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Trans-crustal magma storage in contrasting tectonic settings

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Abstract

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Magmatic plumbing systems comprise magma chambers, sheet intrusions, and conduits which link the Earth's deep interior with the Earth's surface. As such, they are the structural framework of magma transport and storage that is governed by complex physical and chemical processes in magma reservoirs and through the interaction of magma bodies with surrounding crustal rocks over timescales from hours to millions of years. These geological processes, in turn, play a vital role in controlling eruptive behaviour and the magnitude of associated volcanic eruptions that impact the environment as well as human society. Our understanding of the nature and location of magmatic processes and plumbing system architecture remains, however, fragmentary. This lack of knowledge can partly be attributed to limits regarding the spatial resolution of geophysical methods and partly to geochemical uncertainties and errors in associated models. Ongoing advances in analytical techniques increase spatial, temporal, and chemical resolution, hence enabling us to gather more detailed knowledge on the structure and dynamics of magmatic systems, especially for individual volcanoes, but also in respect to the long-term evolution of magmatic provinces and ultimately the Earth as a whole. This process-oriented thesis examines fossil and active magmatic plumbing systems in Iceland, Indonesia, Cameroon, and the Canary Islands by applying a combination of traditional and state-of-the-art petrological and geochemical methods, mineral(-melt) thermobarometric modelling, and isotopic analytical techniques. The results add valuable insights to the growing body of evidence for multi-tiered plumbing systems in a number of volcano-tectonic settings and underline the importance of shallow-level magma storage and its influence on magma evolution and hazardous volcanic eruptions.

Keywords: magma plumbing systems, thermobarometry, oxygen isotope analysis, shallow arc storage systems

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To my family
Mum, Dad, and Jessica

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **Geiger, H.**, Mattsson, T., Deegan, F.M., Troll, V.R., Burchardt, S., Gudmundsson, Ó., Tryggvason, A., Krumbholz, M. and Harris, C. (2016a) Magma plumbing for the 2014-2015 Holuhraun eruption, Iceland. *Geochemistry, Geophysics, Geosystems*, 17: 2953-2968.

II **Geiger, H.**, Barker, A.K. and Troll, V.R. (2016b) Locating the depth of magma supply for volcanic eruptions, insights from Mt. Cameroon. *Scientific Reports,* 6, 33629.

III Deegan, F.M., Whitehouse, M.J., Troll, V.R., Budd, D.A., Harris, C., **Geiger, H.** and Hålenius, U. (2016) Pyroxene standards for SIMS oxygen isotope analysis and their application to Merapi volcano, Sunda arc, Indonesia. *Chemical Geology,* 447: 1-10.

IV **Geiger, H.**, Troll, V.R., Jolis, E.M., Deegan, F.M., Harris, C., Hilton, D.R. and Freda, C. (2018). Multi-level magma plumbing at Agung and Batur volcanoes increases risk of hazardous eruptions. *Scientific Reports,* 8, 10547.

V Deegan, F.M., Troll, V.R. and **Geiger, H.** (2019) Forensic probe of Bali's great volcano, *Eos, Transactions, American Geophysical Union,* 100: 26-30.

VI **Geiger, H.**, Deegan, F.M., Harris, C. and Jensen, M. (in prep.) Felsic magma storage in the core of an ocean island (Gran Canaria, Canary Islands). *Manuscript.*

VII Weis, F., Troll, V.R., Deegan, F.M., **Geiger, H.**, Skogby, H. and Carracedo, J.C. (in prep.) Explosive ocean island volcanism explained by high magmatic water content in OIB magmas. *Manuscript.*

VIII Darmawan, H., Troll, V.R., Walter, T.R., Deegan, F.M., Seraphine, N., **Geiger, H.**, Heap, M.J., Harris, C. and Humaida, H. (in prep.) Mechanical weakening due to hydrothermal alteration leads to failure at andesitic volcanoes. *Manuscript.*

Additional publications

The author also contributed to the following popular science style articles that are included in the appendix.

I Deegan, F.M., Troll, V.R., Bédard, J.H., Evenchick, C.A., Dewing, K., Grasby, S., **Geiger, H.**, Freda, C., Misiti, V. and Mollo, S. (2016) The stiff upper LIP: investigating the High Arctic Large Igneous Province. *Geology Today*, 32: 92-98.

II Troll, V.R., Carracedo, J.C., Jägerup, B., Streng, M., Barker, A.K., Deegan, F.M., Perez-Torrado, F., Rodriguez-Gonzalez, A. and **Geiger, H.** (2017) Volcanic particles in agriculture and gardening. *Geology Today*, 33: 148-154.

III Troll, V.R., Rodriguez-Gonzalez, A., Deegan, F.M., Perez-Torrado, F.M., Carracedo, J.C., Thomaidis, K., **Geiger, H.** and Meade, F.C. (2019) Sacred ground; the Maipés necropolis of north-west Gran Canaria. *Geology Today,* 35: 55-62.

Personal Contributions

All of the papers and manuscripts in this thesis are the result of the combined efforts of various co-authors. My individual contributions to each paper are listed below:

Paper I: I majorly contributed to sample processing and preparation for analysis, and subsequent microprobe analysis. I performed the thermobarometric modelling and contributed to the petrographic and geochemical classification of the samples. Data discussion, figure preparation, and manuscript writing was carried out in collaboration with the key co-authors.

Paper II: This paper stems from an independent research project (15 ECTS credits) that I started during my MSc studies. During my PhD, I performed additional analysis and thermobarometric modelling with help from all co-authors. Data discussion, figure preparation, and manuscript writing was performed in collaboration with all co-authors.

Paper III: I performed the thermobarometric modelling and contributed to writing of the manuscript.

Paper IV: This project was initiated during my MSc studies. During my PhD, I acquired additional microprobe data and conducted stable isotope analysis. I carried out the thermobarometric modelling, petrography, geochemical classification of samples, and figure preparation. The manuscript was written in collaboration with Troll and Deegan, with input from all co-authors.

Paper V: I contributed to manuscript writing and produced the microscopy images.

Paper VI: I collected part of the samples in the field and produced the majority of the analytical data. Figure preparation, data interpretation and manuscript writing was carried out in close collaboration with Deegan.

Paper VII: I contributed to sample collection, preparation, analysis, as well as the thermobarometric modelling and manuscript writing.

Paper VIII: I contributed to sample preparation, petrography, microprobe analysis, and manuscript writing.

Contents

Abbreviations

FEG-EPMA	Field Emission Gun Electron Probe Microanalyser
FTIR	Fourier Transform Infrared Spectroscopy
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
InSAR	Interferometric Synthetic Aperture Radar
LF	Laser Fluorination
Moho	Mohorovičić Discontinuity
MORB	Mid-Ocean Ridge Basalt
OIB	Ocean Island Basalt
SEM	Scanning Electron Microscopy
SHARCS	Shallow Arc Storage Systems
SIMS	Secondary Ion Mass Spectrometry
SMOW	Standard Mean Ocean Water
WDS	Wavelength Dispersive Spectrometry
XRD	X-Ray Powder Diffraction

Introduction

The interest in volcanoes, and by extension their underground workings within magma plumbing systems, can be traced back as far as the ancient Greek and Roman civilizations. Early descriptions of volcanic and magmatic phenomena were, however, commonly interpreted in mythological terms rather than reflecting purely scientific observations. For example, in book 3 of his epic poem *Aeneid* (the legend of Aeneas who escapes from Troy to Italy and is ancestor of the Romans) the Roman writer Publius Vergilius Maro (70-19 B.C.), also known as Virgil, gives a vivid description of an eruption of Mount Etna on Sicily. According to Virgil, Etna "thunders with terrifying crashes, and now hurls forth to the sky a black cloud, smoking with pitch-black eddy and glowing ashes, and uplifts balls of flame and licks the stars – now violently vomits forth rocks, the mountain's uptorn entrails, and whirls molten stone skyward with a roar, and boils up from its lowest depths" (translation by Fairclough, 1994). Virgil credits these natural volcanic occurrences to Enceladus (the Titan Typhon in Greek mythology), who was defeated by Jupiter (Zeus) and buried beneath Etna. Every time the trapped Enceladus moves and breathes, the region around the volcano trembles and flames shoot up from the mountain. Many similar myths emerged in other volcanic regions and it thus comes as no surprise that the name "volcano" for erupting mountains around the world originated from the Roman god of fire, Vulcan, who works in his forge beneath the island of Volcano (Young 2003). Additionally, other natural causes for volcanic eruptions and their origin were also proposed by classical Greek and Roman writers, from theories about air movement and the resulting friction heating of rocks in subterranean voids, over volcanic fires being kindled by sulphur and fossil fuels deep inside the Earth (Sigurdsson 1999). Many of the ancient theories were still held during the Middle Ages when studies of volcanoes receded. Renewed interest in volcanic processes emerged in the sixteenth and seventeenth centuries, and among the scholars studying the origin and history of the globe was Athanasius Kircher (1602-1680), a German Roman Catholic priest who conducted his polymathic studies at the Jesuit College of Rome (Reilly, 1974). Kircher devoted the cosmography *Mundus Subterranean*, one of his 44 books, to understanding Earth's underground phenomena (Kircher 1665). It is in this book that a first concept resembling a magma plumbing system can be found (Figure 1a). The illustration shows a network of underground "fires" which erupt on the surface through volcanoes.

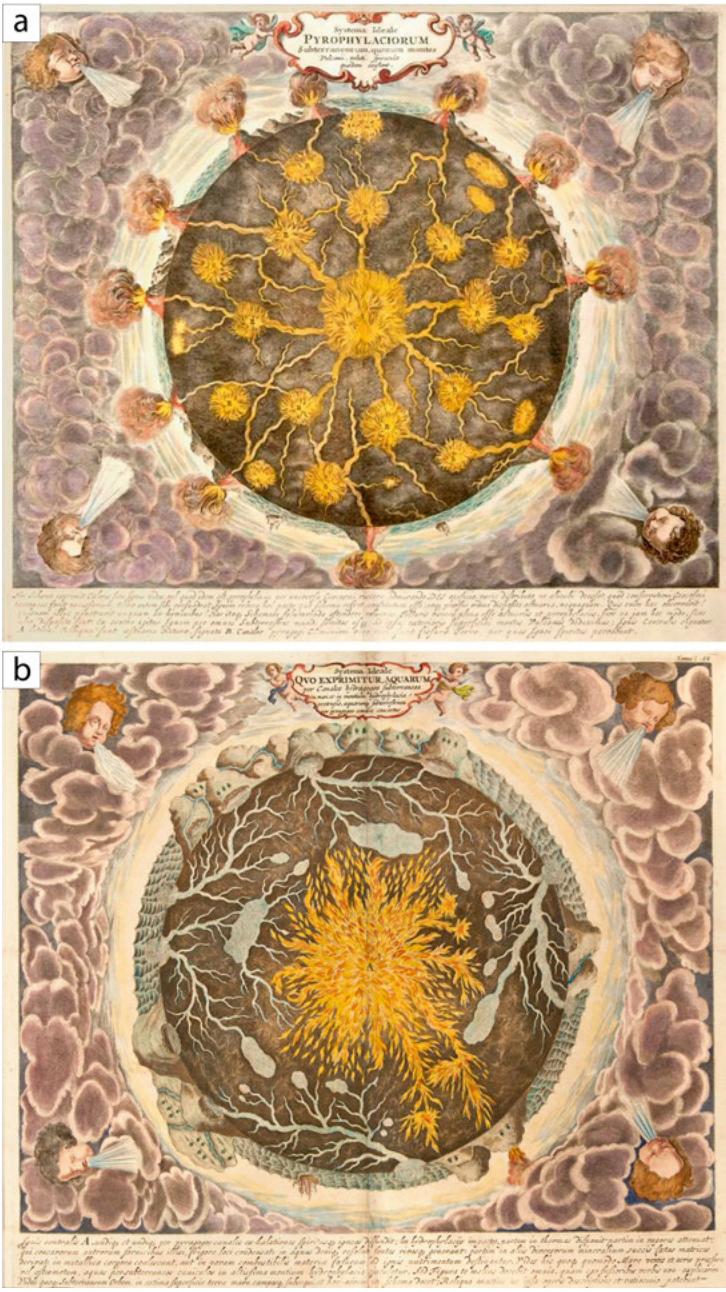


Figure 1. a) “Systema Ideale Pyrophylaciorum Subterraneorum” – Athanasius Kircher’s map of Earth’s volcanic system (colorized, Kircher 1665). Kircher postulated that the Earth has a central fire source in the core of the planet that is connected to the surface via various networks of tunnels and channels. b) “Systema Ideale Quo Exprimitur Aquarum” – Similar to the network of underground fires, Kircher imagined a system of underground rivers and seas that interacted with the system of fires (colorized, Kircher 1665).

However, Kircher believed that water formed a similar underground system and both fire and water "sweetly conspire together in mutual service" (Figure 1b; Kircher 1669). By the end of the eighteenth century, the concept of magma plumbing did not evolve much further than Kircher's ideas. Then, debate flared up as prominent followers of neptunism (e.g. Abraham Gottlob Werner (1749-1817)) and plutonism (e.g. James Hutton (1726-1797)) furiously debated the origin of basalt. By the 1830s, plutonism eventually prevailed through the works of Charles Lyell (1797-1875) and Alexander von Humboldt (1767-1835), and the igneous origin of basalt was universally accepted. This, in turn, also removed the notion of water playing a major role in the crystallisation of basalt and granite. By the time Daly wrote his summary paper on volcanic action in 1911 (*The Nature of Volcanic Action*) and Bowen's work on the evolution of igneous rocks (*The Evolution of the Igneous Rocks*, 1928), most fundamentals of modern concepts of magmatic systems had been introduced. Magmatic plumbing systems were initially viewed as a single, melt-dominated magma chamber that facilitated geochemical processes like magmatic differentiation and which supplied volcanic eruptions. These concepts became the main paradigm for igneous petrology and volcanology for the next century (see Sparks et al. 2019). Increasing understanding of igneous processes were often linked to and successfully explained by the magma chamber paradigm (reviewed in Sparks et al. 2019). However, geophysical methods precluded the proposed large magma chambers (e.g. Sinton and Detrick 1992). Instead, geophysical observations point to a zone of crystal mush with several pockets of magma located beneath a thin and narrow magma lens. Marsh (1996) defined this constellation of a shallow magma chamber with an underlying zone of crystal mush and mobile and ephemeral magma chambers as the "mush column". Further rapid improvement and development in analytical techniques and petrological modelling over the last few decades provided new insight into magma storage geometry and processes (reviewed in Cashman and Sparks 2013; Cashman et al. 2017; Putirka 2017). Thus, current thinking is shifting towards a concept of multi-level magmatic systems spread out throughout the crust (Figure 2; Dahren et al. 2012; Chadwick et al. 2013; Annen et al. 2015; Adam et al. 2016).

The aim of this thesis is to contribute to the current state of knowledge regarding the paradigm shift from a single magma chamber towards a multi-tiered system by characterising ancient and active magma plumbing systems in several contrasting volcano-tectonic settings through a combination of mineralogical, petrological, and geochemical methods, including mineral(-melt) thermobarometric modelling, and isotopic analytical techniques. Study areas include Iceland (hot-spot above a mid-ocean ridge), Cameroon (continental intraplate), the Canary Islands (oceanic hot-spot), and Indonesia (subduction zone). The findings presented in this thesis show that multi-tiered, polybaric magma residence is observed in all cases studied, and appears to exert a fundamental control on the specific eruptive behaviour of individual volcanoes.

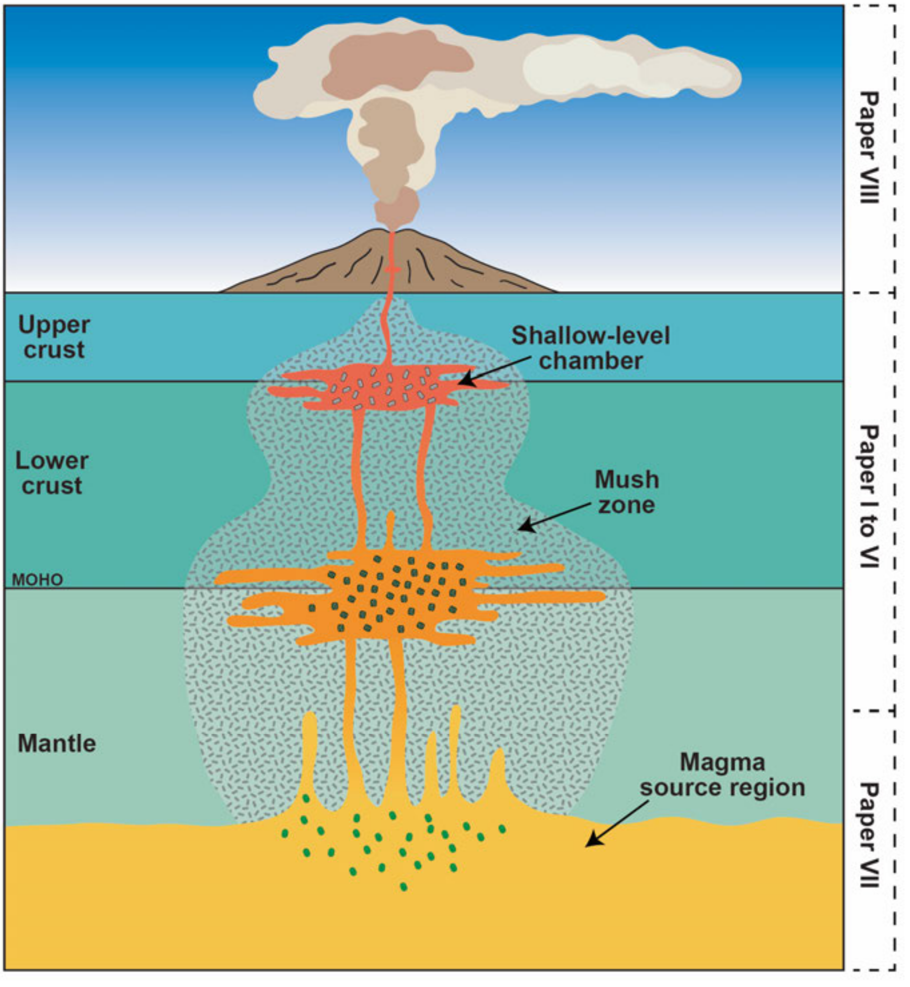


Figure 2. Representative illustration of a modern concept of a magmatic plumbing system. Note the different levels of magma storage throughout the crust, often associated with lithological boundaries (modified after Schmincke 2004). Papers in this thesis that study the different levels of magmatic plumbing systems are indicated on the right.

Methodology

Major and trace element analysis

For all papers, initial preparation of samples for geochemical analysis was carried out at Uppsala University. Weathered surfaces of rock samples were removed prior to crushing in a jaw crusher. Pristine rock chips were powdered and subsequently processed at Activation Laboratories Ltd., Ancaster, Canada, for major and trace element analysis. Sample powders were fused with lithium metaborate/tetraborate and digested in nitric acid prior to analysis. Major elements were measured by inductively coupled plasma optical emission spectrometry (ICP-OES), while trace elements were analysed by inductively coupled plasma mass spectrometry (ICP-MS). Data quality was verified by repeated analysis of internal reference materials. Detection limits are provided in the respective data tables and/or supplementary material of the papers in this thesis.

Elemental microanalysis

Mineral and groundmass compositions as well as scanning electron microscopy (SEM) images for all papers were acquired using the Jeol JXA8530F Hyperprobe Field Emission Gun Electron Probe Microanalyser (FEG-EPMA) and Cameca SX50 electron microprobe at Uppsala University. Wavelength-dispersive spectrometry (WDS) analyses were performed under standard operation conditions of 20 kV accelerating voltage and 15 nA beam current for the Cameca SX50 microprobe (see Andersson 1997 for full analytical details), and 15 kV accelerating voltage and 10 nA beam current for the Jeol JXA8530F Hyperprobe (see Paper IV for full analytical details). Mineral phases and groundmass were analysed using beam diameters of 1-5 µm and 10 µm, respectively, with counting times of 10 s on peaks and 5 s on ±background. Groundmass analyses were carried out in grids of varying size (depending on petrology of the sample) that were averaged to produce representable groundmass compositions.

Mineral (-melt) thermobarometry

Thermobarometric models estimate crystallisation pressure and temperature by applying calibrated equations to geochemical data of various mineral phases, glass, and whole rock compositions, or a combination thereof. Calculated pressures in combination with bedrock density provide a means of calculating depths of crystallisation and hence estimate potential magma storage depth. Commonly used models either make use of exchange reactions between minerals and co-existing melt (Putirka et al. 1996, 2003; Putirka 2005, 2008; Masotta et al. 2013; Neave and Putirka 2017), cation content in minerals and co-existing melt (Johnson and Rutherford 1989; Henry et al. 2005), pressure-sensitive variations in crystal lattice structure (Nimis 1995, 1999; Nimis & Ulmer 1998), or phase relations of a set of minerals (Yang et al. 1996). The choice of thermobarometric model is dependent on the mineral content and the geochemical composition of the analysed magmatic and volcanic products as the models are calibrated for certain mineral phases and restricted compositional ranges.

In order to produce robust pressure and temperature estimates, equilibrium of mineral-melt pairs is of crucial importance for most thermobarometric models. For clinopyroxene(-melt) thermobarometry, the recommended procedure of assessing equilibrium between clinopyroxene and a possible nominal melt is evaluation of the K_D(Fe-Mg) exchange coefficient followed by comparing predicted versus observed mineral components in clinopyroxene (e.g. DiHd, EnFs, CaTs, Jd; Putirka 2008). In case of plagioclase-melt thermobarometry, suitable plagioclase-melt pairs were chosen through the K_D(An-Ab) equilibrium test (Putirka 2005). Both equilibrium test approaches ensure that only equilibrium mineral-melt pairs are considered for further thermobarometric calculations.

When applicable, multiple thermobarometric models were employed for most papers in order to provide independent tests. For full details on choice of thermobarometer and application of equilibrium tests see the respective papers and corresponding supplementary material in this thesis.

Oxygen isotope analysis

Conventional fluorination

In Papers I, IV, and VIII, oxygen isotope ratios were measured in crystal separates and whole rock powders using a Thermo DeltaXP mass spectrometer at the University of Cape Town, South Africa. After powdering the sample, an aliquot of 10 mg was dried at 50°C before degassing under vacuum at 200°C in externally heated Ni vessels on a conventional silicate extraction line (Vennemann and Smith 1990; Fagereng et al. 2008). O_2 was liberated during sample reaction with ClF_3 and then converted to CO_2 using a hot platinized carbon rod. In order to calibrate the raw data to SMOW (Standard Mean Ocean Water), unknowns were run alongside duplicates of the internal quartz standard (MQ) using a $\delta^{18}O$ value of 10.1 for MQ (calibrated against NBS-28). Results are reported in standard δ-notation, where $\delta = (R_{sample}/R_{standard} - 1) \times 1000$ and $R = {}^{18}O/{}^{16}O$. The analytical error is ca. ±0.2‰ (2σ), based on long-term repeated analysis of MQ.

Laser fluorination

In Paper III, laser fluorination of ca. 2.5–3 mg crystal aliquots per independent run was carried out at the University of Cape Town, South Africa (for full analytical details, see Harris & Vogeli 2010). Crystals were hand-picked under a binocular microscope and subsequently cleaned in an ultrasonic bath to ensure that only inclusion-poor grains were used for analysis. Resulting oxygen isotope ratios are reported in standard δ-notation relative to SMOW (Standard Mean Ocean Water), where $\delta = [({}^{18}O/{}^{16}O)_{sample}/({}^{18}O/{}^{16}O)_{SMOW} - 1] * 1000$. The raw data were normalised and corrected for reference gas drift using the internal standard MON GT (Monastery garnet, $\delta^{18}O$ = 5.38‰). For long-term average difference in $\delta^{18}O$ values of MON GT duplicates see Paper III.

Secondary ion mass spectrometry (SIMS)

In Paper III, individual crystals mounted in epoxy were analysed for their oxygen isotope ratios using a Cameca IMS 1280 secondary ion mass spectrometer at the Nordsim ion microprobe facility, Swedish Museum of Natural History, Stockholm. Analyses were performed using a 20 keV Cs^+ primary beam of ca. 2.5 nA in critically-focused mode together with a 5 µm raster to sputter a sample area of ca. 10 µm. Charge compensation was provided by a normal incidence low energy electron gun. Analytical runs comprised a 90 s pre-sputter period with a raster of 20 µm and field aperture centering employing a ^{16}O signal followed by 16 cycles of 4 s integrations (64 s in total) of data acquisition using two Faraday detectors. The multicollector system operated at a common mass resolution of ca. 15000 and the secondary magnet field was regulated at high precision using a Metrolab NMR teslameter. For full analytical details see Nemchin et al. (2006), Whitehouse and Nemchin (2009), and Paper III.

Helium isotope analysis

In Paper IV, clinopyroxene separates were analysed for their helium isotope ratios at the Fluids and Volatiles Laboratory at Scripps Institution of Oceanography in La Jolla, California, USA. A crystal aliquot of ≥2 g was handpicked and cleaned using an acetone-methanol solvent mixture in an ultrasonic bath. An online, electromagnetic crusher attached to the gas purification line of a noble gas spectrometer (MAP 215) was then loaded with ca. 1 g of crystals. The line was pumped to ultrahigh vacuum overnight before crushing the sample with an externally accelerated magnetised steel slug at a frequency of ~120 impacts per minute for 2 minutes (for full method details see Scarsi et al. 2000 and Shaw et al. 2006). Volatiles released from melt inclusions in the crystals during the crushing process were filtered through a combination of cooled charcoal traps as well as titanium and Zr-Al alloy getters in the mass spectrometer purification line. Helium was separated from neon before analysis for abundance and isotopic ratios. Helium ratios are reported as $^{3}He/^{4}He$ relative to SIO air (= 1 R_A) or Murdering Mudpots He (= 16.45 R_A) as standards.

Additional methods

Papers and manuscripts in this thesis also include methods exclusively carried out by co-authors, including Mössbauer analysis (Paper III), Fourier transform infrared spectroscopy (FTIR; Paper VII), X-ray diffraction (XRD), photogrammetry, porosity, density, and uniaxial compressive strength measurements (Paper VIII). These methods are described in depth in the respective papers and manuscripts.

Summary of papers

Paper I

Magma plumbing for the 2014-2015 Holuhraun eruption, Iceland

Magma plumbing for Icelandic rift zones is usually described by one of two models: eruptions are either vertically supplied by magma from deep magma storage levels or through additional lateral transport from shallow-level magma reservoirs (e.g. Sigurdsson and Sparks, 1978; Paquet et al., 2007; Hartley and Thordarson, 2013). The 2014-2015 Holuhraun eruption was preceded and accompanied by seismic activity and caldera subsidence in the Bárðarbunga central volcano some 45 km away from the eventual eruption site. A migrating seismic swarm was recorded, which would hence support a lateral connection between Bárðarbunga and the Holuhraun eruption site, yet the latter was situated within the neighbouring Askja volcanic system (Riel et al., 2015; Sigmundsson et al. 2015). We evaluated this possible lateral connection by examining mineral textures and compositions, whole rock major and trace element data, and oxygen isotope ratios from recent Holuhraun lava samples. Additionally, we applied mineral-melt thermobarometric modelling in order to unravel the plumbing system to the 2014-2015 Holuhraun eruption. Recent Holuhraun eruptives are basaltic in composition, vesicular, and porphyritic. All lava samples contain plagioclase, clinopyroxene, and olivine phenocrysts set in a microlite-bearing groundmass. Centimetre-sized troctolite-gabbro fragments containing plagioclase and minor olivine are also found sporadically. On major and trace element variation diagrams Holuhraun lavas plot among historic Bárðarbunga eruptives, but are notably compositionally different from historic Askja system volcanics. Clinopyroxene-melt and plagioclase-melt thermonbarometry indicate polybaric magma storage, wherein clinopyroxene crystallised at ~17 km depth and plagioclase at ~5 km depth. In conjunction with crystal resorption textures and variations in oxygen isotope values, a model of a multilevel plumbing system that facilitated pre-eruptive magma mixing and crustal assimilation emerges. Paired with geophysical data that supports lateral migration we propose initial vertical magma ascent below Bárðarbunga central volcano, followed by lateral transport of mixed magma within the upper crust to the eventual Holuhraun eruption site (Figure 3).

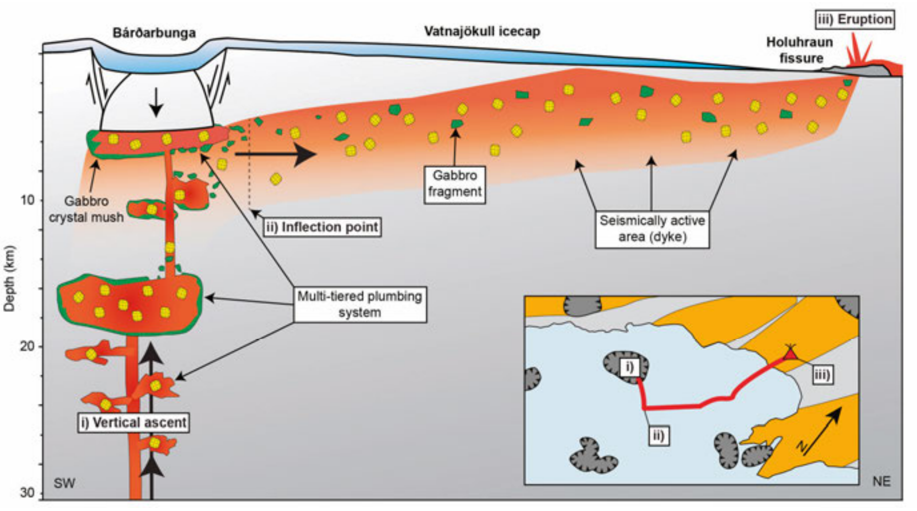


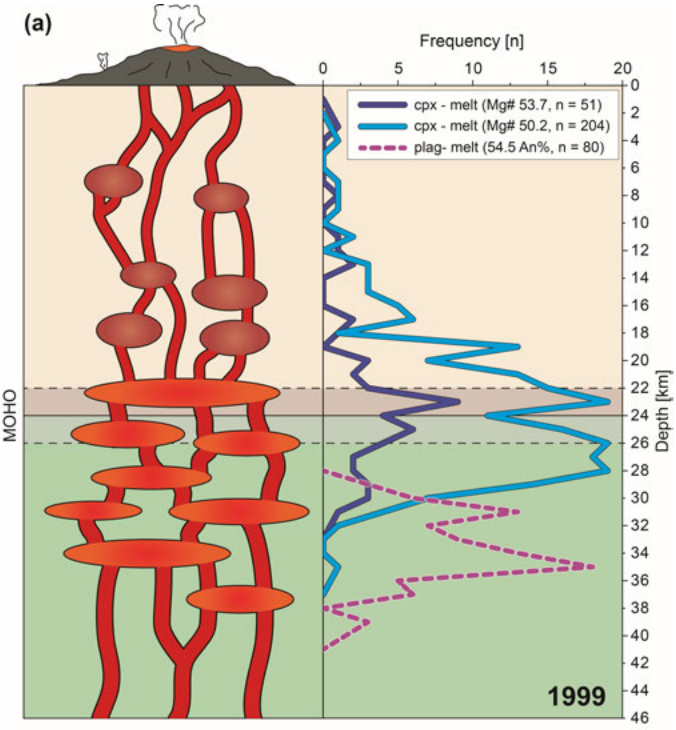
Figure 3. Conceptual model of the magma plumbing system for the 2014–2015 Holuhraun eruption. Considering our results in the context of the current geological framework (e.g., Riel et al., 2015; Sigmundsson et al., 2015), we envisage that (i) magma ascended from ~17 km depth to shallow crustal levels beneath Bárðarbunga in mid-August 2014 where it intersected an existing magma reservoir. (ii) Magma from distinct reservoirs was then aggregated and transported laterally for some distance to produce the final erupted Holuhraun lava (iii). The erupted lava records multiple crystal populations, entrained gabbro fragments, and $\delta^{18}O$-depleted (i.e. crustal) oxygen isotope ratios relative to MORB. The inset shows the propagation of the dyke in schematic cross section and in map view. Caption and figure reproduced from Geiger et al. 2016a.

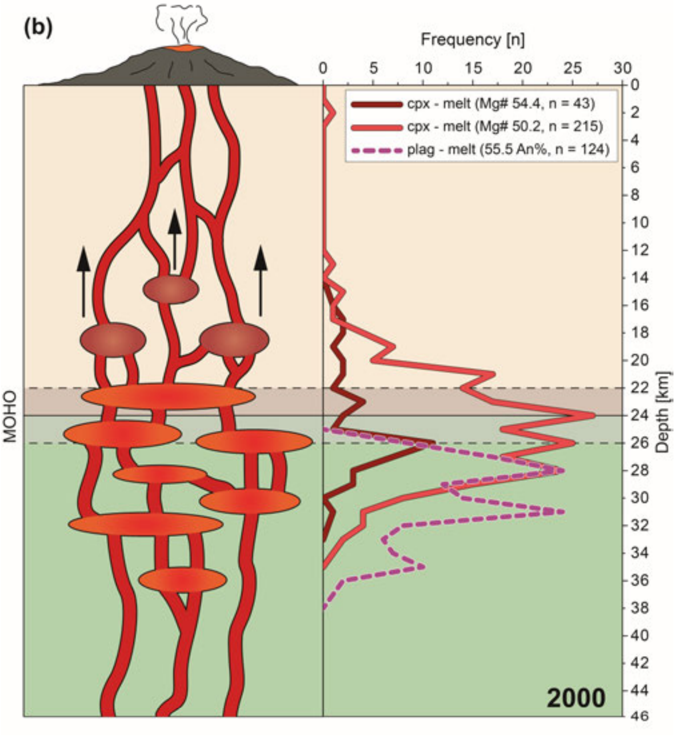
Paper II

Locating the depth of magma supply for volcanic eruptions, insights from Mt. Cameroon

Located on the Atlantic coast of the Republic of Cameroon, Mt. Cameroon is one of the most active volcanoes on the African continent. The flanks of the volcano are densely populated by about half a million people, who are drawn to the area by fertile soils and associated economic benefits. Despite the imminent volcanic risk to a large population, knowledge on the underlying magma plumbing system is scarce. We employed mineral-melt equilibrium thermobarometry on clinopyroxene and plagioclase from the two most recent eruptions in 1999 and 2000 in order to characterise Mt. Cameroon's magma plumbing system (Figure 4). Plagioclase records crystallisation between 26 and 39 km depth for the 1999 and 2000 event, which overlaps with reported earthquake hypocentres between 30 and 55 km depth. Clinopyroxene, in turn, records a dominant zone of crystallisation between 20 and 28 km depth for the 1999 and 2000 eruptions. This observation is also consistent with earlier seismic and petrochemical studies of Mt. Cameroon that suggested a magma reservoir at ≥20 km depth feeding the 1999 and 2000 events. Furthermore, the Moho is located at 24±2km depth in the area, which also overlaps with the magma reservoir detected by clinopyroxene thermobarometry. In addition, clinopyroxene in 1999 eruptive products reveal shallow magma pockets between 3 and 12 km depth, which are not detected in the 2000 lavas. Small-volume evolving magma batches hence appear to actively migrate through the plumbing system during repose intervals. This evolving magma could potentially cause temporary volcanic unrest and explosive flare-ups, and, importantly, the magma pockets may be intersected and remobilized during major eruptions that are fed from sub-Moho magma reservoirs.

Figure 4 (next page). Schematic model of magma plumbing beneath Mt. Cameroon volcano. (a) The 1999 eruption and (b) the 2000 eruption are represented on the basis of our combined mineralogical and thermobarometry results. Both eruptions were predominantly fed from sub-Moho magma reservoirs, but shallower magma pockets existed prior to the 1999 eruption, which are not detected in the mineral data from the 2000 lavas. This observation implies that longer repose intervals, like prior to the 1999 eruption, may allow for ascent and evolution of small magma batches. These migrating pockets may also be a reason for seismic unrest and short explosive outbursts that occurred in-between the major effusive events, e.g. in 1989 and again in 2012. Arrows in b) represent potential post-2000 magma migration. The SEEs are ±0.17 GPa and ±0.25 GPa for clinopyroxene-melt and plagioclase-melt thermobarometry, respectively. Caption and figure reproduced after Geiger et al. 2016b.


(a)
Frequency [n]
0 5 10 15 20
cpx - melt (Mg# 53.7, n = 51)
cpx - melt (Mg# 50.2, n = 204)
plag- melt (54.5 An%, n = 80)
MOHO
Depth [km]
1999


(b)
Frequency [n]
0 5 10 15 20 25 30
cpx - melt (Mg# 54.4, n = 43)
cpx - melt (Mg# 50.2, n = 215)
plag - melt (55.5 An%, n = 124)
MOHO
Depth [km]
2000

Paper III

Pyroxene standards for SIMS oxygen isotope analysis and their application to Merapi volcano, Sunda arc, Indonesia

Oxygen isotope ratios in common silicate minerals are increasingly analysed by secondary ion mass spectrometry (SIMS). However, matrix effects can be problematic during analysis of minerals that are part of solid solution series with large compositional spectrums, which limits the widespread application of SIMS analysis. In order to correct for these matrix effects and to ensure accurate results, standards that are matrix matched to the unknowns need to be characterised through repeated analysis. We performed SIMS homogeneity tests on a new augite standard (NRM-AG-1) from Stromboli, Italy, and an enstatite standard (NRM-EN-2) from Webster, North Carolina to widen the current applicability of SIMS to igneous solid solution mineral groups. Oxygen isotope ratios in the mineral standards were first measured by laser fluorination (LF). Randomly oriented fragments of the pyroxene crystals were then repeatedly analysed by SIMS, yielding a standard deviation in $\delta^{18}O$ of less than ±0.42 and ±0.58‰ (2σ) for NRM-AG-1 and NRM-EN-2, respectively. Further tests verified both standards to be homogeneous on the 20 µm scale and independent of crystallographic orientation, qualifying them as routine mineral standards for SIMS $\delta^{18}O$ analysis. We then tested our new standard materials during SIMS analysis of recently erupted pyroxene crystals from Merapi volcano, Indonesia. SIMS $\delta^{18}O$ values for pyroxene from Merapi overlap within error with LF oxygen isotope ratios, but differ from bulk mineral and whole rock $\delta^{18}O$ values measured by conventional fluorination. The latter can be explained by mineral and glass inclusions that may reflect crustal contamination processes and that can shift $\delta^{18}O$ to higher values. Merapi pyroxene SIMS data exhibits a frequency peak at 5.8‰, which corresponds to a primary mafic magma value of ~6.1‰ when assuming closed system differentiation at Merapi. We also applied clinopyroxene composition barometry after Putirka (2008; Eq. 32b after Nimis 1995) to all Merapi pyroxene analysed in this study. Assuming a H_2O content of 6 wt%, crystallisation pressures between 253 to 601 MPa with a frequency peak at 470 MPa are obtained (Figure 5).

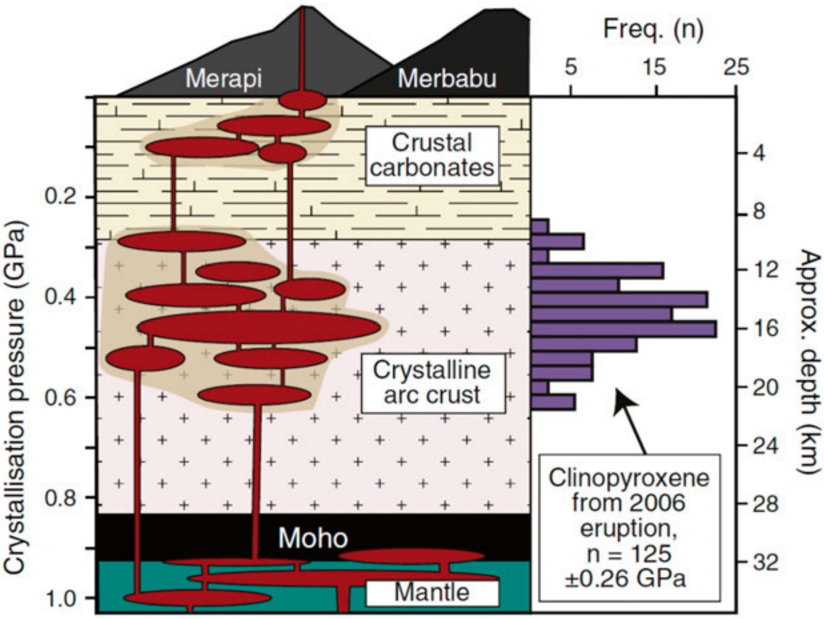


Figure 5. Results of clinopyroxene composition barometry after Putirka (2008, Eq. 32b). The data show that the main pyroxene growth interval was located broadly at 16 km depth beneath Merapi, i.e. within the mid to deep crystalline arc crust. The schematic sketch of the magma plumbing system beneath Merapi (left) is drawn based on Chadwick et al. (2013), Preece et al. (2014), and this study. The Moho depth is taken from Wölbern and Rümpker (2016). While the analysed pyroxene have dominantly grown in the midcrust, upper crustal storage and assimilation has also been identified in previous studies, especially in whole-rock and late grown plagioclase (e.g. Chadwick et al., 2013; Troll et al., 2013) and is likely reflected in some of the pyroxene $\delta^{18}O$ values reported here. Caption and figure reproduced after Deegan et al. 2016.

Paper IV

Multi-level magma plumbing at Agung and Batur volcanoes increases risk of hazardous eruptions

Large volcanic eruptions not only affect populations and infrastructure in their proximity, but can also affect global climate and hence human society as a whole. An understanding of active volcanoes and their magma plumbing systems is hence of paramount importance to support hazard mitigation efforts. Agung and Batur are two active stratovolcanoes on the island of Bali in Indonesia. Despite being densely inhabited and a popular touristic destination, the magma plumbing systems feeding Agung and Batur are relatively little studied. We characterise magma storage depths and isotopic evolution by employing mineral(-melt) equilibrium thermobarometry and oxygen and helium isotope analyses to minerals from the 1963 and 1974 eruptions of Agung and Batur (Figure 6; Agung). Olivine records average $\delta^{18}O$ values of 4.8‰ and hence crystallised from a primitive magma. Clinopyroxene, in turn, shows mantle-like helium (8.62 R_A) and oxygen (5.0–5.8‰) isotope values. For the 1963 eruption of Agung, clinopyroxene crystallised at the crust-mantle boundary between 18 and 22 km depth. In case of Batur, crystallisation depths of 12 to 18 km and 15 to 19 km are obtained for the 1963 and 1974 eruptions, respectively. Plagioclase records magma storage in upper crustal reservoirs at depths of 3 to 7 km for the 1963 eruption of Agung, 2 to 4 km for the 1963 Batur eruption, and 3 to 5 km for the 1974 Batur eruption. Oxygen isotope values for plagioclase range from 5.5 to 6.4‰. These results overlap with available seismic and InSAR studies that point to upper crustal magma storage in the region. Such multi-level plumbing systems could potentially drive replenishing magmas to volatile saturation and exsolution, and hence increase the explosive potential of future eruptions and the consequent hazard impact for the population of Bali.

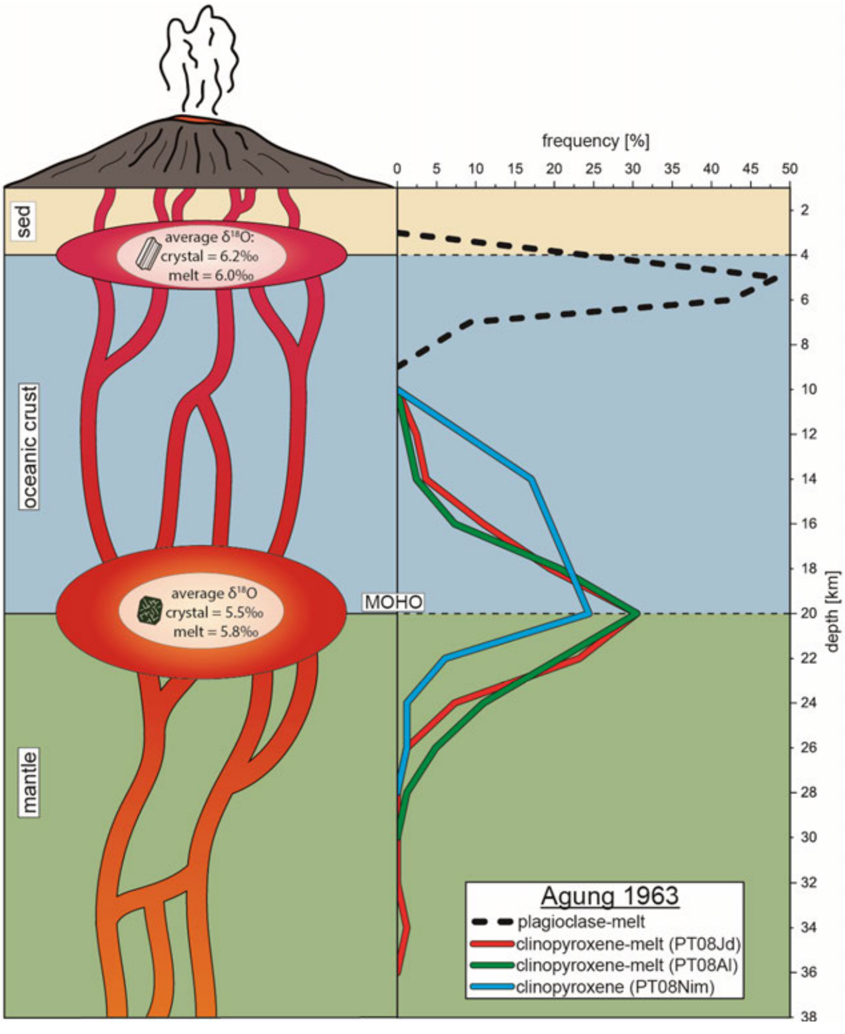


Figure 6. A possible model for the plumbing system beneath Agung based on mineral-melt thermobarometry of the 1963 lavas. Two major magma storage regions are apparent in the frequency plot: one at 18 to 22 km depth, around the Moho, and another at 3 to 7 km depth, likely at the boundary between the upper crustal sedimentary units and the tectonised oceanic-type middle to lower crust. The calculated melt $\delta^{18}O$ values based on clinopyroxene and plagioclase mineral analysis average at 5.8‰ for the lower reservoir and 6.0‰ for the shallow storage level. Caption and figure reproduced after Geiger et al. 2018.

Paper V

Forensic Probe of Bali's Great Volcano

After 54 years of dormancy, Agung volcano on the island of Bali erupted in November 2017 for the first time since 1963 (Gertisser et al. 2018). This eruption resulted in the evacuation of 150,000 inhabitants in the volcano's direct vicinity, but was relatively harmless compared to the 1963 event that had a death toll of at least 1,100 people. With the renewed activity at Agung, it is imperative to understand its underlying magma plumbing system. Geochemical evidence was collected from crystals embedded in 1963 Agung lavas to reconstruct the magma plumbing architecture and its isotopic evolution (see Paper IV). The resulting model of a multi-level plumbing system is similar to results of other studies for volcanoes in the area that exhibit plumbing system geometries that involve deep storage around Moho level and shallow-level storage regions in the mid and upper crust (Figure 7). The shallow arc storage systems (SHARCS) of these magmatic systems is of special significance as this storage region is where magma evolves, crystallises, and volatiles exsolve, potentially driving the system to an eruptive state with relatively little forewarning, as was witnessed during e.g. the 2014 eruption of Kelut volcano, Indonesia.

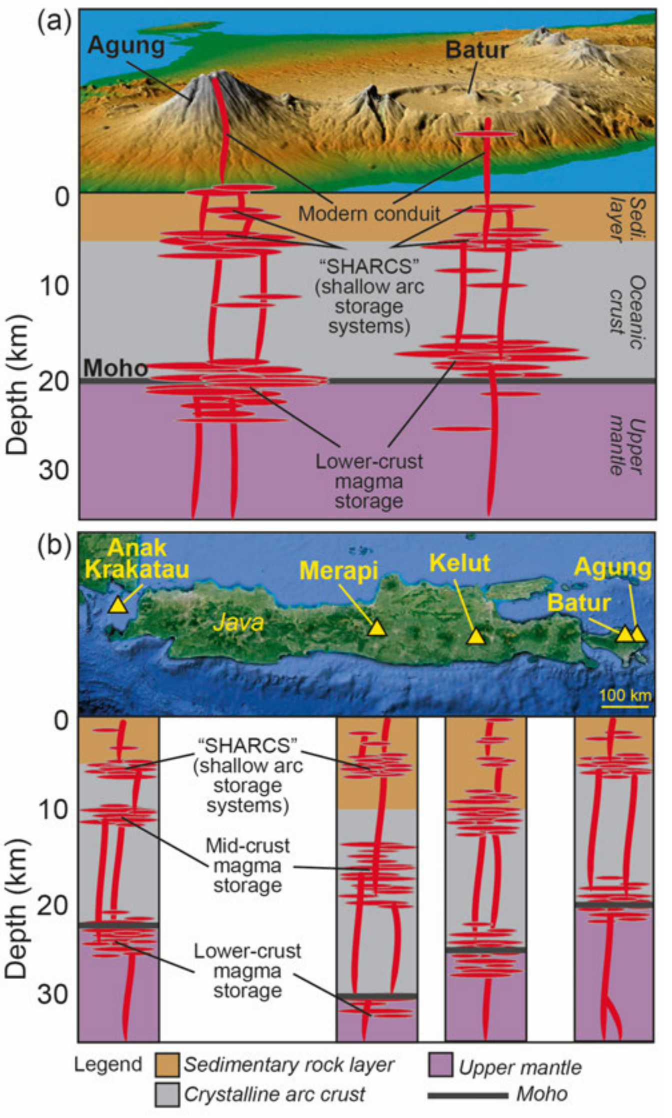


Figure 7. Sketch of Batur and Agung volcanoes with their underlying magma plumbing systems based on data by Geiger et al. (2018) (map courtesy of NASA). (b) Magma plumbing at Anak Krakatau (Sunda Strait), Merapi (Central Java), Kelut (East Java), and Agung and Batur (Bali) based on data presented in Geiger et al. (2018) and references therein (map courtesy of Google Earth). Note the ubiquitous presence of shallow arc storage systems (SHARCS) throughout the region. Moho refers to the Mohorovičić discontinuity, the boundary between Earth's crust and mantle. Caption and figure reproduced after Deegan et al. 2019.

Paper VI

Felsic magma storage in the core of an ocean island (Gran Canaria, Canary Islands)

Products erupted on ocean islands have traditionally been viewed as probes of the Earth's mantle. However, some islands show large compositional variety which reflects magmatic differentiation processes. Gran Canaria, Canary Islands, exhibits large amounts of evolved, felsic material in Miocene and Pliocene ignimbrite deposits and in the island's exposed syenite core. The latter provides a rare opportunity to reconstruct the plumbing system that fed the highly explosive Miocene volcanism. We employed clinopyroxene-melt thermobarometry coupled with major and trace element and oxygen isotope geochemistry in order to determine storage conditions and evolution of the syenite core on Gran Canaria. Samples of eroded-out, fresh nepheline syenites show enrichment of alkali elements as well as elevated Zr and Nb concentrations (up to 955 and 247 ppm, respectively). Oxygen isotope ratios in syenites range from 6.4 to 8.1‰, which is consistent with magma fractionation trends for syenite generation with possible assimilation of older crustal plutonic material. Results from thermobarometric modelling imply syenite crystallisation depth of 5 to 13 km, which coincides with the upper crust beneath Gran Canaria (Figure 8). Based on these results we propose that repeated injection of magmatic material stored at shallow depth during the Miocene facilitated syenite differentiation, re-melting, and distillation towards highly differentiated compositions that fed violent eruption of felsic ignimbrites.

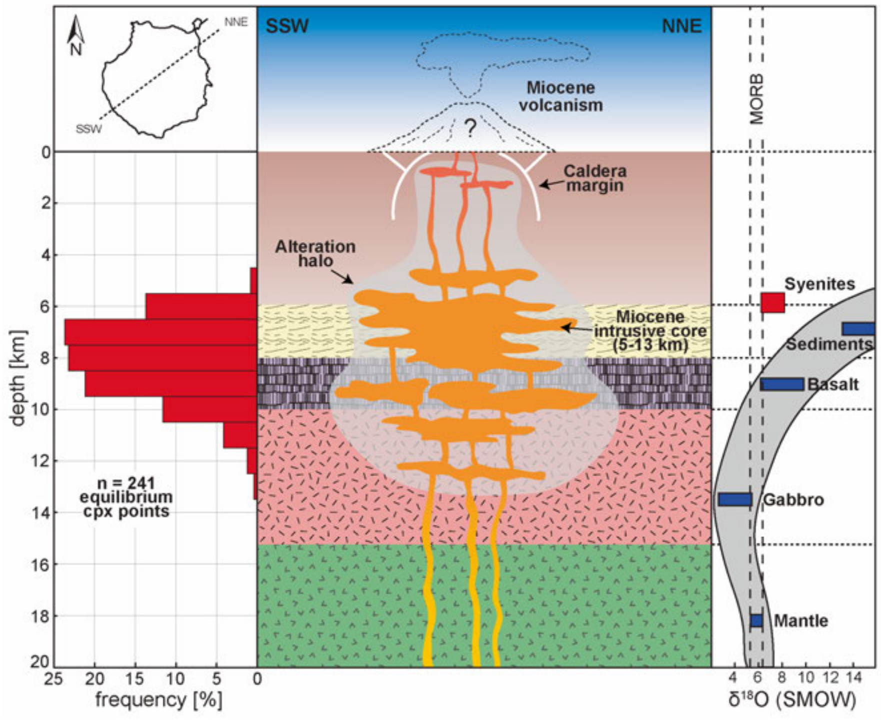


Figure 8. Proposed model for the Miocene magma plumbing system below the current-day Tejeda caldera based on the results of clinopyroxene-melt thermobarometry in this study (left), which point to a main Fataga-age syenite magma storage region between 5 and 13 km depth (centre). Oxygen isotope data for the oceanic crust below Gran Canaria are plotted on the right (data from Hansteen and Troll, 2003) along with new data for fresh, eroded-out syenites in this study. The new syenite data show elevated $\delta^{18}O$ values (compared to MORB) of 6.4 to 8.1‰ and trace element ratios similar to other Fataga magmatic products. We propose that repeated injections of magma at depth potentially triggered syenite re-melting and distillation in the upper parts of the plumbing system, driving magma to highly differentiated compositions. Caption and figure reproduced after Geiger et al. (in prep.).

Paper VII

Explosive ocean island volcanism explained by high magmatic water content in OIB magmas

Ocean island volcanism rarely exhibits explosive eruptions due to the anhydrous (≤1 wt. % H_2O) and dominantly mafic nature of the magmas that feed eruptions. The explosive events that do occur on ocean islands are either driven by volatile segregation processes during magma storage and differentiation (Cashman 2004) or by rapid ascent of volatile-enriched primary mantle melts (Sides et al. 2014). Here we report on crystal-rich ankaramite eruptive products from Tangansoga volcano that is located in the El Golfo giant collapse embayment on El Hierro, Canary Islands, Spain. Tangansoga produced explosive pyroclastic eruptions in the past and it has been suggested that these eruptions were triggered by rapid unloading (Manconi et al. 2009) as a result of the El Golfo giant landslide ca. 87 to 39 ky ago (Masson 1996; Longpré et al. 2011). To determine if a deep magma source was tapped during these eruptions, we analysed water contents in clinopyroxene and olivine from Tanganasoga ankaramite bombs and lavas using Fourier Transform Infrared Spectroscopy (FTIR). After employing water partition coefficients for clinopyroxene and olivine, we find that H_2O content in Tanganasoga clinopyroxene is exceptionally elevated, but the calculated magmatic water content correlates with fractionation indices. In addition, we applied clinopyroxene-melt thermobarometry to compositional data obtained from Tanganasoga clinopyroxene in lava bombs and ankaramite lavas. Crystallisation pressures that correspond to depths between 26 and 45 km for clinopyroxene in lava bombs and between 12 and 25 km for clinopyroxene in ankaramite lavas were obtained, which points to magma storage and fractionation at and below the crust-mantle boundary below El Hierro. Our findings hence do not support a water-rich mantle source, but favour a water-rich upper mantle underplating zone where crystal-laden, mush-type OIB magmas reside and fractionate prior to ascent and eruption (Figure 9).

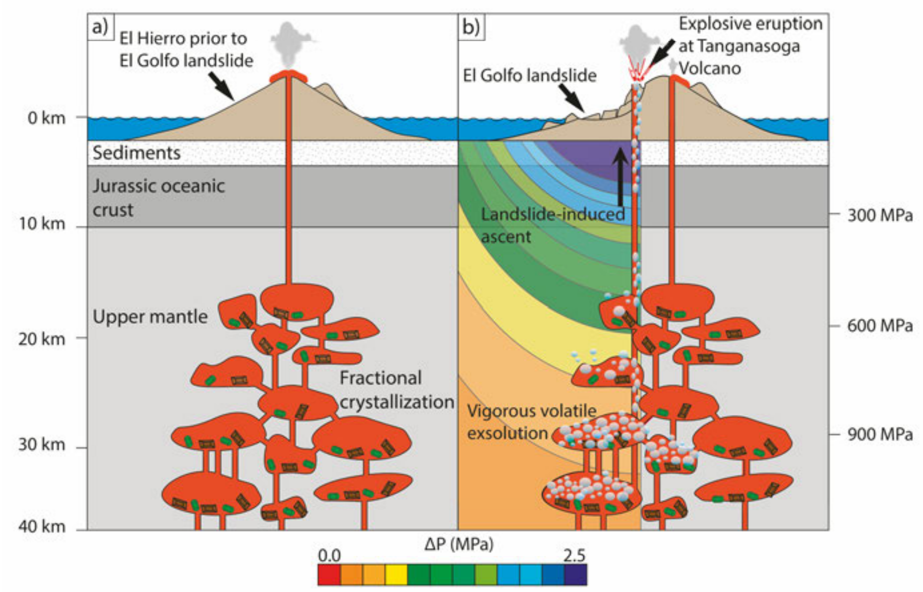


Figure 9. Simplified model of the magma plumbing system underneath El Hierro based on comcepts in Manconi et al. (2009), Stroncik et al. (2009), Gonzalez et al. (2013), Carracedo et al. (2015), Oglialoro et al. (2017) and on our new results. Thermobarometry reveals that clinopyroxene of this study grew dominantly between 12 and 45 km depth, implying that hydrogen incorporation into clinopyroxene structural defects occurred in the upper mantle and up to ~35 km below the Moho beneath El Hierro. The dense and crystal-rich ankaramite magmas are usually hampered in their ascent due to the load of the volcanic edifice (e.g. Pinel & Jaupart, 2000, Carracedo et al. 2015b) and thus underplate the island. Vertical unloading causes a pressure change at depth (Manconi et al. 2009) and allows crystal- but H_2O-rich ankaramite magmas to rapidly ascend and erupt explosively within and around the landslide embayment. Unroofing due to landslide activity thus enables us to better constrain the processes during magma underplating beneath active ocean islands. Caption and figure reproduced after Weis et al. (in prep.).

Paper VIII

Mechanical weakening due to hydrothermal alteration leads to failure at andesitic volcanoes

Hydrothermal alteration modifies the mineralogy of affected rocks and changes their mechanical strength. Dome building volcanoes are often affected by progressive interaction with hydrothermal fluids at temperatures between ~50 and ~500 °C (Ball et al. 2015). This interaction reduces rock strength, dissolves the dome rock, and elevates pore pressure and can lead to potential catastrophic failure of summit domes and flanks without major precursory volcanic unrest. To improve our understanding of how hydrothermal alteration affects dome rocks and promotes mechanical weakening and resulting failure, we investigated mineralogical changes and differences in associated mechanical strength of progressively altered dome rocks from the summit dome complex of Merapi volcano. Merapi is the most active and hazardous volcano in Indonesia. It frequently displays dome building episodes that lead to dome collapse, explosive eruption, and pyroclastic flows. Hydrothermal alteration of Merapi's current dome was first mapped by drone photogrammetry in 2017 and subsequently sampled in 5 zones, representing fresh, slightly altered, moderately altered, highly altered, and fully altered dome rocks (Figure 10). In order to investigate the mechanisms that lead to mechanical failure of the altered dome rocks, we employed wavelength dispersive X-ray spectroscopy (WDS) mapping, X-ray diffraction (XRD), oxygen isotopes, porosity measurements, and mechanical strength tests. Our results show that hydrothermal alteration leads to progressive replacement of the original dome rock with sulfate-dominated alteration minerals, an increase of $\delta^{18}O$ values from 7 to 12‰, and a ten-fold reduction in the rock strength. The latter is sufficient to trigger dome or flank collapse at dome-building, andesitic volcanoes independent of magmatic activity.

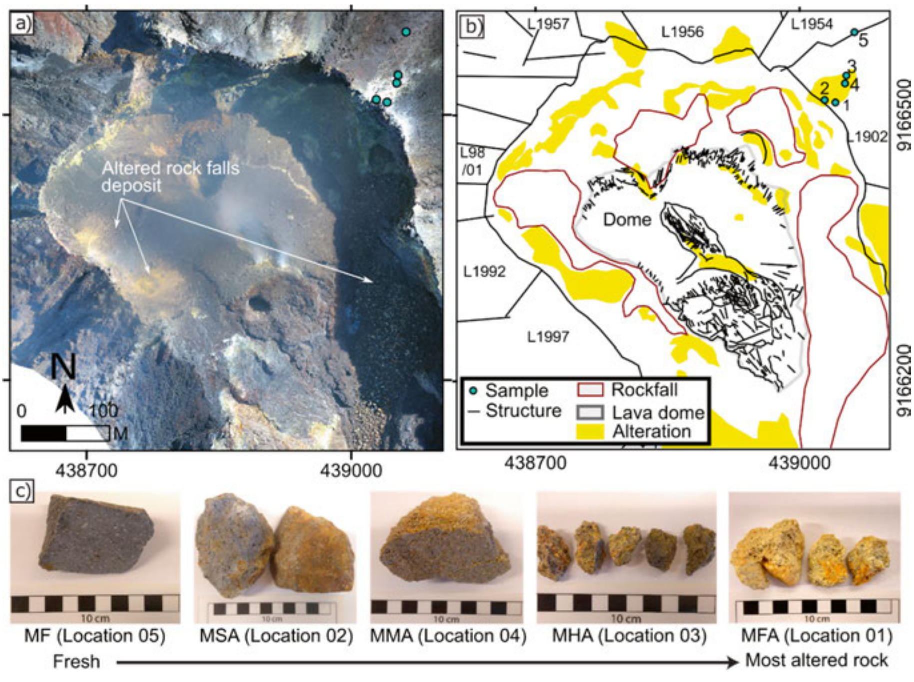


Figure 10. a) Photomosaic of drone images acquired in 2017 used to map hydrothermal alteration at Merapi summit. b) Map of hydrothermal alteration, structures and active fumaroles at Merapi summit, and the sample location of the Merapi dome rocks that are used in this study. c) The Merapi dome rock samples show different degrees of alteration from fresh to intensely altered, as identified by their color changes. Caption and figure reproduced after Darmawan et al. (in prep.).

Conclusions

This thesis investigates magma plumbing systems in various volcano-tectonic settings by using a combination of petrological, geochemical, and isotopic analytical techniques, with a major focus on thermobarometric modelling. The results contribute to our understanding of magma plumbing architecture by underlining the common occurrence of multi-level magma storage and especially the presence of upper crustal magma reservoirs in tectonic settings as diverse as subduction zones to intraplate volcanism. Notably, crustal stratigraphy was found to play an important role during magma emplacement across all volcanic settings studied. Improved understanding of shallow magma bodies may provide vital information in order to explain and better assess sudden and explosive volcanic eruptions and is therefore of relevance to hazard mitigation efforts around the world. Summaries of conclusions from the respective papers and manuscripts are as follows:

Paper I provides petrological insights into magma storage and long-distance lateral magma transport on Iceland. The 2014-2015 Holuhraun eruption was supplied from a complex magmatic plumbing system beneath Bárðarbunga volcano. Crystal resorption and dissolution textures point to magma mixing, likely in mid-crustal reservoir regions as recorded by thermobarometric modelling. After ascending to upper crustal levels, magma interaction with crustal rocks is evident in the presence of gabbro fragments with lower $\delta^{18}O$ values than MORB. Lateral drainage of magma from shallow levels eventually led to eruption at the Holuhraun site some 45 km away from Bárðarbunga central volcano.

Paper II shows that a multi-tiered magma plumbing system fed the 1999 and 2000 eruptions of Mt. Cameroon. Magma for both eruptions was stored around and below the Moho, while shallow-level storage was only recorded by clinopyroxene in lavas from the 1999 eruption. Such temporally evolving shallow magma pockets could potentially trigger future eruptions with little to no warning when intersected by ascending mafic melts, similar to e.g. the widely discussed 2010 Eyjafjallajökull events on Iceland.

Paper III characterises new pyroxene SIMS standards for oxygen isotope analysis and applies them to clinopyroxene from the 2006 eruption of Merapi volcano, Indonesia. Mineral-melt thermobarometry on those clinopyroxene points to a crystallisation peak around 16 km, which is within the mid-level arc crust. Lithological boundaries likely placed constraints on magma ascent by providing a density barrier between the crystalline middle crust and overlying sediments of the upper crust at ~10 km depth.

Papers IV and V examine the magmatic systems beneath Agung and Batur volcanoes on Bali, Indonesia. Results from a set of mineral(-melt) thermobarometric models suggest a polybaric magma storage system for both volcanoes, with crystallisation levels around the Moho and at the transition between sedimentary rocks and the tectonised oceanic basement in the upper crust that is in agreement with InSAR and seismic data. Petrological evidence point to two similar, but separate magma plumbing systems. Recent renewed seismic activity originating below Batur as well as the recent (2018) eruption of Agung, however, point to a present day connection between the two magmatic systems and hence attest to the dynamic and evolving nature of magmatic plumbing systems. In addition, the frequent occurrence of shallow arc storage systems (SHARCS) on Bali and along the Sunda Arc seem to play important roles in potentially facilitating sudden and violent explosive eruptions due to volatile exsolution at these levels.

Paper VI studies the Miocene syenite core of Gran Canaria, Canary Islands. Clinopyroxene-melt thermobarometry points to emplacement of magma between 5 and 13 km depth, which spans most of the lower crust and extents to the upper portions of the oceanic crust beneath the island. Oxygen isotope values are in-line with magma fractionation and syenite recycling at these storage levels, which supplied violent explosive eruptions of ignimbrites at the surface.

Paper VII further examines explosive ocean island volcanism on El Hierro, Canary Islands, that occurred in connection with a major landslide event. In contrast to Paper VI, this study looks at mafic and ultramafic magma compositions. Results from FTIR water contents analysis on clinopyroxene and olivine, and clinopyroxene-melt thermobarometry point to deep, mantle origin of the crystal cargo in lavas from Tanganasoga volcano. However, the obtained elevated H_2O content is in line with regular fractionation and does not point to a water-rich mantle source. Instead, a water-rich, mush-type OIB magma underplating zone may be a viable alternative explanation. This paper provides unique insights into magma plumbing for a mafic magmatic system that underwent rapid decompression due to a mass unloading event (landslide).

Paper VIII focuses on the uppermost part of a volcanic plumbing system and its transition to surface volcanism by investigating near-surface processes at dome volcanoes. This work finds that dome-building volcanoes are prone to sudden and catastrophic dome or flank collapse due to prolonged hydrothermal alteration of dome rocks. Hydrothermal alteration replaces primary minerals with sulfate-dominated alteration minerals, which, in turn, induces mechanical weakening and hence dramatically reduces rock strength and triggers dome or flank collapse at dome-building, andesitic volcanoes.

The research in this thesis thus addresses plumbing systems from mantle depths to shallow crustal levels, and, finally, to surface volcanic phenomena. The results obtained underscore the ubiquity of multi-tiered magma reservoir systems across diverse tectonic regimes.

Summary in Swedish

Magmatiska tillförselsystem består av magmakammare, lagerintrusioner och kanaler som förbinder vulkaner med jordens djupa inre. Således bildar de det strukturella ramverket för transport och förvaring av magma som styrs av komplexa fysikaliska och kemiska processer i magmareservoarer samt genom interaktion med omgivande bergarter i jordskorpan, på tidsskalor från några timmar till flera miljoner år. Dessa geologiska processer spelar i sin tur en viktig roll för typen av vulkanutbrott samt magnituden av de tillhörande naturkatastrofer som utgör ett ständigt hot mot våra samhällen. Vår kunskap om hur magmatiska rörsystem fungerar och hur de är uppbygda är fortfarande bristfällig. Denna kunskapsbrist kan delvis förklaras av den låga upplösningen i de geofysiska mätmetoder som används och delvis av geokemiska osäkerheter i tillhörande modeller. Pågående utveckling av analysmetoder har ökat den optiska, temporala och kemiska upplösningen, vilket gör det möjligt för oss att få en mer detaljerad kunskap om strukturen och dynamiken av magmatiska system inom individuella vulkaner samt om deras roll under den långsiktiga utvecklingen av vulkaniska provinser och i slutändan av hela jorden. Den här processinriktade avhandlingen undersöker fossila och aktiva magmatiska rörsystem på Island, Indonesien, Kamerun och Kanarieöarna genom att kombinera traditionella och nyframtagna petrologiska och geokemiska metoder, termobarometrisk modellering samt isotopanalyser. Resultaten bidrar med nya insikter i flerskiktade magmatiska rörsystem i en rad olika vulkaniska-tektoniska områden, och de understryker vikten av ytnära magmaförvaring och dess inflytande på magmautveckling och farliga vulkanutbrott.

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