene crystals using high-resolution imaging, chemical mapping and analysis of strontium isotopes, which provided details about how the magma changed before eruption. We found that crystals recorded much more variation in strontium isotopes than had been seen in previous studies using bulk rock or glass, which suggests the magmas feeding Campi Flegrei have more varied compositions than previously thought. In addition, we found evidence of several processes happening in the magmatic system pre-eruption: crystallisation of magma as it cools, mixing of different magma batches and interaction between magma and surrounding rock. These processes differed between the two eruptions. For example, Astroni 6 crystals showed more signs of cooling, crystallising and mixing with crustal material, whereas Minopoli 2 crystals showed more evidence of incorporating crustal material during magma ascent and injection of new magma. By studying the individual crystals in detail, we gain a clearer picture of what happens beneath Campi Flegrei prior to eruptions, and how this varies spatially beneath the volcano.

Abstract

Processes occurring before volcanic eruptions can be preserved in crystals formed within the sub-volcanic plumbing system. Here, we combine imaging of crystal textures, trace element mapping, in-situ Sr isotope analysis and thermobarometry in clinopyroxenes to investigate magma evolution before two recent eruptions at Campi Flegrei (southern Italy). Campi Flegrei has produced >70 eruptions in the last 15 kyr and is currently showing significant signs of unrest within a densely populated part of Europe. These eruptions span a wide range of eruptive styles and compositions and have erupted from different vent locations within a larger caldera system. We analysed clinopyroxenes from the Minopoli 2 and Astroni 6 eruptions at Campi Flegrei, chosen as these represent end-member post-15 ka eruptions

based on their major element and isotopic compositions and vent locations. Minopoli 2 was fed by shoshonitic magma with the most radiogenic isotopic composition in the last 15 kyr, from a vent located along pre-existing caldera rim faults in the north-eastern caldera, whereas Astroni 6 was phonolitic, with the most mantle-like isotopic composition and erupted from the central caldera floor. In-situ strontium isotopes show large variations, more than are seen in glass separates from the same eruptions which represent an average of this variation. This includes the least radiogenic compositions reported for Campi Flegrei, suggesting the mantle source is not ubiquitously enriched as was previously suggested. Combining in-situ Sr isotope and Cr concentration variations across crystals shows fractional crystallisation, assimilation-fractional crystallisation and assimilation during turbulent ascent all occurring beneath Campi Flegrei. Comparison between eruptions indicates assimilation-fractional crystallisation is more common in Astroni 6 and assimilation during turbulent ascent and mafic recharge are more common in Minopoli 2. Our results provide new insights into the complex processes operating beneath Campi Flegrei prior to an eruption, and highlights the important information recorded within individual crystals.

4.1 Introduction

Long-lived caldera-forming volcanoes represent significant volcanic hazards worldwide, as they typically remain active for long periods and frequently remain restless after major collapse events (Cole et al., 2005). Due to their longevity, they develop complex magmatic systems where magmas cool, crystallise, mix, mingle and sometimes assimilate surrounding crust before feeding post-collapse eruptions (Cashman and Giordano, 2014). Understanding the processes controlling magmatic evolution (and hence eruption style, Cassidy et al., 2018) before these eruptions is important for hazard forecasting.

Investigating magmatic processes driving current unrest beneath active volcanic systems requires a wide range of techniques including analysis of seismicity, deformation

and gravity (e.g. De Martino et al., 2021; Bianco et al., 2022; Tramelli et al., 2022). Often, current unrest is interpreted in the context of processes recorded in the products of past eruptions, constrained using the chemistry, petrology or components of the volcanic products (e.g. Saunders et al., 2012; Jerram et al., 2018). Evidence of crustal processing is also recorded within the crystal cargo of eruptions. For example, mingling between different magmas can be observed at the crystal scale (Schleicher et al., 2016) and crystal compositions can be used to estimate the pressure and temperature of their formation (Putirka, 2008).

High-resolution studies of crystal textures and compositions have successfully provided information on sub volcanic processes in a wide range of systems. For example, Ubide and Kamber (2018) used trace element maps of clinopyroxenes from Mount Etna (Italy) to track mafic recharge triggering eruptions at the volcano, whilst Jorgenson et al. (2024) used the chemistry of clinopyroxenes from Colli Albani (Italy) to perform thermobarometry and infer that magma accumulated rapidly in the shallow crust prior to caldera-forming eruptions at the volcano. Adams et al. (2021) used the extreme variations in Sr and Nd isotopic composition of individual clinopyroxenes from Savai'i Island (Samoa) to constrain variable mixing between a mantle source and subducted sediments. Crystal isotopic compositions have also been determined in-situ, for example at Stromboli volcano (Italy), where in-situ Sr-isotope data on plagioclase and clinopyroxenes revealed mixing between different magmas and recycling of crystals stored within a cumulate crystal mush reservoir (Francalanci et al., 2012). Some studies have combined trace element and isotopic data in crystals, for example in plagioclase macrocrysts from the 2021 Tajogaite eruption (La Palma, Spain) where trace element zoning indicated the plagioclase cores derived from recycling of antecrysts from evolved mush into mafic recharge magmas, with Sr-isotope data indicating this mush was more radiogenic than the recharge melt (Jegal et al., 2025).

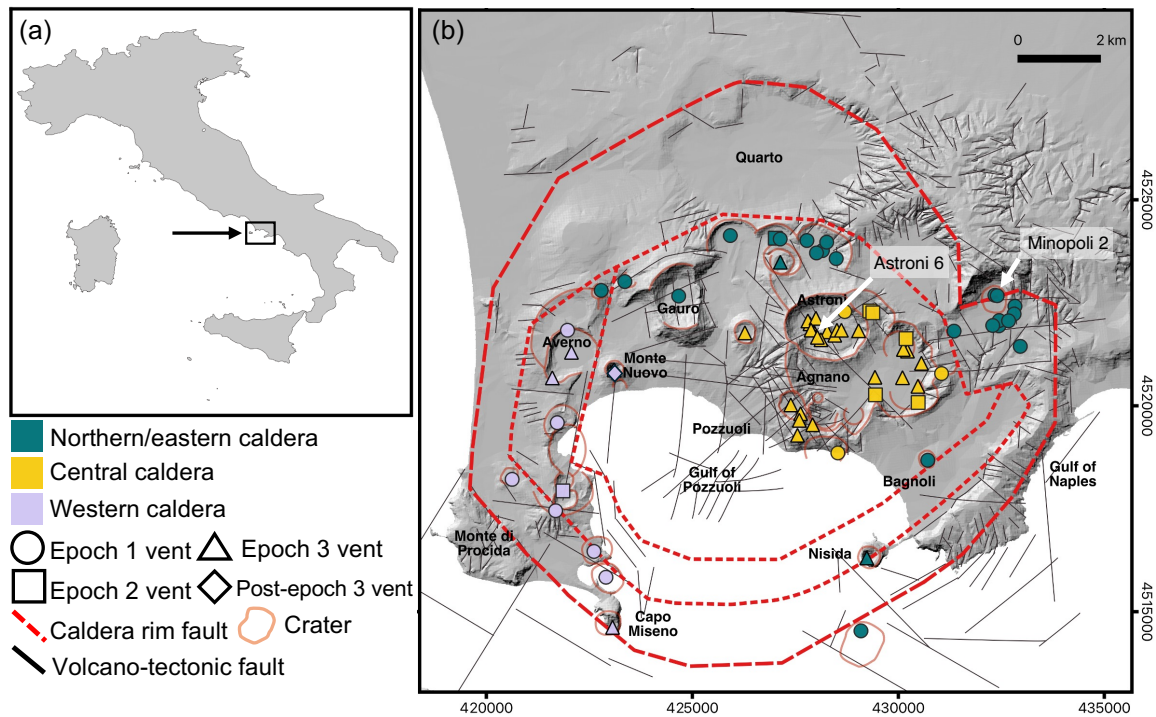


Figure 4.1: Maps showing Campi Flegrei and vent locations for eruptions in the last 15 kyr. (a) Map of Italy showing the location of Campi Flegrei (b) Simplified map of Campi Flegrei showing vent locations in the last 15 kyr, from Smith et al. (2011) and Bevilacqua et al. (2015). Colours refer to the volcano-tectonic setting of the vents, following Amstutz et al. (in press): eruptions in dark green occurred along caldera rim faults in the north and east; eruptions in yellow occurred on the caldera floor in the central caldera; and eruptions in purple occurred along volcano-tectonic (VT) faults in the west of the caldera. Map also shows the distribution of caldera and crater rims (Vitale and Isaia, 2014; Natale et al., 2022a). Vent ages refer to epochs defined in Smith et al. (2011). The vent locations of Minopoli 2 and Astroni 6, sampled in this study, are also indicated.

Here, we investigate magma evolution prior to eruptions of Campi Flegrei (Naples, Italy; Fig. 4.1), in the last 15 kyr, since the last caldera-forming eruption (Neapolitan Yellow Tuff, NYT; Deino et al., 2004). Campi Flegrei is located in a densely populated part of Europe (~1.5 million people live within the caldera, ~3.5 million would be immediately impacted by an eruption) and is currently showing significant signs of unrest, making it one of the most hazardous volcanoes on Earth (Orsi et al., 2004; Bevilacqua et al., 2017).

Specifically, we investigate clinopyroxenes from Minopoli 2 and Astroni 6 eruptions (Fig. 4.1) which represent end-member examples of the range of isotopic, major and trace element compositions, styles and locations of post-15 ka Campi Flegrei eruptions (Isaia et al., 2004; Smith et al., 2011; Arienzo et al., 2015; Amstutz et al., submitted). Clinopyroxene holds a detailed record of magma history, because it crystallises across large pressure and

temperature ranges (Masotta et al., 2013) and elemental diffusion is slow within the crystals for some elements (Dosseto et al., 2010; Müller et al., 2013). In this study, we combine analysis of crystal textures and major and trace element variations across crystals with in-situ Sr-isotope analysis and thermobarometry to build a picture of magmatic storage and processing before eruptions at Campi Flegrei. We find complex histories recorded within clinopyroxenes, involving magma mixing and recharge as well as assimilation of country rock and varying degrees of evolution. Subtle differences between Minopoli 2 and Astroni 6 clinopyroxenes indicates crustal processing varied between these eruptions, which we suggest is linked to the different volcano-tectonic settings of these eruptions.

4.2 Geological setting

The oldest volcanism at Campi Flegrei has been dated to >300 ka (De Vivo et al., 2001; Rolandi et al., 2003; Di Vito et al., 2008; Fernandez et al., 2024), with at least three potential caldera-forming events at ~39 ka (Campanian Ignimbrite [CI], Giaccio et al., 2017), ~29 ka (Masseira del Monte Tuff, Albert et al., 2019) and ~15 ka (Neopolitan Yellow Tuff [NYT], Deino et al., 2004). These eruptions produced a nested caldera structure ~13 km across (Vitale and Isaia, 2014; Natale et al., 2022b, 2024a), with the youngest NYT caldera the site of periods of intense activity separated by quiescence (Di Vito et al., 1999), broadly dividing post-15 ka eruptions into three epochs. Epoch 1 produced ~30 eruptions from ~15–10.6 ka, Epoch 2 produced 8 eruptions from ~9.6–9.1 ka and Epoch 3 produced 28 eruptions from ~5.5–3.5 ka. The most recent eruption was at Monte Nuovo in 1538 CE and is considered separate to Epoch 3 (Piochi et al., 2005; Smith et al., 2011).

Campi Flegrei produces ubiquitously alkali melts (Vineberg et al., 2023) and in the last 15 kyr melt compositions have ranged from shoshonite to phonolite (Smith et al., 2011). The most primitive shoshonitic products generally erupted in Epoch 1 along NYT caldera rim faults in the northern and eastern caldera (Civetta et al., 1991; Smith et al., 2011) with later Epoch 2 and 3 eruptions extending to more evolved compositions and erupting from

the central caldera floor or from vents associated with faults in the western caldera (Smith et al., 2011; Vitale and Isaia, 2014).

Magnetotelluric imaging suggests that the crustal architecture beneath Campi Flegrei is currently characterised by a transcrustal magma system (Isaia et al., 2025) with a main storage zone at ~7.5 km evident in tomographic surveys (Zollo et al., 2008; Bianco et al., 2022) and recent unrest principally driven by shallower magma and/or fluid migration at 2–4 km (De Siena et al., 2010; Calò and Tramelli, 2018; Giacomuzzi et al., 2024). A similar crustal structure appears to have persisted over much of the past 15 kyr with phase equilibria (Amstutz et al., in press), mineral thermobarometry (Astbury et al., 2018; Giordano and Caricchi, 2022) and volatile constraints (Mangiacapra et al., 2008; Arienzo et al., 2010, 2016; Vetere et al., 2011; Fourmentraux et al., 2012; Stock et al., 2016, 2018; Voloschina et al., 2018; Balcone-Boissard et al., 2024) all generally attesting to eruptions being fed by magmas predominantly derived from >7–8 km depth but with shallower (possibly ephemeral) sills ~3–4 km.

Minopoli 2 represents the most primitive eruption from Campi Flegrei in the last 15 kyr having produced shoshonitic magmas (D’Antonio et al., 1999b). It erupted in Epoch 1 (~10 ka; Di Renzo et al., 2011) from a vent located in the north-eastern caldera on the NYT caldera rim fault and producing scoria and minor ash fall, generating <0.1 km³ of magma (dense rock equivalent – DRE; Smith et al., 2011). In contrast, Astroni 6 erupted towards the end of Epoch 3 (4.1–3.8 ka; Isaia et al., 2004), from a vent in the Agnano-Astroni plain in the centre of the caldera. It is one of the largest eruptions in the last 15 kyr, producing 0.12 km³ of trachytic-phonolitic magma; Tonarini et al., 2009). The preserved tuff ring of the Astroni volcano produced 7 eruptions of varying magnitude in the period 4.1–3.8 ka, separated by palaeosols or erosional unconformities (Isaia et al., 2004).

The major element compositions of Minopoli 2 and Astroni 6 bracket the full range of compositions erupted in the last 15 kyr (Smith et al., 2011). This distinct chemistry

extends to their isotopic composition with the eruptions defining two end-members identified in studies of radiogenic isotopic variability (D'Antonio et al., 1999b; Arienzo et al., 2010, 2015, 2016; Di Renzo et al., 2011; Amstutz et al., submitted). Astroni 6 has the most mantle-like isotopic composition of eruptions in the last 15 kyr, with low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ (~ 0.7073 and 0.5125 respectively), whereas Minopoli 2 has the most crustal isotopic composition, with high $^{87}\text{Sr}/^{86}\text{Sr}$ (~ 0.7084) and low $^{143}\text{Nd}/^{144}\text{Nd}$ (~ 0.5123). Previous studies attribute isotopic heterogeneity in post-15 ka Campi Flegrei eruptions to mixing between these two isotopic end-members, along with a third end-member identified as deriving from NYT residual melts with an isotopic composition intermediate to Astroni 6 and Minopoli 2 (D'Antonio et al., 1999b; Arienzo et al., 2010, 2015, 2016; Di Renzo et al., 2011). While the cause of this variation has previously been attributed to both heterogeneous mantle sources (D'Antonio et al., 1999a; Tonarini et al., 2004; Iovine et al., 2018) and assimilation of country rock (Pappalardo et al., 2002; D'Antonio et al., 2007; Di Renzo et al., 2011), Amstutz et al. (submitted) recently demonstrated that eruptions from the north-eastern caldera rim, including Minopoli 2, assimilated small amounts of Palaeozoic metamorphic basement whereas central caldera eruptions, including Astroni 6, assimilated syenitic material using a combination of stable and radiogenic isotope analyses.

4.3 Methods

4.3.1 Sampling and sample preparation

Sample CF78 (Astroni 6) and samples CF9 and CF11 (from the base and top of the Minopoli 2 deposit, respectively), tephra samples collected from proximal deposits, were selected for analysis. Samples were collected by R. Isaia and V. Smith in 2009-2010, documented in Smith et al. (2011). Samples were crushed in a tungsten carbide jaw crusher and sieved, with clinopyroxene handpicked from the 250–500 μm size fraction. Crystals were mounted in epoxy, ground and polished for analysis.

4.3.2 Scanning electron microscopy

Back-scatter electron (BSE) images of ~400 Minopoli 2 pyroxenes were obtained using a Tescan TIGER MIRA3 field emission scanning electron microscope (FEG-SEM) at the iCRAG labs at Trinity College Dublin, Ireland, operated at 20 kV voltage and 300 pA beam current. These images were used to determine clinopyroxene zoning populations to ensure representative crystals were selected for further analysis.

4.3.3 Electron probe microanalysis

Major element analysis of clinopyroxenes from Minopoli 2 representative of the observed zoning textures was performed using a JEOL JXA 8200 wavelength-dispersive electron microprobe in the Research Laboratory for Archaeology and the History of Art, University of Oxford, UK. All analyses were collected with a 15 kV accelerating voltage, a 35 nA beam current and a 3 μm beam (Wieser et al., 2023). On-peak count times were 20s (for Si, Ca, Ti), 30s (for Mn), 40s (for Al, Mg, Fe, K) and 60s (for Na, Cr). Appropriate natural and synthetic standards were used for calibration (listed in Table A3.1), and secondary standards were analysed to check the accuracy and reproducibility of results, compared to the preferred values (results included in Table A3.2). Representative precision estimates from counting statistics are included in Table A3.3. Accuracy was typically better than 2% with precision typically $<\pm 0.5\%$ RSD for Si, and $\sim\pm 2\%$ for other elements, except for Mn ($\pm 8\%$). Major elements were analysed across the crystal (average of 3 spots per crystal) to capture changes in chemistry in the core, mantle and rim. Data were filtered with analyses with totals outside the range 98–101 wt%, which likely resulted from accidental measurement of inclusions or matrix phases or imperfections in the sample surface, excluded from further analysis. All EPMA analyses are included in Table A3.4.

4.3.4 Laser Ablation-Inductively Coupled Plasma Mass Spectrometry

(LA-ICP-MS) analysis

Laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) was carried out at the National Centre for Isotope Geochemistry, University College Dublin, Ireland (NCIG). Trace element maps of selected clinopyroxene crystals were obtained using an Analyte G2 193 nm Excimer laser coupled to a Thermo Scientific iCAP Q-ICP-MS. Details of laser parameters, gas flows and mass spectrometer operation are in Table A3.5. Elemental maps were obtained following the method described in Ubide et al. (2015). Spot size was determined by the size of the mapped crystal and was either 8x8 μm , 10x10 μm or 20x20 μm , translation speeds of 30–75 $\mu\text{m/s}$ and repetition rates of 35–50 Hz were used, dependant on slit size used. The instrument was tuned with scans of the NIST-612 reference glass. Accuracy and precision were monitored using NIST-612, GSD-1G, BHVO and BCR-2G reference materials as secondary standards before and after each clinopyroxene scan; accuracy was typically better than 10% and precision better than 5% for all analysed elements. Elemental maps were built with Iolite v4 (Paton et al., 2011) in semi-quantitative mode with NIST-612 as the external standard, using the CellSpace module (Paul et al., 2012).

Strontium isotope analysis was carried out at NCIG using an Analyte G2 193 nm Excimer laser coupled to a Thermo Scientific Neoma multicollector ICP-MS. Details of laser parameters, gas flows and mass spectrometer operation are given in Table A3.5. Spot Sr-isotope analyses were performed in the same locations as EPMA analyses, using a spot size of 80 x 80 μm and repetition rate of 15 Hz, analyses are in Table A4.3. Strontium isotope transects were collected using a spot size of 50 x 50 μm , repetition rate of 50 Hz and translation speed of 50 $\mu\text{m/s}$. Accuracy and precision were monitored using repeated spot measurements of ML3B and BCR-2G and are given in Table A3.5. Strontium isotope data reduction and interference corrections were performed with Iolite using the data reduction scheme detailed in Mulder et al. (2023). Interference from ^{87}Rb was monitored using the

$^{87}\text{Rb}/^{87}\text{Sr}$ ratio, excluding analyses where the ratio is >0.3 . This includes the first 4 seconds of each transect which were affected by ^{87}Rb arriving at the detector first.

For crystals for which we collected Sr-isotope transects across the crystal, we extracted trace element concentrations across the same transect from the LA-ICP-MS maps. We used the Profile tool in Iolite 4 (Paton et al., 2011) to plot the transect to be extracted from each trace element map, setting the width to the same as the slit size of the laser, and the intervals to the same distance as covered by the 9-rolling mean of $^{87}\text{Sr}/^{86}\text{Sr}$ points used in plots of Sr-isotope transects. Comparison between the ^{88}Sr profiles measured when collecting Sr-isotope transects and trace element maps (Fig. A3.1) provides a method to check both transects cover the same area, by ensuring the relative variation in ^{88}Sr is the same in both transects.

4.3.5 Thermobarometry

Crystallisation pressure and temperature estimates for the studied clinopyroxene crystals were obtained using the clinopyroxene-only machine learning thermobarometer of Ágreda-López et al. (2024). Major element analyses were input alongside analytical uncertainty (2 standard deviation counting statistic errors for each measurement from EPMA, following Wieser et al., 2023). Root mean square errors for the model are ± 56 °C and ± 2.5 kbar, 2σ uncertainty for each returned prediction propagated from analytical uncertainty is obtained from the 98th and 2nd percentiles of the barometer voting distribution.

4.4 Results

4.4.1 Clinopyroxene textures and geochemistry

From the BSE images, where greyscale variations reflect differences in average atomic number (corresponding to differences in Mg#, where $\text{Mg\#} = \text{Mg}/(\text{Mg} + \text{Fe})$; Morgan et al., 2004) we defined six main textural groups in Minopoli 2 and Astroni 6 clinopyroxenes (Fig. 4.2). Normal zoned crystals have a more mafic core with a more evolved rim; this zoning

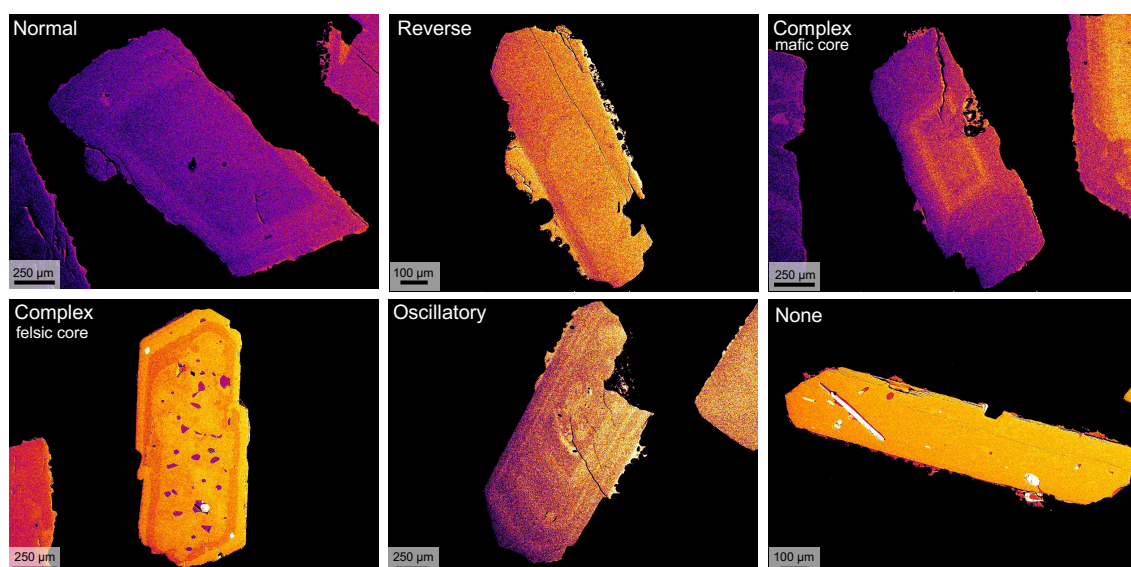


Figure 4.2: False-coloured backscattered electron images showing representative zoning textures in Minopoli 2 and Astroni 6 clinopyroxenes. Other zoning textures are showing in Fig. A3.2.

population is more common in Astroni 6 (Fig. A3.2). In most normal zoned Minopoli 2 crystals, the mafic core is euhedral whereas in Astroni 6 most normally zoned crystals have a resorbed core (Table A3.7). Reverse zoned crystals show the opposite trend, with a more evolved core surrounded by a more mafic rim; these crystals are more common in Minopoli 2. In both eruptions, reverse zoned crystals commonly have resorbed cores. Complex zoning, with either a more mafic or evolved core, is characterised by one distinct zone between the core and rim of the crystal. In these groups, the core and/or zoning in the crystal is commonly resorbed (Fig. A3.2). Oscillatory zoned crystals, with multiple concentric zones of varying composition, are also present in both eruptions but are more commonly observed in Minopoli 2. Unzoned crystals make up the largest proportion of crystals analysed from both eruptions (~50-60%, Fig. A3.2) but this may in part be due to sectioning effects where they represent a section through one zone of a larger zoned crystal. Comparison between the two Minopoli 2 samples shows no major differences in zoning textures, except for a higher percentage of reverse zoned crystals observed in CF9 (24% compared to 10% in CF11, Fig. A3.2).

Analyses from EPMA show that Minopoli 2 and Astroni 6 clinopyroxenes cover a wide compositional range, with Mg ranging from 0.61–1.00 (Fig. 4.3, all EPMA analyses in

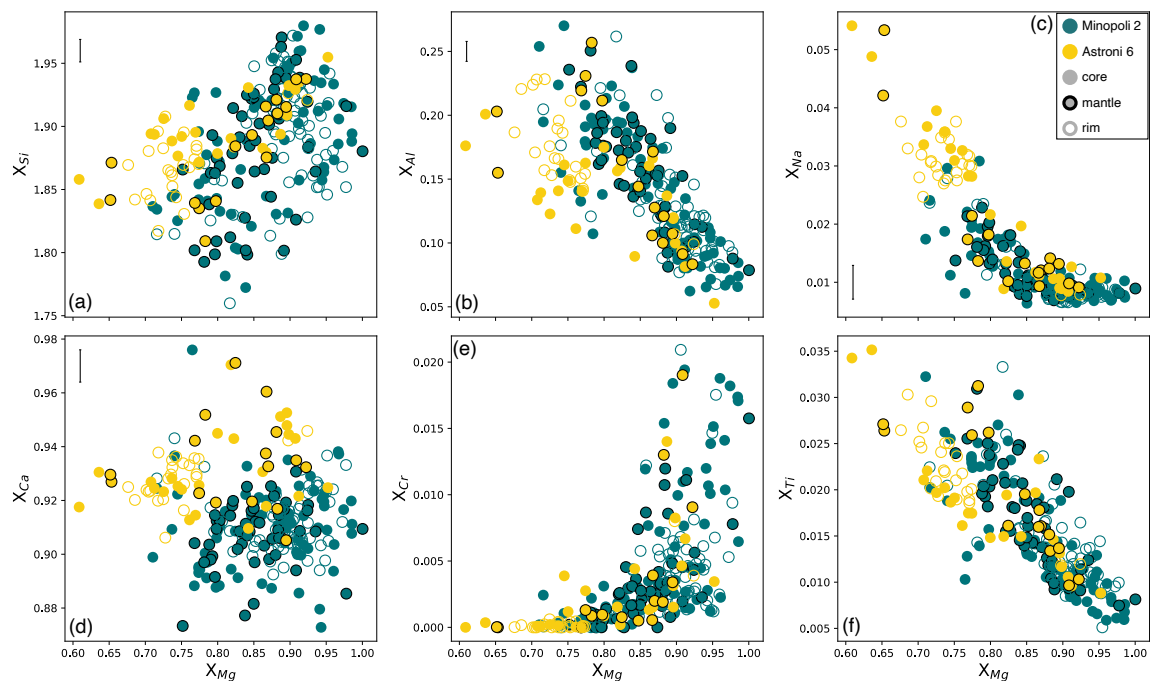


Figure 4.3: Clinopyroxene compositions for Minopoli 2 (dark blue points) and Astroni 6 (yellow points) clinopyroxenes, from the core, mantle and rim of each crystal. Crystal compositions were calculated on a 6O basis, X denotes mole fraction. Characteristic 2σ uncertainties are shown or are less than the size of the data points.

Table A3.4). In general, the compositions of Astroni 6 and Minopoli 2 eruptions overlap, but Minopoli 2 crystals extend to higher Mg, mostly from analyses of crystal cores, and Astroni 6 to lower Mg contents (Mg = 0.71–1.00 for Minopoli 2, Mg = 0.61–0.95 in Astroni 6). Minopoli 2 crystal compositions cover a continuous range without distinct groups. Astroni 6 crystals form two distinct groups: the dominant group, which contains most of the analyses from crystal rims, has low Mg (<0.77) but higher Na (>0.025) and a narrow range of Ca (0.91–0.94) with the other having higher Mg (>0.8), lower Na (<0.02) and variable Ca (0.91–0.97). The higher Mg Astroni 6 group overlaps with the Minopoli 2 clinopyroxenes, which also extend to lower Ca (0.87) with more variable Si (1.76–1.98). The two Minopoli 2 samples show comparable compositions, with the exception of Si; CF11 forms two distinct lower and higher Si groups, whereas CF9 has Si contents intermediate to these groups (Fig. A3.3).

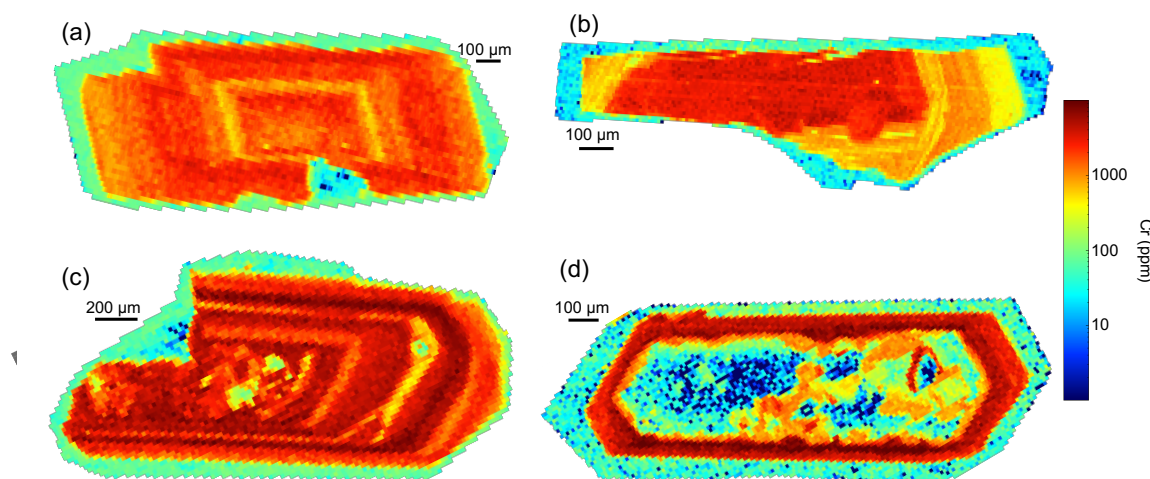


Figure 4.4: Representative Cr element maps for Minopoli 2 and Astroni 6 clinopyroxenes, all trace element maps are shown in Fig. A3.5. Maps are semi-quantitative, higher Cr concentrations are indicated by warmer (orange-red) tones. (a) shows a complex zoned clinopyroxene with a mafic core; (b) shows a complex zoned crystal with a resorbed felsic zone; (c) shows an oscillatory zoned crystal; (d) shows a reverse zoned crystal. The pale blue/green surrounding all clinopyroxenes is matrix material.

The six main textural groups correspond to variable chemistry (Fig. A3.4). The highest Cr_2O_3 is seen in normally zoned Minopoli 2 pyroxene cores, up to 0.73 wt%, whereas reversely zoned crystals have generally low Cr_2O_3 , <0.22 wt% throughout the crystal. A group of Astroni 6 analyses, predominantly crystal rims, forms a distinct low Mg#, high Na_2O and low Cr_2O_3 group in normally zoned crystals, a similar group is also observed in reverse zoned crystals. Crystals with complex zoning do not show clear systematic variation between the cores, mantles and rims, although in complex zoned crystals with more mafic cores the mantles extend to higher Na_2O contents than seen in cores and rims, with the reverse observed in complex zoned crystals with felsic cores where the mantles generally have lower Na_2O .

Trace element maps show clear zoning in the composition of some elements, particularly Cr (Fig. 4.4, Fig. A3.5), even in crystals where major element compositions are fairly homogenous. Zones enriched in Cr also show high concentrations of other compatible elements, such as Sc and Ni, and low concentrations of incompatible elements, such as La, Y and Nd (Fig. A3.5). High Cr zones correspond to the more Mg-rich zones observed in

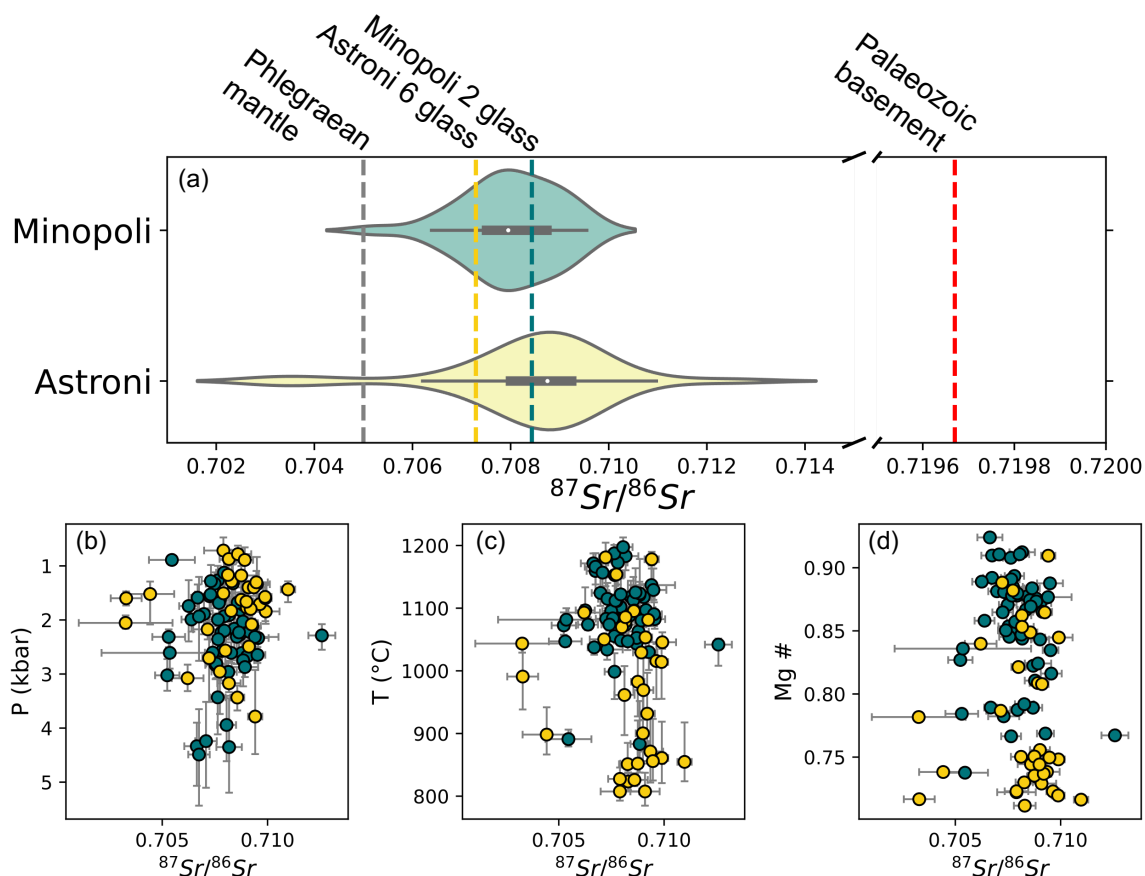


Figure 4.5: Range of Sr isotopes measured in Minopoli 2 and Astroni 6 clinopyroxenes. (a) Violin plot of measured Sr isotopes for Minopoli 2 (green) and Astroni 6 (yellow). For each plot the shaded region shows a kernel density estimate for the measured values and the inner region shows a box plot, the median value is indicated by the white point and the quartiles are shown by the box. Strontium isotope values measured for Minopoli 2 and Astroni 6 glass and the Palaeozoic metamorphic basement, from Amstutz et al. (submitted) are also shown, along with the estimated isotopic composition of the Phlegraean mantle from Mazzeo et al. (2014). (b) and (c) show Sr isotope measurements plotted against pressure and temperature estimates from the clinopyroxenes, from thermobarometry and (d) shows Sr isotope measurements plotted against the Mg# of the clinopyroxenes, from EPMA. Error bars represent 2σ uncertainties.

BSE images. In Fig. 4.4a, a high-Cr zone occurs on only one side of the crystal. This zone is also clearly visible in the La, Y and Sc maps, but the asymmetry across the crystal implies this is a sectioning effect (Welsch et al., 2015).

4.4.2 In-situ Sr isotopes

Strontium isotopes measured in clinopyroxene crystals vary widely with $^{87}\text{Sr}/^{86}\text{Sr}$ ranging 0.703262 to 0.712579 (average uncertainty ± 0.0005 , Fig. 4.5a). This variation is greater in Astroni 6 clinopyroxenes, ($^{87}\text{Sr}/^{86}\text{Sr}$ 0.703262–0.710972), compared to Minopoli 2 ($^{87}\text{Sr}/^{86}\text{Sr}$ 0.705238–0.712579). The most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (0.712579) was measured in the core of

a reverse zoned crystal, whereas the least radiogenic value (0.703262) was measured in the mafic zone of a complex zoned crystal, from Minopoli 2 and Astroni 6 respectively. There is no clear relationship between the isotopic composition of the crystal and its measured Mg# (Fig. 4.5d). However, in 66% of measured Astroni 6 crystals, the Sr-isotope value increases between the core and the rim of the crystal whereas in Minopoli 2 this trend is not observed.

4.4.3 Thermobarometry

Results from clinopyroxene thermobarometry indicate clinopyroxene crystallisation between 0.7–4.7 kbar (SEE= ± 2.5 kbar), with most estimates centred around 1–3 kbar (Fig. 4.5b). Estimates from Astroni 6 clinopyroxenes are generally shallower (mostly <2 kbar) than from Minopoli 2 (a larger proportion the range 2–4.5 kbar), although we note the large SEE means it is not possible to resolve upper crustal reservoirs. Temperature estimates range 790–1226 °C (SEE= ± 57 °C, Fig. 4.5c) with almost all (83%) Astroni 6 estimates <1100 °C.

4.5 Discussion

4.5.1 Constraints on magma storage

Estimates of pressure and temperature of crystallisation from clinopyroxene thermobarometry indicate magma is stored throughout the upper crust, from ~1–5 kbar. Using the average crustal density of 2.3 g/cm³ from Rosi and Sbrana (1987), this corresponds to depths of ~3–20 km with most estimates in the ~4–13 km region. This agrees with the model of a transcrustal magma system suggested previously for Campi Flegrei based on magnetotelluric imaging (Isaia et al., 2025), thermobarometry (Astbury et al., 2018; Giordano and Caricchi, 2022) and glass trace element chemistry (Forni et al., 2018b). While there is overlap in the estimates between both eruptions, Astroni 6 estimates cluster towards lower temperatures and pressures whereas Minopoli 2 estimates are dominated by higher temperatures across a range of pressures, which suggests some differences in the dominant

storage conditions between the magmas feeding these eruptions. Minopoli 2 must have been fed by melts which ascended through the crust whilst remaining hot, possibly indicating rapid ascent as prolonged residence in the upper crust would lead to cooling and crystallisation, consistent with the higher Mg# of these crystals (Fig. A3.6). A similar interpretation was proposed by Giordano and Caricchi (2022) for Campi Flegrei based on the observation of minerals recording high temperatures and low pressures. In contrast, the low temperature Astroni 6 crystals imply magma cooling and crystallising in the crust, consistent with crystals sourced from a transcrustal magma-mush system and the lower Mg# of these crystals which support them crystallising from a more evolved magma (Fig. A3.6).

4.5.2 Geochemical variation between eruptions

The six main zoning textures identified in the studied clinopyroxenes were observed in both Minopoli 2 and Astroni 6, showing a complex pre-eruptive history for both eruptions. However, subtle differences in the proportions of each zoning texture suggest important differences in processes operating before each eruption. Both eruptions contain normally zoned crystals, indicative of progressive evolution of the melt during cooling and crystallisation. However, in Astroni 6 most normally zoned crystals have resorbed cores, suggestive of disequilibrium and attributed to magma recharge with more mafic cores transported to a felsic reservoir (Streck, 2008). In both eruptions, reverse zoned crystals commonly have resorbed cores, this may indicate the more felsic core grew in a relatively evolved and cool reservoir before being entrained within recharge of more mafic melt where the rim grew. Complex zoned crystals, observed in both eruptions, also demonstrate the prevalence of processes such as magma mixing and recharge forming multiple compositional zones in the crystal. This is distinct from oscillatory zoning, more common in Minopoli 2, which has been linked to fluctuations of intensive parameters such as pressure and temperature (Cashman and Blundy, 2000), variation in melt composition or varied growth rates (Streck, 2008; Ubide et al., 2019).

The compositions of some Astroni 6 clinopyroxenes overlap with Minopoli 2 crystals, but other Astroni 6 crystals form a distinct compositional group extending to lower Mg and Cr and high Na; this is predominantly from analyses of crystal rims suggesting these crystals may have resided in a relatively cooler and more evolved reservoir prior to eruption. In contrast, some Minopoli 2 crystals extend to higher Mg and Cr and lower Ca and Ti, these analyses are commonly from the cores of normally zoned crystals consistent with growth in a more mafic magma. The broad range of mineral compositions, combined with diverse crystal textures including those reflective of disequilibrium, supports a complex history involving magma mixing and recharge. This has been suggested previously for Campi Flegrei eruptions, for example by Tonarini et al. (2009) on the basis of variation in B, Sr, and Nd isotopic compositions from Astroni eruption products and Pellulo et al. (2022) on the basis of complex clinopyroxene zoning textures in the Agnano-Monte Spina eruption deposits.

4.5.3 Sr isotope variation

Variations in Sr isotopes measured in clinopyroxenes from both eruptions ($^{87}\text{Sr}/^{86}\text{Sr} = 0.703262\text{--}0.712579$) are much greater than previously measured in mineral separates from individual Campi Flegrei eruptions in the last 15 kyr. These studies generally analysed single or multiple crystals which were dissolved and analysed in bulk with reported $^{87}\text{Sr}/^{86}\text{Sr}$ variation from $\sim 0.706\text{--}0.708$ (de Vita et al., 1999; Tonarini et al., 2009; Di Vito et al., 2011; Arienzo et al., 2015, 2016; Iovine et al., 2018; Pelullo et al., 2022). Although, while Arienzo et al. (2015) analysed mostly single crystals, they also microdrilled sections of clinopyroxenes from Astroni 6, reporting $^{87}\text{Sr}/^{86}\text{Sr}$ varied $0.70600\text{--}0.70757$. Our in-situ analyses also vary significantly more than glass or whole rock analyses of eruptions in the last 15 kyr, which generally have $^{87}\text{Sr}/^{86}\text{Sr}$ between $0.7072\text{--}0.7086$ (e.g. Civetta et al., 1991; Pappalardo et al., 2002; Di Renzo et al., 2011; Di Vito et al., 2011). Minopoli 2 has the most radiogenic glass Sr-isotopic composition in the last 15 kyr (~ 0.708434 , Amstutz et al.,

submitted), whereas Astroni 6 has the least radiogenic (~ 0.707292 , Amstutz et al., submitted). Comparing to our in-situ crystal analyses, these glass values appear to represent an average of the Sr-isotope compositions observed in the crystals, with the full range of isotopic variation erased and the glass recording a homogenous composition. This is consistent with the findings of Arienzo et al. (2015) who showed that the whole-rock analyses of Astroni 6 reflects differing amounts of phenocrysts and glass with variable compositions, although they only recovered one isotopic composition per crystal and so did not observe the full range of isotopic compositions recorded here.

4.5.3.1 Evidence of unradiogenic mantle source feeding post-15 ka eruptions

Our lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values ($0.703262 - 0.705238$ in both Minopoli 2 and Astroni 6) are the least radiogenic values reported at Campi Flegrei and are similar to mantle-derived rocks (Hart et al., 1986). The isotopic composition of the mantle beneath the Phlegraean Volcanic District is not well characterised, largely due to a scarcity of mafic rocks, but previous studies have suggested that the post-NYT Campi Flegrei mantle source may be ubiquitously contaminated by subducted slab components which have enriched primary melt compositions relative to typical mantle values (D'Antonio et al., 2007; Mazzeo et al., 2014; Iovine et al., 2018). In contrast, these low values measured in our clinopyroxenes are comparable to the isotopic composition of high-Mg, K-basaltic lava lithics with near-primary geochemical features erupted from the Solchiaro eruption on nearby Procida, which have $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.705$ (D'Antonio et al., 1999a, 2007; De Astis et al., 2004) and have been suggested to provide an indication of the mantle composition. Our results indicate the Campi Flegrei mantle source cannot be ubiquitously contaminated as the clinopyroxenes preserve evidence of an uncontaminated mantle feeding eruptions throughout the last 15 kyr. The relative scarcity of these low $^{87}\text{Sr}/^{86}\text{Sr}$ values compared to more radiogenic values suggests that they either derive from isolated batches of unradiogenic magma and may not be

reflective of the dominant parental magma feeding the eruptions, or that subsequent magmatic evolution processes obscure primary melt compositions (Shorttle, 2015).

4.5.3.2 *Constraining the cause of Sr-isotope variation*

Previous studies have identified that Campi Flegrei isotopic heterogeneity in the last 15 kyr records mixing between compositionally distinct end-member magmas, which fed isotopically diverse eruptions before residing in the system and mixing to feed subsequent eruptions. The isotopic end-members have been characterised as the NYT residual melts, a new magma feeding Minopoli 2 and third discreet magma batch feeding Astroni 6 (D'Antonio et al., 1999b; Arienzo et al., 2010, 2015, 2016; Di Renzo et al., 2011). Distinct isotopic end-member magmas feeding Minopoli 2 and Astroni 6 is hard to reconcile with our in-situ results as the isotopic compositions recorded in clinopyroxenes from both eruptions cover similar ranges and do not display the distinct compositions that have been suggested previously. It is possible that the crystal cargoes from these eruptions includes antecrysts which resided in different locations within the sub-volcanic plumbing system before being entrained by isotopically distinct carrier melts feeding each eruption. However, the variability is observed in measurements from crystals of all zoning populations, including normal and unzoned crystals which are indicative of autocrysts (Zellmer, 2021).

The source of this isotopic variation remains largely unconstrained but has been previously attributed to mantle source heterogeneity (Iovine et al., 2018) or assimilation of sub-volcanic rocks with heterogeneous isotopic compositions (e.g. Pappalardo et al., 2002; D'Antonio et al., 2007; Di Renzo et al., 2011; Amstutz et al., submitted). On the basis of the relatively short length and timescales (~4 km and 6 ka) between Minopoli 2 and Astroni 6, shorter than has previously been reported for heterogeneity in arcs (Kelemen et al., 2003; Anderson, 2006), we rule out a primary mantle origin for the observed isotopic variation. This is supported by the overlapping $^{87}\text{Sr}/^{86}\text{Sr}$ isotope compositions between clinopyroxenes in the two eruptions which is not consistent with different mantle end-members and supports

Campi Flegrei melts ascending through a complex vertically-extensive magma system within the continental crust (Giordano and Caricchi, 2022) which would act to homogenise signals of primary mantle heterogeneity (Shorttle, 2015). Instead, the observed isotopic diversity is consistent with assimilation of surrounding basement rock. Crustal contaminants suggested by previous studies to contaminate Campi Flegrei magmas include Palaeozoic metamorphic basement, intrusive syenitic residue from past eruptions, arenaceous sediments or wedge-top basin sequences (e.g. Pappalardo et al., 2002; D'Antonio et al., 2007; Di Renzo et al., 2011; Amstutz et al., submitted). Based on its radiogenic Sr-isotope composition ($\sim 0.710 - 0.723$, Rottura et al., 1991; Pappalardo et al., 2002, Amstutz et al., submitted) the Palaeozoic metamorphic basement would be capable of increasing the melt isotopic composition to the radiogenic values ($0.710972 - 0.712579$) observed in the clinopyroxenes. This contaminant has been suggested by other authors based on its isotopic (Pappalardo et al., 2002; Amstutz et al., submitted) and major element (Amstutz et al., in press) variation. Restitic syenite, suggested by Amstutz et al. (submitted) to contaminate the Astroni 6 eruption based on glass isotopic variation is also likely, but as the Sr-isotope composition of the syenite (~ 0.7084) overlaps with our measured clinopyroxene isotopic compositions any assimilation would be difficult to detect.

4.5.4 Coupled trace element and isotopic variation

Further insights into magma history are provided by examining transects across individual clinopyroxene crystals, where variability in trace elements and Sr-isotopes record the differing conditions experienced by the crystal during growth and reveal complex histories.

We compare Sr-isotope variation against Cr concentration across crystals, using Cr as an index of differentiation. In Campi Flegrei melts, chromium is compatible (Villemant, 1988) and chromium-bearing minerals such as clinopyroxene and spinel-group minerals crystallise early (Fowler et al., 2007; Amstutz et al., in press) meaning high Cr concentrations correspond to more mafic melt and Cr concentrations decrease as the melt evolves. This is

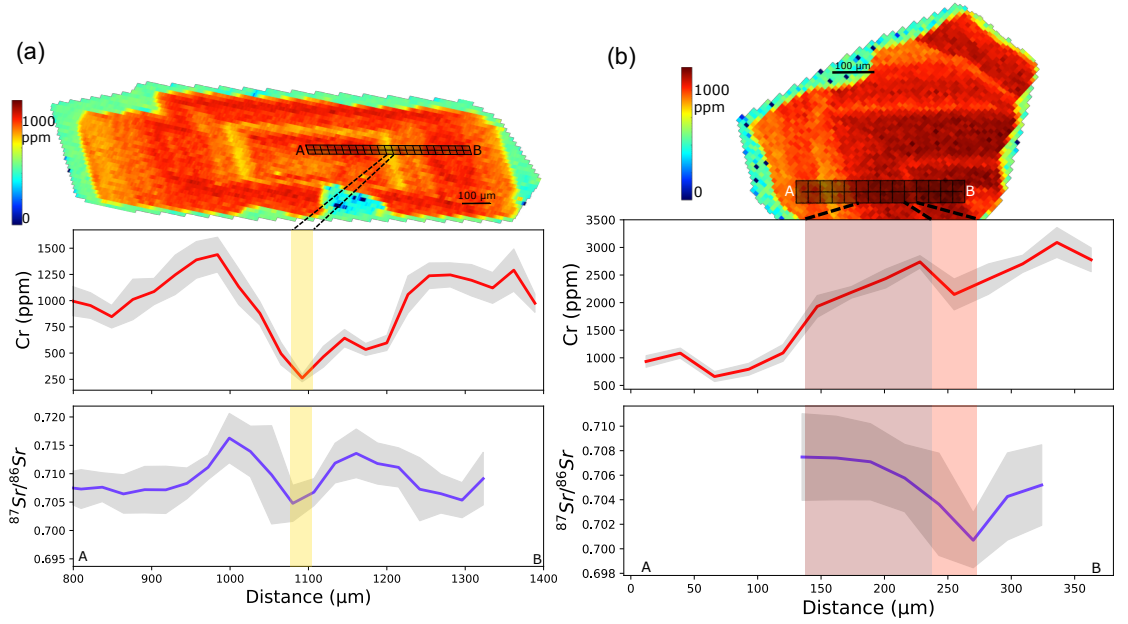


Figure 4.6: Chromium trace element maps of selected clinopyroxenes showing Cr and Sr-isotope variation across the crystal. $^{87}\text{Sr}/^{86}\text{Sr}$ variation was measured on core-to-rim transects across the crystal. Chromium concentrations were extracted from trace element maps of the crystal, following the same transect used in isotopic analysis. Zones identified in the Cr element maps are indicated on the plots by coloured bars. The 9-rolling mean of $^{87}\text{Sr}/^{86}\text{Sr}$ measurements are plotted, with the grey region on the plots represents 2σ uncertainties on the measurements. (a) shows a complex zoned clinopyroxene and (b) shows an oscillatory zoned crystal, both from Minopoli 2. Other measured crystals are showing in Fig. A3.7.

similar to the approach of Ubide and Kamber (2018), who associated Cr-rich zones in clinopyroxenes with mafic recharge triggering eruptions at Mt Etna. Increases in Cr in the clinopyroxenes correlates with increases in other compatible elements, such as Sc and Ni, and decreased concentrations of incompatible elements, such as La, Y and Nd (Fig. A3.5). Therefore, the crystal transects provide a record of both magma evolution and recharge events (on the basis of Cr concentration) as well as contamination with Palaeozoic metamorphic basement (based on variations in Sr-isotopes, Fig. 4.6). These transects show varying trends in Cr and $^{87}\text{Sr}/^{86}\text{Sr}$, representative transects are shown in Fig. 4.6 with all transects in Fig. A3.7. These trends are discussed in turn below and summarised in Fig. 4.7.

4.5.4.1 Fractional crystallisation

In some crystals (e.g. CF9 cpx 62, Fig. A3.7), Cr concentrations gradually decrease from the core to the rim of the crystal whilst Sr-isotope values remain similar. This trend implies the crystal grew during fractional crystallisation of the melt; Cr contents would decrease as the

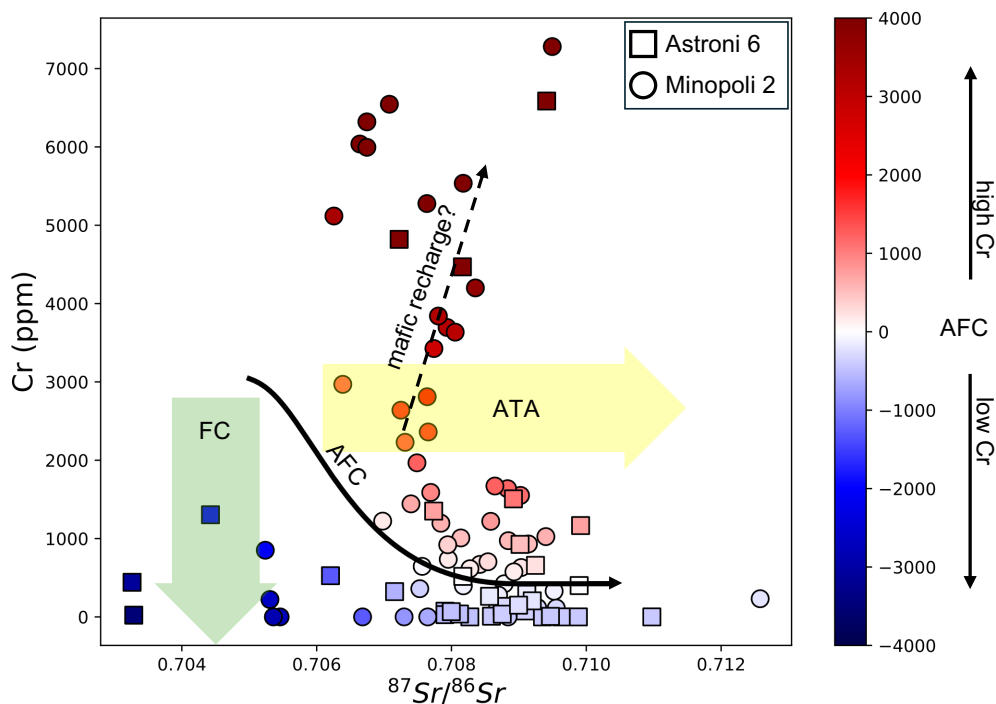


Figure 4.7: Cr and Sr-isotope measurements from Astroni 6 (squares) and Minopoli 2 (circles) clinopyroxenes, coloured by the distance of each point from the assimilation fractional crystallisation model shown by the black line. Pale colours indicate Cr and Sr isotope compositions consistent with AFC, colours towards red indicate Cr is higher than would be consistent with AFC and colours towards blue indicate Cr is lower. AFC modelled using the EC-AFC model of Spera and Bohrsen (2001), with Cr and $^{87}\text{Sr}/^{86}\text{Sr}$ compositions from the Solchiaro eruption of Procida (De Astis et al., 2004) as the starting composition of the model and Palaeozoic metamorphic basement as the assimilant, parameters are given in Table A3.8. Arrows also indicate the expected trends for evolution by fractional crystallisation (FC), assimilation during turbulent ascent (ATA) and mafic recharge.

melt becomes more evolved, but Sr-isotopes are unaffected by fractionation and so would remain the same. Most analyses consistent with this trend are from Astroni 6 (Fig. 4.7), where lower Cr concentration suggests the clinopyroxenes grew within evolved melt.

4.5.4.2 Assimilation-fractional crystallisation

In some crystal zones, Sr-isotopes increase towards more radiogenic values whilst the Cr concentration decreases, illustrated in the narrow felsic zone of the oscillatory zoned Minopoli 2 crystal in Fig. 4.6b. This contrasts with the first trend: the decrease in Cr observed here also reflects the cooling and crystallisation of the melt, but Sr-isotopes increase simultaneously implying assimilation of material with more radiogenic Sr isotope composition. This is indicative of assimilation-fractional crystallisation (AFC), where country rock is progressively assimilated as the melt cools, crystallises and evolves

(DePaolo, 1981). In general, most analyses from Astroni 6 have Cr and $^{87}\text{Sr}/^{86}\text{Sr}$ compositions consistent with magma evolution by either AFC or FC (Fig. 4.7).

4.5.4.3 *Assimilation during turbulent ascent*

A third relationship, observed in Minopoli 2 clinopyroxenes (Fig. 4.7), is defined by both Cr and $^{87}\text{Sr}/^{86}\text{Sr}$ values increasing together, for example in Fig. 4.6a where both $^{87}\text{Sr}/^{86}\text{Sr}$ and Cr increase from the centre of the core outwards towards the narrow euhedral zone around the core. This relationship is inconsistent with AFC because Cr concentrations are high, the opposite of the expected trend during evolution of the melt. This relationship between Cr concentration and Sr-isotope composition implies assimilation of country rock is happening within a mafic melt, decoupled from cooling and crystallisation. We suggest instead these zones record periods of contamination during turbulent ascent of mafic magma (termed Assimilation during Turbulent Ascent – ATA; Moorbath and Thompson, 1980; Huppert and Sparks, 1985). This process has been identified in tectonically diverse magmatic provinces globally, causing crustal assimilation over relatively short timescales and the most mafic magmas within a system to become the most contaminated (e.g. Central Andes, Chile - González-Maurel et al., 2019; Mull, Scotland - Kerr et al., 1995; Puna Plateau, Argentina - Maro et al., 2017; Aeolian arc, Italy - Peccerillo et al., 2004) and has been suggested to explain the glass isotopic composition of Minopoli 2 magmas previously (Amstutz et al., submitted). It is also possible that this trend reflects input from an enriched mantle source, modified by fluids or sediments from the subducted slab which alter the Sr-isotope composition, as has been suggested previously for melts feeding Campi Flegrei eruptions (e.g. Mazzeo et al., 2014; Iovine et al., 2018). However, the calculated increase in Sr-isotope composition from subduction-derived components suggests mantle melts would reach $^{87}\text{Sr}/^{86}\text{Sr}$ of ~ 0.7075 (Iovine et al., 2018), much lower than observed in some of the clinopyroxene zones. In addition, the length and timescales covered by these eruptions are much shorter than previously suggested for variable enrichment of the mantle source

(Kelemen et al., 2003; Gibson et al., 2012); our results are instead consistent with assimilation of radiogenic country rock.

4.5.4.4 Magma mixing

In some zones, both Cr and $^{87}\text{Sr}/^{86}\text{Sr}$ decrease simultaneously (Fig. 4.6a). These zones are unlikely to be related to assimilation processes, as these typically act to increase $^{87}\text{Sr}/^{86}\text{Sr}$ to more radiogenic values (DePaolo, 1981). Decreasing Cr concentration is expected with melt cooling, crystallising and becoming more evolved, but this would not affect Sr isotope values. Instead, this trend is consistent with mixing of melts, between a more mafic and contaminated melt and one which is more evolved but has not been affected by crustal contamination, leading to both Cr and $^{87}\text{Sr}/^{86}\text{Sr}$ decreasing as the mixing progresses. A significant subset of Minopoli 2 clinopyroxenes deviate towards high Cr concentrations,

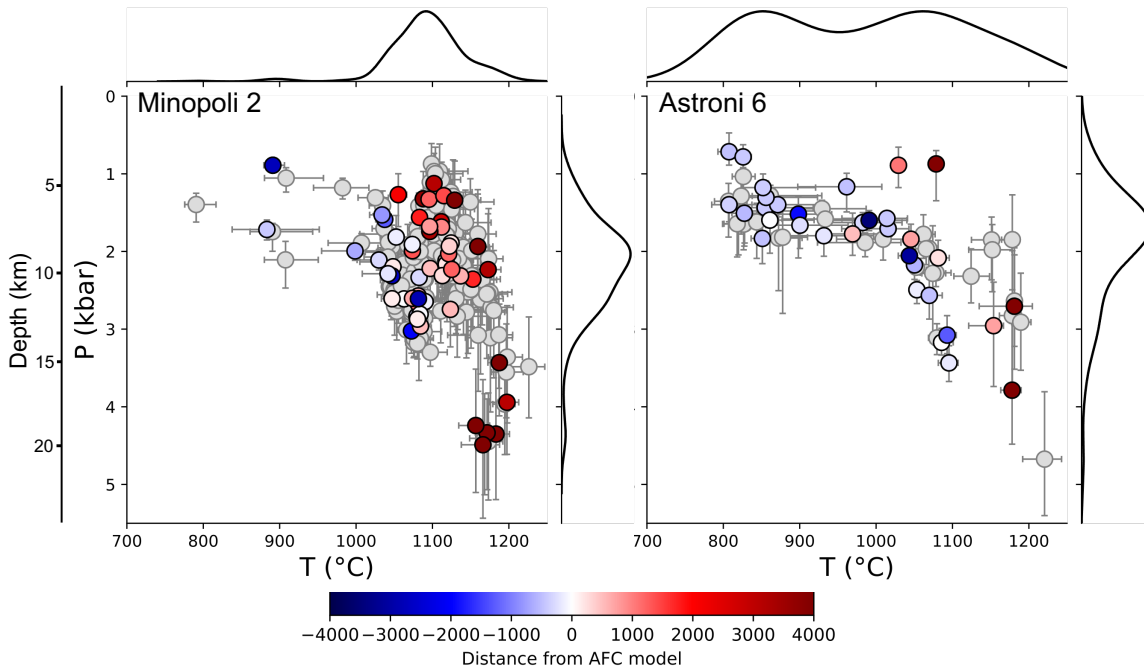


Figure 4.8: Temperature and pressure estimates from Minopoli 2 and Astroni 6 clinopyroxene analyses calculated using the machine learning thermobarometer of Ágreda-López et al. (2024). Root mean square errors for the thermobarometer are 56°C and 2.5 kbar, error bars shown in the plot represent 2σ errors resulting from analytical uncertainty. Pressure estimates have been converted to depth assuming crustal density of 2.3 g/cm³ from Rosi and Sbrana (1987). Where estimates of pressure and temperature have an associated Sr-isotope composition, these are coloured as in Fig. 4.7, based on the distance from the modelled AFC trend.

indicative of recharge with a mafic, high-Cr magma (Figs. 4.7, 4.8); this process is rarely observed in Astroni 6 crystals. Mixing and mingling of different magma batches has been frequently proposed to explain the isotopic and geochemical features of Campi Flegrei eruptions in the last 15 kyr (e.g. Tonarini et al., 2009; Fourmentaux et al., 2012; Pelullo et al., 2022), our results demonstrate that this process has also been preserved within clinopyroxenes growing from these melts.

4.5.5 Insights into the Campi Flegrei sub-volcanic plumbing system

Combining constraints on temperatures and pressures of clinopyroxene growth with Sr isotopes provides insights into the magma plumbing system. Strontium isotope composition is not correlated with temperature, pressure, or evolution of the melt (Fig. 4.5b-d), supporting the interpretation that these crystals did not all experience a simple history of cooling, crystallisation and assimilation during ascent through the crust, which would lead to a negative correlation between these parameters.

Changes in the isotopic composition of magmas feeding the reservoir over time could lead to the diversity of observed isotopic compositions, but it is difficult to reconcile the varied Sr isotope values measured in cores and rims of crystals from both eruptions with magma becoming progressively more or less radiogenic over time. Instead, we envisage a complex sub-volcanic plumbing system with compositionally heterogeneous reservoirs which mix and mingle to feed post-15 ka Campi Flegrei eruptions (Fig. 4.9). Within these reservoirs, magmas ascend and become contaminated with Palaeozoic metamorphic basement, during both AFC and ATA. These reservoirs exist within a crustal scale mush zone beneath Campi Flegrei which likely formed over long time periods as repeated episodes of sill injection and crystallisation formed a network of stacked sills (Annen et al., 2006; Jackson et al., 2018). During the >300ka history of activity, ascending magmas likely assimilated surrounding country rock in the region. However, the Sr-isotopes in clinopyroxenes presented here demonstrate that magmas feeding recent Campi Flegrei

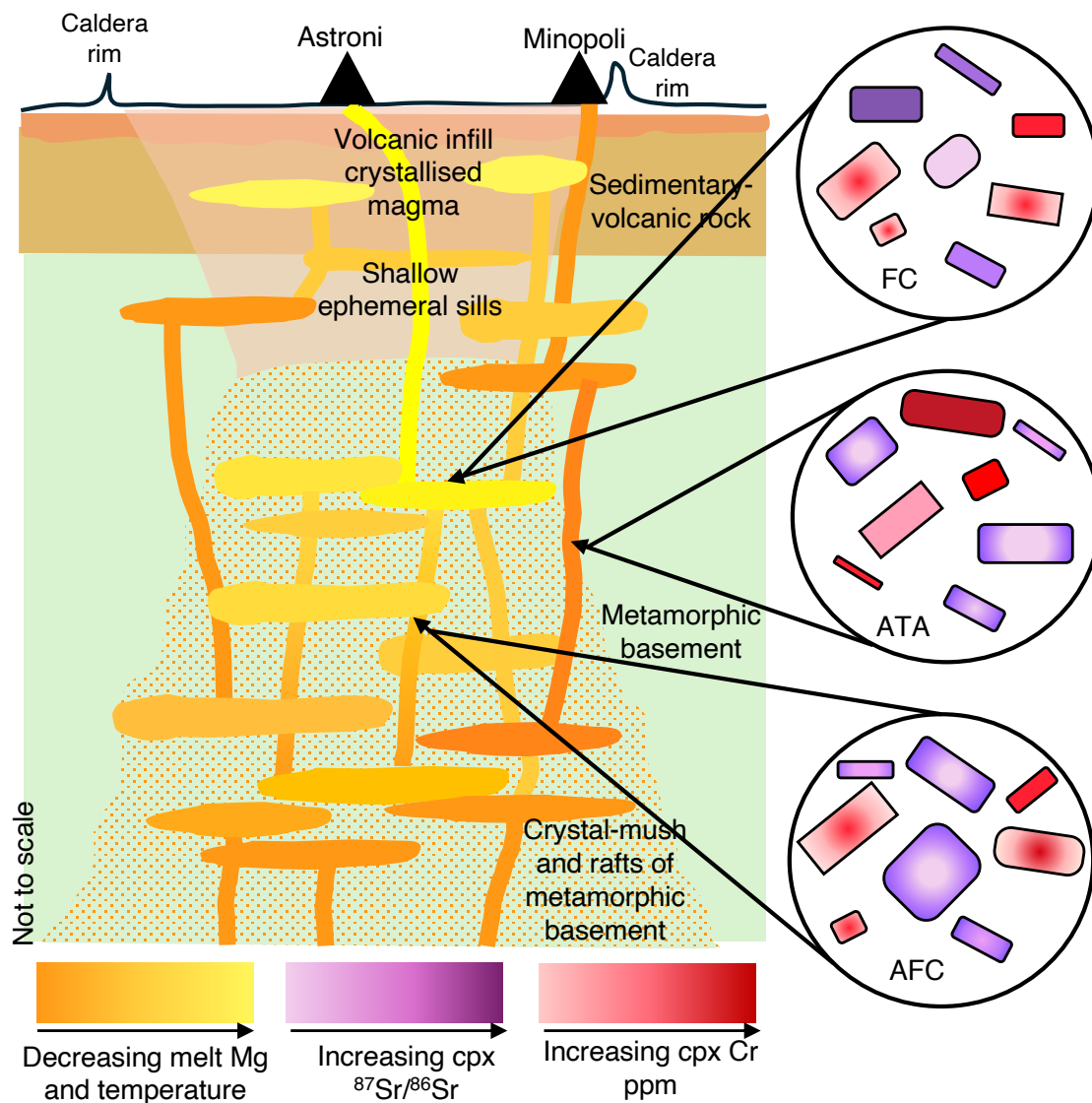


Figure 4.9: Summary schematic of Campi Flegrei sub-volcanic plumbing system. The evolution of crystal Cr and Sr-isotope compositions as a result of assimilation of Palaeozoic metamorphic basement and fractional crystallisation during magma evolution is indicated with separate colour scales. Stacked sills are coloured from dark to pale orange/yellow representing magma cooling and evolution, crystals are coloured from pale to dark purple to indicate increasing $^{87}\text{Sr}/^{86}\text{Sr}$ and from pale to dark red to indicate increasing Cr concentration. During FC, Cr concentrations decrease whilst $^{87}\text{Sr}/^{86}\text{Sr}$ values remain constant (but varied) from the core to rim of a clinopyroxene; during AFC Cr concentrations decrease whilst $^{87}\text{Sr}/^{86}\text{Sr}$ values increase from core to rim and during ATA Cr concentrations remain constant (but varied) while $^{87}\text{Sr}/^{86}\text{Sr}$ values become more radiogenic from core to rim. The location of the Minopoli 2 vent on the caldera rim faults and the Astroni 6 vent in the central caldera is indicated. Not to scale.

eruptions also interacted with country rock. This shows some basement rock must remain alongside restitic magma residue, preserved as selvages or rafts between melt and mush layers. Ascending magmas can assimilate these to varying extents, but geophysical techniques such as magnetotelluric imaging have insufficient spatial resolution to resolve small volumes of melt and remnant country rock within the mush. Some magmas also cool and crystallise without assimilating crustal material, presumably evolving in parts of the magma system where they are surrounded by mush and unable to interact with the basement. The Minopoli 2 and Astroni 6 eruptions sample crystals which formed across all these environments, but in different proportions (Fig. 4.8), likely related to the different tectonic settings of each vent. Minopoli 2 erupted from a vent on the NYT caldera rim fault (Bevilacqua et al., 2015); these ring faults likely provide pathways for mafic magma to ascend to the surface (Cole et al., 2005), assimilating material through ATA. The Astroni 6 vent is in the centre of the caldera, away from major fault systems (Vitale and Isaia, 2014), where ascent of mafic recharge magma was likely stalled by the well-developed magmatic system (Galetto et al., 2017) and the eruption was primarily fed by magma which evolved within this reservoir. This agrees with Amstutz et al. (submitted) who proposed the volcano-tectonic setting of post-15 ka Campi Flegrei eruption vents affected magma evolution on the basis of glass major element and isotopic variations.

4.6 Conclusions

We have shown that clinopyroxene crystals from two recent eruptions of Campi Flegrei record complex magmatic histories. Varied crystal textures and major element compositions attest to processes including magma mixing, recharge of mafic magma and recycling of old crystals into carrier liquids. Comparison with trace element maps of these crystals provide high resolution records of these processes, often revealing detailed zoning patterns not seen in major element variation alone. The wide range of Sr isotopes measured in these crystals also attests to country rock assimilation, likely Palaeozoic metamorphic basement based on

its radiogenic isotopic composition. Measurement of low Sr isotope values ($^{87}\text{Sr}/^{86}\text{Sr} < 0.705$) suggests the mantle source beneath Campi Flegrei is not ubiquitously enriched as has been suggested previously (Mazzeo et al., 2014; Iovine et al., 2018).

Combining trace element (Cr) variations with Sr isotope transects provides novel details regarding processes operating during the growth of individual crystals, extending the information obtainable from trace element maps or bulk rock isotopic measurements in isolation. This method reveals magmas evolving through FC, AFC and ATA, with mafic recharge and mixing of magmas, in agreement with previous studies (Tonarini et al., 2009; Arienzo et al., 2010, 2015, 2016; Di Renzo et al., 2011; Voloschina et al., 2018). Combined with thermobarometry which indicates transcristal magma storage, this approach allows us to reconstruct the histories of individual crystals and reveal a complex sub-volcanic plumbing system feeding the Minopoli 2 and Astroni 6 eruptions. These eruptions are unlikely to be unique amongst post-15 ka Campi Flegrei eruptions, and hence our results provide important insights into the storage and evolution of magmas beneath the volcano.

Acknowledgements

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5. Conclusions

5.1 Summary

This thesis has explored magmatic evolution at Campi Flegrei in the last 15 kyr, focussing on the links between the volcano-tectonic setting of eruption vents and pre-eruptive processes. Through a combination of modelling and geochemical analysis, it provides new insights into the architecture of the sub-volcanic magmatic system.

Firstly, we divided eruptions into three groups based on volcano-tectonic setting. The eruption groups comprise: northern/eastern caldera eruptions along caldera rim faults in the northern and eastern sectors of the caldera, which were either formed or reactivated during the NYT collapse and strike obliquely to the regional lineaments; western caldera eruptions aligned with caldera rim faults and regional tectonic fault systems in the west of the caldera characterised by a different orientation pattern of faults and fractures compared to those in the eastern sector (Vitale and Isaia, 2014); and central caldera eruptions which are not located along major pre-existing planes of crustal weakness (Di Vito *et al.*, 1999; Isaia *et al.*, 2009; Bevilacqua *et al.*, 2015; Natale *et al.*, 2022b).

We used thermodynamic modelling to investigate the variety of major element compositions of Campi Flegrei erupted products in the last 15 kyr, comparing between the three volcano-tectonic groups. Whilst variation in erupted composition across the caldera has been noted by other authors (D'Antonio *et al.*, 1999b; Smith *et al.*, 2011), the causes of this variation were not well constrained and eruptions were previously considered either separately (e.g. Cannatelli *et al.*, 2007; Arienzo *et al.*, 2015, 2016) or on a broad scale (e.g. over long time periods - Pappalardo *et al.*, 2002; or large areas - Iovine *et al.*, 2018). Initially, we tested whether fractional crystallisation of a single parental magma was able to reproduce the compositional variation observed in glass major element data. We developed a Python

script to batch run Rhyolite-MELTS models across a matrix of different pressures, initial oxygen fugacity and initial water contents. We then built on the statistical model of Gleeson *et al.* (2017) to quantitatively compare each model to the literature glass data. These measurements of root mean square error enabled us to evaluate which combination of intensive parameters best reproduced the natural glass data. These best-fit storage conditions varied depending on the volcano-tectonic group of the eruptions, for example those in the

centre of the caldera likely had higher initial water contents (3 wt% compared to 2 wt% in other settings). However, some of the major element variation was not explained by any fractional crystallisation models, leading us to test Rhyolite-MELTS models of assimilation fractional crystallisation. Using the same statistical measure, we found adding an assimilant improved the goodness-of-fit between our models and natural glass data. The best-fit assimilant composition varied between volcano-tectonic group: for eruptions with vents along caldera rim faults in the north-eastern caldera, the glass major element composition was best reproduced by addition of small amounts (5-10%) of Palaeozoic metamorphic basement, whereas compositions of eruptions in the central and western caldera were best reproduced by adding up to 30% syenite, representative of the crystalline remnants of previous eruptions. This represents a significant amount of assimilation but is likely made possible by the elevated thermal state of the crust. Modelling of the thermodynamic limits of assimilation has shown these high percentages of assimilation are feasible especially in crust which has been pre-heated by earlier magma pulses or has an otherwise anomalously steep geotherm (Heinonen *et al.*, 2021). At Campi Flegrei, repeated magma injection has occurred over an extended period (>300 ka; De Vivo *et al.*, 2001) and measurements of the geothermal gradient from deep wells shows it exceeds 150 °C km⁻¹ beneath the caldera (Carlino, 2018), providing the conditions necessary to permit high percentages of assimilation.

To further constrain the effect of assimilation of country rock on post-15 ka eruptions, we investigated the isotopic composition of a selection of eruptions representative of all three volcano-tectonic groups defined in the previous chapter. We measured stable (O-) and radiogenic (Sr-, Nd- and Pb-) isotopic compositions in glass and mineral separates from these eruptions, as well as from samples of potential crustal contaminants. We found significant variation in isotopic composition between eruptions, which correlated with their volcano-tectonic setting. Eruptions from vents associated with caldera rim faults in the north-eastern caldera had the most crust-like isotopic compositions, compared to those in the centre and west of the caldera which were more mantle-like. Using the isotopic compositions of the potential crustal contaminants, we modelled assimilation processes, and found eruptions with more crust-like isotopic compositions are consistent with assimilation of Palaeozoic metamorphic basement, whereas the more mantle-like compositions were likely affected by contamination with syenitic restite. We identified two eruptions, Astroni 6 and Minopoli 2, which represented the end-members of these contrasting isotopic compositions, in agreement with previous studies (e.g. Arienzo *et al.*, 2010, 2015, 2016; Di Renzo *et al.*, 2011). Interestingly, Sr- and Nd- isotopic compositions most clearly demonstrated the inter-eruption variation. The variation in Pb- isotopes was much smaller, possibly because the concentration of Pb in the crustal contaminants was low and so assimilation would not have much effect on isotopic composition. Oxygen isotopic compositions showed considerable variation which we attribute primarily to interaction with meteoric water, with assimilation processes harder to recognise. This includes both low and high temperature alteration, attesting to a well-developed hydrothermal system which has persisted in the last 15 kyr and variably altered the basement material.

We used clinopyroxenes from the two eruptions identified as end-members based on isotopic composition (Astroni 6 and Minopoli 2) to investigate magma evolution recorded in individual crystals. We found that the crystals recorded complex magmatic histories, the

full extent of which was only revealed by combining compositional and isotopic analysis. These attest to processes including magma mixing, recharge of mafic magma, and assimilation of country rock. Assimilation happened both concurrently with magma evolution and decoupled, likely during turbulent ascent of mafic magma. Combining compositional analysis with thermobarometry indicates these processes were occurring in a transcrustal magma system, where melts both ascended hot and were stored, cooling and crystallising in the crust.

Overall, this thesis has found a strong volcano-tectonic control on magmatic evolution and revealed a complex sub-volcanic plumbing system feeding eruptions in the past 15 kyr. This system likely had compositionally heterogeneous reservoirs which mixed and mingled to feed post-15 ka eruptions. Within these reservoirs, magmas become contaminated with Palaeozoic metamorphic basement, as well as syenite which represents the crystalline residue of past eruptions. This contamination occurs both during cooling and crystallisation, but also during turbulent ascent of mafic material. Caldera rim faults, formed or reactivated during the NYT caldera collapse and striking obliquely to the regional lineaments, provide a pathway for ascending magmas to exploit, leading to the distinct, mafic and radiogenic composition of eruptions from vents located along them. In contrast, eruptions from the central caldera are away from major structural lineaments and are fed from the vertically extensive magmatic system, recently imaged by magnetotelluric surveys (Isaia *et al.*, 2025) and previously suggested based on barometry and volatile constraints (e.g. Vetere *et al.*, 2011; Stock *et al.*, 2018; Giordano and Caricchi, 2022; Balcone-Boissard *et al.*, 2024). Here, whilst some magma is also contaminated by the metamorphic basement, some evolved within the residue of past eruptions before mixing with ascending melts. The location of vents in relation to structural features is an important factor in magmatic evolution; pre-existing structures such as the caldera rim faults provide both pathways for magma ascent and exposure to surrounding basement rock, whereas away from these

features magmas appear more isolated from the basement, evolving within syenitic restite. The spatial variation in pre-eruptive processes identified here is likely not unique to Campi Flegrei, and the approaches used in this study could be applied to investigate other long-lived caldera systems, discussed in more detail below. As assimilation affects the compositional evolution of magmas, which in turn influences the magma's physical properties and eruption style (Cassidy *et al.*, 2018), this study highlights the importance of vent location which should be considered in hazard forecasting.

5.2 Future research directions

This work reveals several new avenues for future research, both at Campi Flegrei and other volcanic systems worldwide.

The results presented in this thesis place constraints on processes influencing magma evolution at Campi Flegrei in the last 15 kyr, and how these processes vary spatially across the caldera as a result of different structural settings. Currently, Campi Flegrei is showing significant signs of unrest, including frequent seismic swarms (Giudicepietro *et al.*, 2025), accelerating ground uplift totalling ~1.2 m since 2005 (Bevilacqua *et al.*, 2024), and increasing gas emissions (Cardellini *et al.*, 2017). This year (2025), seismic swarms continued, culminating in several earthquakes > 4 magnitude (Ricciolino *et al.*, 2024). This recent unrest is concentrated in the central caldera, particularly the Solfatara-Pisciarelli region, where uplift, degassing and shallow seismicity are focused. However, a magmatic or hydrothermal source of this unrest remains debated (Gottsmann *et al.*, 2006; Troise *et al.*, 2019). Whilst petrological studies can only reconstruct past eruptive behaviour, integrating petrological insights with monitoring data is a valuable tool for interpreting ongoing unrest and improving hazard assessment, as demonstrated at other active systems (e.g. Blundy and Cashman, 2008; Saunders *et al.*, 2012; Longpré *et al.*, 2025). At Campi Flegrei, this approach is challenging as Monte Nuovo is the only historical eruptions with well-documented pre-eruptive unrest (Di Vito *et al.*, 1987). Nonetheless, efforts to correlate

current geophysical signals with petrological constraints remain crucial, with this study highlighting the importance of the location of future vents in terms of volcano-tectonic setting.

In Chapter 4, I described a combination of methods used to investigate magmatic history at the crystal scale, showing the powerful insights it is possible to gain from individual crystals. This approach could be developed further by combination with diffusion chronometry. This technique has already been combined with trace element mapping, for example by Ubide and Kamber (2018) who used it to constrain timescales of mafic recharge and eruption in clinopyroxenes from Mt Etna. It has also been used in limited studies at Campi Flegrei, where recharge-to-eruption timescales were investigated using barium diffusion in sanidine phenocrysts (Iovine *et al.*, 2017, 2025), and Fe-Mg diffusion in clinopyroxene crystals (Pelullo *et al.*, 2022). Incorporating diffusion chronometry into future crystal-scale investigations would allow integration of the depths and timescales of pre-eruptive processes, which would build a more comprehensive picture of the sub-volcanic plumbing system as well as providing important information for the interpretation of monitoring data. In addition, thermobarometry was conducted using EPMA spot analyses, constraining the pressure of crystallisation in discrete zones of each crystal. However, collecting fully quantitative major element maps via LA-ICP-MS raises the possibility of producing pressure-temperature crystal maps by inputting this data into a thermobarometer. This would make it possible to directly link processes such as assimilation (observed in isotopic analysis) and magma mixing (from textural features) to the pressure and temperature conditions they were occurring at. A further consideration is that in this study, I looked exclusively at clinopyroxene crystals, chosen because they crystallise across a reasonably large range of pressures and temperatures at Campi Flegrei (Fowler *et al.*, 2007; Amstutz *et al.*, in press) and elemental diffusion is slow (Dosseto *et al.*, 2010; Müller *et al.*, 2013) so they potentially preserve protracted histories. However, further work should consider

studying other mineral phases, such as plagioclase, which has already been used extensively to investigate in-situ Sr isotopes at other systems (e.g. recently at Toba, Indonesia - Gao *et al.*, 2025 and Stromboli, Italy - Schiavon *et al.*, 2025). Plagioclase is also likely to continue crystallising towards more evolved, cooler temperatures (Fowler *et al.*, 2007; Amstutz *et al.*, in press) which may provide crucial information on the most evolved (and likely shallowest, assuming a normal geothermal gradient) part of the system which may not be captured in the records of clinopyroxenes.

The link between volcano-tectonic setting and vent location has been well-documented at a variety of caldera systems, with post-collapse eruptions typically occurring in different spatial locations (Lipman, 2000; Robertson *et al.*, 2016; Pérez-Orozco *et al.*, 2021). However, the link between the volcano-tectonic setting of individual eruption vents and sub-volcanic processes, shown by this study to be an important relationship, has not previously been investigated thoroughly. This could be explored at many other caldera systems worldwide, for example at Santorini, Greece, another example of long-lived and currently restless caldera system (Druitt *et al.*, 1999). Throughout its history, it has erupted magmas of a range of compositions and eruption locations have been linked to faulting and stress fields (Bailey *et al.*, 2009; Andújar *et al.*, 2016; Flaherty *et al.*, 2022), but the relationship between these structural settings and erupted compositions is not well constrained. Similarly, caldera centres within the Taupō Volcanic Zone, New Zealand, have produced basaltic to rhyolitic eruptions throughout a 1.6 Ma history (Wilson *et al.*, 2009), with vent location closely linked to regional faulting and structural lineaments (Wilson *et al.*, 1984). Investigations into magma evolution at these and other caldera systems may benefit from consideration of the control exerted by varying volcano-tectonic settings, constraining variation in pre-eruptive processes across the caldera and providing important information for the interpretation of monitoring data.

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Appendix 1

Supplementary material for Chapter 2

Primary standards for EPMA calibration	
Silicon	Wollastonite
Calcium	Wollastonite
Sodium	Jadeite
Aluminium	Jadeite
Iron	Haematite
Titanium	Rutile
Manganese	Fowlerite
Magnesium	Periclase
Potassium	Orthoclase
Phosphorus	TbPO ₄
Chlorine	BaFCl

Table A1.1: List of standards used for calibration of EPMA.

EPMA secondary standard reproducibility						
	StHs6/80-G		ATHO-G		GOR132-G	
	wt%	1 σ	wt%	1 σ	wt%	1 σ
SiO ₂	63.63	0.28	75.66	0.28	45.52	0.11
Na ₂ O	4.51	0.08	3.93	0.54	0.83	0.07
MgO	1.96	0.05	0.10	0.02	22.76	0.37
Al ₂ O ₃	17.65	0.15	12.30	0.11	11.00	0.09
P ₂ O ₅	0.11	0.04	-	-	-	-
K ₂ O	1.27	0.03	2.66	0.04	0.03	0.01
CaO	5.28	0.06	1.68	0.03	8.56	0.08
TiO ₂	0.71	0.02	0.24	0.02	0.30	0.03
MnO	0.08	0.02	0.10	0.02	0.16	0.02
FeO _t	4.38	0.09	3.23	0.06	10.23	0.11
Cl	-	-	0.03	0.01	-	-
Total	99.23		99.83		99.26	
n	24		23		25	

Table A1.2: Compositions of secondary standards used in EPMA. Independent characterisation of these standards can be found in Jochum *et al.* (2006). Precision estimates are given as one standard deviation of multiple analyses (1 σ). n= number of repeat analyses.

XRF secondary standard reproducibility – major elements						
	GSJ JB-1b		GSJ JA-1a		GSJ JR-1	
	wt%	1 σ	wt%	1 σ	wt%	1 σ
Al ₂ O ₃	14.14	0.07	15.48	0.05	12.74	0.02
CaO	9.43	0.05	5.70	0.01	0.68	0.00
Fe ₂ O ₃	8.92	0.05	7.12	0.02	0.86	0.01
K ₂ O	1.28	0.01	0.78	0.01	4.40	0.01
MgO	8.38	0.07	1.50	0.00	0.11	0.00
MnO	0.15	0.00	0.17	0.00	0.10	0.00
Na ₂ O	2.60	0.02	3.90	0.05	4.01	0.01
P ₂ O ₅	0.26	0.00	0.17	0.00	0.02	0.00
SiO ₂	51.37	0.24	63.58	0.13	75.19	0.07
TiO ₂	1.23	0.01	0.86	0.00	0.11	0.00
n	11		13		7	
XRF secondary standard reproducibility – trace elements						
	GSJ JB-1b		GSJ Ja-1a		GSJ JR-1	
	ppm	1 σ	ppm	1 σ	ppm	1 σ
As	3.9	0.3	4.6	0.6	13.4	0.3
Ba	626.6	4.5	359.0	3.4	8.2	2.5
Ce	71.7	1.6	11.7	2.3	46.4	1.6
Co	38.0	1.1	12.3	0.5	0.1	0.3
Cr	448.0	2.5	2.4	1.6	-	-
Cs	3.5	3.4	-	-	19.4	3.3
Cu	52.2	0.7	44.2	0.8	4.8	0.5
Ga	18.5	0.3	18.3	0.2	16.2	0.4
Hf	2.8	0.6	3.1	1.3	4.8	1.3
La	44.1	0.9	7.1	0.7	19.5	0.5
Mn	1096.0	17.9	1203.1	13.5	740.1	18.6
Nb	22.7	0.4	2.8	0.4	18.4	0.0
Nd	25.3	0.7	8.7	0.9	22.4	1.9
Ni	147.0	2.5	1.0	0.2	2.6	0.3
Pb	3.9	0.2	5.8	0.8	19.1	0.3
Rb	39.8	0.9	15.4	0.9	254.2	4.0
Sb	-	-	-	-	1.4	0.5
Sc	24.3	1.0	30.1	1.9	5.2	1.0
Sm	6.4	1.4	4.0	2.4	5.9	1.0
Sn	1.6		1.5	0.3	3.9	0.6
Sr	444.4	7.5	273.5	5.2	28.0	0.9
Th	8.2	1.9	2.7	1.6	30.6	1.7
TiO ₂	12635.9	125.6	8820.1	125.3	989.4	16.5
Tl	-	-	-	-	-	-
U	1.5	0.3	-	-	9.2	0.1
V	212.4	5.5	115.9	2.0	12.0	1.8
W	2.0	0.9	5.4	0.5	1.6	0.1
Y	27.4	0.4	34.6	0.2	42.3	0.6

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Zn	79.0	1.6	88.1	0.4	28.2	0.7
Zr	125.6	1.7	94.7	1.0	98.3	1.6
n	3		3		3	

Table A1.3: Major and trace element compositions of secondary standards used in XRF analysis. These standards are certified reference materials from the Geological Survey of Japan. Precision estimates are given as one standard deviation of multiple analyses (1σ). n= number of repeat analyses.

Sample	Description	UTM E	UTM N	Al ₂ O ₃ (wt%)	CaO (wt%)	FeO (wt%)	K ₂ O (wt%)	MgO (wt%)	Na ₂ O (wt%)	P ₂ O ₅ (wt%)	SiO ₂ (wt%)	TiO ₂ (wt%)	MnO (wt%)	LOI (wt %)	Total
23-FMR-001	upper Jurassic-lower Cretaceous limestone	438820	4560181	0.037	55.344	0.008	0.007	0.619	0.033	0.012	0.659	0.017	0.003	43.684	100.657
23-FMR-003	syn-orogenic wedge-top flysch	440657	4561386	9.831	5.279	1.446	3.301	0.93	1.705	0.076	69.939	0.228	0.035	7.692	100.606
23-FMR-014A	Breccia Museo syenite xenolith	423638	4528503	19.679	6.953	3.153	4.541	1.234	4.515	0.197	58.551	0.486	0.061	0.24	99.938
23-FMR-017	Palaeozoic metamorphic basement gneiss	584970	4367598	17.194	2.789	7.115	1.68	2.866	2.424	0.066	63.302	1.025	0.103	1.05	99.915
Typical RSD (%)				0.21	0.23	0.15	0.40	0.12	0.31	0.81	0.12	0.27	1.08		

As (ppm)	Ba (ppm)	Br (ppm)	Cd (ppm)	Ce (ppm)	Co (ppm)	Cr (ppm)	Cs (ppm)	Cu (ppm)	Ga (ppm)	Hf (ppm)	I (ppm)	La (ppm)	Nb (ppm)	Nd (ppm)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Sm (ppm)	Sr (ppm)	Sn (ppm)
3.6	0	1.4	3.8	12.5	0	0	0	4.2	3.6	0	24.7	4.9	0	0	0	0	0	3.9	0	0
3.7	396.4	1.2	-0.5	29.7	2.1	19.4	4.7	6.9	10.2	1.8	3.5	13.5	9.1	10	9.4	13.9	115.5	3.4	2.4	
7.5	847.9	2.1	2.5	105.3	6.7	0	0	11.7	21.2	5	12.4	52.4	49.8	38.1	3.6	6.1	160.8	10.6	6.4	
0	521	0.7	0.9	91.5	23.1	124	0	35.1	24.4	5.6	8.6	43.7	14.4	38.1	39.7	18.1	58.1	5.6	0	
7.00	0.18	1.67	28.68	3.00	2.00	0.02	16.81	0.20	2.29	27.00	16.26	1.13	0.16	2.07	2.20	0.88	0.09	17.47	19.68	

Sr (ppm)	Te (ppm)	Th (ppm)	U (ppm)	V (ppm)	W (ppm)	Y (ppm)	Yb (ppm)	Zn (ppm)	Zr (ppm)
163.1	7.7	0	2	12.4	1.6	9.4	0	2.4	23.1
111.9	2.6	10.5	0.8	32.9	1.4	17	0	26.8	112.3
915.8	3.3	30.1	8.6	73.6	3.2	32.6	1.6	24.9	329
189.4	0	17.2	2.1	146.8	29.7	37.5	3	75.9	251.4
0.53	48.00	5.53	0.95	1.40	4.82	0.52	8.18	2.52	0.51

Table A1.4: Sampling locations and whole rock major and trace element compositions measured by XRF of potential Campi Flegrei crustal contaminants.

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CF9	cpx67	MI_23	49.32	1.95	0.50	4.57	8.23	16.28	4.42	0.42	7.88	0.17	0.93	93.74
CF9	cpx67	MI_24	49.13	2.01	0.54	4.69	8.00	16.16	4.74	0.40	8.45	0.16	0.92	94.29
CF9	cpx67	MI_25	48.90	1.88	0.49	4.55	7.84	16.28	4.85	0.40	8.69	0.19	0.91	94.07
CF9	cpx67	MI_26	47.80	1.73	0.53	4.43	8.47	16.05	4.92	0.37	9.02	0.22	1.03	93.55
CF9	cpx67	MI_27	48.45	1.88	0.55	4.55	8.44	16.53	4.35	0.41	8.91	0.16	1.02	94.22
CF9	cpx67	MI_28	49.18	2.04	0.43	4.71	8.44	16.18	4.50	0.41	8.19	0.18	0.97	94.25
CF9	cpx67	MI_29	49.13	2.22	0.50	5.14	7.82	17.05	3.84	0.41	7.45	0.17	0.91	93.73
CF9	cpx63	MI_3	51.52	2.59	0.60	6.30	6.52	17.62	2.94	0.48	6.37	0.14	0.92	95.08
CF9	cpx67	MI_30	48.11	1.82	0.49	4.76	8.38	16.24	4.91	0.37	8.62	0.14	1.00	93.85
CF9	cpx67	MI_31	48.84	2.07	0.56	4.78	8.08	16.82	4.47	0.41	8.34	0.15	1.08	94.52
CF9	cpx68	MI_32	47.98	2.07	0.39	4.21	9.44	17.11	4.08	0.36	8.84	0.17	1.13	94.63
CF9	cpx68	MI_33	48.07	2.12	0.40	4.08	8.81	17.28	3.75	0.40	9.11	0.17	1.16	94.17
CF9	cpx69	MI_34	49.40	2.11	0.51	5.36	6.87	17.35	4.31	0.37	8.04	0.11	0.86	94.43
CF9	cpx69	MI_35	49.34	2.15	0.46	5.41	6.83	17.31	4.37	0.37	8.03	0.15	0.90	94.41
CF9	cpx69	MI_36	48.90	1.96	0.47	4.80	8.24	16.77	4.36	0.43	8.29	0.15	0.98	94.37
CF9	cpx69	MI_37	49.15	1.90	0.50	4.75	7.49	15.67	5.26	0.38	9.65	0.17	0.81	94.91
CF9	cpx70	MI_38	48.93	1.97	0.56	5.17	8.38	17.44	4.32	0.40	8.95	0.16	0.91	96.29
CF9	cpx70	MI_39	50.64	2.46	0.45	4.26	7.45	17.55	2.88	0.41	8.59	0.20	0.69	94.88
CF9	cpx63	MI_4	50.92	2.43	0.51	5.96	6.56	17.76	3.03	0.48	6.67	0.13	0.95	94.45
CF9	cpx70	MI_40	51.49	2.61	0.76	5.52	7.82	16.43	2.94	0.46	6.87	0.22	0.80	95.11
CF9	cpx70	MI_42	53.91	2.64	0.33	5.79	6.94	16.94	2.45	0.52	6.40	0.18	0.76	96.10
CF9	cpx71	MI_43	48.87	1.94	0.51	4.82	7.98	16.51	4.51	0.44	8.83	0.14	1.06	94.55
CF9	cpx71	MI_44	48.70	2.04	0.48	4.84	7.80	17.05	4.32	0.41	8.64	0.18	0.99	94.47
CF9	cpx71	MI_45	50.56	2.16	0.51	5.42	7.52	16.42	3.94	0.44	7.28	0.14	0.85	94.39
CF9	cpx71	MI_46	48.91	1.99	0.50	4.84	7.98	16.49	4.42	0.40	8.65	0.16	1.02	94.34
CF9	cpx71	MI_47	48.76	1.82	0.45	4.98	7.92	16.78	4.36	0.40	8.46	0.16	0.91	94.08
CF9	cpx63	MI_5	49.74	2.12	0.57	5.58	7.66	18.63	3.39	0.44	7.76	0.10	0.98	96.00
CF9	cpx63	MI_6	50.20	1.87	0.51	5.16	8.35	18.21	3.97	0.39	8.28	0.13	0.99	97.07
CF9	cpx63	MI_7	49.28	1.94	0.53	5.12	8.36	17.75	4.21	0.37	8.47	0.14	1.01	96.17
CF9	cpx63	MI_8	50.51	2.00	0.48	5.36	7.38	17.67	4.02	0.37	8.36	0.13	0.89	96.29
CF9	cpx63	MI_9	50.07	1.87	0.53	5.13	7.75	17.67	4.19	0.38	8.77	0.12	0.91	96.49
Typical RSD (%)			0.35	7.76	78.10	1.80	1.66	0.84	2.04	77.10	1.26	20.90	7.03	

Host crystal compositions											
Sample	Label	Host	SiO ₂	Na ₂ O	CaO	FeO	Al ₂ O ₃	MgO	TiO ₂	MnO	Total
CF9	cpx63	host_MI	51.54	0.20	23.43	4.07	2.98	16.10	0.49	0.11	98.93
CF9	cpx63	host_MI	50.65	0.20	23.50	5.00	3.55	15.49	0.60	0.12	99.11
CF9	cpx63	host_MI	51.60	0.17	23.53	4.49	2.80	16.03	0.44	0.11	99.17
CF9	cpx63	host_MI	49.33	0.27	23.05	6.58	4.80	14.24	0.88	0.16	99.30
CF9	cpx63	host_MI	50.52	0.27	23.31	6.05	3.70	15.03	0.70	0.15	99.72
CF9	cpx64	host_MI	50.63	0.27	23.21	6.10	3.69	15.03	0.69	0.14	99.76
CF9	cpx65	host_MI	52.30	0.19	23.65	4.43	2.13	16.28	0.35	0.09	99.41
CF9	cpx66	host_MI	51.92	0.24	22.96	4.48	2.45	16.49	0.33	0.13	99.00
CF9	cpx67	host_MI	51.30	0.24	23.40	5.24	2.84	15.58	0.50	0.15	99.24
CF9	cpx67	host_MI	52.36	0.17	23.73	3.70	2.05	16.68	0.27	0.08	99.05
CF9	cpx68	host_MI	49.82	0.21	23.57	6.02	4.76	14.57	0.73	0.13	99.80
CF9	cpx69	host_MI	51.54	0.18	23.50	4.33	3.01	16.23	0.46	0.10	99.34
CF9	cpx69	host_MI	51.78	0.20	23.44	4.90	2.44	16.13	0.44	0.15	99.49
CF9	cpx70	host_MI	50.47	0.29	23.28	6.73	3.79	14.62	0.71	0.17	100.06
CF9	cpx70	host_MI	50.58	0.27	23.30	6.12	3.85	15.03	0.72	0.14	100.01
CF9	cpx70	host_MI	50.71	0.45	23.04	7.73	3.20	14.17	0.54	0.29	100.11
CF9	cpx71	host_MI	51.60	0.19	23.69	4.51	2.72	16.28	0.43	0.13	99.55
CF410	cpx1	host_MI	51.72	0.09	23.79	4.24	2.19	16.51	0.41	0.10	99.05
CF410	cpx1	host_MI	52.24	0.08	23.99	3.58	1.63	17.07	0.34	0.09	99.01
CF410	cpx2	host_MI	52.61	0.12	24.03	3.40	1.58	17.22	0.31	0.09	99.37
CF410	cpx3	host_MI	50.73	0.12	23.74	4.86	2.98	16.00	0.53	0.12	99.08
CF410	cpx8	host_MI	52.28	0.10	23.89	3.36	1.58	17.20	0.29	0.05	98.75
CF410	cpx8	host_MI	50.90	0.05	23.80	4.31	2.34	16.56	0.45	0.11	98.51
CF410	cpx10	host_MI	51.67	0.12	23.99	3.80	1.95	16.72	0.35	0.09	98.70
CF410	cpx11	host_MI	51.94	0.12	23.91	3.25	2.14	17.22	0.31	0.10	98.99
CF410	cpx12	host_MI	50.96	0.09	23.91	4.67	2.43	16.33	0.45	0.10	98.94
CF410	cpx12	host_MI	49.71	0.15	23.29	6.00	3.46	15.14	0.72	0.13	98.59
CF410	cpx13	host_MI	51.15	0.10	23.95	4.03	3.02	16.31	0.42	0.09	99.08
CF410	cpx13	host_MI	52.52	0.11	23.89	3.38	1.56	17.32	0.29	0.08	99.14
CF410	cpx13	host_MI	52.49	0.10	23.97	3.32	1.57	17.30	0.27	0.09	99.11
CF410	cpx14	host_MI	50.74	0.10	23.81	4.29	2.40	16.56	0.45	0.10	98.45
CF410	cpx15	host_MI	52.02	0.07	23.85	3.50	1.73	17.10	0.31	0.06	98.65
CF410	cpx16	host_MI	52.13	0.12	23.82	3.52	1.63	17.32	0.31	0.09	98.94
CF410	cpx17	host_MI	51.75	0.11	23.97	3.78	1.83	16.79	0.36	0.07	98.66
CF410	cpx18	host_MI	51.73	0.13	23.98	3.95	2.14	16.72	0.40	0.08	99.14
CF410	cpx21	host_MI	52.27	0.10	23.76	4.12	1.92	16.94	0.40	0.10	99.61

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CF410	cpx24	host_MI	49.60	0.28	22.96	7.03	3.86	14.54	0.78	0.20	99.25
CF410	cpx23	host_MI	51.36	0.10	23.61	4.68	2.13	16.58	0.45	0.10	99.00
CF410	cpx22	host_MI	51.89	0.12	23.86	3.93	2.00	16.57	0.38	0.10	98.85
CF410	cpx25	host_MI	51.94	0.11	23.91	3.82	1.82	16.85	0.33	0.10	98.87
CF13	cpx1	host_MI	50.00	0.18	23.70	5.10	3.67	15.55	0.55	0.11	98.85
CF13	cpx1	host_MI	49.91	0.13	23.71	5.35	3.79	15.37	0.65	0.12	99.02
CF13	cpx2	host_MI	51.09	0.09	23.52	4.26	2.24	16.87	0.39	0.09	98.55
CF13	cpx2	host_MI	51.45	0.10	23.85	4.19	2.32	16.82	0.41	0.11	99.24
CF13	cpx3	host_MI	50.03	0.29	22.93	6.63	3.13	15.26	0.58	0.13	98.97
CF13	cpx3	host_MI	50.17	0.17	23.41	5.04	3.47	15.89	0.52	0.13	98.81
CF13	cpx6	host_MI	51.41	0.12	23.44	4.20	2.36	17.01	0.35	0.07	98.97
CF13	cpx5	host_MI	51.51	0.10	23.63	4.21	2.55	16.81	0.40	0.11	99.32
CF13	cpx4	host_MI	51.86	0.15	23.85	3.87	2.10	17.05	0.34	0.09	99.30
CF13	cpx14	host_MI	48.79	0.25	22.70	7.36	4.00	14.41	0.77	0.24	98.53
CF13	cpx14	host_MI	48.51	0.27	22.74	7.69	4.23	14.05	0.81	0.24	98.54
CF13	cpx13	host_MI	51.62	0.14	23.64	4.21	2.18	16.99	0.38	0.10	99.25
CF13	cpx12	host_MI	48.87	0.19	22.79	7.16	4.19	14.76	0.80	0.18	98.95
CF13	cpx11	host_MI	49.06	0.40	23.20	7.93	3.41	14.03	0.65	0.31	98.98
CF13	cpx10	host_MI	50.75	0.13	24.10	4.59	3.09	16.24	0.51	0.11	99.53
CF13	cpx18	host_MI	49.82	0.18	23.09	5.46	3.93	15.76	0.72	0.11	99.07
Typical			0.40	15.40	0.65	0.65	1.33	0.84	3.76	11.41	

Table A1.5: Chemical composition of melt inclusions and their host crystals from select Campi Flegrei samples,

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1151.56	1.1	99.46	50.76	0.95	14.85	1.97	4.94	0.16	6.09	11.41	2.15	4.73	2.01
1150.56	1.1	98.92	50.76	0.95	14.90	1.97	4.94	0.16	6.04	11.35	2.16	4.75	2.02
1149.56	1.1	98.38	50.77	0.95	14.96	1.96	4.94	0.16	5.99	11.28	2.17	4.78	2.03
1148.56	1.1	97.85	50.77	0.95	15.01	1.96	4.94	0.16	5.94	11.22	2.18	4.80	2.04
1147.56	1.1	97.33	50.78	0.96	15.07	1.96	4.94	0.16	5.90	11.16	2.19	4.83	2.05
1146.56	1.1	96.81	50.78	0.96	15.13	1.96	4.94	0.17	5.85	11.09	2.21	4.86	2.07
1145.56	1.1	96.30	50.79	0.96	15.18	1.96	4.94	0.17	5.80	11.03	2.22	4.88	2.08
1144.56	1.1	95.79	50.80	0.96	15.24	1.96	4.94	0.17	5.76	10.97	2.23	4.91	2.09
1143.56	1.1	95.29	50.80	0.96	15.29	1.96	4.94	0.17	5.71	10.90	2.24	4.93	2.10
1142.56	1.1	94.80	50.81	0.96	15.34	1.96	4.93	0.17	5.66	10.84	2.25	4.96	2.11
1141.56	1.1	94.31	50.82	0.97	15.40	1.96	4.93	0.17	5.62	10.78	2.26	4.98	2.12
1140.56	1.1	93.83	50.83	0.97	15.45	1.95	4.93	0.17	5.57	10.72	2.27	5.01	2.13
1139.56	1.1	93.35	50.83	0.97	15.51	1.95	4.93	0.17	5.53	10.65	2.28	5.03	2.14
1138.56	1.1	92.88	50.84	0.97	15.56	1.95	4.93	0.17	5.48	10.59	2.29	5.06	2.15
1137.56	1.1	92.41	50.85	0.97	15.61	1.95	4.93	0.17	5.44	10.53	2.30	5.09	2.16
1136.56	1.1	91.95	50.86	0.97	15.66	1.95	4.92	0.17	5.39	10.47	2.31	5.11	2.18
1135.56	1.1	91.50	50.87	0.97	15.72	1.95	4.92	0.17	5.35	10.40	2.33	5.14	2.19
1134.56	1.1	91.05	50.88	0.97	15.77	1.94	4.92	0.18	5.30	10.34	2.34	5.16	2.20
1133.56	1.1	90.60	50.89	0.98	15.82	1.94	4.92	0.18	5.26	10.28	2.35	5.19	2.21
1132.56	1.1	90.17	50.89	0.98	15.87	1.94	4.91	0.18	5.22	10.22	2.36	5.21	2.22
1131.56	1.1	89.73	50.90	0.98	15.92	1.94	4.91	0.18	5.17	10.16	2.37	5.24	2.23
1130.56	1.1	89.30	50.91	0.98	15.97	1.94	4.91	0.18	5.13	10.10	2.38	5.26	2.24
1129.56	1.1	88.88	50.93	0.98	16.03	1.94	4.90	0.18	5.09	10.04	2.39	5.29	2.25
1128.56	1.1	88.46	50.94	0.98	16.08	1.93	4.90	0.18	5.05	9.97	2.40	5.31	2.26
1127.56	1.1	88.05	50.95	0.98	16.13	1.93	4.90	0.18	5.00	9.91	2.41	5.34	2.27
1126.56	1.1	87.64	50.96	0.98	16.18	1.93	4.89	0.18	4.96	9.85	2.42	5.36	2.28
1125.56	1.1	87.23	50.97	0.98	16.23	1.93	4.89	0.18	4.92	9.79	2.43	5.39	2.29
1124.56	1.1	86.83	50.98	0.98	16.27	1.93	4.88	0.18	4.88	9.73	2.44	5.41	2.30
1123.56	1.1	86.44	50.99	0.98	16.32	1.92	4.88	0.19	4.84	9.67	2.45	5.44	2.31
1122.56	1.1	86.05	51.00	0.98	16.37	1.92	4.88	0.19	4.80	9.61	2.46	5.46	2.32
1121.56	1.1	85.66	51.02	0.98	16.42	1.92	4.87	0.19	4.76	9.55	2.47	5.49	2.33
1120.56	1.1	85.28	51.03	0.98	16.47	1.92	4.87	0.19	4.72	9.49	2.48	5.51	2.35
1119.56	1.1	84.90	51.04	0.98	16.52	1.91	4.86	0.19	4.68	9.43	2.49	5.54	2.36
1118.56	1.1	84.53	51.05	0.98	16.56	1.91	4.86	0.19	4.64	9.38	2.50	5.56	2.37
1117.56	1.1	84.16	51.07	0.98	16.61	1.91	4.85	0.19	4.60	9.32	2.51	5.58	2.38
1116.56	1.1	83.80	51.08	0.98	16.66	1.91	4.85	0.19	4.56	9.26	2.52	5.61	2.39
1115.56	1.1	83.44	51.09	0.98	16.70	1.90	4.84	0.19	4.52	9.20	2.53	5.63	2.40
1114.56	1.1	83.08	51.11	0.98	16.75	1.90	4.83	0.19	4.48	9.14	2.54	5.66	2.41
1113.56	1.1	82.73	51.12	0.98	16.80	1.90	4.83	0.19	4.44	9.08	2.55	5.68	2.42
1112.56	1.1	82.38	51.14	0.98	16.84	1.90	4.82	0.19	4.41	9.03	2.57	5.71	2.43
1111.56	1.1	82.04	51.15	0.98	16.89	1.89	4.82	0.20	4.37	8.97	2.58	5.73	2.44

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T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
968.56	1.1	57.52	53.99	0.45	20.67	1.41	3.32	0.28	1.43	3.24	3.56	8.17	3.48
967.56	1.1	57.45	54.00	0.45	20.68	1.41	3.31	0.28	1.42	3.22	3.56	8.18	3.48
966.56	1.1	57.38	54.02	0.44	20.70	1.41	3.30	0.28	1.41	3.20	3.57	8.19	3.49
965.56	1.1	57.30	54.04	0.44	20.71	1.41	3.29	0.28	1.40	3.17	3.57	8.20	3.49
964.56	1.1	57.20	54.14	0.40	20.75	1.37	3.20	0.28	1.40	3.18	3.58	8.22	3.50
963.56	1.1	57.19	54.15	0.39	20.75	1.37	3.19	0.28	1.40	3.18	3.58	8.22	3.50
962.56	1.1	57.18	54.16	0.39	20.75	1.37	3.18	0.28	1.40	3.18	3.58	8.22	3.50
961.56	1.1	56.97	54.20	0.38	20.79	1.36	3.15	0.28	1.37	3.11	3.59	8.25	3.51
960.56	1.1	56.90	54.22	0.38	20.81	1.35	3.14	0.28	1.36	3.09	3.60	8.26	3.52
959.56	1.1	56.83	54.23	0.38	20.82	1.35	3.13	0.28	1.35	3.07	3.60	8.27	3.52
958.56	1.1	56.76	54.25	0.37	20.83	1.35	3.12	0.28	1.34	3.04	3.60	8.28	3.52
957.56	1.1	56.69	54.26	0.37	20.85	1.35	3.11	0.28	1.33	3.02	3.61	8.29	3.53
956.56	1.1	56.62	54.28	0.37	20.86	1.34	3.10	0.28	1.32	3.00	3.61	8.30	3.53
955.56	1.1	56.55	54.29	0.37	20.87	1.34	3.09	0.28	1.31	2.98	3.61	8.31	3.54
954.56	1.1	56.49	54.31	0.36	20.88	1.34	3.08	0.28	1.31	2.96	3.62	8.32	3.54
953.56	1.1	56.41	54.32	0.36	20.89	1.34	3.08	0.28	1.30	2.93	3.62	8.33	3.55
952.56	1.1	56.31	54.34	0.36	20.89	1.34	3.07	0.28	1.29	2.91	3.62	8.35	3.55
951.56	1.1	56.22	54.35	0.36	20.89	1.34	3.07	0.28	1.29	2.88	3.63	8.36	3.56
950.56	1.1	56.12	54.36	0.36	20.89	1.34	3.06	0.28	1.28	2.86	3.63	8.37	3.56
949.56	1.1	56.03	54.38	0.36	20.88	1.34	3.06	0.28	1.28	2.83	3.63	8.39	3.57
948.56	1.1	55.61	54.53	0.31	20.89	1.30	2.97	0.29	1.25	2.79	3.65	8.44	3.59
947.56	1.1	55.42	54.56	0.30	20.88	1.30	2.96	0.29	1.23	2.77	3.65	8.46	3.60
946.56	1.1	55.23	54.60	0.30	20.87	1.30	2.95	0.29	1.21	2.75	3.66	8.47	3.61
945.56	1.1	55.05	54.64	0.29	20.85	1.30	2.94	0.29	1.19	2.72	3.66	8.49	3.62
944.56	1.1	54.87	54.67	0.29	20.84	1.30	2.93	0.29	1.18	2.70	3.67	8.51	3.63
943.56	1.1	54.69	54.71	0.28	20.83	1.29	2.92	0.29	1.16	2.68	3.67	8.53	3.64
942.56	1.1	54.51	54.74	0.27	20.82	1.29	2.91	0.29	1.14	2.65	3.68	8.55	3.64
941.56	1.1	54.33	54.78	0.27	20.81	1.29	2.90	0.29	1.12	2.63	3.68	8.57	3.65
940.56	1.1	54.16	54.81	0.26	20.80	1.29	2.90	0.29	1.10	2.61	3.69	8.59	3.66
939.56	1.1	53.98	54.85	0.26	20.78	1.29	2.89	0.29	1.09	2.58	3.69	8.61	3.67
938.56	1.1	53.82	54.88	0.25	20.77	1.29	2.88	0.29	1.07	2.56	3.70	8.63	3.68
937.56	1.1	53.65	54.91	0.25	20.76	1.28	2.87	0.30	1.05	2.54	3.70	8.64	3.69
936.56	1.1	53.48	54.95	0.24	20.75	1.28	2.86	0.30	1.04	2.52	3.71	8.66	3.70
935.56	1.1	53.32	54.98	0.24	20.74	1.28	2.85	0.30	1.02	2.49	3.71	8.68	3.70
934.56	1.1	53.16	55.01	0.23	20.73	1.28	2.84	0.30	1.01	2.47	3.72	8.70	3.71
933.56	1.1	53.00	55.04	0.23	20.72	1.28	2.83	0.30	0.99	2.45	3.72	8.72	3.72
932.56	1.1	52.84	55.08	0.22	20.70	1.28	2.83	0.30	0.97	2.43	3.72	8.74	3.73
931.56	1.1	52.68	55.11	0.22	20.69	1.28	2.82	0.30	0.96	2.41	3.73	8.76	3.74
930.56	1.1	52.53	55.14	0.21	20.68	1.27	2.81	0.30	0.94	2.39	3.73	8.77	3.75
929.56	1.1	52.38	55.17	0.21	20.67	1.27	2.80	0.30	0.93	2.37	3.73	8.79	3.75
928.56	1.1	52.23	55.20	0.20	20.66	1.27	2.79	0.30	0.92	2.35	3.74	8.81	3.76
927.56	1.1	52.08	55.23	0.20	20.65	1.27	2.78	0.30	0.90	2.33	3.74	8.83	3.77
926.56	1.1	51.93	55.26	0.19	20.64	1.27	2.78	0.30	0.89	2.30	3.74	8.85	3.78
925.56	1.1	51.78	55.28	0.19	20.63	1.27	2.77	0.30	0.87	2.28	3.75	8.86	3.79
924.56	1.1	51.64	55.31	0.19	20.62	1.27	2.76	0.31	0.86	2.26	3.75	8.88	3.80
923.56	1.1	51.50	55.34	0.18	20.61	1.26	2.75	0.31	0.85	2.24	3.75	8.90	3.80
922.56	1.1	51.35	55.37	0.18	20.60	1.26	2.74	0.31	0.83	2.22	3.76	8.92	3.81
921.56	1.1	51.21	55.40	0.17	20.59	1.26	2.73	0.31	0.82	2.20	3.76	8.94	3.82
920.56	1.1	51.08	55.42	0.17	20.58	1.26	2.73	0.31	0.81	2.18	3.76	8.95	3.83
919.56	1.1	50.94	55.45	0.17	20.57	1.26	2.72	0.31	0.79	2.17	3.76	8.97	3.84
918.56	1.1	50.80	55.48	0.16	20.56	1.26	2.71	0.31	0.78	2.15	3.77	8.99	3.85
917.56	1.1	50.67	55.50	0.16	20.55	1.26	2.70	0.31	0.77	2.13	3.77	9.01	3.85
916.56	1.1	50.53	55.53	0.15	20.54	1.25	2.69	0.31	0.76	2.11	3.77	9.02	3.86
915.56	1.1	50.40	55.55	0.15	20.53	1.25	2.68	0.31	0.75	2.09	3.77	9.04	3.87
914.56	1.1	50.27	55.58	0.15	20.52	1.25	2.68	0.31	0.74	2.07	3.78	9.06	3.88
913.56	1.1	50.14	55.60	0.14	20.51	1.25	2.67	0.31	0.72	2.05	3.78	9.08	3.89
912.56	1.1	50.01	55.63	0.14	20.50	1.25	2.66	0.31	0.71	2.03	3.78	9.09	3.89
911.56	1.1	49.89	55.65	0.14	20.49	1.25	2.65	0.32	0.70	2.01	3.78	9.11	3.90
910.56	1.1	49.76	55.68	0.13	20.48	1.25	2.64	0.32	0.69	2.00	3.78	9.13	3.91
909.56	1.1	49.63	55.70	0.13	20.47	1.25	2.64	0.32	0.68	1.98	3.79	9.15	3.92
908.56	1.1	49.51	55.72	0.13	20.46	1.24	2.63	0.32	0.67	1.96	3.79	9.16	3.93
907.56	1.1	49.39	55.75	0.12	20.45	1.24	2.62	0.32	0.66	1.94	3.79	9.18	3.93
906.56	1.1	49.26	55.77	0.12	20.44	1.24	2.61	0.32	0.65	1.92	3.79	9.20	3.94
905.56	1.1	49.14	55.79	0.12	20.43	1.24	2.60	0.32	0.64	1.91	3.79	9.22	3.95
904.56	1.1	49.02	55.81	0.11	20.42	1.24	2.60	0.32	0.63	1.89	3.79	9.23	3.96
903.56	1.1	48.90	55.84	0.11	20.41	1.24	2.59	0.32	0.62	1.87	3.79	9.25	3.97
902.56	1.1	48.79	55.86	0.11	20.40	1.24	2.58	0.32	0.61	1.85	3.80	9.27	3.97
901.56	1.1	48.67	55.88	0.10	20.39	1.23	2.57	0.32	0.60	1.84	3.80	9.28	3.98
900.56	1.1	48.55	55.90	0.10	20.38	1.23	2.57	0.32	0.59	1.82	3.80	9.30	3.99
899.56	1.1	48.44	55.92	0.10	20.37	1.23	2.56	0.32	0.58	1.80	3.80	9.32	4.00
898.56	1.1	48.32	55.94	0.10	20.36	1.23	2.55	0.33	0.57	1.78	3.80	9.34	4.00

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
897.56	1.1	48.21	55.96	0.09	20.35	1.23	2.54	0.33	0.56	1.77	3.80	9.35	4.01
896.56	1.1	48.10	55.98	0.09	20.34	1.23	2.53	0.33	0.55	1.75	3.80	9.37	4.02
895.56	1.1	47.98	56.00	0.09	20.33	1.23	2.53	0.33	0.54	1.73	3.80	9.39	4.03
894.56	1.1	47.87	56.02	0.08	20.32	1.22	2.52	0.33	0.54	1.72	3.80	9.40	4.04
893.56	1.1	47.76	56.04	0.08	20.32	1.22	2.51	0.33	0.53	1.70	3.80	9.42	4.04
892.56	1.1	47.65	56.06	0.08	20.31	1.22	2.50	0.33	0.52	1.69	3.80	9.44	4.05
891.56	1.1	47.54	56.08	0.08	20.30	1.22	2.50	0.33	0.51	1.67	3.80	9.46	4.06
890.56	1.1	47.44	56.10	0.08	20.29	1.22	2.49	0.33	0.50	1.65	3.80	9.47	4.07
889.56	1.1	47.33	56.12	0.07	20.28	1.22	2.48	0.33	0.50	1.64	3.80	9.49	4.08
888.56	1.1	47.22	56.13	0.07	20.27	1.22	2.47	0.33	0.49	1.62	3.80	9.51	4.08
887.56	1.1	47.12	56.15	0.07	20.26	1.22	2.47	0.33	0.48	1.61	3.80	9.52	4.09
886.56	1.1	47.01	56.17	0.07	20.25	1.21	2.46	0.33	0.47	1.59	3.80	9.54	4.10
885.56	1.1	46.91	56.19	0.06	20.24	1.21	2.45	0.33	0.46	1.57	3.80	9.56	4.11
884.56	1.1	46.80	56.20	0.06	20.24	1.21	2.44	0.34	0.46	1.56	3.80	9.57	4.11
883.56	1.1	46.70	56.22	0.06	20.23	1.21	2.44	0.34	0.45	1.54	3.80	9.59	4.12
882.56	1.1	46.59	56.24	0.06	20.22	1.21	2.43	0.34	0.44	1.53	3.80	9.61	4.13
881.56	1.1	46.49	56.25	0.06	20.21	1.21	2.42	0.34	0.44	1.51	3.80	9.62	4.14
880.56	1.1	46.39	56.27	0.05	20.20	1.21	2.42	0.34	0.43	1.50	3.80	9.64	4.15
879.56	1.1	46.29	56.29	0.05	20.19	1.21	2.41	0.34	0.42	1.48	3.80	9.66	4.15
878.56	1.1	46.19	56.30	0.05	20.18	1.20	2.40	0.34	0.41	1.47	3.80	9.68	4.16
877.56	1.1	46.09	56.32	0.05	20.18	1.20	2.39	0.34	0.41	1.45	3.80	9.69	4.17
876.56	1.1	45.99	56.33	0.05	20.17	1.20	2.39	0.34	0.40	1.44	3.80	9.71	4.18
875.56	1.1	45.89	56.35	0.04	20.16	1.20	2.38	0.34	0.40	1.42	3.80	9.73	4.19
874.56	1.1	45.79	56.36	0.04	20.15	1.20	2.37	0.34	0.39	1.41	3.80	9.74	4.19
873.56	1.1	45.69	56.38	0.04	20.14	1.20	2.36	0.34	0.38	1.39	3.80	9.76	4.20
872.56	1.1	45.60	56.39	0.04	20.14	1.20	2.36	0.34	0.38	1.38	3.79	9.78	4.21
871.56	1.1	45.48	56.41	0.04	20.13	1.20	2.35	0.34	0.37	1.36	3.79	9.80	4.21
870.56	1.1	45.37	56.43	0.04	20.12	1.20	2.34	0.35	0.36	1.35	3.79	9.82	4.21
869.56	1.1	45.25	56.45	0.03	20.11	1.19	2.34	0.35	0.36	1.33	3.79	9.84	4.21
868.56	1.1	45.14	56.47	0.03	20.10	1.19	2.33	0.35	0.35	1.31	3.79	9.86	4.22
867.56	1.1	45.03	56.48	0.03	20.09	1.19	2.32	0.35	0.35	1.30	3.79	9.88	4.22
866.56	1.1	44.91	56.50	0.03	20.09	1.19	2.32	0.35	0.34	1.28	3.78	9.90	4.22
865.56	1.1	44.80	56.52	0.03	20.08	1.19	2.31	0.35	0.33	1.27	3.78	9.92	4.22
864.56	1.1	44.69	56.54	0.03	20.07	1.19	2.30	0.35	0.33	1.25	3.78	9.94	4.22
863.56	1.1	44.57	56.56	0.03	20.06	1.19	2.30	0.35	0.32	1.23	3.78	9.96	4.22
862.56	1.1	44.46	56.57	0.02	20.05	1.19	2.29	0.35	0.32	1.22	3.78	9.98	4.23
861.56	1.1	44.35	56.59	0.02	20.05	1.19	2.28	0.35	0.31	1.20	3.77	10.01	4.23
860.56	1.1	44.24	56.61	0.02	20.04	1.19	2.28	0.35	0.31	1.19	3.77	10.03	4.23
859.56	1.1	44.13	56.62	0.02	20.03	1.18	2.27	0.36	0.30	1.17	3.77	10.05	4.23
858.56	1.1	44.02	56.64	0.02	20.02	1.18	2.26	0.36	0.29	1.16	3.77	10.07	4.23
857.56	1.1	43.90	56.66	0.02	20.02	1.18	2.26	0.36	0.29	1.14	3.76	10.09	4.23
856.56	1.1	43.79	56.67	0.02	20.01	1.18	2.25	0.36	0.28	1.13	3.76	10.11	4.23
855.56	1.1	43.68	56.69	0.02	20.00	1.18	2.24	0.36	0.28	1.11	3.76	10.13	4.24
854.56	1.1	43.57	56.70	0.01	19.99	1.18	2.23	0.36	0.27	1.10	3.75	10.15	4.24
853.56	1.1	43.46	56.72	0.01	19.99	1.18	2.23	0.36	0.27	1.08	3.75	10.18	4.24
852.56	1.1	43.35	56.73	0.01	19.98	1.18	2.22	0.36	0.26	1.07	3.75	10.20	4.24
851.56	1.1	43.24	56.75	0.01	19.97	1.18	2.21	0.36	0.26	1.05	3.74	10.22	4.24
850.56	1.1	43.13	56.76	0.01	19.97	1.18	2.21	0.36	0.25	1.04	3.74	10.24	4.24
849.56	1.1	43.02	56.78	0.01	19.96	1.18	2.20	0.36	0.25	1.02	3.74	10.26	4.24
848.56	1.1	42.91	56.79	0.01	19.95	1.17	2.19	0.36	0.24	1.01	3.73	10.28	4.24
847.56	1.1	42.80	56.81	0.01	19.95	1.17	2.19	0.37	0.24	0.99	3.73	10.31	4.25
846.56	1.1	42.69	56.82	0.01	19.94	1.17	2.18	0.37	0.24	0.98	3.72	10.33	4.25
845.56	1.1	42.58	56.83	0.01	19.93	1.17	2.17	0.37	0.23	0.96	3.72	10.35	4.25
844.56	1.1	42.47	56.85	0.01	19.93	1.17	2.17	0.37	0.23	0.95	3.72	10.37	4.25
843.56	1.1	42.36	56.86	0.01	19.92	1.17	2.16	0.37	0.22	0.94	3.71	10.40	4.25
842.56	1.1	42.25	56.87	0.00	19.91	1.17	2.15	0.37	0.22	0.92	3.71	10.42	4.25
841.56	1.1	42.14	56.89	0.00	19.91	1.17	2.15	0.37	0.21	0.91	3.70	10.44	4.25
840.56	1.1	42.03	56.90	0.00	19.90	1.16	2.14	0.37	0.21	0.90	3.70	10.46	4.25
839.56	1.1	41.92	56.91	0.00	19.90	1.16	2.13	0.37	0.20	0.88	3.69	10.49	4.26
838.56	1.1	41.80	56.92	0.00	19.89	1.16	2.12	0.37	0.20	0.87	3.69	10.51	4.26
837.56	1.1	41.69	56.94	0.00	19.89	1.16	2.12	0.38	0.20	0.86	3.68	10.53	4.26
836.56	1.1	41.58	56.95	0.00	19.88	1.16	2.11	0.38	0.19	0.84	3.68	10.56	4.26
835.56	1.1	41.46	56.96	0.00	19.88	1.16	2.10	0.38	0.19	0.83	3.67	10.58	4.26
834.56	1.1	41.35	56.97	0.00	19.87	1.16	2.09	0.38	0.18	0.82	3.66	10.60	4.26
833.56	1.1	41.23	56.98	0.00	19.87	1.15	2.08	0.38	0.18	0.80	3.66	10.63	4.26
832.56	1.1	41.11	57.00	0.00	19.86	1.15	2.08	0.38	0.17	0.79	3.65	10.65	4.26
831.56	1.1	39.54	56.85	0.00	19.92	1.17	2.11	0.40	0.17	0.78	3.66	10.68	4.27
830.56	1.1	37.70	56.67	0.00	20.00	1.19	2.13	0.42	0.16	0.77	3.67	10.71	4.28
829.56	1.1	35.72	56.50	0.00	20.11	1.19	2.12	0.44	0.15	0.76	3.68	10.76	4.29
828.56	1.1	33.76	56.34	0.00	20.24	1.17	2.08	0.46	0.15	0.75	3.70	10.82	4.30
827.56	1.1	32.05	56.19	0.00	20.36	1.15	2.04	0.49	0.14	0.74	3.71	10.88	4.31

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
826.56	1.1	30.58	56.04	0.00	20.47	1.13	2.00	0.51	0.14	0.73	3.73	10.93	4.32
825.56	1.1	29.28	55.90	0.00	20.59	1.11	1.96	0.53	0.14	0.72	3.74	10.98	4.33
824.56	1.1	28.13	55.76	0.00	20.69	1.10	1.92	0.56	0.13	0.71	3.75	11.04	4.34
823.56	1.1	27.10	55.63	0.00	20.80	1.08	1.88	0.58	0.13	0.70	3.77	11.08	4.35
822.56	1.1	26.18	55.51	0.00	20.90	1.06	1.85	0.60	0.13	0.69	3.78	11.13	4.36
821.56	1.1	25.34	55.38	0.00	21.00	1.05	1.82	0.62	0.12	0.68	3.79	11.18	4.37
820.56	1.1	24.58	55.26	0.00	21.09	1.03	1.78	0.64	0.12	0.67	3.80	11.22	4.38
819.56	1.1	23.88	55.15	0.00	21.18	1.02	1.75	0.66	0.12	0.66	3.81	11.26	4.39
818.56	1.1	23.24	55.03	0.00	21.27	1.00	1.72	0.67	0.11	0.65	3.83	11.31	4.41
817.56	1.1	22.64	54.92	0.00	21.36	0.99	1.69	0.69	0.11	0.64	3.84	11.35	4.42
816.56	1.1	22.09	54.81	0.00	21.44	0.98	1.66	0.71	0.11	0.63	3.85	11.39	4.43
815.56	1.1	21.58	54.71	0.00	21.53	0.96	1.63	0.73	0.10	0.62	3.86	11.42	4.44
814.56	1.1	21.10	54.60	0.00	21.61	0.95	1.61	0.74	0.10	0.62	3.87	11.46	4.45
813.56	1.1	20.65	54.50	0.00	21.69	0.94	1.58	0.76	0.10	0.61	3.88	11.50	4.46
812.56	1.1	20.23	54.40	0.00	21.76	0.93	1.55	0.77	0.10	0.60	3.89	11.53	4.47
811.56	1.1	19.83	54.30	0.00	21.84	0.91	1.53	0.79	0.09	0.59	3.90	11.57	4.48
810.56	1.1	19.46	54.20	0.00	21.91	0.90	1.50	0.80	0.09	0.59	3.91	11.60	4.49
809.56	1.1	19.10	54.11	0.00	21.99	0.89	1.48	0.82	0.09	0.58	3.92	11.63	4.50
808.56	1.1	18.77	54.01	0.00	22.06	0.88	1.46	0.83	0.09	0.57	3.93	11.67	4.51
807.56	1.1	18.45	53.92	0.00	22.13	0.87	1.43	0.85	0.08	0.56	3.94	11.70	4.52
806.56	1.1	18.15	53.83	0.00	22.20	0.86	1.41	0.86	0.08	0.56	3.95	11.73	4.53
805.56	1.1	17.86	53.74	0.00	22.27	0.85	1.39	0.88	0.08	0.55	3.96	11.76	4.54
804.56	1.1	17.58	53.65	0.00	22.33	0.84	1.37	0.89	0.08	0.54	3.97	11.79	4.55
803.56	1.1	17.32	53.56	0.00	22.40	0.83	1.35	0.90	0.07	0.54	3.97	11.82	4.56
802.56	1.1	17.07	53.48	0.00	22.46	0.82	1.33	0.92	0.07	0.53	3.98	11.85	4.57
801.56	1.1	16.83	53.39	0.00	22.53	0.81	1.31	0.93	0.07	0.53	3.99	11.87	4.58
800.56	1.1	16.60	53.31	0.00	22.59	0.80	1.29	0.94	0.07	0.52	4.00	11.90	4.59
799.56	1.1	16.38	53.22	0.00	22.65	0.79	1.27	0.96	0.07	0.51	4.01	11.93	4.60
798.56	1.1	16.17	53.14	0.00	22.71	0.78	1.25	0.97	0.06	0.51	4.02	11.95	4.61
797.56	1.1	15.97	53.06	0.00	22.77	0.77	1.23	0.98	0.06	0.50	4.03	11.98	4.62
796.56	1.1	15.77	52.98	0.00	22.83	0.76	1.21	0.99	0.06	0.50	4.03	12.00	4.63
795.56	1.1	15.58	52.90	0.00	22.89	0.75	1.19	1.00	0.06	0.49	4.04	12.03	4.64
794.56	1.1	15.40	52.82	0.00	22.95	0.74	1.18	1.02	0.06	0.49	4.05	12.05	4.65
793.56	1.1	15.22	52.74	0.00	23.00	0.74	1.16	1.03	0.05	0.48	4.06	12.08	4.66
792.56	1.1	15.05	52.66	0.00	23.06	0.73	1.14	1.04	0.05	0.48	4.07	12.10	4.67
791.56	1.1	14.89	52.58	0.00	23.12	0.72	1.13	1.05	0.05	0.47	4.08	12.12	4.68
790.56	1.1	14.73	52.51	0.00	23.17	0.71	1.11	1.06	0.05	0.47	4.08	12.15	4.69
789.56	1.1	14.54	52.44	0.00	23.20	0.70	1.10	1.08	0.05	0.46	4.10	12.17	4.71
788.56	1.1	14.30	52.38	0.00	23.19	0.70	1.08	1.09	0.04	0.47	4.12	12.20	4.73
787.56	1.1	14.08	52.32	0.00	23.17	0.69	1.06	1.11	0.04	0.47	4.14	12.23	4.75
786.56	1.1	13.86	52.27	0.00	23.16	0.68	1.05	1.13	0.04	0.47	4.17	12.26	4.77
785.56	1.1	13.65	52.21	0.00	23.15	0.68	1.03	1.15	0.04	0.47	4.19	12.29	4.80
784.56	1.1	13.46	52.15	0.00	23.13	0.67	1.02	1.16	0.04	0.47	4.21	12.32	4.82
783.56	1.1	13.26	52.10	0.00	23.12	0.66	1.00	1.18	0.03	0.47	4.23	12.35	4.84
782.56	1.1	13.08	52.05	0.00	23.11	0.66	0.99	1.20	0.03	0.48	4.26	12.38	4.87
781.56	1.1	12.90	51.99	0.00	23.10	0.65	0.97	1.21	0.03	0.48	4.28	12.40	4.89
780.56	1.1	12.73	51.94	0.00	23.08	0.64	0.95	1.23	0.03	0.48	4.30	12.43	4.91
779.56	1.1	12.56	51.89	0.00	23.07	0.63	0.94	1.25	0.03	0.48	4.32	12.46	4.94
778.56	1.1	12.11	51.81	0.00	23.09	0.62	0.91	1.29	0.03	0.47	4.27	12.55	4.95
777.56	1.1	11.61	51.74	0.00	23.12	0.60	0.88	1.35	0.02	0.46	4.19	12.67	4.96
776.56	1.1	11.16	51.66	0.00	23.15	0.58	0.85	1.40	0.02	0.45	4.12	12.78	4.98
775.56	1.1	10.74	51.58	0.00	23.18	0.56	0.83	1.46	0.02	0.44	4.05	12.89	4.99
774.56	1.1	10.35	51.50	0.00	23.21	0.55	0.80	1.51	0.02	0.43	3.98	13.00	5.00
773.56	1.1	10.00	51.42	0.00	23.23	0.53	0.77	1.57	0.02	0.43	3.91	13.11	5.02
772.56	1.1	9.67	51.34	0.00	23.26	0.52	0.75	1.62	0.02	0.42	3.84	13.21	5.03
771.56	1.1	9.36	51.27	0.00	23.28	0.50	0.72	1.67	0.02	0.41	3.78	13.31	5.05
770.56	1.1	9.08	51.19	0.00	23.30	0.49	0.70	1.72	0.02	0.40	3.72	13.40	5.06
769.56	1.1	8.81	51.11	0.00	23.32	0.47	0.68	1.78	0.01	0.40	3.65	13.50	5.07
768.56	1.1	8.56	51.03	0.00	23.34	0.46	0.66	1.83	0.01	0.39	3.59	13.59	5.09
767.56	1.1	8.33	50.95	0.00	23.36	0.45	0.64	1.88	0.01	0.38	3.54	13.68	5.10
766.56	1.1	8.11	50.88	0.00	23.38	0.43	0.62	1.93	0.01	0.38	3.48	13.77	5.12
765.56	1.1	7.91	50.80	0.00	23.40	0.42	0.60	1.98	0.01	0.37	3.42	13.86	5.14
764.56	1.1	7.71	50.72	0.00	23.42	0.41	0.58	2.03	0.01	0.37	3.37	13.94	5.15
763.56	1.1	7.53	50.64	0.00	23.43	0.40	0.57	2.08	0.01	0.36	3.32	14.02	5.17
762.56	1.1	7.36	50.57	0.00	23.45	0.39	0.55	2.13	0.01	0.36	3.27	14.10	5.18
761.56	1.1	7.19	50.49	0.00	23.46	0.38	0.53	2.18	0.01	0.35	3.22	14.18	5.20
760.56	1.1	7.04	50.41	0.00	23.47	0.37	0.52	2.22	0.01	0.35	3.17	14.26	5.22
759.56	1.1	6.89	50.33	0.00	23.49	0.36	0.50	2.27	0.01	0.35	3.12	14.33	5.24
758.56	1.1	6.75	50.26	0.00	23.50	0.35	0.49	2.32	0.01	0.34	3.07	14.41	5.25
757.56	1.1	6.62	50.18	0.00	23.51	0.34	0.48	2.37	0.01	0.34	3.03	14.48	5.27
756.56	1.1	6.49	50.10	0.00	23.52	0.33	0.46	2.41	0.01	0.33	2.98	14.55	5.29

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T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
755.56	1.1	6.37	50.03	0.00	23.53	0.32	0.45	2.46	0.01	0.33	2.94	14.62	5.31
754.56	1.1	6.25	49.95	0.00	23.54	0.32	0.44	2.50	0.01	0.33	2.90	14.69	5.33
753.56	1.1	6.14	49.88	0.00	23.55	0.31	0.43	2.55	0.01	0.32	2.85	14.76	5.34
752.56	1.1	6.04	49.80	0.00	23.56	0.30	0.41	2.59	0.01	0.32	2.81	14.82	5.36
751.56	1.1	5.93	49.72	0.00	23.57	0.29	0.40	2.64	0.01	0.32	2.77	14.89	5.38
750.56	1.1	5.84	49.65	0.00	23.57	0.29	0.39	2.68	0.01	0.32	2.74	14.95	5.40
749.56	1.1	5.74	49.57	0.00	23.58	0.28	0.38	2.73	0.01	0.31	2.70	15.01	5.42
748.56	1.1	5.65	49.50	0.00	23.59	0.27	0.37	2.77	0.01	0.31	2.66	15.08	5.44
747.56	1.1	5.56	49.42	0.00	23.59	0.27	0.36	2.81	0.01	0.31	2.62	15.14	5.46
746.56	1.1	5.48	49.35	0.00	23.60	0.26	0.35	2.86	0.01	0.31	2.59	15.20	5.48
745.56	1.1	5.40	49.27	0.00	23.61	0.26	0.34	2.90	0.01	0.30	2.55	15.25	5.50
744.56	1.1	5.32	49.20	0.00	23.61	0.25	0.34	2.94	0.01	0.30	2.52	15.31	5.53
743.56	1.1	5.25	49.12	0.00	23.61	0.24	0.33	2.98	0.01	0.30	2.49	15.37	5.55
742.56	1.1	5.18	49.05	0.00	23.62	0.24	0.32	3.02	0.01	0.30	2.45	15.42	5.57
741.56	1.1	5.11	48.97	0.00	23.62	0.23	0.31	3.07	0.01	0.30	2.42	15.48	5.59
740.56	1.1	5.04	48.90	0.00	23.63	0.23	0.30	3.11	0.01	0.30	2.39	15.53	5.61
739.56	1.1	4.97	48.82	0.00	23.63	0.22	0.30	3.15	0.01	0.29	2.36	15.59	5.64
738.56	1.1	4.91	48.75	0.00	23.63	0.22	0.29	3.19	0.01	0.29	2.33	15.64	5.66
737.56	1.1	4.85	48.67	0.00	23.63	0.21	0.28	3.23	0.01	0.29	2.30	15.69	5.68
736.56	1.1	4.79	48.60	0.00	23.64	0.21	0.27	3.27	0.01	0.29	2.27	15.74	5.71
735.56	1.1	4.73	48.52	0.00	23.64	0.20	0.27	3.31	0.01	0.29	2.24	15.79	5.73
734.56	1.1	4.68	48.45	0.00	23.64	0.20	0.26	3.35	0.01	0.29	2.22	15.84	5.75
733.56	1.1	4.62	48.38	0.00	23.64	0.20	0.26	3.39	0.01	0.29	2.19	15.89	5.78
732.56	1.1	4.57	48.30	0.00	23.64	0.19	0.25	3.43	0.01	0.28	2.16	15.94	5.80
731.56	1.1	4.52	48.23	0.00	23.64	0.19	0.24	3.47	0.01	0.28	2.14	15.98	5.83
730.56	1.1	4.47	48.15	0.00	23.64	0.18	0.24	3.50	0.01	0.28	2.11	16.03	5.85
729.56	1.1	4.42	48.08	0.00	23.64	0.18	0.23	3.54	0.01	0.28	2.09	16.08	5.88
728.56	1.1	4.37	48.00	0.00	23.64	0.18	0.23	3.58	0.01	0.28	2.06	16.12	5.91
727.56	1.1	4.33	47.93	0.00	23.64	0.17	0.22	3.62	0.01	0.28	2.04	16.17	5.93
726.56	1.1	4.28	47.85	0.00	23.64	0.17	0.22	3.66	0.01	0.28	2.01	16.21	5.96
725.56	1.1	4.24	47.78	0.00	23.63	0.17	0.21	3.70	0.00	0.28	1.99	16.25	5.99
724.56	1.1	4.19	47.70	0.00	23.63	0.16	0.21	3.73	0.00	0.28	1.97	16.30	6.01
723.56	1.1	4.15	47.63	0.00	23.63	0.16	0.20	3.77	0.00	0.28	1.95	16.34	6.04
722.56	1.1	4.11	47.56	0.00	23.63	0.16	0.20	3.81	0.00	0.28	1.93	16.38	6.07
721.56	1.1	4.07	47.48	0.00	23.63	0.15	0.19	3.84	0.00	0.28	1.91	16.42	6.10
720.56	1.1	4.03	47.41	0.00	23.62	0.15	0.19	3.88	0.00	0.27	1.88	16.46	6.13
719.56	1.1	4.00	47.33	0.00	23.62	0.15	0.18	3.92	0.00	0.27	1.86	16.50	6.16
718.56	1.1	3.96	47.25	0.00	23.62	0.14	0.18	3.95	0.00	0.27	1.84	16.54	6.19
717.56	1.1	3.92	47.18	0.00	23.61	0.14	0.18	3.99	0.00	0.27	1.83	16.58	6.22
716.56	1.1	3.89	47.10	0.00	23.61	0.14	0.17	4.03	0.00	0.27	1.81	16.62	6.25
715.56	1.1	3.85	47.03	0.00	23.60	0.14	0.17	4.06	0.00	0.27	1.79	16.66	6.28
714.56	1.1	3.82	46.95	0.00	23.60	0.13	0.16	4.10	0.00	0.27	1.77	16.70	6.31
713.56	1.1	3.79	46.88	0.00	23.60	0.13	0.16	4.13	0.00	0.27	1.75	16.73	6.34
712.56	1.1	3.75	46.80	0.00	23.59	0.13	0.16	4.17	0.00	0.27	1.73	16.77	6.37
711.56	1.1	3.72	46.72	0.00	23.59	0.13	0.15	4.20	0.00	0.27	1.72	16.81	6.41
710.56	1.1	3.69	46.65	0.00	23.58	0.12	0.15	4.24	0.00	0.27	1.70	16.84	6.44
709.56	1.1	3.66	46.57	0.00	23.57	0.12	0.15	4.27	0.00	0.27	1.68	16.88	6.47
708.56	1.1	3.63	46.50	0.00	23.57	0.12	0.14	4.31	0.00	0.27	1.67	16.91	6.51
707.56	1.1	3.60	46.42	0.00	23.56	0.12	0.14	4.34	0.00	0.27	1.65	16.95	6.54
706.56	1.1	3.57	46.34	0.00	23.56	0.11	0.14	4.38	0.00	0.27	1.64	16.98	6.58
705.56	1.1	3.55	46.26	0.00	23.55	0.11	0.13	4.41	0.00	0.27	1.62	17.02	6.61
704.56	1.1	3.52	46.19	0.00	23.54	0.11	0.13	4.45	0.00	0.27	1.61	17.05	6.65
703.56	1.1	3.49	46.11	0.00	23.54	0.11	0.13	4.48	0.00	0.27	1.59	17.09	6.68
702.56	1.1	3.47	46.03	0.00	23.53	0.11	0.13	4.52	0.00	0.27	1.58	17.12	6.72
701.56	1.1	3.44	45.95	0.00	23.52	0.10	0.12	4.55	0.00	0.27	1.56	17.15	6.76
700.56	1.1	3.41	45.87	0.00	23.52	0.10	0.12	4.59	0.00	0.27	1.55	17.18	6.79

Table A1.6: Best-fit fractional crystallisation Rhyolite-MELTS model for northern/eastern caldera group eruptions. Liquid remaining is reported in grams, the model begins with 100g of liquid. The starting temperature is the liquidus temperature of the system, calculated by Rhyolite-MELTS.

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1121.88	1.4	99.89	50.27	0.94	14.76	1.38	5.42	0.16	5.98	11.24	2.14	4.71	3.00
1120.88	1.4	99.42	50.27	0.94	14.81	1.38	5.42	0.16	5.94	11.19	2.15	4.73	3.02
1119.88	1.4	98.95	50.27	0.94	14.86	1.38	5.43	0.16	5.89	11.13	2.16	4.75	3.03
1118.88	1.4	98.49	50.27	0.94	14.91	1.38	5.43	0.16	5.85	11.07	2.17	4.77	3.05
1117.88	1.4	98.03	50.27	0.94	14.96	1.38	5.43	0.16	5.81	11.02	2.18	4.79	3.06

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T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1116.88	1.4	97.57	50.27	0.94	15.01	1.38	5.44	0.16	5.76	10.96	2.19	4.82	3.07
1115.88	1.4	97.12	50.27	0.94	15.05	1.38	5.44	0.16	5.72	10.91	2.20	4.84	3.09
1114.88	1.4	96.68	50.27	0.95	15.10	1.38	5.44	0.17	5.68	10.85	2.21	4.86	3.10
1113.88	1.4	96.24	50.27	0.95	15.15	1.38	5.44	0.17	5.63	10.80	2.22	4.88	3.12
1112.88	1.4	95.80	50.27	0.95	15.20	1.38	5.45	0.17	5.59	10.74	2.23	4.91	3.13
1111.88	1.4	95.37	50.27	0.95	15.24	1.38	5.45	0.17	5.55	10.68	2.24	4.93	3.15
1110.88	1.4	94.94	50.27	0.95	15.29	1.38	5.45	0.17	5.51	10.63	2.25	4.95	3.16
1109.88	1.4	94.52	50.27	0.95	15.34	1.38	5.45	0.17	5.47	10.57	2.26	4.97	3.17
1108.88	1.4	94.10	50.27	0.95	15.39	1.38	5.45	0.17	5.42	10.52	2.27	4.99	3.19
1107.88	1.4	93.68	50.27	0.95	15.43	1.38	5.46	0.17	5.38	10.46	2.27	5.02	3.20
1106.88	1.4	93.27	50.27	0.95	15.48	1.38	5.46	0.17	5.34	10.41	2.28	5.04	3.22
1105.88	1.4	92.86	50.28	0.95	15.52	1.38	5.46	0.17	5.30	10.35	2.29	5.06	3.23
1104.88	1.4	92.46	50.28	0.95	15.57	1.38	5.46	0.17	5.26	10.30	2.30	5.08	3.24
1103.88	1.4	92.06	50.28	0.95	15.62	1.38	5.46	0.17	5.22	10.24	2.31	5.11	3.26
1102.88	1.4	91.66	50.28	0.95	15.66	1.38	5.46	0.17	5.18	10.19	2.32	5.13	3.27
1101.88	1.4	91.27	50.29	0.95	15.71	1.38	5.46	0.18	5.14	10.13	2.33	5.15	3.29
1100.88	1.4	90.88	50.29	0.95	15.75	1.38	5.46	0.18	5.10	10.08	2.34	5.17	3.30
1099.88	1.4	90.49	50.29	0.95	15.80	1.38	5.47	0.18	5.06	10.02	2.35	5.19	3.32
1098.88	1.4	90.11	50.30	0.95	15.84	1.38	5.47	0.18	5.02	9.97	2.36	5.22	3.33
1097.88	1.4	89.74	50.30	0.95	15.89	1.38	5.47	0.18	4.98	9.91	2.37	5.24	3.34
1096.88	1.4	89.36	50.30	0.95	15.93	1.38	5.47	0.18	4.94	9.86	2.38	5.26	3.36
1095.88	1.4	88.99	50.31	0.95	15.97	1.38	5.47	0.18	4.90	9.80	2.39	5.28	3.37
1094.88	1.4	88.62	50.31	0.94	16.02	1.38	5.47	0.18	4.86	9.75	2.40	5.30	3.39
1093.88	1.4	88.26	50.32	0.94	16.06	1.38	5.47	0.18	4.82	9.70	2.41	5.33	3.40
1092.88	1.4	87.90	50.32	0.94	16.11	1.38	5.47	0.18	4.79	9.64	2.42	5.35	3.41
1091.88	1.4	87.54	50.33	0.94	16.15	1.38	5.47	0.18	4.75	9.59	2.43	5.37	3.43
1090.88	1.4	87.19	50.33	0.94	16.19	1.38	5.47	0.18	4.71	9.53	2.43	5.39	3.44
1089.88	1.4	86.84	50.34	0.94	16.23	1.38	5.46	0.18	4.67	9.48	2.44	5.41	3.45
1088.88	1.4	86.49	50.34	0.94	16.28	1.38	5.46	0.18	4.64	9.43	2.45	5.43	3.47
1087.88	1.4	86.15	50.35	0.94	16.32	1.38	5.46	0.19	4.60	9.37	2.46	5.46	3.48
1086.88	1.4	85.81	50.36	0.94	16.36	1.38	5.46	0.19	4.56	9.32	2.47	5.48	3.50
1085.88	1.4	85.47	50.36	0.93	16.40	1.38	5.46	0.19	4.52	9.26	2.48	5.50	3.51
1084.88	1.4	85.14	50.37	0.93	16.44	1.38	5.46	0.19	4.49	9.21	2.49	5.52	3.52
1083.88	1.4	84.81	50.38	0.93	16.49	1.37	5.46	0.19	4.45	9.16	2.50	5.54	3.54
1082.88	1.4	84.48	50.38	0.93	16.53	1.37	5.46	0.19	4.41	9.10	2.51	5.56	3.55
1081.88	1.4	84.16	50.39	0.93	16.57	1.37	5.45	0.19	4.38	9.05	2.52	5.58	3.56
1080.88	1.4	83.83	50.40	0.93	16.61	1.37	5.45	0.19	4.34	9.00	2.53	5.61	3.58
1079.88	1.4	83.52	50.41	0.92	16.65	1.37	5.45	0.19	4.31	8.95	2.54	5.63	3.59
1078.88	1.4	83.20	50.41	0.92	16.69	1.37	5.45	0.19	4.27	8.89	2.54	5.65	3.61
1077.88	1.4	82.89	50.42	0.92	16.73	1.37	5.45	0.19	4.24	8.84	2.55	5.67	3.62
1076.88	1.4	82.58	50.43	0.92	16.77	1.37	5.44	0.19	4.20	8.79	2.56	5.69	3.63
1075.88	1.4	82.27	50.44	0.91	16.81	1.37	5.44	0.19	4.17	8.74	2.57	5.71	3.65
1074.88	1.4	81.97	50.45	0.91	16.85	1.37	5.44	0.20	4.13	8.68	2.58	5.73	3.66
1073.88	1.4	81.67	50.46	0.91	16.89	1.37	5.44	0.20	4.10	8.63	2.59	5.75	3.67
1072.88	1.4	81.37	50.47	0.91	16.92	1.37	5.43	0.20	4.06	8.58	2.60	5.78	3.69
1071.88	1.4	81.08	50.48	0.90	16.96	1.37	5.43	0.20	4.03	8.53	2.61	5.80	3.70
1070.88	1.4	80.78	50.49	0.90	17.00	1.37	5.43	0.20	4.00	8.48	2.62	5.82	3.71
1069.88	1.4	80.49	50.50	0.90	17.04	1.37	5.42	0.20	3.96	8.42	2.62	5.84	3.73
1068.88	1.4	80.21	50.51	0.90	17.08	1.37	5.42	0.20	3.93	8.37	2.63	5.86	3.74
1067.88	1.4	79.92	50.52	0.89	17.11	1.36	5.42	0.20	3.90	8.32	2.64	5.88	3.75
1066.88	1.4	79.64	50.53	0.89	17.15	1.36	5.41	0.20	3.87	8.27	2.65	5.90	3.77
1065.88	1.4	79.37	50.54	0.89	17.19	1.36	5.41	0.20	3.83	8.22	2.66	5.92	3.78
1064.88	1.4	79.09	50.55	0.88	17.22	1.36	5.41	0.20	3.80	8.17	2.67	5.94	3.79
1063.88	1.4	78.82	50.56	0.88	17.26	1.36	5.40	0.20	3.77	8.12	2.68	5.96	3.81
1062.88	1.4	78.55	50.57	0.88	17.30	1.36	5.40	0.20	3.74	8.07	2.69	5.98	3.82
1061.88	1.4	78.28	50.58	0.87	17.33	1.36	5.39	0.20	3.71	8.02	2.69	6.00	3.83
1060.88	1.4	78.01	50.59	0.87	17.37	1.36	5.39	0.21	3.67	7.97	2.70	6.02	3.85
1059.88	1.4	77.75	50.61	0.87	17.40	1.36	5.39	0.21	3.64	7.92	2.71	6.04	3.86
1058.88	1.4	77.49	50.62	0.86	17.44	1.36	5.38	0.21	3.61	7.87	2.72	6.07	3.87
1057.88	1.4	77.23	50.63	0.86	17.47	1.36	5.38	0.21	3.58	7.82	2.73	6.09	3.88
1056.88	1.4	76.98	50.64	0.85	17.51	1.35	5.37	0.21	3.55	7.77	2.74	6.11	3.90
1055.88	1.4	76.73	50.66	0.85	17.54	1.35	5.37	0.21	3.52	7.72	2.75	6.13	3.91
1054.88	1.4	76.48	50.67	0.85	17.58	1.35	5.36	0.21	3.49	7.67	2.75	6.15	3.92
1053.88	1.4	76.23	50.68	0.84	17.61	1.35	5.36	0.21	3.46	7.62	2.76	6.17	3.94
1052.88	1.4	75.98	50.70	0.84	17.64	1.35	5.35	0.21	3.43	7.57	2.77	6.19	3.95
1051.88	1.4	75.74	50.71	0.83	17.68	1.35	5.35	0.21	3.41	7.52	2.78	6.21	3.96
1050.88	1.4	75.50	50.72	0.83	17.71	1.35	5.34	0.21	3.38	7.48	2.79	6.23	3.97
1049.88	1.4	75.26	50.74	0.82	17.74	1.35	5.34	0.21	3.35	7.43	2.79	6.24	3.99
1048.88	1.4	75.03	50.75	0.82	17.77	1.35	5.33	0.21	3.32	7.38	2.80	6.26	4.00
1047.88	1.4	74.80	50.77	0.81	17.81	1.35	5.33	0.21	3.29	7.33	2.81	6.28	4.01
1046.88	1.4	74.56	50.78	0.81	17.84	1.34	5.32	0.21	3.26	7.28	2.82	6.30	4.02

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1045.88	1.4	74.34	50.79	0.80	17.87	1.34	5.31	0.22	3.24	7.24	2.83	6.32	4.04
1044.88	1.4	74.11	50.81	0.80	17.90	1.34	5.31	0.22	3.21	7.19	2.84	6.34	4.05
1043.88	1.4	73.89	50.82	0.80	17.93	1.34	5.30	0.22	3.18	7.14	2.84	6.36	4.06
1042.88	1.4	73.67	50.84	0.79	17.96	1.34	5.30	0.22	3.16	7.10	2.85	6.38	4.07
1041.88	1.4	73.45	50.85	0.78	17.99	1.34	5.29	0.22	3.13	7.05	2.86	6.40	4.08
1040.88	1.4	73.23	50.87	0.78	18.02	1.34	5.28	0.22	3.10	7.00	2.87	6.42	4.10
1039.88	1.4	73.02	50.89	0.77	18.05	1.34	5.28	0.22	3.08	6.96	2.88	6.44	4.11
1038.88	1.4	72.80	50.90	0.77	18.08	1.33	5.27	0.22	3.05	6.91	2.88	6.46	4.12
1037.88	1.4	72.59	50.92	0.76	18.11	1.33	5.26	0.22	3.03	6.87	2.89	6.47	4.13
1036.88	1.4	72.39	50.93	0.76	18.14	1.33	5.26	0.22	3.00	6.82	2.90	6.49	4.14
1035.88	1.4	72.18	50.95	0.75	18.17	1.33	5.25	0.22	2.97	6.77	2.91	6.51	4.16
1034.88	1.4	71.98	50.96	0.75	18.20	1.33	5.24	0.22	2.95	6.73	2.91	6.53	4.17
1033.88	1.4	71.78	50.98	0.74	18.23	1.33	5.24	0.22	2.93	6.69	2.92	6.55	4.18
1032.88	1.4	71.58	51.00	0.74	18.26	1.33	5.23	0.22	2.90	6.64	2.93	6.57	4.19
1031.88	1.4	71.38	51.01	0.73	18.28	1.33	5.22	0.22	2.88	6.60	2.94	6.58	4.20
1030.88	1.4	71.18	51.03	0.72	18.31	1.33	5.22	0.22	2.85	6.55	2.94	6.60	4.21
1029.88	1.4	70.99	51.05	0.72	18.34	1.32	5.21	0.23	2.83	6.51	2.95	6.62	4.23
1028.88	1.4	70.80	51.06	0.71	18.37	1.32	5.20	0.23	2.81	6.47	2.96	6.64	4.24
1027.88	1.4	70.61	51.08	0.71	18.39	1.32	5.20	0.23	2.78	6.42	2.97	6.66	4.25
1026.88	1.4	70.43	51.10	0.70	18.42	1.32	5.19	0.23	2.76	6.38	2.97	6.67	4.26
1025.88	1.4	70.24	51.11	0.69	18.45	1.32	5.18	0.23	2.74	6.34	2.98	6.69	4.27
1024.88	1.4	70.06	51.13	0.69	18.47	1.32	5.17	0.23	2.72	6.29	2.99	6.71	4.28
1023.88	1.4	69.88	51.15	0.68	18.50	1.32	5.17	0.23	2.69	6.25	3.00	6.73	4.29
1022.88	1.4	69.70	51.16	0.68	18.52	1.32	5.16	0.23	2.67	6.21	3.00	6.74	4.30
1021.88	1.4	69.52	51.18	0.67	18.55	1.31	5.15	0.23	2.65	6.17	3.01	6.76	4.32
1020.88	1.4	69.35	51.20	0.66	18.57	1.31	5.14	0.23	2.63	6.13	3.02	6.78	4.33
1019.88	1.4	69.18	51.22	0.66	18.60	1.31	5.14	0.23	2.61	6.09	3.02	6.79	4.34
1018.88	1.4	69.00	51.23	0.65	18.62	1.31	5.13	0.23	2.59	6.05	3.03	6.81	4.35
1017.88	1.4	68.84	51.25	0.65	18.65	1.31	5.12	0.23	2.56	6.01	3.04	6.83	4.36
1016.88	1.4	68.67	51.27	0.64	18.67	1.31	5.11	0.23	2.54	5.97	3.04	6.84	4.37
1015.88	1.4	68.50	51.28	0.63	18.70	1.31	5.11	0.23	2.52	5.93	3.05	6.86	4.38
1014.88	1.4	68.34	51.30	0.63	18.72	1.31	5.10	0.23	2.50	5.89	3.06	6.88	4.39
1013.88	1.4	68.18	51.32	0.62	18.74	1.30	5.09	0.23	2.48	5.85	3.06	6.89	4.40
1012.88	1.4	68.02	51.34	0.62	18.77	1.30	5.08	0.24	2.46	5.81	3.07	6.91	4.41
1011.88	1.4	67.86	51.35	0.61	18.79	1.30	5.07	0.24	2.44	5.77	3.08	6.93	4.42
1010.88	1.4	67.70	51.37	0.60	18.81	1.30	5.07	0.24	2.42	5.73	3.08	6.94	4.43
1009.88	1.4	67.55	51.39	0.60	18.84	1.30	5.06	0.24	2.41	5.69	3.09	6.96	4.44
1008.88	1.4	67.40	51.40	0.59	18.86	1.30	5.05	0.24	2.39	5.65	3.10	6.97	4.45
1007.88	1.4	67.24	51.42	0.59	18.88	1.30	5.04	0.24	2.37	5.61	3.10	6.99	4.46
1006.88	1.4	67.09	51.44	0.58	18.90	1.30	5.03	0.24	2.35	5.58	3.11	7.01	4.47
1005.88	1.4	66.95	51.46	0.57	18.92	1.29	5.03	0.24	2.33	5.54	3.12	7.02	4.48
1004.88	1.4	66.80	51.47	0.57	18.95	1.29	5.02	0.24	2.31	5.50	3.12	7.04	4.49
1003.88	1.4	66.65	51.49	0.56	18.97	1.29	5.01	0.24	2.29	5.47	3.13	7.05	4.50
1002.88	1.4	66.51	51.51	0.56	18.99	1.29	5.00	0.24	2.28	5.43	3.14	7.07	4.51
1001.88	1.4	66.37	51.52	0.55	19.01	1.29	4.99	0.24	2.26	5.39	3.14	7.08	4.52
1000.88	1.4	66.23	51.54	0.54	19.03	1.29	4.98	0.24	2.24	5.36	3.15	7.10	4.53
999.88	1.4	66.09	51.56	0.54	19.05	1.29	4.98	0.24	2.22	5.32	3.15	7.11	4.54
998.88	1.4	65.95	51.57	0.53	19.07	1.29	4.97	0.24	2.21	5.29	3.16	7.13	4.55
997.88	1.4	65.82	51.59	0.53	19.09	1.28	4.96	0.24	2.19	5.25	3.17	7.14	4.56
996.88	1.4	65.68	51.61	0.52	19.11	1.28	4.95	0.24	2.17	5.21	3.17	7.16	4.57
995.88	1.4	65.55	51.62	0.52	19.13	1.28	4.94	0.24	2.15	5.18	3.18	7.17	4.58
994.88	1.4	65.41	51.64	0.51	19.15	1.28	4.93	0.24	2.14	5.15	3.18	7.18	4.59
993.88	1.4	65.28	51.66	0.50	19.17	1.28	4.93	0.25	2.12	5.11	3.19	7.20	4.60
992.88	1.4	65.15	51.67	0.50	19.19	1.28	4.92	0.25	2.11	5.08	3.20	7.21	4.60
991.88	1.4	65.03	51.69	0.49	19.21	1.28	4.91	0.25	2.09	5.04	3.20	7.23	4.61
990.88	1.4	64.90	51.70	0.49	19.23	1.28	4.90	0.25	2.07	5.01	3.21	7.24	4.62
989.88	1.4	64.77	51.72	0.48	19.25	1.27	4.89	0.25	2.06	4.98	3.21	7.26	4.63
988.88	1.4	64.65	51.74	0.48	19.27	1.27	4.88	0.25	2.04	4.94	3.22	7.27	4.64
987.88	1.4	64.53	51.75	0.47	19.29	1.27	4.88	0.25	2.03	4.91	3.22	7.28	4.65
986.88	1.4	64.40	51.77	0.47	19.31	1.27	4.87	0.25	2.01	4.88	3.23	7.30	4.66
985.88	1.4	64.28	51.78	0.46	19.33	1.27	4.86	0.25	1.99	4.84	3.23	7.31	4.67
984.88	1.4	64.16	51.80	0.46	19.35	1.27	4.85	0.25	1.98	4.81	3.24	7.33	4.68
983.88	1.4	64.04	51.81	0.45	19.37	1.27	4.84	0.25	1.96	4.78	3.25	7.34	4.68
982.88	1.4	63.93	51.83	0.45	19.38	1.27	4.83	0.25	1.95	4.75	3.25	7.35	4.69
981.88	1.4	63.81	51.85	0.44	19.40	1.26	4.82	0.25	1.93	4.71	3.26	7.37	4.70
980.88	1.4	63.70	51.86	0.44	19.42	1.26	4.82	0.25	1.92	4.68	3.26	7.38	4.71
979.88	1.4	63.56	51.88	0.43	19.44	1.26	4.81	0.25	1.90	4.65	3.27	7.39	4.71
978.88	1.4	63.42	51.90	0.43	19.47	1.26	4.80	0.25	1.89	4.61	3.27	7.41	4.71
977.88	1.4	63.29	51.92	0.42	19.49	1.26	4.79	0.25	1.87	4.58	3.28	7.43	4.72
976.88	1.4	63.16	51.95	0.42	19.51	1.26	4.78	0.25	1.85	4.54	3.29	7.44	4.72
975.88	1.4	63.02	51.97	0.41	19.53	1.26	4.77	0.25	1.84	4.51	3.29	7.46	4.72

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
974.88	1.4	62.89	51.99	0.41	19.55	1.25	4.76	0.25	1.82	4.47	3.30	7.47	4.72
973.88	1.4	62.76	52.01	0.40	19.58	1.25	4.75	0.25	1.80	4.44	3.31	7.49	4.72
972.88	1.4	62.64	52.03	0.40	19.60	1.25	4.74	0.26	1.79	4.40	3.31	7.50	4.72
971.88	1.4	62.51	52.05	0.39	19.62	1.25	4.73	0.26	1.77	4.37	3.32	7.52	4.72
970.88	1.4	62.38	52.07	0.39	19.64	1.25	4.72	0.26	1.76	4.34	3.32	7.53	4.73
969.88	1.4	62.26	52.09	0.38	19.66	1.25	4.71	0.26	1.74	4.30	3.33	7.55	4.73
968.88	1.4	62.14	52.11	0.38	19.68	1.25	4.70	0.26	1.73	4.27	3.34	7.56	4.73
967.88	1.4	62.02	52.13	0.37	19.71	1.25	4.69	0.26	1.71	4.24	3.34	7.58	4.73
966.88	1.4	61.90	52.15	0.37	19.73	1.24	4.68	0.26	1.70	4.20	3.35	7.59	4.73
965.88	1.4	61.78	52.17	0.36	19.75	1.24	4.67	0.26	1.68	4.17	3.35	7.61	4.73
964.88	1.4	61.66	52.19	0.36	19.77	1.24	4.66	0.26	1.67	4.14	3.36	7.62	4.73
963.88	1.4	61.54	52.21	0.36	19.79	1.24	4.65	0.26	1.65	4.11	3.37	7.64	4.74
962.88	1.4	61.42	52.23	0.35	19.81	1.24	4.64	0.26	1.63	4.08	3.37	7.65	4.74
961.88	1.4	61.30	52.25	0.35	19.83	1.24	4.64	0.26	1.61	4.06	3.38	7.66	4.74
960.88	1.4	61.18	52.27	0.35	19.85	1.24	4.63	0.26	1.58	4.03	3.38	7.67	4.74
959.88	1.4	61.06	52.29	0.34	19.87	1.24	4.62	0.26	1.56	4.00	3.39	7.68	4.74
958.88	1.4	60.94	52.31	0.34	19.89	1.24	4.61	0.26	1.54	3.98	3.40	7.69	4.74
957.88	1.4	60.83	52.33	0.34	19.91	1.24	4.60	0.26	1.52	3.95	3.40	7.70	4.74
956.88	1.4	60.71	52.35	0.33	19.93	1.23	4.60	0.26	1.50	3.93	3.41	7.71	4.75
955.88	1.4	60.60	52.37	0.33	19.95	1.23	4.59	0.26	1.48	3.90	3.41	7.72	4.75
954.88	1.4	60.49	52.39	0.33	19.97	1.23	4.58	0.26	1.46	3.88	3.42	7.73	4.75
953.88	1.4	60.38	52.41	0.32	19.98	1.23	4.57	0.27	1.44	3.85	3.43	7.75	4.75
952.88	1.4	60.27	52.43	0.32	20.00	1.23	4.56	0.27	1.42	3.83	3.43	7.76	4.75
951.88	1.4	60.16	52.45	0.32	20.02	1.23	4.56	0.27	1.40	3.81	3.44	7.77	4.75
950.88	1.4	60.05	52.47	0.31	20.04	1.23	4.55	0.27	1.38	3.78	3.44	7.78	4.75
949.88	1.4	59.94	52.49	0.31	20.06	1.23	4.54	0.27	1.36	3.76	3.45	7.79	4.75
948.88	1.4	59.84	52.50	0.31	20.08	1.23	4.53	0.27	1.34	3.73	3.45	7.80	4.76
947.88	1.4	59.73	52.52	0.30	20.09	1.23	4.52	0.27	1.33	3.71	3.46	7.81	4.76
946.88	1.4	59.63	52.54	0.30	20.11	1.23	4.51	0.27	1.31	3.69	3.47	7.82	4.76
945.88	1.4	59.53	52.56	0.30	20.13	1.23	4.51	0.27	1.29	3.66	3.47	7.83	4.76
944.88	1.4	59.43	52.58	0.29	20.15	1.23	4.50	0.27	1.27	3.64	3.48	7.84	4.76
943.88	1.4	59.33	52.60	0.29	20.16	1.22	4.49	0.27	1.25	3.62	3.48	7.85	4.76
942.88	1.4	59.23	52.62	0.29	20.18	1.22	4.48	0.27	1.24	3.59	3.49	7.86	4.76
941.88	1.4	59.13	52.64	0.28	20.20	1.22	4.47	0.27	1.22	3.57	3.49	7.87	4.77
940.88	1.4	59.03	52.66	0.28	20.21	1.22	4.46	0.27	1.20	3.55	3.50	7.88	4.77
939.88	1.4	58.94	52.68	0.28	20.23	1.22	4.45	0.27	1.19	3.53	3.50	7.89	4.77
938.88	1.4	58.84	52.69	0.27	20.25	1.22	4.44	0.27	1.17	3.50	3.51	7.90	4.77
937.88	1.4	58.75	52.71	0.27	20.26	1.22	4.44	0.27	1.16	3.48	3.51	7.91	4.77
936.88	1.4	58.65	52.73	0.27	20.28	1.22	4.43	0.27	1.14	3.46	3.52	7.92	4.77
935.88	1.4	58.56	52.75	0.27	20.30	1.22	4.42	0.27	1.12	3.44	3.52	7.93	4.77
934.88	1.4	58.44	52.77	0.26	20.30	1.22	4.41	0.27	1.11	3.41	3.53	7.94	4.77
933.88	1.4	58.27	52.79	0.26	20.28	1.22	4.42	0.27	1.09	3.38	3.53	7.96	4.78
932.88	1.4	58.09	52.82	0.26	20.27	1.23	4.43	0.28	1.07	3.36	3.54	7.97	4.78
931.88	1.4	57.92	52.84	0.26	20.25	1.23	4.44	0.28	1.06	3.33	3.55	7.99	4.78
930.88	1.4	57.75	52.86	0.26	20.24	1.23	4.45	0.28	1.04	3.30	3.55	8.00	4.78
929.88	1.4	57.58	52.89	0.26	20.22	1.24	4.45	0.28	1.03	3.27	3.56	8.02	4.78
928.88	1.4	57.41	52.91	0.26	20.20	1.24	4.46	0.28	1.01	3.25	3.56	8.04	4.79
927.88	1.4	57.24	52.94	0.26	20.18	1.25	4.47	0.28	1.00	3.22	3.57	8.05	4.79
926.88	1.4	57.08	52.96	0.26	20.17	1.25	4.48	0.28	0.98	3.19	3.58	8.07	4.79
925.88	1.4	56.92	52.98	0.26	20.15	1.25	4.49	0.28	0.97	3.17	3.58	8.08	4.79
924.88	1.4	56.76	53.01	0.25	20.13	1.26	4.49	0.28	0.95	3.14	3.59	8.10	4.80
923.88	1.4	56.60	53.03	0.25	20.11	1.26	4.50	0.28	0.94	3.11	3.59	8.12	4.80
922.88	1.4	56.44	53.05	0.25	20.10	1.27	4.51	0.28	0.92	3.09	3.60	8.13	4.80
921.88	1.4	56.29	53.08	0.25	20.08	1.27	4.52	0.28	0.91	3.06	3.60	8.15	4.80
920.88	1.4	56.13	53.10	0.25	20.06	1.28	4.52	0.29	0.89	3.04	3.61	8.16	4.81
919.88	1.4	55.98	53.12	0.25	20.05	1.28	4.53	0.29	0.88	3.01	3.61	8.18	4.81
918.88	1.4	55.83	53.14	0.24	20.03	1.28	4.54	0.29	0.87	2.98	3.62	8.19	4.81
917.88	1.4	55.68	53.16	0.24	20.02	1.29	4.55	0.29	0.85	2.96	3.62	8.21	4.81
916.88	1.4	55.54	53.19	0.24	20.00	1.29	4.55	0.29	0.84	2.93	3.63	8.22	4.81
915.88	1.4	55.39	53.21	0.24	19.98	1.30	4.56	0.29	0.83	2.91	3.63	8.24	4.82
914.88	1.4	55.25	53.23	0.24	19.97	1.30	4.57	0.29	0.81	2.89	3.64	8.26	4.82
913.88	1.4	55.10	53.25	0.24	19.95	1.30	4.57	0.29	0.80	2.86	3.64	8.27	4.82
912.88	1.4	54.96	53.27	0.24	19.93	1.31	4.58	0.29	0.79	2.84	3.64	8.29	4.82
911.88	1.4	54.82	53.29	0.24	19.92	1.31	4.59	0.29	0.78	2.81	3.65	8.30	4.83
910.88	1.4	54.68	53.31	0.23	19.90	1.32	4.59	0.29	0.76	2.79	3.65	8.32	4.83
909.88	1.4	54.54	53.33	0.23	19.89	1.32	4.60	0.29	0.75	2.76	3.66	8.33	4.83
908.88	1.4	54.41	53.35	0.23	19.87	1.32	4.61	0.29	0.74	2.74	3.66	8.35	4.83
907.88	1.4	54.27	53.37	0.23	19.86	1.33	4.61	0.29	0.73	2.72	3.67	8.36	4.83
906.88	1.4	54.14	53.39	0.23	19.84	1.33	4.62	0.30	0.72	2.69	3.67	8.38	4.84
905.88	1.4	54.00	53.41	0.23	19.83	1.34	4.63	0.30	0.71	2.67	3.67	8.39	4.84
904.88	1.4	53.87	53.43	0.23	19.81	1.34	4.63	0.30	0.69	2.65	3.68	8.41	4.84

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
903.88	1.4	53.74	53.45	0.22	19.79	1.34	4.64	0.30	0.68	2.62	3.68	8.42	4.84
902.88	1.4	53.61	53.47	0.22	19.78	1.35	4.64	0.30	0.67	2.60	3.68	8.44	4.85
901.88	1.4	53.48	53.49	0.22	19.76	1.35	4.65	0.30	0.66	2.58	3.69	8.45	4.85
900.88	1.4	53.35	53.50	0.22	19.75	1.35	4.66	0.30	0.65	2.56	3.69	8.47	4.85
899.88	1.4	53.23	53.52	0.22	19.73	1.36	4.66	0.30	0.64	2.53	3.70	8.48	4.85
898.88	1.4	53.10	53.54	0.22	19.72	1.36	4.67	0.30	0.63	2.51	3.70	8.50	4.85
897.88	1.4	52.97	53.56	0.22	19.70	1.37	4.67	0.30	0.62	2.49	3.70	8.51	4.86
896.88	1.4	52.85	53.58	0.22	19.69	1.37	4.68	0.30	0.61	2.47	3.71	8.53	4.86
895.88	1.4	52.72	53.59	0.22	19.68	1.37	4.68	0.30	0.60	2.45	3.71	8.54	4.86
894.88	1.4	52.60	53.61	0.21	19.66	1.38	4.69	0.30	0.59	2.43	3.71	8.55	4.86
893.88	1.4	52.48	53.63	0.21	19.65	1.38	4.69	0.30	0.58	2.40	3.72	8.57	4.86
892.88	1.4	52.36	53.65	0.21	19.63	1.39	4.70	0.31	0.57	2.38	3.72	8.58	4.87
891.88	1.4	52.24	53.66	0.21	19.62	1.39	4.70	0.31	0.56	2.36	3.72	8.60	4.87
890.88	1.4	52.12	53.68	0.21	19.60	1.39	4.71	0.31	0.55	2.34	3.72	8.61	4.87
889.88	1.4	52.00	53.70	0.21	19.59	1.40	4.71	0.31	0.54	2.32	3.73	8.63	4.87
888.88	1.4	51.88	53.71	0.21	19.57	1.40	4.72	0.31	0.53	2.30	3.73	8.64	4.87
887.88	1.4	51.76	53.73	0.21	19.56	1.40	4.72	0.31	0.52	2.28	3.73	8.66	4.88
886.88	1.4	51.64	53.75	0.21	19.55	1.41	4.73	0.31	0.51	2.26	3.74	8.67	4.88
885.88	1.4	51.31	53.88	0.16	19.55	1.39	4.64	0.31	0.50	2.22	3.75	8.72	4.89
884.88	1.4	51.18	53.90	0.16	19.53	1.39	4.63	0.31	0.49	2.20	3.75	8.74	4.90
883.88	1.4	51.04	53.92	0.15	19.52	1.39	4.63	0.31	0.48	2.18	3.75	8.75	4.90
882.88	1.4	50.91	53.95	0.15	19.50	1.39	4.63	0.31	0.47	2.16	3.75	8.77	4.90
881.88	1.4	50.78	53.97	0.15	19.49	1.40	4.63	0.31	0.46	2.14	3.76	8.79	4.91
880.88	1.4	50.65	53.99	0.14	19.48	1.40	4.63	0.32	0.45	2.12	3.76	8.81	4.91
879.88	1.4	50.51	54.02	0.14	19.46	1.40	4.62	0.32	0.44	2.10	3.76	8.82	4.91
878.88	1.4	50.38	54.04	0.14	19.45	1.40	4.62	0.32	0.44	2.08	3.77	8.84	4.91
877.88	1.4	50.25	54.06	0.13	19.44	1.40	4.62	0.32	0.43	2.06	3.77	8.86	4.92
876.88	1.4	50.12	54.09	0.13	19.42	1.41	4.61	0.32	0.42	2.04	3.77	8.88	4.92
875.88	1.4	49.99	54.11	0.13	19.41	1.41	4.61	0.32	0.41	2.02	3.77	8.89	4.92
874.88	1.4	49.85	54.13	0.12	19.40	1.41	4.61	0.32	0.40	2.00	3.78	8.91	4.93
873.88	1.4	49.72	54.15	0.12	19.38	1.41	4.60	0.32	0.39	1.98	3.78	8.93	4.93
872.88	1.4	49.58	54.18	0.12	19.37	1.41	4.60	0.32	0.38	1.96	3.78	8.95	4.93
871.88	1.4	49.45	54.20	0.12	19.36	1.41	4.59	0.32	0.37	1.94	3.78	8.97	4.93
870.88	1.4	49.31	54.23	0.11	19.35	1.42	4.59	0.32	0.36	1.92	3.79	8.98	4.94
869.88	1.4	49.17	54.25	0.11	19.33	1.42	4.58	0.32	0.36	1.90	3.79	9.00	4.94
868.88	1.4	49.02	54.28	0.11	19.32	1.42	4.57	0.33	0.35	1.88	3.79	9.02	4.94
867.88	1.4	48.87	54.31	0.11	19.31	1.42	4.56	0.33	0.34	1.86	3.79	9.04	4.95
866.88	1.4	48.71	54.34	0.10	19.30	1.42	4.55	0.33	0.33	1.84	3.80	9.06	4.95
865.88	1.4	48.54	54.37	0.10	19.29	1.41	4.53	0.33	0.31	1.82	3.80	9.08	4.95
864.88	1.4	48.35	54.40	0.10	19.28	1.41	4.51	0.33	0.30	1.80	3.81	9.10	4.95
863.88	1.4	48.16	54.44	0.10	19.27	1.41	4.49	0.33	0.29	1.78	3.81	9.12	4.96
862.88	1.4	47.94	54.49	0.10	19.27	1.40	4.46	0.33	0.28	1.76	3.82	9.14	4.96
861.88	1.4	47.72	54.54	0.09	19.26	1.40	4.42	0.33	0.27	1.73	3.82	9.17	4.96
860.88	1.4	47.47	54.59	0.09	19.26	1.39	4.38	0.34	0.25	1.71	3.83	9.19	4.97
859.88	1.4	47.21	54.65	0.09	19.25	1.38	4.33	0.34	0.24	1.69	3.84	9.22	4.97
858.88	1.4	46.93	54.71	0.09	19.25	1.36	4.28	0.34	0.23	1.66	3.85	9.25	4.98
857.88	1.4	46.65	54.78	0.09	19.25	1.35	4.22	0.34	0.22	1.64	3.85	9.28	4.98
856.88	1.4	46.35	54.85	0.09	19.25	1.34	4.16	0.34	0.21	1.61	3.86	9.31	4.98
855.88	1.4	46.05	54.92	0.09	19.25	1.32	4.09	0.35	0.20	1.59	3.87	9.34	4.99
854.88	1.4	45.74	55.00	0.09	19.25	1.30	4.02	0.35	0.19	1.56	3.88	9.37	4.99
853.88	1.4	45.43	55.07	0.09	19.26	1.28	3.95	0.35	0.18	1.54	3.89	9.40	5.00
852.88	1.4	45.12	55.15	0.09	19.26	1.26	3.87	0.35	0.17	1.51	3.90	9.43	5.00
851.88	1.4	44.82	55.23	0.09	19.26	1.25	3.80	0.36	0.16	1.49	3.91	9.46	5.00
850.88	1.4	44.51	55.30	0.09	19.27	1.23	3.72	0.36	0.15	1.46	3.92	9.50	5.01
849.88	1.4	44.20	55.38	0.09	19.27	1.21	3.65	0.36	0.15	1.43	3.93	9.53	5.01
848.88	1.4	43.90	55.45	0.09	19.27	1.19	3.57	0.36	0.14	1.41	3.94	9.56	5.02
847.88	1.4	43.60	55.53	0.09	19.28	1.17	3.50	0.36	0.13	1.38	3.95	9.60	5.02
846.88	1.4	43.31	55.60	0.09	19.28	1.14	3.42	0.37	0.13	1.36	3.95	9.63	5.02
845.88	1.4	43.02	55.67	0.09	19.29	1.12	3.35	0.37	0.12	1.34	3.96	9.66	5.03
844.88	1.4	42.74	55.75	0.09	19.29	1.10	3.27	0.37	0.12	1.31	3.97	9.70	5.03
843.88	1.4	42.46	55.82	0.09	19.29	1.08	3.20	0.37	0.11	1.29	3.97	9.73	5.03
842.88	1.4	42.18	55.88	0.09	19.30	1.06	3.13	0.38	0.11	1.27	3.98	9.76	5.04
841.88	1.4	41.91	55.95	0.09	19.30	1.05	3.06	0.38	0.10	1.24	3.99	9.80	5.04
840.88	1.4	41.64	56.02	0.09	19.31	1.03	2.99	0.38	0.10	1.22	3.99	9.83	5.05
839.88	1.4	41.38	56.08	0.09	19.31	1.01	2.92	0.38	0.10	1.20	4.00	9.87	5.05
838.88	1.4	41.12	56.14	0.09	19.31	0.99	2.86	0.39	0.09	1.17	4.00	9.90	5.05
837.88	1.4	40.87	56.20	0.09	19.32	0.97	2.79	0.39	0.09	1.15	4.01	9.94	5.05
836.88	1.4	40.62	56.26	0.09	19.32	0.95	2.73	0.39	0.09	1.13	4.01	9.97	5.06
835.88	1.4	40.38	56.32	0.09	19.32	0.93	2.67	0.39	0.08	1.11	4.01	10.00	5.06
834.88	1.4	40.14	56.38	0.09	19.32	0.91	2.61	0.40	0.08	1.09	4.02	10.04	5.06
833.88	1.4	39.91	56.44	0.09	19.33	0.90	2.55	0.40	0.08	1.07	4.02	10.07	5.07

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
832.88	1.4	39.67	56.49	0.09	19.33	0.88	2.49	0.40	0.07	1.05	4.02	10.11	5.07
831.88	1.4	39.45	56.54	0.10	19.33	0.86	2.43	0.40	0.07	1.03	4.02	10.14	5.07
830.88	1.4	39.22	56.59	0.10	19.33	0.85	2.37	0.41	0.07	1.01	4.02	10.18	5.08
829.88	1.4	39.00	56.64	0.10	19.34	0.83	2.32	0.41	0.07	0.99	4.02	10.21	5.08
828.88	1.4	38.78	56.69	0.10	19.34	0.81	2.27	0.41	0.07	0.97	4.02	10.25	5.08
827.88	1.4	38.57	56.74	0.10	19.34	0.80	2.21	0.41	0.06	0.95	4.02	10.28	5.08
826.88	1.4	38.36	56.78	0.10	19.34	0.78	2.16	0.41	0.06	0.93	4.02	10.32	5.09
825.88	1.4	38.15	56.83	0.10	19.34	0.77	2.11	0.42	0.06	0.91	4.02	10.35	5.09
824.88	1.4	37.94	56.87	0.10	19.35	0.75	2.06	0.42	0.06	0.89	4.02	10.38	5.09
823.88	1.4	37.74	56.91	0.10	19.35	0.74	2.01	0.42	0.06	0.88	4.02	10.42	5.09
822.88	1.4	37.54	56.96	0.10	19.35	0.72	1.97	0.42	0.05	0.86	4.02	10.45	5.09
821.88	1.4	37.34	57.00	0.10	19.35	0.71	1.92	0.43	0.05	0.84	4.02	10.49	5.10
820.88	1.4	37.15	57.03	0.10	19.35	0.69	1.88	0.43	0.05	0.82	4.01	10.53	5.10
819.88	1.4	36.95	57.07	0.10	19.35	0.68	1.83	0.43	0.05	0.81	4.01	10.56	5.10
818.88	1.4	36.76	57.11	0.10	19.36	0.67	1.79	0.43	0.05	0.79	4.01	10.60	5.10
817.88	1.4	36.57	57.14	0.10	19.36	0.65	1.75	0.44	0.05	0.77	4.00	10.63	5.11
816.88	1.4	36.38	57.18	0.11	19.36	0.64	1.71	0.44	0.05	0.76	4.00	10.67	5.11
815.88	1.4	34.42	57.03	0.11	19.44	0.63	1.67	0.46	0.05	0.75	4.03	10.72	5.13
814.88	1.4	32.48	56.87	0.11	19.52	0.62	1.63	0.49	0.04	0.74	4.06	10.77	5.15
813.88	1.4	30.81	56.71	0.11	19.61	0.61	1.60	0.52	0.04	0.73	4.09	10.82	5.17
812.88	1.4	29.37	56.56	0.11	19.69	0.60	1.56	0.54	0.04	0.73	4.12	10.87	5.19
811.88	1.4	28.10	56.41	0.11	19.76	0.59	1.53	0.57	0.04	0.72	4.15	10.91	5.21
810.88	1.4	26.98	56.27	0.11	19.84	0.58	1.50	0.59	0.04	0.71	4.18	10.96	5.23
809.88	1.4	25.98	56.13	0.11	19.91	0.57	1.47	0.61	0.04	0.71	4.20	11.00	5.25
808.88	1.4	25.08	56.00	0.10	19.98	0.56	1.44	0.63	0.04	0.70	4.23	11.04	5.27
807.88	1.4	24.27	55.87	0.10	20.04	0.55	1.41	0.65	0.04	0.69	4.26	11.08	5.30
806.88	1.4	23.52	55.75	0.10	20.11	0.54	1.38	0.67	0.04	0.69	4.28	11.12	5.32
805.88	1.4	22.84	55.62	0.10	20.17	0.54	1.35	0.69	0.04	0.68	4.31	11.15	5.34
804.88	1.4	22.21	55.51	0.10	20.23	0.53	1.33	0.71	0.04	0.68	4.33	11.19	5.36
803.88	1.4	21.63	55.39	0.10	20.29	0.52	1.30	0.73	0.03	0.67	4.36	11.22	5.37
802.88	1.4	21.10	55.28	0.10	20.35	0.51	1.28	0.75	0.03	0.66	4.38	11.26	5.39
801.88	1.4	20.60	55.16	0.10	20.41	0.50	1.25	0.77	0.03	0.66	4.40	11.29	5.41
800.88	1.4	20.13	55.05	0.10	20.46	0.50	1.23	0.79	0.03	0.65	4.42	11.32	5.43
799.88	1.4	19.69	54.95	0.10	20.52	0.49	1.21	0.80	0.03	0.65	4.45	11.35	5.45
798.88	1.4	19.28	54.84	0.10	20.57	0.48	1.19	0.82	0.03	0.64	4.47	11.38	5.47
797.88	1.4	18.89	54.74	0.10	20.62	0.48	1.16	0.84	0.03	0.64	4.49	11.41	5.49
796.88	1.4	14.56	54.59	0.14	20.48	0.32	0.77	1.09	0.02	0.82	2.83	13.58	5.38
795.88	1.4	14.27	54.49	0.14	20.52	0.31	0.75	1.11	0.02	0.83	2.80	13.64	5.39
794.88	1.4	13.99	54.39	0.14	20.56	0.31	0.73	1.13	0.02	0.84	2.77	13.71	5.40
793.88	1.4	13.73	54.29	0.14	20.59	0.30	0.71	1.15	0.02	0.86	2.74	13.77	5.42
792.88	1.4	13.48	54.19	0.15	20.63	0.29	0.69	1.17	0.02	0.87	2.71	13.84	5.43
791.88	1.4	13.24	54.10	0.15	20.67	0.29	0.68	1.20	0.02	0.88	2.68	13.90	5.44
790.88	1.4	13.01	54.00	0.15	20.71	0.28	0.66	1.22	0.02	0.90	2.66	13.96	5.45
789.88	1.4	12.79	53.91	0.15	20.74	0.27	0.64	1.24	0.02	0.91	2.63	14.02	5.47
788.88	1.4	12.59	53.82	0.16	20.78	0.27	0.63	1.26	0.02	0.92	2.60	14.08	5.48
787.88	1.4	12.39	53.72	0.16	20.81	0.26	0.61	1.28	0.02	0.94	2.57	14.13	5.49
786.88	1.4	12.20	53.63	0.16	20.85	0.26	0.60	1.30	0.02	0.95	2.55	14.19	5.50
785.88	1.4	12.01	53.54	0.16	20.88	0.25	0.58	1.32	0.02	0.96	2.52	14.25	5.52
784.88	1.4	11.84	53.45	0.17	20.91	0.25	0.57	1.34	0.02	0.97	2.49	14.30	5.53
783.88	1.4	11.67	53.36	0.17	20.95	0.24	0.56	1.36	0.02	0.98	2.47	14.36	5.54
782.88	1.4	11.50	53.27	0.17	20.98	0.24	0.54	1.38	0.02	1.00	2.44	14.41	5.55
781.88	1.4	11.35	53.18	0.17	21.01	0.23	0.53	1.40	0.02	1.01	2.42	14.47	5.57
780.88	1.4	11.20	53.10	0.18	21.04	0.23	0.52	1.41	0.02	1.02	2.39	14.52	5.58
779.88	1.4	11.05	53.01	0.18	21.07	0.22	0.51	1.43	0.02	1.03	2.37	14.57	5.59
778.88	1.4	10.91	52.92	0.18	21.10	0.22	0.49	1.45	0.02	1.04	2.34	14.63	5.61
777.88	1.4	10.77	52.84	0.18	21.13	0.21	0.48	1.47	0.02	1.06	2.32	14.68	5.62
776.88	1.4	10.57	52.74	0.16	21.18	0.21	0.47	1.50	0.01	1.03	2.30	14.76	5.64
775.88	1.4	10.43	52.65	0.16	21.21	0.20	0.46	1.52	0.01	1.04	2.28	14.81	5.66
774.88	1.4	10.29	52.56	0.15	21.25	0.20	0.45	1.54	0.01	1.04	2.26	14.87	5.68
773.88	1.4	10.16	52.48	0.15	21.28	0.20	0.44	1.56	0.01	1.04	2.23	14.92	5.69
772.88	1.4	10.03	52.39	0.15	21.31	0.19	0.43	1.58	0.01	1.04	2.21	14.98	5.71
771.88	1.4	9.91	52.31	0.14	21.34	0.19	0.42	1.60	0.01	1.05	2.19	15.03	5.72
770.88	1.4	9.79	52.22	0.14	21.37	0.18	0.41	1.62	0.01	1.05	2.17	15.09	5.74
769.88	1.4	9.68	52.14	0.14	21.40	0.18	0.40	1.64	0.01	1.05	2.15	15.14	5.76
768.88	1.4	9.57	52.06	0.14	21.43	0.18	0.39	1.65	0.01	1.06	2.13	15.19	5.77
767.88	1.4	9.46	51.97	0.13	21.46	0.17	0.38	1.67	0.01	1.06	2.11	15.24	5.79
766.88	1.4	9.36	51.89	0.13	21.49	0.17	0.37	1.69	0.01	1.06	2.09	15.29	5.81
765.88	1.4	9.25	51.81	0.13	21.52	0.17	0.36	1.71	0.01	1.07	2.07	15.34	5.82
764.88	1.4	9.16	51.73	0.12	21.55	0.16	0.35	1.73	0.01	1.07	2.05	15.39	5.84
763.88	1.4	9.06	51.65	0.12	21.58	0.16	0.35	1.75	0.01	1.07	2.03	15.44	5.86
762.88	1.4	8.97	51.57	0.12	21.60	0.16	0.34	1.77	0.01	1.08	2.01	15.49	5.87

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T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
761.88	1.4	8.88	51.49	0.12	21.63	0.15	0.33	1.78	0.01	1.08	1.99	15.54	5.89
760.88	1.4	8.79	51.41	0.11	21.66	0.15	0.32	1.80	0.01	1.08	1.97	15.58	5.91
759.88	1.4	8.71	51.33	0.11	21.69	0.15	0.31	1.82	0.01	1.09	1.95	15.63	5.93
758.88	1.4	8.62	51.25	0.11	21.71	0.14	0.31	1.84	0.01	1.09	1.93	15.68	5.94
757.88	1.4	8.54	51.17	0.10	21.74	0.14	0.30	1.85	0.01	1.09	1.91	15.72	5.96
756.88	1.4	8.47	51.09	0.10	21.77	0.14	0.29	1.87	0.01	1.10	1.89	15.77	5.98
755.88	1.4	8.39	51.01	0.10	21.79	0.14	0.29	1.89	0.00	1.10	1.87	15.81	5.99
754.88	1.4	8.32	50.94	0.10	21.82	0.13	0.28	1.90	0.00	1.10	1.86	15.86	6.01
753.88	1.4	8.24	50.86	0.10	21.84	0.13	0.27	1.92	0.00	1.11	1.84	15.90	6.03
752.88	1.4	8.17	50.78	0.09	21.87	0.13	0.27	1.94	0.00	1.11	1.82	15.94	6.05
751.88	1.4	8.10	50.71	0.09	21.89	0.13	0.26	1.95	0.00	1.11	1.80	15.98	6.07
750.88	1.4	8.04	50.63	0.09	21.92	0.12	0.26	1.97	0.00	1.12	1.78	16.03	6.08
749.88	1.4	7.97	50.55	0.09	21.94	0.12	0.25	1.99	0.00	1.12	1.77	16.07	6.10
748.88	1.4	7.91	50.48	0.08	21.96	0.12	0.25	2.00	0.00	1.12	1.75	16.11	6.12
747.88	1.4	7.84	50.40	0.08	21.99	0.12	0.24	2.02	0.00	1.13	1.73	16.15	6.14
746.88	1.4	7.78	50.33	0.08	22.01	0.11	0.23	2.03	0.00	1.13	1.71	16.19	6.16
745.88	1.4	7.72	50.25	0.08	22.03	0.11	0.23	2.05	0.00	1.13	1.70	16.23	6.18
744.88	1.4	7.66	50.18	0.08	22.06	0.11	0.22	2.07	0.00	1.14	1.68	16.27	6.19
743.88	1.4	7.61	50.10	0.07	22.08	0.11	0.22	2.08	0.00	1.14	1.66	16.31	6.21
742.88	1.4	7.55	50.03	0.07	22.10	0.11	0.21	2.10	0.00	1.15	1.65	16.35	6.23
741.88	1.4	7.49	49.96	0.07	22.12	0.10	0.21	2.11	0.00	1.15	1.63	16.39	6.25
740.88	1.4	7.44	49.88	0.07	22.15	0.10	0.20	2.13	0.00	1.15	1.61	16.43	6.27
739.88	1.4	7.39	49.81	0.07	22.17	0.10	0.20	2.14	0.00	1.16	1.60	16.47	6.29
738.88	1.4	7.34	49.74	0.07	22.19	0.10	0.20	2.16	0.00	1.16	1.58	16.50	6.31
737.88	1.4	7.28	49.66	0.06	22.21	0.10	0.19	2.17	0.00	1.16	1.57	16.54	6.33
736.88	1.4	7.23	49.59	0.06	22.23	0.09	0.19	2.19	0.00	1.17	1.55	16.58	6.35
735.88	1.4	7.19	49.52	0.06	22.25	0.09	0.18	2.20	0.00	1.17	1.53	16.61	6.37
734.88	1.4	7.14	49.44	0.06	22.28	0.09	0.18	2.22	0.00	1.17	1.52	16.65	6.39
733.88	1.4	7.09	49.37	0.06	22.30	0.09	0.18	2.23	0.00	1.18	1.50	16.69	6.41
732.88	1.4	7.04	49.30	0.06	22.32	0.09	0.17	2.25	0.00	1.18	1.49	16.72	6.43
731.88	1.4	7.00	49.23	0.06	22.34	0.09	0.17	2.26	0.00	1.18	1.47	16.76	6.45
730.88	1.4	6.95	49.15	0.05	22.35	0.08	0.16	2.28	0.00	1.18	1.46	16.80	6.47
729.88	1.4	6.91	49.08	0.05	22.37	0.08	0.16	2.29	0.00	1.18	1.45	16.83	6.49
728.88	1.4	6.86	49.01	0.05	22.39	0.08	0.16	2.31	0.00	1.18	1.44	16.87	6.52
727.88	1.4	6.82	48.94	0.05	22.40	0.08	0.15	2.32	0.00	1.18	1.42	16.91	6.54
726.88	1.4	6.77	48.87	0.05	22.42	0.08	0.15	2.34	0.00	1.18	1.41	16.95	6.56
725.88	1.4	6.73	48.80	0.05	22.44	0.08	0.15	2.35	0.00	1.18	1.40	16.98	6.58
724.88	1.4	6.69	48.72	0.05	22.45	0.07	0.14	2.37	0.00	1.18	1.38	17.02	6.61
723.88	1.4	6.65	48.65	0.05	22.47	0.07	0.14	2.38	0.00	1.18	1.37	17.06	6.63
722.88	1.4	6.61	48.58	0.05	22.49	0.07	0.14	2.40	0.00	1.17	1.36	17.09	6.65
721.88	1.4	6.57	48.51	0.05	22.50	0.07	0.13	2.41	0.00	1.17	1.35	17.13	6.67
720.88	1.4	6.53	48.44	0.05	22.52	0.07	0.13	2.43	0.00	1.17	1.33	17.16	6.70
719.88	1.4	6.49	48.37	0.04	22.54	0.07	0.13	2.44	0.00	1.17	1.32	17.20	6.72
718.88	1.4	6.45	48.30	0.04	22.55	0.07	0.13	2.45	0.00	1.17	1.31	17.23	6.75
717.88	1.4	6.41	48.23	0.04	22.57	0.07	0.12	2.47	0.00	1.17	1.30	17.27	6.77
716.88	1.4	6.38	48.16	0.04	22.58	0.06	0.12	2.48	0.00	1.17	1.29	17.30	6.79
715.88	1.4	6.34	48.08	0.04	22.60	0.06	0.12	2.50	0.00	1.17	1.28	17.34	6.82
714.88	1.4	6.30	48.01	0.04	22.61	0.06	0.11	2.51	0.00	1.17	1.26	17.37	6.84
713.88	1.4	6.27	47.94	0.04	22.63	0.06	0.11	2.53	0.00	1.16	1.25	17.40	6.87
712.88	1.4	6.23	47.87	0.04	22.64	0.06	0.11	2.54	0.00	1.16	1.24	17.44	6.89
711.88	1.4	6.20	47.80	0.04	22.66	0.06	0.11	2.55	0.00	1.16	1.23	17.47	6.92
710.88	1.4	6.16	47.73	0.04	22.67	0.06	0.11	2.57	0.00	1.16	1.22	17.50	6.94
709.88	1.4	6.13	47.66	0.04	22.69	0.06	0.10	2.58	0.00	1.16	1.21	17.54	6.97
708.88	1.4	6.10	47.59	0.04	22.70	0.06	0.10	2.60	0.00	1.16	1.20	17.57	7.00
707.88	1.4	6.06	47.52	0.04	22.72	0.05	0.10	2.61	0.00	1.16	1.19	17.60	7.02
706.88	1.4	6.03	47.45	0.04	22.73	0.05	0.10	2.62	0.00	1.16	1.18	17.63	7.05
705.88	1.4	6.00	47.38	0.03	22.74	0.05	0.09	2.64	0.00	1.15	1.17	17.67	7.08
704.88	1.4	5.97	47.30	0.03	22.76	0.05	0.09	2.65	0.00	1.15	1.16	17.70	7.10
703.88	1.4	5.94	47.23	0.03	22.77	0.05	0.09	2.67	0.00	1.15	1.14	17.73	7.13
702.88	1.4	5.91	47.16	0.03	22.78	0.05	0.09	2.68	0.00	1.15	1.13	17.76	7.16
701.88	1.4	5.88	47.09	0.03	22.80	0.05	0.09	2.69	0.00	1.15	1.12	17.79	7.18
700.88	1.4	5.85	47.02	0.03	22.81	0.05	0.08	2.71	0.00	1.15	1.11	17.82	7.21

Table A1.7: Best-fit fractional crystallisation Rhyolite-MELTS model for central caldera group eruptions.

Liquid remaining is reported in grams, the model begins with 100g of liquid. The starting temperature is the liquidus temperature of the system, calculated by Rhyolite-MELTS.

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1154.88	1.6	98.88	50.77	0.95	14.92	1.38	5.49	0.16	6.03	11.36	2.16	4.75	2.02
1153.88	1.6	98.38	50.77	0.96	14.97	1.38	5.49	0.16	5.99	11.30	2.17	4.78	2.03
1152.88	1.6	97.89	50.77	0.96	15.03	1.38	5.50	0.16	5.94	11.24	2.18	4.80	2.04
1151.88	1.6	97.41	50.77	0.96	15.08	1.38	5.50	0.16	5.89	11.18	2.19	4.82	2.05
1150.88	1.6	96.93	50.77	0.96	15.14	1.38	5.51	0.17	5.84	11.13	2.20	4.85	2.06
1149.88	1.6	96.46	50.76	0.96	15.19	1.38	5.51	0.17	5.80	11.07	2.21	4.87	2.07
1148.88	1.6	95.99	50.76	0.97	15.24	1.38	5.51	0.17	5.75	11.01	2.22	4.90	2.08
1147.88	1.6	95.53	50.76	0.97	15.30	1.38	5.52	0.17	5.71	10.95	2.23	4.92	2.09
1146.88	1.6	95.07	50.76	0.97	15.35	1.38	5.52	0.17	5.66	10.90	2.24	4.94	2.10
1145.88	1.6	94.62	50.76	0.97	15.40	1.38	5.52	0.17	5.61	10.84	2.25	4.97	2.11
1144.88	1.6	94.17	50.76	0.97	15.45	1.38	5.53	0.17	5.57	10.78	2.26	4.99	2.12
1143.88	1.6	93.73	50.77	0.98	15.51	1.38	5.53	0.17	5.52	10.72	2.27	5.01	2.13
1142.88	1.6	93.29	50.77	0.98	15.56	1.38	5.53	0.17	5.48	10.67	2.28	5.04	2.14
1141.88	1.6	92.86	50.77	0.98	15.61	1.38	5.54	0.17	5.43	10.61	2.29	5.06	2.15
1140.88	1.6	92.43	50.77	0.98	15.66	1.38	5.54	0.17	5.39	10.55	2.30	5.09	2.16
1139.88	1.6	92.00	50.77	0.98	15.71	1.38	5.54	0.17	5.34	10.50	2.31	5.11	2.17
1138.88	1.6	91.59	50.77	0.99	15.76	1.38	5.54	0.17	5.30	10.44	2.32	5.13	2.18
1137.88	1.6	91.17	50.77	0.99	15.81	1.38	5.55	0.18	5.26	10.38	2.33	5.16	2.19
1136.88	1.6	90.76	50.77	0.99	15.86	1.38	5.55	0.18	5.21	10.33	2.34	5.18	2.20
1135.88	1.6	90.36	50.78	0.99	15.91	1.38	5.55	0.18	5.17	10.27	2.35	5.20	2.21
1134.88	1.6	89.96	50.78	0.99	15.96	1.38	5.55	0.18	5.13	10.22	2.36	5.22	2.22
1133.88	1.6	89.56	50.78	0.99	16.01	1.38	5.55	0.18	5.08	10.16	2.37	5.25	2.23
1132.88	1.6	89.17	50.78	0.99	16.06	1.38	5.56	0.18	5.04	10.10	2.38	5.27	2.24
1131.88	1.6	88.78	50.79	1.00	16.11	1.38	5.56	0.18	5.00	10.05	2.39	5.29	2.25
1130.88	1.6	88.40	50.79	1.00	16.16	1.38	5.56	0.18	4.96	9.99	2.40	5.32	2.26
1129.88	1.6	88.02	50.79	1.00	16.21	1.38	5.56	0.18	4.91	9.94	2.41	5.34	2.27
1128.88	1.6	87.64	50.80	1.00	16.26	1.38	5.56	0.18	4.87	9.88	2.42	5.36	2.28
1127.88	1.6	87.27	50.80	1.00	16.30	1.38	5.56	0.18	4.83	9.83	2.43	5.39	2.29
1126.88	1.6	86.90	50.80	1.00	16.35	1.38	5.56	0.18	4.79	9.77	2.44	5.41	2.30
1125.88	1.6	86.54	50.81	1.00	16.40	1.38	5.56	0.18	4.75	9.72	2.45	5.43	2.31
1124.88	1.6	86.18	50.81	1.00	16.45	1.38	5.56	0.19	4.71	9.66	2.46	5.45	2.32
1123.88	1.6	85.82	50.82	1.00	16.49	1.38	5.56	0.19	4.67	9.61	2.47	5.48	2.33
1122.88	1.6	85.47	50.82	1.00	16.54	1.38	5.56	0.19	4.63	9.55	2.48	5.50	2.34
1121.88	1.6	85.12	50.83	1.00	16.59	1.38	5.56	0.19	4.59	9.50	2.49	5.52	2.35
1120.88	1.6	84.77	50.83	1.01	16.63	1.38	5.56	0.19	4.55	9.45	2.50	5.54	2.36
1119.88	1.6	84.43	50.84	1.01	16.68	1.38	5.56	0.19	4.51	9.39	2.51	5.57	2.37
1118.88	1.6	84.10	50.84	1.01	16.72	1.38	5.56	0.19	4.47	9.34	2.52	5.59	2.38
1117.88	1.6	83.76	50.85	1.01	16.77	1.38	5.56	0.19	4.43	9.29	2.53	5.61	2.39
1116.88	1.6	83.43	50.85	1.01	16.81	1.38	5.56	0.19	4.39	9.23	2.54	5.63	2.40
1115.88	1.6	83.10	50.86	1.01	16.86	1.38	5.56	0.19	4.35	9.18	2.55	5.66	2.41
1114.88	1.6	82.78	50.87	1.01	16.90	1.38	5.56	0.19	4.31	9.13	2.56	5.68	2.42
1113.88	1.6	82.46	50.87	1.01	16.95	1.38	5.56	0.19	4.28	9.07	2.57	5.70	2.43
1112.88	1.6	82.14	50.88	1.01	16.99	1.38	5.56	0.19	4.24	9.02	2.58	5.72	2.43
1111.88	1.6	81.83	50.89	1.01	17.04	1.38	5.56	0.20	4.20	8.97	2.58	5.74	2.44
1110.88	1.6	81.51	50.89	1.01	17.08	1.38	5.55	0.20	4.16	8.91	2.59	5.77	2.45
1109.88	1.6	81.21	50.90	1.01	17.12	1.38	5.55	0.20	4.13	8.86	2.60	5.79	2.46
1108.88	1.6	80.90	50.91	1.01	17.17	1.38	5.55	0.20	4.09	8.81	2.61	5.81	2.47
1107.88	1.6	80.60	50.92	1.01	17.21	1.38	5.55	0.20	4.05	8.76	2.62	5.83	2.48
1106.88	1.6	80.30	50.92	1.01	17.25	1.37	5.55	0.20	4.02	8.71	2.63	5.85	2.49
1105.88	1.6	80.01	50.93	1.01	17.29	1.37	5.54	0.20	3.98	8.65	2.64	5.87	2.50
1104.88	1.6	79.71	50.94	1.01	17.33	1.37	5.54	0.20	3.95	8.60	2.65	5.90	2.51
1103.88	1.6	79.42	50.95	1.01	17.38	1.37	5.54	0.20	3.91	8.55	2.66	5.92	2.52
1102.88	1.6	79.14	50.96	1.01	17.42	1.37	5.54	0.20	3.88	8.50	2.67	5.94	2.53
1101.88	1.6	78.85	50.96	1.01	17.46	1.37	5.53	0.20	3.84	8.45	2.68	5.96	2.54
1100.88	1.6	78.57	50.97	1.00	17.50	1.37	5.53	0.20	3.81	8.40	2.68	5.98	2.55
1099.88	1.6	78.30	50.98	1.00	17.54	1.37	5.53	0.20	3.77	8.35	2.69	6.00	2.55
1098.88	1.6	78.02	50.99	1.00	17.58	1.37	5.53	0.21	3.74	8.30	2.70	6.02	2.56
1097.88	1.6	77.75	51.00	1.00	17.62	1.37	5.52	0.21	3.70	8.25	2.71	6.05	2.57
1096.88	1.6	77.48	51.01	1.00	17.66	1.37	5.52	0.21	3.67	8.20	2.72	6.07	2.58
1095.88	1.6	77.21	51.02	1.00	17.70	1.37	5.52	0.21	3.64	8.15	2.73	6.09	2.59
1094.88	1.6	76.95	51.03	1.00	17.74	1.37	5.51	0.21	3.60	8.10	2.74	6.11	2.60
1093.88	1.6	76.69	51.04	1.00	17.78	1.36	5.51	0.21	3.57	8.05	2.75	6.13	2.61
1092.88	1.6	76.43	51.05	1.00	17.82	1.36	5.51	0.21	3.54	8.00	2.76	6.15	2.62
1091.88	1.6	76.17	51.06	1.00	17.85	1.36	5.50	0.21	3.51	7.95	2.76	6.17	2.63
1090.88	1.6	75.92	51.07	0.99	17.89	1.36	5.50	0.21	3.47	7.90	2.77	6.19	2.63
1089.88	1.6	75.66	51.08	0.99	17.93	1.36	5.49	0.21	3.44	7.85	2.78	6.21	2.64
1088.88	1.6	75.41	51.09	0.99	17.97	1.36	5.49	0.21	3.41	7.80	2.79	6.23	2.65
1087.88	1.6	75.17	51.10	0.99	18.01	1.36	5.49	0.21	3.38	7.75	2.80	6.25	2.66
1086.88	1.6	74.92	51.12	0.99	18.04	1.36	5.48	0.21	3.35	7.70	2.81	6.27	2.67
1085.88	1.6	74.68	51.13	0.99	18.08	1.36	5.48	0.21	3.32	7.66	2.82	6.29	2.68
1084.88	1.6	74.44	51.14	0.99	18.12	1.36	5.47	0.21	3.29	7.61	2.82	6.31	2.69

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1083.88	1.6	74.20	51.15	0.98	18.15	1.36	5.47	0.22	3.25	7.56	2.83	6.33	2.70
1082.88	1.6	73.97	51.16	0.98	18.19	1.35	5.46	0.22	3.22	7.51	2.84	6.35	2.70
1081.88	1.6	73.74	51.17	0.98	18.22	1.35	5.46	0.22	3.19	7.47	2.85	6.37	2.71
1080.88	1.6	73.51	51.19	0.98	18.26	1.35	5.45	0.22	3.16	7.42	2.86	6.39	2.72
1079.88	1.6	73.28	51.20	0.98	18.29	1.35	5.45	0.22	3.14	7.37	2.87	6.41	2.73
1078.88	1.6	73.05	51.21	0.97	18.33	1.35	5.44	0.22	3.11	7.32	2.87	6.43	2.74
1077.88	1.6	72.83	51.22	0.97	18.36	1.35	5.44	0.22	3.08	7.28	2.88	6.45	2.75
1076.88	1.6	72.61	51.24	0.97	18.40	1.35	5.43	0.22	3.05	7.23	2.89	6.47	2.75
1075.88	1.6	72.39	51.25	0.97	18.43	1.35	5.42	0.22	3.02	7.18	2.90	6.49	2.76
1074.88	1.6	72.17	51.26	0.97	18.47	1.35	5.42	0.22	2.99	7.14	2.91	6.51	2.77
1073.88	1.6	71.96	51.28	0.96	18.50	1.34	5.41	0.22	2.96	7.09	2.91	6.53	2.78
1072.88	1.6	71.74	51.29	0.96	18.53	1.34	5.41	0.22	2.94	7.05	2.92	6.55	2.79
1071.88	1.6	71.53	51.30	0.96	18.57	1.34	5.40	0.22	2.91	7.00	2.93	6.57	2.80
1070.88	1.6	71.32	51.32	0.96	18.60	1.34	5.40	0.22	2.88	6.95	2.94	6.59	2.80
1069.88	1.6	71.12	51.33	0.95	18.63	1.34	5.39	0.22	2.85	6.91	2.95	6.61	2.81
1068.88	1.6	70.91	51.34	0.95	18.67	1.34	5.38	0.23	2.83	6.86	2.95	6.63	2.82
1067.88	1.6	70.71	51.36	0.95	18.70	1.34	5.38	0.23	2.80	6.82	2.96	6.65	2.83
1066.88	1.6	70.51	51.37	0.94	18.73	1.34	5.37	0.23	2.77	6.77	2.97	6.67	2.84
1065.88	1.6	70.31	51.39	0.94	18.76	1.33	5.36	0.23	2.75	6.73	2.98	6.68	2.84
1064.88	1.6	70.11	51.40	0.94	18.79	1.33	5.36	0.23	2.72	6.69	2.98	6.70	2.85
1063.88	1.6	69.91	51.42	0.93	18.82	1.33	5.35	0.23	2.70	6.64	2.99	6.72	2.86
1062.88	1.6	69.72	51.43	0.93	18.85	1.33	5.34	0.23	2.67	6.60	3.00	6.74	2.87
1061.88	1.6	69.53	51.45	0.93	18.89	1.33	5.34	0.23	2.65	6.55	3.01	6.76	2.88
1060.88	1.6	69.34	51.46	0.93	18.92	1.33	5.33	0.23	2.62	6.51	3.02	6.78	2.88
1059.88	1.6	69.15	51.48	0.92	18.95	1.33	5.32	0.23	2.60	6.47	3.02	6.80	2.89
1058.88	1.6	68.97	51.49	0.92	18.98	1.33	5.31	0.23	2.57	6.42	3.03	6.81	2.90
1057.88	1.6	68.78	51.51	0.91	19.01	1.32	5.31	0.23	2.55	6.38	3.04	6.83	2.91
1056.88	1.6	68.60	51.53	0.91	19.03	1.32	5.30	0.23	2.52	6.34	3.05	6.85	2.92
1055.88	1.6	68.42	51.54	0.91	19.06	1.32	5.29	0.23	2.50	6.30	3.05	6.87	2.92
1054.88	1.6	68.24	51.56	0.90	19.09	1.32	5.28	0.23	2.48	6.25	3.06	6.89	2.93
1053.88	1.6	68.06	51.57	0.90	19.12	1.32	5.28	0.24	2.45	6.21	3.07	6.91	2.94
1052.88	1.6	67.89	51.59	0.90	19.15	1.32	5.27	0.24	2.43	6.17	3.08	6.92	2.95
1051.88	1.6	67.71	51.61	0.89	19.18	1.32	5.26	0.24	2.41	6.13	3.08	6.94	2.95
1050.88	1.6	67.54	51.62	0.89	19.21	1.31	5.25	0.24	2.38	6.09	3.09	6.96	2.96
1049.88	1.6	67.37	51.64	0.88	19.23	1.31	5.25	0.24	2.36	6.04	3.10	6.98	2.97
1048.88	1.6	67.20	51.66	0.88	19.26	1.31	5.24	0.24	2.34	6.00	3.10	6.99	2.98
1047.88	1.6	67.03	51.67	0.88	19.29	1.31	5.23	0.24	2.32	5.96	3.11	7.01	2.98
1046.88	1.6	66.87	51.69	0.87	19.31	1.31	5.22	0.24	2.30	5.92	3.12	7.03	2.99
1045.88	1.6	66.70	51.71	0.87	19.34	1.31	5.21	0.24	2.27	5.88	3.13	7.05	3.00
1044.88	1.6	66.54	51.72	0.86	19.37	1.31	5.21	0.24	2.25	5.84	3.13	7.06	3.01
1043.88	1.6	66.38	51.74	0.86	19.39	1.30	5.20	0.24	2.23	5.80	3.14	7.08	3.01
1042.88	1.6	66.22	51.76	0.85	19.42	1.30	5.19	0.24	2.21	5.76	3.15	7.10	3.02
1041.88	1.6	66.06	51.78	0.85	19.45	1.30	5.18	0.24	2.19	5.72	3.15	7.11	3.03
1040.88	1.6	65.90	51.79	0.84	19.47	1.30	5.17	0.24	2.17	5.68	3.16	7.13	3.03
1039.88	1.6	65.75	51.81	0.84	19.50	1.30	5.16	0.24	2.15	5.64	3.17	7.15	3.04
1038.88	1.6	65.59	51.83	0.83	19.52	1.30	5.15	0.24	2.13	5.60	3.17	7.17	3.05
1037.88	1.6	65.44	51.85	0.83	19.55	1.30	5.15	0.24	2.11	5.56	3.18	7.18	3.06
1036.88	1.6	65.29	51.87	0.82	19.57	1.29	5.14	0.25	2.09	5.52	3.19	7.20	3.06
1035.88	1.6	65.14	51.88	0.82	19.59	1.29	5.13	0.25	2.07	5.49	3.19	7.21	3.07
1034.88	1.6	65.00	51.90	0.81	19.62	1.29	5.12	0.25	2.05	5.45	3.20	7.23	3.08
1033.88	1.6	64.85	51.92	0.81	19.64	1.29	5.11	0.25	2.03	5.41	3.21	7.25	3.08
1032.88	1.6	64.71	51.94	0.80	19.67	1.29	5.10	0.25	2.01	5.37	3.21	7.26	3.09
1031.88	1.6	64.56	51.96	0.80	19.69	1.29	5.09	0.25	2.00	5.33	3.22	7.28	3.10
1030.88	1.6	64.42	51.98	0.79	19.71	1.28	5.08	0.25	1.98	5.30	3.23	7.30	3.10
1029.88	1.6	64.28	52.00	0.79	19.73	1.28	5.08	0.25	1.96	5.26	3.23	7.31	3.11
1028.88	1.6	64.14	52.01	0.78	19.76	1.28	5.07	0.25	1.94	5.22	3.24	7.33	3.12
1027.88	1.6	64.00	52.03	0.78	19.78	1.28	5.06	0.25	1.92	5.19	3.25	7.34	3.12
1026.88	1.6	63.87	52.05	0.77	19.80	1.28	5.05	0.25	1.91	5.15	3.25	7.36	3.13
1025.88	1.6	63.73	52.07	0.77	19.82	1.28	5.04	0.25	1.89	5.11	3.26	7.37	3.14
1024.88	1.6	63.60	52.09	0.76	19.84	1.28	5.03	0.25	1.87	5.08	3.26	7.39	3.14
1023.88	1.6	63.47	52.11	0.76	19.87	1.27	5.02	0.25	1.86	5.04	3.27	7.41	3.15
1022.88	1.6	63.34	52.13	0.75	19.89	1.27	5.01	0.25	1.84	5.01	3.28	7.42	3.16
1021.88	1.6	63.21	52.15	0.74	19.91	1.27	5.00	0.25	1.82	4.97	3.28	7.44	3.16
1020.88	1.6	63.08	52.17	0.74	19.93	1.27	4.99	0.25	1.81	4.94	3.29	7.45	3.17
1019.88	1.6	62.95	52.18	0.73	19.95	1.27	4.98	0.25	1.79	4.90	3.29	7.47	3.18
1018.88	1.6	62.83	52.20	0.73	19.97	1.27	4.97	0.25	1.77	4.87	3.30	7.48	3.18
1017.88	1.6	62.71	52.22	0.72	19.99	1.26	4.96	0.26	1.76	4.83	3.31	7.50	3.19
1016.88	1.6	62.58	52.24	0.71	20.01	1.26	4.95	0.26	1.74	4.80	3.31	7.51	3.20
1015.88	1.6	62.46	52.26	0.71	20.03	1.26	4.95	0.26	1.73	4.76	3.32	7.52	3.20
1014.88	1.6	62.34	52.28	0.70	20.05	1.26	4.94	0.26	1.71	4.73	3.32	7.54	3.21
1013.88	1.6	62.22	52.30	0.70	20.07	1.26	4.93	0.26	1.70	4.70	3.33	7.55	3.21

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1012.88	1.6	62.10	52.32	0.69	20.09	1.26	4.92	0.26	1.68	4.66	3.34	7.57	3.22
1011.88	1.6	61.99	52.34	0.69	20.11	1.26	4.91	0.26	1.67	4.63	3.34	7.58	3.23
1010.88	1.6	61.87	52.36	0.68	20.13	1.25	4.90	0.26	1.65	4.60	3.35	7.60	3.23
1009.88	1.6	61.76	52.38	0.67	20.14	1.25	4.89	0.26	1.64	4.57	3.35	7.61	3.24
1008.88	1.6	61.65	52.40	0.67	20.16	1.25	4.88	0.26	1.63	4.53	3.36	7.62	3.24
1007.88	1.6	61.53	52.41	0.66	20.18	1.25	4.87	0.26	1.61	4.50	3.36	7.64	3.25
1006.88	1.6	61.42	52.43	0.66	20.20	1.25	4.86	0.26	1.60	4.47	3.37	7.65	3.26
1005.88	1.6	61.31	52.45	0.65	20.22	1.25	4.85	0.26	1.58	4.44	3.37	7.67	3.26
1004.88	1.6	61.21	52.47	0.64	20.23	1.25	4.84	0.26	1.57	4.41	3.38	7.68	3.27
1003.88	1.6	61.10	52.49	0.64	20.25	1.24	4.83	0.26	1.56	4.37	3.39	7.69	3.27
1002.88	1.6	60.99	52.51	0.63	20.27	1.24	4.82	0.26	1.54	4.34	3.39	7.71	3.28
1001.88	1.6	60.89	52.53	0.63	20.29	1.24	4.81	0.26	1.53	4.31	3.40	7.72	3.28
1000.88	1.6	60.78	52.55	0.62	20.30	1.24	4.80	0.26	1.52	4.28	3.40	7.73	3.29
999.88	1.6	60.68	52.57	0.61	20.32	1.24	4.79	0.26	1.51	4.25	3.41	7.75	3.30
998.88	1.6	60.58	52.58	0.61	20.34	1.24	4.78	0.26	1.49	4.22	3.41	7.76	3.30
997.88	1.6	60.48	52.60	0.60	20.35	1.24	4.77	0.26	1.48	4.19	3.42	7.77	3.31
996.88	1.6	60.38	52.62	0.60	20.37	1.23	4.76	0.26	1.47	4.16	3.42	7.78	3.31
995.88	1.6	60.28	52.64	0.59	20.38	1.23	4.76	0.27	1.46	4.13	3.43	7.80	3.32
994.88	1.6	60.18	52.66	0.59	20.40	1.23	4.75	0.27	1.44	4.10	3.43	7.81	3.32
993.88	1.6	60.09	52.68	0.58	20.42	1.23	4.74	0.27	1.43	4.08	3.44	7.82	3.33
992.88	1.6	59.99	52.69	0.57	20.43	1.23	4.73	0.27	1.42	4.05	3.44	7.83	3.33
991.88	1.6	59.89	52.71	0.57	20.45	1.23	4.72	0.27	1.41	4.02	3.45	7.85	3.34
990.88	1.6	59.80	52.73	0.56	20.46	1.23	4.71	0.27	1.40	3.99	3.45	7.86	3.34
989.88	1.6	59.71	52.75	0.56	20.48	1.22	4.70	0.27	1.39	3.96	3.46	7.87	3.35
988.88	1.6	59.61	52.76	0.55	20.50	1.22	4.69	0.27	1.37	3.93	3.46	7.88	3.35
987.88	1.6	59.52	52.78	0.55	20.51	1.22	4.68	0.27	1.36	3.91	3.47	7.90	3.36
986.88	1.6	59.43	52.80	0.54	20.53	1.22	4.67	0.27	1.35	3.88	3.47	7.91	3.37
985.88	1.6	59.34	52.82	0.54	20.54	1.22	4.66	0.27	1.34	3.85	3.48	7.92	3.37
984.88	1.6	59.25	52.84	0.53	20.56	1.22	4.65	0.27	1.33	3.82	3.48	7.93	3.38
983.88	1.6	59.16	52.85	0.53	20.57	1.22	4.64	0.27	1.32	3.80	3.48	7.94	3.38
982.88	1.6	59.08	52.87	0.52	20.59	1.22	4.63	0.27	1.31	3.77	3.49	7.96	3.39
981.88	1.6	58.99	52.89	0.52	20.60	1.21	4.62	0.27	1.30	3.74	3.49	7.97	3.39
980.88	1.6	58.90	52.90	0.51	20.61	1.21	4.61	0.27	1.29	3.72	3.50	7.98	3.40
979.88	1.6	58.82	52.92	0.51	20.63	1.21	4.60	0.27	1.28	3.69	3.50	7.99	3.40
978.88	1.6	58.74	52.94	0.50	20.64	1.21	4.59	0.27	1.27	3.66	3.51	8.00	3.41
977.88	1.6	58.65	52.95	0.50	20.66	1.21	4.58	0.27	1.26	3.64	3.51	8.01	3.41
976.88	1.6	58.57	52.97	0.49	20.67	1.21	4.57	0.27	1.25	3.61	3.52	8.02	3.41
975.88	1.6	58.49	52.99	0.49	20.69	1.21	4.56	0.27	1.24	3.59	3.52	8.04	3.42
974.88	1.6	58.40	53.00	0.48	20.70	1.20	4.55	0.27	1.23	3.56	3.53	8.05	3.42
973.88	1.6	58.32	53.02	0.48	20.71	1.20	4.54	0.27	1.22	3.54	3.53	8.06	3.43
972.88	1.6	58.24	53.04	0.47	20.73	1.20	4.53	0.27	1.21	3.51	3.53	8.07	3.43
971.88	1.6	58.16	53.05	0.47	20.74	1.20	4.52	0.28	1.20	3.49	3.54	8.08	3.44
970.88	1.6	58.08	53.07	0.46	20.76	1.20	4.52	0.28	1.19	3.46	3.54	8.09	3.44
969.88	1.6	58.01	53.08	0.46	20.77	1.20	4.51	0.28	1.18	3.44	3.55	8.10	3.45
968.88	1.6	57.93	53.10	0.45	20.78	1.20	4.50	0.28	1.17	3.41	3.55	8.11	3.45
967.88	1.6	57.85	53.12	0.45	20.80	1.20	4.49	0.28	1.16	3.39	3.56	8.12	3.46
966.88	1.6	57.77	53.13	0.45	20.81	1.19	4.48	0.28	1.15	3.36	3.56	8.14	3.46
965.88	1.6	57.70	53.15	0.44	20.82	1.19	4.47	0.28	1.14	3.34	3.56	8.15	3.47
964.88	1.6	57.61	53.16	0.44	20.83	1.19	4.46	0.28	1.13	3.31	3.57	8.16	3.47
963.88	1.6	57.51	53.18	0.43	20.83	1.19	4.46	0.28	1.13	3.29	3.57	8.17	3.48
962.88	1.6	57.40	53.19	0.43	20.83	1.19	4.45	0.28	1.12	3.26	3.58	8.19	3.48
961.88	1.6	57.30	53.21	0.43	20.82	1.19	4.45	0.28	1.12	3.23	3.58	8.20	3.49
960.88	1.6	57.20	53.22	0.42	20.82	1.19	4.45	0.28	1.11	3.20	3.58	8.22	3.50
959.88	1.6	57.09	53.24	0.42	20.82	1.20	4.45	0.28	1.11	3.18	3.59	8.23	3.50
958.88	1.6	56.99	53.25	0.42	20.82	1.20	4.44	0.28	1.10	3.15	3.59	8.25	3.51
957.88	1.6	56.89	53.27	0.42	20.82	1.20	4.44	0.28	1.10	3.12	3.59	8.26	3.52
956.88	1.6	56.79	53.28	0.41	20.81	1.20	4.44	0.28	1.09	3.09	3.60	8.27	3.52
955.88	1.6	56.69	53.29	0.41	20.81	1.20	4.43	0.28	1.09	3.07	3.60	8.29	3.53
954.88	1.6	56.60	53.31	0.41	20.81	1.20	4.43	0.28	1.08	3.04	3.60	8.30	3.53
953.88	1.6	56.50	53.32	0.40	20.81	1.20	4.43	0.28	1.08	3.02	3.61	8.32	3.54
952.88	1.6	56.40	53.34	0.40	20.80	1.20	4.43	0.28	1.07	2.99	3.61	8.33	3.55
951.88	1.6	56.31	53.35	0.40	20.80	1.20	4.42	0.28	1.07	2.96	3.61	8.34	3.55
950.88	1.6	56.21	53.36	0.40	20.80	1.20	4.42	0.28	1.06	2.94	3.62	8.36	3.56
949.88	1.6	56.12	53.38	0.39	20.80	1.20	4.42	0.29	1.06	2.91	3.62	8.37	3.56
948.88	1.6	56.02	53.39	0.39	20.80	1.20	4.41	0.29	1.05	2.89	3.62	8.39	3.57
947.88	1.6	55.93	53.40	0.39	20.79	1.20	4.41	0.29	1.05	2.86	3.63	8.40	3.58
946.88	1.6	55.84	53.42	0.39	20.79	1.20	4.41	0.29	1.05	2.84	3.63	8.41	3.58
945.88	1.6	55.74	53.43	0.38	20.79	1.20	4.41	0.29	1.04	2.81	3.63	8.43	3.59
944.88	1.6	55.65	53.44	0.38	20.79	1.21	4.40	0.29	1.04	2.79	3.64	8.44	3.59
943.88	1.6	55.56	53.45	0.38	20.78	1.21	4.40	0.29	1.03	2.76	3.64	8.45	3.60
942.88	1.6	55.47	53.47	0.38	20.78	1.21	4.40	0.29	1.03	2.74	3.64	8.47	3.61

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
941.88	1.6	55.38	53.48	0.37	20.78	1.21	4.40	0.29	1.02	2.72	3.64	8.48	3.61
940.88	1.6	55.29	53.49	0.37	20.78	1.21	4.39	0.29	1.02	2.69	3.65	8.49	3.62
939.88	1.6	55.21	53.50	0.37	20.77	1.21	4.39	0.29	1.02	2.67	3.65	8.51	3.62
938.88	1.6	55.12	53.52	0.37	20.77	1.21	4.39	0.29	1.01	2.65	3.65	8.52	3.63
937.88	1.6	55.03	53.53	0.36	20.77	1.21	4.39	0.29	1.01	2.62	3.65	8.53	3.63
936.88	1.6	54.91	53.54	0.36	20.76	1.21	4.39	0.29	1.00	2.60	3.66	8.55	3.64
935.88	1.6	54.78	53.56	0.36	20.74	1.22	4.40	0.29	0.98	2.58	3.66	8.56	3.65
934.88	1.6	54.64	53.57	0.36	20.73	1.22	4.40	0.29	0.97	2.56	3.67	8.57	3.65
933.88	1.6	54.51	53.59	0.36	20.72	1.22	4.41	0.29	0.95	2.54	3.67	8.59	3.66
932.88	1.6	54.39	53.60	0.36	20.71	1.23	4.42	0.29	0.94	2.52	3.67	8.60	3.67
931.88	1.6	54.26	53.62	0.36	20.70	1.23	4.42	0.29	0.92	2.49	3.67	8.61	3.67
930.88	1.6	54.13	53.63	0.35	20.69	1.23	4.43	0.30	0.91	2.47	3.68	8.63	3.68
929.88	1.6	54.01	53.65	0.35	20.68	1.24	4.43	0.30	0.90	2.45	3.68	8.64	3.68
928.88	1.6	53.89	53.66	0.35	20.66	1.24	4.44	0.30	0.88	2.43	3.68	8.66	3.69
927.88	1.6	53.76	53.67	0.35	20.65	1.25	4.44	0.30	0.87	2.41	3.69	8.67	3.70
926.88	1.6	53.64	53.69	0.35	20.64	1.25	4.45	0.30	0.86	2.39	3.69	8.68	3.70
925.88	1.6	53.52	53.70	0.35	20.63	1.25	4.46	0.30	0.84	2.37	3.69	8.70	3.71
924.88	1.6	53.40	53.72	0.35	20.62	1.26	4.46	0.30	0.83	2.35	3.70	8.71	3.71
923.88	1.6	53.28	53.73	0.35	20.61	1.26	4.47	0.30	0.82	2.33	3.70	8.72	3.72
922.88	1.6	53.17	53.74	0.34	20.60	1.26	4.47	0.30	0.81	2.31	3.70	8.73	3.73
921.88	1.6	53.05	53.75	0.34	20.59	1.27	4.48	0.30	0.79	2.29	3.70	8.75	3.73
920.88	1.6	52.93	53.77	0.34	20.58	1.27	4.48	0.30	0.78	2.27	3.71	8.76	3.74
919.88	1.6	52.82	53.78	0.34	20.57	1.27	4.49	0.30	0.77	2.25	3.71	8.77	3.75
918.88	1.6	52.71	53.79	0.34	20.55	1.28	4.49	0.30	0.76	2.23	3.71	8.79	3.75
917.88	1.6	52.59	53.80	0.34	20.54	1.28	4.50	0.30	0.75	2.21	3.71	8.80	3.76
916.88	1.6	52.48	53.82	0.34	20.53	1.28	4.50	0.30	0.73	2.20	3.72	8.81	3.76
915.88	1.6	52.37	53.83	0.34	20.52	1.29	4.51	0.31	0.72	2.18	3.72	8.83	3.77
914.88	1.6	52.26	53.84	0.34	20.51	1.29	4.51	0.31	0.71	2.16	3.72	8.84	3.78
913.88	1.6	52.15	53.85	0.33	20.50	1.29	4.52	0.31	0.70	2.14	3.72	8.85	3.78
912.88	1.6	51.80	53.99	0.27	20.51	1.27	4.42	0.31	0.68	2.11	3.73	8.90	3.80
911.88	1.6	51.67	54.01	0.27	20.50	1.27	4.42	0.31	0.67	2.09	3.73	8.92	3.81
910.88	1.6	51.54	54.03	0.26	20.49	1.27	4.42	0.31	0.66	2.07	3.74	8.94	3.82
909.88	1.6	51.42	54.05	0.26	20.48	1.27	4.41	0.31	0.65	2.05	3.74	8.95	3.83
908.88	1.6	51.29	54.07	0.25	20.47	1.28	4.41	0.31	0.64	2.03	3.74	8.97	3.83
907.88	1.6	51.16	54.09	0.25	20.46	1.28	4.41	0.31	0.63	2.01	3.74	8.98	3.84
906.88	1.6	51.04	54.11	0.24	20.45	1.28	4.40	0.31	0.62	2.00	3.74	9.00	3.85
905.88	1.6	50.91	54.13	0.24	20.44	1.28	4.40	0.31	0.61	1.98	3.75	9.02	3.86
904.88	1.6	50.79	54.14	0.24	20.43	1.28	4.40	0.31	0.60	1.96	3.75	9.03	3.86
903.88	1.6	50.67	54.16	0.23	20.42	1.28	4.39	0.31	0.59	1.94	3.75	9.05	3.87
902.88	1.6	50.54	54.18	0.23	20.41	1.28	4.39	0.31	0.58	1.92	3.75	9.07	3.88
901.88	1.6	50.42	54.20	0.22	20.40	1.28	4.38	0.32	0.57	1.91	3.75	9.08	3.89
900.88	1.6	50.30	54.22	0.22	20.39	1.29	4.38	0.32	0.56	1.89	3.75	9.10	3.89
899.88	1.6	50.18	54.23	0.21	20.38	1.29	4.38	0.32	0.55	1.87	3.76	9.11	3.90
898.88	1.6	50.07	54.25	0.21	20.37	1.29	4.37	0.32	0.54	1.86	3.76	9.13	3.91
897.88	1.6	49.95	54.27	0.21	20.36	1.29	4.37	0.32	0.53	1.84	3.76	9.15	3.92
896.88	1.6	49.83	54.29	0.20	20.35	1.29	4.37	0.32	0.52	1.82	3.76	9.16	3.92
895.88	1.6	49.71	54.30	0.20	20.34	1.29	4.36	0.32	0.51	1.80	3.76	9.18	3.93
894.88	1.6	49.60	54.32	0.19	20.33	1.29	4.36	0.32	0.50	1.79	3.76	9.20	3.94
893.88	1.6	49.48	54.34	0.19	20.32	1.29	4.35	0.32	0.50	1.77	3.76	9.21	3.95
892.88	1.6	49.37	54.35	0.19	20.31	1.30	4.35	0.32	0.49	1.75	3.76	9.23	3.95
891.88	1.6	49.26	54.37	0.18	20.30	1.30	4.35	0.32	0.48	1.74	3.76	9.24	3.96
890.88	1.6	49.14	54.38	0.18	20.29	1.30	4.34	0.32	0.47	1.72	3.77	9.26	3.97
889.88	1.6	49.03	54.40	0.17	20.28	1.30	4.34	0.32	0.46	1.71	3.77	9.28	3.98
888.88	1.6	48.92	54.42	0.17	20.27	1.30	4.33	0.32	0.45	1.69	3.77	9.29	3.98
887.88	1.6	48.81	54.43	0.17	20.26	1.30	4.33	0.32	0.44	1.67	3.77	9.31	3.99
886.88	1.6	48.69	54.45	0.16	20.26	1.30	4.32	0.33	0.44	1.66	3.77	9.32	4.00
885.88	1.6	48.58	54.46	0.16	20.25	1.30	4.32	0.33	0.43	1.64	3.77	9.34	4.01
884.88	1.6	48.47	54.48	0.16	20.24	1.30	4.32	0.33	0.42	1.63	3.77	9.36	4.01
883.88	1.6	48.36	54.49	0.15	20.23	1.31	4.31	0.33	0.41	1.61	3.77	9.37	4.02
882.88	1.6	48.25	54.51	0.15	20.22	1.31	4.31	0.33	0.40	1.59	3.77	9.39	4.03
881.88	1.6	48.14	54.52	0.15	20.21	1.31	4.30	0.33	0.40	1.58	3.77	9.40	4.04
880.88	1.6	48.03	54.54	0.14	20.20	1.31	4.29	0.33	0.39	1.56	3.77	9.42	4.04
879.88	1.6	47.92	54.55	0.14	20.20	1.31	4.29	0.33	0.38	1.55	3.77	9.44	4.05
878.88	1.6	47.81	54.57	0.14	20.19	1.31	4.28	0.33	0.37	1.53	3.77	9.45	4.06
877.88	1.6	47.69	54.58	0.13	20.18	1.31	4.28	0.33	0.36	1.52	3.77	9.47	4.07
876.88	1.6	47.58	54.59	0.13	20.17	1.31	4.27	0.33	0.36	1.50	3.77	9.49	4.07
875.88	1.6	47.47	54.61	0.13	20.16	1.31	4.26	0.33	0.35	1.49	3.77	9.50	4.08
874.88	1.6	47.35	54.63	0.13	20.16	1.31	4.26	0.33	0.34	1.47	3.77	9.52	4.09
873.88	1.6	47.24	54.64	0.12	20.15	1.31	4.25	0.33	0.33	1.46	3.77	9.54	4.10
872.88	1.6	47.12	54.66	0.12	20.14	1.31	4.24	0.34	0.32	1.44	3.77	9.55	4.11
871.88	1.6	47.00	54.67	0.12	20.14	1.31	4.23	0.34	0.31	1.42	3.77	9.57	4.11

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
870.88	1.6	46.87	54.69	0.11	20.13	1.31	4.22	0.34	0.30	1.41	3.77	9.59	4.12
869.88	1.6	46.74	54.71	0.11	20.13	1.31	4.20	0.34	0.30	1.39	3.77	9.61	4.13
868.88	1.6	46.60	54.73	0.11	20.12	1.31	4.19	0.34	0.29	1.38	3.77	9.62	4.14
867.88	1.6	46.45	54.76	0.11	20.12	1.30	4.17	0.34	0.28	1.36	3.78	9.64	4.15
866.88	1.6	46.29	54.78	0.11	20.12	1.30	4.14	0.34	0.27	1.35	3.78	9.66	4.16
865.88	1.6	46.12	54.81	0.10	20.11	1.30	4.12	0.34	0.25	1.33	3.78	9.68	4.17
864.88	1.6	45.93	54.85	0.10	20.12	1.29	4.08	0.34	0.24	1.31	3.78	9.70	4.18
863.88	1.6	45.74	54.88	0.10	20.12	1.28	4.05	0.35	0.23	1.29	3.79	9.73	4.19
862.88	1.6	45.53	54.92	0.10	20.12	1.27	4.00	0.35	0.22	1.28	3.79	9.75	4.20
861.88	1.6	45.32	54.96	0.10	20.12	1.26	3.96	0.35	0.21	1.26	3.79	9.77	4.21
860.88	1.6	45.09	55.01	0.10	20.13	1.25	3.90	0.35	0.20	1.24	3.80	9.80	4.23
859.88	1.6	44.86	55.05	0.10	20.14	1.23	3.85	0.35	0.19	1.22	3.80	9.82	4.24
858.88	1.6	44.62	55.10	0.10	20.14	1.22	3.79	0.35	0.18	1.20	3.81	9.85	4.25
857.88	1.6	44.38	55.15	0.10	20.15	1.20	3.73	0.36	0.17	1.18	3.81	9.87	4.26
856.88	1.6	44.14	55.20	0.09	20.16	1.19	3.67	0.36	0.17	1.17	3.82	9.90	4.28
855.88	1.6	43.90	55.25	0.09	20.17	1.17	3.60	0.36	0.16	1.15	3.82	9.93	4.29
854.88	1.6	43.66	55.30	0.09	20.18	1.15	3.54	0.36	0.15	1.13	3.83	9.96	4.31
853.88	1.6	43.41	55.35	0.09	20.19	1.14	3.47	0.36	0.14	1.11	3.83	9.98	4.32
852.88	1.6	43.17	55.40	0.09	20.20	1.12	3.41	0.37	0.14	1.09	3.84	10.01	4.33
851.88	1.6	42.94	55.45	0.09	20.21	1.10	3.34	0.37	0.13	1.07	3.84	10.04	4.35
850.88	1.6	42.70	55.50	0.10	20.22	1.08	3.27	0.37	0.13	1.06	3.84	10.07	4.36
849.88	1.6	42.47	55.55	0.10	20.23	1.07	3.21	0.37	0.12	1.04	3.85	10.09	4.38
848.88	1.6	42.24	55.60	0.10	20.24	1.05	3.14	0.37	0.11	1.02	3.85	10.12	4.39
847.88	1.6	42.02	55.65	0.10	20.25	1.03	3.08	0.38	0.11	1.00	3.86	10.15	4.41
846.88	1.6	41.79	55.69	0.10	20.26	1.01	3.02	0.38	0.11	0.99	3.86	10.18	4.42
845.88	1.6	41.58	55.73	0.10	20.27	1.00	2.95	0.38	0.10	0.97	3.86	10.20	4.43
844.88	1.6	41.36	55.78	0.10	20.28	0.98	2.89	0.38	0.10	0.95	3.86	10.23	4.45
843.88	1.6	41.15	55.82	0.10	20.29	0.96	2.83	0.38	0.09	0.94	3.87	10.26	4.46
842.88	1.6	40.95	55.86	0.10	20.30	0.94	2.77	0.39	0.09	0.92	3.87	10.29	4.48
841.88	1.6	40.74	55.90	0.10	20.30	0.93	2.71	0.39	0.09	0.91	3.87	10.31	4.49
840.88	1.6	40.54	55.94	0.10	20.31	0.91	2.66	0.39	0.08	0.89	3.87	10.34	4.51
839.88	1.6	40.35	55.98	0.10	20.32	0.89	2.60	0.39	0.08	0.87	3.87	10.37	4.52
838.88	1.6	40.15	56.01	0.10	20.33	0.88	2.55	0.39	0.08	0.86	3.87	10.40	4.53
837.88	1.6	39.96	56.05	0.10	20.34	0.86	2.49	0.39	0.08	0.84	3.87	10.42	4.55
836.88	1.6	39.78	56.08	0.10	20.35	0.85	2.44	0.40	0.07	0.83	3.87	10.45	4.56
835.88	1.6	39.59	56.12	0.10	20.35	0.83	2.39	0.40	0.07	0.82	3.87	10.48	4.58
834.88	1.6	39.41	56.15	0.10	20.36	0.82	2.34	0.40	0.07	0.80	3.87	10.50	4.59
833.88	1.6	39.23	56.18	0.10	20.37	0.80	2.29	0.40	0.07	0.79	3.87	10.53	4.60
832.88	1.6	39.06	56.21	0.10	20.38	0.79	2.24	0.40	0.07	0.77	3.87	10.56	4.62
831.88	1.6	38.89	56.24	0.10	20.38	0.77	2.19	0.41	0.06	0.76	3.87	10.58	4.63
830.88	1.6	38.72	56.26	0.10	20.39	0.76	2.14	0.41	0.06	0.75	3.87	10.61	4.65
829.88	1.6	38.55	56.29	0.11	20.40	0.75	2.10	0.41	0.06	0.73	3.86	10.64	4.66
828.88	1.6	38.39	56.32	0.11	20.41	0.73	2.05	0.41	0.06	0.72	3.86	10.66	4.67
827.88	1.6	38.22	56.34	0.11	20.41	0.72	2.01	0.41	0.06	0.71	3.86	10.69	4.69
826.88	1.6	38.06	56.36	0.11	20.42	0.71	1.97	0.41	0.06	0.69	3.86	10.72	4.70
825.88	1.6	37.90	56.39	0.11	20.42	0.69	1.92	0.42	0.05	0.68	3.86	10.74	4.71
824.88	1.6	37.75	56.41	0.11	20.43	0.68	1.88	0.42	0.05	0.67	3.85	10.77	4.73
823.88	1.6	37.59	56.43	0.11	20.44	0.67	1.84	0.42	0.05	0.66	3.85	10.80	4.74
822.88	1.6	37.39	56.43	0.11	20.45	0.66	1.81	0.42	0.05	0.65	3.85	10.82	4.76
821.88	1.6	37.07	56.41	0.11	20.47	0.65	1.77	0.43	0.05	0.64	3.85	10.83	4.80
820.88	1.6	36.76	56.39	0.11	20.48	0.64	1.74	0.43	0.05	0.64	3.85	10.84	4.83
819.88	1.6	36.45	56.36	0.11	20.50	0.63	1.71	0.43	0.05	0.63	3.85	10.86	4.87
818.88	1.6	36.15	56.33	0.11	20.52	0.62	1.68	0.44	0.05	0.63	3.85	10.87	4.91
817.88	1.6	35.86	56.31	0.11	20.54	0.61	1.65	0.44	0.04	0.62	3.85	10.88	4.94
816.88	1.6	35.56	56.28	0.11	20.56	0.60	1.62	0.44	0.04	0.62	3.86	10.90	4.98
815.88	1.6	35.27	56.25	0.11	20.58	0.59	1.59	0.45	0.04	0.61	3.86	10.91	5.01
814.88	1.6	34.99	56.22	0.11	20.59	0.58	1.56	0.45	0.04	0.61	3.86	10.92	5.05
813.88	1.6	34.71	56.19	0.11	20.61	0.57	1.53	0.45	0.04	0.60	3.86	10.94	5.09
812.88	1.6	34.43	56.16	0.11	20.63	0.56	1.51	0.46	0.04	0.60	3.86	10.95	5.12
811.88	1.6	34.16	56.13	0.11	20.65	0.55	1.48	0.46	0.04	0.60	3.86	10.96	5.16
810.88	1.6	29.20	56.41	0.13	20.53	0.42	1.14	0.54	0.03	0.69	2.69	12.27	5.15
809.88	1.6	28.84	56.38	0.13	20.55	0.41	1.11	0.55	0.03	0.70	2.64	12.32	5.18
808.88	1.6	28.50	56.36	0.13	20.56	0.41	1.08	0.55	0.03	0.71	2.60	12.36	5.21
807.88	1.6	28.17	56.33	0.14	20.57	0.40	1.06	0.56	0.03	0.71	2.56	12.41	5.24
806.88	1.6	27.85	56.30	0.14	20.58	0.39	1.03	0.57	0.03	0.72	2.52	12.46	5.27
805.88	1.6	27.54	56.27	0.14	20.60	0.38	1.01	0.57	0.03	0.73	2.48	12.50	5.30
804.88	1.6	26.42	56.12	0.14	20.70	0.37	0.98	0.60	0.03	0.75	2.42	12.58	5.30
803.88	1.6	25.41	55.98	0.15	20.81	0.36	0.95	0.62	0.03	0.77	2.37	12.65	5.30
802.88	1.6	24.49	55.84	0.16	20.91	0.35	0.93	0.64	0.03	0.79	2.32	12.72	5.30
801.88	1.6	23.65	55.70	0.16	21.01	0.34	0.90	0.67	0.03	0.82	2.27	12.79	5.30
800.88	1.6	22.88	55.57	0.17	21.11	0.34	0.88	0.69	0.03	0.84	2.23	12.85	5.30

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
799.88	1.6	22.17	55.44	0.17	21.21	0.33	0.86	0.71	0.03	0.86	2.18	12.92	5.30
798.88	1.6	21.52	55.31	0.18	21.30	0.32	0.84	0.73	0.03	0.88	2.14	12.98	5.31
797.88	1.6	20.81	55.17	0.18	21.39	0.31	0.81	0.76	0.03	0.88	2.10	13.06	5.31
796.88	1.6	20.13	55.03	0.19	21.49	0.30	0.79	0.78	0.02	0.88	2.05	13.15	5.31
795.88	1.6	19.50	54.89	0.20	21.58	0.30	0.77	0.81	0.02	0.87	2.01	13.23	5.31
794.88	1.6	18.93	54.76	0.20	21.67	0.29	0.75	0.83	0.02	0.87	1.98	13.32	5.31
793.88	1.6	18.39	54.63	0.21	21.76	0.28	0.73	0.86	0.02	0.86	1.94	13.40	5.32
792.88	1.6	17.90	54.50	0.21	21.85	0.27	0.71	0.88	0.02	0.86	1.90	13.47	5.32
791.88	1.6	17.44	54.37	0.22	21.93	0.27	0.69	0.90	0.02	0.86	1.86	13.55	5.32
790.88	1.6	17.01	54.25	0.22	22.02	0.26	0.67	0.93	0.02	0.85	1.83	13.63	5.32
789.88	1.6	16.60	54.13	0.23	22.10	0.25	0.65	0.95	0.02	0.85	1.80	13.70	5.33
788.88	1.6	16.22	54.01	0.23	22.18	0.25	0.63	0.97	0.02	0.84	1.76	13.77	5.33
787.88	1.6	15.87	53.89	0.24	22.25	0.24	0.62	0.99	0.02	0.84	1.73	13.84	5.33
786.88	1.6	15.53	53.78	0.25	22.33	0.24	0.60	1.02	0.02	0.84	1.70	13.91	5.33
785.88	1.6	15.22	53.67	0.25	22.40	0.23	0.58	1.04	0.02	0.83	1.67	13.97	5.34
784.88	1.6	14.72	53.55	0.20	22.55	0.20	0.51	1.07	0.02	0.82	1.63	14.09	5.36
783.88	1.6	14.46	53.44	0.19	22.62	0.20	0.51	1.08	0.02	0.82	1.61	14.15	5.37
782.88	1.6	14.21	53.33	0.19	22.68	0.20	0.51	1.10	0.02	0.81	1.58	14.20	5.37
781.88	1.6	13.98	53.22	0.19	22.74	0.20	0.51	1.12	0.02	0.81	1.55	14.26	5.38
780.88	1.6	13.75	53.11	0.18	22.81	0.20	0.51	1.14	0.02	0.80	1.53	14.31	5.38
779.88	1.6	13.53	53.01	0.18	22.87	0.20	0.50	1.15	0.02	0.80	1.51	14.36	5.39
778.88	1.6	13.33	52.90	0.18	22.93	0.20	0.50	1.17	0.02	0.79	1.48	14.42	5.40
777.88	1.6	13.13	52.80	0.17	22.99	0.20	0.50	1.19	0.02	0.79	1.46	14.47	5.40
776.88	1.6	12.94	52.70	0.17	23.05	0.20	0.50	1.21	0.02	0.78	1.44	14.52	5.41
775.88	1.6	12.75	52.60	0.17	23.11	0.20	0.49	1.22	0.02	0.78	1.41	14.57	5.42
774.88	1.6	12.58	52.50	0.16	23.17	0.20	0.49	1.24	0.02	0.78	1.39	14.62	5.42
773.88	1.6	12.40	52.40	0.16	23.23	0.20	0.49	1.26	0.02	0.77	1.37	14.67	5.43
772.88	1.6	12.24	52.31	0.16	23.29	0.20	0.49	1.27	0.02	0.77	1.35	14.72	5.44
771.88	1.6	12.08	52.21	0.16	23.34	0.20	0.48	1.29	0.02	0.76	1.33	14.76	5.45
770.88	1.6	11.93	52.12	0.15	23.40	0.20	0.48	1.30	0.02	0.76	1.31	14.81	5.45
769.88	1.6	11.78	52.02	0.15	23.45	0.20	0.48	1.32	0.02	0.75	1.29	14.86	5.46
768.88	1.6	11.62	51.93	0.15	23.50	0.20	0.47	1.34	0.02	0.75	1.27	14.91	5.47
767.88	1.6	11.40	51.84	0.14	23.50	0.20	0.47	1.36	0.02	0.75	1.26	14.96	5.49
766.88	1.6	11.20	51.75	0.14	23.50	0.19	0.47	1.39	0.02	0.76	1.25	15.01	5.52
765.88	1.6	11.01	51.66	0.14	23.50	0.19	0.47	1.41	0.03	0.76	1.25	15.06	5.54
764.88	1.6	10.82	51.57	0.13	23.50	0.19	0.46	1.43	0.03	0.76	1.24	15.12	5.56
763.88	1.6	10.64	51.48	0.13	23.50	0.19	0.46	1.46	0.03	0.77	1.23	15.17	5.58
762.88	1.6	10.47	51.40	0.13	23.50	0.19	0.46	1.48	0.03	0.77	1.22	15.22	5.61
761.88	1.6	10.30	51.31	0.12	23.50	0.19	0.45	1.50	0.03	0.77	1.22	15.27	5.63
760.88	1.6	10.15	51.23	0.12	23.50	0.19	0.45	1.53	0.03	0.78	1.21	15.32	5.66
759.88	1.6	9.99	51.14	0.12	23.50	0.19	0.45	1.55	0.03	0.78	1.20	15.37	5.68
758.88	1.6	9.85	51.06	0.12	23.50	0.19	0.44	1.57	0.03	0.78	1.19	15.41	5.70
757.88	1.6	9.71	50.97	0.11	23.50	0.19	0.44	1.59	0.03	0.79	1.19	15.46	5.73
756.88	1.6	9.40	50.93	0.12	23.57	0.12	0.28	1.65	0.02	0.79	1.16	15.62	5.76
755.88	1.6	9.27	50.84	0.12	23.58	0.12	0.27	1.67	0.02	0.79	1.15	15.66	5.78
754.88	1.6	9.15	50.76	0.12	23.58	0.12	0.26	1.69	0.02	0.79	1.14	15.71	5.80
753.88	1.6	9.03	50.68	0.13	23.58	0.11	0.26	1.71	0.02	0.80	1.14	15.76	5.82
752.88	1.6	8.92	50.60	0.13	23.58	0.11	0.25	1.74	0.02	0.80	1.13	15.81	5.84
751.88	1.6	8.81	50.53	0.13	23.58	0.11	0.25	1.76	0.02	0.80	1.12	15.85	5.87
750.88	1.6	8.70	50.45	0.13	23.58	0.11	0.24	1.78	0.02	0.80	1.11	15.90	5.89
749.88	1.6	8.60	50.37	0.13	23.58	0.11	0.24	1.80	0.01	0.81	1.11	15.94	5.91
748.88	1.6	8.50	50.29	0.13	23.58	0.10	0.23	1.82	0.01	0.81	1.10	15.99	5.94
747.88	1.6	8.40	50.21	0.13	23.58	0.10	0.23	1.84	0.01	0.81	1.09	16.03	5.96
746.88	1.6	8.29	50.13	0.13	23.58	0.10	0.22	1.87	0.01	0.81	1.08	16.08	5.99
745.88	1.6	8.19	50.06	0.12	23.58	0.10	0.22	1.89	0.01	0.81	1.08	16.12	6.02
744.88	1.6	8.10	49.98	0.12	23.58	0.10	0.21	1.91	0.01	0.81	1.07	16.17	6.04
743.88	1.6	8.01	49.90	0.12	23.57	0.10	0.21	1.93	0.01	0.81	1.07	16.21	6.07
742.88	1.6	7.92	49.82	0.12	23.57	0.09	0.20	1.95	0.01	0.81	1.06	16.25	6.10
741.88	1.6	7.83	49.75	0.11	23.57	0.09	0.20	1.98	0.01	0.82	1.05	16.30	6.12
740.88	1.6	7.75	49.67	0.11	23.57	0.09	0.19	2.00	0.01	0.82	1.05	16.34	6.15
739.88	1.6	7.67	49.60	0.11	23.57	0.09	0.19	2.02	0.01	0.82	1.04	16.38	6.18
738.88	1.6	7.59	49.52	0.11	23.57	0.09	0.19	2.04	0.01	0.82	1.04	16.42	6.21
737.88	1.6	7.51	49.45	0.10	23.56	0.09	0.18	2.06	0.01	0.82	1.03	16.46	6.23
736.88	1.6	7.43	49.37	0.10	23.56	0.08	0.18	2.08	0.01	0.82	1.02	16.50	6.26
735.88	1.6	7.36	49.29	0.10	23.56	0.08	0.18	2.10	0.01	0.83	1.02	16.54	6.29
734.88	1.6	7.29	49.22	0.10	23.56	0.08	0.17	2.12	0.01	0.83	1.01	16.58	6.32
733.88	1.6	7.22	49.14	0.10	23.55	0.08	0.17	2.14	0.01	0.83	1.01	16.62	6.35
732.88	1.6	7.15	49.07	0.09	23.55	0.08	0.16	2.16	0.01	0.83	1.00	16.66	6.38
731.88	1.6	7.08	49.00	0.09	23.55	0.08	0.16	2.18	0.01	0.83	1.00	16.69	6.41
730.88	1.6	7.02	48.92	0.09	23.54	0.08	0.16	2.20	0.01	0.84	0.99	16.73	6.44
729.88	1.6	6.96	48.85	0.09	23.54	0.07	0.15	2.23	0.01	0.84	0.99	16.77	6.47

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
728.88	1.6	6.89	48.77	0.09	23.54	0.07	0.15	2.25	0.01	0.84	0.98	16.81	6.50
727.88	1.6	6.83	48.70	0.08	23.53	0.07	0.15	2.27	0.01	0.84	0.98	16.84	6.53
726.88	1.6	6.77	48.62	0.08	23.53	0.07	0.14	2.28	0.01	0.84	0.97	16.88	6.56
725.88	1.6	6.72	48.55	0.08	23.53	0.07	0.14	2.30	0.01	0.85	0.97	16.92	6.59
724.88	1.6	6.66	48.48	0.08	23.52	0.07	0.14	2.32	0.01	0.85	0.96	16.95	6.63
723.88	1.6	6.60	48.40	0.08	23.52	0.07	0.14	2.34	0.01	0.85	0.96	16.99	6.66
722.88	1.6	6.55	48.33	0.07	23.52	0.07	0.13	2.36	0.00	0.85	0.95	17.02	6.69
721.88	1.6	6.50	48.25	0.07	23.51	0.07	0.13	2.38	0.00	0.86	0.95	17.06	6.72
720.88	1.6	6.44	48.18	0.07	23.51	0.06	0.13	2.40	0.00	0.86	0.94	17.09	6.75
719.88	1.6	6.39	48.11	0.07	23.50	0.06	0.13	2.42	0.00	0.86	0.94	17.12	6.79
718.88	1.6	6.34	48.03	0.07	23.50	0.06	0.12	2.44	0.00	0.86	0.93	17.16	6.82
717.88	1.6	6.29	47.96	0.07	23.49	0.06	0.12	2.46	0.00	0.86	0.93	17.19	6.86
716.88	1.6	6.25	47.88	0.06	23.49	0.06	0.12	2.48	0.00	0.87	0.92	17.22	6.89
715.88	1.6	6.20	47.81	0.06	23.48	0.06	0.12	2.50	0.00	0.87	0.92	17.26	6.92
714.88	1.6	6.15	47.73	0.06	23.48	0.06	0.11	2.52	0.00	0.87	0.92	17.29	6.96
713.88	1.6	6.11	47.66	0.06	23.47	0.06	0.11	2.53	0.00	0.87	0.91	17.32	6.99
712.88	1.6	6.06	47.58	0.06	23.47	0.06	0.11	2.55	0.00	0.88	0.91	17.35	7.03
711.88	1.6	6.02	47.51	0.06	23.46	0.05	0.11	2.57	0.00	0.88	0.90	17.39	7.07
710.88	1.6	5.97	47.44	0.06	23.46	0.05	0.10	2.59	0.00	0.88	0.90	17.42	7.10
709.88	1.6	5.93	47.36	0.05	23.45	0.05	0.10	2.61	0.00	0.89	0.90	17.45	7.14
708.88	1.6	5.89	47.29	0.05	23.44	0.05	0.10	2.63	0.00	0.89	0.89	17.48	7.18
707.88	1.6	5.85	47.21	0.05	23.44	0.05	0.10	2.65	0.00	0.89	0.89	17.51	7.21
706.88	1.6	5.81	47.13	0.05	23.43	0.05	0.10	2.66	0.00	0.89	0.88	17.54	7.25
705.88	1.6	5.77	47.06	0.05	23.43	0.05	0.09	2.68	0.00	0.90	0.88	17.57	7.29
704.88	1.6	5.73	46.98	0.05	23.42	0.05	0.09	2.70	0.00	0.90	0.88	17.60	7.33
703.88	1.6	5.69	46.91	0.05	23.41	0.05	0.09	2.72	0.00	0.90	0.87	17.63	7.37
702.88	1.6	5.65	46.83	0.05	23.41	0.05	0.09	2.74	0.00	0.90	0.87	17.66	7.41
701.88	1.6	5.62	46.76	0.04	23.40	0.05	0.09	2.76	0.00	0.91	0.87	17.69	7.45
700.88	1.6	5.58	46.68	0.04	23.39	0.05	0.08	2.77	0.00	0.91	0.86	17.71	7.49

Table A1.8: Best-fit fractional crystallisation Rhyolite-MELTS model for western caldera group eruptions.

Liquid remaining is reported in grams, the model begins with 100g of liquid. The starting temperature is the liquidus temperature of the system, calculated by Rhyolite-MELTS.

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1151.6	1.1	99.5	50.76	0.95	14.85	1.97	4.94	0.16	6.09	11.41	2.15	4.73	2.01
1150.6	1.1	98.9	50.76	0.95	14.90	1.97	4.94	0.16	6.04	11.35	2.16	4.75	2.02
1149.6	1.1	98.4	50.77	0.95	14.96	1.96	4.94	0.16	5.99	11.28	2.17	4.78	2.03
1148.6	1.1	97.8	50.77	0.95	15.01	1.96	4.94	0.16	5.94	11.22	2.18	4.80	2.04
1147.6	1.1	97.3	50.78	0.96	15.07	1.96	4.94	0.16	5.90	11.16	2.19	4.83	2.06
1146.6	1.1	96.8	50.78	0.96	15.13	1.96	4.94	0.17	5.85	11.09	2.21	4.86	2.07
1145.6	1.1	96.3	50.79	0.96	15.18	1.96	4.94	0.17	5.80	11.03	2.22	4.88	2.08
1144.6	1.1	95.8	50.80	0.96	15.24	1.96	4.94	0.17	5.76	10.97	2.23	4.91	2.09
1143.6	1.1	95.3	50.80	0.96	15.29	1.96	4.94	0.17	5.71	10.90	2.24	4.93	2.10
1142.6	1.1	94.8	50.81	0.96	15.34	1.96	4.93	0.17	5.66	10.84	2.25	4.96	2.11
1141.6	1.1	94.3	50.82	0.97	15.40	1.96	4.93	0.17	5.62	10.78	2.26	4.98	2.12
1140.6	1.1	93.8	50.83	0.97	15.45	1.95	4.93	0.17	5.57	10.72	2.27	5.01	2.13
1139.6	1.1	93.3	50.83	0.97	15.51	1.95	4.93	0.17	5.53	10.65	2.28	5.03	2.14
1138.6	1.1	92.9	50.84	0.97	15.56	1.95	4.93	0.17	5.48	10.59	2.29	5.06	2.15
1137.6	1.1	92.4	50.85	0.97	15.61	1.95	4.93	0.17	5.44	10.53	2.30	5.09	2.16
1136.6	1.1	92.0	50.86	0.97	15.66	1.95	4.92	0.17	5.39	10.47	2.31	5.11	2.18
1135.6	1.1	91.5	50.87	0.97	15.72	1.95	4.92	0.17	5.35	10.40	2.33	5.14	2.19
1134.6	1.1	91.0	50.88	0.97	15.77	1.94	4.92	0.18	5.30	10.34	2.34	5.16	2.20
1133.6	1.1	90.6	50.89	0.98	15.82	1.94	4.92	0.18	5.26	10.28	2.35	5.19	2.21
1132.6	1.1	90.2	50.89	0.98	15.87	1.94	4.91	0.18	5.22	10.22	2.36	5.21	2.22
1131.6	1.1	89.7	50.90	0.98	15.92	1.94	4.91	0.18	5.17	10.16	2.37	5.24	2.23
1130.6	1.1	89.3	50.91	0.98	15.97	1.94	4.91	0.18	5.13	10.10	2.38	5.26	2.24
1129.6	1.1	88.9	50.93	0.98	16.03	1.94	4.90	0.18	5.09	10.04	2.39	5.29	2.25
1128.6	1.1	88.5	50.94	0.98	16.08	1.93	4.90	0.18	5.05	9.97	2.40	5.31	2.26
1127.6	1.1	88.0	50.95	0.98	16.13	1.93	4.90	0.18	5.00	9.91	2.41	5.34	2.27
1126.6	1.1	87.6	50.96	0.98	16.18	1.93	4.89	0.18	4.96	9.85	2.42	5.36	2.28
1125.6	1.1	87.2	50.97	0.98	16.23	1.93	4.89	0.18	4.92	9.79	2.43	5.39	2.29
1124.6	1.1	86.8	50.98	0.98	16.27	1.93	4.88	0.18	4.88	9.73	2.44	5.41	2.30
1123.6	1.1	86.4	50.99	0.98	16.32	1.92	4.88	0.19	4.84	9.67	2.45	5.44	2.31
1122.6	1.1	86.0	51.00	0.98	16.37	1.92	4.88	0.19	4.80	9.61	2.46	5.46	2.32
1121.6	1.1	85.7	51.02	0.98	16.42	1.92	4.87	0.19	4.76	9.55	2.47	5.49	2.33
1120.6	1.1	85.3	51.03	0.98	16.47	1.92	4.87	0.19	4.72	9.49	2.48	5.51	2.35
1119.6	1.1	84.9	51.04	0.98	16.52	1.91	4.86	0.19	4.68	9.43	2.49	5.54	2.36

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1118.6	1.1	84.5	51.05	0.98	16.56	1.91	4.86	0.19	4.64	9.38	2.50	5.56	2.37
1117.6	1.1	84.2	51.07	0.98	16.61	1.91	4.85	0.19	4.60	9.32	2.51	5.58	2.38
1116.6	1.1	83.8	51.08	0.98	16.66	1.91	4.85	0.19	4.56	9.26	2.52	5.61	2.39
1115.6	1.1	83.4	51.09	0.98	16.70	1.90	4.84	0.19	4.52	9.20	2.53	5.63	2.40
1114.6	1.1	83.1	51.11	0.98	16.75	1.90	4.83	0.19	4.48	9.14	2.54	5.66	2.41
1113.6	1.1	82.7	51.12	0.98	16.80	1.90	4.83	0.19	4.44	9.08	2.55	5.68	2.42
1112.6	1.1	82.4	51.14	0.98	16.84	1.90	4.82	0.19	4.41	9.03	2.57	5.71	2.43
1111.6	1.1	82.0	51.15	0.98	16.89	1.89	4.82	0.20	4.37	8.97	2.58	5.73	2.44
1110.6	1.1	81.7	51.16	0.98	16.93	1.89	4.81	0.20	4.33	8.91	2.59	5.75	2.45
1109.6	1.1	81.4	51.18	0.98	16.98	1.89	4.80	0.20	4.29	8.85	2.60	5.78	2.46
1108.6	1.1	81.0	51.19	0.98	17.02	1.89	4.80	0.20	4.26	8.80	2.60	5.80	2.47
1107.6	1.1	80.7	51.21	0.98	17.07	1.88	4.79	0.20	4.22	8.74	2.61	5.82	2.48
1106.6	1.1	80.4	51.23	0.97	17.11	1.88	4.78	0.20	4.19	8.68	2.62	5.85	2.49
1105.6	1.1	80.1	51.24	0.97	17.15	1.88	4.78	0.20	4.15	8.63	2.63	5.87	2.50
1104.6	1.1	79.7	51.26	0.97	17.20	1.88	4.77	0.20	4.11	8.57	2.64	5.89	2.51
1103.6	1.1	79.4	51.27	0.97	17.24	1.87	4.76	0.20	4.08	8.51	2.65	5.92	2.52
1102.6	1.1	79.1	51.29	0.97	17.28	1.87	4.75	0.20	4.04	8.46	2.66	5.94	2.53
1101.6	1.1	78.8	51.30	0.97	17.32	1.87	4.75	0.20	4.01	8.40	2.67	5.96	2.54
1100.6	1.1	78.5	51.32	0.97	17.37	1.86	4.74	0.20	3.97	8.35	2.68	5.99	2.55
1100.6	1.1	78.5	51.32	0.97	17.37	1.86	4.74	0.20	3.97	8.35	2.68	5.99	2.55
1099.6	1.1	88.4	52.74	0.97	17.37	1.81	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1098.6	1.1	88.4	52.74	0.97	17.37	1.81	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1097.6	1.1	88.4	52.74	0.97	17.37	1.81	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1096.6	1.1	88.4	52.74	0.97	17.37	1.81	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1095.6	1.1	88.4	52.74	0.97	17.37	1.81	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1094.6	1.1	88.4	52.74	0.97	17.37	1.81	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1093.6	1.1	88.4	52.74	0.97	17.37	1.82	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1092.6	1.1	88.4	52.74	0.97	17.37	1.82	4.79	0.18	3.86	7.73	2.65	5.51	2.38
1091.6	1.1	87.6	52.79	0.97	17.46	1.81	4.77	0.18	3.78	7.61	2.68	5.56	2.40
1090.6	1.1	87.3	52.81	0.97	17.50	1.81	4.76	0.18	3.75	7.56	2.68	5.58	2.40
1089.6	1.1	87.1	52.83	0.97	17.54	1.80	4.76	0.18	3.72	7.51	2.69	5.59	2.41
1088.6	1.1	86.8	52.84	0.97	17.57	1.80	4.75	0.18	3.69	7.46	2.70	5.61	2.42
1087.6	1.1	86.5	52.86	0.97	17.61	1.80	4.74	0.19	3.66	7.41	2.71	5.63	2.43
1086.6	1.1	86.2	52.88	0.97	17.65	1.79	4.73	0.19	3.63	7.37	2.72	5.65	2.44
1085.6	1.1	85.9	52.90	0.96	17.68	1.79	4.73	0.19	3.60	7.32	2.72	5.67	2.44
1084.6	1.1	85.7	52.92	0.96	17.72	1.79	4.72	0.19	3.57	7.27	2.73	5.68	2.45
1083.6	1.1	85.4	52.94	0.96	17.75	1.79	4.71	0.19	3.54	7.23	2.74	5.70	2.46
1082.6	1.1	85.1	52.96	0.96	17.79	1.78	4.70	0.19	3.51	7.18	2.75	5.72	2.47
1081.6	1.1	84.9	52.97	0.96	17.82	1.78	4.70	0.19	3.48	7.13	2.76	5.74	2.47
1080.6	1.1	84.6	52.99	0.96	17.86	1.78	4.69	0.19	3.45	7.09	2.76	5.76	2.48
1079.6	1.1	84.3	53.01	0.96	17.89	1.78	4.68	0.19	3.42	7.04	2.77	5.77	2.49
1078.6	1.1	84.1	53.03	0.95	17.93	1.77	4.67	0.19	3.39	6.99	2.78	5.79	2.50
1077.6	1.1	83.8	53.05	0.95	17.96	1.77	4.66	0.19	3.36	6.95	2.79	5.81	2.50
1076.6	1.1	83.6	53.07	0.95	17.99	1.77	4.66	0.19	3.34	6.90	2.79	5.83	2.51
1075.6	1.1	83.3	53.09	0.95	18.03	1.76	4.65	0.19	3.31	6.86	2.80	5.84	2.52
1074.6	1.1	83.1	53.11	0.95	18.06	1.76	4.64	0.19	3.28	6.81	2.81	5.86	2.53
1073.6	1.1	82.8	53.13	0.95	18.09	1.76	4.63	0.19	3.26	6.77	2.82	5.88	2.53
1072.6	1.1	82.6	53.15	0.94	18.12	1.76	4.62	0.19	3.23	6.72	2.82	5.90	2.54
1071.6	1.1	82.4	53.17	0.94	18.16	1.75	4.61	0.19	3.20	6.68	2.83	5.91	2.55
1070.6	1.1	82.1	53.19	0.94	18.19	1.75	4.60	0.19	3.18	6.63	2.84	5.93	2.56
1069.6	1.1	81.9	53.21	0.94	18.22	1.75	4.59	0.20	3.15	6.59	2.85	5.95	2.56
1068.6	1.1	81.7	53.23	0.94	18.25	1.74	4.59	0.20	3.12	6.55	2.85	5.96	2.57
1067.6	1.1	81.4	53.25	0.93	18.28	1.74	4.58	0.20	3.10	6.50	2.86	5.98	2.58
1066.6	1.1	81.2	53.27	0.93	18.31	1.74	4.57	0.20	3.07	6.46	2.87	6.00	2.59
1065.6	1.1	81.0	53.29	0.93	18.34	1.74	4.56	0.20	3.05	6.42	2.88	6.01	2.59
1064.6	1.1	80.8	53.31	0.93	18.37	1.73	4.55	0.20	3.02	6.37	2.88	6.03	2.60
1063.6	1.1	80.5	53.33	0.92	18.40	1.73	4.54	0.20	3.00	6.33	2.89	6.05	2.61
1062.6	1.1	80.3	53.35	0.92	18.43	1.73	4.53	0.20	2.97	6.29	2.90	6.06	2.61
1061.6	1.1	80.1	53.37	0.92	18.46	1.72	4.52	0.20	2.95	6.25	2.90	6.08	2.62
1060.6	1.1	79.9	53.39	0.92	18.49	1.72	4.51	0.20	2.92	6.20	2.91	6.10	2.63
1059.6	1.1	79.7	53.41	0.91	18.52	1.72	4.50	0.20	2.90	6.16	2.92	6.11	2.64
1058.6	1.1	79.5	53.43	0.91	18.55	1.71	4.49	0.20	2.88	6.12	2.93	6.13	2.64
1057.6	1.1	79.3	53.46	0.91	18.58	1.71	4.48	0.20	2.85	6.08	2.93	6.14	2.65
1056.6	1.1	79.1	53.48	0.91	18.61	1.71	4.47	0.20	2.83	6.04	2.94	6.16	2.66
1055.6	1.1	78.9	53.50	0.90	18.64	1.70	4.46	0.20	2.81	6.00	2.95	6.18	2.66
1054.6	1.1	78.7	53.52	0.90	18.67	1.70	4.45	0.20	2.78	5.96	2.95	6.19	2.67
1053.6	1.1	78.5	53.54	0.90	18.69	1.70	4.45	0.20	2.76	5.91	2.96	6.21	2.68
1052.6	1.1	78.3	53.56	0.90	18.72	1.70	4.44	0.20	2.74	5.87	2.97	6.22	2.68
1051.6	1.1	78.1	53.58	0.89	18.75	1.69	4.43	0.21	2.72	5.83	2.97	6.24	2.69
1050.6	1.1	77.9	53.60	0.89	18.78	1.69	4.42	0.21	2.70	5.79	2.98	6.25	2.70
1049.6	1.1	77.7	53.62	0.89	18.80	1.69	4.41	0.21	2.67	5.75	2.99	6.27	2.70

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1048.6	1.1	77.5	53.65	0.88	18.83	1.68	4.40	0.21	2.65	5.71	2.99	6.28	2.71
1047.6	1.1	77.3	53.67	0.88	18.86	1.68	4.39	0.21	2.63	5.68	3.00	6.30	2.72
1046.6	1.1	77.1	53.69	0.88	18.88	1.68	4.38	0.21	2.61	5.64	3.01	6.31	2.72
1045.6	1.1	76.9	53.71	0.88	18.91	1.67	4.37	0.21	2.59	5.60	3.01	6.33	2.73
1044.6	1.1	76.8	53.73	0.87	18.94	1.67	4.36	0.21	2.57	5.56	3.02	6.35	2.74
1043.6	1.1	76.6	53.75	0.87	18.96	1.67	4.34	0.21	2.55	5.52	3.03	6.36	2.74
1042.6	1.1	76.4	53.78	0.87	18.99	1.66	4.33	0.21	2.53	5.48	3.03	6.37	2.75
1041.6	1.1	76.2	53.80	0.86	19.01	1.66	4.32	0.21	2.51	5.44	3.04	6.39	2.76
1040.6	1.1	76.0	53.82	0.86	19.04	1.66	4.31	0.21	2.49	5.41	3.05	6.40	2.76
1039.6	1.1	75.9	53.84	0.86	19.06	1.65	4.30	0.21	2.47	5.37	3.05	6.42	2.77
1038.6	1.1	75.7	53.86	0.85	19.09	1.65	4.29	0.21	2.45	5.33	3.06	6.43	2.77
1037.6	1.1	75.5	53.90	0.85	19.12	1.64	4.27	0.21	2.39	5.32	3.07	6.45	2.78
1036.6	1.1	75.3	53.92	0.85	19.15	1.64	4.26	0.21	2.37	5.28	3.07	6.46	2.79
1035.6	1.1	75.2	53.94	0.84	19.17	1.64	4.24	0.21	2.35	5.25	3.08	6.48	2.79
1034.6	1.1	75.0	53.96	0.84	19.20	1.63	4.23	0.21	2.33	5.21	3.08	6.49	2.80
1033.6	1.1	74.8	53.99	0.84	19.22	1.63	4.22	0.21	2.31	5.18	3.09	6.51	2.81
1032.6	1.1	74.7	54.01	0.83	19.25	1.63	4.21	0.21	2.29	5.14	3.10	6.52	2.81
1031.6	1.1	74.5	54.03	0.83	19.27	1.62	4.20	0.21	2.27	5.11	3.10	6.54	2.82
1030.6	1.1	74.3	54.06	0.83	19.29	1.62	4.19	0.21	2.25	5.07	3.11	6.55	2.82
1029.6	1.1	74.2	54.08	0.82	19.32	1.62	4.17	0.21	2.23	5.04	3.11	6.56	2.83
1028.6	1.1	74.0	54.10	0.82	19.34	1.61	4.16	0.21	2.21	5.00	3.12	6.58	2.84
1027.6	1.1	73.9	54.13	0.81	19.36	1.61	4.15	0.22	2.19	4.97	3.13	6.59	2.84
1026.6	1.1	73.7	54.15	0.81	19.39	1.61	4.14	0.22	2.17	4.94	3.13	6.61	2.85
1025.6	1.1	73.6	54.17	0.81	19.41	1.60	4.13	0.22	2.15	4.90	3.14	6.62	2.85
1024.6	1.1	73.4	54.20	0.80	19.43	1.60	4.12	0.22	2.13	4.87	3.14	6.63	2.86
1023.6	1.1	73.3	54.22	0.80	19.45	1.60	4.10	0.22	2.11	4.84	3.15	6.65	2.87
1022.6	1.1	73.1	54.24	0.79	19.48	1.59	4.09	0.22	2.09	4.80	3.16	6.66	2.87
1021.6	1.1	73.0	54.27	0.79	19.50	1.59	4.08	0.22	2.07	4.77	3.16	6.67	2.88
1020.6	1.1	72.8	54.29	0.79	19.52	1.59	4.07	0.22	2.06	4.74	3.17	6.69	2.88
1019.6	1.1	72.7	54.31	0.78	19.54	1.58	4.05	0.22	2.04	4.71	3.17	6.70	2.89
1018.6	1.1	72.5	54.34	0.78	19.56	1.58	4.04	0.22	2.02	4.67	3.18	6.71	2.90
1017.6	1.1	72.4	54.36	0.77	19.59	1.57	4.03	0.22	2.00	4.64	3.18	6.73	2.90
1016.6	1.1	72.2	54.39	0.77	19.61	1.57	4.02	0.22	1.98	4.61	3.19	6.74	2.91
1015.6	1.1	72.1	54.41	0.76	19.63	1.57	4.01	0.22	1.97	4.58	3.19	6.75	2.91
1014.6	1.1	72.0	54.43	0.76	19.65	1.56	3.99	0.22	1.95	4.55	3.20	6.77	2.92
1013.6	1.1	71.8	54.46	0.76	19.67	1.56	3.98	0.22	1.93	4.52	3.21	6.78	2.92
1012.6	1.1	71.7	54.48	0.75	19.69	1.56	3.97	0.22	1.91	4.49	3.21	6.79	2.93
1011.6	1.1	71.6	54.51	0.75	19.71	1.55	3.96	0.22	1.90	4.46	3.22	6.81	2.93
1010.6	1.1	71.4	54.53	0.74	19.73	1.55	3.94	0.22	1.88	4.43	3.22	6.82	2.94
1009.6	1.1	71.3	54.55	0.74	19.75	1.55	3.93	0.22	1.86	4.40	3.23	6.83	2.95
1008.6	1.1	71.2	54.58	0.73	19.77	1.54	3.92	0.22	1.85	4.37	3.23	6.84	2.95
1007.6	1.1	71.0	54.60	0.73	19.79	1.54	3.90	0.22	1.83	4.34	3.24	6.86	2.96
1006.6	1.1	70.9	54.63	0.72	19.81	1.53	3.89	0.22	1.81	4.31	3.24	6.87	2.96
1005.6	1.1	70.8	54.65	0.72	19.83	1.53	3.88	0.22	1.80	4.28	3.25	6.88	2.97
1004.6	1.1	70.7	54.67	0.71	19.85	1.53	3.87	0.22	1.78	4.25	3.25	6.89	2.97
1003.6	1.1	70.5	54.70	0.71	19.86	1.52	3.85	0.22	1.76	4.22	3.26	6.91	2.98
1002.6	1.1	70.4	54.72	0.70	19.88	1.52	3.84	0.22	1.75	4.19	3.26	6.92	2.98
1001.6	1.1	70.3	54.75	0.70	19.90	1.52	3.83	0.22	1.73	4.17	3.27	6.93	2.99
1000.6	1.1	70.2	54.77	0.69	19.92	1.51	3.82	0.22	1.72	4.14	3.27	6.94	2.99
999.6	1.1	70.0	54.79	0.69	19.94	1.51	3.80	0.22	1.70	4.11	3.28	6.95	3.00
998.6	1.1	69.9	54.82	0.68	19.96	1.51	3.79	0.22	1.68	4.08	3.28	6.97	3.00
997.6	1.1	69.8	54.84	0.68	19.97	1.50	3.78	0.23	1.67	4.06	3.29	6.98	3.01
996.6	1.1	69.7	54.87	0.67	19.99	1.50	3.76	0.23	1.65	4.03	3.29	6.99	3.01
995.6	1.1	69.6	54.89	0.67	20.01	1.49	3.75	0.23	1.64	4.00	3.30	7.00	3.02
994.6	1.1	69.5	54.92	0.66	20.03	1.49	3.74	0.23	1.62	3.97	3.30	7.01	3.02
993.6	1.1	69.3	54.94	0.66	20.04	1.49	3.73	0.23	1.61	3.95	3.31	7.02	3.03
992.6	1.1	69.2	54.97	0.66	20.04	1.49	3.72	0.23	1.59	3.92	3.31	7.04	3.04
991.6	1.1	69.0	55.00	0.66	20.03	1.48	3.71	0.23	1.58	3.89	3.32	7.06	3.05
990.6	1.1	68.8	55.02	0.66	20.03	1.48	3.70	0.23	1.56	3.86	3.32	7.08	3.05
989.6	1.1	68.6	55.05	0.66	20.02	1.48	3.69	0.23	1.54	3.83	3.33	7.10	3.06
988.6	1.1	68.4	55.08	0.65	20.02	1.48	3.69	0.23	1.53	3.80	3.33	7.12	3.07
987.6	1.1	68.2	55.11	0.65	20.01	1.48	3.68	0.23	1.51	3.78	3.34	7.14	3.08
986.6	1.1	68.0	55.14	0.65	20.00	1.48	3.67	0.23	1.50	3.75	3.34	7.16	3.09
985.6	1.1	67.5	55.29	0.60	20.00	1.45	3.58	0.23	1.48	3.71	3.35	7.21	3.11
984.6	1.1	67.3	55.34	0.59	19.99	1.44	3.56	0.23	1.47	3.68	3.36	7.23	3.12
983.6	1.1	67.1	55.38	0.58	19.97	1.44	3.53	0.23	1.45	3.66	3.36	7.26	3.13
982.6	1.1	66.8	55.43	0.58	19.96	1.43	3.51	0.23	1.44	3.63	3.37	7.28	3.14
981.6	1.1	66.6	55.48	0.57	19.95	1.42	3.49	0.23	1.43	3.61	3.37	7.31	3.15
980.6	1.1	66.4	55.52	0.56	19.94	1.42	3.47	0.23	1.41	3.58	3.38	7.33	3.16
979.6	1.1	66.1	55.57	0.55	19.92	1.41	3.45	0.23	1.40	3.56	3.38	7.35	3.17
978.6	1.1	65.9	55.62	0.55	19.91	1.41	3.43	0.23	1.38	3.53	3.38	7.38	3.19

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
977.6	1.1	65.7	55.66	0.54	19.90	1.40	3.40	0.23	1.37	3.51	3.39	7.40	3.20
976.6	1.1	65.5	55.71	0.53	19.89	1.40	3.38	0.23	1.36	3.49	3.39	7.43	3.21
975.6	1.1	65.3	55.75	0.52	19.88	1.39	3.36	0.23	1.34	3.46	3.40	7.45	3.22
974.6	1.1	65.0	55.80	0.52	19.86	1.38	3.34	0.23	1.33	3.44	3.40	7.48	3.23
973.6	1.1	64.8	55.84	0.51	19.85	1.38	3.32	0.23	1.32	3.41	3.40	7.50	3.24
972.6	1.1	64.6	55.88	0.50	19.84	1.37	3.30	0.23	1.30	3.39	3.41	7.52	3.25
971.6	1.1	64.4	55.93	0.49	19.83	1.37	3.28	0.23	1.29	3.36	3.41	7.55	3.26
970.6	1.1	64.2	55.97	0.49	19.82	1.36	3.26	0.23	1.28	3.34	3.42	7.57	3.27
969.6	1.1	64.0	56.01	0.48	19.81	1.36	3.24	0.23	1.26	3.32	3.42	7.60	3.28
968.6	1.1	63.8	56.06	0.47	19.79	1.35	3.22	0.23	1.25	3.29	3.42	7.62	3.29
967.6	1.1	63.6	56.10	0.47	19.78	1.34	3.20	0.23	1.24	3.27	3.43	7.64	3.30
966.6	1.1	63.4	56.14	0.46	19.77	1.34	3.18	0.23	1.23	3.25	3.43	7.67	3.31
965.6	1.1	63.2	56.18	0.45	19.76	1.33	3.16	0.23	1.21	3.22	3.43	7.69	3.32
964.6	1.1	63.0	56.22	0.45	19.75	1.33	3.14	0.23	1.20	3.20	3.44	7.71	3.33
963.6	1.1	62.8	56.26	0.44	19.74	1.32	3.12	0.23	1.19	3.18	3.44	7.74	3.34
962.6	1.1	62.6	56.30	0.44	19.72	1.32	3.10	0.23	1.18	3.16	3.45	7.76	3.35
961.6	1.1	62.4	56.34	0.43	19.71	1.31	3.08	0.23	1.17	3.13	3.45	7.78	3.36
960.6	1.1	62.2	56.38	0.42	19.70	1.30	3.06	0.23	1.16	3.11	3.45	7.81	3.38
959.6	1.1	62.0	56.42	0.42	19.69	1.30	3.04	0.23	1.14	3.09	3.45	7.83	3.39
958.6	1.1	61.8	56.46	0.41	19.68	1.29	3.02	0.23	1.13	3.07	3.46	7.85	3.40
957.6	1.1	61.7	56.50	0.41	19.67	1.29	3.00	0.23	1.12	3.04	3.46	7.88	3.41
956.6	1.1	61.5	56.54	0.40	19.66	1.28	2.98	0.23	1.11	3.02	3.46	7.90	3.42
955.6	1.1	61.3	56.58	0.40	19.65	1.28	2.96	0.23	1.10	3.00	3.47	7.92	3.43
954.6	1.1	61.1	56.62	0.39	19.63	1.27	2.94	0.23	1.09	2.98	3.47	7.94	3.44
953.6	1.1	60.9	56.66	0.38	19.62	1.27	2.92	0.23	1.08	2.96	3.47	7.97	3.45
952.6	1.1	60.8	56.70	0.38	19.61	1.26	2.90	0.23	1.07	2.93	3.47	7.99	3.46
951.6	1.1	60.6	56.73	0.37	19.60	1.25	2.89	0.23	1.06	2.91	3.48	8.01	3.47
950.6	1.1	60.4	56.77	0.37	19.59	1.25	2.87	0.23	1.05	2.89	3.48	8.03	3.48
949.6	1.1	60.2	56.81	0.36	19.58	1.24	2.85	0.23	1.03	2.87	3.48	8.06	3.49
948.6	1.1	60.0	56.84	0.36	19.57	1.24	2.83	0.23	1.02	2.85	3.48	8.08	3.50
947.6	1.1	59.9	56.88	0.35	19.56	1.23	2.81	0.23	1.01	2.83	3.49	8.10	3.51
946.6	1.1	59.7	56.92	0.35	19.55	1.23	2.79	0.23	1.00	2.81	3.49	8.12	3.52
945.6	1.1	59.5	56.95	0.34	19.54	1.22	2.77	0.23	0.99	2.79	3.49	8.15	3.53
944.6	1.1	59.4	56.99	0.34	19.53	1.22	2.76	0.23	0.98	2.76	3.49	8.17	3.54
943.6	1.1	59.2	57.02	0.33	19.51	1.21	2.74	0.23	0.97	2.74	3.50	8.19	3.55
942.6	1.1	59.0	57.06	0.33	19.50	1.20	2.72	0.23	0.96	2.72	3.50	8.21	3.56
941.6	1.1	58.9	57.09	0.32	19.49	1.20	2.70	0.23	0.95	2.70	3.50	8.24	3.57
940.6	1.1	58.7	57.13	0.32	19.48	1.19	2.68	0.23	0.94	2.68	3.50	8.26	3.58
939.6	1.1	58.5	57.16	0.32	19.47	1.19	2.66	0.23	0.94	2.66	3.50	8.28	3.59
938.6	1.1	58.4	57.20	0.31	19.46	1.18	2.65	0.23	0.93	2.64	3.50	8.30	3.60
937.6	1.1	58.2	57.23	0.31	19.45	1.18	2.63	0.23	0.92	2.62	3.51	8.32	3.61
936.6	1.1	58.1	57.27	0.30	19.44	1.17	2.61	0.23	0.91	2.60	3.51	8.35	3.62
935.6	1.1	57.9	57.30	0.30	19.43	1.17	2.59	0.23	0.90	2.58	3.51	8.37	3.63
934.6	1.1	57.8	57.33	0.29	19.42	1.16	2.58	0.23	0.89	2.56	3.51	8.39	3.64
933.6	1.1	57.6	57.37	0.29	19.41	1.16	2.56	0.23	0.88	2.54	3.51	8.41	3.65
932.6	1.1	57.4	57.40	0.29	19.40	1.15	2.54	0.23	0.87	2.52	3.51	8.43	3.66
931.6	1.1	57.3	57.43	0.28	19.39	1.14	2.52	0.23	0.86	2.50	3.51	8.46	3.67
930.6	1.1	57.1	57.46	0.28	19.38	1.14	2.51	0.23	0.85	2.48	3.52	8.48	3.68
929.6	1.1	57.0	57.49	0.27	19.37	1.13	2.49	0.23	0.84	2.46	3.52	8.50	3.69
928.6	1.1	56.8	57.53	0.27	19.36	1.13	2.47	0.23	0.84	2.44	3.52	8.52	3.70
927.6	1.1	56.7	57.56	0.27	19.35	1.12	2.46	0.23	0.83	2.43	3.52	8.54	3.70
926.6	1.1	56.5	57.59	0.26	19.34	1.12	2.44	0.23	0.82	2.41	3.52	8.56	3.71
925.6	1.1	56.4	57.62	0.26	19.33	1.11	2.42	0.23	0.81	2.39	3.52	8.59	3.72
924.6	1.1	56.2	57.65	0.25	19.32	1.11	2.41	0.23	0.80	2.37	3.52	8.61	3.73
923.6	1.1	56.1	57.68	0.25	19.31	1.10	2.39	0.23	0.79	2.35	3.52	8.63	3.74
922.6	1.1	55.9	57.71	0.25	19.30	1.10	2.37	0.23	0.79	2.33	3.52	8.65	3.75
921.6	1.1	55.8	57.74	0.24	19.29	1.09	2.36	0.23	0.78	2.31	3.52	8.67	3.76
920.6	1.1	55.7	57.77	0.24	19.28	1.09	2.34	0.23	0.77	2.29	3.52	8.69	3.77
919.6	1.1	55.5	57.80	0.24	19.27	1.08	2.32	0.23	0.76	2.28	3.52	8.72	3.78
918.6	1.1	55.4	57.83	0.23	19.26	1.07	2.31	0.23	0.75	2.26	3.53	8.74	3.79
917.6	1.1	55.2	57.86	0.23	19.25	1.07	2.29	0.23	0.75	2.24	3.53	8.76	3.80
916.6	1.1	55.1	57.89	0.23	19.24	1.06	2.27	0.23	0.74	2.22	3.53	8.78	3.81
915.6	1.1	55.0	57.92	0.22	19.23	1.06	2.26	0.23	0.73	2.20	3.53	8.80	3.82
914.6	1.1	54.8	57.95	0.22	19.22	1.05	2.24	0.23	0.72	2.19	3.53	8.82	3.83
913.6	1.1	54.7	57.97	0.22	19.21	1.05	2.22	0.23	0.72	2.17	3.53	8.84	3.84
912.6	1.1	54.5	58.00	0.21	19.20	1.04	2.21	0.23	0.71	2.15	3.53	8.87	3.85
911.6	1.1	54.4	58.03	0.21	19.19	1.04	2.19	0.23	0.70	2.13	3.53	8.89	3.86
910.6	1.1	54.3	58.06	0.21	19.18	1.03	2.18	0.23	0.69	2.11	3.53	8.91	3.87
909.6	1.1	54.1	58.08	0.21	19.18	1.03	2.16	0.23	0.69	2.10	3.53	8.93	3.88
908.6	1.1	54.0	58.11	0.20	19.17	1.02	2.15	0.23	0.68	2.08	3.53	8.95	3.89
907.6	1.1	53.9	58.14	0.20	19.16	1.02	2.13	0.23	0.67	2.06	3.53	8.97	3.90

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
906.6	1.1	53.7	58.17	0.20	19.15	1.01	2.11	0.23	0.67	2.05	3.52	8.99	3.91
905.6	1.1	53.6	58.19	0.19	19.14	1.01	2.10	0.23	0.66	2.03	3.52	9.02	3.92
904.6	1.1	53.5	58.22	0.19	19.13	1.00	2.08	0.23	0.65	2.01	3.52	9.04	3.93
903.6	1.1	53.3	58.24	0.19	19.12	1.00	2.07	0.23	0.65	1.99	3.52	9.06	3.94
902.6	1.1	53.2	58.27	0.19	19.11	0.99	2.05	0.23	0.64	1.98	3.52	9.08	3.95
901.6	1.1	53.1	58.30	0.18	19.10	0.98	2.04	0.23	0.63	1.96	3.52	9.10	3.96
900.6	1.1	52.9	58.32	0.18	19.09	0.98	2.02	0.23	0.63	1.94	3.52	9.12	3.97
899.6	1.1	52.8	58.35	0.18	19.08	0.97	2.01	0.23	0.62	1.93	3.52	9.14	3.98
898.6	1.1	52.7	58.37	0.18	19.07	0.97	1.99	0.23	0.61	1.91	3.52	9.16	3.99
897.6	1.1	52.6	58.40	0.17	19.07	0.96	1.98	0.23	0.61	1.89	3.52	9.18	4.00
896.6	1.1	52.4	58.42	0.17	19.06	0.96	1.96	0.23	0.60	1.88	3.52	9.21	4.00
895.6	1.1	52.3	58.44	0.17	19.05	0.96	1.95	0.23	0.59	1.86	3.52	9.23	4.01
894.6	1.1	52.2	58.47	0.16	19.03	0.95	1.94	0.23	0.58	1.85	3.51	9.24	4.02
893.6	1.1	52.0	58.49	0.16	19.02	0.95	1.94	0.23	0.58	1.83	3.51	9.26	4.03
892.6	1.1	51.9	58.52	0.16	19.01	0.95	1.93	0.23	0.57	1.81	3.51	9.28	4.04
891.6	1.1	51.8	58.54	0.15	19.00	0.95	1.92	0.23	0.56	1.80	3.51	9.30	4.05
890.6	1.1	51.7	58.57	0.15	18.98	0.95	1.91	0.23	0.55	1.78	3.51	9.32	4.06
889.6	1.1	51.5	58.59	0.15	18.97	0.94	1.91	0.23	0.54	1.76	3.51	9.33	4.07
888.6	1.1	51.4	58.61	0.14	18.96	0.94	1.90	0.23	0.53	1.75	3.51	9.35	4.07
887.6	1.1	51.3	58.63	0.14	18.95	0.94	1.89	0.23	0.52	1.73	3.51	9.37	4.08
886.6	1.1	51.1	58.66	0.14	18.93	0.94	1.89	0.23	0.52	1.72	3.50	9.39	4.09
885.6	1.1	51.0	58.68	0.13	18.92	0.94	1.88	0.23	0.51	1.70	3.50	9.41	4.10
884.6	1.1	50.9	58.70	0.13	18.91	0.94	1.87	0.23	0.50	1.69	3.50	9.42	4.11
883.6	1.1	50.8	58.72	0.13	18.90	0.93	1.86	0.23	0.49	1.67	3.50	9.44	4.12
882.6	1.1	50.7	58.74	0.13	18.89	0.93	1.86	0.23	0.48	1.66	3.50	9.46	4.13
881.6	1.1	50.5	58.77	0.12	18.87	0.93	1.85	0.23	0.48	1.64	3.49	9.48	4.13
880.6	1.1	50.4	58.79	0.12	18.86	0.93	1.84	0.23	0.47	1.63	3.49	9.50	4.14
879.6	1.1	50.3	58.81	0.12	18.85	0.93	1.84	0.23	0.46	1.61	3.49	9.51	4.15
878.6	1.1	50.2	58.83	0.11	18.84	0.93	1.83	0.23	0.45	1.60	3.49	9.53	4.16
877.6	1.1	50.0	58.85	0.11	18.83	0.92	1.82	0.24	0.45	1.58	3.48	9.55	4.17
876.6	1.1	49.9	58.88	0.11	18.81	0.92	1.81	0.24	0.44	1.56	3.48	9.58	4.17
875.6	1.1	49.8	58.91	0.11	18.80	0.92	1.81	0.24	0.43	1.54	3.48	9.60	4.17
874.6	1.1	49.6	58.93	0.10	18.79	0.92	1.80	0.24	0.42	1.53	3.48	9.62	4.17
873.6	1.1	49.5	58.96	0.10	18.77	0.92	1.79	0.24	0.42	1.51	3.47	9.64	4.17
872.6	1.1	49.3	58.99	0.10	18.76	0.92	1.79	0.24	0.41	1.49	3.47	9.67	4.17
871.6	1.1	49.2	59.01	0.10	18.75	0.91	1.78	0.24	0.40	1.47	3.47	9.69	4.17
870.6	1.1	49.0	59.04	0.09	18.74	0.91	1.77	0.24	0.40	1.46	3.46	9.71	4.17
869.6	1.1	48.9	59.07	0.09	18.72	0.91	1.77	0.24	0.39	1.44	3.46	9.74	4.18
868.6	1.1	48.8	59.09	0.09	18.71	0.91	1.76	0.24	0.38	1.42	3.45	9.76	4.18
867.6	1.1	48.6	59.12	0.09	18.70	0.91	1.75	0.24	0.38	1.41	3.45	9.78	4.18
866.6	1.1	48.5	59.14	0.08	18.69	0.91	1.75	0.24	0.37	1.39	3.45	9.81	4.18
865.6	1.1	48.3	59.17	0.08	18.67	0.91	1.74	0.24	0.36	1.37	3.44	9.83	4.18
864.6	1.1	48.2	59.19	0.08	18.66	0.90	1.73	0.24	0.36	1.36	3.44	9.85	4.18
863.6	1.1	48.1	59.22	0.08	18.65	0.90	1.73	0.24	0.35	1.34	3.43	9.88	4.18
862.6	1.1	47.9	59.24	0.07	18.64	0.90	1.72	0.25	0.35	1.32	3.43	9.90	4.18
861.6	1.1	47.8	59.26	0.07	18.63	0.90	1.71	0.25	0.34	1.31	3.42	9.92	4.19
860.6	1.1	47.6	59.29	0.07	18.61	0.90	1.71	0.25	0.33	1.29	3.42	9.95	4.19
859.6	1.1	47.5	59.31	0.07	18.60	0.90	1.70	0.25	0.33	1.28	3.41	9.97	4.19
858.6	1.1	47.4	59.33	0.06	18.59	0.90	1.69	0.25	0.32	1.26	3.41	9.99	4.19
857.6	1.1	47.2	59.36	0.06	18.58	0.89	1.69	0.25	0.32	1.25	3.40	10.02	4.19
856.6	1.1	47.1	59.38	0.06	18.57	0.89	1.68	0.25	0.31	1.23	3.40	10.04	4.19
855.6	1.1	47.0	59.40	0.06	18.55	0.89	1.67	0.25	0.31	1.21	3.39	10.07	4.19
854.6	1.1	46.8	59.42	0.06	18.54	0.89	1.67	0.25	0.30	1.20	3.39	10.09	4.19
853.6	1.1	46.7	59.45	0.05	18.53	0.89	1.66	0.25	0.30	1.18	3.38	10.11	4.19
852.6	1.1	46.6	59.47	0.05	18.52	0.89	1.65	0.25	0.29	1.17	3.37	10.14	4.19
851.6	1.1	46.4	59.49	0.05	18.51	0.88	1.65	0.25	0.29	1.15	3.37	10.16	4.20
850.6	1.1	46.3	59.51	0.05	18.50	0.88	1.64	0.25	0.28	1.14	3.36	10.19	4.20
849.6	1.1	46.2	59.53	0.05	18.49	0.88	1.64	0.25	0.28	1.12	3.35	10.21	4.20
848.6	1.1	46.0	59.55	0.05	18.48	0.88	1.63	0.26	0.27	1.11	3.35	10.24	4.20
847.6	1.1	45.9	59.57	0.04	18.46	0.88	1.62	0.26	0.27	1.10	3.34	10.26	4.20
846.6	1.1	45.7	59.59	0.04	18.45	0.88	1.62	0.26	0.26	1.08	3.33	10.29	4.20
845.6	1.1	45.6	59.61	0.04	18.44	0.88	1.61	0.26	0.26	1.07	3.33	10.31	4.20
844.6	1.1	45.5	59.63	0.04	18.43	0.87	1.60	0.26	0.25	1.05	3.32	10.34	4.20
843.6	1.1	45.3	59.65	0.04	18.42	0.87	1.60	0.26	0.25	1.04	3.31	10.36	4.20
842.6	1.1	28.2	59.18	0.04	18.73	0.81	1.46	0.32	0.17	1.06	3.29	10.72	4.23
841.6	1.1	23.8	58.90	0.04	18.85	0.81	1.45	0.36	0.15	1.07	3.29	10.85	4.24
840.6	1.1	20.8	58.65	0.03	18.95	0.81	1.44	0.39	0.14	1.07	3.29	10.97	4.26
839.6	1.1	18.6	58.42	0.03	19.05	0.80	1.42	0.42	0.13	1.08	3.29	11.07	4.28
838.6	1.1	16.9	58.20	0.03	19.14	0.80	1.41	0.45	0.12	1.08	3.30	11.17	4.29
837.6	1.1	15.5	58.00	0.03	19.23	0.80	1.40	0.47	0.11	1.08	3.31	11.26	4.31
836.6	1.1	14.5	57.81	0.03	19.31	0.79	1.38	0.49	0.11	1.08	3.33	11.34	4.32

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
835.6	1.1	13.5	57.64	0.02	19.39	0.79	1.37	0.51	0.10	1.08	3.34	11.42	4.34
834.6	1.1	12.8	57.47	0.02	19.46	0.79	1.36	0.53	0.10	1.08	3.35	11.50	4.35
833.6	1.1	12.1	57.31	0.02	19.53	0.78	1.34	0.55	0.09	1.07	3.37	11.57	4.37
832.6	1.1	11.6	57.16	0.02	19.60	0.78	1.33	0.57	0.09	1.07	3.38	11.63	4.38
831.6	1.1	11.1	57.01	0.02	19.67	0.77	1.32	0.58	0.08	1.07	3.39	11.70	4.39
830.6	1.1	10.6	56.87	0.02	19.73	0.77	1.30	0.60	0.08	1.06	3.41	11.76	4.41
829.6	1.1	10.2	56.73	0.02	19.79	0.77	1.29	0.61	0.08	1.06	3.42	11.82	4.42
828.6	1.1	9.9	56.60	0.02	19.85	0.76	1.28	0.62	0.07	1.05	3.44	11.87	4.44
827.6	1.1	9.5	56.48	0.02	19.90	0.76	1.26	0.64	0.07	1.05	3.45	11.93	4.45
826.6	1.1	9.2	56.35	0.01	19.96	0.75	1.25	0.65	0.07	1.05	3.46	11.98	4.46
825.6	1.1	9.0	56.24	0.01	20.01	0.75	1.24	0.66	0.06	1.04	3.48	12.03	4.48
824.6	1.1	8.7	56.12	0.01	20.06	0.74	1.23	0.67	0.06	1.04	3.49	12.08	4.49
823.6	1.1	8.5	56.01	0.01	20.11	0.74	1.21	0.68	0.06	1.03	3.51	12.13	4.50
822.6	1.1	8.3	55.90	0.01	20.16	0.74	1.20	0.70	0.06	1.03	3.52	12.18	4.52
821.6	1.1	8.1	55.79	0.01	20.21	0.73	1.19	0.71	0.05	1.02	3.53	12.23	4.53
820.6	1.1	7.9	55.69	0.01	20.25	0.73	1.18	0.72	0.05	1.02	3.55	12.27	4.54
819.6	1.1	7.7	55.59	0.01	20.30	0.72	1.16	0.72	0.05	1.01	3.56	12.32	4.56
818.6	1.1	7.6	55.49	0.01	20.34	0.72	1.15	0.73	0.05	1.01	3.58	12.36	4.57
817.6	1.1	7.4	55.39	0.01	20.38	0.71	1.14	0.74	0.05	1.00	3.59	12.40	4.58
816.6	1.1	7.3	55.29	0.01	20.43	0.71	1.13	0.75	0.04	1.00	3.60	12.44	4.60
815.6	1.1	7.1	55.20	0.01	20.47	0.70	1.12	0.76	0.04	0.99	3.62	12.48	4.61
814.6	1.1	7.0	55.11	0.01	20.51	0.70	1.11	0.77	0.04	0.99	3.63	12.52	4.62
813.6	1.1	6.9	55.02	0.01	20.55	0.70	1.10	0.78	0.04	0.98	3.64	12.56	4.64
812.6	1.1	6.8	54.93	0.01	20.59	0.69	1.09	0.78	0.04	0.98	3.65	12.60	4.65
811.6	1.1	6.6	54.84	0.01	20.63	0.69	1.07	0.79	0.04	0.97	3.67	12.64	4.66
810.6	1.1	6.5	54.75	0.00	20.66	0.68	1.06	0.80	0.04	0.97	3.68	12.67	4.68
809.6	1.1	6.4	54.67	0.00	20.70	0.68	1.05	0.81	0.03	0.96	3.69	12.71	4.69
808.6	1.1	6.3	54.59	0.00	20.74	0.67	1.04	0.81	0.03	0.95	3.70	12.75	4.70
807.6	1.1	6.3	54.50	0.00	20.77	0.67	1.03	0.82	0.03	0.95	3.72	12.78	4.71
806.6	1.1	6.2	54.42	0.00	20.81	0.67	1.02	0.83	0.03	0.94	3.73	12.82	4.73
805.6	1.1	6.1	54.34	0.00	20.84	0.66	1.01	0.84	0.03	0.94	3.74	12.85	4.74
804.6	1.1	6.0	54.26	0.00	20.88	0.66	1.00	0.84	0.03	0.93	3.75	12.88	4.76
803.6	1.1	5.9	54.19	0.00	20.91	0.65	0.99	0.85	0.03	0.93	3.77	12.92	4.77
802.6	1.1	5.8	54.11	0.00	20.95	0.65	0.98	0.85	0.03	0.92	3.78	12.95	4.78
801.6	1.1	5.8	54.03	0.00	20.98	0.64	0.97	0.86	0.03	0.92	3.79	12.98	4.80

Table A1.9: Best-fit assimilation fractional crystallisation model for northern/eastern caldera group eruptions. Liquid remaining is reported in grams, the model begins with 100g of liquid. The starting temperature is the liquidus temperature of the system, calculated by Rhyolite-MELTS.

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1127.15	1.40	101.11	50.33	0.94	14.66	1.37	5.37	0.16	5.96	11.49	2.12	4.65	2.97
1126.15	1.40	101.03	50.33	0.94	14.67	1.37	5.36	0.16	5.93	11.50	2.12	4.65	2.97
1125.15	1.40	100.96	50.34	0.94	14.68	1.37	5.35	0.16	5.91	11.51	2.12	4.66	2.97
1124.15	1.40	100.89	50.35	0.94	14.69	1.37	5.35	0.16	5.88	11.51	2.12	4.66	2.97
1123.15	1.40	100.81	50.36	0.94	14.70	1.37	5.34	0.16	5.85	11.52	2.12	4.66	2.98
1122.15	1.40	100.74	50.37	0.94	14.71	1.37	5.33	0.16	5.83	11.53	2.12	4.67	2.98
1121.15	1.40	100.67	50.37	0.94	14.72	1.37	5.32	0.16	5.80	11.54	2.13	4.67	2.98
1120.15	1.40	98.95	50.37	0.95	14.90	1.37	5.34	0.16	5.64	11.34	2.16	4.75	3.03
1119.15	1.40	98.49	50.37	0.95	14.95	1.37	5.34	0.16	5.60	11.28	2.17	4.77	3.05
1118.15	1.40	98.02	50.38	0.95	15.00	1.37	5.34	0.16	5.55	11.22	2.18	4.79	3.06
1117.15	1.40	97.57	50.38	0.95	15.04	1.37	5.34	0.16	5.51	11.17	2.19	4.82	3.07
1116.15	1.40	97.12	50.38	0.95	15.09	1.37	5.35	0.16	5.47	11.11	2.20	4.84	3.09
1115.15	1.40	96.67	50.38	0.95	15.14	1.37	5.35	0.16	5.42	11.06	2.21	4.86	3.10
1114.15	1.40	96.23	50.38	0.95	15.19	1.37	5.35	0.16	5.38	11.00	2.22	4.88	3.12
1113.15	1.40	95.79	50.38	0.95	15.23	1.37	5.35	0.16	5.34	10.95	2.23	4.91	3.13
1112.15	1.40	95.35	50.38	0.95	15.28	1.37	5.35	0.17	5.30	10.89	2.24	4.93	3.15
1111.15	1.40	94.92	50.38	0.95	15.33	1.37	5.35	0.17	5.25	10.84	2.25	4.95	3.16
1110.15	1.40	94.50	50.39	0.95	15.38	1.37	5.35	0.17	5.21	10.78	2.26	4.97	3.17
1109.15	1.40	94.08	50.39	0.95	15.42	1.37	5.36	0.17	5.17	10.73	2.27	5.00	3.19
1108.15	1.40	93.66	50.39	0.95	15.47	1.37	5.36	0.17	5.13	10.67	2.28	5.02	3.20
1107.15	1.40	93.25	50.40	0.95	15.52	1.37	5.36	0.17	5.08	10.62	2.29	5.04	3.22
1106.15	1.40	92.84	50.40	0.95	15.56	1.37	5.36	0.17	5.04	10.56	2.30	5.06	3.23
1105.15	1.40	92.43	50.40	0.95	15.61	1.37	5.36	0.17	5.00	10.51	2.30	5.08	3.25
1104.15	1.40	92.03	50.41	0.95	15.65	1.37	5.36	0.17	4.96	10.45	2.31	5.11	3.26
1103.15	1.40	91.63	50.41	0.95	15.70	1.37	5.36	0.17	4.92	10.40	2.32	5.13	3.27
1102.15	1.40	91.24	50.41	0.95	15.74	1.37	5.36	0.17	4.88	10.34	2.33	5.15	3.29
1101.15	1.40	90.85	50.42	0.95	15.79	1.37	5.36	0.17	4.84	10.29	2.34	5.17	3.30

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T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1100.15	1.40	90.46	50.42	0.95	15.83	1.37	5.36	0.17	4.80	10.23	2.35	5.20	3.32
1100.15	1.40	90.46	50.42	0.95	15.83	1.37	5.36	0.17	4.80	10.23	2.35	5.20	3.32
1099.15	1.40	120.10	53.79	0.97	16.22	1.26	5.43	0.13	4.34	8.41	2.37	4.34	2.75
1098.15	1.40	120.10	53.79	0.97	16.22	1.26	5.43	0.13	4.34	8.41	2.37	4.34	2.75
1097.15	1.40	120.10	53.79	0.97	16.22	1.26	5.42	0.13	4.34	8.41	2.37	4.34	2.75
1096.15	1.40	120.10	53.79	0.97	16.22	1.26	5.42	0.13	4.34	8.41	2.37	4.34	2.75
1095.15	1.40	120.10	53.79	0.97	16.22	1.26	5.42	0.13	4.34	8.41	2.37	4.34	2.75
1094.15	1.40	120.10	53.79	0.97	16.22	1.26	5.42	0.13	4.34	8.41	2.37	4.34	2.75
1093.15	1.40	120.10	53.79	0.97	16.22	1.26	5.42	0.13	4.34	8.41	2.37	4.34	2.75
1092.15	1.40	120.10	53.79	0.97	16.22	1.26	5.42	0.13	4.34	8.41	2.37	4.34	2.75
1091.15	1.40	119.50	53.87	0.97	16.30	1.25	5.36	0.13	4.16	8.45	2.38	4.36	2.76
1090.15	1.40	119.42	53.88	0.97	16.31	1.25	5.35	0.13	4.14	8.45	2.38	4.36	2.76
1089.15	1.40	119.35	53.89	0.97	16.32	1.25	5.34	0.13	4.12	8.46	2.39	4.37	2.77
1088.15	1.40	119.27	53.90	0.97	16.33	1.25	5.33	0.13	4.10	8.46	2.39	4.37	2.77
1087.15	1.40	119.20	53.91	0.97	16.34	1.25	5.32	0.13	4.08	8.47	2.39	4.37	2.77
1086.15	1.40	119.13	53.92	0.97	16.35	1.25	5.31	0.13	4.06	8.47	2.39	4.37	2.77
1085.15	1.40	119.05	53.93	0.97	16.36	1.25	5.30	0.13	4.03	8.48	2.39	4.38	2.77
1084.15	1.40	118.98	53.94	0.98	16.37	1.25	5.29	0.13	4.01	8.48	2.39	4.38	2.77
1083.15	1.40	118.91	53.95	0.98	16.38	1.25	5.28	0.13	3.99	8.49	2.40	4.38	2.78
1082.15	1.40	117.29	54.01	0.98	16.54	1.24	5.27	0.13	3.85	8.30	2.43	4.44	2.81
1081.15	1.40	116.93	54.02	0.98	16.57	1.24	5.27	0.13	3.82	8.26	2.43	4.46	2.82
1080.15	1.40	116.56	54.04	0.98	16.61	1.24	5.26	0.13	3.79	8.22	2.44	4.47	2.83
1079.15	1.40	116.20	54.05	0.98	16.64	1.24	5.26	0.13	3.75	8.17	2.45	4.48	2.84
1078.15	1.40	115.85	54.07	0.98	16.68	1.24	5.26	0.13	3.72	8.13	2.45	4.50	2.85
1077.15	1.40	115.49	54.08	0.98	16.71	1.24	5.25	0.13	3.69	8.09	2.46	4.51	2.86
1076.15	1.40	115.14	54.10	0.97	16.74	1.24	5.25	0.13	3.66	8.05	2.47	4.52	2.87
1075.15	1.40	114.79	54.11	0.97	16.78	1.24	5.25	0.13	3.63	8.01	2.47	4.54	2.87
1074.15	1.40	114.45	54.13	0.97	16.81	1.24	5.24	0.13	3.59	7.96	2.48	4.55	2.88
1073.15	1.40	114.11	54.14	0.97	16.85	1.23	5.24	0.14	3.56	7.92	2.49	4.57	2.89
1072.15	1.40	113.77	54.16	0.97	16.88	1.23	5.23	0.14	3.53	7.88	2.50	4.58	2.90
1071.15	1.40	113.43	54.17	0.97	16.91	1.23	5.23	0.14	3.50	7.84	2.50	4.59	2.91
1070.15	1.40	113.10	54.19	0.97	16.94	1.23	5.22	0.14	3.47	7.80	2.51	4.61	2.92
1069.15	1.40	112.77	54.20	0.97	16.98	1.23	5.22	0.14	3.44	7.76	2.52	4.62	2.93
1068.15	1.40	112.44	54.22	0.97	17.01	1.23	5.21	0.14	3.41	7.72	2.52	4.63	2.93
1067.15	1.40	112.12	54.24	0.97	17.04	1.23	5.21	0.14	3.38	7.68	2.53	4.65	2.94
1066.15	1.40	111.79	54.25	0.97	17.07	1.23	5.20	0.14	3.35	7.63	2.54	4.66	2.95
1065.15	1.40	111.48	54.27	0.97	17.11	1.23	5.20	0.14	3.32	7.59	2.54	4.67	2.96
1064.15	1.40	111.16	54.29	0.97	17.14	1.22	5.19	0.14	3.29	7.55	2.55	4.69	2.97
1063.15	1.40	110.85	54.30	0.97	17.17	1.22	5.19	0.14	3.26	7.51	2.56	4.70	2.98
1062.15	1.40	110.53	54.32	0.97	17.20	1.22	5.18	0.14	3.24	7.47	2.56	4.71	2.99
1061.15	1.40	110.23	54.34	0.96	17.23	1.22	5.18	0.14	3.21	7.43	2.57	4.73	2.99
1060.15	1.40	109.92	54.35	0.96	17.26	1.22	5.17	0.14	3.18	7.39	2.58	4.74	3.00
1059.15	1.40	109.62	54.37	0.96	17.29	1.22	5.17	0.14	3.15	7.35	2.58	4.75	3.01
1058.15	1.40	109.32	54.39	0.96	17.32	1.22	5.16	0.14	3.12	7.31	2.59	4.77	3.02
1057.15	1.40	109.02	54.40	0.96	17.35	1.22	5.16	0.14	3.10	7.27	2.60	4.78	3.03
1056.15	1.40	108.72	54.42	0.96	17.38	1.22	5.15	0.14	3.07	7.23	2.60	4.79	3.04
1055.15	1.40	108.43	54.44	0.96	17.41	1.21	5.14	0.14	3.04	7.19	2.61	4.81	3.04
1054.15	1.40	108.14	54.45	0.96	17.44	1.21	5.14	0.14	3.01	7.15	2.62	4.82	3.05
1053.15	1.40	107.85	54.47	0.95	17.47	1.21	5.13	0.14	2.99	7.11	2.62	4.83	3.06
1052.15	1.40	107.56	54.49	0.95	17.50	1.21	5.13	0.14	2.96	7.08	2.63	4.84	3.07
1051.15	1.40	107.28	54.51	0.95	17.53	1.21	5.12	0.14	2.93	7.04	2.63	4.86	3.08
1050.15	1.40	107.00	54.53	0.95	17.56	1.21	5.11	0.14	2.91	7.00	2.64	4.87	3.08
1049.15	1.40	106.72	54.54	0.95	17.59	1.21	5.11	0.14	2.88	6.96	2.65	4.88	3.09
1048.15	1.40	106.44	54.56	0.95	17.62	1.21	5.10	0.14	2.85	6.92	2.65	4.89	3.10
1047.15	1.40	106.17	54.58	0.94	17.65	1.21	5.09	0.15	2.83	6.88	2.66	4.91	3.11
1046.15	1.40	105.89	54.60	0.94	17.68	1.20	5.09	0.15	2.80	6.84	2.67	4.92	3.12
1045.15	1.40	105.62	54.62	0.94	17.70	1.20	5.08	0.15	2.78	6.80	2.67	4.93	3.12
1044.15	1.40	105.35	54.63	0.94	17.73	1.20	5.07	0.15	2.75	6.77	2.68	4.95	3.13
1043.15	1.40	105.09	54.65	0.94	17.76	1.20	5.07	0.15	2.73	6.73	2.68	4.96	3.14
1042.15	1.40	104.82	54.67	0.93	17.79	1.20	5.06	0.15	2.70	6.69	2.69	4.97	3.15
1041.15	1.40	104.56	54.69	0.93	17.81	1.20	5.05	0.15	2.68	6.65	2.70	4.98	3.16
1040.15	1.40	104.30	54.71	0.93	17.84	1.20	5.05	0.15	2.65	6.62	2.70	5.00	3.16
1039.15	1.40	104.04	54.73	0.93	17.87	1.20	5.04	0.15	2.63	6.58	2.71	5.01	3.17
1038.15	1.40	103.79	54.75	0.92	17.89	1.19	5.03	0.15	2.60	6.54	2.72	5.02	3.18
1037.15	1.40	103.54	54.77	0.92	17.92	1.19	5.03	0.15	2.58	6.50	2.72	5.03	3.19
1036.15	1.40	103.28	54.79	0.92	17.95	1.19	5.02	0.15	2.56	6.47	2.73	5.04	3.20
1035.15	1.40	103.03	54.81	0.92	17.97	1.19	5.01	0.15	2.53	6.43	2.73	5.06	3.20
1034.15	1.40	102.79	54.83	0.91	18.00	1.19	5.00	0.15	2.51	6.39	2.74	5.07	3.21
1033.15	1.40	102.54	54.85	0.91	18.03	1.19	5.00	0.15	2.49	6.35	2.75	5.08	3.22
1032.15	1.40	102.30	54.87	0.91	18.05	1.19	4.99	0.15	2.46	6.32	2.75	5.09	3.23
1031.15	1.40	102.06	54.89	0.91	18.08	1.18	4.98	0.15	2.44	6.28	2.76	5.11	3.23

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T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1030.15	1.40	101.82	54.91	0.90	18.10	1.18	4.97	0.15	2.42	6.24	2.76	5.12	3.24
1029.15	1.40	101.58	54.93	0.90	18.13	1.18	4.97	0.15	2.39	6.21	2.77	5.13	3.25
1028.15	1.40	101.34	54.95	0.90	18.15	1.18	4.96	0.15	2.37	6.17	2.78	5.14	3.26
1027.15	1.40	101.11	54.97	0.89	18.18	1.18	4.95	0.15	2.35	6.14	2.78	5.15	3.26
1026.15	1.40	100.87	54.99	0.89	18.20	1.18	4.94	0.15	2.33	6.10	2.79	5.16	3.27
1025.15	1.40	100.64	55.01	0.89	18.22	1.18	4.93	0.15	2.31	6.06	2.79	5.18	3.28
1024.15	1.40	100.41	55.03	0.88	18.25	1.17	4.93	0.15	2.29	6.03	2.80	5.19	3.29
1023.15	1.40	100.19	55.05	0.88	18.27	1.17	4.92	0.15	2.26	5.99	2.80	5.20	3.29
1022.15	1.40	99.96	55.07	0.88	18.30	1.17	4.91	0.15	2.24	5.96	2.81	5.21	3.30
1021.15	1.40	99.74	55.09	0.87	18.32	1.17	4.90	0.15	2.22	5.92	2.82	5.22	3.31
1020.15	1.40	99.52	55.11	0.87	18.34	1.17	4.89	0.15	2.20	5.89	2.82	5.24	3.32
1019.15	1.40	99.30	55.13	0.87	18.37	1.17	4.88	0.16	2.18	5.85	2.83	5.25	3.32
1018.15	1.40	99.08	55.16	0.86	18.39	1.17	4.88	0.16	2.16	5.81	2.83	5.26	3.33
1017.15	1.40	98.86	55.18	0.86	18.41	1.16	4.87	0.16	2.14	5.78	2.84	5.27	3.34
1016.15	1.40	98.65	55.20	0.85	18.43	1.16	4.86	0.16	2.12	5.74	2.84	5.28	3.35
1015.15	1.40	98.43	55.22	0.85	18.46	1.16	4.85	0.16	2.10	5.71	2.85	5.29	3.35
1014.15	1.40	98.22	55.24	0.85	18.48	1.16	4.84	0.16	2.08	5.68	2.86	5.30	3.36
1013.15	1.40	98.01	55.26	0.84	18.50	1.16	4.83	0.16	2.06	5.64	2.86	5.32	3.37
1012.15	1.40	97.80	55.29	0.84	18.52	1.16	4.82	0.16	2.04	5.61	2.87	5.33	3.37
1011.15	1.40	97.60	55.31	0.83	18.54	1.16	4.82	0.16	2.02	5.57	2.87	5.34	3.38
1010.15	1.40	97.39	55.33	0.83	18.56	1.15	4.81	0.16	2.00	5.54	2.88	5.35	3.39
1009.15	1.40	97.19	55.35	0.82	18.58	1.15	4.80	0.16	1.99	5.50	2.88	5.36	3.40
1008.15	1.40	96.99	55.38	0.82	18.61	1.15	4.79	0.16	1.97	5.47	2.89	5.37	3.40
1007.15	1.40	96.71	55.40	0.82	18.60	1.15	4.79	0.16	1.96	5.43	2.89	5.39	3.41
1006.15	1.40	96.43	55.43	0.81	18.60	1.15	4.79	0.16	1.94	5.39	2.90	5.40	3.42
1005.15	1.40	96.16	55.46	0.81	18.60	1.15	4.78	0.16	1.93	5.35	2.90	5.42	3.43
1004.15	1.40	95.88	55.49	0.81	18.60	1.15	4.78	0.16	1.92	5.31	2.91	5.43	3.44
1003.15	1.40	95.62	55.52	0.80	18.60	1.15	4.78	0.16	1.91	5.27	2.91	5.45	3.45
1002.15	1.40	95.35	55.55	0.79	18.59	1.15	4.78	0.16	1.90	5.23	2.92	5.46	3.46
1001.15	1.40	95.09	55.58	0.79	18.59	1.15	4.78	0.16	1.89	5.19	2.92	5.48	3.47
1000.15	1.40	94.83	55.61	0.78	18.58	1.15	4.78	0.16	1.88	5.15	2.93	5.49	3.48
999.15	1.40	94.57	55.64	0.77	18.58	1.15	4.78	0.16	1.87	5.11	2.93	5.51	3.49
998.15	1.40	94.32	55.67	0.77	18.57	1.16	4.78	0.16	1.86	5.07	2.94	5.52	3.50
997.15	1.40	94.07	55.70	0.76	18.57	1.16	4.77	0.16	1.85	5.04	2.94	5.54	3.51
996.15	1.40	93.82	55.73	0.76	18.56	1.16	4.77	0.16	1.84	5.00	2.95	5.55	3.52
995.15	1.40	93.57	55.76	0.75	18.56	1.16	4.77	0.16	1.83	4.96	2.95	5.57	3.53
994.15	1.40	93.32	55.79	0.74	18.56	1.16	4.77	0.17	1.82	4.92	2.96	5.58	3.54
993.15	1.40	93.08	55.82	0.74	18.55	1.16	4.77	0.17	1.81	4.88	2.96	5.59	3.55
992.15	1.40	92.84	55.85	0.73	18.55	1.16	4.77	0.17	1.80	4.85	2.97	5.61	3.55
991.15	1.40	92.60	55.88	0.73	18.54	1.16	4.76	0.17	1.79	4.81	2.97	5.62	3.56
990.15	1.40	92.36	55.91	0.72	18.54	1.16	4.76	0.17	1.78	4.77	2.98	5.64	3.57
989.15	1.40	92.13	55.94	0.72	18.53	1.16	4.76	0.17	1.77	4.74	2.98	5.65	3.58
988.15	1.40	91.90	55.97	0.71	18.53	1.16	4.76	0.17	1.76	4.70	2.98	5.67	3.59
987.15	1.40	90.66	56.16	0.72	18.56	1.13	4.61	0.17	1.60	4.66	3.01	5.74	3.64
986.15	1.40	90.36	56.20	0.72	18.54	1.13	4.60	0.17	1.58	4.64	3.01	5.76	3.65
985.15	1.40	90.07	56.23	0.73	18.53	1.13	4.59	0.17	1.57	4.61	3.02	5.78	3.66
984.15	1.40	89.78	56.27	0.73	18.51	1.13	4.57	0.17	1.55	4.59	3.02	5.80	3.68
983.15	1.40	89.49	56.30	0.73	18.49	1.13	4.56	0.17	1.53	4.57	3.02	5.81	3.69
982.15	1.40	89.20	56.34	0.73	18.47	1.13	4.55	0.17	1.52	4.54	3.03	5.83	3.70
981.15	1.40	88.92	56.37	0.73	18.45	1.12	4.54	0.17	1.50	4.52	3.03	5.85	3.71
980.15	1.40	88.63	56.41	0.74	18.43	1.12	4.52	0.17	1.48	4.50	3.04	5.87	3.72
979.15	1.40	88.30	56.50	0.70	18.45	1.12	4.50	0.17	1.46	4.43	3.05	5.89	3.74
978.15	1.40	88.03	56.54	0.69	18.44	1.12	4.49	0.17	1.44	4.41	3.05	5.91	3.75
977.15	1.40	87.75	56.59	0.69	18.42	1.11	4.47	0.17	1.42	4.38	3.06	5.93	3.76
976.15	1.40	87.46	56.63	0.68	18.41	1.11	4.46	0.17	1.41	4.35	3.06	5.95	3.77
975.15	1.40	87.18	56.68	0.68	18.40	1.11	4.44	0.17	1.39	4.32	3.06	5.97	3.79
974.15	1.40	86.91	56.72	0.67	18.39	1.11	4.43	0.17	1.37	4.29	3.07	5.98	3.80
973.15	1.40	86.63	56.76	0.67	18.37	1.11	4.41	0.17	1.36	4.26	3.07	6.00	3.81
972.15	1.40	86.36	56.81	0.66	18.36	1.11	4.40	0.17	1.34	4.24	3.08	6.02	3.82
971.15	1.40	86.08	56.85	0.66	18.35	1.10	4.38	0.17	1.32	4.21	3.08	6.04	3.83
970.15	1.40	85.81	56.89	0.66	18.34	1.10	4.37	0.17	1.31	4.18	3.09	6.06	3.85
969.15	1.40	85.55	56.94	0.65	18.32	1.10	4.35	0.17	1.29	4.15	3.09	6.08	3.86
968.15	1.40	85.28	56.98	0.65	18.31	1.10	4.33	0.17	1.28	4.13	3.09	6.10	3.87
967.15	1.40	85.01	57.02	0.64	18.30	1.09	4.32	0.17	1.26	4.10	3.10	6.11	3.88
966.15	1.40	84.75	57.06	0.64	18.29	1.09	4.30	0.17	1.24	4.07	3.10	6.13	3.89
965.15	1.40	84.49	57.11	0.64	18.28	1.09	4.29	0.17	1.23	4.04	3.11	6.15	3.91
964.15	1.40	84.23	57.15	0.63	18.26	1.09	4.27	0.17	1.21	4.02	3.11	6.17	3.92
963.15	1.40	83.97	57.19	0.63	18.25	1.09	4.25	0.17	1.20	3.99	3.12	6.19	3.93
962.15	1.40	83.71	57.23	0.62	18.24	1.08	4.24	0.17	1.18	3.96	3.12	6.21	3.94
961.15	1.40	83.46	57.28	0.62	18.23	1.08	4.22	0.17	1.17	3.94	3.12	6.23	3.95
960.15	1.40	83.21	57.32	0.62	18.21	1.08	4.20	0.17	1.15	3.91	3.13	6.24	3.97

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
959.15	1.40	82.95	57.36	0.61	18.20	1.08	4.19	0.17	1.14	3.88	3.13	6.26	3.98
958.15	1.40	82.70	57.40	0.61	18.19	1.07	4.17	0.17	1.12	3.86	3.13	6.28	3.99
957.15	1.40	82.46	57.44	0.61	18.18	1.07	4.15	0.17	1.11	3.83	3.14	6.30	4.00
956.15	1.40	82.21	57.49	0.60	18.17	1.07	4.13	0.17	1.10	3.81	3.14	6.32	4.01
955.15	1.40	81.96	57.53	0.60	18.15	1.06	4.12	0.17	1.08	3.78	3.15	6.34	4.03
954.15	1.40	81.72	57.57	0.60	18.14	1.06	4.10	0.17	1.07	3.75	3.15	6.36	4.04
953.15	1.40	81.48	57.61	0.59	18.13	1.06	4.08	0.17	1.05	3.73	3.15	6.37	4.05
952.15	1.40	81.23	57.65	0.59	18.12	1.06	4.06	0.17	1.04	3.70	3.16	6.39	4.06
951.15	1.40	80.99	57.69	0.59	18.11	1.05	4.04	0.17	1.03	3.68	3.16	6.41	4.07
950.15	1.40	80.76	57.73	0.58	18.09	1.05	4.03	0.17	1.01	3.65	3.16	6.43	4.09
949.15	1.40	80.52	57.78	0.58	18.08	1.05	4.01	0.17	1.00	3.63	3.17	6.45	4.10
948.15	1.40	80.28	57.82	0.58	18.07	1.04	3.99	0.17	0.99	3.60	3.17	6.47	4.11
947.15	1.40	80.05	57.86	0.57	18.06	1.04	3.97	0.17	0.97	3.58	3.17	6.49	4.12
946.15	1.40	79.81	57.90	0.57	18.05	1.04	3.95	0.17	0.96	3.55	3.18	6.50	4.13
945.15	1.40	79.58	57.94	0.57	18.04	1.04	3.93	0.17	0.95	3.53	3.18	6.52	4.15
944.15	1.40	79.35	57.98	0.56	18.02	1.03	3.91	0.17	0.94	3.51	3.18	6.54	4.16
943.15	1.40	79.12	58.02	0.56	18.01	1.03	3.89	0.17	0.92	3.48	3.18	6.56	4.17
942.15	1.40	78.90	58.06	0.56	18.00	1.03	3.87	0.17	0.91	3.46	3.19	6.58	4.18
941.15	1.40	78.67	58.10	0.56	17.99	1.02	3.86	0.17	0.90	3.43	3.19	6.60	4.19
940.15	1.40	78.44	58.14	0.55	17.98	1.02	3.84	0.17	0.89	3.41	3.19	6.61	4.21
939.15	1.40	78.22	58.18	0.55	17.97	1.02	3.82	0.17	0.87	3.39	3.20	6.63	4.22
938.15	1.40	78.00	58.22	0.55	17.95	1.01	3.80	0.17	0.86	3.36	3.20	6.65	4.23
937.15	1.40	77.78	58.26	0.54	17.94	1.01	3.78	0.17	0.85	3.34	3.20	6.67	4.24
936.15	1.40	77.55	58.30	0.54	17.93	1.01	3.76	0.17	0.84	3.31	3.20	6.69	4.26
935.15	1.40	77.34	58.34	0.54	17.92	1.00	3.74	0.17	0.83	3.29	3.21	6.71	4.27
934.15	1.40	77.12	58.38	0.54	17.91	1.00	3.72	0.17	0.82	3.27	3.21	6.73	4.28
933.15	1.40	76.90	58.41	0.53	17.90	1.00	3.70	0.17	0.80	3.25	3.21	6.74	4.29
932.15	1.40	76.69	58.45	0.53	17.88	0.99	3.68	0.17	0.79	3.22	3.21	6.76	4.30
931.15	1.40	76.47	58.49	0.53	17.87	0.99	3.66	0.17	0.78	3.20	3.22	6.78	4.32
930.15	1.40	76.26	58.53	0.53	17.86	0.99	3.64	0.17	0.77	3.18	3.22	6.80	4.33
929.15	1.40	75.84	58.65	0.47	17.84	0.97	3.58	0.17	0.76	3.15	3.22	6.84	4.35
928.15	1.40	75.61	58.70	0.46	17.83	0.97	3.55	0.17	0.75	3.13	3.23	6.86	4.36
927.15	1.40	75.38	58.74	0.46	17.81	0.96	3.53	0.17	0.74	3.11	3.23	6.88	4.38
926.15	1.40	75.15	58.78	0.45	17.80	0.96	3.50	0.17	0.73	3.09	3.23	6.90	4.39
925.15	1.40	74.93	58.82	0.45	17.79	0.95	3.48	0.17	0.72	3.07	3.23	6.92	4.40
924.15	1.40	74.70	58.87	0.44	17.77	0.95	3.46	0.17	0.72	3.05	3.23	6.94	4.42
923.15	1.40	74.48	58.91	0.44	17.76	0.95	3.43	0.17	0.71	3.03	3.23	6.96	4.43
922.15	1.40	74.25	58.95	0.44	17.74	0.94	3.41	0.16	0.70	3.01	3.23	6.98	4.44
921.15	1.40	74.03	58.99	0.43	17.73	0.94	3.39	0.16	0.69	2.99	3.24	7.00	4.46
920.15	1.40	73.81	59.03	0.43	17.71	0.93	3.36	0.16	0.68	2.97	3.24	7.02	4.47
919.15	1.40	73.59	59.07	0.42	17.70	0.93	3.34	0.16	0.67	2.95	3.24	7.04	4.48
918.15	1.40	73.38	59.11	0.42	17.69	0.92	3.31	0.16	0.66	2.93	3.24	7.06	4.50
917.15	1.40	73.16	59.15	0.41	17.67	0.92	3.29	0.16	0.65	2.91	3.24	7.08	4.51
916.15	1.40	72.95	59.19	0.41	17.66	0.91	3.27	0.16	0.64	2.89	3.24	7.10	4.52
915.15	1.40	72.73	59.23	0.41	17.64	0.91	3.24	0.16	0.64	2.87	3.24	7.12	4.54
914.15	1.40	72.52	59.27	0.40	17.63	0.90	3.22	0.16	0.63	2.85	3.24	7.14	4.55
913.15	1.40	72.31	59.31	0.40	17.62	0.90	3.20	0.16	0.62	2.83	3.24	7.16	4.56
912.15	1.40	72.10	59.35	0.39	17.60	0.90	3.17	0.16	0.61	2.81	3.24	7.18	4.58
911.15	1.40	71.90	59.39	0.39	17.59	0.89	3.15	0.16	0.60	2.79	3.25	7.20	4.59
910.15	1.40	71.69	59.43	0.39	17.57	0.89	3.13	0.16	0.59	2.77	3.25	7.22	4.60
909.15	1.40	71.48	59.47	0.38	17.56	0.88	3.10	0.16	0.59	2.75	3.25	7.24	4.62
908.15	1.40	71.28	59.51	0.38	17.55	0.88	3.08	0.16	0.58	2.73	3.25	7.26	4.63
907.15	1.40	71.08	59.54	0.38	17.53	0.87	3.06	0.16	0.57	2.72	3.25	7.28	4.64
906.15	1.40	70.88	59.58	0.37	17.52	0.87	3.03	0.16	0.56	2.70	3.25	7.30	4.66
905.15	1.40	70.68	59.62	0.37	17.51	0.86	3.01	0.16	0.56	2.68	3.25	7.32	4.67
904.15	1.40	70.48	59.66	0.37	17.49	0.86	2.99	0.16	0.55	2.66	3.25	7.34	4.68
903.15	1.40	70.28	59.69	0.36	17.48	0.85	2.96	0.16	0.54	2.64	3.25	7.36	4.70
902.15	1.40	70.09	59.73	0.36	17.47	0.85	2.94	0.16	0.53	2.62	3.25	7.38	4.71
901.15	1.40	69.89	59.77	0.35	17.45	0.84	2.92	0.16	0.53	2.61	3.25	7.40	4.72
900.15	1.40	69.70	59.81	0.35	17.44	0.84	2.90	0.16	0.52	2.59	3.25	7.42	4.73
899.15	1.40	69.51	59.84	0.35	17.42	0.83	2.87	0.16	0.51	2.57	3.25	7.44	4.75
898.15	1.40	69.25	59.90	0.35	17.41	0.83	2.85	0.16	0.51	2.55	3.25	7.46	4.75
897.15	1.40	68.98	59.95	0.34	17.39	0.82	2.82	0.16	0.50	2.52	3.25	7.49	4.75
896.15	1.40	68.72	60.01	0.34	17.38	0.82	2.79	0.16	0.49	2.50	3.25	7.52	4.75
895.15	1.40	68.46	60.06	0.34	17.36	0.81	2.77	0.16	0.48	2.48	3.25	7.55	4.76
894.15	1.40	68.21	60.11	0.33	17.34	0.81	2.74	0.16	0.47	2.45	3.25	7.57	4.76
893.15	1.40	67.95	60.17	0.33	17.33	0.80	2.71	0.16	0.46	2.43	3.25	7.60	4.76
892.15	1.40	67.70	60.22	0.33	17.31	0.79	2.69	0.16	0.46	2.41	3.25	7.63	4.76
891.15	1.40	67.45	60.27	0.33	17.29	0.79	2.66	0.16	0.45	2.38	3.24	7.66	4.76
890.15	1.40	67.20	60.33	0.32	17.28	0.78	2.63	0.16	0.44	2.36	3.24	7.68	4.77
889.15	1.40	66.95	60.38	0.32	17.26	0.78	2.61	0.16	0.43	2.34	3.24	7.71	4.77

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
888.15	1.40	66.70	60.43	0.32	17.25	0.77	2.58	0.16	0.43	2.31	3.24	7.74	4.77
887.15	1.40	66.45	60.48	0.32	17.23	0.77	2.56	0.16	0.42	2.29	3.24	7.77	4.77
886.15	1.40	66.21	60.54	0.31	17.21	0.76	2.53	0.16	0.41	2.27	3.24	7.79	4.77
885.15	1.40	65.97	60.59	0.31	17.20	0.75	2.50	0.16	0.41	2.25	3.24	7.82	4.77
884.15	1.40	65.73	60.64	0.31	17.18	0.75	2.48	0.16	0.40	2.23	3.23	7.85	4.78
883.15	1.40	65.49	60.69	0.31	17.17	0.74	2.45	0.16	0.39	2.20	3.23	7.88	4.78
882.15	1.40	65.25	60.74	0.30	17.15	0.74	2.43	0.16	0.39	2.18	3.23	7.90	4.78
881.15	1.40	65.01	60.79	0.30	17.13	0.73	2.40	0.16	0.38	2.16	3.23	7.93	4.78
880.15	1.40	64.78	60.84	0.30	17.12	0.73	2.38	0.16	0.37	2.14	3.23	7.96	4.78
879.15	1.40	64.55	60.89	0.30	17.10	0.72	2.35	0.16	0.37	2.12	3.22	7.99	4.78
878.15	1.40	64.31	60.94	0.30	17.09	0.71	2.33	0.16	0.36	2.10	3.22	8.01	4.78
877.15	1.40	64.08	60.99	0.29	17.07	0.71	2.31	0.16	0.36	2.08	3.22	8.04	4.79
876.15	1.40	63.85	61.04	0.29	17.06	0.70	2.28	0.16	0.35	2.06	3.21	8.07	4.79
875.15	1.40	63.63	61.08	0.29	17.04	0.70	2.26	0.16	0.34	2.03	3.21	8.10	4.79
874.15	1.40	63.40	61.13	0.29	17.03	0.69	2.23	0.16	0.34	2.01	3.21	8.12	4.79
873.15	1.40	63.18	61.18	0.29	17.01	0.69	2.21	0.16	0.33	1.99	3.20	8.15	4.79
872.15	1.40	62.95	61.23	0.28	17.00	0.68	2.19	0.16	0.33	1.97	3.20	8.18	4.79
871.15	1.40	62.73	61.27	0.28	16.98	0.67	2.16	0.16	0.32	1.95	3.20	8.21	4.79
870.15	1.40	62.51	61.32	0.28	16.97	0.67	2.14	0.16	0.32	1.93	3.19	8.23	4.79
869.15	1.40	62.29	61.37	0.28	16.95	0.66	2.12	0.16	0.31	1.91	3.19	8.26	4.80
868.15	1.40	62.07	61.41	0.28	16.93	0.66	2.09	0.16	0.31	1.89	3.19	8.29	4.80
867.15	1.40	61.85	61.46	0.27	16.92	0.65	2.07	0.16	0.30	1.87	3.18	8.32	4.80
866.15	1.40	61.64	61.50	0.27	16.90	0.65	2.05	0.16	0.30	1.85	3.18	8.34	4.80
865.15	1.40	61.42	61.55	0.27	16.89	0.64	2.02	0.16	0.29	1.84	3.17	8.37	4.80
864.15	1.40	61.21	61.59	0.27	16.87	0.64	2.00	0.16	0.29	1.82	3.17	8.40	4.80
863.15	1.40	61.00	61.64	0.27	16.86	0.63	1.98	0.16	0.28	1.80	3.16	8.43	4.80
862.15	1.40	60.78	61.68	0.26	16.84	0.62	1.96	0.16	0.28	1.78	3.16	8.45	4.80
861.15	1.40	60.57	61.73	0.26	16.83	0.62	1.94	0.15	0.27	1.76	3.15	8.48	4.80
860.15	1.40	60.37	61.77	0.26	16.81	0.61	1.91	0.15	0.27	1.74	3.15	8.51	4.80
859.15	1.40	60.16	61.81	0.26	16.80	0.61	1.89	0.15	0.26	1.72	3.14	8.54	4.80
858.15	1.40	59.95	61.86	0.26	16.79	0.60	1.87	0.15	0.26	1.70	3.14	8.56	4.80
857.15	1.40	59.75	61.90	0.26	16.77	0.60	1.85	0.15	0.26	1.69	3.13	8.59	4.81
856.15	1.40	59.54	61.94	0.25	16.76	0.59	1.83	0.15	0.25	1.67	3.13	8.62	4.81
855.15	1.40	59.34	61.98	0.25	16.74	0.59	1.81	0.15	0.25	1.65	3.12	8.65	4.81
854.15	1.40	59.13	62.03	0.25	16.73	0.58	1.79	0.15	0.24	1.63	3.12	8.67	4.81
853.15	1.40	58.93	62.07	0.25	16.71	0.58	1.77	0.15	0.24	1.62	3.11	8.70	4.81
852.15	1.40	58.73	62.11	0.25	16.70	0.57	1.75	0.15	0.24	1.60	3.10	8.73	4.81
851.15	1.40	58.53	62.15	0.25	16.68	0.57	1.73	0.15	0.23	1.58	3.10	8.76	4.81
850.15	1.40	58.33	62.19	0.24	16.67	0.56	1.71	0.15	0.23	1.56	3.09	8.79	4.81
849.15	1.40	58.14	62.23	0.24	16.65	0.56	1.69	0.15	0.22	1.55	3.08	8.81	4.81
848.15	1.40	57.94	62.27	0.24	16.64	0.55	1.67	0.15	0.22	1.53	3.08	8.84	4.81
847.15	1.40	57.74	62.31	0.24	16.63	0.55	1.65	0.15	0.22	1.51	3.07	8.87	4.81
846.15	1.40	57.55	62.35	0.24	16.61	0.54	1.63	0.15	0.21	1.50	3.06	8.90	4.81
845.15	1.40	57.35	62.39	0.24	16.60	0.54	1.61	0.15	0.21	1.48	3.06	8.92	4.81
844.15	1.40	57.16	62.43	0.24	16.58	0.53	1.59	0.15	0.21	1.46	3.05	8.95	4.81
843.15	1.40	56.97	62.47	0.23	16.57	0.53	1.57	0.15	0.20	1.45	3.04	8.98	4.81
842.15	1.40	56.78	62.51	0.23	16.55	0.52	1.55	0.15	0.20	1.43	3.03	9.01	4.81
841.15	1.40	56.59	62.54	0.23	16.54	0.52	1.53	0.15	0.20	1.42	3.03	9.04	4.81
840.15	1.40	56.40	62.58	0.23	16.53	0.51	1.51	0.15	0.19	1.40	3.02	9.06	4.81
839.15	1.40	56.21	62.62	0.23	16.51	0.51	1.49	0.15	0.19	1.38	3.01	9.09	4.81
838.15	1.40	56.02	62.66	0.23	16.50	0.50	1.48	0.15	0.19	1.37	3.00	9.12	4.81
837.15	1.40	55.83	62.69	0.23	16.48	0.50	1.46	0.15	0.19	1.35	2.99	9.15	4.81
836.15	1.40	55.65	62.73	0.22	16.47	0.49	1.44	0.15	0.18	1.34	2.99	9.18	4.81
835.15	1.40	55.46	62.77	0.22	16.46	0.49	1.42	0.15	0.18	1.32	2.98	9.20	4.81
834.15	1.40	55.27	62.80	0.22	16.44	0.48	1.41	0.15	0.18	1.31	2.97	9.23	4.81
833.15	1.40	55.09	62.84	0.22	16.43	0.48	1.39	0.15	0.17	1.29	2.96	9.26	4.81
832.15	1.40	54.91	62.87	0.22	16.41	0.47	1.37	0.15	0.17	1.28	2.95	9.29	4.81
831.15	1.40	54.72	62.91	0.22	16.40	0.47	1.35	0.15	0.17	1.26	2.94	9.32	4.81
830.15	1.40	54.54	62.94	0.22	16.39	0.46	1.34	0.15	0.17	1.25	2.93	9.34	4.81
829.15	1.40	54.36	62.98	0.22	16.37	0.46	1.32	0.15	0.16	1.24	2.92	9.37	4.81
828.15	1.40	54.17	63.01	0.21	16.36	0.45	1.30	0.15	0.16	1.22	2.91	9.40	4.81
827.15	1.40	53.99	63.05	0.21	16.35	0.45	1.29	0.15	0.16	1.21	2.90	9.43	4.81
826.15	1.40	53.81	63.08	0.21	16.33	0.44	1.27	0.15	0.16	1.19	2.89	9.46	4.81
825.15	1.40	53.63	63.12	0.21	16.32	0.44	1.25	0.15	0.15	1.18	2.88	9.49	4.81
824.15	1.40	53.45	63.15	0.21	16.31	0.44	1.24	0.15	0.15	1.17	2.87	9.51	4.81
823.15	1.40	50.95	63.28	0.21	16.22	0.43	1.22	0.15	0.15	1.18	2.84	9.51	4.81
822.15	1.40	47.01	63.49	0.21	16.08	0.43	1.21	0.16	0.14	1.21	2.79	9.47	4.81
821.15	1.40	43.81	63.69	0.21	15.94	0.42	1.20	0.17	0.14	1.24	2.74	9.43	4.81
820.15	1.40	41.15	63.88	0.21	15.81	0.42	1.19	0.18	0.14	1.27	2.70	9.39	4.81
819.15	1.40	38.89	64.07	0.21	15.69	0.42	1.18	0.19	0.14	1.30	2.66	9.35	4.81
818.15	1.40	36.95	64.24	0.21	15.57	0.41	1.16	0.19	0.13	1.32	2.62	9.31	4.82

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
817.15	1.40	35.26	64.42	0.21	15.46	0.41	1.15	0.20	0.13	1.34	2.58	9.28	4.82
816.15	1.40	33.77	64.58	0.21	15.35	0.40	1.14	0.21	0.13	1.37	2.55	9.24	4.82
815.15	1.40	32.44	64.74	0.21	15.24	0.40	1.13	0.21	0.13	1.39	2.52	9.20	4.82
814.15	1.40	31.25	64.90	0.21	15.14	0.40	1.12	0.22	0.13	1.41	2.49	9.16	4.82
813.15	1.40	30.17	65.05	0.21	15.04	0.39	1.11	0.22	0.13	1.43	2.46	9.13	4.83
812.15	1.40	29.20	65.20	0.21	14.95	0.39	1.10	0.23	0.12	1.45	2.44	9.09	4.83
811.15	1.40	28.30	65.34	0.21	14.85	0.39	1.09	0.23	0.12	1.47	2.41	9.06	4.83
810.15	1.40	27.48	65.48	0.21	14.76	0.38	1.08	0.24	0.12	1.49	2.39	9.02	4.84
809.15	1.40	26.73	65.62	0.20	14.67	0.38	1.07	0.24	0.12	1.51	2.36	8.99	4.84
808.15	1.40	26.02	65.76	0.20	14.58	0.38	1.06	0.25	0.12	1.53	2.34	8.95	4.84
807.15	1.40	25.37	65.89	0.20	14.50	0.37	1.05	0.25	0.12	1.54	2.32	8.92	4.84
806.15	1.40	24.77	66.02	0.20	14.41	0.37	1.04	0.26	0.12	1.56	2.30	8.88	4.85
805.15	1.40	24.20	66.15	0.20	14.33	0.37	1.03	0.26	0.12	1.58	2.28	8.85	4.85
804.15	1.40	23.66	66.27	0.20	14.25	0.37	1.02	0.26	0.11	1.59	2.26	8.82	4.85
803.15	1.40	23.16	66.40	0.20	14.17	0.36	1.01	0.27	0.11	1.61	2.24	8.78	4.85
802.15	1.40	22.69	66.52	0.20	14.09	0.36	1.00	0.27	0.11	1.63	2.22	8.75	4.86
801.15	1.40	22.24	66.64	0.20	14.01	0.36	0.99	0.28	0.11	1.64	2.20	8.72	4.86
800.15	1.40	21.82	66.76	0.20	13.94	0.35	0.98	0.28	0.11	1.66	2.18	8.69	4.86
799.15	1.40	21.42	66.87	0.20	13.86	0.35	0.97	0.28	0.11	1.67	2.16	8.65	4.87
798.15	1.40	21.04	66.99	0.20	13.79	0.35	0.96	0.29	0.11	1.69	2.15	8.62	4.87
797.15	1.40	20.68	67.10	0.19	13.72	0.35	0.95	0.29	0.11	1.70	2.13	8.59	4.87
796.15	1.40	20.33	67.21	0.19	13.64	0.34	0.94	0.29	0.11	1.72	2.11	8.56	4.87
795.15	1.40	20.00	67.32	0.19	13.57	0.34	0.93	0.30	0.11	1.73	2.10	8.53	4.88
794.15	1.40	19.69	67.43	0.19	13.50	0.34	0.93	0.30	0.11	1.74	2.08	8.50	4.88
793.15	1.40	19.39	67.54	0.19	13.44	0.33	0.92	0.30	0.11	1.76	2.07	8.47	4.88
792.15	1.40	19.10	67.65	0.19	13.37	0.33	0.91	0.30	0.10	1.77	2.05	8.44	4.89
791.15	1.40	18.82	67.75	0.19	13.30	0.33	0.90	0.31	0.10	1.78	2.04	8.41	4.89
790.15	1.40	18.56	67.86	0.19	13.24	0.33	0.89	0.31	0.10	1.80	2.02	8.38	4.89
789.15	1.40	18.30	67.96	0.19	13.17	0.32	0.88	0.31	0.10	1.81	2.01	8.35	4.89
788.15	1.40	18.06	68.06	0.19	13.11	0.32	0.87	0.32	0.10	1.82	2.00	8.32	4.90
787.15	1.40	17.82	68.16	0.19	13.04	0.32	0.87	0.32	0.10	1.84	1.98	8.29	4.90
786.15	1.40	17.59	68.26	0.18	12.98	0.32	0.86	0.32	0.10	1.85	1.97	8.26	4.90
785.15	1.40	17.37	68.36	0.18	12.92	0.31	0.85	0.32	0.10	1.86	1.96	8.23	4.91
784.15	1.40	17.16	68.46	0.18	12.85	0.31	0.84	0.33	0.10	1.87	1.94	8.20	4.91
783.15	1.40	16.96	68.55	0.18	12.79	0.31	0.83	0.33	0.10	1.88	1.93	8.18	4.91
782.15	1.40	16.76	68.65	0.18	12.73	0.31	0.83	0.33	0.10	1.90	1.92	8.15	4.91
781.15	1.40	16.57	68.75	0.18	12.67	0.30	0.82	0.33	0.10	1.91	1.91	8.12	4.92
780.15	1.40	16.38	68.84	0.18	12.61	0.30	0.81	0.34	0.10	1.92	1.89	8.09	4.92
779.15	1.40	16.20	68.93	0.18	12.55	0.30	0.80	0.34	0.10	1.93	1.88	8.06	4.92
778.15	1.40	16.02	69.03	0.18	12.49	0.30	0.79	0.34	0.10	1.94	1.87	8.04	4.92
777.15	1.40	15.86	69.12	0.18	12.44	0.29	0.79	0.34	0.10	1.95	1.86	8.01	4.93
776.15	1.40	15.69	69.21	0.18	12.38	0.29	0.78	0.35	0.09	1.97	1.85	7.98	4.93
775.15	1.40	15.53	69.30	0.17	12.32	0.29	0.77	0.35	0.09	1.98	1.84	7.95	4.93
774.15	1.40	15.38	69.39	0.17	12.27	0.29	0.76	0.35	0.09	1.99	1.83	7.93	4.94
773.15	1.40	15.22	69.48	0.17	12.21	0.29	0.76	0.35	0.09	2.00	1.82	7.90	4.94
772.15	1.40	15.08	69.57	0.17	12.15	0.28	0.75	0.36	0.09	2.01	1.80	7.87	4.94
771.15	1.40	14.93	69.65	0.17	12.10	0.28	0.74	0.36	0.09	2.02	1.79	7.85	4.94
770.15	1.40	14.80	69.74	0.17	12.04	0.28	0.74	0.36	0.09	2.03	1.78	7.82	4.95
769.15	1.40	14.66	69.83	0.17	11.99	0.28	0.73	0.36	0.09	2.04	1.77	7.79	4.95
768.15	1.40	14.53	69.91	0.17	11.94	0.27	0.72	0.36	0.09	2.05	1.76	7.77	4.95
767.15	1.40	14.40	70.00	0.17	11.88	0.27	0.71	0.37	0.09	2.06	1.75	7.74	4.95
766.15	1.40	14.27	70.08	0.17	11.83	0.27	0.71	0.37	0.09	2.07	1.74	7.71	4.96
765.15	1.40	14.15	70.17	0.16	11.78	0.27	0.70	0.37	0.09	2.08	1.73	7.69	4.96
764.15	1.40	14.03	70.25	0.16	11.72	0.27	0.69	0.37	0.09	2.09	1.72	7.66	4.96
763.15	1.40	13.91	70.33	0.16	11.67	0.26	0.69	0.37	0.09	2.10	1.71	7.64	4.96
762.15	1.40	13.80	70.41	0.16	11.62	0.26	0.68	0.38	0.09	2.11	1.71	7.61	4.97
761.15	1.40	13.69	70.50	0.16	11.57	0.26	0.67	0.38	0.09	2.12	1.70	7.59	4.97
760.15	1.40	13.58	70.58	0.16	11.52	0.26	0.67	0.38	0.09	2.13	1.69	7.56	4.97
759.15	1.40	13.47	70.66	0.16	11.47	0.26	0.66	0.38	0.09	2.14	1.68	7.53	4.97
758.15	1.40	13.37	70.74	0.16	11.42	0.25	0.65	0.38	0.09	2.15	1.67	7.51	4.98
757.15	1.40	13.27	70.82	0.16	11.37	0.25	0.65	0.39	0.09	2.16	1.66	7.48	4.98
756.15	1.40	13.06	71.04	0.16	11.33	0.23	0.59	0.39	0.06	2.09	1.66	7.47	4.98
755.15	1.40	12.95	71.12	0.16	11.29	0.23	0.58	0.40	0.06	2.10	1.65	7.44	4.98
754.15	1.40	12.86	71.20	0.16	11.24	0.23	0.58	0.40	0.06	2.10	1.64	7.41	4.98
753.15	1.40	12.76	71.28	0.16	11.20	0.23	0.58	0.40	0.06	2.10	1.64	7.38	4.98
752.15	1.40	12.66	71.36	0.16	11.16	0.22	0.57	0.40	0.06	2.10	1.63	7.35	4.98
751.15	1.40	12.57	71.44	0.16	11.11	0.22	0.57	0.41	0.05	2.11	1.62	7.32	4.98
750.15	1.40	12.48	71.52	0.16	11.07	0.22	0.56	0.41	0.05	2.11	1.62	7.30	4.98
749.15	1.40	12.39	71.59	0.16	11.03	0.22	0.56	0.41	0.05	2.11	1.61	7.27	4.99
748.15	1.40	12.30	71.67	0.16	10.98	0.22	0.55	0.42	0.05	2.11	1.60	7.24	4.99
747.15	1.40	12.21	71.75	0.16	10.94	0.22	0.55	0.42	0.05	2.12	1.60	7.22	4.99

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
746.15	1.40	12.13	71.83	0.16	10.90	0.22	0.54	0.42	0.05	2.12	1.59	7.19	4.99
745.15	1.40	12.05	71.91	0.16	10.85	0.21	0.54	0.43	0.04	2.12	1.58	7.17	4.99
744.15	1.40	11.97	71.98	0.16	10.81	0.21	0.53	0.43	0.04	2.12	1.58	7.14	4.99
743.15	1.40	11.89	72.06	0.16	10.77	0.21	0.53	0.43	0.04	2.12	1.57	7.12	4.99
742.15	1.40	11.81	72.14	0.16	10.73	0.21	0.53	0.43	0.04	2.12	1.56	7.09	4.99
741.15	1.40	11.73	72.21	0.16	10.68	0.21	0.52	0.44	0.04	2.12	1.56	7.07	5.00
740.15	1.40	11.66	72.29	0.16	10.64	0.21	0.52	0.44	0.04	2.12	1.55	7.04	5.00
739.15	1.40	11.58	72.37	0.16	10.60	0.21	0.51	0.44	0.04	2.12	1.54	7.02	5.00
738.15	1.40	11.51	72.44	0.16	10.55	0.20	0.51	0.45	0.04	2.12	1.54	6.99	5.00
737.15	1.40	11.44	72.52	0.15	10.51	0.20	0.50	0.45	0.03	2.13	1.53	6.97	5.00
736.15	1.40	11.37	72.59	0.15	10.47	0.20	0.50	0.45	0.03	2.13	1.52	6.94	5.00
735.15	1.40	11.30	72.67	0.15	10.43	0.20	0.49	0.45	0.03	2.13	1.52	6.92	5.00
734.15	1.40	11.23	72.74	0.15	10.39	0.20	0.49	0.46	0.03	2.13	1.51	6.90	5.01
733.15	1.40	11.16	72.82	0.15	10.35	0.20	0.49	0.46	0.03	2.13	1.50	6.87	5.01
732.15	1.40	11.10	72.89	0.15	10.31	0.20	0.48	0.46	0.03	2.13	1.50	6.85	5.01
731.15	1.40	11.03	72.97	0.15	10.26	0.19	0.48	0.46	0.03	2.13	1.49	6.82	5.01
730.15	1.40	10.97	73.04	0.15	10.22	0.19	0.47	0.47	0.03	2.13	1.49	6.80	5.01
729.15	1.40	10.91	73.11	0.15	10.18	0.19	0.47	0.47	0.03	2.13	1.48	6.78	5.01
728.15	1.40	10.84	73.19	0.14	10.14	0.19	0.46	0.47	0.03	2.13	1.47	6.75	5.01
727.15	1.40	10.78	73.26	0.14	10.10	0.19	0.46	0.48	0.02	2.13	1.47	6.73	5.02
726.15	1.40	10.72	73.33	0.14	10.06	0.19	0.46	0.48	0.02	2.13	1.46	6.71	5.02
725.15	1.40	10.66	73.40	0.14	10.02	0.19	0.45	0.48	0.02	2.14	1.46	6.69	5.02
724.15	1.40	10.61	73.47	0.14	9.98	0.18	0.45	0.48	0.02	2.14	1.45	6.66	5.02
723.15	1.40	10.55	73.55	0.14	9.94	0.18	0.44	0.49	0.02	2.14	1.44	6.64	5.02
722.15	1.40	10.49	73.62	0.14	9.90	0.18	0.44	0.49	0.02	2.14	1.44	6.62	5.02
721.15	1.40	10.44	73.69	0.14	9.87	0.18	0.43	0.49	0.02	2.14	1.43	6.59	5.02
720.15	1.40	10.38	73.76	0.14	9.83	0.18	0.43	0.49	0.02	2.14	1.43	6.57	5.02
719.15	1.40	10.33	73.83	0.13	9.79	0.18	0.42	0.50	0.02	2.14	1.42	6.55	5.02
718.15	1.40	10.28	73.90	0.13	9.75	0.18	0.42	0.50	0.02	2.14	1.41	6.53	5.03
717.15	1.40	9.51	73.88	0.13	9.68	0.17	0.40	0.54	0.01	2.23	1.40	6.51	5.05
716.15	1.40	8.79	73.86	0.13	9.60	0.16	0.39	0.58	0.01	2.32	1.39	6.49	5.07
715.15	1.40	8.18	73.83	0.12	9.53	0.16	0.37	0.63	0.01	2.41	1.38	6.47	5.09
714.15	1.40	7.66	73.80	0.12	9.45	0.15	0.35	0.67	0.01	2.51	1.38	6.45	5.12
713.15	1.40	7.20	73.77	0.12	9.38	0.15	0.34	0.71	0.00	2.60	1.37	6.43	5.14
712.15	1.40	6.80	73.74	0.11	9.30	0.14	0.32	0.75	0.00	2.69	1.37	6.40	5.16
711.15	1.40	6.44	73.71	0.11	9.23	0.14	0.31	0.80	0.00	2.78	1.36	6.38	5.19
710.15	1.40	6.13	73.68	0.11	9.15	0.13	0.30	0.84	0.00	2.88	1.36	6.35	5.21
709.15	1.40	5.84	73.65	0.10	9.08	0.13	0.28	0.88	0.00	2.97	1.36	6.32	5.23
708.15	1.40	5.58	73.61	0.10	9.00	0.12	0.27	0.92	0.00	3.06	1.36	6.29	5.26
707.15	1.40	5.34	73.58	0.10	8.93	0.12	0.26	0.96	0.00	3.16	1.35	6.26	5.28
706.15	1.40	5.12	73.55	0.10	8.86	0.11	0.25	1.00	0.00	3.25	1.35	6.23	5.31
705.15	1.40	4.92	73.51	0.10	8.78	0.11	0.24	1.04	0.00	3.34	1.35	6.20	5.33
704.15	1.40	4.81	73.45	0.10	8.71	0.12	0.26	1.07	0.00	3.43	1.35	6.17	5.35
703.15	1.40	4.67	73.40	0.10	8.65	0.12	0.26	1.10	0.00	3.52	1.35	6.13	5.37
702.15	1.40	4.54	73.35	0.11	8.58	0.12	0.27	1.13	0.00	3.60	1.35	6.10	5.39
701.15	1.40	4.41	73.30	0.11	8.51	0.13	0.28	1.16	0.00	3.69	1.35	6.06	5.41
700.15	1.40	4.29	73.25	0.11	8.44	0.13	0.29	1.19	0.00	3.78	1.35	6.03	5.43

Table A1.10: Best-fit assimilation fractional crystallisation model for central caldera group eruptions. Liquid remaining is reported in grams, the model begins with 100g of liquid. The starting temperature is the liquidus temperature of the system, calculated by Rhyolite-MELTS.

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1154.9	1.6	98.9	50.77	0.95	14.92	1.38	5.49	0.16	6.03	11.36	2.16	4.75	2.02
1153.9	1.6	98.4	50.77	0.96	14.97	1.38	5.49	0.16	5.99	11.30	2.17	4.78	2.03
1152.9	1.6	97.9	50.77	0.96	15.03	1.38	5.50	0.16	5.94	11.24	2.18	4.80	2.04
1151.9	1.6	97.4	50.77	0.96	15.08	1.38	5.50	0.16	5.89	11.18	2.19	4.83	2.05
1150.9	1.6	96.9	50.77	0.96	15.14	1.38	5.51	0.17	5.84	11.13	2.20	4.85	2.06
1149.9	1.6	96.5	50.76	0.96	15.19	1.38	5.51	0.17	5.80	11.07	2.21	4.87	2.07
1148.9	1.6	96.0	50.76	0.97	15.24	1.38	5.51	0.17	5.75	11.01	2.22	4.90	2.08
1147.9	1.6	95.5	50.76	0.97	15.30	1.38	5.52	0.17	5.71	10.95	2.23	4.92	2.09
1146.9	1.6	95.1	50.76	0.97	15.35	1.38	5.52	0.17	5.66	10.90	2.24	4.94	2.10
1145.9	1.6	94.6	50.76	0.97	15.40	1.38	5.52	0.17	5.61	10.84	2.25	4.97	2.11
1144.9	1.6	94.2	50.76	0.97	15.45	1.38	5.53	0.17	5.57	10.78	2.26	4.99	2.12
1143.9	1.6	93.7	50.77	0.98	15.51	1.38	5.53	0.17	5.52	10.72	2.27	5.01	2.13
1142.9	1.6	93.3	50.77	0.98	15.56	1.38	5.53	0.17	5.48	10.67	2.28	5.04	2.14
1141.9	1.6	92.9	50.77	0.98	15.61	1.38	5.54	0.17	5.43	10.61	2.29	5.06	2.15
1140.9	1.6	92.4	50.77	0.98	15.66	1.38	5.54	0.17	5.39	10.55	2.30	5.09	2.16

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1139.9	1.6	92.0	50.77	0.98	15.71	1.38	5.54	0.17	5.34	10.50	2.31	5.11	2.17
1138.9	1.6	91.6	50.77	0.99	15.76	1.38	5.54	0.17	5.30	10.44	2.32	5.13	2.18
1137.9	1.6	91.2	50.77	0.99	15.81	1.38	5.55	0.18	5.26	10.38	2.33	5.16	2.19
1136.9	1.6	90.8	50.77	0.99	15.86	1.38	5.55	0.18	5.21	10.33	2.34	5.18	2.20
1135.9	1.6	90.4	50.78	0.99	15.91	1.38	5.55	0.18	5.17	10.27	2.35	5.20	2.21
1134.9	1.6	90.0	50.78	0.99	15.96	1.38	5.55	0.18	5.13	10.22	2.36	5.22	2.22
1133.9	1.6	89.6	50.78	0.99	16.01	1.38	5.55	0.18	5.08	10.16	2.37	5.25	2.23
1132.9	1.6	89.2	50.78	0.99	16.06	1.38	5.56	0.18	5.04	10.10	2.38	5.27	2.24
1131.9	1.6	88.8	50.79	1.00	16.11	1.38	5.56	0.18	5.00	10.05	2.39	5.29	2.25
1130.9	1.6	88.4	50.79	1.00	16.16	1.38	5.56	0.18	4.96	9.99	2.40	5.32	2.26
1129.9	1.6	88.0	50.79	1.00	16.21	1.38	5.56	0.18	4.91	9.94	2.41	5.34	2.27
1128.9	1.6	87.6	50.80	1.00	16.26	1.38	5.56	0.18	4.87	9.88	2.42	5.36	2.28
1127.9	1.6	87.3	50.80	1.00	16.30	1.38	5.56	0.18	4.83	9.83	2.43	5.39	2.29
1126.9	1.6	86.9	50.80	1.00	16.35	1.38	5.56	0.18	4.79	9.77	2.44	5.41	2.30
1125.9	1.6	86.5	50.81	1.00	16.40	1.38	5.56	0.18	4.75	9.72	2.45	5.43	2.31
1124.9	1.6	86.2	50.81	1.00	16.45	1.38	5.56	0.19	4.71	9.66	2.46	5.45	2.32
1123.9	1.6	85.8	50.82	1.00	16.49	1.38	5.56	0.19	4.67	9.61	2.47	5.48	2.33
1122.9	1.6	85.5	50.82	1.00	16.54	1.38	5.56	0.19	4.63	9.55	2.48	5.50	2.34
1121.9	1.6	85.1	50.83	1.00	16.59	1.38	5.56	0.19	4.59	9.50	2.49	5.52	2.35
1120.9	1.6	84.8	50.83	1.01	16.63	1.38	5.56	0.19	4.55	9.45	2.50	5.54	2.36
1119.9	1.6	84.4	50.84	1.01	16.68	1.38	5.56	0.19	4.51	9.39	2.51	5.57	2.37
1118.9	1.6	84.1	50.84	1.01	16.72	1.38	5.56	0.19	4.47	9.34	2.52	5.59	2.38
1117.9	1.6	83.8	50.85	1.01	16.77	1.38	5.56	0.19	4.43	9.29	2.53	5.61	2.39
1116.9	1.6	83.4	50.85	1.01	16.81	1.38	5.56	0.19	4.39	9.23	2.54	5.63	2.40
1115.9	1.6	83.1	50.86	1.01	16.86	1.38	5.56	0.19	4.35	9.18	2.55	5.66	2.41
1114.9	1.6	82.8	50.87	1.01	16.90	1.38	5.56	0.19	4.31	9.13	2.56	5.68	2.42
1113.9	1.6	82.5	50.87	1.01	16.95	1.38	5.56	0.19	4.28	9.07	2.57	5.70	2.43
1112.9	1.6	82.1	50.88	1.01	16.99	1.38	5.56	0.19	4.24	9.02	2.58	5.72	2.43
1111.9	1.6	81.8	50.89	1.01	17.04	1.38	5.56	0.20	4.20	8.97	2.58	5.74	2.44
1110.9	1.6	81.5	50.89	1.01	17.08	1.38	5.55	0.20	4.16	8.91	2.59	5.77	2.45
1109.9	1.6	81.2	50.90	1.01	17.12	1.38	5.55	0.20	4.13	8.86	2.60	5.79	2.46
1108.9	1.6	80.9	50.91	1.01	17.17	1.38	5.55	0.20	4.09	8.81	2.61	5.81	2.47
1107.9	1.6	80.6	50.92	1.01	17.21	1.38	5.55	0.20	4.05	8.76	2.62	5.83	2.48
1106.9	1.6	80.3	50.92	1.01	17.25	1.37	5.55	0.20	4.02	8.71	2.63	5.85	2.49
1105.9	1.6	80.0	50.93	1.01	17.29	1.37	5.54	0.20	3.98	8.65	2.64	5.87	2.50
1104.9	1.6	79.7	50.94	1.01	17.33	1.37	5.54	0.20	3.95	8.60	2.65	5.90	2.51
1103.9	1.6	79.4	50.95	1.01	17.38	1.37	5.54	0.20	3.91	8.55	2.66	5.92	2.52
1102.9	1.6	79.1	50.96	1.01	17.42	1.37	5.54	0.20	3.88	8.50	2.67	5.94	2.53
1101.9	1.6	78.9	50.96	1.01	17.46	1.37	5.53	0.20	3.84	8.45	2.68	5.96	2.54
1100.9	1.6	78.6	50.97	1.00	17.50	1.37	5.53	0.20	3.81	8.40	2.68	5.98	2.55
1100.9	1.6	78.6	50.97	1.00	17.50	1.37	5.53	0.20	3.81	8.40	2.68	5.98	2.55
1099.9	1.6	105.9	53.27	0.86	18.41	1.15	4.61	0.15	2.85	7.69	3.26	5.71	1.97
1098.9	1.6	105.6	53.29	0.86	18.44	1.15	4.60	0.15	2.83	7.64	3.27	5.73	1.98
1097.9	1.6	105.3	53.30	0.86	18.48	1.15	4.60	0.15	2.80	7.60	3.28	5.74	1.98
1096.9	1.6	105.0	53.31	0.86	18.51	1.15	4.59	0.15	2.77	7.56	3.29	5.76	1.99
1095.9	1.6	104.7	53.33	0.86	18.55	1.15	4.58	0.15	2.74	7.52	3.30	5.78	2.00
1094.9	1.6	104.5	53.34	0.86	18.58	1.15	4.58	0.15	2.71	7.48	3.30	5.79	2.00
1093.9	1.6	104.2	53.36	0.86	18.61	1.15	4.57	0.15	2.68	7.43	3.31	5.81	2.01
1092.9	1.6	103.9	53.37	0.86	18.64	1.14	4.57	0.15	2.65	7.39	3.32	5.82	2.01
1091.9	1.6	103.6	53.39	0.86	18.68	1.14	4.56	0.15	2.63	7.35	3.33	5.84	2.02
1090.9	1.6	103.3	53.40	0.86	18.71	1.14	4.55	0.15	2.60	7.31	3.34	5.86	2.02
1089.9	1.6	103.0	53.41	0.86	18.74	1.14	4.55	0.16	2.57	7.27	3.35	5.87	2.03
1088.9	1.6	102.8	53.43	0.86	18.77	1.14	4.54	0.16	2.54	7.23	3.35	5.89	2.03
1087.9	1.6	102.5	53.44	0.86	18.80	1.14	4.53	0.16	2.52	7.19	3.36	5.90	2.04
1086.9	1.6	102.2	53.46	0.85	18.84	1.14	4.53	0.16	2.49	7.15	3.37	5.92	2.04
1085.9	1.6	102.0	53.47	0.85	18.87	1.14	4.52	0.16	2.46	7.11	3.38	5.93	2.05
1084.9	1.6	101.7	53.49	0.85	18.90	1.13	4.51	0.16	2.44	7.07	3.39	5.95	2.06
1083.9	1.6	101.4	53.50	0.85	18.93	1.13	4.51	0.16	2.41	7.03	3.39	5.96	2.06
1082.9	1.6	101.2	53.52	0.85	18.96	1.13	4.50	0.16	2.39	6.99	3.40	5.98	2.07
1081.9	1.6	100.9	53.54	0.85	18.99	1.13	4.49	0.16	2.36	6.95	3.41	5.99	2.07
1080.9	1.6	100.7	53.55	0.85	19.02	1.13	4.49	0.16	2.34	6.91	3.42	6.01	2.08
1079.9	1.6	100.4	53.57	0.85	19.05	1.13	4.48	0.16	2.31	6.87	3.43	6.02	2.08
1078.9	1.6	100.2	53.58	0.85	19.08	1.13	4.47	0.16	2.29	6.83	3.43	6.04	2.09
1077.9	1.6	99.9	53.60	0.84	19.11	1.12	4.46	0.16	2.26	6.80	3.44	6.05	2.09
1076.9	1.6	99.7	53.61	0.84	19.14	1.12	4.46	0.16	2.24	6.76	3.45	6.07	2.10
1075.9	1.6	99.4	53.63	0.84	19.16	1.12	4.45	0.16	2.21	6.72	3.46	6.08	2.10
1074.9	1.6	99.2	53.64	0.84	19.19	1.12	4.44	0.16	2.19	6.68	3.47	6.10	2.11
1073.9	1.6	99.0	53.66	0.84	19.22	1.12	4.43	0.16	2.16	6.64	3.47	6.11	2.11
1072.9	1.6	98.7	53.68	0.84	19.25	1.12	4.43	0.16	2.14	6.60	3.48	6.13	2.12
1071.9	1.6	98.5	53.69	0.84	19.28	1.12	4.42	0.16	2.12	6.57	3.49	6.14	2.12
1070.9	1.6	98.3	53.71	0.83	19.30	1.11	4.41	0.16	2.09	6.53	3.50	6.16	2.13

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T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
1069.9	1.6	98.0	53.72	0.83	19.33	1.11	4.40	0.16	2.07	6.49	3.50	6.17	2.13
1068.9	1.6	97.8	53.74	0.83	19.36	1.11	4.40	0.16	2.05	6.46	3.51	6.19	2.14
1067.9	1.6	97.6	53.76	0.83	19.39	1.11	4.39	0.16	2.03	6.42	3.52	6.20	2.14
1066.9	1.6	97.3	53.77	0.83	19.41	1.11	4.38	0.16	2.00	6.38	3.53	6.21	2.15
1065.9	1.6	97.1	53.79	0.82	19.44	1.11	4.37	0.16	1.98	6.35	3.53	6.23	2.15
1064.9	1.6	96.9	53.81	0.82	19.47	1.10	4.36	0.17	1.96	6.31	3.54	6.24	2.16
1063.9	1.6	96.7	53.82	0.82	19.49	1.10	4.36	0.17	1.94	6.27	3.55	6.26	2.16
1062.9	1.6	96.5	53.84	0.82	19.52	1.10	4.35	0.17	1.92	6.24	3.56	6.27	2.17
1061.9	1.6	96.3	53.86	0.82	19.54	1.10	4.34	0.17	1.90	6.20	3.56	6.29	2.17
1060.9	1.6	96.0	53.87	0.82	19.57	1.10	4.33	0.17	1.87	6.17	3.57	6.30	2.18
1059.9	1.6	95.8	53.89	0.81	19.59	1.10	4.32	0.17	1.85	6.13	3.58	6.31	2.18
1058.9	1.6	95.6	53.91	0.81	19.62	1.10	4.31	0.17	1.83	6.09	3.58	6.33	2.19
1057.9	1.6	95.4	53.93	0.81	19.64	1.09	4.31	0.17	1.81	6.06	3.59	6.34	2.19
1056.9	1.6	95.2	53.94	0.81	19.66	1.09	4.30	0.17	1.79	6.02	3.60	6.36	2.20
1055.9	1.6	94.9	53.97	0.81	19.66	1.09	4.30	0.17	1.78	5.98	3.61	6.38	2.20
1054.9	1.6	94.6	53.99	0.81	19.66	1.09	4.30	0.17	1.77	5.93	3.61	6.40	2.21
1053.9	1.6	94.2	54.01	0.81	19.66	1.09	4.30	0.17	1.75	5.89	3.62	6.42	2.22
1052.9	1.6	93.9	54.04	0.80	19.66	1.09	4.30	0.17	1.74	5.84	3.63	6.44	2.22
1051.9	1.6	93.6	54.06	0.80	19.66	1.09	4.29	0.17	1.72	5.80	3.64	6.46	2.23
1050.9	1.6	93.3	54.08	0.80	19.66	1.10	4.29	0.17	1.71	5.76	3.65	6.48	2.24
1049.9	1.6	93.0	54.11	0.80	19.66	1.10	4.29	0.17	1.70	5.71	3.65	6.50	2.25
1048.9	1.6	92.7	54.13	0.80	19.66	1.10	4.29	0.17	1.69	5.67	3.66	6.52	2.25
1047.9	1.6	92.5	54.15	0.80	19.66	1.10	4.29	0.17	1.67	5.63	3.67	6.54	2.26
1046.9	1.6	92.2	54.17	0.80	19.65	1.10	4.29	0.17	1.66	5.58	3.68	6.56	2.27
1045.9	1.6	91.9	54.20	0.80	19.65	1.10	4.29	0.17	1.65	5.54	3.68	6.58	2.27
1044.9	1.6	91.6	54.22	0.80	19.65	1.10	4.29	0.17	1.63	5.50	3.69	6.60	2.28
1043.9	1.6	91.3	54.24	0.80	19.65	1.10	4.29	0.18	1.62	5.46	3.70	6.62	2.29
1042.9	1.6	91.0	54.26	0.80	19.65	1.10	4.28	0.18	1.61	5.42	3.71	6.64	2.30
1041.9	1.6	90.8	54.28	0.79	19.65	1.10	4.28	0.18	1.60	5.38	3.71	6.66	2.30
1040.9	1.6	90.5	54.31	0.79	19.65	1.10	4.28	0.18	1.59	5.33	3.72	6.68	2.31
1039.9	1.6	90.2	54.33	0.79	19.65	1.10	4.28	0.18	1.57	5.29	3.73	6.70	2.32
1038.9	1.6	90.0	54.35	0.79	19.64	1.10	4.28	0.18	1.56	5.25	3.73	6.72	2.32
1037.9	1.6	89.7	54.37	0.79	19.64	1.10	4.28	0.18	1.55	5.21	3.74	6.74	2.33
1036.9	1.6	89.5	54.39	0.79	19.64	1.10	4.28	0.18	1.54	5.17	3.75	6.76	2.34
1035.9	1.6	89.2	54.42	0.79	19.64	1.10	4.27	0.18	1.53	5.13	3.75	6.78	2.34
1034.9	1.6	88.9	54.44	0.79	19.64	1.10	4.27	0.18	1.52	5.09	3.76	6.79	2.35
1033.9	1.6	88.7	54.46	0.79	19.64	1.10	4.27	0.18	1.51	5.05	3.77	6.81	2.36
1032.9	1.6	88.4	54.48	0.78	19.63	1.10	4.27	0.18	1.49	5.01	3.77	6.83	2.36
1031.9	1.6	88.2	54.50	0.78	19.63	1.10	4.27	0.18	1.48	4.98	3.78	6.85	2.37
1030.9	1.6	87.9	54.52	0.78	19.63	1.11	4.27	0.18	1.47	4.94	3.79	6.87	2.38
1029.9	1.6	87.7	54.54	0.78	19.63	1.11	4.26	0.18	1.46	4.90	3.79	6.89	2.38
1028.9	1.6	87.5	54.57	0.78	19.63	1.11	4.26	0.18	1.45	4.86	3.80	6.91	2.39
1027.9	1.6	87.2	54.59	0.78	19.62	1.11	4.26	0.18	1.44	4.82	3.81	6.93	2.40
1026.9	1.6	87.0	54.61	0.78	19.62	1.11	4.26	0.18	1.43	4.79	3.81	6.94	2.40
1025.9	1.6	86.8	54.63	0.77	19.62	1.11	4.26	0.18	1.42	4.75	3.82	6.96	2.41
1024.9	1.6	86.5	54.65	0.77	19.62	1.11	4.26	0.18	1.41	4.71	3.83	6.98	2.42
1023.9	1.6	86.3	54.67	0.77	19.62	1.11	4.25	0.19	1.40	4.67	3.83	7.00	2.42
1022.9	1.6	86.1	54.69	0.77	19.61	1.11	4.25	0.19	1.39	4.64	3.84	7.02	2.43
1021.9	1.6	85.9	54.71	0.77	19.61	1.11	4.25	0.19	1.38	4.60	3.84	7.03	2.43
1020.9	1.6	85.6	54.73	0.77	19.61	1.11	4.25	0.19	1.37	4.56	3.85	7.05	2.44
1019.9	1.6	85.4	54.75	0.76	19.61	1.11	4.25	0.19	1.36	4.53	3.85	7.07	2.45
1018.9	1.6	85.2	54.77	0.76	19.60	1.11	4.24	0.19	1.35	4.49	3.86	7.09	2.45
1017.9	1.6	85.0	54.79	0.76	19.60	1.11	4.24	0.19	1.34	4.46	3.87	7.11	2.46
1016.9	1.6	84.8	54.81	0.76	19.60	1.11	4.24	0.19	1.33	4.42	3.87	7.12	2.47
1015.9	1.6	84.5	54.83	0.76	19.60	1.11	4.24	0.19	1.33	4.39	3.88	7.14	2.47
1014.9	1.6	84.3	54.85	0.76	19.59	1.11	4.24	0.19	1.32	4.35	3.88	7.16	2.48
1013.9	1.6	84.1	54.87	0.75	19.59	1.11	4.23	0.19	1.31	4.32	3.89	7.18	2.48
1012.9	1.6	83.9	54.89	0.75	19.59	1.11	4.23	0.19	1.30	4.28	3.89	7.19	2.49
1011.9	1.6	83.7	54.91	0.75	19.59	1.11	4.23	0.19	1.29	4.25	3.90	7.21	2.50
1010.9	1.6	83.5	54.93	0.75	19.58	1.12	4.23	0.19	1.28	4.21	3.90	7.23	2.50
1009.9	1.6	83.3	54.95	0.75	19.58	1.12	4.23	0.19	1.27	4.18	3.91	7.24	2.51
1008.9	1.6	83.1	54.97	0.74	19.58	1.12	4.22	0.19	1.27	4.15	3.92	7.26	2.51
1007.9	1.6	82.9	54.99	0.74	19.57	1.12	4.22	0.19	1.26	4.11	3.92	7.28	2.52
1006.9	1.6	82.7	55.01	0.74	19.57	1.12	4.22	0.19	1.25	4.08	3.93	7.30	2.53
1005.9	1.6	82.5	55.03	0.74	19.57	1.12	4.22	0.19	1.24	4.05	3.93	7.31	2.53
1004.9	1.6	82.3	55.05	0.74	19.56	1.12	4.22	0.19	1.23	4.01	3.94	7.33	2.54
1003.9	1.6	82.1	55.07	0.73	19.56	1.12	4.21	0.19	1.23	3.98	3.94	7.35	2.54
1002.9	1.6	81.9	55.09	0.73	19.56	1.12	4.21	0.20	1.22	3.95	3.95	7.36	2.55
1001.9	1.6	81.8	55.11	0.73	19.56	1.12	4.21	0.20	1.21	3.92	3.95	7.38	2.56
1000.9	1.6	81.6	55.12	0.73	19.55	1.12	4.21	0.20	1.20	3.89	3.95	7.40	2.56
999.9	1.6	81.4	55.14	0.72	19.55	1.12	4.21	0.20	1.20	3.85	3.96	7.41	2.57

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
998.9	1.6	81.2	55.16	0.72	19.54	1.12	4.20	0.20	1.19	3.82	3.96	7.43	2.57
997.9	1.6	81.0	55.18	0.72	19.54	1.12	4.20	0.20	1.18	3.79	3.97	7.44	2.58
996.9	1.6	80.8	55.20	0.72	19.54	1.12	4.20	0.20	1.17	3.76	3.97	7.46	2.59
995.9	1.6	80.7	55.22	0.71	19.53	1.12	4.20	0.20	1.17	3.73	3.98	7.48	2.59
994.9	1.6	80.5	55.24	0.71	19.53	1.12	4.20	0.20	1.16	3.70	3.98	7.49	2.60
993.9	1.6	80.3	55.26	0.70	19.52	1.12	4.19	0.20	1.16	3.67	3.99	7.51	2.60
992.9	1.6	80.1	55.28	0.70	19.52	1.13	4.19	0.20	1.15	3.64	3.99	7.52	2.61
991.9	1.6	80.0	55.30	0.69	19.51	1.13	4.19	0.20	1.15	3.61	3.99	7.54	2.61
990.9	1.6	79.8	55.32	0.69	19.50	1.13	4.19	0.20	1.14	3.58	4.00	7.56	2.62
989.9	1.6	79.6	55.34	0.68	19.50	1.13	4.19	0.20	1.13	3.55	4.00	7.57	2.62
988.9	1.6	79.5	55.36	0.68	19.49	1.13	4.19	0.20	1.13	3.52	4.01	7.59	2.63
987.9	1.6	79.3	55.38	0.68	19.49	1.13	4.18	0.20	1.12	3.49	4.01	7.60	2.64
986.9	1.6	79.1	55.40	0.67	19.48	1.13	4.18	0.20	1.12	3.46	4.01	7.62	2.64
985.9	1.6	79.0	55.42	0.67	19.48	1.13	4.18	0.20	1.11	3.43	4.02	7.63	2.65
984.9	1.6	78.8	55.44	0.66	19.47	1.13	4.18	0.20	1.11	3.40	4.02	7.65	2.65
983.9	1.6	78.6	55.46	0.66	19.46	1.13	4.18	0.20	1.10	3.37	4.03	7.66	2.66
982.9	1.6	77.6	55.62	0.67	19.52	1.10	4.01	0.20	0.97	3.33	4.05	7.76	2.69
981.9	1.6	77.4	55.65	0.67	19.50	1.10	4.00	0.20	0.96	3.31	4.06	7.78	2.70
980.9	1.6	77.2	55.67	0.67	19.49	1.09	3.99	0.20	0.95	3.29	4.06	7.81	2.71
979.9	1.6	76.9	55.69	0.67	19.48	1.09	3.98	0.20	0.93	3.27	4.06	7.83	2.72
978.9	1.6	76.7	55.72	0.68	19.47	1.09	3.96	0.20	0.92	3.25	4.07	7.85	2.72
977.9	1.6	76.5	55.74	0.68	19.46	1.09	3.95	0.20	0.91	3.23	4.07	7.87	2.73
976.9	1.6	76.3	55.76	0.68	19.44	1.09	3.94	0.20	0.90	3.21	4.07	7.89	2.74
975.9	1.6	76.0	55.79	0.68	19.43	1.09	3.92	0.20	0.88	3.19	4.08	7.92	2.75
974.9	1.6	75.8	55.81	0.68	19.42	1.08	3.91	0.20	0.87	3.17	4.08	7.94	2.76
973.9	1.6	75.6	55.83	0.69	19.41	1.08	3.90	0.20	0.86	3.15	4.08	7.96	2.76
972.9	1.6	75.4	55.86	0.69	19.40	1.08	3.88	0.20	0.85	3.13	4.09	7.98	2.77
971.9	1.6	75.2	55.88	0.69	19.39	1.08	3.87	0.20	0.84	3.11	4.09	8.01	2.78
970.9	1.6	74.9	55.90	0.69	19.38	1.08	3.85	0.20	0.83	3.09	4.09	8.03	2.79
969.9	1.6	74.7	55.93	0.69	19.37	1.08	3.84	0.20	0.81	3.07	4.10	8.05	2.80
968.9	1.6	74.5	55.95	0.70	19.35	1.07	3.82	0.20	0.80	3.05	4.10	8.07	2.81
967.9	1.6	74.3	56.03	0.66	19.37	1.07	3.80	0.20	0.79	2.99	4.11	8.10	2.81
966.9	1.6	74.1	56.05	0.65	19.37	1.07	3.79	0.20	0.78	2.97	4.12	8.11	2.82
965.9	1.6	73.9	56.08	0.65	19.36	1.06	3.77	0.20	0.76	2.94	4.12	8.14	2.83
964.9	1.6	73.7	56.11	0.65	19.35	1.06	3.76	0.20	0.75	2.92	4.12	8.16	2.84
963.9	1.6	73.5	56.14	0.65	19.35	1.06	3.74	0.20	0.74	2.90	4.13	8.18	2.84
962.9	1.6	73.3	56.17	0.65	19.34	1.06	3.73	0.20	0.73	2.88	4.13	8.20	2.85
961.9	1.6	73.1	56.19	0.64	19.33	1.05	3.71	0.19	0.72	2.85	4.13	8.23	2.86
960.9	1.6	72.9	56.22	0.64	19.32	1.05	3.69	0.19	0.71	2.83	4.14	8.25	2.87
959.9	1.6	72.7	56.25	0.64	19.32	1.05	3.68	0.19	0.70	2.81	4.14	8.27	2.88
958.9	1.6	72.5	56.28	0.64	19.31	1.05	3.66	0.19	0.69	2.79	4.14	8.29	2.88
957.9	1.6	72.3	56.30	0.64	19.30	1.04	3.64	0.19	0.68	2.76	4.15	8.31	2.89
956.9	1.6	72.1	56.33	0.64	19.29	1.04	3.63	0.19	0.67	2.74	4.15	8.34	2.90
955.9	1.6	71.9	56.36	0.63	19.29	1.04	3.61	0.19	0.66	2.72	4.15	8.36	2.91
954.9	1.6	71.7	56.38	0.63	19.28	1.04	3.59	0.19	0.65	2.70	4.16	8.38	2.92
953.9	1.6	71.5	56.41	0.63	19.27	1.03	3.58	0.19	0.64	2.68	4.16	8.40	2.92
952.9	1.6	71.3	56.43	0.63	19.27	1.03	3.56	0.19	0.63	2.66	4.16	8.43	2.93
951.9	1.6	71.1	56.46	0.63	19.26	1.03	3.54	0.19	0.62	2.64	4.17	8.45	2.94
950.9	1.6	70.9	56.49	0.63	19.25	1.02	3.53	0.19	0.61	2.62	4.17	8.47	2.95
949.9	1.6	70.7	56.51	0.63	19.24	1.02	3.51	0.19	0.60	2.59	4.17	8.49	2.96
948.9	1.6	70.5	56.54	0.62	19.24	1.02	3.49	0.19	0.59	2.57	4.17	8.51	2.96
947.9	1.6	70.3	56.56	0.62	19.23	1.02	3.47	0.19	0.58	2.55	4.18	8.54	2.97
946.9	1.6	70.1	56.59	0.62	19.22	1.01	3.46	0.19	0.57	2.53	4.18	8.56	2.98
945.9	1.6	69.9	56.62	0.62	19.22	1.01	3.44	0.19	0.56	2.51	4.18	8.58	2.99
944.9	1.6	69.7	56.64	0.62	19.21	1.01	3.42	0.19	0.55	2.49	4.18	8.60	3.00
943.9	1.6	69.6	56.67	0.62	19.20	1.00	3.40	0.19	0.54	2.47	4.19	8.63	3.01
942.9	1.6	69.4	56.69	0.62	19.20	1.00	3.39	0.19	0.53	2.45	4.19	8.65	3.01
941.9	1.6	69.2	56.71	0.62	19.19	1.00	3.37	0.19	0.52	2.43	4.19	8.67	3.02
940.9	1.6	68.7	56.85	0.54	19.19	0.98	3.29	0.19	0.52	2.40	4.20	8.72	3.04
939.9	1.6	68.5	56.88	0.53	19.18	0.97	3.27	0.19	0.51	2.38	4.20	8.75	3.05
938.9	1.6	68.3	56.91	0.53	19.17	0.97	3.24	0.19	0.50	2.37	4.20	8.78	3.06
937.9	1.6	68.1	56.94	0.52	19.16	0.96	3.22	0.19	0.50	2.35	4.20	8.80	3.07
936.9	1.6	67.9	56.97	0.52	19.15	0.96	3.20	0.19	0.49	2.33	4.20	8.83	3.08
935.9	1.6	67.7	57.00	0.51	19.14	0.96	3.17	0.19	0.48	2.31	4.20	8.85	3.09
934.9	1.6	67.5	57.03	0.51	19.14	0.95	3.15	0.19	0.47	2.29	4.21	8.88	3.10
933.9	1.6	67.3	57.06	0.50	19.13	0.95	3.13	0.19	0.47	2.28	4.21	8.90	3.11
932.9	1.6	67.1	57.09	0.50	19.12	0.94	3.11	0.19	0.46	2.26	4.21	8.93	3.12
931.9	1.6	66.9	57.12	0.49	19.11	0.94	3.08	0.19	0.45	2.24	4.21	8.95	3.13
930.9	1.6	66.7	57.15	0.49	19.11	0.93	3.06	0.19	0.45	2.22	4.21	8.98	3.13
929.9	1.6	66.5	57.18	0.48	19.10	0.93	3.04	0.18	0.44	2.20	4.21	9.01	3.14
928.9	1.6	66.3	57.20	0.48	19.09	0.92	3.01	0.18	0.43	2.19	4.21	9.03	3.15

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
927.9	1.6	66.1	57.23	0.48	19.08	0.92	2.99	0.18	0.42	2.17	4.21	9.06	3.16
926.9	1.6	65.9	57.26	0.47	19.08	0.91	2.97	0.18	0.42	2.15	4.21	9.08	3.17
925.9	1.6	65.7	57.29	0.47	19.07	0.91	2.95	0.18	0.41	2.14	4.21	9.11	3.18
924.9	1.6	65.5	57.32	0.46	19.06	0.90	2.92	0.18	0.41	2.12	4.22	9.13	3.19
923.9	1.6	65.3	57.34	0.46	19.05	0.90	2.90	0.18	0.40	2.10	4.22	9.16	3.20
922.9	1.6	65.1	57.37	0.45	19.05	0.89	2.88	0.18	0.39	2.08	4.22	9.18	3.21
921.9	1.6	64.9	57.40	0.45	19.04	0.89	2.85	0.18	0.39	2.07	4.22	9.21	3.22
920.9	1.6	64.7	57.42	0.44	19.03	0.88	2.83	0.18	0.38	2.05	4.22	9.23	3.23
919.9	1.6	64.5	57.45	0.44	19.02	0.88	2.81	0.18	0.38	2.03	4.22	9.26	3.24
918.9	1.6	64.4	57.48	0.44	19.02	0.87	2.79	0.18	0.37	2.02	4.22	9.29	3.25
917.9	1.6	64.2	57.50	0.43	19.01	0.87	2.76	0.18	0.36	2.00	4.22	9.31	3.26
916.9	1.6	64.0	57.53	0.43	19.00	0.86	2.74	0.18	0.36	1.99	4.22	9.34	3.27
915.9	1.6	63.8	57.56	0.42	18.99	0.86	2.72	0.18	0.35	1.97	4.22	9.36	3.28
914.9	1.6	63.6	57.58	0.42	18.99	0.85	2.70	0.18	0.35	1.95	4.22	9.39	3.29
913.9	1.6	63.4	57.61	0.42	18.98	0.85	2.67	0.18	0.34	1.94	4.22	9.41	3.29
912.9	1.6	63.3	57.63	0.41	18.97	0.84	2.65	0.18	0.34	1.92	4.22	9.44	3.30
911.9	1.6	63.1	57.66	0.41	18.97	0.84	2.63	0.18	0.33	1.91	4.22	9.46	3.31
910.9	1.6	62.9	57.68	0.40	18.96	0.83	2.61	0.18	0.33	1.89	4.22	9.49	3.32
909.9	1.6	62.7	57.70	0.40	18.95	0.83	2.58	0.18	0.32	1.87	4.22	9.51	3.33
908.9	1.6	62.5	57.73	0.40	18.95	0.82	2.56	0.18	0.32	1.86	4.21	9.54	3.34
907.9	1.6	62.4	57.75	0.39	18.94	0.82	2.54	0.18	0.31	1.84	4.21	9.56	3.35
906.9	1.6	62.2	57.78	0.39	18.93	0.81	2.52	0.18	0.31	1.83	4.21	9.59	3.36
905.9	1.6	62.0	57.80	0.38	18.93	0.81	2.50	0.18	0.30	1.81	4.21	9.62	3.37
904.9	1.6	61.8	57.82	0.38	18.92	0.80	2.48	0.18	0.30	1.80	4.21	9.64	3.38
903.9	1.6	61.7	57.85	0.38	18.91	0.80	2.45	0.18	0.29	1.78	4.21	9.67	3.39
902.9	1.6	61.5	57.87	0.37	18.91	0.79	2.43	0.18	0.29	1.77	4.21	9.69	3.40
901.9	1.6	61.3	57.89	0.37	18.90	0.79	2.41	0.17	0.28	1.75	4.21	9.72	3.41
900.9	1.6	61.2	57.91	0.37	18.89	0.78	2.39	0.17	0.28	1.74	4.21	9.74	3.42
899.9	1.6	61.0	57.93	0.36	18.89	0.78	2.37	0.17	0.28	1.72	4.21	9.77	3.43
898.9	1.6	60.8	57.96	0.36	18.88	0.77	2.35	0.17	0.27	1.71	4.20	9.79	3.44
897.9	1.6	60.6	57.98	0.36	18.87	0.77	2.33	0.17	0.27	1.69	4.20	9.82	3.45
896.9	1.6	60.5	58.00	0.35	18.87	0.76	2.31	0.17	0.26	1.68	4.20	9.84	3.46
895.9	1.6	60.3	58.02	0.35	18.86	0.76	2.29	0.17	0.26	1.67	4.20	9.87	3.47
894.9	1.6	60.1	58.04	0.35	18.85	0.75	2.27	0.17	0.25	1.65	4.20	9.89	3.47
893.9	1.6	60.0	58.06	0.34	18.85	0.75	2.25	0.17	0.25	1.64	4.20	9.92	3.48
892.9	1.6	59.8	58.08	0.34	18.84	0.74	2.23	0.17	0.25	1.62	4.19	9.94	3.49
891.9	1.6	59.7	58.10	0.34	18.83	0.74	2.21	0.17	0.24	1.61	4.19	9.97	3.50
890.9	1.6	59.5	58.12	0.34	18.83	0.73	2.19	0.17	0.24	1.60	4.19	9.99	3.51
889.9	1.6	59.3	58.14	0.33	18.82	0.73	2.17	0.17	0.24	1.58	4.19	10.02	3.52
888.9	1.6	59.2	58.16	0.33	18.81	0.72	2.15	0.17	0.23	1.57	4.19	10.04	3.53
887.9	1.6	59.0	58.17	0.33	18.81	0.72	2.13	0.17	0.23	1.55	4.18	10.07	3.54
886.9	1.6	58.8	58.19	0.32	18.80	0.71	2.11	0.17	0.22	1.54	4.18	10.09	3.55
885.9	1.6	58.7	58.21	0.32	18.79	0.71	2.09	0.17	0.22	1.53	4.18	10.12	3.56
884.9	1.6	58.5	58.23	0.32	18.79	0.70	2.07	0.17	0.22	1.51	4.18	10.14	3.57
883.9	1.6	58.4	58.25	0.31	18.78	0.70	2.05	0.17	0.21	1.50	4.17	10.17	3.58
882.9	1.6	58.2	58.26	0.31	18.78	0.69	2.03	0.17	0.21	1.49	4.17	10.19	3.59
881.9	1.6	58.1	58.28	0.31	18.77	0.69	2.01	0.17	0.21	1.47	4.17	10.22	3.60
880.9	1.6	57.9	58.30	0.31	18.76	0.68	1.99	0.17	0.20	1.46	4.16	10.24	3.61
879.9	1.6	57.7	58.32	0.30	18.76	0.68	1.97	0.17	0.20	1.45	4.16	10.27	3.62
878.9	1.6	57.6	58.33	0.30	18.75	0.67	1.95	0.17	0.20	1.44	4.16	10.29	3.63
877.9	1.6	57.4	58.35	0.30	18.74	0.67	1.94	0.17	0.19	1.42	4.16	10.32	3.64
876.9	1.6	57.3	58.36	0.30	18.74	0.67	1.92	0.17	0.19	1.41	4.15	10.34	3.65
875.9	1.6	57.1	58.38	0.29	18.73	0.66	1.90	0.17	0.19	1.40	4.15	10.37	3.66
874.9	1.6	57.0	58.39	0.29	18.73	0.66	1.88	0.17	0.19	1.39	4.15	10.40	3.67
873.9	1.6	56.8	58.41	0.29	18.72	0.65	1.86	0.17	0.18	1.37	4.14	10.42	3.68
872.9	1.6	56.7	58.42	0.29	18.71	0.65	1.84	0.17	0.18	1.36	4.14	10.45	3.69
871.9	1.6	56.5	58.44	0.28	18.71	0.64	1.83	0.17	0.18	1.35	4.13	10.47	3.70
870.9	1.6	56.4	58.45	0.28	18.70	0.64	1.81	0.16	0.17	1.34	4.13	10.50	3.71
869.9	1.6	56.2	58.47	0.28	18.70	0.63	1.79	0.16	0.17	1.33	4.13	10.52	3.72
868.9	1.6	56.1	58.48	0.28	18.69	0.63	1.77	0.16	0.17	1.31	4.12	10.55	3.73
867.9	1.6	55.9	58.49	0.27	18.68	0.62	1.76	0.16	0.17	1.30	4.12	10.57	3.74
866.9	1.6	55.8	58.51	0.27	18.68	0.62	1.74	0.16	0.16	1.29	4.12	10.60	3.75
865.9	1.6	55.6	58.52	0.27	18.67	0.61	1.72	0.16	0.16	1.28	4.11	10.62	3.76
864.9	1.6	55.5	58.53	0.27	18.67	0.61	1.71	0.16	0.16	1.27	4.11	10.65	3.77
863.9	1.6	55.3	58.55	0.26	18.66	0.60	1.69	0.16	0.16	1.26	4.10	10.67	3.78
862.9	1.6	55.1	58.55	0.26	18.66	0.60	1.67	0.16	0.15	1.25	4.10	10.69	3.79
861.9	1.6	54.7	58.53	0.26	18.66	0.60	1.66	0.16	0.15	1.25	4.10	10.71	3.82
860.9	1.6	54.3	58.50	0.26	18.65	0.60	1.65	0.16	0.15	1.24	4.10	10.72	3.85
859.9	1.6	53.9	58.48	0.25	18.65	0.59	1.64	0.16	0.15	1.24	4.11	10.73	3.88
858.9	1.6	53.5	58.45	0.25	18.65	0.59	1.63	0.17	0.15	1.24	4.11	10.74	3.91
857.9	1.6	53.1	58.43	0.25	18.65	0.59	1.62	0.17	0.15	1.24	4.11	10.75	3.94

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
856.9	1.6	52.7	58.40	0.24	18.65	0.59	1.61	0.17	0.15	1.24	4.11	10.76	3.97
855.9	1.6	52.3	58.38	0.24	18.65	0.58	1.60	0.17	0.14	1.24	4.11	10.77	3.99
854.9	1.6	51.9	58.35	0.24	18.65	0.58	1.59	0.17	0.14	1.24	4.12	10.78	4.02
853.9	1.6	51.6	58.33	0.23	18.65	0.58	1.58	0.17	0.14	1.24	4.12	10.80	4.05
852.9	1.6	51.2	58.30	0.23	18.64	0.58	1.57	0.17	0.14	1.24	4.12	10.81	4.08
851.9	1.6	50.8	58.28	0.23	18.64	0.57	1.56	0.17	0.14	1.24	4.12	10.82	4.11
850.9	1.6	50.4	58.25	0.23	18.64	0.57	1.55	0.17	0.14	1.24	4.13	10.83	4.14
849.9	1.6	50.1	58.22	0.22	18.64	0.57	1.54	0.17	0.14	1.23	4.13	10.84	4.17
848.9	1.6	49.7	58.20	0.22	18.64	0.57	1.53	0.17	0.14	1.23	4.13	10.85	4.21
847.9	1.6	49.3	58.17	0.22	18.64	0.57	1.52	0.17	0.13	1.23	4.13	10.86	4.24
846.9	1.6	49.0	58.14	0.21	18.63	0.56	1.51	0.17	0.13	1.23	4.14	10.87	4.27
845.9	1.6	48.6	58.11	0.21	18.63	0.56	1.50	0.17	0.13	1.23	4.14	10.88	4.30
844.9	1.6	48.3	58.08	0.21	18.63	0.56	1.49	0.17	0.13	1.23	4.14	10.89	4.33
843.9	1.6	47.9	58.06	0.21	18.63	0.56	1.49	0.17	0.13	1.23	4.14	10.90	4.36
842.9	1.6	47.6	58.03	0.20	18.63	0.55	1.48	0.18	0.13	1.23	4.15	10.91	4.39
841.9	1.6	47.2	58.00	0.20	18.63	0.55	1.47	0.18	0.13	1.23	4.15	10.92	4.43
840.9	1.6	46.9	57.97	0.20	18.62	0.55	1.46	0.18	0.13	1.23	4.15	10.93	4.46
839.9	1.6	46.5	57.94	0.20	18.62	0.55	1.45	0.18	0.13	1.23	4.16	10.94	4.49
838.9	1.6	46.2	57.91	0.19	18.62	0.55	1.44	0.18	0.12	1.22	4.16	10.95	4.52
837.9	1.6	45.9	57.88	0.19	18.62	0.54	1.43	0.18	0.12	1.22	4.16	10.96	4.56
836.9	1.6	45.5	57.85	0.19	18.62	0.54	1.42	0.18	0.12	1.22	4.17	10.97	4.59
835.9	1.6	45.2	57.82	0.18	18.61	0.54	1.41	0.18	0.12	1.22	4.17	10.98	4.62
834.9	1.6	44.9	57.78	0.18	18.61	0.54	1.40	0.18	0.12	1.22	4.17	10.99	4.66
833.9	1.6	44.6	57.75	0.18	18.61	0.54	1.39	0.18	0.12	1.22	4.18	11.00	4.69
832.9	1.6	44.2	57.72	0.18	18.61	0.53	1.39	0.18	0.12	1.22	4.18	11.01	4.73
831.9	1.6	43.9	57.69	0.17	18.60	0.53	1.38	0.18	0.12	1.22	4.19	11.02	4.76
830.9	1.6	43.6	57.65	0.17	18.60	0.53	1.37	0.18	0.12	1.22	4.19	11.03	4.79
829.9	1.6	43.3	57.62	0.17	18.60	0.53	1.36	0.18	0.12	1.22	4.19	11.04	4.83
828.9	1.6	43.0	57.59	0.17	18.60	0.52	1.35	0.19	0.11	1.22	4.20	11.05	4.86
827.9	1.6	42.7	57.55	0.17	18.60	0.52	1.34	0.19	0.11	1.22	4.20	11.06	4.90
826.9	1.6	42.3	57.52	0.16	18.59	0.52	1.33	0.19	0.11	1.22	4.21	11.07	4.94
825.9	1.6	42.0	57.48	0.16	18.59	0.52	1.33	0.19	0.11	1.21	4.21	11.08	4.97
824.9	1.6	41.7	57.45	0.16	18.59	0.52	1.32	0.19	0.11	1.21	4.21	11.09	5.01
823.9	1.6	41.4	57.41	0.16	18.59	0.51	1.31	0.19	0.11	1.21	4.22	11.10	5.05
822.9	1.6	41.1	57.38	0.15	18.58	0.51	1.30	0.19	0.11	1.21	4.22	11.11	5.08
821.9	1.6	40.8	57.34	0.15	18.58	0.51	1.29	0.19	0.11	1.21	4.23	11.12	5.12
820.9	1.6	40.5	57.30	0.15	18.58	0.51	1.28	0.19	0.11	1.21	4.23	11.13	5.16
819.9	1.6	40.2	57.27	0.15	18.57	0.51	1.28	0.19	0.11	1.21	4.24	11.14	5.19
818.9	1.6	39.9	57.23	0.15	18.57	0.50	1.27	0.19	0.11	1.21	4.24	11.15	5.23
817.9	1.6	39.7	57.19	0.14	18.57	0.50	1.26	0.19	0.11	1.21	4.25	11.16	5.27
816.9	1.6	39.4	57.15	0.14	18.57	0.50	1.25	0.20	0.10	1.21	4.25	11.17	5.31
815.9	1.6	39.1	57.11	0.14	18.56	0.50	1.24	0.20	0.10	1.21	4.26	11.17	5.35
814.9	1.6	38.8	57.07	0.14	18.56	0.50	1.24	0.20	0.10	1.21	4.26	11.18	5.39
813.9	1.6	38.5	57.04	0.13	18.56	0.49	1.23	0.20	0.10	1.21	4.27	11.19	5.43
812.9	1.6	38.2	56.99	0.13	18.55	0.49	1.22	0.20	0.10	1.21	4.27	11.20	5.47
811.9	1.6	37.9	56.95	0.13	18.55	0.49	1.21	0.20	0.10	1.21	4.28	11.21	5.51
810.9	1.6	37.7	56.91	0.13	18.55	0.49	1.21	0.20	0.10	1.21	4.28	11.22	5.55
809.9	1.6	37.4	56.87	0.13	18.54	0.49	1.20	0.20	0.10	1.20	4.29	11.23	5.59
808.9	1.6	37.1	56.83	0.12	18.54	0.49	1.19	0.20	0.10	1.20	4.30	11.24	5.63
807.9	1.6	36.8	56.79	0.12	18.54	0.48	1.18	0.20	0.10	1.20	4.30	11.25	5.67
806.9	1.6	36.6	56.74	0.12	18.53	0.48	1.18	0.20	0.10	1.20	4.31	11.25	5.71
805.9	1.6	36.3	56.70	0.12	18.53	0.48	1.17	0.21	0.10	1.20	4.31	11.26	5.76
804.9	1.6	36.0	56.66	0.12	18.53	0.48	1.16	0.21	0.10	1.20	4.32	11.27	5.80
803.9	1.6	35.8	56.61	0.12	18.52	0.48	1.15	0.21	0.09	1.20	4.33	11.28	5.84
802.9	1.6	35.0	56.52	0.11	18.53	0.47	1.15	0.21	0.09	1.21	4.35	11.31	5.88
801.9	1.6	33.9	56.39	0.11	18.55	0.47	1.14	0.22	0.09	1.21	4.39	11.34	5.91
800.9	1.6	32.9	56.27	0.11	18.56	0.47	1.13	0.22	0.09	1.22	4.43	11.37	5.94
799.9	1.6	31.9	56.16	0.11	18.58	0.47	1.12	0.23	0.09	1.23	4.46	11.41	5.96
798.9	1.6	31.1	56.04	0.10	18.59	0.47	1.11	0.23	0.09	1.24	4.50	11.44	5.99
797.9	1.6	30.3	55.93	0.10	18.60	0.47	1.10	0.24	0.09	1.24	4.53	11.47	6.02
796.9	1.6	29.6	55.82	0.10	18.62	0.47	1.10	0.24	0.09	1.25	4.57	11.50	6.05
795.9	1.6	28.9	55.71	0.10	18.63	0.47	1.09	0.24	0.09	1.25	4.60	11.53	6.08
794.9	1.6	28.2	55.61	0.10	18.64	0.47	1.08	0.25	0.08	1.26	4.64	11.56	6.11
793.9	1.6	27.6	55.50	0.09	18.65	0.47	1.07	0.25	0.08	1.27	4.67	11.58	6.14
792.9	1.6	26.4	55.46	0.10	18.71	0.40	0.90	0.26	0.06	1.27	4.76	11.67	6.19
791.9	1.6	25.9	55.36	0.10	18.72	0.39	0.89	0.27	0.05	1.27	4.79	11.69	6.22
790.9	1.6	25.4	55.27	0.10	18.73	0.39	0.88	0.28	0.05	1.28	4.83	11.72	6.25
789.9	1.6	24.9	55.17	0.11	18.74	0.39	0.87	0.28	0.05	1.28	4.86	11.74	6.28
788.9	1.6	24.4	55.08	0.11	18.75	0.38	0.85	0.29	0.05	1.29	4.90	11.76	6.31
787.9	1.6	24.0	54.99	0.11	18.75	0.38	0.84	0.29	0.05	1.29	4.93	11.78	6.34
786.9	1.6	23.6	54.90	0.11	18.76	0.38	0.83	0.30	0.04	1.29	4.96	11.81	6.36

APPENDIX 1. SUPPLEMENTARY MATERIAL FOR CHAPTER 2

T (°C)	P (kbars)	liq mass (g)	SiO ₂ (wt%)	TiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	FeO (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	H ₂ O (wt%)
785.9	1.6	23.2	54.81	0.11	18.77	0.37	0.82	0.30	0.04	1.30	4.99	11.83	6.39
784.9	1.6	22.8	54.73	0.12	18.78	0.37	0.80	0.31	0.04	1.30	5.03	11.85	6.42
783.9	1.6	22.5	54.64	0.12	18.78	0.36	0.79	0.31	0.04	1.30	5.06	11.87	6.45
782.9	1.6	22.1	54.55	0.12	18.79	0.36	0.78	0.32	0.04	1.31	5.09	11.89	6.48
781.9	1.6	21.8	54.47	0.12	18.80	0.36	0.77	0.32	0.04	1.31	5.12	11.91	6.51
780.9	1.6	21.5	54.39	0.12	18.80	0.35	0.76	0.32	0.04	1.31	5.15	11.93	6.54
779.9	1.6	21.2	54.30	0.13	18.81	0.35	0.74	0.33	0.03	1.32	5.18	11.95	6.57
778.9	1.6	20.9	54.22	0.13	18.82	0.35	0.73	0.33	0.03	1.32	5.22	11.97	6.60
777.9	1.6	20.5	54.13	0.11	18.83	0.34	0.72	0.34	0.03	1.31	5.26	11.98	6.64
776.9	1.6	20.3	54.04	0.11	18.85	0.34	0.71	0.34	0.03	1.32	5.30	11.99	6.68
775.9	1.6	20.0	53.95	0.11	18.86	0.34	0.70	0.35	0.03	1.32	5.33	12.00	6.71
774.9	1.6	19.7	53.87	0.11	18.86	0.33	0.69	0.35	0.03	1.32	5.37	12.02	6.74
773.9	1.6	19.5	53.79	0.10	18.87	0.33	0.68	0.36	0.03	1.32	5.40	12.03	6.78
772.9	1.6	19.2	53.70	0.10	18.88	0.33	0.67	0.36	0.03	1.33	5.43	12.05	6.81
771.9	1.6	19.0	53.62	0.10	18.89	0.32	0.66	0.37	0.03	1.33	5.47	12.06	6.84
770.9	1.6	18.7	53.54	0.10	18.90	0.32	0.65	0.37	0.02	1.33	5.50	12.07	6.88
769.9	1.6	18.5	53.46	0.10	18.90	0.32	0.64	0.38	0.02	1.33	5.53	12.09	6.91
768.9	1.6	18.3	53.37	0.09	18.91	0.31	0.63	0.38	0.02	1.33	5.57	12.10	6.95

Table A1.11: Best-fit assimilation fractional crystallisation model for western caldera group eruptions. Liquid remaining is reported in grams, the model begins with 100g of liquid. The starting temperature is the liquidus temperature of the system, calculated by Rhyolite-MELTS.

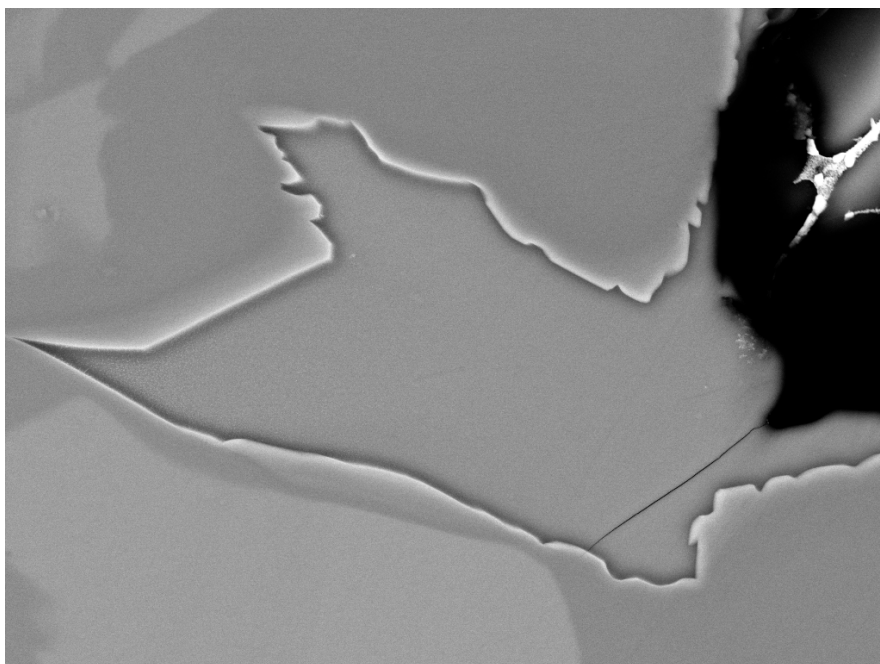


Figure A1.1: Back-scattered electron image of the clinopyroxene-hosted melt inclusion used as the starting composition in the models in this study. The melt inclusion is CF410_cpx12_MI18 from Fondo Riccio, sample CF410. Image was obtained at the iCRAG labs at Trinity College Dublin, Ireland, using a Tescan S8000 MIRA 4 FEG-SEM.

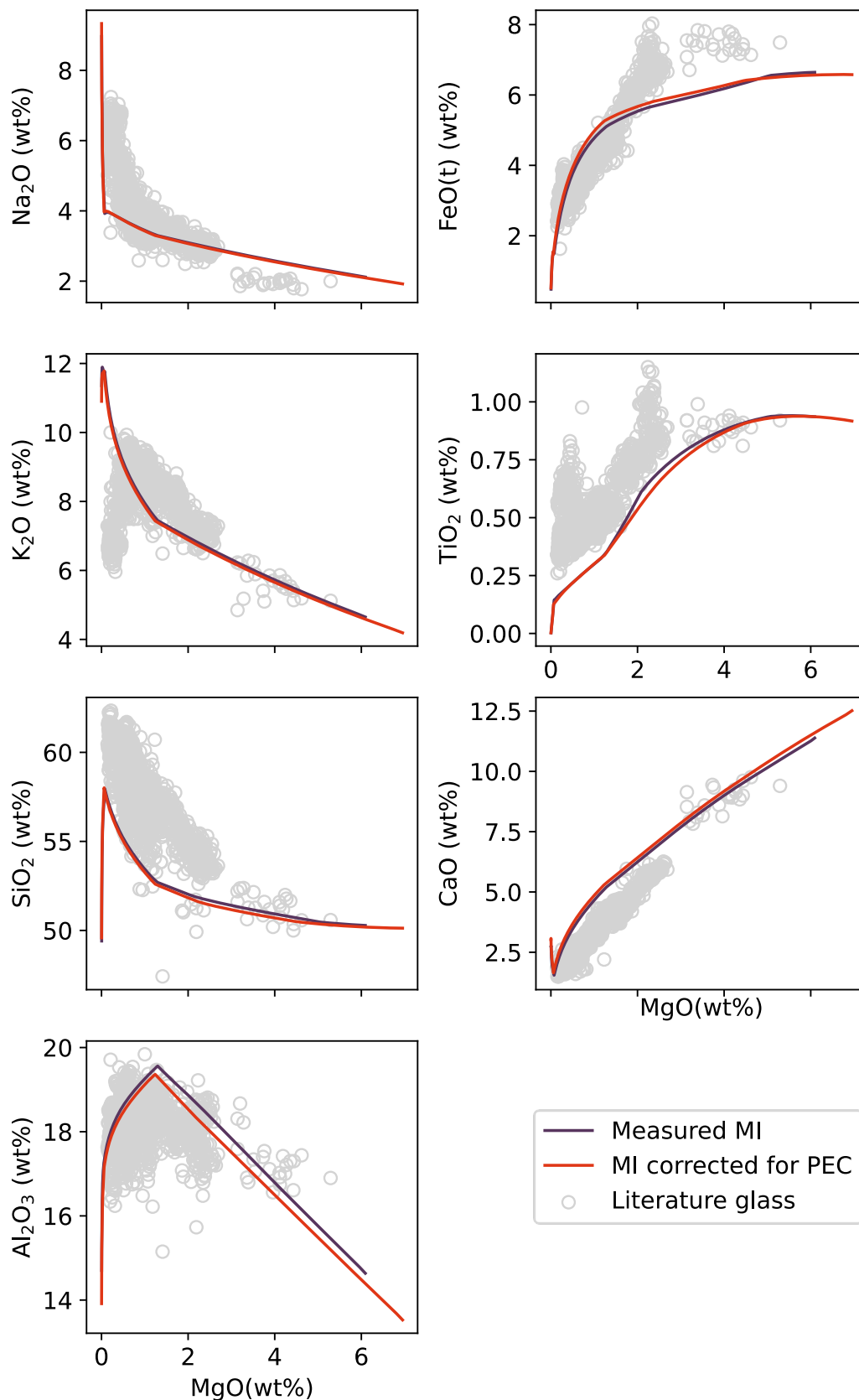


Figure A1.2: Comparison of Rhyolite-MELTS models run with different starting compositions. Both models are run with the same intensive parameters of $P=140$ MPa, $L_{f02}=QFM$ and $L_{H2O} = 2$ wt%. The purple line uses the composition of the most mafic melt inclusion measured in this study, CF410_cpx12_MI18, which is the starting composition used throughout the rest of this study. The red line shows a model run using a starting composition recalculated from CF410_cpx12_MI18 using the post-entrapment crystallisation correction detailed in Fowler et al. (2007).

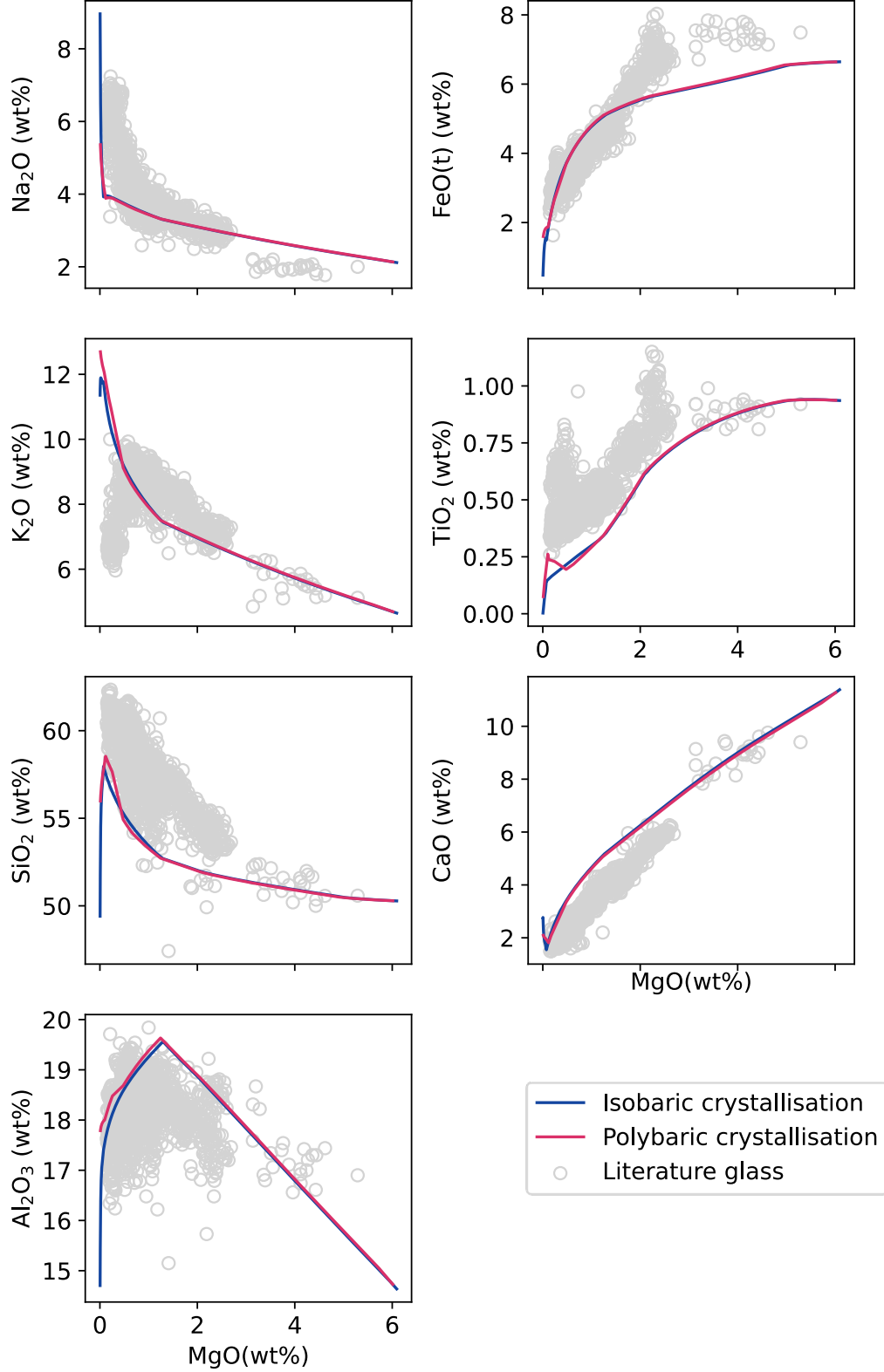


Figure A1.3: Results of Rhyolite-MELTS models run under isobaric and polybaric conditions. Both models were run with $L_{\text{FO2}}=\text{QFM}$ and $L_{\text{H2O}} = 2 \text{ wt\%}$. The blue line shows isobaric crystallisation at 160 MPa, which corresponds to a depth of $\sim 7\text{km}$ assuming an average crustal density of 2300 kg cm^{-3} after Rosi and Sbrana (1987). The red line shows polybaric crystallisation; the model starts at a pressure of 160 MPa and after $\sim 50\%$ crystallisation the pressure is reduced to 70 MPa, equivalent to depths of $\sim 7\text{km}$ and $\sim 3\text{km}$ respectively. These depths were chosen to represent the main magma storage regions at Campi Flegrei identified by previous studies (e.g. Stock et al., 2018, Petrelli et al., 2023). The polybaric model fails to converge at low temperatures ($\sim 800^\circ\text{C}$, with $\sim 15\%$ liquid remaining). Grey circles show literature glass data.

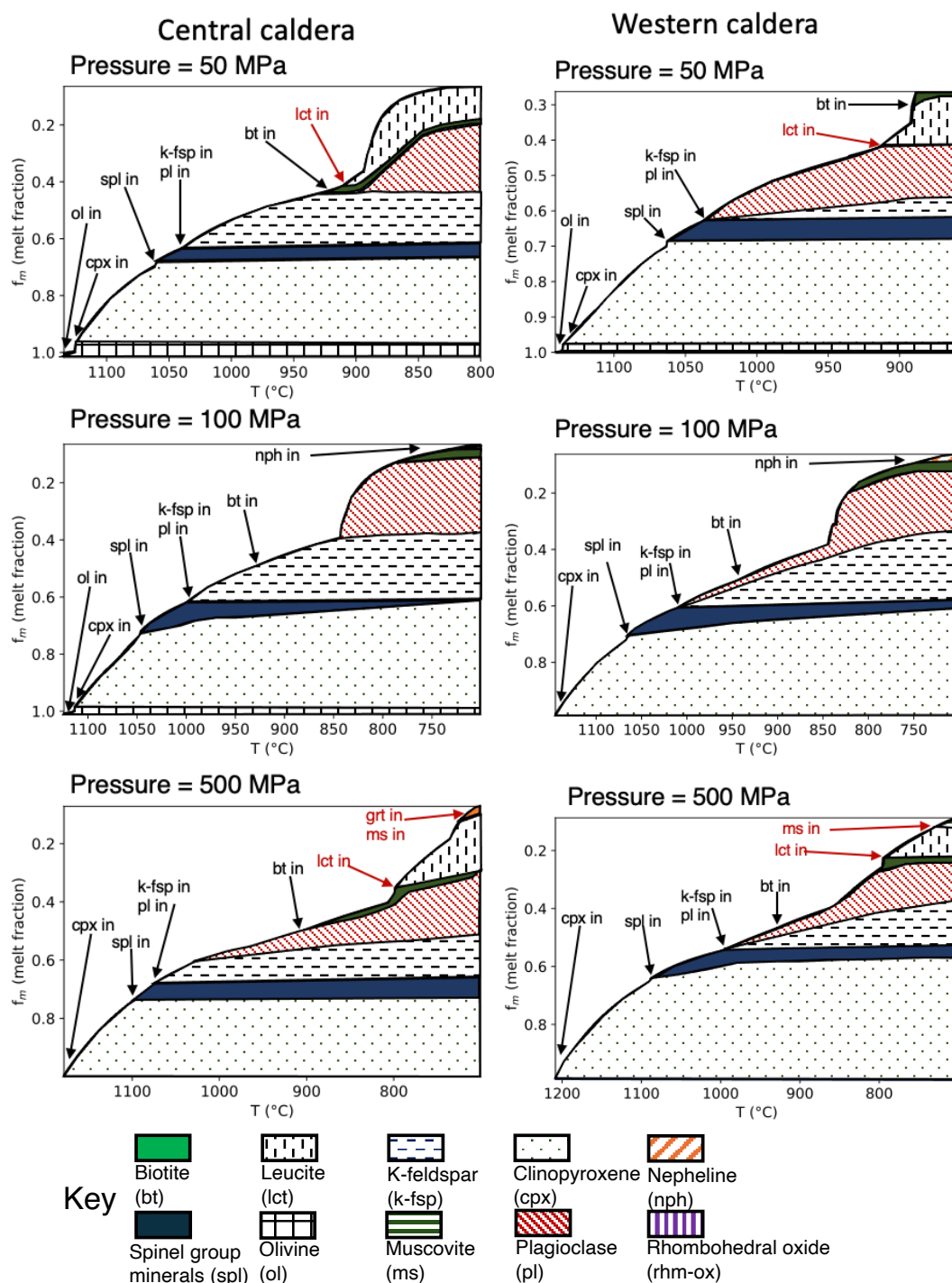


Figure A1.4: Phase proportions as a function of magma temperature for fractional crystallisation MELTS models at different pressures. Central caldera models are run at $L_{f02} = \text{QFM}$ and initial $L_{\text{H}_2\text{O}} = 3 \text{ wt\%}$. Western caldera models are run at $L_{f02} = \text{QFM}$ and initial $\text{H}_2\text{O} = 2 \text{ wt\%}$. Cpx, clinopyroxene; spl, spinel group minerals; k-fsp, alkali feldspar; pl, plagioclase feldspar; bt, biotite; lct, leucite; ms, muscovite; ol, olivine; nph, nepheline; rhm-ox, rhombohedral oxide. Phases highlighted in red are not observed in natural Campi Flegrei samples in the major crystallising assemblage.

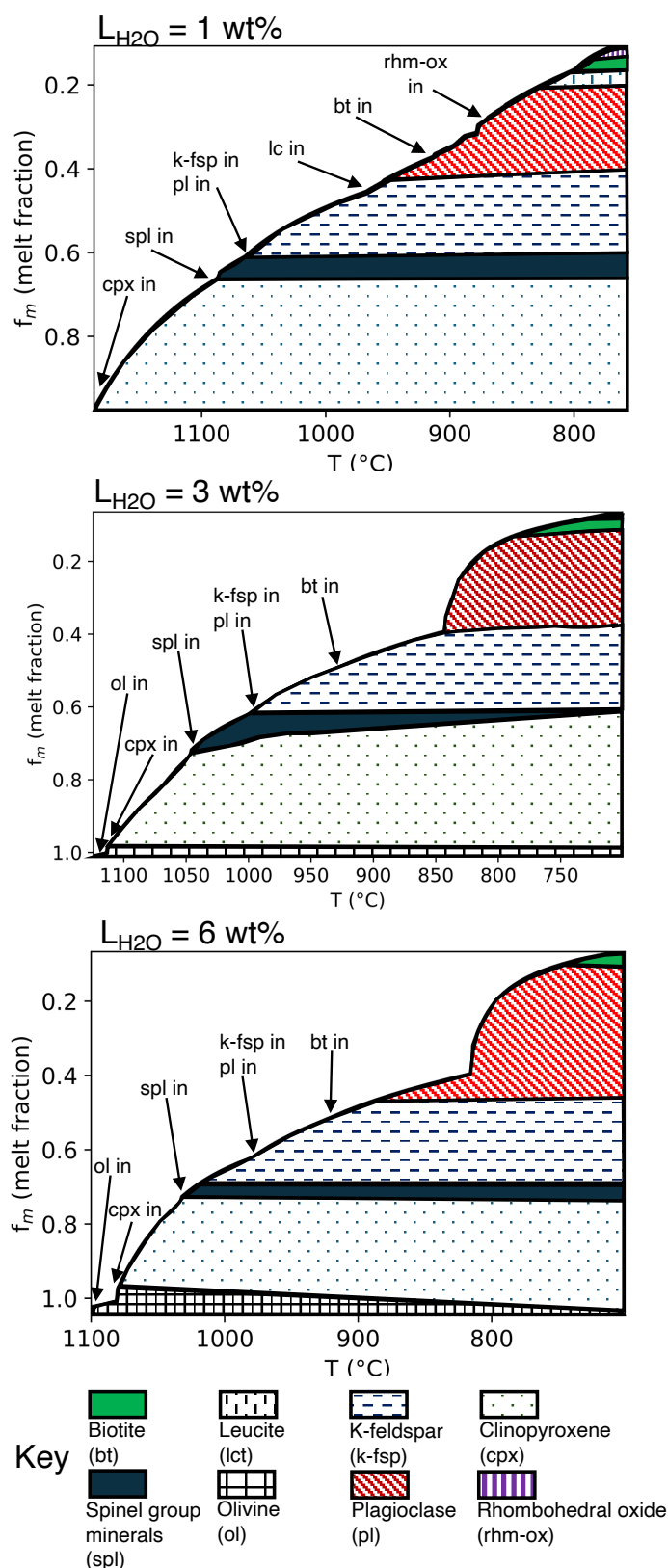


Figure A1.5: Phase proportions as a function of magma temperature for fractional crystallisation Rhyolite-MELTS models at different initial L_{H_2O} . Models are run at $L_{fO_2} = \text{QFM}$ and initial pressure = 140 MPa. Cpx, clinopyroxene; spl, spinel group minerals; k-fsp, alkali feldspar; pl, plagioclase feldspar; bt, biotite; lct, leucite; ms, muscovite; ol, olivine; neph, nepheline; rhm-ox, rhombohedral oxide.

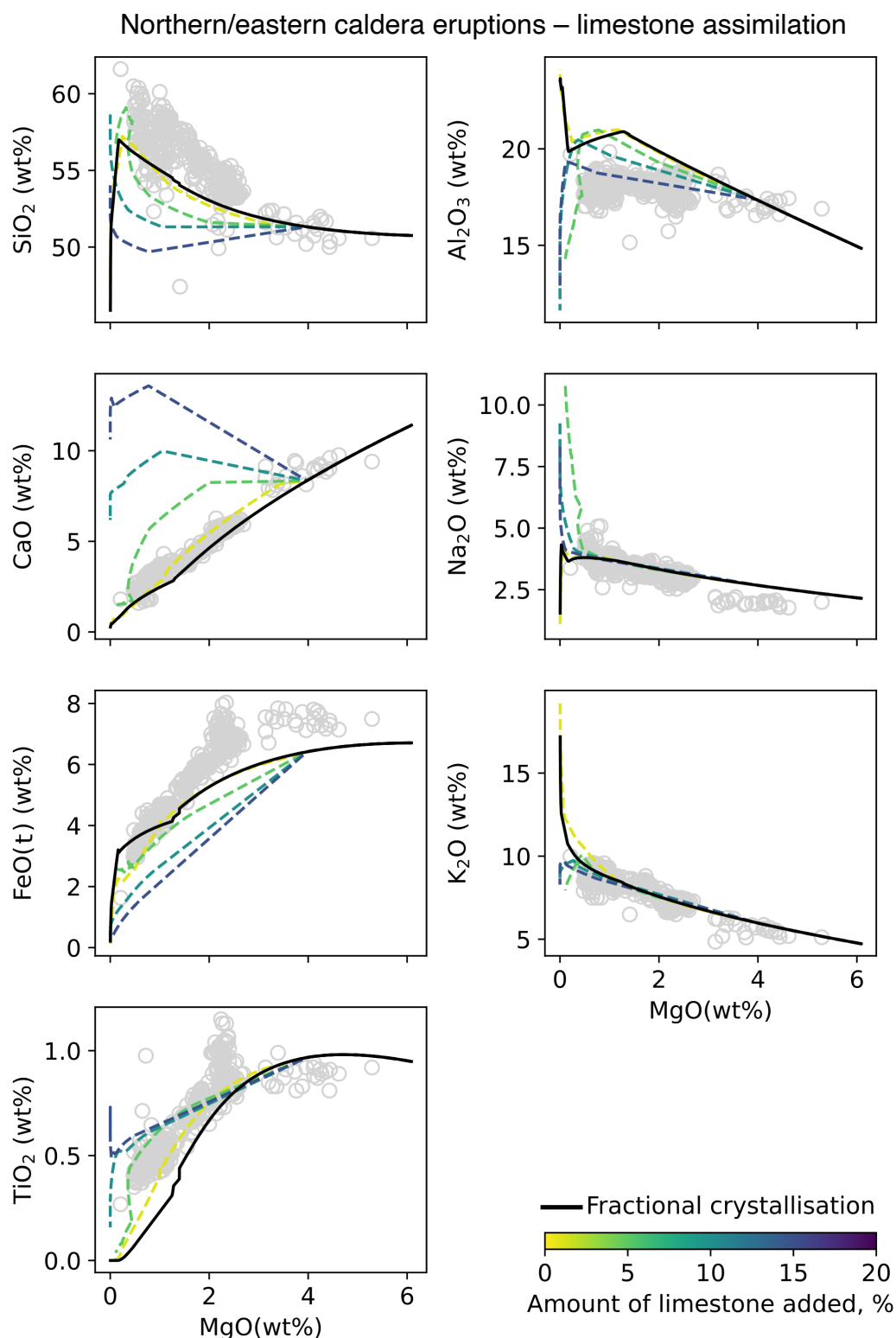


Figure A1.6: Results of assimilation-fractional crystallisation models of limestone assimilation for northern/eastern caldera group eruptions. Grey circles show northern/eastern caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions (L_{fO_2} =QFM+1, L_{H_2O} = 2 wt%, pressure=110 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

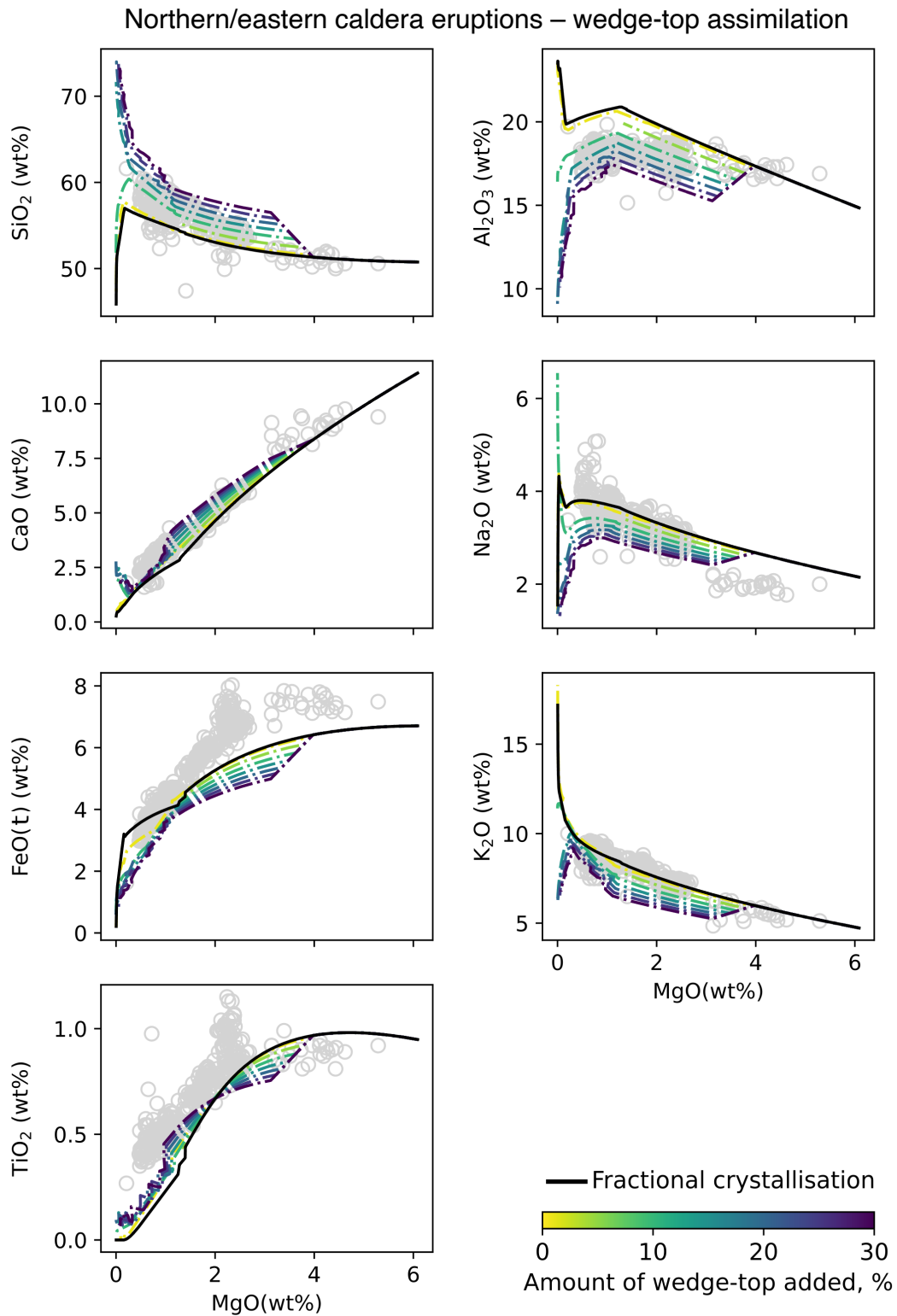


Figure A1.7: Results of assimilation-fractional crystallisation models of wedge-top deposits assimilation for northern/eastern caldera group eruptions. Grey circles show northern/eastern caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{fO2}=QFM+1$, $L_{H2O} = 2$ wt%, pressure=110 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

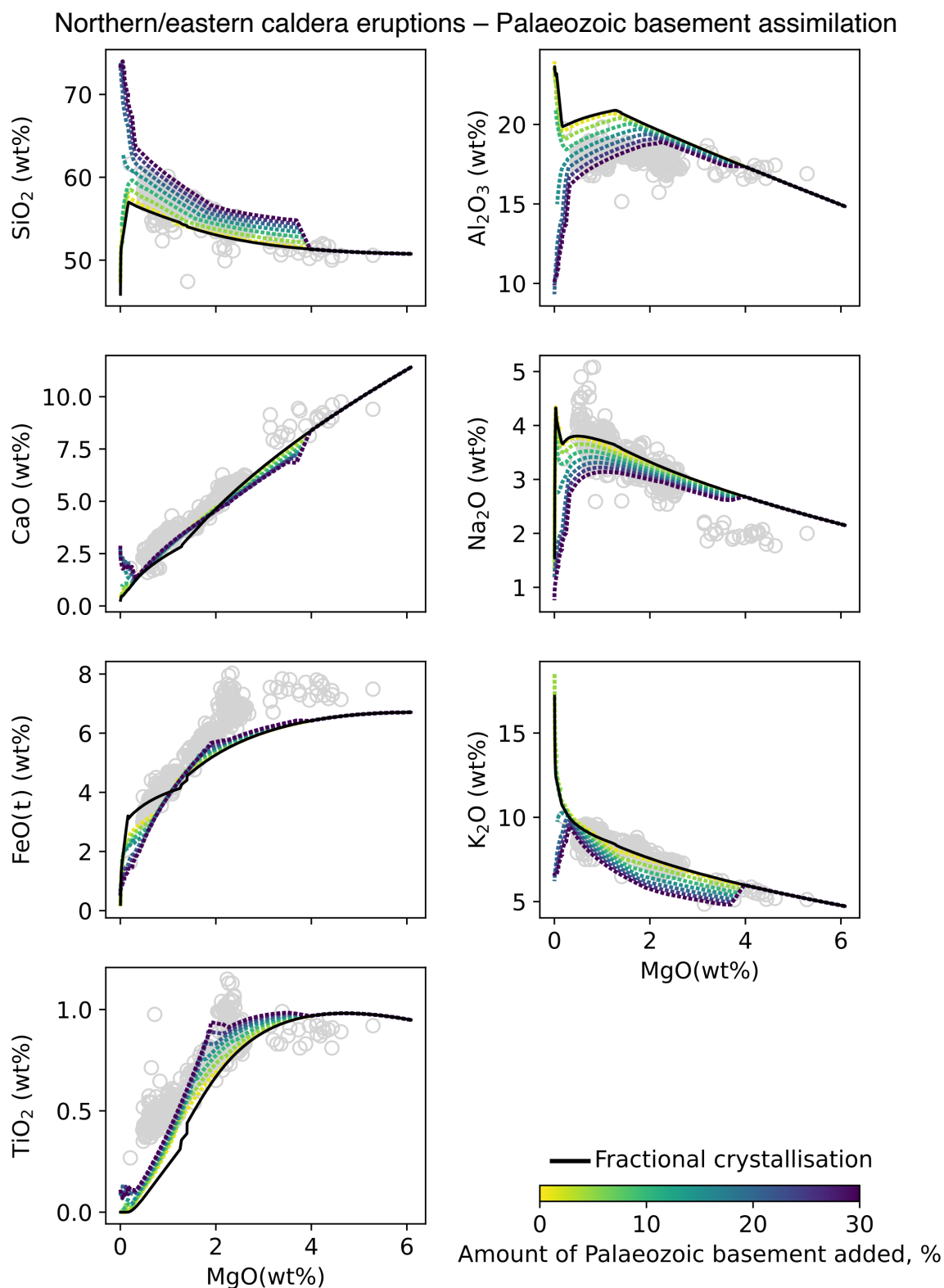


Figure A1.8: Results of assimilation-fractional crystallisation models of Palaeozoic metamorphic basement assimilation for northern/eastern caldera group eruptions. Grey circles show northern/eastern caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{fO2}=QFM+1$, $L_{H2O} = 2$ wt%, pressure=110 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

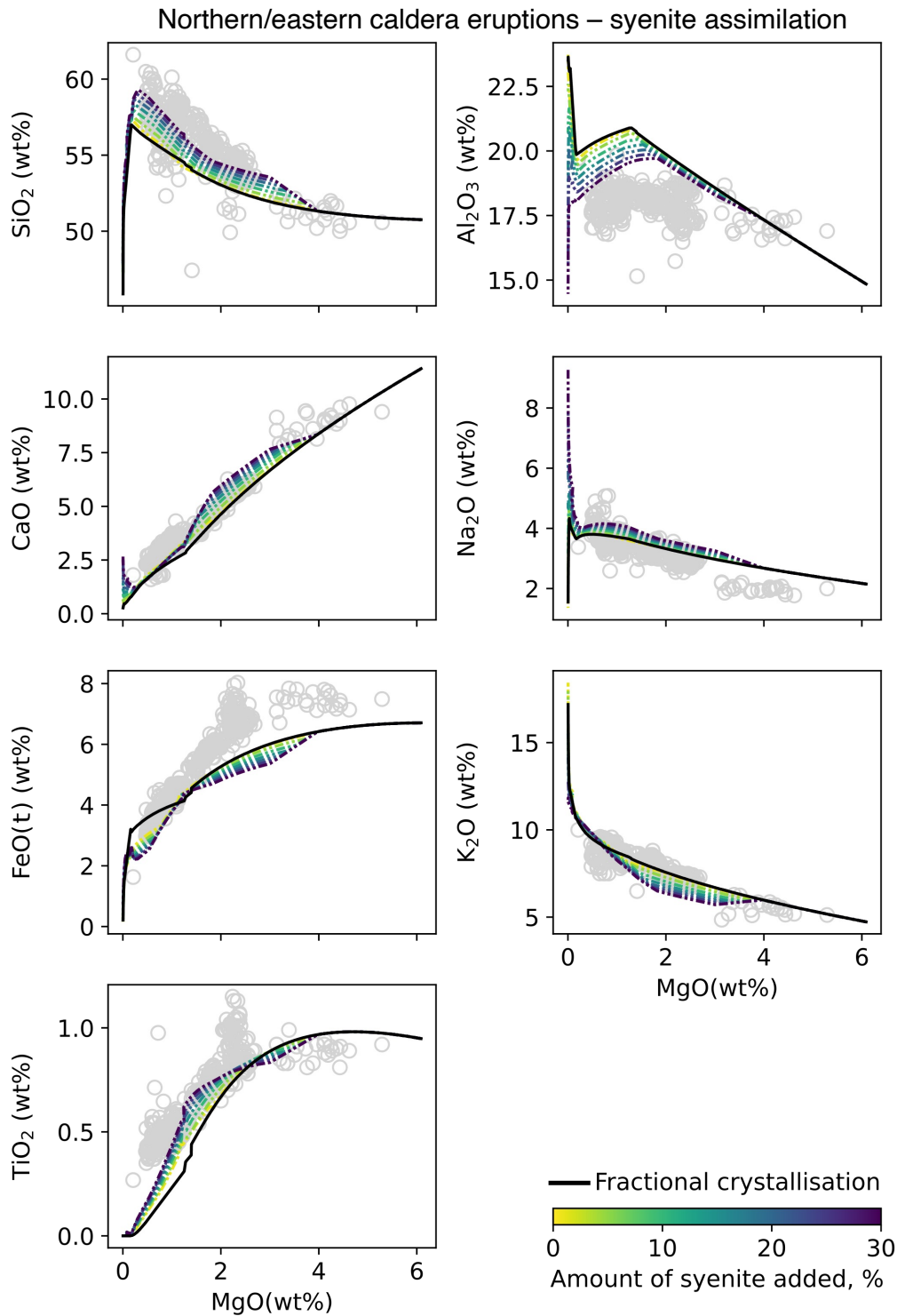


Figure A1.9: Results of assimilation-fractional crystallisation models of syenite assimilation for northern/eastern caldera group eruptions. Grey circles show northern/eastern caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{fO2}=QFM+1$, $L_{H2O} = 2$ wt%, pressure=110 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

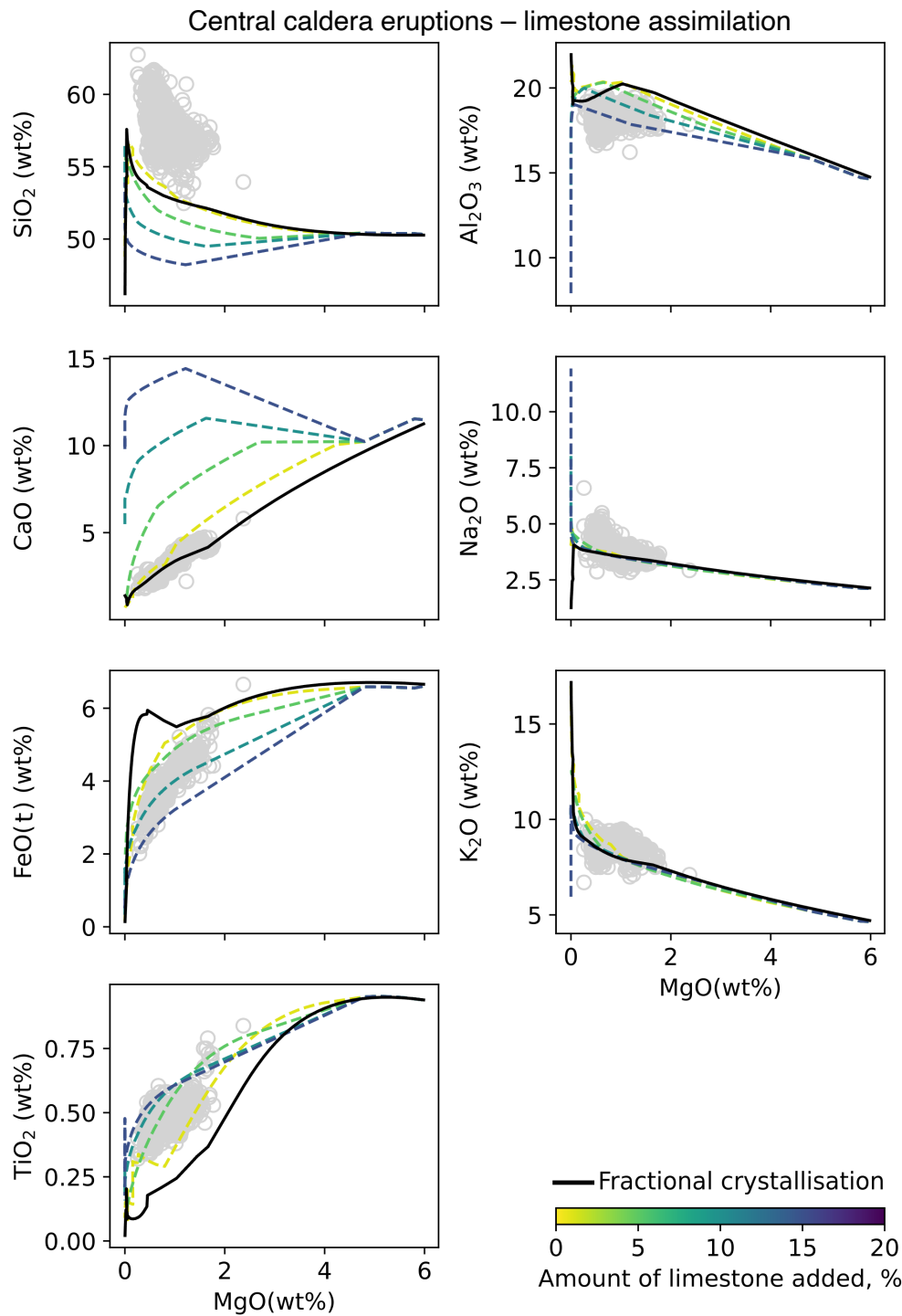


Figure A1.10: Results of assimilation-fractional crystallisation models of limestone assimilation for central caldera group eruptions. Grey circles show central caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions (L_{fO_2} =QFM, L_{H_2O} = 3 wt%, pressure=140 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

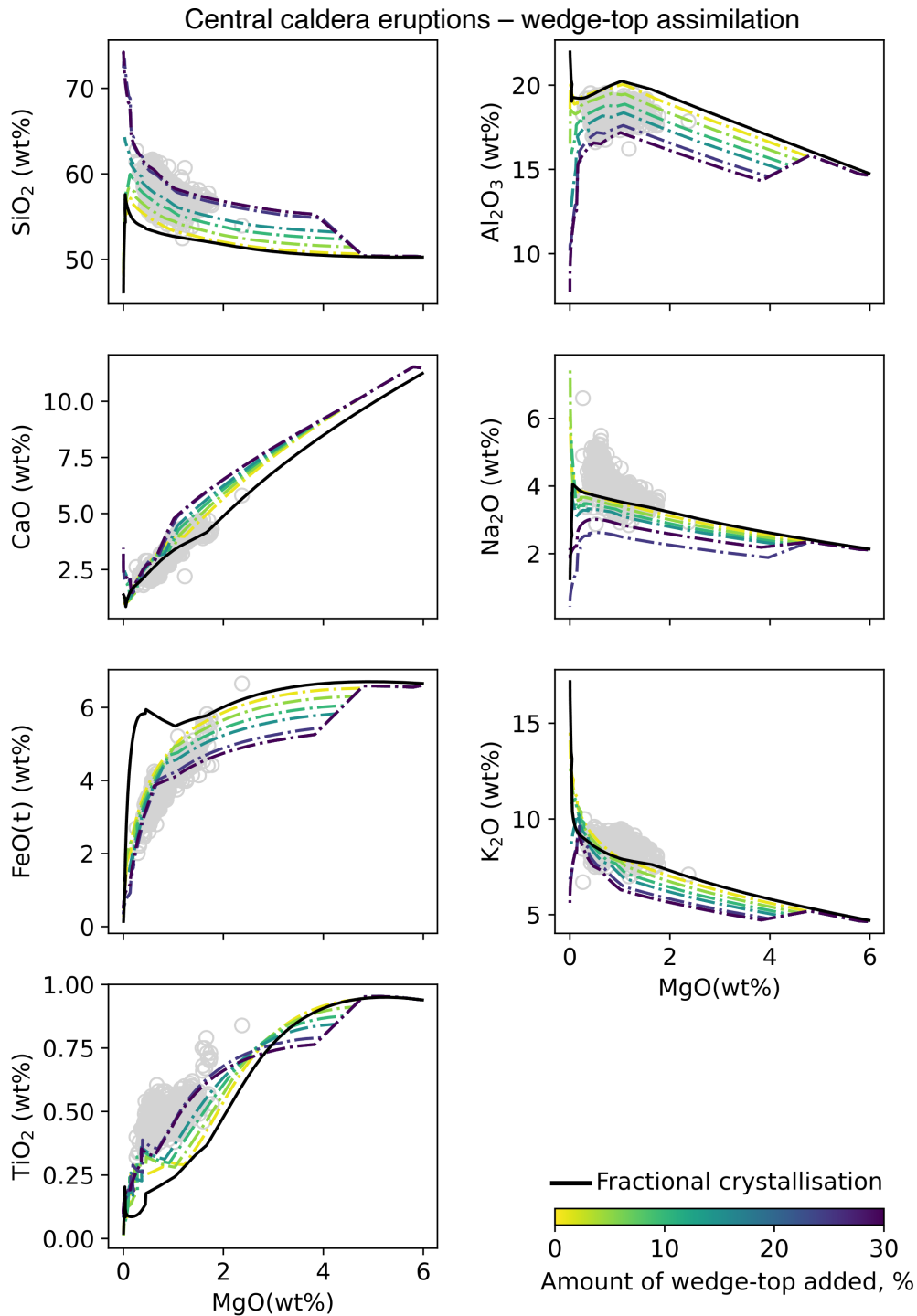


Figure A1.11: Results of assimilation-fractional crystallisation models of wedge-top deposits assimilation for central caldera group eruptions. Grey circles show central caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{\text{FeO}}=\text{QFM}$, $L_{\text{H}_2\text{O}} = 3 \text{ wt\%}$, pressure=140 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

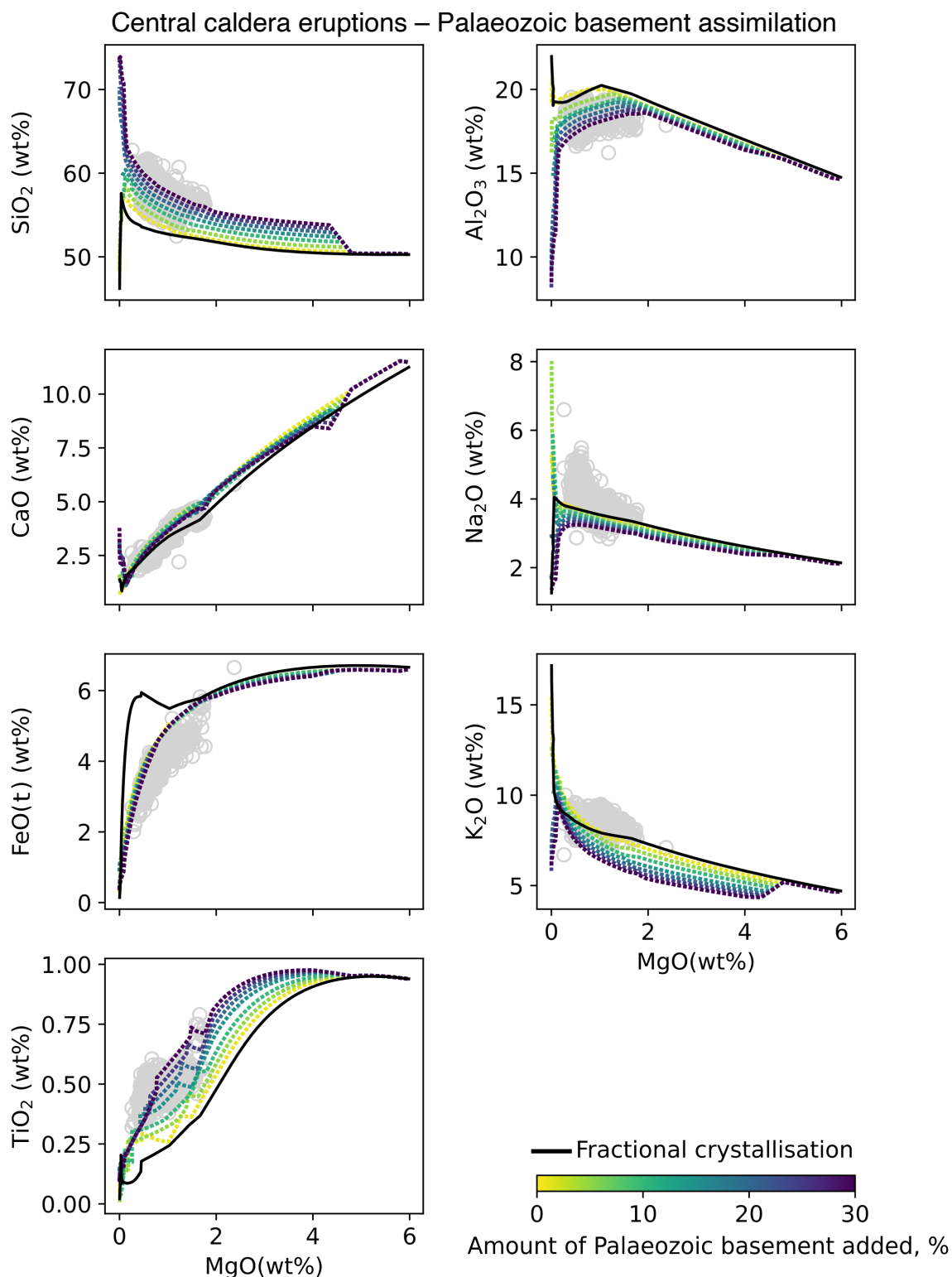


Figure A1.12: Results of assimilation-fractional crystallisation models of Palaeozoic metamorphic basement assimilation for central caldera group eruptions. Grey circles show central caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions (L_{fO_2} =QFM, L_{H_2O} = 3 wt%, pressure=140 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

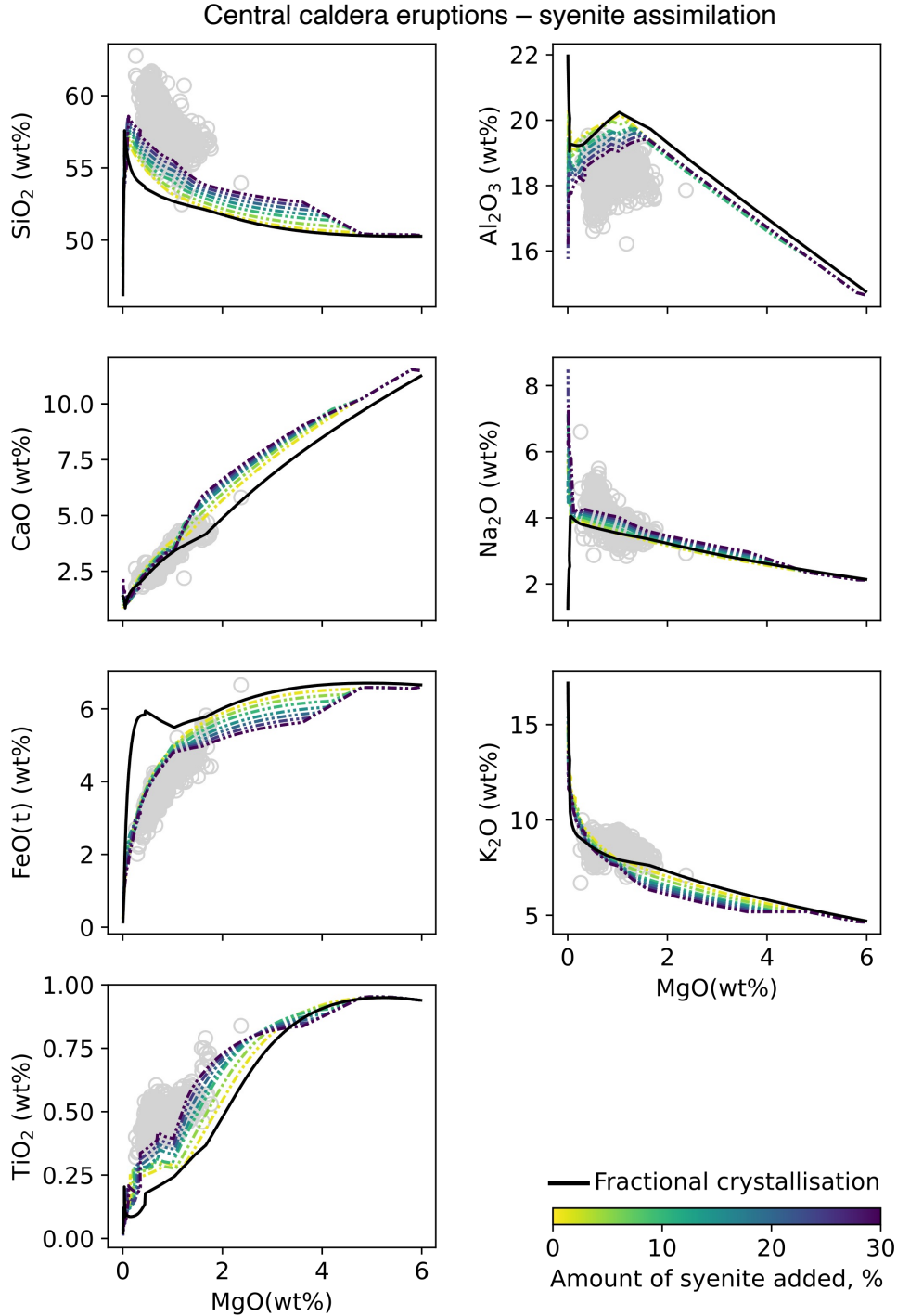


Figure A1.13: Results of assimilation-fractional crystallisation models of syenite assimilation for central caldera group eruptions. Grey circles show central caldera group eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions (L_{fO_2} =QFM, L_{H_2O} = 3 wt%, pressure=140 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

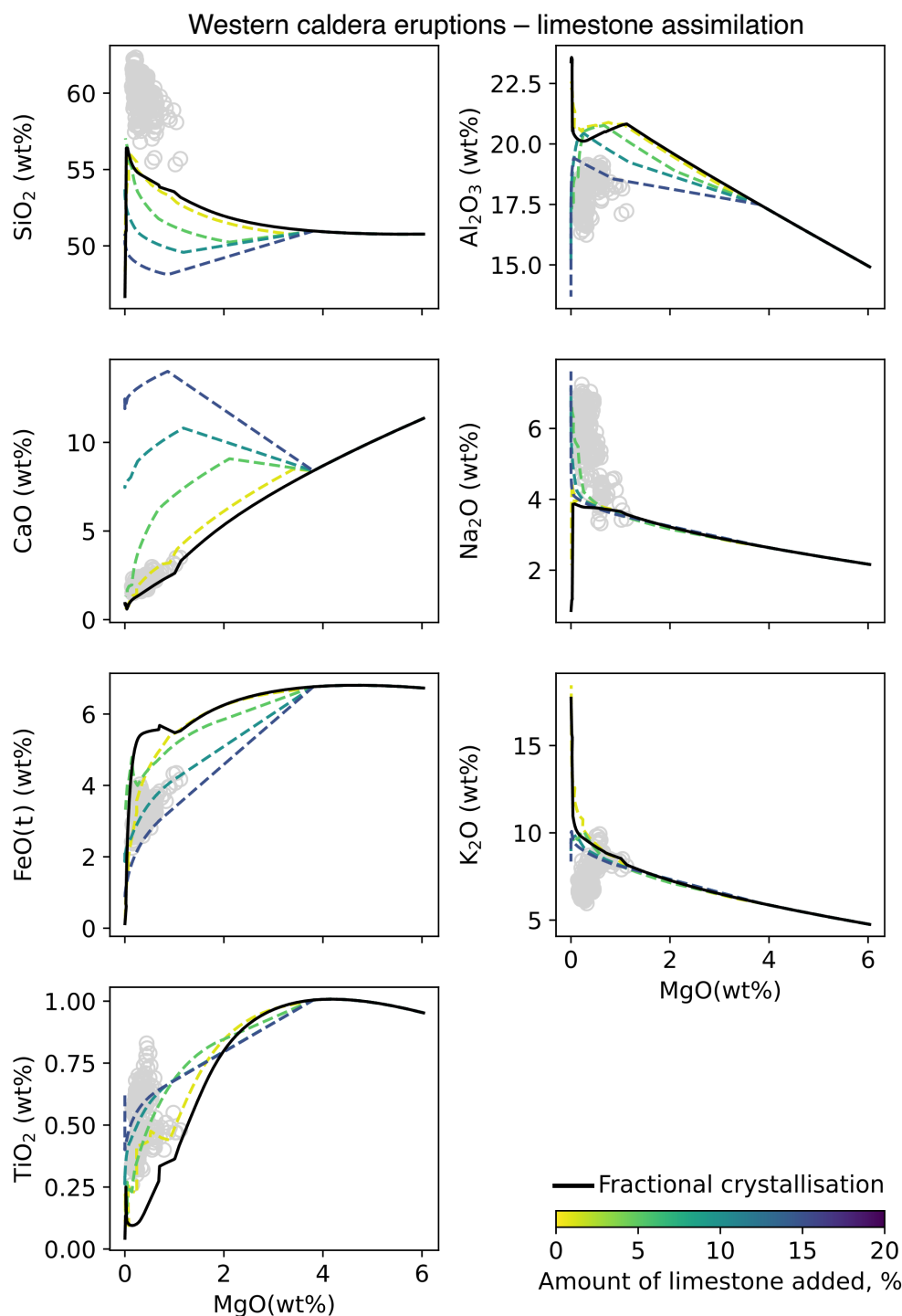


Figure A.14: Results of assimilation-fractional crystallisation models for limestone assimilation for western caldera group eruptions. Grey circles show western caldera eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions (L_{fO_2} =QFM, L_{H_2O} = 2 wt%, pressure=160 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

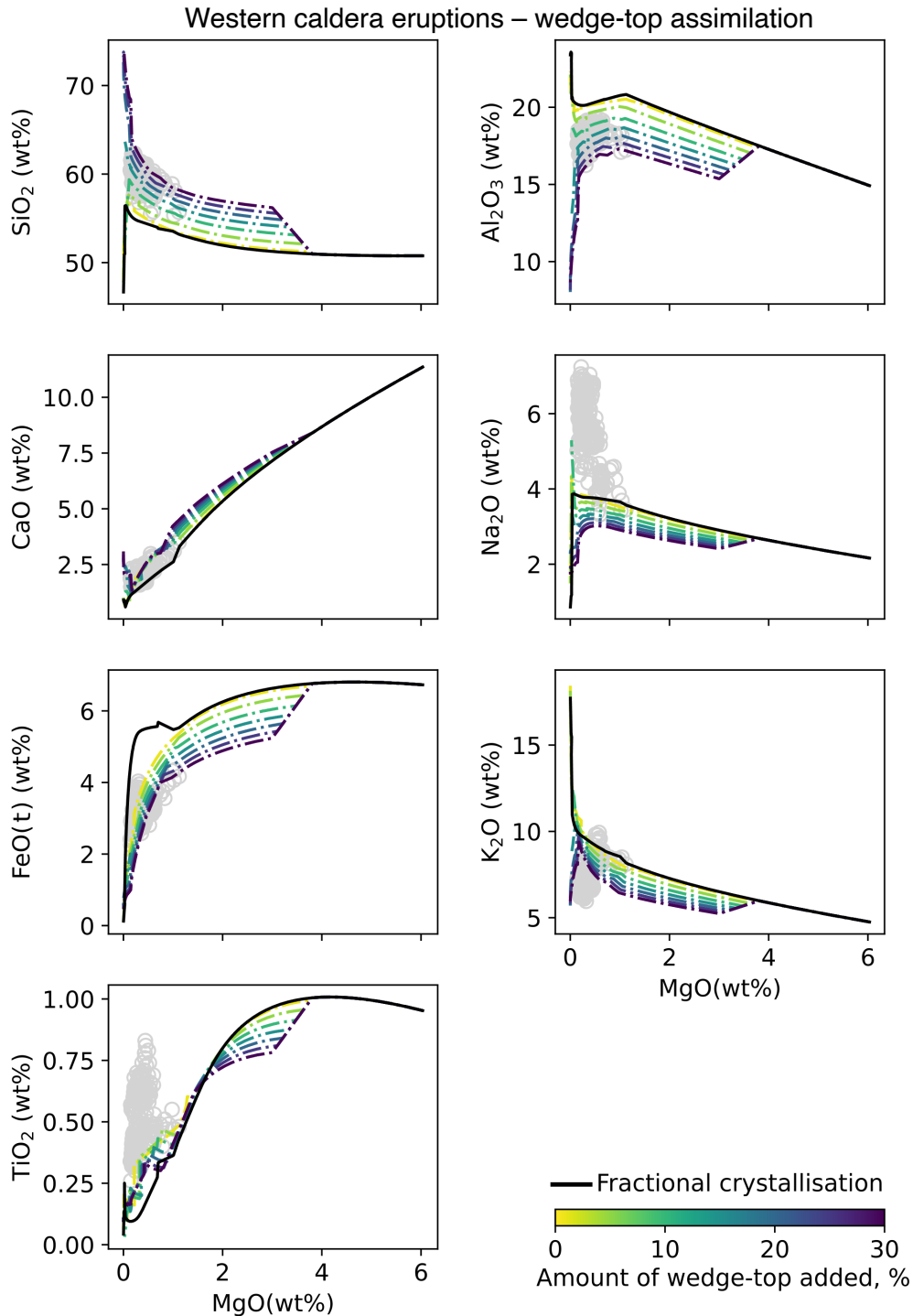


Figure A1.15: Results of assimilation-fractional crystallisation models for wedge-top deposits assimilation for western caldera group eruptions. Grey circles show western caldera eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{\text{FeO}}=\text{QFM}$, $L_{\text{H}_2\text{O}} = 2 \text{ wt\%}$, pressure=160 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

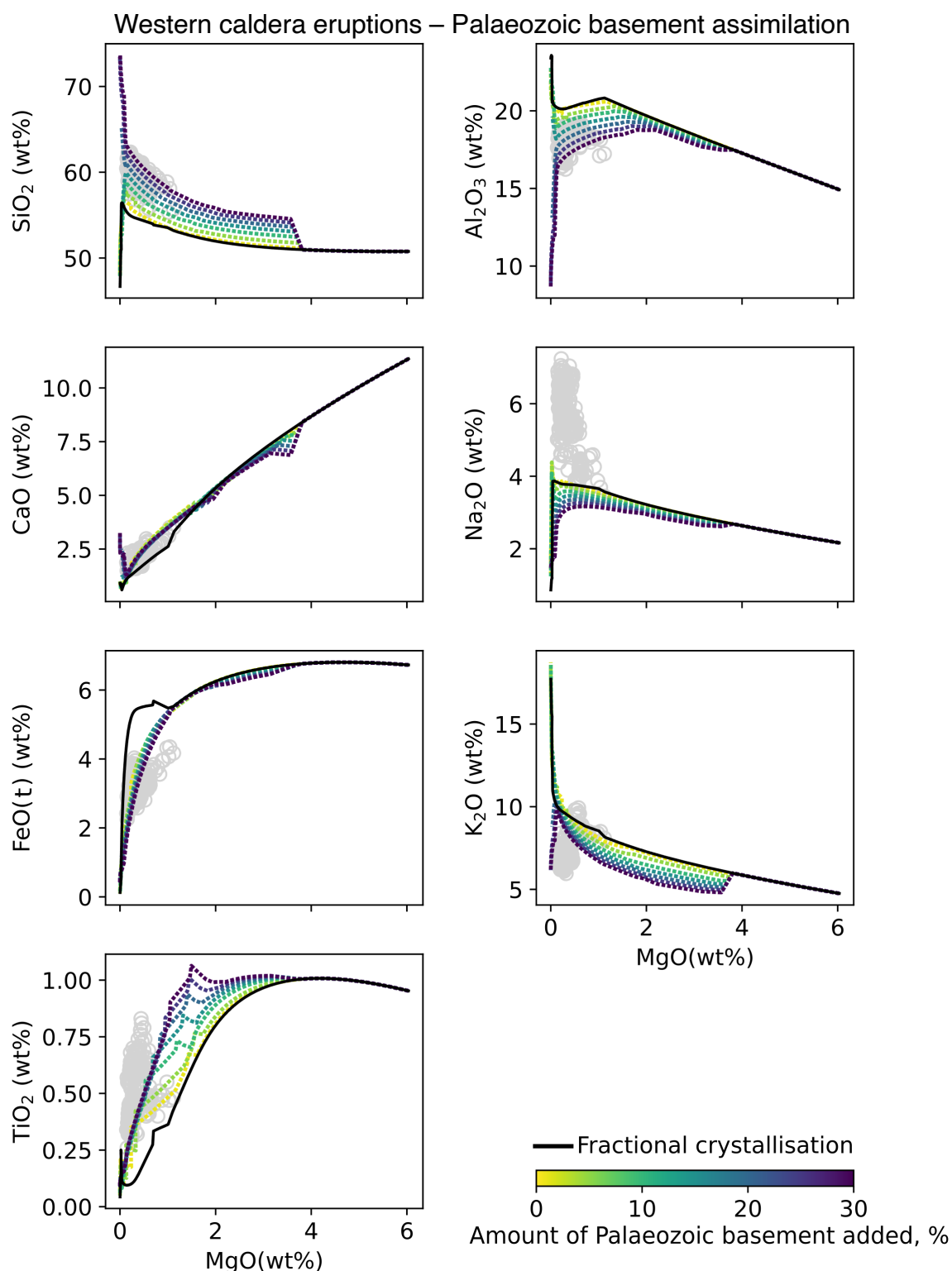


Figure A1.16: Results of assimilation-fractional crystallisation models for Palaeozoic metamorphic basement assimilation for western caldera group eruptions. Grey circles show western caldera eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{fO2}=QFM$, $L_{H2O} = 2$ wt%, pressure=160 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m=0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

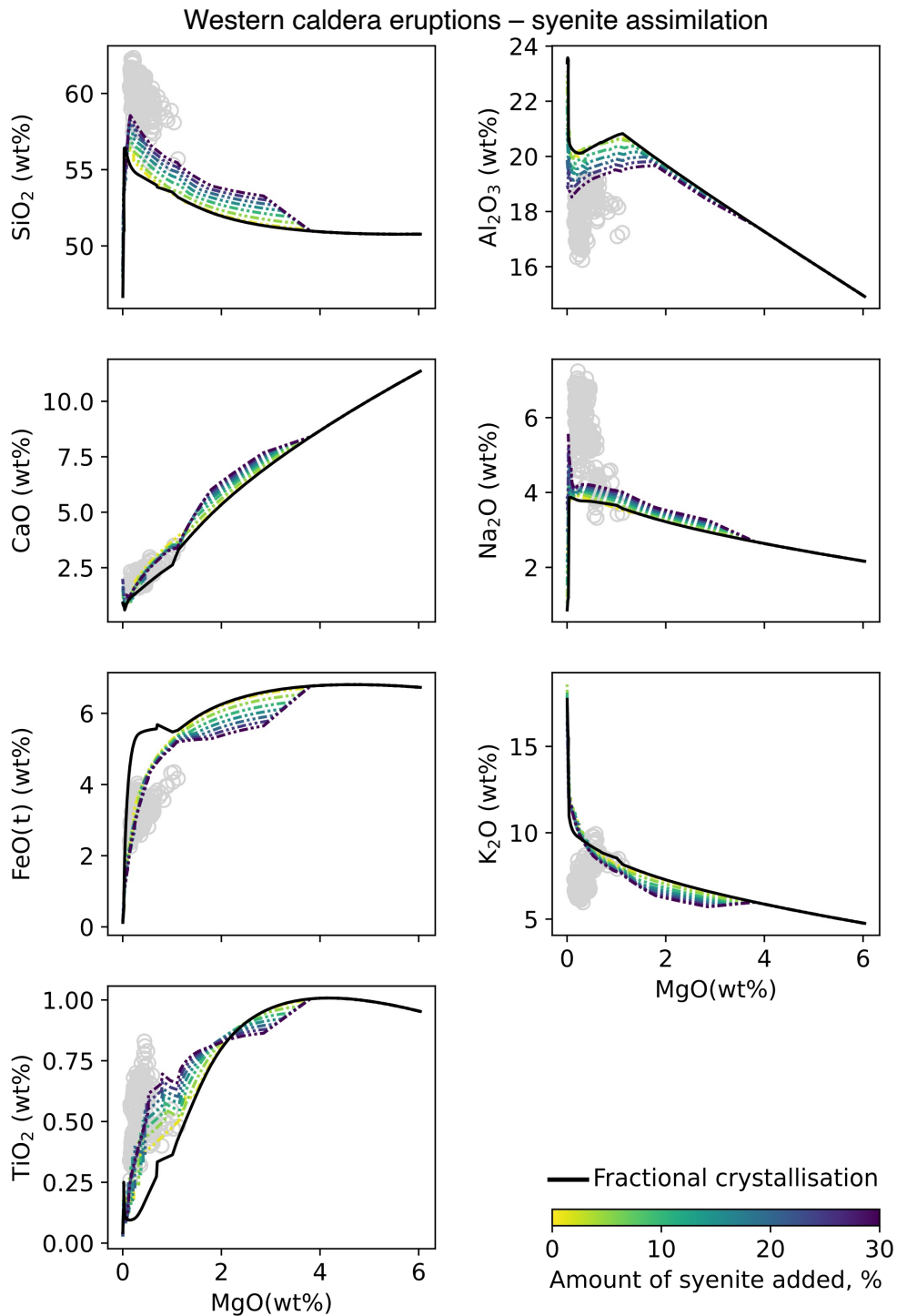


Figure A1.17: Results of assimilation-fractional crystallisation models for syenite assimilation for western caldera group eruptions. Grey circles show western caldera eruption glass data. Assimilant was added en masse at 1100°C. Each line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{\text{FeO}} = \text{QFM}$, $L_{\text{H}_2\text{O}} = 2 \text{ wt\%}$, pressure=160 MPa) and addition of a specified amount of assimilant. The amount of assimilant added is indicated by the colour of the line from yellow to blue, with yellow indicating 1% assimilant added relative to 100% melt (equivalent to $M_a/M_m = 0.01$ where M_a/M_m is the ratio of assimilant to melt) and dark blue indicating 20-30%. The black line shows the best-fit FC Rhyolite-MELTS model.

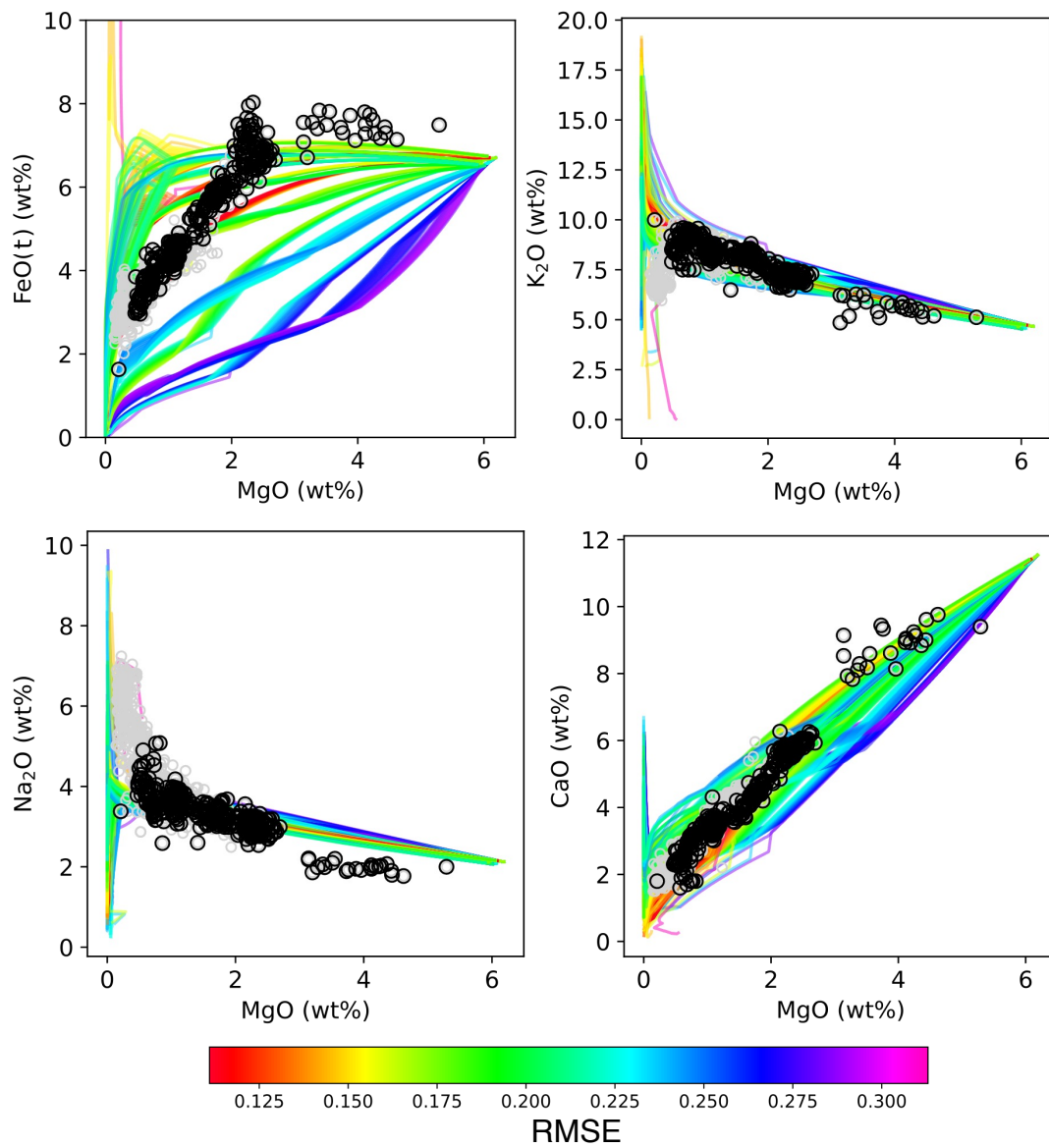


Figure A1.18: Results of all Rhyolite-MELTS models of fractional crystallisation for northern/eastern caldera eruptions. Grey points represent all literature glass data for eruptions in the last 15 kyr, black points are literature glass data for the eastern caldera group eruptions. Each line represents the liquid line of descent predicted by Rhyolite-MELTS for a parental magma cooling and crystallising under a given pressure, L_{H_2O} and L_{fO_2} . Each model is coloured according to the RMSE value indicating the goodness-of-fit between the model and natural data; red indicates a better fit, blue/purple indicates a worse fit.

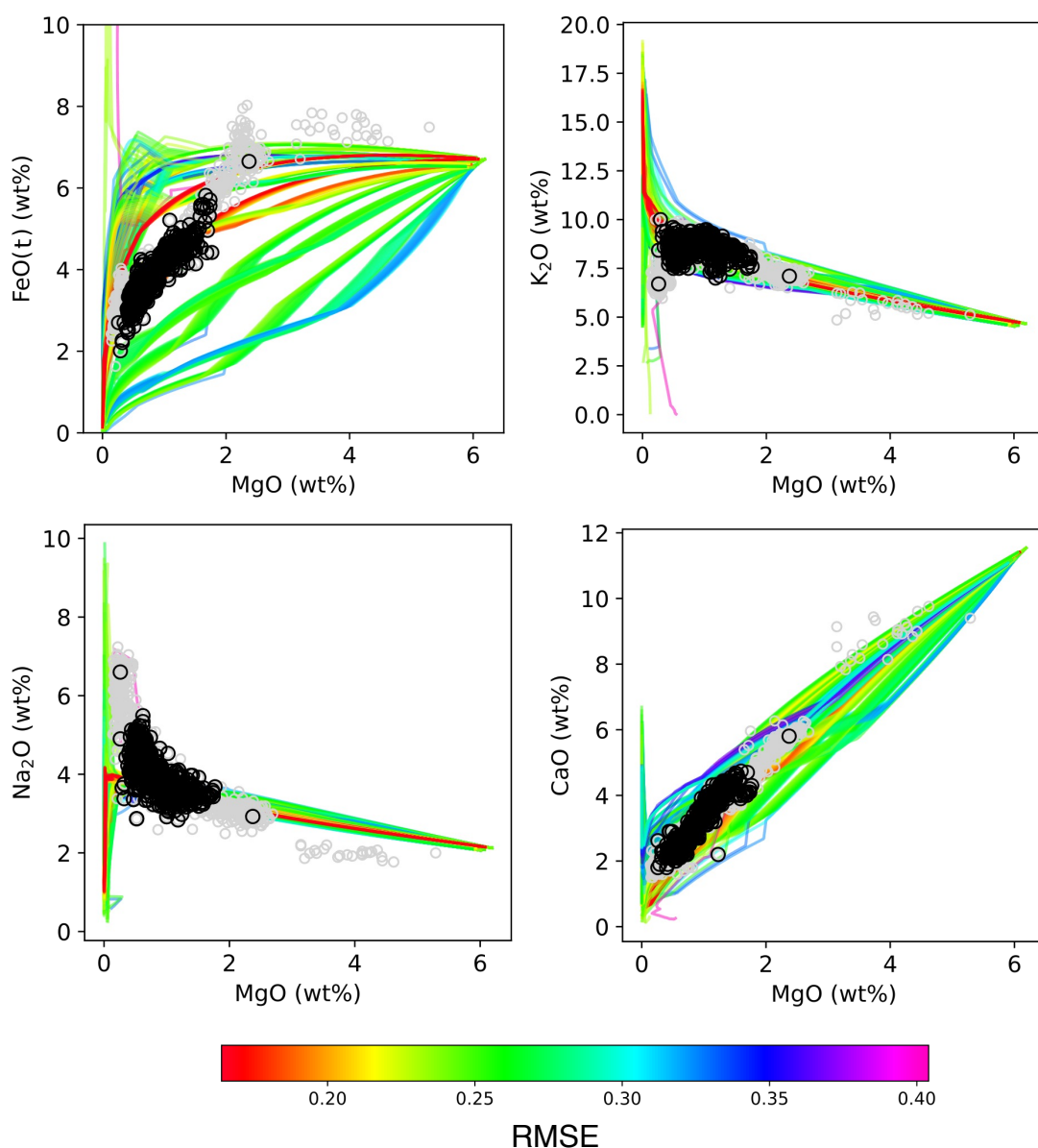


Figure A1.19: Results of all Rhyolite-MELTS models of fractional crystallisation for central caldera eruptions. Grey points represent all literature glass data for eruptions in the last 15 kyr, black points are literature glass data for the central caldera group eruptions. Each line represents the liquid line of descent predicted by Rhyolite-MELTS for a parental magma cooling and crystallising under a given pressure, L_{H_2O} and L_{fO_2} . Each model is coloured according to the RMSE value indicating the goodness-of-fit between the model and natural data; red indicates a better fit, blue/purple indicates a worse fit.

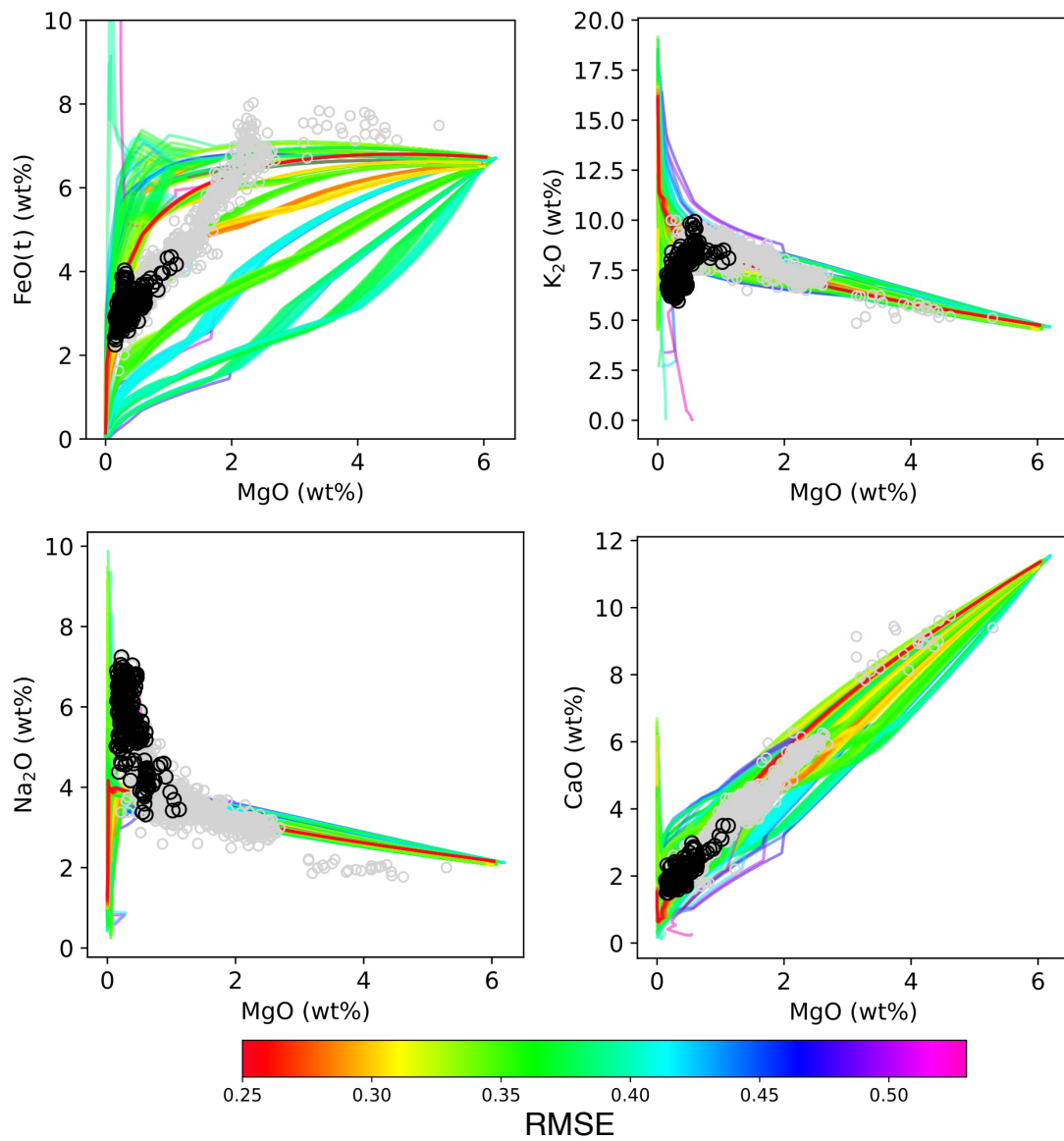


Figure A1.20: Results of all Rhyolite-MELTS models of fractional crystallisation for western caldera eruptions. Grey points represent all literature glass data for eruptions in the last 15 kyr, black points are literature glass data for the western caldera group eruptions. Each line represents the liquid line of descent predicted by Rhyolite-MELTS for a parental magma cooling and crystallising under a given pressure, L_{H_2O} and L_{fO_2} . Each model is coloured according to the RMSE value indicating the goodness-of-fit between the model and natural data; red indicates a better fit, blue/purple indicates a worse fit.

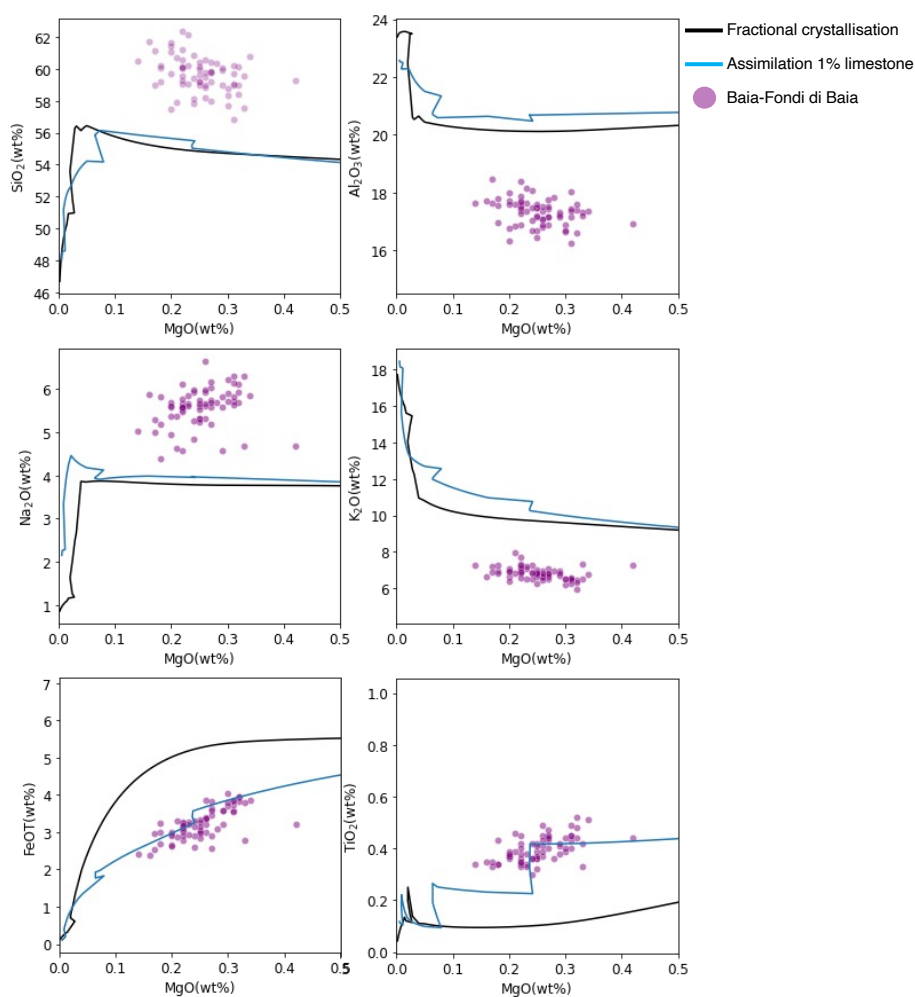


Figure A1.21: Results of assimilation-fractional crystallisation models for limestone assimilation for Baia-Fondi di Baia eruption. Purple circles show Baia-Fondi di Baia eruption glass data. Assimilant was added en masse at 1100°C. The blue line represents a Rhyolite-MELTS model run at the best-fit fractional crystallisation conditions ($L_{\text{fO}_2}=\text{QFM}$, $L_{\text{H}_2\text{O}} = 2 \text{ wt\%}$, pressure=160 MPa) and addition of 1% of limestone relative to 100% melt. The black line shows the best-fit FC Rhyolite-MELTS model.

Appendix 2

Supplementary material for Chapter 3

	SRM987	JNdi-1
	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd
	0.710275 ± 0.0000031	0.5120971 ± 0.0000024
	0.710285 ± 0.0000031	0.5120951 ± 0.0000018
	0.710259 ± 0.0000029	0.5120942 ± 0.0000022
	0.710280 ± 0.0000026	0.5120971 ± 0.0000013
	0.710283 ± 0.0000025	
	0.710270 ± 0.0000030	
	0.710277 ± 0.0000026	
	0.710275 ± 0.0000029	
Long-term average	0.710266 ± 0.000022	0.5120963 ± 0.0000049
Accepted value	0.71025	0.512115

Table A2.1: Measured and accepted values for the SRM987 and JNdi-1 standards. Standards were measured alongside unknown samples during Sr and Nd isotopic analysis in April – July 2023 and March – June 2024. Long-term reproducibility represents average of measurements in the period 2015 – 2024. Accepted value of SRM987 from National Institute of Standards and Technology, Gaithersburg, USA and of JNdi-1 from Tanaka et al. (2000).

	UWG2	GP147	YP2
	δ ¹⁸ O (‰)	δ ¹⁸ O (‰)	δ ¹⁸ O (‰)
	5.9	7.1	16.4
	5.6	7.5	16.4
	5.7	7.2	16.4
	5.9	7.4	16.3
	5.8	7.2	16.2
	5.8	7.2	16.6
	5.8	7.3	16.4
	5.9	7.2	16.5
		7.2	16.3
			16.5
			16.4
			16.3
Accepted value	5.8	7.25	16.4

Table A2.2: Measured and accepted values for the international and internal lab standards UWG2 (University of Wisconsin garnet standard, Valley et al., 1995), GP147 (garnet standard) and YP2 (internal quartz standard) measured alongside unknown samples during O isotope analysis.

Eruption samples				
Sample	Eruption	Sr (ppm)	Pb (ppm)	Nd (ppm)
CF310	Fondi di Baia	16.2	63.9	74.0
CF25	Pisani 1	828	38.3	41.6
CF195	Monte Nuovo	29.9	78.1	77.7
CF410	Fondo Riccio	845	40.7	43.6
CF54	Agnano-Monte Spina	610	54.3	47.0
CF9	Minopoli 2	734	28.1	38.4
CF78	Astroni 6	699	49.2	42.8
CF86	Averno 2	49.5	73.5	90.0
CF100	Sartania 1	93.8	70.6	78.5
CF2	Pomici Principali	931	48.6	46.2
CF13	Minopoli 1	800	27.3	41.9
CF4	Soccavo 4	782	45.3	45.4
CF424	Agnano 3	371	52.5	51.1
CF415	Solfatara	321	53.4	50.3
CF99	St Martino	419	52.9	50.3
CF93	Bacoli	420	52.7	48.7
CF66	Cigliano	374	54.4	55.6
CF94	Gauro	822	38.5	41.6
CF391	Nisida	402	44.9	48.1
CF62	Paleoastroni 2	242	57.6	58.3
CF92	Capo Miseno	454	48.8	45.9
Basement samples				
Sample	Lithology	Sr (ppm)	Pb (ppm)	Nd (ppm)
23-FMR-003	Wedge-top flysch	98.2	13.4	12.2
23-FMR-017	Palaeozoic gneiss	166	18.3	40.9
23-FMR-14A	Syenite	768	8.08	41.8
23-FMR-001	Limestone	161	b.d.l.	0.18

Table A2.3: Strontium, neodymium and lead concentrations of the analysed samples, determined by solution ICP-MS of an aliquot of each sample analysed for isotopic composition and used in AFC and ATA isotopic mixing models.

Palaeozoic Gneiss					Syn-Orogenic Wedge-Top Deposits				
Thermal parameters	Teq	850	°C		Thermal parameters	Teq	850	°C	
	Tlm	1140	°C		Thermal parameters	Tlm	1140	°C	
	Tm0	1140	°C			Tm0	1140	°C	
	Tla	950	°C			Tla	950	°C	
	Ta0	750	°C			Ta0	400	°C	
	Ts	700	°C			Ts	700	°C	
	Cpm	1464	J/kg K			Cpm	1464	J/kg K	
	Cpa	1378	J/kg K			Cpa	1378	J/kg K	
	hcry	396000	J/kg			hcry	396000	J/kg	
	hfus	270000	J/kg			hfus	270000	J/kg	
Magma	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)		Magma	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)	
	699	0.707292	1.16			699	0.707292	1.16	
	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)		Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)
	43	0.512493	0.25	6.8		43	0.512493	0.25	6.8
	Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)		Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)
Assimilant	49	19.04	39.15	0.2	Assimilant	49	19.04	39.15	0.2
	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)			Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)	
	166	0.71967	0.3			98	0.720471	0.1	
	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)		Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)
	41	0.512101	0.25	8.5		12	0.512154	0.1	12.3
	Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)		Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)
	27		38.914	0.1		13	18.578	38.691	0.1

Table A2.4: EC-AFC (Spera and Bohrsen, 2001) parameters for Campi Flegrei magma contamination by different potential basement lithologies.

Syenite					Hydrothermally altered syenite				
Thermal parameters	Teq	850	°C		Thermal parameters	Teq	850	°C	
	Tlm	1140	°C		Thermal parameters	Tlm	1140	°C	
	Tm0	1140	°C			Tm0	1140	°C	
	Tla	950	°C			Tla	950	°C	
	Ta0	700	°C			Ta0	700	°C	
	Ts	700	°C			Ts	700	°C	
	Cpm	1464	J/kg K			Cpm	1464	J/kg K	
	Cpa	1378	J/kg K			Cpa	1378	J/kg K	
	hcry	396000	J/kg			hcry	396000	J/kg	
	hfus	270000	J/kg			hfus	270000	J/kg	
Magma	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)		Magma	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)	
	699	0.707292	1.16			699	0.707292	1.16	
	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)		Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)
	43	0.512493	0.25	6.8		43	0.512493	0.25	6.8
	Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)	Assimilant Assimilant	Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)
Assimilant	49	19.04	39.15	0.2		49	19.04	39.15	0.2
	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)			Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)	
	768	0.70838	2			768	0.70838	2	
	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)		Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)
	42	0.512438	0.25	13.2		42	0.512438	0.25	1.8
	Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)		Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	D _o (Pb)
	8	19.091	39.15	0.2		8	19.091	39.15	0.2

Table A2.4: continued

Table A2.4: continued

Mesozoic limestone					Hydrothermal calcite				
Thermal parameters	Teq	850	°C		Thermal parameters	Teq	850	°C	
	Tlm	1140	°C			Tlm	1140	°C	
	Tm0	1140	°C			Tm0	1140	°C	
	Tla	950	°C			Tla	950	°C	
	Ta0	400	°C			Ta0	400	°C	
	Ts	700	°C			Ts	700	°C	
	Cpm	1464	J/kg K			Cpm	1464	J/kg K	
	Cpa	1378	J/kg K			Cpa	1378	J/kg K	
	hcry	396000	J/kg			hcry	396000	J/kg	
	hfus	270000	J/kg			hfus	270000	J/kg	
Magma	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)		Magma	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)	
	699	0.707292	1.16			699	0.707292	1.16	
	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)		Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)
	43	0.512493	0.25	6.8		43	0.512493	0.25	6.8
Assimilant	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)		Assimilant	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)	
	166	0.708639	1			166	0.7091	1	
	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)		Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	D _o (Nd)	δ ¹⁸ O (‰)
	1	0.512288	0.15	22.4		1	0.512288	0.15	14.9

Abbreviations: Teq = equilibration temperature; Tlm = magma liquidus temperature; Tm0 = initial magma temperature; Tla = wall-rock liquidus temperature; Ta0 = initial Wall-rock temperature; Ts = solidus temperature; Cpm = magma specific heat capacity; Cpa = assimilant specific heat capacity; hcry = crystallization enthalpy; hfus = fusion enthalpy; D_o = bulk distribution coefficient. Bulk distribution coefficients were calculated from mineral partition coefficients and the proportions of these minerals predicted in the phase assemblage of the best-fits Rhyolite-MELTS model of Amstutz et al. (in press). Mineral partition coefficients were obtained from GERM (2015) Geochemical Earth Reference Model Partition Coefficient Database (<http://earthref.org/KDD/>) and are from Marks et al. (2004), Nagasawa (1973) and Villemant (1988). To model assimilation of hydrothermal calcite we used the average average δ¹⁸O (14.9‰) measured by Buono et al. (2024) in Campi Flegrei lithics and ⁸⁷Sr/⁸⁶Sr = 0.7091 from average seawater from Spooner (1976)

	$^{87}\text{Sr}/^{86}\text{Sr}$	Sr (ppm)	$^{143}\text{Nd}/^{14}\text{Nd}$	Nd (ppm)	$^{206}\text{Pb}/^{20}\text{Pb}$	$^{208}\text{Pb}/^{20}\text{Pb}$	Pb (ppm)	$\delta^{18}\text{O}$ (‰)
Magma	0.707 292	699	0.5124 93	42.8	19.04	39.15	49	6.8
End members - potential assimilant lithologies								
Palaeozoic gneiss	0.719 670	166	0.5121 01	40.9	18.85	38.91	18	8.5
Wedge-top flysch	0.720 471	98	0.5121 54	12.2	18.58	38.68	13	12.3
Syenite	0.708 380	768	0.5124 38	41.8	19.09	39.15	8	13.2
Limestone	0.708 639	161	0.5122 88	0.2	-	-	-	22.4

Table A2.5: End member compositions used to model ATA, using binary mixing models (see Langmuir et al., 1978).

Sample	Eruption	Material analysed	$\delta^{18}\text{O}_{\text{mineral}}$	$\text{SiO}_{2\text{w.r}}$ (wt%)	$\delta^{18}\text{O}_{\text{melt}}$ *
CF9	Minopoli 2	feldspar	8.7	53.33 ^a	8.7
CF9	Minopoli 2	clinopyroxene	6.9	53.33 ^a	7.4
CF78	Astroni 6	feldspar	8.2	56.66 ^c	8.3
CF78	Astroni 6	clinopyroxene	6.8	56.63 ^c	7.5
CF86	Averno 2	feldspar	7.5	60.89 ^a	7.7
CF86	Averno 2	clinopyroxene	7.5	60.89 ^a	8.5
CF410	Fondo Riccio	feldspar	8.3	53.35 ^b	8.3
CF410	Fondo Riccio	clinopyroxene	7.2	53.35 ^b	7.7

Table A2.6: Calculated $\delta^{18}\text{O}_{\text{melt}}$ values from measured $\delta^{18}\text{O}_{\text{mineral}}$ for select eruptions in the last 15 kyr. * $\delta^{18}\text{O}_{\text{melt}}$ is calculated using the formula $\Delta(\text{melt-min}) = a[\text{SiO}_2 \text{ wt\%}] + b$ from Bindeman et al. (2004).
a: Iovine et al., 2018; b: D'Antonio et al., 1999; c: Tonarini et al., 2009

Initial magma composition*	
SiO ₂	51.07
TiO ₂	0.95
Al ₂ O ₃	14.82
FeO	6.75
MnO	0.16
MgO	6.23
CaO	11.62
K ₂ O	4.70
Na ₂ O	2.14
H ₂ O	2.00
Wallrock composition*	
SiO ₂	64.64
TiO ₂	1.05
Al ₂ O ₃	17.54
FeO	5.77
Fe ₂ O ₃	0.84
MgO	2.92
CaO	2.85
Na ₂ O	2.47
K ₂ O	1.71
H ₂ O	0.20

Table A2.7: Starting compositions used in AFC model in Fig. 7c, using Magma Chamber Simulator (Bohrson et al., 2020; Heinonen et al., 2020). *Initial magma and wall rock compositions are from Amstutz et al. (2025, in press). Isotopic compositions from this study.

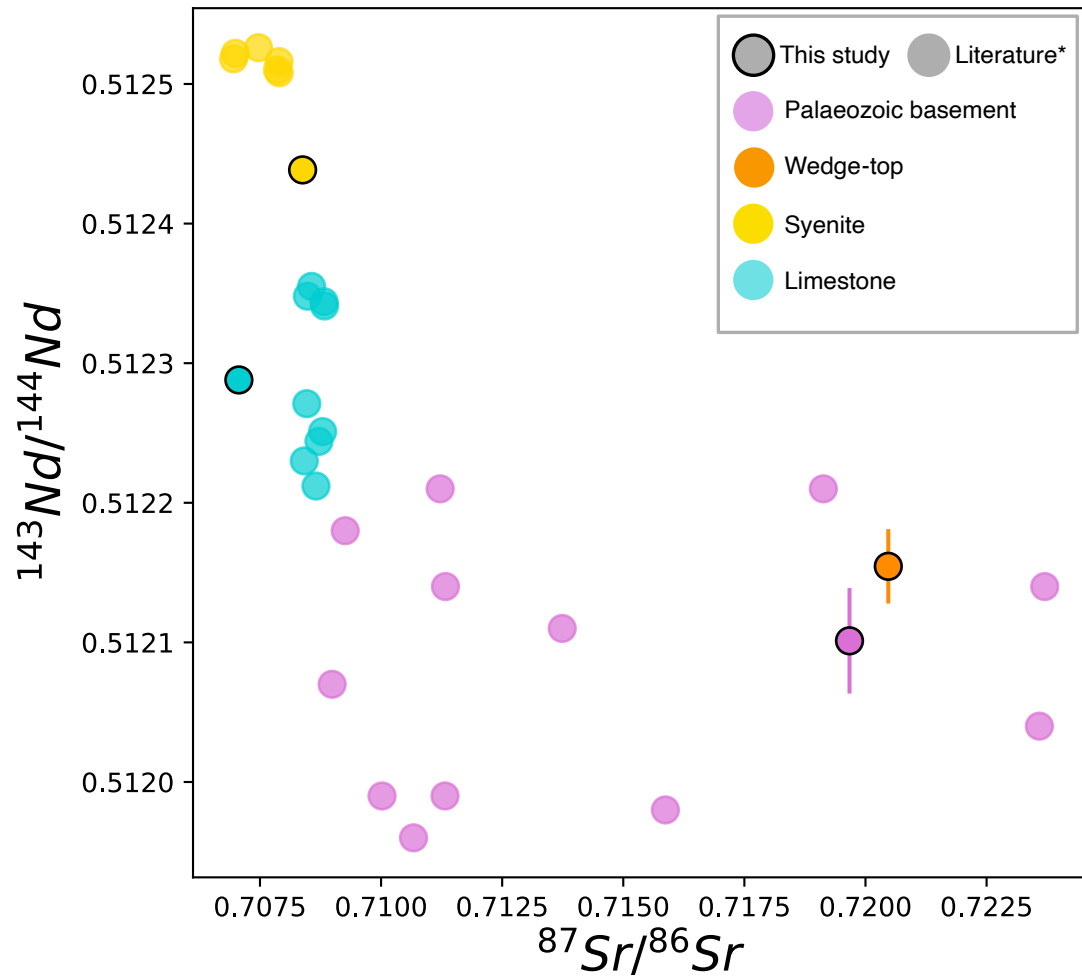


Figure A2.1: Range of isotopic compositions measured in potential crustal contaminants of Campi Flegrei magmas, with points coloured by different basement lithologies.

*Literature data for Palaeozoic metamorphic basement from Rottura et al. (1991) and Pappalardo et al. (2002); syenite from Gebauer et al. (2014); Mesozoic limestone from Cornacchia et al. (2018).

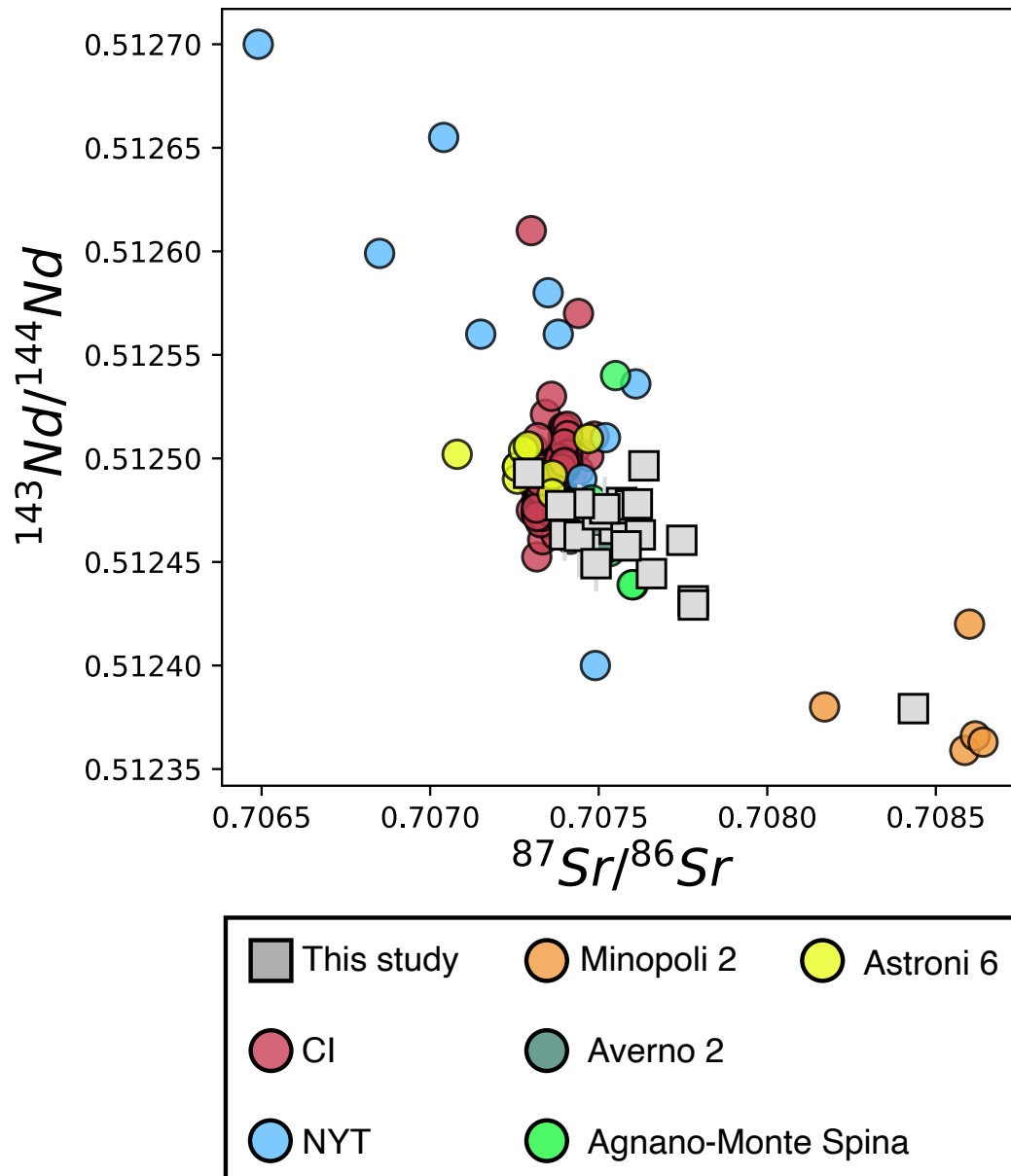


Figure A2.2: Range of isotopic compositions measured in Campi Flegrei erupted products. Grey squares show compositions in post-15 ka eruptions measured in this study. Circles show compositions measured in selected individual Campi Flegrei eruptions, from the literature. Literature data from Pappalardo et al., 2002; Tonarini et al., 2004; D'Antonio et al., 2007; Arienzo et al., 2009; Tonarini et al., 2009; Arienzo et al., 2010; Di Renzo et al., 2011; Di Vito et al., 2011; Arienzo et al., 2015; Di Salvo et al., 2020.

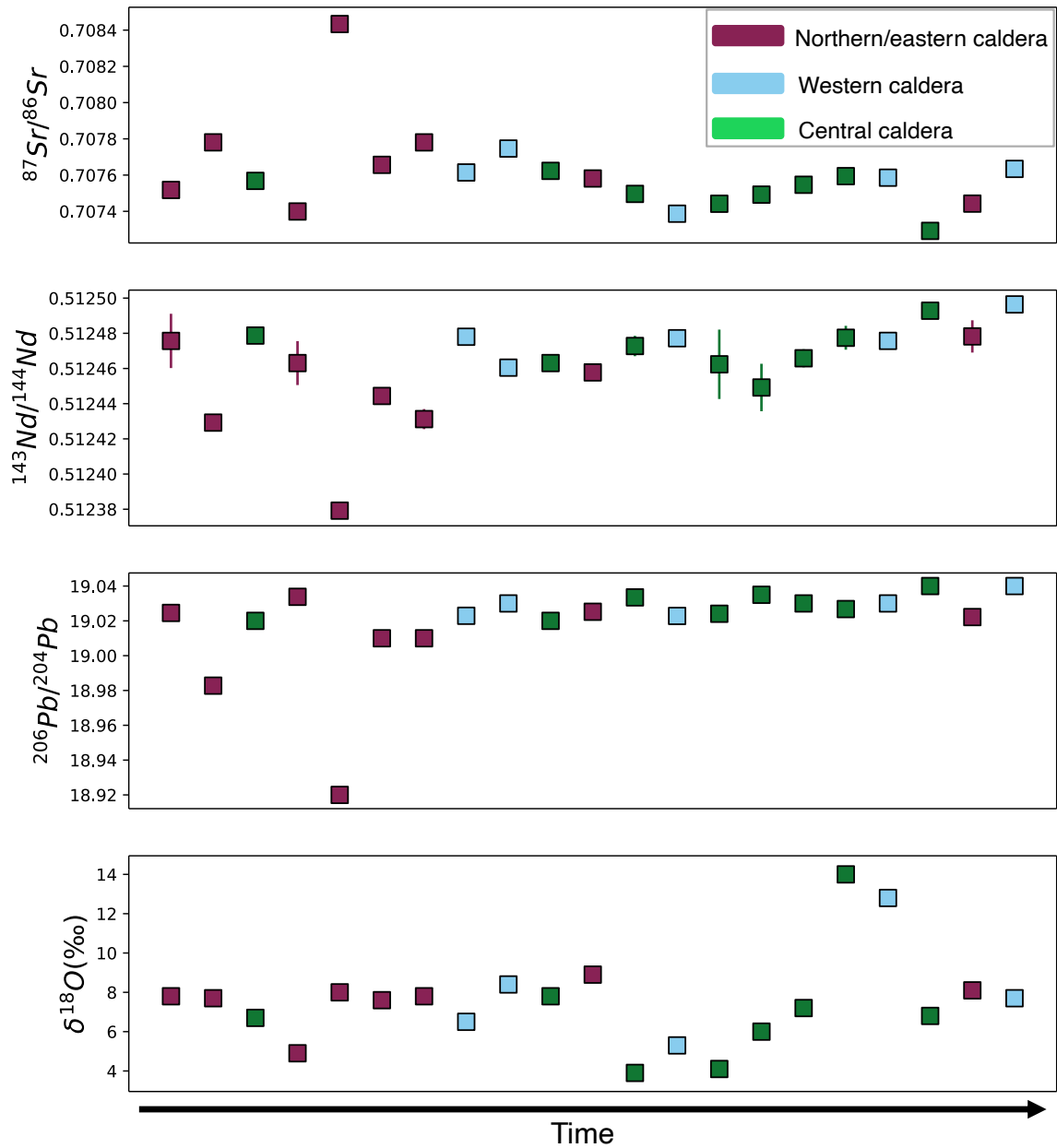


Figure A2.3: Plots of $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $\delta^{18}\text{O}$ over time for post-15 ka Campi Flegrei eruptions. Samples are coloured by volcano-tectonic setting. Error of ± 2 s.e. is shown by error bars or is within the symbol size. Eruptions are in relative order from the oldest eruption to the most recent.

Appendix 3

Supplementary material for Chapter 4

Primary standards for EPMA calibration	
Silicon	Wollastonite
Calcium	Wollastonite
Sodium	Jadeite
Aluminium	Jadeite
Iron	Haematite
Titanium	Rutile
Manganese	Fowlerite
Chromium	Chromite
Magnesium	Periclase
Potassium	Orthoclase

Table A3.1: List of standards used for calibration of EPMA.

EPMA secondary standard reproducibility						
	Smithsonian augite		Smithsonian Cr augite		Smithsonian diopside	
	wt%	1 σ	wt%	1 σ	wt%	1 σ
SiO ₂	50.49	0.14	50.69	0.27	55.75	0.25
Na ₂ O	1.31	0.03	0.84	0.02	0.13	0.06
MgO	16.25	0.24	17.18	0.19	18.23	0.17
Al ₂ O ₃	8.37	0.24	7.63	0.24	0.14	0.12
CaO	16.02	0.19	17.11	0.17	25.73	0.38
TiO ₂	0.87	0.02	0.51	0.01	-	-
MnO	0.14	0.01	0.12	0.01	0.03	0.01
FeOt	6.24	0.15	4.62	0.12	0.22	0.03
Cr ₂ O ₃	0.13	0.03	0.89	0.02	-	-
Total	99.83		99.60		100.24	
n	22		22		17	

Table A3.2: Compositions of secondary standards used in EPMA. Independent characterisation of these standards can be found in Jarosewich et al. (1987) and Jarosewich et al. (1979). Precision estimates are given as one standard deviation of multiple analyses (1 σ). n= number of repeat analyses.

EPMA counting statistic uncertainties		
	Absolute	Relative
	wt%	%
SiO ₂	0.09	0.17
Na ₂ O	0.01	6.14
MgO	0.03	0.20
Al ₂ O ₃	0.02	0.92
CaO	0.04	0.21
TiO ₂	0.02	4.10
MnO	0.01	9.73
FeOt	0.05	1.13
Cr ₂ O ₃	0.04	28.48

Table A3.3: Representative EPMA precision estimates, based on counting statistics. All precision estimates are one standard deviation (1 σ) and absolute and relative precisions are shown.

APPENDIX 3: SUPPLEMENTARY MATERIAL FOR CHAPTER 4

Label	SiO ₂ (wt%)	Na ₂ O (wt%)	FeO (wt%)	MnO (wt%)	Al ₂ O ₃ (wt%)	MgO (wt%)	CaO (wt%)	Cr ₂ O ₃ (wt%)	TiO ₂ (wt%)	Total (wt%)
Minopoli 2										
CF11_5_cpx102_c	52.62	0.12	3.96	0.10	2.68	16.26	22.91	0.17	0.34	99.17
CF11_5_cpx102_m	50.94	0.13	4.86	0.12	4.02	15.31	22.92	0.12	0.74	99.17
CF11_5_cpx102_r	52.16	0.11	4.02	0.09	2.55	16.12	23.13	0.19	0.44	98.82
CF11_5_cpx105_c	52.22	0.13	3.90	0.10	2.92	16.11	23.11	0.53	0.41	99.42
CF11_5_cpx105_m	51.16	0.16	5.02	0.11	3.65	15.48	23.06	0.07	0.58	99.28
CF11_5_cpx105_r	50.26	0.16	5.75	0.13	5.08	14.42	22.93	0.01	0.86	99.59
CF11_5_cpx107_c	52.39	0.11	3.99	0.10	2.57	16.38	23.17	0.21	0.41	99.34
CF11_5_cpx107_m	51.59	0.16	4.67	0.12	3.54	15.86	22.75	0.09	0.50	99.27
CF11_5_cpx107_r	51.55	0.14	4.93	0.12	3.70	15.26	23.03	0.15	0.57	99.44
CF11_5_cpx109_c	51.52	0.30	7.68	0.29	3.01	13.77	22.17	0.02	0.46	99.22
CF11_5_cpx109_m1	52.36	0.12	3.93	0.09	2.83	15.98	23.34	0.11	0.46	99.22
CF11_5_cpx109_m2	50.42	0.18	6.40	0.15	4.02	14.41	22.90	0.03	0.73	99.23
CF11_5_cpx109_m3	50.35	0.19	6.44	0.14	4.01	14.51	22.95	0.05	0.75	99.40
CF11_5_cpx109_r	51.30	0.12	4.36	0.12	2.96	16.35	23.18	0.10	0.52	99.00
CF11_5_cpx111_c	49.35	0.26	7.52	0.18	5.08	13.22	22.71	0.01	0.93	99.26
CF11_5_cpx111_m	52.78	0.11	3.94	0.08	2.32	16.34	23.36	0.17	0.42	99.52
CF11_5_cpx111_r	51.32	0.12	4.49	0.12	3.19	15.94	23.17	0.14	0.53	99.02
CF11_5_cpx112_c	50.21	0.17	5.05	0.11	3.43	16.50	23.93	0.04	0.69	100.12
CF11_5_cpx112_m	52.24	0.13	3.20	0.08	1.85	18.64	23.58	0.55	0.30	100.56
CF11_5_cpx112_r	49.95	0.17	5.36	0.12	3.38	16.94	22.89	0.28	0.60	99.69
CF11_5_cpx119_c	50.95	0.18	6.25	0.14	3.81	14.47	22.88	0.11	0.83	99.62
CF11_5_cpx119_r	53.22	0.11	4.11	0.10	2.33	16.37	23.18	0.12	0.39	99.94
CF11_5_cpx12_c	53.80	0.11	3.47	0.13	1.51	17.18	22.34	0.41	0.25	99.21
CF11_5_cpx12_r	53.09	0.12	4.21	0.13	2.35	16.23	22.68	0.13	0.39	99.32
CF11_5_cpx133_c	53.02	0.11	3.94	0.12	2.15	16.41	23.26	0.12	0.37	99.50
CF11_5_cpx133_m	52.88	0.13	4.00	0.10	2.50	16.13	23.09	0.37	0.38	99.58
CF11_5_cpx133_r	52.46	0.16	4.29	0.11	3.12	15.65	22.98	0.42	0.49	99.68
CF11_5_cpx135_c	50.06	0.23	6.81	0.16	4.52	14.14	22.63	0.07	0.90	99.52
CF11_5_cpx135_r	52.26	0.14	4.68	0.10	3.41	15.57	22.99	0.08	0.56	99.79
CF11_5_cpx138_c	50.58	0.18	6.40	0.14	4.51	14.54	22.40	0.05	0.84	99.65
CF11_5_cpx138_r	52.10	0.13	4.34	0.08	2.98	16.00	23.20	0.18	0.50	99.51
CF11_5_cpx141_c	53.48	0.12	3.69	0.09	1.86	16.75	22.91	0.40	0.31	99.62
CF11_5_cpx141_r	52.68	0.13	4.17	0.12	2.27	16.42	22.92	0.17	0.41	99.29
CF11_5_cpx142_c	51.00	0.15	4.26	0.13	2.61	17.39	23.59	0.37	0.39	99.89
CF11_5_cpx142_m	51.14	0.12	5.01	0.12	2.62	17.21	23.26	0.08	0.45	100.01
CF11_5_cpx142_r	51.61	0.11	4.25	0.12	1.93	17.66	23.67	0.09	0.35	99.78
CF11_5_cpx145_c	52.45	0.11	3.66	0.10	1.74	18.31	23.55	0.23	0.28	100.42
CF11_5_cpx145_r	50.91	0.13	4.89	0.10	3.52	16.54	23.37	0.16	0.58	100.20
CF11_5_cpx151_c	53.10	0.12	3.82	0.11	2.01	16.47	23.16	0.34	0.36	99.49
CF11_5_cpx151_m	51.56	0.13	4.60	0.11	3.46	15.60	23.06	0.30	0.51	99.33
CF11_5_cpx151_r	52.92	0.09	4.28	0.09	2.13	16.35	22.89	0.06	0.36	99.18
CF11_5_cpx159_c	49.94	0.27	7.45	0.24	4.00	13.89	22.29	0.01	0.80	98.88
CF11_5_cpx159_m	50.69	0.16	5.54	0.13	3.95	14.85	23.12	0.09	0.74	99.27
CF11_5_cpx159_r	51.82	0.11	4.32	0.11	2.73	16.31	23.20	0.20	0.44	99.23
CF11_5_cpx160_c	51.31	0.13	4.23	0.09	2.42	17.45	23.58	0.35	0.41	99.97
CF11_5_cpx160_r1	51.40	0.13	4.08	0.11	2.56	17.25	23.73	0.15	0.40	99.81
CF11_5_cpx160_r2	50.90	0.12	3.77	0.09	2.16	18.02	23.94	0.33	0.36	99.69
CF11_5_cpx162_c	48.30	0.24	7.10	0.16	5.13	14.74	23.18	0.02	0.97	99.86
CF11_5_cpx162_r	50.65	0.12	4.49	0.12	2.36	17.51	23.99	0.04	0.53	99.81
CF11_5_cpx163_c	51.56	0.11	4.51	0.13	2.36	17.74	23.21	0.08	0.36	100.05
CF11_5_cpx163_m	49.19	0.15	5.36	0.12	4.40	16.33	23.36	0.03	0.77	99.70
CF11_5_cpx163_r	51.44	0.12	4.08	0.09	2.28	17.96	23.44	0.18	0.35	99.95
CF11_5_cpx167_c	52.14	0.14	4.38	0.12	3.14	15.70	23.21	0.26	0.53	99.62
CF11_5_cpx167_m1	52.99	0.13	3.56	0.10	2.25	16.75	23.18	0.38	0.35	99.69
CF11_5_cpx167_m2	52.00	0.13	4.56	0.11	3.21	15.37	23.13	0.25	0.50	99.26
CF11_5_cpx167_r	49.97	0.18	6.06	0.12	4.42	14.55	22.91	0.04	0.88	99.14
CF11_5_cpx168_c	51.61	0.11	5.53	0.13	3.21	13.77	24.45	0.01	0.37	99.20
CF11_5_cpx168_m	52.87	0.11	4.11	0.12	2.19	16.50	22.59	0.07	0.34	98.90
CF11_5_cpx168_r	51.65	0.12	5.24	0.15	2.86	15.88	22.50	0.04	0.60	99.04
CF11_5_cpx26_c	52.20	0.13	4.58	0.11	3.38	15.94	22.51	0.11	0.50	99.46
CF11_5_cpx26_m	52.07	0.13	5.05	0.12	3.58	15.43	22.28	0.06	0.68	99.39
CF11_5_cpx26_r	53.09	0.13	3.96	0.10	2.76	15.95	22.87	0.20	0.43	99.50
CF11_5_cpx3_c	53.64	0.10	3.65	0.08	1.85	16.61	22.85	0.26	0.30	99.37
CF11_5_cpx3_m	49.82	0.19	7.34	0.18	5.34	13.46	21.77	0.01	0.85	98.96
CF11_5_cpx3_r	52.56	0.12	4.33	0.10	3.07	15.39	22.74	0.20	0.48	98.99
CF11_5_cpx38_c	50.80	0.20	6.75	0.20	4.08	13.91	22.39	0.03	0.83	99.19
CF11_5_cpx38_m1	53.41	0.12	3.67	0.10	1.87	16.15	23.20	0.29	0.33	99.15
CF11_5_cpx38_m2	53.35	0.10	4.14	0.10	2.13	16.18	22.99	0.12	0.36	99.46
CF11_5_cpx38_r	53.56	0.09	3.58	0.09	1.77	16.47	23.13	0.22	0.31	99.23
CF11_5_cpx44_c	51.85	0.13	4.64	0.12	3.61	15.62	22.43	0.12	0.51	99.03
CF11_5_cpx44_m	51.02	0.13	4.98	0.11	4.12	15.02	22.87	0.16	0.65	99.05

APPENDIX 3. SUPPLEMENTARY MATERIAL FOR CHAPTER 4

Label	SiO ₂ (wt%)	Na ₂ O (wt%)	FeO (wt%)	MnO (wt%)	Al ₂ O ₃ (wt%)	MgO (wt%)	CaO (wt%)	Cr ₂ O ₃ (wt%)	TiO ₂ (wt%)	Total (wt%)
CF11_5_cpx44_r	52.13	0.12	3.93	0.10	2.70	16.28	23.06	0.22	0.41	98.96
CF11_5_cpx60_c1	51.67	0.21	6.83	0.19	3.14	14.35	22.22	0.00	0.56	99.17
CF11_5_cpx60_c2	48.93	0.24	7.82	0.15	5.74	12.70	22.35	0.01	1.14	99.09
CF11_5_cpx60_m	50.74	0.22	6.79	0.17	3.68	14.25	22.50	0.01	0.69	99.06
CF11_5_cpx60_r	51.18	0.17	5.87	0.15	2.84	15.24	22.49	0.03	0.58	98.54
CF11_5_cpx62_c	48.78	0.24	7.23	0.17	4.75	15.03	22.51	0.07	0.84	99.62
CF11_5_cpx62_r	50.70	0.13	4.37	0.09	2.78	17.26	23.65	0.16	0.46	99.61
CF11_5_cpx63_c	52.88	0.13	3.52	0.07	2.32	16.31	23.06	0.63	0.35	99.27
CF11_5_cpx63_m	51.62	0.13	4.87	0.10	3.92	15.13	22.82	0.10	0.65	99.34
CF11_5_cpx63_r	52.31	0.13	4.01	0.08	2.57	16.17	23.20	0.16	0.42	99.05
CF11_5_cpx64_c	51.01	0.11	4.68	0.10	3.14	16.81	23.72	0.09	0.51	100.17
CF11_5_cpx64_r	48.75	0.13	5.70	0.12	4.55	16.15	22.88	0.03	0.74	99.05
CF11_5_cpx71_c	52.10	0.09	4.11	0.10	3.82	15.52	23.33	0.04	0.47	99.58
CF11_5_cpx71_m	52.70	0.12	4.45	0.10	2.79	16.06	22.84	0.06	0.43	99.55
CF11_5_cpx71_r	50.70	0.13	4.64	0.10	3.50	15.81	23.00	0.08	0.59	98.54
CF11_5_cpx72_c	51.99	0.14	3.81	0.09	3.35	15.56	23.27	0.41	0.46	99.07
CF11_5_cpx72_r	52.57	0.12	3.89	0.09	2.41	16.67	22.88	0.20	0.36	99.20
CF11_5_cpx76_c	48.26	0.16	5.98	0.13	5.48	15.32	23.44	0.01	1.10	99.88
CF11_5_cpx76_m1	48.84	0.21	6.90	0.18	4.47	15.32	22.99	0.05	0.89	99.86
CF11_5_cpx76_r	47.96	0.18	6.57	0.14	6.05	14.93	23.11	0.03	1.21	100.17
CF11_5_cpx78_c	53.29	0.10	4.30	0.13	2.03	16.64	22.48	0.05	0.36	99.38
CF11_5_cpx78_m	52.11	0.11	4.73	0.11	3.13	15.26	23.37	0.04	0.52	99.38
CF11_5_cpx78_r	52.99	0.09	4.37	0.11	2.04	16.34	22.99	0.04	0.38	99.34
CF11_5_cpx79_c	51.33	0.12	4.43	0.08	2.53	17.49	23.70	0.04	0.47	100.19
CF11_5_cpx79_r	51.18	0.12	4.36	0.11	2.81	17.19	23.71	0.18	0.50	100.15
CF11_5_cpx8_c	53.03	0.11	4.06	0.11	2.50	15.96	22.95	0.25	0.38	99.35
CF11_5_cpx8_r	53.07	0.12	3.86	0.07	2.62	16.12	22.91	0.24	0.42	99.44
CF11_5_cpx89_c	54.18	0.09	3.38	0.08	1.45	16.86	23.35	0.16	0.29	99.85
CF11_5_cpx89_m	51.69	0.18	5.25	0.13	3.35	14.88	23.18	0.09	0.56	99.31
CF11_5_cpx89_r	52.88	0.10	4.14	0.11	2.02	15.95	23.25	0.06	0.39	98.90
CF11_5_cpx9_c	48.82	0.15	6.27	0.13	6.13	13.36	23.03	0.04	0.91	98.83
CF11_5_cpx9_m	52.20	0.11	4.50	0.11	3.23	15.45	23.20	0.06	0.54	99.39
CF11_5_cpx9_r	52.56	0.11	4.24	0.12	2.23	16.38	22.92	0.07	0.40	99.03
CF11_5_cpx93_c	48.90	0.25	7.12	0.20	4.46	14.99	22.99	0.00	0.91	99.83
CF11_5_cpx93_m	50.12	0.12	4.81	0.11	3.55	16.72	23.84	0.16	0.72	100.14
CF11_5_cpx93_r	49.94	0.14	5.27	0.12	4.05	16.24	23.35	0.13	0.67	99.92
CF11_5_cpx96_c	52.98	0.10	4.29	0.11	2.27	16.38	23.03	0.09	0.41	99.66
CF11_5_cpx96_r	49.21	0.22	5.93	0.13	4.92	14.82	22.61	0.04	0.93	98.82
CF9_2_cpx45_r	51.43	0.11	4.28	0.12	2.14	16.96	22.42	0.06	0.36	97.88
CF9_2_cpx51_m	49.83	0.14	4.79	0.10	4.11	15.48	22.51	0.09	0.66	97.71
CF9_2_cpx66_c	51.68	0.13	3.87	0.09	2.05	17.02	22.95	0.27	0.35	98.42
CF9_2_cpx66_m	51.71	0.11	3.45	0.08	2.01	17.70	22.30	0.27	0.27	97.90
CF9_2_cpx67_c	48.63	0.24	6.83	0.18	4.39	14.59	22.18	0.06	0.76	97.87
CF9_2_cpx67_r	50.96	0.12	4.08	0.10	2.77	16.73	22.95	0.09	0.45	98.25
CF9_3_cpx12_m	50.28	0.25	7.46	0.21	3.33	15.04	22.81	0.00	0.56	99.95
CF9_3_cpx12_m	49.47	0.32	7.73	0.28	4.07	14.23	22.69	0.00	0.70	99.49
CF9_3_cpx12_r	52.35	0.11	4.44	0.14	1.98	17.34	23.13	0.07	0.39	99.96
CF9_3_cpx14_c	50.10	0.16	5.08	0.13	4.03	15.80	23.32	0.07	0.69	99.38
CF9_3_cpx14_m	48.42	0.30	8.02	0.23	5.07	13.84	22.67	0.00	0.91	99.46
CF9_3_cpx14_r	51.86	0.11	4.55	0.12	2.24	17.41	22.93	0.05	0.39	99.65
CF9_3_cpx15_c	52.63	0.11	2.66	0.07	1.53	18.15	23.59	0.60	0.22	99.56
CF9_3_cpx15_r	49.46	0.16	5.21	0.13	4.99	15.97	22.84	0.06	0.86	99.68
CF9_3_cpx27_c	52.82	0.12	3.18	0.08	2.15	17.58	23.38	0.53	0.32	100.16
CF9_3_cpx27_m	51.17	0.13	5.03	0.12	3.63	16.02	23.07	0.14	0.57	99.88
CF9_3_cpx27_r	52.91	0.11	3.85	0.08	1.90	17.63	23.29	0.24	0.32	100.32
CF9_3_cpx4_c	52.78	0.12	2.78	0.08	1.66	17.98	23.54	0.63	0.22	99.79
CF9_3_cpx4_r	49.58	0.23	6.63	0.15	4.18	15.18	22.94	0.10	0.76	99.74
CF9_3_cpx48_c	52.39	0.15	3.25	0.08	1.99	18.34	23.51	0.60	0.25	100.56
CF9_3_cpx48_r	51.82	0.13	3.91	0.11	2.21	17.58	23.78	0.51	0.36	100.41
CF9_3_cpx5_c	49.51	0.21	6.27	0.16	4.23	15.44	23.21	0.10	0.68	99.82
CF9_3_cpx5_r	51.84	0.11	4.32	0.10	2.60	17.09	23.71	0.15	0.43	100.35
CF9_3_cpx53_c	50.31	0.14	5.15	0.13	4.06	16.24	23.69	0.08	0.65	100.47
CF9_3_cpx53_m	49.25	0.19	6.66	0.15	4.60	15.38	23.25	0.11	0.90	100.50
CF9_3_cpx53_r	51.02	0.12	4.40	0.08	2.84	17.32	23.80	0.21	0.50	100.30
CF9_3_cpx56_c	51.87	0.12	4.26	0.09	2.37	17.12	23.84	0.07	0.42	100.17
CF9_3_cpx56_m	48.80	0.27	7.80	0.20	4.59	14.49	23.16	0.00	0.90	100.23
CF9_3_cpx56_r	51.17	0.12	4.36	0.12	2.99	16.89	23.90	0.16	0.52	100.22
CF9_3_cpx58_c	52.83	0.10	3.14	0.08	1.57	17.99	24.25	0.36	0.29	100.62
CF9_3_cpx58_m	49.18	0.23	7.30	0.16	4.30	14.88	23.16	0.02	0.82	100.05
CF9_3_cpx58_r	52.27	0.10	4.28	0.10	2.19	17.09	23.76	0.10	0.38	100.29
CF9_3_cpx68_c	52.13	0.10	3.21	0.09	1.88	17.92	24.20	0.49	0.31	100.32
CF9_3_cpx68_r	49.36	0.33	7.86	0.27	3.94	14.33	23.15	0.00	0.74	99.97

APPENDIX 3: SUPPLEMENTARY MATERIAL FOR CHAPTER 4

Label	SiO ₂ (wt%)	Na ₂ O (wt%)	FeO (wt%)	MnO (wt%)	Al ₂ O ₃ (wt%)	MgO (wt%)	CaO (wt%)	Cr ₂ O ₃ (wt%)	TiO ₂ (wt%)	Total (wt%)
CF9_3_cpx76_c	50.58	0.43	8.99	0.50	2.45	14.18	22.41	0.00	0.50	100.04
CF9_3_cpx76_m	50.63	0.15	5.63	0.13	3.56	16.09	23.71	0.00	0.66	100.56
CF9_3_cpx76_r	48.86	0.39	8.61	0.30	4.03	13.37	23.70	0.00	0.73	100.00
CF9_4_cpx1_c	49.80	0.27	7.53	0.22	4.77	14.03	22.54	0.01	0.85	100.02
CF9_4_cpx1_r	52.07	0.11	4.44	0.11	2.62	16.82	23.08	0.10	0.41	99.75
CF9_4_cpx11_c	52.75	0.12	4.07	0.11	2.43	17.05	23.14	0.15	0.34	100.15
CF9_4_cpx11_m	52.04	0.12	4.80	0.12	2.97	16.20	23.09	0.10	0.45	99.89
CF9_4_cpx11_r	52.89	0.11	4.35	0.11	2.22	16.88	23.20	0.09	0.36	100.21
CF9_4_cpx12_c	50.94	0.14	5.63	0.12	4.32	15.23	23.14	0.05	0.75	100.30
CF9_4_cpx12_m	50.67	0.22	7.16	0.17	4.29	14.42	22.79	0.03	0.74	100.49
CF9_4_cpx12_r	53.09	0.11	4.37	0.11	2.27	16.79	23.17	0.08	0.36	100.35
CF9_4_cpx15_c	52.83	0.12	4.61	0.13	2.40	17.03	23.31	0.05	0.41	100.90
CF9_4_cpx15_m	51.91	0.12	4.28	0.09	2.68	17.10	23.62	0.20	0.42	100.43
CF9_4_cpx21_c	53.66	0.11	2.89	0.07	1.68	17.53	23.64	0.48	0.24	100.30
CF9_4_cpx21_r	53.53	0.13	2.71	0.07	1.59	17.65	23.66	0.61	0.19	100.13
CF9_4_cpx23_c	49.93	0.18	6.46	0.13	4.93	14.68	23.15	0.02	0.90	100.37
CF9_4_cpx23_m	52.50	0.14	4.16	0.10	3.00	16.31	23.47	0.42	0.43	100.52
CF9_4_cpx23_r	51.64	0.12	5.12	0.12	4.03	15.39	23.16	0.15	0.58	100.30
CF9_4_cpx24_m	49.08	0.28	7.70	0.23	4.47	14.53	23.03	0.02	0.86	100.22
CF9_4_cpx29_c	53.29	0.10	4.51	0.12	2.11	17.42	22.44	0.10	0.34	100.42
CF9_4_cpx29_m	49.96	0.13	5.84	0.15	5.53	15.36	22.38	0.06	0.88	100.30
CF9_4_cpx29_r	53.14	0.11	4.02	0.12	2.05	17.13	23.27	0.17	0.36	100.35
CF9_4_cpx3_c	51.69	0.12	4.33	0.10	3.31	16.37	23.30	0.18	0.52	99.92
CF9_4_cpx3_r	52.09	0.10	4.74	0.11	3.37	16.24	23.34	0.11	0.52	100.64
CF9_4_cpx35_c	52.25	0.14	3.81	0.10	2.84	16.79	23.21	0.67	0.37	100.19
CF9_4_cpx35_m	51.04	0.15	5.43	0.11	4.36	15.63	22.92	0.10	0.62	100.36
CF9_4_cpx35_r	51.86	0.12	4.16	0.08	2.74	16.72	23.38	0.13	0.46	99.65
CF9_4_cpx40_c	53.11	0.15	4.17	0.10	2.33	16.78	23.14	0.38	0.33	100.49
CF9_4_cpx40_r	52.51	0.11	4.50	0.13	2.32	16.79	23.18	0.05	0.37	99.95
CF9_4_cpx41_c	50.01	0.27	7.61	0.19	4.45	14.32	22.74	0.04	0.81	100.44
CF9_4_cpx41_r	51.45	0.12	4.96	0.09	3.57	16.39	23.10	0.09	0.51	100.27
CF9_4_cpx43_c	49.54	0.34	8.82	0.34	4.46	12.97	23.30	0.08	0.73	100.57
CF9_4_cpx43_m	52.79	0.13	3.75	0.09	2.35	17.05	23.52	0.15	0.33	100.16
CF9_4_cpx43_r	48.75	0.33	9.00	0.33	4.67	12.90	23.27	0.00	0.80	100.05
CF9_4_cpx45_c	50.23	0.29	7.61	0.22	4.39	14.06	22.62	0.02	0.83	100.26
CF9_4_cpx45_r	52.47	0.11	4.35	0.11	3.02	16.24	23.54	0.12	0.46	100.43
CF9_4_cpx48_c	50.19	0.21	7.15	0.19	4.37	14.59	23.03	0.02	0.82	100.55
CF9_4_cpx48_m	50.57	0.25	7.86	0.19	3.80	14.50	22.59	0.00	0.66	100.41
CF9_4_cpx48_r	52.48	0.09	4.58	0.10	2.61	16.70	23.19	0.06	0.43	100.24
CF9_4_cpx5_c	53.36	0.11	3.39	0.07	1.91	17.25	23.75	0.16	0.29	100.29
CF9_4_cpx5_r	53.05	0.11	3.76	0.10	2.67	16.76	23.51	0.24	0.42	100.62
CF9_4_cpx50_c	49.78	0.41	8.40	0.40	3.55	13.39	23.57	0.01	0.67	100.18
CF9_4_cpx50_r	50.55	0.33	7.94	0.34	2.77	14.17	23.52	0.00	0.51	100.14
CF9_4_cpx53_c	53.29	0.15	3.11	0.08	1.88	17.75	22.99	0.65	0.22	100.12
CF9_4_cpx53_r	52.48	0.14	3.77	0.11	2.83	16.72	23.28	0.73	0.36	100.41
CF9_4_cpx54_c	51.49	0.12	5.39	0.14	3.31	15.37	23.73	0.06	0.54	100.15
CF9_4_cpx54_m	48.64	0.22	7.31	0.16	5.77	14.22	22.71	0.04	1.12	100.18
CF9_4_cpx54_r	51.84	0.13	4.34	0.10	2.65	16.79	23.45	0.09	0.44	99.82

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APPENDIX 3. SUPPLEMENTARY MATERIAL FOR CHAPTER 4

Label	SiO ₂ (wt%)	Na ₂ O (wt%)	FeO (wt%)	MnO (wt%)	Al ₂ O ₃ (wt%)	MgO (wt%)	CaO (wt%)	Cr ₂ O ₃ (wt%)	TiO ₂ (wt%)	Total (wt%)
CF78_cpx3_c	50.40	0.46	9.55	0.54	3.02	12.63	23.02	0.00	0.75	100.36
CF78_cpx3_m	48.96	0.72	10.72	0.71	3.44	11.47	22.64	0.00	0.92	99.57
CF78_cpx3_r	49.47	0.51	8.78	0.40	3.35	13.36	23.07	0.00	0.74	99.69
CF78_cpx20_c	48.50	0.73	11.76	0.66	3.90	10.66	22.35	0.00	1.19	99.76
CF78_cpx20_r	49.01	0.45	9.27	0.33	4.98	12.24	22.85	0.01	1.07	100.21
CF78_cpx31_c	50.26	0.49	8.77	0.40	3.18	13.15	23.06	0.00	0.72	100.03
CF78_cpx31_m	48.34	0.57	10.67	0.48	4.52	11.47	22.77	0.00	0.95	99.78
CF78_cpx31_r	49.09	0.49	8.93	0.38	3.71	13.04	23.02	0.00	0.77	99.42
CF78_cpx75_c	52.01	0.13	3.71	0.09	2.75	16.35	24.21	0.11	0.48	99.83
CF78_cpx75_m	48.40	0.19	6.01	0.11	5.83	14.05	23.77	0.03	1.11	99.49
CF78_cpx75_r	52.70	0.11	3.45	0.07	2.48	16.47	24.06	0.28	0.43	100.05
CF78_cpx78_c	50.70	0.54	8.87	0.52	2.77	12.94	22.92	0.01	0.70	99.97
CF78_cpx78_r	50.68	0.42	8.52	0.39	3.56	12.86	22.95	0.01	0.72	100.11
CF78_cpx113_c	48.34	0.66	10.77	0.53	4.48	11.21	22.83	0.01	1.23	100.07
CF78_cpx113_r	49.71	0.52	9.37	0.42	4.21	12.06	22.96	0.00	0.94	100.20
CF78_cpx17_c	50.13	0.50	9.14	0.48	3.13	12.65	22.84	0.00	0.78	99.65
CF78_cpx17_m	51.90	0.20	4.58	0.13	2.79	16.08	23.25	0.45	0.48	99.87
CF78_cpx17_r	49.14	0.47	8.83	0.42	3.72	12.93	22.82	0.00	0.84	99.19
CF78_cpx27_c	49.83	0.45	8.39	0.35	3.63	13.27	22.93	0.13	0.66	99.63
CF78_cpx27_m	51.15	0.13	3.79	0.05	3.97	15.87	24.45	0.14	0.65	100.20
CF78_cpx27_r	48.65	0.47	8.67	0.37	4.17	13.14	23.06	0.00	0.88	99.41
CF78_cpx50_c	51.19	0.45	8.35	0.51	2.52	13.63	22.75	0.00	0.57	99.98
CF78_cpx50_m	49.34	0.25	6.93	0.17	4.81	14.34	23.00	0.03	0.93	99.81
CF78_cpx50_r	48.50	0.38	8.60	0.28	4.75	13.39	22.90	0.01	0.83	99.64
CF78_cpx95_c	49.65	0.39	7.94	0.29	3.66	13.78	22.92	0.09	0.62	99.34
CF78_cpx95_m	51.98	0.18	5.34	0.16	2.47	16.29	22.93	0.12	0.49	99.96
CF78_cpx95_r	50.19	0.44	8.91	0.34	3.87	12.61	23.00	0.00	0.87	100.22
CF78_cpx104_c	50.57	0.39	8.17	0.30	3.18	13.77	22.77	0.00	0.62	99.77
CF78_cpx104_m	49.19	0.30	6.93	0.18	5.25	13.92	23.09	0.04	0.92	99.83
CF78_cpx104_r	49.02	0.34	8.63	0.25	5.15	12.62	22.95	0.00	0.95	99.90
CF78_cpx114_c	52.91	0.13	3.28	0.07	2.32	16.50	24.14	0.29	0.43	100.05
CF78_cpx114_m1	51.22	0.18	5.81	0.13	3.31	15.38	23.22	0.02	0.70	99.98
CF78_cpx114_m2	53.16	0.13	3.40	0.09	1.94	16.97	23.87	0.31	0.38	100.26
CF78_cpx114_m3	51.68	0.17	4.93	0.11	2.94	15.83	23.62	0.07	0.58	99.94
CF78_cpx114_r	52.55	0.11	3.38	0.08	2.30	16.95	24.15	0.13	0.43	100.09
CF78_cpx121_c	50.43	0.43	8.05	0.34	3.36	13.41	22.99	0.04	0.68	99.72
CF78_cpx121_m	51.15	0.14	4.77	0.09	3.80	15.01	24.61	0.03	0.58	100.18
CF78_cpx121_r	51.26	0.39	8.28	0.33	3.49	13.11	22.72	0.00	0.69	100.28
CF78_cpx128_c	52.12	0.27	6.43	0.21	2.05	15.25	22.92	0.15	0.54	99.96
CF78_cpx128_m	53.03	0.14	2.96	0.06	2.12	16.68	23.88	0.66	0.35	99.88
CF78_cpx128_r	49.18	0.39	8.71	0.24	5.06	12.54	22.97	0.00	0.89	99.98
CF78_cpx134_c	50.48	0.30	6.11	0.12	3.99	14.42	23.70	0.03	0.53	99.67
CF78_cpx134_m1	52.27	0.17	4.49	0.12	2.31	16.08	24.01	0.07	0.55	100.07
CF78_cpx134_m2	49.20	0.24	6.74	0.13	4.98	13.79	23.52	0.00	1.03	99.64
CF78_cpx134_m3	51.80	0.16	5.26	0.13	2.43	15.72	23.66	0.02	0.57	99.77
CF78_cpx134_r	50.38	0.41	8.28	0.29	3.99	13.01	22.99	0.02	0.74	100.12
CF78_cpx1_c	52.14	0.15	3.96	0.08	2.78	16.41	24.17	0.05	0.50	100.25
CF78_cpx1_r	49.95	0.37	8.21	0.26	4.31	13.22	23.25	0.01	0.79	100.38
CF78_cpx7_c	53.41	0.15	3.37	0.09	1.22	17.45	23.58	0.12	0.32	99.73
CF78_cpx7_r	49.04	0.38	8.20	0.25	4.40	13.09	23.04	0.01	0.88	99.30
CF78_cpx8_c	52.46	0.18	4.36	0.13	1.87	16.59	23.32	0.23	0.35	99.49
CF78_cpx8_r	49.34	0.41	8.03	0.31	3.45	13.69	23.04	0.00	0.70	98.97
CF78_cpx44_c	52.40	0.12	3.72	0.11	2.16	16.53	23.90	0.16	0.38	99.48
CF78_cpx44_r	49.53	0.44	8.09	0.35	3.38	13.62	23.09	0.00	0.70	99.18
CF78_cpx71_c	50.74	0.19	5.76	0.15	3.63	14.86	23.71	0.01	0.70	99.74
CF78_cpx71_r	49.76	0.43	8.14	0.35	3.20	13.67	22.95	0.00	0.66	99.17
CF78_cpx74_c	51.01	0.16	4.84	0.10	3.83	15.79	23.25	0.05	0.84	99.87
CF78_cpx74_r	50.13	0.41	8.15	0.36	3.18	13.75	23.06	0.00	0.66	99.69
CF78_cpx86_c	50.88	0.16	4.88	0.08	3.68	15.63	23.48	0.05	0.71	99.55
CF78_cpx86_r	50.64	0.40	8.15	0.34	3.35	13.50	22.85	0.00	0.67	99.90
CF78_cpx106_c	51.51	0.15	3.63	0.06	3.16	16.18	24.15	0.48	0.53	99.85
CF78_cpx106_r	47.95	0.42	8.96	0.27	5.11	12.71	23.10	0.00	1.04	99.55
CF78_cpx122_c	51.01	0.12	5.04	0.10	3.58	14.81	24.44	0.05	0.54	99.69
CF78_cpx122_r	49.46	0.41	8.28	0.32	3.59	13.52	23.07	0.02	0.77	99.44

Table A3.4: Chemical composition of Minopoli 2 and Astroni 6 clinopyroxenes, measured by EPMA.

Crystal mapping				
Laser parameters	Fluence (J/cm ²)	2.7		
	Spot size (μm)*	8x8 / 10x10 / 20x20		
	Stage translation speed (μm/s)*	25 / 30 / 75		
	Repetition rate (Hz)*	50 / 50 / 35		
Gas flows	He (l/min)	0.5 total (0.3 l/min into laser cell, 0.2 l/min into the laser cup)		
	Ar (l/min)	0.75 l/min make-up (nebulizer) Ar, 0.8 l/min auxiliary gas, 14 l/min cooling gas		
	N ₂ (ml/min)	9		
ICP-MS parameters	Analytes	7Li, 23Na, 24Mg, 27Al, 29Si, 43Ca, 45Sc, 48Ti, 51V, 52Cr, 57Fe, 60Ni, 71Ga, 85Rb, 88Sr, 89Y, 139La, 146Nd		
	Individual dwell times (ms)	1-50		
Sr-isotope spots				
Laser parameters	Fluence (J/cm ²)	2.7		
	Spot size (μm)	80 x 80		
	Repetition rate (Hz)	15		
Gas flows	He (l/min)	0.5 total (0.3 l/min into laser cell, 0.2 l/min into the laser cup)		
	Ar (l/min)	0.75 l/min make-up (nebulizer) Ar, 0.8 l/min auxiliary gas, 14 l/min cooling gas		
	N ₂ (ml/min)	9		
ICP-MS parameters	Analytes	82Kr, 83Kr, 84Sr, 86Sr, 87Sr, 88Sr, 85Rb		
	Individual dwell times (ms)	30		
*Spatial resolution was adjusted using a combination of spot size, translation speed and repetition rate depending on the crystal grain size.				
Sr-isotope transects				
Laser parameters	Fluence (J/cm ²)	2.7		
	Spot size (μm)	50 x 50		
	Stage translation speed (μm/s)	30		
	Repetition rate (Hz)	50		
Gas flows	He (l/min)	0.5 total (0.3 l/min into laser cell, 0.2 l/min into the laser cup)		
	Ar (l/min)	0.75 l/min make-up (nebulizer) Ar, 0.8 l/min auxiliary gas, 14 l/min cooling gas		
	N ₂ (ml/min)	9		
ICP-MS parameters	Analytes	82Kr, 83Kr, 84Sr, 86Sr, 87Sr, 88Sr, 85Rb		
Summary of Sr isotope results on reference materials. Recommended values are from GeoRem				
(http://georem.mpch-mainz.gwdg.de/).				
Reference Material	Mean measured 87Sr/86Sr	2SD	Recommended 87Sr/86Sr	2SD
ML3B	0.703491	0.000565554	0.703849	0.000015
BCR-2G	0.704681	0.000980364	0.705003	0.000004

Table A3.5: Instrument parameters used for LA-ICPMS experiments

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	84Sr/86Sr	84Sr/86Sr 2SE	84Sr/88Sr	84Sr/88Sr 2SE	87Rb/86Sr	87Rb/86Sr 2SE	87Sr/86Sr	87Sr/86Sr 2SE
Minopoli 2 - CF11								
CF11cpx112m	0.056970	0.000876	0.006802	0.000105	0.018645	0.001256	0.708174	0.000604
CF11cpx112r	0.055543	0.000716	0.006632	0.000086	0.002752	0.000284	0.707640	0.000375
CF11cpx133c	0.056897	0.000702	0.006793	0.000084	0.000548	0.000270	0.706979	0.000415
CF11cpx133m	0.056436	0.000811	0.006738	0.000097	0.000737	0.000314	0.707934	0.000376
CF11cpx133r	0.056058	0.000797	0.006693	0.000095	0.000419	0.000301	0.708354	0.000399
CF11cpx151c	0.056421	0.000838	0.006737	0.000100	0.000180	0.000284	0.707739	0.000463
CF11cpx151m	0.056488	0.000901	0.006745	0.000108	0.000732	0.000305	0.706388	0.000473
CF11cpx151r	0.056450	0.000977	0.006740	0.000117	-0.000071	0.000355	0.709034	0.000519
CF11cpx6c	0.057384	0.000967	0.006852	0.000115	-0.000043	0.000473	0.708092	0.000531
CF11cpx6m	0.057160	0.000825	0.006825	0.000099	0.000685	0.000281	0.707574	0.000442
CF11cpx6r	0.055841	0.000769	0.006667	0.000092	0.000798	0.000308	0.707848	0.000466
CF11cpx60c	0.057026	0.000602	0.006809	0.000072	0.001088	0.000205	0.706681	0.000306
CF11cpx60r	0.056148	0.000606	0.006704	0.000072	0.000480	0.000262	0.708698	0.000348
CF11cpx60m	0.056558	0.000930	0.006753	0.000111	0.000826	0.000393	0.708685	0.000440
CF11cpx62c	0.056608	0.000744	0.006759	0.000089	0.001199	0.000270	0.707952	0.000339
CF11cpx62r	0.055506	0.000911	0.006627	0.000109	0.000609	0.000348	0.708832	0.000432
CF11cpx64c	0.056633	0.000752	0.006762	0.000090	0.001038	0.000318	0.709142	0.000448
CF11cpx64m	0.056292	0.000849	0.006721	0.000101	0.000799	0.000354	0.710078	0.000371
CF11cpx64r	0.056735	0.000888	0.006774	0.000106	0.000740	0.000379	0.709523	0.000418
CF11cpx112c	0.056821	0.000843	0.006784	0.000101	-0.000106	0.000408	0.707530	0.000484
CF11cpx17c	0.057029	0.000617	0.006809	0.000074	0.002393	0.000421	0.708942	0.000342
CF11cpx17m	0.056816	0.001431	0.006784	0.000171	0.001536	0.000484	0.707379	0.000611
CF11cpx17r	0.055853	0.001011	0.006669	0.000121	0.004088	0.000554	0.707349	0.000484
CF11cpx44c	0.056303	0.000948	0.006723	0.000113	0.000453	0.000365	0.707843	0.000401
CF11cpx44m	0.057225	0.001047	0.006833	0.000125	0.000417	0.000395	0.709024	0.000429
CF11cpx44r	0.056311	0.000914	0.006724	0.000109	0.000630	0.000318	0.707312	0.000441
CF11cpx159c	0.056546	0.000711	0.006752	0.000085	0.000200	0.000293	0.709278	0.000402
CF11cpx159m	0.057859	0.001311	0.006908	0.000157	0.001002	0.000391	0.705238	0.000578
CF11cpx159r	0.056556	0.000739	0.006753	0.000088	0.000519	0.000292	0.707488	0.000419
CF11cpx25c	0.055685	0.000739	0.006649	0.000088	0.000767	0.000250	0.707068	0.000379
CF11cpx25m	0.056968	0.000919	0.006802	0.000110	0.000784	0.000341	0.707819	0.000396
CF11cpx25r	0.056381	0.000747	0.006732	0.000089	0.000602	0.000276	0.707622	0.000370
CF11cpx63c	0.056798	0.000865	0.006782	0.000103	0.000449	0.000307	0.706745	0.000423
CF11cpx63m	0.055414	0.000933	0.006616	0.000111	0.001724	0.000417	0.708139	0.000400
CF11cpx63r	0.055997	0.000920	0.006686	0.000110	0.000582	0.000327	0.707692	0.000369
CF11cpx68c	0.056426	0.000957	0.006737	0.000114	-0.000200	0.000430	0.709097	0.000469
CF11cpx65m	0.056562	0.000814	0.006753	0.000097	0.000419	0.000300	0.708124	0.000394
CF11cpx65r	0.056093	0.000794	0.006697	0.000095	0.000278	0.000295	0.707300	0.000414
CF11cpx167c	0.055569	0.000983	0.006635	0.000117	0.000710	0.000416	0.707250	0.000492
CF11cpx167m	0.054845	0.001040	0.006548	0.000124	0.000031	0.000387	0.707806	0.000458
CF11cpx167r	0.055420	0.001090	0.006617	0.000130	-0.000012	0.000446	0.708783	0.000488
CF11cpx168c	0.056153	0.001175	0.006705	0.000140	-0.000092	0.000467	0.709554	0.000496
CF11cpx168m	0.057781	0.000944	0.006899	0.000113	0.003153	0.000537	0.708421	0.000491
CF11cpx168r	0.057495	0.000972	0.006865	0.000116	0.000637	0.000392	0.708176	0.000450
Minopoli 2 - CF9								
CF92_cpx65c	0.055400	0.000706	0.006615	0.000084	0.001624	0.000294	0.707228	0.000412
CF92_cpx65m	0.055779	0.000762	0.006660	0.000091	0.000596	0.000318	0.707981	0.000458
CF92_cpx65r	0.055960	0.000865	0.006682	0.000103	0.000086	0.000306	0.707683	0.000468
CF93_cpx4c	0.055838	0.001035	0.006667	0.000124	0.000893	0.000370	0.705981	0.000433
CF93_cpx4r	0.056179	0.000767	0.006708	0.000092	0.000784	0.000299	0.707071	0.000411
CF93_cpx15c	0.056479	0.001074	0.006744	0.000128	0.001485	0.000464	0.706641	0.000594
CF93_cpx15m	0.057941	0.001019	0.006918	0.000122	0.001422	0.000360	0.707130	0.000445
CF93_cpx15r	0.057376	0.001062	0.006851	0.000127	0.001042	0.000410	0.707566	0.000481
CF93_cpx48c	0.056867	0.000910	0.006790	0.000109	0.001485	0.000382	0.706745	0.000509
CF93_cpx48m	0.057331	0.000900	0.006845	0.000107	0.000646	0.000381	0.707887	0.000454
CF93_cpx48r	0.057227	0.000773	0.006833	0.000092	0.000672	0.000304	0.706256	0.000450
CF93_cpx76c	0.059670	0.001333	0.007125	0.000159	0.008873	0.002424	0.705458	0.001090
CF93_cpx76m	0.058131	0.000901	0.006941	0.000108	0.295007	0.003490	0.705358	0.003241
CF93_cpx76r	0.057160	0.000877	0.006825	0.000105	0.000394	0.000373	0.708840	0.000434
CF94_cpx15c	0.053331	0.001397	0.006368	0.000167	0.000734	0.000247	0.712116	0.000856
CF94_cpx15m	0.055958	0.000804	0.006681	0.000096	0.000573	0.000342	0.708120	0.000550
CF94_cpx15r	0.052644	0.001579	0.006286	0.000188	0.001027	0.000214	0.712733	0.001353
CF94_cpx21c	0.055298	0.001290	0.006603	0.000154	0.001244	0.000451	0.707703	0.000512
CF94_cpx21r	0.057357	0.001172	0.006848	0.000140	0.001319	0.000573	0.707174	0.000590
CF94_cpx21m	0.056408	0.000986	0.006735	0.000118	0.001350	0.000383	0.707798	0.000477
CF94_cpx23c	0.057518	0.001006	0.006868	0.000120	0.003193	0.000400	0.709177	0.000527
CF94_cpx23m	0.055998	0.000916	0.006686	0.000109	0.000261	0.000354	0.706946	0.000504
CF94_cpx23r	0.055764	0.001068	0.006658	0.000128	-0.000542	0.000418	0.707989	0.000465
CF92cpx40c	0.055182	0.000810	0.006589	0.000097	0.000754	0.000313	0.706812	0.000407
CF92cpx40m	0.054633	0.001141	0.006523	0.000136	0.000506	0.000456	0.708354	0.000526
CF92cpx40r	0.056202	0.001163	0.006711	0.000139	0.000164	0.000351	0.707714	0.000467

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	84Sr/86Sr	84Sr/86Sr 2SE	84Sr/88Sr	84Sr/88Sr 2SE	87Rb/86Sr	87Rb/86Sr 2SE	87Sr/86Sr	87Sr/86Sr 2SE
CF92cpx67c	0.057594	0.000855	0.006877	0.000102	0.001733	0.000339	0.708274	0.000445
CF92cpx67m	0.056533	0.000702	0.006750	0.000084	0.000615	0.000301	0.707165	0.000535
CF92cpx67r	0.056508	0.000858	0.006747	0.000102	0.000382	0.000334	0.707944	0.000527
CF93cpx12c	0.055406	0.001043	0.006615	0.000125	0.029696	0.000636	0.707297	0.000737
CF93cpx12m	0.056581	0.000753	0.006756	0.000090	0.000296	0.000271	0.707648	0.000470
CF93cpx12r	0.056626	0.000817	0.006761	0.000098	0.000332	0.000300	0.708541	0.000377
CF93cpx27c	0.055373	0.000858	0.006612	0.000102	0.000723	0.000317	0.707635	0.000372
CF93cpx27m	0.056246	0.000836	0.006716	0.000100	0.000655	0.000299	0.707399	0.000372
CF93cpx27r	0.057760	0.000886	0.006897	0.000106	0.000584	0.000340	0.707655	0.000394
CF93cpx58c	0.056660	0.000750	0.006765	0.000089	0.000596	0.000341	0.708055	0.000447
CF93cpx58m	0.057141	0.001029	0.006823	0.000123	0.001642	0.000419	0.705307	0.000776
CF93cpx58r	0.056454	0.001138	0.006741	0.000136	0.037936	0.001308	0.709400	0.001120
CF94cpx29c	0.056193	0.001062	0.006709	0.000127	0.000819	0.000413	0.708843	0.000528
CF94cpx29m	0.057644	0.001687	0.006883	0.000201	0.000497	0.000535	0.708926	0.000626
CF94cpx29r	0.057232	0.000903	0.006834	0.000108	0.000610	0.000335	0.708644	0.000365
CF94cpx45c	0.055387	0.000761	0.006613	0.000091	0.002066	0.000371	0.712579	0.000639
CF94cpx45r	0.056723	0.000711	0.006773	0.000085	0.000628	0.000256	0.708582	0.000384
CF94cpx53c	0.057080	0.001144	0.006815	0.000137	0.001190	0.000388	0.707079	0.000510
CF94cpx53m	0.054337	0.001357	0.006488	0.000162	0.000521	0.000494	0.709038	0.000630
CF94cpx53r	0.055215	0.001097	0.006593	0.000131	0.001573	0.000540	0.709495	0.000614
Astroni 6 - CF78								
CF78cpx74r	0.057288	0.001306	0.006840	0.000156	0.006702	0.001424	0.708753	0.000831
CF78cpx78c	0.061386	0.002060	0.007330	0.000246	0.002344	0.000788	0.707903	0.000915
CF78cpx78m	0.061288	0.001485	0.007318	0.000177	0.000743	0.000630	0.709693	0.000650
CF78cpx78r	0.060236	0.001333	0.007192	0.000159	0.001703	0.000610	0.709094	0.000694
CF78cpx104c	0.057087	0.000885	0.006816	0.000106	0.001074	0.000412	0.708119	0.000479
CF78cpx104m	0.057641	0.000581	0.006882	0.000069	0.264562	0.003167	0.703262	0.002226
CF78cpx104r	0.056828	0.000493	0.006785	0.000059	0.000556	0.000189	0.709633	0.000306
CF78cpx106c	0.056119	0.000622	0.006701	0.000074	0.000152	0.000246	0.707224	0.000319
CF78cpx106m	0.055846	0.000683	0.006668	0.000082	0.000554	0.000252	0.707321	0.000299
CF78cpx106r	0.056467	0.001010	0.006742	0.000121	0.039005	0.002844	0.703287	0.000733
CF78cpx17m	0.056734	0.000768	0.006774	0.000092	0.000478	0.000270	0.708162	0.000442
CF78cpx17r	0.058578	0.001133	0.006994	0.000135	0.018303	0.001693	0.707904	0.000560
CF78cpx27m	0.056125	0.000700	0.006701	0.000084	0.000517	0.000254	0.707736	0.000397
CF78cpx27r	0.056541	0.000626	0.006751	0.000075	0.000395	0.000272	0.708272	0.000408
CF78cpx74m	0.057092	0.001159	0.006817	0.000138	0.000720	0.000461	0.709508	0.000516
CF78cpx17c	0.057783	0.001026	0.006899	0.000123	0.000416	0.000362	0.708296	0.000514
CF78cpx27c	0.056604	0.001319	0.006759	0.000157	0.000772	0.000450	0.704425	0.001143
CF78cpx50c	0.061125	0.001421	0.007298	0.000170	0.003994	0.000605	0.708593	0.000633
CF78cpx50m	0.058040	0.001080	0.006930	0.000129	0.001011	0.000430	0.707156	0.000687
CF78cpx50r	0.057349	0.000632	0.006847	0.000075	0.000990	0.000230	0.708751	0.000317
CF78cpx74c	0.058209	0.000917	0.006950	0.000109	0.000316	0.000409	0.708168	0.000554
CF78cpx95c	0.056331	0.000806	0.006726	0.000096	0.000414	0.000274	0.709017	0.000472
CF78cpx95m	0.056867	0.001027	0.006790	0.000123	0.004000	0.000437	0.709915	0.000654
CF78cpx95r	0.056317	0.000606	0.006724	0.000072	0.000864	0.000234	0.710972	0.000339
CF78cpx122c	0.057281	0.001214	0.006839	0.000145	0.000317	0.000407	0.706205	0.000752
CF78cpx122m	0.056815	0.000655	0.006784	0.000078	0.001197	0.000265	0.707658	0.000420
CF78cpx122r	0.056261	0.000933	0.006718	0.000111	0.001629	0.000341	0.708995	0.000343
CF78cpx128c	0.056380	0.000673	0.006732	0.000080	0.000493	0.000292	0.708919	0.000392
CF78cpx128m	0.055981	0.000692	0.006684	0.000083	0.000394	0.000253	0.709412	0.000337
CF78cpx128r	0.056465	0.000489	0.006742	0.000058	0.000238	0.000179	0.709882	0.000306
CF78cpx71c	0.056584	0.000649	0.006756	0.000077	0.001263	0.000243	0.707997	0.000333
CF78cpx71r	0.055751	0.001236	0.006657	0.000148	0.000623	0.000358	0.709468	0.000542
CF78cpx121c	0.056529	0.000652	0.006750	0.000078	0.000651	0.000269	0.709894	0.000298
CF78cpx121m	0.055992	0.000631	0.006685	0.000075	0.000444	0.000244	0.708564	0.000329
CF78cpx121r	0.057638	0.001110	0.006882	0.000133	0.000481	0.000324	0.709350	0.000604
CF78cpx134c	0.056618	0.000587	0.006760	0.000070	0.000275	0.000220	0.709117	0.000310
CF78cpx134m	0.056666	0.000632	0.006766	0.000075	0.000362	0.000204	0.709246	0.000303
CF78cpx134r	0.055500	0.000635	0.006627	0.000076	0.001573	0.000310	0.709198	0.000361

Table A3.6: Spot Sr isotopic data determined by LA-ICPMS on Campi Flegrei clinopyroxenes.

APPENDIX 3. SUPPLEMENTARY MATERIAL FOR CHAPTER 4

		Minopoli 2	Astroni 6
Normal zoning	Euhedral	16	5
	Very thin felsic zone	5	6
	Resorbed core	3	24
Reverse zoning	Euhedral	9	1
	Resorbed core	53	8
Complex zones, mafic core	Euhedral felsic zone	12	1
	Resorbed felsic zone	25	10
	Resorbed core	5	-
Complex zones, felsic core	Euhedral mafic zone	1	-
	Diffuse mafic zone	5	4
	Resorbed core	4	-
Oscillatory zones		57	8
No zones		198	96

Table A3.7: Frequency of different textural groups observed in Minopoli 2 and Astroni 6 clinopyroxenes

Thermal parameters	Teq	700	°C
	Tlm	1140	°C
	Tm0	1140	°C
	Tla	950	°C
	Ta0	750	°C
	Ts	700	°C
	Cpm	1464	J/kg K
	Cpa	1378	J/kg K
	hcry	396000	J/kg
	hfus	270000	J/kg
Magma	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)
	699	0.705	1.16
	Cr (ppm)	D _o (Cr)	
	338	3	
Assimilant	Sr (ppm)	⁸⁷ Sr/ ⁸⁶ Sr	D _o (Sr)
	166	0.71967	0.3
	Cr (ppm)	D _o (Cr)	
	120	0.3	

Abbreviations: Teq = equilibration temperature; Tlm = magma liquidus temperature; Tm0 = initial magma temperature; Tla = wall-rock liquidus temperature; Ta0 = initial Wall-rock temperature; Ts = solidus temperature; Cpm = magma specific heat capacity; Cpa = assimilant specific heat capacity; hcry = crystallization enthalpy; hfus = fusion enthalpy; D_o = bulk distribution coefficient.

Thermal parameters and the isotopic composition of the Palaeozoic metamorphic basement were taken from Amstutz et al. (submitted). Trace element composition of the Palaeozoic basement was taken from Amstutz et al. (in press). The Solchiaro eruption of Procida was used as the starting magma composition, parameters from De Astis et al. (2004).

Table A3.8: EC-AFC (Spera and Bohrson, 2001) parameters used to model Campi Flegrei magma contamination by Palaeozoic metamorphic basement.

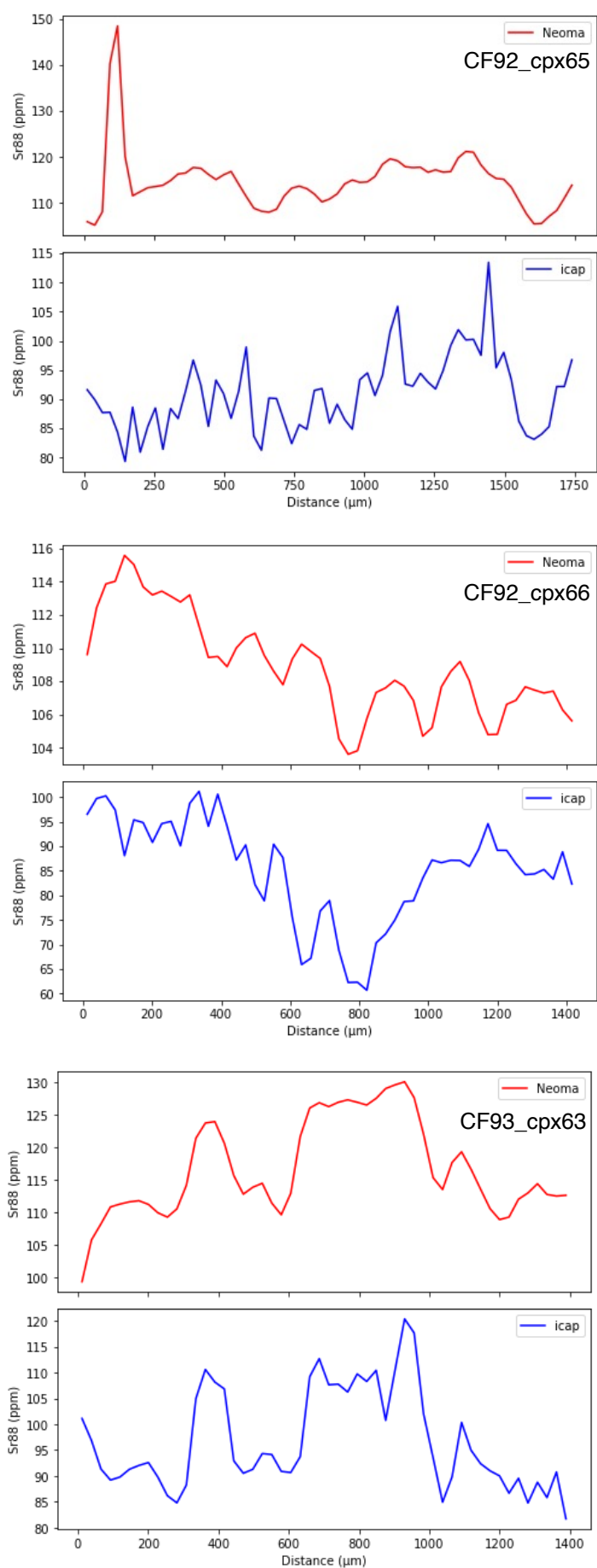


Figure A3.1: Comparison of ^{88}Sr from clinopyroxene transects. Red line is semi-quantitative ^{88}Sr measured during Sr isotopic analysis (Thermo Scientific Neoma), blue line is semi-quantitative ^{88}Sr extracted from profiles across trace element crystal maps (Thermo Scientific iCAP).

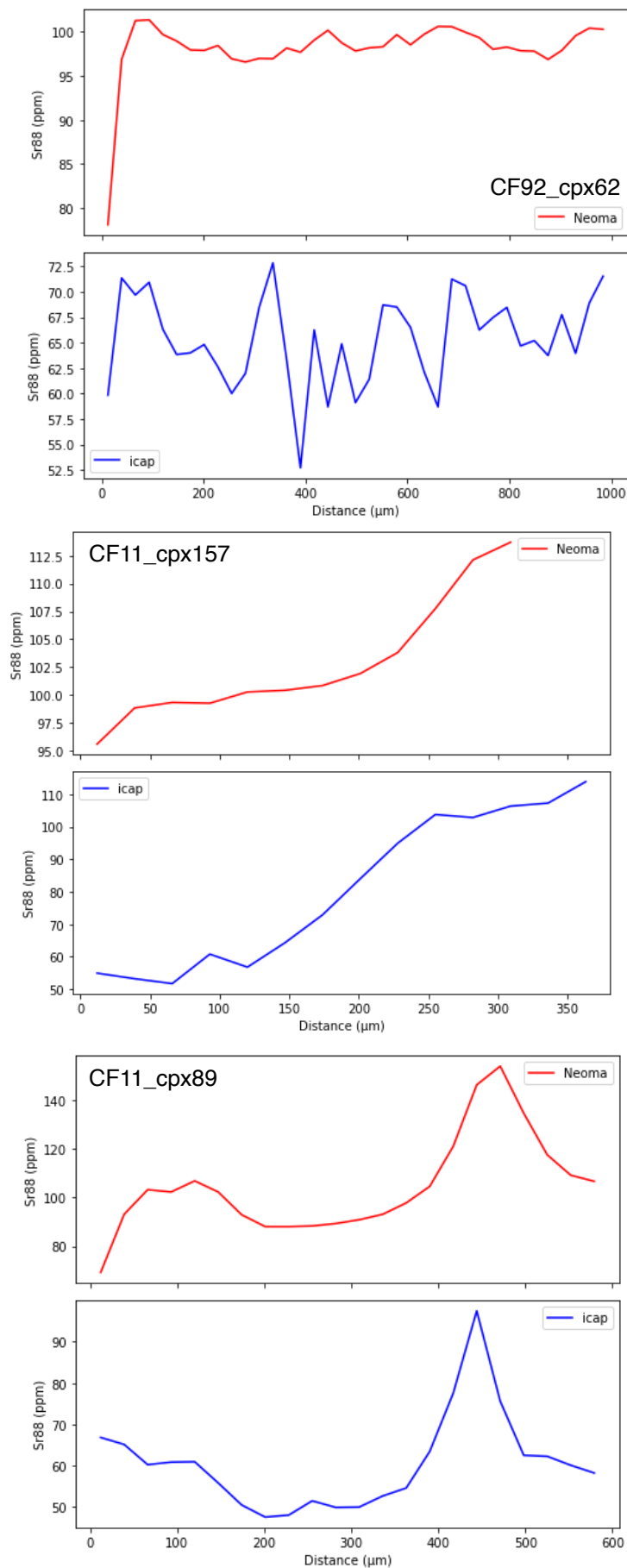


Figure A3.1 (continued)

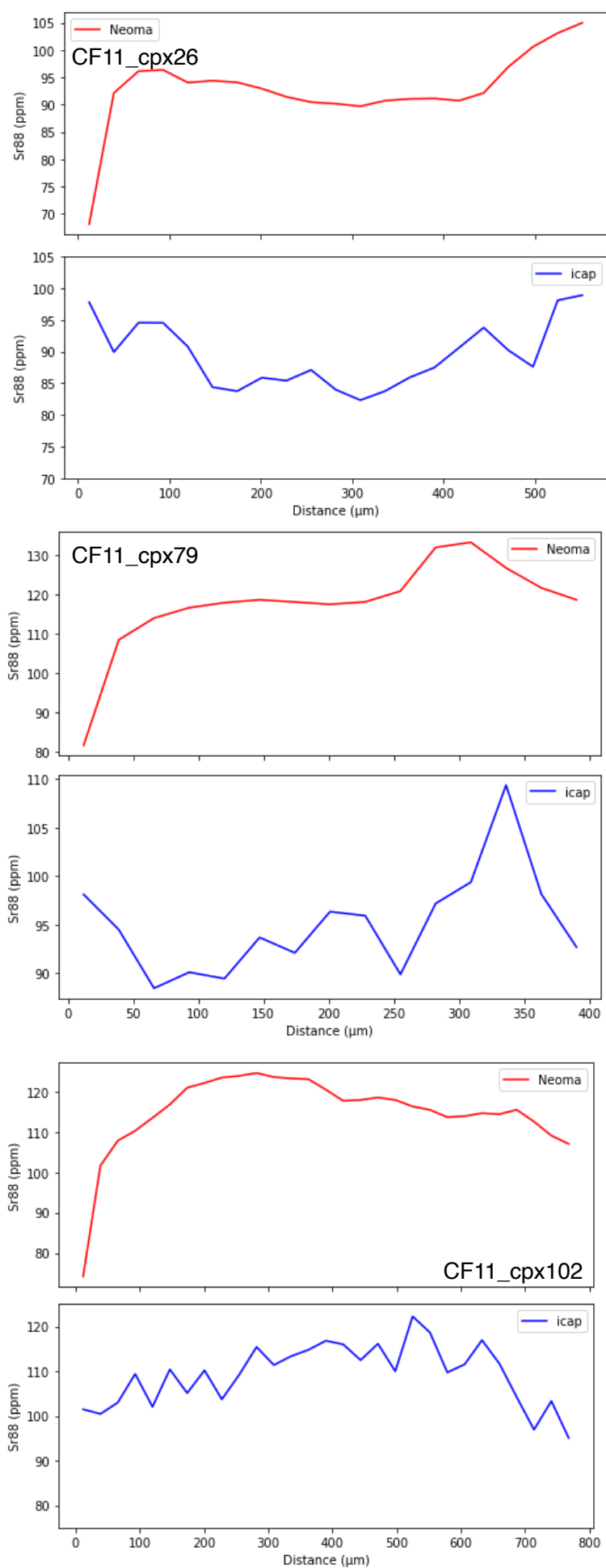


Figure A3.1 (continued)

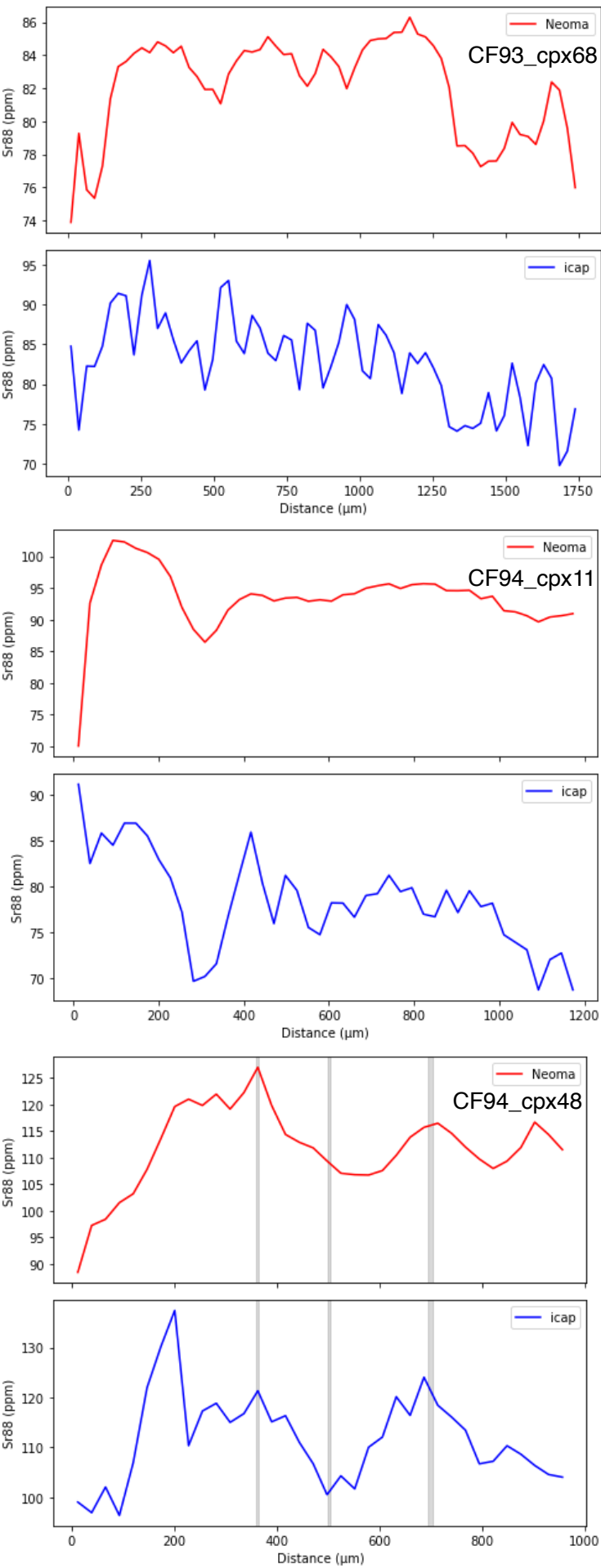
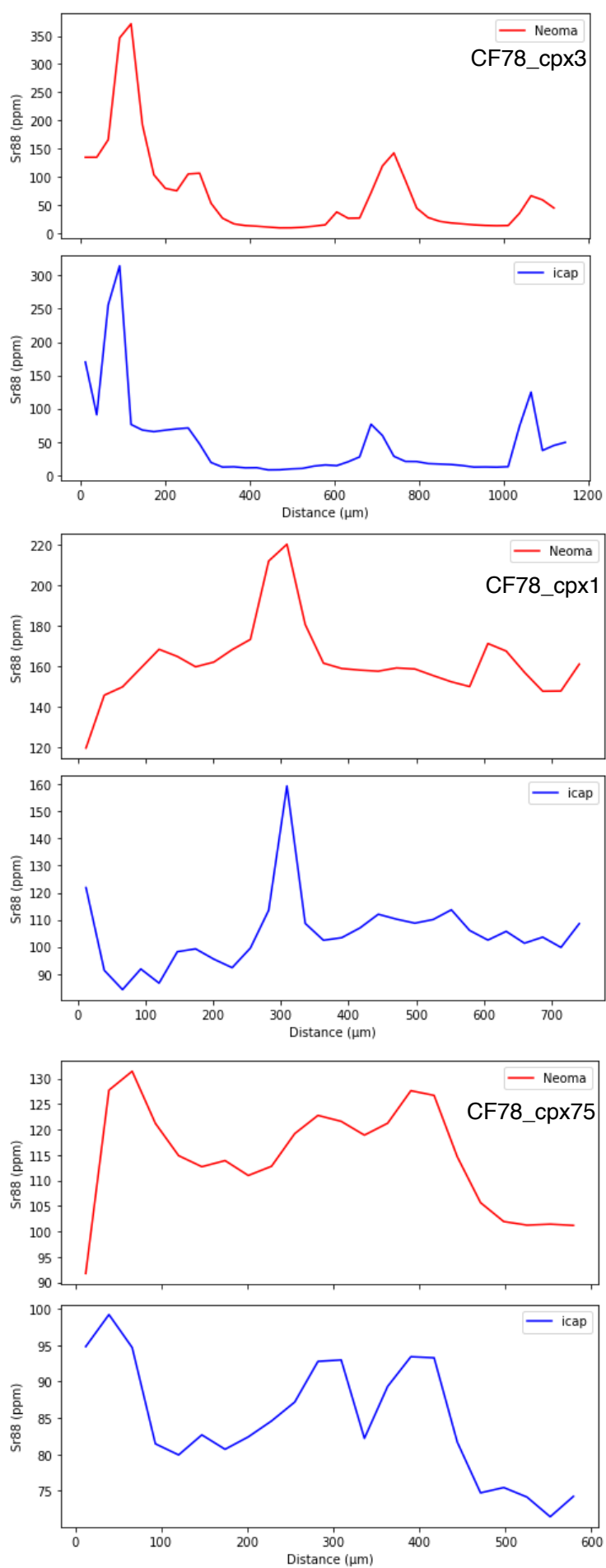


Figure A3.1 (continued)

Figure A3.1 (continued)



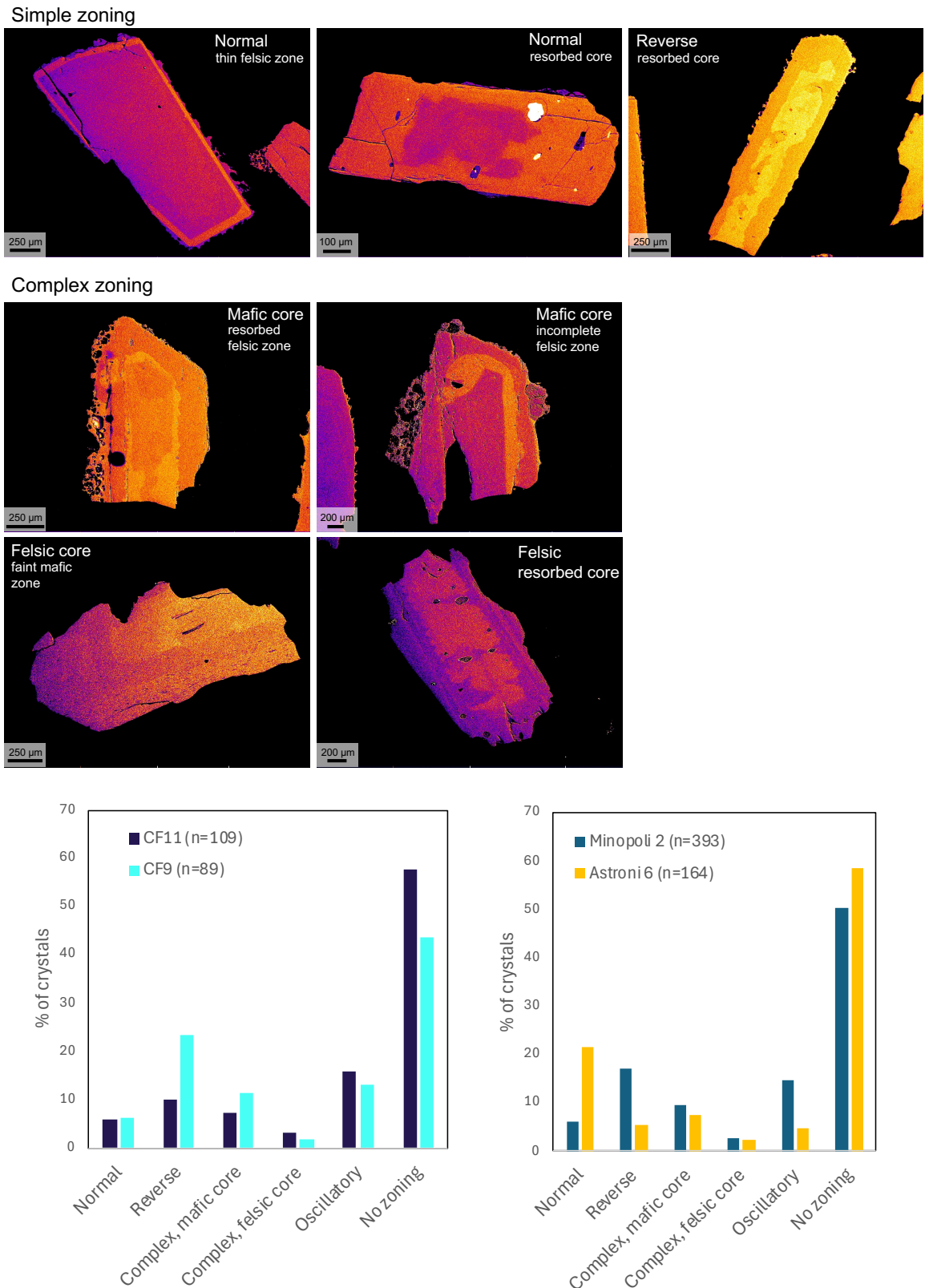


Figure A3.2: False-coloured BSE images showing zoning textures in Minopoli and Astroni clinopyroxenes, and comparison of the proportion of zoning textures occurring in Minopoli 2 and Astroni 6.

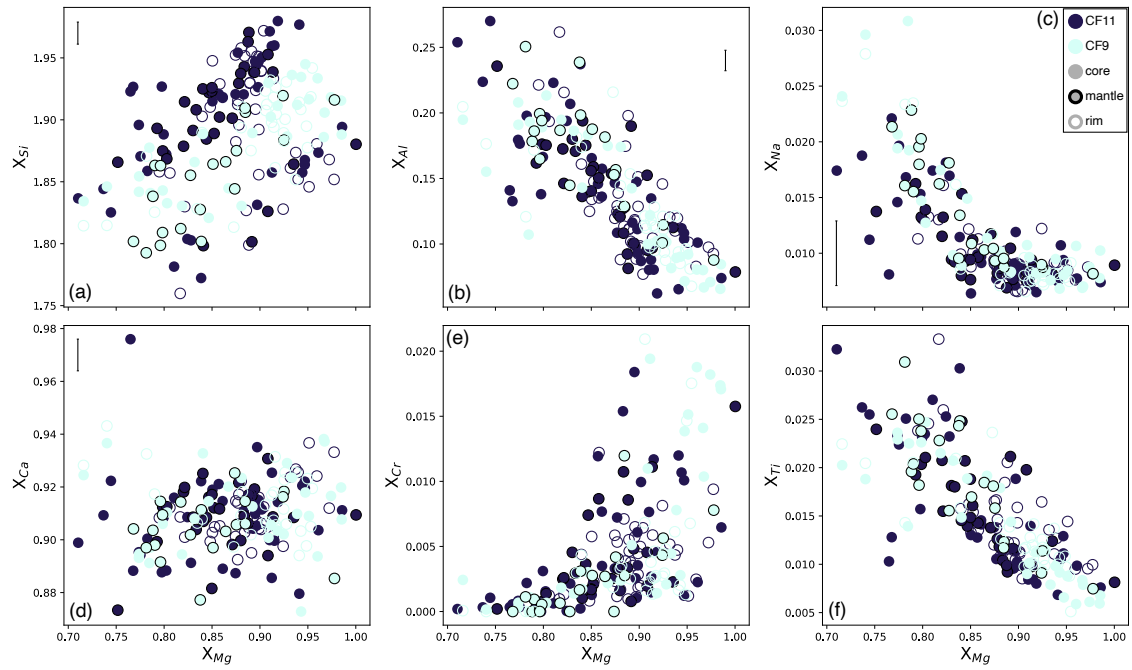


Figure A3.3: Clinopyroxene compositions from the two Minopoli 2 samples. Crystal compositions were calculated on a 6 O basis, X denotes mole fraction. Characteristic 2σ uncertainties are shown or are less than the size of the data points.

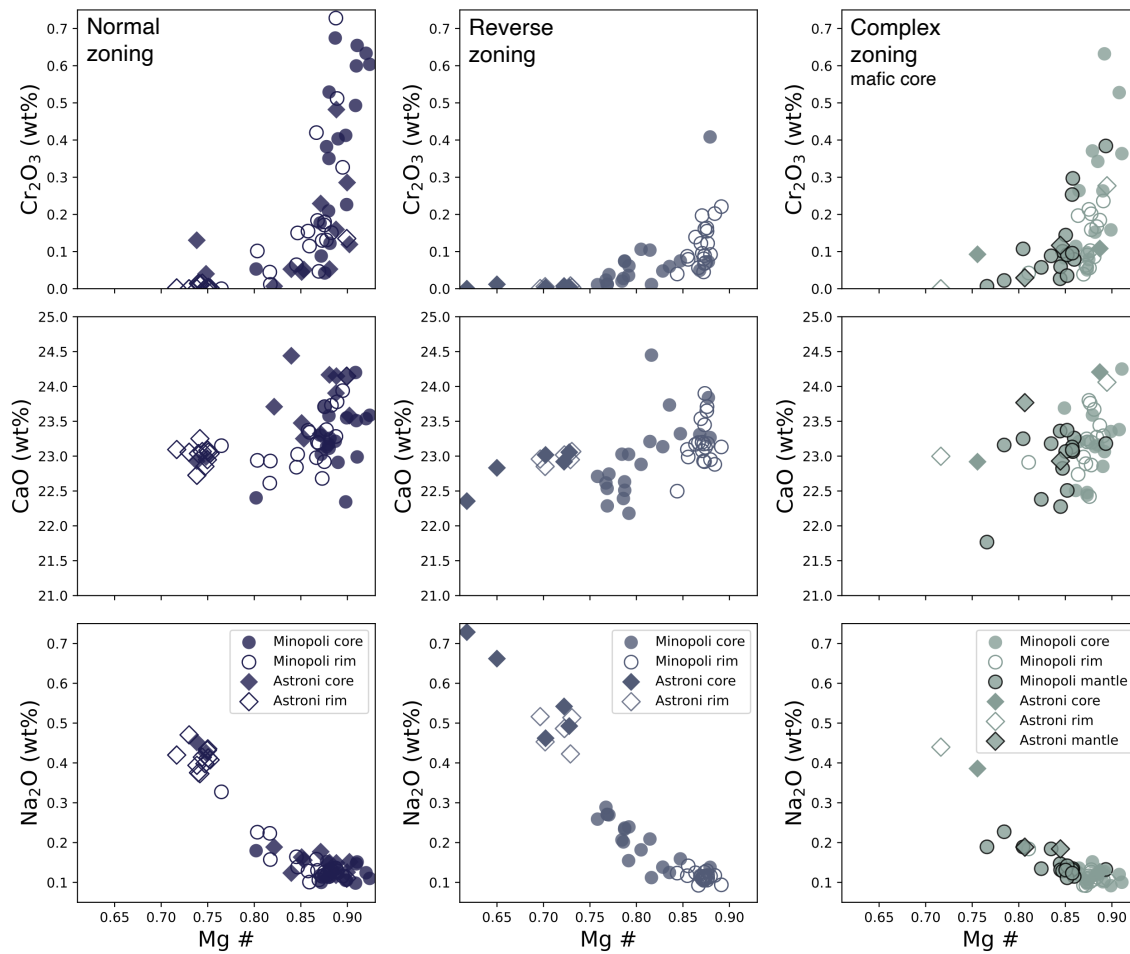


Figure A3.4: Clinopyroxene compositions from Minopoli and Astroni, separated by textural types. Circles are Minopoli 2 analyses, diamonds are Astroni 6. Markers with no fill are for analyses from the rim of the crystal; filled markers with black outlines are from the mantle and filled markers with no outline are from the core.

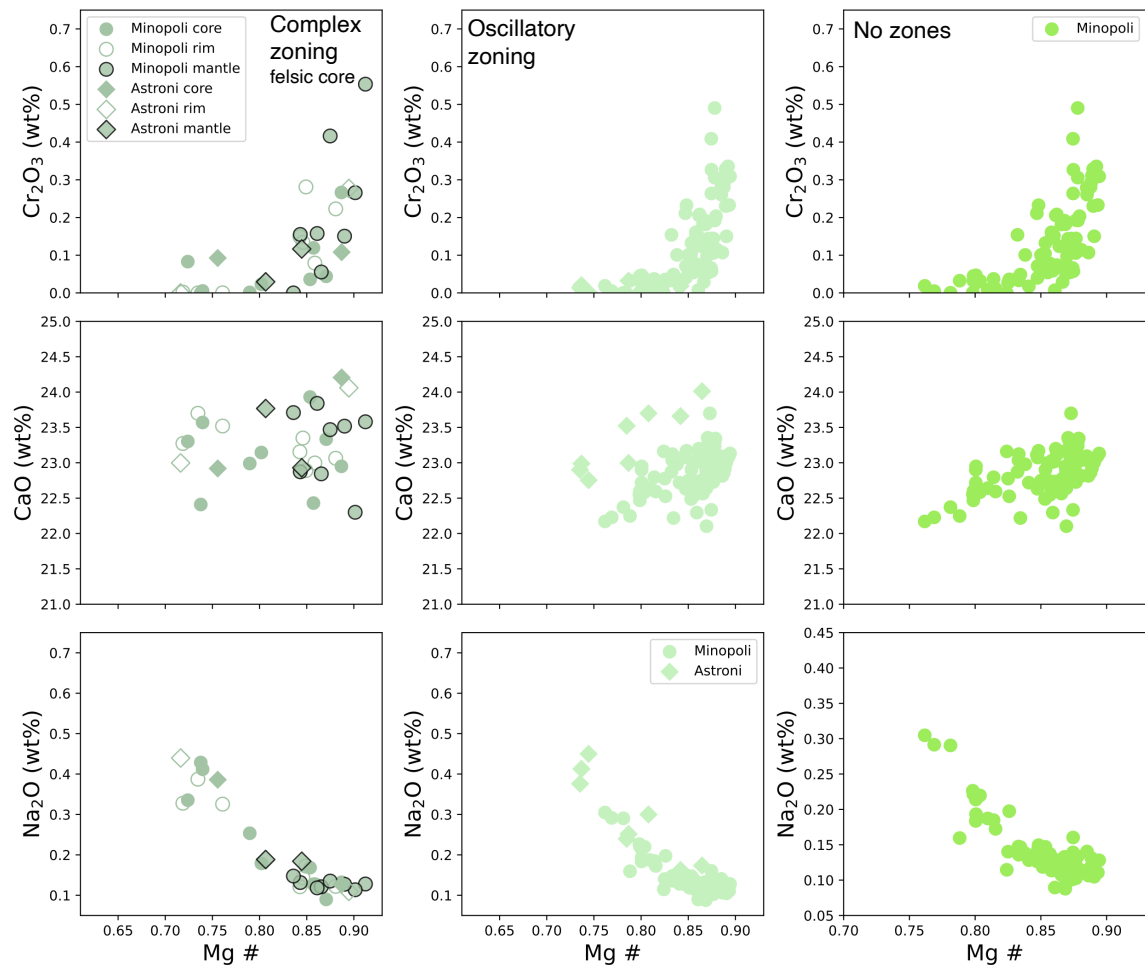
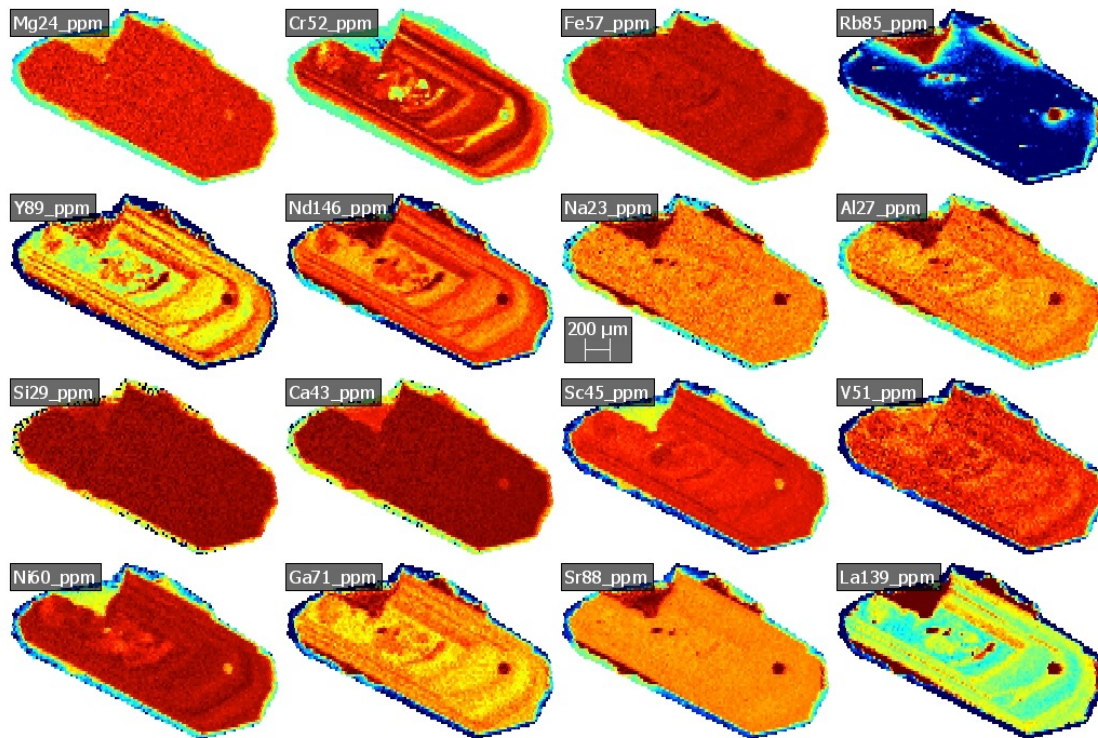


Figure A3.4 (continued)

Minopoli 2 CF9_2 cpx_65



Minopoli 2 CF11 cpx_79

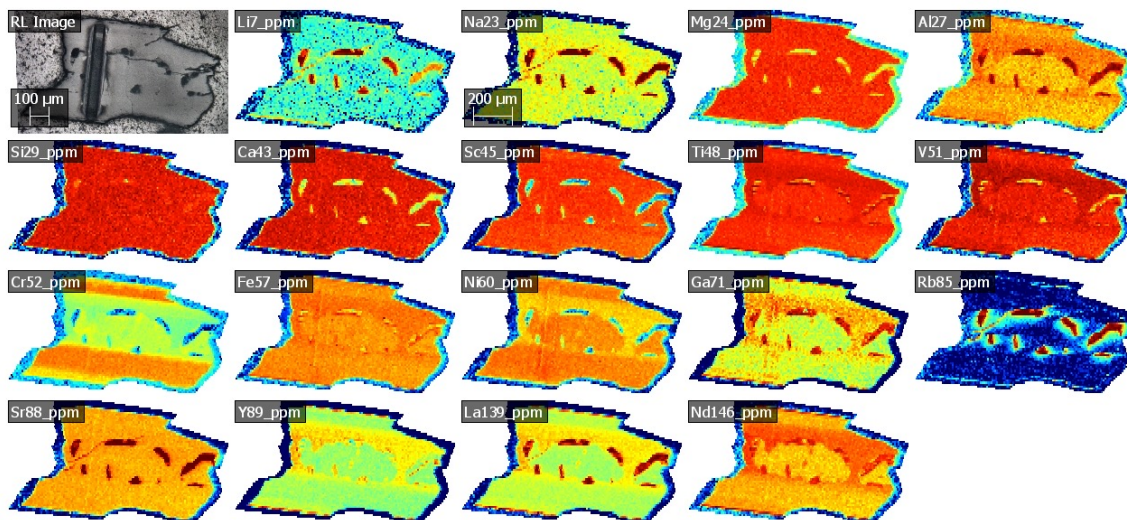


Figure A3.5: Trace element maps collected for Minopoli 2 and Astroni 6 clinopyroxenes. Maps are semi-quantitative, warmer (red – orange) colours represent higher concentrations of the specified element.

Minopoli 2 CF9_2 cpx_66

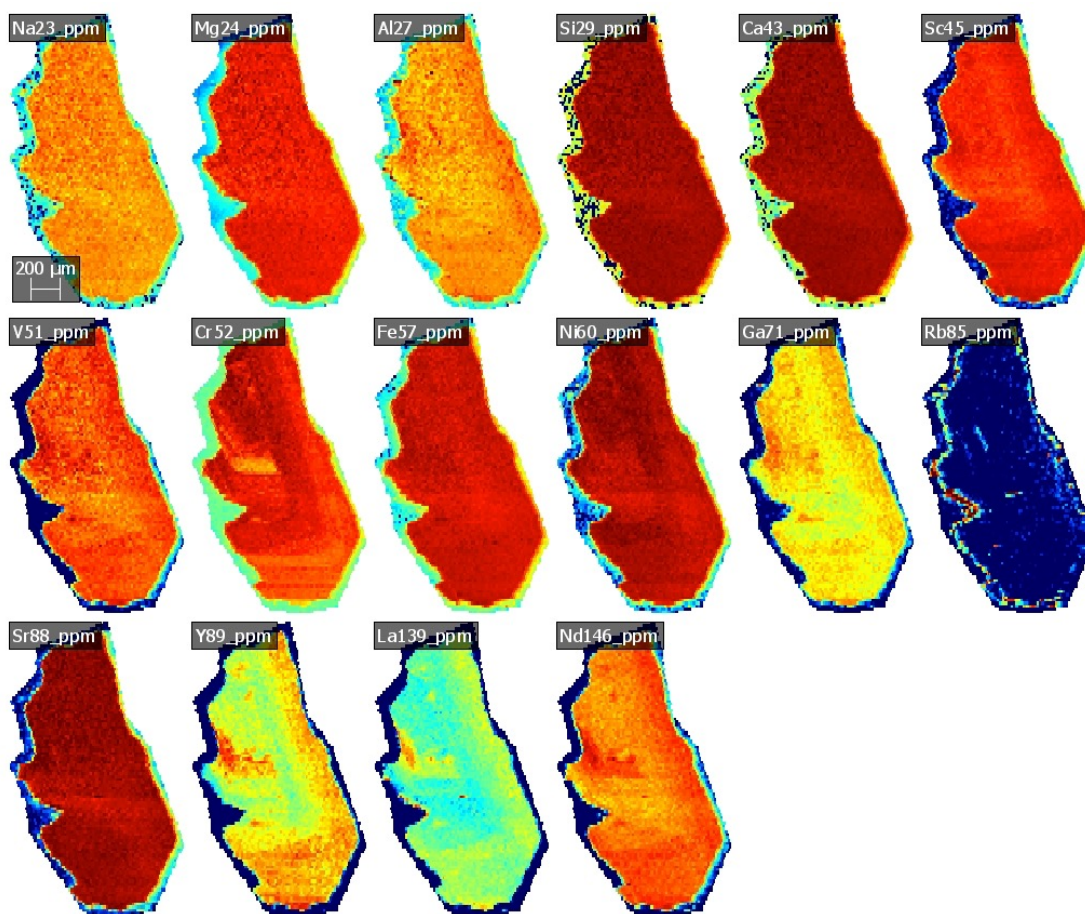


Figure A3.5 (continued)

Minopoli 2 CF9_2 cpx_53

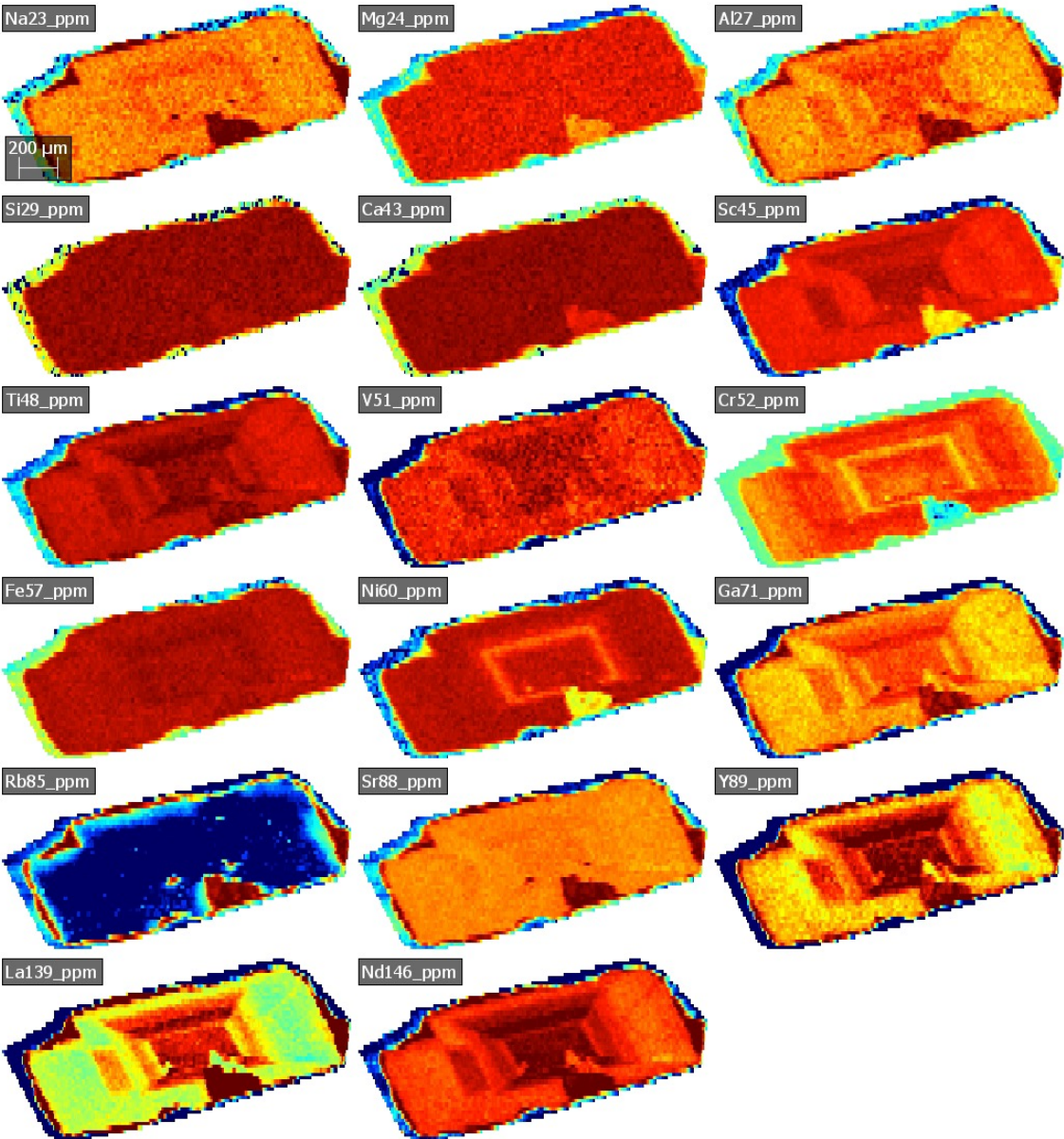
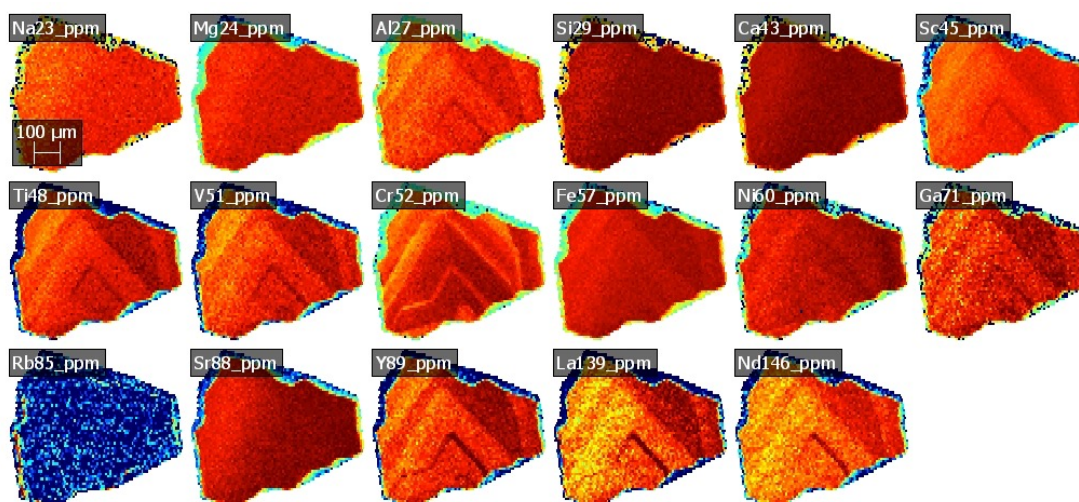


Figure A3.5 (continued)

Minopoli 2 CF11 cpx_157



Minopoli 2 CF11 cpx_26

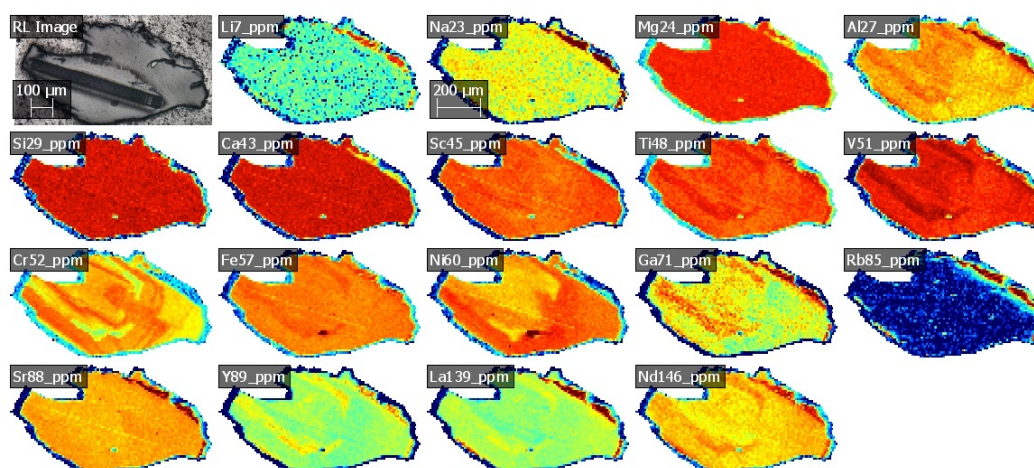
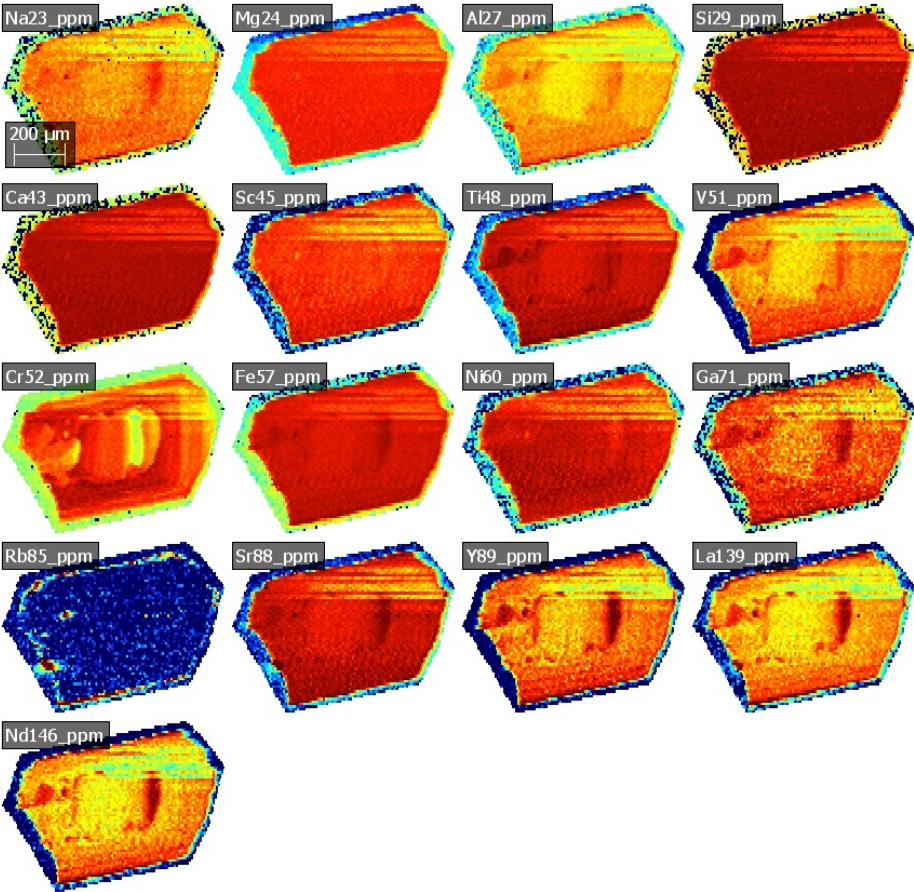


Figure A3.5 (continued)

Minopoli 2 CF11 cpx_89



Minopoli 2 CF11 cpx_102

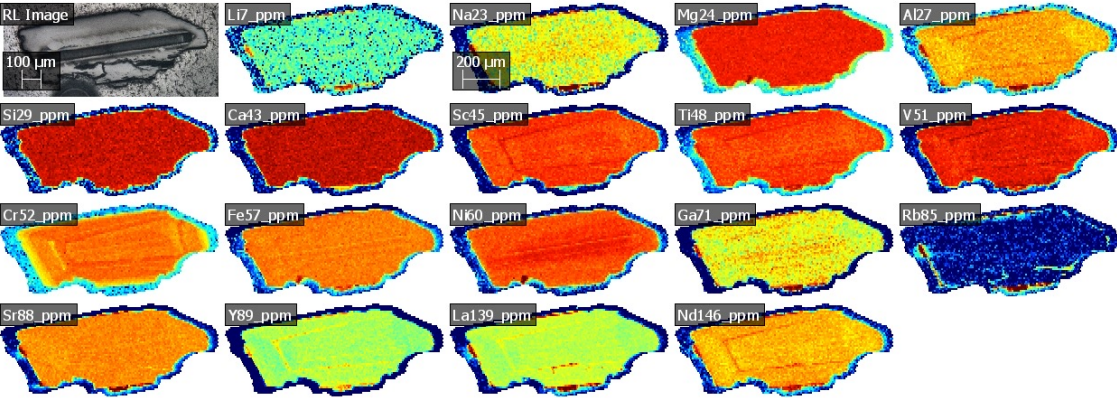
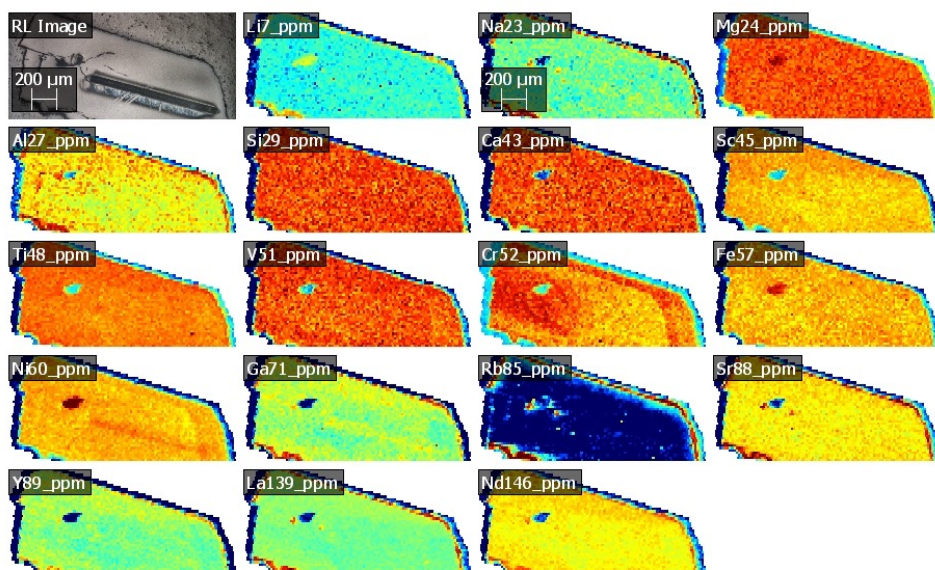


Figure A3.5 (continued)

Minopoli 2 CF9_2 cpx_62



Minopoli 2 CF9_4 cpx_11

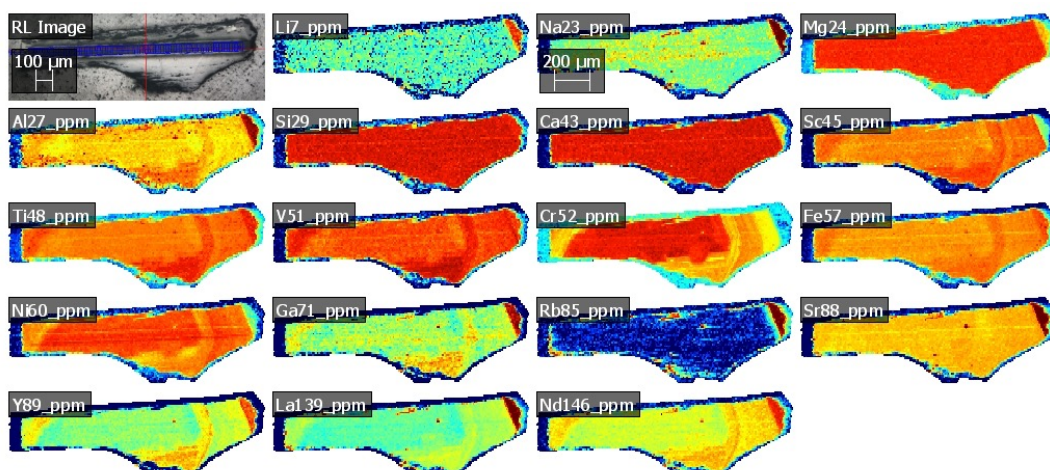


Figure A3.5 (continued)

Minopoli 2 CF9_3 cpx_68

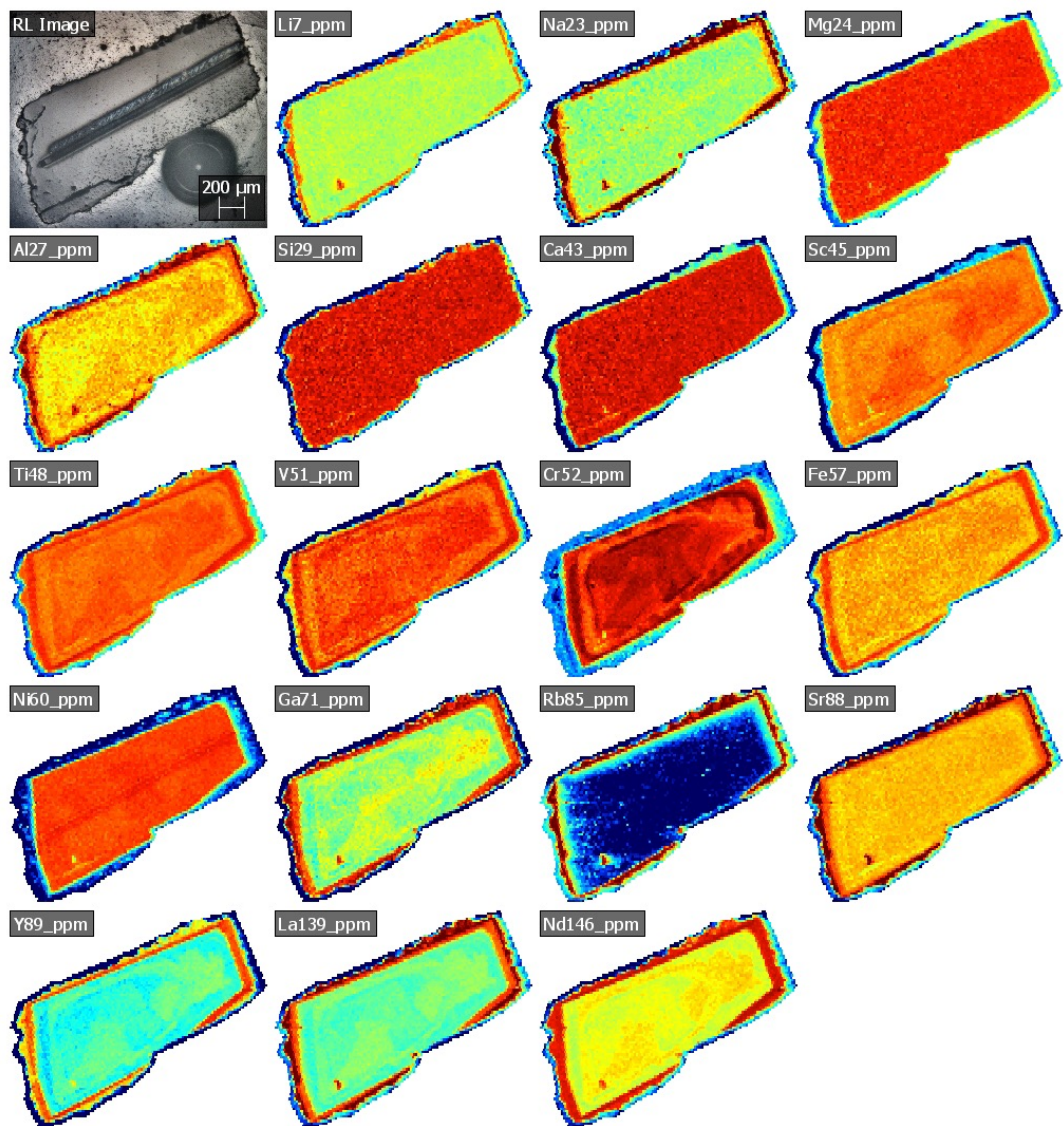


Figure A3.5 (continued)

Minopoli 2 CF9_4 cpx_48

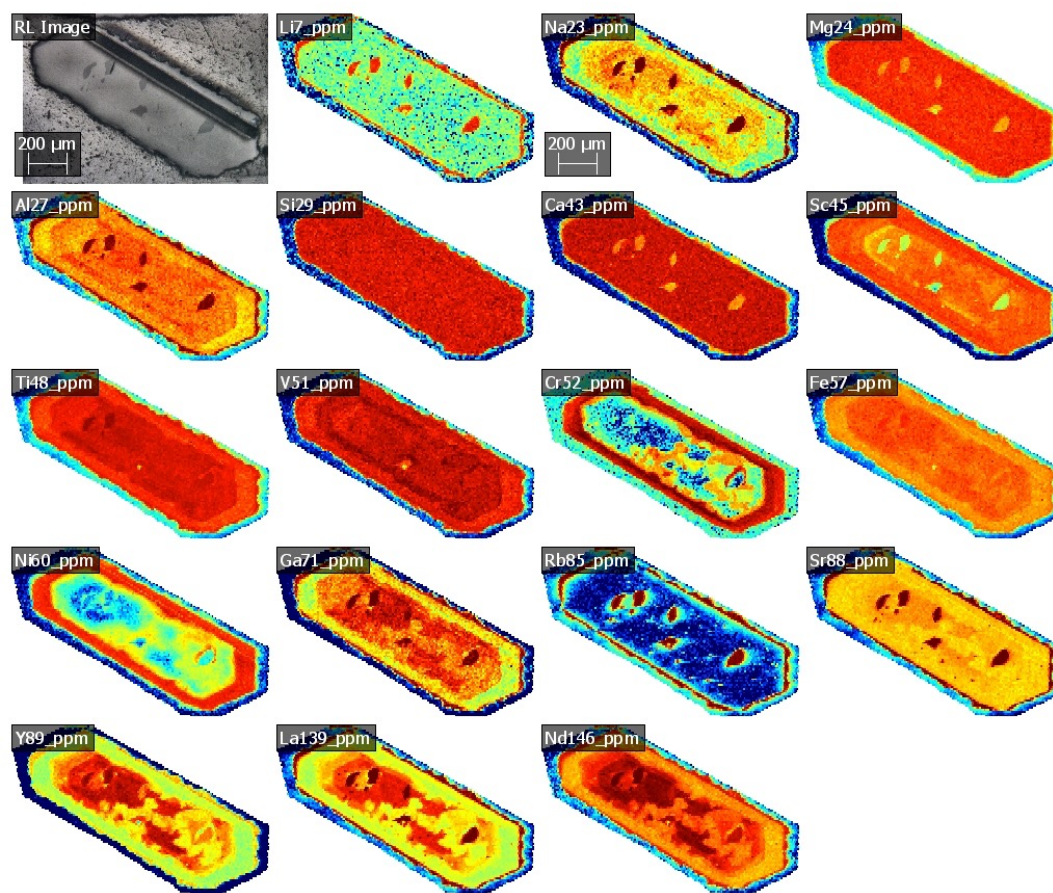
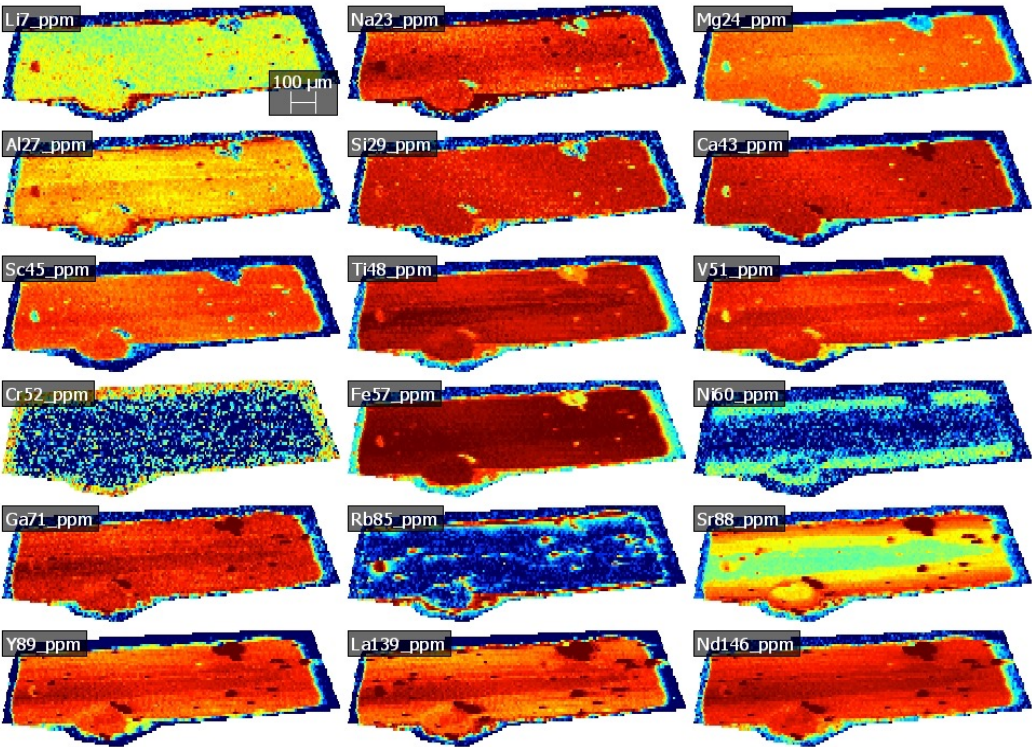


Figure A3.5 (continued)

Astroni 6 CF78 cpx_20



Astroni 6 CF78 cpx_1

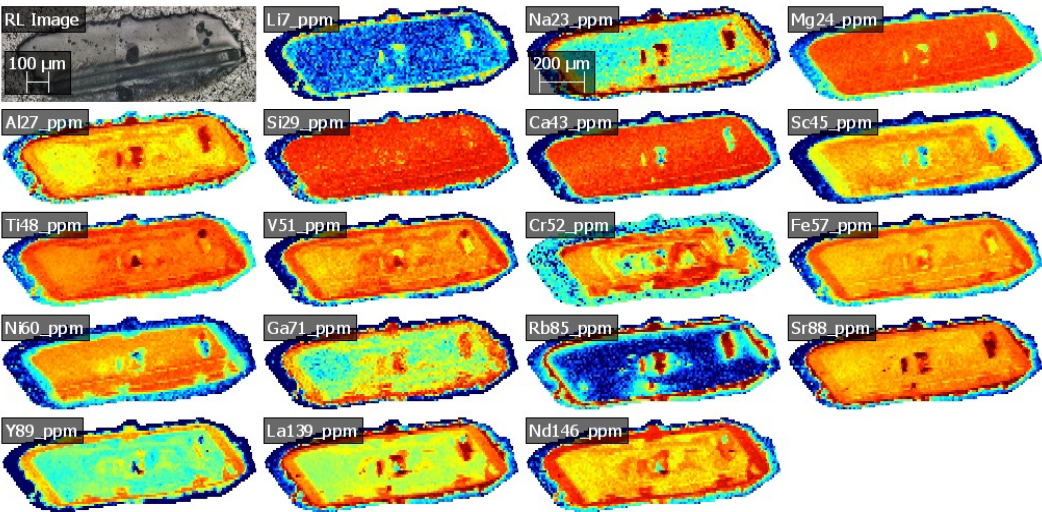


Figure A3.5 (continued)

Astroni 6 CF78 cpx_3

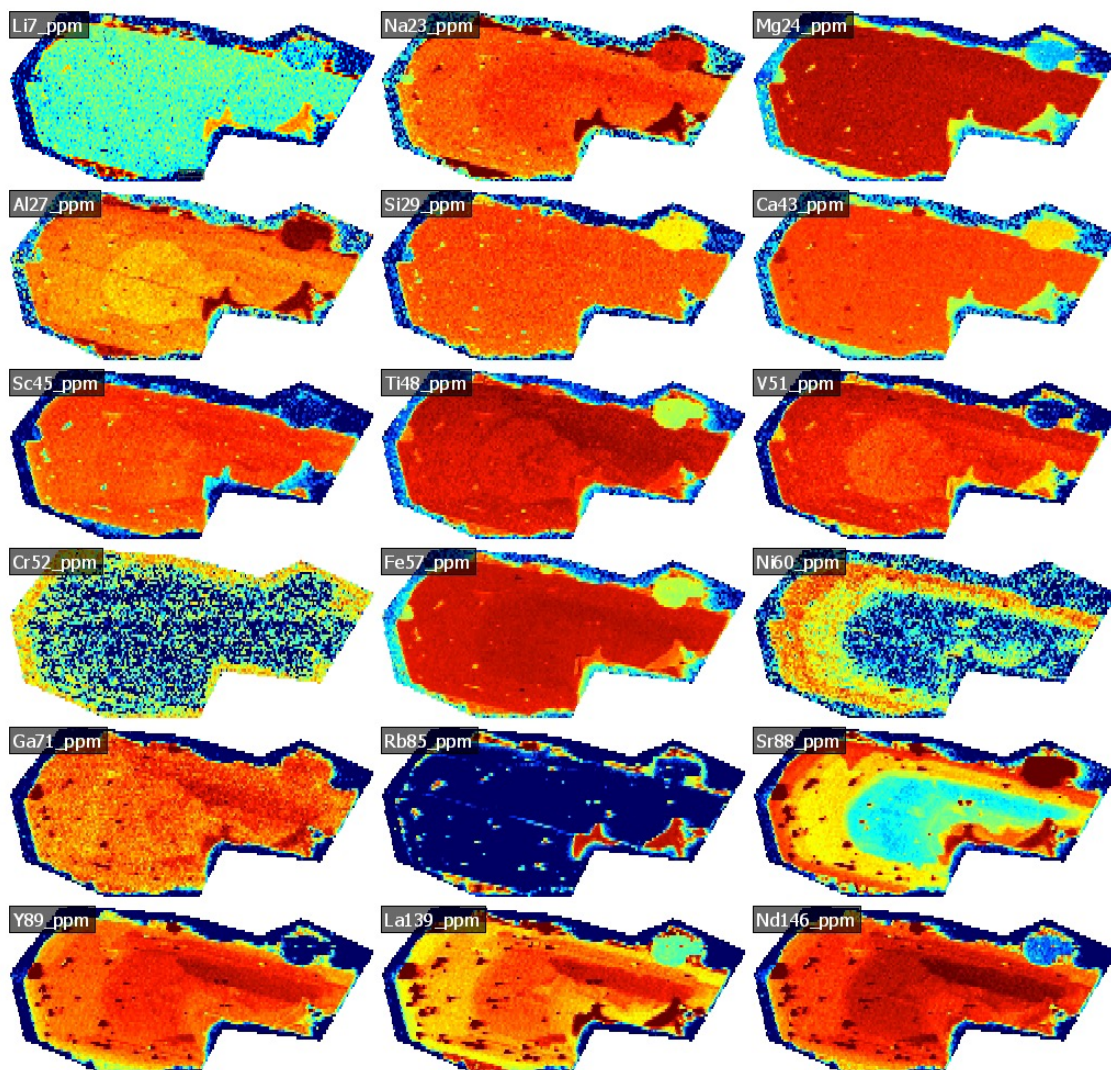
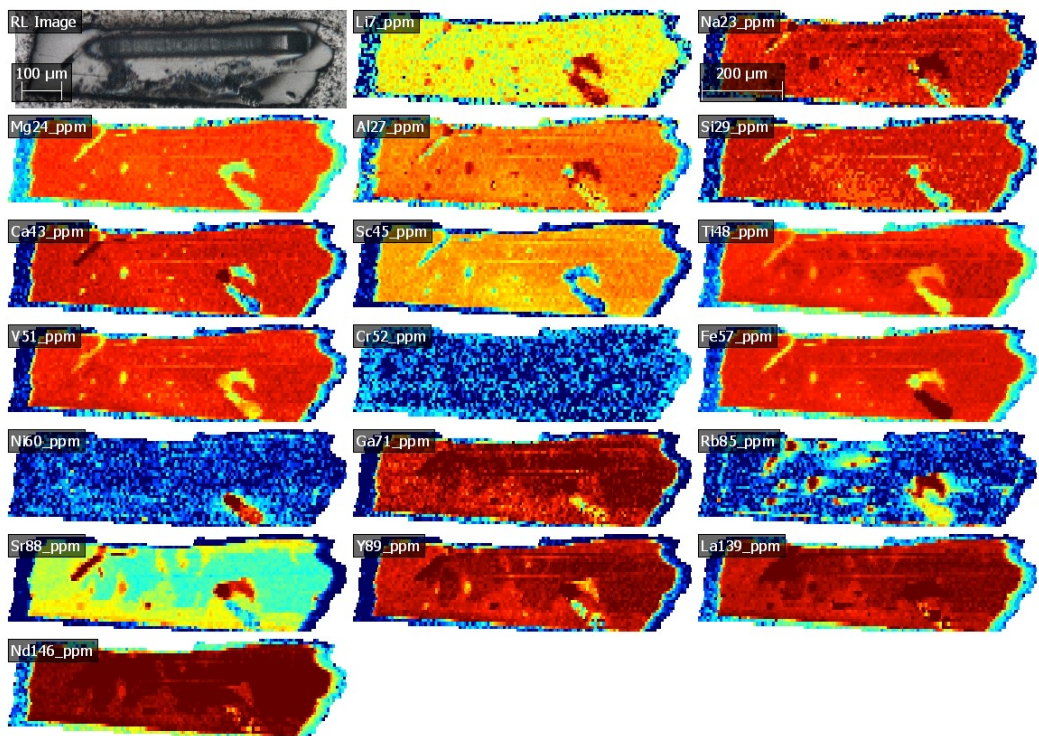


Figure A3.5 (continued)

Astroni 6 CF78 cpx_113



Astroni 6 CF78 cpx_75

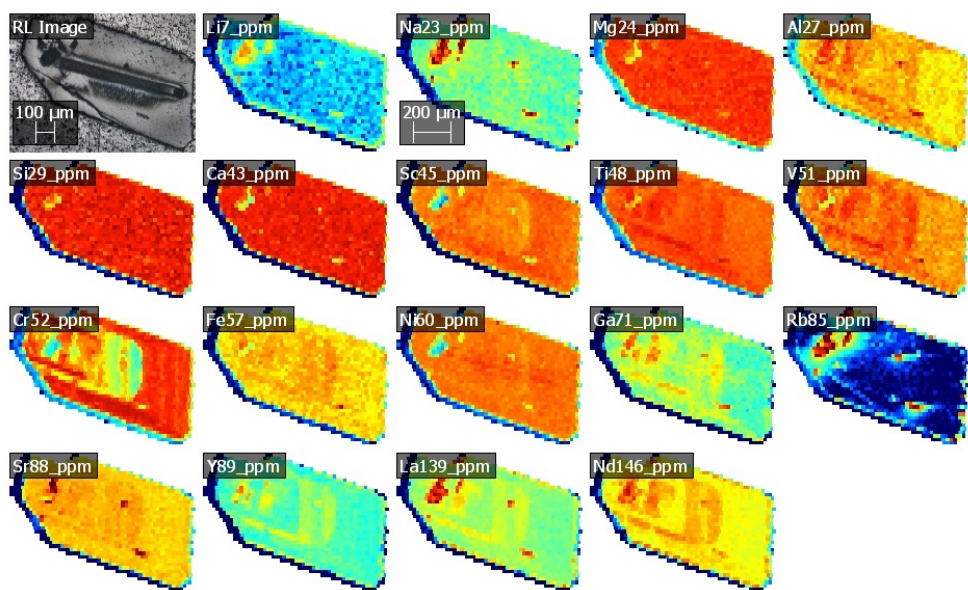


Figure A3.5 (continued)

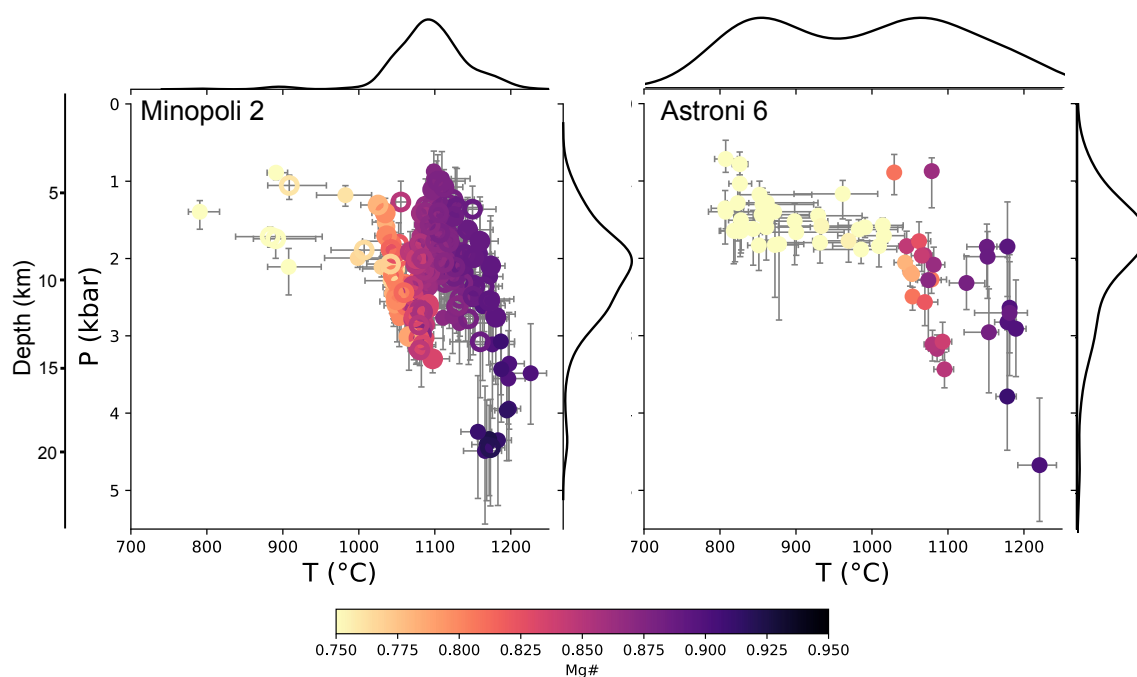


Figure A3.6: Temperature and pressure estimates from Minopoli 2 and Astroni 6 clinopyroxene analyses calculated using the machine learning thermobarometer of Ágreda-López et al. (2024). Root mean square errors for the thermobarometer are 56 °C and 2.5 kbar, error bars shown in the plot represent 2 σ errors resulting from analytical uncertainty. Pressure estimates have been converted to depth assuming crustal density of 2.3 g/cm³ from Rosi and Sbrana (1987). Points are coloured according to Mg# of the clinopyroxene, filled points represent measurements of crystal cores and outlined points are from crystal rims.

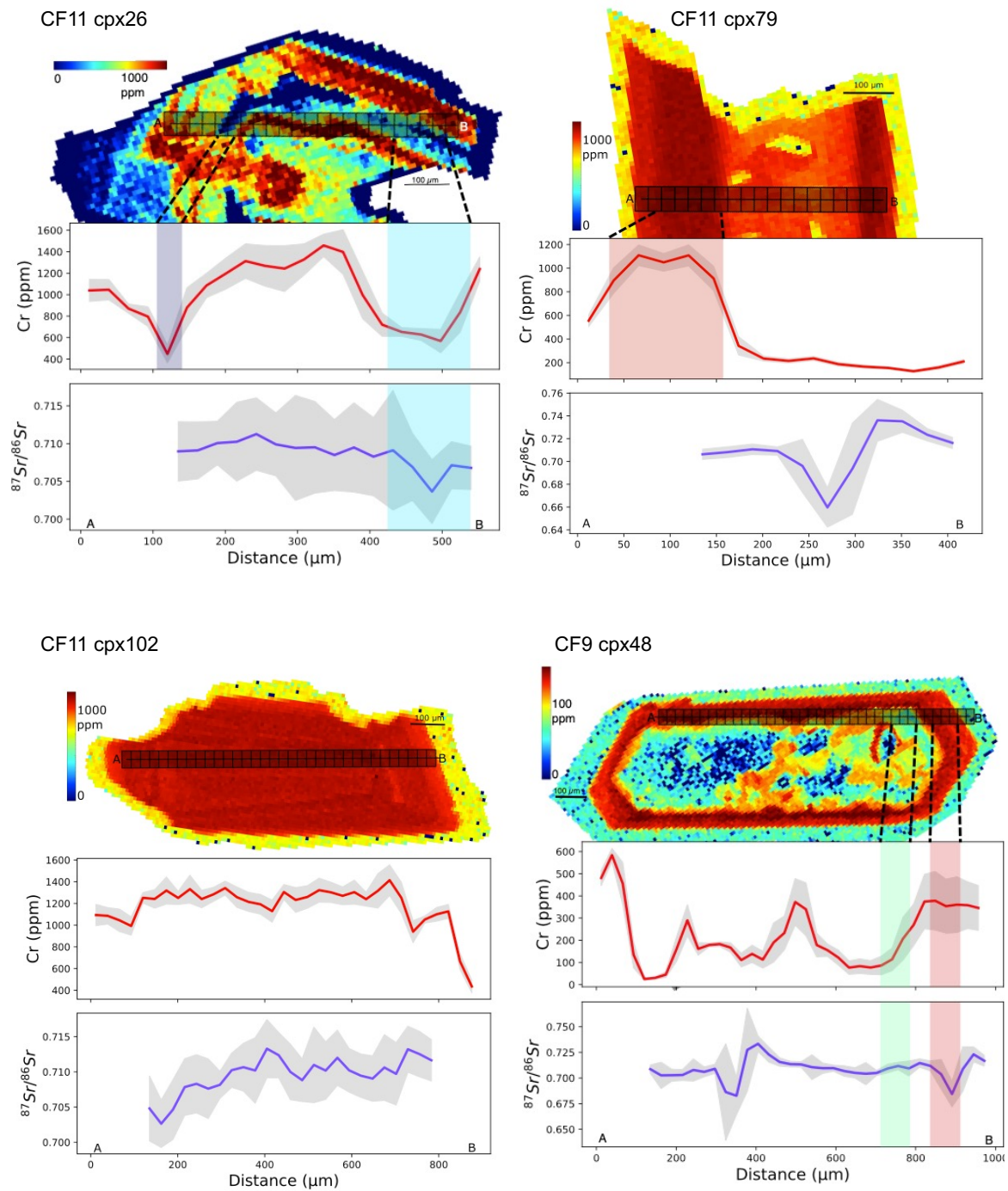
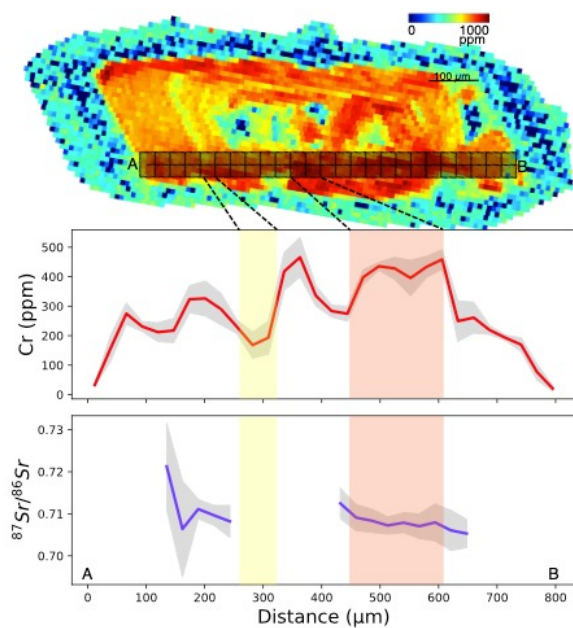
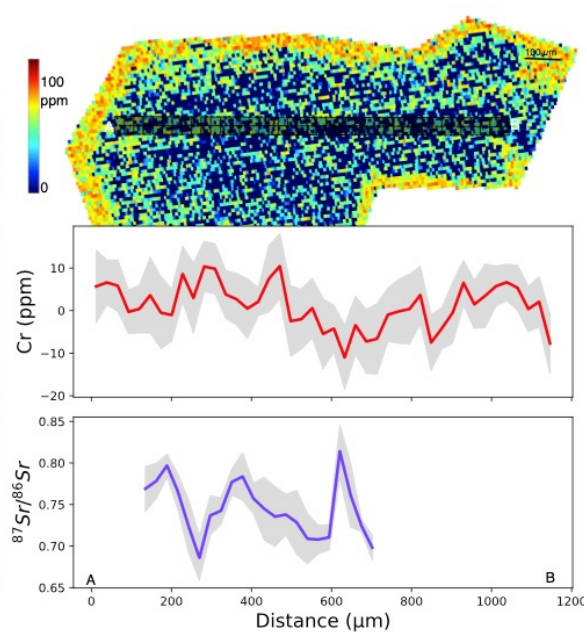


Figure A3.7: Chromium trace element maps of selected clinopyroxenes showing Cr and Sr-isotope variation across the crystal. $^{87}\text{Sr}/^{86}\text{Sr}$ variation was measured on core-to-rim transects across the crystal. Chromium concentrations were extracted from trace element maps of the crystal, following the same transect used in isotopic analysis. Zones identified in the Cr element maps are indicated on the plots by coloured bars. The 9-rolling mean of $^{87}\text{Sr}/^{86}\text{Sr}$ measurements are plotted, with the grey region on the plots represents 2 σ uncertainties on the measurements.

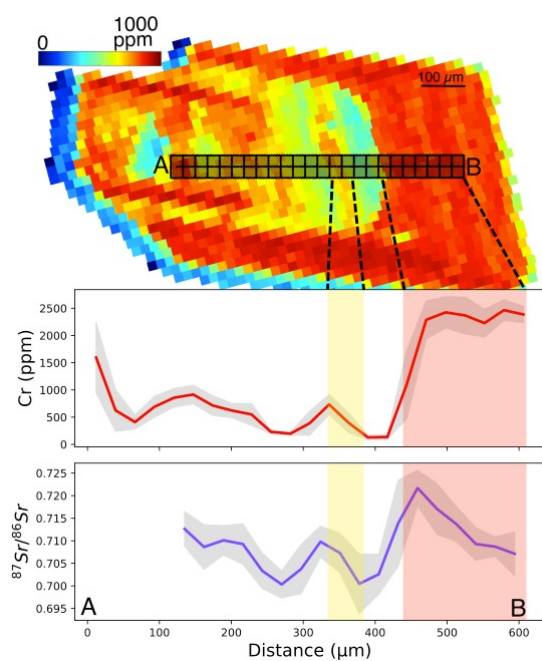
CF78 cpx1



CF78 cpx3



CF78 cpx75



CF9 cpx62

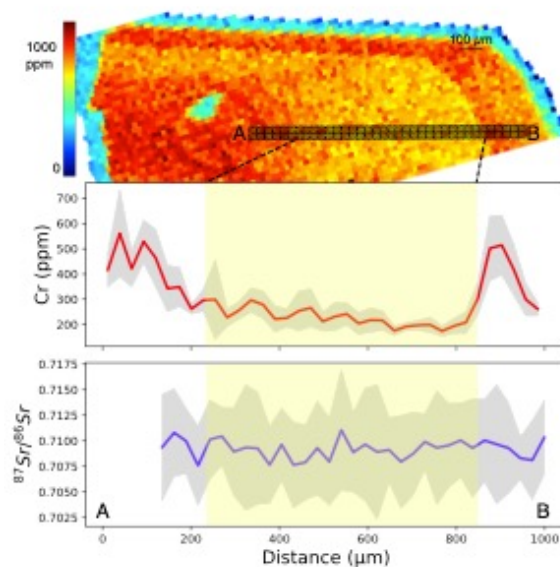
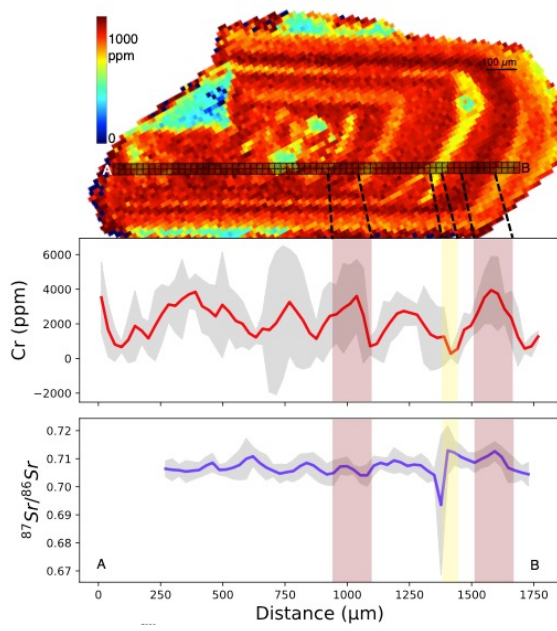
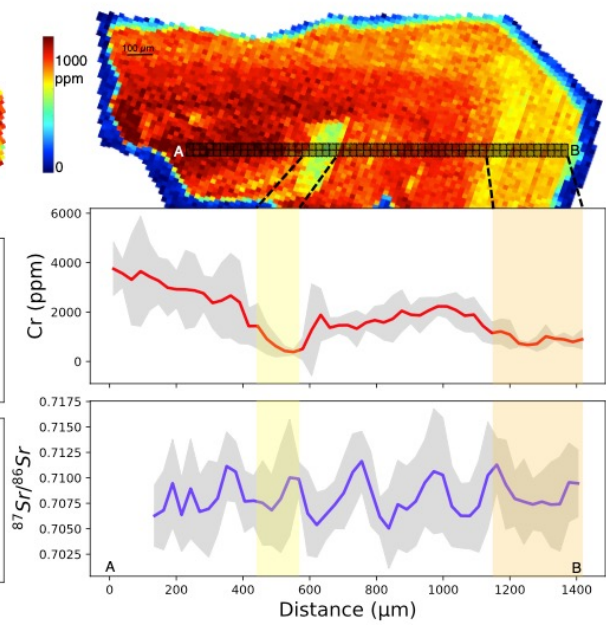


Figure A3.7 (continued)

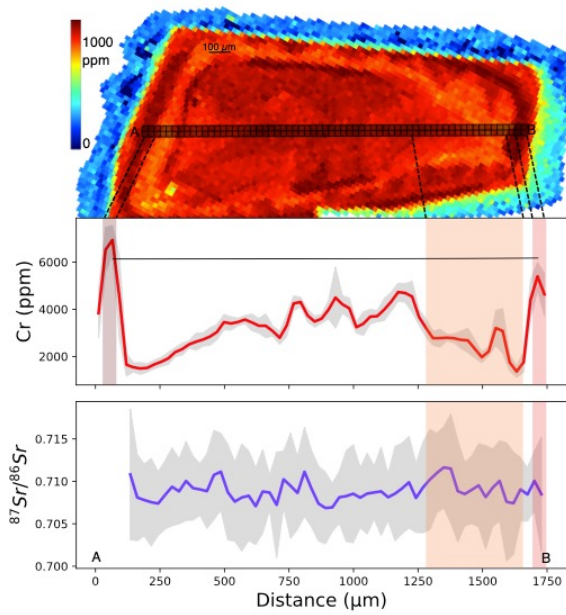
CF9 cpx65



CF9 cpx66



CF9 cpx68



CF9 cpx11

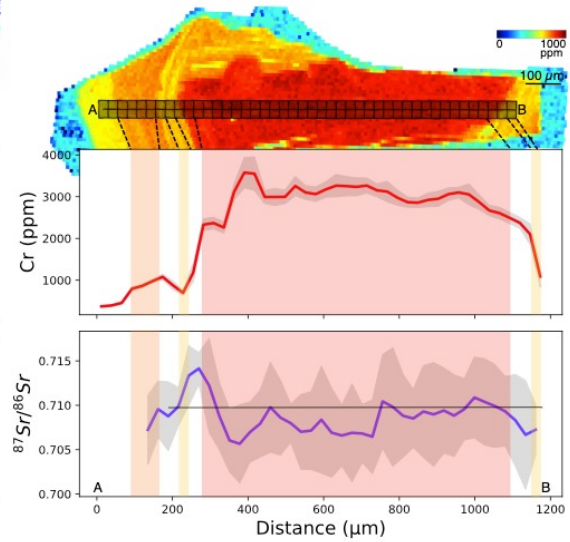


Figure A3.7 (continued)

Appendix 4

Conference abstracts

4.1 Volcanic and Magmatic Studies Group (VMSG), Manchester (Virtual), January 2022

Poster: The impact of mush assimilation on magma evolution at the Campi Flegrei caldera, Italy

Fay Amstutz^{1*}, Michael Stock¹, Victoria Smith², Roberto Isaia³

¹Department of Geology, Trinity College Dublin, Dublin 2, Ireland. ²School of Archaeology, University of Oxford, Oxford, UK. ³Instituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Naples, Italy.

The recent conceptual shift from understanding of sub-volcanic magma systems as liquid-dominated magma chambers to transcrustal mush zones raises important questions about the interaction between ascending magmas and magma residues in the crust. While mushes and ascending magmas may originate from a common source and be compositionally related, mush zones can exist within the crust for millennia, attaining a high degree of compositional heterogeneity. Furthermore, mushes are poorly consolidated and could be easily assimilated into ascending magmas than ridged country rock. While assimilated, mush-derived crystals and melts are difficult to identify in erupted products, they could exert an important control on the compositional and rheological evolution of ascending magmas and thus the timing and style of eruptions.

Campi Flegrei (central Italy) provides an ideal location to assess how mush dynamics impact volcanism at the Earth's surface because it has produced ~60 eruptions in the past 15 kyr that span a wide range of styles and compositions, but the magmatic system has been active for >60 kyr and hosts a transcrustal mush zone. There have been three caldera forming

eruptions at Campi Flegrei in the last 40 ka (CI, ~40 kyr; MdMT, ~29 kyr; NYT, ~15 kyr), which define distinct cycles within the magmatic system. As major eruptions are associated with periods of mush zone reorganisation, following caldera eruptions there are systematic changes in composition and magma-mush interactions.

This project will determine the amount of pre-eruptive mush assimilation in sequential Campi Flegrei eruptions, correlating this with eruption frequency, style and composition. Our initial investigation of published whole rock and glass data show that successive eruptions follow a single liquid line of descent, but some whole-rock analyses plot with anomalous major element compositions, consistent with crystal accumulation, particularly potassium feldspar. Additionally, glass data record the eruption of compositionally distinct liquids that cannot be related by fractional crystallisation and may indicate mixing between ascending magmas and melts in the pore space of a mush. These data are being investigated using Rhyolite-MELTS models to identify temporal trends in the assimilation of mush components.

4.2 VMSG, London, UK, January 2023

Poster: Determining magma storage conditions at Campi Flegrei (Italy) through thermodynamic forward modelling

Amstutz F.¹, Stock M.¹, Smith V.², Isaia R.³

¹Department of Geology, Trinity College Dublin, Dublin 2, Ireland. ²School of Archaeology, University of Oxford, Oxford, UK. ³Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Naples, Italy. Campi Flegrei volcano (CF, central Italy) has produced >60 eruptions in the last 15 kyr. These span a wide range of eruptive styles (lava domes to explosive Plinian events) and compositions (basanites to phonolites) and occurred in different spatial/structural locations within a larger caldera system. Geophysical and petrological data support multi-level magma storage beneath CF, with post-15 kyr eruptions primarily fed by mid- to lower-crustal storage zones and ephemeral sills at shallow levels. However, several authors have identified that

the major element compositions of CF magmas cannot be produced through simple fractional crystallisation, and instead suggest that country rock assimilation must play a significant role in controlling their compositional evolution.

The Rhyolite-MELTS software package allows thermodynamic modelling of phase equilibria in hydrous silicic systems and has been used previously to constrain the range of intensive variables (i.e. magma storage conditions) which could produce the observed compositional diversity of pre-15 kyr CF eruption deposits. Following this, we ran >2000 Rhyolite-MELTS models of fractional crystallisation, with starting compositions chosen from the most primitive glass compositions measured in post-15 kyr CF deposits. We varied the model pressure (from 50 to 500 MPa), initial water content (from 0.5 to 6 wt%) and oxygen fugacity (from QFM-2 to +3). We built on recent studies to statistically assess the fit between our model outputs and a literature composition of glass analyses from recent CF eruptions. This allowed us to identify a set of intensive variables which produced the best fit and hence represent the most likely conditions of natural magma storage. Dividing eruptions into different time periods and locations within the CF caldera allows us to place spatial and temporal constraints on variations in magma storage conditions.

We find that CF eruptions are best produced by models with oxygen fugacity at QFM to QFM +1, initial water contents of 3 – 4 wt% and pressures of 300 to 500 MPa, although best-fit conditions vary across the caldera. However, our results are consistent with previous studies in failing to fully reproduce the diversity of CF magma compositions for all elements through fractional crystallisation and highlight the important role of country rock assimilation. More advanced thermodynamic models can predict how assimilating different types/quantities of crustal material impact phase equilibria during magma evolution and are currently being incorporated into our investigation. As with other storage conditions, the results of these models will be used to identify spatial variations in assimilation dynamics at

different times and in different locations around the caldera, demonstrating how crustal assimilation plays an important role in dictating the timing and style of eruptions.

4.3 VMSG, Bristol, UK, January 2024

Poster: Isotopic constraints on volcano tectonically controlled assimilation at Campi Flegrei caldera.

Fay Amstutz¹, Michael Stock¹, Victoria Smith², Roberto Isaia³, Stefano Vitale⁴, Adrian Boyce⁵, David van Acken⁶, J. Stephen Daly⁶.

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Campi Flegrei volcano, central Italy, has produced >60 eruptions since the last caldera forming eruption at 15 kyr. These span a wide range of eruptive styles (lava domes to Plinian events) and compositions (basanites to phonolites). These eruptions occurred in different spatial/structural locations within the larger caldera system, with early vents often located on the structural boundary of the pre-existing caldera system and later eruptions migrating towards the centre of the caldera. Geophysical and petrological data support multi-level magma storage beneath Campi Flegrei, with post-15 kyr eruptions primarily fed by mid- to lower-crustal storage zones and ephemeral shallow sills. Several authors have identified that the major element compositions of Campi Flegrei magmas cannot be produced through simple fractional crystallisation, and instead suggest that country rock assimilation must play a significant role in controlling their compositional evolution. Despite this, the role of assimilation has yet to be systematically investigated in post-15 kyr eruptions, and the type/composition of the assimilant and extent of contamination are poorly defined.

The isotopic composition of volcanic rocks can provide insights into mantle and crustal processes prior to their final ascent and eruption. In particular, combined radiogenic and stable isotopes afford unique insights into the type and extent of crustal assimilation. In this study, we characterised the oxygen, strontium and neodymium isotopic compositions of mineral and glass separates from post-15 kyr Campi Flegrei eruptions alongside potential basement rocks. The eruptions cover the full range of spatial, temporal, and compositional variability to assess the crustal controls on assimilation dynamics.

We find variability in the $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ compositions of post-15 kyr Campi Flegrei eruptions, outside the range expected for typical mantle-derived magmas evolving through fractional crystallisation. Instead, our data point to an important role of assimilation in the Campi Flegrei sub-volcanic system and differences in the isotopic composition of individual eruptions attest to variations in either the amount or type of assimilated material. Isotopic differences correlate with the vent location within the pre-existing caldera structure; eruptions along caldera rim faults have isotopic compositions which deviate further from typical mantle source values than those erupted from the centre of the caldera or along regional tectonic faults, consistent with more extensive assimilation. Comparison with the isotopic compositions of potential basement rocks suggest that Hercynian metamorphic basement or shallow flysch sequences are the most likely crustal contaminants at Campi Flegrei, in contrast with the extensive limestone assimilation at nearby Vesuvius.

4.4 VMSG, Dublin, Ireland, January 2025

Talk: Volcano-tectonic controls on magma evolution at Campi Flegrei, a long-lived caldera system.

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Campi Flegrei volcano (southern Italy) is one of the most hazardous volcanoes on Earth, having produced >70 eruptions in the past 15 kyr and currently showing significant signs of unrest within a densely populated part of Europe. Eruptions at Campi Flegrei in the last 15 kyr span a wide range of eruptive styles (lava domes to Plinian events) and compositions (basanites to phonolites) which broadly correlate with the different spatial/structural locations of vents within the larger caldera system. Eruptions that followed the last caldera forming eruption at 15 ka were often mafic and from vents located on caldera rim faults, while the vents for most eruptions in the last 5.5 kyr migrated towards the centre of the caldera and extended to more evolved compositions. The structural setting of vents also correlates with variability in the glass O, Sr, Nd, and Pb isotope composition of the erupted products: eruptions along caldera rim faults have isotopic compositions which deviate further from typical mantle source values than those from the centre of the caldera or along regional tectonic faults.

Thermodynamic modelling of fractional crystallisation using the Rhyolite-MELTS software package allowed us to identify a set of intensive variables (pressure, initial water content, liquidus oxygen fugacity) which best reproduce the liquid line of descent of natural glass data from post-15 ka Campi Flegrei eruptions. Our results are consistent with previous studies in failing to fully reproduce the diversity of Campi Flegrei magmas for all major elements through fractional crystallisation alone and highlight the important role of country rock assimilation. This is consistent with variability in the isotopic composition of eruptions, outside the range expected for typical mantle-derived magmas evolving through fractional crystallisation. Isotopic variation between eruptions attests to variations in either the amount

or type of assimilated material; comparison with the isotopic compositions of potential basement rocks suggest that Palaeozoic metamorphic basement is the most likely contaminant of eruptions from caldera rim faults whereas syenitic restite is likely contaminating central and western caldera eruptions. Isotopic models of assimilation also suggest that whilst assimilation is coupled to fractional crystallisation in the evolved eruptions from the central caldera, it is decoupled in the more mafic caldera rim eruptions. Our results demonstrate a link between the spatial and structural location of vents within the Campi Flegrei caldera system and the processes operating within its magmatic system, suggesting magmatic evolution at long-lived caldera systems is inherently tied to the volcano-tectonic setting of vents. This provides important information for the assessment of future hazard scenarios at Campi Flegrei.

4.5 IAVCEI Scientific Assembly, Geneva, Switzerland, July 2025

Poster: Volcano-tectonic controls on magma evolution at Campi Flegrei, a long-lived caldera system.

Amstutz, F.M.¹, Stock, M.J.¹, Smith, V.C.², Isaia, R.³, Vitale, S.⁴, Carter, E.J.^{1,5}, Natale, J.⁶, Boyce, A.⁷, van Acken, D.⁸, Daly, J.S.⁸

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Campi Flegrei volcano (Italy) is one of the most hazardous volcanoes on Earth, having produced >70 eruptions in the past 15 kyr and currently showing signs of unrest within a densely populated region. Eruptions in the last 15 kyr span a range of eruptive styles and compositions, broadly correlating with different spatial/structural locations of vents within

the larger caldera system. Variability in glass O, Sr, Nd, and Pb isotope composition of erupted products also correlates with vent structural setting: eruptions along caldera rim faults have isotopic compositions which deviate further from typical mantle source values than those from the central or western caldera.

Rhyolite-MELTS thermodynamic modelling allowed identification of intensive variables (pressure, water content, oxygen fugacity) which best reproduce the liquid line of descent of glass data from post-15 ka Campi Flegrei eruptions. Our results are consistent with previous studies in failing to fully reproduce the compositional diversity of Campi Flegrei magmas through fractional crystallisation alone, highlighting the important role of country rock assimilation. Isotopic variation between eruptions, outside the range expected for typical mantle-derived magmas evolving through fractional crystallisation, attests to variations in the amount/type of assimilated material. Comparison with potential basement rocks suggests Palaeozoic metamorphic basement is the likely contaminant of eruptions from caldera rim faults whereas syenitic restite likely contaminates central and western caldera eruptions.

Our results demonstrate a link between vents' spatial/structural locations and processes operating within the magmatic system, suggesting magmatic evolution at long-lived caldera systems is inherently tied to the volcano-tectonic setting of vents.