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Processes of Magma-crust Interaction

*Insights from Geochemistry
and Experimental Petrology*

FRANCES M. DEEGAN



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Abstract

Deegan, F. M. 2010. Processes of Magma-crust Interaction. Insights from Geochemistry and Experimental Petrology. Acta Universitatis Upsaliensis. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 777. 46 pp. Uppsala. ISBN 978-91-554-7924-4.

This work focuses on crustal interaction in magmatic systems, drawing on experimental petrology and elemental and isotope geochemistry. Various magma-chamber processes such as magma-mixing, fractional crystallisation and magma-crust interaction are explored throughout the papers comprising the thesis. Emphasis is placed on gaining insights into the extent of crustal contamination in ocean island magmas from the Canary Islands and the processes of magma-crust interaction observed both in nature and in experiments. This research underscores that the compositions of ocean island magmas, even primitive types which are classically used as probes of the mantle, are susceptible to modification by crustal contamination. The principal mechanisms of contamination identified from work on both Tenerife and Gran Canaria (Canary Islands) are assimilation and partial melting of the pre-existing island edifice and intercalated sediments by newly arriving magma (i.e. “island recycling”). The information that we can gain from studying solidified magma and entrained crustal xenoliths concerning the rates and mechanisms of crustal assimilation is, however, limited. To address this shortcoming, a series of time-variable crustal carbonate assimilation experiments were carried out at magmatic pressure and temperature using natural materials from Merapi volcano, Indonesia. A temporally constrained reaction series of carbonate assimilation in magma has hence been constructed. The experiments were analysed using *in-situ* techniques to observe the progressive textural, elemental, and isotopic evolution of magma-carbonate interaction. Crucially, carbonate assimilation was found to liberate voluminous crustally-derived CO₂ on a timescale of only seconds to minutes in the experiments. This points to the role of rapid crustal degassing in volcanic volatile budgets, and, pertinently, in magnifying hazardous volcanic behaviour. This thesis, therefore, delivers detailed insights into the processes of magma-crust interaction from experiments and geochemistry. The outcomes confirm that crustal processes are significant factors in both, i) ocean island magma genesis, and ii) magma differentiation towards compositions with greater explosive potential which can, in turn, manifest as hazardous volcanism.

Keywords: Canary Island magmatism, HP-HT experimental petrology, magma-crust interaction, Merapi volcano, radiogenic isotopes (Sr, Nd, Pb), stable isotopes (O, B).

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To my family

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals. Reprints were made with permission from the respective publishers.

- I Wiesmaier, S., **Deegan, F.M.**, Troll, V.R., Carracedo, J.C., Chadwick, J.P., Chew, D. (2010) Magma mixing in the 1100 AD Montaña Reventada composite eruption, Tenerife, Canary Islands: Interaction between rift zone and central volcano plumbing systems. *Contributions to Mineralogy and Petrology*, *accepted*.
 - II Delcamp, A., Troll, V.R., van Wyk de Vries, B., Carracedo, J.C., Petronis, M.S., Pérez-Torrado, F.J., **Deegan, F.M.** (2010) Stabilisation and destabilization of ocean island rift-zones: the NE-rift of Tenerife, Canary Islands. *Bulletin of Volcanology*, *submitted*.
 - III **Deegan, F.M.**, Troll, V.R., Barker, A.K., Chadwick, J.P., Harris, C., Delcamp, A., Carracedo, J.C. (2010) Crustal versus source processes recorded on the North East volcanic rift zone of Tenerife, Canary Islands. *Manuscript*.
 - IV **Deegan, F.M.**, Troll, V.R., Deyhle, A., Harris, C., Hansteen, T.H. (2010) Boron isotopes in feldspar phenocrysts from peralkaline ignimbrite 'A', Gran Canaria: Tracing magmatic processes on ocean islands. *Geochimica et Cosmochimica Acta*, *submitted*.
 - V **Deegan, F.M.**, Troll, V.R., Freda, C., Misiti, V., Chadwick, J.P., McLeod, C.L., Davidson, J.P. (2010) Magma-carbonate interaction processes and associated CO₂ release at Merapi volcano, Indonesia: insights from experimental petrology. *Journal of Petrology*, 51:1027-1051.
- A popular science style article follows paper V:
- Deegan, F.M.**, Troll, V.R., Freda, C., Misiti, V., Chadwick, J.P. (2011) Fast and furious; crustal CO₂ loss at Merapi volcano, Indonesia. *Geology Today*, *accepted*.

Personal contributions

All of the manuscripts in this thesis are the result of a combination of efforts from the various authors. My individual contribution to each is described as follows:

Paper I: I performed the majority of the initial sample processing, all Sr-Nd-Pb chemical separation and preparation for analysis, and the TIMS data acquisition. I also contributed to petrography, data discussion, and manuscript writing.

Paper II: I provided field assistance, performed the initial sample processing with Delcamp, and contributed to petrography and geochemical classification of the samples.

Paper III: I performed the initial sample processing with Delcamp, all Sr-Nd-Pb chemical separation and preparation for analysis, and contributed to TIMS data acquisition. I also contributed to oxygen isotope data acquisition. I performed the data reduction and modelling, organised and coordinated the data discussion, and carried out the figure and manuscript preparation.

Paper IV: Authors 1 and 2 contributed equally to this paper. I contributed to data discussion and performed the geochemical modelling, figure preparation, and manuscript writing in collaboration with Troll.

Paper V: I performed the HP-HT experiments and subsequent micro-analysis with supervision from Freda and Misiti and carried out micro-milling of the experimental products in collaboration with McLeod and Davidson. I performed the data reduction and plotting, organised and coordinated the data discussion, and carried out the figure and manuscript preparation.

Popular science article: I worked closely with Troll and Freda in writing the article and preparing the figures.

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Abbreviations

AFC	Assimilation and fractional crystallisation
DMM	Depleted MORB mantle
EMPA	Electron microprobe analysis
HIMU	High μ mantle component ($\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$)
HP-HT	High pressure and high temperature
ICP-MS	Inductively coupled plasma mass spectrometry
MC-ICP-MS	Multi collector inductively coupled plasma mass spectrometry
MORB	Mid-ocean ridge basalt
NERZ	Northeast rift zone
SEM	Scanning electron microscopy
SIMS	Secondary ion mass spectrometry
TIMS	Thermal ionisation mass spectrometry

1. Introduction

1.1 Scope and structure of the thesis

The subject of this thesis is magma-crust interaction, which is approached by studying both natural rock samples and high pressure-high temperature (HP-HT) experimental products. Magma-crust interaction encompasses a range of processes, including crustal partial melting (anatexis), assimilation, and degassing. These processes are recognized as being important in magma differentiation and are often closely associated with other magma chamber processes such as magma mixing and fractional crystallisation (Fig. 1.1).

This thesis takes two approaches to providing insights into the processes of magma-crust interaction, and can hence be considered as comprising two complementary parts. The first approach (part 1) utilises the chemical information preserved in erupted and intruded magma to examine crustal processes in ocean island magmatic systems (the Canary Islands). The second approach (part 2) employs HP-HT experimental petrology to look at the actual mechanisms and rates of magma-crust interaction under controlled laboratory conditions, using natural materials from Merapi volcano, Indonesia.

By way of introduction, some background information on the problem of magma-crust interaction is given in section 1.2. This is followed by a brief overview of the two approaches taken in this research, which form parts 1 and 2 of the thesis, in section 1.3.

The methodology is given in section 2, including an explanatory note on the experimental design. A summary of the papers comprising this thesis are then presented in section 3. The main conclusions arising from the papers are given in section 4. Finally, a popularised summary of the thesis is provided in Swedish in section 5.

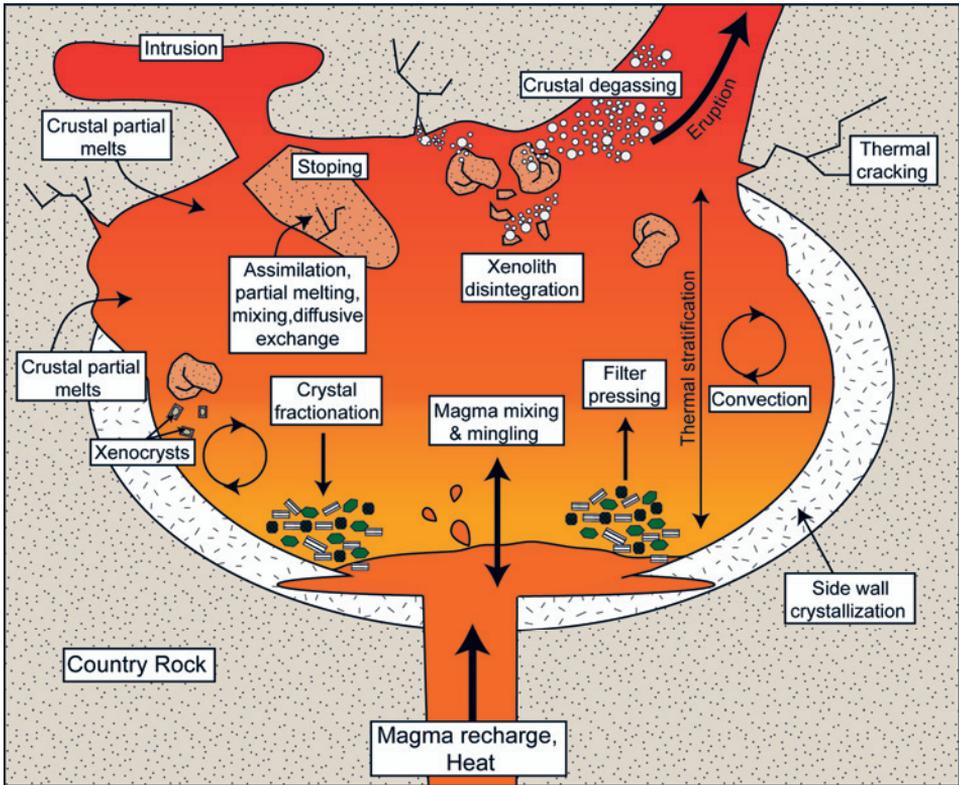


Figure 1.1: Schematic sketch showing various magma chamber processes (not to scale). Some of these processes, e.g., magma mixing (paper I), fractional crystallisation (papers III-IV), crustal partial melting (paper IV), crustal assimilation (papers III-V), and crustal degassing (paper V), are examined in detail in the thesis. Sketch modified after Troll (2001).

1.2 Background

General overview

When magma ascends from its deep mantle source towards the surface it must traverse the earth's crust, where it is stored in shallow-level magma chambers prior to either eruption or subsurface solidification. While magma resides in crustal magma chambers it can undergo a multitude of physio-chemical processes such as magma mixing, fractional crystallisation, crustal assimilation, and degassing (Fig. 1.1). These processes act together to drive the magma to more evolved compositions, which consequently have greater explosive potential. Work that improves our understanding of these processes is hence important in terms of understanding magmatic evolution and in predicting and mitigating potentially hazardous volcanism.

The role of crustal interaction in magmatic differentiation has been given variable attention within the scientific community over the past *ca.* 170 years. Crustal contamination has been considered as having a role in magma genesis since the seminal work of Bowen (1928). Over the last 60 years, however, discussion of the importance of crustal interaction in magmatic evolution underwent a “*decline and renaissance*” (O’Hara, 1998). Renewed interest in this topic has been aided by the application of geochemical tools such as radiogenic and stable isotope geochemistry and the advent of *in-situ* micro-analytical methods (e.g. Harris *et al.*, 2000; Davidson *et al.*, 2005). These approaches have elucidated the role of many of the processes summarised in Fig. 1.1. Some of these processes include: thermal cracking of crust, xenoliths, and stopped blocks; xenolith disintegration; crustal degassing; assimilation coupled with fractional crystallisation (AFC); partial, bulk crustal and xenolith melting; “selective” melting or dissolution; physical mingling between melts; and chemical mixing between melts. Many of these are explored by, e.g., DePaolo (1981); Blichert-Toft *et al.* (1992); Clarke *et al.* (1998); Knesel and Davidson (1996); Troll and Schmincke (2002); Dallai *et al.* (2004); Barnes *et al.* (2005); Troll *et al.* (2004, 2005); Garcia-Moreno *et al.* (2006); Freda *et al.* (2008); Gaeta *et al.* (2009); Acosta-Vigil *et al.* (2010); and Mollo *et al.* (2010). Note that these fundamental processes of magma-crust interaction occur across all volcano-tectonic settings.

The work contained in this thesis, in turn, contributes to our understanding of crustal processes and underscores the importance of magma-crust interaction in magmatic evolution and in driving the generation of magma with high explosive potential.

Crustal contamination in nature

Crustal contamination is a well documented phenomenon at many volcano-tectonic settings, in particular continental settings where thick, differentiated crust exists. Good examples are continental margin subduction systems, many of which carry geochemical signatures indicative of crustal involvement in their genesis (e.g. Hildreth and Moorbath, 1988; Davidson *et al.*, 1990; Davidson *et al.*, 2005).

Recognition of crustal contamination in the oceanic environment (ocean islands and mid-ocean ridges) is generally less well acknowledged than in continental settings (e.g. Davis *et al.*, 1998). In ocean island magma genesis, for instance, assimilation of ocean crust is believed to be minimal, due to the relatively thin crust through which ocean island magmas pass. Ocean island magmas have therefore traditionally been presumed to represent “probes” of the mantle, recording their source isotope characteristics (e.g. Zindler and Hart, 1986; Gerlach *et al.*, 1988; Cousens *et al.*, 1990; Hoffman, 1997). It is becoming increasingly apparent, however, that processes such as internal island recycling and crustal contamination can play a significant role in

ocean island magma genesis (e.g. Bohrson and Reid, 1997; Thirlwall *et al.*, 1997; Garcia *et al.*, 1998; Gee *et al.*, 1998; Kent *et al.*, 1999; Harris *et al.*, 2000; Wolff *et al.*, 2000; Gurenko *et al.*, 2001; Troll and Schmincke, 2002; Hansteen and Troll, 2003; Wang and Eiler, 2008; see papers III and IV). It is therefore crucial to identify crustal contamination in ocean island magmas before attempting to characterise mantle sources (cf. Marcantonio *et al.*, 1995; paper III).

Where assimilation occurs during magma storage within the pre-existing island edifice, recognition of crustal contamination becomes challenging. Major and trace element variations may not be useful indicators of contamination in this case, given that the newly arriving magma and the existing island edifice may be chemically very similar (e.g. Wolff *et al.*, 2000; Wisemaier, 2010). In cases where the island edifice is compositionally heterogeneous due to the presence of differentiated (felsic) and variably altered erupted and plutonic products, recognition of island recycling may be achieved by using reliable tracers of material that has undergone surface or near surface alteration, such as oxygen isotopes (Thirlwall *et al.*, 1997; Garcia *et al.*, 1998; Harris *et al.*, 2000; Wolff *et al.*, 2000; Hansteen and Troll, 2003; Wang and Eiler, 2008). Isotopes of B, Sr, and Nd have also been demonstrated useful in tracing island recycling (see papers III and IV).

Experimental insights into magma-crust interaction

Fragments of crustal material entrained in solidified magma (i.e. “xenoliths”) constitute the end-products, or near end-products, of magma-crust interaction (Fig. 1.2). Such occurrences can provide valuable information on the nature of magma-crust interaction (e.g. Hickey-Vargas *et al.*, 1995; Michaud, 1995; Hansteen and Troll, 2003; Fulignati *et al.*, 2004; Aparicio *et al.*, 2006; Chadwick *et al.*, 2007; Álvarez-Valero and Waters, 2010). However, detailed understanding of the mechanisms and rates involved and the associated chemical exchanges at the magma-crust interface is very limited. Studies utilising experimental petrology can simulate crustal interaction under controlled P-T-X conditions and hence provide detailed insights into these problems (e.g. Watson, 1982; Watson and Jurewicz, 1984; Johnston and Wyllie, 1988; Beard *et al.*, 1993; Sachs and Strange, 1993; McLeod and Sparks, 1998; Knesel and Davidson, 1996, 2002; García-Moreno *et al.*, 2006; Freda *et al.*, 2008; Mollo *et al.*, 2010). Experimental petrology is therefore a valuable tool in understanding the processes of magma-crust interaction and is employed in paper V of this thesis.

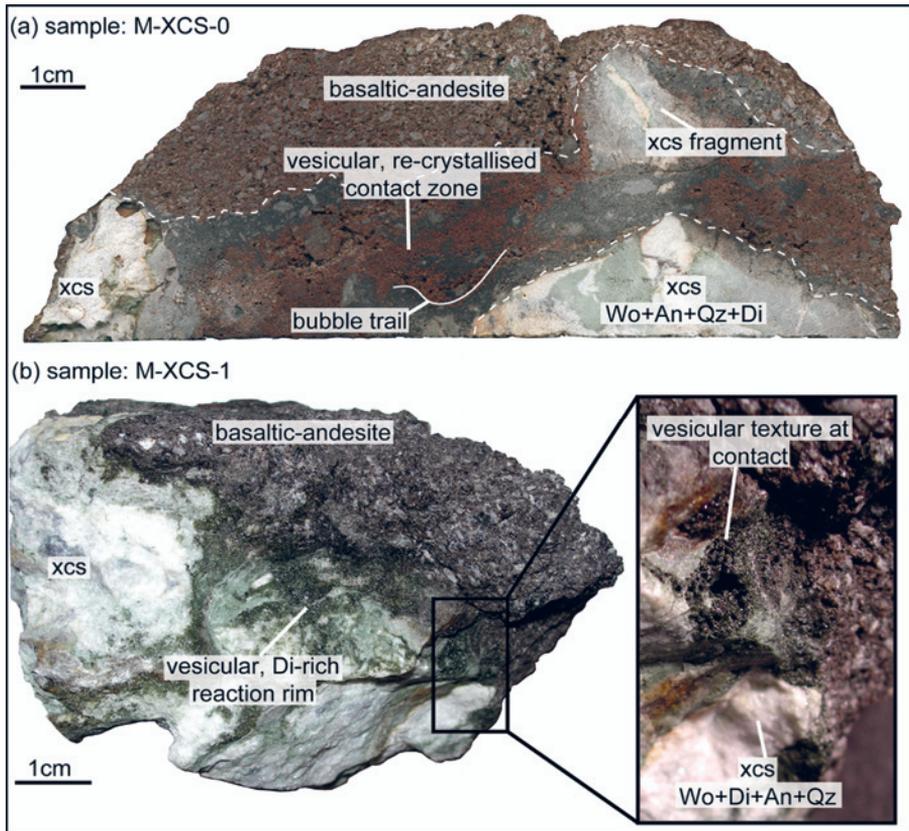


Figure 1.2: Examples of calc-silicate xenoliths (“xcs”) entrained in host basaltic-andesite from Merapi volcano, Indonesia. Samples display intensely developed xenolith-magma contact zones with vesicular textures and skarn-type mineral assemblages. Mineral abbreviations: Wo = wollastonite, Di = diopside, An = anorthite, Qz = quartz. Mineral assemblages are listed in order of decreasing abundance. Such occurrences provide the basis for experimental investigations of magma-crust interaction.

1.3 Approach

Part 1: Crustal contamination in nature

In this part of the thesis, crustal interaction is investigated in an ocean island volcano-tectonic environment (Canary Islands). Crustal contamination in this environment has classically been considered minimal due to the relatively thin ocean crust traversed by magma on ascent (Wilson, 1997). Many recent studies have pointed to a significant role for crustal interaction in ocean island magma genesis, however (see section 1.2). This part of the thesis begins with a study of progressive magma mixing processes between two

genetically distinct magma systems on Tenerife (paper I). This is followed by two papers (II and III) focusing on dykes of the Northeast rift zone (NERZ) on Tenerife. These can be considered companion papers, with paper II providing the field-based context for the geochemical study presented in paper III. Paper III highlights the role of crustal contamination and island recycling in the geochemical evolution of the rift zone, which mainly comprises relatively primitive (low-Si) magmas. Identification of the geochemical repercussions of this process allows the data to be screened for contamination-related “noise” and the primary, mantle derived “signal” to be resolved. Finally, a study of crustal melting, assimilation, and island recycling in a highly evolved (high-Si) magma system on Gran Canaria is presented in paper IV.

Part 2: Processes and rates of crustal carbonate assimilation

In contrast to part one of the thesis, which examines crustal interaction in nature, part two focuses on the processes of magma-crust interaction under controlled experimental conditions (paper V). Natural materials from Merapi volcano (basaltic andesite and crustal carbonate) were used in a series of HP-HT, time variable, carbonate dissolution experiments. Analysis of the experiments provided valuable and detailed information about the textural, chemical, and isotopic evolution of carbonate assimilation. This study also generated startling implications for the timescales of carbonate degassing and the consequent repercussions for hazardous volcanic behaviour (See the short article accompanying paper V).

2. Methodology

The research presented in this thesis draws on a number of geochemical tools and HP-HT experimental petrology. The following techniques have been employed, with a detailed description of the method used, including laboratory procedures, analytical precision and accuracy, etc., given in the papers indicated.

- i) Elemental and isotope analyses: major and trace elements, O-Sr-Nd-Pb isotopes. Details are provided in paper III and the corresponding appendix.
- ii) Non-traditional stable isotopes: boron. Details are provided in paper IV.
- iii) HP-HT experimental petrology. Details are provided in paper V.
- iv) In-situ micro-analysis and sampling: EPMA, micro-milling followed by micro-Sr isotope analysis. Details are provided in paper V.

A summary of the geochemical analytical techniques are given here. A note on the HP-HT experimental design is also given here as it differs substantially from previous experimental investigations of crustal assimilation.

2.1 Elemental analysis

Initial preparation of rock samples for geochemical analysis was carried out at Trinity College Dublin, Ireland. This involved crushing and milling pristine rock chips to a fine powder. Details are given in the appendix to paper III.

Major and trace elements (XRF)

Major and trace elements were analysed by X-Ray Fluorescence (XRF) at IFM-Geomar, Kiel, Germany. Fused glass beads were formed from sample powders and analysed using an automated Philips PW1480 X-ray spectrometer following the method given in Abratis *et al.* (2002) and references therein. Water and CO₂ contents were measured by IR photometry at Geomar.

Trace and rare earth elements (ICP-MS)

Trace and rare earth elements were analysed by inductively coupled plasma mass spectrometry (ICP-MS). In preparation for ICP-MS analysis samples were acid digested and precisely diluted 4000-5000 times in 5 % HNO₃ in a

class 100 clean laboratory at the Vrije Universiteit (VU), Amsterdam, the Netherlands. The full procedure and analytical precision is given in the appendix to paper III. Analysis was carried out using a Quadrupole Thermo X-Series II ICP-MS at the VU following the standard procedure and instrument settings in Eggins *et al.* (1997).

2.2 Stable isotope analysis

Oxygen

All oxygen isotope data were obtained at the University of Cape Town (UCT), South Africa following the procedure given in Vennemann and Smith (1990) and Fagereng *et al.* (2008). Oxygen was produced by reacting ca. 10 mg of sample powder with ClF_3 at 550 °C for at least 4 hours. The liberated O_2 was then converted to CO_2 using a hot platinized carbon rod and captured in a break-seal glass tube under vacuum. Analysis was carried out on a Finnigan Mat Delta XP mass spectrometer in dual inlet mode. The results are reported in standard δ -notation relative to the SMOW (Standard Mean Ocean Water) scale. During the course of this study, the analytical error was ca. ± 0.1 ‰ (1σ) for all samples. Individual crystal analyses were carried out using the laser fluorination vacuum line at UCT. Full analytical details for the laser line are given in Harris and Vogeli (2010).

Boron (concentration and isotope ratios)

Boron concentrations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (JY 170 Ultratrace) at IFM-Geomar, Germany, following the procedure outlined in Heinrichs and Hermann (1990). External reproducibility was better than 1 %. Boron was separated from the samples using the method given in Deyhle (2001). Isotope analysis was carried out by thermal emission mass spectrometry using a Finnigan MAT262 RPQ²⁺ system operating in static positive mode at IFM-Geomar with reproducibility ($2\sigma_{\text{mean}}$) of ± 0.13 ‰. The $^{11}\text{B}/^{10}\text{B}$ ratios of the samples are reported using the conventional delta notation ($\delta^{11}\text{B}$) as ‰ deviation from the standard NBS 951.

2.3 Radiogenic isotope analysis

Sample digestion and separation of Sr, Nd, and Pb was carried out at the VU, Amsterdam. Full procedural details are given in the appendix to paper III.

Strontium (TIMS)

Strontium isotope measurements were performed on a Finnigan MAT 262 TIMS system operating in static mode at the VU, Amsterdam. Instrumental mass fractionation was corrected by normalizing to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ using an exponential correction law. Values obtained for internal and procedural standards and blanks are given in paper III.

Neodymium, Lead (MC-ICP-MS)

Neodymium and lead isotopes were measured using a Finnigan Neptune multi collector ICP-MS (MC-ICP-MS) at the VU, Amsterdam. The method used to measure Nd isotope ratios is given in Luais *et al.* (1997). Pb isotopes were analysed using the method of standard-sample bracketing. Full details of the method used, the instrument settings, analytical reproducibility and data reduction are given in Elburg *et al.* (2005). Values obtained for internal and procedural standards and blanks are given in paper III.

2.4 Experimental petrology and micro-analysis

Experimental design

The experiments presented in paper V were designed to provide temporally-constrained insights into the processes of magma-carbonate interaction. Experimental petrology techniques have previously been used to examine the processes of assimilation and contamination in magmatic systems (e.g. Watson, 1982; Watson and Jurewicz, 1984; Johnston and Wyllie, 1988; Beard *et al.*, 1993; Sachs and Strange, 1993; McLeod and Sparks, 1998; Knesel and Davidson, 2002; García-Moreno *et al.*, 2006). The experimental approach taken in paper V, however, differs substantially from these works. Firstly, paper V focuses on assimilation of crustal carbonate in magma, which is generally less frequently investigated than fusion and assimilation of silicic crustal components. Indeed, some experimental studies of limestone assimilation have been carried out previously, but they contrast this work in that they have largely focused on the phase assemblages resulting from carbonate digestion, rather than on the processes of progressive carbonate assimilation (Freda *et al.*, 2008; Iacono Marziano *et al.*, 2008; Mollo *et al.*, 2010). Secondly, the experiments described in paper V were carried out using very short and progressively increasing dwell times (0 to 300 s). This is much shorter than any other experimental study of crustal assimilation in the literature in which experiments typically run for hours to days (e.g. Watson, 1982; Beard *et al.*, 1993; García-Moreno *et al.*, 2006). This experimental design therefore allows for preservation of the transient textures in the experimental products and for subsequent examination of some features of mass transport

and intra-melt homogenisation at the contaminated melt front as carbonate assimilation proceeds.

All experiments were carried out at the HP-HT laboratory of Experimental Volcanology and Geophysics at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy (see <http://roma1.rm.ingv.it/laboratories/hp-ht-lab>). Experiments were performed with the piston cylinder apparatus at $T = 1200\text{ }^{\circ}\text{C}$, $P = 0.5\text{ GPa}$, and with dwell times of 0, 60, 90, 150, and 300 s. The dwell time is the length of time that the experiment was held at the experimental temperature, with 0 s being an experiment that was immediately quenched on reaching $1200\text{ }^{\circ}\text{C}$. The piston cylinder reaches $1200\text{ }^{\circ}\text{C}$ after only 6 minutes, which is sufficiently fast to ensure preservation of the carbonate phase in the shortest duration experiments. This allows for subsequent inspection of the interaction between carbonate and melt over a timescale of minutes after the experimental temperature is reached. It is for this reason that the piston cylinder was selected as the most appropriate instrument for this study.

Generally, two experiments were run simultaneously in order to construct a reaction series of carbonate assimilation under both anhydrous and hydrous ($\text{H}_2\text{O} = 2.5\text{ wt. \%}$) conditions. For some runs, however, a third carbonate-free control experiment was inserted into the piston cylinder assembly (Fig. 2.1). A full explanation of the experimental conditions used, preparation of the starting materials, and details of the experimental procedure are provided in paper V.

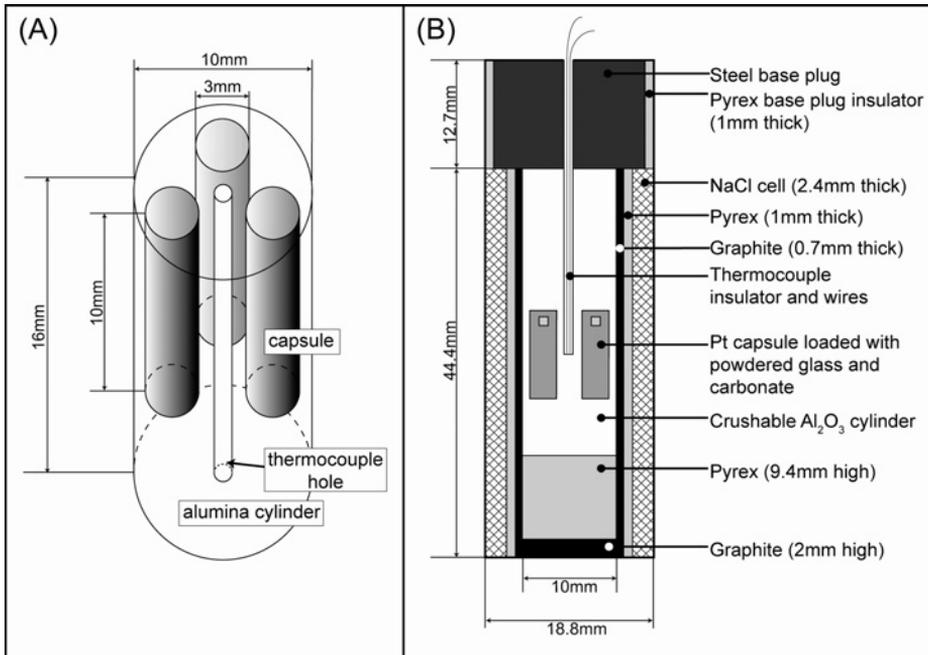


Figure 2.1: (A) Sketch of the capsule configuration used to run three experiments simultaneously. This allowed for a carbonate-free control experiment to be run under the same conditions as the hydrous and anhydrous de-carbonation experiments. (B) Sketch of the NaCl-crushable alumina-pyrex assembly constructed to encase the experimental capsules in the piston cylinder. Hydrous experiments were additionally encased in pyrophyllite to prevent water loss (Freda *et al.* 2001). See paper V for experimental procedure.

Micro-analysis

Elemental micro-analyses and scanning electron microscopy (SEM) imaging of the experimental products was carried out the INGV Rome, Italy, using a JEOL-JXA8200 EDS-WDS combined instrument. Microprobe WDS analyses were performed using an accelerating voltage of 15 kV, a beam current of 5 nA, and a beam diameter of 5 μm for glass and 1 μm for mineral analyses. See Iezzi *et al.*, 2008 for analytical details and paper V for the average standard deviation (1σ) of each element in the analysed standards.

Two experiments, with dwell times of 0 s and 300 s, were selected for micro-sampling and Sr isotope analysis. Micro-sampling was carried out in the Arthur Holmes Isotope Geology Laboratory at Durham University, UK, using a New WaveTM MicromillTM following the techniques given in Charlier *et al.* (2006) and references therein. Strontium was separated from the samples at Durham using micro-Sr column chemistry as described by Charlier *et al.* (2006) in preparation for TIMS analysis. Strontium isotope analy-

sis was performed at Durham using a Thermo-Finnigan Triton TIMS operating in static mode. Details of the procedure used to load small Sr samples, as well as TIMS running conditions, and data correction are given in Font *et al.* (2008). Values for standards and blanks can be found in paper V. Aliquots of the dissolved samples were also analysed for their trace element concentrations by ICP-MS using a Thermo Electron Element II system at Durham University. Procedural details can be found in Font *et al.* (2008).

3. Summary of the papers

3.1 Paper I

Magma mixing at Montaña Reventada, Tenerife

Paper I addresses magma mixing in a composite eruption deposit at Montaña Reventada, Tenerife, Canary Islands. Montaña Reventada comprises a lower basanite (mafic) and thick upper phonolite (felsic) unit, unlike many zoned eruption deposits which commonly show the inverse. The latter types of zoned eruption deposits are thought to reflect eruption of co-genetic magma from large, compositionally stratified magma chambers (e.g. Freundt and Schmincke, 1992; Troll and Schmincke, 2002). However, mixed magmas have also been explained by forced intrusion of a genetically distinct magma into another, which can then remobilise the pre-existing magma and trigger an eruption (e.g. Turner, 1980). The key aims of this paper are to establish whether the Montaña Reventada magmas co-existed for any appreciable amount of time in a stratified magma chamber and if they are co-genetic. The results, in turn, have implications for interaction between different magma plumbing systems (i.e. a rift zone and central volcano) on ocean islands.

At Montaña Reventada, a sharp interface separates the magma end-members and chilled margins within the basanite indicate that it was still hot when the cooler phonolite was emplaced, i.e., the two magmas erupted in quick succession. The phonolite contains abundant mafic inclusions that exhibit a variety of textures including quenched foam, chilled margins, and features indicative of physical mingling. The observed textures reflect progressive magma mixing processes and indicate an initially stark temperature contrast between the magma end-members.

Montaña Reventada basanite, phonolite, and a selection of inclusions were analysed for major and trace elements and Sr-Nd-Pb isotopes to constrain the geochemical consequences of mixing. The data show the inclusions to be derived from binary mixing of basanite and phonolite end-members in ratios of 2:1 to 4:1. Interestingly, although the basanite and phonolite erupted from the same conduit, their contrasting $^{206}\text{Pb}/^{204}\text{Pb}$ ratios show that they are genetically distinct (19.7193(21)-19.7418(31) versus 19.7671(18)-19.7807(23), respectively).

It is hence argued in paper 1 that the Montaña Reventada basanite and phonolite interacted just prior to eruption and for a limited time only. Given that Montaña Reventada erupted from the transition zone between two plumbing systems – the phonolitic Teide-Pico Viejo central complex and the basanitic Northwest rift zone – it appears likely that a rift zone basanite dyke intersected a previously emplaced phonolite magma chamber. This resulted in eruption of geochemically and texturally unaffected basanite, with the inclusion-rich phonolite subsequently following into the established conduit.

3.2 Paper II

Structural development of the NERZ, Tenerife

Paper II introduces the Northeast volcanic rift zone on Tenerife (NERZ) and examines its structural development and the close link between rift zone growth and flank collapse.

Rift zones on ocean islands are major volcanic alignments associated with intense dyke intrusion that play a crucial role in island growth. They are frequently organised in a triple-armed pattern, with lateral flank collapses located between the rift-arms (e.g. Carracedo, 1994, 1996; Walter and Troll, 2003). Several models have been proposed to explain the structure of oceanic rift zones and the intimate link between rift zone growth and the initiation of lateral collapses. The NERZ on Tenerife offers a unique opportunity to investigate this link, as three successive collapses (1 – Micheque, 2 – Güímar, 3 – Orotava) are located on the two sides of the rift, which itself is very well exposed and therefore suitable for detailed mapping and sampling (Fig. 3.1).

Systematic and detailed mapping was carried out on the dykes of the NERZ. Their orientation and distribution indicate a complex and changing strain and stress field. Dykes were intruded along the rift, but also radiate from several nodes along the rift.

Paper II concludes from the dyke pattern that flank creep was a key mechanism that accommodated the intense intrusive activity along the rift. Flank creep was initiated by intrusions, but eventually worked to localise intrusive activity itself. With continued magma supply, flank creep allowed temporary relaxation of the rift. However, at some time a critical point was reached, beyond which further intrusion lead to flank failure and sector collapse. During the early stages of growth, a rift may be influenced by regional stress/strain fields and by pre-existing structures, but subsequent development depends on the local stress/strain fields that are effectively controlled by the rift-zone, flank creep, intrusive complex spreading and the changing collapse-related topography.

This work shows that volcanic rift-zones are a highly dynamic and changing geological and morphological environment and provides a detailed field-basis for the geochemical study presented in paper III.

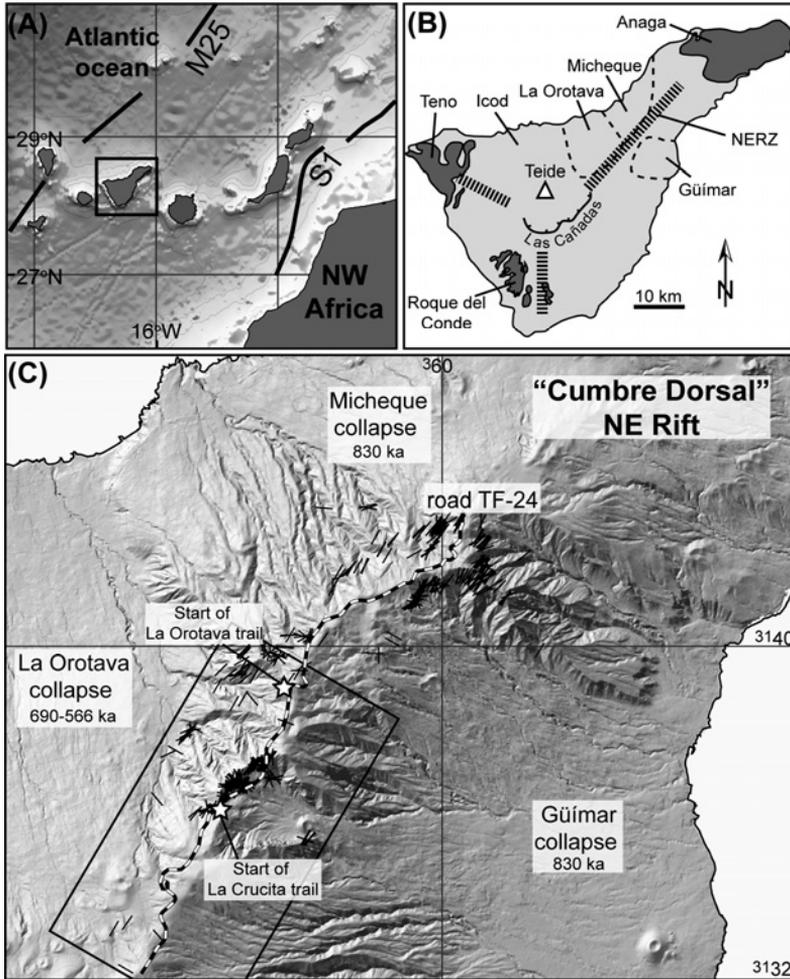


Figure 3.1: (A) Map of the Canary Archipelago, located off the coast of NW Africa between magnetic anomalies S1 (175 Ma) and M25 (156 Ma) (Roeser, 1982) with Tenerife highlighted. (B) Simplified geological map of Tenerife. (C) Shaded relief map of the NERZ showing the distribution of the investigated dykes along the rift (short black lines) and the three collapse depressions flanking the ridge. The thick black and white line is the road TF-24 along which there is excellent exposure of the dykes of the NERZ. The black box delimits the sampling area for the geochemical study presented in paper III.

3.3 Paper III

Crustal versus source processes on the NERZ, Tenerife

Paper III presents insights into the petrologic evolution of the NERZ, and evaluates the role of crustal assimilation in rift zone magma genesis. A key aim of this paper is to disentangle the isotopic effects of crustal interaction from the mantle source signal.

Assimilation of crustal material in ocean island magma genesis is generally considered minimal, especially for relatively primitive, low-Si magma types. Several works have shown, however, that crustal assimilation in oceanic settings does indeed need to be accounted for, especially before attempting to characterise mantle source components (e.g. Marcantonio *et al.*, 1995; Thirlwall *et al.*, 1997; Harris *et al.*, 2000; Wang and Eiler, 2008). To address this goal, paper III presents major and trace element and O-Sr-Nd-Pb isotope data for a suite of dykes along the NERZ on Tenerife (Fig. 3.1).

Fractional crystallisation is the major processes controlling major and trace element variability in the dykes. Variable degrees of low temperature alteration in combination with ca. 10-20 % assimilation of hydrothermally altered island edifice modified the original $\delta^{18}\text{O}$ and the Sr-Nd isotope composition of the dykes (Fig. 3.2, 3.3), but had little to no discernable effect on Pb isotopes. Minor sediment contamination, however, may have affected the Pb isotope composition of two samples plotting to high $^{207}\text{Pb}/^{204}\text{Pb}$ values.

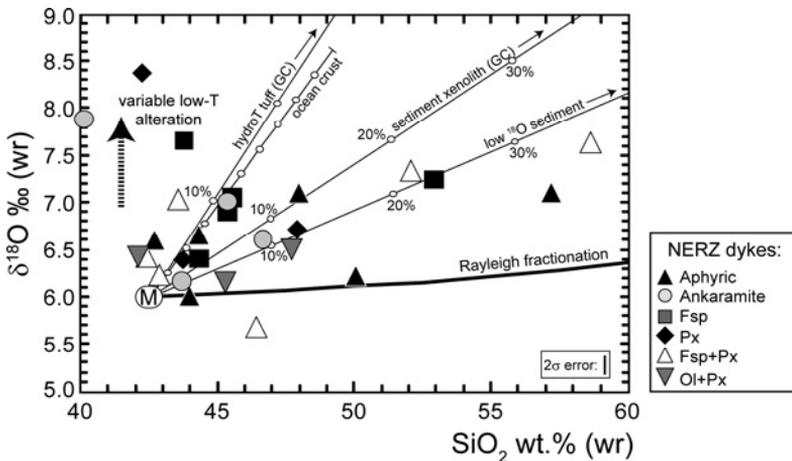


Figure 3.2: A $\delta^{18}\text{O}$ versus SiO_2 plot for dykes of the NERZ. Most of the dykes exhibit large and variable deviation from the trend expected for a magmatic suite related by fractional crystallisation (Rayleigh fractionation from a mantle parent, “M”). Mixing models are shown to illustrate that some of the $\delta^{18}\text{O}$ variability in the dykes can be explained by mixing between a parental mantle source and hydrothermally altered edifice rock and/or ocean sediment. A mixing line is also shown for ocean crust (layer 2 from Hansteen and Troll, 2003). Symbols on the mixing lines are 10 % mixing increments. See paper III for details and discussion.

Subsequent to screening of the data for shallow level contamination, the underlying isotope systematics of the NERZ reflects a mixture principally between DMM and young HIMU-type mantle components. Trace element patterns are also consistent with a HIMU-dominated source.

The $^{206}\text{Pb}/^{204}\text{Pb} - ^{207}\text{Pb}/^{204}\text{Pb}$ isotope composition of the NERZ supports a model of initiation and growth of the rift from the Central Shield volcano (Roque del Conde) as has recently been proposed based on geochronology (Guillou *et al.*, 2004; Carracedo *et al.*, 2010). The similar isotope signature of the Miocene Central Shield, the Miocene-Pliocene NE rift and the Pliocene Las Cañadas central volcano suggests that the source feeding the central part of Tenerife Island was almost constant through the Miocene to Pliocene. This can be explained by the presence of a discrete blob of HIMU material, ≤ 100 km in vertical extent, occupying the melting zone beneath central Tenerife from the Miocene to Pliocene (cf. Hoernle and Schmincke, 1993). Recent central magmatism on Tenerife probably reflects greater entrainment of DMM material, perhaps due to waning of the blob with time.

This study demonstrates the variety of processes giving rise to petrologic variability in rift zone magmas. Isotopes of O, Sr, and Nd have been used to recognise assimilation of pre-existing island edifice (“island recycling”) and Pb isotopes suggest a minor role for contamination by ocean sediments. Island recycling was facilitated by migration of magma through a compositionally heterogeneous volcanic pile, which includes hydrothermally altered felsic components (cf. Wolff *et al.*, 2000). Conversely, after removal of potentially contaminated samples, Pb isotopes allowed insight into the sources of the rift and the relationship between the rift and central magmatism on Tenerife from the Miocene to Pliocene.

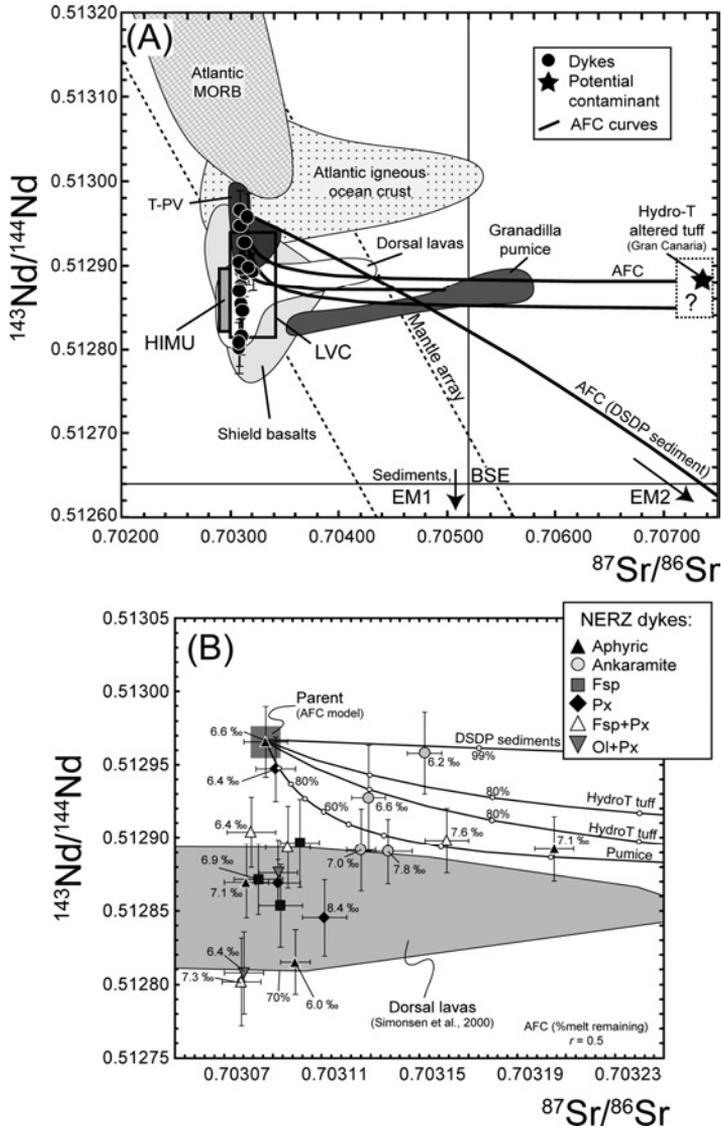


Figure 3.3: Sr versus Nd isotope diagram for dykes of the NERZ. (A) The rift zone dykes form a vertical array in Sr-Nd isotope space, spanning the range reported for Tenerife. AFC evolutionary paths using various potential contaminants are shown for reference. (B) Detailed view of the Sr and Nd isotope variation within the NERZ dykes. Error bars are 2 standard deviations. Values (in ‰) given beside some samples are the corresponding $\delta^{18}\text{O}$ values. Assimilation of hydrothermally altered edifice can reproduce the trend to high $^{87}\text{Sr}/^{86}\text{Sr}$ with minor change in $^{143}\text{Nd}/^{144}\text{Nd}$ isotopes. See paper III for additional data sources and discussion.

3.4 Paper IV

Boron isotopes as tracers of crustal contamination

Paper IV examines crustal interaction in a highly evolved (i.e. high-Si) magma system on Gran Canaria, Canary Islands. In this paper, new boron isotope data for a suite of feldspar samples from Miocene peralkaline ignimbrite 'A' are presented, in addition to a range of local crustal rock types. A key aim of this work is to test the utility of boron isotopes in feldspar as tracers for magma chamber and differentiation processes in evolved ocean island magmas. These are the first boron isotope data for a suite of ocean island feldspars, and are moreover presented in the context of corresponding trace element, O, and Sr isotope data.

Ignimbrite 'A' (13.63 ± 0.04 Ma) comprises three chemically distinct end-member magma types: a comenditic trachyte and two comenditic rhyolites. Previously published trace element and Sr-O isotope variations in ignimbrite 'A' feldspars record a history of fractional crystallisation, magma-mixing, and crustal assimilation within a shallow-level magma chamber (Troll, 2001; Troll and Schmincke, 2002; Hansteen and Troll, 2003). Boron concentrations and $\delta^{11}\text{B}$ in feldspar from the least to the most evolved ignimbrite 'A' end-member magmas range from 37.1 to 51.5 ppm and from -3.6 to $+3.5$ ‰, respectively. Trends in the boron data towards relatively high $\delta^{11}\text{B}$ values confirm a combination of fractional crystallisation and progressive contamination of trachyte to rhyolite magmas (Fig. 3.4). The combined B (ppm) – $\delta^{11}\text{B}$ – $\delta^{18}\text{O}$ data suggest that the principal contaminant is a partial melt of the island's intrusive core. In order to account for the elevated $\delta^{11}\text{B}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$ signature of the most evolved rhyolite end-member, however, contamination by a partial melt of oceanic sedimentary rock is also required.

In paper IV, we hence argue for selective contamination of ignimbrite 'A' by various components of the oceanic crust and island core. The importance of the role of contamination by crustal partial melts and island recycling is highlighted in this paper. Finally, the correlation between our model and previously published geochemical models for ignimbrite 'A' demonstrates the usefulness of boron isotopes in feldspar as a geochemical tool to study magma chamber processes.

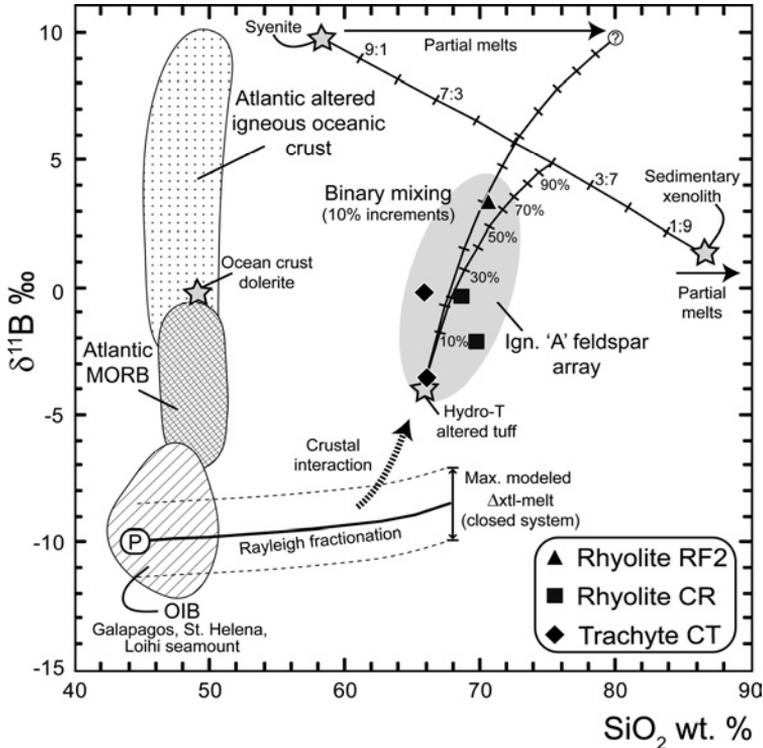


Figure 3.4: Boron isotopic variation in the ignimbrite 'A' feldspar data depicted on a $\delta^{11}\text{B}$ - SiO_2 plot. A closed system Rayleigh-type fractionation curve from an OIB-type parental melt (labeled "P", parent) is shown for comparison. Ignimbrite 'A' feldspars have relatively high $\delta^{11}\text{B}$ values, which cannot be explained by closed system crystal fractionation alone. The most evolved rhyolite (RF2) can be explained by a binary mixing model wherein RF2 derived 60 % of its ^{11}B from an approx. 4:6 mixture of syenite (island core) and siliciclastic sediment (oceanic crust layer 1) when starting from the CT trachyte composition. Binary mixing curves are calculated using B concentrations in the crustal end-members equivalent to 50 % partial melting. Boron isotopes are assumed not to fractionate significantly during partial melting. The increase in SiO_2 expected from partial melting of the crustal end-members is indicated with an arrow. Contamination by a high-silica partial melt of the syenite end-member may alternatively account in full for the variation in the ignimbrite 'A' feldspars. See paper IV for details of the models and additional data sources.

3.5 Paper V

Magma-carbonate interaction and crustal CO_2 release at Merapi volcano

Paper V presents an experimental study of magma-carbonate interaction using natural materials from Merapi volcano, Indonesia. At Merapi, there is

considerable petrologic evidence for ongoing, late-stage interaction between the magmatic system and the crustal carbonate underlying the volcano. Calc-silicate xenoliths within Merapi basaltic-andesite erupted rocks display textures indicative of intense interaction between magma and crustal carbonate, and Merapi feldspar phenocrysts frequently contain individual crustally contaminated cores and zones (Chadwick *et al.*, 2007).

A series of time-variable de-carbonation experiments was carried out at magmatic pressure and temperature (0.5 GPa and 1200 °C) in order to resolve the interaction processes between magma and limestone in detail and to create a time-integrated reaction sequence of carbonate assimilation in magma. The experiments were imaged and analysed using *in-situ* methods to determine the elemental and strontium isotope composition of the experimental products and to trace the textural, the chemical, and the isotopic evolution of carbonate assimilation (Fig. 3.5, 3.6).

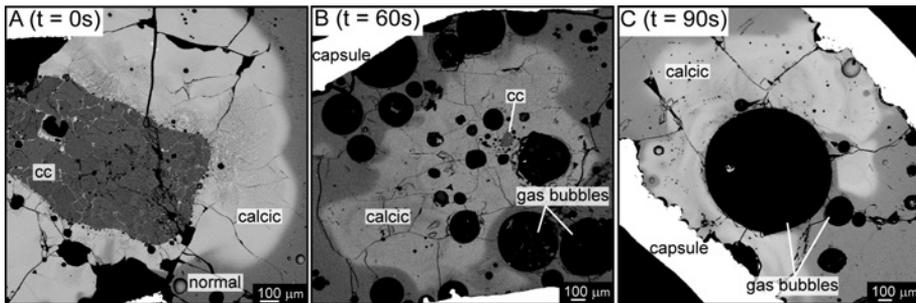


Fig. 3.5: Secondary electron microscopy images documenting progressive carbonate assimilation in experiment. The carbonate grain (cc) diminishes in size drastically after only 60s at 1200°C (A and B), releasing abundant CO₂ bubbles (black spheres) and generating a Ca-enriched contaminated melt (bright glass, labelled “calcic”). After 90s, the carbonate has almost totally assimilated (C) resulting in a large, coalesced CO₂ bubble surrounded by contaminated melt.

The major processes of magma-carbonate interaction identified in the experiments are: i) rapid decomposition and degassing of carbonate, ii) generation of a Ca-enriched, highly radiogenic strontium contaminated melt, distinct from the starting material composition, iii) intense CO₂ vesiculation, particularly within the contaminated zones, iv) physical mingling between the contaminated and unaffected melt domains, and v) chemical mixing between melts (Fig. 3.5, 3.6). The experiments reproduce many of the features of magma-carbonate interaction observed in the natural Merapi xenoliths and feldspars phenocrysts. The Ca-rich, high ⁸⁷Sr/⁸⁶Sr contaminated melt produced in the experiments is considered here as a precursor to the Ca-rich (often “hyper-calcic”) phases found in the xenoliths and the high-Ca, high-⁸⁷Sr/⁸⁶Sr contaminated zones in Merapi feldspar. The xenoliths also exhibit

micro-vesicular textures which can be linked to the CO₂ liberation process seen in the experiments.

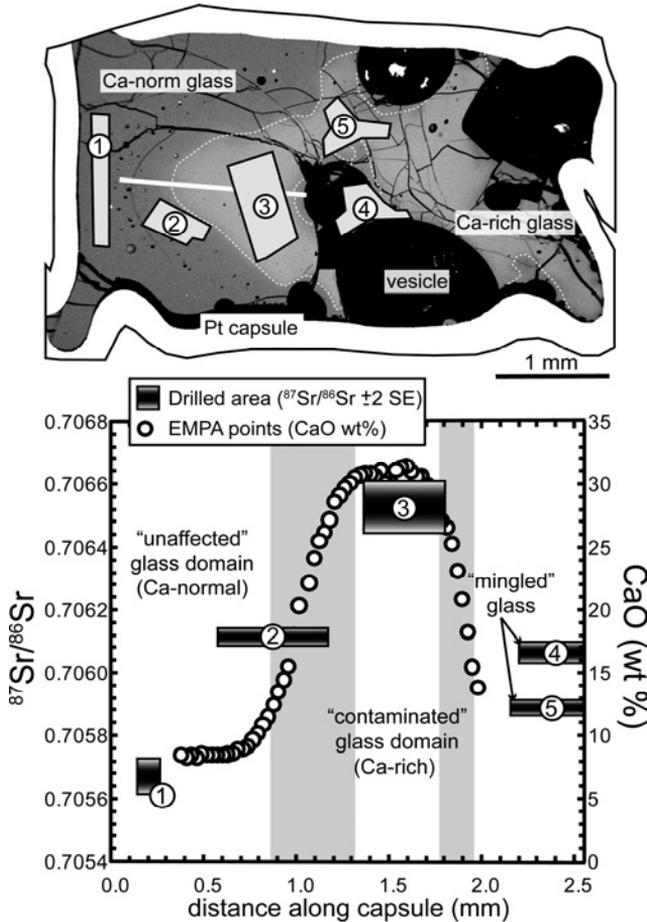


Figure 3.6: ⁸⁷Sr/⁸⁶Sr and CaO wt. % profiles in a 300 s experiment. Micro-drilled areas are shown as numbered polygons on the BSE images, and correspond to the numbered rectangles on the plot. The length of the rectangles corresponds to the area drilled and their height includes ± 2 SE. Grey shaded vertical bars represent the glass interfacial regions, i.e., the diffuse contact zone between contaminated glass and unaffected glass defined by steady exchange of Si and Ca.

This study, therefore, provides well-constrained petrological insights into the problem of crustal interaction at Merapi and points toward the substantial impact of such interaction on the volatile budget and eruptive behaviour of the volcano. It is demonstrated that voluminous amounts of CO₂ can be liberated from crustal carbonate after only 90 s at the experimental temperature (Fig. 3.5). At shallower depths than investigated in this study (i.e. < 10-15 km), CO₂ bubble nucleation and growth is expected to be even more rapid

since CO₂ solubility exhibits positive pressure dependence. It is hence conceivable that carbonate assimilation in nature can add bursts of CO₂ on the order of 32,000 t day⁻¹ to the volcanic volatile budget, as exemplified at Popocatépetl volcano, Mexico (Goff *et al.*, 2001).

Finally, sudden CO₂ bubble nucleation and coalescence will magnify the explosive potential of magma (cf. Alidibirov and Dingwell, 1996) and may hence change the volcano's eruptive style with very little forewarning. Volcanoes like Merapi that occur in densely populated areas and are located over carbonate crust (e.g. Popocatépetl, Mexico and Vesuvius, Italy) hence pose a serious challenge for emergency response teams due to the potentially erratic nature of events unfolding during CO₂-driven volcanic crises. [*See the short article accompanying paper V "Fast and furious ..." for further discussion.*]

4. Conclusions

This work focuses on crustal interaction in magmatic systems, which has been approached by studying both natural rock samples and high pressure-high temperature (HP-HT) experimental products. Magma-crust interaction encompasses a range of processes, including crustal partial melting (anatexis), assimilation, and degassing. These processes are recognised as being important in magma differentiation and in ultimately driving magma to evolved compositions with increased explosive potential. These, and other closely associated magma chamber processes such as magma mixing and fractional crystallisation, are explored throughout the papers comprising this thesis.

This thesis takes two approaches to providing insights into the processes of magma-crust interaction. The first approach utilises the chemical information preserved in erupted and intruded magma to examine crustal processes in ocean island magmatic systems (the Canary Islands). The second approach employs HP-HT experimental petrology to look at the actual mechanisms and rates of magma-crust interaction under controlled laboratory conditions, using natural materials from Merapi volcano, Indonesia.

This research underscores that the compositions of ocean island magmas, even primitive types which are classically used as probes of the mantle, are susceptible to modification by crustal contamination. The principal mechanisms of contamination identified from work on both Tenerife and Gran Canaria (Canary Islands) are assimilation and partial melting of the pre-existing island edifice and intercalated sediments by newly arriving magma (i.e. “island recycling”).

The information that we can gain from studying solidified magma and entrained crustal xenoliths concerning the rates and mechanisms of crustal assimilation is, however, limited. To address this shortcoming, a series of time-variable crustal carbonate assimilation experiments were carried out at magmatic pressure and temperature using natural materials from Merapi volcano, Indonesia. A temporally constrained reaction series of carbonate assimilation in magma has hence been constructed. The experiments were analysed using *in-situ* techniques to observe the progressive textural, elemental, and strontium isotopic evolution of magma-carbonate interaction. Crucially, carbonate assimilation was found to liberate voluminous crustally-derived CO₂ on a timescale of only seconds to minutes in the experiments.

This points to the role of rapid crustal degassing in volcanic volatile budgets, and, pertinently, in magnifying hazardous volcanic behaviour.

This thesis, therefore, delivers detailed insights into the processes of magma-crust interaction from experiments and geochemistry. The outcomes confirm that crustal processes are significant factors in both, i) ocean island magma genesis, and ii) magma differentiation towards compositions with greater explosive potential which can, in turn, manifest as hazardous volcanism.

5. Summary in Swedish

Växelverkan mellan magma och jordskorpa: insikter från geokemi och experimentell petrologi

Syftet med denna avhandling är att öka förståelsen för de processer som verkar i en magmakammare, med fokus på växelverkan mellan magma och jordskorpa. Magma som härstammar från djupa delar av manteln måste på sin väg mot ytan korsa jordskorpan. I ytliga magmakammare kan magman ansamlas innan den blir del av ett vulkanutbrott eller stelnar under jordytan. När magma stannar upp i en magmakammare i skorpan genomgår den en mängd fysikaliska och kemiska processer såsom magma mixning, fraktionerad kristallisation, assimilering av skorpan dvs. sidoberget och avgasning (Fig. 1.1). Detta leder till att magman får en mer evolverad sammansättning, vilket följaktligen kan ge mer explosiva utbrott. Undersökningar som ökar vår förståelse för dessa processer är av vikt för att kunna förutspå och minimera riskerna runt potentiellt farliga vulkaner.

I denna avhandling har två metoder tillämpats för att förstå den geochemiska utvecklingen i magmatiska system. Med den första metoden har djup- och ytbergarter samlats in för de ger en inblick i hur magmans utvecklats i dess resa genom skorpan. Tolkningarna av geochemiska data från dessa bergartsprover har använts för att identifiera de magmatiska processerna och spåra samverkan mellan magma och skorpa. I en kontrollerad laboratoriemiljö har sedan de identifierade processerna studerats i detalj för att kunna beräkna vilken hastighet och i vilken skala processerna verkar. Dessa metoder är summerade nedan.

1. Kanarieöarna; ett “naturligt laboratorium” för studier av processer i skorpan.

Del ett i avhandlingen inriktar sig på magmatism vid bildandet av oceanöar. Syftet är att bättre förstå den geochemiska förändringen som sker då en primitiv magma övergår till en evolverad magma i en oceanö och vilken roll växelverkan mellan magma och skorpa har. Största fokus ligger på de platser där den magmatiska aktiviteten är som störst dvs. i vulkaniska riftzoner där bildandet av oceanön sker. På grund av detta så karakteriseras dessa sprickrika riftzoner av att det är mycket tätt mellan intrusioner av tabulära kroppar s.k.

gångarbergarter. Dessa sprickor verkade som kanaler för magman på dess väg mot ytan. Undersökningarna av magmatiska processer i riftzoner har gjorts på Teneriffa (artikel I - II). I dessa artiklar studeras olika processer såsom magmamixning, fraktionerad kristallisation och växelverkan i skorpan och deras betydelse för bildandet och utvecklingen av magmatiska riftzoner. Eftersom de gångar som verkade som transportsystem för magman i Nordöstra riftzonen (NERZ) är så väl exponerade, ger det oss ett fönster till de övre delarna av det magmatiska systemet som en gång i tiden låg under Teneriffa. NERZ utgör således ett utmärkt "naturligt laboratorium" för att undersöka växelverkan mellan magma och skorpa vid bildandet av relativt primitiv magma under oceanöar. Undersökningen har visat att assimilering av tidigare bildad ömaterial dvs. stelnad magma och möjligen oceansediment med den nya magman kan förändra den geokemiska karaktären hos den. Det är i kontrast till de tidigare antagandena att det sker en minimal växelverkan mellan ny magma och skorpan i dessa tektoniska miljöer. I denna tektoniska miljö där magman härstammar från djupa delar av manteln, så måste växelverkan i skorpan uppmärksammas och beräknas innan slutsatser kan dras om geokemin och förhållandena i manteln. I artikel IV studerades växelverkan i skorpan på Gran Canaria och hur det bidragit till en avsevärt evolverad magma. Vid undersökningen testades tillämpbarheten av ett nytt geokemiskt instrument. Denna artikel ger intressanta bevis för vilken roll assimilering av äldre ömaterial spelar vid bildandet av fraktionerade oceanömagmor som leder till potentiellt mer explosiva och farliga utbrott. Konsekvenserna av de framlagda resultaten i avhandlingen har inte bara betydelse för Kanarieöarna utan för bildandet av oceanömagmor i allmänhet.

2. Experiment med fokus på assimilering av skorpa; Merapi, Indonesien.

Tidigare arbeten har identifierat assimileringsepisoder av karbonat (kalksten) i magman under Merapi, Indonesien. I experimentell miljö tilläts bergarter från Merapi och kalksten att växelverka med varandra under realistiska magmatiska tryck- och temperaturförhållanden, med varierande tidintervall (upp till 300 s) för att erhålla en tidsintegrerad reaktionsserie för hur karbonat assimileras i magman. Artikel V erbjuder väldefinierade iakttagelser av reaktionshastighet och de processerna som verkar vid assimilering av karbonat. Tack vare tillämpandet av in-situ mikroanalytiska metoder presenteras i denna artikel en ny detaljnivå i vår förståelse av dessa processer. Iakttagelsen att assimilering av karbonat är mycket snabbare än tidigare antaget och att processen medföljer en kraftig tillväxt av koldioxidbubblor är ett mycket viktigt resultat i artikel V. Eftersom kraftig och hastig tillväxt av bubblor ökar explosiviteten vid vulkanutbrott, så har dessa fynd viktig innebörd för utbrottsdynamiken och riskminimering vid Merapivulkanen och det diskuteras

i den populärvetenskapliga artikeln som medföljer artikel V (“Fast and furious; crustal CO₂ release at Merapi volcano, Indonesia”). Detta är av största relevans eftersom Merapi inte bara tätbefolkad men även en av de mest aktiva vulkanerna på Jorden. Ytterligare en implikation av detta arbete berör de rådande modellerna för den vulkaniska CO₂ budgeten på Jorden. Dessa modeller omgärdas av stora osäkerheter då kortvariga voluminösa utbrott av vulkaniskt CO₂ kan inträffa under mycket korta tidsrymder, såsom dagar och veckor.

Denna avhandling ger sammanfattningsvis en insikt i de processer som verkar i skorpan under bildandet av oceanömma och betonar den roll som assimilering i skorpan hos både primitiv och fraktionerade magmor. Viktiga processer som assimilering av gammalt ömaterial och med skorpan, och mixandet av partiell olika partiella smältor spelar en avgörande roll bildandet av kontinental miljö med en tjock differentierad skorpa så väl som oceanöar. Slutligen presenteras en detaljerad studie genom experiment av de processer och med vilken hastighet karbonat från skorpan assimileras och avgasas. Detta arbete betonar den roll som jordskorpans processer kan ha i att skapa potentiellt vulkanutbrott.

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