Magma plumbing architecture in Indonesia and the North Atlantic Igneous Province

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Abstract

Magma plumbing systems represent the physical framework of magma transport and storage from the source region in the mantle, through the crust, until reaching the surface in a volcanic eruption. Characterising the different aspects of magma plumbing, in particular the distribution of magma storage zones throughout the crust, is of key importance to better understand the behaviour of individual volcanoes. In particular, shallow crustal magma storage and associated magma-crust interaction processes could potentially explain some of the world's most unpredictable and explosive volcanoes. This thesis studies magma plumbing architecture in the Sunda Arc (Indonesia), and the North Atlantic Igneous Province, based on elemental and isotope geochemistry, and derived petrological modelling.

In this study, I have employed petrological models, so-called geothermobarometers, to calculate pressures and temperatures (P-T) of crustal magma storage. Geothermobarometers are calibrated thermodynamic formulations based on the composition of magmatic minerals and their co-existing melt as a function of the P-T conditions of crystallisation. Using the calculated P-T estimates, I was able to derive the depth of magma storage, and thereby reconstruct the architecture of magma storage systems. A number of different geothermobarometers based on different mineral phases, including plagioclase, clinopyroxene and olivine, were used for this purpose.

The geothermobarometric modelling was combined with additional elemental and isotope geochemical analyses, as well as collaborations with geophysical investigations. These additional approaches were used to corroborate the findings of the geothermobarometric modelling, and also to model and quantify magma-crust interaction processes that take place during crustal magma storage, such as assimilation of crustal lithologies into the magmatic system.

The findings of this thesis build upon the growing body of evidence in support of the prevalence of shallow magma storage in different volcanic settings worldwide. This realisation is relevant to volcano monitoring and hazard mitigation worldwide.

Keywords: magma plumbing, geothermobarometry, plagioclase, clinopyroxene, magma-crust interaction, hazard mitigation

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List of Papers

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


VIII Budd, D.A., Troll, V.R., Dahren, B. & Burchardt, S. Persistent two-tiered magma pumping beneath Katla volcano, Iceland. Manuscript in review. Geochemistry, Geophysics and Geosystems, submitted

Additional publications

The author also contributed to the following published papers that are included in the appendix

I Jamshidi, K., Ghasemi, H., Troll, V. R., Sadeghian, M., & Dahren, B. (2015) Magma storage and plumbing of adakite-type post-ophiolite intrusions in the Sabzevar ophiolitic zone, northeast Iran. Solid Earth, 6(1), 49–72


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All of the manuscripts in this thesis are the result of the combined efforts of all listed authors. My personal contribution to each paper is described below.

**Paper I:** 70%. This study was initiated during my undergraduate studies. During my PhD project, I performed additional analytical work and updated the modelling. The text and illustrations were also prepared during the PhD, and the geophysical aspects were integrated with the help of my co-authors.

**Paper II:** 10%. My contribution to paper II consisted of integrating the petrological aspect of the study (see Paper I) with the tomographic model provided by the geophysics team.

**Paper III:** 15%. I took part in the field work and rock sampling at Gunung Kelut, and contributed to the sample preparation for geochemical analyses. I also assisted the first author with the geothermobarometric modelling.

**Paper IV:** 10%. I took part in two field work campaigns on Java, during which we collected rock and gas samples on Merapi, and I helped document artwork as well as historical and geological sites relevant to the paper.

**Paper V:** 70%. I took part in a field campaign to the Faroe Islands in 2011. I performed the analytical work and modelling.

**Paper VI:** 60%. I took part in a field campaign to the Faroe Islands in 2011. I performed most of the analytical work and modelling.

**Paper VII:** 60%. Analytical work was performed partly by me, and partly by Albers under my supervision. The modelling was performed by me.

**Paper VIII:** 15%. The approach to the modelling was coordinated in collaboration with me. The supplementary material regarding the Eyafjalla-jökull eruption in 2010 is mostly my work.
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Abbreviations

(EC-)AFC (Energy Constrained-) Assimilation and Fractional Crystallization
FEG-EPMA Field-Emission Gun Electron Probe Microanalyser
FIBG Faroe Islands Basalt Group
LIP Large Igneous Province
MORB Mid-Ocean Ridge Basalt
OIB Ocean Island Basalt
IAB Island Arc Basalt
REE Rare Earth Element
SEM Scanning Electron Microscopy
TIMS Thermal Ionization Mass Spectrometry
Introduction

The aim of this thesis is to study the architecture of volcanic magma plumbing systems and the complex interplay between the crust and the intruding magma. I apply elemental and isotope geochemical modelling to describe the magma plumbing systems at volcanoes in the Sunda Arc (Indonesia) and the North Atlantic Igneous Province.

A magma plumbing system encompasses the transport and storage of magma during its ascent from the source region in the mantle, through the crust, until emplacement or eruption at the Earth’s surface (Fig. 1; cf. Galland et al., 2015). The study of magma plumbing systems, in general terms as well as for specific volcanoes, is of key importance for understanding magma-crust interaction, magmatic evolution, and predicting the eruptive behaviour of different volcanoes (Cooper & Kent, 2014; Annen et al., 2015). Magma ascent is often impeded by the mechanical properties of the relatively brittle and solid crust, and/or lateral density contrasts between crustal lithologies that causes it to stall and pond in magma pockets, where it may reside for considerable amounts of time (Gudmundsson et al., 2011). Magmatic evolution, including fractional crystallisation and assimilation of country rock, is primarily a function of time and heat transfer, both of which are provided by intra-crustal magma storage. Magma plumbing systems therefore provide the structural framework of magma channels and storage regions that control magmatic evolution and magma-crust interaction, which in turn wields a great influence on the character of the subsequent volcanic eruptions.

The architecture of these magma plumbing systems remains one of the big enigmas in magmatic geology (Marsh, 2013; Price et al., 2005). A better understanding of magma transport and storage will enable us to describe and predict the highly variable eruptive behaviour of individual volcanoes (Annen et al., 2015; Galland et al., 2015). Furthermore, the location of magma reservoirs controls the nature and character of magma-crust interaction, such as magmatic stoping, partial melting and assimilation of crustal components. Additions of crustal components to the magma can influence its composition and volatile contents, and in turn also the explosivity of the subsequent eruption (Burchardt, 2009; Troll et al., 2012b).

Magma plumbing systems are studied using a range of different methods based on geophysics, structural geology and field observations, as well as petrology and geochemistry. In the following section, I will give a short
overview of the potential and limitations of the most common methods used in these different disciplines to study magmatic plumbing systems. I will then describe the petrological and geochemical methods and models I have used to study magmatic plumbing systems in this thesis.

Figure 1. A schematic illustration over a typical magma plumbing system, such as discussed in this thesis. The zoomed in part of the image illustrates some of the many different magma-crust interaction processes that take place during magma storage in the crust.

In seismic tomography, the subsurface features of the bedrock are imaged based on recorded seismic P and S waves. The measured seismic waves map variations in density in the crust, and can also detect the presence of liquid, such as magma pockets (cf. Riedel et al., 2005; Koulakov et al., 2013). Tomographic models are generally thought to be relatively accurate, but suffer from a limited spatial resolution. In any given tomographic model, the spatial resolution is directly dependant on the distribution, depth of origin and wavelength of the seismic waves that are included in the model (Riedel et al., 2005; Koulakov et al., 2013). Based on these constraints, the detection
limits of these models are typically restricted to magma bodies of about 1000 meters, in ideal conditions, gradually increasing with depth (cf. Koulakov et al., 2013; Soosalu and Einarsson, 2004). In other words, seismic tomography may struggle to resolve small volume magma pockets, as well as magma storage in the lower crust.

Volcano geodesy studies crustal deformation in response to magma chamber inflation or deflation, which is commonly recorded using radar (InSAR), satellite laser ranging (SLR) or direct GPS measurements (Trota et al., 2006; Chaussard and Amelung, 2012; Geirsson et al., 2012). Geodesy is ideally suited for detecting changes in the magmatic plumbing system, and in particular the intrusion of concentrated volumes of magma into the upper crust. Conversely, geodetic modelling is less suited for studying steady-state magma plumbing systems, and magmatic intrusions that are distributed among multiple small volume pockets in the crust.

The study of ancient solidified magmatic systems that are exposed by erosion provides an invaluable view to the interior of these magma bodies and intrusions, which are otherwise inaccessible. Famous localities include the Rum Igneous Centre, the Skaergaard intrusion, and the sheet intrusions of the Ardnamurchan Igneous Centre (McBirney, 1996; Burchardt et al., 2013; Emeleus and Troll, 2014). These fossilized magma chambers and intrusions form the foundations of our understanding of currently active magma storage and magma-crust interaction.

In igneous petrology, the fractionation pathways and magma-crust interaction that takes place during magma ascent and storage is characterised using analyses of the chemical composition and isotope signatures of whole rock, glass, and minerals. The composition of some magmatic minerals, such as plagioclase and clinopyroxene, is a function of mineral-melt equilibria at defined temperatures and pressures (i.e. depth). The mineral composition thus serves as a chemical record of the thermodynamic conditions during crystallisation, which is in turn a proxy for magma storage. The depth and temperature of crystallisation in a magmatic rock is calculated by applying calibrated thermodynamic formulations, so called geothermobarometers, to known mineral and melt compositions (Putirka, 2008). Another geochemical toolset available to investigate magma-crust interaction is the study of stable and radiogenic isotope signatures of magmatic rocks and minerals. A wide range of isotope systems, such as $^{87}$Sr/$^{86}$Sr, $^{143}$Nd/$^{144}$Nd, $\delta^{18}$O and various Pb isotopes, are used to identify the “geochemical fingerprints” of the primary mantle source and the basement lithologies with which the magma interacts during crustal storage and ascent. Advanced Assimilation and Fractional Crystallisation (AFC) modelling allows us to both identify the contaminant(s), and quantify the relative contribution of crustal material to the magma body (Bohrson and Spera, 2001; DePaolo, 1981; Spera and Bohrson, 2001).
Geochemical and petrological methods, such as igneous geothermobarometers and isotope geochemistry, have a different temporal resolution compared to geophysical and geodetic methods. By looking at different eruptive units from a single volcano, it is possible to evaluate changes in the magmatic plumbing system in the past, which in turn greatly enhances our ability to make predictions about the potential nature of future eruptions. In contrast, geophysical and geodetic approaches exclusively deal with the current state of magma storage, as seismic waves and crustal deformation is recorded in real-time. A reconstruction of the evolution of magma plumbing systems over geological time is therefore not possible using a geophysical approach. Also, unlike e.g. seismic tomography and geodesy, the resolution of thermobarometry is not limited by the size of individual magma bodies. In fact, there is no theoretical detection limit for thermobarometric models, as long as the duration of magma storage is sufficient for crystallisation to take place. While geothermobarometry and other geochemical models are ideally suited to study magma plumbing evolution over time, they are not suitable for real-time applications, as one can only perform geochemical analyses of erupted rocks and minerals.

For the reasons outlined above, the characterisation of active magma plumbing systems is best achieved by integrating evidence derived from both geochemical and geophysical modelling, as demonstrated in Paper I, II, VII and VIII.

This thesis seeks to apply a combination of traditional and cutting edge petrological and geochemical methodologies to characterize pre-eruptive magmatic processes and magma plumbing architecture recorded in the studied volcanic rocks. I combine whole rock geochemistry with mineral-scale microanalysis of major elements, trace elements and isotope signatures. These geochemical data allow to model magmatic plumbing systems and petrological processes such as magma-crust interaction and assimilation.

The papers in this thesis focus on a number of volcanic regions in two different field areas, namely the volcanic Sunda Arc of Indonesia, and the North Atlantic Igneous Province (NAIP). These two regions are geographically distant from each other, and represent different tectonic regimes. By studying the magma plumbing systems at these contrasting volcanic regions I hope to derive conclusions that are not only relevant for these specific regions, but are also applicable to volcanic areas elsewhere.

In addition to papers I to VIII, three papers have been added as an appendix (A1, A2 and A3). These papers were co-authored during my graduate studies, but as they are not directly related to my main research project, they are only included here in the appendix, and will not be discussed further.
1.2 Part 1 - Volcanoes in the Sunda Arc

The first part (Papers I to IV) deals with volcanoes in the Sunda Arc (Indonesia), specifically Anak Krakatau, Gunung Kelut (sometimes also spelled "Kelud") and Gunung Merapi (Fig. 2). The Sunda Arc represents a typical subduction zone setting, where the Indian and Australian plates subduct beneath the Sunda plate (Bock, 2003; Kopp et al., 2001; Newcomb and McCann, 1987).

![Simplified map of the Sunda Arc (Indonesia), with our field locations marked. Redrawn after Gertisser & Keller (2003) and Hamilton (1979).](image)

In a subduction zone setting, magma generation is initiated by the subducted oceanic plate as volatiles are released from the downgoing slab into the overlying mantle wedge. These volatiles lower the ambient melting point of the mantle rocks, which results in partial melting and magma generation. Island Arc magmas are characterised by a high initial H$_2$O, and Large-Ion Lithophile elements such as K, Sr, Ba, Pb and the light Rare Earth Elements (REE) (Wilson, 1989). After partial melting in the mantle, the magmas then have to ascend through both the mantle and the crust of the overlying volcanic arc before erupting at the surface. The overlying arc crust is a significant impediment to the ascending magmas, which frequently leads to the development of complex plumbing systems with multi-level magma storage.
(cf. Annen et al., 2015). As magma is stalled in the relatively cool crust, it evolves by fractional crystallisation and crustal assimilation towards more felsic compositions with higher SiO₂ contents and further addition of crustal volatiles. Felsic (SiO₂-rich) magmas that are rich in volatiles tend to produce more explosive eruptions, with deadly pyroclastic flows, and occasionally even super-eruptions like those at Toba (Indonesia, ~73 Ka) and Taupo (New Zealand, ~26.5 Ka) that erupted volumes in the order of 1000 km³ (Charlier et al., 2005; Rampino and Self, 1992). Furthermore, volcanic arcs also grow thicker as they mature, which makes magma ascent progressively more challenging with time, which in turn results in a higher proportion of evolved magmas and associated explosive eruptions (Wilson, 1989; Annen et al., 2015).

Anak Krakatau is one of the most well-known volcanoes on the planet, infamous for its cataclysmic caldera forming eruption in 1883 that resulted in more than 36 000 casualties (Carey et al., 1996). Over the last couple of centuries, Anak Krakatau has been more or less continuously active, and access to the Krakatau islands is often restricted by the Indonesian Directorate of Volcanology and Geological Hazards Mitigation (Wunderman, 2012).

To the east of Krakatau lies the island of Java, home to almost 150 million people and more than 20 active volcanoes. Two of the most hazardous volcanoes on Java are Kelut and Merapi. Kelut, and its associated crater lake, is perhaps most known for its deadly lahars, but the eruptions themselves also pose a significant threat. The effusive eruption of Kelut in 2007/2008, discussed in Paper IV was relatively minor, but the following eruption in February 2014 was highly explosive and covered most of central and eastern Java in a blanket of dacitic ash. Despite the scarcity of pre-eruptive precursors prior to the 2014 eruption, more than 80 000 local residents were successfully evacuated by the authorities, who thereby likely saved hundreds of lives (Muir et al., 2014).

The city of Yogyakarta, the cultural capital of central Java, sprawls across the lowland on the southern flank of Merapi. Since 1994, Merapi has had four major explosive eruptions, resulting in hundreds of fatalities and the destruction of property and infrastructure. Moreover, volcanic eruptions at Merapi are often coupled with earthquakes along the Opak River fault, like the one in 2006 that caused over 6000 deaths (Troll et al., 2015).

Understanding the magmatic plumbing systems of the individual Sunda Arc volcanoes is of key importance to characterise and predict their eruptive behaviour, thus enabling more timely and efficient hazard mitigation.
1.3 Part 2 - The North Atlantic igneous province

The second part of this thesis (Papers V to VIII) investigates the Icelandic volcanoes Hekla and Katla, and the remnants of the Paleogene Faroe Islands Basalt Group (FIBG), that are part of the North Atlantic Igneous Province (NAIP).

The magmatism in the North Atlantic Igneous province commenced more than 60 million years ago during the breakup of the ancient supercontinent Laurasia and the consequent opening of the North Atlantic at 55 million years ago (Fig. 3; Ritchie & Hitchen, 1996; Torsvik et al., 2001; Hansen et al., 2009). The continental rift opened between what is today Greenland and north-western Europe, and the resulting volcanic activity formed a Large Igneous Province (LIP) that covers parts of what is today Greenland, the Faroe Islands, Scotland, Ireland as well as offshore suboceanic volcanic provinces such as the Hatton and Rockall banks (Hitchen, 2004; Jolley and Bell, 2002).

Figure 3. A reconstruction of the plate tectonic configuration about 55 million years ago when the North Atlantic opened. Based on the geological and geographical information in Ritchie & Hitchen, (1996), Torsvik et al. (2001) and Hansen et al. (2009). See also Fig. 4 for comparison.
The North Atlantic magmatism has two sources: the extension-driven decompressional melting of the upper mantle, and the mantle plume that is currently positioned under Iceland (Schilling, 1973; Wolfe et al., 1997). When the continental or oceanic crust is rifted by tectonic extension, the ambient lithostatic pressure is lowered in the underlying mantle rocks. This reduces the melting point of rocks and minerals, which in turn leads to magma generation. The magmas generated by decompression of the upper mantle generally have low volatile contents and tend to be relatively depleted in incompatible elements such as potassium and sodium (Wilson, 1989). The typical erupted volcanic rocks in extensional settings are called Mid-Oceanic Ridge Basalts (MORB). As the name implies, these MORBs are commonly found at oceanic spreading ridges and on the seafloor, which makes them the most commonly occurring volcanic rock on the planet.

![The North Atlantic today](image)

*Figure 4.* The current locations of the Faroe Islands and Iceland, in relation to the Mid-Atlantic spreading ridge, Greenland and northwestern Europe.
Mantle plumes, or Hot Spots, are thought to be thermal anomalies in the mantle that originate from deep within the earth interior (Schilling, 1973; Wilson, 1989; Wolfe et al., 1997). Mantle plumes locally elevate the ambient temperature of the mantle, which leads to magma generation from widespread and low grade partial melting and associated volcanism. Hot Spot volcanoes are commonly found at oceanic islands like Hawaii, the Azores, the Canary Islands and Iceland, and the typical erupted rock type is aptly called Ocean Island Basalts (OIB). Similar to MORBs, OIBs have a low volatile content, but OIBs have a more varied geochemical fingerprint due to a much more heterogeneous magma source and lower degrees of partial melting (Wilson, 1989). OIBs are typically enriched in incompatible elements and are undersaturated in silica relative to MORB (Wilson, 1989).

Volcanoes in Ocean Island and extensional settings commonly erupt effusively, i.e. not explosively. Classical examples are the lava lake on Kilauea (Hawaii), and the recent six-month long fissure eruption on Bardarbunga, Iceland. More explosive eruptions, and the formation of stratovolcanoes, do occur however. Famous examples of Ocean Island stratovolcanoes are Teide on the Canary Islands, and Pico de Fogo on Cap Verde.

Papers V and VI study the volcanic rocks of the Faroe Islands Basalt Group. The FIBG is part of the North Atlantic LIP and consists of an up to 6 km thick sequence of basaltic lava flows and mafic intrusives (Passey & Jolley, 2009). These lavas are emplaced on a ~30km thick segment of ancient continental crust, which in turn is likely intruded by significant volumes of mafic rocks coeval with the FIBG (England et al., 2005; Harland et al., 2009; Richardson et al., 1998).

Today, most of the subaerial volcanism in the NAIP is located on Iceland. Iceland is positioned above the present-day location of the North Atlantic mantle plume, and is also intersected by the Mid-Atlantic Ridge, which is the active spreading ridge that separates the American continent from Europe and Africa. For this thesis, I investigate the Icelandic volcanoes Hekla and Katla (Papers VII and VIII). Both Hekla and Katla range among Iceland’s most active and hazardous volcanoes, despite being quite different from each other in terms of composition and eruptive style (Thordarson & Larsen, 2007; Thordarson & Höskuldsson 2008).

Hekla’s eruptions are notoriously difficult to predict, often giving very short warning times before eruptions. The most recent eruption of Hekla, in the spring of 2000, was predicted only about 80 minutes prior to onset, and complete evacuation measures could not be implemented before the initial Plinian eruption (Höskuldsson et al., 2007; Soosalu et al., 2005).

The subglacial volcano Katla is known for its explosive eruptions and voluminous tephras, some of which are estimated to be several cubic kilometres in volume (Óladóttir et al., 2008). Moreover, Katla’s eruptions also often melt significant volumes of the overlying Mýrdalsjökull glacier, which has resulted in numerous devastating jökulhlaups (Óladóttir et al., 2008).
The methods employed in this study are explained in section 2. A summary of each of the papers that comprise this thesis is presented in section 3. The main conclusions of the research are summarized in section 4, followed by a popularised summary (Swedish) in section 5.
Methodology

The data presented in this study have been acquired using geochemical techniques for analysis of major elements, trace elements, and radiogenic isotope signatures. Analyses have been performed on whole rock powders and mineral separates, as well as using high resolution techniques such as micromilling and electron microprobe analysis on μm scale. A brief description of each of the analytical techniques and derived petrological models is provided below.

2.1 Elemental microanalysis

Mineral, groundmass and glass compositions as well as elemental maps (papers V, VI, VII, VIII and IX) were analysed by the Field Emission Gun Electron Probe Microanalyser (FEG-EPMA) source JEOL JXA-8530F Hyperprobe at CEMPEG (Centre for Experimental Mineralogy, Petrology and Geochemistry), Uppsala University, Sweden, following the procedure outlined in Barker et al. (2015). Elemental mapping was performed by Wavelength Dispersive X-ray Spectroscopy (WDS) using a 4 μm beam and an accelerating voltage of 15 kV. The quantitative spot analyses were run by WDS using a 15 kV accelerating voltage and 10 nA probe current. The PRZ correction is routinely used. International mineral standards and pure element oxides were used for calibration of WDS analyses. Counting times of 10 seconds for peak positions and 5 seconds for upper and lower background were applied and all elements were analysed by Kα spectral lines. Detection limits are below 90 ppm for major elements, while minor and trace elements have detection limits of ≤135 ppm.

Pyroxene and olivine analyses were run with a 1 μm beam diameter, whereas plagioclase was analysed with a defocused beam of 3 to 5 μm. Groundmass analyses were performed with a defocused beam with a diameter of 10 to 20 μm. Analytical precision was measured on Smithsonian Institute mineral standards. The resulting analyses show that major elements with concentrations >5 wt% have uncertainties of less than 2.2% while minor elements with concentrations below 5 wt% show uncertainties below ≤10%.

For paper I and II, compositions of mineral, glass, melt inclusions and groundmass where analysed at two different EPMA facilities, a Cameca SX 50 at Uppsala University (Sweden) and a JEOL JXA-8200 Superprobe at
Copenhagen University (Denmark). For the Cameca EPMA, an accelerating voltage of 20 kV and a current of 15 nA were used, while the JEOL EPMA used an accelerating voltage of 15 kV and a current of 15 nA. The beam diameter was generally 1 to 2 µm, though a 10 to 15 µm defocused spot was used for the analysis of groundmass and glass composition. International reference materials were used for calibration and standardization (e.g. Andersson 1997). For elements with abundances greater than 1 wt%, the reproducibility is <±10%, while for abundances less than 1 wt%, the reproducibility is >±10%.

2.2 Radiogenic isotope analyses

Isotopes of Sr, Pb and Nd were analysed on hand-picked groundmass and plagioclase separates at the Department of Geosciences and Natural Resource Management, University of Copenhagen, following the procedure outlined in Søager et al. (2015). Each sample (~500 mg) was leached in HCl at 120°C and then digested in HF and HNO₃. For Pb-isotopes, the samples were run through anion exchange columns by elution of other elements in HBr, and Pb was collected in HCl. Pb-isotope analyses were performed on a VG 54-30 MC-TIMS using the double spike technique (Baker et al., 2004). The solution from the Pb-columns was used for separation of Sr and Nd. The samples were loaded onto cation exchange columns and Sr was extracted in 2 M HCl (Søager et al., 2015). Subsequently, Nd was collected in HCl, and separated with Eichrom LN resin in HCl. The Sr and Nd isotope analyses were run on the VG 54-30 MC-TIMS. The isotope results were compared to the international standard NBS987 for Sr and JNd for Nd.

The analysed isotopic signatures are used in EC-AFC and Binary mixing models in Paper VI, to identify and quantify the contribution of crustal materials to the FIBG magmas (Bohrson and Spera, 2001; DePaolo and Wasserburg, 1979; Spera and Bohrson, 2001).

2.3 Isotope microanalysis

In situ microdrilling was performed on plagioclase phenocrysts for paper VI at the Arthur Holmes Isotope Laboratory, Department of Earth Sciences, Durham University, UK, following the procedure se Charlier et al. (2006). Individual zones within the plagioclase crystals were extracted for analysis using a New Wave Micromill™, and the mineral powder was collected in a drop of ultra pure water. The sample slurry was extracted and passed through Sr Spec extraction chromatographic resin in order to isolate the Sr fraction (Charlier et al., 2006; Horwitz et al., 1992). The fraction collected from column chemistry was analysed for Sr isotopes with a Thermo Fisher Triton TIMS, and was monitored against the international Sr standard NBS-987.
2.4 Additional geochemical analyses and models

The papers in this thesis also employ additional data and models acquired from co-workers and commercial labs. These data include 1) oxygen isotope data in papers III and VI, 2) helium isotope data in paper VI, 3) major and trace element analysis of whole rock samples in papers III, VI, VII and VIII, and 4) Seismic tomography in paper II. These methods are described in the respective papers.

2.5 Geothermobarometry

The papers in this thesis employ a number of different igneous thermometers and barometers, based on the mineral composition of plagioclase, clinopyroxene, olivine, and their respective equilibria with co-existing melt. These models are described in detail by Putirka (1999, 2005, 2008) and Putirka et al. (1996, 2003).

Mineral-melt thermobarometry is based on the composition of the mineral phase as a function of co-existing melt and the prevalent temperature(s) and pressure(s) at the time of formation (Putirka, 2008). Using the two measured parameters: mineral and melt composition, the temperature and pressure of mineral formation can be calculated in a system where the thermodynamics and compositional variations are experimentally constrained (Putirka, 2008).

The plagioclase-melt thermobarometer used in papers I, II, III, VI, VII and VIII was calibrated by Putirka (2005, 2008), based on anorthite crystallisation equilibria and anorthite-albite exchange reactions between mineral and melt. The thermometer used is equation 24a, and the barometer is equation 25a (Putirka, 2008).

In papers I, II, III, VI, VII and VIII, I have also employed a number of formulations based on clinopyroxene-melt equilibria (Putirka, 2008; Putirka et al., 1996, 2003) and clinopyroxene composition (Nimis and Ulmer, 1998; Nimis, 1999, 1995; Putirka, 2008). The clinopyroxene-melt models are based on either jadeite-diopside/hedenbergite or aluminium exchange between melt and mineral phase.

When applicable, I have consistently employed multiple thermobarometric models, in order to reduce over-reliance on any individual model.

Selecting a suitable equilibrium melt composition is of key importance for accurate results in the thermobarometric models. For this reason, mineral-melt equilibrium tests are performed using exchange coefficients of major elements and/or mineral components between mineral and melt (Duke, 1976; Putirka, 2008, 1999).

The lithostatic pressures calculated in the geobarometric models are converted to depth using the formula
\[
\frac{P}{\rho \cdot g} = \text{Depth (m)}
\]

where P is expressed in Pascal, \( \rho \) is the bedrock density (kg m\(^{-3} \)) and g is the acceleration due to gravity (9.81 ms\(^{-2} \)). Where possible, I use approximate densities of the known stratigraphy (e.g. papers I and III) or average crustal densities (Papers VI, VII and VIII).
3. Summary of the papers

3.1 Papers I & II

Magma plumbing and storage at Anak Krakatau volcano, Indonesia

Papers I and II are the results of a tandem project of Uppsala University in collaboration with the Institute for Petroleum Geology and Geophysics, Novosibirsk (Russia). Our approach combines petrology and geophysics to investigate the magma plumbing system of Anak Krakatau volcano as recorded in (a) mineral chemical compositions in recently erupted basaltic andesites from Anak Krakatau volcano and (b) seismic tomography derived from local earthquakes. Both petrological and seismic methods are able to detect the location of magma bodies, but suffer from their respective inherent limitations, as discussed in the introduction of this thesis. Therefore, integrated geophysical and petrological surveys offer increased potential for a comprehensive characterization of magma plumbing at active volcanic complexes.

Krakatau is one the most active subduction zone volcanoes on the planet, with an average extrusive growth rate of about 7 cm/week. It is perhaps most renowned for its cataclysmic caldera forming eruption of 1883, which resulted in more than 36,000 casualties. The currently active edifice – Anak Krakatau – is situated on the rim of the 1883 caldera, and has had numerous extended eruptive periods in the last decades. Eruptions at Anak Krakatau are usually effusive and/or strombolian, with the occasional more explosive eruption with ash falls reaching the mainland (Wunderman, 2012).

Previous petrological studies of Anak Krakatau have proposed shallow magma storage beneath the volcano (2 to 8 km; Camus et al., 1987; Gardner et al., 2012; Mandeville et al., 1996), while existing seismic evidence points towards mid- to deep-crustal magma storage zones, at 9 and 22 km (Harjono et al., 1989). The petrological part of his study (paper I) comprises multiple geothermometers and geobarometers based on clinopyroxene, plagioclase and olivine mineral compositions and equilibria with co-existing melt, to determine magma crystallisation depths. The geobarometry shows that clinopyroxene in Anak Krakatau lavas crystallized at a depth of 8–12 km, while plagioclase records both shallow crustal (3–7 km) and sub-Moho (23–28 km) levels of crystallization. The seismic tomography study (Paper II) is a result of the KRAKMON project for multiparameter monitoring of Anak
Krakatau. A network of stations was installed on Sumatra, Java and the islands surrounding Anak Krakatau. More than 700 local seismic events were recorded in 2005 and 2006, which were used to perform a tomographic inversion for P and S wave velocities and for the Vp/Vs ratio. The tomography suggests two magma storage regions in the crust, located at <7 km and >7 km respectively. These two storage regions coincide remarkably well with the upper two storage regions detected by the petrological approach. Due to the spatial configuration of the seismometers and the source earthquakes used in the seismic study, it was not possible to accurately resolve S-wave attenuation at depths greater than ~15 km.

The three magma storage regions revealed by the petrological models, two of which are independently detected by the seismic tomography, coincide with well-constrained major lithological boundaries in the crust beneath Anak Krakatau (Ōba et al., 1983), which implies that magma ascent and storage at Anak Krakatau is strongly controlled by crustal properties, such as density contrasts and changes in mechanical properties (Gudmundson, 2011; Chaussard & Amelung, 2012).

In summary, the combination of petrological and geophysical methods employed to characterise magma plumbing beneath Anak Krakatau in this study is very promising. This approach is mutually beneficial to both petrologists and geophysicists, as it bridges the different inherent shortcomings of both geochemical and geophysical modelling.

Figure 5. The combined findings of the seismic tomography and the mineral-melt thermobarometry suggest a magma plumbing system with three main storage levels below Anak Krakatau.
3.2 Paper III

The magma plumbing system of the 2007/2008 eruption of Kelut volcano, Indonesia

Paper III investigates the effusive dome eruption of Gunung Kelut (sometimes also referred to as Kelud) volcano that took place between November 2007 and May 2008 (De Bélizal et al., 2012). Kelut volcano, East Java, is an active volcanic complex that periodically hosts a summit crater lake that has been the source of some of Indonesia’s most destructive lahars (Mastin and Witter, 2000). In 2007 to 2008, an effusive eruption led to the formation of a 260 meter high and 400 meter wide lava dome that displaced most of the crater lake. The 2007/2008 Kelut dome comprised crystal-rich basaltic andesite with a texturally complex crystal cargo as well as glomerocrysts of varying magmatic mineral assemblages. In addition, the lavas also contained a wide range of magmatic and crustal xenoliths, including metabasalts, cumulates, skarn type calc-silicates and metavolcaniclastic rocks. Paper III presents petrographic, whole rock major and trace element data, mineral chemistry, as well as oxygen isotope data for both whole rocks and minerals. The combined findings of these analyses and models indicate a complex regime of magma mixing, decompression-driven resorption, degassing, crystallisation and crustal assimilation within the Kelut system prior to extrusion of the dome. Detailed investigation of plagioclase textures and crystal size distribution analyses provide evidence for magma mixing as a significant pre-eruptive process that aggregate multiple crystal cargoes into the final erupted lava. Distinct magma storage zones are proposed, with a deeper zone at lower crustal levels (>15 km depth) or near the crust-mantle boundary, a second zone at mid-crustal levels (~10 km depth) and several magma storage zones distributed throughout the uppermost crust (<10 km depth).

The range of δ18O values in the dome rocks span from +5.4 to +7.6 ‰, whereas metabasaltic and calc-silicate xenoliths are characterised by δ18O values of +6.2 and +10.3 ‰, respectively. Also the δ18O of individual pyroxene crystals are considerably lower (5.4 to 6.7 ‰) than for plagioclase (6.7 to 7.6 ‰), which we attribute to crystallisation of pyroxenes in the lower to mid-crust, where crustal contamination is either absent or masked by assimilation of material having similar δ18O values as the ascending magmas. The low-δ18O pyroxene population is mixed with isotopically distinct plagioclase and pyroxenes that crystallised from a more contaminated magma in the upper crustal system. Binary bulk mixing models suggest that shallow-level, recycled volcaniclastic sedimentary rocks together with calc-silicates and/or limestones are the most likely contaminants of the 2007/2008 Kelut magma.

Oxygen isotopic data are either similar or moderately elevated relative to mantle values, and is best explained by assimilation of a combination of upper crustal lithologies. The bulk mixing models indicate that differentia-
tion from basalt to basaltic andesite composition that dominate the 2007/2008 dome eruption occurred prior to any assimilation of upper crustal material, while more evolved compositions found in melt inclusions and groundmass suggest further differentiation within the shallow storage region.

The Kelut 2007/2008 lava dome provides geochemical evidence for a complex magma system made up of a deep storage region in the lower crust, a mid-crustal storage zone, and a shallow plexus of magma pockets. Mixing processes occur in the mid- to upper crustal system, where multiple texturally distinct plagioclase populations are combined. Multiple magma mixing events and incremental magma evolution is recorded within single plagioclase crystals.

3.3 Paper IV

Ancient oral traditions at Merapi volcano, Indonesia

Paper IV investigates ancient Javanese oral traditions, and their link to the eruptive record of the volcano Merapi, on the Indonesian island Java. Merapi volcano is among the most hazardous volcanoes on the planet, with the regional capital of Yogyakarta located on its southern flank. In Javanese folklore, the volcanic activity of Merapi is pictured as the interaction between the Spirit Kings who inhabits the volcano and the Queen of the South Sea at Parangtritis beach at the coast south of Merapi. The royal palace (Kraton) in Yogyakarta is positioned half-way between Merapi and Parangtritis beach, along the Merapi–Kraton–South Sea axis, and was thought to bring balance between these mystical forces.

In 2006 and 2010 Merapi erupted explosively and both eruptions were followed by earthquakes, after which the eruptions grew more violent in response. These earthquakes appear to influence the magma supply system beneath Merapi, and a positive feedback loop has recently been suggested between the volcano and local earthquake patterns (Chadwick et al., 2007; Deegan et al., 2010; Troll et al., 2012a; Voight et al., 2000). The 2006 earthquakes centered along the NE–SW trending Opak River fault to the south of the volcano that reaches the Southern Sea at Parangtritis beach, which is the fabled residence of the Queen of the South Sea. Our interpretation of the Merapi–Kraton–South Sea axis is that folklore was used by local residents in the past to describe their observations of the complex interplay between earthquakes and volcanic eruptions. Moreover, we propose that the volcano–earthquake interaction that has been documented after recent Merapi eruptions has occurred frequently in historic times as well. These oral traditions would therefore have served to maintain hazard awareness between generations in the Javanese communities. In fact, they could be useful
even today in helping to foster effective dialogues with the communities around the volcano’s slopes.

3.4 Papers V and VI

A geochemical probe to see below the Faroe Islands Basalt Group

Papers V and VI investigate the lavas and intrusives of the ~6 km thick Faroe Islands Basalt Group (FIBG), that formed during the break-up of Laurasia and the opening of the North Atlantic. The lavas are emplaced ontop of ~30 km of unidentified ancient continental crust.

In Paper V, we investigate the composition and distribution of plagioclase phenocrysts in lavas, dykes and sills from the Faroe Islands Basalt Group (FIBG). The previously available literature on the FIBG contains a large number of bulk chemical analyses, but mineral chemical data is very sparse. In Paper V to provide plagioclase compositional information for the FIBG by systematically examining compositions of plagioclase feldspar from a series of representative basaltic rock samples that cover the exposed part of FIBG. Plagioclase is the most abundant phenocryst phase in the FIBG, and is commonly used to help constrain magmatic processes and magma storage conditions that are recorded as textural and/or chemical variations.

The range of anorthite contents of plagioclase from the FIBG have a distinct bimodal distribution and can be separated into two dominant populations, one with \( \sim \text{An}_{60-80} \) and another with \( \sim \text{An}_{80-91} \). Moreover, each of the individual analysed rock samples contains plagioclase of one population only.

Paper VI builds upon the findings of Paper V, and provides further geochemical analyses and petrological modelling.

Previous deep drilling projects on the Faroe Islands have failed to reach the base of the basalt pile, which means that the composition of the underlying crust is still unknown. The aim of this study is to characterise the magma plumbing system that fed the Faroese lavas, and to construct a virtual geochemical probe into the underlying continental crust by means of isotope mixing and crustal assimilation modelling.

This study presents geochemical analyses of basaltic samples from the FIBG and a suite of representative basement lithologies from the continental shelf of the UK sector of the Faroe-Shetland basin, and from mainland Scotland and the Shetland Islands. The geochemical analyses provided here are (1) in-situ mineral chemistry of phenocrysts from the FIBG, (2) whole rock major and trace elements from the FIBG and the selected crustal lithologies, (3) Sr, Nd and Pb isotopes of whole rocks and mineral separates from the FIBG and crustal samples, (4) in situ \( ^{87}\text{Sr} / ^{86}\text{Sr} \) signatures of plagioclase phenocrysts in FIBG samples, and (5) O and He isotope signatures in FIBG
rocks. Based on the derived data, we then performed mineral-melt geothermobarometry to provide a model for the magma plumbing system that fed the FIBG lavas. This was then combined with EC-AFC trends for the measured isotope signatures to identify and quantify the contribution of crustal components to the FIBG magmas.

Our study finds that the FIBG was fed by a two-tiered magma plumbing system with a lower magma reservoir at ~20 km depth, and a more shallow storage region at about ~6 km (Fig. 6). Furthermore, we find that lavas stored in the shallow magma storage zone record assimilation of a granitoid or gneiss endmember, with a possible further addition of a metasandstone component.

Figure 6. A reconstruction of the magma plumbing system that fed the lavas of the Faroe Islands Basalt Group. The two storage regions appear to be separated from each other, as indicated by petrographic observations, as well as whole rock and mineral compositions. The deep storage region could be related to the rifting between Greenland and Europe, and the associated decompressional melting of the upper depleted mantle.
3.5 Paper VII

Explaining Hekla’s short fused eruptions

Monitoring active volcanoes with geophysical, geodetic, and geochemical techniques has led to significant progress in eruption forecasting in the last decades. This progress is based on a better understanding of the precursory signals caused by magma transport prior to an eruption (Sparks, 2003). However, some volcanoes elude timely forecasting of eruptions as they show little or no precursory signals. The Icelandic volcano Hekla is exceptionally difficult to predict, often erupting within a few tens of minutes after the first precursory volcanic tremors (Gudmundsson et al., 1992; Höskuldsson et al., 2007; Sturkell et al., 2013). Since Hekla has erupted approximately once every 10 years since 1970, and is responsible for >90% of the intermediate and 25% of the silicic magmas erupted in Iceland over the last 1100 years (Thorarinsson et al., 1972; Grönvold et al., 1983; Gudmundsson et al., 1992; Höskuldsson et al., 2007; Thordarson and Larsen, 2007), it is imperative to resolve Hekla’s temperamental nature. Various configurations of the magma plumbing structure beneath Hekla have been proposed, but there is as of yet no consensus on the matter nor an explanation for Hekla’s short-fused behaviour.

One possible explanation to the short precursor times of <80 min may be exceptionally fast magma ascent rates. If the magma is stored in the lower crust, as suggested by Soosalu and Einarsson (2004), magma ascent rates of up to 5 ms\(^{-1}\) would be required to transport the magma to the surface in the time from the first precursory signals. Alternatively, magma may be stored in reservoirs in the upper crust, which would reduce transport distances significantly, and therefore require more moderate magma ascent rates of \(\leq 1\) ms\(^{-1}\), which is similar to what has been recorded for explosive eruptions at e.g. Mt St Helens (Rutherford and Gardner, 1999), Chaiten (Castro and Dingwell, 2009), Soufrière Hills (Devine et al., 1998), and Pinatubo (Scandone et al., 2007). In paper VII, we present the first detailed geothermobarometric study on Hekla eruptive products of the 1980/81 and 2000 eruptions to constrain current magma storage depths and contribute to a better understanding of Hekla’s short fused behaviour. We employ calibrated mineral-melt thermobarometry formulations, based on clinopyroxene and plagioclase mineral data and associated host rock compositions from the 1980/81 and 2000 eruptions.

Our thermobarometric calculations indicate mineral crystallisation depths for both plagioclase and clinopyroxene mainly in the range of 0 to 10 km, with only small differences between the calculated depths for the two different eruptions. Therefore, we propose that this upper crustal storage level has been active since at least before the 1980/81 eruption.
While the bulk of the magma storage is probably located in the lower crust as indicated by geophysical and geodetic evidence (Geirsson et al., 2012; Höskuldsson et al., 2007; Ofeigsson et al., 2011; Soosalu and Einarsson, 2004), our petrological investigation concludes that this deep reservoir feeds magma into the upper crust. This shallow magma storage region is likely made up of a plexus of interconnected pockets dispersed throughout the crust above 10 km depth. The volume of each individual pocket is presumably less than the resolution of the geophysical methods employed by e.g. Soosalu and Einarsson (2004). Furthermore, we suggest that these magma pockets are connected by a series of conduits that readily dilate when fresh magma is fed from below. This filled up plexus of smaller magma reservoirs could explain the extremely short time between the first precursor tremors and the onset of an eruption, as the system might behave like a connected fluid reservoir where input at the base will rapidly translate to the surface, causing an eruption shortly after initial unrest.

3.6 Paper VIII

Persistent shallow magma storage at Katla volcano, Iceland

Paper VIII investigates the magma plumbing system at Katla, and its evolution over the last 8 ky. Katla is renowned as one of northern Europe’s most active and hazardous volcanic systems due to its frequent eruptions during the Holocene. Katla’s eruptive record is evident from more than 200 Holocene tephra layers on Iceland, erupted over the last 8.4 ky (Larsen, 2000), with an average of one event every 48 years in historical time (Óladóttir et al., 2005). The last major eruption that broke through the glacier that covers Katla occurred in 1918. As Katla and neighbouring Eyjafjallajökull appear to be linked in their eruptive cycles (Thordarson and Larsen, 2007), we could potentially face a Katla eruption in the near future, following the 2010 eruption of Eyjafjallajökull.

A central question for prediction of future eruptive behaviour at Katla is the state of the magma supply system. Previous seismic and geodetic investigations have identified a shallow level low-velocity zone within the volcanic edifice. Active uplift of portions of the summit caldera are attributed to a shallow (≤5 km) magma reservoir beneath Katla (Gudmundsson et al., 1994; Soosalu et al., 2006). Although a wealth of compositional data on Katla tephras are available, a shallow-level storage zone has not yet been confirmed by petrological methods. Indeed, a simple plumbing system with direct supply from depth is indicated by previous petrological studies (Óladóttir et al., 2008), which is in conflict with the seismic and geodetic findings.
Here we test for the existence of a shallow reservoir beneath Katla using plagioclase-melt and clinopyroxene-melt thermobarometry based on 1500 single analysis points from pyroxene, feldspar, and glass from four age-constrained tephra samples of the last 8 ky. Our results confirm the presence of deep (10 to 25 km) as well as shallow (<8 km) magma reservoirs at Katla. These features are broadly consistent in the four examined samples, which span the last 8 ky. We therefore propose that this two-tiered magma plumbing system is a long-lived feature that has persisted at Katla for many thousands of years.

The risk for northern Europe is that either this resident shallow-level magma system becomes highly evolved (and thus volatile-rich), priming the system for an unexpected explosive outburst (Owen et al., 2013) or, more significantly, replenishment of fresh mafic magmas could intersect the evolved parts of this shallow reservoir and cause a major explosive eruption. This would likely be similar to, but potentially considerably larger than, the infamous 2010 Eyjafjallajökull event (cf. Moune et al., 2012; Sigmundsson et al., 2010). Considering that the 1918 Katla eruption produced an ash column of ~14 km height (Larsen, 2000), we ought to optimise our disaster response and mitigation plans against the effects of explosive volcanism on northern Europe.
4. Conclusions

The study of magma plumbing systems, in general terms as well as for specific volcanoes, is of key importance for understanding magma-crust interaction, magmatic evolution, and for predicting the eruptive behaviour of different volcanoes (cf. Cooper & Kent, 2014; Annen et al., 2015). Volcanoes with shallow magma storage tend to be more explosive and unpredictable because of the reduced travel distances for final magma ascent to the surface, but also due to the potential additions of silicic and volatile-rich crustal components to the magma. Moreover, a late addition of crustal volatiles might provide the magma with the “final push” to make it to the surface (cf. Troll et al., 2012a; 2012b; Jolis et al., 2015).

In this thesis, I have studied the magma plumbing systems and associated magma-crust interaction processes at subduction zone volcanoes in the Sunda Arc (Indonesia), as well as active and extinct parts of the North Atlantic Igneous Province.

In recent years, there has been a growing body of evidence supporting the notion of upper crustal magma storage, emphasising the role of crustal stratigraphy and local stress regimes as important factors controlling the emplacement of magma storage bodies (e.g. Gudmundsson, 2011; Menand, 2011; Chaussard & Amelung 2012; Zang et al., 2012; Annen et al., 2015). In this thesis, I provide further evidence for multi-tiered magma storage at several different volcanic regions in very different geotectonic settings. Notably, I have shown that shallow magma storage (≤6 km depth) is or has been present in all of the studied volcanoes, and that the location of magma storage zones frequently correlates with crustal discontinuities (Fig. 7). Moreover, the eruptive behaviour at the hazardous and unpredictable volcanoes Hekla, Kelut and Anak Krakatau have been shown to be in part related to their respective shallow magma storage.

The diversity of the volcanic regions studied in this thesis is of key importance, as the conclusions derived can be considered to be at least partly applicable also to other magmatic systems. The realisation that upper crustal magma storage is more common than previously thought may thus help explain the eruptive behaviour at explosive and unpredictable volcanoes worldwide. The findings presented in this thesis are therefore also of relevance to hazard mitigation and volcano monitoring around the world.
Figure 7. Simplified comparison over the magma plumbing systems modelled for this thesis. Multitiered and shallow magma storage has been found in all studied regions (Note that the magma plumbing system model for Merapi is based on previous research; Chadwick et al., 2012)
5. Summary in Swedish


I den andra delen av avhandlingen undersöker jag resterna av den stora vulkaniska provinsen på Färöarna som var aktiv för mer än 50 miljoner år sedan, samt de isländska vulkanerna Hekla och Katla. Ögruppen Färöarna är en del av den vulkaniska provins som bildades när Nordatlanten började öppna sig för cirka 55 miljoner år sedan och Grönland fortfarande satt ihop med nordvästra Europa. När kontinenterna började dras isär bildades enorma mängder magma som trängde upp och rann ut i massiva lavaflöden som täckte stora delar av östra Grönland och det som idag är Färöarna. Resterna av lavatäcket på Färöarna är än idag 6 km tjockt, och jag har studerat dessa

På grund av de fysikaliska egenskaperna hos den ytliga jordskorpan har magmareservoarer i den övre delen av jordskorpan länge ansetts vara ovanliga. Eftersom den övre jordskorpan är kall och spröd borde det nämligen vara svårt för magman att skapa utrymme i den. Den nedre delen av jordskorpan är däremot betydligt varmare och mjukare, och därför lättare för magman att skapa utrymme i. Magmareservoarer har därför antagits äga rum på större djup i jordskorpan, och kanske framförallt i gränsskiktet mellan jordskorpan och den underliggande manteln. Under senare år har allt fler forskare börjat ifrågasätta den uppfattningen, och många tror nu att ytliga magmareservoarer är betydligt vanligare än man tidigare trott. I denna avhandling presenterar jag nya modeller för magmatransport och lagring i sex olika vulkaniska miljöer, och trots att dessa magmatiska system är geologiskt mycket olika har jag hittat tre gemensamma drag för deras underliggande magmareservoarer:

1. Magmareservoarerna vid dessa vulkaner är fördelade på minst två, och ibland fler, huvudsakliga områden i jordskorpan.
2. Alla har ytligt liggande magmareservoarer i de övre 6 kilometrarna av jordskorpan.
3. Vid flera av vulkanerna påvisar jag hur magmareservoarer ofta återfinns vid skarpa, horisontella gränsskikt i jordskorpans stratigrafi.

Dessa slutsatser indikerar att ytliga magmareservoarer är ännu mer vanligt förekommande än man tidigare trott, vilket i sin tur kan betyda att interaktion mellan magma och skorpa är ett viktigare och mer vanligt förekommande fenomen. Exempelvis så har denna avhandling visat på hur utbrotten hos de oberäkneliga och explosiva vulkanerna Hekla, Anak Krakatau och Kelut i stor utsträckning påverkas av deras respektive ytliga magmaförvar. Inom vulkanforskningen bör vi därför uppdatera vårt synsätt på vulkaners underliggande struktur, både för enskilda vulkaner och för vulkaniska sy-
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"He said that academia reminded him of a badly run circus. The faculty members were like underfed animals -- weary of their cages, which were never large enough to begin with -- and they responded sluggishly to the whip. The trapeze artists fell with monotonous regularity into poorly strung nets. The clowns looked hungry. The tent leaked. The crowd was inattentive, shouting incoherently at inappropriate moments. And when the show was over, no one cheered." - Susan Hubbard.

During my years at Uppsala University, I have met many friends and colleagues whom I will always remember. A special thanks goes to all of the PhD students at the department. It was great getting to know you all! And I am forever grateful for the support from my “Team” - David, Sylvia and Kirsten. All for one, one for all.

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