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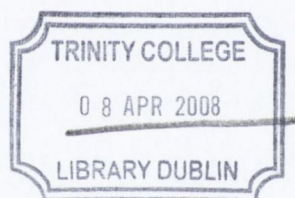
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**CRUSTAL PROCESSES IN VOLCANIC SYSTEMS: CASE STUDIES FROM
NORTHERN IRELAND, NEW ZEALAND, AND INDONESIA.**

JANE P. CHADWICK

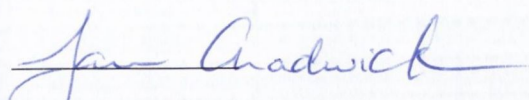
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Jane P. Chadwick

SUMMARY

It is evident that modification of primary melts from the mantle is significant in magma petrogenesis as primitive magmas are only rarely observed as erupted lavas at the Earth's surface. Ascent and density filtering of primary arc magmas in the crust promotes modification of these melts by numerous processes, most importantly crystallisation and crustal contamination. However, modification can also be due to a combination of these processes, magma mixing and degassing. It is possible to identify the products of these processes in the resulting geochemistry of erupted magmas. However, these signals are often difficult to discern.

Petrology and geochemistry provide a means of identifying and potentially quantifying igneous differentiation processes; whole rock major, trace element, and isotope data can be used to track changes and evolution of the magma systems. However, without careful ground-truthing using petrography and in-situ analytical techniques, whole-rock data may only represent a blurred average of a more complex record of processes.

Utilising such petrological and geochemical techniques, this work evaluates variations in rock samples due to differentiation processes, specifically magma-crust interaction, operating beneath the three study areas; Slieve Gullion, Merapi Volcano, and the Taupo Volcanic Zone. These results are in the context of magmatic evolution in three different geo-tectonic settings; intra-plate (Ireland), continental (New Zealand) and oceanic arc volcanism (Java, Indonesia).

The Palaeogene volcanism of Slieve Gullion, in South Armagh and Louth is discussed in Chapter 2. Magma-crust interaction in a shallow intra-continental system is investigated using traditional geochemical and petrological techniques. The influence of crustal contamination on isotope composition is recorded in the geochemistry of magmas from virtually all British and Irish Palaeogene Centres and Slieve Gullion ring-dyke magmas are no exception, with evidence for contamination with Southern Uplands-type local Palaeozoic Mid-to-Upper crustal sedimentary rocks and Caledonian granitic crust, emphasising the severe effect of crustal heterogeneity on ascending mantle magmas. Additional contamination of Slieve Gullion magmas (e.g. for basaltic dyke sample) in the deep crust cannot be ruled out since the evidence for such an event would be strongly obscured by upper crustal contamination events. The Sr and Nd isotope ratios of the Slieve Gullion ring-dyke magmas are consistent with at least two stages of contamination during upper crustal residence and storage and support petrographic, major and trace element evidence which indicates that there is a strong genetic link between porphyritic rhyolite and granite. Fractionating magmas of basaltic and intermediate composition are contaminated by local sedimentary rocks, giving rise to rhyolite magmas that experience additional late shallow contamination by the most fusible portions of the Newry Granodiorite. The last stages of fractionation and contamination potentially occur in a zoned rhyolite magma chamber, which was tapped, with ascending magma forming a composite ring-dyke complex.

Chapter 3 addresses continental arc volcanism of North Island, New Zealand and the distinction between magma-crust interaction at source and in the lithosphere employing Hf isotope analysis. Despite representing the least evolved products of the New Zealand continental subduction zone system, and thus the most likely to reflect primary melt signatures, Ruapehu, Taranaki, and particularly the Taupo Volcanic Zone basalt samples show evidence for crustal contamination, in contrast to samples from the oceanic Tonga-Kermadec arc. All samples analysed are displaced from both MORB compositions and from Kermadec and Tonga samples for $^{176}\text{Hf}/^{177}\text{Hf}$ isotopes. Samples with the lowest SiO_2 contents have the lowest, i.e. most crustal $^{176}\text{Hf}/^{177}\text{Hf}$ isotope ratios, with a negative correlation apparent in the TVZ basalt samples analysed. This indicates Hf isotope variation, at least in these samples is not a source contamination effect. Despite a lack of a similar trend in the Ruapehu and Taranaki samples, crustal contamination is also a factor for these centres based on the presence of variably metamorphosed crustal xenoliths and geochemical

heterogeneity reported in the literature. This portion of the study highlights the inherent danger in using whole rock geochemical systems in isolation to assess processes and evolution of crystalline porphyritic samples. Little evolved basaltic rocks may be influenced strongly by shallow crustal contamination. Thus, care must be taken when using apparently relatively un-evolved volcanic products to assess source compositions and mechanisms.

Chapter 4, which forms the main body of work in this thesis, addresses recent oceanic arc volcanism at Merapi Volcano in Java, Indonesia and resolving magma petrogenesis and evolution in the crustal and the nature of the magmatic system feeding volcanism using a fusion of traditional and innovative geochemical and textural techniques in conjunction with geophysical constraints. Findings from analysis of fumarole gas and inclusions and crystals hosted in recent eruptive products suggest the presence of a large and complex plumbing system feeding volcanism. This system is largely located in the mid-to deep crust with a network of multiple potentially ephemeral chambers feeding volcanism. This considerable volume of melt in the crust may evolve to from a large-volume explosive system in central Java, through repeated melt injections and melting of the surrounding country rock. Crystals, xenolith and gas compositions provide strong evidence for significant interaction between Merapi magma and the local crust, which is masked in bulk rock geochemistry.

As in the New Zealand study, this illustrates the dangers inherent in building models of magma petrogenesis based solely on whole-rock geochemical data from crystal-rich arc lavas, or indeed any one analytical technique used in isolation (e.g. CSD). The relatively chemically monotonous whole rock compositions of Merapi basaltic-andesites, disguises a multitude of complex processes occurring throughout the crust and into the upper mantle with significant impact on the Merapi magmatic and volcanic systems. These basaltic-andesites more than likely were never a true liquid but rather a mix of crystals and melts from multiple sources.

Chapter 5 compares the results discussed in the previous three chapters in the context of magma-crust interaction in volcanic systems in different tectonic settings. For Slieve Gullion, and intra-continental plate setting, whole rock isotope techniques allowed for identification of a multi-event evolution for ring dyke magmas due to the highly radiogenic and variable nature of the country rocks. For New Zealand samples in a continental arc setting, Hf isotopes identified crustal contamination in the most primitive erupted products and highlighted the significant geochemical heterogeneity in more evolved and crystalline samples. This is mirrored in the more detailed geochemical and petrographic study of oceanic arc eruptives from Merapi volcano. Even in this relatively simple tectonic setting with immature arc-crust, the significance of crustal processes and particularly of shallow-level contamination has been previously underrated, and has significant implications for understanding the evolution and eruptive behaviour of the volcano and this hazard prediction.

With the advent of more accurate and precise analytical techniques, subtle signatures that may previously have gone unrecognised may be identified. From these three studies, combined with similar published results for other systems (e.g. Ruapehu: Price *et al.*, 2005; Arenal: Lundstrom & Tepely, 2006), it appears that high degrees of geochemical complexity within individual units is the norm rather than the exception for magmatic systems of a significant size and/or degree of evolution. This variability is now resolvable using new and combined analytical approaches.

ACKNOWLEDGEMENTS

Firstly I would like to thank my supervisor, Valentin Troll for all of his academic, organisational, financial, and moral support with this project. He equipped me with all the skills I need to get along in the academic world and for that I owe him a lot. I am also very grateful to Tod Waight for his instruction, supervision, input and his patience in teaching me the dark art of isotope geochemistry. Discussions and input from Ralf Gertisser, Daniel Morgan, Catherine Ginibre, Jon Davidson, Robert Ellam, David Peate, Frank Tepley, Joel Baker, Darren Chertkoff, and Diana Wagner were also much appreciated.

I would also like to thank Trinity College Dublin and the EU Marie Curie Scheme, for their financial support and the Danish Lithosphere Centre, and Durham University for the use of their excellent research facilities.

For showing me how to work complicated machines thanks to Martin, Toby, Birit, Catherine, and Dan. For their much-appreciated technical, administrative, financial and moral support thank you Maura, Declan, Frank, Neil, Robbie, Mags, John, Laurie and Betty. Thanks also to John for giving me an opportunity to teach as a BC tutor, it cemented my ambition of becoming a lecturer.

For making my visits to Indonesia truly memorable, for helping out with logistics, and sample collection, I owe many thanks to Lothar Schwarzkopf, Mas Majhum, Mas Taufik, and Mairi Gardner.

For all their discussions, support, and distractions (geological and non geological) I need to thank all my fellow VAMPS, past and present, especially Marc-Antoine, Eoghan, Brian, Fiona, Graeme, Sebastian, Paul, Eleanor, and Liz. For similar reasons I need to thank the DLC girls; Joanna, Abi, Nadine, Anna, Anna, and Friis. Friday beer will never be the same.

Thanks a million to the postgrad girls, Eloise, Jo, Aileen, and Sarah for the yoga classes, wine, and chocolate, and just generally putting up with me for so long. Thanks to my office mates past and present; Becky, Aileen, Stuart, Ben, Brian, Sophie, Maja, and Hudson for their advice, support and food. Also want to thank the rest of the postgrads in the happy Geology Postgrad Family, my years here as a TCD have been so much fun down to you.

Finally I would like to thank my family and my old friends for all of their love and support, especially Ciaran and Stue, my grandmother Theresa, my sisters, Ruthie and Sarah, but most of all my mom Ann and dad John. They never gave me dumbed down answers to my many questions when I was small and always encouraged me in my endeavours; they kindled my thirst for knowledge and my love of science, I wouldn't have made it this far without their support and encouragement, so thanks.

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CHAPTER 1 – INTRODUCTION

1.1 General Introduction

As far back as Empedocles (c. 490-430 B.C.) (Sigurdsson, 1999), volcanoes have been a documented source of intense curiosity and study, particularly the structure and evolution of the sub-surface magmatic system that drives surface volcanism. As with many fields of geology, the inherent difficulty in trying to understand both the chemical and physical evolution of the volcanic and magmatic system is that often only a very small percentage of these systems is ever observed or accessible for research. In active systems, the expelled products of the volcano are analysed and hypotheses are drawn about the associated supply system from the results obtained. For extinct and eroded volcanoes, the supply system may be partially exposed providing analogues to help unravel a volcano's interior. Therefore, hypotheses based on modern systems are required to comment on the potential volcanism of ancient centres and the evolution and dynamics of magmatic systems remain insufficiently constrained.

It is evident that modification of primary melts from the mantle is significant in magma petrogenesis, as primitive magmas are only rarely observed as erupted lavas at the Earth's surface. Ascent and density filtering (Annen *et al.*, 2006) of primary arc magmas in the crust promotes modification of these melts by numerous processes, most importantly crystallisation (Bowen, 1928; Gill, 1981; Rogers & Hawkesworth, 1989; Grove *et al.*, 2002, 2003) and crustal contamination (Grove *et al.*, 1988; Davidson & Tepley, 1997). However, modification can also be due to a combination of these processes (e.g. De Paolo, 1981), as well as magma mixing (e.g. Eichelberger, 1978; Hildreth & Moorbath, 1988) and degassing (Hammer *et al.*, 2000). It is possible to identify the products of these processes in the resulting geochemistry of erupted magmas, however these signals are often difficult to discern (e.g. Troll & Schminke, 2002).

Petrology and geochemistry provides a means of identifying and potentially quantifying igneous differentiation processes; whole rock major, trace element, and

isotope data can be used to track changes and evolution of the magma systems. However, without careful ground-truthing using petrography and in-situ analytical techniques, whole-rock data may only represent a blurred average of a more complex record of processes.

1.2 Thesis aims and structure

The main aims of this thesis are:

- a) To utilise petrological and geochemical techniques in conjunction to evaluate variations in rock samples and put these variations in a context of differentiation processes, specifically magma-crust interaction, operating beneath the three study areas; Slieve Gullion, Merapi Volcano, and the Taupo Volcanic Zone.
- b) To address these results in the context of magmatic evolution in three different geotectonic settings; intra-plate (Ireland), oceanic (Java, Indonesia) and continental arc volcanism (New Zealand).

Due to the tectonically and geographically diverse nature of the study areas, the main body of this thesis will be presented in three parts that will address the first main aim stated above. Chapter 2 will focus on the Palaeogene volcanism of Slieve Gullion, in South Armagh and Louth, where magma-crust interaction in the chamber is investigated using traditional geochemical and petrological techniques. Chapter 3 will address volcanism of the Taupo Volcanic Zone, New Zealand to resolve magma-crust interaction at source employing Hf isotope analysis. Chapter 4, which forms the main body of work in this thesis, will deal with recent volcanism at Merapi Volcano in Java, Indonesia and resolving magma petrogenesis and evolution in the crust. This section will also address the nature of the magmatic system feeding volcanism using a combination of traditional and innovative geochemical and textural techniques in conjunction with geophysical constraints. Finally, chapter 5 will address the second main aim stated above by comparing the results discussed in the previous three chapters and drawing them together to form an account of magma-crust interaction in volcanic systems in

general, summarising the main conclusions of chapters 2, 3, and 4 and suggesting further areas for research.

CHAPTER 2 – SLIEVE GULLON IGNEOUS CENTRE, IRELAND

2.1 Introduction

Large igneous provinces (LIPs) are characterised by voluminous mafic magmatism, including lava flows, associated magma conduits (sills and dikes) and intrusions, all emplaced over geologically short timescales (Coffin & Eldholm, 1994), produced by a combination of thermal anomalies in the mantle and thinning of the lithosphere. The magmatic rocks of the North Atlantic Igneous Province (NAIP), with an estimated volume of $5\text{--}10 \times 10^6 \text{ km}^3$ (White & McKenzie, 1989; Eldholm & Grue, 1994; Holbrook *et al.*, 2001; Saunders *et al.*, 1997), are a prime example of this phenomenon, and considerable work has been done to characterise the mantle sources and processes involved in their formation (e.g. Upton *et al.*, 1983; Ellam & Stuart, 2000). However, as well as this characteristic large-volume mafic magmatic activity, more evolved magmas sited in central volcanic complexes are a significant feature of the NAIP, particularly in the NW British and Irish sector, the British Palaeogene Igneous Province (BIPIP) (Bell & Emeleus 1988; Bryan *et al.*, 2002). A major focus in the study of the BIPIP has long been the origin these highly silicic rocks (cf. Gamble, 1979; Meighan, *et al.*, 1984; Thompson *et al.*, 1986; Sparks, 1988; Bell, & Emeleus 1988; Bell & Williamson, 2002; Troll, *et al.*, 2004). Geochemical diversity in BIPIP magmatic rocks has been previously attributed to multiple heterogeneous mantle sources (e.g. asthenosphere, lithosphere, depleted lithosphere, etc.) as well as crustal-level processes, including fractionation and assimilation. The influence of crustal contamination on isotope composition is recorded in the geochemistry of magmas from virtually all British and Irish Palaeogene volcanic complexes (e.g. Kerr *et al.* 1999; Ellam & Stuart, 2000; Bell & Williamson, 2002; Geldmacher *et al.*, 2002; Troll, *et al.*, 2004).

The British-Irish Palaeogene Igneous Province (BIPIP) is an ideal natural laboratory for studying the influence of crust on ascending mafic magmas. The province is underlain

by structurally and geochemically relatively well-characterised crust that is divided by major structures into numerous isotopically distinct tectono-stratigraphic terranes (Figure 2.1). As well as this, being old (Archean to Palaeozoic) crust, the distinct isotopic signature of these crustal terranes are also markedly dissimilar to primary melt compositions (Dickin, 1981). Thus, even limited interaction with this crust may be easily identified using standard isotopic geochemical techniques. In addition, there is a full spectrum of magmatic compositions in the province, from ultra-mafic intrusions to highly evolved rhyolitic ignimbrites (e.g. Bell & Emeleus, 2005). The crustal terranes that underlie the BIPIP have in many cases, imprinted their own distinctive elemental and isotopic characteristics on ascending magmas and variations in magmatic isotopic composition are in many cases, a reflection of the basement geology and lithospheric provinciality in the northwest Britain and Ireland (Gamble *et al.*, 1992; Geldmacher *et al.* 2002). This highlights the potentially important control of crustal rocks on the geochemistry magmas of the BIPIP, particularly for the evolved rocks of the central volcanic complexes.

Although the intrusive history of the Slieve Gullion Igneous centre and the geochemistry of the central complex has been investigated in previous studies (e.g. Richey & Thomas, 1932; Reynolds, 1951; Emeleus, 1962; McDonnell *et al.* 2004), the petrogenetic history, and the role of the crust in the formation of the highly evolved rocks of the Slieve Gullion ring-dyke has so far been incompletely assessed.

Ring-dykes, such as Slieve Gullion, in counties Armagh and Louth in Ireland, are approximately circular, sub-volcanic, sheet intrusions in plan view that form during coupled intrusion and subsidence cycles in a caldera-type magmatic system. Models for their formation were pioneered by a series of studies of the BIPIP centres in northwest Scotland (Bailey *et al.*, 1924; Richey, 1928; Richey & Thomas, 1932; Anderson, 1936). It is now widely accepted that these types of structure form as a result of stress fields in the proximity of a inflating and deflating magma reservoir (e.g. Lafrance & John, 2001; Walter & Troll, 2001) (Figure 2.2). Pressure in the magma chamber can lead to shear fracturing of the local country rock, which then results in a pressure release, followed by

subsidence, forming outward-dipping ring shaped fractures (Walter & Troll, 2001; Kennedy & Stix, 2007). These fractures are exploited by rising magma (Phillips, 1974), which may cool to form a ring-shaped dyke, or a ring-dyke (Sparks 1988; Kennedy & Stix, 2006). This phase of activity is typically followed by the intrusion of a central complex, which completes the intrusion and subsidence cycle (Kresten 1980; Ike, 1983; Lipman, 1984). Surface erosion of overlying volcanic features may expose these ring-dykes and provides us with a link between surface volcanic rocks and the magmatic system feeding eruption.

Many such systems have been described from the Palaeogene Centres in both Scotland and Ireland (e.g. Bailey *et al.* 1924; Richey & Thomas, 1932; Anderson, 1936). These intrusions commonly display marked compositional diversity (e.g. Sparks, 1988) and have thus been used in pioneering studies of magma storage processes.

As Slieve Gullion is one of the few Palaeogene Centres south of the Highland Boundary Fault, its contamination history is an ideal testing ground for the influence of variable crust on evolved British-Irish Palaeogene Igneous Province magmas. Here we employ Sr and Nd isotope geochemistry to unravel the petrogenesis of the Slieve Gullion ring-dyke magmas, with the aim of shedding light on storage and differentiation mechanisms prevalent in the Slieve Gullion system.

2.2 Geological Background

The Palaeogene Slieve Gullion Igneous Complex, together with the Antrim lavas and igneous complexes at Carlingford and the Mourne Mountains, form the NE Ireland portion of the British-Irish Palaeogene Igneous Province (BIPIP) (e.g. Upton, 1988; Gamble *et al.*, 1999). The BIPIP is sited in Northern Ireland and Scotland and traverses distinct crustal terranes including Lewisian rocks in the north of the province to the Palaeozoic rocks which underlie the Irish centres in the south (Fig. 2.1). Based on isotopic and paleomagnetic studies (Emeleus 1991; Musset *et al.*, 1988; Emeleus & Bell, 2005), the majority of igneous activity in the BIPIP occurred between 57–62 Ma. The province comprised broadly contemporaneous extrusions of thick sequences of

basaltic lava, with major central volcanoes and shallowly emplaced silicic and mafic intrusions formed during the latter stages of activity. This magmatic activity is believed to have been the result of plume-related crustal attenuation during the Palaeogene, which ultimately resulted in the opening of the North East Atlantic Ocean (White & McKenzie, 1989; Saunders *et al.* 1997).

The Slieve Gullion Igneous Complex is situated west of the Mourne Mountains in south County Armagh, with its SE section within north County Louth (Figure 2.3). It consists of a sheeted composite central complex that forms Slieve Gullion mountain (577m) and an encompassing sub-circular ring dyke. This central complex consists of horizontal layers of roughly contemporaneous porphyritic granite and dolerite, with evidence of liquid-liquid contacts between mafic and felsic units (Richey & Thomas 1932; Reynolds, 1951; Bailey & McCallien, 1956; Gamble, *et al.*, 1979; Gamble *et al.* 1992; Gamble *et al.*, 1999). This central intrusive complex is separated from the prominent, slightly older, silicic ring-dyke complex, which is approximately 12 km in diameter, by a moat of lower poorly exposed ground with limited outcrop of weathered Newry Granodiorite (Richey & Thomas, 1932; Reynolds, 1951; Emeleus, 1962; Elwell *et al.*, 1974; Gamble, 1979; Gamble, *et al.*, 1992). The ring dyke complex is comprised of a series of hills that form an arcuate ridge, known as the 'Ring of Gullion' with porphyric rhyolite and granite comprising the dominant lithologies with lesser breccia, agglomerate and cataclasite also present. This ring bridges the contact between the SW portion of the Caledonian Newry Granodiorite pluton (Meighan & Neeson, 1979) and the Lower Palaeozoic sedimentary rocks of the Longford-Down Terrane in the south (Richey and Thomas; 1932; Emeleus, 1962) and this contact may have been exploited as a zone of weakness (Gamble, *et al.*, 1992). Relative age relations between the ring dyke and the central intrusion are based on field data that indicate the ring dyke pre-dates the central complex (Emeleus, 1962). Rb-Sr whole rock dating yields ages of 58.5 ± 2.3 Ma (MSWD = 3.74) for the ring dyke, and 57.6 ± 1.0 Ma (MSWD = 0.65) for the younger central complex (O'Connor, 1988). Recent U-Pb zircon crystallisation ages of 56.5 ± 1.3 Ma (Gamble *et al.*, 1999) have been obtained from the early ring dyke rocks and within uncertainty of the Rb-Sr data.

At Slieve Gullion, the ring complex contains two principal lithologies, commonly referred to as porphyritic felsite and porphyritic granophyre (Figure 2.4 a-c), which under modern nomenclature correspond to porphyritic rhyolite and porphyritic micro-granite respectively (Gillespie & Styles, 1999). There is a Si-enriched porphyritic rhyolite concentrated at the outer margins of the ring-dyke in an approximately 1 metre wide zone, which grades into a less Si-enriched porphyritic rhyolite towards the interior of the intrusion (Emeleus, 1962; McDonnell *et al.* 2004). Porphyritic granite samples also show a Si-enriched facies, which is in turn concentrated in the central part of the intrusion. The several-metre thick Si-enriched porphyritic granite passes outwards into lower Si compositions (McDonnell *et al.* 2004). The ring-dyke rocks are surrounded by a series of older brecciated country rocks known historically as the Forkhill agglomerate (principally brecciated granodiorite) and the Camlough Breccia (brecciated Palaeozoic sedimentary rocks) (Richey & Thomas, 1932; Emeleus, 1962; McDonnell *et al.* 2004). Also present in the centre, are limited outcrops of Palaeogene basalt together with abundant Palaeogene dolerite and gabbro dyke intrusions (Richey & Thomas, 1932; Emeleus, 1962).

Earlier work recognised the complex rock relationships between the rocks in the Slieve Gullion ring dyke (e.g. Emeleus, 1956; Emeleus, 1962) and believed them to be the result of a two-stage intrusion history. Recent work by McDonnell *et al.* (2004) has further investigated the relationship between the porphyritic rhyolite and granite of the ring-dyke based on fieldwork, whole rock major and trace element analysis and density and viscosity modelling. These data indicate that the high-Si ring-dyke rocks define a distinct geochemical trend, as do the low-Si ring-dyke rocks, with some evidence for both groups being contemporaneous and formed in a single event (McDonnell *et al.* 2004) (Figure 2.5). However, some structural and textural evidence suggests that in places these units may have been formed by more than one event (Stevenson *et al.*, *in press*) that were closely related temporally given some contact relationships. The major and trace element geochemistry of these rocks, indicates that these Si-groups originated from the same parent magma rather than representing separate and discrete magmatic bodies (McDonnell *et al.*, 2004). The magma chamber where both magmas are believed

to have evolved was envisaged by McDonnell *et al.*, (2004), as a large concentrically zoned and internally stratified chamber, and this model may be used to explain the distribution of porphyritic rhyolite and granite across the ring-dyke intrusion.

2.2 Field occurrence and petrography

2.2.1 Pre-Palaeogene Country Rocks: Lower Palaeozoic metasedimentary rocks and Newry Granodiorite

The metasedimentary rocks are part of the Central Belt of the Lower Palaeozoic Longford Down-Terrane, an extension of the Southern Uplands terrane of Scotland. These Lower Palaeozoic successions crop out to the west of the Slieve Gullion centre (Figure 2.3). They vary in lithology from coarse semi-pelites to fine pelites across the area, and the rocks in the southwest are considerably more fine-grained the more northerly outcrops. Chlorite, muscovite and quartz (up to 1mm) are the dominant minerals present with small amounts of detrital feldspar.

These sediments were intruded (425Ma; Meighan *et al.* 2003) by the Newry Granodiorite pluton, part of the Caledonian granite suite of Britain and Ireland (Meighan & Neeson, 1979; Meighan *et al.* 2003). Outcrop of the granodiorite is predominantly located on the central, moat-like plain between Slieve Gullion and the ring-dyke where it is typically heavily weathered. It is a coarse-grained Granodiorite, and the mineralogy consists of equigranular grains of quartz, feldspar and varying amounts of biotite and hornblende visible in hand specimen (hornblende measuring 2-3mm in diameter). Smaller amounts of primary titanite and epidote and secondary muscovite identified in thin-section (Figure 2.4)

The depositional basement to these country rocks is enigmatic. However, Caledonian lamprophyre dykes (415 ± 12 Ma K–Ar) (Anderson & Oliver, 1996), which intrude into the greywakes of the Central Belt of the Longford-Down Terrane, host incognate xenoliths which are believed to be fragments of the unexposed basement in the area. The xenoliths are typically basic-volcanic schists and mylonites which were

metamorphosed at a depth of 7 – 30 km. Their geochemistry is similar to calc-alkaline magmatic-arc basalts (Anderson & Oliver, 1996).

2.2.3 Slieve Gullion Centre

2.2.3a Forkhill Breccias

Richey & Thomas (1932) and Emeleus (1962) identified the Forkhill breccias, which crop out in the south-west of the Slieve Gullion ring complex, as the oldest members of the complex. This relative dating was based on the lack of porphyritic rhyolite fragments in the breccia, and on the local presence of intrusive veins of rhyolite (Richey & Thomas, 1932). The Forkhill breccias are primarily comprised of angular fragments of the dominant country rocks in the area, namely the Lower Palaeozoic metasediments and the Caledonian Newry Granodiorite, with less common fragments of older Palaeogene basalt and trachyte lavas. The matrix in these breccias consists of fine particles of the rock types mentioned above. Given the lack of juvenile igneous material present in these rocks, and the relationship between the clast types and the country rock in the area, the Forkhill breccias were originally interpreted as vent agglomerates formed by the *in-situ* shattering of country rock due to pre-eruptive gas explosions and ring fault movement (Richey & Thomas, 1932; and Emeleus, 1962). The presence of Palaeogene basalts clasts was interpreted as evidence explosion close to the surface. A recent study by Stevenson *et al.*, (*in press*) describes this unit as volcano-sedimentary in origin (a mega-breccia). The veining of the breccias by the porphyritic rhyolite would then potentially indicate a near-surface contact between these two units, however the precise nature of the rock relationship remains enigmatic.

2.2.3.b Porphyritic Rhyolite

The porphyritic rhyolite crops out predominantly in the southwest of the complex, where it forms the majority of the ring-dyke e.g. at Forkhill (IJ 0059 1603), (Figure 2.3). The porphyritic rhyolite is hypocristalline, and consists of a very fine-grained to glassy, grey to blue-grey matrix containing 20-30% phenocrysts (Figure 2.4 a, c). Phenocrysts in order of abundance include coarse quartz (10-15%) and feldspar (10%; mostly sanidine

with rare plagioclase), both measuring about approximately 3 mm in diameter on average. Lesser (<1%) xenocryst of clino-pyroxene and fayalitic olivine along with <5% opaques such as zircon and magnetite are also present. The crystals are typically euhedral but subhedral crystals formed by fragmentation or embayments are not uncommon. Glass shards and small rounded, basaltic clasts (5mm in diameter) are also evident in hand sample and in thin section. Also apparent are cm-scale lenses of material identified by previous authors as flow banding or fiamme (Richey & Thomas, 1932; Emeleus, 1962; Bell & Emeleus, 1988; McDonnell *et al.*, 2004). In thin section, these structures possess a micrographic texture, enveloping phenocrysts of quartz and feldspar and are, at times, more coarsely crystalline than the groundmass surrounding the porphyritic rhyolite. The combined field and petrographic evidence provides inconclusive evidence for this unit being either intrusive or effusive, indicating these rocks may be a transitional facies between the subvolcanic and volcanic units (Emeleus, 1962; Gamble *et al.*, 1992; McDonnell *et al.*, 2004).

At some marginal locations within the porphyritic rhyolite, e.g. Mullaghbawn golf course (IH 9880 1812), outcrops contain abundant xenoliths of Newry Granodiorite (Figure 2.4 d, e). In thin section, many of the xenoliths display pockets of glass between minerals (former melt), suggesting partial melting of some portions of the Newry country rock (Figure 2.4 f). Trails of xenoliths, xenocrysts, and fiamme (Bell & Emeleus, 1988) help to define flow fabrics within the porphyritic rhyolite (see McDonnell *et al.* 2004). Away from the margins of the rhyolite, xenoliths are rare (Emeleus, 1962).

2.2.3.c Porphyritic Micro-granite

Porphyritic micro-granite forms the bulk of the ring-dyke, particularly in the north of the centre, but west of Mullaghbawn porphyritic granite may be found together with porphyritic rhyolite in one outcrop (Emeleus, 1962; McDonnell *et al.* 2004) (Figure 2.3, 2.4.a). Outcrops of porphyritic granite are absent further south (Figure 2.3).

The porphyritic granite consists of 35-45% phenocrysts contained within a fine grey-pink matrix. The dominant phenocrysts are quartz (15%) and feldspar (18-20%).

The latter is often complexly zoned, but amphibole, clinopyroxene, opaque minerals, minor fayalitic olivine and zircon are also present, thus exhibiting a similar principal mineralogy as the porphyritic rhyolite. An average quartz phenocryst measures 2mm in diameter, with feldspar crystals considerably larger at up to 2-3 cm in length but on average between 0.7 and 1 cm (Figure 2.4.b). These feldspars belong predominantly to the sanidine-orthoclase series with only minor plagioclase present (Emeleus, 1962). Both types have variable shapes with euheadral to anhedral inclusion-rich crystals.

2.2.3.d Palaeogene Basaltic Dykes

Numerous small dykes of basaltic composition crosscut the ring complex. To obtain a representative Palaeogene mafic Slieve Gullion composition, we sampled one of the basaltic dykes at Forkhill quarry (IJ 0059 1603). We used this sample instead of down-faulted pre ring-dyke basalts or some of the small basalt clasts in the ring-dyke as these flows and clasts are generally either highly altered or difficult to extract.

2.3 Analytical methods

Samples were prepared by removing all weathered surfaces and cutting rough apparently inclusion-free blocks to between 8-10 cm³ in size. The blocks were crushed using a jaw crusher and the resulting chips were hand-picked under a stereomicroscope to eliminate weathered fragments and country rock xenoliths. Samples were then powdered by hand using an agate mortar and pestle.

Sr and Nd ion chromatography and isotopic analyses were carried out at the Isotope Geosciences Unit of the Scottish Universities Research and Reactor Center (SUERC), East Kilbride, Scotland by Robert Ellam. Powdered samples were weighed into in teflon screw-top beakers and dissolved using HF-HNO₃-HCl digestion. Rb and Sr were separated in 2.5 N HCl using Bio-Rad AG50W X8 200–400 mesh cation exchange resin. Nd was separated in a mixture of acetic acid (CH³COOH), methanol (CH₃OH) and nitric acid (HNO₃) using Bio-Rad AG1x8 200–400 mesh anion exchange resin. Total procedure blanks for Sr and Nd were less than 0.3 ng.

Sr samples were loaded onto single Ta filaments with 1N phosphoric acid, and Nd samples were loaded directly onto triple Ta–Re–Ta filaments. Sr and Nd samples were analysed on a VG Sector 54-30 multiple collector mass spectrometer. The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were corrected for mass fractionation using $^{87}\text{Sr}/^{86}\text{Sr} = 0.1194$ and an exponential law, and $^{143}\text{Nd}/^{144}\text{Nd} = 0.7219$ and an exponential law. The VG Sector 54-30 mass spectrometer was operated in peak-jumping mode with data collected as 15 blocks of 10 ratios when measuring Sr isotope compositions, and as 12 blocks of 10 ratios when measuring Nd isotope compositions. Total procedure blanks for Sr and Nd were < 300 pg. NIST SRM987 yielded an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.710254 ± 22 (2 SD, $n = 34$) and the internal laboratory Nd standard (JM) yielded an $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.511511 ± 8 (2 SD, $n = 12$) during this study.

2.4. Results

Representative samples from the ring-dyke, the country rocks, and a local Palaeogene basalt dyke were selected for Sr and Nd isotope analysis from the sample suite of McDonnell *et al.* (2004). Sr and Nd isotopic data for the selected samples are given in Table 1 and are illustrated in Figures 2.6 and 2.7. All isotope ratios for the ring-dyke rocks were age-corrected to 57 Ma according to Rb–Sr whole rock isotopic age reported by O'Connor (1988).

The isotopic end-members of our sample set are the Paleogene basalt dyke and the Lower Palaeozoic sedimentary rocks of the Longford-Down Terrane. The Paleogene basalt dyke has the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ (0.705948 ± 18), and the highest $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512799 ± 22 . The most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ value was obtained from the Lower Palaeozoic sedimentary rock (0.722829 ± 18) with a $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512134 ± 7 . Our data is consistent with previously reported values for similar lithologies in Scotland in O'Nions *et al.* (1983), Halliday (1984), and McCormick (1989), although it lies at the radiogenic end of the spectrum. The Newry Granodiorite shows a lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.708136) and a low $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512328, consistent with data presented in McCormick (1989) and Dempsey *et al.* (1990). The ring-dyke rocks cover a range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from 0.0.707673 to 0.713593 with a restricted variability in $^{143}\text{Nd}/^{144}\text{Nd}$,

ranging from 0.512384 to 0.512455 (Figure 2.7.a). The low-Si rocks classified by McDonnell *et al.* (2004) are higher in radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ than the high-Si rocks (Figure 2.6).

2.5. Discussion

2.5.1 Contamination of the ring-dyke magmas

A major focus in the study of the BIPI has long been the origin of the highly silicic rocks found in igneous centres (cf. Gamble, 1979; Meighan, *et al.*, 1984; Thompson *et al.*, 1986; Sparks, 1988; Bell & Williamson, 2002; Troll, *et al.*, 2004). Rocks of mafic compositions dominate the total magma budget in the British Palaeogene Igneous Province, providing an ample heat source for crustal anatexis (cf. Annen *et al.*, 2006) and a mechanism for producing fractionated silicic magmas (e.g. Gamble, *et al.*, 1992). Based on the poor surface exposure at Slieve Gullion, approximately equal proportions of mafic and felsic rocks appear to be present (Gamble *et al.*, 1992). However, gravity studies of the Irish BIPI centres (Cook & Murphy, 1952) combined with subsurface excavations and drill cores in the area, indicate larger volumes of mafic to ultramafic rocks at depth beneath Slieve Gullion.

The observed variations in Sr and Nd isotopes in the ring-dyke magmas indicate substantial crustal modification of a fractionating, mantle-derived, magma. This is in keeping with the conclusions of McDonnell *et al.* (2004), who suggested that certain trends seen in trace element data (e.g. Pb vs. Zr; Figure 2.5) may be explained by open system fractionation, and assimilation of either Longford Down sedimentary rocks and/or Newry Granodiorite. A similar scenario has been suggested by Gamble *et al.* (1992), for the Slieve Gullion Central Complex. However, the magmas of the ring-complex have considerably higher radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ than the magmas of the Slieve Gullion central complex, indicating variation in the impact and/or extent of crustal assimilation between these distinct phases of magmatism.

In a plot of $^{87}\text{Sr}/^{86}\text{Sr}$ against $^{143}\text{Nd}/^{144}\text{Nd}$ (Figure 2.7), there is a marked trend towards the field defined by Longford-Down sedimentary rocks. However, this is the converse of that expected for conventional assimilation with progressive fractionation

(AFC) (DePaolo, 1981). Instead of increasing $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with increased SiO_2 , the low-Si ring-dyke rocks are the most radiogenic. This negative correlation with $^{87}\text{Sr}/^{86}\text{Sr}$ is also evident when plotted against SiO_2 and Sr (ppm) (Figure 2.6).

One possible explanation is a two-stage contamination process for the magmatic evolution of the ring-dyke magmas, with two contaminating end-members involved: the Longford-Down sedimentary rock and the Newry Granodiorite. Based on work by O'Connor (1988), and Gamble *et al.* (1992), a parental magma of depleted mantle-like isotopic composition can be envisaged for the Slieve Gullion centre and for much of the British Palaeogene Igneous Province as a whole (see also Ellam & Stuart, 2000). These magmas would have been highly susceptible to crustal contamination by more radiogenic crustal rocks due to their relatively low Rb/Sr and Sr isotope ratios. Using such a MORB-type basalt as a parental end-member, Sr and Nd isotopic ratios similar to those observed in the low-Si dyke rocks can be produced by an AFC-type process (DePaolo, 1981), involving the assimilation of Lower Palaeozoic sedimentary rock ($r = 8.5$, $\sim 10\text{--}15\%$ solidification where r = the ratio of the rate of assimilation to the rate of fractional crystallisation). Such an AFC curve also intersects the isotopic ratios of the analysed Palaeogene basalt dyke that cuts the Slieve Gullion ring-dyke at Forkhill ($\sim 5\%$ solidification, Figure 2.7). In contrast, an AFC curve using the Slieve Gullion basaltic dyke rock as a starting composition (Figure 2.7) fails to produce an intersection with the low-Si ring-dyke rocks even for high assimilation rates. The best AFC-fit is thus given by a MORB-type starting composition, with a good match between modelled and measured isotope ratios and trace elements. Binary mixing curves are also presented for both scenarios. In the first model (MORB- Longford-Down sedimentary rock) (Figure 2.7), only the high-Si ring-dyke rocks can be produced, failing to explain the low-Si compositions. In the second case (Slieve Gullion basaltic dyke – Longford-Down sedimentary rocks) (Figure 2.7), binary mixing can produce isotopic compositions similar to the low-Si ring-dyke rocks (60% Basalt, 40% Sedimentary rock). However, the modelled concentrations of Sr and Nd ppm (Sr = 164 ppm, Nd = 16) are not matched with the values observed in the samples (Sr = 35 ppm, Nd = 76). The best fit for this first stage of contamination is thus the AFC curve with a MORB starting composition ($r = 0.85$; solidification $\sim 10\text{--}15\%$).

The decreasing $^{87}\text{Sr}/^{86}\text{Sr}$ trend from low-Si to high-Si ring-dyke rocks may in turn, be explained by a subsequent selective assimilation of the most fusible portions of Newry Granodiorite, which possesses lower $^{87}\text{Sr}/^{86}\text{Sr}$ than the local sedimentary rock and similar $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Figure 2.7). This late contamination can be approximated as either binary mixing or as an AFC process, since both are mathematically possible (Figure 2.7) though none produces a perfect fit for observed trace-element concentrations. Since certain trace elements seem particularly affected by Newry Granodiorite contamination (McDonnell *et al.* 2004), it is conceivable that partial/selective contamination was the dominant mode of interaction (cf. Davidson & Tepley, 1997; Duffield & Ruiz, 1998; Knesel & Davidson, 2002). This is particularly likely as Newry Granodiorite is lower in SiO_2 than any of the ring-dyke rocks. Partial melting textures in thin section suggest, however, a minimum melt fraction along quartz-feldspar grain boundaries, thus very probably providing a high-Si contaminant (Figure 2.4 d,e,f). However, this partial melt would also be enriched in high $^{87}\text{Sr}/^{86}\text{Sr}$ indicating that the isotopic signature of the ring-dyke rocks may be heavily influenced by assimilation of Newry Granodiorite. The abundant occurrence of xenoliths and xenocryst trails, particularly in the marginal porphyritic rhyolite ring-dyke facies, suggests that besides interaction in the storage chamber (partial melting textures), incorporation of Newry Granodiorite also happened very late, i.e. in the conduit. Although such samples were avoided for analysis, it is possible that some xenocrysts were contained in our porphyritic rhyolite and granite samples (cf. Emeleus & Smith, 1959). For example, our most affected high-Si ring-dyke sample may well follow a binary mixing curve as a result of bulk incorporation of crystals and fragments from the country rock.

Assimilation of Longford-Down sedimentary rocks is in accord with earlier findings on the Slieve Gullion Central Intrusion (Gamble *et al.* 1992). However, contamination by Newry Granodiorite was considered unlikely for these younger Slieve Gullion rocks (Gamble *et al.*, 1992), although petrographic and geochemical evidence is strong in the earlier ring-dyke rocks of this study. A number of reasonable explanations may be invoked for this; a) the earlier ring-dyke magmas may have removed all easily fusible material from the Newry country rock, causing the subsequent Central Intrusion

magma batches to experience little contamination or b) the earlier magmas may have shielded the later ones from intensive interaction with the country rocks (cf. Thompson *et al.* 1986; Kerr *et al.* 1999). However, when considered in conjunction with our data, the data of Gamble, *et al.*, (1992) plot well within the ring-dyke trend. It is conceivable that these later Slieve Gullion rocks share a very similar history to the ring-dyke rocks, a feature that may be blurred by the strong Longford-Down sedimentary rock contamination trend. However, the limited data set ($n=3$) of Gamble *et al.* (1992) does not facilitate a more detailed exploration.

2.5.2 Nature of the Slieve Gullion magma chamber

Trace-element and major-element data presented in McDonnell *et al.* (2004) suggest that the two distinct groups of both porphyritic rhyolite and granite (a Si-rich group and a Si-poor group) most likely represent two compositional extremes that originated from a single parent and evolved through dominantly convective fractionation and contamination in a zoned magma chamber. The porphyritic rhyolites represent the liquid interior and the porphyritic granites the mushy chamber wall equivalents (McDonnell *et al.* 2004) (Figure 2.8). This chamber structure, where a high-Si rhyolite magma was overlying a low-Si rhyolite, both encompassed by their more crystalline porphyritic granite equivalents, is supported by viscosity and density calculations (McDonnell *et al.* 2004) and may be the result of a process akin to convective fractionation (cf. Wörner & Schmincke, 1984; Sparks, 1988; Wolff, *et al.*, 1990). In contrast, the mushy chamber-wall porphyritic granites formed from the arrest of crystals in inward-migrating solidification zones and were modified by post-cumulus crystal growth and interstitial melt migration (cf. Marsh 1996).

Although our isotope data alone are of limited applicability to reconstructing magma chamber processes, they offer a way of testing the model put forward by McDonnell *et al.* (2004). Our data show the high-Si rhyolite to be most strongly affected by crustal contamination, in this instance by Newry Granodiorite, a feature that is common in composite felsic systems (e.g. Wörner, *et al.*, 1985; Druitt & Bacon, 1989). In addition, both porphyritic granites show a range of isotope ratios that are less

radiogenic than the range of their rhyolitic counterparts, which may be a function of the removal of interstitial liquid due to convective fractionation (i.e. feldspar accumulation).

When contamination is initiated in such a scenario, the melt fraction of the magma would be most strongly affected in the beginning of such an assimilation process. Subsequently, crystals that grow from this melt will increasingly take up the contaminant in their outermost growth zones (Davidson & Tepley, 1997; Duffield & Ruiz, 1998). Crystals that mainly grew before contamination will show a change from core to rim with the rims reflecting the contamination most strongly. In the Slieve Gullion porphyritic granite magmas, which are thought to have lost interstitial melt during the last phase of crustal storage, the similar to lower radiogenic whole rock values relative to their rhyolitic counterparts might imply that the arrested feldspars predominantly record a previous stage of differentiation and contamination in their cores (e.g. with Longford Down sedimentary rocks). The whole rock value of the crystal-rich porphyritic granite samples, being essentially a mixture of melt and crystals of various generations, would accordingly be less reflective of the latest stage of contamination, i.e. contamination with Newry Granodiorite, even though this stage may be represented in small overgrowth rims of the resident feldspars (cf. Duffield & Ruiz, 1998). The high percentage (up to 35%) and large size (up to 3 cm) of the feldspar phenocrysts in the porphyritic granite samples may imply that the bulk of these crystals (now represented as crystal cores) grew before or during contamination by Longford-Down sedimentary rocks and prior to the main onset of Newry Granodiorite contamination (Figure 5). This solution we present is not unique, however it does provide an explanation that is consistent with the model of McDonnell *et al.* (2004), and the petrographic and geochemical evidence which indicates that these magmas evolved in the same reservoir, and were intruded, emplaced, and potentially erupted close to, if not contemporaneously.

2.6 Conclusions

The influence of crustal contamination on isotope composition is recorded in the geochemistry of magmas from virtually all British Palaeogene Centres (e.g. Kerr *et al.*

1999; Ellam & Stuart, 2000; Bell & Williamson, 2002; Geldmacher *et al.* 2002). It has been shown by Geldmacher *et al.*, (2002) that Palaeogene magmas that rose through different crustal terranes were exposed to different country rocks and thus record a different contamination history. These authors argue that magmas from the Rum Centre were mainly contaminated by Lewisian gneisses that form the upper crust north of the Moine Thrust Belt. Magmas at Ardnamurchan, however, were contaminated with Lewisian gneisses in the lower crust, with subsequent additional assimilation of Moine metasedimentary rock in the upper crust. Slieve Gullion lies south of the Northern Belt Median Fault (southern Uplands Fault equivalent in Ireland, Morris 1987) and should therefore display a markedly different contamination history to those centres that intruded Archaean basement terranes in northern Scotland. The Slieve Gullion ring-dyke magmas record evidence for contamination with Southern Uplands-type local Palaeozoic Mid-to-Upper crustal sedimentary rocks plus shallow contamination with Caledonian granitic crust, emphasising the severe effect of crustal heterogeneity on ascending mantle magmas (c.f. Ellam & Stuart, 2000). An additional earlier contamination of Slieve Gullion magmas (e.g. for the basaltic dyke sample) in the deep crust cannot be ruled out since the evidence for such an event would be strongly obscured by the two upper crustal contamination events. Additionally, the nature of the deep crust beneath the Longford-Down Terrane is poorly constrained. Xenoliths in Carboniferous lamprophyre dykes in Co. Down (Anderson & Oliver, 1996), suggest that an ancient island arc-type basement underlies the Longford-Down sedimentary rocks, and that this may in turn, be underlain by Avalonian or exotic terranes (cf. Trewin & Rollin, 2002). Evidence for lower crustal magma-crust contamination could be preserved in the cores of some of the strongly-zoned feldspar phenocrysts of the ring-dyke rocks and awaits *in situ* analytical approaches.

The Sr and Nd isotope ratios of the Slieve Gullion ring-dyke magmas can be explained by two stages of contamination during upper crustal residence and storage and support petrographic, major and trace element evidence which indicates that a strong genetic link between the porphyritic rhyolite and granite. We propose a model whereby fractionating magmas of basaltic and intermediate composition are contaminated by local sedimentary

rocks, giving rise to rhyolite magmas that experience additional late shallow contamination by the most fusible portions of the Newry Granodiorite. We envisage the last stages of fractionation and contamination to occur in a zoned rhyolite magma chamber with high-Si magma being stored in the upper part of the chamber, recording the most extensive crustal contamination in this system. This magma reservoir was tapped and ascending magma utilised existing weaknesses in the crust, forming a composite ring-dyke complex.

Table 2.1 Slieve Gullion Sr and Nd Isotopic Data

Sample No.	Rock Type	$^{87}\text{Sr}/^{86}\text{Sr}_m$	Rb (ppm)	Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$ (57 Ma)	$^{143}\text{Nd}/^{144}\text{Nd}_m$	Sm (ppm)	Nd (ppm)	$^{143}\text{Nd}/^{144}\text{Nd}$ (57 Ma)
SG-G1	Gran.	0.733007 ± 18	186	21	0.711787 ± 18	0.512468 ± 8	12	62	0.512424 ± 8
SG-G2	Gran.	0.731903 ± 16	217	27	0.712917 ± 16	0.512496 ± 7	10	59	0.512455 ± 7
SG-G6	Gran.	0.729047 ± 16	183	25	0.711693 ± 16	0.512468 ± 6	10	49	0.512424 ± 6
SG-G7	Gran.	0.724919 ± 16	165	33	0.713006 ± 16	0.512426 ± 7	14	78	0.512384 ± 7
SG-G8	Gran.	0.724644 ± 16	165	36	0.713593 ± 16	0.512429 ± 8	14	77	0.512387 ± 8
SG-F3	Rhyolite	0.728937 ± 19	173	24	0.711906 ± 19	0.512433 ± 7	10	57	0.512391 ± 7
SG-F4	Rhyolite	0.729342 ± 18	169	25	0.713275 ± 18	0.512458 ± 6	9	49	0.512417 ± 6
SG-F5	Rhyolite	0.747525 ± 16	181	12	0.710796 ± 16	0.512465 ± 6	12	59	0.512419 ± 6
SG-F6	Rhyolite	0.747823 ± 18	195	12	0.707673 ± 18	0.512471 ± 7	16	79	0.512425 ± 7
SG-NG-3	N.G.	0.708177 ± 23	10	563	0.708136 ± 23	0.512363 ± 8	5	30	0.512328 ± 8
SG-PS-2	L.D.S.	0.724985 ± 20	124	149	0.722829 ± 20	0.512195 ± 7	5	20	0.512134 ± 7
SG-PB3	P.B.D.	0.705967 ± 18	1	179	0.705948 ± 18	0.512799 ± 22	4	12	0.512799 ± 22

Gran. = Porphyritic granite, Rhyolite = Porphyritic rhyolite N.G. = Newry granodiorite, L.D.S. = Longford-Down metasedimentary rock,
P.B.D. = Palaeogene basalt dyke

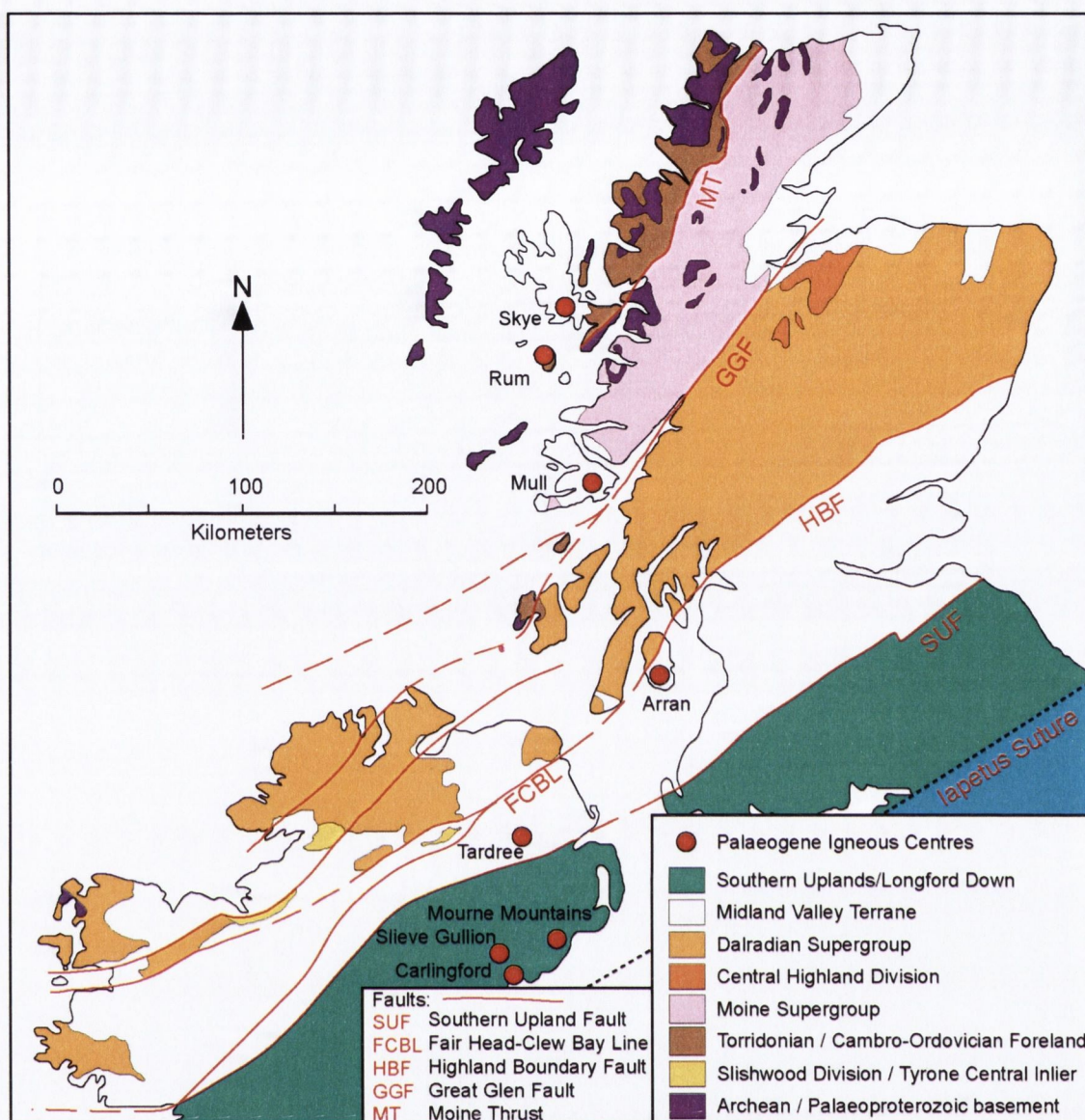


Figure 2.1 Geological sketch map displaying major terrane boundaries of the north of Ireland and Scotland with the igneous centres of the BPIP (terrane map courtesy of D. Chew).

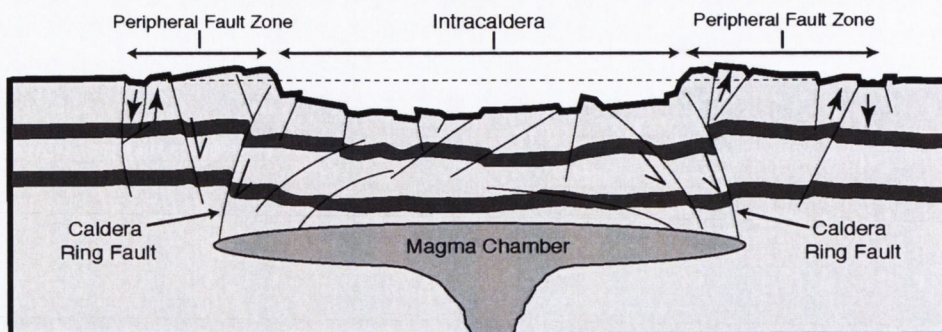


Figure 2.2 Schematic diagram of the formation of ring fractures and caldera collapse relative to a magmatic plumbing system (after Walter & Troll, 2001).

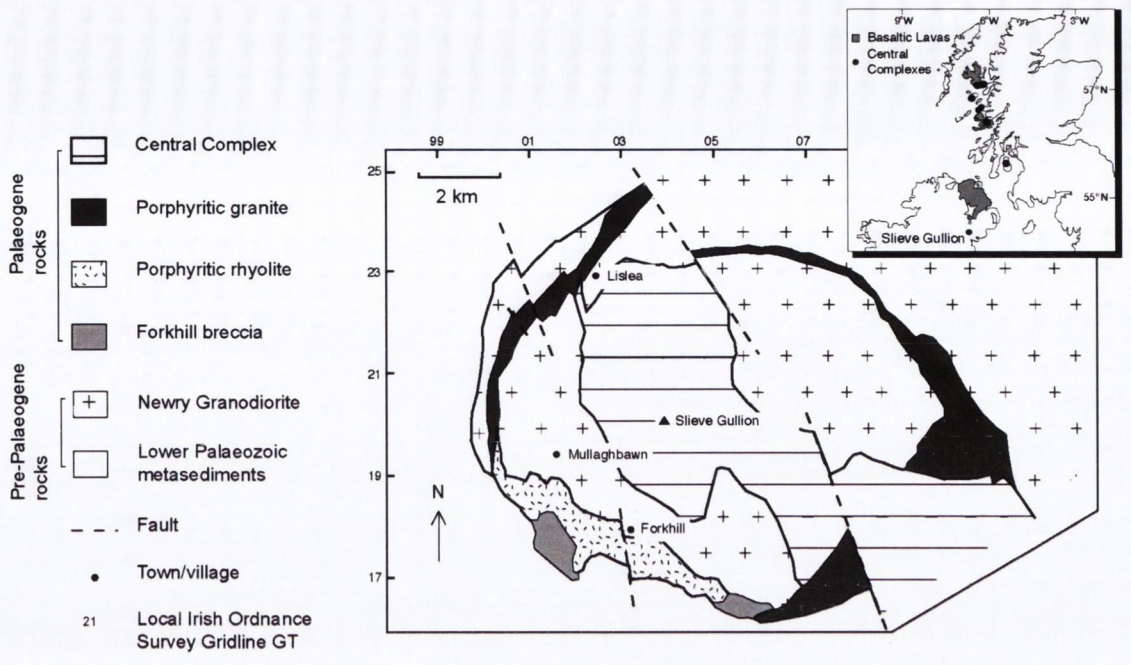


Figure 2.3. Geological map of the Slieve Gullion Ring Complex after McDonnell *et al.*, (2004) with inset with regional location. Grid system from the Ordnance Survey of Ireland.

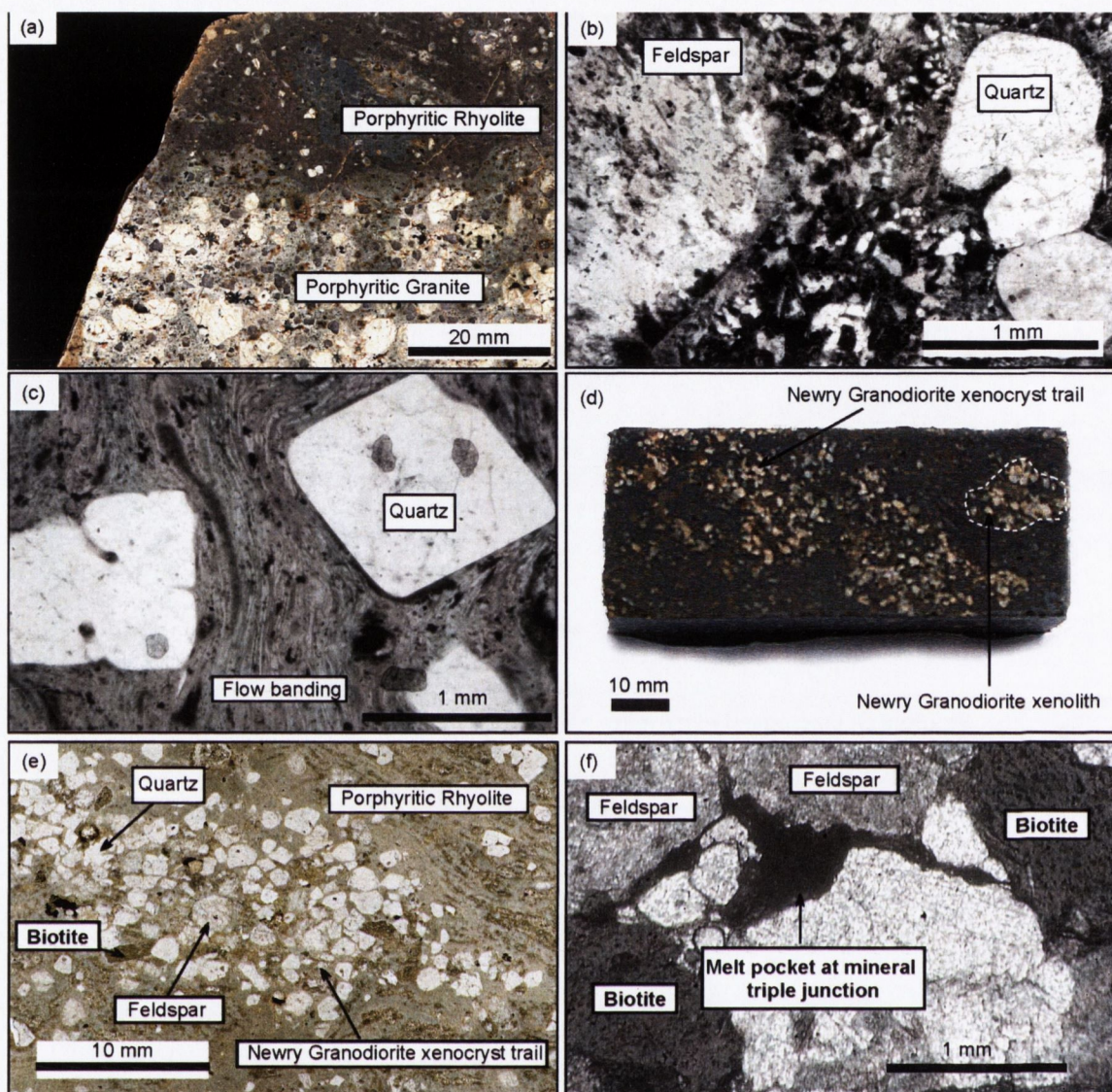


Figure 2.4. (a) Porphyritic rhyolite and porphyritic granite in contact in hand sample (from McDonnell et al. 2004). (b) Thin section photomicrograph of porphyritic granite sample in PPL. (c) Thin section photomicrograph of porphyritic rhyolite sample in PPL. (d) Newry Granodiorite xenolith and xenocryst trails in a hand sample of porphyritic rhyolite from Mullaghbawn Golf course (IH 9880 1812). (e) Newry Granodiorite xenolith and xenolith trail in a thin section of porphyritic rhyolite in PPL. (f) Thin section photomicrograph of partial melting textures in a Newry Granodiorite xenolith in PPL.

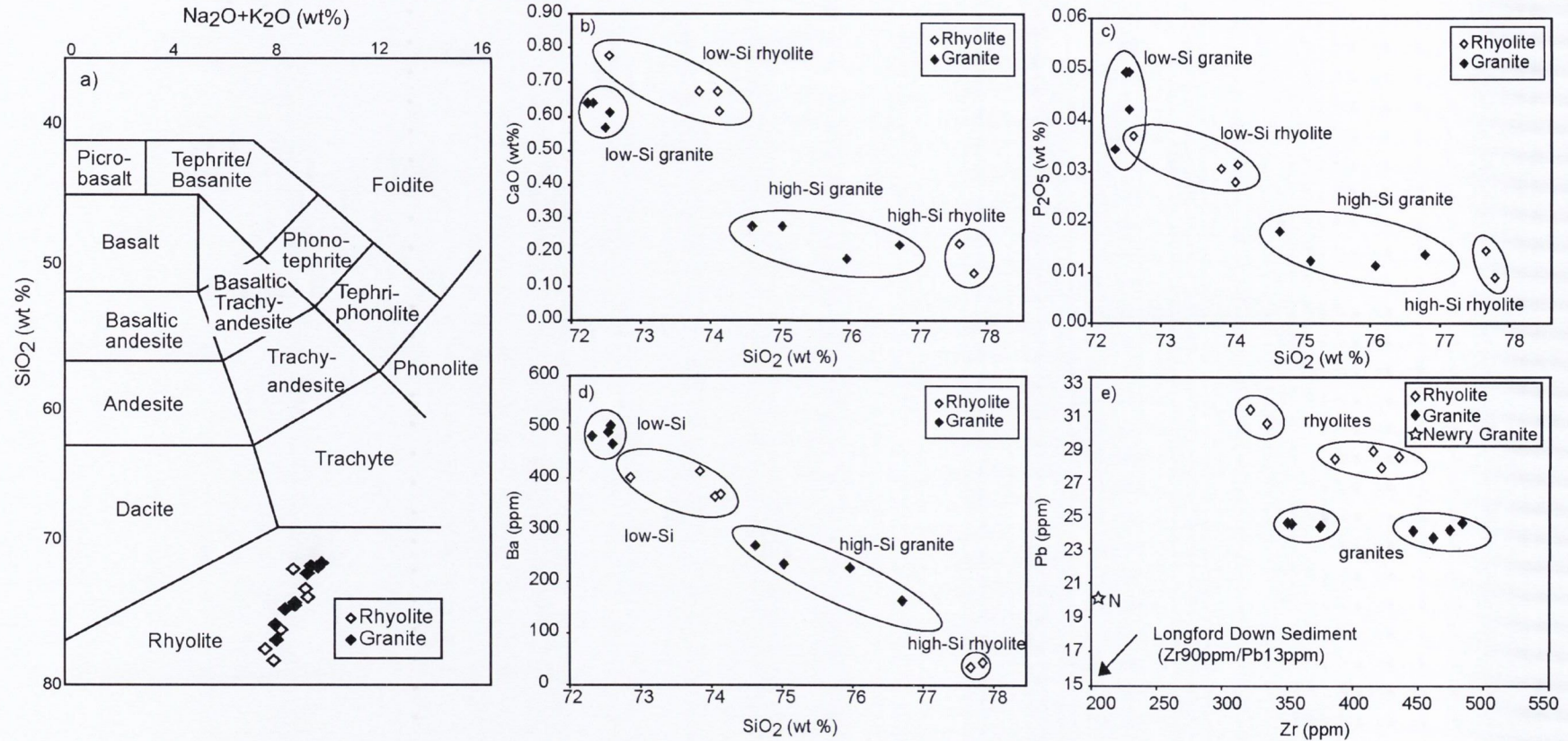


Figure 2.5 All figures are after McDonnell *et al.*, 2004. (a) TAS plot of the porphyritic rhyolite and granite samples analysed. All ring-complex magmas plot in the rhyolite field and are chemically similar. (b) CaO vs. SiO_2 with porphyritic rhyolite and granite each forming two separate groups of data; high-Si and low-Si porphyritic rhyolite and high-Si and low-Si porphyritic granite. Both granite sub-groups have similar or lower CaO concentrations than their associated rhyolite fields. (c) Different geochemical sub-groups are evident for a plot of P_2O_5 vs. SiO_2 . (d) Ba vs. SiO_2 with the same distinct data fields evident. As with CaO, granite samples have higher Ba than their corresponding rhyolite group consistent with the granite samples representing a crystal-rich unit rich in feldspar within the magma chamber. (e) Pb vs. Zr. plot illustrating the four same groups as in previous plots. However both granite groups have lower Pb values than the corresponding rhyolite groups indicating potential for selective contamination.

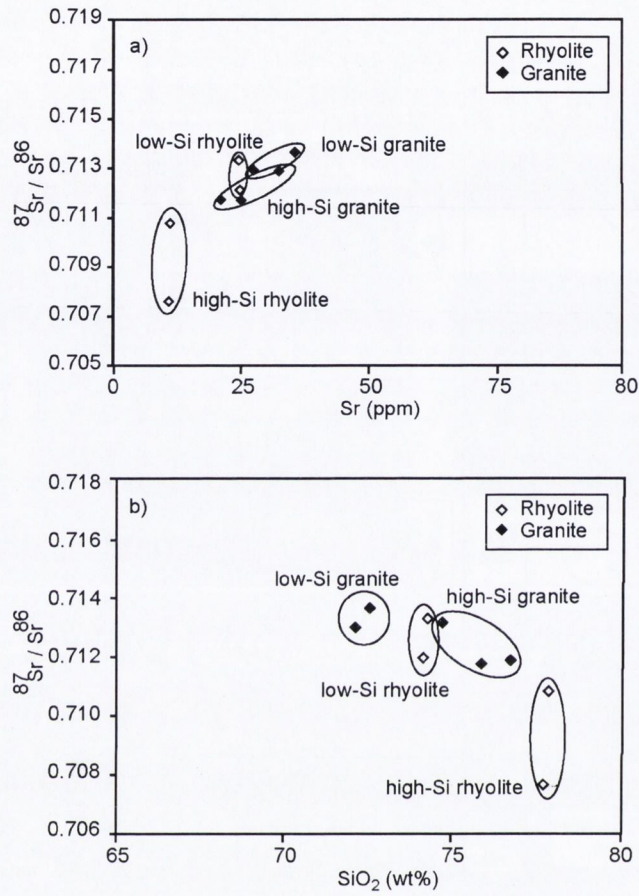


Figure 2.6. (a) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Sr (ppm) plot for Slieve Gullion ring-dyke magmas. Note the same negative correlation with $^{87}\text{Sr}/^{86}\text{Sr}$. Errors are smaller than symbol size. (b) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO_2 plot for Slieve Gullion ring-dyke magmas. Petrographic groups of McDonnell *et al.*, (2004), are indicated by ellipses. Note the marked trend of increasing $^{87}\text{Sr}/^{86}\text{Sr}$ with decreasing SiO_2 .

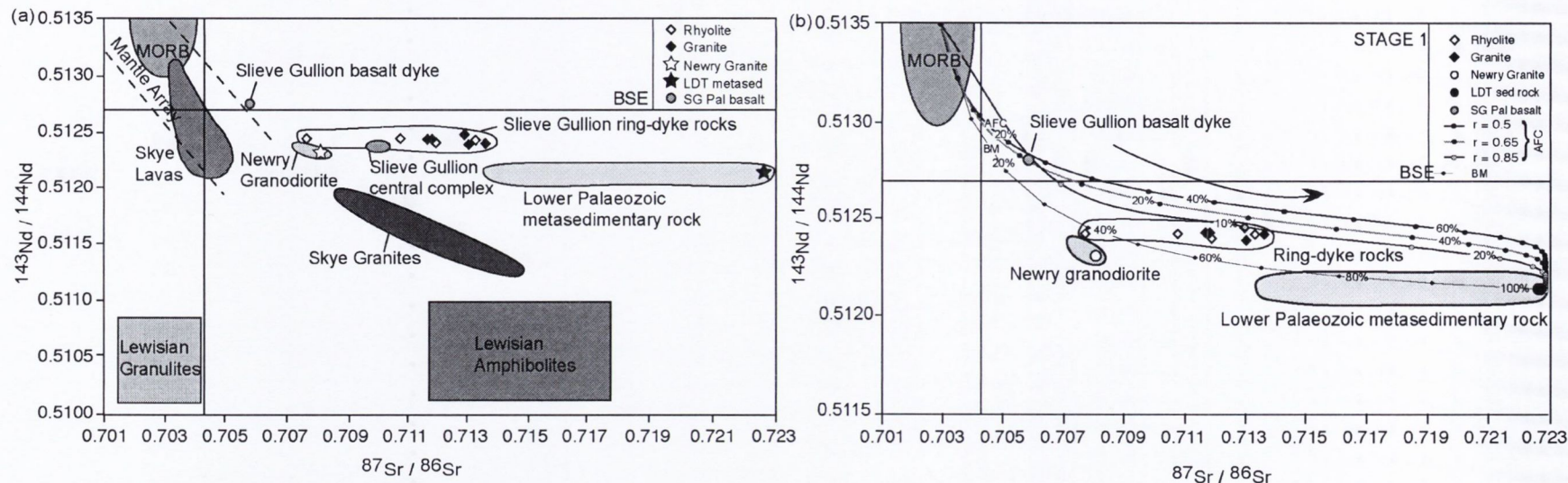


Figure 2.7 (a) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ summary diagram showing data from Slieve Gullion ring-dyke in relation to depleted mantle, the Slieve Gullion basalt dyke sample (SG Pal basalt) and local Longford-Down country rocks (LDT metased.). Fields from Skye (for reference) and Lewisian amphibolites and granulites are from Dickin (1981). Slieve Gullion central complex samples are from Gamble et al. (1992), Lower Palaeozoic metasedimentary rock field from Halliday (1984) and Newry Granodiorite from Dempsey et al. (1990). Errors are smaller than symbol size. (b) Binary Mixing curves using MORB-type starting composition and Longford-Down metasedimentary rock as contaminant. Arrow indicates evolutionary trend. Compositions similar to the low-Si dyke rocks are achieved by AFC (~ 10-15% solidification) with relatively high assimilation rates ($r = 0.85$). Note basalt dyke sample lies on AFC curve ($r = 0.85$ at ~ 5% solidification).

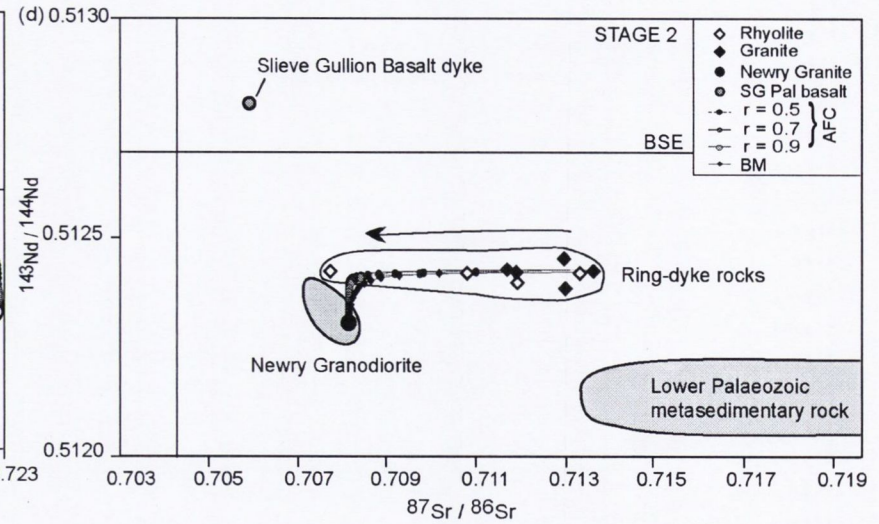
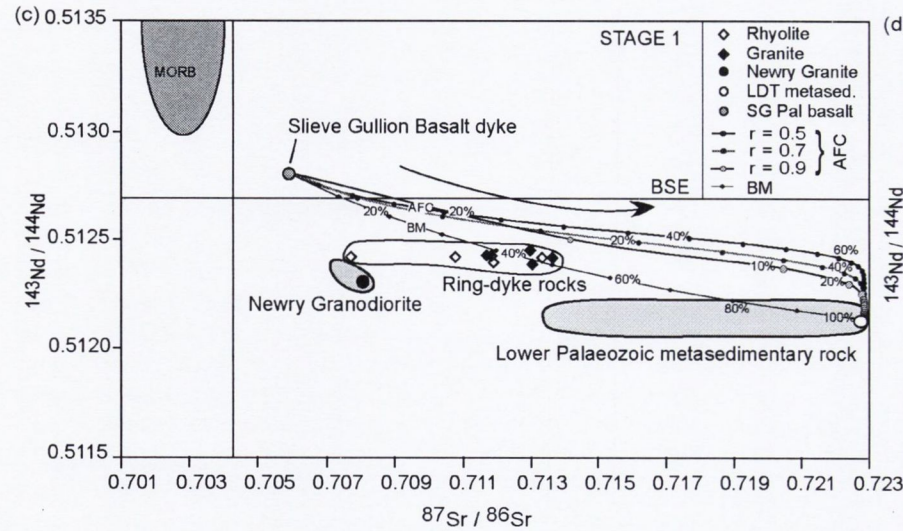


Figure 2.7. (c) AFC and Binary Mixing (BM) curves using the Slieve Gullion basaltic dyke sample as a starting composition and Longford Down metasedimentary rock as contaminant. Arrow indicates evolutionary trend. Note even high r -values fail to produce an intersection with low-Si ring-dyke rocks. (d) Contamination by Newry Granodiorite modelled by AFC and BM using low-Si porphyritic granite as a starting composition. Arrow indicates evolutionary trend. This trend accounts for the negative correlation in $^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO_2 , (towards less radiogenic Sr ratios).

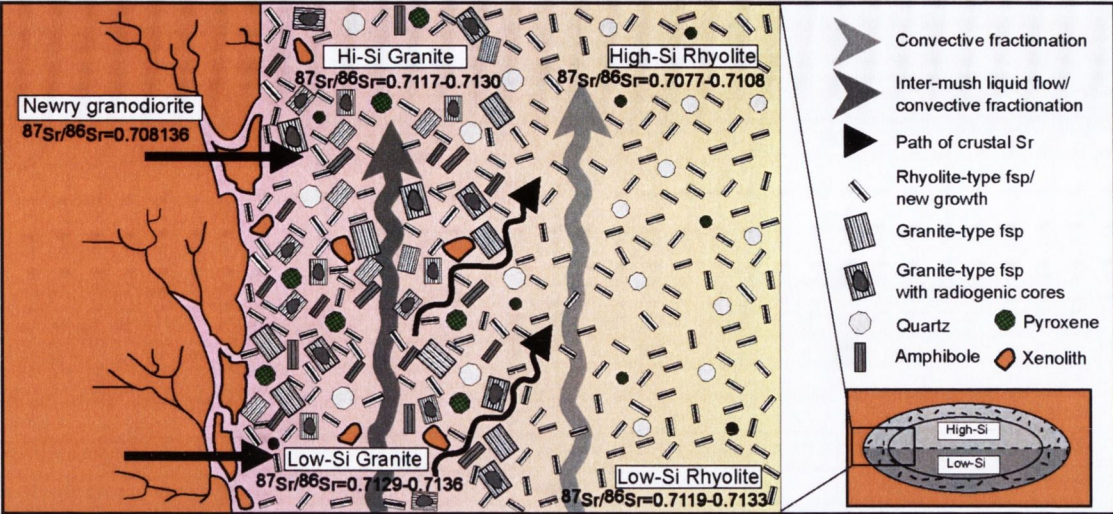


Figure 2.8 Schematic diagram of a zoned Slieve Gullion ring-dyke magma chamber in vertical contact with Newry granodiorite chamber wall. Convective fractionation (grey vertical arrows) combined with crustal assimilation (black horizontal arrows) redistributes radiogenic crustal Sr from the chamber wall to chamber top (diagonal arrows), concentrating the liquid that is most strongly contaminated by Newry granodiorite country-rock in the roof zone of the chamber. The higher Sr isotope ratios in the porphyritic granites are likely to be a function of the high abundance and large size of its complexly zoned feldspars, which probably reflect former stages of contamination by radiogenic Longford-Down metasedimentary rocks in many crystal cores. This suggests that the main volume of feldspar in the porphyritic granite magmas grew before the onset of the second contamination stage (Newry granodiorite) that provided much less radiogenic Sr to the system, potentially causing thin feldspar overgrowth rims with lower Sr isotope ratios to form.

CHAPTER 3 – TAUPO VOLCANIC ZONE

3.1 Introduction

As indicated by numerous geochemical studies, subduction-related magmas are thought to originate in the mantle wedge, (e.g. Grove & Kinzler, 1986; McCulloch & Gamble, 1991) with melt production triggered by addition of fluids and/or melt derived from the subducting slab (Nicholls & Ringwood, 1973; Hawkesworth *et al.*, 1979; Arculus & Powell, 1986; Turner *et al.*, 1997; Elliott *et al.*, 1997). During ascent, these primary melts may then interact with the overlying lithosphere (Graham & Hackett, 1987; Graham *et al.*, 1995; Dungan *et al.*, 2001). However, the extent of this interaction and its effect on magma composition can be difficult to assess. Commonly, the effect of interaction with the overlying lithosphere is only considered for studies of evolved continental arc magmas. Even in continental settings, source contamination by fluids, melts, and subducted sediments and contamination of primary melts by assimilation of lithospheric mantle or crustal rocks during ascent may produce similar geochemical characteristics (e.g. Davidson, 1996). Additional complications arise when the subducted sediment and the overlying lithospheric crust are of a broadly similar composition, as in the case in many arcs including the Banda arc (Vroon *et al.*, 1993), the Luzon arc (McDermott *et al.*, 1993) and in the Kermadec-New Zealand arc (Gamble *et al.*, 1996). Recognizing and quantifying crustal contamination in arc magmas is essential to any successful model of subduction-related volcanism and to understanding the chemical evolution of continental crust over time.

The high field strength elements (HFSE; Nb, Ta, Zr, and Hf), typically depleted in arc magmas relative to REE and large ion lithophile elements (LILE), are thought to most faithfully represent source compositions and processes in subduction zone settings (Perfit *et al.*, 1980; White & Patchett, 1984; Salters & Hart, 1991; Pearce & Peate, 1995). The exact origin of these depletions is controversial, with debate over the roles of the mantle wedge, and melts and fluids from the subducting slab and the sub-arc crust

(Saunders *et al.*, 1980; Peacock *et al.*, 1994; Turner *et al.*, 1997). However, it is generally accepted that this geochemical, arc-type signature is generated by mass flux processes (of fluids and/or melts), from the subducting plate to the mantle wedge (Pearce & Peate, 1995; Münker *et al.*, 2004). The actual composition of the mantle wedge in a subduction-zone setting is dependent on a number of factors including the composition of the mantle prior to subduction, degree of enrichment by fluids and melts from the subducting slab, and by the degree of partial melting it has experienced (McCulloch & Gamble, 1991; Gamble, 1996). In trying to assess the nature of the mantle contribution and impact of contamination on magma compositions, Hf, one of the HFSE, has advantages over U–Th–Pb, and Rb–Sr systems as it is thought to be relatively immobile and thus useful as a potential window to the pre-subduction nature of the mantle wedge, allowing source characterisation (Pearce *et al.*, 2007).

The Hf isotope systematics were first reported by Patchett & Tatsumoto, (1980). However, Hf isotopes have not been used to their full capacity in the study of volcanic systems due to analytical difficulties, including the low ionization efficiency of Hf by thermal ionisation mass spectrometry (TIMS). With the advent of multi-collector, inductively-coupled, plasma mass-spectrometry (MC-ICPMS), a number of studies have identified that Hf isotope compositions in arc lavas diverge from compositions in paired back-arc spreading centres that are thought to sample the same mantle (Vroon *et al.*, 1998; Woodhead *et al.*, 2001). This has been taken to indicate that Hf compositions in these arc rocks may have had significant input from sediments, either from the slab or potentially through shallower contamination and not from the mantle wedge (e.g., White & Patchett, 1984; Woodhead *et al.*, 2001). The Hf isotope system may then be used to trace interaction with crust, especially where samples show correlation with indices of fractionation such as SiO₂ (e.g. the Antilles; Woodhead *et al.*, 2001).

As the southward continental extension of the oceanic Tonga-Kermadec Arc (Figure 3.1), the Taupo Volcanic Zone (TVZ), provides a unique natural laboratory to attempt to characterise source contamination versus the impact of the overlying crust on arc magmas using the Hf isotope system (Gamble *et al.*, 1996). This arc is virtually unbroken over ~3000 km, and is the result of the collision and subduction of the Pacific

plate beneath the Australian Plate (Gamble *et al.*, 1990), with the transition from oceanic to continental settings allowing comparison of geochemical signatures between areas of different overlying crust.

Utilising the Hf isotopic analysis of volumetrically rare basaltic magmas from the TVZ, the mantle wedge sources for the magma feeding volcanism in this area may be constrained and compared to data from the oceanic Tonga-Kermadec arc (e.g. Woodhead *et al.* 2001). This can potentially highlight the impact of changes in overlying crust on magmatic evolution. This information, coupled with Hf analyses of relatively primitive lavas from Ruapehu and Taranaki, volcanoes sited on different crustal terrains, and lower crustal xenoliths from Ruapehu, may allow further distinction between source and crustal contamination processes in TVZ magma petrogenesis. In Pb, Nd, and Hf isotope studies of the oceanic Tonga-Kermadec arc, the mantle source for these subduction zone magmas is thought to have a depleted MORB-type character (Gamble *et al.*, 1996; Pearce *et al.*, 1999; Woodhead *et al.*, 2001; Pearce *et al.*, 2007). In a plot of Th/Yb vs. Ba/La this arc is characterised by high Ba/La ratios and low Th/Yb (Figure 3.2), indicating an input of fluids into the mantle wedge rather than slab melting, e.g. as has been proposed for the Sunda arc (Woodhead *et al.*, 2001). As Hf has been found to be fluid immobile in the Tonga-Kermadec arc (Pearce *et al.*, 2007), fluids from the slab should therefore not affect $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the mantle wedge, and thus should give a clear indication into source composition or highlight the influence of crustal signatures in these arc rocks.

3.2 *Regional Tectonic and Geological Setting*

The Taupo volcanic zone (TVZ) and Mt. Taranaki are active volcanic systems that are the continental extension (Hikurangi) of the Tonga-Kermadec convergent plate margin on the North Island of New Zealand (Ewart *et al.*, 1977) (Figure 3.1). Both oceanic and continental volcanism in this region is generated from the orthogonal to oblique collision and subduction of the Pacific plate beneath the Indo-Australian plate (Cole *et al.*, 1986; Cole, 1990; Wilson *et al.*, 1995). Volcanism along the oceanic and continental sections of this arc are thought to be relatively synchronous (Gamble *et al.*, 1993), with the age of the subducting Pacific plate also relatively constant along the length of the arc. However, the rate of subduction decreases from the far northern portion of the arc (Tonga ~ 100 mm/y) to its southern termination (Kermadec ~ 50 mm/y; Hikurangi ~ 44 mm/y) (de Mets *et al.*, 1990; Graham *et al.*, 1992), as does the angle of subduction, which becomes progressively shallower and more oblique to the south (Jarrard, 1986). This oblique collision, particularly in the south of the arc, has led to accelerated exhumation of the sedimentary and basement terranes of the New Zealand continental crust, with deposition of these material into the Hikurangi and Kermadec trenches, resulting in potential recycling of upper crustal lithologies into the subduction zone system (Gamble, *et al.*, 1996 and references therein).

The New Zealand basement is comprised of a number of tectono-stratigraphic terranes and igneous suites (Coombs *et al.*, 1985; Bradshaw, 1997). The Western and Eastern Provinces make up the bulk of the basement of the North Island, with the Median Tectonic Zone (MTZ) lying between the two. The Western Terrane is comprised of two main terranes dominated by Paleozoic metasedimentary rocks and Devonian, Carboniferous and Early Cretaceous intrusives (Muir *et al.*, 1994; Waight *et al.*, 1997). In the North Island, the Eastern Province includes Palaeozoic to Mesozoic volcanogenic and sedimentary units including the Torlesse and Waipapa Terranes, which are exposed in the axial ranges to the east of the TVZ and assumed to be present beneath Ruapehu and the TVZ. This Ruapehu and Taranaki volcanoes are sited on contrasting sides of this terrane boundary, with the Mesozoic Torlesse and Waipapa sub-terrane underlying Ruapehu

and the TVZ and granitic to gabbroic basement rocks of the MTZ and potentially the Eastern Province underlying Taranaki (Kimborough, 1993; Mortimer *et al.*, 1997). This variation in crustal composition is reflected in entrained xenoliths common in Taranaki and Ruapehu lavas, as well as TVZ basalts. Xenoliths entrained in Taranaki lavas are typically igneous plagioclase–hornblende–clinopyroxene assemblages (Price *et al.*, 1999), whereas xenoliths found in Ruapehu lavas and TVZ basalts are generally meta-sediments, fragments of older rhyolitic eruptives, or two-pyroxene granulites (Gamble *et al.*, 1993; Price *et al.*, 1999). As well as lithological variation between these terranes, there are also differences in the thickness of the crust from east to west. Active rifting and extension has led to lithospheric thinning beneath the Taupo volcanic zone, with the crust under this volcanic centre thought to be intensely faulted and relatively thin (~15 km), with a high heat flow (~700 mWm⁻²). However recent seismic data reported by Harrison and White (2006), identifies a quartzo-feldspathic crust (>16km), underlain by an area of heavily intruded or underplated lower crust with at least 1 % partial melt present from 16 to 30 km depth beneath the TVZ. The Moho is marked by a strong seismic reflector at 30 km depth. This has provided conditions for frequent, voluminous evolved volcanism (Stern, 1986; Cole *et al.*, 1986; Stern, 1987; Cole, 1990; Bibby *et al.*, 1995; Wilson *et al.*, 1995). In contrast the crust underlying the volcanoes of the Taranaki province is thicker (~25 km) and has a normal heat flow (Price *et al.*, 1999).

As the mantle wedge across the arc is thought to be chemically similar, it has been proposed that geochemical variation between Taranaki and the andesitic centres of the Taupo volcanic zone (e.g. Ruapehu), may be a function of crustal architecture, with additional complexity due to variable slab fluid flux and disparity in partial melting, (Graham & Hackett, 1987; Price *et al.*, 1999; Price *et al.*, 2005).

Despite these differences between volcanic centres across the arc, there are broad patterns in whole rock geochemistry between Ruapehu and Taranaki (Price *et al.*, 1999), including increasing K₂O and ⁸⁷Sr/⁸⁶Sr with time. This potentially reflects increased crustal involvement during the evolution of these large volcanic centres (Graham & Hackett, 1987; Stewart *et al.*, 1996; Price *et al.* 2005).

Along arc geochemical variation is also thought to arise from source and process variation moving north from an oceanic setting (Tonga-Kermadec) to a southern continental setting (Hikurangi). Eruptive products along the oceanic arc are dominantly basaltic with some rhyolitic volcanism, while rhyolite dominates the volcanics of New Zealand (>90%) with much reduced andesitic activity and rare basalts ($\approx 1\%$) (Cole, 1986).

3.3 Hf isotope analysis

The samples analysed for Hf isotopes in this study consist of volumetrically rare basaltic magmas from the Taupo Volcanic Zone, which comprise less than 1% of the eruptive deposits in this area, which are dominated by voluminous rhyolitic magmas (Gamble *et al.*, 1993). These basalts are typically aphyric basaltic rocks with small amounts of olivine microcrysts, erupted from monogenetic scoria cones and vents north of Lake Taupo and Mount Ruapehu with samples taken from a <100 km section along the amalgamated volcanic front and back-arc (Cole *et al.*, 1990; Gamble *et al.*, 1993). Samples analysed here were previously characterised for major, trace and REE elements, as well as Pb, Sr, and Nd by Gamble *et al.* (1993, 1996). The geochemical signatures of these continental arc basalts were found to have no time-related correlations, and overlapped with their oceanic counterparts in the south Kermadec arc, suggesting a relatively minimal role for crustal contamination in their formation (Gamble *et al.*, 1996).

A sub-suite of samples characterised by Valente, (1995), Schnieder, (1995), Price *et al.*, (1997, 1999), Waight & Price (1999), and Waight (*unpublished data*), including selected porphyritic basaltic to basaltic-andesite lavas from Ruapehu and Taranaki strato-volcanoes as well as crustal xenoliths entrained in Ruapehu lavas were also analysed. A data set with available geochemical data for all samples used is included in Appendix A. Also included in Appendix A are data for comparison including data from Tonga-Kermadec arc and the Sunda arc (Woodhead *et al.*, 2001; Pearce *et al.* 2007 and references therein).

Hafnium isotope analyses were performed at the Danish Lithosphere Centre, Copenhagen and measured using an Axiom multi collector inductively coupled plasma mass spectrometer (MC-ICPMS).

3.3.1 Sample Preparation

Homogeneous whole rock sample powders were digested using a flux fusion method (Bizzaro *et al.*, 2003; Ulfbeck *et al.*, 2003). The samples were prepared in a HEPA filtered laminar flow hood, and all acids used during the procedure were distilled. The flux fusion method required the use of 0.6ml graphite crucibles. The crucibles were pre-ignited for 1 – 2 minutes at 1100°C before use to prevent the sample sticking once molten. After pre-ignition, 100mg of sample was measured into the crucible, sandwiched between 300mg of an ultra-pure LiBO₂ (lithium metaborate) flux. The crucibles were then placed in the furnace at 1100°C for ~5 minutes until the sample and flux was completely molten and removed quickly and poured into 15ml of 2M HNO₃ in a 23ml Savillex beaker. The samples were then placed on a shaker and agitated for up to ten minutes until the sample completely dissolved. Standard sample JB-2, and blank measurements of the flux were also subjected to the same procedure. 100mg of a (~) 40ppb ¹⁸⁰Hf spike was added to each blank analysis at the acid solution stage to ensure acid - spike - sample homogeneity.

3.3.2 Chemistry

Two stages of column chemistry were performed to separate Hf, with detailed descriptions of chemical protocol outlined by Bizzaro *et al.* (2003) and Ulfbeck *et al.* (2003). The first stage was performed on large glass columns, which are stored in concentrated (14M) HNO₃ between uses. Anion exchange resin (AG 50W - X8, 100 - 200 mesh) was carefully loaded onto these columns to ensure no bubbles formed. The resin was then cleaned and pre-treated before loading of the sample (see Table 3.1). The sample was loaded onto the column through filter paper to ensure that no residual graphite or re-precipitated flux was also loaded onto the resin, and the elution sequence is documented in Table 3.2. The HFSE+REE cut was collected into 23ml beakers, and

evaporated ready for the second stage of chemistry. The beakers used had been cleaned for at least 1hr with hot 14M HNO₃, and rinsed thoroughly with Milli-Q deionised water.

A second sequence of chemistry using mini columns, was carried out to separate Hf from the HFSE and REE. These mini-columns had been leached in 7M HCl with a small amount of HF. Approximately 0.3ml of TEVA spec resin was loaded onto each column and treated following the procedure outlined in Table 3.1.

The dried HFSE+REE cut was re-dissolved in 1ml 10.5M HNO₃, and samples were loaded onto mini-columns using disposable pipettes to minimise disturbance of the resin bed. The REE were then collected using the sequence outlined in Table 3.2 into 7ml Savillex beakers and retained in case of errors with chemistry. The Hf was subsequently collected (see Table 3.2) into the 23ml beakers, which were cleaned for 1hr with hot 14M HNO₃ and rinsed thoroughly with Milli-Q deionised water. The samples were evaporated and the Hf mini column step was then repeated on the Hf sample to ensure that possible interferences from REE oxides such as GdO and DyO during data acquisition were reduced to a minimum. The Hf sample was then evaporated and ready for analysis.

3.3.3 Analyses by MC-ICPMS

Samples were dissolved in 1ml of 0.2% ultra-pure HNO₃ with a drop of HF for >1 hour prior to analysis to ensure complete dissolution of the sample. Samples were introduced into the mass spectrometer via an Aridus desolvating nebuliser using Argon as the sweep gas. After each measurement, the nebuliser tip was carefully washed with Milli-Q water, and the system washed out with 2% HNO₃ with trace HF to ensure removal of Hf from the system before introduction of the following sample. Measurements were made in static mode with the collector array described in Table 3.3, allowing measurement of five Hf isotopes and also monitoring of Yb, Lu, Ta and W for potential isobaric interferences (see Table 3.3). These interferences were corrected for during data acquisition using parameters outlined in Ulfbeck *et al.* (2003). Analyses were made over 2 blocks of 100 measurements, and sample measurements were interspersed with measurement of a Hf standard solution with procedural Hf blanks of ~ 50 pg.

3.4 Hf isotope results

Results of $^{176}\text{Hf}/^{177}\text{Hf}$ isotope analyses are reported in Table 3.4 and are represented graphically in Figures 3.3 to 3.5. $^{176}\text{Hf}/^{177}\text{Hf}$ ratios for the TVZ basalts range from 0.282872 to 0.283025 with a similar to slightly higher values obtained for the Taranaki samples ranging from 0.282920 to 0.283070 (Figure 3.3a). The Ruapehu lava samples have generally higher $^{176}\text{Hf}/^{177}\text{Hf}$ isotope compositions ranging from 0.283003 to 0.283112, with xenoliths hosted in Ruapehu lavas yielding similar to much lower ratios from 0.283034 to 0.282680. The sedimentary Torlesse mudstones and argillites had the lowest $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282669 to 0.282629 with a sample of Waipapa sandstone yielding a value in this range of 0.282666, and typical TVZ rhyolites yielding higher values of 0.282902 and 0.282921 (Figure 3.3a).

In a plot of $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{176}\text{Hf}/^{177}\text{Hf}$ (Figure 3.3b), TVZ, Taranaki and Ruapehu lavas overlap considerably, particularly for $^{143}\text{Nd}/^{144}\text{Nd}$ (from Gamble *et al.*, 1993; Gamble *et al.*, 1996; Price *et al.* 1999; Waight & Price 2001; Waight, *unpub. data*). However there are apparent differences in $^{176}\text{Hf}/^{177}\text{Hf}$ compositions relative to $^{143}\text{Nd}/^{144}\text{Nd}$ between samples, with the TVZ samples possessing lower ratios than those from Taranaki and Ruapehu, with the latter having the highest Hf isotope compositions obtained in this study (e.g. R04-04; 0.283112: Table 3.4). All igneous samples are significantly displaced from the Pacific MORB data field. The Ruapehu hosted xenoliths and rhyolitic crustal samples plot in similar field as the igneous samples with one xenolith plotting lower, with a similar isotopic composition as the sedimentary crustal lithologies (Figure 3.3b). Sr isotopes also have a limited range in Taranaki, Ruapehu and TVZ samples analysed (Gamble *et al.*, 1996), with Ruapehu xenoliths the only samples possessing significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Figure 3.4c).

In a plot of Th/Yb vs $^{176}\text{Hf}/^{177}\text{Hf}$ (Figure 3.4) the Ruapehu samples R04-04 and T6-15 (Table 3.1), again plot with data from the Kermadec arc, with all other igneous samples analysed (Ruapehu, Taranaki and TVZ basalts), showing relatively lower Hf isotope ratios and somewhat higher Th/Yb ratios.

Plotting SiO_2 vs. $^{176}\text{Hf}/^{177}\text{Hf}$ (Figure 3.5), there is again significant overlap between the igneous samples analysed. However, the group of samples with the lowest

SiO₂ contents, the TVZ basalts also possess the lowest ¹⁷⁶Hf/¹⁷⁷Hf isotope ratios (Figure 3.5a), forming a negative correlation (Figure 3.5b). There is no clear correlation evident in the other analysed groups of igneous rocks (e.g. Taranaki and Ruapehu), or data from the Tonga and Kermadec arcs, which have relatively flat arrays with no apparent relationship between SiO₂ and ¹⁷⁶Hf/¹⁷⁷Hf (Figure 3.4a).

3.5 Discussion

3.5.1 Nature of the Mantle source

In a previous study, the oceanic Tonga-Kermadec subduction system was classified as a fluid-dominated, high-Ba/La, arc (Ba/La ratios of 27 to 113; Figure 3.2; Woodhead *et al.*, 2001). High Ba/La ratios are typically coupled with low Th/Yb ratios, extreme ²³⁸U/²³⁰Th, high boron contents and δ¹¹B isotope ratios (e.g. Mariana), and thus are linked to an addition of fluids to the mantle wedge from the subducting slab rather than addition of melts (McCulloch & Gamble, 1991; Turner *et al.*, 1997; Peacock *et al.*, 1999; Woodhead *et al.*, 2001). The TVZ basalts have overlapping but generally lower Ba/La ratios (12 to 34; for references see Figures 3.2 and 3.3b) than the rocks from the oceanic Tonga-Kermadec arc (27-113; Figures 3.2 and 3.3b), and than ratios in the Ruapehu samples (28 to 57; Figures 3.2 and 3.3b) and Taranaki samples (31 to 61; Figures 3.2 and 3.3b). There is similar overlap with the oceanic arc in the Th/Yb ratios for the TVZ basalts (≤ 1; for references see Figures 3.2 and 3.3a) and Ruapehu samples (Th/Yb of 1 to 2), with Taranaki samples having similar to slightly higher ratios (1 to 4; Figures 3.2 and 3.3a). However, these variations are relatively slight when compared to a sediment-dominated high-Th/Yb arc such as the Sunda arc (Figure 3.3a). The main geochemical distinction between the oceanic rocks of the Tonga-Kermadec arc and their continental counterparts is markedly lower ¹⁷⁶Hf/¹⁷⁷Hf ratios, indicating a relative increase in sedimentary input, via fluids or melts into these magmas from the subducting slab or from the overlying crust. This contrasts with results obtained using other isotope systems (e.g. Sr and Pb) where there was significant overlap between oceanic south Kermadec and continental TVZ radiogenic isotopes (Gamble *et al.*, 1996).

However, unlike other isotopic systems such as Sr, which is thought to be fluid-mobile, experimental and empirical studies of the Hf isotope system indicate that this HFSE is effectively immobile during slab dehydration (Tatsumi *et al.*, 1986; McCulloch & Gamble, 1991; You *et al.*, 1996; Pearce & Peate, 1995; Münker *et al.*, 2004; Kessel *et al.*, 2005; Pearce *et al.*, 2007). Despite studies that have questioned this premise (e.g. Woodhead *et al.*, 2001), Hf isotopes, in tandem with Nd, remain a powerful tool for identifying source (mantle wedge) characteristics (e.g. Pearce *et al.*, 1999; Münker *et al.*, 2004; Pearce *et al.*, 2007). As Hf has been proposed to be immobile in the Tonga-Kermadec system (Pearce *et al.*, 2007), in a fluid-dominated arc with generally low Th/Yb ratios, the subducting oceanic plate and sedimentary cover should thus have little to no impact on the source isotope signature. This is supported by the displacement of the most primitive samples analysed in this study, as well as samples from the Tonga-Kermadec arc, away from the Pacific MORB reference field (Pearce *et al.*, 1999). Samples with the highest Hf and Nd isotope ratios appear to have a closer affinity with depleted MORB compositions, consistent with previous Sr, Nd and Pb isotope studies of this region (e.g. Gamble *et al.* 1996). However unlike Nd, there is significant variation in Hf isotopes away from MORB compositions with the least evolved samples analysed, the TVZ basalts, possessing the lowest, i.e. most ‘crustal ratios’ with little to no overlap between continental samples and their oceanic counterparts (Figure 3.4). Therefore, there is a difference in sediment input between the oceanic and continental arcs either at source or in the upper crust traversed. On a plot of $^{176}\text{Hf}/^{177}\text{Hf}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ the difference between source or crustal contamination is not evident as the subducted sediment and the sedimentary basement (Torlesse and Waipapa) possess similar compositions. As mentioned previously, this similarity is not unusual given that oblique subduction has lead to rapid uplift, erosion and deposition of the New Zealand continental basement lithologies into the Hikurangi Trench (Gamble *et al.*, 1996). Thus, taken in isolation, the $^{176}\text{Hf}/^{177}\text{Hf}$ isotope data could be interpreted as either source or crustal contamination.

3.5.2 Distinction between source and crustal contamination

When $^{176}\text{Hf}/^{177}\text{Hf}$ is plotted against an index of fractionation, some distinction may be drawn on the origin of the sedimentary input to the geochemical signature of these rocks. In a plot of $^{176}\text{Hf}/^{177}\text{Hf}$ vs. SiO_2 , there is a broad negative correlation evident in the TVZ basalts (Figure 3.5). With increasing SiO_2 , $^{176}\text{Hf}/^{177}\text{Hf}$ isotopes for these samples decline, indicating the operation of a crustal AFC type process. Similar negative correlations are not present in the oceanic Kermadec and Tonga rocks, which possess flat lying linear trends with high Hf isotope ratios even with much higher SiO_2 contents up to 70 wt %. This suggests that while potentially not a significant process for the oceanic arc, late crustal contamination is indeed a significant in the continental portion of the arc. This contrasts with previous studies, which proposed that the bulk of isotopic variation in the TVZ samples, was due to source contamination (e.g. Gamble *et al.*, 1996) with crustal contamination of lesser importance.

Unlike the TVZ basalts, there is no evident correlation between the analysed Ruapehu and Taranaki samples for $^{176}\text{Hf}/^{177}\text{Hf}$ and SiO_2 . The presence of meta-sedimentary xenoliths of restitic origin (Graham *et al.*, 1990) with similar to significantly lower $^{176}\text{Hf}/^{177}\text{Hf}$ ratios in Ruapehu lavas provides strong evidence for an input of sedimentary melts into arc magmas. Detailed geochemical studies have shown that crustal contamination is indeed an important process for Taranaki and in particular Ruapehu where high heat flow, thinning of the silicic crust and melting of an underplated lower-crust allows voluminous rhyolite formation via crustal anatexis and re-mobilisation of older igneous products (Price *et al.*, 2005 and references therein), however, this is not directly evident in their $^{176}\text{Hf}/^{177}\text{Hf}$ isotope ratios.

Thus it is evident that assimilation of crustal material is an important process for these centres and the lack of a clear geochemical contamination signal in $^{176}\text{Hf}/^{177}\text{Hf}$ isotope ratios for Taranaki and Ruapehu could be a function of the limited number of samples analysed. However even a small amount of assimilation of continental Hf, with zircon as a likely carrier, would substantially modify the $^{176}\text{Hf}/^{177}\text{Hf}$ isotope signature of the magma. The complexity of the plumbing systems feeding these volcanoes may be a

factor (Price *et al.* 2005), resulting in variation in the apparent impact or extent of crustal contamination. Geochemical variability over the short term, heterogeneity in crystal populations and entrained volcanic and meta-sedimentary xenoliths indicate a complex plumbing system of numerous magma reservoirs or dyke and sill type feeders for these volcanoes (Price *et al.*, 2005). This type of system has been proposed for other large andesitic volcanoes, e.g. Tatara San Pedro (Dungan *et al.*, 2001) and results in geochemical complexity due to large contact area with the country rock and isolation of magma batches in a network of distinct reservoirs. The action of crystal recycling, accumulation, magma mixing and assimilation may collectively act to obscure typical liquid trends in highly-crystalline porphyritic magmas such as the samples analysed from Ruapehu and Taranaki. Also given the fact that these two centres are large and relatively long-lived, extensive magmatism may result in the removal of fusible components from the surrounding country rock, with side wall crystallisation, potentially insulating separate magma batches from direct contact with this crust and thus, large amounts of crustal assimilation (c.f. Thompson *et al.* 1986; Kerr *et al.* 1999). Conversely, the effects of assimilation of crustal material may appear relatively more extreme in the aphyric TVZ basaltic samples as they probably represent true liquids, sourced from monogenetic cones and vents which are thought to have ascended through the crust as individual batches of hot magma (Gamble *et al.*, 1993) and are thus highly susceptible to assimilation. This is in keeping with work by Huppert and Sparks (1985), Kerr *et al.* (1995), and Peate *et al.* (In Press), which show that hotter, mafic magmas with primitive compositions rising swiftly through the lithosphere can assimilate significant amounts of crust with limited fractionation. These magmas then show a more 'crustal' signature as compared to cooler and more evolved samples, which formed in larger and longer-lived systems.

3.6 Conclusions and Implications

Upper crustal sediments of the North Island (Torlesse and Waipapa) as well as subducted sediments have overlapping compositions and are essentially the same with respect to $^{176}\text{Hf}/^{177}\text{Hf}$, providing a challenge for discerning between source and crustal contamination. Despite representing the least evolved products of the continental

subduction zone system, and thus the most likely to reflect primary melt signatures, Ruapehu, Taranaki and particularly the TVZ basalt samples show evidence for crustal contamination in contrast to samples from the oceanic Tonga-Kermadec arc which have been proposed to have been largely unaffected by source contamination (Woodhead *et al.*, 2001). All New Zealand samples analysed here are displaced from MORB compositions and from Kermadec and Tonga samples for $^{176}\text{Hf}/^{177}\text{Hf}$ isotopes. Samples with the lowest SiO_2 contents have the lowest, i.e. most crustal $^{176}\text{Hf}/^{177}\text{Hf}$ isotope ratios with a negative correlation apparent in the TVZ basalt samples analysed indicating that this is not a source contamination effect. Despite a lack of a similar trend between such an index of fractionation and $^{176}\text{Hf}/^{177}\text{Hf}$ isotopes in the Ruapehu and Taranaki samples, crustal contamination is also a factor for these centres based on the presence of variably metamorphosed crustal xenoliths and geochemical heterogeneity reported in the literature.

This study therefore highlights the inherent danger in using whole rock geochemical systems in isolation to assess processes and evolution of highly crystalline porphyritic samples. Even in systems where crustal contamination is known to be occurring, geochemical signatures in whole rock samples can be indistinct. Whole rock geochemical data should therefore be used in conjunction with careful petrographic and mineral analysis, with only samples of limited crystallinity and complexity likely to give true liquid compositions. Secondly, this study shows that even in basalts that have experienced only a limited extent of differentiation may be influenced strongly by shallow crustal contamination, and that this variation may not be discernable from source contamination using other isotopic systems. Thus, care must be taken when using apparently relatively un-evolved volcanic products to assess source compositions and mechanisms.

Table 3.1 Cleaning sequence for resin after loading onto columns

Column	Step	Resin
Glass Column (AG 50W - X8 resin)	Cleaning Sequence	2 x 20ml 6M HCl
	Pre-Loading	10ml 2M HCl
Hf Mini Column (~ 0.3ml TEVA spec resin)	Cleaning Sequence	~ 1ml 10.5M HCl
		~ 3ml 0.6M HCl
	Pre-Loading	~ 0.5ml 10.5M HCl
		~ 1ml 3M HNO3
Nd Mini Column (~ 0.3ml RE spec resin)		~ 1ml MQ
	Cleaning Sequence	~ 1ml 3M HNO3
		~ 1ml MQ
		~ 1ml 3M HNO3
	Pre-Loading	~ 0.5ml 3M HNO3

Table 3.2 Procedure for elution of matrix, HFSE and REE, and collection of Hf

Column	Step	Acid
Glass Column (AG 50W - X8 resin)	Elute Matrix	~ 25ml 2M HCl
	Elute Ba	~ 30ml 2M HNO3
	Elute HFSE + REE	?20ml 6M HCl
Mini Column (~ 0.3ml TEVA spec resin)	Collect REE	~ 3ml 10.5M HCl
	Collect Hf	~ 3ml 6M HCl

Table 3.3. Faraday Collector Array Used for Hf MC-ICPMS Measurements (*after* Bizzaro *et al.*, 2003; Ulfbeck *et al.*, 2003)

Collector	L4	L3	L2	L1	AX	H1	H2	H3	H4
Mass	173	175	176	177	178	179	180	181	182
Isotope	Yb	Lu	Hf, Lu, Yb	Hf	Hf	Hf	Hf, Ta, W	Ta	W

Table 3.4 Hf Isotope data for all samples analysed by MC-ICPMS

Sample	Type	$^{176}\text{Hf}/^{177}\text{Hf}$	2SE	ϵ_{HF}
TVZ Basalts¹				
TVZ-12	Tatua	0.282999	0.000007	8.0
TVZ-14	Ongaroto	0.282887	0.000003	4.1
TVZ-15	Kakuki	0.283003	0.000003	8.2
TVZ-13	Tatua	0.283025	0.000003	8.9
TVZ-5	Atiamuri	0.282916	0.000002	5.1
TVZ-6	Ben Lomond	0.282960	0.000002	6.6
TVZ-7	Trig 9474	0.282931	0.000009	5.6
TVZ-8	Rotokawau E	0.282919	0.000004	5.2
TVZ-9	Rotokawau W	0.282872	0.000003	3.5
TVZ-17	Harry Johnson	0.282910	0.000002	4.9
Taranaki²				
T90-46	Young ring plain	0.282920	0.000003	5.3
T90-42a	Old ring plain	0.282999	0.000002	8.1
T89-21	Warwicks Castle	0.282974	0.000002	7.2
T89-11	Fanthams	0.282992	0.000002	7.9
T89-24	Staircase	0.283070	0.000002	10.6
Ruapehu³				
R95-20	Whangaehu gorge	0.283003	0.000003	8.2
R04-04	Ruapehu basalt	0.283112	0.000003	12.1
T6-27	Te Herenga Ridge	0.283089	0.000006	11.3
T6-15	Te Herenga Ridge	0.283109	0.000002	12.0
Ruapehu Xen.⁴				
R97-50b		0.282979	0.000002	7.4
R97-75b		0.282912	0.000002	5.0
R97-92x2		0.282922	0.000003	5.4
R97-87x1		0.283034	0.000003	9.4
R97-92x1		0.282910	0.000002	5.0
R97-104x	Meta-sed. xen.	0.282680	0.000002	-3.2
Local Crust⁴				
ZI/03	rhyolite	0.282902	0.000002	4.7
ZI/01	rhyolite	0.282921	0.000002	5.3
P23553	Waipapa sst.	0.282666	0.000002	-3.7
P54703	Torlesse sst./mst.	0.282666	0.000002	-3.7
P55908	Torlesse sst./mst.	0.282635	0.000002	-4.8
P55962	Torlesse sst./mst.	0.282669	0.000002	-3.6
P55907	Torlesse sst./mst.	0.282629	0.000002	-5.0

¹ Described by Gamble et al., 1993, 1996² Described by Price et al., 1999³ Described by Valente, 1995, and Waight et al., 1999⁴ Unpublished Waight

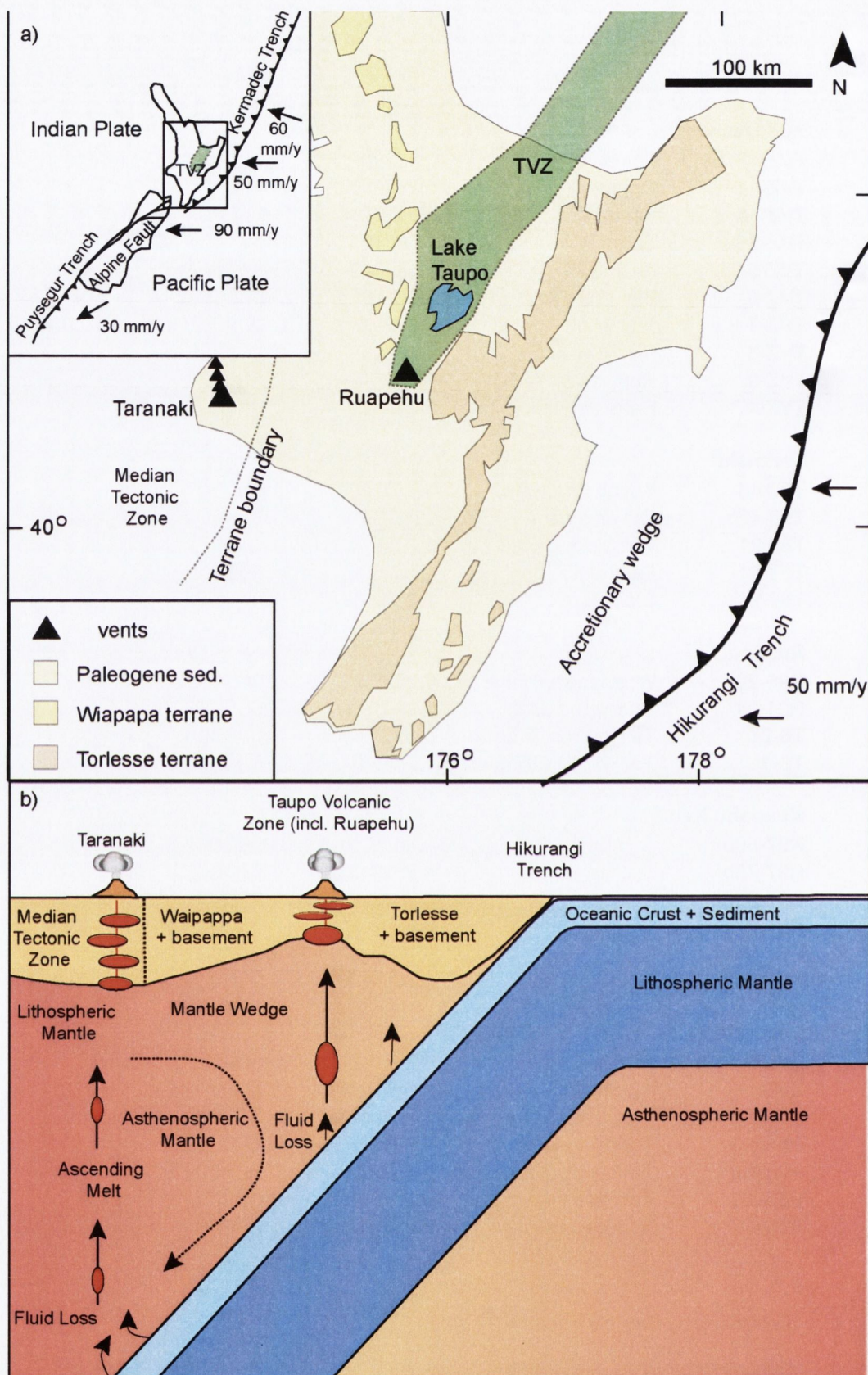


Figure 3.1 a) Sketch map North Island (after Waight et al., 1999), New Zealand, showing location of the Taupo volcanic zone, Ruapehu and Taranaki volcanoes relative to outcrop of Torlesse and Waipapa terrane basement and the Hikurangi Trench. Inset showing location relative to the south Kermadec arc. b) Schematic cross-section through the New Zealand subduction zone system.

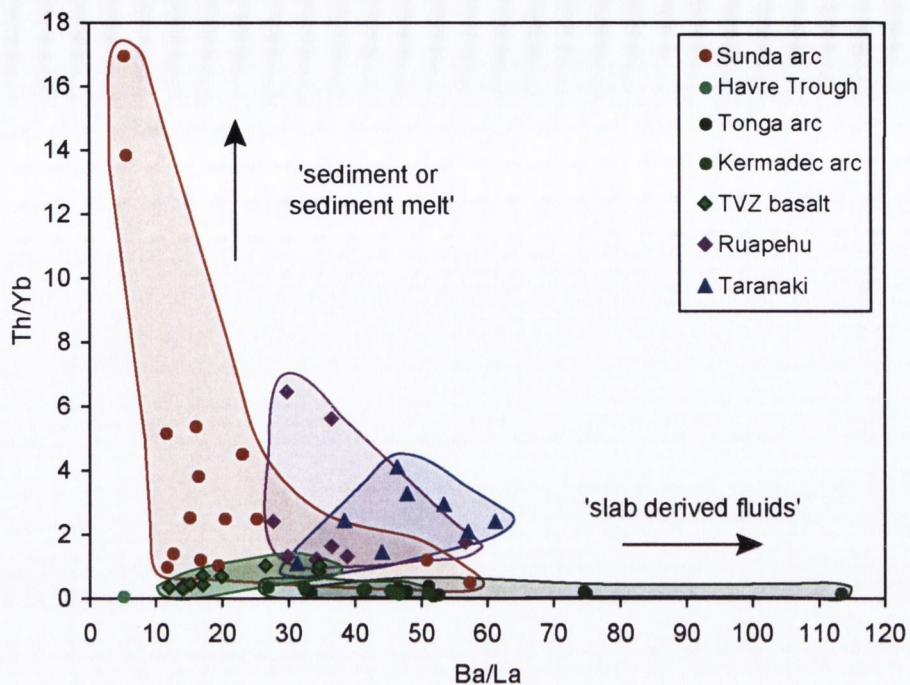


Figure 3.2 Ba/La vs. Th/Yb samples analysed in this study plotted relative to data for the Havre Trough and the Kermadec, Tonga, and Sunda arcs (from Woodhead *et al.*, 2001). Ba/La vs. Th/Yb is used to classify different oceanic arc 'types'; fluid dominated (Ba/La arcs) and sediment dominated (Th/Yb arcs). The Tonga-Kermadec arc is a high Ba/La arc with generally low Th/Yb ratios. In the continental extension of this arc, Ruapehu, Taranaki, and to a lesser extent, TVZ samples plot away from the x-axis with slightly higher Th/Yb ratios indicating an increased input from sediments and or fractional crystallisation (e.g. Woodhead *et al.*, 2001).

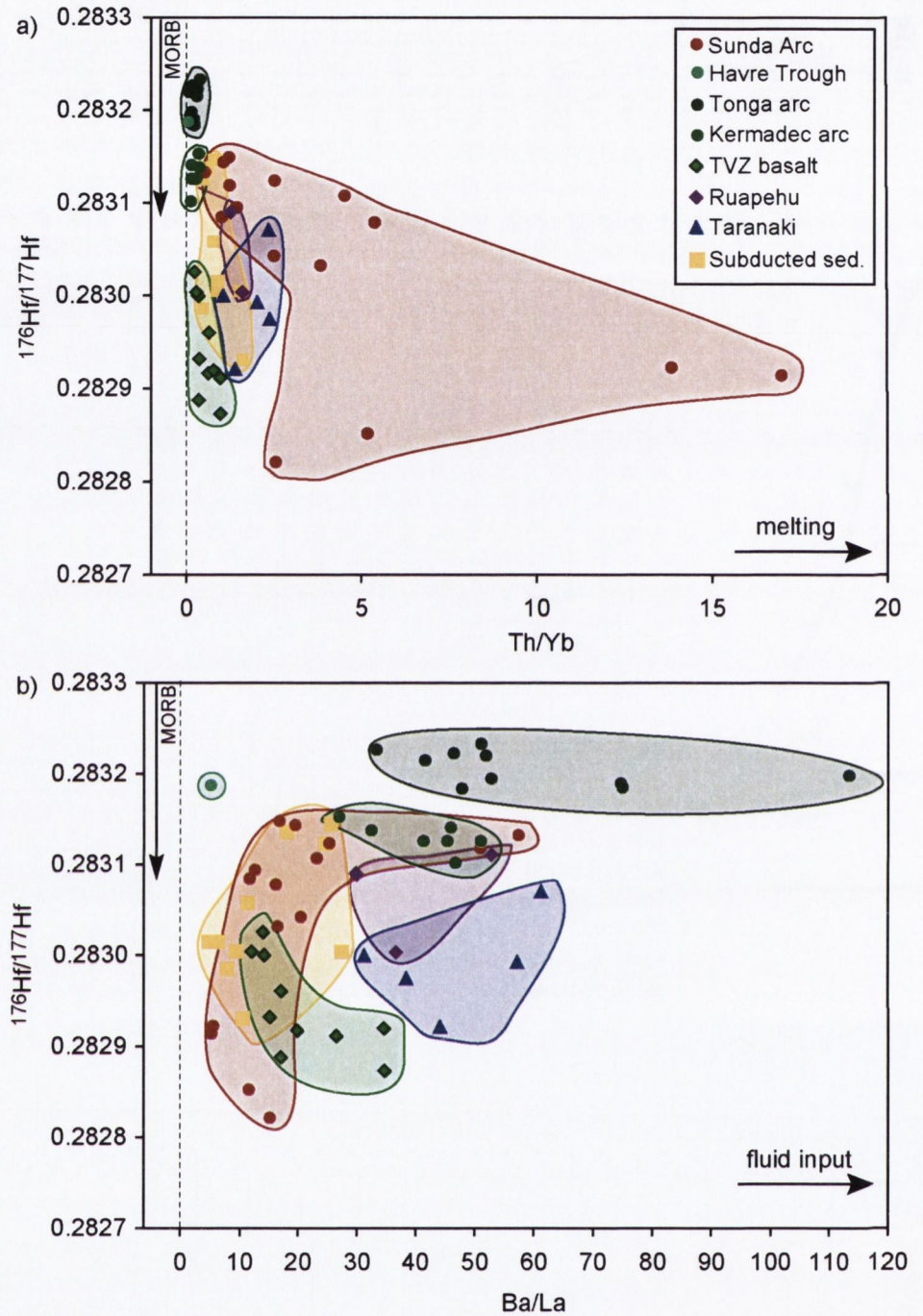


Figure 3.3 a) Th/Yb and b) Ba/La vs. $^{176}\text{Hf}/^{177}\text{Hf}$ for Ruapehu, Taranaki and TVZ samples plotted relative to data for Pacific Ocean sediments, the Tonga, Kermadec and Sunda arcs and the Havre trough (after Woodhead *et al.*, 2001). The vertical black arrow denotes the range of typical MORB compositions reported by Nowell *et al.*, 1998).

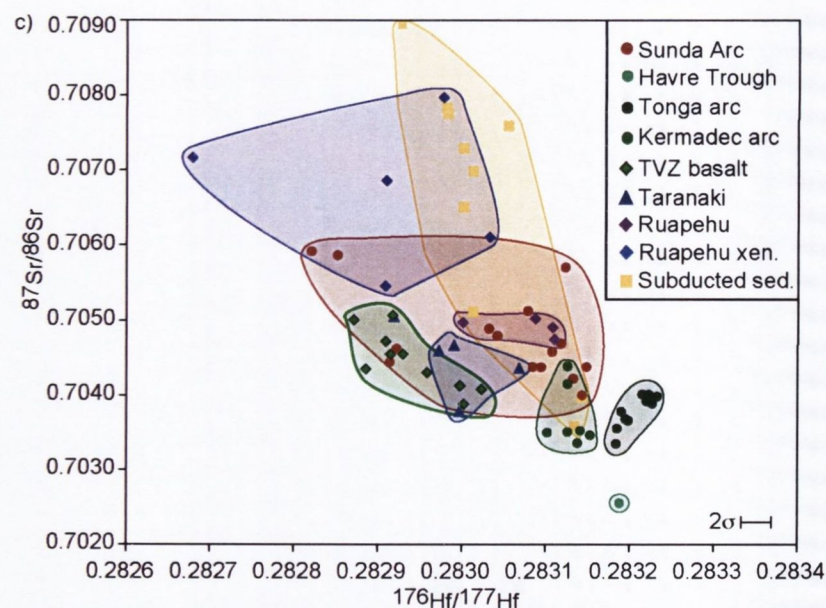
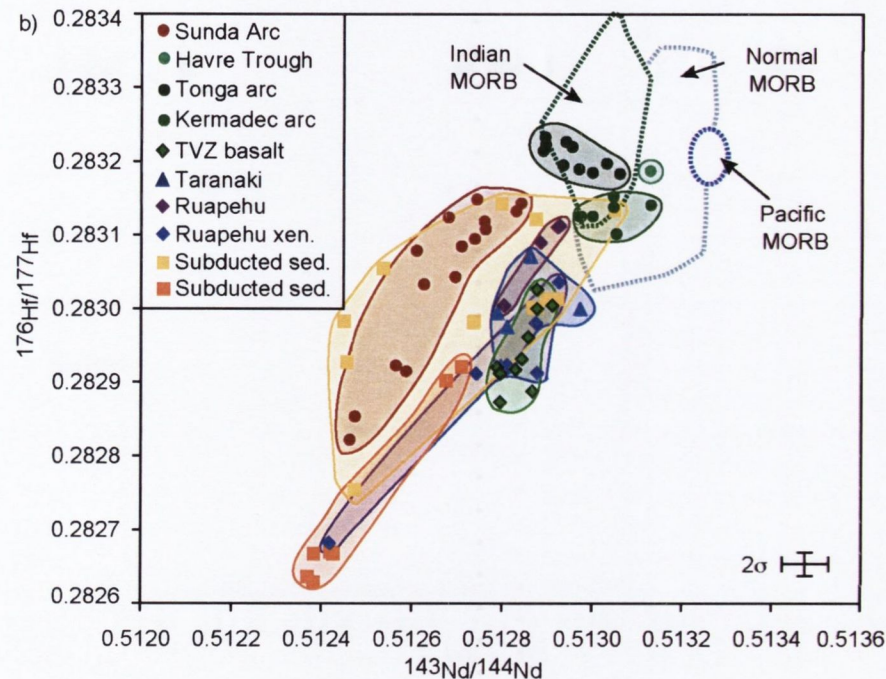
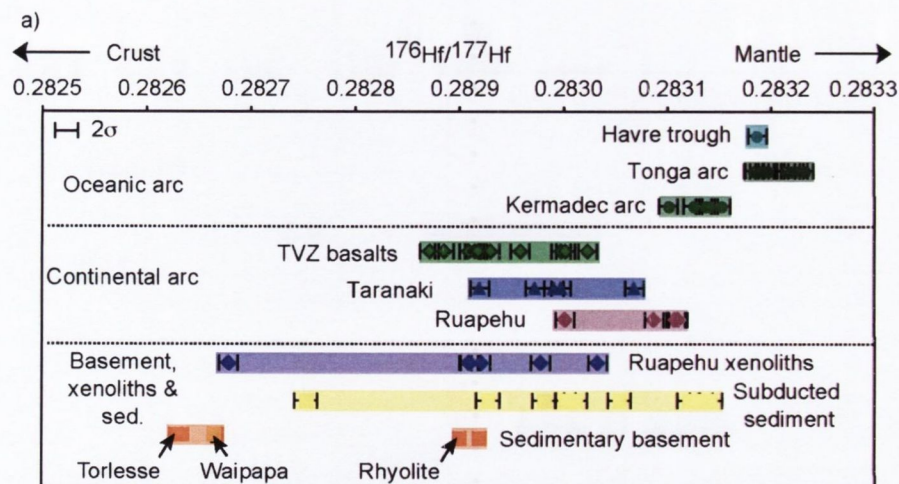


Figure 3.4 a) $^{176}\text{Hf}/^{177}\text{Hf}$ variation diagram illustrating ranges in compositions for samples analysed in this study, relative to data for the oceanic Tonga and Kermadec arc, Havre trough, and subducted sediments for the region (Pearce et al., 1999, 2007; Woodhead et al., 2001). b) $^{176}\text{Hf}/^{177}\text{Hf}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ plot for crust (Torlesse, Waipapa and Rhyolites), Ruapehu, Taranaki and TVZ samples relative to data for the Havre trough, Tonga, Kermadec, and Sunda arcs, as well as subducted sediment (references as in a). Also included are data fields for Pacific MORB (Pearce et al., 1999; Woodhead et al., 2001), Indian MORB (Salters, 1996; Nowell et al., 1998; Chauvel & Blichert-Toft, 2001), Normal MORB (Ito et al., 1987; Salters & Hart, 1991; Chauvel & Blichert-Toft 2001). Tonga-Kermadec arc data and the sample from the Havre Trough plot within MORB reference fields but are displaced from Pacific MORB indicating limited or absent input from the subducting oceanic slab (Woodhead et al., 2001). Data indicate a strong sedimentary influence on Hf and Nd isotope ratios for magmas from the continental New Zealand arc, particularly in the TVZ samples. c) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{176}\text{Hf}/^{177}\text{Hf}$ plot showing overlap in Sr isotope range for TVZ, Taranaki and Ruapehu samples (references as in a) which are slightly higher than Tonga, Kermadec, and Havre Trough samples.

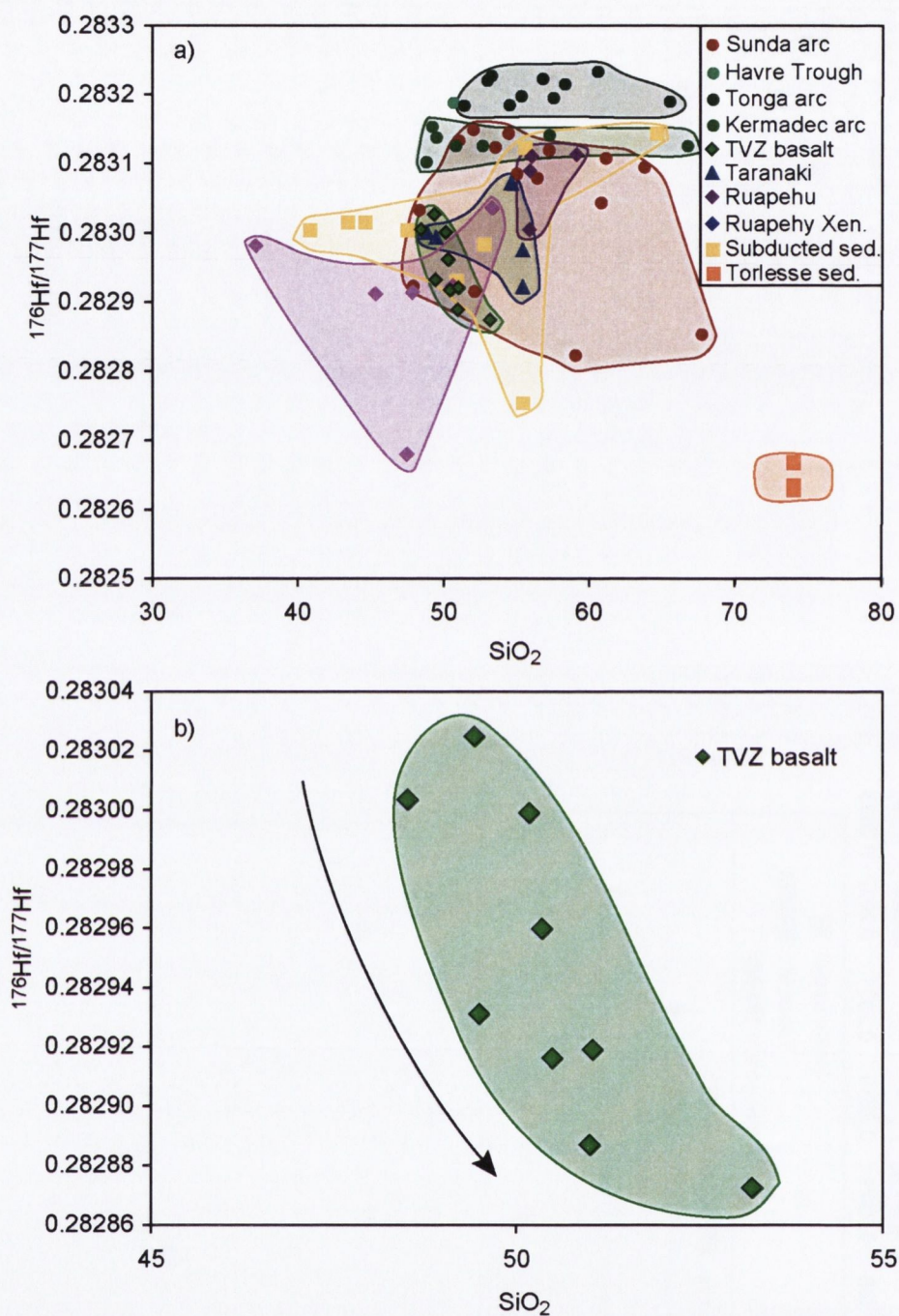


Figure 3.5 a) SiO_2 vs. $^{176}\text{Hf}/^{177}\text{Hf}$ diagram for TVZ, Taranaki, and Ruapehu samples plotted relative to Torlesse sediments and data from the literature for reference (Tonga, Kermadec, and Sunda arcs, the Havre trough, and Pacific ocean sediments from Pearce *et al.*, 1999; Woodhead *et al.*, 2001; Pearce *et al.*, 2007). b) SiO_2 vs. $^{176}\text{Hf}/^{177}\text{Hf}$ diagram for TVZ basalts showing distinct correlation between increasing SiO_2 and decreasing Hf isotope ratio.

CHAPTER 4 – MERAPI VOLCANO

4.1 Introduction

In 1967, Dickinson and Hatherton first correlated K_2O content of volcanic rocks from Kermadec volcanoes to depth to the underlying Wadati–Benioff zone and effectively identified a link between subduction and the generation of andesite. Since this seminal work, oceanic arcs have been a testing ground for understanding subduction processes and crustal components beneath continental and oceanic crust. Understanding the processes involved in magma petrogenesis at arcs is integral for assessing sediment recycling and mass flux of material (e.g. Rea & Ruff, 1996) and to understanding the evolution of continental crust (Annen *et al.*, 2006).

Island arc magmas are typically thought to exhibit geochemical characteristics that are generated by variable source components in combination with differentiation processes (Figure 4.1). The mantle wedge above the subducting slab is generally thought to be the most volumetrically significant source component in arc magma petrogenesis (e.g. Arculus & Powell, 1986) and on the basis of geochemical studies, is generally inferred to have a mid-ocean ridge type (MORB) (Perfit *et al.*, 1980), or depleted MORB (Woodhead *et al.*, 1993; Elliot *et al.*, 1997) chemistry. The subducting oceanic plate and its sediment cover are further two components (Ellam & Hawksworth 1988; Kay, 1980; Gamble *et al.*, 1996, 1997; Price *et al.*, 1999). These three sources and their varying compositions, are thought to be the prime constituents involved in the production of primary arc magmas (e.g. Davies & Stevenson, 1992; Tatsumi & Eggins, 1995). However, given that primary magmas are only rarely observed in arc settings (Annen *et al.*, 2006), it is evident that other factors are at work, and that modification of these melts during their ascent to the surface may be significant in arc magma petrogenesis as well. The effect of interaction between melt and the overlying lithosphere is commonly only considered for studies of evolved continental arc magmas. However, there is mounting evidence that indicates shallow crustal interaction may also

be significant for island arc settings (e.g. Tamura *et al.*, 2002; Smith *et al.*, 2003; Smith *et al.*, 2006).

Continental and oceanic subduction zones produce volcanic rocks of diverse compositions, and lavas from individual volcanic centres may have a silica range of more than 20 wt%. This compositional spectrum is the product of varied magmatic processes, including crystallization (Bowen, 1928; Gill, 1981; Rogers & Hawkesworth, 1989; Grove *et al.*, 2002, 2003), magma mixing (Hildreth & Moorbath, 1988) and crustal assimilation (Grove *et al.*, 1988; Davidson & Tepley, 1997) in combination with source processes. Numerous studies of arc lavas have attempted to highlight the importance of differentiation processes and the difficulties involved with discerning source characteristics due to the action of fractional crystallisation, magma mixing, and addition of variable amounts of crustal material during petrogenesis (e.g., Davidson *et al.*, 1990). Contamination by the lithosphere is particularly important in subduction zones where there is a high heat flux, facilitating bulk assimilation of crustal material, assimilation of partial crustal melts and or selective exchange of specific elements (e.g. De Paolo, 1981; Leeman, 1983; Huppert & Sparks, 1985; Wilson, 1997).

Our understanding of the nature, scale and location of physical processes operating in the crustal magmatic system of subduction zone volcanoes remains in its formative stages. Identification of a crustal component in magma genesis through whole rock radiogenic isotopes often yields limited information about where and when this contamination has taken place; at source (ie. from the subducting slab), or in the crust during ascent. Identifying the nature of the assimilated crust is integral for assessing the impact of contamination. However, in many cases this is difficult to constrain, particularly where basement exposure is poor or where there is a lack of entrained crustal xenoliths within the magma. Where these pre-requisites are known, one can test magma-crust interaction by analysing components incorporated in these arc magmas to gain further information about where in the system the addition(s) may take place.

Analysing igneous and meta-sedimentary inclusions incorporated in lavas can yield sub-surface information, as disaggregated xenolithic material is potentially a source of heterogeneity at a sub-crystal and crystal scale and these fragments may preserve unique records of crystallisation and crustal interaction. Analysing crustal xenoliths yields a direct measure of the nature of the host rock to magma reservoirs and preserves a snapshot of magma-crust interaction.

Crystalline components within volcanic rocks also potentially preserve individual records of shallow level process (e.g. Davidson & Tepley, 1997; Zellmer *et al.*, 1999) (Figure 4.2). Using this premise, modern *in situ* analytical techniques can be utilized to unravel the differentiation history of volcanoes. This not only accounts for the effects of differentiation and constrains the nature of the original source, but also gives a means of quantifying the mechanisms and fluxes of late crustal contamination. In addition, coarsely crystalline inclusions in arc magmas, often regarded as crystallisation residues, may reflect differentiation processes that have operated on the magmas of these arcs (e.g. Beard, 1986; Fichaut *et al.*, 1989; Beard & Borgia, 1989; Heliker, 1995). Analysing their petrography, mineralogy, and geochemistry can yield information on what processes are occurring, and potentially where they occur, in the sub-volcanic plumbing system. A more comprehensive identification of magmatic structure is possible by combining petrochemical information with geophysical data of the system.

Surface expressions of volcanism, including eruptive products and gas effusions, can be utilised to establish late stage process including the presence and extent of shallow magma-crust interaction. He and C isotope analysis of gas samples of volatiles in high temperature fumarole gases can be used to evaluate the extent of magma crust interaction. However, shallow crustal assimilation is rarely considered significant for modifying He and C isotope signatures in volcanic gases at oceanic arcs (eg. Sano & Marty 1995; Hilton *et al.* 2002). The $\delta^{13}\text{C}$ ratio of magmatic CO_2 is generally considered to be in the range of -6 to -8 (Javoy *et al.* 1986; Marti & Tolstikhin 1998). Open and closed system degassing can alter this ratio to more negative values, however markedly light signatures in fumarole gases for C (e.g. $\delta^{13}\text{C} \geq -4$) suggests that CO_2 may be

derived from a non-magmatic, high- $\delta^{13}\text{C}$ source (e.g. limestone in the overriding crust with $\delta^{13}\text{C} \sim 0$). However, this system used in isolation may not give a distinction as to whether contamination is at source or in the crust. Source contamination is believed to have little or no significant effect on mantle He signatures (average mantle $^3\text{He}/^4\text{He } R_A = 8.5$) at oceanic arcs (Hilton *et al.*, 2002). Subsequently, anomalously low $^3\text{He}/^4\text{He}$ in fumarole gases suggests a late input of crustal He (continental crust $^3\text{He}/^4\text{He } R_A = 0.1$ to 0.001). Therefore these isotopes used in conjunction can identify the nature of crustal contamination in the subduction system.

By combining traditional and new analytical techniques, it is therefore possible to comprehensively identify and assess magmatic processes potentially masked in conventional whole rock geochemistry. Merapi volcano, in Java, Indonesia is an excellent natural laboratory to investigate magma-crust interaction and magmatic process in the crust for numerous reasons. The non-igneous basement to Merapi is dominantly comprised of carbonate (Van Bemmelen, 1949), which, if assimilated, should have significant impacts on magmatic and volcanic activity (e.g. Goff *et al.*, 2001). In addition, Merapi has a high eruptive activity and significant fumarole flux, and its lavas are rich in zoned plagioclase, metasedimentary xenoliths (*c.f.* Camus *et al.*, 2000), enclaves and coarsely crystalline igneous inclusions for study.

Recent studies of the central Java crust has shed light on the large scale structure (Smith & Sandwell, 1997; Smyth *et al.*, 2005; Waltham *et al.*, 2006; Koulakov *et al.*, 2007; Wagner *et al.*, 2007; Chadwick *et al.*, *submitted*) and by integrating this information into results obtained from petrochemical work, we can effectively describe the processes that are occurring beneath Merapi volcano and identify the approximate location and scale of the system beneath the volcano. A more complete understanding of the magmatic system feeding Merapi volcanism has obvious social implications for hazard prediction for the local population living in the shadow of this volcano, as well as scientific interest in how we consider Merapi and similar persistently active subduction zone systems elsewhere.

4.2 Geological Setting

The Merapi complex is situated on the active volcanic front of the Sunda arc (Figure 4.3), which extends >3000 km from the Andaman Islands north of Sumatra to the centre of the island of Flores and forms 76% of Indonesia's Holocene volcanoes (Simkin & Siebert, 1994). This extensive arc is the result of the northward orthogonal subduction (6.7-7cm/yr; Tregoning *et al.*, 1994) of the Indo-Australian Plate, thought to form a continuous slab, beneath the Eurasian plate (Hamilton, 1979; Jarrard, 1986). The regional subduction history for the Sunda arc dates back to the Permian (Katili, 1975).

Merapi forms part of a cross Java chain of volcanoes including Ungaran, Telemoyo, and Merbabu (Camus *et al.*, 2000). The active arc in East to Central Java is bound to the south by the Southern Mountains Zone, remnants of the earlier Eocene to Miocene volcanic arc, and to the north by the Kendeng and Rembang Zones (Figure 4.4, Smyth *et al.*, 2005). The Kendeng Zone is the main Cenozoic depocentre for the region, (Smyth *et al.*, 2005), and is thought to contain between 8 km (de Genevraye & Samuel, 1972) and 11 km (Untung & Sato, 1978) of sediment. This sediment covers a basement of uncertain composition, generally considered as immature, arc crust, which extends approximately 25 km below the surface (Curry *et al.*, 1977; Hamilton, 1979; Jarrard, 1986, Van Bemmelen, 1949). The upper crust in this area to the south of Merapi is comprised of a sequence of Cenozoic marine limestones and marls and volcanoclastic sediments (Figure 4.5) with units up to 2 km thick (van Bemmelen, 1949) that crop out proximal to Merapi and can be found as abundant, thermally metamorphosed sedimentary xenoliths (c.f. Camus *et al.*, 2000).

Merapi volcano, in central Java, is a large Quaternary strato-volcano, formed in the Late Pleistocene (Purbawinata, 1996) with frequent eruptions occurring in historic and prehistoric times (Voight *et al.*, 2000a). Merapi is located in central Java (Figure 4.3) and is regarded as the most active and dangerous volcano in Indonesia (Camus *et al.*, 2000), with an estimated 3000 – 5000 fatalities since 1672 (Simkin & Siebert, 1994) and eruptions approximately every two years for the past two decades (1980, 1982, 1984, 1986, 1992, 1994, 1996/7 and 1998; Voight *et al.*, 2000). The volcano is currently

characterized by periods of active and persistent dome growth and collapse producing block and ash flows and surges with intermittent more explosive events. Dome growth periods that last for several years are usually interrupted by short explosive events, lasting hours to days (Camus *et al.*, 2000; Gertisser & Keller, 2003b; Andreastuti, *et al.*, 2000; Newhall, *et al.*, 2000). However, the stratigraphic record for Merapi indicates that frequent large explosive eruptions have occurred regularly in the past with potential for the volcano to revert to this more explosive eruptive style in the future (Camus *et al.*, 2000; Gertisser & Keller, 2003b; Andreastuti, *et al.*, 2000; Newhall, *et al.*, 2000), thus posing a significant hazard to the city of Yogyakarta, 25 km to the south, as well as the densely populated areas at the base of the volcano (Siswowidjoyo *et al.*, 1995; Andreastuti *et al.*, 2000; Camus *et al.*, 2000; Itoh *et al.*, 2000; Newhall *et al.*, 2000; Thouret *et al.*, 2000 and Voight *et al.*, 2000b).

Van Bemmelen produced the first detailed record of the structure and evolution of Merapi volcano in 1949. In this work, he identified an older edifice, Old Merapi, outcropping on the northeast to east flank of the volcano, and an overlying younger active volcanic centre, New Merapi (van Bemmelen, 1949; del Marmol, 1989; Newhall *et al.*, 2000). Recent work by Newhall *et al.* (2000) and Gertisser (2001) dates the initiation of volcanism of Old Merapi, at 9630 ± 60 ^{14}C yr BP and 11792 ± 90 ^{14}C yr BP respectively. Earlier volcanism during a proto or ancient Merapi stage has been identified by other workers using U/Th dating which dates the oldest units at 40 000 years BP (Berthommier, 1990; Camus *et al.*, 2000, Newhall *et al.*, 2000). This older volcanism is evident at the hills of of Gunung Turgo and Gunung Plawangan on Merapi's southern slopes (van Bemmelen, 1949; Camus *et al.*, 2000). Berthommier (1990) and Camus *et al.* (2000) proposed that Gunung Bibi, on the north-eastern flank of Old Merapi, is yet an older pre-Merapi volcanic remnant, underlying Ancient Merapi. Del Marmol (1989) and Newhall *et al.* (2000) in turn, proposed that Gunung Bibi was a parasitic cone on the Merapi edifice. However, a sample from this location has been K/Ar dated at $67,000 \pm 25,000$ y BP (Berthommier, 1990), and given its highly eroded nature and morphology this older age appears more likely (Camus *et al.*, 2000).

Merapi dome growth is typically associated with deep and shallow earthquakes (volcanotectonic seismic events) (Ratdomopurbo & Poupinet, 2000). However, some pyroclastic eruptions at Merapi are associated only with shallow hybrid seismic events and tremors (Ratdomopurbo & Poupinet, 2000; Hidayat *et al.*, 2000). Eruptions associated with deep volcanotectonic earthquakes, are believed to indicate magma migration from below the volcanic edifice (Ratdomopurbo & Poupinet, 2000). However, eruptions associated with shallow seismic activity are characterised by hybrid earthquakes, multi-phase events and tremors and potentially indicate shallow processes as eruption triggers in a high-level system (Ratdomopurbo & Poupinet, 2000).

The identification of an aseismic zone at a depth of approximately 2.5 to 3 km below the summit in 1995, was taken to indicate the existence of a shallow magma storage system beneath Merapi (Ratdomopurbo & Poupinet, 2000) in agreement with petrological results (Gertisser & Keller, 2003b). However deeper storage chambers have also been postulated on the basis of mineral geobarometry, suggesting a quasi-steady state magma supply system beneath Merapi (Gertisser, 2001). High-resolution gravity data has identified a high-density body deep beneath the volcanic summit of Mt. Merapi, (Tiede *et al.*, 2005) and GPS and tilt data (Westerhaus *et al.*, 1998; Beauducel & Cornet, 1999) and seismic data (Wasserman *et al.*, 1998) do not provide evidence for an edifice-hosted shallow magma reservoir. Many previous geophysical studies in Central Java have focused on the internal structure of the Merapi edifice (Maercklin *et al.* 2000; Wegler & Lühr 2001; Müller *et al.*, 2002; Müller & Haak 2004), however no conclusive evidence for an edifice-hosted chamber has been found and the deeper structure beneath the volcano supplying melt is also poorly understood. Recent work (Koulikov *et al.*, 2006, Wagner *et al.*, 2006; Chadwick *et al.*, *submitted*), has identified a large tomographic anomaly in the crust and upper mantle beneath Merapi and Central Java, which indicates that the magma supply system beneath the volcano is far more extensive than previously thought.

Recent volcanic activity at Merapi has been largely restricted to fumarolic degassing and the extrusion of relatively homogenous, viscous, crystal- and inclusion-rich dome-forming lavas (Gertisser & Keller, 2003b). Merapi currently degasses continuously

through high temperature fumaroles ($>500^{\circ}\text{C}$) with two high-temperature fumarole fields located near the Merapi summit, Gendol and Woro, (Zimmer & Erzinger, 2003). Recent volcanics exhibit a high-K basaltic-andesite composition (Bahar, 1984; del Marmol, 1989; Hammer *et al.*, 2000; Gertisser & Keller, 2003a). These samples display a relatively restricted spread in whole rock isotopic ratios and have been interpreted as displaying minimal interaction with the crust at shallow levels (Gertisser & Keller, 2003a) but providing strong evidence for source variability and fractionation, resulting in progressive changes in the compositions of magmas erupted from the volcano through time (Gertisser & Keller, 2003b). However, well developed crystal zonation, and the presence of numerous inclusions of both igneous and sedimentary origin in recent deposits suggest the operation of varied magmatic processes (cf. Renzulli *et al.* 2001, 2003). In a large and long-lived system such as Merapi, intra-crustal processes are likely to be significant in magmatic evolution, and their identification and location is integral to understanding the dynamics of the volcano.

4.3 *Analytical Techniques*

4.1.1 Whole rock techniques

4.1.1.1 Sample preparation

Selected samples of porphyritic lavas and crystalline inclusions were hand crushed in an agate mortar and pestle, the samples were then sieved and resulting rock chips (0.5 – 0.7mm) were hand picked using a binocular microscope. These chips were washed, dried, and then powdered using an agate mortar and pestle followed by a final phase of powdering in a ceramic TEMA © mill.

4.1.1.2 X-Ray Diffraction analysis (XRD)

Powdered calc-silicate samples were analysed by X-Ray Diffraction (XRD) by A. Calder at the Facility for Earth and Environmental Analysis (FEEA), St. Andrews University, Scotland using a PW1050 with a fixed divergence slit and a graphite monochromator. Siemens Diffrac-AT software package was used for identification of unknown diffraction patterns in conjunction with an ICDD database and quantification of multiple phases was carried out using Siroquant software.

4.1.1.3 Major and trace element analyses - X-Ray Fluorescence (XRF)

Selected samples were powdered to < 65 µm, homogenised and then dried at 105°C prior to analysis by X-Ray Fluorescence spectrometry (XRF) at GEOMAR, Kiel University. Fused glass beads were formed and analysed by D. Rau using an automated Phillips © PW1480 X-ray spectrometer. The beads were irradiated with primary X-rays which were absorbed according to Beer's law, generating a secondary X-ray emission spectrum, which is characteristic for each element in the sample. All analyses were carried out using a Rh X-ray tube and calibrated to international geological reference standards, BHVO-1, JA-2, JB-2, JB-3 and JR-1. H₂O and CO₂ were analysed on ignition of samples

at 1200°C using a Rosemount © CWA5003 infrared photometer (e.g. Troll & Schminke, 2002). Standard analyses are reported by Abratis *et al.* (2002).

4.1.1.4 Rare Earth Element analyses - Inductively Coupled Mass Spectrometry (ICPMS)

ICP-MS is a multi-element analytical method, which allows the quantification of concentrations of isotopes and trace elements, including rare earth elements (REE). Rare earth elements were analysed by inductively coupled plasma–mass spectrometry (ICP-MS) at the Rock Geochemical Laboratory of the Geological Survey of Denmark and Greenland in Copenhagen. The samples were prepared using a modified version of the method described by Turner *et al.* (1999) and were analysed using a PerkinElmer © 6100 DRC Quadrupole ICP-MS with a Meinhard nebulizer. Detection limits and analytical precision range from <100 ppb to <1 ppt, and relative analytical precision is typically ~2 to 5% (one standard deviation).

4.1.1.5 Radiogenic Isotope analyses – Multi Collector–Inductively coupled Mass Spectrometry (MC-ICPMS)

Nd and Pb isotopic analyses were performed at the Danish Lithosphere Centre and measured using an Axiom multi collector inductively coupled plasma mass spectrometer (MC-ICPMS).

4.3.1.5.a Lead Isotopes

The sample powders were prepared in 7ml Savillex © beakers within a Class 10 Laminar Flow Hood. Seastar ultra pure acids were used throughout the procedure. All samples were hot-acid (7M HCl) leached for 1 hour to remove anthropogenic Pb contamination, then thoroughly rinsed with Milli-Q deionised water prior to acid digestion. JB-2 was used as the standard during the procedure, but was not acid leached prior to acid

digestion. Samples, standards and blanks were then subjected to the acid digestion procedure outlined in Figure 4.6.

Following acid digestion, the resulting dried residues were re-dissolved in 1 ml of 1M HBr to bring Pb into solution for anion exchange column chemistry. The mini columns (1ml pipette tips) and fibreglass frits used for this procedure were leached for 1 week prior to chemistry in 3.5M HCl to reduce blanks, and were thoroughly rinsed with Milli-Q deionised water prior to use. The mini columns, fibreglass frits and anion exchange resins used for this procedure were all discarded after use.

Approximately 0.3ml of anion exchange resin was loaded on to each column, and was cleaned and prepared for sample loading following the procedure outlined in Table 4.1. Each sample was then loaded onto a mini-column with a new, and clean pipette tip.

All elements excluding Pb were then eluted from the column following chemistry sequence 1 (Table 4.2). The Pb was then eluted following sequence 2 (Table 4.2), and collected into cleaned Savillex beakers.

The samples were then evaporated before repeating the column chemistry to ensure all other elements are removed completely. Following the second stage of column chemistry and evaporation, 0.03 μ l of 14M HNO₃ was added and the sample re-evaporated to help take up the Pb into solution prior to analysis.

The samples were dissolved in 1ml 0.2% HNO₃, on a hotplate for 2 – 3 hours prior to analysis to ensure complete dissolution of Pb. 80ppb Pb standard solutions of acid-leached SRM 981 were produced in 1.5ml of 0.2% HNO₃, see Baker *et al.*, (2004) for details.

Samples were introduced into the mass spectrometer via an aridus desolvating nebuliser using argon as the sweep gas. After each analysis, the nebuliser tip was thoroughly washed with Milli-Q deionised water and the system washed out with 2% HNO₃ for up to

5 minutes, to reduce baseline Pb levels before introduction of the next sample. Data were collected by static multi-collection with the collectors set up as shown in Table 4.3. On-peak zeros were measured for approximately 1 minute prior to every analysis, while still aspirating 0.2% HNO₃ to take Pb memory in the system into account (see Baker *et al.*, 2004).

Samples were analysed between measurements of the SRM 981 standard with 2 – 5 samples between standards. Values of SRM 981 during this study (n = 14) were $^{206}\text{Pb}/^{204}\text{Pb} = 16.9418 \pm 10$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4990 \pm 11$ and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7245 \pm 34$. Duplicate analyses of these standards, JB-2 and samples indicate an external reproducibility of < 60 ppm (2 sd) for all ratios with total procedural blanks <100 pg.

4.3.1.5.b Neodymium Isotopes

The sample powders (200mg) were prepared in 15ml Savillex beakers within a Class 10 Laminar Flow Hood. Distilled acids were used throughout the procedure. All samples were hot-acid (6M HCl) leached at 120° for two hours to remove alteration products, then thoroughly rinsed with Milli-Q deionised water prior to acid digestion. JB-2 was used as the standard during the procedure, but was not acid leached prior to acid digestion. Samples, standards and blanks were then subjected to the acid digestion procedure outlined in Figure 4.6.

Following acid digestion, the resulting dried residues were re-dissolved in 1 ml of 2M HCL to bring the sample into solution for anion exchange column chemistry. Cleaned glass columns were used for this procedure and were thoroughly rinsed with Milli-Q deionised water prior to use.

Approximately 4.5ml of AG50W-X8 100-200 mesh resin was loaded on to each column, and was cleaned and prepared for sample loading following the procedure outlined in Table 4.4. Each sample was then loaded onto the columns with a new, and clean pipette tip.

Nd is separated from the dissolved sample following chemistry sequence 2 (Table 4.5) and collected into cleaned Savillex beakers.

Nd samples were then dissolved in 0.2% HNO₃ for 1 hour and cooled prior to moving to beakers for analysis. 1:10 dilutions were made for all samples and then altered accordingly to produce samples suitable for analysis. Samples were analysed in between a standard solution (AMES Nd + Sm), at a rate of every 2 – 4 samples. AMES values during this study (n=9) were 0.51211 ± 7 and the total procedural blank was < 95 pg.

4.3.1.6 Radiogenic isotope analyses -Thermal Ionisation Mass Spectrometry (TIMS)

4.3.1.6.a Strontium Isotopes

The sample powders (200mg) were prepared in 15ml Savillex © beakers within a Class 10 Laminar Flow Hood. Distilled acids were used throughout the procedure. All samples were hot-acid (6M HCl) leached at 120° for two hours to remove alteration products, then thoroughly rinsed with Milli-Q deionised water prior to acid digestion. JB-2 was used as the standard during the procedure, but was not acid leached prior to acid digestion. Samples, standards and blanks were then subjected to the conventional HF-HNO₃-HCL acid dissolution technique outlined in Figure 4.6.

Approximately 4.5ml of AG50W-X8 100-200 mesh resin was loaded on to each column, and was cleaned and prepared for sample loading following the procedure outlined in Table 4.4. Each sample was then loaded onto the columns with a new, and clean pipette tip. Sr was separated from the dissolved sample, eluted following chemistry sequence 1 (Table 4.5) and then collected into cleaned Savillex beakers and dried down prior to analysis.

The Sr cut was loaded onto on Ta filaments in 1M phosphoric acid and analysed using a VG Sector 54-IT TIMS at the Geocentre, Copenhagen. Analyses were undertaken in

dynamic mode with a three-peak jump sequence and an average total procedural blank of 10 ± 8 pg (2σ). Sr results were corrected for mass fractionation using the exponential law and an $^{86}\text{Sr}/^{88}\text{Sr}$ ratio of 0.1194. ^{87}Rb interference on Sr was corrected using ^{85}Rb .

4.3.1.7 Stable Isotope analyses – ICPMS

We analysed andesite whole rocks, calc-silicate inclusions and local local chalks for C and O isotopes. Silicate material was analysed by Geo-Chemische Analysen (GCA), a German analytical company which specialises in stable isotope analysis. Carbonate samples were analysed with R. Goodhue at the Geochemical Laboratory, Trinity College Dublin using a Thermo Delta^{plus} Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS). For $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis of carbonates, a CTC Analytics CombiPal Autosampler with a thermostated hot block and FMI acid pump is interfaced to the Delta^{plus} via a Thermo GasBench II.

0.6mg of each sample was weighed into a clean dry round-bottomed borosilicate exetainer using a Sartorius MC5 microbalance. The exetainer was capped with a new septum and racked in the hotblock. Each sample exetainer was flush filled with 100mL/min flow of helium for five minutes and then a double needle configuration was set up on the autosampler. Each sample was dosed with 5 drops of phosphoric acid by the acid needle and allowed to equilibrate for 91 minutes at 72°C before the sample needle filled a 100 μL loop on the valco valve in the Gas Bench. 10 sequential aliquots of CO_2 were introduced to the spectrometer and the first and the last peaks discarded. Average ^{13}C and ^{18}O values of the eight peaks were recorded

The International Atomic Energy Authority standard CO-1 was used to correct each batch of unknown samples to primary standard values (VPDB for ^{13}C and SMOW for ^{18}O). An internal standard (Cranford dolomite) was run with each batch of samples and is used as a cross check to monitor machine stability. 239 replicates of Cranford dolomite run in 20 sample batches from the period between 16.02.05 and 23.02.06 gave a one SD of 0.06‰ for ^{13}C and 0.11‰ for ^{18}O . These values are consistent with the stated precision recorded by Thermo for the GasBench II. Four replicates of a Java crust samples gave a one SD of 0.06‰ for ^{13}C and 0.11‰ for ^{18}O .

4.3.2 *In situ* techniques

4.3.2.1 Sample preparation

Polished thick sections (150 μ m) of selected basaltic-andesite and inclusion samples from the 1994 and 1998 block and ash flow deposits were mounted on glass slides of 48 mm x 28 mm.

4.3.2.2 Electron Microprobe (EMP)

Electron microprobe analysis (EMPA) is a non-destructive method for determining the chemical composition of solid materials and elements from fluorine (Z=9) to uranium (Z=92). Concentrations as low as 100ppm can be detected. A high-energy focused beam of electrons is used to generate X-rays characteristic of the elements within a sample. During wavelength dispersive analysis (WDS), the resulting X-rays are diffracted by analyzing crystals (TAP, PET, LIF) and counted using gas-flow and sealed proportional detectors. The intensity of X-rays from standards of a known composition are then compared with those from the unknown materials to determine their composition. Atomic number effects (e.g. backscattered electrons), absorption and fluorescence in the sample are iteratively corrected online.

Major element EMP analyses for this study were carried out using a JEOL JXA-8200 Superprobe at the Geologisk Institute of Copenhagen. A thin (200 angström) carbon coating was applied to selected thick sections (150 μ m) prior to analysis to minimise charging. Analysis locations were selected using backscatter electron images, allowing positioning accurate to approximately 1 μ m. Samples were analysed for Si, Ti, Al, Fe, Mg, Ca, Na, K, Mn, Cr, and Ni with Ba and Sr for selected crystals.

An electron beam current of 15 to 30 nA was used to produce X-rays from the sample. A count time of 30 seconds off peak and 30 seconds on peak was used in order to increase counting statistics and reduce uncertainty on analyses. A beam diameter of 2 μm was used and. Na was analysed at the beginning of the sequence to minimise loss. Na counts were monitored during analysis and remained stable over the measurement time. Relative analytical precision $[(\text{standard deviation/mean}) \times 100]$ was $< 2\%$ for Si, Al and Ca, $< 3\%$ for Na and K, $< 5\%$ for Fe, $< 10\%$ for Ti, and $< 10\%$ for Mg, based on repeated analysis of natural and synthetic mineral and glass standards.

4.3.2.3 Micro-drill

Micro sampling of crystal components for analysis of Sr isotope ratios was performed at the Department of Earth Sciences in Durham using a New Wave Micromill employing the techniques described by Charlier *et al.* (2006) and references therein. Analysis locations were selected using backscatter electron images and a binocular zoom microscope coupled with a linked computer workstation running specialist software that integrates the stage, mill and microscope optics and allowed for precise location of the drill points reproducible to $\pm 1 \mu\text{m}$. The depth of drill points was controlled by this set up and vertical movement is accommodated via movement in the microscope head/mill assembly reproducible to $\pm 1 \mu\text{m}$. Using tungsten carbide mill bits, multiple shallow points were milled along discrete zones in selected crystals. The number of drills per zone depended on Sr ppm content of the feldspar, as a return of 3 ng of Sr was required for analysis. Milling was carried out under a single drop of Milli-Q deionised water, which collected drilled sample dust. This slurry was then pipetted from the polished sample surface using disposable micropipettes and transferred directly to 3.5 mL screw top Savillex beakers for processing and analysis. Procedural blanks were taken throughout the process by milling within a water droplet above the surface of the sample so that no grinding occurs. The blank is then pipetted up and treated in identical fashion to the samples. After processing, samples were analysed using a Thermo-Finnigan Triton TIMS at Durham University, with average total procedural blanks between $12 \pm 8 \text{ pg}$ (2σ) and multiple analyses of NBS 987 averaging at 0.710261 ± 0.000017 (2σ) ($n = 13$)

(within error of the value $^{87}\text{Sr}/^{86}\text{Sr} = 0.710248 \pm 0.000023 \ 2\sigma$ ($n = 427$) reported by Thirlwall, 1991).

4.3.3 Stable and radiogenic Isotope analyse of fumarole gases

High-temperature ($> 500^\circ \text{C}$) fumarole gas samples were taken in July 2002, September 2003, and March 2005 from the Woro fumarole field at Merapi summit. The isotopic ratios of CO_2 and He gas samples were measured by M. Zimmer at GFZ Potsdam using a Finnigan DELTAplusXL continuous flow isotope ratio mass spectrometer and a Micromass MM5400 noble gas mass spectrometer respectively.

4.3.4 Textural analysis: Crystal Size Distribution (CSD)

Crystal size distribution data are determined from two-dimensional sections through rock samples in the form of thin sections with later conversion of two-dimensional data into three-dimensional parameters (Higgins, 2000). Stereology may be used to determine size, shape and number of crystals in volume of rock based on a 2D section, and may yield important information regarding crystallisation and solidification processes during cooling (Higgins, 2000).

Standard thin sections of selected basaltic-andesite samples from the 1998 block and ash flow deposits were mounted on glass slides of 48 mm x 28 mm. As the samples are massive and lack any observable fabric, the sections were randomly orientated. The sections produced were scanned using a medical slide scanner generating high-resolution (2820 dpi) colour images of the thin section surface.

The scanned images were imported into Adobe Illustrator, and using the layers option, the different minerals were digitised using the pen tool in separate layers. The outline of the crystals in thin section was verified with a polarising microscope. The line thickness was set to 1 pixel width in order to obtain accurate measurement of crystal volume when using the CSD software. Each mineral was given a different grey-scale fill and kept in

separate layers for ease of processing. These greyscale images of crystals were analysed using Imagetool, a downloadable shareware package. The image was calibrated in millimetres and the greyscale threshold values for each mineral type were defined. Each peak is selected individually and analysed with the software measuring different parameters including long-axis length, short-axis length, perimeter, area, elongation, roundness, major angle orientation, and minor angle orientation. The area of the section is also measured. This data is exported to an Excel document and an edge correction of 1 pixel (in mm) is added to the raw data prior to input into the CDS package to account for error associated with the outline thickness.

Further corrections are applied using the CDS corrections (created by Higgins) to account for cut effect (Sahagian & Proussevitch, 1998) and the intersection effect (Higgins, 1994). An input of section area, crystal shape (based on the aspect ratio between relative long and short axes of crystals and comparison with graphs by Higgins, 1996), the rock fabric, and roundness of crystals are also required in order to produce a CSD plot for a thin section. A plot of crystal size vs. the log of the population density was then produced from the output data of the CSD corrections software (Figure 4.32).

4.4 Petrology and geochemistry of inclusions in recent Merapi lavas; implications for volcanic plumbing in arc settings.

In subduction zone settings, primary mafic magma is generated in the mantle wedge (Davies & Stevenson, 1992; Sisson & Bronto, 1998). However, as previously discussed, volcanic rocks in equilibrium with mantle compositions are atypical in subduction zone settings. Modification of primary melts is therefore significant in arc magma petrogenesis. Ascent and density filtering of primary arc magmas in the crust promotes modification of these primary melts by numerous processes, most importantly crystallisation and crustal contamination, but can also be due to a combination of these processes and by magma mixing and degassing (Bowen, 1928; De Paolo, 1981; Gill, 1981; Hildreth & Moorbath 1988; Rogers & Hawkesworth, 1989; Davidson & Tepley, 1997; Grove *et al.*, 1998, 2002, 2003; Annen *et al.*, 2006). These processes can be identified in the resulting whole rock geochemistry of erupted magmas; however, they are often difficult to discern. Incorporation of crystalline igneous material and fragments of the surrounding country rock into arc magmas is well documented (Grove *et al.*, 1988; Renzulli & Santi, 1997; Renzulli *et al.*, 2003; Dungan & Davidson, 2004). By analysing such inclusions hosted in the erupted magmas, it is possible to gain more direct information about the sub-volcanic system that feeds these volcanoes, the magmas' intra-crustal evolution, and the basement the magmas traverse on ascent.

Crystalline igneous inclusions hosted in lavas provide a means of analysing varied crystallisation environments or processes. These igneous inclusions in lavas may preserve distinct records of crystallisation during ascent. Such inclusions have been identified in previous studies as fractionation residues reflecting crustal processes operating in arc magmas (Beard, & Borgia, 1989; Heliker, 1995). Comagmatic igneous inclusions may preserve distinct records of these processes, incompletely preserved, homogenised, and or blurred in host magma whole rock geochemistry. Individual megacrysts are common in arc settings and have been identified in previous studies as high-pressure phenocrysts crystallising from their host magma (cognate), or fragments of coarsely crystalline zones that crystallised from partially solidified magmas (co-magmatic/co-genetic) over a range

of pressure and temperature conditions (e.g., Irving, 1974; Irving & Frey, 1984; Bodinier *et al.*, 1987).

As a decade volcano (Newhall *et al.*, 1994), Merapi has been subject to numerous studies in recent years. However, the physical and chemical characteristics of the magmatic system that feeds this volcano remains incompletely understood. Given the relative geochemical homogeneity of recent lavas (Gertisser & Keller, 2003b) we have analysed a suite of igneous and meta-sedimentary inclusions as well as local crustal samples in order to investigate the processes occurring beneath Merapi volcano in more detail. Petrography, geochemistry and geobarometric calculations based on empirically and experimentally calibrated published formulations were utilised to assist in unravelling the petrogenetic history of recent Merapi basaltic-andesites and to gain insight into the nature of the magmatic plumbing system feeding its volcanism.

4.4.1 Terminology

The terms used to describe the inclusions present in recent Merapi deposits are defined as follows. The term “xenolith” is used to refer to fragments of thermally metamorphosed country rock foreign to the magmatic system, in this case, of sedimentary origin. The term “enclave” is used to refer to cognate igneous inclusions that display liquid and or chilled contacts with the host magma. “Megacryst” refers to crystals of > 5 mm size, in this case amphibole which appears to be in disequilibrium with the host basaltic-andesite. “Plutonic lithic fragments” refer to predominantly medium- to coarsely crystalline inclusions of igneous origin encased within Merapi lava. These plutonic lithics may represent: a) a coarsely crystalline portion of currently erupting magma, i.e. cognate; b) genetically related to the erupting magma but a precursor to current eruptive products i.e. crystalline fragments of an earlier magma batch or co-magmatic; or c) genetically unrelated to the magmatic system i.e. xenolithic (*sensu lato*). These plutonic lithics typically possess up to 10% glass and patchy groundmass. Volcanic textures such as vesiculated glass and finely crystalline interstitial groundmass belie the essentially plutonic nature of these inclusions and are interpreted as a late modification due to incorporation into an erupting magma. Nomenclature used for discussing the plutonic

inclusions is after Streckisen (1976) and Le Maitre (1989). The term “felsic” is loosely used to refer to lithics that are mineralogically dominated by feldspar and the term “mafic” to refer to lithics that are mineralogically dominated by pyroxene and amphibole.

4.4.2 Petrography and Mineralogy of Xenoliths, Megacrysts and Country Rock

Inclusions of igneous and meta-sedimentary compositions were identified in the 1994 and 1998 block and ash flows and their associated deposits. The deposits are a result of multiple collapses of the actively growing dome at Merapi during the 1994 and 1998 eruptive events. The inclusions comprise a small percentage of the total deposits estimated to be approximately 2.5-3 km³ for the 1994 event (Abdurachman *et al.*, 2000) and approximately 2.5-4.3 km³ for the 1998 event (Schwarzkopf *et al.*, 2005). The samples for this study were collected in 1999. Samples from the 1998 eruptive episode were taken from Jurangero quarry at Kali Putih, an eroded channel approximately 5 km southwest of the Merapi summit (Figure 4.3). Samples from the 1994 deposits were collected from Kali Boyong. Inclusions contained in the 1994 and 1998 Merapi deposits are relatively abundant, and may be classified into four main groups: 1) Group I are plutonic lithic fragments, 2) Group II are magmatic enclaves, 3) Group III are megacrysts and 4) Group IV meta-sedimentary xenoliths. Mineral names, structural formulae and end-members were calculated using Leake *et al.* (1997) for amphibole and Morimoto *et al.* (1988) for pyroxenes, with feldspar nomenclature after Deer *et al.* (1992). All raw mineralogical data for minerals analysed are compiled as Excel files in the Electronic Appendix X on the CD attached.

4.4.2.1 Plutonic Inclusions

The plutonic lithic fragments are typically 5 to 10 cm in diameter, sub-rounded, and may be subdivided based on modal mineralogy into mafic amphibole- and clinopyroxene-gabbros and more felsic leucogabbros, anorthosites and diorites (see Figure 4.7 and Table 4.6 for modal mineral abundances and textures). Contact with the host basaltic andesite is typically quite sharp with alignment of crystals in the host lava along boundaries and a

concentration of oxides in the rim of the inclusion. However there is no evidence for chilled margins (Figure 4.7), indicating the inclusions were significantly heated upon incorporation into the host melt. In some cases, (e.g. 8-P-3, Figure 4.13b) contacts appear diffuse with infiltration of host andesite into the inclusions. Both sub-groups are typically medium to coarse grained and holocrystalline. Occasionally, the lithics display asymmetric, millimetre to centimetre thick, mineral-layering indicative of the action of crystal settling (Wager & Brown, 1967) and/or *In situ* growth (Campbell, 1978) (Figure 4.7d). These cumulates may possess up to 10% vesiculated glass or patchy microcrystalline groundmass in a framework of plagioclase, pyroxene and amphibole crystals. This groundmass is interpreted to be a late stage addition due to incorporation into Merapi host basaltic-andesite magma due to the presence of rounded vesicles and the lack of re-melting or rounded textures in adjacent plagioclase crystals. Crystals in rare samples (2 samples) without groundmass or glass show sub-solidus textural re-equilibration along boundaries between plagioclase crystals (apparent dihedral angles of approximately 120° eg. Hunter 1987) (Figure 4.7e) indicating these inclusions were fully crystalline upon incorporation into the host magma. Representative analyses for minerals in these inclusions are presented in Table 4.7.

Mafic lithics are mineralogically dominated by amphibole and pyroxene with oxides (titanomagnetite, spinel, ilmenite), lesser plagioclase and rare anhedral apatite and titanite accessory phases occurring between crystal boundaries (Table 4.6). Plagioclase is the dominant phase in the felsic lithics (Table 4.6) with lesser pyroxene, amphibole, oxides, and accessory minerals including apatite and titanite. In both sub-groups diopsidic to augitic clinopyroxenes occur, with Ca-rich clinopyroxene present only in the mafic inclusions ($\text{Wo}_{41-56}\text{En}_{27-45}\text{Fs}_{7-24}$) (Figure 4.8), are anhedral to subhedral, and occasionally normally zoned. Amphibole is in general present as large laths > 5 mm, which are dominantly magnesio-hastingsite with some pargasite and hornblende (after Leake *et al.*, 1997). The amphibole laths often possess perfect cleavage and pronounced reaction rims populated by oxides and finely crystalline pyroxene and plagioclase. The presence of appreciable amounts of amphibole in these inclusions indicates a hydrous system, as water is required to stabilize such hydrous minerals (Meurer & Claeson, 2002).

Plagioclase crystals are typically zoned, subhedral and exhibit an unusually broad range in An mol% composition from 4 to 95% (Figure 4.9). The majority of plagioclase crystals analysed lie in two compositional groups, anorthite (An_{90}), and labradorite (An_{50-70}) (Figure 4.11). The feldspar population in the felsic inclusions is unimodal, mainly bytownite and anorthite. The mafic inclusions have a bimodal range from andesitic to anorthitic plagioclase ($An_{30-95}Ab_{5-61}Or_{0-18}$), present as rare zoned crystals 1-5mm in size, but more commonly as smaller crystals < 1mm. Late feldspar in the groundmass and infilling cracks of both mafic and felsic inclusions is of a more constrained composition ($An_{52-58}Ab_{41-52}Or_{2-3}$, $n = 982$) with a limited number of analyses ($n = 5$, not included above) falling in the Na-sanidine to anorthoclase fields. These compositions appear to be the result of late crystallisation

4.4.2.2 Magmatic Enclaves

The magmatic enclaves are generally restricted in size, to a few centimetres in diameter (Figure 4.12), and are most commonly basaltic to basaltic-andesite in composition. They typically possess elliptical shapes with lobate contacts with the host basaltic-andesite and often show distinct chilled margins (Figure 4.12a). They are finely crystalline, with small phenocrysts < 1mm of plagioclase and pyroxene (Figure 4.12c) set in a glassy to microcrystalline matrix, with elongate to acicular plagioclase microcrysts. Diopsidic to augitic clinopyroxenes ($Wo_{27-46}En_{27-44}Fs_{11-52}$) are typically anhedral to subhedral, with simple zoning and plot within the published range (Gertisser, 2001) of compositions for Merapi basaltic andesite (Figure 4.8). Hornblende is present in all samples and forms small laths with strong reaction rims. Plagioclase crystals also form relatively small elongate laths (Figure 4.12c), normally zoned and form a strongly bimodal population trend (Figure 4.11c), with crystal rims and micro-crystals in the groundmass typically possessing compositions of andesite to labradorite An_{49-65} (average An ~ 57 and 54 respectively) and crystal cores of more calcic bytownite compositions (An_{70-90}), (average An ~ 82, $n=15$) (Figure 4.10). Representative mineral analyses for these inclusions are presented in Table 4.7.

4.4.2.3 Amphibole Megacrysts

Amphibole megacrysts range in size from 0.5 cm up to 5cm and are primarily hosted in Merapi basaltic andesite (Figure 4.13a). However, one heavily embayed and resorbed megacryst was found within a felsic plutonic inclusion (8-P-3) (Figure 4.13b). In thin section, the samples are dark reddish brown in colour, strongly pleochroic and often show perfect cleavage. All of the observed megacrysts are typically anhedral with strong disequilibrium textures including pronounced reaction rims and embayed textures (Figure 4.13). These reaction rims are fine-grained, and comprised of intergrowths of clinopyroxene, plagioclase and titanomagnetite and also occur along the cleavages planes of many crystals. Opaque replacement (Garcia & Jacobson, 1979), occurs at the rims and along cleavage planes of several of the megacrysts (Figure 4.13c), and is likely to be a late oxidation effect. The rims also contain plagioclase crystals, < 0.5 mm, with cracks and embayments in the crystal infilled by larger plagioclase laths and clinopyroxene 0.5 - 1 mm. The analysed megacrysts are magnesio-hastingsite to ferro-edenite (after Leake *et al.*, 1997), and of similar compositions to amphibole observed in the mafic plutonic inclusions. Representative analyses of these inclusions are presented in Table 4.7.

4.4.2.4 Meta-sedimentary Xenoliths

The mineralogy and geochemistry of the metasedimentary xenoliths will be included in this section, 4.4, with more detailed discussion of their formation and implications for the Merapi magmatic system outlined in the subsequent section 4.5.

Meta-sedimentary xenoliths hosted in Merapi magmas may be subdivided into two main types; calc-silicate skarns (Figure 4.14; Table 4.8, xcs-1, xcs-3, xcs-7, xcs-9), and less common, more silicic, metamorphosed, volcaniclastic sediments (Figure 4.14, Table 4.8; xcs-2, xcs-4; Table 4.10; 8-S-1, 8-S-2).

The calc-silicate xenoliths have been observed as xenoliths in the basaltic andesite and in the igneous inclusions, basaltic enclaves and felsic plutonic inclusions, described above. At magma - calc-silicate xenolith contacts, the magma is frequently highly vesicular, with undulose and digitated contact zones without pronounced chilled margins

indicating a low temperature gradient between country rock/xenolith and the magma. The calc-silicate xenoliths have a characteristic skarn-type mineralogy of wollastonite and diopside with lesser amounts of plagioclase, quartz, tremolite, and rare garnet, apatite, titanite and opaques in some of the samples, identified both petrographically and by XRD analysis (Figure 4.14, Table 4.8). The relative abundances of these minerals fluctuates between samples, and is likely to be a function of heterogeneity in the original protolith, potentially a carbonate of variable purity, and also due to a degree of interaction with the host andesite.

Variability in the protolith and degree of metamorphism also appear to be responsible for the spread in data for more silicic metamorphosed volcanoclastic sediments. These samples occasionally possess primary sedimentary structures including lamination and grading present as alternating bands of medium to fine grain size with variable mineralogy (Figure 4.14). Commonly, these primary sedimentary textures are thermally overprinted. Alternating layers comprised primarily of quartz and plagioclase or plagioclase and diopside are most common, with rare zircon and titanomagnetite present as small (0.05 mm) grains.

Plagioclase crystals in both xenolith types are typically euhedral laths (Figure 4.14); these can be normally zoned and exhibit a significant range in composition from anorthite to andesine, with feldspars in the calc-silicate xenoliths typically restricted to values between 80 and 100 An mol % (Figure 4.15b).

As well as zonation being present within individual crystals, there is zoning evident on the scale of a hand-sample (Figure 4.14). Many of the calc-silicate xenoliths possess strong reaction rims at their margins where the host basaltic-andesite magma has infiltrated the less affected cores. The reaction rims can be several cm in diameter and are marked by an increase in oxides (titanomagnetite) (Figure 4.14b). These distinct rims, present in several of these xenoliths, have mineral assemblages that are closer to magmatic signatures than the cores. There is an increase in the amount of wollastonite towards the cores of these xenoliths (up to 70%) and a dominance of diopside and anorthite in the rims (Figure 4.14b, Table 4.8). The more silicic xenoliths also possess reaction rims. However, they are not as strongly developed (<0.5 cm diameter) as those observed in the calc-silicate xenoliths (Figure 4.14c).

4.4.2.5 Country Rock

The country rock in the area proximal to Merapi was described by Van Bemmelen, (1949) as a sequence of Cenozoic marine limestones and marls and volcanoclastic sediments with units up to 2 km thick. There is little further information on these units in more recent literature, and good exposure is rare due to dense tropical vegetation and habitation in the area surrounding the volcano. Samples of local crust were obtained from quarries south of Merapi at Sindet and Wonosari and from the carbonate platform, which forms the cliffs at Parangtritis (Figure 4.3).

The units outcropping in quarries at Sindet and Wonosari ~10 km south of Yogyakarta and 30 km south of Merapi, are light grey to dun Miocene volcanic agglomerates of basaltic andesite composition. These units are inter-bedded with tuffaceous marly clays of the Jampang and Jiwo series of Eocene to Lower Miocene age (Figure 4.16 a, b, & c). The source of the tephra and volcanoclastic units is likely the old Eocene to Miocene arc, the roots of which form the Southern Mountains Zone in Central and East Java (Smyth, *et al.*, 2005) (Figure 4.4, 3.5). The volcanoclastic sediments are poorly sorted and are normally graded (Figure 4.17 a, b, c), with sub-rounded lithic fragments and coarse crystalline material (1-2 mm) at the base, and finer material toward the top (< 0.2 mm) (Figure 4.17e). In thin section radiolaria (Figure 4.17e), pollen or spores (Figure 4.17f) and numerous foraminifera types are visible including unfragmented examples of *Globigerina*, *Cycloclypeus*, and *Nummulites*.

The cliffs (25-100 m) at Parangtritis are part of the Gunung Kidul, a plateau that runs along the southern coast of Central and East Java (Haryono & Day, 2004). This topographic high to the south of Merapi volcano is largely comprised of Miocene carbonates of the Wonosari Formation, which consists of massive coral reef limestone in the south, and bedded chalky limestone in the north (Balazs 1968; van Bemmelen, 1970, Waltham *et al.*, 1983; Surono *et al.*, 1992). It often exhibits karst-style weathering in the field (Figure 4.16d). The total thickness of this unit is estimated to be greater than 650 m,

and the platform is underlain by older Miocene volcanic and volcanoclastic rocks (Waltham *et al.*, 1983). The coral reef limestone is lithologically highly variable, but dominated by rudstones, packstones, and framestones with interspersed lenses of volcanic ash (Waltham *et al.*, 1983).

Samples taken from Parangtritis were bedded limestone (Figure 4.17d) with numerous bioherms of Hexacorals and large foraminifera including *Lepidocyclina sp.*, *Miogypsina*, and *Flosculinella globulosa* (Figure 4.17g & h).

4.4.3 Geochemistry of Plutonic Inclusions and Enclaves

4.4.3.1 Major and Trace Elements

The major and trace elements for the representative analysed plutonic inclusions and enclaves are listed in Table 4.9. As SiO_2 is typically used as an index of differentiation for arc lavas (Davidson *et al.*, 2005), Harker diagrams for the most illustrative elements are shown in Figure 4.18 with additional variation diagrams using MgO (Fenner diagrams) as the index element (due to the less evolved nature of some samples) presented in Figure 4.19.

The plutonic lithic fragments show a relatively broad range in SiO_2 between 40 and 55 wt %, while the reported field for recent and historic high-K basaltic-andesite series is ~ 52–56 wt% (Gertisser & Keller, 2003a; Gertisser & Keller, 2003b). Analysed magmatic enclaves have a more restricted range of 49 - 52 wt% SiO_2 and the 1994 and 1998 basaltic-andesites analysed in this study possess slightly higher contents ranging from 52 to 55 wt%. The plutonic lithic fragments also show a more extensive range in MgO (3-11 wt %), with the mafic inclusions possessing the highest values (9-11 wt %) and lower values recorded for the felsic inclusions (~3-8 wt %), while analysed magmatic enclaves also record values of 3-8 MgO wt%. MgO wt % values for the basaltic andesite samples analysed are 2-4 wt %, which correlates with the published range for recent and historic high-K basaltic-andesite rocks from Merapi (Gertisser and Keller, 2003; Gertisser and Keller, 2003b).

Fe_2O_3 , MgO , CaO and TiO_2 contents are highest in mafic plutonic inclusions, and all samples show relatively linear negative arrays when these elements are plotted against SiO_2 (Figure 4.18). This division between mafic plutonic inclusions, enclaves and the lava samples, is more evident in plots using MgO as index of differentiation (Figure 4.19). Diffuse positive trends are observed between SiO_2 and Al_2O_3 , with more constrained trends with Na_2O , K_2O , Ba and Rb (Figure 4.18). P_2O_5 shows scattered both positive and negative arrays with increasing SiO_2 (Figure 4.18) and decreasing MgO (Figure 4.19) respectively.

4.4.3.2 Rare Earth elements (REE)

REE data are included in Table 4.9 and plotted on chondrite-normalised multi-element variation diagrams in Figure 4.20. The enclaves are similar to Merapi basaltic-andesites (from Gertisser & Keller, 2003a), and possess flat patterns with elevated LREE, flat HREE and a slight negative EU anomaly present in one sample (Figure 4.20c). Many of the plutonic inclusions are also similar to Merapi host rocks, especially for the light REE (La-Sm) (Figure 4.20b, 1994 inclusions). However, several samples (e.g. 1998 plutonic inclusions; Figure 4.20a) show moderate to marked depletion in LREE, with both subsets showing an enrichment in middle to heavy REE (HREE) relative to Merapi host rocks (Figure 4.20) with a few samples showing positive Eu anomalies. The inclusions from the 1994 deposits possess generally higher REE contents, particularly the LREE than samples from the 1998 deposits.

4.4.3.3 Whole Rock Isotopes

Sr, Nd and Pb isotope data analysed for this study are listed in Table 4.9 and plotted in Figure 4.21. The Sr and Nd isotope ratios for enclaves and plutonic inclusions, largely fall within a range defined by published lava data for Merapi volcano (Gertisser & Keller, 2003a). Sample 4.P-2 falls outside this range with a much lower $^{143}\text{Nd}/^{144}\text{Nd}$ ratio relative to the other samples, but a similar Sr isotope ratio (Figure 4.21a). The enclaves range from 0.70550 to 0.70571 for $^{87}\text{Sr}/^{86}\text{Sr}$ and 0.51270 to 0.51272 for $^{143}\text{Nd}/^{144}\text{Nd}$ while the

plutonic inclusions have a range for $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70529-0.70574 and of 0.51256 to 0.51272 for $^{143}\text{Nd}/^{144}\text{Nd}$.

$^{206}\text{Pb}/^{204}\text{Pb}$ ratios for plutonic inclusions range from 18.71 to 18.75 and enclaves range from 18.76 to 18.80, with the analysed samples falling broadly within the range of published data for Merapi host rocks (Figure 4.21 b, c, d). $^{207}\text{Pb}/^{204}\text{Pb}$ ratios for plutonic inclusions and enclaves are more restricted with ranges from 15.65 to 15.69 and 15.69 to 15.70 respectively. $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are also relatively restricted, with inclusions and enclaves ranging from 39.04 to 39.14 and 39.14 to 39.18 respectively. The published range in host rocks is from 39.02 to 39.22. In a $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ plot, data for inclusions and enclaves largely fall within the reference field for Merapi host rocks (Gertisser & Keller, 2003a and references therein). Positive correlations can be seen in plots of $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ (Figure 4.21c) and $^{208}\text{Pb}/^{204}\text{Pb}$ (Figure 4.21d). The data largely plot within the Merapi and Indian Ocean OIB fields, and plot well above the Northern Hemisphere Reference Line (NHRL) (Figure 4.21 c & d).

4.4.4 Geochemistry of meta-sedimentary xenoliths

4.4.4.1 Major and Trace Elements

The major and trace elements for the analysed xenolith samples are listed in Table 4.10. SiO_2 is again used for Harker variation diagrams for ease of comparison to other data and the most illustrative plots are shown in Figure 4.22. Significant major and trace element variation is present in these analysed xenolith samples with the volcanoclastic xenoliths possessing significantly higher SiO_2 (up to 83 wt%) than the calc silicate types (up to 64 wt%). Analyses of garnet grade metamorphosed calc-silicate samples, and reaction rims of zoned calc-silicate samples show whole-rock major element signatures that overlap with, and in some cases exceed the range present in host Merapi magmas with elevated Fe_2O_3 , MgO , TiO_2 and Al_2SiO_5 , (Figure 4.22). The cores of analysed calc-silicates have lower Fe_2O_3 , MgO , TiO_2 and Al_2SiO_5 , and higher CaO than the host lavas.

4.4.4.2 Rare Earth elements (REE)

REE data are included in Table 4.10 and plotted on a chondrite-normalised multi-element variation diagram in Figure 4.23. Although rocks of a sedimentary origin are typically normalised to a sedimentary standard, use of chondrite normalisation is not uncommon (Rollinson, 1993), and has been used here for ease of reference given the xenoliths incorporation into the Merapi magma system. The volcanoclastic xenoliths have similar patterns to Merapi basaltic-andesites (from Gertisser & Keller, 2003a), with slightly depleted LREE in a few samples. They have relatively flat patterns overall with two samples possessing a slight negative EU anomaly (Figure 4.23). The calc-silicate xenolith analyses consist of core and rim sections of one sample (XCS-1). Both samples possess a concave REE pattern with lower LREE and HREE, and a positive EU anomaly. However, the xenolith rim (XCS-1r) has less fractionated LREE and HREE than the core (XCS-1c) and a flatter pattern overall, similar to the Merapi host rock.

4.4.4.3 Whole Rock Isotopes

Sr, Nd and Pb isotope data analysed for meta-sedimentary xenoliths are listed in Table 4.10 and plotted in Figure 4.21. The data extends the published range for crustal xenoliths (Gertisser & Keller, 2003a) hosted in Merapi deposits significantly.

In a $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{144}\text{Nd}/^{143}\text{Nd}$ plot, two of the group IV inclusions analysed (one volcanoclastic xenolith and one calc-silicate xenolith) fall within a range defined by published data for Merapi volcano (Gertisser & Keller, 2003a). The other samples plot well outside the Merapi data field, with lower $^{144}\text{Nd}/^{143}\text{Nd}$ ratios and more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values (Figure 4.21a). The volcanoclastic xenoliths range from 0.70567 to 0.70736 for $^{87}\text{Sr}/^{86}\text{Sr}$ and 0.51247 to 0.51272 $^{143}\text{Nd}/^{144}\text{Nd}$, while the calc-silicate xenoliths have a range of $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.70584 to 0.70787 and 0.51251 to 0.51272 for $^{143}\text{Nd}/^{144}\text{Nd}$.

$^{206}\text{Pb}/^{204}\text{Pb}$ ratios for calc-silicate xenoliths range from 18.75 to 18.79, significantly less radiogenic than a previously published analysis (19.73; Gertisser & Keller, 2003a), and volcanoclastic xenoliths range from 18.76 to 18.85. $^{207}\text{Pb}/^{204}\text{Pb}$ ratios for calc-silicate and volcanoclastic xenoliths range from 15.67 to 15.71 and 15.66 to 15.68 respectively, with the calc-silicate xenoliths again, less radiogenic than a previously

published value (15.75; Gertisser & Keller, 2003a). $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are also relatively restricted, with calc-silicate and volcanoclastic xenoliths ranging from 39.04 to 39.11 and 39.05 to 39.12 respectively with the published analysis of 41.44 (Gertisser & Keller, 2003a). In Pb isotope plots, many of the analysed xenoliths of both types fall within the range of published data for Merapi host rocks ((Figure 4.21 b, c, d) and this is also true of a $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ plot, (Gertisser, 2001).

4.4.5 Geochemistry of representative crustal samples

Major, trace element and isotope analyses of carbonate and clastic crustal samples taken from Wonosari and Parangtitis are presented in Table 4.11. CO_2 loss on ignition combined with loss of any organic material present in the sedimentary rocks analysed (Dean, 1974) accounts for the low totals for both carbonate samples and correlates well with the high proportion of bioclastic material observed in thin section (Figure 4.17; Table 4.11). The volcanoclastic sample analysed (VC-1) possesses major element and compositions similar to Merapi basaltic andesite, and intermediate subduction zone volcanic rock in general (Table 4.11).

4.4.6 Discussion

4.4.6.1 Nature of igneous inclusions and implications for Merapi magma system

Before using the geochemistry of the igneous inclusions as a tool to interpret the evolution and structure of the Merapi magmatic system, we must establish that these inclusions are indeed from the magma system and not foreign xenolithic material from the deep crust incorporated into Merapi magma on ascent.

4.4.6.1.a Magmatic enclaves

The presence of basaltic enclaves in volcanic rocks of intermediate composition has have previously been interpreted as products of mixing between partially molten- to molten cogenetic magmas (e.g., Bacon, 1986, Eichelberger *et al.*, 2000). Textural relations such

as lobate to elliptical shapes, chilled margins, finer grain size, acicular to elongate crystal groundmass, and lower degree of crystallinity overall, suggest relatively quick solidification of blobs of magma on contact with cooler host melt formed as a result of magma mingling rather than hybridization (Bacon, 1986). Given the textural relations of liquid to chilled contacts with the host basaltic andesite, the enclaves analysed here are interpreted to be cognate igneous inclusions indicative of magma mixing in the Merapi plumbing system as had been proposed by previous authors (e.g. Boudon *et al.*, 1993; Camus *et al.*, 2000).

Geochemical evidence is in support of these textural characteristics, with pyroxene and plagioclase compositions largely plotting within the reference field for Merapi basaltic-andesite (Figure 4.8, 3.9, 3.11). Normal zoning from bytownite cores to labradorite to andesine rims and groundmass crystals is likely to be due to changes in physical and chemical conditions upon incorporation into the host Merapi andesite. Fluctuations in the An content of plagioclase can result from variation in a number of physical and chemical factors including melt composition, temperature, pressure and the water content of the magma (e.g. Beard & Borgia, 1989; Housh & Luhr, 1991; Sisson & Grove, 1993; Panjasawatwong *et al.*, 1995). Using an empirical equation for the equilibrium near-liquidus plagioclase composition in an anhydrous melt (Panjasawatwong *et al.*, 1995; Results in Appendix B) calculated An contents for basaltic enclaves are ~ 75 to ~50 An mol% for temperatures between 1200 and 800 °C at a pressures of 500 MPa, the pressure at which the majority of Merapi basaltic-andesite crystallisation is thought to occur (Gertisser, 2001). Extrapolating to lower pressures not accounted for in the model of Panjasawatwong *et al.*, (1995), raises the calculated An content by ~10%, and raising pressures up to 1000 MPa lowers compositions by ~10% (Figure 4.11). Thus, the calcic bytownite cores present in the basaltic enclaves may be formed due to variation in physical parameters such as temperature and pressure, potentially aided by hydrous conditions as evidenced by the presence of amphibole. The lower An mol % rims of andesine to labradorite compositions and groundmass crystals potentially formed due to interaction with the host basaltic andesite.

In Harker diagrams, the analysed enclaves generally plot within the host basaltic andesite field or with slightly more mafic compositions along fractionation trends (Figure

4.19), reflecting variations in mineralogy and lower crystal contents overall with less plagioclase and higher modal percent pyroxene. Lower Na_2O , K_2O , Al_2O_3 may reflect lower feldspar concentrations with higher MgO , Fe_2O_3 , TiO_2 , and CaO indicative of the relative higher volume of clinopyroxene (Figure 4.18). Their REE patterns also overlap with the host basaltic andesite with a slight enrichment in HREE potentially due to the presence of amphibole (Figure 4.20). The radiogenic isotope ratios of the enclaves provide further evidence for the cogenetic nature of the enclaves as they consistently plot within the Merapi basaltic andesite field (Figure 4.21). As the enclaves are mineralogically and geochemically similar to the host basaltic-andesite but vary somewhat in major and REE composition, they potentially record evolution from a hydrous, amphibole-bearing basaltic magma to the drier, amphibole-poor host basaltic andesites.

Although analysed for major elements only, the mixed andesite samples distinguished in the field on the basis of colour (4-A1 and 4-A2; Figure 4.12b, Table 4.9) are essentially mineralogically and compositionally identical. However their fluid contacts support the concept of dynamic mixing and mingling processes acting in the Merapi magma plumbing system. The andesite magmas show evidence for reheating and recrystallisation at higher temperatures including reverse-zoned plagioclase with dusty sieve-textured rims. Similar textures have been reported from many mingled and hybrid magmas and is thought to form by reheating plagioclase above its solidus temperature, but below its liquidus with subsequent rapid recrystallisation trapping glass in a more calcic rim (Tsuchiyama, 1985; Nakamura & Shimakita, 1996). Again using the empirical equation for the equilibrium near-liquidus plagioclase composition in an anhydrous melt (Panjasawatwong *et al.*, 1995: Results in Appendix B), calculated An contents for plagioclase in the basaltic-andesite are ~ 86 to ~ 65 An mol% (Figure 4.15), for temperatures between 1200 and 800°C, at pressure of 500 MPa (Gertisser, 2001), and for the least evolved groundmass composition reported by Schwarzkopf *et al.*, (2001) including errors. Extrapolating to lower pressures again raises the calculated An content by $\sim 10\%$, and raising pressures up to 1000 MPa lowers An compositions by $\sim 25\%$. Using the average groundmass composition reported by Schwarzkopf *et al.* (2001) gives a lower range of equilibrium plagioclase compositions, ranging between ~ 70 and 50 An mol %

for the physical conditions outlined above (Figure 4.15). Thus the calcic anorthite cores and zones present in the basaltic-andesites cannot be formed due to variation in physical parameters such as temperature and pressure and require a different source. The lower andesine to labradorite zones, rims and groundmass crystals potentially formed from the more evolved groundmass compositions reported by Schwarzkopf *et al.* (2001).

4.4.6.1.b Plutonic Inclusions

Before using the geochemistry of the plutonic inclusions as a tool to interpret the evolution of the Merapi magmatic system, we must establish whether these inclusions formed from Merapi magmas. If so, are they chilled liquids, or crystal cumulates? The bulk rock compositions of plutonic rocks are likely to vary significantly from the liquid composition from which they formed due to the action of crystal accumulation and melt segregation and migration (e.g. McBirney, 1995). This may be established by assessing crystal textures, whole rock composition and whether there is equilibrium between mafic minerals and the whole rock.

Numerous geochemical studies of subduction zone volcanoes have identified plutonic igneous inclusions in lavas as crystal fractionation residues, inferred to reflect differentiation processes that have operated on the magmas of these arcs (e.g. Beard, 1986, Fichaut *et al.*, 1989, Beard & Borgia, 1989, Heliker, 1995; Costa, *et al.*, 2002).

The majority of plutonic inclusions analysed here possess clear petrographic evidence of crystal accumulation, such as uniformly coarse crystal sizes, alignment of minerals, modal mineral layering, mono-mineralogy, and disequilibrium textures such as heavily zoned or resorbed/embayed crystals. Thus major, trace element and REE trends observed in the whole rock geochemistry must be interpreted with respect to their formation mechanism as cumulates.

Zoned and embayed crystals indicate disequilibrium and the polygonal crystal boundaries in two of the samples indicate prolonged periods of high temperature subsolidus conditions (Holness, 2005). Like the basaltic enclaves, pyroxene and plagioclase compositions largely plot within the reference field for Merapi basaltic-andesite (Figure 4.8, 4.9, 4.11), with a few slightly more calcic clinopyroxene compositions. The plutonic

inclusions also possess more calcic plagioclase than the basaltic enclaves with compositions extending up to An_{95} . This highly calcic feldspar may be a function of increased H_2O contents in a crystalline mush, which is supported by the presence of significant amounts of hydrous amphibole in these inclusions, particularly in the mafic plutonic fragments. However this high anorthite feldspar may also be due to the presence of mafic liquids with high Ca/Na, or due to interaction with a country rock high in Ca. These factors cannot be distinguished without further investigation of the interstitial glasses present in some inclusions, and detailed micro-isotopic analysis of crystals in the inclusions.

These plutonic inclusions also show chemical evidence for mineral accumulation relative to Merapi basaltic andesites. Significant variability in Al_2O_3 , FeO, TiO_2 , P_2O_5 , K_2O and SiO_2 correspond to variations in the modal abundances of amphibole, plagioclase, apatite, and Fe–Ti oxides, with scatter in the data supporting their identification as cumulates. FeO_2O_3 , MgO, CaO and TiO_2 contents are highest in mafic plutonic inclusions indicating an increased abundance of pyroxene and amphibole (Figure 4.18). This division between mafic plutonic inclusions, enclaves and the other samples analysed, is more evident in plots using MgO as index of differentiation (Figure 4.19). Many samples are consistent with binary mixtures of pyroxene and plagioclase, or pyroxene and amphibole, as reflected in the high modal percentages of these minerals. The mafic samples are rich in MgO, TiO_2 , and poor in K_2O and Na_2O , reflecting a high modal percentage of mafic minerals.

However the plutonic inclusions possess Ca/Na values ranging from compositions similar to Merapi basaltic andesite (2-3; from Gertisser & Keller, 2003a) to much higher values (2.75-17). This significant variation indicates other factors than pure crystal accumulation. Interaction with country rock or fluid migration may have contributed to the bulk compositional variation in these inclusions. P_2O_5 shows scattered positive and negative arrays with increasing SiO_2 (Figure 4.18) and decreasing MgO (Figure 4.19) respectively. The majority of the inclusions possess significantly lower (< 0.2 wt %) or significantly higher (> 0.5 wt%) P_2O_5 than the host basaltic-andesite, and these trends may be interpreted to reflect a depletion or enrichment in apatite. Plutonic inclusions with low P_2O_5 contents (Figure 4.18; < 0.2 wt%) do not contain significant amounts of apatite,

potentially indicating a loss of enriched melt prior to complete crystallization / entrainment in Merapi basaltic-andesite. This has been reported for similar plutonic inclusions in San Pedro volcano in Chile (Costa *et al.*, 2002). These authors proposed P_2O_5 variability was due to a combination of processes involving liquid loss from a crystal pile before or after apatite crystallisation, and not just melt loss from a plagioclase, pyroxenes olivine cumulate, as the partition coefficients for P in these minerals are < 0.1 (e.g. Rollinson, 1993). However, the enrichment in apatite may alternatively be due to interaction with carbonate host rock or melts, as apatite is a common mineral in contact metamorphosed carbonate rocks. As mentioned previously, calc-silicate inclusions were observed in one of the felsic plutonic inclusions (Troll *et al.*, 2003). However, distinction between these hypotheses would require geochemical analysis of the apatite crystals in both the meta-sedimentary and plutonic inclusions.

As with the basaltic enclaves, many of the REE patterns for plutonic inclusions also overlap with the host basaltic andesite (Figure 4.20). However, there is a moderate to marked depletion in LREE relative to Merapi host rocks in several of the samples from the 1998 eruption. This agrees with a low plagioclase/clinopyroxene modal ratio and low apatite content in these samples with loss of interstitial liquid rich in REE potentially amplifying this effect. Enrichment in middle REE (Figure 4.20), particularly in the samples from the 1994 eruption is likely to be a reflection of a dominance of amphibole (hornblende), clinopyroxene, and titanite in these samples (Rollinson, 1993) with potential amplification of heavy REE enrichment related to interaction with enriched fluids or calc-silicate xenoliths and melts. Flat to positive Eu anomalies reflect plagioclase accumulation, also potentially amplified by loss of interstitial liquid rich in REE with a negative Eu signature.

Sr and Nd and Pb isotope ratios for plutonic inclusions largely fall within a range defined by published data for Merapi volcano (Gertisser & Keller, 2003a and references therein), confirming their cogenetic nature. One sample (4.P-2) falls well outside this range with a much lower $^{143}Nd/^{144}Nd$ ratio relative to the other samples indicating this may be an chemical procedural error given the sample possess similar Sr and Pb isotopes as well as, major, trace, REE element compositions (Figure 4.21a). It is unlikely that any geological process that could alter the Nd isotope composition so considerably would not

have an effect on major, trace element, or other isotopic compositions. Sr isotope ratios obtained for representative samples of inclusions plotted relative to local crust, host andesite, and Holocene basalts show a step-wise progression from lower radiogenic Sr values to higher radiogenic values (Figure 4.24). There is an apparent overlap between the older Medium-K series, with similarities in Sr ppm and SiO₂ variation between the Holocene Merapi basalts and the mafic plutonic inclusions in particular (Figure 4.26). Thus isotopic evidence confirms these plutonic inclusions formed in the Merapi magmatic system. However, given their overlap with the older magma series, (e.g. Holocene basalts) some of the inclusions may not have formed from the same magma batch as the host andesite, but rather represent relics of older magmas in the system, remobilized at a later date.

4.4.6.1.c Amphibole Megacrysts

The same is likely to be true of the amphibole megacrysts, with strong geochemical (Table 4.7) and petrographic evidence for a link between plutonic inclusions and these isolated large crystals (8-P-3) (Figure 4.13b). Their strong disequilibrium textures (Figure 4.13) indicate they were not crystallised directly from the host Merapi basaltic-andesite but rather from a more hydrous, deeper magma source within the plumbing system of the volcano. The fine-grained reaction rims on the amphibole megacrysts and many of the phenocrysts present in Merapi basaltic-andesite are likely to be formed by volatile loss from the magma during ascent (Devine et al., 1998; Rutherford & Devine, 2003) or because of reheating. These reaction rims are not as well developed or absent in smaller amphibole phenocrysts contained within Merapi pumice ejecta (Gertisser, *pers. comm.* 2006). This may indicate the rims present in the dome samples studied here, form due to slower ascent rates from depth, allowing storage outside the amphibole stability field at pressures less than ~150 MPa. The extent of reaction rims can in principle, be used to estimate magma ascent rates and has been applied in previous studies (Rutherford & Hill, 1993; Devine et al., 1998). However, this awaits experimental data for amphibole rim development specific for Merapi magmas in order to relate measurements of these reaction rims to semi-quantitative magma ascent rates. As there is extensive petrographic

evidence of reheating in the Merapi magma system, such as mafic mixing and mingling textures, plagioclase sieve textures etc., reheating of the magma may also have produced some of the amphibole reaction textures, particularly where the crystal boundaries are rounded. Amphibole has been shown to be an unstable phase in Soufriere Hills basaltic to andesitic magmas above $\sim 875^{\circ}\text{C}$ in the pressure-temperature experiments of Barclay et al. (1998). However these features are difficult to distinguish from ascent/decompression-induced reaction textures, and experimental work specific to Merapi magmas would need to be carried out to clarify the nature of these reaction rims.

4.4.6.2 Physical structure the Merapi plumbing system

The petrography and geochemistry of the igneous inclusions analysed confirms that they are petrogenetically linked to Merapi magma system. It is therefore possible to use the intrinsic conditions of their formation to describe stages or levels of Merapi magmatism, potentially not recorded in the host volcanics. Thus, geobarometric calculations using minerals from these inclusions provide a significant tool to better assess the physical characteristics of crystallisation of the magmatic plumbing system.

There are a paucity of suitable geobarometers for garnet-free mafic to intermediate rocks in the literature and even for thermodynamically well constrained metamorphic assemblages, uncertainties on crystallisation pressures can be up to several hundred MPa. The geobarometric calculations presented here therefore offer a first order pressure approximation. Analysis of other assemblages (rare olivine, Fe-oxides etc.) required for constraints that are more concrete. For mineral structural formulae and barometric calculations for pyroxene and amphibole see Appendices C and D respectively. Gertisser (2001) calculated a range of crystallisation temperatures from 920 to 1050°C for the Merapi volcanics. An intermediate temperature of 1000°C has been used for geobarometric calculations, given the mafic nature of the enclaves and inclusions presented in Figures 4.26, 4.27 and 4.29, with calculations run for temperatures across the range defined by Gertisser (2001) showing generally limited fluctuation in calculated pressures.

A link between clinopyroxene crystal chemistry and pressure of crystallization has been discussed in the literature for over twenty years (Dal Negro *et al.* 1982; Dal Negro *et al.*, 1984; Dal Negro *et al.* 1989; Manoli & Molin 1988). More recent work by Nimis and Ulmer (1998) and Nimis (1995, 1999) detailed a correlation between clinopyroxene crystal chemistry and pressure, providing an opportunity to constrain the depth of magma crystallisation and magmatic plumbing systems feeding volcanoes. According to Nimis and Ulmer (1998), and Nimis (1995, 1999), pressure can be expressed as linear function of unit cell volume, V_{cell} and M_1 site volume, V_{M1} , resulting in an equation that relates V_{cell} and V_{M1} to the crystallisation pressure of clinopyroxene. The standard error on prediction of pressure crystallization values is up to ± 200 MPa (Nimis, 1999) but generally around 140 MPa. However, recent work on hydrous and high-SiO₂ experimental compositions has highlighted inherent weaknesses in this model, which appears to underestimate crystallization pressures for more evolved and or more hydrous systems and has inherent uncertainty higher than the value reported by Nimis & Ulmer (1998) with a standard deviation between measured and calculated pressures of ~ 1240 MPa (Purika *et al.*, 2003). If this is a reliable test of the model any pressure variation of less than 1240 MPa would be insignificant. However, despite this work by Purika *et al.*, (2003) the barometer of Nimis (1999) remains widely used in the absence of more reliable alternatives and for a relatively mafic water poor system such as Merapi, errors are likely to be closer to the values reported by Nimis 1999.

Thus despite uncertainties, the Nimis (1999) barometer was applied to electron microprobe analyses of pyroxenes from igneous inclusions and enclaves in the Merapi lavas. A range of pyroxene crystallisation pressures (Nimis, 1999) from 65 to 1300 MPa (± 200) was obtained (Figure 4.26a), with a concentration of values between 400 and 700 MPa. Results for host Merapi basaltic andesite range from 200 to 900 MPa with the bulk of pyroxene crystals forming between 400 and 500 MPa (Gertisser, 2001). Assuming a range of 64 to 1300 MPa, and reasonable densities for the Merapi edifice (2.6 g/cm³), Javan crust (2.8 g/cm³), and upper mantle (3.3 g/cm³), the bulk of pyroxenes in the basaltic andesites crystallised in a mid to deep crustal reservoir. The pyroxenes in the igneous inclusions then potentially crystallised as shallow as ~ 3 km beneath the summit to as deep as ~ 45 km, with the bulk of crystallisation occurring in a diffuse zone, also in

the mid to lower crust (Figure 4.26a). Pyroxenes in felsic plutonic inclusions have crystallisation pressures between 65 and 720 MPa, with lower pressures generally confined to the rims of crystals and the majority of crystallisation occurring at pressures of between 300 and 400 MPa. Pyroxenes in mafic plutonic inclusions have similar crystallisation pressures to the felsic inclusions with values > 300 MPa and up to 720 MPa. Basaltic enclave pyroxenes have the deepest pressures ranging from ~ 300 MPa to 1300 MPa (Figure 4.26a).

Several studies have illustrated that the chemistry of amphibole is also sensitive to a number of factors including pressure, temperature, oxygen and water fugacities (e.g., Spear, 1981; Wones & Gilbert, 1981; Helz, 1982). Amphibole is a common phase in arc rocks that is stable up to ca. 3100 MPa and 1100°C (Schulze, 1987) with numerous empirical and experimentally calibrated thermo-barometers for silicic magmas (e.g., Hammarstrom and Zen, 1986; Hollister *et al.*, 1987; Johnson & Rutherford, 1989; Schmidt, 1992; Holland & Blundy, 1994). In their 1989 paper, Johnson & Rutherford experimentally calibrated the Al in hornblende barometer for an assemblage of hornblende, biotite, quartz, sanidine, plagioclase, sphene, magnetite or ilmenite and applied it to post-Bishop tuff volcanic rocks from Long Valley caldera. Although the assemblage present at Merapi is not ideal, the experimental Al in hornblende barometer of Johnson & Rutherford (1989) was applied to electron microprobe analyses of amphiboles from igneous inclusions and enclaves in the Merapi lavas. Lacking quartz and biotite, the equation provides an upper limit for pressure, as the Al_2O_3 content of the coexisting amphibole is higher than it would be otherwise (Johnson & Rutherford, 1989). The complexity of amphibole chemistry and thus the uncertainty of mineral recalculations must also be considered when assessing information obtained using the barometer of Johnson & Rutherford (1989).

The calculations give largely overlapping results with those obtained by pyroxene geobarometry, with a range of crystallisation pressures from 400 to 1600 MPa (Figure 4.26b) and the majority of data falling between 500 and 800 MPa. Calculated results from felsic inclusions range between 400 and 800 MPa while crystallisation pressures for mafic inclusions are more restricted, between 500 MPa to 600 MPa. Amphiboles in

basaltic enclaves range between 300 and 700 MPa. Crystallisation pressures for large amphibole megacrysts are high and are concentrated between 700 and 800 MPa, with a small number of higher values up to 1600 MPa (Figure 4.26b).

Although only approximations, results from geobarometry on igneous inclusions found in Merapi lavas suggest a crystallisation record for minerals in these inclusions spanning the depth of the crust and into the upper mantle. As these inclusions are taken to represent cognate enclaves or more coarsely crystalline fragments of parental Merapi magma, the spread of pressure results suggests the presence of melt in numerous pockets with evolution in numerous magma reservoirs at different levels in the crust and upper mantle beneath this volcano.

4.4.6.3 Comparison of Geo-barometric Results with Geophysical Data

Comparison of the crystallisation pressures obtained in this study with seismic data from Ratdomopurbo & Poupinet (2000), shows a link between seismic anomalies in the shallow crust beneath Merapi and the lower crystallisation pressures of ~ 300 to 400 MPa obtained from a small number of analysed samples (Figure 4.27). However, more-recent geophysical studies were unable to locate the proposed shallow magma reservoir reported by Ratdomopurbo & Poupinet (2000). GPS and tilt data (Westerhaus *et al.*, 1998; Beauducel & Cornet, 1999) and seismic data (Wasserman *et al.*, 1998) do not support the presence of a shallow magma reservoir within or just below the Merapi edifice, and these studies found no evidence for the source of erupted lavas. These studies and others focused on the internal structure of the Merapi edifice (Maercklin *et al.* 2000; Wegler & Lühr 2001; Müller *et al.* 2002; Müller & Haak 2004), with the deeper structure beneath Merapi and Central Java remaining poorly defined. Given the small number of low crystallisation pressures obtained in this study, late crystallization may occur in ephemeral magma pockets in the shallow crust prior to eruption and/or on ascent in the conduit. However, the bulk of magma storage feeding volcanism must occur at deeper levels below the volcano.

Comparison of pressure estimates with tomographic data produced by the German MERapi AMphibious EXperiments (MERAMEX) study shows strong linkages between physical anomalies beneath Merapi and crystallisation pressures (Chadwick *et al.*, *submitted*).

In 2004, MERAMEX acquired active and passive seismic data in Central Java, Indonesia. The natural seismic activity for onshore Central Java was recorded using a temporary seismological network consisting of 106 seismometers in combination with Earth data loggers (EDL) (Figure 4.28). Offshore, the network was augmented by nine Ocean Bottom Hydrophone and five Ocean Bottom Seismometer stations (Wagner *et al.* 2007, Koulakov *et al.*, 2007). Koulakov *et al.* (2007) and Wagner *et al.* (2007) applied several synthetic tests including classical checkerboard tests, tests using realistic anomalies and tests applying different data subsets to check the reliability of the detected anomalies and the results proved to be robust.

The identified P (Vp) and S (Vs) wave velocity anomalies show a reduction in seismic velocities of $> 30\%$ and are largely located in the Kendeng basin just north of the active Sumbing, Merapi and Lawu volcanoes (Figure 4.28). The Kendeng basin is the main Cenozoic depocentre for the region (Smyth *et al.* 2005). It contains between 8 km (de Genevraye & Samuel, 1972) and 11 km (Untung & Sato, 1978) of sediment and overlies a basement of uncertain composition, extending approximately 25 km below the surface (Jarrard, 1986; Curray *et al.*, 1977; van Bemmelen, 1949). The velocity anomaly is elliptical and has a diameter of ~ 80 km east-west and 30 km north-south (Figure 4.28b). The size and amplitude of this anomaly decreases with depth, yet it is still evident in the upper mantle down to 50 km. It is inclined towards the slab and has an elevated Vp/Vs ratio of 1.9 (Koulakov *et al.*, 2007) relative to the crustal average of 1.7. The Vp and Vs anomalies are highly correlated with the largest amplitudes of the anomaly located between Merapi and Lawu volcanoes.

This tomographic anomaly correlates in size shape and location with a strong gravity low that exceeds -58 mgal (Untung & Sato 1978; Smith & Sandwell 1997; Smyth *et al.* 2005) picked out on Bouguer gravity maps and is largely contained within the Kendeng zone (Smith & Sandwell 1997; Smyth *et al.* 2005). This basin extends ~ 400 km east-west and ~ 100 -120 km north-south and is thought to contain between eight and

eleven kilometers of sediment (Untung & Sato, 1978; Smith *et al.*, 2005). While several previous studies interpreted this gravity low as a basin and rift system, Smyth *et al.* (2005) proposed no crustal thinning in the area, and suggested that flexural loading of the crust by the volcanic chain contributed to the subsidence in this region. Waltham *et al.* (2006) forward modeled this gravity data and required a high-density volcanic arc to replicate the gravity low accurately and proposed the presence of additional buried loads to account for the anomaly, specifically loading caused by magmatic underplating.

The strong low-velocity anomaly and the elevated V_p/V_s ratio combined with the gravimetric data are indicators for an unusually high fluid content in this area of the central Javan crust (Chadwick *et al.*, *submitted*). Given the marked seismic velocity anomaly, its extent to the upper mantle and its location in the back-arc of the long-lived and highly active Sunda arc, this fluid is likely to be a magmatic melt system in the crust and upper mantle of Central Java. An average reduction of 20 % in V_p combined with the observed 9 % increase in V_p/V_s corresponds to a melt fraction of 13 - 25 % *in situ*. This estimate is based on an effective elastic moduli model of composite rocks (Berryman, 1995), assuming melt is present as randomly oriented elongate pockets with a bulk modulus of ~24 GPa, typical of silicate melts (Webb & Courtial, 1996). The lower estimate of 13 % melt includes a weakening of the host rock matrix by intense fracturing. The upper 25 % estimate applies to unfractured host rock (Rabbell *et al.*, 2004) and is below the critical melt fraction of 30 – 35 %, above which, the shear strength of partially melted rock is expected to approach zero (van der Molen & Paterson, 1979). As only a limited number of earthquakes occur within the low velocity zone, a melt volume in the upper range of the calculated percentage is most likely (Chadwick *et al.*, *submitted*).

Tomographic velocity lows beneath recognised caldera systems (Masturyono *et al.* 2001; Harrison & White 2004; Husen *et al.* (2004) correspond in size, amplitude and depth range to the identified anomaly. Weiland *et al.* (1995) identified wave attenuation of 35 to 30 % beneath Long Valley caldera, California. Miller & Smith (1999) reported an anomaly with up to 15% attenuation beneath Yellowstone, also in the USA, and Husen *et al.* (2004) confirmed the presence of large volume melt body at > 8 km depth. Low-velocity anomalies with a high ratio of P- to S-wave velocity (V_p/V_s) beneath the Taupo

volcanic zone, New Zealand are taken to, denote the presence of partial melt in the crust (Harrison & White, 2004). Tomography and seismicity analyses of Toba caldera, Indonesia, the largest Quaternary caldera on Earth (Masturyono *et al.*, 2001), identified a strong, shallow, negative anomaly with reductions in seismic velocities of up to 37 % in the upper 10 km of crust and continuity of lower velocities to the upper mantle. This anomaly and a corresponding gravity low are thought to be formed by partially-molten material in a large volume magmatic system with mantle roots (Masturyono *et al.*, 2001).

In addition, the strong gravity low present in the Kendeng zone of Central Java (Smyth *et al.*, 2005; de Genevraye & Samuel, 1972; Untung & Sato 1978; Smith & Sandwell 1997; Waltham *et al.* 2006) (Fig. 4.28), is similar in amplitude to the gravity low attributed to the presence of melt below Toba caldera (Masturyono *et al.*, 2001). Thus, the main distinction between documented large-volume magmatic systems (e.g. Yellowstone, Long Valley, Taupo, Toba, etc.) and the anomaly in Central Java is the lack of an associated large-scale caldera system and catastrophic caldera-forming (CCF) eruptive products.

Given the absence of directly associated large-volume eruptive products, the co-magmatic igneous inclusions from Merapi Volcano, sited at the southern margin of the low-velocity anomaly, act as a probe into the crust of Central Java. Combined with geochemical and petrological evidence, the geobarometric calculations indicate that within this zone, there are melt bodies where magma mixing, crystallisation, crystal settling and assimilation occur. Due to the resolution of the tomographic study (Koulakov *et al.*, 2007; Wagner *et al.*, 2007), individual structures of < 15 km size are not resolvable and thus appear as one large anomaly. This anomaly is therefore unlikely to be the result of one large body in the crust but is rather a plexus of smaller magma reservoirs (Chadwick *et al.*, *submitted*) (Figure 4.29).

These geophysical anomalies in Central Java then represent numerous bodies of solidified, crystal-rich, semi-molten and molten magma pockets and adjacent crust (Figure 4.29). The exceptionally high amplitudes of the low-velocity anomaly in the uppermost 10 km of the crust may be amplified by sedimentary deposits as well as

hydrothermal fluids and gas in the Kendeng basin. However, these deposits could not produce the observed strong velocity and gravity lows in isolation, nor the continuity of the velocity anomaly to deeper depth sections of the crust and upper mantle. The viscoelastic combination of crystal-rich melt, solidified magma, and heated host rock would represent a comparatively impermeable matrix, acting as a barrier to ascending fluids and melts from the mantle wedge, potentially redirecting flow along the bottom of the velocity anomaly to the periphery of the system. Surface expressions of hydrothermal fluid flux are evident at Merapi volcano (Commer *et al.*, 2006) and in Central Java, including geothermal systems such as the Dieng Plateau and active mud volcanoes, like Kuwu and the Sangiran dome co-incident with the periphery of the anomaly (Figure 4.30).

It is thought that peripheral andesitic to rhyolitic volcanism is a precursor to the formation of large volume silicic caldera systems (Price *et al.*, 2005). Such peripheral strato-cone volcanism has been identified at Toba caldera (Harrison & White, 2004), and Long Valley caldera (Metz & Mahood, 1985), and at smaller systems such as Uzon caldera (Belousov *et al.*, 2005). In addition, precursory intermediate volcanism has been identified in ancient ring complexes thought to represent the exhumed roots of caldera systems, e.g. Osippe ring complex in New Hampshire, USA (Kennedy & Stix, 2006). This implies that the crust must be thermally pre-conditioned by extensive mafic to intermediate volcanism before rhyolitic magma volumes typical of so called, catastrophic caldera forming eruptions, are produced. Similar to Ruapehu volcano in New Zealand, thought to be in this pre-conditioning stage (Price *et al.*, 2005), Merapi lavas are high in groundmass silica (Schwarzkopf *et al.*, 2001), indicating that rhyolite liquid is already present beneath this volcano. In conjunction, geophysical and petrochemical results give strong evidence for the presence of a large magmatic system supplying Merapi volcano and the adjacent volcanic systems in Central Java, with numerous interconnected melt bodies resulting in a low-velocity anomaly of $> 55000 \text{ km}^3$. In time, and given sustained heat flux through repeated injections of melt (*c.f.* Annen & Sparks, 2002), this system then has the potential to evolve into a much larger and more explosive ‘caldera-type’

system, capable of producing a catastrophic caldera forming eruption, and is a potential supervolcano in the making.

4.4.7 Implications and Conclusions

The petrology and geochemistry of the igneous and metasedimentary inclusions is significant for understanding petrogenesis and structure of the Merapi magma system as a whole. The geochemistry and petrology of igneous inclusions in particular, provides evidence for a complex open-system feeding Merapi volcanism with, mixing, mingling, crystallisation, crystal accumulation, crustal contamination, and periodical recharge.

Underplating of a hot mafic magma beneath a more fractionated highly crystalline reservoir combined with intrusion of these mafic magmas into such reservoirs would result in remobilisation of highly crystalline resident magma via reheating and partial melting. This would aid the formation of mafic enclaves (mingling) in the andesitic magma through buoyancy or forceful injection with the later potentially resulting in fragmentation of earlier-formed crystalline material to form angular inclusions (plutonic inclusions), and convection forming mixing textures. Magma mixing has the potential to initiate eruption (e.g., Sparks *et al.*, 1977), and may be identified using volcano-seismology. Several eruptive events at arc volcanoes have been documented where mixing is believed to have been followed by eruption within a relatively short period of time (e.g. Pallister *et al.*, 1992). Given the deep level of storage at Merapi indicated by the combined geobarometric and geophysical studies, it is integral for the deep seismic activity of this volcano to be monitored to better assess the link between replenishment and eruption.

Recycled cumulates have been widely recognised in arc magmas (e.g. Tepley *et al.*, 2000; Turner *et al.*, 2003; Dungan & Davidson, 2006) and given the long-lived nature of Merapi volcanism it is sensible to conclude that a significant mass of cumulate material has accumulated in the crust and that this material is fortuitously incorporated into ascending magmas. In conjunction with geophysical data, there is strong evidence for the presence of a semi-molten crystalline mush beneath Merapi. This complex plumbing system has implications for magmatic evolution at Merapi, as there is a high

likelihood of disequilibrium assemblages present in lavas and there is the potential for increased magma-crust contact area. This large mass of semi-molten to molten magma would be likely to lower the thermal barrier against assimilative recycling of the crust, which will be discussed in detail in the subsequent section, and even allow incorporation of mafic to ultramafic lithologies, the plutonic roots of the magmatic system (e.g., Heliker, 1995; Dungan & Davidson, 2006). This also has significant implications for geochemical mass balance assessments of the Merapi magma system, as partial assimilation of its own plutonic roots could potentially overprint primary geochemical signatures, important for source studies (Dungan & Davidson, 2006). Thus mass balance models for the Merapi system need to take account of the heterogeneity of Merapi magmas at a crystal scale.

Geobarometry on minerals in the igneous inclusions indicates that the processes of mixing, mingling, crystallisation, accumulation, and assimilation are not likely to be occurring in one static chamber, but numerous, interconnected and potentially ephemeral reservoirs beneath Merapi. The main zone of andesite formation is located at mid to lower crustal levels (Gertisser, 2001) with less common shallower crystallisation depths indicating late crystallisation on ascent and possibly temporal higher-level crustal melt pockets or conduits. Therefore a traditional view of one or two large magma reservoirs, at least for the Merapi magmatic system, does not apply. Multiple chambered systems have been proposed for other volcanoes (e.g. Power et al., 2002; Myers et al., 2002; Price et al., 2004). Such a large and complex plumbing system has long-term implications for hazard assessment and monitoring at Merapi as the volcano may be a relatively small surface expression of a much larger magmatic system developing in the crust. This has significant implications for the study of large-volume volcanic systems. The identification of such a system beneath Merapi and the other centres in Central to East Java also has scientific implications. Despite extensive work to characterise the structure and eruptive products of large volcanic centres, studies investigating their pre-eruptive origin have been restricted, as the last identified super-eruption occurred at Toba caldera, in Sumatra, Indonesia approximately 74,000 years ago (Bindeman, 2006 and references therein).

4.5 *Crustal assimilation at Merapi volcano, Java Indonesia: insights from crystal isotope stratigraphy and stable isotope gas chemistry*

Arc magmas typically display chemical and petrographic characteristics indicative of crustal contamination either at source or in the crust (Hildreth & Moorbath, 1988, Davidson *et al.*, 1990). Isotopic heterogeneity at Merapi has been attributed to variable degrees of source contamination deep in the Sunda-arc subduction zone system based on whole rock geochemical data (Gertisser & Keller, 2003a; Debaille *et al.*, 2006). These authors argued that shallow contamination at Merapi was unlikely due to a lack of systematic variation in whole rock isotopes with SiO₂. Trends towards elevated whole rock $\delta^{18}\text{O}$ were attributed to possible post-eruptive hydration and exchange of oxygen between ground water and volcanic glass (Gertisser & Keller, 2003a).

However, increasing numbers of *in situ* isotope studies have highlighted limitations inherent in whole rock isotope analysis of phenocryst-rich volcanic rocks and challenged the assumption that the crystals contained within these samples grew from a magma with the bulk composition of that whole rock (e.g. Davidson & Tepley, 1997; Wolff *et al.*, 1999; Ramos *et al.*, 2005). These studies have identified heterogeneity at the mineral- and sub-mineral scale, with whole rock isotopic ratios regarded as representing the sum of the magma's component parts rather than a representation of a true liquid (cf. Price *et al.*, 2005). *In situ* isotope profiles measured across a phenocryst may record petrogenetic processes that are masked in the whole rock isotope ratios (Figure 4.2). Given the crustal stability field of plagioclase (cf. Ramos *et al.*, 2005), it is an ideal phase for identifying crustal petrogenetic processes in magma systems via *in situ* Sr isotope analysis. Plagioclase crystals in intermediate arc magmas typically have a high Sr content, are often complexly zoned and given the minerals slow isotopic equilibration rates with respect to Sr (Giletti & Casserly, 1994), typically preserve magmatic Sr isotopic compositions, thus recording changing isotopic compositions of a magma with time. In

addition, the technique has been utilised to identify the presence of xenocrysts in various magmatic systems (e.g. Perini *et al.*, 2003).

Crystal isotope stratigraphy in feldspar (Davidson & Tepley, 1997) is thus a powerful tool for assessing the impact of complex shallow-level open system processes at arc volcanoes such as Merapi volcano, where plagioclase is the dominant mineral phase and eruptive products have up to 60 % crystallinity. Although source contamination may play a significant role in Merapi magma petrogenesis, the occurrence of shallower processes may be volumetrically significant and could have important repercussions for magma evolution and potentially eruptive behaviour. As noted in section 4.4, the presence of metasedimentary xenoliths in recent eruptives indicates the interaction between Merapi magma and local crust (cf. Renzulli *et al.*, 2001; 2003). Although the occurrence has been noted and samples have been described by previous workers (e.g. Kerinec, 1982; Clocchiatti *et al.*, 1982; Camus *et al.*, 2000, Gertisser & Keller, 2003a), detailed geochemical analyses of these xenoliths and an investigation of their significance with respect to the Merapi magmatic system and volcanism is lacking.

Discounting shallow crustal assimilation as a significant process for Merapi magmas is potentially drawn from an assumed composition of the underlying arc crust e.g. a relatively anhydrous and basic igneous nature, or a typical continental SiO₂-rich composition. These lithologies would be likely to have a noticeable impact on Merapi whole rock geochemistry (cf. Smith *et al.*, 2006). However, in studies of ocean arc systems where crustal assimilation has been considered and tested using detailed petrography and geochemistry, this process appears to have a significant impact and shows marked parallels to continental settings where the importance of crustal assimilation has long been established (e.g. Tamura & Tatsumi, 2002; Smith *et al.*, 2003; Smith *et al.*, 2006).

The possibility of contamination of Merapi and Sunda arc magmas by upper crustal lithologies is not new and has been proposed by previous workers (Luais, 1986; Hemond, 1986; Turner & Foden, 2001). Gasparon *et al.* (1994) reported considerable crustal contamination of recent Sunda arc lavas based on a He isotope study. However,

despite these studies, a crustal input to Merapi magmas, bar those incorporated at source has generally been considered to have a minor or insignificant impact (e.g Debaille *et al.*, 2006). Based on this petrochemical study of Merapi lavas, xenoliths and gases, we argue that shallow crustal processes, particularly late-stage crustal contamination, may play a significant role in magma evolution, having potential implications for the general evaluation of element fluxes in subduction zones and importantly the eruptive behaviour of arc volcanoes.

4.5.1 Eruptive Behaviour of Merapi Volcano and potential Eruption Triggers

Merapi's eruptive behaviour is currently characterised by active dome growth and small-volume pyroclastic flows, so called block and ash flows. Dome growth periods typically last for several years and are punctuated by short explosive events, lasting hours to days (Camus *et al.*, 2000; Gertisser & Keller, 2003b; Andreastuti *et al.*, 2000). Merapi has a long term record of frequent large explosive eruptions (Camus *et al.*, 2000; Gertisser & Keller, 2003b; Andreastuti *et al.*, 2000; Newhall *et al.*, 2000). It is estimated that Merapi has caused up to 1500 casualties in the last 100 years alone, a period that is considered a time of relatively low explosivity compared with the volcano's longer term record (Newhall *et al.*, 2000).

The high levels of mortality associated with Merapi eruptions is linked to numerous factors including a high density of population surrounding the volcano and poor infrastructure, as well as difficulties in the prediction of short-lived explosive events. The seismic signals preceding eruption events are often equivocal, and monitoring seismologists at Merapi refer to the 'source mechanism problem' for the signals received from the volcano (e.g. Ratdomopurbo & Poupinet, 2000; Richter *et al.*, 2000). Eruptions associated with deep volcanotectonic earthquakes are believed to indicate magma migration from below the volcanic edifice (Ratdomopurbo & Poupinet, 2000) and this is supported by petrological and geobarometric results outlined in section 4.4 which confirm mixing and mingling processes in the Merapi magmatic system. However, some eruptions have limited or absent recognised seismic precursors, while

others are associated with shallow hybrid earthquakes, multi-phase events and tremors that may indicate shallow gas movement (Ratdomopurbo & Poupinet, 2000).

4.5.2 Petrology and Geochemistry: basaltic andesite and xenolith plagioclase

The samples for this study are thick sections cut from the basaltic-andesite clasts and xenolith samples from the July, 1998 block-and-ash flow deposits. 1998 block-and-ash flow deposits are comprised of three components; a basal avalanche, a low-density ground surge, and an ash layer (Schwarzkopf *et al.*, 2005). The basaltic-andesite and xenoliths samples analysed in this study are clasts from the poorly sorted basal avalanche, sourced from the 1998 dome. Decimetre- to centimetre-sized blocks are set in a fine ash matrix, with the largest blocks in the deposits typically between 1 and 3 m in size with rare exceptions of up to 20 m diameter. The clasts are dominantly juvenile material (up to 80% for clasts >3 cm) including highly porphyritic basaltic-andesite and lesser scoria (between 5%-40% of clasts >3 cm) (Schwarzkopf *et al.*, 2005). The crustal xenoliths are fragments enclosed in Merapi basaltic andesite and comprise a small proportion of the total erupted volume that is estimated to be approximately 2.5-4.3 km³ for the 1998 deposits (Schwarzkopf *et al.*, 2005).

4.5.2.1 Basaltic-Andesite Plagioclase

Merapi basaltic-andesite hosts a large population of plagioclase crystals, which range in size from groundmass crystals (<1 mm) to large phenocrysts (approximately 1 - 6 mm). On the basis of texture, composition, and zoning patterns, different types of plagioclase may be distinguished with four main types of plagioclase phenocryst texture observed: oscillatory zoning, patchy zoning, sieve textures, and clear homogenous feldspar.

Type 1 crystals (Figure 4.31a) are phenocrysts (>1mm), with highly calcic cores (An₈₀₋₇₀), which are relatively homogenous, anhedral to subhedral and sometimes show patchy or oscillatory zoning. The core is surrounded by zoned rims with a gradual shift in An content from the core to andesine to labradorite rims. Sieve textures and patchy zoning are common, with small remnant sodic patches present throughout the crystal.

Sieve-textured zones are commonly located near the outer part of the crystal and marked by slight increases in An content.

Type 2 crystals (Figure 4.31b) are phenocrysts (>1mm) with relatively homogenous, anhedral to subhedral, highly calcic cores ($> \text{An}_{80}$). There is a marked transition from these cores to zoned rims of andesine to labradorite composition. The sieve-textured regions are commonly located near the outer part of the crystal with patchy zoning present throughout.

Type 3 crystals (Figure 4.31c) are phenocrysts (>1mm), reverse zoned with patchy anhedral cores of andesine to labradorite compositions surrounded by relatively thick (up to 1 mm) homogenous calcic feldspar ($> \text{An}_{80}$) with a mantle of less calcic normally to sieve textured feldspar.

Type 4 crystals are normally zoned microlites and small phenocrysts (typically <1 mm), with homogenous euhedral cores surrounded by fine oscillatory zoning, with no marked resorption surfaces and of andesine to labradorite composition. Previous studies have concluded that these microlites and their zoning patterns are a function of severe degassing of the dome magmas during shallow ascent (Hammer *et al.*, 2000) and will not be discussed in this study.

Basic 2D raw data from CSD analysis are included in Appendix E with results of CSD analysis of the 1998 Merapi basaltic presented in Figure 4.32.

The CSD analysis of plagioclase from the 1998 basaltic andesite is relatively linear, with an overall CSD intercept (n_0) of 2.22, a slope of -1.85 and an R^2 value of 0.98, the latter suggesting a single plagioclase population (R^2 value > 0.98) which does not pick out the different crystal types discussed above identified by petrographic internal textures and chemistry. There is a slight concave upwards kink at the 1mm size fraction, where the CSD curve moves below the calculated regression line, indicating a slightly larger proportion of bigger crystals, potentially reflecting the presence of both groundmass (0.1 to 1 mm) and phenocryst populations (1 to 5.37 mm) of plagioclase (e.g. Higgins, 1996). These prospective sub-populations have intercepts and slopes of 3.36 and -3.4 (groundmass) and 1.39 and -1.63 (phenocrysts) respectively. The CSD plot is also kinked downwards at smallest crystal sizes (< 0.1 mm), implying fewer small crystals

than expected in a simple log-linear distribution and is most likely an artefact of the measuring process reflecting the difficulty in measuring every crystal in the smaller crystal size classes.

Major-element and Sr-isotope variation in Merapi basaltic-andesite phenocrysts are presented in Tables 4.12 and 4.13 and Figures 4.33 to 4.35. Core-to-rim variation is observed in all feldspar samples, with both normal- and reverse-zoned crystals present. The two main feldspar compositions are anorthite ($An_{>90}$), characteristic of basaltic – ultrabasic magmas and skarn settings and labradorite (An_{50-70}) that is more typical of a basaltic - andesitic magma. Individual crystals commonly show variations in mole fraction An from An_{34} to An_{95} (Figure 4.33). Transitions between zones appear very sharp, and are often marked by resorption surfaces (Figure 4.32) with marked shifts in An content of up to 40 mol % (Figure 4.33). Under normal magmatic conditions, a positive correlation between An mol% and other indicators of degree of evolution in feldspar (e.g. MgO wt%, FeO wt%) would be expected (Ginibre *et al.*, 2003). However, the analysed crystals appear to show a decoupling trend between high anorthite content and MgO and FeO wt% compositions through a distinctly negative correlation (Figure 4.33).

Core-to-rim variations in $^{87}\text{Sr}/^{86}\text{Sr}$ are also present in all samples (Figure 4.34) and the range in $^{87}\text{Sr}/^{86}\text{Sr}$ for plagioclase phenocrysts ($0.70568 - 0.70628 \pm 1$) markedly exceeds that recorded in recent Merapi whole rock ratios ($0.70571 - 0.70574 \pm 1$; Gertisser & Keller, 2003), (Figure 4.35). The most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio obtained from the sampled crystals was from a zone with high An of approximately 90 mol% (Figure 4.34b). Radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (≥ 0.70590) is coupled with An content of greater than 90 mol% and low $^{87}\text{Sr}/^{86}\text{Sr}$ (≤ 0.70585) is coupled with An of 40-60 mol% in three of the four phenocrysts sampled in this study. The fourth crystal (Figure 4.34a) shows a much lower range in $^{87}\text{Sr}/^{86}\text{Sr}$ with a lower range in X_{An} and lacks extreme dissolution surfaces. The outer crystal rims appear to be in equilibrium with the groundmass ($^{87}\text{Sr}/^{86}\text{Sr}$ of $0.70581 - 0.70591 \pm 1$), whereas feldspar in the inner zones and cores are typically in Sr isotopic disequilibrium with the analysed groundmass (Figure 4.34).

4.5.2.2 Sedimentary xenolith feldspar

For petrology and whole rock major-element, trace-element, REE, and isotopic analyses of sedimentary xenolith samples see previous sections 4.4.2.4 and 4.4.4. Sr-isotope compositions of analysed plagioclase crystals in these meta-sedimentary xenoliths are presented in Figures 4.34 and 4.35 and Tables 4.12 and 4.13.

Plagioclase from the formerly calcareous, meta-sedimentary xenoliths is typically unzoned, homogenous, and highly calcic ($>An_{80}$) (Figure 4.31d). Some crystals show patchy zoning with more sodic compositions. Major element compositions of the analysed feldspar strongly correlate with the high CaO low MgO cores in the magma-hosted plagioclase crystals (Figure 4.33). The $^{87}Sr/^{86}Sr$ ratios obtained for these metamorphic plagioclases ($0.70598 - 0.70602 \pm 4$) overlaps with the $^{87}Sr/^{86}Sr$ range observed in the high $^{87}Sr/^{86}Sr$, high An, low MgO plagioclase crystal cores (Figures 4.34 and 4.35).

4.5.3 $\delta^{13}C_{CO_2}$ and He isotope geochemistry of lavas, crust, calcareous xenoliths and fumarole gases

Basaltic andesite lavas have $\delta^{13}C$ values of -23.3 to -27.5‰ . These $\delta^{13}C$ values of the lavas are characteristic for low-concentration, reduced carbon present, i.e. strongly degassed igneous rocks (-27 to -15‰ ; Allard, 1983; Holloway & Blank, 1994). This points towards generally low partial CO_2 pressures in the basaltic andesite magmas consistent with the zoning present in Merapi microlites, thought to be a function of severe degassing of the dome magmas during shallow ascent (Hammer *et al.*, 2000).

The local limestones, a potential representative constituent of the subvolcanic basement (Gertisser & Keller, 2003a), have $\delta^{13}C$ values of -0.7 to -2.2‰ , characteristic for marine and biogenic carbonates (Hoefs, 1996). Calcareous xenoliths, discussed in section 4.4 of this work, show $\delta^{13}C$ values of -22.2 to -24.9‰ , implying that the xenoliths experienced additional severe CO_2 outgasing (cf. Holloway & Blank, 1994). Fumarole gases taken from Merapi summit, have $\delta^{13}C_{CO_2}$ values of -3.5 to -4.4‰ , consistent with a previously published analysis of Merapi fumarole gas of approximately

-3.9‰ (Allard, 1983). These values (avg. $\delta^{13}\text{C} \sim -4$) are lighter than pure magmatic (mantle-derived) CO_2 of $\delta^{13}\text{C} \sim -6$ to -8 (Javoy *et al.*, 1986; Marti & Tolstikhin, 1998). Elevated $\delta^{13}\text{C}$ gas values are not commonly produced by either open or closed system degassing (Holloway & Blank, 1994), and suggest that much of the CO_2 in the fumaroles may actually be non-magmatic. Merapi gas has a low $^3\text{He}/^4\text{He}$ Ra value of 3.6 ± 0.5 with a reported range from published literature of 5.5 to 6.5 (n=5) (Hilton *et al.*, 2002). For a complete table of data from Troll *et al.* (*In Prep*), see Appendix F.

4.5.4 Discussion

4.5.4.1 Source of crystalline isotopic heterogeneity in Merapi basaltic-andesite

Inter-crystal $^{87}\text{Sr}/^{86}\text{Sr}$ heterogeneity of plagioclase is thought to be associated with processes such as magma mixing and crustal assimilation (Davidson & Tepley, 1997; Ramos *et al.*, 2005). A geochemical profile for a plagioclase crystal growing undisturbed in a primary magma experiencing assimilation of a more silicic and radiogenic crustal material (e.g. AFC) would show increasing $^{87}\text{Sr}/^{86}\text{Sr}$ with decreasing An mol %, MgO wt% and FeO wt% from the crystal core outwards. In the case of mafic magma replenishment with less contaminated magma, or introduction of xenocrysts sourced from a more mafic magma or lithology, the converse would be the case (Davidson & Tepley, 1997). The former appears to be a likely hypothesis for one of the plagioclase phenocrysts analysed for Sr isotopes (Figure 4.34a). However, simple magma mixing, mafic replenishment or AFC processes cannot explain the profiles observed in the other crystals analysed. Feldspar with the highest An mol % typically has the most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 4.34b-d) and a negative correlation with MgO wt% and FeO wt% (Figure 4.33). The lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the cores of two of the plagioclase crystals (Figure 4.34b & c), appears to be a late internal dissolution effect that has been developed simultaneously with the rim. This is evident by the corresponding geochemical signatures and the patchy replacement texture present and a channel from the exterior to the interior of the crystal is visible in Figure 4.34c. This situation indicates that caution is required when interpreting stratigraphic positions in Merapi plagioclase crystals as reflecting a

straightforward temporal sequence from core to rim and limits the applications of techniques where a sequential growth sequence is assumed, e.g. as in diffusion modeling.

As discussed in a previous section (4.4.6.1.a), fluctuations in the An content of plagioclase can result from variation in a number of physical factors including melt temperature, pressure and the water content of the magma (e.g. Duncan & Green, 1987; Beard & Borgia, 1989; Housh & Luhr, 1991; Sisson & Grove, 1993). However, the marked variation in An mol % present in the analysed crystals, coupled with the variation in Sr isotope ratios, requires the action of open-system processes rather than changes in physical parameters. A xenocrystic origin for these high An mol %, high radiogenic Sr crystal cores (Figure 4.34 b-d) is therefore considered likely, given their strong similarities with the feldspar hosted in the meta-sedimentary xenoliths (Figures 4.33 and 4.34).

The meta-sedimentary xenoliths found throughout the recent pyroclastic deposits (Figure 4.14) indicate contact metamorphism between country-rock and Merapi magmas in the mid to upper crust (Camus *et al.*, 2000). The presence of wollastonite in the calc-silicate xenoliths (Table 4.8) is evidence for a reaction of Ca-rich carbonate with basaltic-andesitic magma at temperatures $> 600^{\circ}\text{C}$ ($\text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{CaSiO}_3 + \text{CO}_2$; Bowen, 1940; Tracey & Frost, 1991; Deer, *et al.*, 1992). Wollastonite is unstable below 400°C (Milke & Metz, 2002) and the abundance of this mineral along with anorthite and diopside in these xenoliths (Table 4.8), coupled with limited occurrence of lower grade assemblages (e.g. tremolite & quartz), indicates relatively rapid cooling following their formation. The likely protoliths for these xenoliths are the Cenozoic carbonate and volcanoclastic lithologies present in the Kendeng basin, with a maximum thickness of 11 km (Smyth *et al.*, 2005), and/or the Cenozoic carbonates, marls, and volcanics of the Southern Mountain zone (Figures 4.5 and 4.16). There is limited information published on the physical characteristics of the Merapi magma plumbing system. However, as discussed in the previous section (4.4.6.2) there is evidence that the bulk of magma storage is sited in the mid- to lower crust (Westerhaus *et al.*, 1998; Beauducel & Cornet, 1999; Ratdomopurbo & Poupinet, 2000; Gertisser, 2001; Gertisser & Keller, 2003b; Chadwick *et al.* submitted), with some evidence for limited shallow crystallisation. This indicates

that these reactions probably occurred in the mid-crust under significant heat and pressure with potential late stage shallower inputs.

The calc-silicate and volcanoclastic xenolith whole-rock geochemistry confirms interaction with the host andesite and the reaction process between country rock and magma is evident in their mineralogy and major element composition (Figure 4.21). Several calc-silicate samples possess a dominance of wollastonite in the core and an increasingly magmatic signature (Figure 4.21, Table 4.10) with a dominance of anorthite and diopside towards the rim (Table 4.8). Bulk compositions thus in part represent the final product of an exchange of material between the xenoliths and Merapi magma. Taking a recent Merapi magma that is relatively undifferentiated with respect to SiO₂ and MgO (51.85 wt% SiO₂, 18.53 wt% Al₂O₃, 8.6 wt% Fe₂O₃, 3.9 wt% MgO, and 9.58 wt% CaO; Gertisser & Keller, 2003a), the chemical potential contrast between this magma and meta-sedimentary xenoliths depends on the exact composition of the original sedimentary protolith. However, using the compositions of the xenoliths themselves, significant contrasts for Si, Al, Ca, Mg, and potentially Fe are probable. Thus, the xenoliths may have gained Al, Ti, Fe and Mg (supported by the occurrence of titanomagnetite almost exclusively in the reaction rims of the calc-silicate xenoliths), with variable transfer of Si and Ca depending on starting composition. This transfer may have been achieved by direct melting and mixing of fusible components and / or by fluid interaction with encompassing Merapi magmas. REE element signatures of the rim and core of one calc-silicate xenolith (XCS-1) confirm a conversion process requiring transfer of melts and or fluids with the rim sample enriched in LREE and HREE relative to the core (Figure 4.23). Vesicular textures at lava-xenolith interfaces indicate intense fluid interaction, potentially due to CO₂ release (Troll *et al.*, 2003, Figure 4.14), and metasomatic alteration is typical in the formation of skarns (*cf.* Barton *et al.*, 1991).

The overlap between the geochemical characteristics of the anorthite present in the xenolith rims and the high-An regions of some zoned phenocrysts suggests that this feldspar is likely the equivalent of the high ⁸⁷Sr/⁸⁶Sr, high-An, low-Mg, low-Fe plagioclase in the basaltic-andesite lavas. However, highly calcic feldspar (An_{>80}) is also present in the plutonic inclusions and basaltic enclaves discussed in section 4.4. These crystals do not possess the marked negative correlation between high An mol% and other

indicators of differentiation e.g. FeO (Figure 4.33) present in the anomalous anorthite in the basaltic andesite and calc-silicates and thus potentially formed due to variations in physical conditions (see section 4.4.6.1), e.g. in zones of increased H₂O content or enriched melts in the Merapi magmatic system. Microsampling of feldspar in the plutonic and basaltic enclave crystals is required for a definitive answer on the origin of these high An mol% crystals, however, given current information, they do not appear to be the same as the high An mol %, high radiogenic Sr, low FeO feldspar hosted in Merapi basaltic andesites. The anomalous crystal cores hosted in the basaltic andesite likely formed via a complex contact metamorphic-metasomatic process with a sedimentary protolith. This would accounts for the apparent decoupling between An mol % and MgO wt% and FeO wt%, together with relatively high radiogenic Sr in these crystals. Several previous studies have addressed limestone assimilation by mafic magmas (e.g. Tilley, 1952; Joesten, 1977; Baker & Black, 1980; Joesten *et al.*, 1994; Owens, 2000). These authors noted changes in the chemical composition and mineralogy of the mafic magma, including resorption of primary igneous minerals such as olivine and the crystallisation of Ca–Al-rich phases such as plagioclase and clinopyroxene. In these studies, calc-silicate minerals such as wollastonite and grossular and to a lesser extent anorthite are envisaged to form at or near the magma–crust/xenolith interface.

4.5.4.2 Quantitative modelling of crustal interaction

Considering the $^{87}\text{Sr}/^{86}\text{Sr}$ range for the Merapi system as a whole, both groundmass and crystal Sr isotope ratios exceed the range seen in the whole rocks. Rather than a source processes, this indicates significant late-stage contamination in the crust given the stability field of plagioclase (Ramos *et al.*, 2005), which is obscured in whole rock isotope ratios. Heterogeneous groundmass and melt inclusions as reported by Schwarzkopf *et al.*, (2001) as well as small basaltic inclusions (Troll *et al.*, 2003) incorporated into whole rocks, are likely to result in generally suppressed $^{87}\text{Sr}/^{86}\text{Sr}$ whole-rock values. As discussed in section 4.4, there is extensive evidence of magma mixing and mafic replenishment apparent in recent Merapi whole rocks (Gertisser & Keller, 2003b; Troll *et al.*, 2003; Chadwick *et al.*, *In prep.*); and previous workers have argued

for the process of magma mixing during recent eruptions (Camus *et al.*, 2000). This mixing is likely to buffer $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the system as represented by whole-rock analyses.

Despite representing an averaged composition of a heterogeneous mass of crystals and mixed melts, whole rock analyses of recent Merapi basaltic andesite and those of assimilants (xenoliths and country rock) were used to model crustal process using the energy constrained assimilation and fractional crystallization (EC-AFC) model of Spera & Bohrsen (2001), to roughly constrain the potential interaction between magma and crust. Thermal and geochemical parameters are listed in Table 4.14 and results plotted in Figure 4.36.

Two models to assess the input of crust to the Merapi magma system were produced. The first model consists of a reservoir in which fractionating mafic Merapi magma is contaminated by heterogeneous thermally altered country rocks (as represented by the calcareous and volcanoclastic xenoliths)(Figure 4.36a). The xenolith inclusions were used given the lack of sufficient data for central Java crustal lithologies. The second model incorporates contamination of Merapi magmas by carbonate crust as represented by a crustal sample from the Wonosari Formation (Figure 4.36b).

In the simulations, the melt temperature was assumed to be 1200°C ($T_{\text{lm}} = T_{\text{m0}}$) based on petrochemical data (Gertisser, 2001). A temperature of 700°C (T_{a0}) was assigned to the Merapi basement consistent with a mid-crustal magma storage discussed previously and geophysical data suggesting a high heat flux in Central Java and the area beneath Merapi Volcano (Wagner *et al.*, 2007, Chadwick *et al.*, *submitted*, Koulakov *et al.*, *In Press*). The liquidus temperature of the crustal rocks (T_{la}) is assumed to be 1000°C based on experimental and empirical studies (Joesten *et al.*, 1994; Lentz, 1999; Owens, 2000, Wenzel *et al.*, 2001, Wenzel *et al.*, 2002) and the solidus temperature of the magma is 800°C (T_{s}). Sr is assumed to be mildly incompatible to compatible in the assimilants (bulk D_0 of 0.7– 1) depending on composition (e.g. Barnes *et al.*, 2005), and compatible in the magma given the dominance of plagioclase (bulk D_0 of 1). The model requires the definition of the equilibration temperature (T_{eq}), which describes the approach of the system to equilibrium during the process of heat exchange, and is equal to or higher than

eruptive temperature (Spera & Bohrsen, 2001). An equilibration temperature of 950°C is used in the models.

The calculated EC-AFC curves represent the geochemical paths simulated by interaction between a recent Merapi magma with a heterogeneous Javan crust as represented by xenoliths and Wonosari Limestone. These models indicate that contamination of this Merapi magma with 0.08-0.4 mass of assimilated melt with 40 to 50% crystallisation replicates the full range in Sr isotope ratios observed in recent Merapi eruptives (< 1900 C¹⁴y bp after Gertisser & Keller, 2003b). The curves modelled using xenolith compositions as an assimilant suggest multiple crustal sources contribute to the range in Sr isotopic compositions observed in Merapi lavas and contamination by pure limestone compositions accounts for a portion of the data (Figure 4.36). These calculations are potentially only a minimum estimate of the importance of crustal material in the Merapi system, given the fact that the incorporation of solid crustal material (such as the xenoliths themselves), crystal transfer, and the buffering effect of mafic replenishment has not been taken into account in these models.

As mentioned at the start of this chapter, contamination of magmas by upper crustal lithologies was largely discounted as a significant process at Merapi due to a lack of systematic variation between isotope ratios and SiO₂ (Gertisser & Keller, 2003a; Debaille *et al.*, 2006). However, this argument assumes that the potential assimilant has considerably different SiO₂ (e.g. high SiO₂) and given that impure carbonate and volcanoclastic deposits are the dominant sedimentary lithologies beneath Merapi, sizable amounts of assimilation may not have a significant effect on major element compositions, specifically SiO₂. Using the most silica-rich contaminant modelled above (XCS-4; SiO₂ composition of 83.07), an addition of 10% crustal material would only raise SiO₂ by 3 wt%. In addition incorporation of ultrabasic material with compositions represented by the igneous inclusions discussed in section 4.4 also has the potential to mask contamination by sedimentary units in this large and complex system.

Thus, assimilation of crustal material at Merapi may be a significant process that is largely unaccounted for in current geochemical models. Of the magmatic phenocrysts analysed for Sr isotope zoning in this study, three out of four crystals appear to have xenocrystic cores and all have individual contaminated zones. An element of sampling

bias may be a factor here, as large, complexly zoned crystals were selected for drilling. However, a negative correlation between MgO wt%, FeO wt% and An mole% is observed in over 80% of the feldspar microprobe traverses (18 of 25 crystal traverses), and is clearly evident for feldspars with An mole% > 85 (Figure 4.33), indicating that xenocrystic material is likely to be present in a significant percentage of Merapi crystals. Using a conservative estimate of 10-20% bulk xenocrystic material, a Merapi basaltic-andesite with 60% crystals, might contain between 6 - 12% crystalline material from non-magmatic crustal sources, in addition to assimilated crustal melts that generate high $^{87}\text{Sr}/^{86}\text{Sr}$ plagioclase overgrowth zones. Both anatectic melts and incorporated solids contribute to the range in Sr isotope ratios observed in whole rocks. This situation has significant implications for mass balance calculations and geochemical modeling of the petrogenesis of Merapi magmas, as there is significant late-stage crustal input that is not accounted for using the whole-rock data alone (e.g. Gertisser & Keller 2003a; Debaille *et al.*, 2006).

4.5.4.3 Approximation of timescales of interaction

Diffusion modelling using the model of Giletti & Casserly (1994) was carried out to constrain a maximum crystal residence age assuming that diffusion of Sr acts to eliminate isotopic disequilibrium within crystals and their host melt (see Appendix G for calculated data). Sr isotope and major element variation in one of the crystals appears to represent a relatively unbroken growth history in Merapi magma and was thus selected for modelling (Figure 4.34a). Given the spatial resolution of the isotope profiles, one-dimensional diffusion modelling yields very crude maximum crystal residence times for this crystal from 25 to 200 years, assuming magmatic temperatures of 950-1050°C (Gertisser, 2001). However, given the relatively sharp transitions in An mol% apparent in other crystals between cores and outer zones, crystal residence times at the lower end of the calculated age range appear likely. Although only a first order approximation, the calculated residence times indicate relatively swift modification of magmatic Sr and/or transfer of foreign crystalline material, occurring at crustal depths. Further work, requiring detailed trace element traverses by ion probe, with careful petrographic ground-truthing and

diffusion modelling (c.f. Zellmer *et al.*, 2003), is required to constrain these timescales further.

Approximations of crystal residence times may also be calculated using the results of the CSD analysis (see Appendix E for data). With a growth rate of 1×10^{-11} cm/s (Higgins, 1996), the slopes of the regression lines yield crystal residence times of 171 years (total population, R^2 of 0.98), 93 years (groundmass population, R^2 of 0.99), and 195 years (phenocryst population, R^2 of 0.99) (Figure 4.32). However as evident by major element and isotope geochemistry, there appear to be multiple sources for the plagioclase crystals hosted in the basaltic andesite that are not well resolved by this initial CSD study. This could be due to a number of factors including potential noise brought on by the action of numerous processes e.g. crystal settling or accumulation via fracturing of crystals, as well as oversimplification of crystal shapes. However, this requires further study before the results can be used confidently to describe the plagioclase populations in these crystal- rich basaltic andesites.

4.5.4.4 Impact of crustal assimilation on volcanic system

Carbonate assimilation appears to be a significant and relatively geologically rapid process occurring in the crustal Merapi magma plumbing system. This assimilation of carbonate sediment has the potential to alter the volatile budget of Merapi lavas significantly, which might influence the eruptive behavior of the volcano. Conversion of limestone to a diopside-wollastonite assemblage, as seen in the Merapi calc-silicate xenoliths (Figure 4.14 and 4.22), would liberate CO_2 (Goff *et al.*, 2001; Troll *et al.*, 2003; Gaeta *et al.*, 2005). This additional CO_2 would be relatively insoluble in the melt in a crustal basaltic-andesite system (Holloway & Blank, 1994) and could result in rapid volatile saturation of the magma, potentially triggering an eruption (Troll *et al.*, 2003). The abundance of calc-silicate xenoliths in the Merapi lavas indicates that the volatile budget of the Merapi magmas may have been significantly modified by carbonate assimilation prior to eruption.

This contrasts with the more conventional view that source contamination processes dominate the CO₂ output in the Indonesian subduction system (Allard, 1983; Poorter *et al.*, 1993; Hilton *et al.*, 2002). These authors concluded that source contamination is the governing process in contributing high $\delta^{13}\text{C}_{\text{CO}_2}$ to the volatile output of the Sunda and the Banda arcs and the majority of island arc systems of the Pacific ring of fire. Allard (1983), however, pointed out that the high $\delta^{13}\text{C}$ values of fumarole gases may also be affected by late crustal assimilation. Low $^{230}\text{Th}/^{232}\text{Th}$ ratios in Merapi lavas (Gertisser, *unpub. data*) and Sunda arc volcanic rocks as a whole (Plank & Langmuir, 1998) indicate an essentially carbonate-free, silici-clastic subducted sediment component in the Sunda arc region. These results are consistent with the a low carbonate content in DSDP sediments from the subducted Indian plate (DSDP Site 262, Java Trench) that averages only about 1% carbonate with a total organic carbon content of 0.17% Poorter *et al.*, 1993; Plank & Langmuir, 1998). Subducted carbonate contents increase to the east by up to seven times (DSDP site 262, Timor Through) but are believed to be lower to the West (Java Trench), suggesting that very little carbonate is in fact subducted and available to be added at the source of Merapi magmas. Assuming the fumarole CO₂ to be purely subduction related (ie. **M**antle, subducted **L**imestone and subducted **S**ediment; **M** + **L** + **S**), then >70% of Merapi CO₂ would be limestone (L) derived (Hilton *et al.*, 2002; Troll *et al.*, 2003). Thus the limestone and sediment components calculated from Merapi fumarole gases are not balanced with the input of L and S endmember components into the subduction zone system with L strongly outweighing the S component (Hilton *et al.*, 2002) (ie. excess limestone component). This points towards an additional source of carbonate, such as shallow contamination, to account for this imbalance (Troll *et al.*, 2003).

The influence of shallow processes on the $\delta^{13}\text{C}$ CO₂ gas composition (Figure 4.38) is reflected in lavas and calc-silicate xenoliths that are strongly out-gassed ($\delta^{13}\text{C} \geq -24\text{‰}$). Whereas fumarole gases are elevated ($\delta^{13}\text{C} \sim 4\text{‰}$) relative to pure mantle derived CO₂ (Marti & Tolstikhin, 1998) ($\delta^{13}\text{C} \sim -6$ to -8). Combining the elevated $\delta^{13}\text{C}$ CO₂ values with He isotopes, the relative contribution of the volatile sources can be assessed (Sano & Marty, 1995; Hilton *et al.*, 2002). The Earth's mantle stores primordial He and the average mantle $^3\text{He}/^4\text{He}/R_A$ is 8.5. In the continental crust, $^3\text{He}/^4\text{He}/R_A = 0.1$ to 0.001.

Subduction of ocean crust and small portions of sediment does not significantly affect mantle He signatures in arc lavas and thus, these magmas generally possess mantle values, similar to the regional values in Java of $^3\text{He}/^4\text{He}/R_A = 8$ to 9 (Hilton & Craig, 1989; Sanyo & Marty, 1995; Goff *et al.*, 1998; Fischer & Marty, 2005). Reported Merapi gas values are comparatively low $^3\text{He}/^4\text{He}/R_A$, between 5.5 to 6.5 ($n=5$) (Hilton *et al.*, 2002). This compares reasonably well with a control sample analysed by Troll *et al.*, (2003), yielding $^3\text{He}/^4\text{He}/R_A$ of 3.6 ± 0.5 , suggesting substantial crustal He input of potentially > 30% (Figure 4.39).

Combined with the petrological observations of the abundant calc-silicate xenoliths that display severe interaction textures (Figure 4.14), the most likely source of the ‘excess’ CO_2 is identified in form of crustal limestone interacting with Merapi magma reservoirs (Troll *et al.*, 2003). Limestone degassing is very effective and violent interaction between limestone and magma has been successfully simulated under lab conditions (V. Troll *pers. comm.*). As re-dissolving CO_2 back into the melt is extremely unlikely at this level (Holloway & Blank, 1994), crustal inputs would be added directly to the volatile output of the volcano and thus increase the chamber pressure dramatically, adding to the explosive character of eruptions (Troll *et al.*, 2003). The effect of limestone-magma interaction can be evaluated assuming a crustal Merapi magma chamber of a significant size or a system of ephemeral chambers of similar volume but with higher magma-limestone contact areas, as supported by the combined tomographic and geobarometric data discussed in section 4.4. Limestone units in the region are up to 2 km thick (van Bemmelen, 1949), and assimilation of a volume of limestone 80 x 80 x 80 m, digested in a magma reservoir over one week, would produce a CO_2 output of ca. 60,000t/day on average, contrasting several hundred t/day during normal background activity at Merapi [$\sim 700\text{t/day}$]. This output is strongly dependant on the surface area of the xenolith. Disintegration and interaction with numerous smaller blocks would allow for more rapid digestion and consequent gas production in the early stages of magma-xenolith interaction. In marked contrast, the same volume of CO_2 can be produced by a basalt injection, but would require a volume of basalt that fits into a cube of 440 m side length (Goff *et al.*, 2001; Troll *et al.*, 2003). Catastrophic limestone assimilation through wall

rock instability caused by either volcanic or regional earthquakes and/or magma recharge could trigger eruptions by sudden over-pressurisation, giving very limited precursor warning signals in contrast to much slower magmatic replenishments that are associated with deep volcano tectonic (VT) earthquakes in the run-up time to an eruption.

This crustal CO₂ source could explain apparent imbalances between volatile output and magma reservoir capacity observed at other large stratovolcanoes such as Volcán Popocatépetl in Mexico. CO₂ output at Popocatépetl is consistently high, with daily outputs of 6400 tons/day (Gerlach *et al.*, 1997) and up to a staggering 100 000 tons/day (Goff *et al.*, 1998; 2001). Calc-silicate inclusions similar to those observed at Merapi have been noted in Plinian pumice deposits from Popocatépetl (Siebe *et al.*, 1996), and the volcano itself is sited on carbonate (Kolisnik, 1990).

4.5.5 Conclusions and implications

Strontium isotope stratigraphy results from plagioclase crystals in Merapi basaltic andesites differ from previous micro-analytical studies of other volcanic centres (e.g. Davidson & Tepley, 1997; Tepley *et al.*, 1999; Tepley *et al.*, 2000) that report consistent and systematic core to rim variation in $^{87}\text{Sr}/^{86}\text{Sr}$ in crystals from a given eruption. Merapi crystals show limited systematic variation, with all crystals possessing similar rim compositions but a broad range in Sr ratios and overall variation in the remaining portions of the crystals. This non-systematic nature of isotope variation indicates that a simple scenario of changing magma compositions or physical parameters with time does not apply for Merapi and requires diverse sources and processes to be involved in the formation of these crystals and the resulting host bulk rock.

The measurable and significant isotopic heterogeneity within these crystals combined with results from the metasedimentary xenoliths and the isotopic results for analysed Merapi gas and local crust indicates that there is a significant volumetric contribution to the magma from crustal carbonate to the isotopic and volatile budgets of the magma system. The observed variations in analysed crystals appear to be the result of two main processes: 1) incorporation of xenocrysts sourced from formerly calcareous country rock,

forming high An mol%, low MgO wt %, high $^{87}\text{Sr}/^{86}\text{Sr}$ plagioclase cores (Figure 4.34b,c), and 2) conventional assimilation with fractional crystallisation (AFC) forming magmatic rims and internal reaction zones (Figure 4.34a) with increasing $^{87}\text{Sr}/^{86}\text{Sr}$ and decreasing An mol% rim-ward. The apparent decoupling of different chemical systems such as An mol% and MgO wt% can be resolved due to the growth conditions and metamorphic nature of the crystals. Therefore, An mol% is not a reliable proxy for degree of evolution for the Merapi magma in which these crystals are found. This situation creates significant uncertainties for mass balance, geochemical modelling and hazard assessment considerations, which are based solely on whole rock data for Merapi (Gertisser & Keller, 2003a; Debaille *et al.*, 2006).

In addition, the potential late-stage crustal volatile addition to purely mantle and slab-derived volatiles in arc magmas, poses uncertainties in large-scale estimates of gas emission because crustal input is rarely taken into account in arc systems (Hilton *et al.*, 2002). Attempts to evaluate volatile transfer, purely from the subducted slab and the mantle source may yield overestimated slab and mantle contributions when crustal contamination is neglected (e.g. Hilton & Craig, 1989). Estimations on pre-eruptive volatile concentrations using a petrological approach (e.g. Wallace *et al.*, 1995; Wallace, 2003) would also potentially underestimate the CO_2 volatile budget in such a scenario as it is unlikely that the CO_2 released from magma-carbonate interaction would redissolve back into the melt at shallow levels (e.g. Hallaway & Blank, 1994). Melt inclusions trapped during early crystal growth may not contain a crustal volatile component at all.

In addition, from a hazard mitigation point of view, sudden over-pressurisation due to chamber wall instabilities and consequent interaction with limestone may provide very limited or potentially unconventional seismic warning signals. A geophysical study of shallow level seismicity at Vesuvius (between ~2 and 6 km below the summit), suggested seismicity was being triggered by stress and pressure changes due to degassing and gas movement beneath the volcano (Pandolfi *et al.* 2006). Since the volcano's last recorded eruption in 1944, Vesuvius has been in a period of relative quiescence with no eruption events, but with extensive fumarolic activity and moderate seismicity, with shallow gas over-pressurisation thought to be capable of triggering earthquakes such as the 3.9 M event in 1999 (Pandolfi *et al.* 2006). Vesuvius, like Merapi, is a large

stratovolcano sited on carbonate crust with calc-silicate xenoliths present in recent magmas (Pandolfi *et al.* 2006). Thus a late-stage crustal volatile addition to purely mantle and slab-derived volatile sources by shallow-level contamination could trigger seismic events and eruptions independently of magmatic recharge or fractional crystallisation by sudden over-pressurisation and consequent violent gas release from shallow-level ephemeral reservoirs and eruptive conduits. In particular, a significant contribution to the volatile budget via limestone assimilation may have profound effects on understanding the drivers for eruption at Merapi and other volcanoes sited on carbonate crust, e.g. Popocatepetl in Mexico and in Vesuvius in Italy. Thus shallow level crustal contamination processes can be volumetrically significant without being immediately evident in bulk rock compositions and quite possibly influence eruptive behaviour. Hence our understanding of explosive volcanism may require a re-think of how such systems are considered.

4.6 *Summary of findings and implications*

The overall findings from analysis of fumarole gas and inclusions and crystals hosted in recent Merapi basaltic-andesites are

- the magmatic system feeding Merapi volcanism is large and complex with limited evidence for a chamber in the edifice (Figure 4.40)
- there is predominantly mid- to deep-crustal storage with a network of multiple potentially ephemeral chambers feeding volcanism
- that hazard prediction methods focusing on shallow level signals may therefore miss potential signals of eruptions
- eruptions may be fed from relatively deep mid-crustal reservoirs
- there is a considerable volume of melt in the crust with potential for evolution of a large-volume volcanic system in central Java, through repeated melt injections and melting of surrounding country rock
- there is already a significant interaction between Merapi magma and the local crust, which is masked in bulk rock geochemistry
- apparent decoupling of chemical systems dictates that An mol% cannot be used as a proxy for degree of evolution of Merapi magma and potentially other similar systems, at least where anomalously high Ca feldspar is present
- crystals, xenolith and gas compositions indicate a large contribution of crustal material to Merapi magma system
- de-carbonation of carbonate xenoliths releases CO₂ and appears to contribute to volatile isotopic signatures in Merapi fumarole gases
- addition of volatiles as a potential source of over-pressurisation and may contribute to shallow seismicity and even be a non-magmatic eruption trigger

In addition, this study illustrates the dangers inherent in building models of magma petrogenesis based solely on whole-rock geochemical data for crystal-rich arc lavas, or indeed on any one analytical technique used in isolation (e.g. CSD). The relatively chemically monotonous whole rock compositions of Merapi basaltic-andesites, disguise a multitude of complex processes occurring throughout the crust and into the upper mantle

with significant impact on the Merapi magmatic and volcanic systems. These basaltic-andesites more than likely were never a true liquid but rather a mix of crystals and melts from multiple sources, which experienced numerous processes, and have been homogenised in a large volume system. Similar hypotheses have recently been proposed for other large andesitic systems (e.g. Price et al., 2005), indicating that this complexity may be the norm for magmatic arc systems of significant size rather than the exception, and is now resolvable using new and combined analytical approaches.

Table 4.1 Cleaning sequence for resin (once loaded into columns) and pipette tips used for Pb analysis

	Resin	Pipette Tips (used for sample loading)
Cleaning Sequence	1.5ml 7M HCl 0.75ml Deionised H ₂ O 1.5ml 7M HCl 0.75 Deionised H ₂ O	1ml 7M HCl 1ml 1M HBr 1ml MQ
Pre-Loading	1.5ml 1M Hbr	

Table 4.2 Procedure for elution of matrix and Pb

Sequence	Acid
1) Elute Matrix	2ml 1M Hbr
2) Collect Pb	3ml 7M HCl

Table 4.3 Faraday Collector array used during Pb analysis by MC-ICPMS (after Baker *et al.*, 2003)

Collector	L4	L3	L2	L1	AX	H1	H2	H3	H4
Mass	200	201	202	203	204	205	206	207	208
Isotope	Hg	Hg	Hg	Tl	Pb	Tl	Pb	Pb	Pb
Interference	WO+	ReO+	WO+	ReO+	Hg	-	-	-	-

Table 4.4 Sample preparation and cleaning for Nd and Sr analysis

Preparation			
Add to samples	1ml	2M HCl	Place in ultra-sonic bath for 10 min
Wash Columns	5 ml	2M HCl	
Load samples into centrifuge tubes and centrifuge for 20 minutes.			
Pipette samples onto column ensuring no solids transferred			

Table 4.5 Anion exchange chemistry for extraction of Sr and Nd

	Volume	Liquid	Notes
Sequence 1			
Rinse	2 ml	2N HCl	
Rinse	30 ml	2M HCl	
Collect Sr + Rb	10ml	2N HCl	in 15ml teflon beaker
Sequence 2			
Rinse	5ml	MilliQ Water	
Rinse	30ml	2M HNO3	
Rinse	5ml	MilliQ Water	
Collect Nd + Sm	10 ml	6M HCl	in 15ml teflon beaker

Table 4.6 Mineralogy and textural features of representative igneous inclusions

Sample	Rock Type	Average Grain Size	Modal Mineralogy (~ vol%)				Texture	
			Cpx	Amph.	Plag.	Opaque		Glass/gm
Felsic plutonic xenoliths								
8-P-1	Leucogabbro	Medium	43	0	54	3	0	Holocrystalline, seriate, embayed cpx, poikilitic unzoned plag. Intergranular texture in places with cpx.
8-P-4	Leucogabbro	Medium	22	4	66	8	0	Holocrystalline, seriate, 120° dihedral angles + kinked twinning in plag, resorbed cpx. and amph.
4-P-1	Anorthosite	Medium	4	0	89	1	6	Holocrystalline, med un-zoned plag
4-P-2	Leucogabbro	Coarse	10	35	42	3	10	Hypocrystalline, large amph in fine crystalline plag matrix with med zone plag crystals + vesiculated glass
4-P-5	Leucogabbro	Medium	17	29	44	7	3	Layered, plag+cpx+opaque. and amph.+plag.+opaque layers, euhedral to subhedral crystal, long axis aligned parallel to layers
Mafic plutonic xenoliths								
8-P-8	Amph. gabbro	Medium	17	41	34	5	3	Seriate, anhedral crystals of amph with seriate plag and cpx
8-P-10	Amph. gabbro	Coarse	15	64	11	7	3	Seriate, coarse anhedral amph. in matrix of fine cpx. and plag.
8-P-12	Cpx. gabbro	Medium	63	12	12	7	6	Seriate, coarse anhedral amph. in matrix of fine cpx. and plag,
Enclaves								
8-B-1	Basalt	Fine	19	2	21	4	54	Porphyritic with phenocrysts of relatively simply zoned plag, cpx and oxides, fluid contacts with host basaltic andesite
4-B-1	Basalt	Fine	18	4	23	4	51	Porphyritic with phenocrysts of relatively simply zoned plag, cpx and oxides, fluid contacts with host basaltic andesite

Grain sizes; coarse > 5mm, med 1-5 mm, fine < 1mm

Amph. = Amphibole, cpx = clinopyroxene, plag = plagioclase, gm = groundmass

Table 4.7 Representative mineral analyses for plutonic inclusions, enclaves and amphibole megacrysts

a) Amphibole

Type	Plutonic inclusion			Basaltic enclaves			Megacrysts	
Sample	4-P-5	8-P-5	8-P-12	8-B-1	8-B-1	4-B-1	AM-108	AM-108
Crystal	A-1	A-2	A-1	A-1	A-2	A-1	A-4	A-7
wt%								
SiO ₂	41.72	40.57	40.02	43.26	42.99	40.8	39.82	40.44
TiO ₂	2.54	2.42	1.73	2.2	2.41	2.18	1.95	1.87
Al ₂ O ₃	11.55	13.6	14.66	10.66	11.06	13.33	14.6	14.5
FeO*	14.94	12.74	12.59	12.76	12.5	13.17	10.59	10.72
MnO	0.42	0.2	0.23	0.39	0.45	0.19	0.18	0.17
MgO	11.91	12.78	12.9	13.98	13.71	13.07	14.37	14.23
CaO	11.21	12.04	11.89	11.13	11.16	11.48	12.41	12.49
Na ₂ O	2.56	2.6	2.2	2.54	2.44	2.44	2.28	2.24
K ₂ O	1	0.87	1.05	0.9	1.02	0.91	1.22	1.29
Total	97.85	97.8	97.26	97.8	97.72	97.56	97.42	97.94
H ₂ O	2.03	2.04	2.04	2.06	2.06	2.05	2.05	2.06

Structural formulae on the basis of 23 O

Si	6.175	5.974	5.876	6.297	6.272	5.973	5.822	5.891
Al ^(iv)	1.825	2.026	2.124	1.703	1.728	2.027	2.178	2.109
Al ^(vi)	0.189	0.334	0.412	0.126	0.174	0.273	0.337	0.38
Ti	0.283	0.268	0.191	0.24	0.264	0.24	0.214	0.205
Cr	0	0	0	0	0	0	0	0
Fe ³⁺	0.593	0.452	0.765	0.74	0.657	0.81	0.648	0.547
Fe ²⁺	1.256	1.116	0.781	0.813	0.868	0.802	0.647	0.758
Mn	0.053	0.025	0.028	0.048	0.055	0.024	0.022	0.021
Mg	2.627	2.805	2.823	3.033	2.981	2.852	3.131	3.089
Ca	1.778	1.9	1.871	1.736	1.745	1.801	1.945	1.95
Na	0.734	0.741	0.626	0.716	0.69	0.692	0.646	0.632
K	0.189	0.162	0.197	0.168	0.189	0.17	0.228	0.24

b) Pyroxene

Type	Plutonic inclusion				Basaltic enclaves			
Sample	8-P-1	8-P-4	8-P-12	8-P-10	8-B-1	8-B-1	4-B-1	4-B-1
	Px-2a	Px-1a	Px-1a	Px-1a	Px-1a	Px-2a	Px-2	Px-4
wt%								
SiO ₂	50.96	52.21	51.45	46.69	51.76	51.26	48.44	51.21
TiO ₂	0.46	0.38	0.48	1.16	0.44	0.41	0.79	0.37
Al ₂ O ₃	2.36	2.71	2.8	7.11	1.68	2.03	5.61	2.6
Cr ₂ O ₃	0.04	0.41	0.01	0.02	0.02	0.08	0.01	0.04
FeO*	8.94	4.31	8.58	8.23	8.26	8.22	9.63	8.23
MnO	0.43	0.07	0.44	0.22	0.59	0.57	0.28	0.43
MgO	14.57	15.7	14.8	12.46	15.02	14.54	12.95	15.07
CaO	21.14	23.61	21.04	23.31	20.97	21.12	21.78	21.16
Na ₂ O	0.52	0.23	0.37	0.31	0.35	0.4	0.37	0.33
Total	99.42	99.63	99.96	99.51	99.08	98.63	99.85	99.44

Structural formulae on the basis of 6 O

Si	1.696	1.738	1.712	1.554	1.723	1.706	1.612	1.704
Al ^(iv)	0.101	0.081	0.094	0.257	0.065	0.074	0.194	0.096
Al ^(vi)	0.003	0.037	0.028	0.055	0.009	0.016	0.052	0.017
Ti	0.012	0.01	0.012	0.029	0.011	0.01	0.02	0.009
Cr	0.001	0.008	0	0	0	0.002	0	0.001
Fe ³⁺	0.109	0.028	0.065	0.159	0.057	0.061	0.123	0.081
Fe ²⁺	0.17	0.105	0.201	0.098	0.201	0.197	0.177	0.175
Mn	0.006	0.001	0.006	0.003	0.008	0.008	0.004	0.006
Mg	0.361	0.389	0.367	0.309	0.372	0.361	0.321	0.374
Ca	0.377	0.421	0.375	0.416	0.374	0.377	0.388	0.377
Na	0.008	0.004	0.006	0.005	0.006	0.006	0.006	0.005

c) Feldspar

Type	Felsic Plutonic Inclusion				Mafic Plutonic Inclusion			
Sample	8-P-1	8-P-1	8-P-4	8-P-4	8-P-10	8-P-10	8-P-11	8-P-11
Crystal	P2core	P2rim	P2	P6	P1	P5	P2core	P2rim
wt%								
SiO ₂	52.38	45.56	52.742	43.56	48.79	47.99	44.475	56.66
Al ₂ O ₃	29.88	33.87	28.273	34.54	31.88	32.64	35.096	26.646
FeO*	0.591	0.729	0.472	0.391	0.511	0.47	0.485	0.423
CaO	12.96	18.01	11.139	18.91	15.18	16.2	19.064	9.461
Na ₂ O	4.014	1.388	5.022	0.865	2.978	2.311	0.701	5.907
K ₂ O	0.287	0.039	0.385	0.037	0.176	0.148	0.024	0.489
BaO	0	0	0	0	0	0	0	0
Total	100.1	99.59	98.033	98.31	99.51	99.76	99.845	99.586
Or	2	0	2	0	1	1	0	3
Ab	35	12	44	8	26	20	6	52
An	63	88	54	92	73	79	94	46

Basalt enclaves							
8-B-1	8-B-1	8-B-1	8-B-1	4-B-1	4-B-1	4-B-2	4-B-2
GM-1	GM-2	GM-3	GM-4	P1core	P1rim	P1core	P1rim
55.487	52.52	51.74	55.417	46.49	54.47	50.94	52.1
27.68	28.75	29.9	27.921	33.324	27.72	30.13	29.29
0.421	0.439	0.515	0.546	0.467	0.514	1.07	0.692
10.475	11.97	13.05	10.294	17.211	10.81	14.24	12.96
5.512	4.733	3.994	5.571	1.777	5.262	2.819	3.984
0.431	0.345	0.259	0.429	0.083	0.376	0.781	0.543
0.086	0.05	0.052	0.049	0.014	0.049	0.069	0.071
100.09	98.81	99.51	100.23	99.366	99.19	100	99.64
2.448	1.961	1.498	2.4456	0.4815	2.155	4.587	3.106
47.582	40.89	35.11	48.268	15.667	45.83	25.16	34.63
49.97	57.15	63.39	49.286	83.852	52.01	70.25	62.26

Table 4.8 Modal mineralogy of metasedimentary xenoliths by XRD with xenolith rock type, textural features and mineralogy

DEPOSIT	SAMPLE	ROCK TYPE	TYPE	Grain Size	Mineralogy (relative vol.%)								By XRD	
					Wo	An	Di	Trm	Qtz	Gros	Opaque		Most Abundant	Traces
1998 BAF	XCS-1R	Calc-silicate Xen	XEN RIM	fine	6	30	60	2	1	0	1		Di / An	Wo / Qtz/ Trm
1998 BAF	XCS-1C	Calc-silicate Xen	XEN CORE	medium	70	5	7	0	18	0	0		Wo/ Qtz	Di / An
1998 BAF	XCS-2	Volcano-clastic Xen	XEN WR	fine / medium	3	50	10	0	34	0	3		Qtz / An	Di / Wo
1998 BAF	XCS-3	Calc-silicate Xen	XEN WR	medium	70	10	3	0	10	5	2		Wo/ Qtz	An/Gros
1998 BAF	XCS-4	Volcano-clastic Xen	XEN WR	fine / medium	5	15	11	0	67	0	2		Qtz / An	Di / Wo
1998 BAF	XCS-7R	Calc-silicate Xen	XEN RIM	fine	57	24	16	0	0	0	3		An / Di	Wo
1998 BAF	XCS-7T	Calc-silicate Xen	XEN TRANS	fine	11	67	22	0	0	0	0		Wo / An	Di
1998 BAF	XCS-7C	Calc-silicate Xen	XEN CORE	medium	47	37	16	0	0	0	0		Wo / Di	An
1998 BAF	XCS-9	Calc-silicate Xen	XEN WR	medium	32	47	20	0	0	0	1		Di / An	Wo

XEN RIM = xenolith rim, XEN CORE= xenolith core, XEN WR= xenolith whole rock, XEN TRANS= transition zone from core to rim
Wollastonite (Wo), Anorthite (An), Diopside (Di), Tremolite (Trm), Quartz (Qtz), Grossular (Gros).

Table 4.9 Major element (wt%), trace element (ppm) and isotopic compositions of Merapi plutonic inclusions, enclaves, and basaltic andesite host rock

Sample type	Plutonic Inclusions from the 1998 Deposit											
	8-P-1	8-P-2	8-P-3	8-P-4	8-P-5	8-P-6	8-P-7	8-P-8	8-P-9	8-P-10	8-P-11	8-P-12
Major Elements (XRF)												
SiO ₂	49.21	42.89	48.07	45.22	42.74	51.51	41.04	41.14	47.14	40.21	41.60	44.29
TiO ₂	0.52	1.20	1.20	1.00	0.74	1.22	1.15	1.78	1.07	1.97	2.18	1.51
Al ₂ O ₃	18.54	18.40	17.27	21.23	26.66	17.50	21.08	18.50	18.72	11.97	14.91	9.83
Fe ₂ O ₃	7.91	15.04	13.36	12.01	10.37	12.28	14.15	14.17	12.14	19.49	18.19	16.59
MnO	0.19	0.23	0.27	0.21	0.10	0.26	0.19	0.21	0.25	0.18	0.23	0.21
MgO	5.02	5.65	4.70	4.25	2.73	3.68	5.36	7.85	4.23	10.56	9.21	10.22
CaO	16.65	15.24	11.71	14.26	16.13	8.83	16.24	13.43	12.58	13.52	10.10	16.69
Na ₂ O	1.72	1.47	2.67	1.98	1.18	3.21	0.95	1.91	2.51	1.40	2.23	1.10
K ₂ O	0.55	0.22	0.87	0.36	0.20	1.65	0.19	0.61	0.65	0.59	0.76	0.35
P ₂ O ₅	0.41	0.58	0.35	0.09	0.04	0.35	0.61	0.77	0.22	0.06	0.06	0.07
Trace Elements (XRF)												
Co	32	56	46	45	38	36	53	53	43	73	63	67
Cr	23	26	34	25	19	18	20	30	21	198	18	157
Ni	2	6	2	2	2	2	3	24	2	30	2	20
V	134	389	363	407	326	306	415	456	340	852	640	700
Zn	66	106	139	104	50	137	100	100	121	103	119	87
Ce	10	26	30	14	10	37	35	20	31	12	21	31
La	14	14	14	14	14	14	14	14	14	14	14	14
Nb	2	5	7	5	2	8	4	7	3	5	7	5
Ga	17	23	20	20	17	20	20	22	22	19	17	13
Pb	14	10	21	8	4	15	6	11	4	11	7	16
Pr	4	4	5	4	4	4	6	4	6	6	4	4
Rb	15	4	18	8	5	37	4	6	16	6	8	4
Ba	130	159	254	148	72	399	76	172	217	152	213	98
Sr	505	583	543	638	703	552	693	536	653	228	350	183
Th	4	4	4	4	4	4	4	4	4	4	4	4
Y	16	22	25	14	8	27	20	32	21	18	27	20
Zr	52	48	64	39	30	96	35	56	52	43	68	43
Total	100.85	101.10	100.65	100.79	101.05	100.68	101.12	100.55	99.69	100.13	99.66	101.04
Alkali Index												
Fe#	0.06	-2.61	0.12	0.18	-0.90	0.10	-0.10	-0.23	0.13	-0.12	-0.36	0.19
Mg#	61.18	72.69	73.98	73.86	79.16	76.94	72.53	64.35	74.16	64.86	66.39	61.88
	38.82	27.31	26.02	26.14	20.84	23.06	27.47	35.65	25.84	35.14	33.61	38.12

Sample type Name	Plutonic Inclusions from the 1998 Deposit											
	8-P-1	8-P-2	8-P-3	8-P-4	8-P-5	8-P-6	8-P-7	8-P-8	8-P-9	8-P-10	8-P-11	8-P-12
Trace elements (ICP-MS)												
Ba	172.62	130.49	271.07	166.57	88.61	441.20	88.22	176.07	254.15	131.62	220.34	111.43
Rb	12.03	2.80	18.62	5.36	2.24	37.40	1.44	3.56	13.00	4.22	7.41	5.01
Sr	500.42	578.30	531.92	612.75	657.15	539.56	679.79	519.13	654.79	237.91	362.23	188.74
Pb	6.23	4.22	9.84	5.29	2.71	14.70	2.06	3.74	8.43	2.70	4.97	3.35
Zr	47.40	31.85	51.66	30.94	15.16	87.16	19.85	40.71	41.36	38.75	52.78	34.89
Nb	1.40	1.62	2.30	1.44	0.64	4.01	1.22	3.19	1.89	1.51	2.63	1.20
Hf	1.49	1.12	1.49	1.00	0.48	2.33	0.81	1.57	1.21	1.37	1.77	1.31
Ta	0.10	0.09	0.15	0.10	0.04	0.25	0.06	0.16	0.12	0.09	0.15	0.08
Th	2.49	1.19	2.94	1.18	0.48	5.41	0.47	0.93	2.08	1.17	1.29	0.95
U	0.51	0.27	0.66	0.27	0.11	1.22	0.10	0.21	0.46	0.25	0.33	0.21
Y	16.77	22.55	22.26	14.30	6.00	25.39	19.82	34.61	20.37	18.93	27.03	17.24
Ni	11.10	8.52	12.90	8.80	5.83	6.22	10.19	24.20	6.61	31.37	7.56	22.38
Cr	14.77	12.24	16.06	10.28	0.76	5.13	10.05	26.54	6.08	185.23	2.12	162.84
Co	24.54	34.83	30.35	29.68	30.36	25.64	36.93	44.39	27.35	57.63	46.13	45.82
V	145.51	383.64	365.78	430.19	394.79	315.46	447.45	503.64	333.71	886.64	603.12	693.38
La	9.87	8.68	12.61	5.69	2.64	17.46	6.40	10.74	10.25	4.68	6.02	4.52
Ce	21.05	20.11	25.95	12.29	5.35	34.24	15.97	27.39	20.77	11.69	14.85	10.77
Pr	3.08	3.21	3.76	1.88	0.82	4.74	2.73	4.64	2.97	1.96	2.60	1.77
Nd	13.65	15.29	16.58	8.74	3.90	19.61	13.81	23.15	13.24	9.78	13.38	8.89
Sm	3.38	4.33	4.12	2.44	1.12	4.72	4.05	6.89	3.48	3.22	4.37	2.87
Eu	0.98	1.36	1.36	0.99	0.52	1.44	1.30	1.99	1.33	1.05	1.43	0.95
Gd	3.20	4.28	4.21	2.52	1.09	4.71	4.02	6.72	3.64	3.28	4.68	3.04
Tb	0.50	0.71	0.67	0.41	0.18	0.75	0.64	1.12	0.59	0.57	0.82	0.53
Dy	2.95	4.07	4.02	2.54	1.14	4.46	3.79	6.45	3.50	3.35	4.84	3.13
Ho	0.61	0.86	0.82	0.53	0.24	0.93	0.77	1.34	0.73	0.72	1.01	0.65
Er	1.62	2.14	2.18	1.40	0.58	2.49	1.92	3.37	1.93	1.76	2.60	1.61
Tm	0.25	0.34	0.35	0.22	0.09	0.40	0.28	0.47	0.30	0.27	0.39	0.26
Yb	1.60	1.94	2.11	1.38	0.56	2.60	1.68	2.86	1.86	1.53	2.35	1.52
Lu	0.26	0.29	0.32	0.21	0.09	0.38	0.24	0.42	0.28	0.23	0.34	0.23
Sc	19.44	29.17	25.38	26.35	18.32	18.45	30.67	57.02	23.87	91.17	61.10	88.02
Cu	26.34	97.78	46.90	89.08	105.59	44.27	39.87	46.53	79.52	36.92	71.56	21.15
Zn	60.24	100.30	129.01	92.06	57.72	129.11	97.08	101.62	109.62	110.17	118.57	89.34
Ga	17.37	20.40	20.46	20.06	20.04	20.58	21.07	19.50	19.89	17.77	18.11	15.65
Cs	1.02	0.23	1.58	0.45	0.15	3.08	0.11	0.23	1.12	0.24	0.93	0.42

Sample type Name	Plutonic Inclusions from the 1998 Deposit											
	8-P-1	8-P-2	8-P-3	8-P-4	8-P-5	8-P-6	8-P-7	8-P-8	8-P-9	8-P-10	8-P-11	8-P-12
Isotopic Ratios												
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512686			0.512720				0.512719		0.512700		0.512694
2SE	0.000011			0.000008				0.000007		0.000009		0.000008
ε Nd	0.940			1.603				1.576		1.217		1.083
⁸⁷ Sr/ ⁸⁶ Sr	0.705741			0.705621				0.705290		0.705631		0.705741
2SE	0.000016			0.000020				0.000020		0.000026		0.000016
²⁰⁶ Pb/ ²⁰⁴ Pb	18.765			18.759				18.753		18.706		18.758
2SE	0.002			0.002				0.002		0.002		0.002
²⁰⁷ Pb/ ²⁰⁴ Pb	15.692			15.683				15.682		15.674		15.683
2SE	0.001			0.001				0.001		0.001		0.001
²⁰⁸ Pb/ ²⁰⁴ Pb	39.142			39.114				39.105		39.051		39.112
2SE	0.003			0.003				0.003		0.003		0.003

Sample type Name	Plutonic Inclusions from the 1994 Deposit					Basaltic Enclaves				Basaltic Andesite				
	4-P-1	4-P-2	4-P-3	4-P-4	4-P-5	8-B-1	8-B-2	4-B-1	4-B-2	4-A-1	4-A-2	99-85	99-101	99-159
Major Elements (XRF)														
SiO ₂	53.30	50.08	52.89	46.16	46.75	49.06	52.61	50.86	52.09	52.27	53.49	54.69	54.63	51.71
TiO ₂	0.78	0.87	0.83	1.69	1.19	1.28	1.60	0.85	0.94	0.84	0.80	0.75	0.73	0.88
Al ₂ O ₃	19.07	18.71	18.87	13.78	18.86	15.00	17.05	18.03	19.47	19.31	19.38	18.81	19.02	18.33
Fe ₂ O ₃	8.51	10.77	9.26	12.90	12.71	13.02	12.56	10.00	10.02	9.25	8.77	8.03	7.82	9.70
MnO	0.18	0.19	0.20	0.23	0.24	0.36	0.25	0.18	0.20	0.20	0.20	0.21	0.19	0.20
MgO	3.20	4.16	3.34	11.00	4.16	7.84	4.30	4.55	3.23	3.14	2.94	2.63	2.56	3.80
CaO	9.58	9.80	9.34	10.50	11.96	10.48	7.68	9.82	9.66	9.60	9.11	8.44	8.44	9.55
Na ₂ O	3.15	2.70	3.32	2.21	2.78	2.68	3.17	2.90	2.96	3.31	3.51	3.74	3.74	3.19
K ₂ O	1.68	1.37	2.01	1.15	0.80	0.61	1.16	1.55	1.16	1.84	2.01	2.09	2.08	1.89
P ₂ O ₅	0.30	0.37	0.32	0.10	0.71	0.15	0.33	0.23	0.24	0.31	0.32	0.33	0.33	0.31
Trace Elements (XRF)														
Co	26	36	26	52	47	63	41	32	27	26	22	45	45	40
Cr	25	18	20	276	24	347	18	22	18	19	18	18	18	20
Ni	2	2	2	127	3	94	2	2	2	2	2	2	2	2
V	199	234	212	377	323	203	400	272	226	217	200	167	159	233
Zn	86	92	93	96	131	146	129	80	101	95	94	97	93	92
Ce	23	30	37	23	46	23	26	10	14	34	31	54	33	25
La	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Nb	5	8	5	7	7	8	8	8	8	6	7	5	8	6
Ga	20	17	21	18	18	15	25	15	20	18	20	17	16	17
Pb	19	18	14	15	10	9	22	19	18	17	16	10	21	17
Pr	4	4	4	4	4	5	4	4	4	4	4	4	4	4
Rb	34	34	45	19	16	11	29	34	26	41	46	50	51	44
Ba	480	315	447	391	184	270	378	380	307	441	464	493	479	459
Sr	623	551	570	322	650	489	492	557	495	580	579	573	578	580
Th	6	9	4	4	4	4	4	4	4	4	5	5	6	5
Y	23	26	27	37	32	23	34	20	27	26	25	26	26	24
Zr	88	87	97	86	58	82	112	72	100	86	94	105	106	88
Total	99.94	99.20	100.55	99.92	100.37	100.73	100.93	99.14	100.11	100.27	100.71	99.89	99.73	99.77
Alkali Index														
Fe#	0.08	0.10	0.09	0.18	0.16	0.09	0.08	0.10	0.08	0.09	0.09	0.08	0.09	0.10
Mg#	72.67	72.14	73.49	53.97	75.34	62.42	74.50	68.73	75.62	74.66	74.89	75.33	75.34	71.85
	27.33	27.86	26.51	46.03	24.66	37.58	25.50	31.27	24.38	25.34	25.11	24.67	24.66	28.15

Sample type Name	Plutonic Inclusions from the 1994 Deposit					Basaltic Enclaves				Basaltic Andesite				
	4-P-1	4-P-2	4-P-3	4-P-4	4-P-5	8-B-1	8-B-2	4-B-1	4-B-2	4-A-1	4-A-2	99-85	99-101	99-159
Trace elements (ICP-MS)														
Ba	530.47	326.26	487.29	381.32	241.56	315.40	489.14	409.12	345.86					
Rb	34.54	32.55	45.91	19.78	16.28	9.80	36.45	35.38	24.85					
Sr	608.50	548.80	564.87	328.37	662.68	486.70	618.37	561.92	490.46					
Pb	22.39	13.66	13.08	9.07	9.99	7.76	26.73	15.08	13.48					
Zr	50.18	82.97	80.22	70.79	46.05	70.66	120.81	64.45	93.15					
Nb	3.44	3.38	3.86	4.68	3.36	5.48	5.07	2.49	4.04					
Hf	1.44	2.22	2.23	2.54	1.51	2.06	3.38	1.80	2.51					
Ta	0.22	0.22	0.25	0.29	0.17	0.36	0.31	0.17	0.26					
Th	5.88	5.84	5.79	1.62	2.24	1.74	4.09	5.10	4.30					
U	1.00	1.15	1.21	0.40	0.56	0.39	0.91	1.17	0.99					
Y	22.41	25.23	24.52	39.58	33.48	26.55	41.48	19.49	26.40					
Ni	6.48	2.97	6.15	138.16	11.94	103.03	5.41	9.72	3.22					
Cr	9.83	1.28	7.66	276.48	7.51	328.51	1.37	12.72	1.69					
Co	16.82	22.96	21.22	42.38	31.12	42.63	32.99	26.82	18.56					
V	196.46	225.71	214.97	360.86	315.91	176.51	497.36	274.15	213.75					
La	17.55	18.31	17.47	9.86	19.48	10.17	19.61	13.69	13.90					
Ce	33.36	37.85	34.44	25.53	40.24	22.75	40.97	26.10	28.35					
Pr	4.33	5.25	4.51	4.34	5.81	3.38	6.04	3.39	3.84					
Nd	17.78	22.51	18.71	21.17	25.57	15.02	26.60	14.12	16.66					
Sm	4.19	5.22	4.48	6.44	6.33	3.88	6.72	3.34	4.08					
Eu	1.32	1.51	1.32	1.96	1.79	1.47	1.91	1.06	1.31					
Gd	4.31	5.17	4.61	6.66	6.28	4.14	7.10	3.55	4.27					
Tb	0.65	0.77	0.70	1.13	0.97	0.73	1.13	0.55	0.71					
Dy	3.78	4.41	4.08	6.93	5.68	4.54	6.97	3.19	4.29					
Ho	0.79	0.91	0.86	1.44	1.18	0.99	1.49	0.67	0.93					
Er	2.13	2.39	2.33	3.79	3.04	2.60	3.85	1.79	2.47					
Tm	0.35	0.38	0.36	0.59	0.47	0.43	0.62	0.29	0.42					
Yb	2.13	2.37	2.30	3.51	2.87	2.75	3.83	1.78	2.62					
Lu	0.33	0.36	0.36	0.53	0.43	0.44	0.58	0.28	0.41					
Sc	16.49	17.05	18.13	49.54	21.28	36.67	46.33	29.61	15.26					
Cu	30.68	23.91	23.55	28.46	278.52	455.48	424.78	47.21	20.92					
Zn	81.25	88.96	85.06	90.40	118.57	127.12	149.95	75.39	89.48					
Ga	18.64	18.89	19.18	16.01	20.37	15.53	28.17	17.60	19.56					
Cs	2.99	2.99	3.48	0.70	2.23	0.66	3.13	3.28	2.47					

Sample type Name	Plutonic Inclusions from the 1994 Deposit					Basaltic Enclaves				Basaltic Andesite				
	4-P-1	4-P-2	4-P-3	4-P-4	4-P-5	8-B-1	8-B-2	4-B-1	4-B-2	4-A-1	4-A-2	99-85	99-101	99-159
Isotopic Ratios														
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512685	0.512569			0.512697	0.512720		0.512705						
2SE	0.000008	0.000008			0.000005	0.000006		0.000007						
ε Nd	0.923	-1.354			1.153	1.603		1.309						
⁸⁷ Sr/ ⁸⁶ Sr	0.705436	0.705746			0.705698	0.705712		0.705503						
2SE	0.000152	0.000014			0.000016	0.000018		0.000020						
²⁰⁶ Pb/ ²⁰⁴ Pb	18.768	18.849			18.763	18.763		18.798						
2SE	0.002	0.002			0.002	0.002		0.002						
²⁰⁷ Pb/ ²⁰⁴ Pb	15.691	15.654			0.001	15.691		15.695						
2SE	0.001	0.001			0.001	0.001		0.001						
²⁰⁸ Pb/ ²⁰⁴ Pb	39.144	39.041			39.112	39.135		39.178						
2SE	0.003	0.003			0.003	0.003		0.003						

Table 4.10 Major element (wt%), trace element (ppm) and isotopic compositions of Merapi metasedimentary xenoliths

Sample type Name	Calc-silicate xenoliths							Volcaniclastic xenoliths			
	XCS-1R	XCS-1C	M-XCS-7R	M-XCS-7T	M-XCS-7C	M-XCS-3	M-XCS-9	XCS-2	XCS-4	8-S-1	8-S-2
Major Elements (XRF)											
SiO ₂	48.76	61.02	53.74	54.64	54.93	64.70	49.21	70.27	83.07	45.81	39.46
TiO ₂	0.49	0.02	0.62	0.37	0.15	0.07	0.60	0.51	0.51	0.76	1.36
Al ₂ O ₃	10.48	0.61	14.07	8.67	5.06	2.52	15.75	12.50	4.51	17.17	19.01
Fe ₂ O ₃	11.10	1.59	8.07	5.27	3.40	1.55	7.83	4.14	2.79	15.74	15.20
MnO	0.34	0.22	0.26	0.28	0.29	0.27	0.23	0.11	0.11	0.27	0.21
MgO	6.19	0.83	3.32	2.23	1.15	0.51	3.76	1.91	0.86	3.82	5.91
CaO	21.62	35.88	16.96	27.02	34.29	29.18	21.61	8.27	8.19	14.61	14.06
Na ₂ O	0.53	0.01	2.07	1.37	0.76	0.57	1.11	1.77	0.13	1.98	1.57
K ₂ O	0.33	0.01	0.84	0.74	0.68	0.92	0.34	0.23	0.02	0.34	0.38
P ₂ O ₅	0.19	0.05	0.20	0.10	0.06	0.04	0.20	0.11	0.05	0.17	0.31
Trace Elements (XRF)											
Co	114	43	59	50	42	53	65	56	59	53	61
Cr	43	18	71	36	18	18	18	96	644	59	22
Ni	18	2	21	8	2	2	6	4	8	20	2
V	91	12	138	80	22	12	114	72	44	281	482
Zn	108	16	101	70	41	26	97	48	54	96	95
Ce	10	10	42	10	25	10	24	29	31	19	30
La	14	14	14	14	14	14	14	14	14	14	14
Nb	2	2	5	2	2	2	3	2	2	8	4
Ga	13	8	15	8	8	8	15	13	8	18	19
Pb	4	4	6	4	8	4	6	8	5	14	6
Pr	5	4	4	4	4	4	4	4	4	11	4
Rb	11	n.a.	22	21	21	27	11	6	n.a.	6	4
Ba	63	n.a.	243	199	102	43	122	234	184	177	179
Sr	710	425	424	319	235	66	442	359	171	372	610
Th	n.a.	5	n.a.	5	8	5	7	4	5	4	4
Y	18	21	19	18	15	7	29	24	35	21	20
Zr	93	13	94	70	49	25	127	100	238	84	48
Total	100.21	100.29	100.32	100.82	100.84	100.38	100.75	99.95	100.42	100.81	97.67
Alkali Index											
Fe#	0.03	0.00	0.05	0.03	0.02	0.01	0.04	0.01	0.00	0.14	-0.09
Mg#	64.20	65.70	70.85	70.27	74.73	75.24	67.56	68.43	76.44	80.47	72.00
	35.80	34.30	29.15	29.73	25.27	24.76	32.44	31.57	23.56	19.53	28.00

Sample type	Calc-silicate xenoliths						Volcaniclastic xenoliths				
Name	XCS-1R	XCS-1C	M-XCS-7R	M-XCS-7T	M-XCS-7C	M-XCS-3	M-XCS-9	XCS-2	XCS-4	8-S-1	8-S-2
Trace elements (ICP-MS)											
Ba	108.48	1.75							184.17	159.40	154.63
Rb	10.61	0.08							0.41	5.93	3.22
Sr	710.55	433.88							154.37	395.41	638.57
Pb	3.12	0.71							4.11	9.33	3.57
Zr	46.48	2.56							25.07	58.88	32.29
Nb	4.98	0.45							5.69	2.99	1.54
Hf	1.36	0.10							0.84	1.73	1.27
Ta	1.45	0.75							1.46	0.21	0.08
Th	3.84	0.30							4.27	2.66	0.97
U	1.27	0.12							0.82	0.50	0.20
Y	18.34	20.77							27.91	20.91	21.48
Ni	33.03	8.40							46.40	16.43	6.93
Cr	44.44	1.80							472.17	49.93	1.37
Co	112.38	54.64							76.70	25.01	40.32
V	80.21	4.45							30.69	258.87	470.79
La	10.82	1.96							15.16	11.00	6.24
Ce	20.55	5.19							29.27	23.18	15.70
Pr	3.11	1.04							4.34	3.22	2.58
Nd	12.95	6.13							17.42	13.65	12.99
Sm	3.65	2.93							3.85	3.36	3.82
Eu	1.88	1.79							0.96	0.80	1.27
Gd	3.59	3.12							4.18	3.30	3.90
Tb	0.54	0.56							0.70	0.55	0.65
Dy	3.03	3.12							4.32	3.33	3.84
Ho	0.60	0.61							0.87	0.73	0.79
Er	1.57	1.38							2.14	1.97	1.97
Tm	0.25	0.19							0.32	0.32	0.30
Yb	1.60	1.03							1.79	2.05	1.74
Lu	0.24	0.12							0.25	0.33	0.26
Sc	12.27	3.79							6.26	20.85	36.21
Cu	160.33	3.89							7.00	116.50	214.06
Zn	91.37	14.19							34.67	87.77	93.93
Ga	10.94	0.64							4.15	18.63	19.43
Cs	0.77	0.02							0.16	0.87	0.16

Sample type	Calc-silicate xenoliths							Volcaniclastic xenoliths			
Name	XCS-1R	XCS-1C	M-XCS-7R	M-XCS-7T	M-XCS-7C	M-XCS-3	M-XCS-9	XCS-2	XCS-4	8-S-1	8-S-2
Isotopic Ratios											
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512507	0.512567				0.512716			0.512467	0.512722	0.512693
2SE	0.000011	0.000007				0.000008			0.000006	0.000008	0.000007
ε Nd	-2.550	-1.395				1.527			-3.338	1.637	1.077
⁸⁷ Sr/ ⁸⁶ Sr	0.707655	0.707866				0.705842			0.707361	0.706620	0.705671
2σ	0.000056	0.000018				0.00002			0.000016	0.00002	0.000024
²⁰⁶ Pb/ ²⁰⁴ Pb	18.789	18.753				18.754			18.850	18.757	18.760
2σ	0.002	0.002				0.002			0.002	0.002	0.002
²⁰⁷ Pb/ ²⁰⁴ Pb	15.715	15.673				15.684			15.658	15.681	15.684
2σ	0.001	0.001				0.001			0.001	0.001	0.001
²⁰⁸ Pb/ ²⁰⁴ Pb	39.043	0.003				39.109			39.053	39.105	39.116
2σ	0.003	0.003				0.003			0.003	0.003	0.003

Table 4.11 The inorganic geochemical whole-rock major element (wt%), trace element (ppm) and isotopic compositions of Merapi Country rocks

Sample type		Carbonate		Clastic sed.
Name		LST1	LST3	J-VC-1
Major Elements (XRF)				
SiO ₂		0.28	0.04	58.78
TiO ₂		0.01	0.01	0.89
Al ₂ O ₃		0.13	0.03	15.35
Fe ₂ O ₃		0.01	0.01	8.58
MnO		0.00	0.00	0.15
MgO		0.40	0.35	2.18
CaO		56.72	57.06	5.17
Na ₂ O		0.12	0.11	2.81
K ₂ O		0.00	0.00	1.17
P ₂ O ₅		0.03	0.02	0.14
Trace Elements (XRF)				
Co		3.00	7.00	29.00
Cr		0.00	3.00	18.00
Ni		0.00	0.00	4.00
V		5.00	6.00	130.00
Zn		4.00	2.00	100.00
Ce		0.00	0.00	18.00
La		0.00	15.00	385.00
Nb		11.00	16.00	2.00
Ga		3.00	6.00	19.00
Pb		13.00	16.00	16.00
Pr		0.00	4.00	58.00
Rb		2.00	2.00	23.00
Ba		0.00	0.00	138.00
Sr		102.00	124.00	225.00
Th		7.00	0.00	2.00
Y		5.00	7.00	31.00
Zr		18.00	26.00	105.00
Total		57.72	57.64	95.35
H2O	in %	0.15	0.14	5.54
LOI		44.93	44.82	0.24
Isotopic Ratios				
⁸⁷ Sr/ ⁸⁶ Sr		0.70880		0.70719
2σ		0.00013		0.00018
²⁰⁶ Pb/ ²⁰⁴ Pb		20.119		18.533
2σ		0.002		0.002
²⁰⁷ Pb/ ²⁰⁴ Pb		15.726		15.624
2σ		0.001		0.001
²⁰⁸ Pb/ ²⁰⁴ Pb		38.832		38.716
2σ		0.003		0.003

Table 4.12 Representative EMP Feldspar Analyses for Merapi basaltic-andesite and meta-sedimentary xenoliths

	Basaltic-andesite							
	101-C2 RIM	101-C6 RIM	159-C9 RIM	159-C9 RIM	101-C2 CORE	101-C6 CORE	159-C9 CORE	159-C9 CORE
wt%								
SiO ₂	55.73	55.90	57.73	51.95	45.98	44.77	45.44	45.46
TiO ₂	0.02	0.04	0.04	0.032	0.03	0.01	0.01	0.00
Al ₂ O ₃	27.89	27.82	26.84	30.445	34.37	35.25	34.48	34.70
FeO	0.58	0.48	0.46	0.49	0.49	0.42	0.47	0.46
MgO	0.05	0.04	0.03	0.043	0.03	0.01	0.04	0.04
CaO	10.44	10.37	9.28	13.453	18.06	19.08	18.55	18.53
Na ₂ O	5.30	5.48	6.03	3.775	1.32	0.71	1.02	0.98
K ₂ O	0.41	0.45	0.59	0.246	0.06	0.02	0.05	0.04
Total	100.66	100.81	101.28	100.751	100.62	100.40	100.23	100.36
mol%								
Ab	46.74	47.61	52.23	33.20	11.67	6.30	8.99	8.68
An	50.86	49.85	44.40	65.38	87.97	93.56	90.73	91.10
Or	2.40	2.55	3.38	1.42	0.36	0.14	0.28	0.22

	Calc-silicate							
	XCS1C-C1 CORE	XCS1C-C2 CORE	XCS2-C1 RIM	XCS2-C1 CORE	XCS2-C2 RIM	XCS2-C2 CORE	XCS3-C1 CORE	XCS3-C1 CORE
wt%								
SiO ₂	44.20	43.42	53.31	44.20	46.11	42.51	42.90	43.47
TiO ₂	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.00
Al ₂ O ₃	35.42	36.10	28.45	35.42	34.23	35.85	36.04	36.03
FeO	0.41	0.10	0.95	0.41	0.63	0.19	0.19	0.52
MgO	0.03	0.00	0.05	0.03	0.03	0.01	0.00	0.00
CaO	19.83	20.37	12.41	19.83	17.77	20.61	20.46	20.13
Na ₂ O	0.37	0.03	4.27	0.37	1.30	0.00	0.02	0.08
K ₂ O	0.00	0.00	0.39	0.00	0.05	0.00	0.00	0.01
Total	100.36	100.05	99.83	100.29	100.16	99.18	99.69	100.38
mol%								
Ab	3.24	0.30	37.52	3.24	11.66	0.00	0.17	0.69
An	96.76	99.70	60.25	96.76	88.02	99.98	99.81	99.27
Or	0.00	0.00	2.23	0.00	0.32	0.02	0.02	0.04

Basaltic-andesite sample names: first number indicates the whole-rock sample followed by crystal number e.g. 101-C6 is whole-rock 101, crystal C6

Table 4.13 Crystal-isotope stratigraphy Sr ratios for plagioclase in Merapi BAF 1998 eruptive products

Sample	Location	$^{87}\text{Sr}/^{86}\text{Sr}$	2SE
A) BA-101-C2	1-Core	0.705699	0.000016
Basaltic Andesite	2-Inner Zone	0.705688	0.000016
	3-Outer Zone	0.705743	0.000011
	4-Rim	0.705795	0.000019
B) BA-159-C9	1-Core	0.705841	0.000014
Basaltic Andesite	2-Inner zone	0.706277	0.000012
	3-Rim	0.705769	0.000013
C) BA-159-C3	1-Core	0.705846	0.000014
Basaltic Andesite	2-Inner zone	0.705854	0.000017
	3-Mid Zone	0.705992	0.000013
	4-Outer Zone	0.705902	0.000020
	5-Rim	0.705807	0.000015
D) BA-101-C6	1-Core	0.705845	0.000017
Basaltic Andesite	2-Inner zone	0.705682	0.000006
	3-Outer zone	0.705712	0.000006
	4-Rim	0.705813	0.000009
BA-159-GM	Groundmass	0.705812	0.000018
Basaltic Andesite	Groundmass	0.705912	0.000028
XCS-102	C1	0.706018	0.000052
Calc-silicate Xen	C2	0.705985	0.000023

BA= Basaltic-andesite block and ash flow. Location numbers and letters A, B, C, D correlate to crystals and zones sampled respectively, illustrated in Figure 4.34

Table 4.14 EC–AFC parameters used for quantitative modelling of Sr-isotopic variations at Merapi Volcano

Compositional parameters (Curves in Fig. 6a)					Thermal parameters	
	XCS-1r	XCS-1c	XCS-3	XCS-4		
Element	Sr (ppm)	Sr (ppm)	Sr (ppm)	Sr (ppm)	t _{lm}	1280 °C
Magma: conc.	595	595	595	595	t _{m0}	1280 °C
Bulk D ₀	1	1	1.5	1.5	t _{la}	1000 °C
Assimilant: conc.	710	434	66	154	t _{a0}	700 °C
Bulk D ₀	0.7	0.7	0.7	1	t _s	800 °C
Isotope	⁸⁷ Sr / ⁸⁶ Sr	⁸⁷ Sr / ⁸⁶ Sr	⁸⁷ Sr / ⁸⁶ Sr	⁸⁷ Sr / ⁸⁶ Sr	cpm	1484 J/kg K
Ratio magma	0.70554	0.70554	0.70554	0.70554	cpa	1370 J/kg K
Ratio assimilant	0.70765	0.70787	0.70584	0.70736	hcry	396000 J/kg
					hfus	250000 J/kg
Compositional parameters (Curves in Fig. 6b)						
	CRUST 1a	CRUST 1b	CRUST 1c	CRUST 1d		
Element	Sr	Sr	Sr	Sr		
Magma: conc.	595	595	595	595		
Bulk D ₀	1	1	1	1		
Assimilant: conc.	1000	500	1000	500		
Bulk D ₀	0.7	0.7	0.7	0.7		
Isotope	⁸⁷ Sr / ⁸⁶ Sr	⁸⁷ Sr / ⁸⁶ Sr	⁸⁷ Sr / ⁸⁶ Sr	⁸⁷ Sr / ⁸⁶ Sr		
Ratio magma	0.70554	0.70554	0.70554	0.70554		
Ratio assimilant	0.70735	0.70735	0.70693	0.70693		

Terminology from Spera and Bohrsen (2001): t_{lm} = liquidus of magma; t_{m0} = initial temperature of magma; t_{la} = liquidus of assimilant; t_{a0} = initial temperature of assimilant; t_s = solidus temperature; cpm = magma isobaric specific heat capacity; cpa = assimilant isobaric specific heat capacity; hcry = enthalpy of crystallization; hfus = enthalpy of fusion.

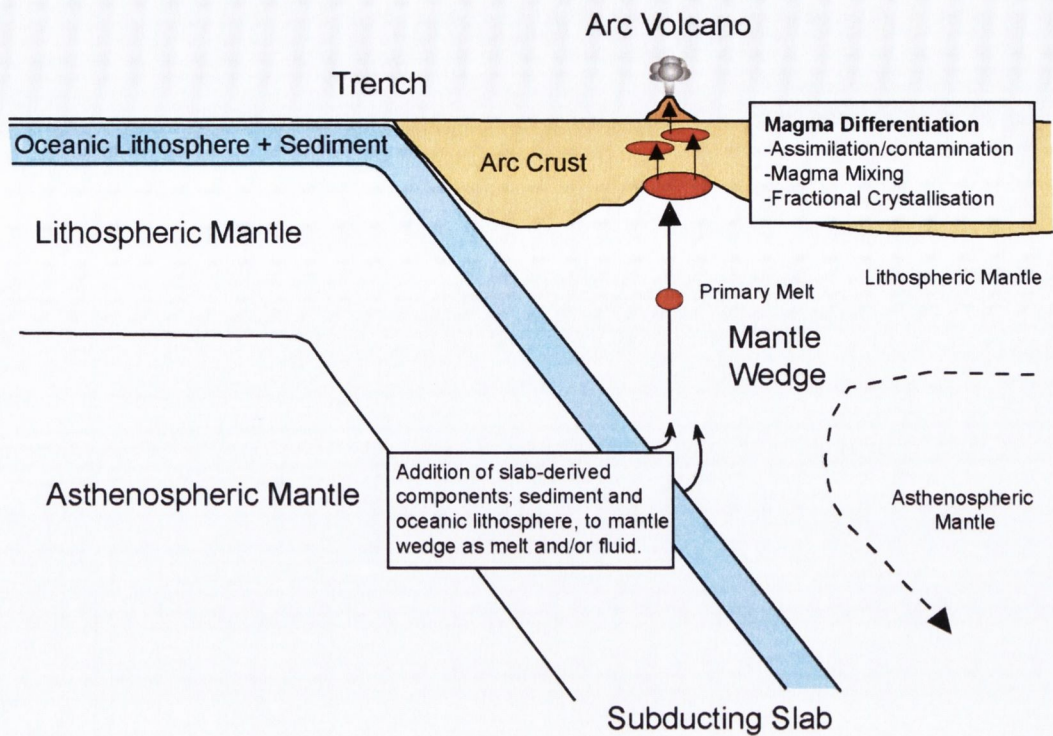


Figure 4.1. Schematic diagram of subduction zone volcanism illustrating variable source components (mantle wedge, subducted lithosphere, and subducted sediment) and differentiation mechanisms involved in arc magma production and evolution

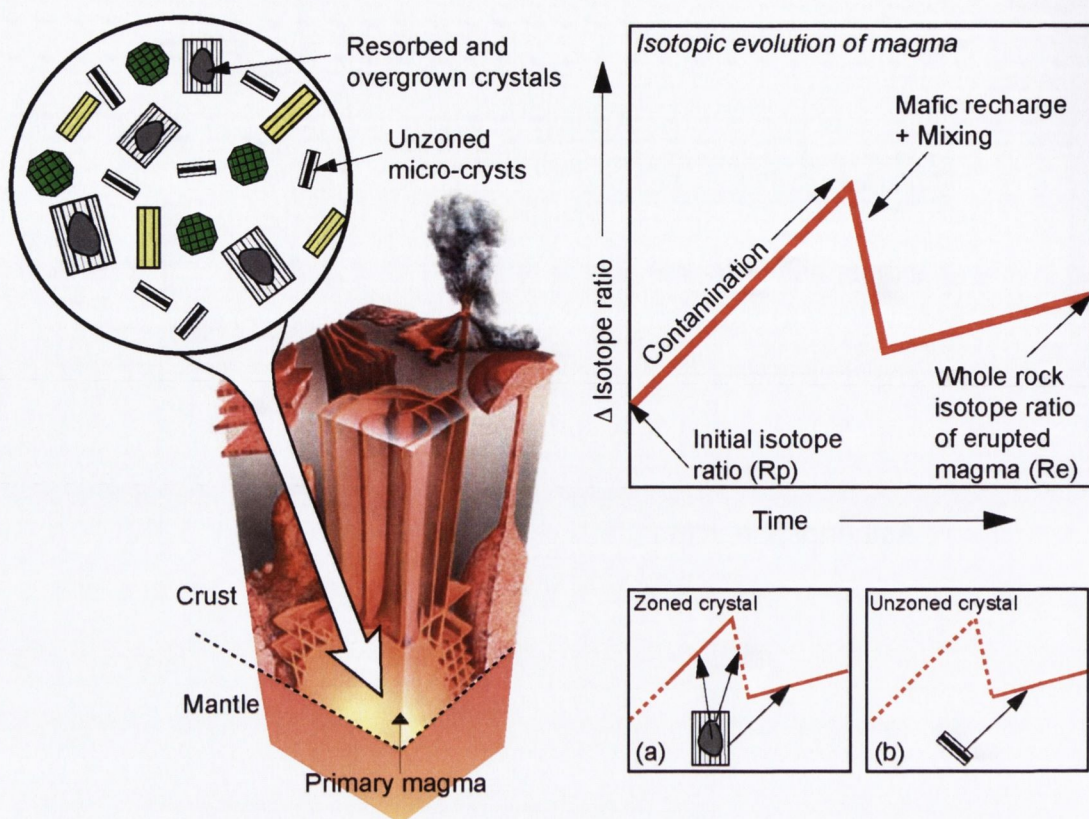


Figure 4.2 Schematic diagram illustrating characteristics of crystal isotope stratigraphy applied to a phenocryst-rich magma (after Davidson *et al.*, 2007). Primary magma ascending from the mantle possesses an isotope signature (R_p), which may be altered by differentiation processes such as contamination, mixing and recharge, during ascent and storage. The resulting whole rock isotope ratio of the erupted magma (R_e) has a different isotope ratio than the initial composition. However it only records one snapshot of the isotopic evolution of the magma. Individual crystals within the whole rock may preserve a record of this isotopic evolution with respect to time according to when they crystallise. Early-formed crystals may record an almost complete record (a) while crystals formed late may preserve only the final stages of evolution (b).

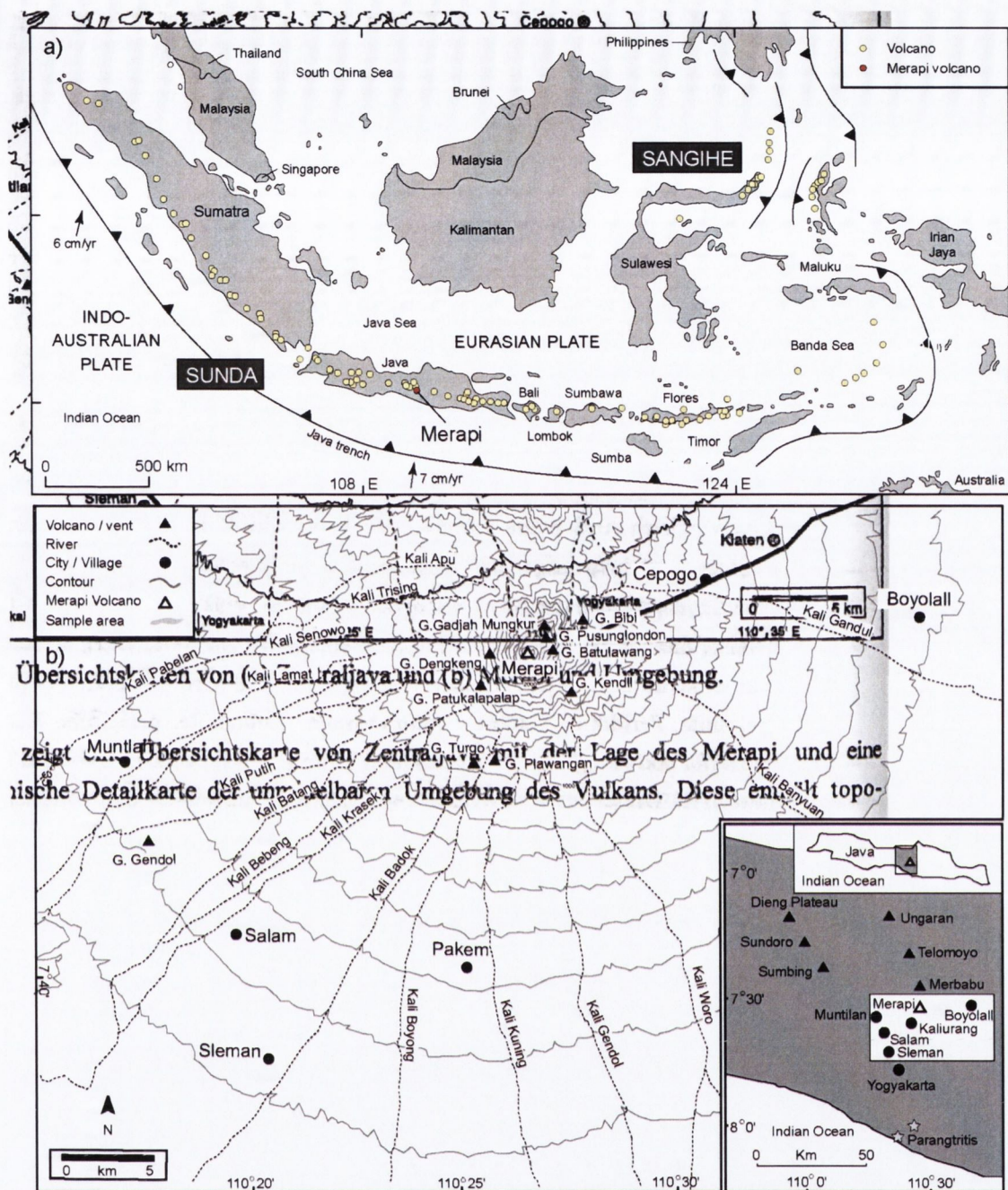


Figure 4.3. a) Location of Merapi volcano relative to the the Sunda Arc subduction zone system (after Gertisser & Keller, 2003a). b) Sketch map of the summit of Merapi with inset showing the location of Merapi relative to other Quaternary volcanoes in the area (triangles) and areas of significant population (filled circles) in Central Java (after Gertisser & Keller, 2003b). Sampling location for Merapi deposits at Kali Putih (1998) and Kali Boyong (1994) highlighted in grey, and the location of crust samples are on the highlighted inset map with star symbols.

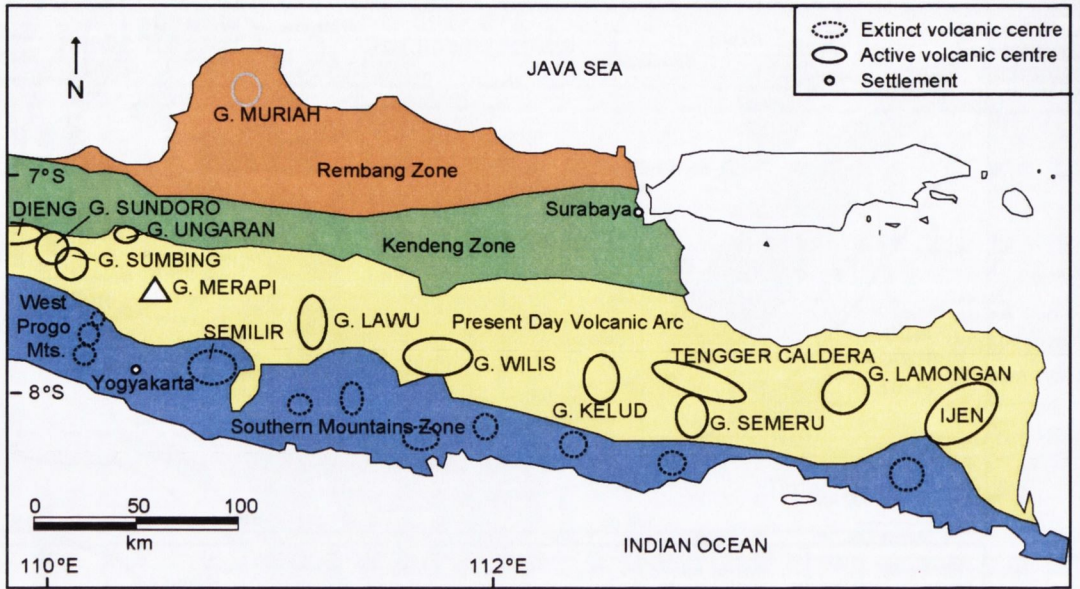


Figure 4.4 Simplified crustal structure of Central and East Java (after Smyth *et al.*, 2005), showing Southern Mountains Zone (blue), the present day volcanic arc (yellow), the Kendeng basin (green), and the Rembang Zone (orange). Older Miocene arc volcanoes are represented by dashed ellipses and volcanic centers of the active arc are outlined by solid ellipses.

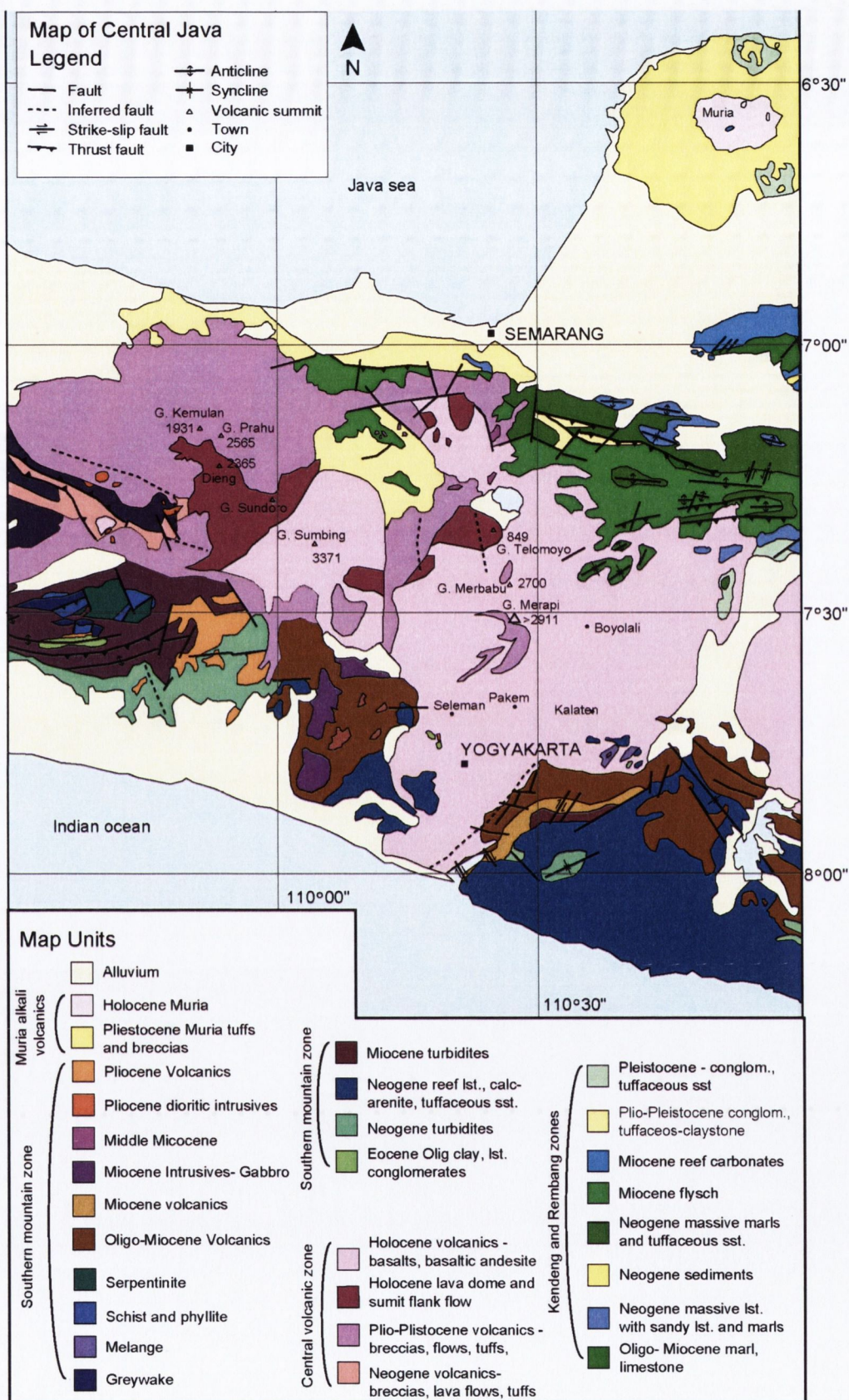


Figure 4.5 Simplified geological map of Central Java, showing the main lithological units (from Map: Geological research and development centre, Indonesia, 1999). Much of Central Java is poorly exposed, especially, the lower slopes of the active volcanoes and the area around Yogyakarta which has a high population density.

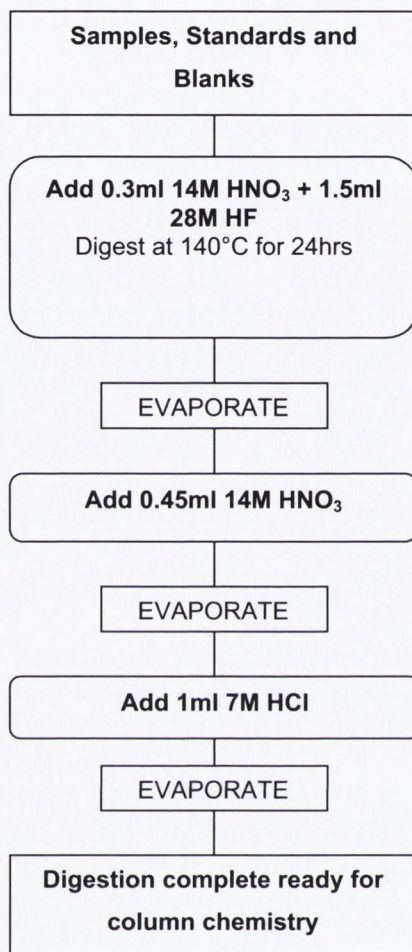


Figure 4.6 Acid digestion sequence used prior to all whole rock isotope ratio chemistry.

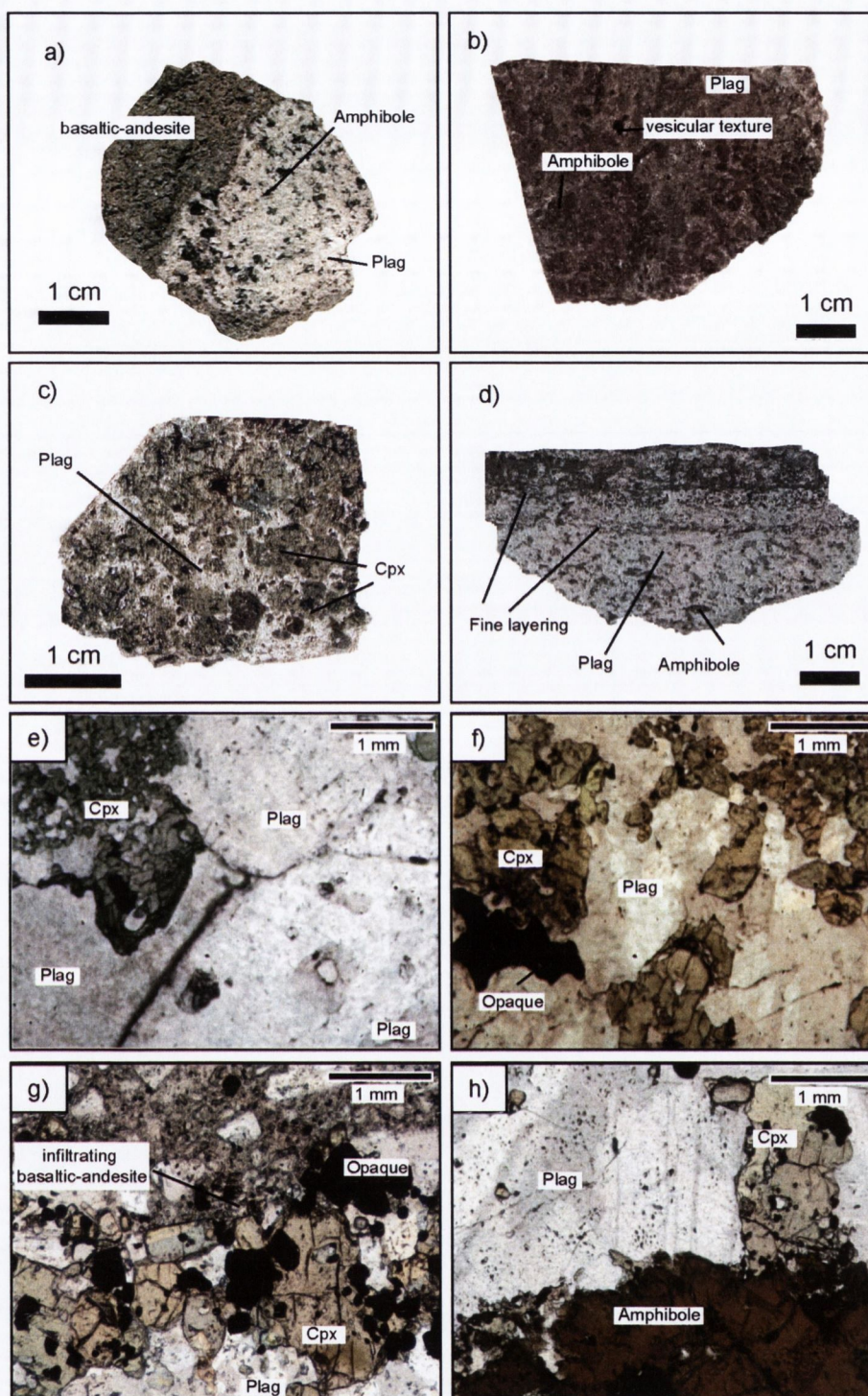


Figure 4.7. a) Felsic plutonic inclusion (leucogabbro) that is coarsely crystalline and plagioclase rich. b) Mafic plutonic inclusion (amphibole gabbro) that is amphibole rich and contains vesiculated glass. c) Mafic plutonic inclusion (clinopyroxene gabbro) that contains vesiculated glass. d) Layered felsic plutonic inclusion (lucogabbro) with alternating plagioclase-rich and amphibole-rich bands and alignment of long axes of crystals parallel to layering. e) PPL image of triple junction between three plagioclase crystals and a heavily resorbed clinopyroxene crystal engulfed in a plagioclase poikiloblast (8-P-1). f) PPL image of a felsic plutonic inclusion with closely interlocking texture between plagioclase and clinopyroxene with an irregularly shaped opaque crystal (8-P-4). g) PPL image of sharp contact between a pyroxene gabbro and an the host andesite (8-P-12). h) PPL image of large amphibole crystal with reaction rim of opaques (8-P-10).

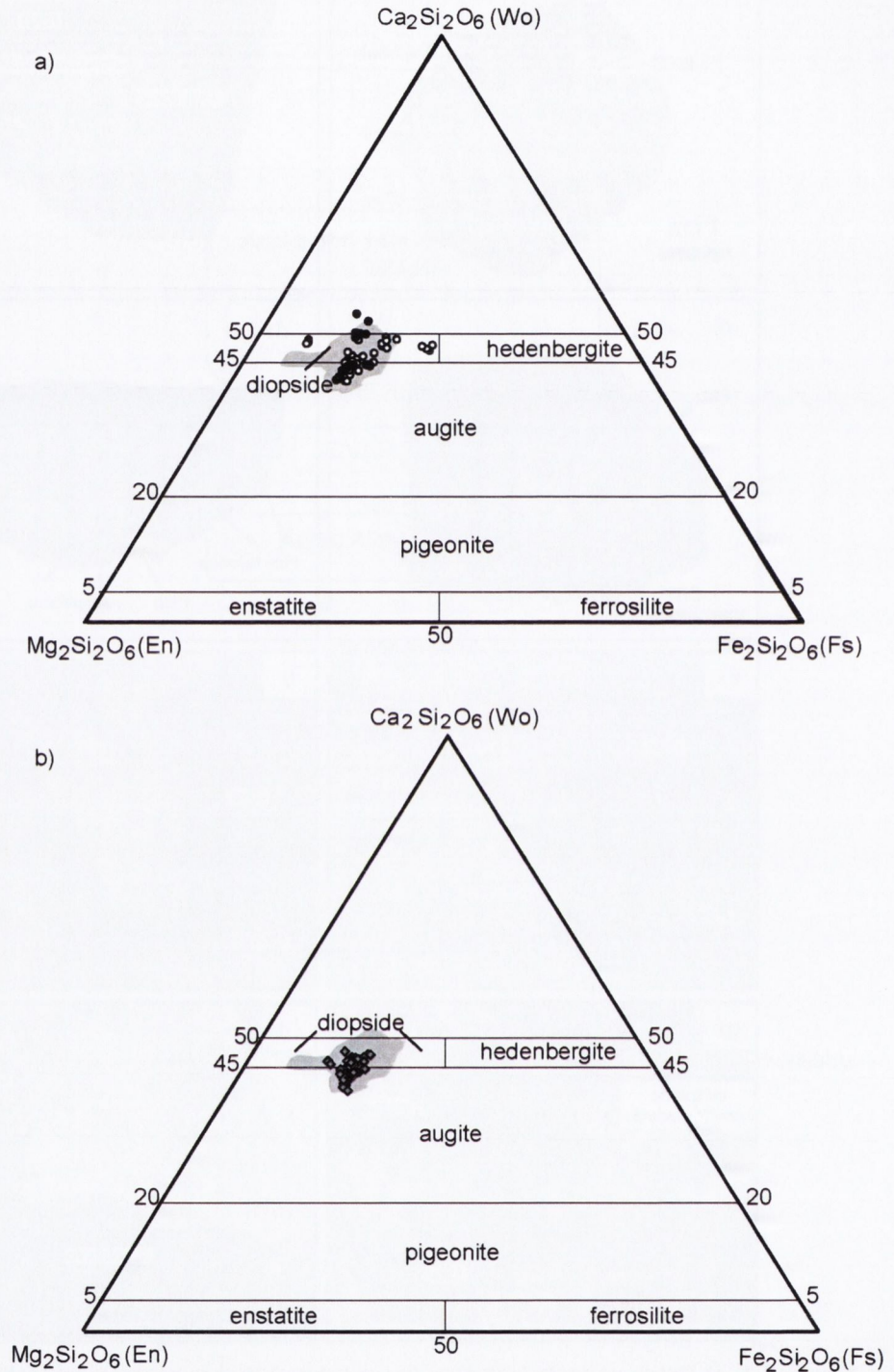


Figure 4.8. Compositional ranges and nomenclature for Ca-Mg-Fe pyroxenes (*after* Morimoto, *et al.*, 1988). Grey shaded area represents compositions from Merapi andesites and basaltic andesites from Gertisser, 2001. a) Pyroxene compositions from plutonic inclusions, black circles = mafic inclusions, white circles = felsic inclusions. b) Pyroxene compositions from enclaves (grey diamonds).

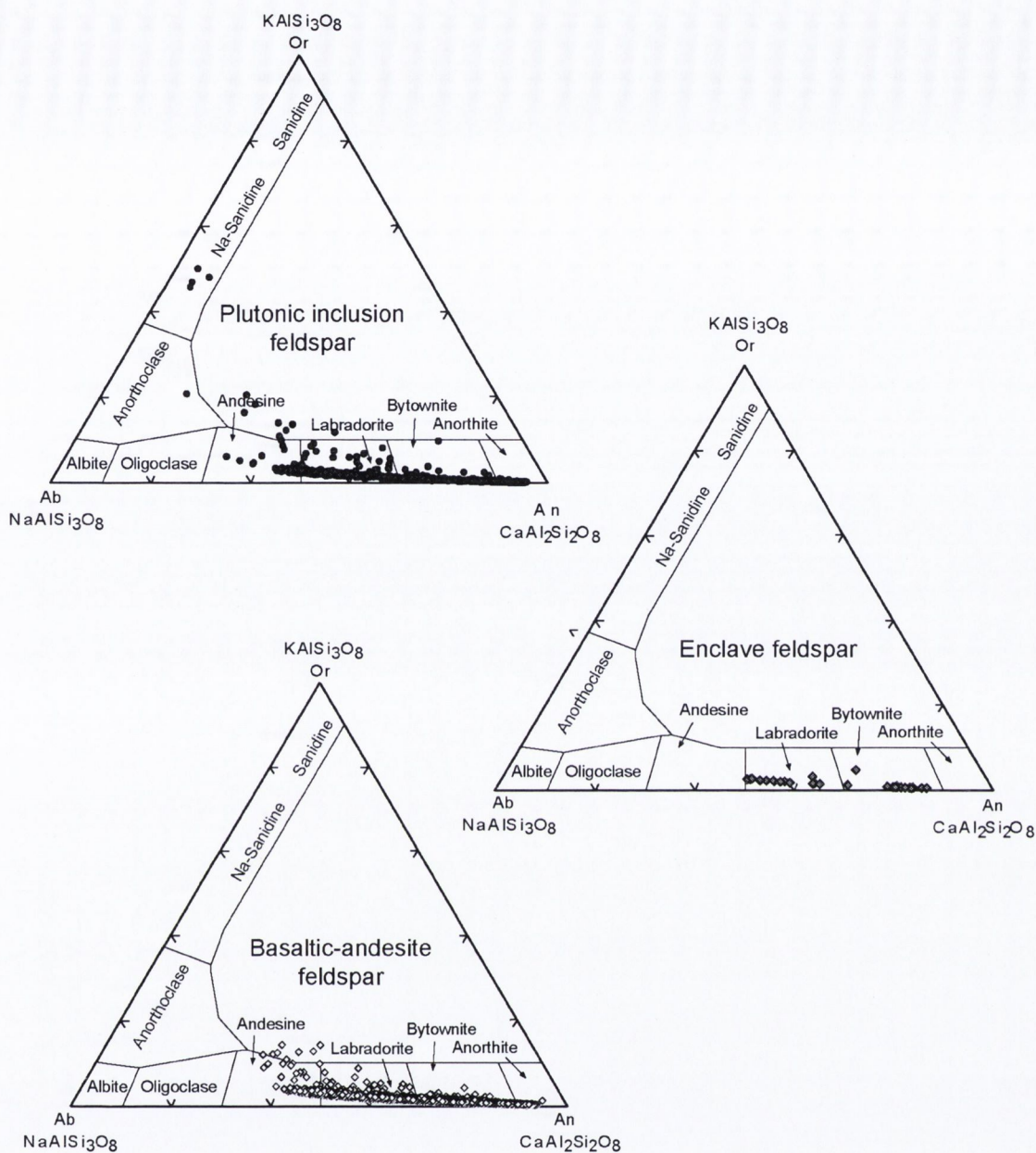


Figure 4.9. Ternary feldspar nomenclature and composition diagrams for crystals in plutonic inclusions, enclaves and the host basaltic andesite.

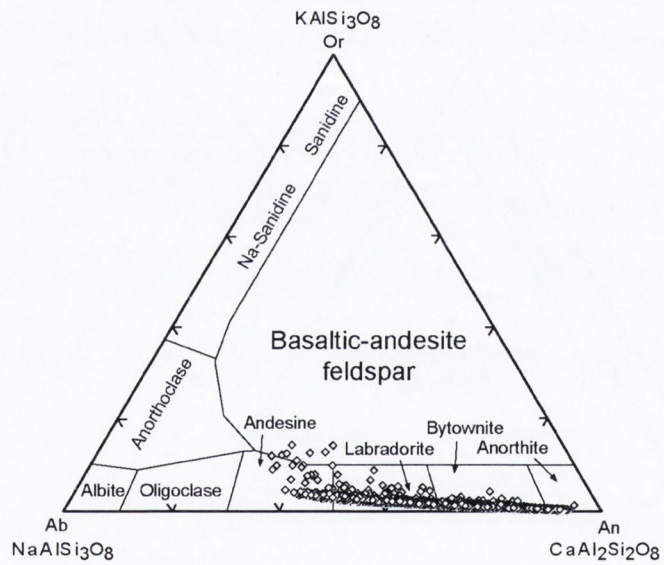
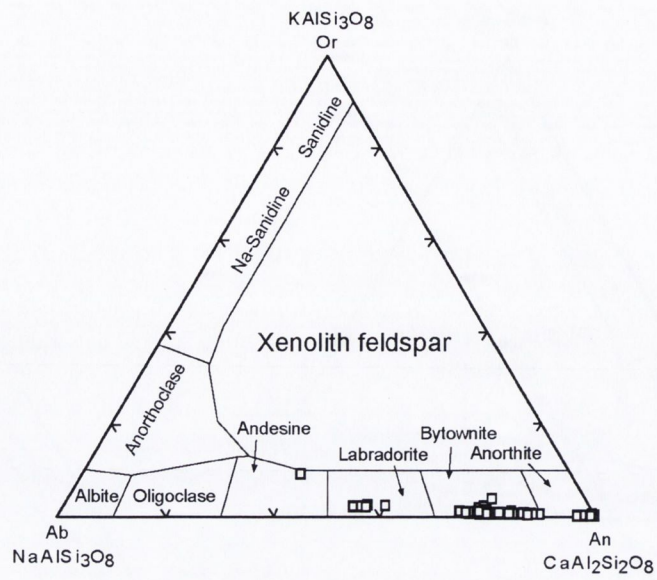


Figure 4.10. Ternary feldspar nomenclature and composition diagrams for crystals in meta-sedimentary xenoliths and the host basaltic andesite for comparison.

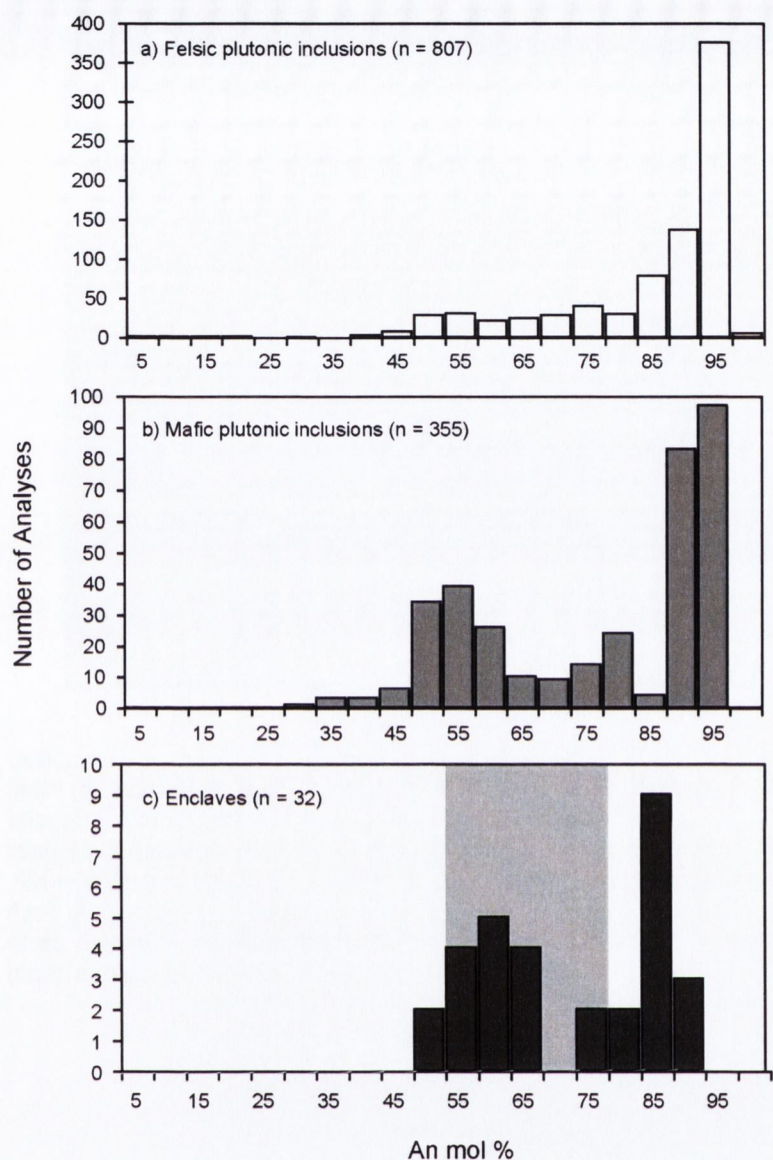


Figure 4.11. Histograms of An mol % composition of analyses of feldspar from a) felsic plutonic inclusions, b) mafic plutonic inclusions, and c) enclaves. Light grey zone in part c represents ideal plagioclase compositions calculated using the empirical equation of Panjasawatwong *et al.* (1995). Due to a lack of suitable groundmass compositions, such calculations could not be carried out for plutonic inclusions.

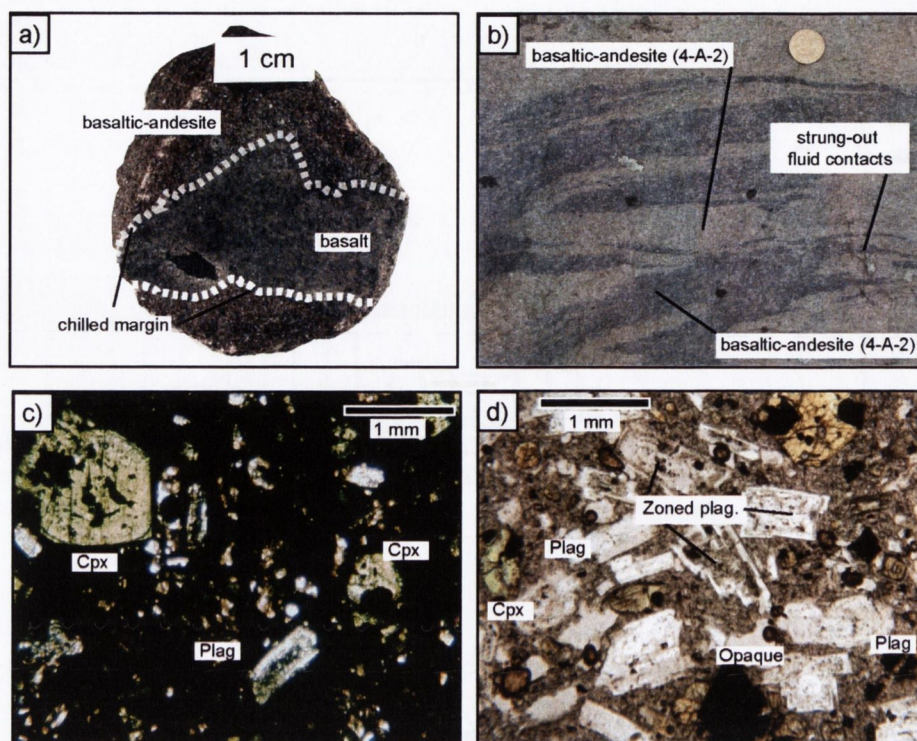


Figure 4.12. a) Hand sample of a basaltic enclave (8-B-1) in basaltic andesite with chilled fluid contact with host rock. White dashed lines highlight margin of basalt enclave. b) Field photograph of andesite mixing textures in outcrop with coin for scale. Darker andesite has (4-A-1), strung out lenticular shapes indicating fluid-fluid relationships with the lighter andesite (4-A-2). c) Photomicrograph of a thick section (150 μm) basaltic inclusion in XP. Inclusion contains significantly less plagioclase, and smaller crystal sizes generally than the highly porphyritic basaltic andesite host rock in d). Basaltic andesite contains up to 60% crystals by volume, dominantly zoned plagioclase with lesser clinopyroxene (cpx) and opaques.

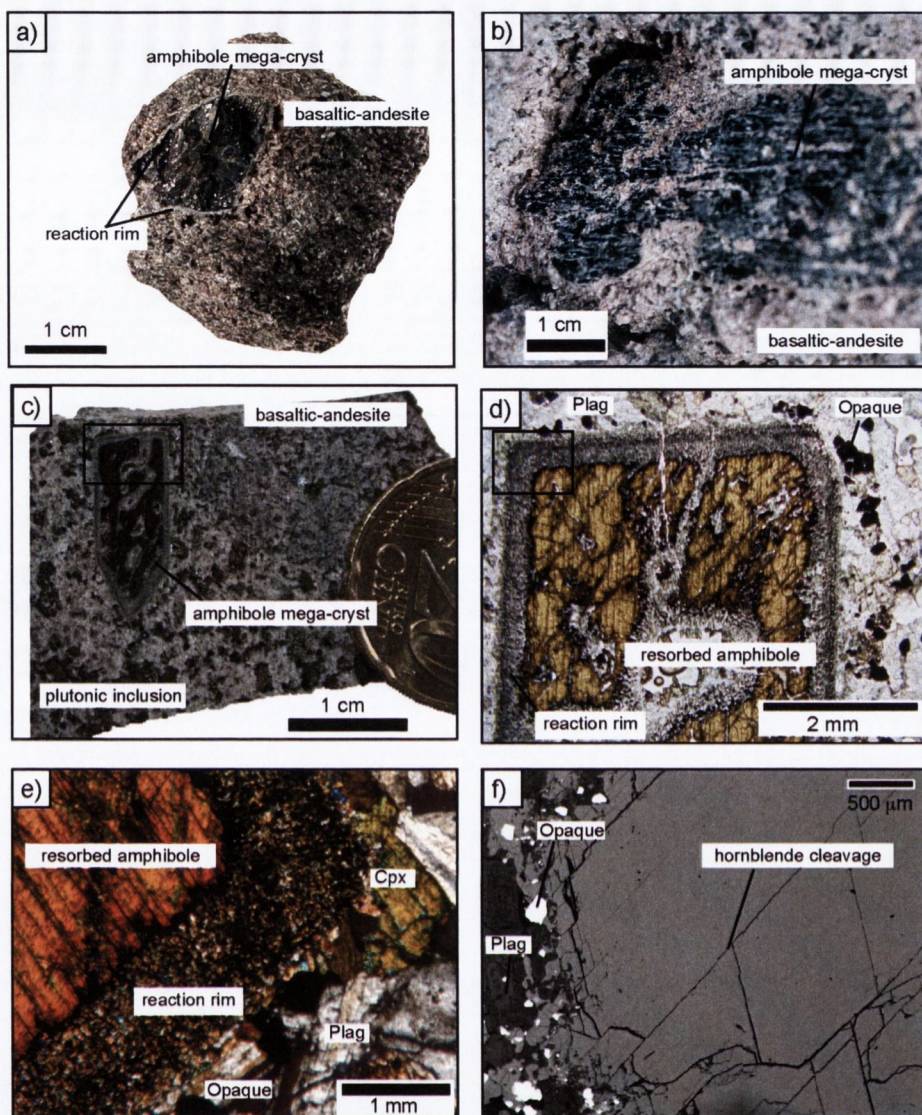


Figure 4.13. b) Field photograph of a strongly resorbed amphibole megacryst with clear cleavage in host basaltic andesite. c) Hand sample of plutonic inclusion (8-P-3) with a diffuse contact with host basaltic andesite. A small heavily-resorbed amphibole mega-cryst with a well developed reaction rim traverses the contact. Black box denotes area represented in d). Photomicrograph of resorbed amphibole megacryst in PPL with typical cleavage at 120 degrees. Black box denotes area represented in e). Photomicrograph of amphibole megacryst in XP showing presence of plagioclase, clinopyroxene, and opaques in granular reaction rim. f) BSE image of portion of an amphibole megacryst with obvious hornblende cleavage and an irregular rim with intergrown plagioclase.

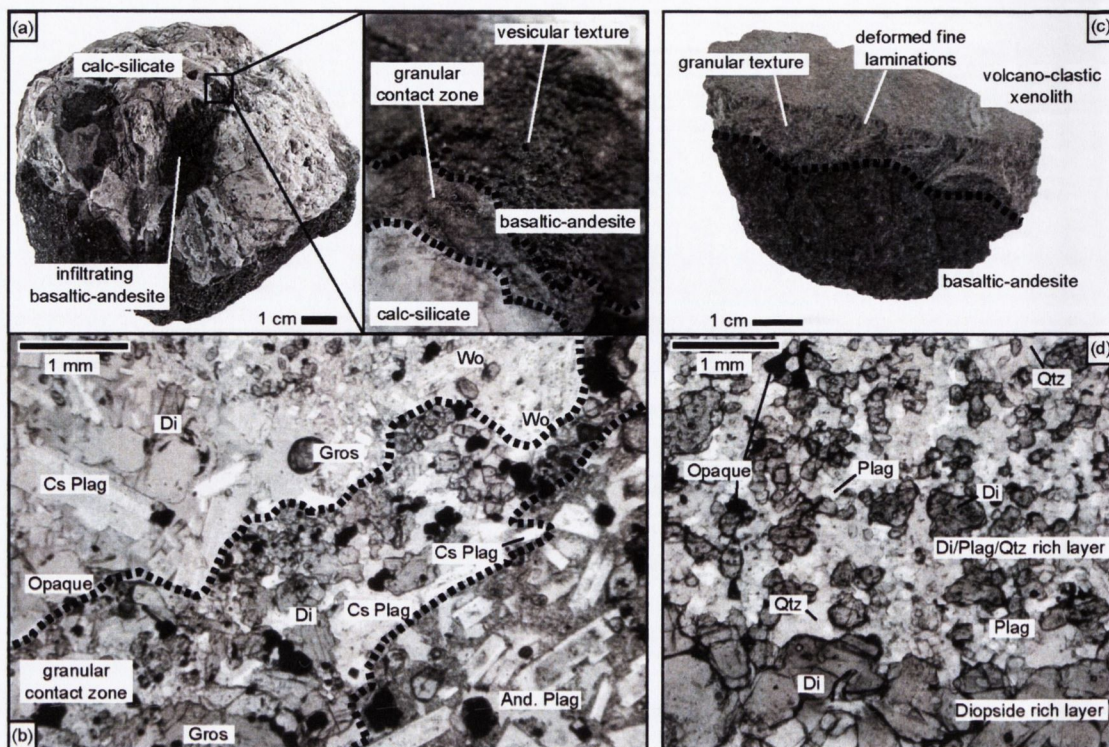


Figure 4.14 (a) Representative calc-silicate xenolith (XCS-3), with well-developed reaction rim. Inset shows highly vesicular contact between calc-silicate and host andesite highlighted with dashed lines. (b) Photomicrograph (PPL) of calc-silicate xenolith-andesite contact zone highlighted with dashed lines. Contact zone is diffuse with plagioclase laths (Cs Plag), grossular (Gros), diopside (Di), and wollastonite (Wo) evident in the calc-silicate xenolith. Large zoned plagioclase (And. Plag) form the dominant phase in the basaltic-andesite. Note just right of center is a calc-silicate plagioclase crystal being incorporated into the basaltic-andesite. (c) Representative volcaniclastic xenolith (XCS-2), with sharp contact with host basaltic-andesite and primary layering preserved. (d) Photomicrograph (PPL) of volcaniclastic xenolith illustrating variation in grain size and mineralogy between layers.

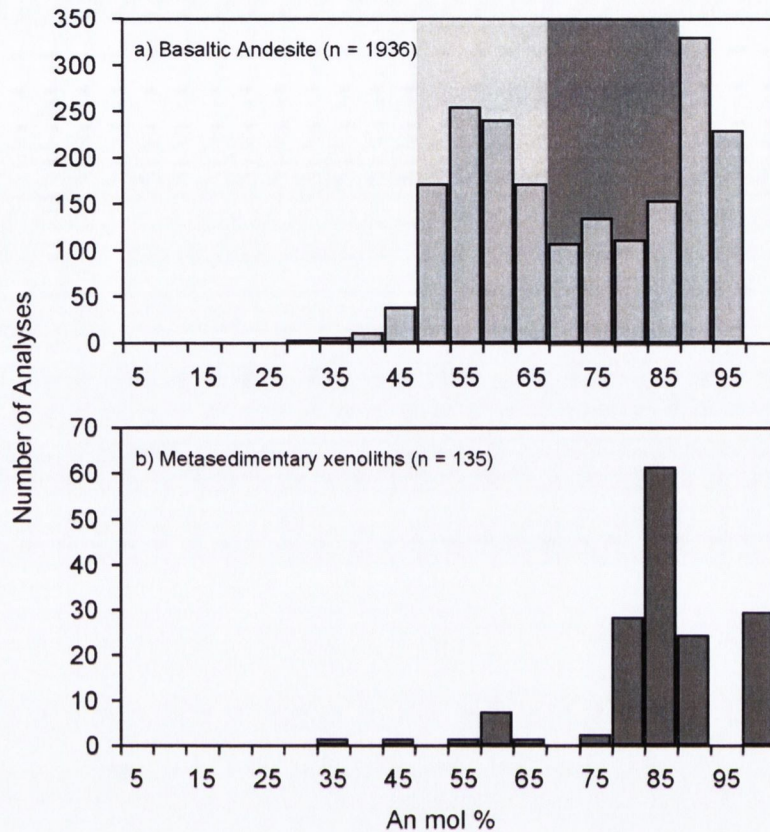


Figure 4.15 Histograms of An mol % composition of analyses of feldspar from a) host basaltic-andesite, b) metasedimentary inclusions. Grey zones in a) represent ideal plagioclase compositions for Merapi basaltic andesite calculated using groundmass compositions from Schwarzkopf *et al.* (2001) and the empirical equation of Panjasawatwong *et al.* (1995). Light grey zone represents plagioclase in equilibrium with average groundmass composition (An₅₀₋₇₀), and darker zone represents feldspar in equilibrium with least evolved groundmass composition (An₆₅₋₈₆) reported by Schwarzkopf *et al.* (2001).

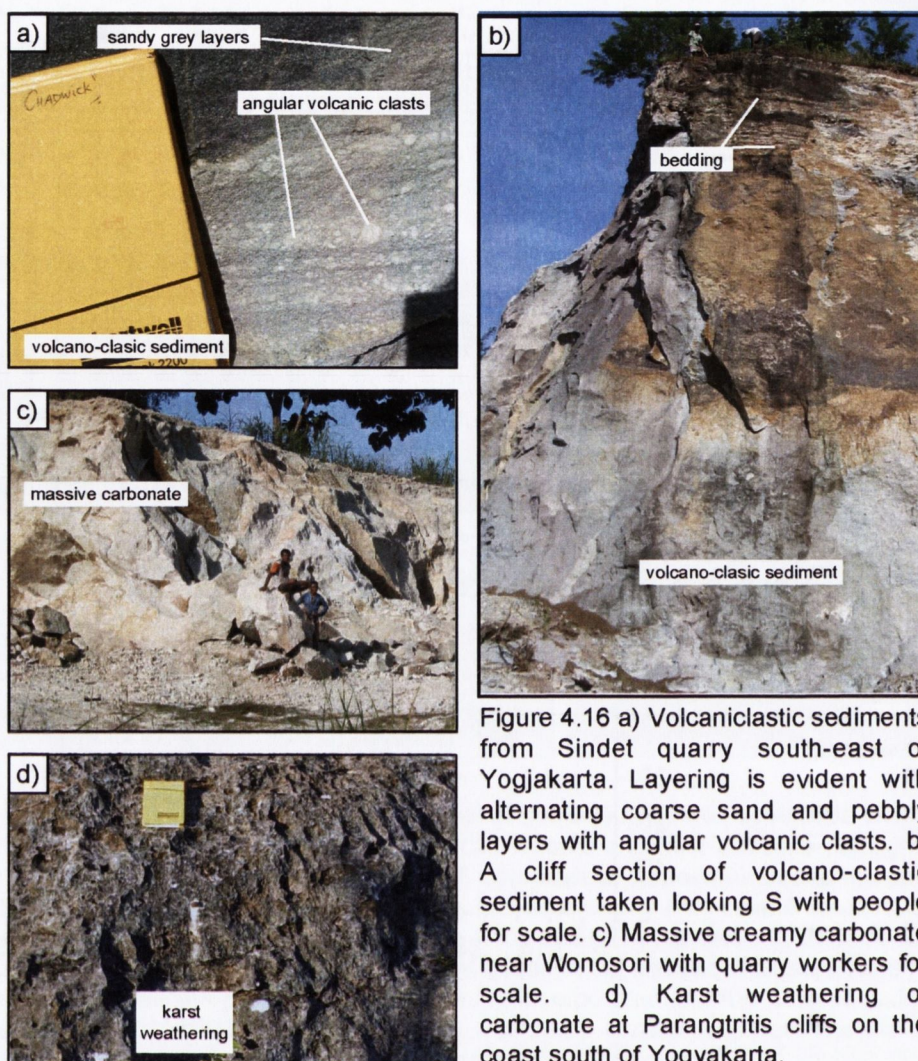


Figure 4.16 a) Volcaniclastic sediments from Sindet quarry south-east of Yogyakarta. Layering is evident with alternating coarse sand and pebbly layers with angular volcanic clasts. b) A cliff section of volcano-clastic sediment taken looking S with people for scale. c) Massive creamy carbonate near Wonosori with quarry workers for scale. d) Karst weathering of carbonate at Parangtritis cliffs on the coast south of Yogyakarta.

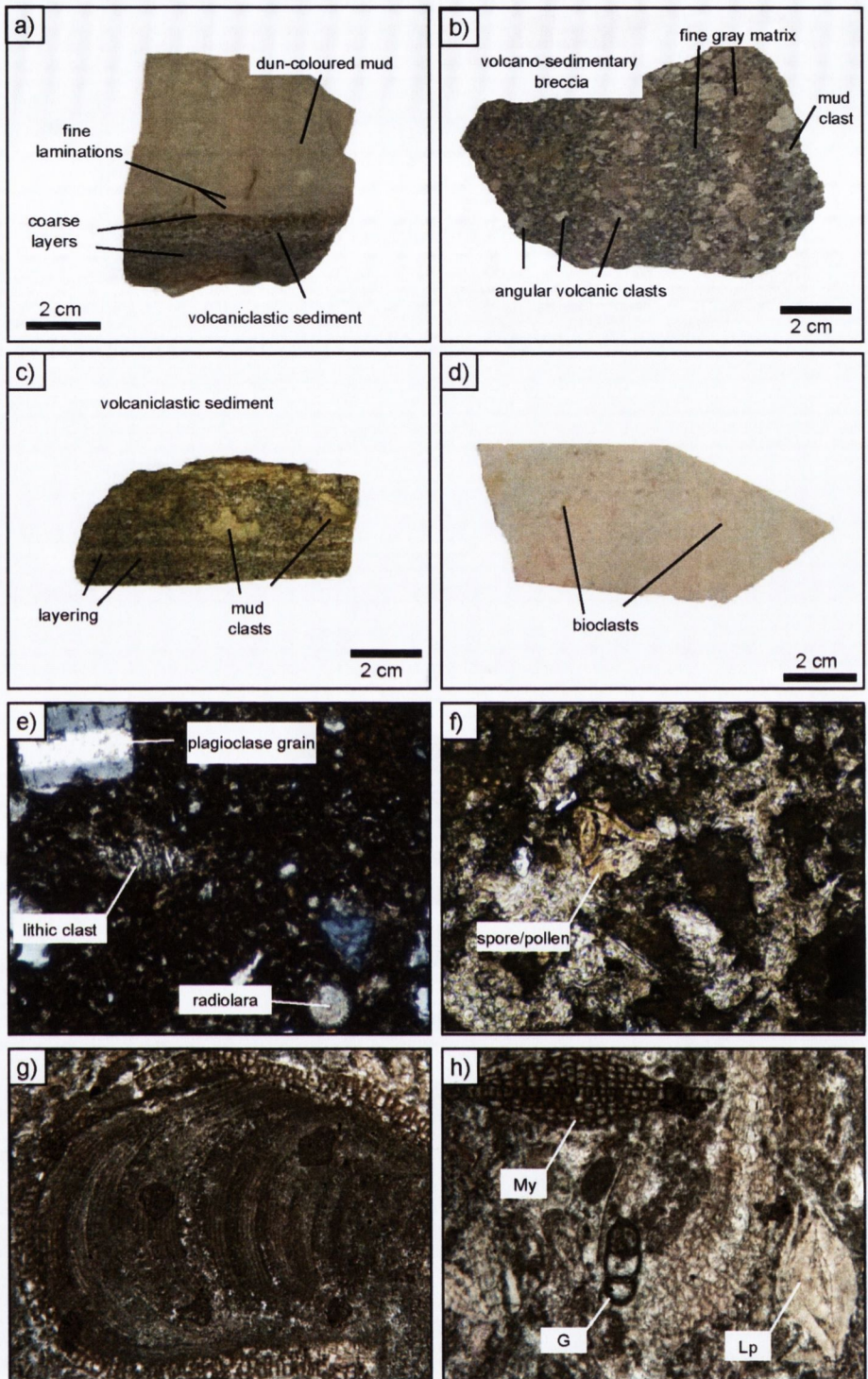


Figure 4.17. a). Hand sample of crust from Sindet quarry south-east of Yogyakarta. Dun-coloured mud is overlying coarse volcaniclastic sandstone. Mud shows fine laminations and layering is also evident in the coarser sediment. b) A breccia from the same quarry with angular volcanic and sedimentary clasts supported in a fine gray granular matrix. c) Volcano-clastic sandstone from the same quarry with mud 'pick-up' clasts indicating deposition in rapid flow. d) Hand sample of creamy carbonate from Parangtritis with subtle bioclasts present. e) Photomicrograph of dun-mudstone under XP with twinned feldspar grain and a radiolara present. f) Photomicrograph of volcano-clastic sandstone under PPL with a spore/pollen grain present. g) Photomicrograph of carbonate under PPL with large algae fossil present, with further fossils including three types of foraminifera; *Myogypsina* (My), *Lepidocyclina* (Lp), and *Globigerina* (G) in the same unit illustrated in h).

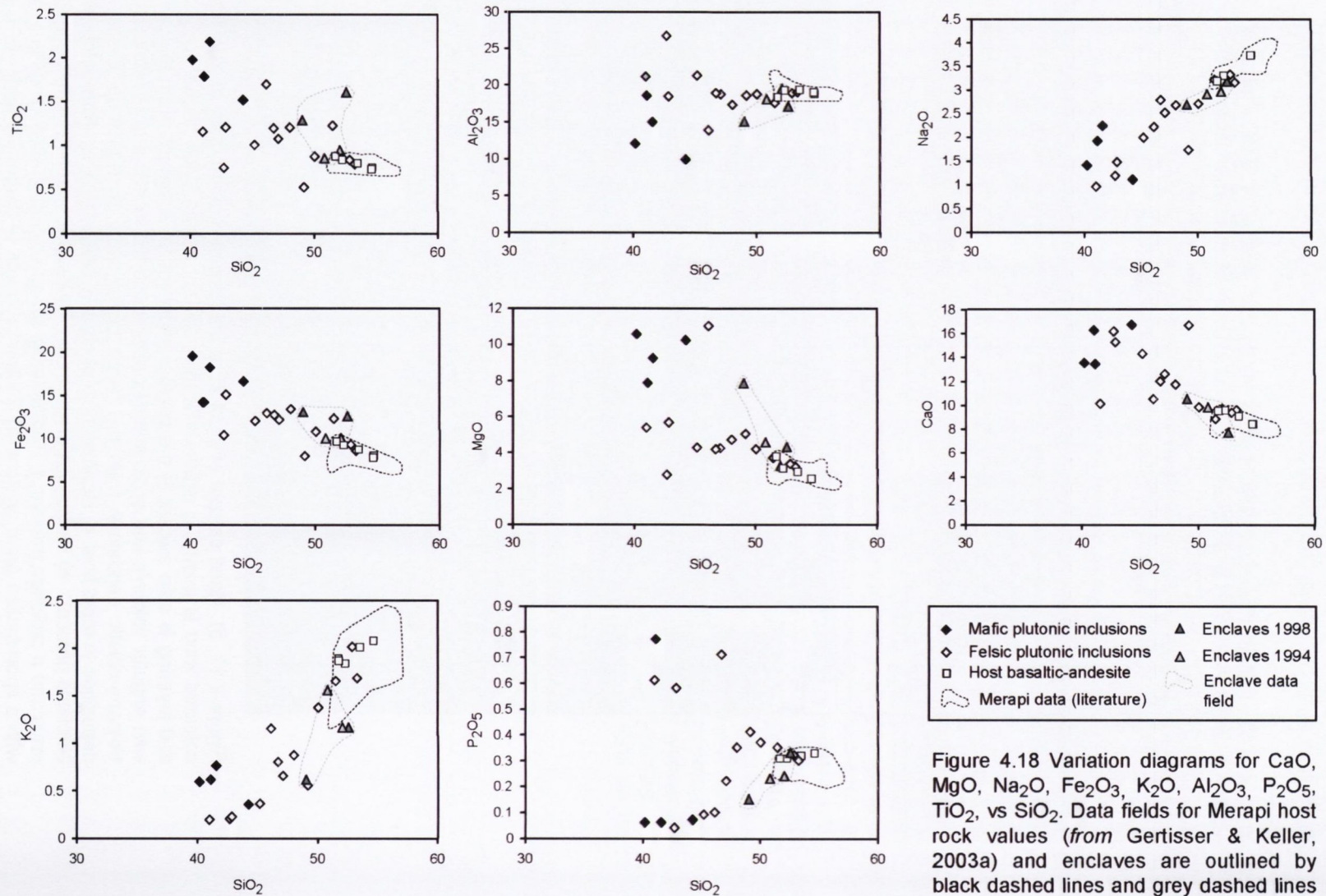


Figure 4.18 Variation diagrams for CaO , MgO , Na_2O , Fe_2O_3 , K_2O , Al_2O_3 , P_2O_5 , TiO_2 , vs SiO_2 . Data fields for Merapi host rock values (from Gertisser & Keller, 2003a) and enclaves are outlined by black dashed lines and grey dashed lines respectively.

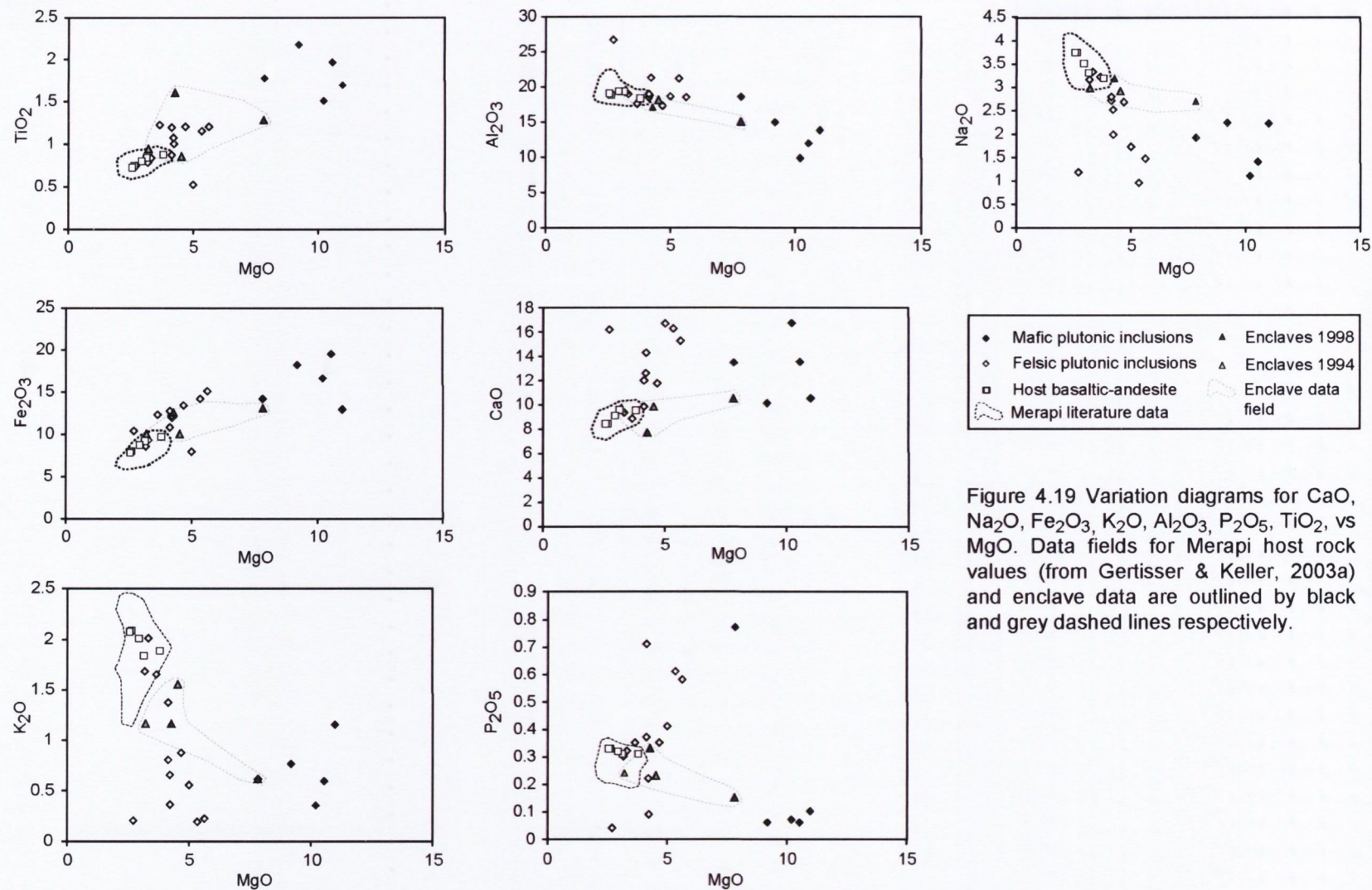


Figure 4.19 Variation diagrams for CaO , Na_2O , Fe_2O_3 , K_2O , Al_2O_3 , P_2O_5 , TiO_2 , vs MgO . Data fields for Merapi host rock values (from Gertisser & Keller, 2003a) and enclave data are outlined by black and grey dashed lines respectively.

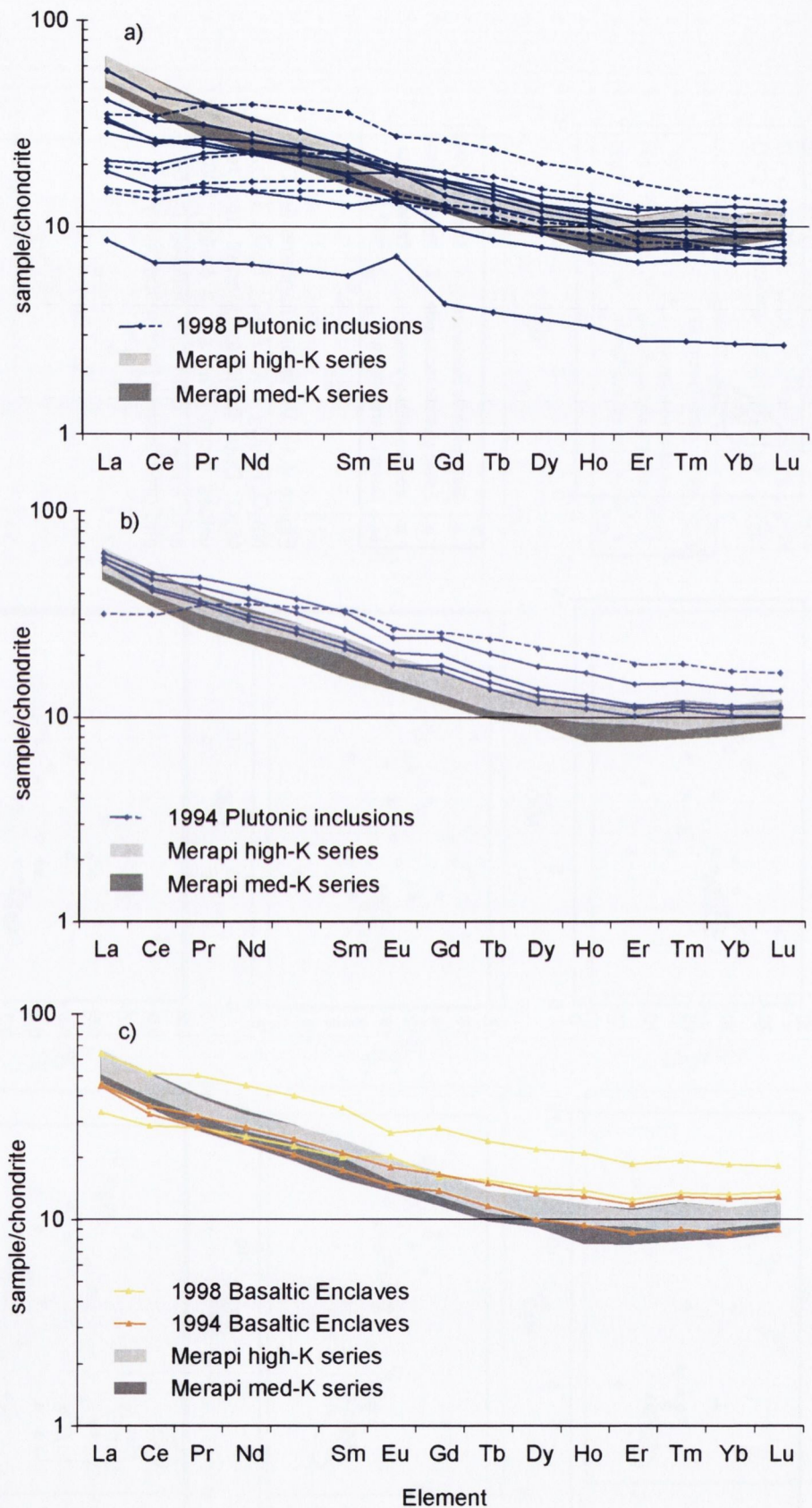


Figure 4.20 Chondrite-normalised rare earth element diagram for Merapi plutonic inclusions, and enclaves with Merapi High- and Medium-K series (*after* Gertisser & Keller, 2003a) shown for comparison. Dashed lines denote mafic inclusions classified on the basis of petrology. Chondrite data are from Sun & McDonough (1989). Pm was not analysed, the point is average between Nd and Sm.

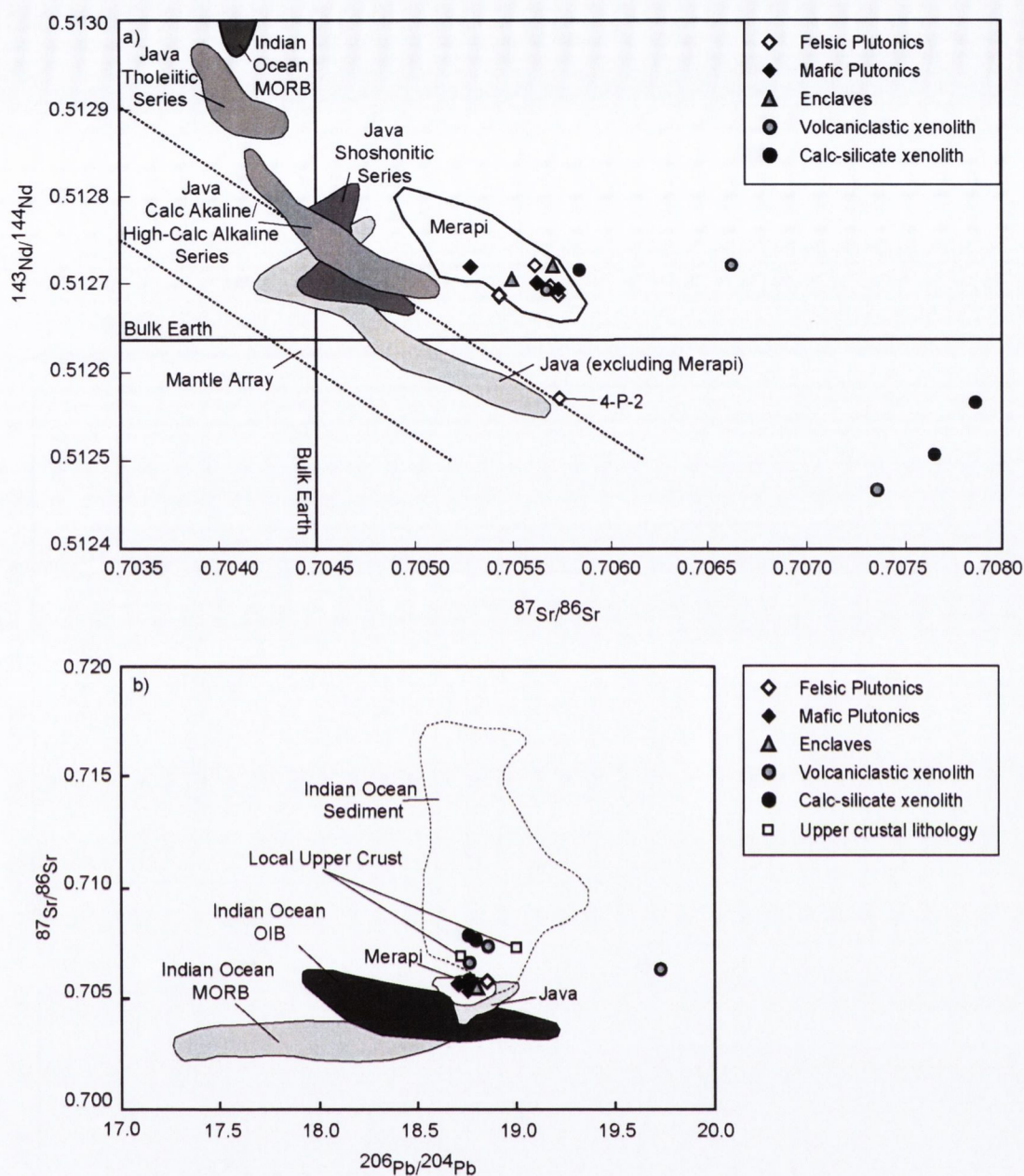


Figure 4.21 a) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ diagram illustrating data from Merapi plutonic inclusions, enclaves and xenoliths relative to the Mantle array, Merapi lava compositions and data from other Javanese volcanoes (after Gertisser & Keller, 2003a). b) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagram illustrating data from Merapi plutonic inclusions, enclaves and xenoliths relative to Indian Ocean MORB, Indian Ocean OIB, local upper crust, and Indian Ocean sediment (after Gertisser & Keller, 2003a).

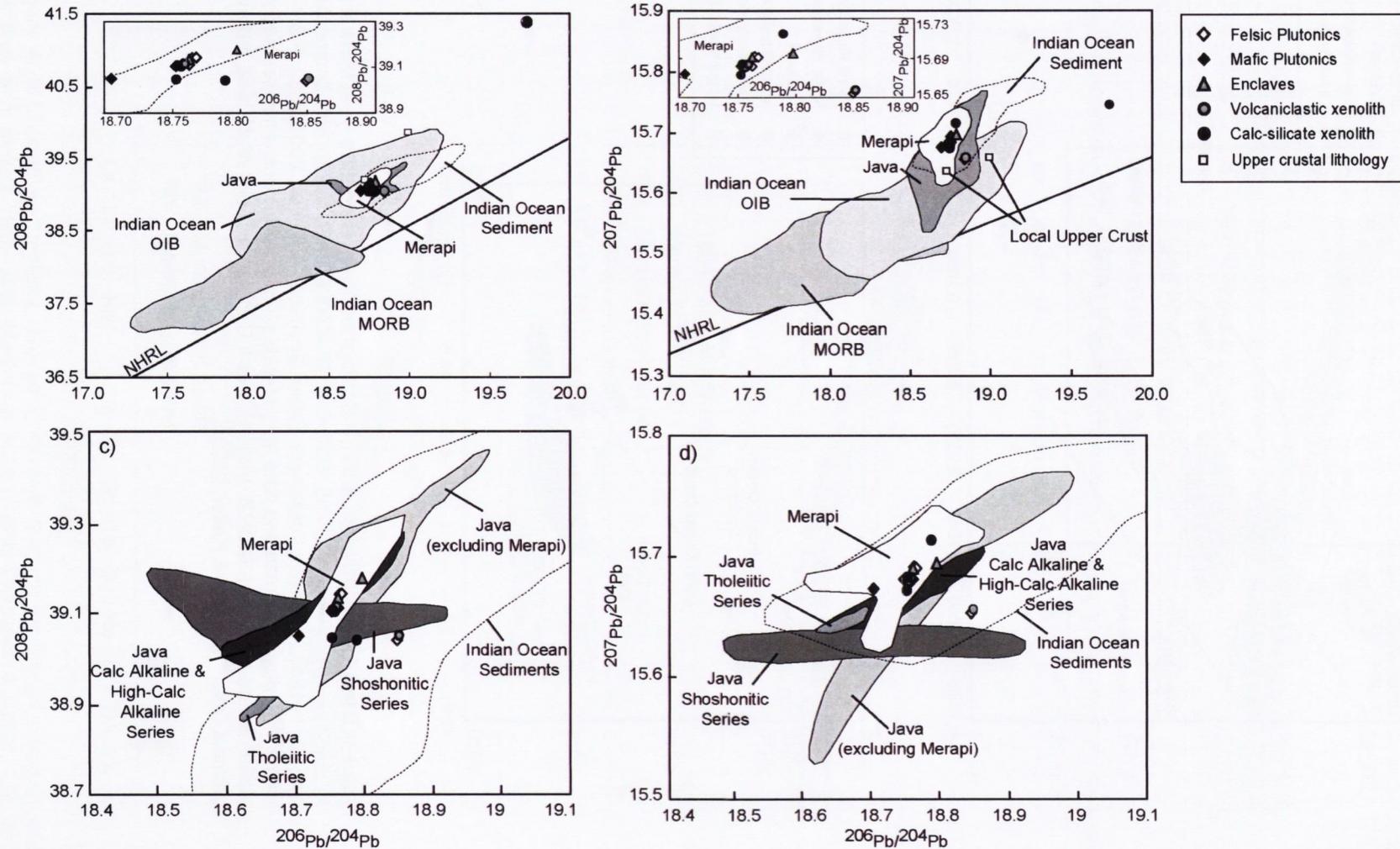


Figure 4.21 c) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams and d) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams, both showing data from Merapi plutonic inclusions, enclaves and xenoliths relative to Merapi lava compositions and data from other Javanese volcanics, Indian Ocean MORB, Indian Ocean OIB, Local upper crust, Indian Ocean sediment, xenoliths, Javan crust (after Gertisser & Keller, 2003a).

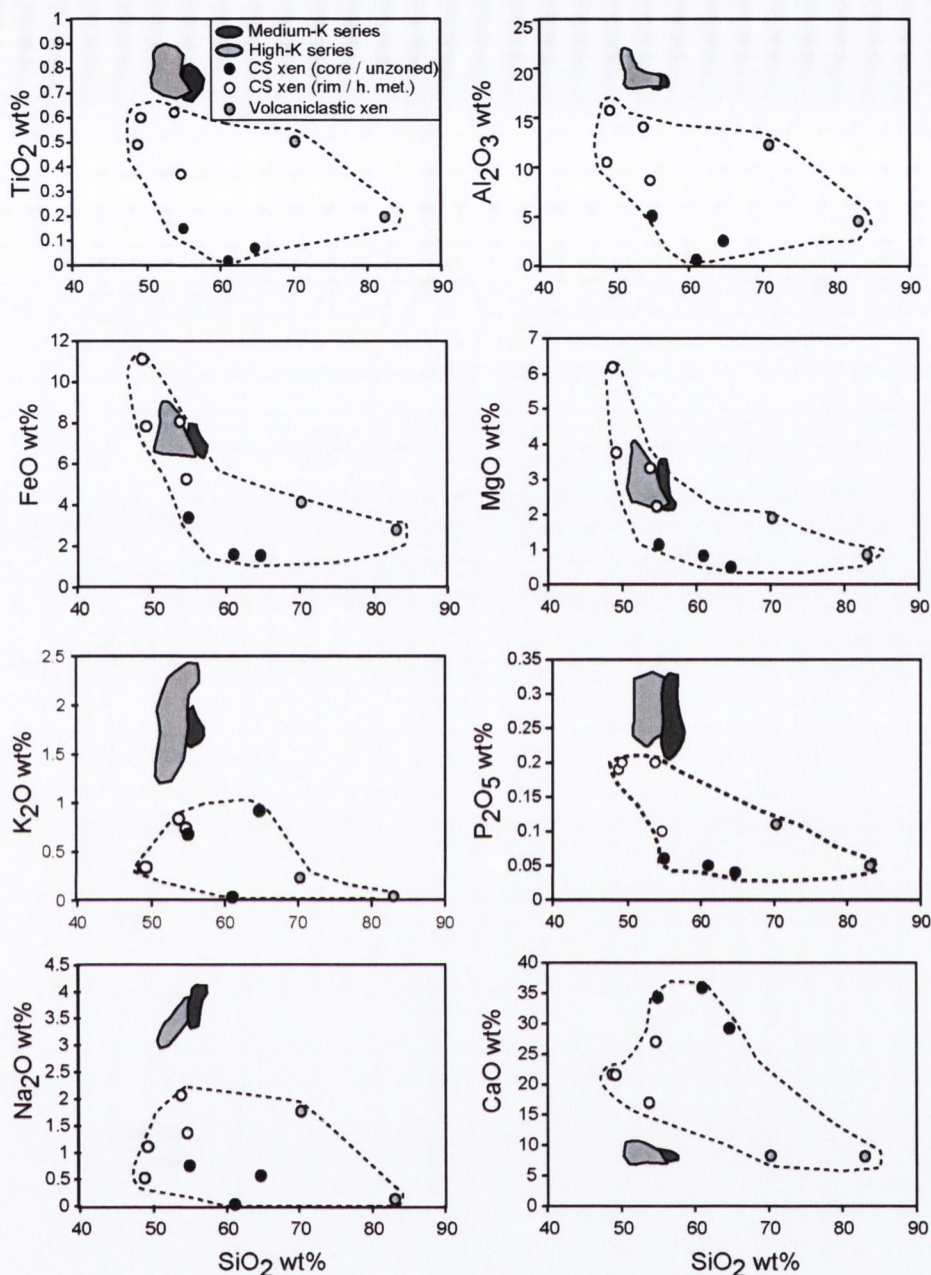


Figure 4.22 Harker diagrams for Merapi metasedimentary xenoliths relative to the Merapi basaltic-andesites (from Gertisser & Keller, 2003a). The xenolith samples show significant geochemical variation, particularly in SiO_2 . Volcaniclastic xenoliths (volcaniclastic xen.), cores and unzoned calc-silicate xenolith samples (CS core / unzoned) and highly metamorphosed rims and calc-silicate xenolith samples (CS rim / h. met.) are highlighted. A transition from calc-silicate xenolith interiors (cores and relatively unmetamorphosed samples) to more magmatic signatures at the rims or in highly metamorphosed samples is evident (eg. FeO and MgO).

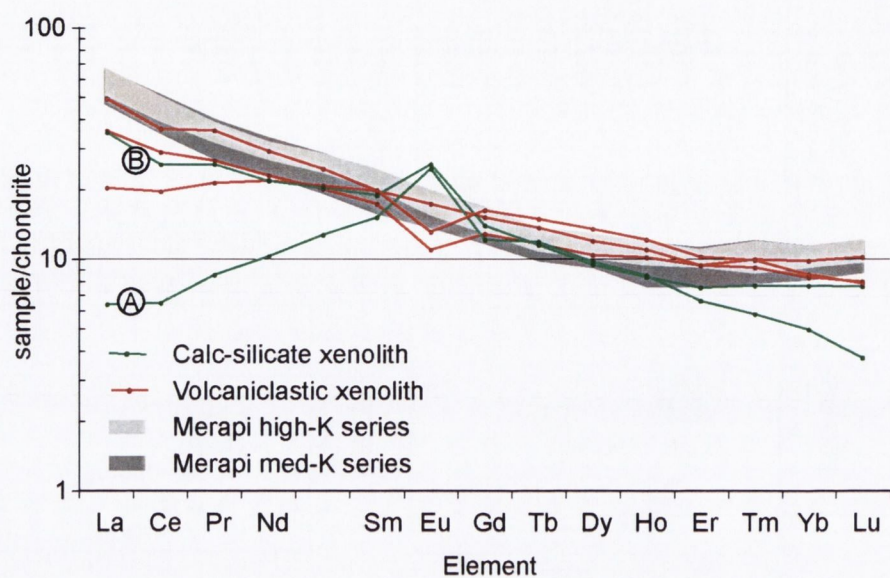


Figure 4.23 Chondrite normalised rare earth element diagram for Merapi xenoliths relative to Merapi High- and Medium-K series (*after* Gertisser & Keller, 2003a). Calc-silicate (xcs-1) core sample labeled A, and corresponding rim labelled B. Chondrite data from Sun & McDonough (1989).

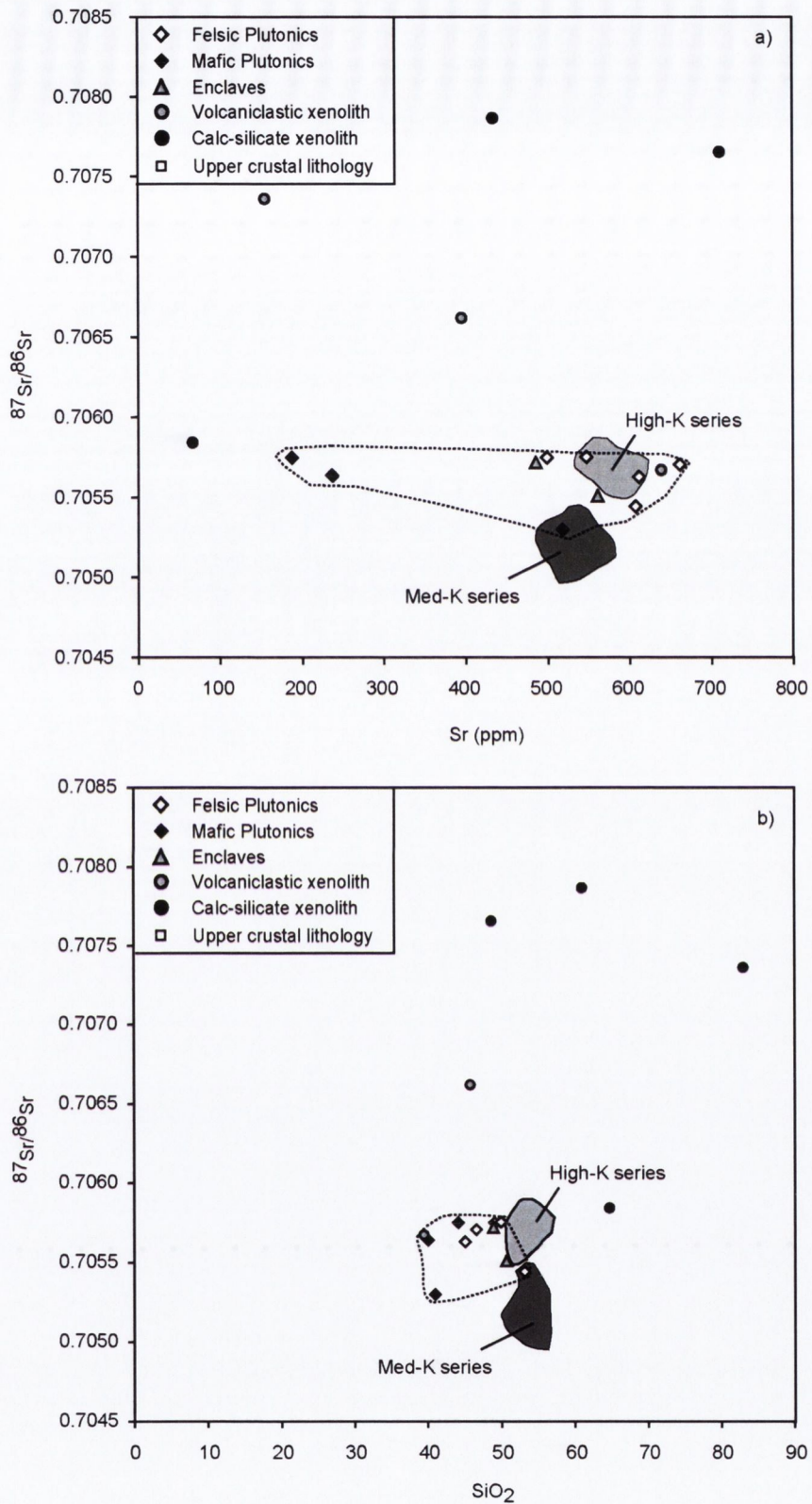


Figure 4.24. a) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Sr ppm diagram showing plutonic inclusions and enclaves (data field highlighted by black dashed line), relative to xenoliths (calc-silicate and volcaniclastic), and Merapi volcanics (from Gertisser & Keller, 2003a). b) $^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO_2 diagram showing plutonic inclusions, enclaves, and xenoliths relative to Merapi volcanics (from Gertisser & Keller, 2003a).

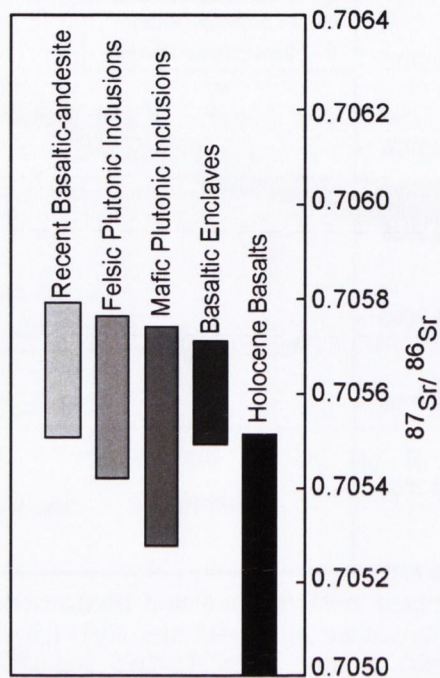


Figure 4.25. Sr isotope variation diagram for inclusions plotted relative to recent Merapi basaltic andesite block-and-ash flow deposits and Holocene basalts (from Gertisser and Keller 2003). The stepwise progression in Sr isotopic ratios from more mafic to more felsic inclusions may reflect increasing interaction with the crust and storage during ascent.

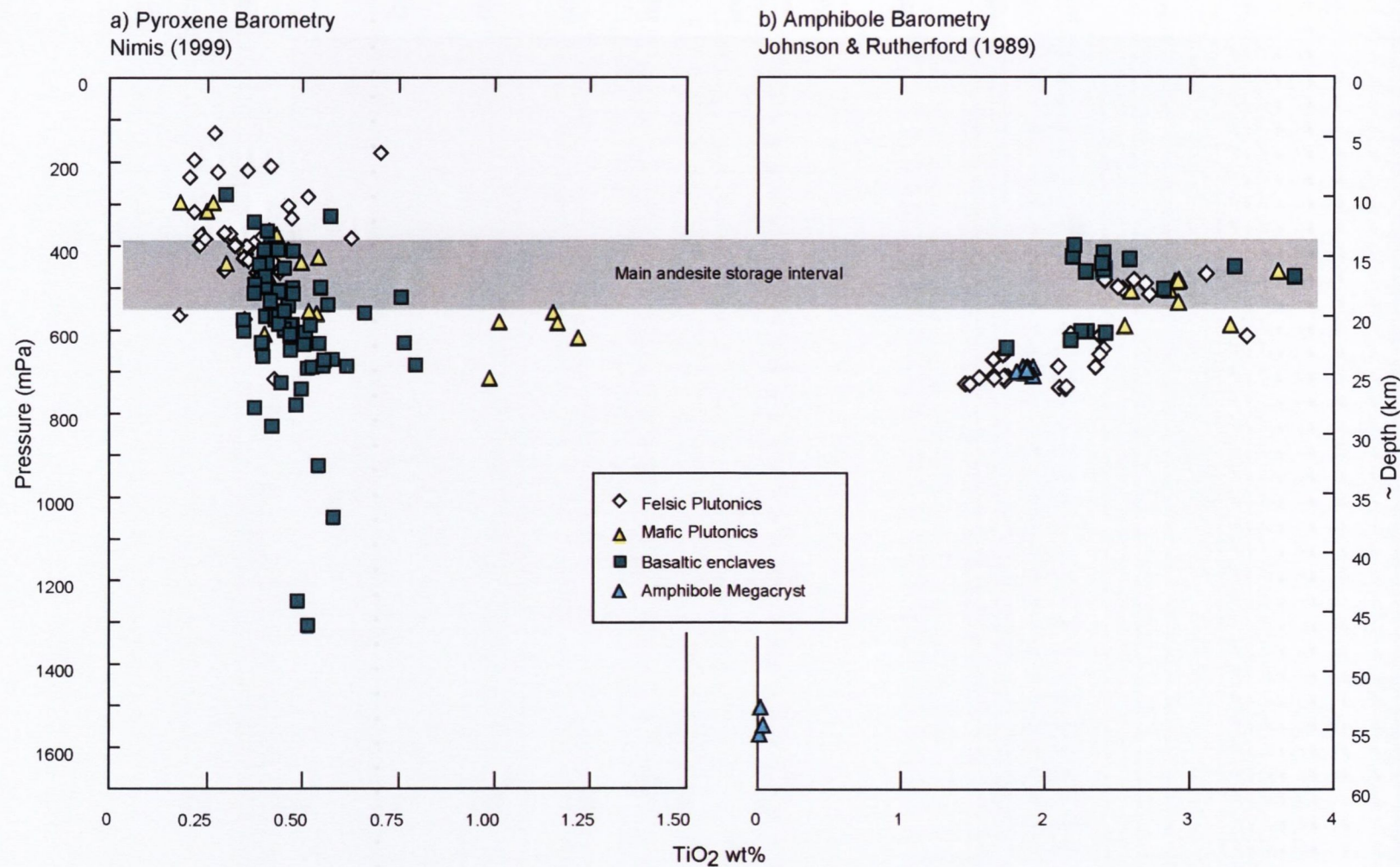


Figure 4.26. Results of pyroxene a) and amphibole b) barometry plotted relative to TiO_2 wt% content of crystals and approximate depth of crystallisation. Main zone of andesite crystallisation (from Gertisser, 2001) shown for comparison. Pyroxene crystallisation pressures show a broad range with amphibole crystallisation restricted to higher pressures.

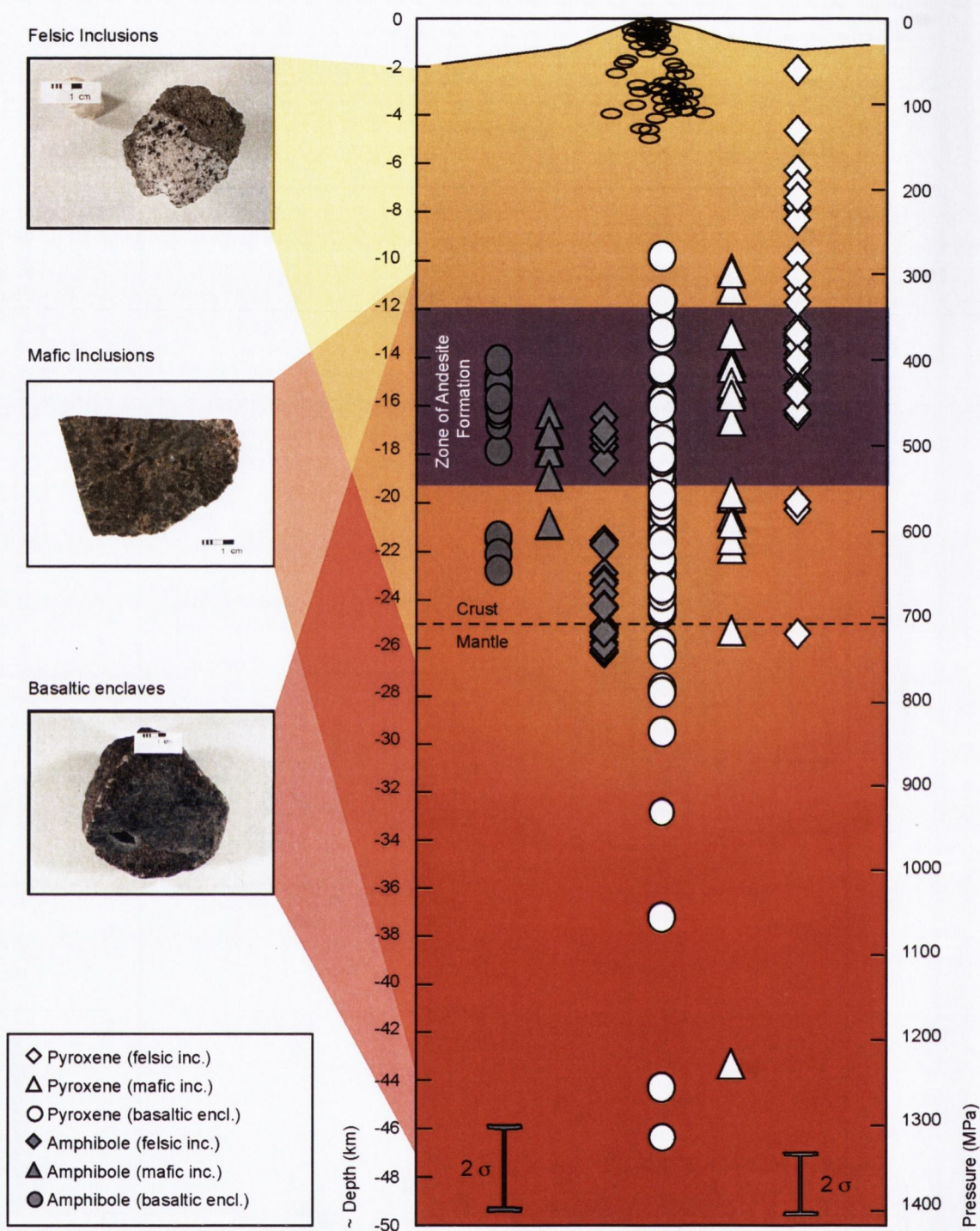


Figure 4.27 Geobarometric crystallisation pressures for plutonic and mafic inclusions and basaltic enclaves plotted relative to volcano-tectonic seismic data from Ratdomopurbo and Poupinet (2000). Open ellipses represent locus of shallow seismic activity beneath the volcano with a 'seismic gap' identified by these authors at approximately 3 km depth showing overlap with the shallowest crystallisation pressures obtained from pyroxenes in felsic plutonic inclusions.

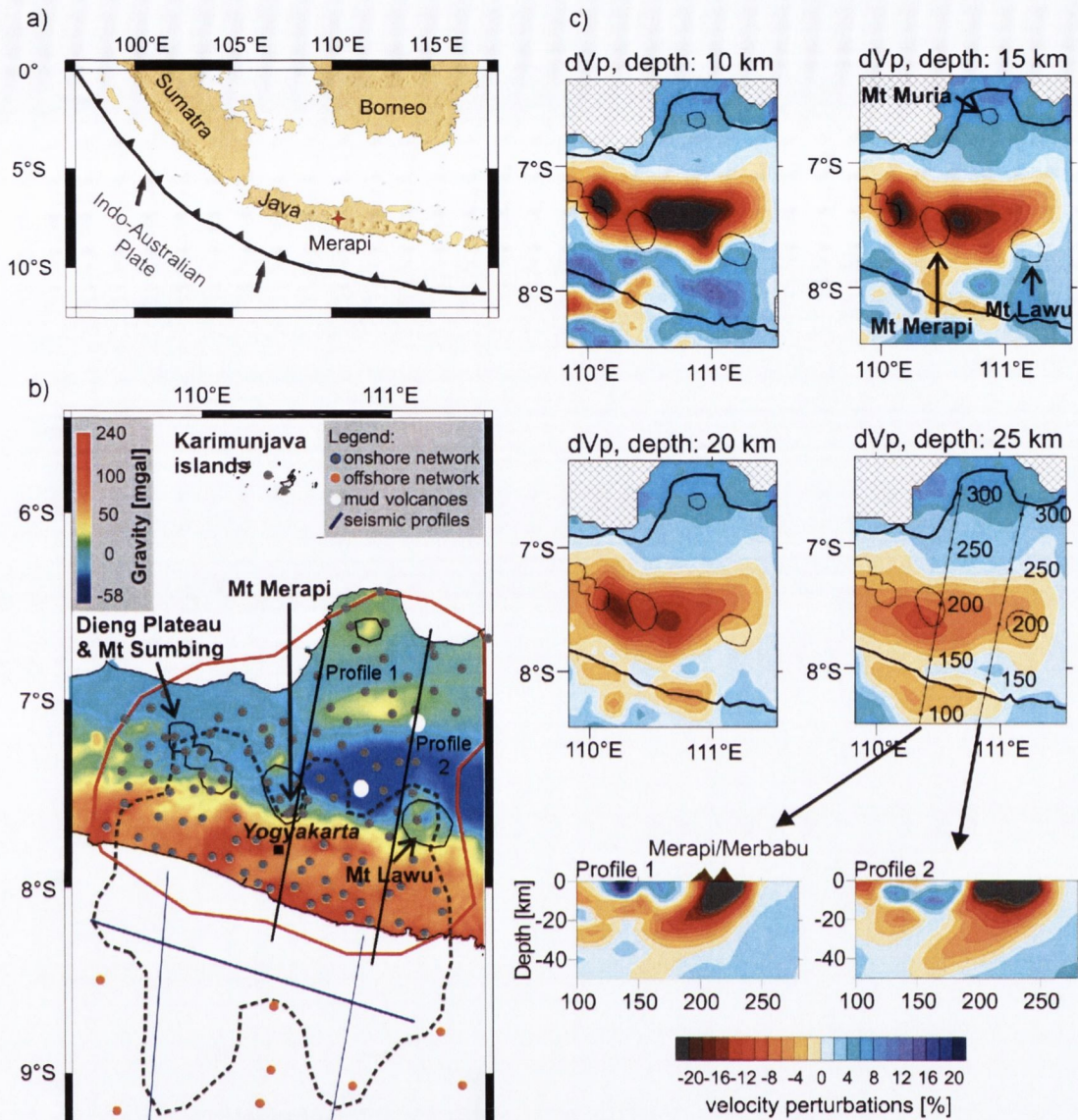


Figure 4.28. Figure from Chadwick et al. (submitted) a) Location map of the Sunda Arc with Merapi highlighted with a red star. b) The MERAMEX seismic network superimposed over a gravimetric map (after Smyth et al. 2005) of Central Java. The box marks the research area of the MERAMEX project. The area enclosed in red is covered by passive seismic data and the area surrounded by a dashed black line is covered by active seismic data. These areas are identified as locations with good recovery of 30 km size checkerboard anomalies at 5 km depth (Koulakov et al. 2007; Wagner et al. 2007). c) Tomographic results showing P-velocity perturbations in percent after the inversion of both active and passive seismic data. Open ellipses represent volcanoes labelled in 1a. The upper four diagrams are horizontal sections at 10, 15, 20 and 25 km depth, the bottom diagrams show vertical sections along profiles 1 & 2 with Merapi and Merbabu represented on profile one.

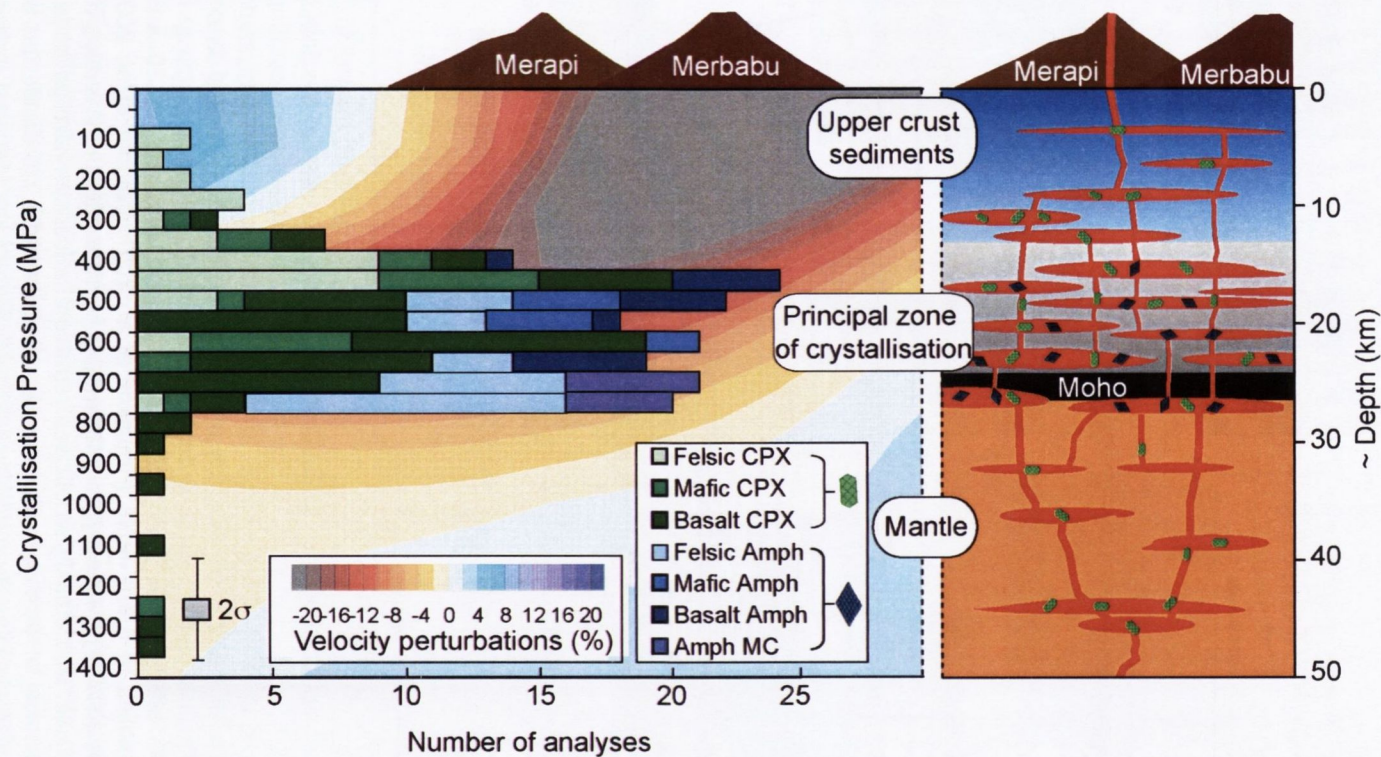


Figure 4.29 Histogram of pressure calculations for pyroxene (CPX) and amphibole (Amph) crystals from enclaves, felsic and mafic plutonic inclusions, and amphibole megacrysts plotted relative to a profile through the tomographic anomaly. Cluster of crystallisation pressures between 400 and 800 MPa are evident with a total range from 100 to 1350 MPa. A schematic cross section of a system of interconnected magma reservoirs spanning the crust and into the upper mantle beneath Merapi volcano is included and reflects results from geobarometric and geophysical studies. Note that the vertical height of Merapi and Merbabu are exaggerated.

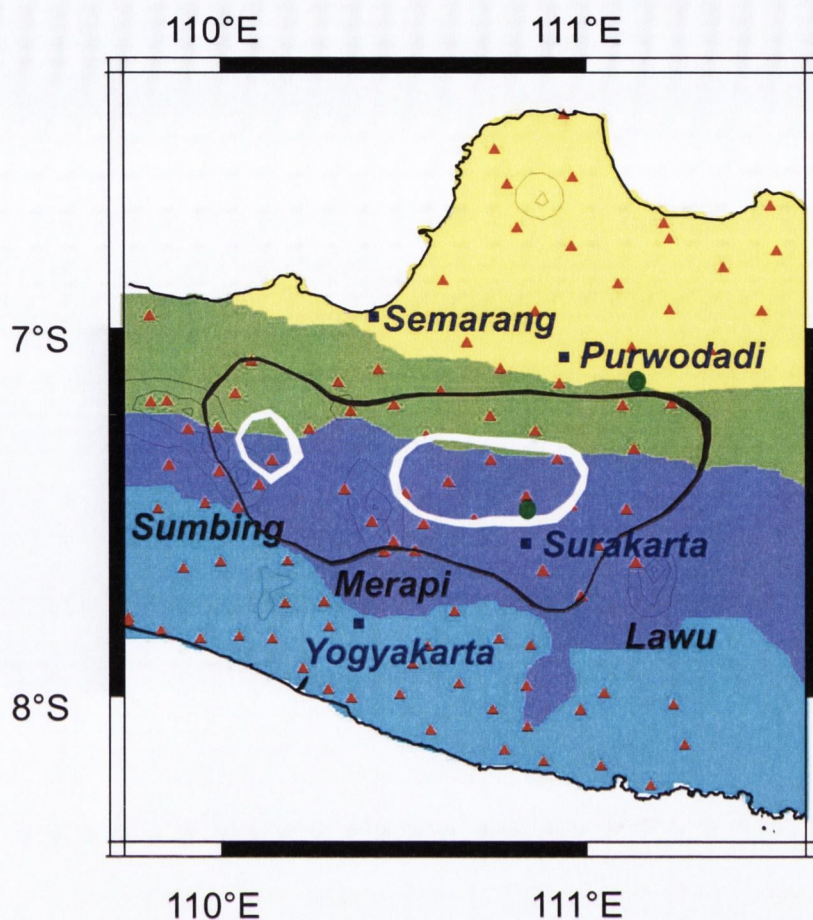


Figure 4.30 after Wagner, 2007. Map showing the zones identified by Smyth et al., (2005) in different colours; the Rembang zone in yellow, the Kendeng zone in green, the present day arc in purple and the Southern mountains zone in blue. The outline of the entire extent to the geophysical anomaly is marked by the thick black line with white lines enclosing the anomaly at 10 km depth. The green dots represent Kuwu mud volcano and the Sangiran dome which are roughly coincident with the periphery of the anomaly and the red triangles representing seismic receiver stations. Volcano topography is outlined in light grey with contours representing 1000 m intervals.

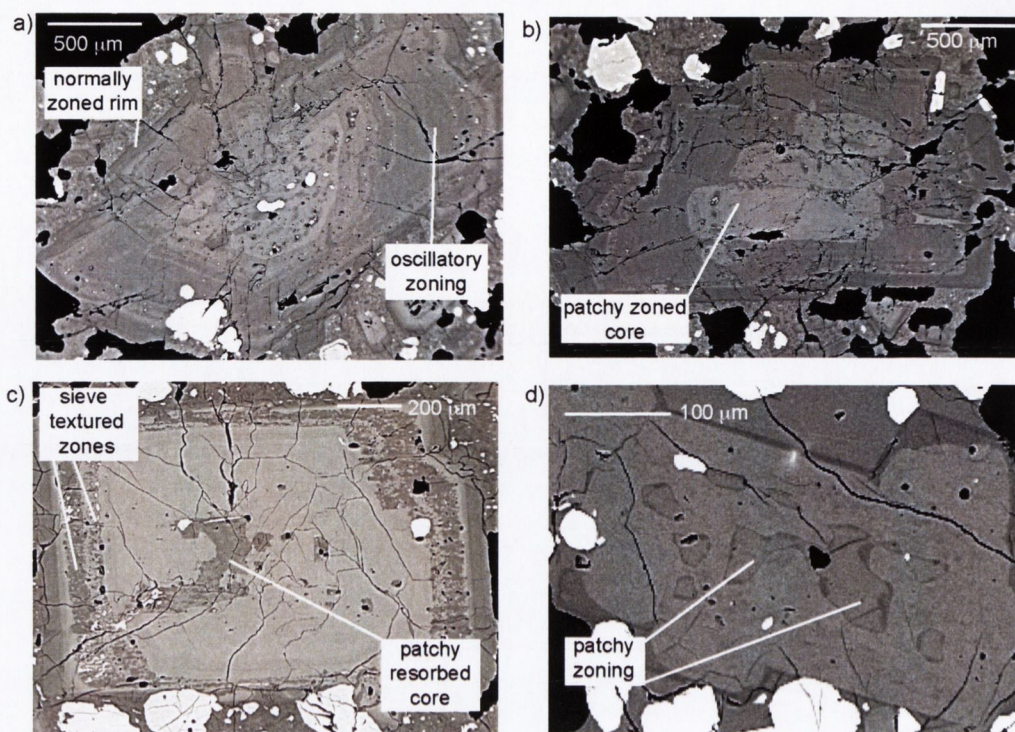


Figure 4.31 a), b), c) Back-scatter electron images of examples of the dominant phenocryst types in the 1998 basaltic andesite studied, see text for descriptions of different crystal types. d) Plagioclase crystal from a calc-silicate xenolith (xcs-102; c1) for reference.

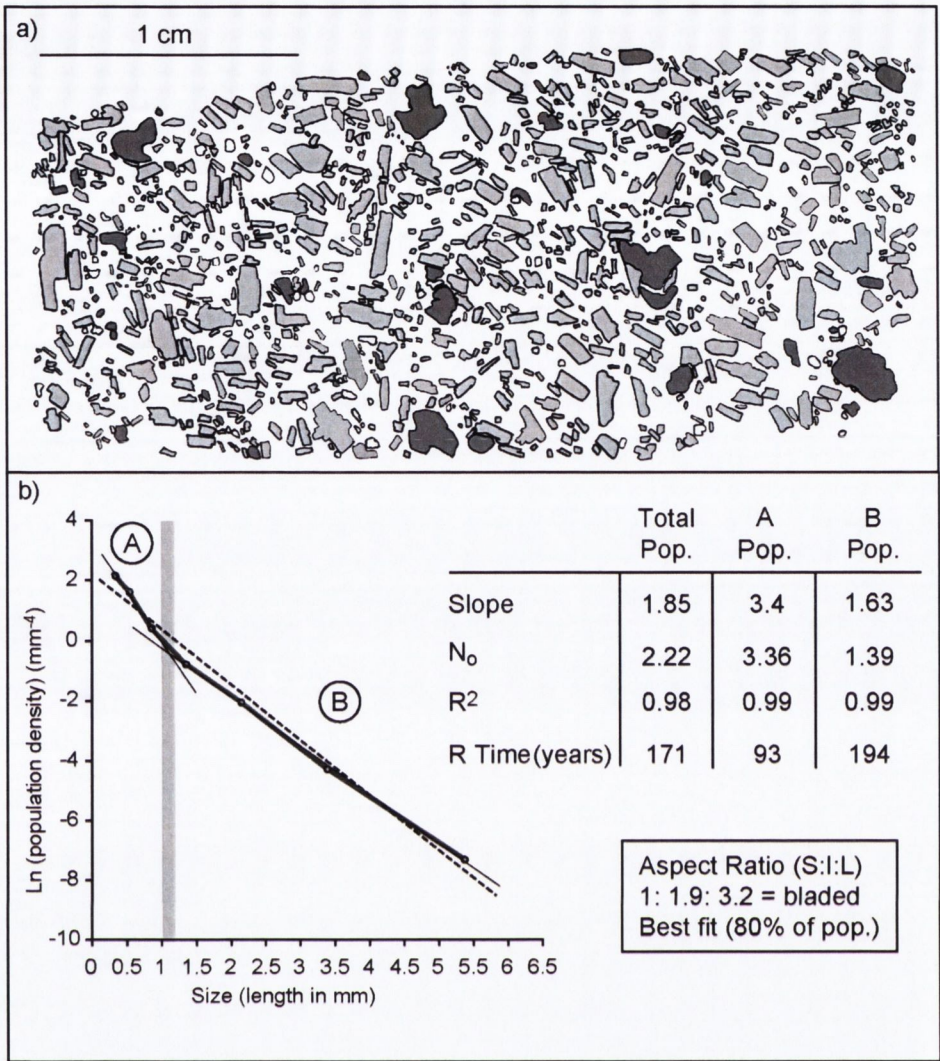


Figure 4.32 a) Greyscale image of 1998 BAF Merapi basaltic andesite crystal population with white filled shapes representing oxides, darker gray shapes representing pyroxene crystals (not analysed due to small sample numbers of <100) and lighter grey shapes representing plagioclase crystals ($n=987$). b) Crystal size distribution plot for 1998 Merapi basaltic-andesite (thick dark gray line) with relatively linear (regression analysis represented by black dashed line). Slight kink in population at ~ 1 mm size fraction (represented by light grey bar, separating two potential populations; A, groundmass crystals (~ 0.1 to 1 mm) and B, phenocrysts (~ 1 to 5.37 mm) with regressions for separate populations represented by thin black lines. Inset graph summarizes results of CSD analysis with crystal residence times (R time) calculated using a plagioclase growth rate of $10^{-11} \text{ cm s}^{-1}$ (Higgins, 1998). Stereological conversions from 2-D to 3-D measurements were determined following the methods of Higgins (2000).

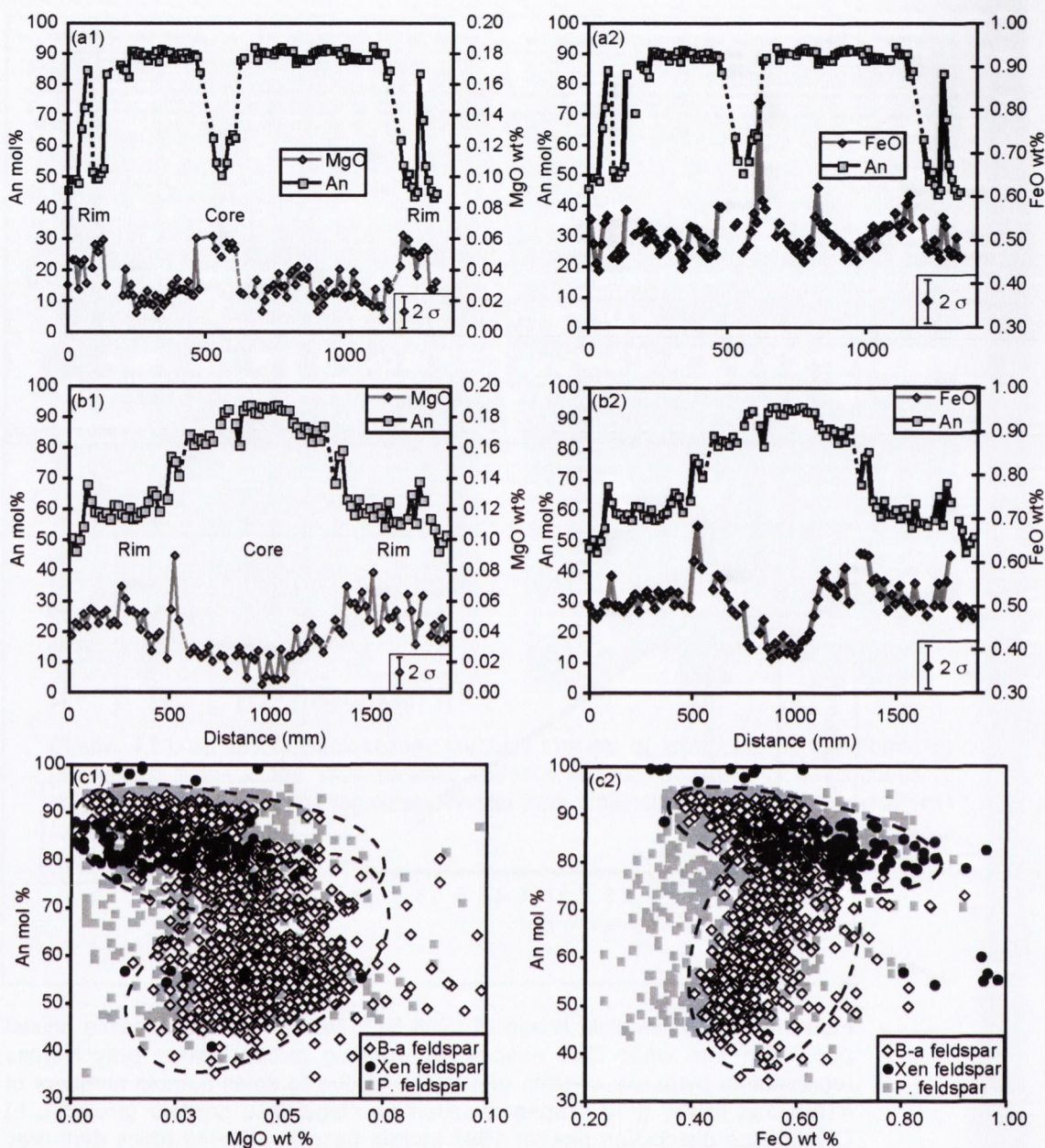


Figure 4.33 An mol % profiles plotted relative to MgO wt% (a1 & b1) and FeO wt% (a2 & b2) profiles for normally zoned (a) and reverse zoned (b) plagioclase crystals from Merapi basaltic-andesite. Sharp jumps in An content of up to 40 mol % reflect major changes in growth conditions and are located near dissolution surfaces. An mol % content is negatively correlated with MgO wt % and FeO wt%. (c) A plot of all analyses of basaltic-andesite (B-a feldspar, $n = 1936$), xenolith feldspar (Xen. feldspar, $n = 155$), and plutonic inclusion feldspar (P. feldspar, $n = 800$). A negative correlation exists for An compositions of > 85 mol % and a positive correlation for < 85 mol % in the basaltic andesite and xenolith feldspar but not evident for the plutonic feldspar. Dashed ellipses highlight the two dominant trends for basaltic andesite and xenolith feldspar for MgO wt% (c1) and FeO wt% (c2).

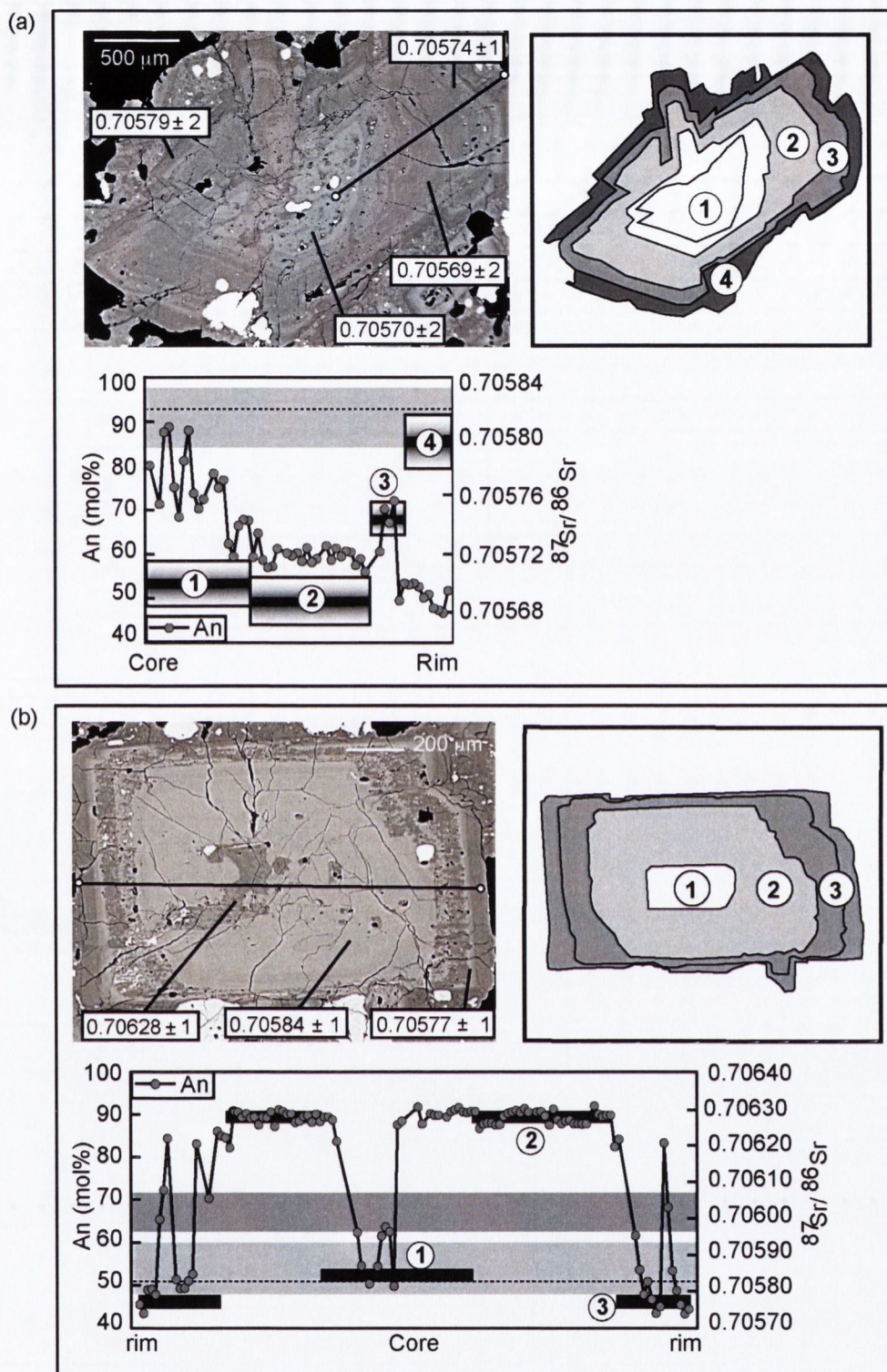


Figure 4.34 From Chadwick *et al.* (*In Press*), showing $^{87}\text{Sr}/^{86}\text{Sr}$ and An mol % zoning profiles for plagioclase phenocrysts (a and b with crystals c and d continued on following page) in comparison to groundmass (light grey bar) and plagioclase from a metamorphosed sedimentary xenolith (dark grey bar). Lower limit of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for xenolith whole-rock analyses delimited by dashed line. The rectangles represent $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (y axis) and the length and height of these bars corresponds to the drilled area and analytical error (2σ) respectively. Back-scattered electron images illustrate zoning patterns and locations of electron microprobe traverses (with multi-part traverses labeled a and b). Circled numbers correspond to drilled zones listed in Table 3.13.

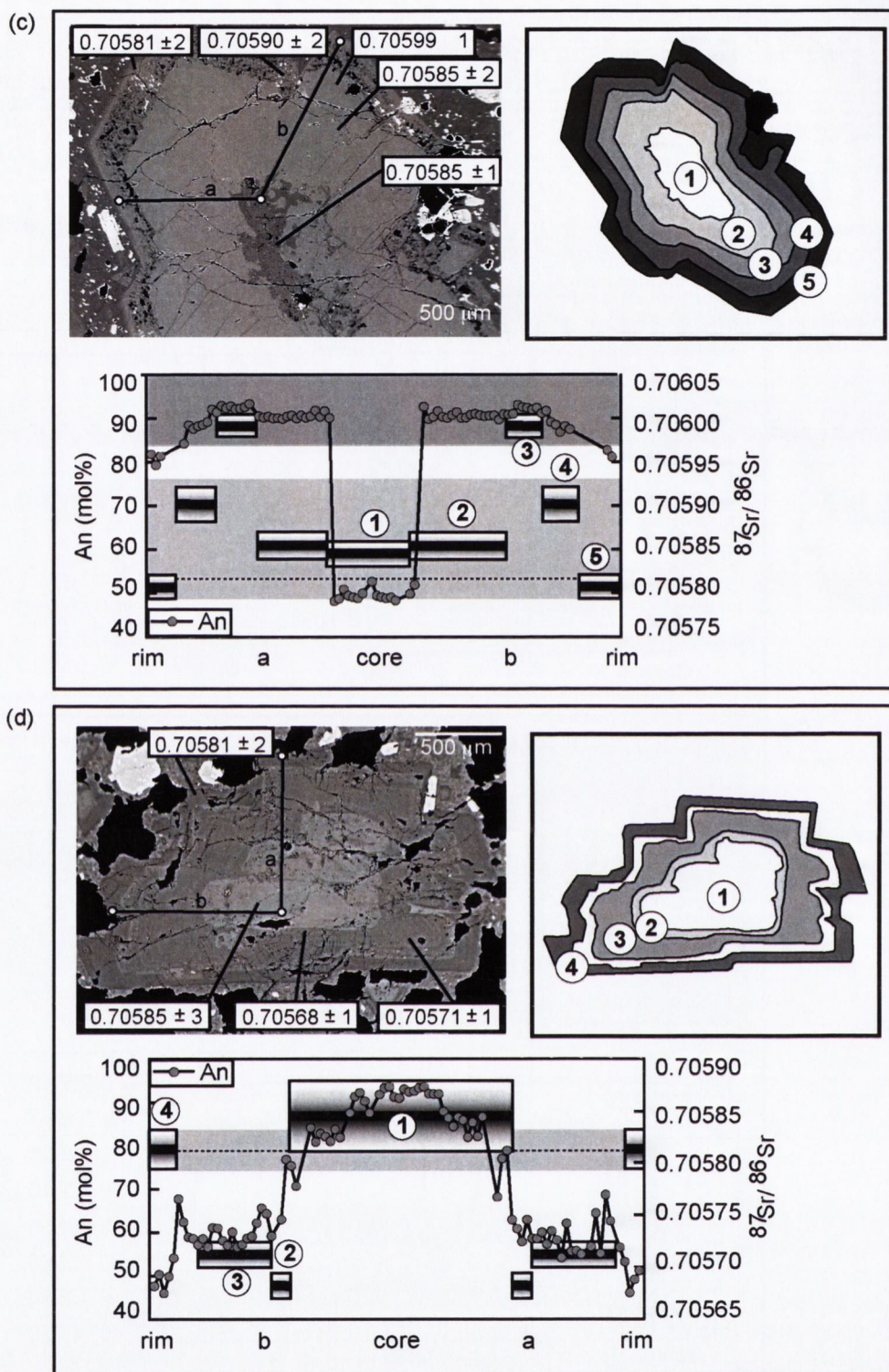


Figure 4.34 Continued, see previous page for details.

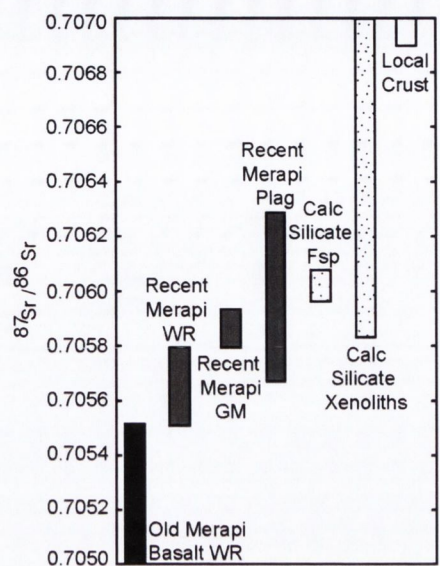


Figure 4.34 from Chadwick *et al.* (*In Press*) showing $^{87}\text{Sr}/^{86}\text{Sr}$ values for plagioclase (plag) and groundmass (GM) from 1998 Merapi basaltic andesite, and feldspar from a calc-silicate xenolith (Fsp) plotted relative to a local carbonatite crust, recent basaltic-andesite (WR), and Holocene basalts taken from Gertisser and Keller (2003a).

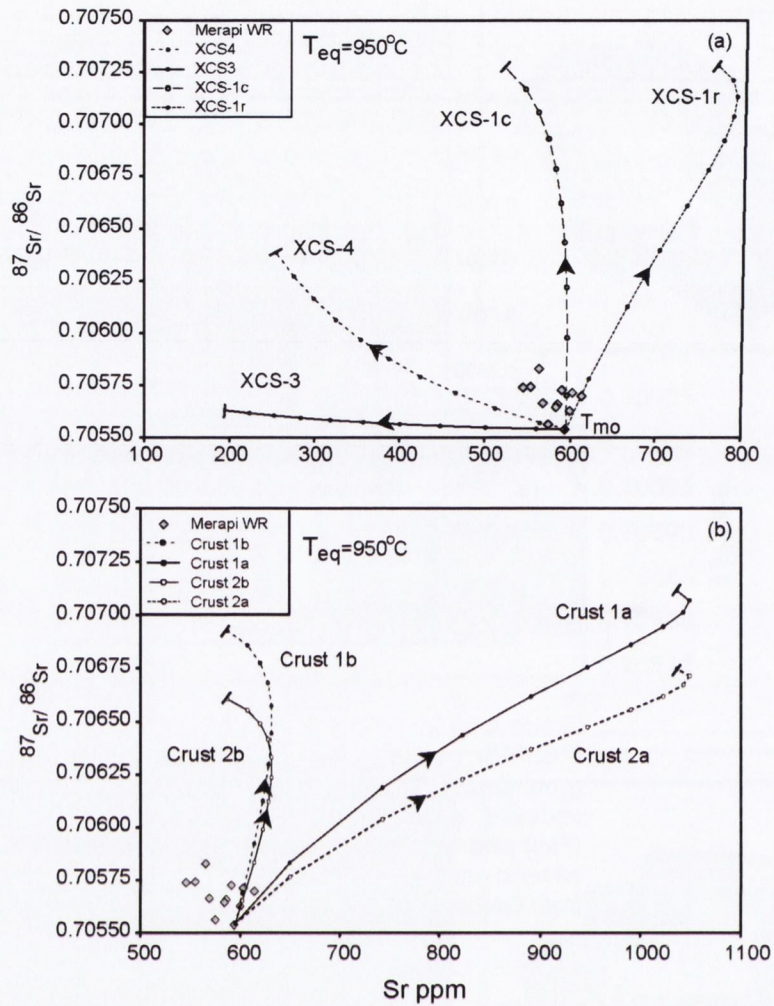


Figure 4.36 From Chadwick *et al.* (*In Press*), showing Sr ppm vs $^{87}\text{Sr}/^{86}\text{Sr}$ data for recent Merapi basaltic-andesite (Gertisser & Keller, 2003a), Central Javan crust, Merapi xenoliths and results from EC-AFC modeling (Bhorson & Spera 2001; Spera & Bhorson, 2001) with parameters used listed in Table 4.14. Arrows indicate direction of falling magma temperature (T_m) and each symbol on the EC-AFC curve represents a normalised temperature increment of 0.01 ($\sim 15^\circ\text{C}$). a) Models using xenolith compositions as assimilants encompass the Merapi basaltic-andesite data field. b) Models using Javan carbonate crust as an assimilant do not account for the entire range observed in recent Merapi basaltic-andesite.

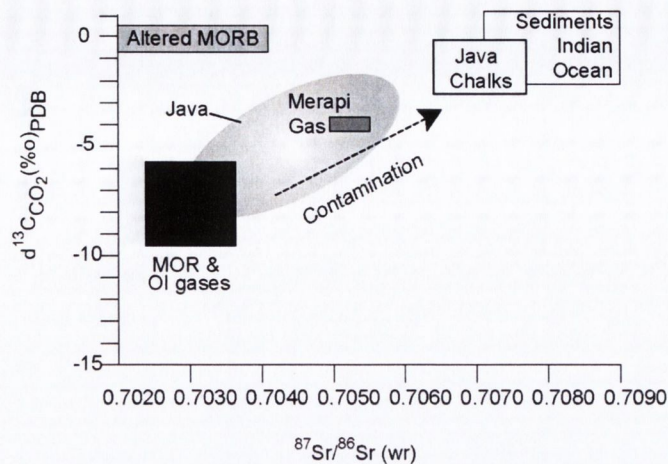


Figure 4.37 After Troll et al. (2003) showing $^{87}\text{Sr}/^{86}\text{Sr}$ whole rock vs. $\delta^{13}\text{C}_{\text{CO}_2}$ isotope ratios for Java gas samples (from Allard, 1983) with Merapi samples and end-member components including, mid ocean ridge (MOR), ocean islands (OI), Javanese upper crustal carbonate and Indian ocean sediment compositions. The data indicate contamination of Merapi volcanic gases with limestone derived CO_2 either from the subducting slab or from a shallower crustal contamination process.

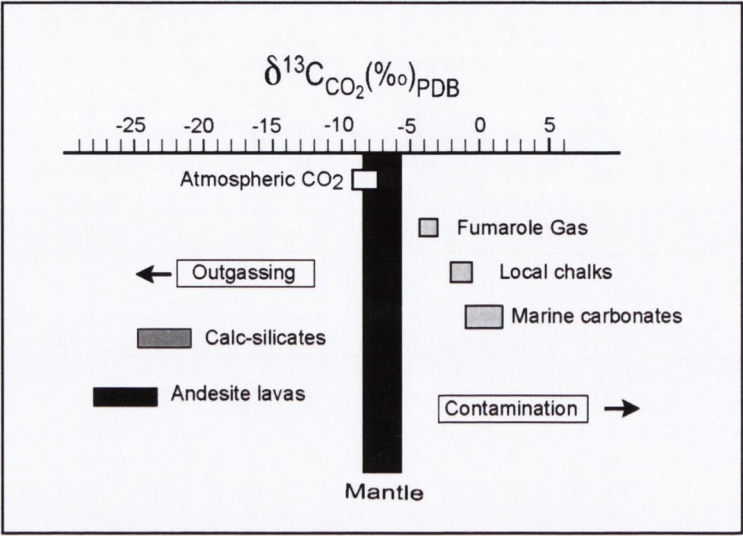


Figure 4.38 After Troll *et al.* (2003) showing $\delta^{13}\text{C}_{\text{CO}_2}$ of rock and gas samples from Merapi; Reference fields for mantle, crust and atmospheric CO_2 are from Hoefs (1996) and Holloway & Blank (1994). Andesite and calc-silicates are strongly out-gassed, whereas the fumarole samples are elevated relative to lava and average mantle values, suggesting a potentially substantial addition of organic CO_2 due to magma-xenolith interaction.

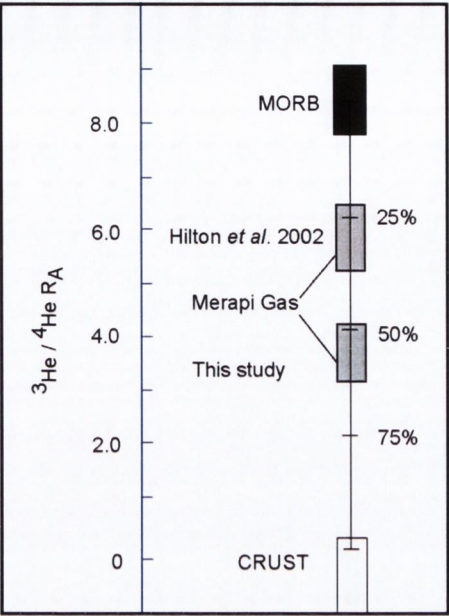


Figure 4.39 After Troll *et al.* (2003) showing He isotope ratios for Merapi gas samples (from Hilton *et al.*, 2002) and from this study. Mantle derived gas and crustal He compositions are from Sanyo & Marty (1995) and Hilton *et al.*, (2002). The Merapi data indicate a deviation from magmatic signatures and an input of crustal derived He of > 25%.

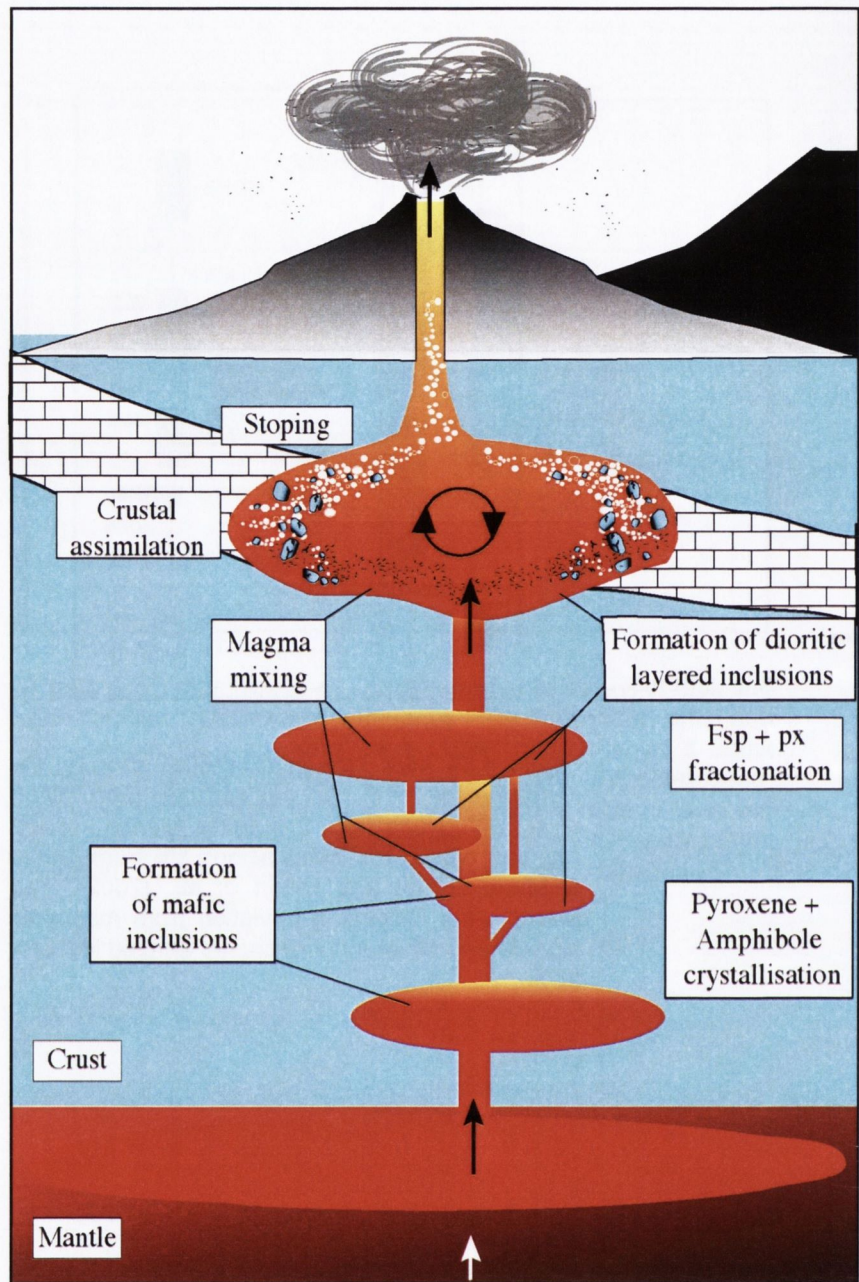


Figure 4.40. Schematic diagram illustrating processes occurring beneath Merapi including: ponding of mafic magma and fractionation of amphibole and pyroxene at the base of the crust, storage of magma in multiple reservoirs throughout the crust where mixing and crystal accumulation occur, and interaction with the crust resulting in contamination, and xenocryst and volatile incorporation.

CHAPTER 5 – CONCLUSIONS AND FURTHER WORK

5.1 Crustal processes in an continental inter-plate volcanic systems: Slieve Gullion, Ireland

Extensive interaction with the crust is not unusual for this tectonic setting, with strong evidence for crustal contamination recorded in the geochemistry of magmas from virtually all British and Irish Palaeogene Centres (e.g. Kerr *et al.* 1999; Ellam & Stuart, 2000; Bell & Williamson, 2002; Geldmacher *et al.* 2002) and even from basaltic plateau lavas in the British and Irish Paleogene Igneous Province (Thompson *et al.*, 1986). The voluminous magmas of the BPIP resulted in a sizeable heat influx, aiding crustal assimilation and anatexis across the region. Given the highly radiogenic and variable nature of the crustal terranes across the province, even limited interaction with the crust can be detected in whole rock isotope ratios of volcanic products.

The Sr and Nd isotope whole rock geochemical data for the Slieve Gullion ring-dyke magmas are consistent with at least two stages of contamination during upper crustal residence and storage and support petrographic, major and trace element evidence which indicates that a strong genetic link between the porphyritic rhyolite and granite. Taking primary melt of MORB composition typical for this region, the geochemical signatures in Slieve Gullion ring dyke magmas are replicated by fractionation and contamination by local sedimentary rocks with additional late and shallow contamination by the most fusible portions of the Newry Granodiorite.

Cross-cutting basaltic dykes also show evidence of crustal contamination and an earlier lower crustal event cannot be ruled out as the evidence for such an event would be strongly obscured by upper crustal contamination events, and the nature of the deep crust beneath the Longford-Down Terrane is poorly constrained. Xenoliths in Carboniferous lamprophyres in Co. Down (Anderson & Oliver, 1996), suggest that an ancient island arc-type basement underlies the Longford-Down sedimentary rocks, and that this may in turn, be underlain by Avalonian or exotic terranes (cf. Trewhin & Rollin, 2002). Basaltic magmas would be likely to be preferentially contaminated by rocks with low fusion temperatures such as metabasites, particularly in the lower crust (Huppert &

Sparks, 1985). Evidence for lower crustal magma-crust contamination may be preserved in the cores of some of the strongly zoned feldspar phenocrysts of the ring-dyke rocks and awaits *in situ* analytical approaches (cf. Chadwick *et al.*, *In Press*)

5.2 Magma crust interaction in a continental arc setting: New Zealand

Interaction and assimilation of the crust is a recognised process in continental arc settings (e.g. Tepley *et al.*, 1999; Lassen volcanic center, Western USA). However, even in continental settings, source contamination and contamination of primary melts by lithospheric rocks during ascent may produce similar geochemical characteristics (e.g. Davidson, 1996), with additional complications from geochemical parallels between subducted sediment and the overlying lithospheric crust (McDermott *et al.*, 1993; Vroon *et al.*, 1993; Gamble *et al.*, 1996).

The $^{176}\text{Hf}/^{177}\text{Hf}$ isotope system is thought to be an effective ‘window’ into source contamination processes in fluid-dominated subduction zone systems as it has been found to be largely immobile (e.g. Munker *et al.*, 2004; Pearce *et al.*, 2007). The sedimentary crustal terranes of the North Island (Torlesse and Waipapa) as well as subducted sediments have overlapping compositions with respect to $^{176}\text{Hf}/^{177}\text{Hf}$, providing a challenge for discerning between source and crustal contamination. However, despite representing the least evolved products of the continental subduction zone system, and thus the most likely to reflect primary melt signatures, Ruapehu, Taranaki and particularly the TVZ basalt samples show evidence for crustal contamination. The samples with the lowest SiO_2 , (the TVZ basalts) have the lowest, most ‘crustal’ $^{176}\text{Hf}/^{177}\text{Hf}$ isotope ratios with an apparent negative correlation, indicating that this is not a source contamination effect. Despite a lack of a similar trend between such an index of fractionation and $^{176}\text{Hf}/^{177}\text{Hf}$ isotopes in the Ruapehu and Taranaki samples, crustal contamination is also likely to be a factor for these centres, based on the presence of variably metamorphosed crustal xenoliths and geochemical heterogeneity reported in the literature. The lack of a clear crustal contamination signal in $^{176}\text{Hf}/^{177}\text{Hf}$ isotope ratios of samples from these centres may be a function of limited sample size. However, the complexity of the plumbing systems feeding these volcanoes may also

contribute to a lack of systematic trends, resulting in variation in the apparent impact or extent of crustal contamination (Price *et al.* 2005). The short term geochemical variability, multiple crystal populations and entrained volcanic, plutonic and meta-sedimentary xenoliths indicate a complex plumbing system of numerous magma reservoirs or dyke and sill type feeders for these volcanoes (Price *et al.*, 2005). The action of crystal recycling, accumulation, magma mixing and assimilation may act to obscure typical liquid trends in highly crystalline porphyritic magmas such as the samples analysed from Ruapehu and Taranaki. Also given the fact that the Ruapehu and Taranaki systems are large-volume and long-lived volcanic centres, extensive magmatism may result in partial or temporary insulation of separate magma batches from large amounts of crustal assimilation or the most fusible portions of the country rock being depleted (c.f. Thompson *et al.* 1986; Kerr *et al.* 1999). Even a small amount of assimilation of continental Hf, with zircon as a likely carrier, would substantially modify the $^{176}\text{Hf}/^{177}\text{Hf}$ isotope signature of the magma. Conversely, the effects of assimilation of crustal material may appear relatively more extreme in the aphyric TVZ basaltic samples as they probably represent true liquids, sourced from monogenetic cones and vents which are thought to have ascended through the crust as individual batches (Gamble *et al.*, 1993) and are thus highly susceptible to assimilation.

This study highlights the inherent risk involved in using whole rock geochemical systems in isolation, particularly for studies using a limited number of samples, to assess the processes and evolution of highly crystalline porphyritic rocks. Even in systems where crustal contamination is known to be occurring, as in continental New Zealand, geochemical signatures in whole rock samples can be equivocal. Whole rock geochemical data should therefore be used in conjunction with careful petrographic and mineral analysis. Samples of limited crystallinity and degree of evolution appear to be likely to give an approximation of true liquid compositions.

5.3 Magma crust interaction in an island-arc setting: Indonesia

Ocean arc magmas are typically thought to exhibit geochemical characteristics that are generated by variable source components in combination with differentiation processes (Figure 4.1). In many geochemical models of island arc petrogenesis only three components are considered; the mantle wedge, the subducting oceanic plate and its sediment cover (e.g. Debaille *et al.*, 2006). These three components and their varying compositions, are thought to be the prime constituents involved in the production of arc magmas (e.g. Davies & Stevenson, 1992; Tatsumi & Eggins, 1995). However, primary magmas are only rarely observed in island arc settings (Annen *et al.*, 2006). Thus modification of these melts during their ascent to the surface is important for some island arc magmas as well. Despite this fact, as discussed above with respect to the New Zealand volcanics, the effect of interaction between melt and the overlying lithosphere is commonly only considered for studies of evolved continental arc magmas. Ruling out shallow crustal assimilation as a significant process for many arc magmas is potentially a result of the expectation that arc magmas should fit a 'shallow-crustal contamination' trend, based on an assumed composition of the arc crust of a typical continental SiO₂-rich composition which would have a noticeable impact on whole rock geochemistry (cf. Smith *et al.*, 2006).

However, in studies of ocean arc systems where crustal assimilation has been considered and tested using detailed petrography and geochemistry, this process appears to have a significant impact and shows marked parallels to continental settings where the importance of crustal assimilation has long been established (e.g. Davidson, 1986; Tamura & Tatsumi, 2002; Smith *et al.*, 2003; Smith *et al.*, 2006). Isotopic heterogeneity at Merapi has been attributed to variable degrees of source contamination deep in the Sunda-arc subduction zone system based on whole rock geochemical data (Gertisser & Keller, 2003; Debaille *et al.*, 2006). These authors argued that shallow contamination at Merapi was unlikely due to a lack of systematic variation in whole rock isotopes with SiO₂.

Based on analysis of crystalline components, inclusions and xenoliths from recent lavas, it appears that the magmatic system feeding Merapi volcanism is large and

complex with predominantly mid- to deep-crustal storage with a network of multiple potentially ephemeral chambers feeding surface volcanism. As seen in the case of Ruapehu and Taranaki, such a magmatic plumbing system results in a heterogeneous mix of crystal and melt within a single eruptive unit, which does not necessarily represent a melt composition. In addition, this considerable volume allows for the potential evolution of a large-volume rhyolitic system in central Java, similar to systems already present in e.g. New Zealand or Western USA, through repeated melt injections and anatexis of surrounding country rock. Crystal, gas and xenolith geochemistry indicates that there is already a significant interaction between Merapi magma and the local crust, which is masked in the homogenized bulk rock geochemistry.

This study then builds on the conclusions drawn from the Hf isotope study of New Zealand rocks and illustrates the dangers inherent in building models of magma petrogenesis based solely on whole-rock geochemical data for crystal-rich arc lavas, or indeed on any one analytical technique used in isolation (e.g. CSD). Whole rock compositions of recent Merapi basaltic-andesites, disguise a multitude of processes occurring throughout the crust and the upper mantle with significant potential for impact on the Merapi magmatic and volcanic systems.

5.4 Implications for volcanic systems in general

This study utilised varied analytical techniques to assess magmatic processes in three different geological settings. For Slieve Gullion, an intra-continental plate setting, whole rock isotope techniques allowed for identification of a multi-event evolution for ring-dyke magmas due to the highly radiogenic and variable nature of the country rocks. For New Zealand samples in a continental arc setting, Hf isotopes identified crustal contamination in the most 'primitive' erupted products and highlighted the significant geochemical heterogeneity in more evolved and highly crystalline samples. This conclusion was mirrored in the more detailed geochemical and petrographic study of oceanic arc eruptives from Merapi volcano. Even in this relatively simple tectonic setting with immature arc-crust, the significance of crustal processes and particularly of shallow-level contamination has been previously underrated, and has significant

implications for understanding the evolution and eruptive behaviour of the volcano and thus hazard prediction.

With the advent of more accurate and precise analytical techniques, subtle signatures that may previously have gone unrecognised may be identified. From these three studies combined with similar published results for other systems (e.g. Ruapehu: Price *et al.*, 2005; Arenal: Lundstrom & Tepley, 2006), it appears that high degrees of geochemical complexity within individual units is the norm rather than the exception for magmatic systems of significant size and / or degree of evolution and is now resolvable using new and combined analytical approaches.

5.5 Further areas for research

Further to the conclusions discussed above there is significant potential for further research arising from this study, with follow-on projects already being pursued in some cases.

Based on whole-rock geochemistry, Slieve Gullion ring dyke magmas experienced at least a two-stage contamination history. However, additional events, particularly a lower crustal event, could not be ruled out. The evolutionary history of these samples could be further constrained using microsampling techniques similar to those employed for Merapi samples. The ring-dyke rocks contain large zoned and well-preserved sanidine crystals ideal for *in situ* Pb analysis by laser and lesser plagioclase, which could yield complimentary Sr isotope data. Micro-sampling of Sr from these BIPIP plagioclase crystals is complicated by low Sr contents overall and the need for an age correction. However, an analytical approach targeting multiple mineral phases may provide additional information about the processes and sources involved in the formation of the Slieve Gullion ring-dyke magmas. This research has been incorporated into a larger micro-analytical study of igneous centres in the BIPIP being undertaken in Trinity College and is currently being pursued by F. Meade, V. Troll, and J Chadwick.

A larger sample set including offshore TVZ samples and the most aphyric Ruapehu and Taranaki samples could yield additional information about source vs. crustal contamination for the New Zealand transitional arc setting. In addition, analyses of xenoliths and crustal samples highlighted a need for better constraints on crustal end members used extensively in geochemical modelling, particularly for Hf isotopes. Data fields for crustal end-members often comprise only a few samples, which may not be representative, and may overlap considerably with other reservoirs.

Several areas of future research have arisen from the results of the work carried out on Merapi volcano samples including:

- *In situ* Sr analysis of feldspars and glass compositions hosted in plutonic inclusions and sedimentary xenoliths to further constrain the source of high An feldspar in these samples, and in the Merapi magmatic system. The origin of high An mol% feldspar in arc volcanics is a source of debate and is as yet unresolved (e.g. Lundstrom & Tepley, 2006). Such a study such could contribute to this debate considerably. Coupled with this, further *in situ* analysis of basaltic andesite hosted plagioclase crystals by LA-MC-ICMPS would assess the scale of crystal heterogeneity in Merapi lavas. Although less accurate, the LA-MC-ICMPS method allows rapid analysis of a large population of crystals.
- Further microprobe and trace element analysis of amphibole crystals within the plutonic cumulate inclusions, and mega-crysts could yield important information about ‘wet’ basalt crystallisation deep in the crust beneath Merapi (e.g. Meurer & Claeson, 2002). This research is currently in progress in collaboration with B. Schultz and V. Troll.
- Experimental analysis of amphibole breakdown for Merapi pumice, lava, and megacryst samples similar to studies done for Mount St Helens eruptives (Rutherford & Hill, 1993), and Soufriere Hills, Montserrat (Rutherford & Devine, 2003) could yield information on ascent rates. This research has been recently undertaken by R. Gertisser at the University of Keele, UK.
- Further CSD analysis of lavas, enclaves and inclusions. Initial results appeared to miss crystal populations identified by geochemical techniques. A detailed study

including the inclusions may provide answers to this question. Potential interfering processes include crystal accumulation, and resorption.

In addition, a broader study utilising an analytical approach combining analyses of gases and lavas with magma-carbonate interaction experiments could test hypotheses raised by this study of Merapi volcano study including:

- The link between surface volatile isotope signature and late-stage assimilation of carbonate in shallow magma reservoirs and that this process generates a non-magmatic source of volcanic CO₂.

This could be undertaken with samples from other volcanic systems sited on carbonate crust with lavas hosting calc-silicate inclusions e.g. Popocatepetl, Mexico (a volcano famous for its anomalous CO₂ output). C. Siebe (Instituto de Geofísica, UNAM, Mexico) has been contacted about suitable samples and discussions are underway to pursue this research project in the near future.

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APPENDIX A

Appendix A is the geochemical database used for the study of North Island, New Zealand discussed in Chapter 3. The data-set is after Woodhead *et al.*, 2001 and Pearce *et al.*, 2007 (and references therein) and includes whole rock, major, trace, and rare earth element data as well as Sr, Nd and Pb isotope data for onshore samples which are referenced in the text in Chapter 3.

RUAPEHU

	Sample No.	Location	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
RUAPEHU													
Price <i>et al.</i> , 1997;1999	R95/18	Whangaeahu gorge	57.99	0.68	19.22	2.14	3.45	0.09	2.34	7.44	3.88	1.19	0.11
Price <i>et al.</i> , 1997;1999	R95/20	Whangaeahu gorge	55.98	0.68	15.15	2.08	5.26	0.13	6.65	8.78	2.90	0.94	0.08
Valente, 1995	T6-7	Te Herenga Ridge	56.32	0.70	16.94	2.24	6.11	0.15	4.87	7.93	3.25	0.67	0.08
Valente, 1995	T6-27	Te Herenga Ridge	56.02	0.67	17.60	2.82	4.97	0.14	4.67	7.48	3.36	0.79	0.09
Price <i>et al.</i> , 1997;1999	R95/16	Rangataua	58.99	0.73	17.03	6.96		0.12	3.33	6.47	3.35	1.73	0.12
Price <i>et al.</i> , 1997;1999	R95/26	Whangaeahu gorge	56.82	0.63	16.76	7.42		0.13	5.32	7.89	3.42	0.89	0.09
Waight & Price 1999	R97/39	Mangaturuturu	61.46	0.69	16.12	0.65	4.75	0.12	3.43	5.88	3.35	2.01	0.15
Schneider, 1995	T5-16	Whakapapaiti Valley	63.90	0.73	14.94	0.80	3.92	0.09	3.49	5.03	3.33	2.89	0.16
Schneider, 1995	T5-71	Whakapapaiti Valley	61.65	0.87	16.54	0.84	4.68	0.09	2.80	5.53	3.79	2.08	0.15
Valente, 1995	T6-15	Te Herenga Ridge	56.12	0.67	17.36	2.95	5.05	0.14	4.95	7.93	3.38	0.82	0.09
Valente, 1995	T6-65	Te Herenga Ridge	56.98	0.68	16.50	1.87	5.12	0.13	5.10	7.47	3.10	1.38	0.11
Waight & Price 1999	R97/81	Knoll Ridge	59.22	0.67	16.79	1.22	5.22	0.14	4.18	7.00	3.53	1.59	0.14
Price & Stewart 2004	R04/04	Whangaeahu gorge	59.22										
RUAPEHU XENOLITHS													
Waight & Price 1999	R97/92x1		45.44	2.84	18.09	3.75	8.52	0.14	7.89	9.37	1.59	0.45	0.41
Waight & Price 1999	R97/92x2		50.66	0.58	13.75	2.05	7.33	0.22	13.55	7.40	1.42	0.17	0.12
Waight & Price 1999	R97/87x1		53.36	0.69	18.94	0.46	7.82	0.13	4.37	9.64	2.55	0.23	0.18
Waight & Price 1999	R97/75b		47.95	1.84	15.05	1.40	10.93	0.20	8.26	10.90	1.30	0.14	0.21
Waight & Price 1999	R97/104x		47.57	1.17	25.98	4.08	3.68	0.06	3.23	8.28	3.69	0.42	0.25
Waight & Price 1999	R97/50b		37.22	2.80	20.54	6.81	10.46	0.23	6.18	9.91	0.83	1.15	0.35
TARANAKI													
Price <i>et al.</i> ,1999	T89/10	Summit	53.92	0.98	17.44	4.66	3.22	0.17	3.75	8.36	3.90	2.42	0.34
	T89/11	Fanthams	49.54	1.17	16.39	4.82	5.51	0.17	6.40	11.09	2.99	1.53	0.26
	T89/15	Summit	54.57	0.98	17.78	4.13	3.65	0.17	3.55	8.19	3.69	2.50	0.39
	T89/24	Staircase	54.70	0.94	17.48	3.94	4.10	0.17	3.87	8.49	3.90	2.22	0.29
	T89/21	Warwicks Castle	55.51	0.78	18.37	3.52	3.87	0.18	3.01	8.28	3.65	1.99	0.35
	T90/21	Staircase	55.77	0.85	17.36	4.41	3.26	0.16	3.68	8.39	3.68	2.23	0.28
	T90/42A	Old ring plain	48.92	1.58	16.21	4.76	5.87	0.18	6.75	10.57	2.87	1.20	0.35
	T90/46	Young ring plain	55.51	0.89	18.24	3.31	3.98	0.18	3.04	8.26	3.78	2.02	0.32
TVZ BASALTS													
Gamble <i>et al.</i> . (1993)	TVZ-12	Tatua	50.19	1.33	17.13	1.24	8.25	0.17	6.14	10.49	3.22	0.37	0.24
and	TVZ-14	Ongaroto	51.02	1.07	15.49	1.18	7.84	0.13	9.20	10.18	2.61	0.56	0.27
Gamble <i>et al.</i> , (1996)	TVZ-15	Kakuku	48.52	0.89	18.09	1.05	6.99	0.13	9.12	11.16	2.49	0.27	0.14
	TVZ-13	Tatua	49.43	1.15	17.78	1.12	7.84	0.15	7.46	11.68	2.95	0.31	0.20
	TVZ-5	Atiamuri	50.51	1.26	16.81	1.26	8.40	0.18	5.80	10.60	3.06	0.64	0.21
	TVZ-6	Ben Lomond	50.37	1.11	17.50	1.25	8.33	0.18	6.06	10.48	2.72	0.39	0.18
	TVZ-7	Trig 9474	49.50	0.98	19.22	1.24	8.27	0.19	6.94	12.00	2.25	0.30	0.12
	TVZ-8	Rotokawau E	51.06	0.80	17.75	1.14	7.57	0.19	6.31	11.86	2.34	0.55	0.10
	TVZ-9	Rotokawau W	53.24	0.93	16.86	1.20	8.02	0.17	5.24	9.93	2.87	0.78	0.13
	TVZ-17	Harry Johnson											

KERMADEC ARC	Sample No.	Location	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
Kermadec	7088	Raoul	57.27	1.23	14.10	13.31		0.23	2.93	7.52	2.69	0.62	0.19
Kermadec	10415	Macaulay	48.81	0.55	17.33	2.16	6.62	0.17	8.27	13.70	1.31	0.14	0.01
Kermadec	14840	Esperance	50.83	1.00	18.54	4.69	7.65	0.29	4.47	8.89	2.27	0.33	0.06
Kermadec	7005	Raoul	66.78	0.61	13.65	6.38		0.18	1.21	4.66	3.84	0.60	0.10
Kermadec	10378	Macaulay	49.50	0.70	17.99	11.56		0.20	4.74	12.99	1.80	0.52	0.10
Kermadec	10380	Macaulay	49.20	0.89	15.67	13.15		0.23	7.25	12.29	2.01	0.40	0.07
Kermadec	14831	L'Esperance	52.66	1.05	17.66	13.53		0.24	4.85	8.63	1.98	0.33	0.14
TONGA ARC													
South Tonga	ATA8-8	Ata	51.40	0.75	17.50	11.18		0.19	5.53	11.50	1.99	0.55	0.14
Central Tonga	23208	Tofua	54.54	0.51	16.60	11.22		0.15	4.48	10.02	1.90	0.51	0.11
Central Tonga	111550-1	Hunga	55.35	0.60	15.57	11.26		0.19	4.80	9.82	1.82	0.35	0.07
Central Tonga	LATE 13	Late	57.57	0.80	14.14	12.82		0.21	3.29	8.42	2.42	0.70	0.12
Central Tonga	FON8	Fonualai	65.57	0.59	14.02	8.76		0.19	1.44	5.71	3.02	1.13	0.20
North Tonga	NTT28/2	N'topatapu	58.35	0.52	15.25	12.80		0.21	2.95	8.69	1.78	0.44	0.09
North Tonga	NTT26/1	N'topatapu	56.85	0.52	15.59	13.29		0.28	2.82	9.42	1.83	0.53	0.11
North Tonga	NT64-T8	N'topatapu	60.62	0.57	12.90	12.00		0.19	2.85	8.11	2.18	0.56	0.10
North Tonga	TAF3/2	Tafahi	53.29	0.38	15.83	11.23		0.18	6.61	12.00	1.24	0.14	0.06
North Tonga	TAF40	Tafahi	52.99	0.46	15.57	11.83		0.24	6.67	12.44	1.39	0.19	0.07
HAVRE TROUGH													
Havre Tr.	PPTUW	Havre Tr.	50.66	1.49	16.07	9.22		0.16	7.49	10.26	3.95	0.29	0.18
LESSER ANTILLES													
	M8301	Martinique	51.24	1.95	15.72	13.67		0.21	4.59	8.44	2.80	0.92	0.29
	M8272	Martinique	61.40	0.67	17.02	6.14		0.10	2.17	5.79	2.82	2.21	0.13
	M8270	Martinique	59.39	0.55	20.32	4.58		0.09	1.01	7.13	3.67	1.48	0.13
	M8268	Martinique	62.86	0.44	17.26	5.69		0.15	2.08	5.28	3.31	1.42	0.12
	M8230	Martinique	58.54	0.57	17.89	7.55		0.19	2.93	7.51	2.99	0.91	0.14
	M8234	Martinique	54.92	0.80	18.68	8.79		0.18	4.17	9.22	3.07	0.80	0.13
	M8236	Martinique	51.42	0.92	19.06	9.43		0.18	4.95	10.07	2.52	0.66	0.10
	M8321	Martinique											
	M8328	Martinique											
MARIANA ARC													
	AN-1	Anatahan	51.66	0.73	18.54	10.34		0.19	4.97	10.34	2.53	0.57	0.13
	AN-12B	Anatahan	63.31	0.82	15.03	8.14		0.22	1.55	4.70	4.19	1.71	0.33
	SA-2	Sarigan	53.00	0.75	15.81	9.97		0.19	6.03	10.89	2.50	0.72	0.14
	SA-P	Sarigan	60.48	0.81	16.30	7.90		0.19	2.57	6.35	3.94	1.25	0.21
	SA-B	Sarigan	53.05	0.75	15.73	9.89		0.19	6.32	10.81	2.48	0.64	0.13
	GU-6	Guguan	51.96	0.82	17.64	10.36		0.20	5.38	10.47	2.51	0.55	0.11
	GU-9	Guguan	50.84	0.85	20.01	10.10		0.18	3.96	11.01	2.50	0.45	0.10
	GU-10	Guguan	51.08	0.88	19.70	10.27		0.19	4.01	10.79	2.49	0.49	0.10
	GU-20	Guguan	53.35	0.82	18.19	10.05		0.20	4.28	9.89	2.63	0.50	0.10
	GU-21	Guguan	53.28	0.81	18.06	10.07		0.20	4.27	10.10	2.61	0.50	0.10
	ALA-1	Alamagan	54.50	0.80	17.67	9.39		0.18	4.48	9.07	2.80	0.95	0.15
	PA-4	Pagan	51.17	0.91	15.90	12.34		0.22	5.43	10.53	2.61	0.75	0.14
	PA-5	Pagan	51.19	0.91	15.89	12.41		0.22	5.35	10.63	2.51	0.74	0.15
	PA-F3B	Pagan	49.19	0.65	16.94	11.37		0.21	7.26	11.84	1.96	0.48	0.10
	AG-1A	Agrigan	50.70	0.79	16.70	12.75		0.23	4.92	10.41	2.62	0.73	0.15
	AG-6	Agrigan	54.69	0.86	16.78	11.03		0.24	3.29	8.07	3.34	1.43	0.27
	AS-2	Asuncion	54.55	0.72	17.40	9.63		0.18	4.60	9.73	2.51	0.58	0.10
	M-1	Maug	50.59	1.05	17.65	13.05		0.22	3.96	10.56	2.43	0.38	0.11
	U1	Uracas	53.72	0.74	19.70	9.61		0.18	2.61	9.79	2.83	0.69	0.13
	U2	Uracas	58.83	0.63	18.14	7.46		0.15	2.63	7.88	3.28	0.86	0.14
	U4	Uracas	57.84	0.66	18.06	7.74		0.16	3.03	8.26	3.24	0.87	0.14
	U7	Uracas	53.59	0.77	19.63	9.55		0.19	2.57	9.93	2.86	0.77	0.14

KERMADEC ARC	Sc	V	Cr	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu	Hf	Ta	Pb	Th	U
7088	41	294	4	4	102	122	13	9	188	37	75	1	0	202	4	13		12	4	1	5	1	5		3	4	1	2	0	3	1	0
10415	46	280	159	56	107	59	16	3	203	10	17	0	0	49	1	3	1	3	1	0	1	0	2	0	1	1	0	1	0	1	0	0
14840	37	331	5	13	30	127	20	7	243	20	40	0	0	151	3	9	1	7	2	1	3	0	3	1	2	2	0	1	0	2	1	0
7005	21	44	0	1			1	9	151	38	68	1	1	199	4	11	##	10	3	1	4	1	5	1	4	4	1	2		3	1	0
10378	41	345	25	27	125	75	16	11	277	15	36	1	0	123	4	9		7	2	1	2	0	2	0	1	1	0	1	0	2	1	0
10380	49	411	72	39	185	87	16	8	236	17	38	1	0	126	5	10	##	8	2	1	3	0	3	1	2	2	0	1	0	2	1	0
14831	39	436	5	11	8	107	18	7	220	22	41	0	0	136	3	9	##	7	2	1	3	1	3	1	2	2	0	1	0	3	1	0
TONGA ARC																																
ATA8-8	39	361	32	41	85	86	16	10	263	16	39	1	0	186	4	9	##	6	2	1	3	0	3	1	2	2	0	1	0	5	0	0
23208	36	307	28	21	98	86	15	7	228	14	26	1	0	133	2	5	##	4	1	1	2	0	2	1	1	2	0	1	0	3	0	0
111550-1	40	305	53	33	128	83	15	4	174	14	28	1	0	144	1	4	##	3	1	0	2	0	2	0	1	1	0	1	0	2	0	0
LATE 13	41	395	15	31	129	111	16	9	224	19	37	1	0	153	3	7	##	5	2	1	2	0	3	1	2	2	0	1	0	2	0	0
FON8	25	95	4	2	26	113	19	18	304	23	46	1	0	277	4	9	##	7	2	1	3	0	3	1	2	2	0	1	0	4	0	0
NTT28/2	51	363	14	13	173		14	4	208	11	19	2	0	120	3	6	##	5	1	0	2	0	2	0	1	1	0	1	0	2	0	0
NTT26/1	53	431	9	10	215	84	13	6	202	11	19	1	0	107	2	5	##	4	1	0	1	0	2	0	1	1	0	1	0	2	0	0
NT64-T8	46	352	1	5	244	96	15	9	22	11	24	2	0	139	3	7	##	4	1	0	2	0	2	0	1	1	0	1	0	8	1	0
TAF3/2	49	305	86	43	131		13	2	142	9	13	1	0	43	1	3	##	2	1	0	1	0	1	0	1	1	0	0	0	2	0	0
TAF40	49	350	363	78	83		14	3	142	9	11	0	0	41	1	2	##	2	1	0	1	0	1	0	1	1	0	0	0	1	0	0
HAVRE TROUGH																																
PPTUW	34	246	280	97	58	78	16	1	169	34	126	2	0	20	4	13	#	12	4	1			5	1		3	0	3		1	0	0
LESSER ANTILLES																																
M8301	49	440	11	14	162	118		45	171	50	166	4	1	228	15	33	5	22	6	2	8		9		5	5	1	5	0	12	4	2
M8272	22	114	4	6	41	65		128	181	24	140	5	5	399	25	47	6	23	5	1	4		4		2	2	0	4	0	14	14	3
M8270	17	59			43	52		57	248	31	108	3	2	247	12	25	3	15	4	1	5		5		3	3	0	3	0	9	5	1
M8268	11	54		2	20	52		52	252	17	77	3	2	293	17	29	4	14	3	1	3		3		2	2	0	2	0	10	6	1
M8230	17	141	5	5	37	70		24	279	22	92	3	1	167	11	22	3	13	3	1	3		4		2	2	0	3	0	6	3	1
M8234	29	254	16	6	107	71		20	302	22	72	2	1	132	8	17	2	11	3	1	3		4		2	2	0	2	0	5	2	1
M8236	41		25	10	105	72		8	333	15	37	1	0	76	4	9	1	6	2	1	2		3		2	2	0	1	0	4	1	0
M8321	37							139	236	30	149	5	8	352	21	40	5	20	5	1	5		5		3	3	0	4	0	17	11	4
M8328	21							44	469	34	183	5	2	346	19	39	5	22	5	2	5		5		4	4	1	5	0	14	5	1
MARIANA ARC																																
AN-1	33	273	24	18	115	80	17	10	387	20	49	1	0	197	6	12	2	9	3	1	3	1	3	1	2	2	0	1	0	3	1	0
AN-12B	49	4	1	28	106			30	322	45	106	3	1	430	15	30	5	21	5	1	6	1	6	1	4	4		4		3	2	1
SA-2	37	251	86	31	109	73	15	12	390	20	64	2	0	293	7	15	2	10	3	1	3	1	3	1	2	2	0	2	0	4	1	0
SA-P		107	22	8	37	92		18	352	35	111	3	1	419	10	23	3	17	4	1	5	1	6	1	4	4	1	3		5	2	1
SA-B	31	218	120	33	64	68		11	386	21	60			313	8	15	2	10	3	1	3											
GU-6	38	287	45	22	128	82	16	9	283	23	61	1	0	164	4	9	1	7	2	1	3	1	4	1	2	2	0	2	0	3	0	0
GU-9	30	298	11	12	109	72	18	8	307	20	55	1	0	163	3	8	1	7	2	1	3	1	3	1	2	2	0	1	0	2	0	0
GU-10	29	316	10	11	32	80	17	8	302	20	57	1	0	154	3	8	1	7	2	1	3	1	3	1	2	2	0	1	0	2	0	0
GU-20	34	273	28	12	108	86	17	8	278	23	61	1	0	168	3	8	1	7	2	1	3	1	4	1	3	3	0	2	0	4	0	0
GU-21	35	271	29	13	59	84	17	8	276	23	60	1	0	164	3	8	1	7	2	1	3	1	4	1	3	3	0	2	0	2	0	0
ALA-1	33	238	28	15	110	77		15	275	27	79	1	1	249	6	14	2	11	3	1	4		5		3	3	0	2	0	5	1	0
PA-4	43	383	39	20	154	98	17	14	335	23	60	1	1	201	5	12	2	9	3	1	3	1	4	1	2	2	0	2	0	3	1	0
PA-5	40	373	36	21	177	93		10	300	21	49	1	0	189	5	11	2	9	3	1	3		4		2	2	0	2	0	4	1	0
PA-F3B	42	280	60	35	123	76	16	10	311	15	42	1	0	171	3	8	1	6	2	1	2	0	3	1	2	2	0	1	0	2	0	0
AG-1A	43	355	9	9	50	92	17	16	345	21	56	1	0	154	7	15	2	10	3	1	3	1	3	1	2	2	0	1	0	2	1	0
AG-6	32	213	4	5	50	104		31	344	30	91	2	1	241	12	24	4	17	5	1	5		5		3	3	0	3	0	5	1	1
AS-2	33	252	17	12	80	72	16	9	267	24	63	1	0	198	5	11	2	8	3	1	3	1	4	1	2	2	0	2	0	2	1	0
M-1	44	377	18	6	221	100		6	287	24	44	1	0	143	4	9	1	8	3	1	3		4		3	3	0	1	0	4	0	0
U1	31	236	8	5	120	78	18	13	393	23	63	2	0	279	8	17	2	11	3	1	4	1	4	1	3	3	0	2	0	3	1	0
U2	27	176	8	5	101	68	17	15	328	26	76	2	0	351	8	16	2	11	3	1	4	1	4	1	3	3	0	2	0	4	1	0
U4	27	164	9	5	108	70	16	14	335	25	73	2	0	317	7	15	2	10	3	1	3	1	4	1	2	3	0	2	0	3	1	0
U7	31	236	6	7	156	83	18	13	383	25	60	2	0	277	8	17	2	11	3	1	4	1	4	1	3	2	0	2	0	3	1	0

SUNDA ARC	Sc	V	Cr	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu	Hf	Ta	Pb	Th	U
7414	22	102	4	0	10	67	18	48	240	50	242	7	1	298	24	52	7	31	8	2	8		8		5	5	1	7	0	22	7	2
11498	29	188	32	12	28	75	18	19	358	29	108	3	1	164	14	31	4	20	5	1	5		5		3	3	0	3	0	7	3	1
7421	17	182	6	2	28	85	19	44	545	26	99	4	4	471	19	37	5	20	5	1	5		5		3	3	0	3	0	18	7	2
7678	17	122	6	4	20	72	18	72	328	31	186	7	3	410	20	41	5	22	5	1	5		5		3	3	1	5	1	10	8	2
7422	18	118	2	0	64	89	20	26	399	26	97	3	2	585	11	25	3	15	4	1	4		5		3	3	0	3	0	12	3	1
7423	24	262	4	4	50	86	20	13	373	22	64	2	1	430	7	17	2	11	3	1	4		4		3	2	0	2	0	8	1	0
9047	27	236	12	8	82	76	21	16	322	21	71	3	1	159	9	20	3	12	3	1	4		4		2	2	0	2	0	7	3	1
71-1002	15	110	44	14	18			70	365	22	176	11	3	498	22	39	5	18	4	1	4		4		2	2	0	4	1	16	10	2
13672	27	206	4	4	120	86	21	20	400	22	76	4	1	230	12	24	3	15	4	1	4		4		2	2	0	2	0	8	2	1
71-969	10	170	26	11	46			199	1581	34	304	84	7	898	169	276	28	95	16	4	12		7		3	3	0	6	4	21	50	10
71-970	23	260	17	17	110			375	1820	47	312	66	9	1062	190	337	37	138	25	6	18	1	10		4	3	0	6	3	15	42	7
71-979	17	160	8	8	30			84	498	25	136	8	4	496	31	57	6	25	5	2	5		4		2	3	0	3	1	18	14	3
71-982	38	290	71	24	125			56	480	22	93	10	3	386	23	45	5	23	5	2	5		4		2	2	0	3	1	13	8	2
71-985	30	232						82	393	36	190	7	3	362	24	50	6	26	6	2	6		6		4	4	1	5	1	20	9	2
71-989	14	92						129	165	30	181	5	6	368	32	51	8	29	6	1	6		5		3	3	0	5	1	20	15	3

SUBDUCTED SEDIMENT

2R-4, 60-61	20	156	29	28	168	145		83	196	66	150	10	5	339	32	75	##	35	9	2	10	2	10	2	6	6	1	4	1	48	10	2
3R-2, 59-60	27	218	9	7	119	105	13	26	136	27	89	2	1	168	7	17	##	11	3	1	4	1	4	1	3	3	0	3	0	11	1	1
4R-4, 140-141	24	252	101	28	113	135	19	72	132	22	277	37	1	221	23	66	##	24	6	2	6	1	5	1	2	2	0	7	3	4	3	1
7R-1, 92-93	23	187	199	119	69	90	15	15	299	20	137	16	1	91	14	33	##	19	5	2	5	1	4	1	2	2	0	4	1	1	1	1
8R-3, 86-87	20	165	203	159	61	83	14	10	101	19	127	16	0	61	13	29	##	17	4	1	4	1	4	1	2	1	0	3	1	1	1	1
9R-1, 108-110	25	227	235	72	87	85	17	22	87	23	151	18	0	403	15	38	##	20	5	2	5	1	4	1	2	2	0	4	1	1	1	1
5R-2, 144-146								49	173	79	118	7	3	298	37	52	##	39	8	2	11	2	11	2	7	9	1	3	0	36	4	1
6R-4, 139-141	7	74	32	36		21	18	20	245	20	114	2	1	295	12	23	##	15	3	1	4	1	3	1	2	3	0	3	0	10	2	1
12R-2, 137-139								28	541	51	90	6	1	390	34	40	##	36	7	2	8	1	7	1	4	4	1	2	0	23	3	1
17R-4, 123-125								19	200	19	161	1	1	125	7	18	##	11	3	1	3	1	3	1	2	2	0	4	0	6	1	0
T-251	15	72	23	18	48	121	14	42	446	30	103	3		541	13	28																
S936	8	77	40	27	26	88	17	112	227	25	163	11		680	20	49																

Local Sediments

ZI/03

ZI/01

P54703

P55908

P23553

P55962

P55907

SUNDA ARC	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	eNd	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	¹⁷⁶ Hf/ ¹⁷⁷ Hf	e Hf		Th/Yb	Ba/La
7414	0.704380	0.512740	1.99	18.654	15.640	38.854	0.283095			1.43	12.68
11498	0.704388	0.512711	1.42	18.658	15.638	38.858	0.283085			1.00	11.71
7421	0.705707	0.512681	0.84	18.763	15.694	39.150	0.283124			2.51	25.23
7678	0.704801	0.512697	1.15	18.601	15.607	38.621	0.283043			2.50	20.52
7422	0.704700	0.512761	2.40	18.630	15.640	38.876	0.283119			1.23	50.91
7423	0.704225	0.512831	3.76	18.565	15.617	38.728	0.283133			0.53	57.41
9047	0.704387	0.512745	2.09	18.774	15.680	39.106	0.283149			1.22	16.79
71-1002	0.704590	0.512764	2.46	18.698	15.666	39.000	0.283108			4.53	23.14
13672	0.704007	0.512843	4.00	18.566	15.607	38.736	0.283144			1.06	19.44
71-969	0.704451	0.512588	-0.98	18.680	15.600	39.108	0.282915			16.96	5.30
71-970	0.704628	0.512565	-1.42	18.672	15.598	39.083	0.282923			13.84	5.60
71-979	0.705133	0.512611	-0.53	18.802	15.681	39.113	0.283079			5.38	16.16
71-982	0.704895	0.512627	-0.21	18.879	15.688	39.167	0.283033			3.83	16.52
71-985	0.705921	0.512463	-3.41	18.904	15.717	39.332	0.282822			2.55	15.17
71-989	0.705868	0.512475	-3.18	18.912	15.723	39.365	0.282853			5.17	11.66
SUBDUCTED SEDIMENT											
2R-4, 60-61	0.708970	0.512460	-3.51	18.804	15.640	38.776	0.282929	5.54		1.59	10.64
3R-2, 59-60		0.512879	4.66	18.748	15.594	38.637	0.283123	12.42		0.46	24.56
4R-4, 140-141	0.706510	0.512882	4.72	19.176	15.626	38.942	0.283003	8.16		1.49	9.55
7R-1, 92-93	0.706990	0.512901	5.09				0.283014	8.56		0.83	6.40
8R-3, 86-87	0.705116	0.512927	5.60	19.218	15.569	38.858	0.283014	8.56		0.88	4.81
9R-1, 108-110	0.707290	0.512872	4.53	19.066	15.538	38.695	0.283003	8.19		0.83	27.43
5R-2, 144-146	0.707750	0.512454	-3.63	18.765	15.646	38.781	0.282984	7.49		0.45	7.99
6R-4, 139-141	0.703980	0.512803	3.18	18.662	15.583	38.485	0.283144	13.16		0.76	25.65
12R-2, 137-139	0.707590	0.512541	-1.93	18.771	15.594	38.594	0.283056	10.03		0.75	11.50
17R-4, 123-125	0.703590	0.513054	8.08	18.614	15.557	38.330	0.283135	12.83		0.59	18.12
T-251	0.707833	0.512739	1.97	17.952	15.562	37.778	0.282983				41.62
S936	0.709749	0.512475	-3.18	18.774	15.619	38.647	0.282754				34.00
Local Sediments											
ZI/03		0.51268	0.77				0.282902	4.66			
ZI/01		0.5127116	1.44				0.282921	5.33			
P54703		0.5123854	-4.93				0.282666	-3.66			
P55908		0.5123715	-5.20				0.282635	-4.77			
P23553		0.5124272	-4.11				0.282666	-3.67			
P55962		0.5124219	-4.22				0.282669	-3.57			
P55907		0.512384	-4.95				0.282629	-4.99			

APPENDIX B

Model An mol% compositions of Merapi feldspar calculated using groundmass and whole rock compositions of Merapi lavas and the equation of Panjasawatwong *et al.*, 1995. This is an empirical equation for calculating the equilibrium near-liquidus plagioclase composition. Temperatures used were between 1200 and 800 °C and a pressure of 500 MPa, the pressure at which the majority of Merapi basaltic-andesite crystallisation is thought to occur (Gertisser, 2001). Extrapolating to lower pressures is not accounted for in the model of Panjasawatwong *et al.*, (1995), however this is thought to raise the calculated An content by ~10%, while increasing pressures up to 1000 MPa lowers An mol% compositions by ~10%.

APPENDIX C

Clinopyroxene EMP data, mineral calculations and geobarometry results using the equations of Nimis, 1999. Clinopyroxene crystal chemistry is linked to pressure of crystallization (Dal Negro *et al.* 1982; Dal Negro *et al.*, 1984; Dal Negro *et al.* 1989; Manoli & Molin 1988). Pressure can be expressed as linear function of unit cell volume, V_{cell} and M_1 site volume, V_{M1} , resulting in an equation that relates V_{cell} and V_{M1} to the crystallisation pressure of clinopyroxene. The standard error on prediction of pressure crystallization values is up to ± 200 MPa (Nimis, 1999) but generally around 140 MPa.

APPENDIX C

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Sum	Si	Ti cat6	Al	Al4	Al6	Cr cat12	Fe	Fe2	Fe3 cat8	Mn cat2	Mg	Ca cat4	Na cat5	AlM1	Si*	AlT cat14	AlM1 cat7	Sum T-sites	Sum M-sites	Mn cat2	Ca cat4	Na cat5	cat6 XT1	cat7 XALM1	cat8 XFET	cat12 XCR	RFe2T	RMgT
8P1-Pyx-a-1	52.03	0.22	1.55	0.00	8.71	0.63	14.11	21.59	0.45	99.30	1.95	0.01	0.07	0.05	0.02	0.00	0.27	0.22	0.06	0.02	0.79	0.87	0.03	0.02	1.95	0.05	0.02	2.00	2.00	0.02	0.87	0.03	0.01	0.02	0.06	0.00	0.22	0.79
8P1-Pyx-a-2	50.92	0.63	2.78	0.00	8.49	0.45	13.79	22.03	0.53	99.61	1.90	0.02	0.12	0.10	0.02	0.00	0.26	0.18	0.09	0.01	0.77	0.88	0.04	0.02	1.90	0.10	0.02	2.00	2.00	0.01	0.88	0.04	0.02	0.02	0.09	0.00	0.18	0.77
8P1-Pyx-a-3	51.70	0.28	1.48	0.00	8.64	0.50	14.28	21.77	0.51	99.15	1.93	0.01	0.07	0.07	0.00	0.00	0.27	0.18	0.09	0.02	0.80	0.87	0.04	0.00	1.93	0.07	0.00	2.00	2.00	0.02	0.87	0.04	0.01	0.00	0.09	0.00	0.18	0.80
8P1-Pyx-c-1	51.61	0.39	2.39	0.00	8.73	0.45	14.51	21.77	0.50	100.34	1.91	0.01	0.10	0.09	0.01	0.00	0.27	0.17	0.10	0.01	0.80	0.86	0.04	0.01	1.91	0.09	0.01	2.00	2.00	0.01	0.86	0.04	0.01	0.01	0.10	0.00	0.17	0.80
8P1-Pyx-c-2	50.76	0.44	2.33	0.00	9.07	0.58	14.76	20.61	0.49	99.04	1.90	0.01	0.10	0.10	0.00	0.00	0.28	0.17	0.11	0.02	0.82	0.83	0.04	0.00	1.90	0.10	0.00	2.00	2.00	0.02	0.83	0.04	0.01	0.00	0.11	0.00	0.17	0.82
8P1-Pyx-c-3	50.96	0.46	2.36	0.04	8.94	0.43	14.57	21.14	0.52	99.42	1.90	0.01	0.10	0.10	0.00	0.00	0.28	0.17	0.11	0.01	0.81	0.84	0.04	0.00	1.90	0.10	0.00	2.00	2.00	0.01	0.84	0.04	0.01	0.00	0.11	0.00	0.17	0.81
8P1-Pyx-r-1	47.85	0.94	4.55	0.06	11.68	0.31	11.12	22.77	0.43	99.70	1.81	0.03	0.20	0.19	0.01	0.00	0.37	0.21	0.16	0.01	0.63	0.92	0.03	0.01	1.81	0.19	0.01	2.00	2.00	0.01	0.92	0.03	0.03	0.01	0.16	0.00	0.21	0.63
8P4-Pyx-c-1	52.21	0.31	2.57	0.39	4.29	0.15	15.78	23.87	0.24	99.81	1.92	0.01	0.11	0.08	0.03	0.01	0.13	0.08	0.05	0.00	0.86	0.94	0.02	0.03	1.92	0.08	0.03	2.00	2.00	0.00	0.94	0.02	0.01	0.03	0.05	0.01	0.08	0.86
8P4-Pyx-c-2	52.08	0.35	2.59	0.37	4.56	0.03	15.97	23.47	0.23	99.65	1.91	0.01	0.11	0.09	0.02	0.01	0.14	0.09	0.05	0.00	0.87	0.92	0.02	0.02	1.91	0.09	0.02	2.00	2.00	0.00	0.92	0.02	0.01	0.02	0.05	0.01	0.09	0.87
8P4-Pyx-c-3	52.21	0.38	2.71	0.41	4.31	0.07	15.70	23.61	0.23	99.63	1.92	0.01	0.12	0.08	0.04	0.01	0.13	0.10	0.03	0.00	0.86	0.93	0.02	0.04	1.92	0.08	0.04	2.00	2.00	0.00	0.93	0.02	0.01	0.04	0.03	0.01	0.10	0.86
8P4-Pyx-r-1	51.32	0.52	2.55	0.00	8.73	0.33	13.82	22.33	0.39	99.97	1.91	0.01	0.11	0.09	0.02	0.00	0.27	0.20	0.07	0.01	0.77	0.89	0.03	0.02	1.91	0.09	0.02	2.00	2.00	0.01	0.89	0.03	0.01	0.02	0.07	0.00	0.20	0.77
8P4-Pyx-r-2	51.18	0.36	2.06	0.00	8.60	0.46	14.40	21.98	0.38	99.41	1.91	0.01	0.09	0.09	0.00	0.00	0.27	0.17	0.10	0.01	0.80	0.88	0.03	0.00	1.91	0.09	0.00	2.00	2.00	0.01	0.88	0.03	0.01	0.00	0.10	0.00	0.17	0.80
8P4-Pyx-r-3	50.66	0.70	2.66	0.00	8.50	0.40	13.30	22.75	0.49	99.46	1.90	0.02	0.12	0.10	0.01	0.00	0.27	0.18	0.09	0.01	0.74	0.91	0.04	0.01	1.90	0.10	0.01	2.00	2.00	0.01	0.91	0.04	0.02	0.01	0.09	0.00	0.18	0.74
8P5-Pyx-a-1	51.50	0.43	2.40	0.01	8.97	0.60	14.76	20.01	0.47	99.14	1.93	0.01	0.11	0.07	0.03	0.00	0.28	0.23	0.05	0.02	0.82	0.80	0.03	0.03	1.93	0.07	0.03	2.00	2.00	0.02	0.80	0.03	0.01	0.03	0.05	0.00	0.23	0.82
8P5-Pyx-a-2	51.69	0.35	2.15	0.00	9.22	0.62	14.77	20.42	0.48	99.70	1.92	0.01	0.09	0.08	0.02	0.00	0.29	0.21	0.07	0.02	0.82	0.81	0.03	0.02	1.92	0.08	0.02	2.00	2.00	0.02	0.81	0.03	0.01	0.02	0.07	0.00	0.21	0.82
8P5-Pyx-a-3	52.13	0.30	1.40	0.00	8.92	0.65	14.99	20.43	0.33	99.14	1.95	0.01	0.06	0.05	0.01	0.00	0.28	0.24	0.04	0.02	0.84	0.82	0.02	0.01	1.95	0.05	0.01	2.00	2.00	0.02	0.82	0.02	0.01	0.01	0.04	0.00	0.24	0.84
8P8-Pyx-a-1	51.37	0.19	1.95	0.00	10.43	0.72	13.32	21.19	0.45	99.62	1.93	0.01	0.09	0.07	0.01	0.00	0.33	0.25	0.08	0.02	0.74	0.85	0.03	0.01	1.93	0.07	0.01	2.00	2.00	0.02	0.85	0.03	0.01	0.01	0.08	0.00	0.25	0.74
8P8-Pyx-a-2	51.45	0.25	1.88	0.04	9.83	0.75	13.31	21.30	0.48	99.30	1.94	0.01	0.08	0.06	0.02	0.00	0.31	0.24	0.07	0.02	0.75	0.86	0.03	0.02	1.94	0.06	0.02	2.00	2.00	0.02	0.86	0.03	0.01	0.02	0.07	0.00	0.24	0.75
8P8-Pyx-a-3	51.51	0.24	1.98	0.00	10.36	0.86	13.51	20.90	0.46	99.82	1.93	0.01	0.09	0.07	0.02	0.00	0.32	0.25	0.07	0.03	0.75	0.84	0.03	0.02	1.93	0.07	0.02	2.00	2.00	0.03	0.84	0.03	0.01	0.02	0.07	0.00	0.25	0.75
8P10-Pyx-a-1	46.70	1.15	7.03	0.05	8.62	0.27	12.19	23.27	0.30	99.58	1.75	0.03	0.31	0.25	0.06	0.00	0.27	0.11	0.15	0.01	0.68	0.93	0.02	0.06	1.75	0.25	0.06	2.00	2.00	0.01	0.93	0.02	0.03	0.06	0.15	0.00	0.11	0.68
8P10-Pyx-a-2	46.69	1.16	7.11	0.02	8.23	0.22	12.46	23.31	0.31	99.51	1.74	0.03	0.31	0.26	0.06	0.00	0.26	0.10	0.16	0.01	0.69	0.93	0.02	0.06	1.74	0.26	0.06	2.00	2.00	0.01	0.93	0.02	0.03	0.06	0.16	0.00	0.10	0.69
8P10-Pyx-a-3	47.06	1.01	6.54	0.06	7.96	0.09	12.84	23.07	0.37	99.00	1.76	0.03	0.29	0.24	0.05	0.00	0.25	0.09	0.16	0.00	0.72	0.93	0.03	0.05	1.76	0.24	0.05	2.00	2.00	0.00	0.93	0.03	0.03	0.05	0.16	0.00	0.09	0.72
8P10-Pyx-a-4	47.57	0.99	6.58	0.02	7.75	0.19	12.49	23.01	0.31	98.91	1.79	0.03	0.29	0.21	0.08	0.00	0.24	0.14	0.10	0.01	0.70	0.93	0.02	0.08	1.79	0.21	0.08	2.00	2.00	0.01	0.93	0.02	0.03	0.08	0.10	0.00	0.14	0.70
8P10-Pyx-a-5	46.65	1.22	7.39	0.07	8.62	0.12	12.21	23.30	0.30	99.88	1.74	0.03	0.32	0.26	0.06	0.00	0.27	0.12	0.15	0.00	0.68	0.93	0.02	0.06	1.74	0.26	0.06	2.00	2.00	0.00	0.93	0.02	0.03	0.06	0.15	0.00	0.12	0.68
8P11-Pyx-b-1	51.62	0.50	2.35	0.00	8.63	0.49	14.40	21.43	0.35	99.75	1.92	0.01	0.10	0.08	0.02	0.00	0.27	0.22	0.05	0.02	0.80	0.85	0.02	0.02	1.92	0.08	0.02	2.00	2.00	0.02	0.85	0.02	0.01	0.02	0.05	0.00	0.22	0.80
8P11-Pyx-b-2	51.45	0.41	2.37	0.00	8.55	0.59	14.51	21.28	0.42	99.58	1.92	0.01	0.10	0.08	0.02	0.00	0.27	0.19	0.07	0.02	0.80	0.85	0.03	0.02	1.92	0.08	0.02	2.00	2.00	0.02	0.85	0.03	0.01	0.02	0.07	0.00	0.19	0.80
8P11-Pyx-b-3	51.41	0.54	2.74	0.00	8.99	0.70	14.51	21.53	0.40	100.81	1.89	0.02	0.12	0.11	0.01	0.00	0.28	0.18	0.09	0.02	0.80	0.85	0.03	0.01	1.89	0.11	0.01	2.00	2.00	0.02	0.85	0.03	0.02	0.01	0.09	0.00	0.18	0.80
8P11-Pyx-b-4	52.50	0.30	1.70	0.05	8.66	0.68	14.98	21.13	0.39	100.39	1.94	0.01	0.07	0.06	0.01	0.00	0.27	0.21	0.06	0.02	0.82	0.84	0.03	0.01	1.94	0.06	0.01	2.00	2.00	0.02	0.84	0.03	0.01	0.01	0.06	0.00	0.21	0.82
8P12-Pyx-a-1	51.76	0.40	2.26	0.00	8.76	0.51	15.13	20.45	0.41	99.67	1.92	0.01	0.10	0.08	0.02	0.00	0.27	0.21	0.06	0.02	0.84	0.81	0.03	0.02	1.92	0.08	0.02	2.00	2.00	0.02	0.81	0.03	0.01	0.02	0.06	0.00	0.21	0.84
8P12-Pyx-a-2	51.25	0.54	2.86	0.02	8.75	0.51	14.86	20.98	0.36	100.12	1.90	0.01	0.12	0.10	0.02	0.00	0.27	0.19	0.08	0.02	0.82	0.83	0.03	0.02	1.90	0.10	0.02	2.00	2.00	0.02	0.83	0.03	0.01	0.02	0.08	0.00	0.19	0.82
8P12-Pyx-a-3	51.45	0.48	2.80	0.01	8.58	0.44	14.80	21.04	0.37	99.96	1.91	0.01	0.12	0.09	0.03	0.00	0.27	0.20	0.06	0.01	0.82	0.84	0.03	0.03	1.91	0.09	0.03	2.00	2.00	0.01	0.84	0.03	0.01	0.03	0.06	0.00	0.20	0.82
8P12-Pyx-a-4	51.52	0.52	2.74	0.01	8.86	0.37	14.78	21.07	0.39	100.26	1.90	0.01	0.12	0.10	0.02	0.00	0.27	0.20	0.07	0.01	0.81	0.83	0.03	0.02	1.90	0.10	0.02	2.00	2.00	0.01	0.83	0.03	0.01	0.02	0.07	0.00	0.20	0.81
8P12-Pyx-a-5	51.89	0.27	1.70	0.03	9.27	0.80	14.56	21.24	0.31	100.06	1.93	0.01	0.07	0.07	0.00	0.00	0.29	0.21	0.07	0.03	0.81	0.85	0.02	0.00	1.93	0.07	0.00	2.00										

APPENDIX C

4P2-Pyx-c-1	49.85	0.27	3.26	0.04	13.33	0.85	9.90	21.98	0.61	100.09	1.89	0.01	0.15	0.11	0.04	0.00	0.42	0.33	0.09	0.03	0.56	0.89	0.05	0.04	1.89	0.11	0.04	2.00	2.00	0.03	0.89	0.05	0.01	0.04	0.09	0.00	0.33	0.56
4P2-Pyx-c-2	51.15	0.38	2.40	0.01	9.82	0.58	14.00	21.07	0.35	99.74	1.91	0.01	0.11	0.09	0.02	0.00	0.31	0.23	0.08	0.02	0.78	0.84	0.03	0.02	1.91	0.09	0.02	2.00	2.00	0.02	0.84	0.03	0.01	0.02	0.08	0.00	0.23	0.78
4P2-Pyx-c-3	51.15	0.31	2.54	0.00	9.44	0.46	14.13	21.51	0.40	99.93	1.90	0.01	0.11	0.10	0.01	0.00	0.29	0.20	0.09	0.01	0.78	0.86	0.03	0.01	1.90	0.10	0.01	2.00	2.00	0.01	0.86	0.03	0.01	0.01	0.09	0.00	0.20	0.78
4P2-Pyx-c-4	51.59	0.36	2.48	0.07	9.13	0.50	13.93	21.69	0.36	100.09	1.92	0.01	0.11	0.08	0.03	0.00	0.28	0.22	0.06	0.02	0.77	0.86	0.03	0.03	1.92	0.08	0.03	2.00	2.00	0.02	0.86	0.03	0.01	0.03	0.06	0.00	0.22	0.77
4P2-Pyx-c-5	52.25	0.24	1.59	0.09	9.44	0.64	14.88	20.88	0.32	100.32	1.94	0.01	0.07	0.06	0.00	0.00	0.29	0.23	0.07	0.02	0.82	0.83	0.02	0.00	1.94	0.06	0.00	2.00	2.00	0.02	0.83	0.02	0.01	0.00	0.07	0.00	0.23	0.82
4P2-Pyx-c-6	52.37	0.19	1.46	0.00	9.39	0.73	15.19	19.94	0.37	99.62	1.95	0.01	0.06	0.05	0.01	0.00	0.29	0.24	0.05	0.02	0.84	0.80	0.03	0.01	1.95	0.05	0.01	2.00	2.00	0.02	0.80	0.03	0.01	0.01	0.05	0.00	0.24	0.84
4P2-Pyx-a-1	52.15	0.22	1.40	0.00	9.18	0.50	14.47	21.65	0.27	99.83	1.94	0.01	0.06	0.06	0.01	0.00	0.29	0.23	0.06	0.02	0.80	0.86	0.02	0.01	1.94	0.06	0.01	2.00	2.00	0.02	0.86	0.02	0.01	0.01	0.06	0.00	0.23	0.80
4P2-Pyx-a-2	51.90	0.21	1.65	0.02	9.27	0.45	14.66	21.54	0.31	100.01	1.93	0.01	0.07	0.07	0.00	0.00	0.29	0.21	0.08	0.01	0.81	0.86	0.02	0.00	1.93	0.07	0.00	2.00	2.00	0.01	0.86	0.02	0.01	0.00	0.08	0.00	0.21	0.81
4P2-Pyx-a-3	50.20	0.42	3.34	0.04	9.49	0.50	13.32	22.01	0.43	99.74	1.87	0.01	0.15	0.13	0.02	0.00	0.30	0.19	0.11	0.02	0.74	0.88	0.03	0.02	1.87	0.13	0.02	2.00	2.00	0.02	0.88	0.03	0.01	0.02	0.11	0.00	0.19	0.74
4P2-Pyx-a-4	50.22	0.46	3.26	0.00	9.65	0.51	13.51	22.02	0.38	100.01	1.87	0.01	0.14	0.13	0.01	0.00	0.30	0.18	0.12	0.02	0.75	0.88	0.03	0.01	1.87	0.13	0.01	2.00	2.00	0.02	0.88	0.03	0.01	0.01	0.12	0.00	0.18	0.75
4P2-Pyx-a-5	51.38	0.24	2.51	0.00	9.43	0.47	14.14	21.50	0.37	100.04	1.91	0.01	0.11	0.09	0.02	0.00	0.29	0.21	0.08	0.01	0.78	0.86	0.03	0.02	1.91	0.09	0.02	2.00	2.00	0.01	0.86	0.03	0.01	0.02	0.08	0.00	0.21	0.78
4P5-Pyx-a-1	51.59	0.35	2.09	0.01	8.46	0.70	14.25	21.37	0.38	99.19	1.93	0.01	0.09	0.07	0.02	0.00	0.26	0.21	0.05	0.02	0.79	0.86	0.03	0.02	1.93	0.07	0.02	2.00	2.00	0.02	0.86	0.03	0.01	0.02	0.05	0.00	0.21	0.79
4P5-Pyx-a-2	51.94	0.25	1.81	0.04	8.43	0.73	14.18	21.55	0.39	99.31	1.94	0.01	0.08	0.06	0.02	0.00	0.26	0.22	0.05	0.02	0.79	0.86	0.03	0.02	1.94	0.06	0.02	2.00	2.00	0.02	0.86	0.03	0.01	0.02	0.05	0.00	0.22	0.79
4P5-Pyx-a-3	51.65	0.33	2.12	0.05	8.37	0.67	13.98	21.71	0.42	99.29	1.93	0.01	0.09	0.07	0.03	0.00	0.26	0.21	0.05	0.02	0.78	0.87	0.03	0.03	1.93	0.07	0.03	2.00	2.00	0.02	0.87	0.03	0.01	0.03	0.05	0.00	0.21	0.78
4P5-Pyx-a-4	51.09	0.24	1.56	0.03	10.55	0.71	13.03	21.55	0.34	99.08	1.93	0.01	0.07	0.07	0.00	0.00	0.33	0.26	0.07	0.02	0.73	0.87	0.02	0.00	1.93	0.07	0.00	2.00	2.00	0.02	0.87	0.02	0.01	0.00	0.07	0.00	0.26	0.73
4P5-Pyx-a-5	51.22	0.42	2.39	0.03	10.36	0.63	12.95	21.91	0.39	100.29	1.91	0.01	0.11	0.09	0.02	0.00	0.32	0.25	0.07	0.02	0.72	0.88	0.03	0.02	1.91	0.09	0.02	2.00	2.00	0.02	0.88	0.03	0.01	0.02	0.07	0.00	0.25	0.72
4P5-Pyx-b-1	52.22	0.30	1.92	0.00	9.22	0.57	13.82	21.65	0.43	100.13	1.94	0.01	0.08	0.06	0.03	0.00	0.29	0.24	0.04	0.02	0.77	0.86	0.03	0.03	1.94	0.06	0.03	2.00	2.00	0.02	0.86	0.03	0.01	0.03	0.04	0.00	0.24	0.77
4P5-Pyx-b-2	51.75	0.36	2.17	0.00	8.95	0.63	14.06	21.40	0.46	99.79	1.93	0.01	0.10	0.07	0.02	0.00	0.28	0.22	0.06	0.02	0.78	0.85	0.03	0.02	1.93	0.07	0.02	2.00	2.00	0.02	0.85	0.03	0.01	0.02	0.06	0.00	0.22	0.78
4P5-Pyx-b-3	51.84	0.33	2.15	0.00	8.74	0.64	14.11	21.67	0.45	99.93	1.93	0.01	0.09	0.07	0.02	0.00	0.27	0.21	0.06	0.02	0.78	0.86	0.03	0.02	1.93	0.07	0.02	2.00	2.00	0.02	0.86	0.03	0.01	0.02	0.06	0.00	0.21	0.78
4P5-Pyx-b-4	51.45	0.43	2.25	0.05	8.02	0.57	14.15	21.65	0.42	98.97	1.93	0.01	0.10	0.07	0.03	0.00	0.25	0.20	0.05	0.02	0.79	0.87	0.03	0.03	1.93	0.07	0.03	2.00	2.00	0.02	0.87	0.03	0.01	0.03	0.05	0.00	0.20	0.79
4P5-Pyx-b-5	50.97	0.47	2.51	0.00	8.25	0.45	14.34	21.95	0.42	99.37	1.90	0.01	0.11	0.10	0.01	0.00	0.26	0.17	0.09	0.01	0.80	0.88	0.03	0.01	1.90	0.10	0.01	2.00	2.00	0.01	0.88	0.03	0.01	0.01	0.09	0.00	0.17	0.80
8B1-Pyx-a-1	51.26	0.41	2.03	0.08	8.22	0.57	14.54	21.12	0.40	98.63	1.93	0.01	0.09	0.07	0.02	0.00	0.26	0.20	0.06	0.02	0.81	0.85	0.03	0.02	1.93	0.07	0.02	2.00	2.00	0.02	0.85	0.03	0.01	0.02	0.06	0.00	0.20	0.81
8B1-Pyx-a-2	51.62	0.41	1.99	0.04	9.12	0.66	14.53	21.11	0.32	99.80	1.92	0.01	0.09	0.08	0.01	0.00	0.28	0.22	0.07	0.02	0.81	0.84	0.02	0.01	1.92	0.08	0.01	2.00	2.00	0.02	0.84	0.02	0.01	0.01	0.07	0.00	0.22	0.81
8B1-Pyx-a-3	51.20	0.37	2.17	0.08	10.01	0.60	13.79	21.08	0.37	99.67	1.92	0.01	0.10	0.08	0.01	0.00	0.31	0.24	0.07	0.02	0.77	0.85	0.03	0.01	1.92	0.08	0.01	2.00	2.00	0.02	0.85	0.03	0.01	0.01	0.07	0.00	0.24	0.77
8B1-Pyx-a-4	51.76	0.44	1.68	0.02	8.26	0.59	15.02	20.97	0.35	99.08	1.93	0.01	0.07	0.07	0.01	0.00	0.26	0.20	0.06	0.02	0.84	0.84	0.03	0.01	1.93	0.07	0.01	2.00	2.00	0.02	0.84	0.03	0.01	0.01	0.06	0.00	0.20	0.84
8B1-Pyx-a-5	51.97	0.39	1.80	0.04	8.60	0.49	14.83	20.85	0.38	99.34	1.94	0.01	0.08	0.06	0.02	0.00	0.27	0.22	0.05	0.02	0.82	0.83	0.03	0.02	1.94	0.06	0.02	2.00	2.00	0.02	0.83	0.03	0.01	0.02	0.05	0.00	0.22	0.82
8B1-Pyx-b-1	51.98	0.39	1.85	0.03	8.25	0.68	15.11	21.10	0.39	99.77	1.93	0.01	0.08	0.07	0.01	0.00	0.26	0.19	0.07	0.02	0.84	0.84	0.03	0.01	1.93	0.07	0.01	2.00	2.00	0.02	0.84	0.03	0.01	0.01	0.07	0.00	0.19	0.84
8B1-Pyx-b-2	51.95	0.40	1.79	0.04	8.50	0.61	15.11	20.70	0.40	99.49	1.93	0.01	0.08	0.07	0.01	0.00	0.26	0.20	0.06	0.02	0.84	0.83	0.03	0.01	1.93	0.07	0.01	2.00	2.00	0.02	0.83	0.03	0.01	0.01	0.06	0.00	0.20	0.84
8B1-Pyx-b-3	51.82	0.41	1.67	0.01	8.42	0.55	15.12	21.11	0.35	99.46	1.93	0.01	0.07	0.07	0.00	0.00	0.26	0.19	0.07	0.02	0.84	0.84	0.03	0.00	1.93	0.07	0.00	2.00	2.00	0.02	0.84	0.03	0.01	0.00	0.07	0.00	0.19	0.84
8B1-Pyx-b-4	50.79	0.46	2.83	0.11	9.49	0.69	14.06	20.71	0.34	99.47	1.90	0.01	0.12	0.10	0.03	0.00	0.30	0.23	0.07	0.02	0.78	0.83	0.02	0.03	1.90	0.10	0.03	2.00	2.00	0.02	0.83	0.02	0.01	0.03	0.07	0.00	0.23	0.78
8B1-Pyx-b-5	52.04	0.47	1.76	0.01	8.72	0.65	14.94	20.61	0.40	99.60	1.94	0.01	0.08	0.06	0.01	0.00	0.27	0.22	0.05	0.02	0.83	0.82	0.03	0.01	1.94	0.06	0.01	2.00	2.00	0.02	0.82	0.03	0.01	0.01	0.05	0.00	0.22	0.83
4B1-Pyx-1-c	50.49	0.57	2.82	0.00	9.18	0.47	14.85	20.28	0.34	98.99	1.89	0.02	0.12	0.11	0.01	0.00	0.29	0.20	0.09	0.01	0.83	0.81	0.02	0.01	1.89	0.11	0.01	2.00	2.00	0.01	0.81	0.02	0.02	0.01	0.09	0.00	0.20	0.83
4B1-Pyx-1-c	50.32	0.48	2.49	0.00	8.44	0.32	15.05	20.92	0.38	98.38	1.89	0.01	0.11	0.11	0.00	0.00	0.26	0.15	0.11	0.01	0.84	0.84	0.03	0.00	1.89	0.11	0.00	2.00	2.00	0.01	0.84	0.03	0.01	0.00	0.11	0.00	0.15	0.84
4B1-Pyx-1-c	50.88	0.30	3.09	0.06	9.29	0.54	13.98	21.33	0.40	99.87	1.89	0.01	0.14	0.11	0.03	0.00	0.29	0.20	0.09	0.02	0.78	0.85	0.03	0.03	1.89	0.11	0.03	2.00	2.00	0.02	0.85	0.03	0.01	0.03	0.09			

APPENDIX C

4B1-Pyxa-1	51.23	0.51	3.13	0.01	9.14	0.37	14.92	20.52	0.38	100.20	1.89	0.01	0.14	0.11	0.03	0.00	0.28	0.21	0.07	0.01	0.82	0.81	0.03	0.03	1.89	0.11	0.03	2.00	2.00	0.01	0.81	0.03	0.01	0.03	0.07	0.00	0.21	0.82
4B1-Pyxa-2	50.51	0.66	2.84	0.00	9.47	0.47	15.29	20.05	0.33	99.61	1.88	0.02	0.12	0.12	0.00	0.00	0.29	0.19	0.11	0.01	0.85	0.80	0.02	0.00	1.88	0.12	0.00	2.00	2.00	0.01	0.80	0.02	0.02	0.00	0.11	0.00	0.19	0.85
4B1-Pyxa-3	50.23	0.47	3.52	0.01	8.91	0.47	14.44	21.07	0.35	99.46	1.87	0.01	0.15	0.13	0.03	0.00	0.28	0.18	0.10	0.01	0.80	0.84	0.03	0.03	1.87	0.13	0.03	2.00	2.00	0.01	0.84	0.03	0.01	0.03	0.10	0.00	0.18	0.80
4B1-Pyxa-4	50.37	0.54	3.45	0.00	8.77	0.31	14.59	20.88	0.33	99.24	1.88	0.02	0.15	0.12	0.03	0.00	0.27	0.19	0.08	0.01	0.81	0.83	0.02	0.03	1.88	0.12	0.03	2.00	2.00	0.01	0.83	0.02	0.02	0.03	0.08	0.00	0.19	0.81
4B1-Pyxa-5	49.47	0.55	4.44	0.00	7.87	0.17	14.29	22.41	0.26	99.44	1.84	0.02	0.19	0.16	0.03	0.00	0.24	0.13	0.12	0.01	0.79	0.89	0.02	0.03	1.84	0.16	0.03	2.00	2.00	0.01	0.89	0.02	0.02	0.03	0.12	0.00	0.13	0.79
4B1-Pyxa-6	49.93	0.53	4.24	0.05	8.58	0.31	13.88	21.51	0.39	99.41	1.86	0.01	0.19	0.14	0.05	0.00	0.27	0.18	0.09	0.01	0.77	0.86	0.03	0.05	1.86	0.14	0.05	2.00	2.00	0.01	0.86	0.03	0.01	0.05	0.09	0.00	0.18	0.77
4B1-Pyxa-7	50.39	0.40	3.40	0.00	9.09	0.33	14.00	20.95	0.42	98.98	1.89	0.01	0.15	0.11	0.04	0.00	0.29	0.21	0.08	0.01	0.78	0.84	0.03	0.04	1.89	0.11	0.04	2.00	2.00	0.01	0.84	0.03	0.01	0.04	0.08	0.00	0.21	0.78
4B1-Pyxa-8	50.59	0.55	3.34	0.03	9.28	0.55	14.61	20.40	0.41	99.76	1.88	0.02	0.15	0.12	0.03	0.00	0.29	0.20	0.09	0.02	0.81	0.81	0.03	0.03	1.88	0.12	0.03	2.00	2.00	0.02	0.81	0.03	0.02	0.03	0.09	0.00	0.20	0.81
4B1-Pyxa-9	49.79	0.58	4.27	0.00	8.92	0.21	13.63	21.49	0.42	99.30	1.86	0.02	0.19	0.14	0.05	0.00	0.28	0.19	0.09	0.01	0.76	0.86	0.03	0.05	1.86	0.14	0.05	2.00	2.00	0.01	0.86	0.03	0.02	0.05	0.09	0.00	0.19	0.76
4B1-Pyxa-10	50.68	0.44	3.27	0.03	9.15	0.39	14.40	21.07	0.37	99.80	1.88	0.01	0.14	0.12	0.03	0.00	0.28	0.19	0.09	0.01	0.80	0.84	0.03	0.03	1.88	0.12	0.03	2.00	2.00	0.01	0.84	0.03	0.01	0.03	0.09	0.00	0.19	0.80
4B1-Pyxa-11	50.88	0.44	2.99	0.02	9.22	0.43	14.40	20.21	0.36	98.96	1.91	0.01	0.13	0.09	0.04	0.00	0.29	0.24	0.05	0.01	0.80	0.81	0.03	0.04	1.91	0.09	0.04	2.00	2.00	0.01	0.81	0.03	0.01	0.04	0.05	0.00	0.24	0.80
4B1-Pyxa-12	51.29	0.48	2.89	0.04	9.02	0.36	14.93	20.00	0.34	99.35	1.91	0.01	0.13	0.09	0.04	0.00	0.28	0.24	0.04	0.01	0.83	0.80	0.02	0.04	1.91	0.09	0.04	2.00	2.00	0.01	0.80	0.02	0.01	0.04	0.04	0.00	0.24	0.83
4B1-Pyxa-13	51.34	0.44	2.40	0.00	8.91	0.37	14.86	20.85	0.40	99.56	1.91	0.01	0.11	0.09	0.02	0.00	0.28	0.20	0.08	0.01	0.82	0.83	0.03	0.02	1.91	0.09	0.02	2.00	2.00	0.01	0.83	0.03	0.01	0.02	0.08	0.00	0.20	0.82
4B1-Pyxa-14	50.94	0.40	2.43	0.00	9.13	0.35	14.97	20.59	0.40	99.20	1.90	0.01	0.11	0.10	0.01	0.00	0.28	0.19	0.10	0.01	0.83	0.82	0.03	0.01	1.90	0.10	0.01	2.00	2.00	0.01	0.82	0.03	0.01	0.01	0.10	0.00	0.19	0.83
4B1-Pyxa-15	51.13	0.42	2.86	0.01	8.60	0.37	14.55	20.03	0.40	98.37	1.92	0.01	0.13	0.08	0.05	0.00	0.27	0.24	0.03	0.01	0.82	0.81	0.03	0.05	1.92	0.08	0.05	2.00	2.00	0.01	0.81	0.03	0.01	0.05	0.03	0.00	0.24	0.82
4B1-Pyxa-16	51.44	0.47	2.46	0.01	8.68	0.53	15.10	20.57	0.38	98.64	1.91	0.01	0.11	0.09	0.02	0.00	0.27	0.20	0.07	0.02	0.84	0.82	0.03	0.02	1.91	0.09	0.02	2.00	2.00	0.02	0.82	0.03	0.01	0.02	0.07	0.00	0.20	0.84
4B1-Pyxa-17	51.31	0.45	2.59	0.00	8.42	0.42	14.85	20.82	0.39	99.24	1.91	0.01	0.11	0.09	0.03	0.00	0.26	0.20	0.06	0.01	0.82	0.83	0.03	0.03	1.91	0.09	0.03	2.00	2.00	0.01	0.83	0.03	0.01	0.03	0.06	0.00	0.20	0.82
4B1-Pyxa-18	50.81	0.51	2.99	0.00	9.29	0.48	14.56	20.59	0.40	99.61	1.89	0.01	0.13	0.11	0.02	0.00	0.29	0.20	0.09	0.01	0.81	0.82	0.03	0.02	1.89	0.11	0.02	2.00	2.00	0.01	0.82	0.03	0.01	0.02	0.09	0.00	0.20	0.81
4B1-Pyxa-19	51.02	0.50	2.78	0.00	8.95	0.54	15.06	19.86	0.35	99.05	1.91	0.01	0.12	0.09	0.03	0.00	0.28	0.22	0.06	0.02	0.84	0.80	0.03	0.03	1.91	0.09	0.03	2.00	2.00	0.02	0.80	0.03	0.01	0.03	0.06	0.00	0.22	0.84
4B1-Pyxa-20	50.02	0.52	3.80	0.00	9.11	0.39	14.25	21.18	0.37	99.63	1.86	0.01	0.17	0.14	0.03	0.00	0.28	0.18	0.11	0.01	0.79	0.84	0.03	0.03	1.86	0.14	0.03	2.00	2.00	0.01	0.84	0.03	0.01	0.03	0.11	0.00	0.18	0.79
4B1-Pyxa-21	48.44	0.79	5.61	0.01	9.63	0.28	12.95	21.78	0.37	99.85	1.81	0.02	0.25	0.19	0.05	0.00	0.30	0.18	0.12	0.01	0.72	0.87	0.03	0.05	1.81	0.19	0.05	2.00	2.00	0.01	0.87	0.03	0.02	0.05	0.12	0.00	0.18	0.72
4B1-Pyxa-22	49.00	0.62	5.10	0.00	9.41	0.27	13.16	21.68	0.35	99.58	1.83	0.02	0.22	0.17	0.05	0.00	0.29	0.19	0.11	0.01	0.73	0.87	0.03	0.05	1.83	0.17	0.05	2.00	2.00	0.01	0.87	0.03	0.02	0.05	0.11	0.00	0.19	0.73
4B1-Pyxa-23	50.03	0.57	3.53	0.00	9.10	0.48	14.40	21.06	0.35	99.51	1.86	0.02	0.16	0.14	0.02	0.00	0.28	0.17	0.11	0.02	0.80	0.84	0.03	0.02	1.86	0.14	0.02	2.00	2.00	0.02	0.84	0.03	0.02	0.02	0.11	0.00	0.17	0.80
4B1-Pyxa-24	51.31	0.56	2.91	0.06	9.77	0.35	14.97	20.12	0.32	100.36	1.90	0.02	0.13	0.10	0.02	0.00	0.30	0.23	0.07	0.01	0.82	0.80	0.02	0.02	1.90	0.10	0.02	2.00	2.00	0.01	0.80	0.02	0.02	0.02	0.07	0.00	0.23	0.82
4B1-Pyxa-25	48.54	0.76	4.36	0.00	11.58	0.37	13.81	20.19	0.36	99.97	1.81	0.02	0.19	0.19	0.00	0.00	0.36	0.19	0.17	0.01	0.77	0.81	0.03	0.00	1.81	0.19	0.00	2.00	2.00	0.01	0.81	0.03	0.02	0.00	0.17	0.00	0.19	0.77
4B1-Pyxa-26	48.31	0.76	5.53	0.05	9.92	0.42	13.04	21.67	0.33	100.02	1.80	0.02	0.24	0.20	0.04	0.00	0.31	0.17	0.14	0.01	0.72	0.87	0.02	0.04	1.80	0.20	0.04	2.00	2.00	0.01	0.87	0.02	0.02	0.04	0.14	0.00	0.17	0.72
4B1-Pyxa-27	50.22	0.44	3.76	0.00	8.76	0.30	13.69	21.99	0.33	99.48	1.87	0.01	0.17	0.13	0.04	0.00	0.27	0.19	0.09	0.01	0.76	0.88	0.02	0.04	1.87	0.13	0.04	2.00	2.00	0.01	0.88	0.02	0.01	0.04	0.09	0.00	0.19	0.76
4B1-Pyxa-28	50.22	0.43	3.44	0.05	9.42	0.23	14.06	21.05	0.44	99.33	1.88	0.01	0.15	0.12	0.03	0.00	0.29	0.19	0.10	0.01	0.78	0.84	0.03	0.03	1.88	0.12	0.03	2.00	2.00	0.01	0.84	0.03	0.01	0.03	0.10	0.00	0.19	0.78
4B1-Pyxa-29	50.40	0.47	3.55	0.03	9.22	0.37	13.66	21.14	0.50	99.34	1.88	0.01	0.16	0.12	0.04	0.00	0.29	0.20	0.08	0.01	0.76	0.85	0.04	0.04	1.88	0.12	0.04	2.00	2.00	0.01	0.85	0.04	0.01	0.04	0.08	0.00	0.20	0.76
4B1-Pyxa-30	50.01	0.43	3.78	0.00	9.21	0.36	13.71	21.49	0.47	99.45	1.87	0.01	0.17	0.13	0.03	0.00	0.29	0.18	0.11	0.01	0.76	0.86	0.03	0.03	1.87	0.13	0.03	2.00	2.00	0.01	0.86	0.03	0.01	0.03	0.11	0.00	0.18	0.76
4B1-Pyxa-31	50.14	0.44	3.90	0.00	9.41	0.32	13.71	21.49	0.41	99.80	1.87	0.01	0.17	0.13	0.04	0.00	0.29	0.19	0.10	0.01	0.76	0.86	0.03	0.04	1.87	0.13	0.04	2.00	2.00	0.01	0.86	0.03	0.01	0.04	0.10	0.00	0.19	0.76
4B1-Pyxa-32	51.11	0.35	2.93	0.02	9.07	0.29	14.35	20.96	0.36	99.44	1.91	0.01	0.13	0.09	0.04	0.00	0.28	0.22	0.06	0.01	0.80	0.84	0.03	0.04	1.91	0.09	0.04	2.00	2.00	0.01	0.84	0.03	0.01	0.04	0.06	0.00	0.22	0.80
4B1-Pyxa-33	50.71	0.50	3.84	0.03	9.01	0.35	13.66	21.67	0.41	100.17	1.88	0.01	0.17	0.12	0.05	0.00	0.28	0.21	0.07	0.01	0.75	0.86	0.03	0.05	1.88	0.12	0.05	2.00	2.00	0.01	0.86	0.03	0.01	0.05	0.07	0.00	0.21	0.75
4B1-Pyxa-34	52.01	0.35	2.21	0.00	8.94	0.42	15.01	20.69	0.39	100.01	1.93	0.01	0.10	0.07	0.02	0.00	0.28	0.22	0.06	0.01	0.83	0.82	0.03	0.02	1.93	0.07	0.02	2.00	2.00	0.01	0.82	0.03	0.01					

APPENDIX C

Sample	CA= CNM	R3	KD	AAA=a	KD-1	BBB= b	DDD= c	cat1**	FeM2 cat1	MgM2 cat3	cat4 XCA	cat5 XNA	FeM1 cat9	MgM1 cat11	Vcell	VM1	P(BA)	XFE	XMG	XAC	XdNA	XdFET= XES	XJD	XddNA	XdALO	XCATS	XCC	XDI	XHD	XEN	XFS	XAC+ XJD
8P1-Pyx-a-1	0.92	0.08	0.13	-0.87	0.39	-0.02	0.05	0.05	0.03	0.87	0.03	0.16	0.76		440.64	11.95	0.00	0.24	0.79	0.03	0.00	0.02	0.00	0.00	0.02	0.03	0.23	0.63	0.19	0.08	0.02	0.03
8P1-Pyx-a-2	0.93	0.12	0.13	-0.87	0.34	-0.01	0.04	0.04	0.03	0.88	0.04	0.14	0.74		440.73	11.88	0.00	0.19	0.77	0.04	0.00	0.05	0.00	0.00	0.02	0.06	0.20	0.62	0.16	0.07	0.02	0.04
8P1-Pyx-a-3	0.93	0.09	0.13	-0.87	0.35	-0.01	0.04	0.04	0.03	0.87	0.04	0.14	0.77		440.96	11.95	0.00	0.20	0.80	0.04	0.00	0.05	0.00	0.00	0.00	0.02	0.20	0.65	0.16	0.07	0.02	0.04
8P1-Pyx-c-1	0.91	0.12	0.13	-0.87	0.35	-0.02	0.05	0.05	0.04	0.86	0.04	0.12	0.76		440.61	11.89	0.00	0.19	0.80	0.04	0.00	0.06	0.00	0.00	0.01	0.03	0.19	0.62	0.14	0.08	0.02	0.04
8P1-Pyx-c-2	0.88	0.12	0.13	-0.87	0.38	-0.02	0.06	0.06	0.06	0.83	0.04	0.11	0.77		440.39	11.89	0.00	0.19	0.82	0.04	0.00	0.08	0.00	0.00	0.00	0.03	0.19	0.59	0.14	0.11	0.03	0.04
8P1-Pyx-c-3	0.90	0.13	0.13	-0.87	0.37	-0.02	0.06	0.06	0.05	0.84	0.04	0.11	0.76		440.57	11.89	0.00	0.18	0.81	0.04	0.00	0.07	0.00	0.00	0.00	0.03	0.18	0.61	0.14	0.10	0.02	0.04
8P1-Pyx-r-1	0.96	0.20	0.14	-0.86	0.33	-0.01	0.02	0.02	0.01	0.92	0.03	0.19	0.62		442.67	11.88	0.00	0.22	0.63	0.03	0.00	0.12	0.00	0.00	0.01	0.07	0.26	0.54	0.19	0.03	0.01	0.03
8P4-Pyx-c-1	0.96	0.09	0.13	-0.87	0.23	0.00	0.02	0.02	0.02	0.94	0.02	0.07	0.84		440.09	11.85	0.00	0.09	0.86	0.02	0.00	0.03	0.00	0.00	0.03	0.05	0.09	0.77	0.08	0.04	0.00	0.02
8P4-Pyx-c-2	0.94	0.09	0.13	-0.87	0.26	-0.01	0.02	0.02	0.04	0.92	0.02	0.07	0.84		440.02	11.85	0.00	0.09	0.87	0.02	0.00	0.03	0.00	0.00	0.02	0.06	0.10	0.76	0.08	0.05	0.01	0.02
8P4-Pyx-c-3	0.95	0.09	0.13	-0.87	0.26	-0.01	0.02	0.02	0.03	0.93	0.02	0.08	0.83		439.85	11.84	0.00	0.11	0.86	0.02	0.00	0.01	0.00	0.00	0.04	0.07	0.11	0.76	0.09	0.05	0.01	0.02
8P4-Pyx-r-1	0.93	0.10	0.13	-0.87	0.37	-0.01	0.04	0.04	0.03	0.89	0.03	0.16	0.74		440.98	11.92	0.00	0.21	0.77	0.03	0.00	0.04	0.00	0.00	0.02	0.05	0.22	0.63	0.17	0.06	0.02	0.03
8P4-Pyx-r-2	0.92	0.11	0.13	-0.87	0.34	-0.01	0.04	0.04	0.04	0.88	0.03	0.13	0.77		441.07	11.92	0.00	0.18	0.80	0.03	0.00	0.07	0.00	0.00	0.00	0.02	0.19	0.64	0.15	0.08	0.02	0.03
8P4-Pyx-r-3	0.96	0.12	0.13	-0.87	0.31	-0.01	0.02	0.02	0.02	0.91	0.04	0.15	0.73		441.40	11.91	0.00	0.19	0.74	0.04	0.00	0.05	0.00	0.00	0.01	0.05	0.20	0.64	0.16	0.04	0.01	0.04
8P5-Pyx-a-1	0.85	0.10	0.13	-0.87	0.46	-0.03	0.09	0.09	0.06	0.80	0.03	0.14	0.76		439.47	11.89	0.00	0.25	0.82	0.03	0.00	0.02	0.00	0.00	0.03	0.06	0.23	0.56	0.17	0.13	0.04	0.03
8P5-Pyx-a-2	0.87	0.10	0.13	-0.87	0.43	-0.03	0.08	0.08	0.06	0.81	0.03	0.14	0.76		439.94	11.90	0.00	0.23	0.82	0.03	0.00	0.04	0.00	0.00	0.02	0.04	0.22	0.57	0.16	0.12	0.03	0.03
8P5-Pyx-a-3	0.86	0.06	0.13	-0.87	0.46	-0.03	0.08	0.08	0.05	0.82	0.02	0.15	0.78		440.10	11.96	0.00	0.26	0.84	0.02	0.00	0.02	0.00	0.00	0.01	0.03	0.23	0.59	0.18	0.12	0.04	0.02
8P8-Pyx-a-1	0.91	0.10	0.13	-0.87	0.43	-0.02	0.06	0.06	0.03	0.85	0.03	0.19	0.71		440.98	11.96	0.00	0.27	0.74	0.03	0.00	0.05	0.00	0.00	0.01	0.02	0.27	0.57	0.21	0.08	0.03	0.03
8P8-Pyx-a-2	0.92	0.09	0.13	-0.87	0.41	-0.02	0.05	0.05	0.03	0.86	0.03	0.19	0.72		440.86	11.96	0.00	0.27	0.75	0.03	0.00	0.03	0.00	0.00	0.02	0.03	0.26	0.58	0.21	0.08	0.03	0.03
8P8-Pyx-a-3	0.90	0.10	0.13	-0.87	0.44	-0.03	0.07	0.07	0.03	0.84	0.03	0.18	0.72		440.74	11.96	0.00	0.28	0.75	0.03	0.00	0.04	0.00	0.00	0.02	0.03	0.27	0.56	0.21	0.09	0.03	0.03
8P10-Pyx-a-1	0.96	0.24	0.14	-0.86	0.24	0.00	0.02	0.02	0.02	0.93	0.02	0.10	0.66		441.02	11.69	0.14	0.12	0.68	0.02	0.00	0.13	0.00	0.00	0.06	0.12	0.15	0.57	0.10	0.04	0.01	0.02
8P10-Pyx-a-2	0.96	0.25	0.14	-0.86	0.23	0.00	0.02	0.02	0.02	0.93	0.02	0.08	0.67		440.88	11.68	0.58	0.10	0.69	0.02	0.00	0.14	0.00	0.00	0.06	0.12	0.13	0.59	0.09	0.04	0.01	0.02
8P10-Pyx-a-3	0.95	0.24	0.14	-0.86	0.23	0.00	0.02	0.02	0.03	0.93	0.03	0.07	0.69		440.72	11.69	0.64	0.09	0.72	0.03	0.00	0.13	0.00	0.00	0.05	0.11	0.12	0.61	0.08	0.04	0.01	0.03
8P10-Pyx-a-4	0.95	0.21	0.14	-0.86	0.27	-0.01	0.03	0.03	0.02	0.93	0.02	0.11	0.68		440.28	11.70	0.97	0.14	0.70	0.02	0.00	0.08	0.00	0.00	0.08	0.13	0.17	0.59	0.12	0.04	0.01	0.02
8P10-Pyx-a-5	0.96	0.25	0.14	-0.86	0.25	-0.01	0.02	0.02	0.02	0.93	0.02	0.09	0.66		440.88	11.68	0.64	0.12	0.68	0.02	0.00	0.13	0.00	0.00	0.06	0.13	0.15	0.57	0.10	0.04	0.01	0.02
8P11-Pyx-b-1	0.90	0.09	0.13	-0.87	0.41	-0.02	0.06	0.06	0.04	0.85	0.02	0.15	0.76		440.38	11.92	0.00	0.23	0.80	0.02	0.00	0.03	0.00	0.00	0.02	0.05	0.23	0.60	0.17	0.09	0.03	0.02
8P11-Pyx-b-2	0.90	0.10	0.13	-0.87	0.39	-0.02	0.06	0.06	0.04	0.85	0.03	0.13	0.76		440.28	11.90	0.00	0.21	0.80	0.03	0.00	0.04	0.00	0.00	0.02	0.04	0.21	0.60	0.16	0.10	0.03	0.03
8P11-Pyx-b-3	0.90	0.12	0.13	-0.87	0.38	-0.02	0.06	0.06	0.04	0.85	0.03	0.13	0.75		440.57	11.89	0.00	0.21	0.80	0.03	0.00	0.06	0.00	0.00	0.01	0.04	0.20	0.59	0.15	0.10	0.02	0.03
8P11-Pyx-b-4	0.89	0.08	0.13	-0.87	0.42	-0.02	0.07	0.07	0.05	0.84	0.03	0.14	0.78		440.22	11.94	0.00	0.23	0.82	0.03	0.00	0.03	0.00	0.00	0.01	0.03	0.22	0.61	0.17	0.11	0.03	0.03
8P12-Pyx-a-1	0.86	0.10	0.13	-0.87	0.44	-0.03	0.08	0.08	0.06	0.81	0.03	0.13	0.78		439.76	11.90	0.00	0.22	0.84	0.03	0.00	0.04	0.00	0.00	0.02	0.04	0.21	0.58	0.16	0.12	0.03	0.03
8P12-Pyx-a-2	0.87	0.11	0.13	-0.87	0.41	-0.02	0.07	0.07	0.06	0.83	0.03	0.12	0.76		440.08	11.87	0.00	0.21	0.82	0.03	0.00	0.05	0.00	0.00	0.02	0.05	0.20	0.58	0.15	0.11	0.03	0.03
8P12-Pyx-a-3	0.88	0.11	0.13	-0.87	0.42	-0.03	0.07	0.07	0.05	0.84	0.03	0.13	0.76		439.93	11.88	0.00	0.21	0.82	0.03	0.00	0.04	0.00	0.00	0.03	0.06	0.21	0.59	0.15	0.11	0.03	0.03
8P12-Pyx-a-4	0.87	0.11	0.13	-0.87	0.42	-0.03	0.07	0.07	0.05	0.83	0.03	0.13	0.76		440.08	11.88	0.00	0.21	0.81	0.03	0.00	0.04	0.00	0.00	0.02	0.05	0.21	0.58	0.15	0.11	0.03	0.03
8P12-Pyx-a-5	0.89	0.09	0.13	-0.87	0.41	-0.02	0.06	0.06	0.04	0.85	0.02	0.15	0.76		440.77	11.96	0.00	0.24	0.81	0.02	0.00	0.05	0.00	0.00	0.00	0.02	0.23	0.60	0.18	0.10	0.03	0.02

APPENDIX C

4P2-Pyx-c-1	0.97	0.14	0.14	-0.86	0.43	-0.01	0.03	0.03	0.01	0.89	0.05	0.30	0.55	442.28	11.98	0.00	0.36	0.56	0.05	0.00	0.05	0.00	0.00	0.04	0.06	0.39	0.48	0.31	0.04	0.02	0.05
4P2-Pyx-c-2	0.89	0.10	0.13	-0.87	0.43	-0.03	0.07	0.07	0.04	0.84	0.03	0.16	0.74	440.67	11.93	0.00	0.25	0.78	0.03	0.00	0.05	0.00	0.00	0.02	0.04	0.24	0.57	0.18	0.10	0.03	0.03
4P2-Pyx-c-3	0.90	0.12	0.13	-0.87	0.39	-0.02	0.06	0.06	0.04	0.86	0.03	0.14	0.74	440.73	11.91	0.00	0.21	0.78	0.03	0.00	0.07	0.00	0.00	0.01	0.03	0.21	0.60	0.16	0.09	0.02	0.03
4P2-Pyx-c-4	0.91	0.10	0.13	-0.87	0.41	-0.02	0.06	0.06	0.03	0.86	0.03	0.17	0.74	440.57	11.92	0.00	0.24	0.77	0.03	0.00	0.03	0.00	0.00	0.03	0.05	0.24	0.60	0.19	0.08	0.03	0.03
4P2-Pyx-c-5	0.87	0.08	0.13	-0.87	0.44	-0.03	0.08	0.08	0.05	0.83	0.02	0.15	0.77	440.48	11.96	0.00	0.25	0.82	0.02	0.00	0.04	0.00	0.00	0.00	0.02	0.23	0.59	0.18	0.11	0.03	0.02
4P2-Pyx-c-6	0.85	0.07	0.13	-0.87	0.48	-0.04	0.09	0.09	0.06	0.80	0.03	0.15	0.78	439.76	11.95	0.00	0.26	0.84	0.03	0.00	0.02	0.00	0.00	0.01	0.02	0.24	0.57	0.18	0.14	0.04	0.03
4P2-Pyx-a-1	0.90	0.07	0.13	-0.87	0.42	-0.02	0.06	0.06	0.04	0.86	0.02	0.16	0.77	440.99	11.98	0.00	0.24	0.80	0.02	0.00	0.04	0.00	0.00	0.01	0.02	0.23	0.62	0.19	0.09	0.03	0.02
4P2-Pyx-a-2	0.89	0.09	0.13	-0.87	0.40	-0.02	0.06	0.06	0.04	0.86	0.02	0.14	0.77	440.93	11.96	0.00	0.22	0.81	0.02	0.00	0.06	0.00	0.00	0.00	0.01	0.21	0.62	0.17	0.09	0.03	0.02
4P2-Pyx-a-3	0.93	0.14	0.13	-0.87	0.35	-0.01	0.04	0.04	0.03	0.88	0.03	0.14	0.71	440.98	11.87	0.00	0.20	0.74	0.03	0.00	0.08	0.00	0.00	0.02	0.05	0.21	0.59	0.16	0.07	0.02	0.03
4P2-Pyx-a-4	0.92	0.14	0.13	-0.87	0.35	-0.01	0.05	0.05	0.03	0.88	0.03	0.14	0.72	441.17	11.88	0.00	0.20	0.75	0.03	0.00	0.09	0.00	0.00	0.01	0.04	0.21	0.59	0.16	0.07	0.02	0.03
4P2-Pyx-a-5	0.90	0.11	0.13	-0.87	0.40	-0.02	0.06	0.06	0.04	0.86	0.03	0.15	0.74	440.60	11.91	0.00	0.22	0.78	0.03	0.00	0.06	0.00	0.00	0.02	0.03	0.22	0.60	0.17	0.09	0.03	0.03
4P5-Pyx-a-1	0.91	0.09	0.13	-0.87	0.40	-0.02	0.06	0.06	0.04	0.86	0.03	0.15	0.76	440.35	11.93	0.00	0.23	0.79	0.03	0.00	0.03	0.00	0.00	0.02	0.04	0.23	0.61	0.18	0.09	0.03	0.03
4P5-Pyx-a-2	0.91	0.08	0.13	-0.87	0.39	-0.02	0.05	0.05	0.03	0.86	0.03	0.16	0.76	440.43	11.94	0.00	0.24	0.79	0.03	0.00	0.02	0.00	0.00	0.02	0.04	0.23	0.62	0.19	0.08	0.03	0.03
4P5-Pyx-a-3	0.92	0.09	0.13	-0.87	0.38	-0.02	0.05	0.05	0.03	0.87	0.03	0.16	0.75	440.46	11.93	0.00	0.23	0.78	0.03	0.00	0.02	0.00	0.00	0.03	0.05	0.23	0.62	0.18	0.08	0.02	0.03
4P5-Pyx-a-4	0.92	0.08	0.13	-0.87	0.42	-0.02	0.05	0.05	0.02	0.87	0.02	0.21	0.71	441.68	12.01	0.00	0.28	0.73	0.02	0.00	0.05	0.00	0.00	0.00	0.02	0.28	0.58	0.22	0.07	0.03	0.02
4P5-Pyx-a-5	0.93	0.10	0.13	-0.87	0.41	-0.02	0.05	0.05	0.02	0.88	0.03	0.20	0.70	441.37	11.96	0.00	0.27	0.72	0.03	0.00	0.04	0.00	0.00	0.02	0.04	0.27	0.57	0.22	0.07	0.03	0.03
4P5-Pyx-b-1	0.91	0.08	0.13	-0.87	0.42	-0.02	0.06	0.06	0.03	0.86	0.03	0.18	0.74	440.58	11.95	0.00	0.26	0.77	0.03	0.00	0.01	0.00	0.00	0.03	0.04	0.25	0.60	0.20	0.08	0.03	0.03
4P5-Pyx-b-2	0.91	0.10	0.13	-0.87	0.40	-0.02	0.06	0.06	0.04	0.85	0.03	0.16	0.75	440.41	11.92	0.00	0.24	0.78	0.03	0.00	0.03	0.00	0.00	0.02	0.04	0.23	0.60	0.18	0.09	0.03	0.03
4P5-Pyx-b-3	0.92	0.10	0.13	-0.87	0.38	-0.02	0.05	0.05	0.03	0.86	0.03	0.16	0.75	440.50	11.92	0.00	0.23	0.78	0.03	0.00	0.03	0.00	0.00	0.02	0.04	0.23	0.61	0.18	0.08	0.02	0.03
4P5-Pyx-b-4	0.92	0.09	0.13	-0.87	0.38	-0.02	0.05	0.05	0.03	0.87	0.03	0.15	0.76	440.33	11.91	0.00	0.22	0.79	0.03	0.00	0.02	0.00	0.00	0.03	0.05	0.22	0.62	0.17	0.08	0.02	0.03
4P5-Pyx-b-5	0.92	0.12	0.13	-0.87	0.34	-0.01	0.04	0.04	0.04	0.88	0.03	0.12	0.76	440.76	11.89	0.00	0.18	0.80	0.03	0.00	0.06	0.00	0.00	0.01	0.04	0.18	0.63	0.14	0.08	0.02	0.03
8B1-Pyx-a-1	0.90	0.09	0.13	-0.87	0.39	-0.02	0.06	0.06	0.04	0.85	0.03	0.14	0.77	440.30	11.92	0.00	0.22	0.81	0.03	0.00	0.03	0.00	0.00	0.02	0.04	0.21	0.61	0.16	0.10	0.03	0.03
8B1-Pyx-a-2	0.89	0.09	0.13	-0.87	0.42	-0.02	0.07	0.07	0.05	0.84	0.02	0.15	0.76	440.58	11.94	0.00	0.24	0.81	0.02	0.00	0.04	0.00	0.00	0.01	0.03	0.23	0.59	0.18	0.10	0.03	0.02
8B1-Pyx-a-3	0.89	0.10	0.13	-0.87	0.43	-0.03	0.07	0.07	0.04	0.85	0.03	0.17	0.73	440.83	11.95	0.00	0.26	0.77	0.03	0.00	0.05	0.00	0.00	0.01	0.04	0.25	0.57	0.19	0.10	0.03	0.03
8B1-Pyx-a-4	0.88	0.08	0.13	-0.87	0.41	-0.02	0.07	0.07	0.05	0.84	0.03	0.14	0.79	440.31	11.93	0.00	0.22	0.84	0.03	0.00	0.03	0.00	0.00	0.01	0.03	0.21	0.61	0.16	0.11	0.03	0.03
8B1-Pyx-a-5	0.88	0.08	0.13	-0.87	0.44	-0.03	0.07	0.07	0.05	0.83	0.03	0.15	0.77	440.11	11.93	0.00	0.24	0.82	0.03	0.00	0.02	0.00	0.00	0.02	0.04	0.22	0.60	0.17	0.11	0.03	0.03
8B1-Pyx-b-1	0.89	0.09	0.13	-0.87	0.39	-0.02	0.06	0.06	0.05	0.84	0.03	0.13	0.79	440.23	11.92	0.00	0.21	0.84	0.03	0.00	0.04	0.00	0.00	0.01	0.03	0.20	0.61	0.15	0.11	0.03	0.03
8B1-Pyx-b-2	0.87	0.08	0.13	-0.87	0.42	-0.03	0.07	0.07	0.05	0.83	0.03	0.13	0.78	440.05	11.92	0.00	0.22	0.84	0.03	0.00	0.03	0.00	0.00	0.01	0.04	0.21	0.60	0.16	0.11	0.03	0.03
8B1-Pyx-b-3	0.88	0.08	0.13	-0.87	0.40	-0.02	0.06	0.06	0.05	0.84	0.03	0.13	0.79	440.47	11.93	0.00	0.21	0.84	0.03	0.00	0.04	0.00	0.00	0.00	0.03	0.20	0.62	0.15	0.11	0.03	0.03
8B1-Pyx-b-4	0.88	0.11	0.13	-0.87	0.44	-0.03	0.08	0.08	0.05	0.83	0.02	0.15	0.74	440.24	11.90	0.00	0.25	0.78	0.02	0.00	0.04	0.00	0.00	0.03	0.06	0.24	0.55	0.18	0.11	0.04	0.02
8B1-Pyx-b-5	0.87	0.08	0.13	-0.87	0.44	-0.03	0.08	0.08	0.05	0.82	0.03	0.15	0.78	440.06	11.93	0.00	0.24	0.83	0.03	0.00	0.02	0.00	0.00	0.01	0.04	0.23	0.59	0.17	0.12	0.03	0.03
4B1-Pyx-1-c	0.85	0.12	0.13	-0.87	0.44	-0.03	0.08	0.08	0.07	0.81	0.02	0.12	0.76	440.07	11.88	0.00	0.22	0.83	0.02	0.00	0.06	0.00	0.00	0.01	0.05	0.21	0.56	0.15	0.13	0.03	0.02
4B1-Pyx-1-c	0.88	0.12	0.13	-0.87	0.37	-0.02	0.06	0.06	0.06	0.84	0.03	0.10	0.78	440.50	11.88	0.00	0.16	0.84	0.03	0.00	0.08	0.00	0.00	0.00	0.03	0.16	0.61	0.12	0.11	0.02	0.03
4B1-Pyx-1-c	0.90	0.13	0.13	-0.87	0.39	-0.02	0.06	0.06	0.04	0.85	0.03	0.14	0.73	440.30	11.87	0.00	0.22	0.78	0.03	0.00	0.06	0.00	0.00	0.03	0.05	0.22	0.58	0.16	0.09	0.03	0.03
4B1-Pyx-1-c	0.87	0.10	0.13	-0.87	0.43	-0.03	0.07	0.07	0.05	0.84	0.03	0.14	0.76	440.10	11.90	0.00	0.23	0.81	0.03	0.00	0.03	0.00	0.00	0.02	0.05	0.22	0.58	0.17	0.11	0.03	0.03
4B1-Pyx-1-r	0.86	0.11	0.13	-0.87	0.43	-0.03	0.08	0.08	0.06	0.82	0.02	0.13	0.76	440.04	11.88	0.00	0.22	0.82	0.02	0.00	0.05	0.00	0.00	0.02	0.05	0.21	0.57	0.15	0.12	0.03	0.02
4B1-Pyx-1-r	0.86	0.10	0.13	-0.87	0.45	-0.03	0.08	0.08	0.06	0.82	0.02	0.13	0.77	439.86	11.89	0.00	0.23	0.83	0.02	0.00	0.03	0.00	0.00	0.02	0.05	0.22	0.58	0.16	0.12	0.03	0.02
4B1-Pyx-1-r	0.86	0.11	0.13	-0.87	0.44	-0.03	0.08	0.08	0.06	0.82	0.03	0.13	0.76	439.64	11.86	0.00	0.22	0.83	0.03	0.00	0.03	0.00	0.00	0.03	0.07	0.21	0.57	0.15	0.12	0.03	0.03
4B1-Pyx-1-r	0.86	0.11	0.13	-0.87	0.43	-0.03	0.08	0.08	0.06	0.82	0.02	0.12	0.76	440.24	11.89	0.00	0.21	0.82	0.02	0.00	0.06	0.00	0.00	0.01	0.05	0.21	0.57	0.15	0.12	0.03	0.02
4B1-Pyx-1-r	0.87	0.11	0.13	-0.87	0.43	-0.03	0.08	0.08	0.06	0.83	0.02	0.14	0.75	439.98	11.87	0.00	0.23	0.81	0.02	0.00	0.04	0.00	0.00	0.03	0.06	0.22	0.57	0.16	0.11	0.03	0.02

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4B1-Pyx-a-1	0.85	0.12	0.13	-0.87	0.44	-0.03	0.08	0.08	0.07	0.81	0.03	0.12	0.76	439 69	11.86	0.00	0.22	0.82	0.03	0.00	0.05	0.00	0.00	0.03	0.06	0.21	0.56	0.15	0.13	0.03	0.03
4B1-Pyx-a-2	0.84	0.13	0.13	-0.87	0.44	-0.03	0.08	0.08	0.08	0.80	0.02	0.11	0.77	440 15	11.88	0.00	0.20	0.85	0.02	0.00	0.08	0.00	0.00	0.00	0.04	0.19	0.55	0.13	0.14	0.03	0.02
4B1-Pyx-a-3	0.88	0.14	0.13	-0.87	0.38	-0.02	0.06	0.06	0.06	0.84	0.03	0.11	0.75	440 15	11.84	0.00	0.19	0.80	0.03	0.00	0.08	0.00	0.00	0.03	0.05	0.19	0.58	0.14	0.11	0.03	0.03
4B1-Pyx-a-4	0.87	0.13	0.13	-0.87	0.41	-0.03	0.07	0.07	0.06	0.83	0.02	0.12	0.75	439 95	11.84	0.00	0.20	0.81	0.02	0.00	0.06	0.00	0.00	0.03	0.06	0.20	0.57	0.14	0.11	0.03	0.02
4B1-Pyx-a-5	0.92	0.16	0.13	-0.87	0.31	-0.01	0.04	0.04	0.04	0.89	0.02	0.09	0.75	440 49	11.79	0.00	0.13	0.79	0.02	0.00	0.10	0.00	0.00	0.03	0.06	0.14	0.63	0.11	0.08	0.01	0.02
4B1-Pyx-a-6	0.90	0.15	0.13	-0.87	0.37	-0.02	0.06	0.06	0.05	0.86	0.03	0.12	0.73	439 93	11.80	0.00	0.19	0.77	0.03	0.00	0.06	0.00	0.00	0.05	0.08	0.20	0.58	0.14	0.09	0.02	0.03
4B1-Pyx-a-7	0.88	0.13	0.13	-0.87	0.41	-0.02	0.07	0.07	0.05	0.84	0.03	0.14	0.73	439 94	11.85	0.00	0.22	0.78	0.03	0.00	0.05	0.00	0.00	0.04	0.06	0.22	0.57	0.16	0.10	0.03	0.03
4B1-Pyx-a-8	0.86	0.13	0.13	-0.87	0.43	-0.03	0.08	0.08	0.06	0.81	0.03	0.12	0.75	439 82	11.85	0.00	0.21	0.81	0.03	0.00	0.06	0.00	0.00	0.03	0.06	0.21	0.55	0.15	0.12	0.03	0.03
4B1-Pyx-a-9	0.90	0.15	0.13	-0.87	0.38	-0.02	0.06	0.06	0.04	0.86	0.03	0.13	0.72	440 04	11.81	0.00	0.20	0.76	0.03	0.00	0.06	0.00	0.00	0.05	0.08	0.21	0.57	0.15	0.09	0.02	0.03
4B1-Pyx-a-10	0.88	0.13	0.13	-0.87	0.40	-0.02	0.07	0.07	0.05	0.84	0.03	0.13	0.74	440 15	11.86	0.00	0.21	0.80	0.03	0.00	0.06	0.00	0.00	0.03	0.05	0.21	0.57	0.15	0.11	0.03	0.03
4B1-Pyx-a-11	0.85	0.11	0.13	-0.87	0.47	-0.04	0.09	0.09	0.06	0.81	0.03	0.15	0.75	439 56	11.87	0.00	0.25	0.80	0.03	0.00	0.03	0.00	0.00	0.04	0.07	0.24	0.55	0.17	0.12	0.04	0.03
4B1-Pyx-a-12	0.83	0.10	0.13	-0.87	0.49	-0.04	0.10	0.10	0.07	0.80	0.02	0.14	0.76	439 30	11.87	0.00	0.25	0.83	0.02	0.00	0.02	0.00	0.00	0.04	0.07	0.23	0.55	0.16	0.14	0.04	0.02
4B1-Pyx-a-13	0.87	0.11	0.13	-0.87	0.42	-0.03	0.07	0.07	0.06	0.83	0.03	0.13	0.77	440 18	11.89	0.00	0.21	0.82	0.03	0.00	0.05	0.00	0.00	0.02	0.04	0.20	0.59	0.15	0.11	0.03	0.03
4B1-Pyx-a-14	0.86	0.12	0.13	-0.87	0.42	-0.03	0.07	0.07	0.06	0.82	0.03	0.11	0.77	440 24	11.89	0.00	0.20	0.83	0.03	0.00	0.07	0.00	0.00	0.01	0.03	0.19	0.58	0.14	0.12	0.03	0.03
4B1-Pyx-a-15	0.85	0.09	0.13	-0.87	0.48	-0.04	0.09	0.09	0.06	0.81	0.03	0.15	0.76	439 10	11.87	0.00	0.25	0.82	0.03	0.00	0.00	0.00	0.00	0.05	0.08	0.24	0.56	0.17	0.12	0.04	0.03
4B1-Pyx-a-16	0.86	0.10	0.13	-0.87	0.43	-0.03	0.08	0.08	0.06	0.82	0.03	0.12	0.77	439 89	11.89	0.00	0.21	0.84	0.03	0.00	0.04	0.00	0.00	0.02	0.04	0.20	0.58	0.15	0.12	0.03	0.03
4B1-Pyx-a-17	0.87	0.10	0.13	-0.87	0.42	-0.03	0.07	0.07	0.06	0.83	0.03	0.13	0.77	439 85	11.88	0.00	0.21	0.82	0.03	0.00	0.03	0.00	0.00	0.03	0.05	0.21	0.59	0.15	0.11	0.03	0.03
4B1-Pyx-a-18	0.87	0.12	0.13	-0.87	0.43	-0.03	0.08	0.08	0.06	0.82	0.03	0.13	0.75	440 02	11.87	0.00	0.22	0.81	0.03	0.00	0.06	0.00	0.00	0.02	0.05	0.21	0.56	0.15	0.12	0.03	0.03
4B1-Pyx-a-19	0.84	0.10	0.13	-0.87	0.47	-0.04	0.09	0.09	0.07	0.80	0.03	0.13	0.77	439 43	11.87	0.00	0.24	0.84	0.03	0.00	0.04	0.00	0.00	0.03	0.06	0.22	0.55	0.15	0.14	0.04	0.03
4B1-Pyx-a-20	0.88	0.15	0.13	-0.87	0.38	-0.02	0.06	0.06	0.05	0.84	0.03	0.11	0.74	440 22	11.83	0.00	0.19	0.79	0.03	0.00	0.08	0.00	0.00	0.03	0.06	0.19	0.57	0.14	0.10	0.02	0.03
4B1-Pyx-a-21	0.91	0.20	0.13	-0.87	0.36	-0.02	0.05	0.05	0.04	0.87	0.03	0.12	0.68	440 38	11.76	0.00	0.19	0.72	0.03	0.00	0.10	0.00	0.00	0.05	0.10	0.21	0.54	0.14	0.08	0.02	0.03
4B1-Pyx-a-22	0.90	0.18	0.13	-0.87	0.37	-0.02	0.06	0.06	0.04	0.87	0.03	0.13	0.69	440 21	11.78	0.00	0.20	0.73	0.03	0.00	0.08	0.00	0.00	0.05	0.09	0.21	0.55	0.15	0.08	0.02	0.03
4B1-Pyx-a-23	0.88	0.15	0.13	-0.87	0.38	-0.02	0.06	0.06	0.06	0.84	0.03	0.11	0.74	440 35	11.84	0.00	0.19	0.80	0.03	0.00	0.08	0.00	0.00	0.02	0.05	0.19	0.57	0.13	0.11	0.03	0.03
4B1-Pyx-a-24	0.83	0.11	0.13	-0.87	0.49	-0.04	0.10	0.10	0.07	0.80	0.02	0.14	0.75	439 76	11.88	0.00	0.24	0.82	0.02	0.00	0.05	0.00	0.00	0.02	0.06	0.23	0.54	0.16	0.14	0.04	0.02
4B1-Pyx-a-25	0.85	0.19	0.13	-0.87	0.43	-0.03	0.08	0.08	0.07	0.81	0.03	0.11	0.70	440 87	11.83	0.00	0.21	0.77	0.03	0.00	0.14	0.00	0.00	0.00	0.05	0.21	0.49	0.13	0.13	0.04	0.03
4B1-Pyx-a-26	0.90	0.20	0.13	-0.87	0.35	-0.02	0.06	0.06	0.04	0.87	0.02	0.12	0.68	440 58	11.77	0.00	0.19	0.72	0.02	0.00	0.11	0.00	0.00	0.04	0.09	0.20	0.53	0.14	0.09	0.02	0.02
4B1-Pyx-a-27	0.91	0.14	0.13	-0.87	0.36	-0.02	0.05	0.05	0.04	0.88	0.02	0.14	0.73	440 44	11.85	0.00	0.20	0.76	0.02	0.00	0.06	0.00	0.00	0.04	0.06	0.21	0.60	0.16	0.08	0.02	0.02
4B1-Pyx-a-28	0.88	0.14	0.13	-0.87	0.40	-0.02	0.07	0.07	0.05	0.84	0.03	0.13	0.73	440 23	11.84	0.00	0.20	0.78	0.03	0.00	0.07	0.00	0.00	0.03	0.05	0.20	0.57	0.15	0.10	0.03	0.03
4B1-Pyx-a-29	0.90	0.14	0.13	-0.87	0.40	-0.02	0.06	0.06	0.04	0.85	0.04	0.14	0.72	440 02	11.84	0.00	0.22	0.76	0.04	0.00	0.05	0.00	0.00	0.04	0.07	0.22	0.57	0.16	0.09	0.03	0.04
4B1-Pyx-a-30	0.90	0.16	0.13	-0.87	0.36	-0.02	0.05	0.05	0.04	0.86	0.03	0.12	0.72	440 33	11.83	0.00	0.19	0.76	0.03	0.00	0.08	0.00	0.00	0.03	0.06	0.20	0.58	0.14	0.09	0.02	0.03
4B1-Pyx-a-31	0.90	0.15	0.13	-0.87	0.38	-0.02	0.06	0.06	0.04	0.86	0.03	0.13	0.72	440 29	11.83	0.00	0.20	0.76	0.03	0.00	0.07	0.00	0.00	0.04	0.06	0.21	0.57	0.15	0.09	0.02	0.03
4B1-Pyx-a-32	0.87	0.11	0.13	-0.87	0.43	-0.03	0.08	0.08	0.05	0.84	0.03	0.14	0.75	439 95	11.88	0.00	0.23	0.80	0.03	0.00	0.04	0.00	0.00	0.04	0.06	0.22	0.58	0.17	0.11	0.03	0.03
4B1-Pyx-a-33	0.90	0.13	0.13	-0.87	0.39	-0.02	0.06	0.06	0.04	0.86	0.03	0.15	0.72	440 07	11.84	0.00	0.22	0.75	0.03	0.00	0.04	0.00	0.00	0.05	0.08	0.23	0.58	0.17	0.08	0.02	0.03
4B1-Pyx-a-34	0.86	0.09	0.13	-0.87	0.44	-0.03	0.08	0.08	0.06	0.82	0.03	0.14	0.77	439 87	11.91	0.00	0.23	0.83	0.03	0.00	0.03	0.00	0.00	0.02	0.04	0.22	0.58	0.16	0.12	0.03	0.03
4B1-Pyx-a-35	0.85	0.10	0.13	-0.87	0.45	-0.03	0.08	0.08	0.07	0.81	0.02	0.12	0.78	440 04	11.91	0.00	0.22	0.85	0.02	0.00	0.05	0.00	0.00	0.01	0.03	0.20	0.58	0.15	0.13	0.03	0.02
4B1-Pyx-a-36	0.88	0.11	0.13	-0.87	0.42	-0.03	0.07	0.07	0.05	0.85	0.02	0.14	0.75	439 84	11.87	0.00	0.22	0.80	0.02	0.00	0.03	0.00	0.00	0.04	0.06	0.22	0.59	0.16	0.10	0.03	0.02
4B1-Pyx-a-37	0.90	0.10	0.13	-0.87	0.41	-0.02	0.06	0.06	0.04	0.86	0.02	0.15	0.74	440 06	11.88	0.00	0.23	0.78	0.02	0.00	0.03	0.00	0.00	0.04	0.07	0.23	0.59	0.18	0.09	0.03	0.02
4B1-Pyx-a-38	0.89	0.15	0.13	-0.87	0.39	-0.02	0.06	0.06	0.04	0.85	0.04	0.14	0.71	440 25	11.84	0.00	0.21	0.75	0.04	0.00	0.07	0.00	0.00	0.04	0.06	0.22	0.56	0.16	0.09	0.03	0.04
4B1-Pyx-a-39	0.87	0.11	0.13	-0.87	0.46	-0.03	0.08	0.08	0.05	0.83	0.04	0.17	0.72	439 48	11.85	0.00	0.26	0.76	0.04	0.00	0.01	0.00	0.00	0.06	0.08	0.25	0.55	0.19	0.10	0.03	0.03
4B1-Pyx-a-40	0.87	0.13	0.13	-0.87	0.42	-0.03	0.08	0.08	0.06	0.83	0.03	0.13	0.74	439 89	11.85	0.00	0.22	0.79	0.03	0.00	0.06	0.00	0.00	0.03	0.06	0.21	0.56	0.15	0.11	0.03	0.03
4B1-Pyx-a-41	0.90	0.11	0.13	-0.87	0.33	-0.01	0.05	0.05	0.06	0.88	0.01	0.09	0.80	440 34	11.86	0.00	0.14	0.86	0.01	0.00	0.07	0.00	0.00	0.02	0.04	0.14	0.67	0.10	0.09	0.01	0.01
4B1-Pyx-a-42	0.90	0.11</																													

APPENDIX C

Sample	V1	V2	V3	V4	ZZZ= Zc	dT	DM10 =d	XBB= K	XT= alpha	DVT	dP	VcCor	DVP	VM1Cor	Temp (°C)	P (MPa)	Approx. Depth
8P1-Pyx-a-1	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1731.03	0.00	0.47	3205.29	454.63	-0.02	12.40	1000	320.53	11.88
8P1-Pyx-a-2	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1786.95	0.00	0.46	3845.88	454.26	-0.03	12.32	1000	384.59	14.21
8P1-Pyx-a-3	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1745.70	0.00	0.47	2263.94	455.24	-0.02	12.40	1000	226.39	8.45
8P1-Pyx-c-1	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1776.88	0.00	0.46	3862.62	454.12	-0.03	12.33	1000	386.26	14.27
8P1-Pyx-c-2	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1783.64	0.00	0.46	4658.41	453.51	-0.03	12.32	1000	465.84	17.17
8P1-Pyx-c-3	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1784.77	0.00	0.46	4121.31	453.92	-0.03	12.32	1000	412.13	15.21
8P1-Pyx-r-1	0.00	0.00	0.00	0.00	2.22	975.00	2.08	1855.77	0.00	0.44	530.21	457.36	0.00	12.32	1000	53.02	2.08
8P4-Pyx-c-1	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1759.48	0.00	0.46	3827.43	453.70	-0.03	12.29	1000	382.74	14.14
8P4-Pyx-c-2	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1761.26	0.00	0.46	4121.61	453.49	-0.03	12.28	1000	412.16	15.21
8P4-Pyx-c-3	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1756.27	0.00	0.47	4668.62	453.15	-0.03	12.28	1000	466.86	17.20
8P4-Pyx-r-1	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1764.42	0.00	0.46	2842.50	455.01	-0.02	12.36	1000	284.25	10.56
8P4-Pyx-r-2	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1762.67	0.00	0.46	2225.00	455.29	-0.02	12.37	1000	222.50	8.31
8P4-Pyx-r-3	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1782.93	0.00	0.46	1807.78	455.79	-0.01	12.36	1000	180.78	6.79
8P5-Pyx-a-1	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1759.93	0.00	0.46	7223.84	451.72	-0.05	12.30	1000	722.38	26.51
8P5-Pyx-a-2	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1759.80	0.00	0.46	5775.48	452.75	-0.04	12.33	1000	577.55	21.23
8P5-Pyx-a-3	0.00	0.00	0.00	0.00	2.07	975.00	2.08	1720.02	0.00	0.47	4611.89	453.52	-0.03	12.40	1000	461.19	17.00
8P8-Pyx-a-1	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1745.82	0.00	0.47	2980.21	455.03	-0.02	12.41	1000	298.02	11.06
8P8-Pyx-a-2	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1741.70	0.00	0.47	3194.48	454.85	-0.02	12.41	1000	319.45	11.84
8P8-Pyx-a-3	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1746.73	0.00	0.47	3732.22	454.47	-0.03	12.40	1000	373.22	13.79
8P10-Pyx-a-1	0.00	0.00	0.00	0.00	2.28	975.00	2.07	1929.50	0.00	0.42	5620.59	453.37	-0.03	12.09	1000	562.06	20.67
8P10-Pyx-a-2	0.00	0.00	0.00	0.00	2.28	975.00	2.07	1935.00	0.00	0.42	5870.65	453.10	-0.04	12.07	1000	587.07	21.58
8P10-Pyx-a-3	0.00	0.00	0.00	0.00	2.27	975.00	2.07	1921.26	0.00	0.43	5848.98	452.98	-0.04	12.08	1000	584.90	21.50
8P10-Pyx-a-4	0.00	0.00	0.00	0.00	2.24	975.00	2.07	1895.07	0.00	0.43	7195.09	452.17	-0.04	12.09	1000	719.51	26.40
8P10-Pyx-a-5	0.00	0.00	0.00	0.00	2.28	975.00	2.07	1938.79	0.00	0.42	6226.94	452.96	-0.04	12.06	1000	622.69	22.88
8P11-Pyx-b-1	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1751.58	0.00	0.47	4418.48	453.80	-0.03	12.35	1000	441.85	16.29
8P11-Pyx-b-2	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1763.39	0.00	0.46	4741.50	453.51	-0.03	12.33	1000	474.15	17.47
8P11-Pyx-b-3	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1781.72	0.00	0.46	4297.63	453.90	-0.03	12.32	1000	429.76	15.85
8P11-Pyx-b-4	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1736.49	0.00	0.47	4448.57	453.65	-0.03	12.38	1000	444.86	16.40
8P12-Pyx-a-1	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1757.40	0.00	0.47	6130.50	452.44	-0.04	12.32	1000	613.05	22.53
8P12-Pyx-a-2	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1778.98	0.00	0.46	5643.58	452.87	-0.04	12.30	1000	564.36	20.75
8P12-Pyx-a-3	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1771.06	0.00	0.46	5939.77	452.65	-0.04	12.30	1000	593.98	21.83
8P12-Pyx-a-4	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1773.52	0.00	0.46	5580.38	452.92	-0.04	12.30	1000	558.04	20.52
8P12-Pyx-a-5	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1736.56	0.00	0.47	3002.36	454.78	-0.02	12.41	1000	300.24	11.14

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4P2-Pyx-c-1	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1781.25	0.00	0.46	1342.28	457.05	-0.01	12.44	1000	134.23	5.09
4P2-Pyx-c-2	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1758.75	0.00	0.47	3953.54	454.24	-0.03	12.37	1000	395.35	14.60
4P2-Pyx-c-3	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1771.41	0.00	0.46	3734.71	454.33	-0.03	12.34	1000	373.47	13.80
4P2-Pyx-c-4	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1754.14	0.00	0.47	4044.91	454.16	-0.03	12.36	1000	404.49	14.93
4P2-Pyx-c-5	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1732.48	0.00	0.47	3761.99	454.19	-0.03	12.40	1000	376.20	13.90
4P2-Pyx-c-6	0.00	0.00	0.00	0.00	2.08	975.00	2.08	1723.92	0.00	0.47	5695.38	452.72	-0.04	12.38	1000	569.54	20.94
4P2-Pyx-a-1	0.00	0.00	0.00	0.00	2.08	975.00	2.08	1719.17	0.00	0.48	1981.81	455.50	-0.01	12.44	1000	198.18	7.42
4P2-Pyx-a-2	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1738.08	0.00	0.47	2385.32	455.18	-0.02	12.41	1000	238.53	8.89
4P2-Pyx-a-3	0.00	0.00	0.00	0.00	2.16	975.00	2.08	1801.00	0.00	0.45	3661.40	454.54	-0.02	12.31	1000	366.14	13.54
4P2-Pyx-a-4	0.00	0.00	0.00	0.00	2.16	975.00	2.08	1799.92	0.00	0.46	3067.56	454.95	-0.02	12.32	1000	306.76	11.37
4P2-Pyx-a-5	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1763.60	0.00	0.46	4014.64	454.13	-0.03	12.35	1000	401.46	14.82
4P5-Pyx-a-1	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1744.15	0.00	0.47	4324.86	453.85	-0.03	12.36	1000	432.49	15.95
4P5-Pyx-a-2	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1732.07	0.00	0.47	3863.29	454.17	-0.03	12.39	1000	386.33	14.27
4P5-Pyx-a-3	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1744.78	0.00	0.47	4027.03	454.09	-0.03	12.37	1000	402.70	14.87
4P5-Pyx-a-4	0.00	0.00	0.00	0.00	2.09	975.00	2.09	1728.18	0.00	0.47	642.99	456.76	0.00	12.48	1000	64.30	2.52
4P5-Pyx-a-5	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1754.80	0.00	0.47	2132.27	455.76	-0.01	12.41	1000	213.23	7.97
4P5-Pyx-b-1	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1733.58	0.00	0.47	3716.22	454.39	-0.03	12.40	1000	371.62	13.74
4P5-Pyx-b-2	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1752.58	0.00	0.47	4381.06	453.86	-0.03	12.36	1000	438.11	16.16
4P5-Pyx-b-3	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1751.69	0.00	0.47	4021.25	454.09	-0.03	12.36	1000	402.13	14.85
4P5-Pyx-b-4	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1751.31	0.00	0.47	4405.43	453.78	-0.03	12.35	1000	440.54	16.25
4P5-Pyx-b-5	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1776.62	0.00	0.46	3360.45	454.49	-0.02	12.33	1000	336.05	12.44
8B1-Pyx-a-1	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1751.06	0.00	0.47	4418.92	453.70	-0.03	12.35	1000	441.89	16.29
8B1-Pyx-a-2	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1745.00	0.00	0.47	3733.58	454.28	-0.03	12.38	1000	373.36	13.80
8B1-Pyx-a-3	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1752.47	0.00	0.47	3434.00	454.64	-0.02	12.39	1000	343.40	12.71
8B1-Pyx-a-4	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1738.12	0.00	0.47	4113.00	453.86	-0.03	12.38	1000	411.30	15.18
8B1-Pyx-a-5	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1735.96	0.00	0.47	4817.07	453.40	-0.03	12.37	1000	481.71	17.74
8B1-Pyx-b-1	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1747.71	0.00	0.47	4457.89	453.60	-0.03	12.36	1000	445.79	16.44
8B1-Pyx-b-2	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1744.13	0.00	0.47	4992.63	453.22	-0.03	12.36	1000	499.26	18.38
8B1-Pyx-b-3	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1742.56	0.00	0.47	3661.20	454.17	-0.03	12.38	1000	366.12	13.54
8B1-Pyx-b-4	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1770.20	0.00	0.46	5452.96	453.17	-0.04	12.32	1000	545.30	20.06
8B1-Pyx-b-5	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1739.09	0.00	0.47	5028.15	453.25	-0.03	12.37	1000	502.82	18.51
4B1-Pyx-1-c	0.00	0.00	0.00	0.00	2.13	#####	2.08	1782.34	0.00	0.48	3304.51	454.65	-0.02	12.34	1050	330.45	12.24
4B1-Pyx-1-c	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1785.13	0.00	0.46	4127.23	453.82	-0.03	12.31	1000	412.72	15.23
4B1-Pyx-1-c	0.00	0.00	0.00	0.00	2.14	#####	2.08	1783.93	0.00	0.48	2789.19	455.16	-0.02	12.34	1050	278.92	10.36
4B1-Pyx-1-c	0.00	0.00	0.00	0.00	2.11	825.00	2.08	1760.39	0.00	0.39	#####	447.66	-0.08	12.21	850	1255.57	43.31
4B1-Pyx-1-r	0.00	0.00	0.00	0.00	2.13	875.00	2.08	1776.68	0.00	0.41	#####	449.17	-0.07	12.22	900	1054.46	37.10
4B1-Pyx-1-r	0.00	0.00	0.00	0.00	2.11	825.00	2.08	1760.69	0.00	0.39	#####	447.19	-0.09	12.20	850	1313.68	45.10
4B1-Pyx-1-r	0.00	0.00	0.00	0.00	2.12	925.00	2.08	1777.12	0.00	0.44	9296.11	450.14	-0.06	12.23	950	929.61	33.24
4B1-Pyx-1-r	0.00	0.00	0.00	0.00	2.13	#####	2.08	1778.29	0.00	0.51	176.07	457.00	0.00	12.39	1100	17.61	0.69
4B1-Pyx-1-r	0.00	0.00	0.00	0.00	2.13	#####	2.08	1777.51	0.00	0.53	0.00	457.82	0.01	12.41	1150	0.00	0.00

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4B1-Pyx-a-1	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1784.66	0.00	0.46	6951.11	451.95	-0.05	12.27	1000	695.11	25.51
4B1-Pyx-a-2	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1792.11	0.00	0.46	5612.45	452.84	-0.04	12.30	1000	561.24	20.64
4B1-Pyx-a-3	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1804.48	0.00	0.45	5886.14	452.76	-0.04	12.26	1000	588.61	21.64
4B1-Pyx-a-4	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1795.89	0.00	0.46	6357.46	452.40	-0.04	12.26	1000	635.75	23.35
4B1-Pyx-a-5	0.00	0.00	0.00	0.00	2.18	975.00	2.07	1833.37	0.00	0.45	5004.44	453.36	-0.03	12.21	1000	500.44	18.43
4B1-Pyx-a-6	0.00	0.00	0.00	0.00	2.17	975.00	2.07	1820.71	0.00	0.45	6919.48	452.12	-0.04	12.21	1000	691.95	25.40
4B1-Pyx-a-7	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1792.86	0.00	0.46	6483.79	452.40	-0.04	12.26	1000	648.38	23.81
4B1-Pyx-a-8	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1799.69	0.00	0.46	6897.90	452.04	-0.05	12.26	1000	689.79	25.32
4B1-Pyx-a-9	0.00	0.00	0.00	0.00	2.17	975.00	2.07	1822.75	0.00	0.45	6741.12	452.31	-0.04	12.21	1000	674.11	24.75
4B1-Pyx-a-10	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1792.61	0.00	0.46	5766.55	452.86	-0.04	12.28	1000	576.66	21.20
4B1-Pyx-a-11	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1769.39	0.00	0.46	7301.36	451.77	-0.05	12.29	1000	730.14	26.79
4B1-Pyx-a-12	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1764.44	0.00	0.46	7832.53	451.30	-0.05	12.28	1000	783.25	28.72
4B1-Pyx-a-13	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1766.98	0.00	0.46	5082.15	453.23	-0.03	12.32	1000	508.22	18.71
4B1-Pyx-a-14	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1775.23	0.00	0.46	4985.50	453.27	-0.03	12.32	1000	498.55	18.36
4B1-Pyx-a-15	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1758.77	0.00	0.46	8349.11	450.95	-0.06	12.28	1000	834.91	30.31
4B1-Pyx-a-16	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1766.45	0.00	0.46	5901.38	452.61	-0.04	12.31	1000	590.14	21.69
4B1-Pyx-a-17	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1765.98	0.00	0.46	6005.46	452.56	-0.04	12.30	1000	600.55	22.07
4B1-Pyx-a-18	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1785.99	0.00	0.46	6079.00	452.62	-0.04	12.29	1000	607.90	22.34
4B1-Pyx-a-19	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1769.70	0.00	0.46	7442.78	451.54	-0.05	12.29	1000	744.28	27.30
4B1-Pyx-a-20	0.00	0.00	0.00	0.00	2.16	975.00	2.08	1815.07	0.00	0.45	5918.13	452.79	-0.04	12.24	1000	591.81	21.75
4B1-Pyx-a-21	0.00	0.00	0.00	0.00	2.22	975.00	2.07	1872.68	0.00	0.44	6874.19	452.42	-0.04	12.15	1000	687.42	25.23
4B1-Pyx-a-22	0.00	0.00	0.00	0.00	2.20	975.00	2.07	1847.79	0.00	0.44	6904.67	452.33	-0.04	12.18	1000	690.47	25.34
4B1-Pyx-a-23	0.00	0.00	0.00	0.00	2.16	975.00	2.08	1809.79	0.00	0.45	5418.18	453.12	-0.04	12.26	1000	541.82	19.93
4B1-Pyx-a-24	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1774.32	0.00	0.46	6745.58	452.12	-0.05	12.30	1000	674.56	24.76
4B1-Pyx-a-25	0.00	0.00	0.00	0.00	2.21	975.00	2.08	1856.74	0.00	0.44	5243.94	453.48	-0.03	12.24	1000	524.39	19.30
4B1-Pyx-a-26	0.00	0.00	0.00	0.00	2.22	975.00	2.07	1873.76	0.00	0.44	6338.00	452.81	-0.04	12.16	1000	633.80	23.28
4B1-Pyx-a-27	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1799.83	0.00	0.46	5104.98	453.44	-0.03	12.27	1000	510.50	18.79
4B1-Pyx-a-28	0.00	0.00	0.00	0.00	2.16	975.00	2.08	1804.73	0.00	0.45	5775.72	452.90	-0.04	12.26	1000	577.57	21.23
4B1-Pyx-a-29	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1802.52	0.00	0.45	6510.00	452.45	-0.04	12.25	1000	651.00	23.91
4B1-Pyx-a-30	0.00	0.00	0.00	0.00	2.17	975.00	2.08	1817.11	0.00	0.45	5695.72	453.00	-0.04	12.24	1000	569.57	20.94
4B1-Pyx-a-31	0.00	0.00	0.00	0.00	2.16	975.00	2.08	1812.91	0.00	0.45	5868.78	452.92	-0.04	12.25	1000	586.88	21.57
4B1-Pyx-a-32	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1769.87	0.00	0.46	6055.46	452.65	-0.04	12.30	1000	605.55	22.25
4B1-Pyx-a-33	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1799.81	0.00	0.46	6372.75	452.58	-0.04	12.25	1000	637.27	23.41
4B1-Pyx-a-34	0.00	0.00	0.00	0.00	2.10	975.00	2.08	1751.17	0.00	0.47	5774.01	452.72	-0.04	12.33	1000	577.40	21.23
4B1-Pyx-a-35	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1758.15	0.00	0.47	5321.74	453.00	-0.04	12.34	1000	532.17	19.58
4B1-Pyx-a-36	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1771.26	0.00	0.46	6324.52	452.45	-0.04	12.29	1000	632.45	23.23
4B1-Pyx-a-37	0.00	0.00	0.00	0.00	2.11	975.00	2.08	1765.34	0.00	0.46	5691.18	452.95	-0.04	12.31	1000	569.12	20.93
4B1-Pyx-a-38	0.00	0.00	0.00	0.00	2.17	975.00	2.08	1814.93	0.00	0.45	6134.92	452.76	-0.04	12.25	1000	613.49	22.54
4B1-Pyx-a-39	0.00	0.00	0.00	0.00	2.13	975.00	2.08	1778.32	0.00	0.46	7892.21	451.47	-0.05	12.26	1000	789.22	28.90
4B1-Pyx-a-40	0.00	0.00	0.00	0.00	2.14	975.00	2.08	1795.49	0.00	0.46	6659.75	452.25	-0.04	12.26	1000	665.97	24.45
4B1-Pyx-a-41	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1776.66	0.00	0.46	4101.63	453.73	-0.03	12.29	1000	410.16	15.14
4B1-Pyx-a-42	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1774.58	0.00	0.46	4756.19	453.30	-0.03	12.28	1000	475.62	17.52
4B1-Pyx-a-43	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1778.40	0.00	0.46	4923.08	453.21	-0.03	12.28	1000	492.31	18.13
4B1-Pyx-a-44	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1799.87	0.00	0.46	5163.81	453.27	-0.03	12.26	1000	516.38	19.01
4B1-Pyx-a-45	0.00	0.00	0.00	0.00	2.15	975.00	2.08	1804.47	0.00	0.45	5573.93	453.01	-0.04	12.26	1000	557.39	20.50
4B1-Pyx-a-46	0.00	0.00	0.00	0.00	2.12	975.00	2.08	1770.64	0.00	0.46	5143.74	453.13	-0.03	12.31	1000	514.37	18.93
4B1-Pyx-a-47	0.00	0.00	0.00	0.00	2.09	975.00	2.08	1741.25	0.00	0.47	4547.97	453.50	-0.03	12.37	1000	454.80	16.76

APPENDIX D

Amphibole EMP data, mineral calculations, and geobarometry results using the equations of Johnson and Rutherford, 1989. Mineral calculations for amphibole are based on 23 oxygens with $\text{Fe}^{2+}/\text{Fe}^{3+}$ estimation assuming 13 cations. Amphibole chemistry is sensitive to pressure, temperature, oxygen and water fugacities (e.g., Spear, 1981; Wones & Gilbert, 1981; Helz, 1982). Johnson & Rutherford (1989) experimentally calibrated the Al in hornblende barometer for an assemblage of hornblende, biotite, quartz, sanidine, plagioclase, sphene, magnetite or ilmenite. Given the mineral assemblage present in Merapi lavas and the inherent complexity of amphibole chemistry and thus the uncertainty of mineral recalculations, the barometer of Johnson & Rutherford (1989) provides an upper limit for crystallisation pressures.

APPENDIX D

Sample										Reformatted oxide %											Total
	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O*	
8P4-A-1	39.67	2.10	14.81	12.41	0.14	12.69	12.22	2.47	0.88	39.67	2.10	14.81	4.65	8.22	0.14	12.69	12.22	2.47	0.88	2.03	99.88
8P4-A-2	39.57	2.16	14.92	12.83	0.14	12.69	12.37	2.61	0.92	39.57	2.16	14.92	4.64	8.65	0.14	12.69	12.37	2.61	0.92	2.04	100.70
8P4-A-3	41.20	2.17	14.85	11.77	0.16	12.16	11.71	2.84	1.04	41.20	2.17	14.85	1.27	10.62	0.16	12.16	11.71	2.84	1.04	2.04	100.06
8P4-B-1	40.57	2.42	13.60	12.74	0.20	12.78	12.04	2.60	0.87	40.57	2.42	13.60	4.08	9.06	0.20	12.78	12.04	2.60	0.87	2.04	100.25
8P4-B-2	40.52	2.39	13.83	12.96	0.24	13.01	11.80	2.66	0.90	40.52	2.39	13.83	5.95	7.60	0.24	13.01	11.80	2.66	0.90	2.05	100.95
8P4-B-3	40.95	2.39	13.21	12.85	0.18	13.17	11.89	2.71	0.83	40.95	2.39	13.21	5.07	8.28	0.18	13.17	11.89	2.71	0.83	2.05	100.72
8P4-C-1	41.19	1.72	13.93	9.59	0.07	14.99	12.33	2.04	1.79	41.19	1.72	13.93	4.48	5.56	0.07	14.99	12.33	2.04	1.79	2.06	100.16
8P4-C-2	41.28	1.65	14.00	9.05	0.14	14.76	12.25	2.04	1.61	41.28	1.65	14.00	3.54	5.87	0.14	14.76	12.25	2.04	1.61	2.05	99.19
8P4-C-3	40.17	2.36	14.26	12.76	0.20	13.01	12.14	2.60	0.88	40.17	2.36	14.26	5.34	7.96	0.20	13.01	12.14	2.60	0.88	2.05	100.96
8P12-A-1	41.81	2.86	11.76	12.07	0.34	14.14	11.41	2.57	0.87	41.81	2.86	11.76	6.65	6.08	0.34	14.14	11.41	2.57	0.87	2.06	100.55
8P12-A-2	42.01	2.87	11.81	12.15	0.28	14.19	11.42	2.55	0.87	42.01	2.87	11.81	6.78	6.04	0.28	14.19	11.42	2.55	0.87	2.07	100.89
8P12-A-3	41.97	2.90	11.52	12.02	0.33	14.30	11.51	2.52	0.87	41.97	2.90	11.52	6.58	6.10	0.33	14.30	11.51	2.52	0.87	2.06	100.65
8P12-A-4	41.95	2.94	11.40	12.01	0.40	14.06	11.35	2.73	0.90	41.95	2.94	11.40	5.70	6.87	0.40	14.06	11.35	2.73	0.90	2.05	100.36
8P12-A-5	41.85	2.60	11.82	12.00	0.37	14.37	11.45	2.62	0.84	41.85	2.60	11.82	7.26	5.47	0.37	14.37	11.45	2.62	0.84	2.06	100.70
8P12-B-1	40.96	3.62	11.73	18.19	0.37	15.50	9.57	1.12	0.15	40.96	3.62	11.73	20.21	0.00	0.37	15.50	9.57	1.12	0.15	2.16	105.38
8P12-B-2	41.00	2.93	12.61	18.84	0.49	13.25	9.06	1.21	0.27	41.00	2.93	12.61	20.94	0.00	0.49	13.25	9.06	1.21	0.27	2.13	103.88
8P12-B-3	43.14	2.56	13.52	10.10	0.39	16.81	10.43	1.44	0.38	43.14	2.56	13.52	11.23	0.00	0.39	16.81	10.43	1.44	0.38	2.15	102.03
8P12-B-4	42.22	3.29	13.57	16.03	0.45	12.91	10.09	1.66	0.31	42.22	3.29	13.57	17.82	0.00	0.45	12.91	10.09	1.66	0.31	2.16	104.47
8P12-B-5	42.79	2.93	11.74	15.08	0.26	13.10	12.70	1.40	0.12	42.79	2.93	11.74	8.46	7.47	0.26	13.10	12.70	1.40	0.12	2.10	103.06
4P2-A-1	40.15	1.76	14.65	13.11	0.20	13.06	12.10	2.18	1.14	40.15	1.76	14.65	7.44	6.41	0.20	13.06	12.10	2.18	1.14	2.06	101.14
4P2-A-2	40.02	1.73	14.66	12.59	0.23	12.90	11.89	2.20	1.05	40.02	1.73	14.66	6.92	6.36	0.23	12.90	11.89	2.20	1.05	2.04	100.00
4P2-A-3	39.92	1.73	14.46	12.52	0.15	13.05	11.99	2.16	1.16	39.92	1.73	14.46	6.64	6.54	0.15	13.05	11.99	2.16	1.16	2.04	99.83
4P2-A-4	40.07	1.65	14.50	12.79	0.11	13.02	12.12	2.18	1.07	40.07	1.65	14.50	6.66	6.79	0.11	13.02	12.12	2.18	1.07	2.04	100.21
4P2-A-5	39.93	1.71	14.58	13.26	0.21	12.75	12.18	2.16	1.16	39.93	1.71	14.58	6.69	7.24	0.21	12.75	12.18	2.16	1.16	2.05	100.65
4P2-B-1	39.51	1.66	14.65	13.10	0.30	13.14	11.78	2.29	1.16	39.51	1.66	14.65	8.89	5.10	0.30	13.14	11.78	2.29	1.16	2.05	100.52
4P2-B-2	39.70	1.46	14.69	12.55	0.21	13.03	11.90	2.31	1.06	39.70	1.46	14.69	7.24	6.03	0.21	13.03	11.90	2.31	1.06	2.03	99.65
4P2-B-3	39.81	1.89	14.12	12.44	0.19	13.34	11.94	2.24	1.03	39.81	1.89	14.12	7.34	5.83	0.19	13.34	11.94	2.24	1.03	2.04	99.77
4P2-B-4	39.82	1.49	14.81	12.35	0.10	13.36	12.23	2.13	1.14	39.82	1.49	14.81	7.10	5.96	0.10	13.36	12.23	2.13	1.14	2.05	100.18
4P2-B-5	40.30	1.55	14.65	12.48	0.14	13.18	11.90	2.21	1.13	40.30	1.55	14.65	7.16	6.04	0.14	13.18	11.90	2.21	1.13	2.05	100.32

APPENDIX D

Sample										Reformatted oxide %											Total
	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O*	
4P5-A-1	41.72	2.54	11.55	14.94	0.42	11.91	11.21	2.56	1.00	41.72	2.54	11.55	5.32	10.15	0.42	11.91	11.21	2.56	1.00	2.03	100.41
4P5-A-2	41.76	2.51	11.53	15.11	0.42	11.90	11.37	2.44	0.99	41.76	2.51	11.53	5.43	10.22	0.42	11.90	11.37	2.44	0.99	2.03	100.60
4P5-A-3	41.47	2.73	11.75	15.06	0.35	11.85	11.22	2.50	0.99	41.47	2.73	11.75	5.60	10.02	0.35	11.85	11.22	2.50	0.99	2.03	100.50
4P5-A-4	41.98	2.70	11.46	15.23	0.30	11.93	11.46	2.64	0.96	41.98	2.70	11.46	4.50	11.18	0.30	11.93	11.46	2.64	0.96	2.04	101.14
4P5-A-5	41.85	2.62	11.25	15.05	0.31	11.93	11.70	2.52	0.92	41.85	2.62	11.25	3.87	11.57	0.31	11.93	11.70	2.52	0.92	2.02	100.56
4P5-B-1	43.44	2.10	14.30	18.53	0.48	7.78	11.14	2.44	0.33	43.44	2.10	14.30	2.10	16.64	0.48	7.78	11.14	2.44	0.33	2.06	102.82
4P5-B-2	42.29	2.18	13.24	20.29	0.63	8.23	10.49	2.41	0.26	42.29	2.18	13.24	8.57	12.58	0.63	8.23	10.49	2.41	0.26	2.06	102.94
4P5-B-3	44.06	3.40	13.26	15.10	0.58	8.84	11.32	2.19	0.39	44.06	3.40	13.26	0.00	15.10	0.58	8.84	11.32	2.19	0.39	2.05	101.20
4P5-B-4	39.86	3.12	11.40	23.44	0.63	9.87	9.81	1.94	0.27	39.86	3.12	11.40	21.58	4.02	0.63	9.87	9.81	1.94	0.27	2.09	104.58
4P5-B-5	41.40	2.42	11.57	22.03	0.63	9.57	10.67	1.84	0.29	41.40	2.42	11.57	15.52	8.06	0.63	9.57	10.67	1.84	0.29	2.08	104.05
8B1-A-1	42.20	3.32	10.94	12.08	0.38	14.07	11.11	2.54	1.00	42.20	3.32	10.94	6.11	6.57	0.38	14.07	11.11	2.54	1.00	2.05	100.29
8B1-A-2	41.81	2.83	11.58	13.09	0.36	12.97	11.25	2.46	0.98	41.81	2.83	11.58	5.29	8.32	0.36	12.97	11.25	2.46	0.98	2.03	99.88
8B1-A-3	42.12	3.73	11.28	11.94	0.26	13.78	11.28	2.71	1.11	42.12	3.73	11.28	3.83	8.49	0.26	13.78	11.28	2.71	1.11	2.05	100.63
8B1-A-4	43.49	2.41	10.50	11.33	0.23	14.60	11.38	2.48	0.98	43.49	2.41	10.50	4.86	6.96	0.23	14.60	11.38	2.48	0.98	2.06	99.93
8B1-A-5	42.86	2.59	10.67	11.45	0.38	14.47	11.32	2.52	0.97	42.86	2.59	10.67	5.48	6.52	0.38	14.47	11.32	2.52	0.97	2.05	99.81
8B1-B-1	42.97	2.29	11.13	11.72	0.34	14.25	11.06	2.54	1.09	42.97	2.29	11.13	6.14	6.19	0.34	14.25	11.06	2.54	1.09	2.06	100.05
8B1-B-2	43.26	2.20	10.66	12.76	0.39	13.98	11.13	2.54	0.90	43.26	2.20	10.66	6.76	6.67	0.39	13.98	11.13	2.54	0.90	2.06	100.54
8B1-B-3	42.99	2.41	11.06	12.50	0.45	13.71	11.16	2.44	1.02	42.99	2.41	11.06	5.98	7.11	0.45	13.71	11.16	2.44	1.02	2.06	100.38
8B1-B-4	43.70	2.21	10.21	11.61	0.38	14.28	11.35	2.45	0.97	43.70	2.21	10.21	4.54	7.53	0.38	14.28	11.35	2.45	0.97	2.05	99.65
8B1-B-5	42.94	2.40	10.89	12.64	0.51	13.93	11.04	2.48	0.94	42.94	2.40	10.89	7.25	6.11	0.51	13.93	11.04	2.48	0.94	2.06	100.54
4B1-C-1	41.01	2.29	13.04	12.89	0.19	13.25	11.26	2.35	0.90	41.01	2.29	13.04	7.88	5.80	0.19	13.25	11.26	2.35	0.90	2.05	100.00
4B1-C-2	40.94	2.42	13.10	12.60	0.27	13.37	11.45	2.41	0.81	40.94	2.42	13.10	7.38	5.96	0.27	13.37	11.45	2.41	0.81	2.05	100.15
4B1-C-3	41.23	2.25	13.15	13.09	0.30	13.42	11.55	2.40	0.87	41.23	2.25	13.15	8.00	5.89	0.30	13.42	11.55	2.40	0.87	2.07	101.12
4B1-C-4	40.80	2.18	13.33	13.17	0.19	13.07	11.48	2.44	0.91	40.80	2.18	13.33	7.35	6.55	0.19	13.07	11.48	2.44	0.91	2.05	100.35
4B1-C-5	41.20	1.74	13.59	11.90	0.16	13.57	11.68	2.33	1.03	41.20	1.74	13.59	6.35	6.19	0.16	13.57	11.68	2.33	1.03	2.05	99.89
MC108-A-1	40.38	1.95	14.20	10.60	0.16	14.32	12.50	2.24	1.30	40.38	1.95	14.20	4.76	6.32	0.16	14.32	12.50	2.24	1.30	2.05	100.18
MC108-A-2	40.22	1.84	14.33	10.74	0.10	14.36	12.39	2.32	1.25	40.22	1.84	14.33	5.47	5.82	0.10	14.36	12.39	2.32	1.25	2.05	100.16
MC108-A-3	39.82	1.95	14.60	10.59	0.18	14.37	12.41	2.28	1.22	39.82	1.95	14.60	5.89	5.29	0.18	14.37	12.41	2.28	1.22	2.05	100.06
MC108-A-4	39.76	1.79	14.34	10.71	0.12	14.33	12.18	2.35	1.26	39.76	1.79	14.34	6.18	5.15	0.12	14.33	12.18	2.35	1.26	2.04	99.50
MC108-A-5	40.74	1.85	14.23	10.65	0.06	14.24	12.23	2.34	1.27	40.74	1.85	14.23	4.85	6.28	0.06	14.24	12.23	2.34	1.27	2.05	100.16
MC108-A-6	40.44	1.87	14.50	10.72	0.17	14.23	12.49	2.24	1.29	40.44	1.87	14.50	4.99	6.23	0.17	14.23	12.49	2.24	1.29	2.06	100.50
MC108-A-7	40.31	1.90	14.31	10.63	0.19	14.32	12.29	2.37	1.28	40.31	1.90	14.31	5.33	5.84	0.19	14.32	12.29	2.37	1.28	2.05	100.19
MC108-A-8	40.42	1.79	14.47	10.77	0.10	14.25	12.34	2.31	1.20	40.42	1.79	14.47	5.44	5.87	0.10	14.25	12.34	2.31	1.20	2.06	100.24
MC108-A-9	40.72	1.89	14.41	10.62	0.04	14.25	12.41	2.14	1.26	40.72	1.89	14.41	4.95	6.17	0.04	14.25	12.41	2.14	1.26	2.06	100.29

APPENDIX D Structural formulae on the basis of 23 ox.

Sample	Si	Al iv	Al vi	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Na	K	OH*	Total	(Ca+Na) (B)	Na (B)	(Na+K) (A)	Mg/(Mg+Fe2)	Fe3/(Fe3+Alvi)	Sum of S2	P (MPa)	~ Depth
8P4-A-1	5.85	2.15	0.43	0.23	0.00	0.52	1.01	0.02	2.79	1.93	0.71	0.17	2.00	17.80	2.00	0.07	0.80	0.73	0.55	13	743	27
8P4-A-2	5.81	2.19	0.39	0.24	0.00	0.51	1.06	0.02	2.78	1.95	0.74	0.17	2.00	17.86	2.00	0.05	0.86	0.72	0.57	13	746	27
8P4-A-3	6.06	1.94	0.63	0.24	0.00	0.14	1.31	0.02	2.66	1.84	0.81	0.20	2.00	17.85	2.00	0.16	0.85	0.67	0.18	13	742	27
8P4-B-1	5.97	2.03	0.33	0.27	0.00	0.45	1.12	0.02	2.80	1.90	0.74	0.16	2.00	17.80	2.00	0.10	0.80	0.72	0.57	13	652	24
8P4-B-2	5.92	2.08	0.30	0.26	0.00	0.65	0.93	0.03	2.83	1.85	0.75	0.17	2.00	17.76	2.00	0.15	0.76	0.75	0.69	13	661	24
8P4-B-3	5.99	2.01	0.27	0.26	0.00	0.56	1.01	0.02	2.87	1.86	0.77	0.16	2.00	17.79	2.00	0.14	0.79	0.74	0.67	13	618	23
8P4-C-1	5.99	2.01	0.38	0.19	0.00	0.49	0.68	0.01	3.25	1.92	0.58	0.33	2.00	17.83	2.00	0.08	0.83	0.83	0.56	13	665	24
8P4-C-2	6.05	1.95	0.47	0.18	0.00	0.39	0.72	0.02	3.22	1.92	0.58	0.30	2.00	17.80	2.00	0.08	0.80	0.82	0.45	13	677	25
8P4-C-3	5.87	2.13	0.32	0.26	0.00	0.59	0.97	0.02	2.83	1.90	0.74	0.16	2.00	17.80	2.00	0.10	0.80	0.74	0.64	13	693	25
8P12-A-1	6.09	1.91	0.11	0.31	0.00	0.73	0.74	0.04	3.07	1.78	0.72	0.16	2.00	17.67	2.00	0.22	0.67	0.81	0.87	13	508	19
8P12-A-2	6.09	1.91	0.11	0.31	0.00	0.74	0.73	0.03	3.07	1.77	0.72	0.16	2.00	17.65	2.00	0.23	0.65	0.81	0.87	13	508	19
8P12-A-3	6.11	1.89	0.08	0.32	0.00	0.72	0.74	0.04	3.10	1.79	0.71	0.16	2.00	17.67	2.00	0.21	0.67	0.81	0.90	13	489	18
8P12-A-4	6.13	1.87	0.10	0.32	0.00	0.63	0.84	0.05	3.06	1.78	0.77	0.17	2.00	17.72	2.00	0.22	0.72	0.78	0.87	13	484	18
8P12-A-5	6.08	1.92	0.10	0.28	0.00	0.79	0.66	0.05	3.11	1.78	0.74	0.16	2.00	17.67	2.00	0.22	0.67	0.82	0.89	13	510	19
8P12-B-1	5.68	1.92	0.00	0.38	0.00	2.11	0.00	0.04	3.21	1.42	0.30	0.03	2.00	17.09	1.66	0.24	0.09	1.00	1.00	13	465	17
8P12-B-2	5.77	2.09	0.00	0.31	0.00	2.22	0.00	0.06	2.78	1.36	0.33	0.05	2.00	16.96	1.69	0.33	0.05	1.00	1.00	13	538	20
8P12-B-3	6.02	1.98	0.24	0.27	0.00	1.18	0.00	0.05	3.49	1.56	0.39	0.07	2.00	17.24	1.77	0.21	0.24	1.00	0.83	13	594	22
8P12-B-4	5.86	2.14	0.08	0.34	0.00	1.86	0.00	0.05	2.67	1.50	0.45	0.06	2.00	17.01	1.95	0.45	0.06	1.00	0.96	13	593	22
8P12-B-5	6.10	1.90	0.07	0.31	0.00	0.91	0.89	0.03	2.78	1.94	0.39	0.02	2.00	17.35	2.00	0.06	0.35	0.76	0.93	13	488	18
4P2-A-1	5.84	2.16	0.36	0.19	0.00	0.81	0.78	0.02	2.83	1.89	0.61	0.21	2.00	17.71	2.00	0.11	0.71	0.78	0.70	13	717	26
4P2-A-2	5.88	2.12	0.41	0.19	0.00	0.76	0.78	0.03	2.82	1.87	0.63	0.20	2.00	17.69	2.00	0.13	0.69	0.78	0.65	13	727	27
4P2-A-3	5.88	2.12	0.39	0.19	0.00	0.74	0.81	0.02	2.86	1.89	0.62	0.22	2.00	17.73	2.00	0.11	0.73	0.78	0.66	13	715	26
4P2-A-4	5.88	2.12	0.39	0.18	0.00	0.74	0.83	0.01	2.85	1.91	0.62	0.20	2.00	17.73	2.00	0.09	0.73	0.77	0.65	13	714	26
4P2-A-5	5.85	2.15	0.37	0.19	0.00	0.74	0.89	0.03	2.79	1.91	0.61	0.22	2.00	17.74	2.00	0.09	0.74	0.76	0.66	13	719	26
4P2-B-1	5.78	2.22	0.31	0.18	0.00	0.98	0.62	0.04	2.87	1.85	0.65	0.22	2.00	17.71	2.00	0.15	0.71	0.82	0.76	13	723	27
4P2-B-2	5.85	2.15	0.40	0.16	0.00	0.80	0.74	0.03	2.86	1.88	0.66	0.20	2.00	17.74	2.00	0.12	0.74	0.79	0.67	13	733	27
4P2-B-3	5.86	2.14	0.31	0.21	0.00	0.81	0.72	0.02	2.93	1.88	0.64	0.19	2.00	17.72	2.00	0.12	0.72	0.80	0.72	13	690	25
4P2-B-4	5.84	2.16	0.39	0.16	0.00	0.78	0.73	0.01	2.92	1.92	0.60	0.21	2.00	17.74	2.00	0.08	0.74	0.80	0.67	13	736	27
4P2-B-5	5.89	2.11	0.41	0.17	0.00	0.79	0.74	0.02	2.87	1.86	0.63	0.21	2.00	17.70	2.00	0.14	0.70	0.80	0.66	13	721	26

APPENDIX D Structural formulae on the basis of 23 ox.

Sample	Si	Al iv	Al vi	Ti	Cr	Fe ³⁺	Fe ²⁺	Mn	Mg	Ca	Na	K	OH*	Total	(Ca+Na) (B)	Na (B)	(Na+K) (A)	Mg/(Mg+Fe2)	Fe3/(Fe3+Alvi)	Sum of S2	P (MPa)	~ Depth
4P5-A-1	6.17	1.83	0.19	0.28	0.00	0.59	1.26	0.05	2.63	1.78	0.73	0.19	2.00	17.70	2.00	0.22	0.70	0.68	0.76	13	506	19
4P5-A-2	6.17	1.83	0.18	0.28	0.00	0.60	1.26	0.05	2.62	1.80	0.70	0.19	2.00	17.69	2.00	0.20	0.69	0.67	0.77	13	503	19
4P5-A-3	6.13	1.87	0.18	0.30	0.00	0.62	1.24	0.04	2.61	1.78	0.72	0.19	2.00	17.68	2.00	0.22	0.68	0.68	0.78	13	520	19
4P5-A-4	6.18	1.82	0.17	0.30	0.00	0.50	1.38	0.04	2.62	1.81	0.75	0.18	2.00	17.74	2.00	0.19	0.74	0.66	0.75	13	495	18
4P5-A-5	6.20	1.80	0.17	0.29	0.00	0.43	1.43	0.04	2.64	1.86	0.72	0.17	2.00	17.75	2.00	0.14	0.75	0.65	0.72	13	485	18
4P5-B-1	6.32	1.68	0.77	0.23	0.00	0.23	2.02	0.06	1.69	1.74	0.69	0.06	2.00	17.49	2.00	0.26	0.49	0.45	0.23	13	691	25
4P5-B-2	6.16	1.84	0.43	0.24	0.00	0.94	1.53	0.08	1.79	1.64	0.68	0.05	2.00	17.36	2.00	0.36	0.36	0.54	0.69	13	615	23
4P5-B-3	6.43	1.57	0.72	0.37	0.00	0.00	1.84	0.07	1.92	1.77	0.62	0.07	2.00	17.40	2.00	0.23	0.46	0.51	0.00	13	619	23
4P5-B-4	5.73	1.93	0.00	0.34	0.00	2.33	0.48	0.08	2.11	1.51	0.54	0.05	2.00	17.10	2.00	0.49	0.10	0.81	1.00	13	470	17
4P5-B-5	5.98	1.97	0.00	0.26	0.00	1.69	0.97	0.08	2.06	1.65	0.52	0.05	2.00	17.22	2.00	0.35	0.22	0.68	1.00	13	486	18
8B1-A-1	6.17	1.83	0.05	0.36	0.00	0.67	0.80	0.05	3.06	1.74	0.72	0.19	2.00	17.64	2.00	0.26	0.64	0.79	0.93	13	451	17
8B1-A-2	6.17	1.83	0.18	0.31	0.00	0.59	1.03	0.05	2.85	1.78	0.70	0.18	2.00	17.66	2.00	0.22	0.66	0.74	0.77	13	505	19
8B1-A-3	6.15	1.85	0.10	0.41	0.00	0.42	1.04	0.03	3.00	1.77	0.77	0.21	2.00	17.74	2.00	0.23	0.74	0.74	0.81	13	476	18
8B1-A-4	6.35	1.65	0.15	0.26	0.00	0.53	0.85	0.03	3.17	1.78	0.70	0.18	2.00	17.66	2.00	0.22	0.66	0.79	0.78	13	418	15
8B1-A-5	6.27	1.73	0.11	0.28	0.00	0.60	0.80	0.05	3.16	1.78	0.71	0.18	2.00	17.67	2.00	0.22	0.67	0.80	0.84	13	432	16
8B1-B-1	6.27	1.73	0.18	0.25	0.00	0.67	0.76	0.04	3.10	1.73	0.72	0.20	2.00	17.65	2.00	0.27	0.65	0.80	0.79	13	464	17
8B1-B-2	6.30	1.70	0.13	0.24	0.00	0.74	0.81	0.05	3.03	1.74	0.72	0.17	2.00	17.62	2.00	0.26	0.62	0.79	0.85	13	428	16
8B1-B-3	6.27	1.73	0.17	0.26	0.00	0.66	0.87	0.06	2.98	1.74	0.69	0.19	2.00	17.62	2.00	0.26	0.62	0.77	0.79	13	459	17
8B1-B-4	6.40	1.60	0.17	0.24	0.00	0.50	0.92	0.05	3.12	1.78	0.70	0.18	2.00	17.66	2.00	0.22	0.66	0.77	0.75	13	400	15
8B1-B-5	6.25	1.75	0.12	0.26	0.00	0.79	0.74	0.06	3.02	1.72	0.70	0.17	2.00	17.60	2.00	0.28	0.60	0.80	0.87	13	444	16
4B1-C-1	6.01	1.99	0.25	0.25	0.00	0.87	0.71	0.02	2.89	1.77	0.67	0.17	2.00	17.60	2.00	0.23	0.60	0.80	0.77	13	606	22
4B1-C-2	5.99	2.01	0.25	0.27	0.00	0.81	0.73	0.03	2.91	1.79	0.68	0.15	2.00	17.63	2.00	0.21	0.63	0.80	0.77	13	609	22
4B1-C-3	5.98	2.02	0.23	0.25	0.00	0.87	0.71	0.04	2.90	1.80	0.67	0.16	2.00	17.63	2.00	0.20	0.63	0.80	0.79	13	605	22
4B1-C-4	5.97	2.03	0.27	0.24	0.00	0.81	0.80	0.02	2.85	1.80	0.69	0.17	2.00	17.66	2.00	0.20	0.66	0.78	0.75	13	627	23
4B1-C-5	6.03	1.97	0.37	0.19	0.00	0.70	0.76	0.02	2.96	1.83	0.66	0.19	2.00	17.68	2.00	0.17	0.68	0.80	0.65	13	645	24
MC108-A-1	5.90	2.10	0.35	0.21	0.00	0.52	0.77	0.02	3.12	1.96	0.63	0.24	2.00	17.84	2.00	0.04	0.84	0.80	0.60	13	689	25
MC108-A-2	5.88	2.12	0.35	0.20	0.00	0.60	0.71	0.01	3.13	1.94	0.66	0.23	2.00	17.83	2.00	0.06	0.83	0.81	0.64	13	698	26
MC108-A-3	5.82	2.18	0.34	0.21	0.00	0.65	0.65	0.02	3.13	1.94	0.65	0.23	2.00	17.82	2.00	0.06	0.82	0.83	0.66	13	718	26
MC108-A-4	5.85	2.15	0.33	0.20	0.00	0.68	0.63	0.01	3.14	1.92	0.67	0.24	2.00	17.83	2.00	0.08	0.83	0.83	0.67	13	705	26
MC108-A-5	5.95	2.05	0.39	0.20	0.00	0.53	0.77	0.01	3.10	1.91	0.66	0.24	2.00	17.81	2.00	0.09	0.81	0.80	0.58	13	689	25
MC108-A-6	5.89	2.11	0.38	0.20	0.00	0.55	0.76	0.02	3.09	1.95	0.63	0.24	2.00	17.82	2.00	0.05	0.82	0.80	0.59	13	707	26
MC108-A-7	5.89	2.11	0.35	0.21	0.00	0.59	0.71	0.02	3.12	1.92	0.67	0.24	2.00	17.83	2.00	0.08	0.83	0.81	0.62	13	696	26
MC108-A-8	5.90	2.10	0.38	0.20	0.00	0.60	0.72	0.01	3.10	1.93	0.65	0.22	2.00	17.81	2.00	0.07	0.81	0.81	0.61	13	706	26
MC108-A-9	5.93	2.07	0.40	0.21	0.00	0.54	0.75	0.01	3.09	1.94	0.60	0.23	2.00	17.78	2.00	0.06	0.78	0.80	0.57	13	700	26

APPENDIX E

Raw Crystal Size Distribution (CSD) data used in the production of fFigure 4.32. The image analysis software measures the different parameters of a 2D greyscale image of the rocks crystals, including long-axis length, short-axis length, perimeter, area, elongation, roundness, major angle orientation, and minor angle orientation. The area of the section is also measured. This raw information is then corrected and used to produce log plots (e.g. Figure 4.32).

APPENDIX E

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
Mean	0.13	1.39	0.5	-10.87	0.22	22.05	2.38	0.59	0.32	0.67			362714.09
Std. Dev.	0.23	1.2	0.42	48.1	0.19	53.65	0.99	0.13	0.25	0.11			648910.27
#1	0.99	5.27	1.98	-24.87	0.66	65.03	3.01	0.45	1.12	0.57	-16,252,040	-802,041	2777137
#2	0.16	2.08	0.77	-25.2	0.25	65.1	3.04	0.48	0.46	0.6	-4,822,066	-4,842,067	460768
#3	0.57	3.79	1.19	-15.57	0.71	74.69	1.67	0.5	0.85	0.72	-9,682,034	-9,702,035	1597915
#4	0.02	0.59	0.22	-63.43	0.09	26.57	2.4	0.58	0.14	0.65	-13,112,080	-13,132,081	45254
#5	0.05	1.09	0.42	24.08	0.16	-66.04	2.61	0.58	0.26	0.62	-18,202,070	-18,222,071	151844
#6	0.08	1.43	0.58	-30.55	0.17	58.57	3.36	0.51	0.33	0.56	-5,492,061	-5,512,062	233750
#7	0.01	0.44	0.16	-23.96	0.08	66.04	2	0.69	0.12	0.73	-3,532,073	-3,552,074	30481
#8	0.2	2.45	0.83	-35.41	0.34	54.78	2.45	0.41	0.5	0.6	-6,112,048	-6,132,049	555764
#9	0.66	4.21	1.55	-12.79	0.71	77.4	2.18	0.47	0.92	0.59	-7,662,024	-7,682,025	1852796
#10	0.14	1.79	0.56	-56.31	0.41	34.33	1.38	0.55	0.42	0.76	-12,232,044	-12,252,045	393822
#11	0.09	1.19	0.41	49.9	0.37	-40.46	1.11	0.8	0.34	0.83	-2,452,046	-2,472,047	251328
#12	0.74	4.33	1.53	-14.85	0.69	74.8	2.23	0.49	0.97	0.63	-11,052,008	(-967,2009)	2070464
#13	0.03	1.58	0.66	-34.47	0.08	57.99	8.61	0.15	0.19	0.29	-3,062,038	-3,082,039	83215
#14	0.02	0.62	0.22	8.43	0.1	-80.54	2.24	0.56	0.15	0.66	-6,822,052	-6,842,053	47685
#15	0.02	0.69	0.25	-66.8	0.1	24.44	2.52	0.57	0.17	0.67	-13,012,045	-13,032,046	60588
#16	0.04	0.89	0.33	-21.54	0.14	66.37	2.34	0.64	0.23	0.68	-1,702,040	-1,722,041	112574
#17	0.12	1.7	0.59	8.81	0.32	-81.25	1.82	0.54	0.4	0.68	-20,592,030	-20,612,031	349877
#18	0.04	0.92	0.32	37.75	0.18	-50.53	1.78	0.61	0.23	0.71	-17,532,033	-17,552,034	114818
#19	0.03	0.83	0.3	-12.53	0.13	79.38	2.27	0.61	0.21	0.69	-3,902,027	-3,922,028	93874
#20	0.01	0.52	0.2	48.37	0.1	-41.63	2	0.66	0.14	0.69	-12,722,030	-12,742,031	40205
#21	0.02	0.66	0.26	-59.35	0.11	30.26	2.26	0.72	0.18	0.69	-3,612,007	-3,632,008	69377
#22	0.33	2.87	1	-47.32	0.47	42.21	2.11	0.51	0.65	0.65	-12,161,970	-12,181,971	931260
#23	0.01	0.39	0.14	-69.44	0.08	18.43	1.8	0.81	0.11	0.79	-1,482,007	-1,502,008	26928
#24	0.09	1.68	0.6	-48.3	0.21	41.82	2.89	0.42	0.34	0.57	-3,751,982	-3,771,983	260678
#25	0.75	4.2	1.51	-19.9	0.63	70.14	2.42	0.53	0.98	0.64	-20,391,954	(-11,1955)	2092156
#26	0	0.28	0.1	-75.96	0.04	11.31	2.43	0.74	0.08	0.75	-1,341,981	-1,361,982	12716
#27	0.03	0.79	0.3	74.05	0.11	-17.1	2.68	0.52	0.18	0.61	-16,181,967	-16,201,968	72182
#28	1.3	6.17	2.57	-8.03	0.64	81.97	4	0.43	1.28	0.5	-28,991,943	-5,351,944	3630792
#29	0.15	1.83	0.59	-8.02	0.38	81.35	1.54	0.56	0.44	0.75	-24,501,961	-24,521,962	419441
#30	0.01	0.37	0.12	-58.39	0.09	33.69	1.41	0.85	0.11	0.87	-15,111,969	-15,131,970	26180
#31	0.01	0.4	0.15	-26.57	0.07	63.43	2	0.77	0.11	0.76	-9,691,968	-9,711,969	27115
#32	0.03	0.84	0.3	-30.7	0.11	59.74	2.68	0.51	0.19	0.63	-26,211,958	-26,231,959	80036
#33	0.05	1.26	0.47	-47.79	0.15	40.6	3.15	0.4	0.25	0.54	-15,711,949	-15,731,950	142681
#34	0.14	1.88	0.7	-80.54	0.35	9.46	2	0.51	0.43	0.61	-18,221,923	-18,241,924	402237
#35	0.05	1	0.35	-41.19	0.21	48.18	1.67	0.64	0.26	0.73	-22,401,952	-22,421,953	143242
#36	0.19	2.38	0.84	56.46	0.27	-32.74	3.1	0.43	0.5	0.59	-9,571,922	-9,591,923	544918
#37	0.03	0.75	0.29	-30.96	0.11	57.53	2.68	0.56	0.18	0.63	-4,601,955	-4,621,956	70686
#38	0.04	0.85	0.31	-43.92	0.16	45	1.89	0.69	0.23	0.74	-11,231,948	-11,251,949	112200
#39	0.36	2.98	1.08	-17.2	0.48	-106.89	2.25	0.51	0.68	0.63	-13,821,927	-13,841,928	1015223

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#40	0.02	0.5	0.17	20.22	0.12	-70.35	1.36	0.75	0.14	0.84	-9,721,951	-9,741,952	42636
#41	0.02	0.54	0.19	-39.81	0.13	50.19	1.5	0.86	0.16	0.83	-5,021,945	-5,041,946	56100
#42	0.04	0.84	0.29	-45	0.2	45	1.47	0.73	0.23	0.79	-15,151,937	-15,171,938	115753
#43	0.3	2.78	0.85	-38.75	0.52	51.34	1.62	0.49	0.62	0.73	-17,501,909	-17,521,910	845053
#44	0.17	1.88	0.66	-16.43	0.36	74.05	1.86	0.6	0.46	0.7	-22,961,925	-22,981,926	475167
#45	0.58	4.02	1.34	-16.67	0.62	73.01	2.18	0.45	0.86	0.64	-3,211,900	-3,231,901	1611566
#46	0.16	1.94	0.71	-11.31	0.3	-101	2.36	0.54	0.46	0.64	-6,681,926	-6,701,927	455719
#47	0.24	2.12	0.69	-24.44	0.41	65.46	1.67	0.69	0.56	0.81	-21,911,905	-21,931,906	686103
#48	0.54	3.22	1.1	-43.79	0.61	46.08	1.79	0.66	0.83	0.76	-31,991,873	-3,621,874	1512830
#49	0.03	0.84	0.34	-27.18	0.1	61.39	3.32	0.5	0.19	0.56	-7,761,925	-7,781,926	78727
#50	0.05	0.95	0.34	-33.31	0.21	56.31	1.66	0.71	0.25	0.74	-5,211,915	-5,231,916	142494
#51	0.07	1.27	0.46	-75.47	0.16	14.74	2.84	0.52	0.29	0.64	-11,351,898	-11,371,899	185504
#52	0.04	1.15	0.48	-4.93	0.1	85.24	4.83	0.43	0.24	0.5	-26,601,914	-26,621,915	125664
#53	0.04	0.86	0.3	53.75	0.18	-35.84	1.68	0.63	0.22	0.72	-30,921,895	-30,941,896	104720
#54	0.04	0.88	0.3	-39.4	0.17	50.91	1.76	0.6	0.22	0.73	-8,131,891	-8,151,892	103224
#55	0.29	2.58	0.9	-33.84	0.37	56.66	2.41	0.54	0.6	0.67	-15,151,868	-15,171,869	802978
#56	0.04	0.96	0.38	-30.96	0.11	59.74	3.36	0.5	0.22	0.57	-10,421,890	-10,441,891	103037
#57	0.04	1.01	0.38	-49.4	0.15	40.6	2.5	0.55	0.24	0.63	-5,411,882	-5,431,883	124542
#58	0.07	1.33	0.52	-4.47	0.15	86.82	3.56	0.51	0.3	0.57	-9,231,888	-9,251,889	199155
#59	0.38	2.77	0.91	-58.16	0.55	31.55	1.67	0.62	0.69	0.76	-32,991,851	(-766,1852)	1055615
#60	0.05	0.97	0.34	33.31	0.18	123.69	1.94	0.63	0.24	0.72	-26,821,882	-26,841,883	132022
#61	0.05	0.9	0.33	-66.61	0.22	23.75	1.48	0.83	0.26	0.79	-4,401,874	-4,421,875	150348
#62	0.05	1.05	0.4	-20.28	0.13	68.2	3.04	0.52	0.24	0.6	-5,871,880	-5,891,881	129030
#63	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-9,561,891	-9,581,892	187
#64	0.21	2.16	0.85	-13.9	0.33	75.62	2.58	0.57	0.52	0.61	-19,871,870	-19,891,871	598026
#65	0.1	1.47	0.57	-10.67	0.22	79.51	2.56	0.6	0.36	0.63	-27,701,864	-27,721,865	290037
#66	0.37	2.97	1.12	-29.18	0.37	60.57	3.07	0.52	0.68	0.61	-33,971,841	(-784,1842)	1026630
#67	0.02	0.77	0.31	-45	0.08	45	3.86	0.48	0.17	0.54	-17,831,863	-17,851,864	63580
#68	0.16	2.18	0.86	-37.3	0.25	53.13	3.52	0.43	0.45	0.53	-18,531,844	-18,551,845	452540
#69	0.09	1.43	0.51	7.35	0.22	-83.66	2.3	0.55	0.34	0.66	-7,511,859	-7,531,860	250206
#70	0.04	0.94	0.34	-74.62	0.13	14.93	2.67	0.56	0.23	0.66	-16,101,851	-16,121,852	111639
#71	0.03	0.73	0.24	7.85	0.16	-81.03	1.52	0.75	0.2	0.84	-3,951,856	-3,971,857	88451
#72	0.06	1.27	0.49	-68.55	0.19	19.98	2.57	0.5	0.29	0.58	-10,861,840	-10,881,841	179894
#73	0.01	0.46	0.18	-24.23	0.05	63.43	3.27	0.5	0.1	0.58	-5,741,861	-5,761,862	23562
#74	0.01	0.58	0.25	-53.13	0.08	40.6	3.25	0.56	0.14	0.56	-17,971,853	-17,991,854	41327
#75	0.07	1.19	0.45	-39.14	0.19	50.19	2.37	0.64	0.3	0.67	-38,811,845	-38,831,846	200838
#76	0.03	0.67	0.24	-22.17	0.16	-111.25	1.51	0.72	0.18	0.76	-9,271,856	-9,291,857	71247
#77	0.03	0.98	0.39	-36.38	0.08	49.4	5.12	0.36	0.19	0.49	-21,531,850	-21,551,851	77231
#78	0.04	1	0.37	-22.04	0.17	67.17	2.2	0.48	0.22	0.59	-1,121,848	-1,141,849	106590
#79	0.03	0.66	0.21	-72.26	0.19	17.65	1.14	0.77	0.19	0.86	-31,241,849	-31,261,850	75548
#80	0.01	0.52	0.15	15.52	0.13	-75.96	1.13	0.62	0.13	0.85	-22,771,851	-22,791,852	37400

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#81	0.01	0.45	0.17	-75.96	0.07	14.04	2.5	0.58	0.11	0.65	-10,631,846	-10,651,847	25993
#82	0.06	1.02	0.38	-25.46	0.18	63.43	2.08	0.68	0.27	0.7	-12,711,836	-12,731,837	156706
#83	0.09	1.47	0.55	-74.52	0.25	14.93	2.17	0.53	0.34	0.61	-16,291,816	-16,311,817	252263
#84	0.67	3.84	1.37	27.79	0.69	-61.93	1.97	0.57	0.92	0.67	-29,771,802	-6,811,803	1869252
#85	0.12	2.11	0.86	-47.32	0.19	43.26	4.49	0.34	0.39	0.46	-11,151,814	-11,171,815	339031
#86	0.89	4.76	1.81	-50.69	0.6	38.9	3.02	0.49	1.07	0.59	-21,871,758	-4,681,759	2495889
#87	0.01	0.47	0.16	-51.34	0.12	39.29	1.35	0.78	0.13	0.85	-2,521,839	-2,541,840	38896
#88	0.03	0.8	0.29	-30.14	0.11	59.74	2.58	0.61	0.2	0.68	-6,211,838	-6,231,839	86207
#89	0.02	0.81	0.34	5.57	0.07	96.34	4.55	0.36	0.15	0.46	-30,701,839	-30,721,840	52360
#90	0.03	0.76	0.26	-43.73	0.17	46.97	1.55	0.75	0.21	0.8	-4,311,832	-4,331,833	95744
#91	0.07	1.14	0.45	75.2	0.19	-14.62	2.31	0.69	0.3	0.67	-28,921,819	-28,941,820	200090
#92	0.44	3.43	1.23	-32.53	0.51	58.09	2.41	0.47	0.75	0.61	-34,521,788	-11,789	1243924
#93	0.27	2.39	0.95	-32.32	0.36	58.13	2.66	0.59	0.58	0.62	-27,551,807	-27,571,808	749683
#94	0.1	1.49	0.52	-59.04	0.25	29.98	2.14	0.56	0.36	0.68	-15,561,807	-15,581,808	278630
#95	0.14	1.65	0.6	-27.61	0.29	63.43	2.05	0.63	0.42	0.7	-19,581,808	-19,601,809	383537
#96	0.09	1.66	0.68	-56.31	0.18	33.69	3.83	0.41	0.34	0.5	-10,301,803	-10,321,804	249271
#97	0.1	1.4	0.53	-67.38	0.25	23.2	2.13	0.62	0.35	0.66	-8,141,805	-8,161,806	269093
#98	0.01	0.45	0.15	25.2	0.09	-63.43	1.68	0.76	0.12	0.81	-17,601,829	-17,621,830	33660
#99	0.1	1.65	0.62	30.96	0.18	-59.93	3.45	0.44	0.35	0.56	-9,461,810	-9,481,811	266475
#100	0.15	1.7	0.61	-53.75	0.29	36.87	2.13	0.64	0.43	0.71	-26,531,790	-26,551,791	412896
#101	0.1	1.49	0.52	12.72	0.28	-78.02	1.88	0.54	0.35	0.67	-13,531,806	-13,551,807	267971
#102	0.03	0.66	0.23	81.87	0.15	-6.34	1.56	0.73	0.18	0.78	-21,521,805	-21,541,806	71808
#103	0.77	4.36	1.64	-6.28	0.58	-96.52	2.86	0.51	0.99	0.6	-4,451,776	-4,471,777	2147882
#104	0.15	2.18	0.75	-70.18	0.33	20.22	2.26	0.41	0.44	0.59	-28,361,775	-28,381,776	431783
#105	0.02	0.62	0.21	-64.44	0.15	25.2	1.36	0.71	0.17	0.8	-2,491,806	-2,511,807	60401
#106	0.01	0.48	0.16	-30.47	0.12	58.39	1.29	0.8	0.14	0.85	-17,631,810	-17,651,811	41140
#107	0.01	0.45	0.15	-9.46	0.11	81.25	1.39	0.86	0.13	0.88	-16,881,805	-16,901,806	38148
#108	0.02	0.67	0.24	56.31	0.16	-34.51	1.49	0.68	0.18	0.75	-15,071,798	-15,091,799	68068
#109	0.04	0.84	0.28	-25.82	0.16	66.04	1.75	0.63	0.21	0.75	-7,061,791	-7,081,792	99110
#110	0.04	0.8	0.28	-50.83	0.23	39.29	1.23	0.79	0.23	0.8	-17,871,791	-17,891,792	113509
#111	0.05	0.92	0.32	-59.53	0.19	30.96	1.69	0.69	0.24	0.75	-27,831,772	-27,851,773	130152
#112	0.09	1.41	0.47	-79.08	0.26	10.95	1.84	0.55	0.33	0.7	-26,021,756	-26,041,757	244409
#113	0.04	0.85	0.29	-59.04	0.16	30.47	1.77	0.66	0.22	0.77	-1,931,772	-1,951,773	105468
#114	0.18	2.03	0.85	-2.2	0.33	-92.86	2.6	0.53	0.47	0.56	-36,421,765	-36,441,766	490501
#115	0.33	2.88	1.11	-16.7	0.4	73.41	2.77	0.5	0.64	0.58	-42,091,754	(-484,1755)	914617
#116	0.39	3.46	1.32	-28.78	0.38	60.71	3.45	0.41	0.71	0.54	-11,071,733	-11,091,734	1106292
#117	0.01	0.48	0.19	-53.62	0.06	33.69	3.27	0.51	0.11	0.57	-35,311,772	-35,331,773	26180
#118	0.42	3.26	1.36	11.45	0.36	-78.18	3.79	0.5	0.73	0.54	-40,031,760	-3,621,761	1179222
#119	0.03	0.81	0.28	-39.17	0.12	50.71	2.45	0.58	0.2	0.69	-35,021,766	-35,041,767	84337
#120	0.23	2.15	0.68	6.19	0.44	-83.54	1.57	0.61	0.54	0.79	-14,661,745	-14,681,746	631125
#121	0.03	0.83	0.33	-65.32	0.11	22.62	3.13	0.52	0.19	0.57	-21,281,762	-21,301,763	79288

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#122	0.02	0.65	0.22	-33.11	0.18	56.31	1.27	0.69	0.17	0.76	-10,411,768	-10,431,769	64702
#123	0.03	0.73	0.23	-29.25	0.17	60.95	1.39	0.71	0.2	0.84	-6,511,761	-6,531,762	84337
#124	0.1	1.66	0.62	8.34	0.24	-82.15	2.59	0.48	0.37	0.59	-15,461,761	-15,481,762	294151
#125	0.09	1.74	0.59	-22.99	0.28	67.89	2.08	0.36	0.33	0.56	-41,181,757	-41,201,758	240295
#126	0.09	1.33	0.46	-36.25	0.3	52.82	1.53	0.63	0.34	0.74	-2,191,747	-2,211,748	250767
#127	0.17	2.13	0.79	-47.09	0.3	42.8	2.63	0.48	0.47	0.59	-13,771,733	-13,791,734	484704
#128	0.05	1.09	0.45	29.36	0.12	-61.7	3.73	0.47	0.24	0.53	-19,471,761	-19,491,762	126412
#129	0.33	2.86	1.11	0.42	0.33	-90	3.32	0.51	0.65	0.58	-16,751,749	-16,771,750	921162
#130	0.01	0.4	0.14	-40.24	0.1	48.37	1.41	0.81	0.11	0.82	-9,671,762	-9,691,763	28985
#131	0.01	0.47	0.19	-55.62	0.05	30.96	3.95	0.53	0.11	0.58	-10,651,759	-10,671,760	25806
#132	0.02	0.58	0.2	-9.46	0.12	81.87	1.72	0.67	0.15	0.76	-8,751,757	-8,771,758	49742
#133	0.12	1.66	0.6	-24.83	0.25	65.1	2.39	0.56	0.4	0.66	-31,431,739	-31,451,740	345576
#134	0.01	0.57	0.22	-63.43	0.07	29.74	3.33	0.46	0.12	0.55	-19,941,752	-19,961,753	32538
#135	0.12	1.65	0.59	72.32	0.28	-16.86	2.1	0.54	0.38	0.65	-20,461,723	-20,481,724	326128
#136	0.04	1.04	0.41	-23.5	0.11	67.38	3.86	0.5	0.23	0.57	-27,331,750	-27,351,751	119680
#137	0.02	0.65	0.26	20.14	0.1	-71.57	2.53	0.73	0.18	0.68	-2,761,753	-2,781,754	68442
#138	0.02	0.55	0.19	-37.87	0.13	52.43	1.39	0.75	0.15	0.82	-19,201,747	-19,221,748	50864
#139	0.02	0.48	0.16	63.43	0.14	-25.02	1.22	0.9	0.14	0.88	-33,191,744	-33,211,745	46189
#140	0.03	0.73	0.24	76.43	0.18	-13.39	1.38	0.7	0.19	0.8	-1,661,729	-1,681,730	82841
#141	0.66	4.15	1.49	-6.31	0.58	83.57	2.55	0.48	0.92	0.62	-8,431,693	-8,451,694	1847747
#142	0.05	0.93	0.34	6.95	0.19	97.43	1.78	0.69	0.25	0.73	-35,001,728	-35,021,729	132957
#143	0.05	1.08	0.41	25.02	0.14	-66.37	2.84	0.57	0.26	0.64	-2,681,724	-2,701,725	147543
#144	0.02	0.65	0.25	-75.07	0.09	16.7	2.97	0.54	0.15	0.6	-6,441,723	-6,461,724	51425
#145	0.02	0.77	0.3	74.05	0.09	-15.26	3.19	0.49	0.17	0.58	-17,661,720	-17,681,721	65637
#146	0.01	0.47	0.17	-58.57	0.05	26.57	3.14	0.52	0.11	0.62	-19,721,729	-19,741,730	25432
#147	0.05	0.99	0.37	20.85	0.18	110.85	2	0.65	0.26	0.69	-30,401,726	-30,421,727	143242
#148	0.23	2.91	1.07	-17.74	0.34	72	3.12	0.35	0.55	0.51	-18,821,704	-18,841,705	655996
#149	0.13	1.85	0.66	-38.44	0.27	52.43	2.45	0.49	0.41	0.63	-5,111,705	-5,131,706	377740
#150	0.02	0.59	0.19	22.25	0.13	-68.2	1.47	0.65	0.15	0.79	-27,371,726	-27,391,727	51238
#151	0.03	0.79	0.27	68.84	0.15	-22.38	1.81	0.57	0.19	0.7	-35,441,716	-35,461,717	79662
#152	0.03	0.75	0.28	-24.3	0.14	64.98	2.05	0.67	0.2	0.7	-10,151,718	-10,171,719	84150
#153	0.23	2.24	0.8	-28.66	0.41	61.39	1.96	0.58	0.54	0.67	-4,221,703	-4,241,704	640662
#154	0.08	1.2	0.46	68.01	0.21	-22.62	2.16	0.67	0.31	0.68	-27,931,701	-27,951,702	212993
#155	0.12	1.63	0.65	-82.07	0.21	8.75	3.03	0.56	0.39	0.6	-19,971,687	-19,991,688	333047
#156	0.01	0.51	0.19	22.25	0.07	-69.44	2.78	0.54	0.12	0.62	-15,201,713	-15,221,714	31977
#157	0.26	2.52	0.92	31.14	0.36	-58.82	2.53	0.51	0.57	0.63	-2,501,684	-2,521,685	724999
#158	0.02	0.54	0.19	-52.13	0.12	36.87	1.52	0.69	0.14	0.76	-14,031,708	-14,051,709	44506
#159	0.01	0.41	0.13	10.62	0.08	102.53	1.77	0.69	0.11	0.81	-16,581,711	-16,601,712	25024
#160	0.01	0.49	0.15	-74.48	0.1	14.04	1.51	0.65	0.13	0.83	-29,951,708	-29,971,709	35343
#161	0.01	0.45	0.15	40.6	0.12	-50.71	1.3	0.74	0.12	0.82	-36,411,711	-36,431,712	33473
#162	0.03	0.73	0.26	-57.8	0.17	32.91	1.58	0.75	0.2	0.77	-27,121,702	-27,141,703	89199

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#163	0.2	2	0.69	-39.72	0.39	50.96	1.77	0.61	0.5	0.72	-42,511,677	(-3596,1678)	547162
#164	0.13	1.6	0.64	-33.08	0.29	56.31	2.18	0.63	0.4	0.63	-34,761,690	-34,781,691	358479
#165	0.02	0.65	0.24	-19.65	0.13	71.57	1.88	0.66	0.17	0.69	-19,601,703	-19,621,704	62271
#166	0.06	1.08	0.41	35.27	0.17	-54.78	2.41	0.68	0.28	0.69	-32,931,690	-32,951,691	175593
#167	0.11	1.67	0.6	16.48	0.25	107.24	2.44	0.51	0.38	0.63	-5,751,690	-5,771,691	316591
#168	0.08	1.13	0.36	59.93	0.34	-30.26	1.05	0.81	0.32	0.9	-27,511,687	-27,531,688	230197
#169	0.16	1.96	0.76	-61.78	0.29	28.74	2.63	0.53	0.45	0.6	-41,321,657	-41,341,658	452727
#170	0.01	0.46	0.16	40.91	0.1	-48.37	1.65	0.7	0.12	0.76	-35,821,696	-35,841,697	33473
#171	0.02	0.56	0.2	45	0.14	-42.71	1.36	0.79	0.16	0.81	-22,341,692	-22,361,693	55539
#172	1.4	5.42	1.74	-2.96	1.39	86.97	1.25	0.6	1.34	0.77	-29,831,610	(-294,2703)	3928683
#173	0.03	0.95	0.38	-38.09	0.15	53.75	2.53	0.47	0.21	0.54	-35,201,687	-35,221,688	93313
#174	0.02	0.58	0.18	35.84	0.15	-53.75	1.19	0.8	0.16	0.91	-6,501,691	-6,521,692	59840
#175	0.04	0.98	0.4	-16.59	0.13	71.57	3.1	0.49	0.22	0.55	-42,121,691	-42,141,692	105842
#176	0.04	0.86	0.29	-23.63	0.2	65.56	1.45	0.76	0.24	0.84	-36,761,684	-36,781,685	125103
#177	0.11	1.64	0.54	-32.01	0.29	57.65	1.86	0.5	0.37	0.68	-36,161,675	-36,181,676	296021
#178	0.09	1.41	0.55	-19.25	0.22	70.2	2.51	0.57	0.34	0.62	-14,621,678	-14,641,679	251889
#179	0.02	0.88	0.36	82.23	0.07	-7.13	5.51	0.39	0.18	0.48	-15,221,669	-15,241,670	67507
#180	0.48	3.61	1.44	-21.01	0.41	69.04	3.49	0.46	0.78	0.55	-16,491,655	(-1529,1656)	1350327
#181	0.02	0.56	0.21	-33.69	0.16	55.49	1.3	0.84	0.16	0.8	-981,676	-1,001,677	59840
#182	0.6	3.9	1.44	-8.5	0.47	81.03	3.05	0.49	0.87	0.61	-6,231,633	-6,251,634	1676455
#183	0.03	1.15	0.44	-38.16	0.08	53.13	5.34	0.29	0.2	0.46	-9,591,661	-9,611,662	86955
#184	0.03	0.69	0.25	-14.93	0.11	77.01	2.33	0.66	0.18	0.71	-17,941,666	-17,961,667	71060
#185	0.08	1.47	0.55	-21.96	0.25	68.55	2.22	0.49	0.33	0.6	-40,611,654	-40,631,655	233937
#186	0.01	0.45	0.15	36.25	0.1	-55.01	1.52	0.79	0.13	0.84	-27,371,662	-27,391,663	36278
#187	0.4	3.11	1.14	-9.94	0.44	80.36	2.59	0.52	0.71	0.63	-18,521,633	-18,541,634	1111154
#188	0.03	0.76	0.28	52.13	0.11	-36.03	2.51	0.57	0.18	0.65	-19,651,651	-19,671,652	73491
#189	0.06	1.18	0.4	-12.91	0.21	76.5	1.92	0.58	0.28	0.71	-24,621,648	-24,641,649	178398
#190	0.02	0.68	0.27	79.7	0.08	-12.53	3.64	0.62	0.17	0.62	-19,411,649	-19,431,650	63580
#191	0.08	1.32	0.49	22.69	0.23	-67.07	2.11	0.59	0.32	0.66	-37,161,646	-37,181,647	228514
#192	0.04	0.85	0.31	-81.03	0.15	9.46	2.11	0.64	0.22	0.69	-39,671,643	-39,691,644	103224
#193	0.43	3.25	1.26	-76.5	0.46	13.3	2.73	0.51	0.74	0.58	-26,271,592	(-972,1593)	1192499
#194	0.07	1.16	0.37	-53.88	0.28	35.54	1.33	0.65	0.3	0.8	-4,101,642	-4,121,643	195041
#195	0.21	2.44	0.74	-52.62	0.38	38.09	1.93	0.46	0.52	0.71	-20,391,624	-20,411,625	602140
#196	0.18	1.87	0.64	35.11	0.48	-55.49	1.34	0.65	0.48	0.75	-11,731,629	-11,751,630	510884
#197	0.09	1.4	0.52	-41.19	0.24	49.18	2.19	0.6	0.34	0.66	-14,791,630	-14,811,631	258621
#198	0.02	0.71	0.29	-38.16	0.06	56.31	4.94	0.39	0.14	0.48	-33,131,639	-33,151,640	43197
#199	0.01	0.46	0.17	46.97	0.13	-42.51	1.26	0.86	0.14	0.81	-13,221,642	-13,241,643	40766
#200	0.01	0.49	0.16	45	0.09	-45	1.75	0.67	0.13	0.78	-13,541,642	-13,561,643	34969
#201	0.01	0.44	0.16	-59.53	0.08	32.01	2.09	0.69	0.11	0.71	-13,751,639	-13,771,640	28985
#202	0.03	0.65	0.25	9.46	0.12	98.13	2.15	0.78	0.18	0.74	-31,981,639	-32,001,640	74052
#203	0.48	3.02	1.12	-45.89	0.65	43.98	1.72	0.66	0.78	0.7	-8,211,597	-8,231,598	1347522

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#204	0.04	0.9	0.36	-31.18	0.16	59.53	2.25	0.65	0.23	0.64	-24,971,626	-24,991,627	117623
#205	0.13	1.63	0.6	79	0.24	-11.69	2.48	0.63	0.41	0.69	-42,111,604	-42,131,605	374000
#206	0.01	0.5	0.19	-52.13	0.08	40.6	2.47	0.64	0.13	0.68	-17,601,630	-17,621,631	35530
#207	0.5	3.19	0.92	79.29	0.67	-10.49	1.37	0.61	0.8	0.86	-2,101,577	-2,121,578	1393150
#208	0.04	0.9	0.31	-19.86	0.15	-109.44	2.12	0.6	0.22	0.71	-12,891,629	-12,911,630	107899
#209	0.01	0.45	0.18	62.24	0.06	-23.2	2.82	0.53	0.1	0.6	-26,681,628	-26,701,629	24123
#210	0.02	0.78	0.29	-57.65	0.09	33.69	3.28	0.43	0.16	0.56	-17,061,620	-17,081,621	58157
#211	0.07	1.23	0.44	53.97	0.2	-34.99	2.23	0.54	0.29	0.65	-27,391,612	-27,411,613	183447
#212	0.02	0.61	0.24	75.96	0.13	-14.93	1.86	0.67	0.16	0.67	-1,581,620	-1,601,621	55352
#213	0.21	1.99	0.69	-46.91	0.36	42.27	1.9	0.65	0.51	0.74	-10,711,594	-10,731,595	574838
#214	0.07	1.32	0.5	-29.05	0.18	62.24	2.88	0.5	0.3	0.59	-22,321,610	-22,341,611	195789
#215	0.14	1.72	0.71	19.48	0.25	-70.97	2.84	0.59	0.42	0.59	-23,151,609	-23,171,610	385968
#216	0.02	0.71	0.28	-35.54	0.1	55.01	2.82	0.55	0.17	0.6	-39,201,611	-39,221,612	62645
#217	0.17	1.72	0.55	-79.7	0.48	10.74	1.14	0.71	0.46	0.84	-24,261,591	-24,281,592	471427
#218	0.12	1.72	0.62	41.26	0.22	-48.01	2.82	0.52	0.39	0.63	-3,371,597	-3,391,598	340153
#219	0.56	3.62	1.28	-23.29	0.53	66.57	2.4	0.54	0.84	0.66	-31,121,563	-3,671,564	1563320
#220	0.02	0.63	0.24	-38.05	0.07	54.46	3.4	0.5	0.14	0.6	-33,531,610	-33,551,611	44506
#221	0.02	0.67	0.23	-22.93	0.12	66.8	1.85	0.57	0.16	0.7	-26,861,611	-26,881,612	57222
#222	0.61	3.89	1.46	-19.24	0.51	71.27	2.87	0.51	0.88	0.6	-40,031,566	(-1005,1567)	1714229
#223	0.1	1.52	0.54	33.21	0.25	-56.82	2.12	0.54	0.35	0.66	-13,971,601	-13,991,602	277134
#224	0.07	1.26	0.5	-60.49	0.18	30.07	2.77	0.57	0.3	0.61	-16,371,592	-16,391,593	201960
#225	0.15	1.87	0.72	-79.58	0.29	9.73	2.49	0.53	0.43	0.6	-42,461,574	-42,481,575	411961
#226	0.01	0.48	0.19	-59.04	0.06	33.69	3.23	0.58	0.12	0.61	-33,701,603	-33,721,604	29546
#227	0.73	4.84	1.63	-43.38	0.58	46.7	2.79	0.39	0.96	0.59	-24,401,539	-3,291,540	2032503
#228	0.01	0.36	0.12	47.73	0.1	-41.63	1.23	0.88	0.11	0.89	-17,441,603	-17,461,604	25993
#229	0.03	0.81	0.25	7.59	0.2	-82.87	1.25	0.6	0.2	0.81	-19,241,595	-19,261,596	87516
#230	0.01	0.55	0.18	-20.85	0.1	70.02	1.92	0.61	0.14	0.75	-15,291,598	-15,311,599	41514
#231	0.27	2.41	0.86	-53.13	0.4	36.63	2.16	0.58	0.58	0.68	-4,641,561	-4,661,562	745569
#232	1.37	5.91	2	76.99	0.93	-13.18	2.14	0.49	1.32	0.66	-12,591,479	-1,462,594	3850704
#233	0.05	0.97	0.34	38.23	0.22	-52.7	1.59	0.64	0.25	0.72	-14,821,583	-14,841,584	133892
#234	0.12	1.93	0.77	-14.04	0.19	74.74	4.16	0.41	0.39	0.51	-18,071,584	-18,091,585	342771
#235	0.01	0.3	0.11	-63.43	0.05	30.96	2.3	0.73	0.08	0.74	-15,501,591	-15,521,592	14399
#236	0.01	0.47	0.19	-30.96	0.08	57.99	2.47	0.78	0.13	0.7	-16,661,588	-16,681,589	38896
#237	0.14	1.71	0.65	-42.95	0.3	47.2	2.15	0.58	0.42	0.64	-34,241,564	-34,261,565	379797
#238	0.03	0.86	0.31	83.99	0.15	-6.34	2.11	0.56	0.21	0.66	-28,631,570	-28,651,571	92752
#239	0	0.27	0.09	-26.57	0.05	59.04	1.92	0.62	0.07	0.73	-2,971,586	-2,991,587	9724
#240	0.06	1.31	0.54	-24.23	0.12	66.8	4.32	0.45	0.28	0.52	-38,431,575	-38,451,576	172227
#241	0.09	1.41	0.52	-71.57	0.25	19.03	2.06	0.54	0.33	0.64	-35,551,560	-35,571,561	239173
#242	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-40,861,586	-40,881,587	187
#243	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-15,511,584	-15,531,585	187
#244	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-16,831,584	-16,851,585	187

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#245	0.31	2.89	1.07	-60.69	0.37	29.43	2.92	0.47	0.63	0.59	-16,631,520	-16,651,521	879835
#246	0.45	3.13	1.12	28.81	0.49	-60.85	2.3	0.58	0.76	0.68	-37,611,533	-3,541,534	1260006
#247	0.1	1.66	0.65	-59.9	0.23	29.25	2.78	0.44	0.35	0.54	-42,741,541	-42,761,542	269654
#248	0.91	4.94	1.79	-32.31	0.63	57.76	2.85	0.47	1.08	0.6	-9,001,503	(-779,1504)	2553485
#249	0.01	0.32	0.1	-24.44	0.08	66.04	1.23	0.79	0.09	0.9	-2,781,573	-2,801,574	17391
#250	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-3,001,576	-3,021,577	187
#251	0.01	0.46	0.17	-20.22	0.09	68.2	1.88	0.74	0.13	0.76	-3,021,569	-3,041,570	35156
#252	0.24	2.45	0.9	11.51	0.38	-78.93	2.35	0.51	0.55	0.62	-22,441,545	-22,461,546	676753
#253	0.31	2.56	0.94	-38.66	0.41	51.52	2.31	0.59	0.63	0.67	-33,061,527	(-1661,1528)	864127
#254	0.03	0.9	0.38	42.36	0.1	-45	3.61	0.44	0.19	0.51	-28,251,557	-28,271,558	79662
#255	0.12	1.97	0.71	-6.63	0.26	82.87	2.68	0.38	0.39	0.55	-17,531,552	-17,551,553	328933
#256	0.01	0.31	0.13	-39.81	0.05	45	2.76	0.74	0.09	0.67	-19,161,566	-19,181,567	16269
#257	0.05	0.85	0.28	18.97	0.24	109.65	1.14	0.8	0.24	0.88	-29,001,556	-29,021,557	129591
#258	0.06	1.07	0.4	61.86	0.16	-27.9	2.54	0.62	0.27	0.68	-3,961,543	-3,981,544	159137
#259	0.01	0.49	0.18	76.61	0.06	-15.95	2.97	0.58	0.12	0.67	-1,521,550	-1,541,551	30481
#260	0.51	3.59	1.41	81.35	0.48	-8.82	2.95	0.5	0.8	0.57	-34,521,465	-4,381,466	1424192
#261	0.03	1.02	0.42	-25.56	0.11	63.43	3.8	0.42	0.21	0.51	-20,251,545	-20,271,546	97988
#262	0.12	1.64	0.64	-24.93	0.23	65.22	2.73	0.54	0.38	0.6	-27,701,539	-27,721,540	324071
#263	0.94	5.23	1.77	-52.5	0.68	37.69	2.6	0.43	1.09	0.62	-18,081,462	-1,751,463	2627537
#264	0.02	0.65	0.27	-64.98	0.1	24.44	2.74	0.65	0.17	0.62	-16,141,538	-16,161,539	61149
#265	0.2	2.02	0.63	-19.86	0.45	69.93	1.38	0.62	0.5	0.81	-25,631,517	-25,651,518	559317
#266	0.03	0.79	0.3	-31.5	0.1	59.04	3.12	0.51	0.18	0.6	-8,511,538	-8,531,539	70686
#267	0.04	1.06	0.36	9.25	0.19	99.87	1.87	0.42	0.22	0.61	-14,081,536	-14,101,537	103972
#268	0.03	0.87	0.34	-78.96	0.11	12.99	3.13	0.56	0.21	0.61	-11,551,525	-11,571,526	95744
#269	0.04	0.81	0.27	52.43	0.23	-36.47	1.15	0.76	0.23	0.84	-40,651,533	-40,671,534	111639
#270	0.51	3.39	1.11	-8.49	0.59	-98.81	1.89	0.55	0.8	0.72	-5,251,501	-5,271,502	1415403
#271	0.17	1.98	0.71	-41.74	0.32	48.12	2.24	0.53	0.46	0.65	-3,051,502	-3,071,503	464695
#272	0.02	0.51	0.18	71.57	0.12	-19.65	1.49	0.85	0.15	0.82	-21,611,530	-21,631,531	48246
#273	0.03	0.77	0.27	-40.03	0.15	49.4	1.77	0.66	0.2	0.75	-27,031,526	-27,051,527	87516
#274	0.08	1.35	0.5	-4.69	0.21	85.6	2.35	0.53	0.31	0.63	-28,961,523	-28,981,524	215237
#275	0.13	1.96	0.81	-85.38	0.24	3.95	3.42	0.41	0.4	0.49	-34,981,484	-35,001,485	353617
#276	0.15	2	0.76	63.98	0.24	-26.57	3.22	0.46	0.43	0.57	-13,541,491	-13,561,492	413457
#277	0.02	0.54	0.19	25.46	0.12	-65.22	1.62	0.77	0.15	0.79	-2,551,525	-2,571,526	49555
#278	0.02	0.78	0.33	24.68	0.07	-63.43	4.55	0.43	0.16	0.49	-38,871,520	-38,891,521	59279
#279	0.03	0.73	0.3	-65.56	0.12	23.2	2.38	0.67	0.19	0.64	-36,681,514	-36,701,515	78540
#280	0.03	0.74	0.26	10.95	0.13	100.62	1.94	0.62	0.19	0.72	-14,751,518	-14,771,519	76296
#281	0.18	2.05	0.67	-52.43	0.3	37.18	2.25	0.52	0.47	0.71	-20,771,490	-20,791,491	492745
#282	0.03	0.96	0.4	-60.26	0.1	28.61	3.86	0.47	0.21	0.53	-17,231,502	-17,251,503	97427
#283	0.11	1.58	0.65	-67.93	0.23	22.93	2.83	0.57	0.38	0.58	-33,361,483	-33,381,484	318087
#284	0.38	3.13	1.29	80.54	0.36	-9.25	3.63	0.49	0.7	0.54	-33,891,435	(-637,1436)	1066087
#285	0.07	1.22	0.46	-80.71	0.2	9.46	2.29	0.59	0.3	0.65	-42,191,487	-42,211,488	194293

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#286	0.04	0.97	0.37	82.41	0.12	-7.59	3	0.51	0.22	0.59	-28,241,490	-28,261,491	107151
#287	0.02	0.55	0.19	-28.81	0.11	59.74	1.64	0.67	0.14	0.77	-28,541,501	-28,561,502	45254
#288	0.02	0.61	0.21	-17.74	0.1	70.02	2.24	0.61	0.15	0.71	-39,511,500	-39,531,501	50490
#289	0.04	0.78	0.28	-49.76	0.15	40.6	1.85	0.76	0.22	0.78	-27,121,493	-27,141,494	103785
#290	0.01	0.37	0.12	61.7	0.09	-26.57	1.32	0.82	0.11	0.89	-15,001,499	-15,021,500	25432
#291	0.05	0.9	0.32	-35.71	0.23	53.53	1.38	0.77	0.25	0.78	-37,261,493	-37,281,494	140250
#292	0.04	0.98	0.36	-84.81	0.18	5.19	2	0.56	0.23	0.65	-6,171,483	-6,191,484	121363
#293	0.18	2.05	0.7	54.46	0.38	-35.39	1.85	0.53	0.48	0.68	-14,331,462	-14,351,463	500038
#294	0.01	0.49	0.17	-50.91	0.1	38.66	1.61	0.75	0.14	0.8	-7,751,494	-7,771,495	40392
#295	0.56	3.47	1.17	-20.09	0.6	70.08	1.94	0.59	0.85	0.73	-21,311,440	(-589,1441)	1577906
#296	0.03	0.84	0.31	-12.2	0.12	78.69	2.47	0.61	0.21	0.68	-26,321,492	-26,341,493	96305
#297	0.06	1.52	0.59	-66.28	0.12	24.78	5.03	0.32	0.27	0.46	-17,281,461	-17,301,462	164186
#298	0.04	1.04	0.41	-27.6	0.13	63.43	3.17	0.49	0.23	0.57	-24,521,481	-24,541,482	118558
#299	0.07	1.36	0.53	55.08	0.19	-34.38	2.81	0.47	0.3	0.56	-27,541,464	-27,561,465	193919
#300	0.02	0.57	0.21	74.36	0.11	-12.99	1.95	0.77	0.16	0.75	-27,811,482	-27,831,483	56287
#301	0.09	1.22	0.44	-30.41	0.29	59.86	1.49	0.77	0.34	0.79	-35,601,472	-35,621,473	258434
#302	0.19	2.07	0.66	10.62	0.39	100.84	1.7	0.55	0.49	0.73	-22,491,460	-22,511,461	524535
#303	0.02	0.62	0.21	-59.42	0.14	30.96	1.46	0.78	0.17	0.84	-18,891,474	-18,911,475	67133
#304	0.01	0.5	0.16	-49.09	0.09	41.19	1.87	0.66	0.13	0.79	-28,951,477	-28,971,478	36091
#305	0.09	1.34	0.53	-9.75	0.17	81.47	3.21	0.61	0.33	0.63	-39,981,472	-40,001,473	242913
#306	0.27	2.66	0.97	-48.08	0.31	41.76	3.15	0.47	0.58	0.6	-29,051,432	(-2835,1433)	747813
#307	0.03	0.68	0.24	-59.04	0.13	29.74	1.81	0.69	0.18	0.76	-25,061,463	-25,081,464	71621
#308	0.17	2.12	0.81	-68.63	0.25	21.45	3.28	0.49	0.47	0.58	-26,421,428	-26,441,429	487135
#309	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-26,391,474	-26,411,475	187
#310	0.54	3.87	1.43	-46.39	0.51	43.7	2.82	0.45	0.83	0.58	-29,691,401	-1,351,402	1514513
#311	0.02	0.49	0.16	36.87	0.13	-52.43	1.22	0.85	0.14	0.88	-37,191,465	-37,211,466	45628
#312	0.01	0.35	0.11	12.99	0.07	-75.96	1.62	0.67	0.09	0.83	-39,301,466	-39,321,467	17952
#313	0.04	0.93	0.38	-48.47	0.12	39.29	3.29	0.52	0.21	0.56	-38,161,451	-38,181,452	101541
#314	0.03	0.84	0.34	-60.95	0.13	29.74	2.55	0.59	0.21	0.61	-10,191,447	-10,211,448	92565
#315	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-26,351,464	-26,371,465	187
#316	0.06	1.04	0.35	51.55	0.26	-38.66	1.36	0.72	0.28	0.79	-23,231,442	-23,251,443	172040
#317	0.74	4.68	1.7	-22.62	0.54	67.71	3.16	0.42	0.97	0.57	-35,901,387	(-568,1388)	2064293
#318	0.01	0.45	0.16	-63.43	0.09	26.57	1.8	0.84	0.13	0.8	-39,581,452	-39,601,453	37961
#319	0.03	0.73	0.27	57.26	0.17	-32.91	1.64	0.74	0.2	0.74	-25,951,447	-25,971,448	88264
#320	0.01	0.42	0.15	-25.2	0.07	60.26	2.33	0.72	0.11	0.73	-19,591,450	-19,611,451	27676
#321	0.03	0.72	0.25	42.4	0.16	-47.12	1.63	0.62	0.18	0.71	-28,471,442	-28,491,443	72369
#322	0.06	1.13	0.4	-29.74	0.19	61.19	2.12	0.63	0.29	0.72	-6,711,431	-6,731,432	179894
#323	0.04	1.12	0.42	27.55	0.14	-61.93	3.05	0.4	0.23	0.53	-23,871,439	-23,891,440	112387
#324	0.03	0.66	0.22	-66.25	0.14	23.63	1.56	0.74	0.18	0.81	-37,051,440	-37,071,441	71247
#325	0.05	1.22	0.47	74.74	0.13	-14.93	3.67	0.42	0.25	0.54	-19,111,423	-19,131,424	137819
#326	0.08	1.48	0.51	-39.81	0.2	51.71	2.58	0.45	0.32	0.62	-1,681,426	-1,701,427	219351

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#327	0.72	4.57	1.49	5.68	0.76	95.59	1.97	0.44	0.96	0.65	-9,201,394	-9,221,395	2027641
#328	0.49	3.98	1.44	46.15	0.44	-43.49	3.28	0.39	0.79	0.55	-27,411,380	(-387,1381)	1372767
#329	0.01	0.4	0.15	-32.01	0.03	56.31	5.23	0.41	0.08	0.52	-22,921,432	-22,941,433	14212
#330	0.02	0.82	0.35	-21.8	0.07	-110.56	5.04	0.38	0.16	0.46	-37,431,429	-37,451,430	57783
#331	0.17	2.08	0.7	-37.41	0.39	52.65	1.79	0.51	0.47	0.67	-25,261,410	-25,281,411	489940
#332	0.8	4.47	1.5	-5	0.78	85.19	1.93	0.5	1.01	0.67	-30,821,378	(-740,1379)	2245870
#333	0.02	0.69	0.26	-51.34	0.08	36.87	3.2	0.5	0.16	0.6	-10,281,416	-10,301,417	54043
#334	0.11	1.53	0.6	76.72	0.21	-13.5	2.88	0.59	0.37	0.62	-28,361,391	-28,381,392	307054
#335	0.08	1.31	0.46	-17.47	0.25	72.76	1.86	0.58	0.32	0.69	-41,621,413	-41,641,414	221595
#336	0.03	0.7	0.23	32.01	0.17	-58.57	1.34	0.77	0.19	0.84	-37,831,413	-37,851,414	82841
#337	0.02	0.62	0.22	-31.33	0.13	60.26	1.67	0.73	0.17	0.76	-21,971,416	-21,991,417	61897
#338	0.1	1.86	0.63	-23.89	0.27	64.98	2.31	0.36	0.36	0.57	-3,321,396	-3,341,397	280313
#339	0.01	0.34	0.11	21.04	0.07	-69.44	1.63	0.71	0.09	0.81	-39,681,414	-39,701,415	18513
#340	0.09	1.37	0.49	39.56	0.26	-51.34	1.86	0.64	0.35	0.71	-1,131,395	-1,151,396	266101
#341	0.06	1.05	0.37	63.43	0.24	-25.71	1.49	0.68	0.28	0.76	-24,601,398	-24,621,399	168300
#342	0.11	1.56	0.63	-77.96	0.21	11.31	3.01	0.58	0.38	0.6	-33,101,379	-33,121,380	315282
#343	0.02	0.53	0.21	-18.43	0.09	73.3	2.42	0.79	0.15	0.72	-38,671,408	-38,691,409	48807
#344	0.04	0.9	0.33	-7.13	0.21	-96.84	1.6	0.69	0.24	0.72	-6,531,395	-6,551,396	124729
#345	0.15	2.03	0.69	-64.94	0.33	24.68	2.09	0.46	0.44	0.63	-2,431,373	-2,451,374	420002
#346	0.01	0.5	0.2	-31.76	0.08	57.99	2.62	0.73	0.14	0.68	-18,401,399	-18,421,400	41140
#347	0.01	0.5	0.19	67.75	0.07	-20.56	2.78	0.52	0.12	0.59	-23,081,392	-23,101,393	29359
#348	0.02	0.63	0.24	-39.56	0.1	48.37	2.48	0.61	0.16	0.64	-10,571,392	-10,591,393	54230
#349	0.03	0.79	0.26	34.7	0.16	-55.49	1.63	0.68	0.21	0.81	-32,561,392	-32,581,393	95557
#350	0.03	0.7	0.25	56.82	0.14	-32.74	1.87	0.69	0.19	0.73	-12,271,385	-12,291,386	76109
#351	0.02	0.63	0.21	-59.42	0.1	30.96	2.19	0.55	0.15	0.71	-32,021,387	-32,041,388	48246
#352	0.01	0.48	0.17	-10.78	0.06	81.87	3.02	0.5	0.11	0.62	-8,191,393	-8,211,394	26180
#353	0.32	2.66	0.88	35.17	0.5	-55.01	1.76	0.57	0.64	0.73	-5,941,355	-5,961,356	898535
#354	0.02	0.62	0.23	-24.78	0.12	66.8	1.88	0.68	0.16	0.69	-15,971,387	-15,991,388	57596
#355	0.43	3.02	1.08	-53.3	0.53	36.87	2.03	0.6	0.74	0.69	-10,761,337	-10,781,338	1218679
#356	0.21	2.45	0.93	-26.57	0.32	62.78	2.9	0.45	0.52	0.56	-21,941,359	-21,961,360	600831
#357	0.06	1.17	0.35	-26.57	0.26	63.43	1.36	0.54	0.27	0.79	-23,321,375	-23,341,376	164186
#358	0.02	0.75	0.31	-41.76	0.07	45	4.42	0.42	0.15	0.5	-7,671,376	-7,691,377	52173
#359	0.05	1.27	0.52	-34.19	0.12	56.31	4.44	0.36	0.24	0.46	-36,951,372	-36,971,373	127534
#360	0.26	2.73	1.03	24.33	0.3	-66.19	3.4	0.44	0.58	0.56	-42,391,354	(-1631,1355)	731357
#361	0.01	0.44	0.16	38.66	0.13	-50.19	1.23	0.94	0.14	0.87	-40,991,379	-41,011,380	41327
#362	0.07	1.3	0.49	-80.38	0.2	9.46	2.46	0.54	0.3	0.62	-26,801,355	-26,821,356	203269
#363	0.04	1	0.37	-59.47	0.14	32.74	2.72	0.52	0.23	0.62	-34,281,359	-34,301,360	114070
#364	0.02	0.68	0.23	-21.04	0.1	70.02	2.38	0.46	0.15	0.64	-32,211,372	-32,231,373	47311
#365	0.19	2.19	0.77	-14.77	0.35	74.98	2.22	0.49	0.49	0.64	-41,281,354	(-3959,1355)	530893
#366	0.01	0.31	0.1	28.61	0.08	-60.95	1.22	0.94	0.1	0.93	-18,381,376	-18,401,377	20009
#367	0.04	0.91	0.32	-45	0.15	45	2.15	0.58	0.22	0.68	-17,101,360	-17,121,361	106020

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#368	0.07	1.16	0.47	17.18	0.2	-73.74	2.3	0.69	0.3	0.65	-38,061,364	-38,081,365	204578
#369	0.03	0.96	0.41	-13.76	0.08	77.47	5.47	0.38	0.19	0.46	-11,721,369	-11,741,370	78166
#370	0.01	0.56	0.18	-7.77	0.11	81.25	1.69	0.57	0.13	0.74	-24,241,368	-24,261,369	39644
#371	0.04	0.75	0.28	58.17	0.19	-30.96	1.46	0.8	0.21	0.77	-38,901,362	-38,921,363	100419
#372	0.02	0.75	0.29	61.26	0.1	-28.61	2.82	0.5	0.17	0.58	-18,661,358	-18,681,359	62271
#373	0.02	0.49	0.17	39.09	0.13	-50.19	1.32	0.9	0.15	0.87	-32,491,365	-32,511,366	47498
#374	0.17	2	0.79	-43.32	0.27	47.49	2.96	0.54	0.47	0.6	-25,641,338	-25,661,339	482273
#375	0.06	1.39	0.54	-49.3	0.14	40.24	3.87	0.42	0.29	0.53	-20,171,342	-20,191,343	181764
#376	0.02	0.75	0.31	-80.79	0.09	10.3	3.35	0.56	0.18	0.58	-15,361,349	-15,381,350	69751
#377	0.02	0.66	0.25	27.41	0.12	-61.7	2.06	0.73	0.18	0.72	-39,501,357	-39,521,358	69751
#378	0.15	2.23	0.75	-80.03	0.27	10.62	2.84	0.38	0.44	0.58	-16,271,323	-16,291,324	425051
#379	0.02	0.6	0.22	34.29	0.1	-55.01	2.18	0.68	0.16	0.72	-18,321,355	-18,341,356	54043
#380	0.09	1.16	0.41	-35.27	0.32	54.29	1.27	0.8	0.33	0.81	-1,741,347	-1,761,348	240482
#381	0.06	1.12	0.4	-83.02	0.18	7.77	2.22	0.56	0.27	0.66	-13,481,337	-13,501,338	156519
#382	0.2	2.38	0.96	-75.26	0.25	14.93	3.8	0.45	0.51	0.53	-34,671,298	-34,691,299	572407
#383	0.03	0.87	0.36	13.09	0.09	-79.7	3.95	0.51	0.2	0.55	-2,981,355	-3,001,356	86394
#384	0.04	1.1	0.45	-50.86	0.1	41.63	4.6	0.4	0.22	0.49	-14,371,337	-14,391,338	107525
#385	0.03	0.92	0.36	74.41	0.13	-14.93	2.88	0.51	0.21	0.58	-7,891,337	-7,911,338	96866
#386	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-16,991,358	-17,011,359	187
#387	0.02	0.71	0.24	80.22	0.11	-8.75	2.24	0.54	0.17	0.69	-9,621,343	-9,641,344	61149
#388	0.03	1.01	0.4	81.87	0.1	-9.46	4.07	0.42	0.21	0.51	-32,901,336	-32,921,337	94996
#389	0.25	2.49	1.01	12.13	0.3	102.53	3.36	0.51	0.57	0.56	-12,161,336	-12,181,337	703494
#390	0.01	0.3	0.12	-66.8	0.04	21.8	2.83	0.75	0.08	0.67	-15,841,348	-15,861,349	15334
#391	0.02	0.55	0.18	-20.85	0.11	68.96	1.61	0.65	0.14	0.76	-4,301,344	-4,321,345	43384
#392	0.12	1.55	0.55	-11.98	0.27	77.66	2.06	0.61	0.39	0.7	-24,521,335	-24,541,336	328372
#393	0.04	0.93	0.34	-47.91	0.19	41.42	1.84	0.51	0.21	0.62	-32,411,334	-32,431,335	98175
#394	1.28	6.58	2.58	78.3	0.61	-11.61	4.23	0.37	1.28	0.5	-26,381,188	-2,452,386	3586473
#395	0.01	0.45	0.17	57.09	0.07	-35.54	2.35	0.65	0.11	0.69	-13,781,335	-13,801,336	28798
#396	0.01	0.52	0.19	25.46	0.09	-63.43	2.08	0.68	0.14	0.71	-8,451,333	-8,471,334	40205
#397	0.05	1.04	0.41	52.22	0.15	-38.16	2.84	0.53	0.24	0.58	-11,421,316	-11,441,317	127908
#398	0.04	0.8	0.27	77.66	0.2	-11.77	1.34	0.76	0.22	0.83	-40,341,317	-40,361,318	109769
#399	0.03	0.94	0.34	-61.61	0.12	28.3	2.85	0.48	0.21	0.61	-23,521,317	-23,541,318	95557
#400	0.06	1.17	0.41	-77.35	0.21	13.5	1.95	0.58	0.28	0.69	-27,021,307	-27,041,308	177650
#401	0.1	1.48	0.53	-24.59	0.24	64.29	2.17	0.55	0.35	0.66	-22,371,309	-22,391,310	269841
#402	0.03	0.83	0.32	-66.04	0.11	26.57	2.94	0.6	0.21	0.64	-35,081,310	-35,101,311	93500
#403	0.18	2.02	0.63	-8.24	0.43	-98.75	1.46	0.55	0.48	0.76	-37,631,301	-37,651,302	504152
#404	0.02	0.74	0.28	-42.61	0.1	48.37	2.82	0.55	0.17	0.63	-35,671,314	-35,691,315	66385
#405	0.52	3.72	1.27	-32.36	0.51	57.32	2.46	0.48	0.82	0.65	-29,851,279	-661,280	1470194
#406	0.67	4.26	1.55	-10.01	0.63	80.29	2.46	0.46	0.92	0.59	-20,081,277	(-281,1278)	1873553
#407	0.04	0.83	0.33	-38.88	0.14	49.76	2.34	0.68	0.22	0.67	-35,871,306	-35,891,307	104720
#408	0.17	1.93	0.69	-79.09	0.37	11.31	1.84	0.58	0.47	0.68	-5,721,270	-5,741,271	482647

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#409	0.18	3	1.03	85.91	0.38	-3.73	2.74	0.25	0.48	0.47	-2,501,250	-2,521,251	507892
#410	0.04	0.93	0.37	-69.15	0.12	19.65	3.02	0.59	0.23	0.62	-34,371,293	-34,391,294	114631
#411	0.03	0.71	0.26	68.2	0.12	-19.65	2.17	0.66	0.18	0.69	-11,191,298	-11,211,299	73865
#412	0.02	0.56	0.23	-21.04	0.09	68.2	2.59	0.67	0.15	0.64	-21,291,306	-21,311,307	47311
#413	0.08	1.41	0.52	24.96	0.19	-64.54	2.75	0.51	0.32	0.62	-21,821,289	-21,841,290	229075
#414	0.04	0.99	0.33	-69.78	0.17	20.22	2	0.54	0.23	0.7	-13,241,294	-13,261,295	117249
#415	0.07	1.21	0.39	-44.14	0.26	46.27	1.49	0.62	0.3	0.78	-24,251,290	-24,271,291	200090
#416	0.21	2.55	1	-16.65	0.26	73.81	3.78	0.41	0.52	0.52	-32,251,286	-32,271,287	587180
#417	0.02	0.67	0.25	-51.63	0.12	39.29	2.15	0.58	0.16	0.65	-33,661,293	-33,681,294	58718
#418	0.03	0.65	0.21	43.45	0.2	-45	1.09	0.77	0.18	0.84	-18,691,297	-18,711,298	71808
#419	0.07	1.28	0.47	-21.25	0.2	68.63	2.35	0.55	0.3	0.64	-22,831,287	-22,851,288	201212
#420	0.22	2.3	0.86	-24.13	0.35	65.22	2.45	0.52	0.53	0.61	-40,511,270	(-3009,1271)	608124
#421	0.04	1.01	0.37	-36.87	0.16	51.34	2.34	0.55	0.24	0.65	-12,071,286	-12,091,287	124992
#422	0.01	0.39	0.16	-71.57	0.06	15.95	2.61	0.74	0.11	0.69	-39,891,293	-39,911,294	25245
#423	0.04	1.16	0.48	-74.05	0.1	14.04	4.71	0.39	0.23	0.48	-18,851,270	-18,871,271	116688
#424	0.03	0.81	0.31	-18.43	0.1	70.02	3.24	0.49	0.18	0.58	-35,341,284	-35,361,285	71060
#425	0.17	1.9	0.68	16.04	0.35	106.31	1.95	0.59	0.47	0.69	-14,911,271	-14,931,272	478720
#426	0.09	1.18	0.4	-39.21	0.34	50.91	1.19	0.81	0.34	0.85	-15,591,275	-15,611,276	254320
#427	0.02	0.57	0.2	-21.37	0.1	70.02	2.11	0.66	0.15	0.73	-4,161,285	-4,181,286	47311
#428	0.02	0.61	0.23	50.71	0.09	-41.19	2.67	0.51	0.14	0.6	-13,741,280	-13,761,281	42262
#429	0.05	1.18	0.47	19.38	0.11	-68.96	4.11	0.44	0.25	0.53	-23,771,274	-23,791,275	136510
#430	0.53	3.47	1.23	-20.6	0.56	69.44	2.2	0.55	0.82	0.67	-8,831,220	-8,851,221	1485154
#431	0.13	1.43	0.47	27.01	0.38	-63.43	1.22	0.8	0.41	0.87	-27,711,265	-27,731,266	362780
#432	0.03	0.77	0.28	-20.56	0.18	69.15	1.52	0.7	0.2	0.73	-41,531,274	-41,551,275	92378
#433	0.31	2.44	0.89	62.73	0.5	-26.98	1.77	0.64	0.62	0.7	-26,981,232	(-2321,1233)	855151
#434	0.07	1.17	0.37	29.43	0.25	-60.95	1.45	0.66	0.3	0.82	-31,231,265	-31,251,266	197025
#435	0.01	0.37	0.13	71.57	0.08	-18.43	1.67	0.82	0.11	0.84	-34,931,273	-34,951,274	25806
#436	2.31	8.47	3.28	88	1.01	-1.85	3.23	0.4	1.71	0.52	-42,161,088	-2,292,417	6459728
#437	0.12	1.74	0.69	-77.76	0.21	11.31	3.33	0.5	0.39	0.56	-11,381,234	-11,401,235	335478
#438	0.01	0.52	0.22	-56.89	0.06	33.69	3.81	0.56	0.12	0.55	-18,001,265	-18,021,266	33473
#439	0.06	1.05	0.4	-52.43	0.2	38.29	2.03	0.65	0.27	0.67	-41,001,256	-41,021,257	158576
#440	1.67	6.86	1.9	64.54	1.56	-25.36	1.21	0.45	1.46	0.77	-3,881,144	-3,902,062	4686220
#441	0.34	3.58	1.2	43.62	0.46	-46.43	2.59	0.34	0.66	0.55	-21,781,222	-21,801,223	959871
#442	0.02	0.62	0.24	80.22	0.08	-11.31	2.89	0.64	0.16	0.65	-22,991,259	-23,011,260	53669
#443	0.01	0.5	0.17	-43.03	0.12	47.73	1.38	0.69	0.13	0.8	-35,461,265	-35,481,266	39083
#444	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-991,272	-1,011,273	187
#445	0.01	0.34	0.12	-36.87	0.07	54.46	1.74	0.78	0.1	0.78	-32,751,268	-32,771,269	20009
#446	0.11	1.58	0.58	61.26	0.27	-28.89	2.13	0.54	0.37	0.64	-1,121,240	-1,141,241	301818
#447	0.03	0.75	0.27	-58.74	0.13	29.74	2.03	0.57	0.18	0.68	-34,081,257	-34,101,258	72182
#448	0.01	0.48	0.17	60.95	0.11	-26.57	1.53	0.72	0.13	0.78	-17,291,261	-17,311,262	37587
#449	0.09	1.28	0.44	-74.93	0.29	14.83	1.53	0.72	0.34	0.78	-37,281,248	-37,301,249	260678

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#450	0.06	0.94	0.35	49.69	0.24	-40.82	1.49	0.85	0.28	0.78	-38,581,254	-38,601,255	166617
#451	0.49	3.76	1.27	-42.92	0.55	46.81	2.32	0.44	0.79	0.62	-16,311,216	(-1479,1217)	1379312
#452	0.09	1.48	0.6	-30.03	0.24	59.04	2.54	0.53	0.34	0.57	-7,221,245	-7,241,246	260304
#453	0.21	2.69	1.07	23.43	0.26	-65.85	4.12	0.37	0.52	0.49	-24,021,238	-24,041,239	595782
#454	0.11	1.67	0.65	-52.7	0.22	36.03	2.91	0.5	0.38	0.58	-17,521,230	-17,541,231	311168
#455	0.02	0.58	0.22	-34.29	0.1	59.04	2.28	0.6	0.14	0.66	-30,681,255	-30,701,256	45815
#456	0.07	1.16	0.38	-50.19	0.27	40.03	1.44	0.69	0.31	0.8	-13,301,244	-13,321,245	207570
#457	0.02	0.69	0.25	-29.05	0.12	61.7	2.09	0.58	0.17	0.66	-22,601,251	-22,621,252	61897
#458	0.02	0.59	0.21	48.18	0.13	-42.51	1.57	0.74	0.16	0.77	-32,441,248	-32,461,249	56287
#459	0.02	0.61	0.21	27.55	0.13	-63.43	1.66	0.79	0.17	0.81	-24,971,250	-24,991,251	64141
#460	0.02	0.49	0.17	37.41	0.12	-50.71	1.51	0.85	0.14	0.82	-10,951,247	-10,971,248	45067
#461	0.03	1.04	0.45	-51.67	0.1	41.63	4.55	0.36	0.2	0.44	-18,121,231	-18,141,232	86394
#462	0.01	0.46	0.16	-53.13	0.09	33.69	1.85	0.68	0.12	0.74	-30,301,247	-30,321,248	31977
#463	0.26	2.46	0.84	-58.94	0.54	30.82	1.55	0.54	0.57	0.68	-33,311,212	(-2586,1213)	725560
#464	0.03	0.72	0.28	74.74	0.11	-17.1	2.51	0.66	0.19	0.67	-12,721,234	-12,741,235	76857
#465	0.03	0.75	0.28	71.57	0.14	-17.35	2.08	0.69	0.2	0.7	-35,621,232	-35,641,233	86768
#466	0.06	0.99	0.38	60.71	0.18	-30.07	2.14	0.71	0.27	0.69	-35,891,228	-35,911,229	155771
#467	0.1	1.56	0.61	35.8	0.2	-55.01	3.08	0.5	0.35	0.57	-1,791,223	-1,811,224	273207
#468	0.19	2.17	0.83	-83.22	0.34	6.95	2.46	0.52	0.5	0.6	-15,351,200	-15,371,201	542861
#469	0.01	0.49	0.18	-63.43	0.07	29.74	2.77	0.56	0.12	0.64	-23,181,235	-23,201,236	29920
#470	0.04	0.77	0.27	72.12	0.19	-17.65	1.41	0.88	0.23	0.86	-37,831,229	-37,851,230	115753
#471	0.04	1	0.36	-6.48	0.15	83.66	2.45	0.45	0.21	0.59	-20,961,231	-20,981,232	99510
#472	0.04	0.92	0.3	4.76	0.19	94.97	1.56	0.65	0.24	0.8	-11,861,226	-11,881,227	122111
#473	0.02	0.52	0.18	-69.15	0.12	19.65	1.51	0.8	0.15	0.81	-13,521,222	-13,541,223	48807
#474	0.03	0.74	0.28	71.03	0.11	-17.1	2.49	0.62	0.19	0.67	-31,001,214	-31,021,215	76109
#475	0.02	0.9	0.4	84.17	0.05	-9.46	8.1	0.32	0.16	0.41	-10,711,205	-10,731,206	58531
#476	0.17	1.93	0.72	-51.95	0.33	38	2.16	0.56	0.46	0.64	-19,631,192	-19,651,193	463760
#477	0.1	1.53	0.59	-22.99	0.19	67.75	3.02	0.51	0.35	0.6	-27,661,204	-27,681,205	267971
#478	0.02	0.61	0.22	-51.01	0.1	38.66	2.11	0.73	0.16	0.75	-40,411,215	-40,431,216	59653
#479	0.07	1.24	0.47	-11.11	0.17	78.69	2.8	0.54	0.29	0.62	-12,241,211	-12,261,212	184569
#480	0.02	0.65	0.23	36.47	0.12	-53.13	1.91	0.67	0.17	0.73	-23,551,212	-23,571,213	63954
#481	0.26	2.59	0.9	-42.41	0.36	46.85	2.5	0.48	0.57	0.64	-29,901,189	-29,921,190	714901
#482	0.04	0.95	0.37	19.23	0.14	-69.44	2.67	0.56	0.23	0.61	-20,391,213	-20,411,214	112387
#483	0.02	0.63	0.25	14.93	0.07	-75.96	3.77	0.52	0.14	0.57	-23,991,215	-24,011,216	45628
#484	0.03	0.73	0.22	-6.34	0.19	82.57	1.17	0.65	0.19	0.84	-19,201,206	-19,221,207	76857
#485	0.3	3.49	1.2	12.15	0.43	102.17	2.82	0.31	0.62	0.52	-37,511,186	(-1303,1187)	849354
#486	0.01	0.44	0.15	49.4	0.14	-40.24	1.08	0.88	0.13	0.88	-28,341,211	-28,361,212	38522
#487	0.06	1.1	0.34	-76.29	0.27	14.04	1.28	0.61	0.27	0.8	-10,101,195	-10,121,196	165682
#488	0.02	0.63	0.21	11.31	0.12	-78.69	1.67	0.76	0.17	0.83	-13,751,207	-13,771,208	66011
#489	0.19	1.98	0.72	-13.88	0.34	76.29	2.07	0.61	0.49	0.69	-32,431,189	-32,451,190	533698
#490	0.09	1.29	0.41	-80.73	0.31	9.21	1.32	0.71	0.35	0.85	-35,421,185	-35,441,186	264231

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#491	0.62	3.91	1.41	-21.37	0.66	68.86	2.15	0.51	0.89	0.63	-20,811,153	(-371,1154)	1749946
#492	0.07	1.35	0.56	14.44	0.16	104.74	3.47	0.47	0.29	0.53	-22,781,195	-22,801,196	191488
#493	0.01	0.7	0.28	-71.57	0.05	18.43	5.5	0.27	0.12	0.41	-18,731,188	-18,751,189	30107
#494	0.94	6.56	1.4	5.68	1.26	-84.44	1.11	0.28	1.1	0.78	-28,481,120	(-396,2743)	2645676
#495	0.07	1.09	0.35	-15.02	0.27	74.29	1.28	0.72	0.29	0.85	-34,251,184	-34,271,185	189057
#496	0.08	1.24	0.47	20.32	0.2	-68.63	2.33	0.66	0.32	0.69	-24,471,180	-24,491,181	229449
#497	0.03	0.68	0.25	-31.61	0.16	59.53	1.55	0.77	0.19	0.76	-34,711,190	-34,731,191	79288
#498	0.13	1.63	0.62	-61.75	0.25	29.05	2.46	0.62	0.41	0.66	-5,621,162	-5,641,163	369699
#499	0.04	0.91	0.34	73.3	0.14	-17.35	2.49	0.58	0.22	0.65	-2,611,176	-2,631,177	108460
#500	0.24	2.41	0.91	33.98	0.44	-55.71	2.08	0.52	0.56	0.61	-6,961,165	-6,981,166	680680
#501	0.11	1.59	0.55	2.56	0.29	93.27	1.91	0.57	0.38	0.7	-1,751,169	-1,771,170	320518
#502	0.04	1.14	0.46	-68.01	0.11	22.62	4.31	0.39	0.23	0.49	-40,361,165	-40,381,166	112387
#503	0.02	0.6	0.22	-52.7	0.11	36.03	1.94	0.74	0.16	0.76	-23,371,174	-23,391,175	58718
#504	0.01	0.52	0.18	-20.85	0.1	-109.98	1.92	0.64	0.13	0.73	-31,781,181	-31,801,182	39270
#505	0.06	1.43	0.55	-50.41	0.13	39.81	4.32	0.38	0.28	0.51	-19,871,150	-19,891,151	171479
#506	0.47	3.87	1.41	80.65	0.41	-9.27	3.47	0.39	0.77	0.55	-16,811,090	(-1590,1091)	1311618
#507	0.02	0.63	0.22	-55.71	0.15	33.69	1.48	0.73	0.17	0.79	-29,201,161	-29,221,162	65637
#508	0.04	0.81	0.27	-33.69	0.21	57.53	1.24	0.7	0.22	0.81	-34,601,161	-34,621,162	101728
#509	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-37,141,170	-37,161,171	187
#510	0.02	0.58	0.18	-35.84	0.16	53.13	1.11	0.77	0.16	0.88	-18,421,160	-18,441,161	56661
#511	0.05	1.09	0.42	-52.03	0.17	39.09	2.52	0.58	0.26	0.62	-16,271,147	-16,291,148	153153
#512	0.03	0.77	0.28	-52.13	0.19	37.87	1.5	0.69	0.2	0.73	-27,561,155	-27,581,156	92378
#513	0.8	4.89	1.67	84.65	0.6	-5.48	2.78	0.42	1.01	0.61	-41,061,068	-2,882,978	2249049
#514	0	0.22	0.08	-18.43	0.03	75.96	2.3	0.76	0.06	0.8	-22,921,162	-22,941,163	8415
#515	0.02	0.57	0.22	21.8	0.11	-67.38	2.07	0.74	0.16	0.71	-38,821,156	-38,841,157	54230
#516	0.01	0.4	0.13	-29.74	0.08	60.95	1.57	0.74	0.11	0.84	-22,331,156	-22,351,157	26741
#517	0.02	0.64	0.25	-31.61	0.1	59.04	2.62	0.62	0.16	0.64	-17,981,150	-18,001,151	56100
#518	0.04	0.83	0.3	40.6	0.18	-50.53	1.67	0.74	0.23	0.75	-2,461,140	-2,481,141	113509
#519	0.01	0.43	0.15	56.31	0.11	-32.47	1.38	0.71	0.12	0.78	-10,271,144	-10,291,145	29359
#520	0.58	4.15	1.4	-58.63	0.49	31.29	2.86	0.42	0.86	0.61	-22,211,073	(-438,1074)	1613436
#521	0.01	0.5	0.19	-64.54	0.06	23.2	3.05	0.56	0.12	0.62	-10,041,135	-10,061,136	30855
#522	0.45	3.5	1.26	-5.56	0.5	84.38	2.52	0.47	0.76	0.6	-23,821,112	(-992,1113)	1271787
#523	0.13	1.62	0.59	22.99	0.34	-67.17	1.74	0.64	0.41	0.7	-33,711,126	-33,731,127	373813
#524	0.15	1.51	0.51	-42.4	0.43	47.29	1.17	0.8	0.43	0.85	-35,891,119	-35,911,120	408221
#525	0.17	1.95	0.72	-31.52	0.29	59.04	2.51	0.57	0.47	0.65	-10,981,118	-11,001,119	486013
#526	0.02	0.68	0.27	15.71	0.1	-75.96	2.69	0.67	0.18	0.65	-38,601,132	-38,621,133	69564
#527	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-2,631,138	-2,651,139	187
#528	0.01	0.35	0.12	23.2	0.06	-66.8	2	0.76	0.1	0.77	-18,171,134	-18,191,135	20383
#529	0.15	2.02	0.7	3.33	0.33	92.86	2.15	0.47	0.44	0.63	-32,721,115	-32,741,116	426360
#530	0.02	0.63	0.24	14.04	0.09	-73.3	2.76	0.62	0.16	0.67	-23,091,129	-23,111,130	55165
#531	0.04	0.89	0.28	-39.17	0.21	51.34	1.36	0.68	0.23	0.82	-11,781,121	-11,801,122	120615

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#532	0.21	2.37	0.9	16.3	0.31	106.99	2.93	0.48	0.52	0.58	-1,661,113	-1,681,114	601579
#533	0.48	3.77	1.28	71.33	0.64	-18.67	2	0.42	0.78	0.61	-8,041,061	-8,061,062	1337985
#534	0.07	1.1	0.43	-57.53	0.18	32.28	2.32	0.69	0.29	0.68	-30,311,108	-30,331,109	184195
#535	0.02	0.49	0.18	50.53	0.11	-41.99	1.64	0.81	0.14	0.79	-37,641,121	-37,661,122	43945
#536	0.03	0.92	0.38	30.96	0.1	-59.04	4	0.43	0.19	0.51	-37,421,114	-37,441,115	82093
#537	0.16	2.03	0.78	-24.69	0.27	64.98	2.89	0.48	0.45	0.57	-21,191,098	-21,211,099	441133
#538	0.01	0.46	0.19	-55.62	0.08	32.01	2.44	0.7	0.12	0.66	-38,081,118	-38,101,119	33847
#539	0.02	0.61	0.22	-66.25	0.08	23.96	2.77	0.55	0.14	0.65	-10,181,114	-10,201,115	45628
#540	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-16,121,125	-16,141,126	187
#541	0.04	0.97	0.38	-66.16	0.11	22.62	3.62	0.48	0.21	0.55	-18,431,100	-18,451,101	99858
#542	0.03	0.85	0.33	-18.89	0.12	70.35	2.7	0.49	0.19	0.58	-36,531,113	-36,551,114	80223
#543	0.01	0.47	0.18	-27.76	0.05	63.43	3.2	0.49	0.11	0.6	-31,571,114	-31,591,115	24310
#544	0.02	0.63	0.23	34.82	0.13	-55.3	1.77	0.67	0.16	0.72	-2,501,110	-2,521,111	59279
#545	0.28	2.44	0.82	-7.41	0.43	82.33	1.92	0.59	0.6	0.73	-38,581,081	(-1598,1082)	786709
#546	0.01	0.47	0.19	-25.46	0.03	56.31	6.45	0.36	0.09	0.47	-17,761,111	-17,781,112	17765
#547	0.08	1.51	0.6	83.75	0.14	-6.71	4.29	0.42	0.31	0.52	-15,321,080	-15,341,081	216359
#548	0.01	0.45	0.15	-53.75	0.12	36.87	1.24	0.85	0.13	0.87	-21,811,106	-21,831,107	38335
#549	0.01	0.4	0.16	23.96	0.06	-66.8	2.59	0.7	0.11	0.66	-39,301,109	-39,321,110	25058
#550	0.02	0.52	0.2	-29.74	0.1	59.04	2.07	0.73	0.14	0.72	-36,751,106	-36,771,107	44132
#551	0.09	1.52	0.48	21.8	0.31	111.8	1.57	0.48	0.33	0.69	-9,341,092	-9,361,093	245344
#552	0.14	2.01	0.79	-59.74	0.22	31.33	3.61	0.42	0.42	0.52	-7,181,064	-7,201,065	379049
#553	0.03	0.76	0.25	74.58	0.19	-14.62	1.27	0.72	0.2	0.83	-6,871,087	-6,891,088	91443
#554	0.04	1.03	0.41	-74.85	0.13	14.04	3.02	0.53	0.24	0.59	-8,771,074	-8,791,075	124542
#555	0.46	4.04	1.42	-65.94	0.59	23.72	2.42	0.35	0.76	0.54	-14,341,030	-14,361,031	1280015
#556	0.03	0.78	0.33	82.87	0.07	-6.34	4.45	0.53	0.18	0.55	-25,001,076	-25,021,077	72369
#557	0.02	0.74	0.31	-69.62	0.1	19.98	3.19	0.53	0.17	0.56	-39,391,078	-39,411,079	65263
#558	0.13	1.89	0.7	-21.18	0.22	68.2	3.19	0.46	0.41	0.58	-5,261,061	-5,281,062	369886
#559	1.57	6.04	1.98	69.17	1.1	-20.85	1.79	0.54	1.41	0.72	-3,282,967	-3,501,946	4391508
#560	0.03	0.71	0.26	-77.28	0.16	11.89	1.64	0.82	0.2	0.79	-33,581,074	-33,601,075	92378
#561	0.98	4.94	1.77	-5.84	0.72	84.16	2.44	0.5	1.11	0.63	-35,981,033	-4,562,605	2731696
#562	0.48	3.65	1.34	-19.54	0.47	70.62	2.87	0.45	0.78	0.58	-10,331,037	-10,351,038	1348644
#563	0.03	0.81	0.31	-26.57	0.12	61.7	2.57	0.57	0.19	0.62	-9,861,078	-9,881,079	82841
#564	0.02	0.58	0.17	-70.71	0.14	20.56	1.24	0.75	0.16	0.92	-40,581,078	-40,601,079	55352
#565	0.07	1.34	0.52	52.05	0.24	-38.05	2.17	0.5	0.3	0.58	-12,391,057	-12,411,058	201025
#566	0.01	0.27	0.1	65.56	0.06	-23.2	1.59	0.99	0.08	0.86	-40,251,080	-40,271,081	15708
#567	0.17	2.19	0.75	88.75	0.32	-1.47	2.36	0.45	0.47	0.62	-16,081,036	-16,101,037	477037
#568	1.04	4.72	1.4	-37.41	1.14	52.56	1.22	0.59	1.15	0.82	-1,471,005	-1,492,475	2920940
#569	0.02	0.63	0.22	-33.11	0.09	56.31	2.54	0.58	0.15	0.69	-31,511,072	-31,531,073	51986
#570	0.01	0.34	0.1	71.57	0.08	-18.43	1.33	0.67	0.09	0.86	-18,091,077	-18,111,078	17204
#571	0.01	0.51	0.16	-53.13	0.12	36.87	1.33	0.66	0.13	0.81	-17,621,069	-17,641,070	38148
#572	0	0.22	0.08	66.04	0.05	-26.57	1.47	1.07	0.07	0.89	-39,561,075	-39,581,076	11220

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#573	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,911,078	-1,931,079	187
#574	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-2,821,077	-2,841,078	187
#575	0.02	0.67	0.26	-37.23	0.08	49.4	3.41	0.46	0.15	0.57	-10,021,066	-10,041,067	46750
#576	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,951,076	-1,971,077	187
#577	0.02	0.57	0.18	71.57	0.15	-19.44	1.23	0.73	0.16	0.86	-2,801,067	-2,821,068	53108
#578	0.02	0.8	0.32	-70.64	0.11	21.04	2.82	0.45	0.17	0.53	-21,611,061	-21,631,062	64141
#579	0.01	0.48	0.18	35.84	0.09	-56.31	2.05	0.74	0.13	0.72	-30,541,067	-30,561,068	37961
#580	0.45	3.81	1.26	-32.56	0.76	57.67	1.65	0.39	0.76	0.6	-19,261,019	(-1472,1020)	1262624
#581	0.05	1.13	0.39	-61.29	0.23	29.25	1.67	0.53	0.26	0.67	-15,601,048	-15,621,049	149787
#582	0.02	0.67	0.26	68.2	0.11	-22.62	2.49	0.65	0.17	0.65	-17,311,047	-17,331,048	64141
#583	0.16	2.01	0.78	-34.35	0.26	55.3	3.03	0.51	0.46	0.58	-20,331,033	-20,351,034	456280
#584	0.02	0.55	0.19	37.87	0.13	-50.19	1.46	0.82	0.16	0.85	-22,711,056	-22,731,057	54604
#585	0.04	0.81	0.31	4.51	0.15	-86.82	2.11	0.74	0.22	0.71	-30,951,053	-30,971,054	106964
#586	0.02	0.61	0.22	12.99	0.12	-77.91	1.86	0.72	0.16	0.75	-18,431,052	-18,451,053	59092
#587	0.22	2.82	0.99	-41.99	0.3	47.2	3.29	0.35	0.53	0.53	-17,491,006	-17,511,007	610742
#588	0.2	2.19	0.73	-48.15	0.48	41.55	1.53	0.52	0.5	0.68	-21,041,015	-21,061,016	550902
#589	0.34	3.09	1.13	-39.43	0.36	50.53	3.15	0.45	0.66	0.58	-5,091,006	-5,111,007	959684
#590	0.01	0.34	0.12	-23.2	0.08	66.04	1.55	0.93	0.11	0.84	-38,971,043	-38,991,044	24310
#591	0.01	0.48	0.16	-63.43	0.08	23.96	2.04	0.65	0.12	0.75	-40,491,038	-40,511,039	33847
#592	0.68	4.7	1.64	-61.78	0.65	27.86	2.54	0.39	0.93	0.57	-2,264,968	-183,217	1910392
#593	0.02	0.61	0.24	74.05	0.07	-14.04	3.53	0.59	0.15	0.62	-16,441,030	-16,461,031	48246
#594	0.09	1.41	0.56	-57.01	0.21	32.47	2.61	0.59	0.35	0.62	-25,931,014	-25,951,015	263857
#595	0.02	0.66	0.24	-13.57	0.08	78.69	2.93	0.54	0.15	0.63	-28,731,026	-28,751,027	51799
#596	0.03	0.71	0.28	15.26	0.11	-72.9	2.51	0.69	0.19	0.67	-38,321,027	-38,341,028	77044
#597	0.08	1.31	0.51	85.39	0.22	-4.24	2.3	0.62	0.33	0.65	-3,769,999	-37,711,000	237677
#598	1.19	5.36	2.04	81.93	0.73	-7.77	2.81	0.52	1.23	0.6	-620,902	-6,222,190	3337576
#599	0.04	1.03	0.43	71.22	0.1	-18.43	4.18	0.44	0.22	0.51	-29,531,000	-29,551,001	105094
#600	0.03	0.69	0.23	30.26	0.2	-60.26	1.15	0.86	0.2	0.89	-10,821,012	-10,841,013	89760
#601	0.03	0.69	0.25	-56.82	0.12	33.69	2.15	0.67	0.18	0.71	-11,151,009	-11,171,010	70873
#602	0.04	0.88	0.31	10.71	0.17	-78.69	1.85	0.64	0.22	0.73	-15,161,013	-15,181,014	109769
#603	0.04	0.87	0.31	26.57	0.15	-63.43	2.13	0.67	0.23	0.73	-29,061,006	-29,081,007	113509
#604	0.19	2.23	0.78	52.65	0.34	-37.15	2.31	0.49	0.5	0.64	-1,276,981	-1,278,982	544731
#605	0.13	1.75	0.63	-77.96	0.27	12.34	2.34	0.52	0.4	0.65	-3,937,981	-3,939,982	359788
#606	0.04	1.04	0.41	73.74	0.14	-17.35	2.98	0.45	0.22	0.55	-2,463,988	-2,465,989	109395
#607	0.05	1.2	0.47	-9.95	0.14	79.99	3.35	0.45	0.26	0.54	-26,681,004	-26,701,005	143803
#608	0.18	1.95	0.66	-51.01	0.37	39.64	1.78	0.6	0.48	0.72	-3,713,975	-3,715,976	507144
#609	0.02	0.77	0.3	-36.25	0.08	53.13	3.72	0.45	0.17	0.54	-3,908,999	-39,101,000	60027
#610	0.02	0.63	0.22	-31.33	0.14	59.04	1.54	0.75	0.17	0.79	-38,051,003	-38,071,004	66011
#611	0.13	1.58	0.52	-67.04	0.29	22.99	1.79	0.63	0.4	0.76	-894,978	-896,979	351373
#612	0.08	1.29	0.49	-62.15	0.21	27.55	2.31	0.59	0.32	0.65	-3,156,979	-3,158,980	219725
#613	0.02	0.84	0.35	-68.2	0.05	26.57	6.42	0.31	0.15	0.42	-3,979,980	-3,981,981	49181

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#614	0.02	0.64	0.25	75.07	0.08	-18.43	3.27	0.57	0.15	0.61	-1,838,981	-1,840,982	52734
#615	0.47	3.33	1.15	-11.87	0.5	77.77	2.3	0.54	0.78	0.67	-2,691,961	(-538,962)	1330131
#616	0.02	0.61	0.23	-12.09	0.09	79.7	2.56	0.63	0.15	0.66	-2,791,988	-2,793,989	51986
#617	0.14	1.81	0.64	-23.96	0.28	65.7	2.32	0.52	0.42	0.65	-1,981,969	-1,983,970	380358
#618	0.06	1	0.35	-32.57	0.22	56.89	1.56	0.77	0.28	0.8	-1,150,978	-1,152,979	170544
#619	0.02	0.55	0.21	71.57	0.1	-19.98	2.16	0.69	0.15	0.71	-4,037,980	-4,039,981	47124
#620	0.11	1.43	0.48	70.94	0.36	-19.65	1.3	0.68	0.37	0.79	-1,652,961	-1,654,962	309298
#621	0.07	1.15	0.45	-84.81	0.19	4.97	2.39	0.7	0.31	0.68	-3,359,960	-3,361,961	206822
#622	0.02	0.6	0.24	-42.27	0.11	48.01	2.21	0.65	0.15	0.63	-2,866,968	-2,868,969	51612
#623	0.05	1.22	0.52	-53.31	0.1	34.99	5.21	0.4	0.25	0.47	-3,176,950	-3,178,951	133518
#624	0.02	0.64	0.21	-45	0.1	45	2	0.53	0.15	0.71	-1,529,965	-1,531,966	48620
#625	0.08	1.27	0.46	66.14	0.25	-23.2	1.87	0.64	0.32	0.7	-2,549,951	-2,551,952	230010
#626	0.01	0.44	0.16	-26.57	0.05	63.43	3	0.56	0.11	0.64	-2,065,967	-2,067,968	24684
#627	0.07	1.47	0.59	-22.99	0.16	68.75	3.71	0.41	0.3	0.51	-3,614,960	-3,616,961	199155
#628	0.01	0.55	0.22	17.1	0.05	-71.57	4.3	0.5	0.12	0.55	-831,969	-833,970	33473
#629	0.03	0.76	0.25	29.05	0.17	-60.95	1.5	0.72	0.21	0.81	-954,958	-956,959	92565
#630	0.49	3.72	1.52	-70.49	0.38	19.98	3.97	0.44	0.79	0.52	-3,805,886	-673,887	1370710
#631	0.02	0.67	0.26	-38.66	0.1	51.34	2.5	0.57	0.16	0.62	-771,959	-773,960	57035
#632	0.13	1.68	0.61	-53.13	0.27	37.57	2.29	0.55	0.4	0.65	-3,866,932	-3,868,933	350438
#633	0.4	2.85	0.95	-35.88	0.52	54.57	1.82	0.61	0.71	0.75	-305,910	-307,911	1110219
#634	0.01	0.52	0.2	-34.99	0.07	54.46	2.84	0.58	0.13	0.63	-2,018,957	-2,020,958	35156
#635	0.09	1.46	0.6	-50.49	0.19	39.81	3.15	0.55	0.34	0.57	-989,934	-991,935	260865
#636	0.02	0.52	0.18	-13.39	0.12	78.69	1.41	0.8	0.15	0.85	-1,609,953	-1,611,954	48994
#637	0.2	2.5	0.76	-48.93	0.37	41.42	2.05	0.41	0.51	0.67	-1,766,915	-1,768,916	566236
#638	0.01	0.46	0.17	8.13	0.06	-81.87	3	0.6	0.11	0.65	-823,954	-825,955	28237
#639	0.01	0.5	0.17	29.05	0.11	-59.74	1.48	0.75	0.14	0.82	-1,740,953	-1,742,954	41888
#640	0.02	0.55	0.22	-29.48	0.1	61.39	2.11	0.76	0.15	0.71	-2,897,951	-2,899,952	51051
#641	0.01	0.48	0.16	-71.57	0.12	19.65	1.28	0.74	0.13	0.85	-3,770,949	-3,772,950	38148
#642	0.01	0.4	0.15	-29.36	0.07	63.43	2.05	0.74	0.11	0.73	-1,849,951	-1,851,952	26367
#643	0.03	0.63	0.22	-31.33	0.14	59.04	1.54	0.84	0.18	0.83	-279,944	-281,945	74239
#644	0.02	0.68	0.27	79.7	0.09	-10.3	3	0.6	0.17	0.61	-791,938	-793,939	61710
#645	0.02	0.57	0.19	-33.02	0.11	59.74	1.72	0.62	0.14	0.73	-3,740,943	-3,742,944	44319
#646	0.01	0.46	0.17	14.04	0.09	-73.3	1.97	0.76	0.13	0.76	-1,156,944	-1,158,945	36278
#647	0.01	0.4	0.13	-52.43	0.08	36.87	1.64	0.7	0.11	0.8	-1,878,941	-1,880,942	25058
#648	0.02	0.54	0.17	70.71	0.12	-19.65	1.43	0.78	0.15	0.87	-937,931	-939,932	49742
#649	0.01	0.48	0.17	-20.22	0.08	71.57	2.13	0.64	0.12	0.74	-1,520,934	-1,522,935	32912
#650	0.04	0.95	0.35	64.03	0.12	-24.78	3.03	0.5	0.21	0.6	-3,570,916	-3,572,917	99484
#651	0.04	0.91	0.32	-55.49	0.15	36.25	2.09	0.61	0.23	0.71	-3,383,918	-3,385,919	113135
#652	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-291,933	-293,934	187
#653	0.1	1.38	0.48	70.02	0.29	-19.44	1.62	0.65	0.36	0.74	-4,129,911	-4,131,912	278256
#654	0	0.27	0.11	-48.01	0.03	33.69	3.73	0.73	0.07	0.67	-2,054,927	-2,056,928	11781

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#655	0.02	0.65	0.22	-33.11	0.11	57.53	2.11	0.54	0.15	0.68	-2,746,922	-2,748,923	51425
#656	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-134,929	-136,930	187
#657	0.01	0.52	0.19	-64.54	0.06	23.2	3.05	0.52	0.12	0.63	-1,593,919	-1,595,920	31790
#658	0.01	0.55	0.24	-75.96	0.06	15.95	3.96	0.54	0.13	0.55	-4,162,916	-4,164,917	37213
#659	0.02	0.94	0.37	81.16	0.07	-6.34	5.03	0.3	0.16	0.44	-1,215,898	-1,217,899	59840
#660	0.01	0.56	0.2	-34.99	0.09	56.31	2.26	0.56	0.13	0.68	-3,538,914	-3,540,915	40018
#661	0.03	0.69	0.27	-12.34	0.12	78.69	2.14	0.72	0.19	0.69	-2,706,915	-2,708,916	76109
#662	0.04	0.95	0.31	-43.92	0.21	45	1.47	0.62	0.24	0.78	-4,055,902	-4,057,903	124168
#663	0.06	1.08	0.37	-60.57	0.2	28.61	1.79	0.62	0.27	0.74	-2,462,896	-2,464,897	161381
#664	0.07	1.91	0.74	-17.24	0.12	74.05	6.26	0.23	0.29	0.39	-1,028,905	-1,030,906	187000
#665	1.22	5.85	2.15	-22.85	0.74	67.14	2.92	0.45	1.24	0.58	-2,722,855	-2,012,118	3404522
#666	0.05	0.94	0.35	-77.91	0.17	11.31	2.11	0.7	0.25	0.71	-113,895	-115,896	138380
#667	0.01	0.38	0.14	61.93	0.05	-26.57	2.53	0.63	0.1	0.69	-2,552,907	-2,554,908	20383
#668	0.15	2.02	0.75	-61.19	0.29	28.74	2.58	0.45	0.43	0.58	-2,104,878	-2,106,879	406912
#669	0.01	0.61	0.25	14.93	0.04	-78.69	6.09	0.34	0.11	0.45	-790,910	-792,911	28050
#670	0.03	0.73	0.28	11.98	0.12	-77.91	2.36	0.66	0.19	0.68	-3,181,904	-3,183,905	77792
#671	1.02	4.76	1.58	-19.93	0.83	69.97	1.89	0.57	1.14	0.72	-3,449,852	-4,512,352	2863905
#672	0.06	1.13	0.4	-30.76	0.17	58.57	2.32	0.57	0.27	0.68	-764,884	-766,885	162503
#673	0.56	4.19	1.52	-23.12	0.57	67.13	2.68	0.4	0.84	0.55	-3,080,844	-3,253,601	1557897
#674	0.01	0.44	0.16	-40.91	0.09	48.81	1.87	0.77	0.12	0.76	-1,688,891	-1,690,892	33660
#675	0.16	2.01	0.82	-60.89	0.25	29.05	3.26	0.51	0.46	0.56	-3,855,852	-3,857,853	461329
#676	0.01	0.44	0.15	-70.56	0.1	19.98	1.54	0.7	0.12	0.79	-2,496,890	-2,498,891	29920
#677	0.02	0.62	0.22	19.09	0.11	-68.96	1.98	0.69	0.17	0.73	-1,122,880	-1,124,881	60027
#678	0.09	1.59	0.6	-40.6	0.19	48.58	3.25	0.46	0.35	0.57	-1,538,862	-1,540,863	262174
#679	0.72	4.09	1.36	-74.29	0.71	15.95	1.9	0.54	0.95	0.7	-1,572,810	(-569,2954)	2003331
#680	0.02	0.55	0.19	-77.74	0.12	12.09	1.64	0.75	0.15	0.79	-4,167,877	-4,169,878	51425
#681	0.01	0.32	0.12	50.71	0.06	-39.81	1.82	0.75	0.09	0.75	-851,879	-853,880	16830
#682	0.06	1.15	0.44	-72.58	0.14	16.39	3.02	0.54	0.27	0.61	-1,166,860	-1,168,861	156893
#683	0.12	1.59	0.6	53.91	0.32	-35.71	1.85	0.62	0.4	0.67	-2,194,851	-2,196,852	348755
#684	0.06	1.06	0.39	58.63	0.27	-31.26	1.47	0.68	0.28	0.71	-823,860	-825,861	170918
#685	0.46	3.37	1.21	3.87	0.53	93.52	2.28	0.51	0.77	0.63	-1,784,836	(-1527,837)	1295723
#686	1.39	5.9	2.2	-65.15	0.88	25.14	2.48	0.5	1.33	0.61	-3,694,751	-3,961,852	3903812
#687	0.03	0.72	0.25	-14.93	0.17	75.96	1.51	0.76	0.2	0.79	-2,024,867	-2,026,868	87516
#688	0.05	1.08	0.42	-4.48	0.15	86.82	2.84	0.55	0.26	0.61	-3,604,866	-3,606,867	144364
#689	0.17	2.13	0.82	-33.69	0.24	56.31	3.5	0.46	0.46	0.56	-888,847	-890,848	468435
#690	0.21	2.09	0.81	-13.47	0.3	75.96	2.66	0.6	0.52	0.64	-504,851	-506,852	586058
#691	0.04	1.02	0.46	-80.71	0.1	9.46	4.58	0.5	0.23	0.51	-1,144,848	-1,146,849	117810
#692	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,136,874	-1,138,875	187
#693	0.1	1.53	0.5	5.62	0.33	95.71	1.52	0.53	0.35	0.71	-1,239,853	-1,241,854	275825
#694	0.24	3.2	1.27	-21.94	0.27	68.84	4.67	0.3	0.56	0.44	-1,413,846	-1,415,847	679745
#695	0.01	0.46	0.18	-35.84	0.04	53.13	4.44	0.42	0.1	0.53	-2,065,863	-2,067,864	20196

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#696	0	0.3	0.1	61.39	0.05	-30.96	2.15	0.68	0.08	0.76	-2,475,865	-2,477,866	13277
#697	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,923,868	-1,925,869	187
#698	0.02	0.57	0.2	-61.39	0.12	28.3	1.7	0.74	0.16	0.76	-2,897,858	-2,899,859	53482
#699	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,922,867	-1,924,868	187
#700	0.39	3.22	1.23	-2.29	0.38	-92.44	3.19	0.47	0.7	0.57	-1,963,839	-1,965,840	1087218
#701	0.02	0.64	0.23	39.29	0.12	-50.71	2	0.67	0.17	0.72	-4,067,854	-4,069,855	61336
#702	0.05	0.93	0.36	65.77	0.21	-25.56	1.72	0.66	0.24	0.67	-217,841	-219,842	126412
#703	0.02	0.47	0.16	51.34	0.13	-37.57	1.17	0.87	0.14	0.89	-968,853	-970,854	43384
#704	0.09	1.18	0.39	-68.88	0.32	21.25	1.22	0.78	0.33	0.86	-2,864,837	-2,866,838	242165
#705	0.01	0.52	0.21	76.5	0.08	-12.53	2.79	0.64	0.13	0.63	-2,246,845	-2,248,846	39083
#706	0.02	0.65	0.25	95.71	0.03	0	7.54	0.5	0.15	0.59	-3,172,840	-3,174,841	46750
#707	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-2,079,856	-2,081,857	187
#708	0.22	2.27	0.84	4.44	0.29	-85.1	2.94	0.54	0.53	0.63	-4,076,824	(-2879,825)	617287
#709	1.16	6.37	2.39	-29.89	0.68	60.34	3.54	0.36	1.21	0.51	-944,777	(-377,2101)	3245011
#710	0.01	0.54	0.18	-46.85	0.1	41.63	1.82	0.58	0.13	0.73	-688,841	-690,842	37774
#711	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-128,850	-130,851	187
#712	0.18	2.12	0.86	23.63	0.25	-66.8	3.44	0.51	0.48	0.56	-161,827	-163,828	510884
#713	0.02	0.54	0.19	67.75	0.09	-21.8	2.21	0.67	0.14	0.73	-4,198,838	-4,200,839	43758
#714	0.07	1.31	0.4	49.14	0.29	-40.43	1.38	0.51	0.3	0.75	-2,919,831	-2,921,832	197098
#715	0.02	0.6	0.21	-35.54	0.11	53.97	1.9	0.68	0.16	0.75	-3,201,840	-3,203,841	55352
#716	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-151,844	-153,845	187
#717	0.03	0.72	0.27	-74.29	0.14	16.39	1.88	0.71	0.19	0.72	-2,469,827	-2,471,828	83402
#718	0.29	2.69	0.99	-21.71	0.34	67.69	2.89	0.5	0.6	0.61	-3,556,803	(-1815,804)	799238
#719	0.03	0.8	0.3	9.46	0.12	98.13	2.58	0.54	0.19	0.63	-1,312,835	-1,314,836	77979
#720	0.05	1.01	0.34	-65.9	0.19	23.2	1.82	0.6	0.25	0.73	-3,326,824	-3,328,825	136136
#721	0.02	0.7	0.24	54.69	0.11	-36.03	2.16	0.51	0.16	0.66	-2,280,828	-2,282,829	55913
#722	0.01	0.47	0.14	76.76	0.09	-15.26	1.53	0.7	0.12	0.87	-1,209,828	-1,211,829	34221
#723	0.05	1.14	0.44	15.07	0.19	-75.38	2.27	0.52	0.26	0.59	-2,152,821	-2,154,822	150348
#724	0.01	0.49	0.18	-56.31	0.09	33.69	2	0.63	0.12	0.7	-543,826	-545,827	33660
#725	0.03	0.87	0.34	-68.96	0.1	18.43	3.3	0.5	0.2	0.58	-1,180,812	-1,182,813	85646
#726	0.08	1.76	0.72	122.97	0.16	34.51	4.54	0.33	0.32	0.45	-1,254,790	-1,256,791	229449
#727	0.02	0.65	0.24	61.7	0.14	-28.07	1.74	0.71	0.17	0.72	-2,331,818	-2,333,819	66759
#728	0.08	1.37	0.5	-37.06	0.19	53.62	2.6	0.55	0.32	0.64	-889,810	-891,811	228140
#729	0.03	0.76	0.27	-10.3	0.14	79.99	1.94	0.71	0.2	0.75	-513,818	-515,819	92378
#730	0.1	1.68	0.68	21.04	0.18	-68.2	3.88	0.45	0.36	0.52	-302,796	-304,797	280874
#731	0.03	0.84	0.31	-74.88	0.12	15.95	2.63	0.61	0.21	0.67	-572,800	-574,801	96118
#732	0.02	0.64	0.23	-71.57	0.1	18.43	2.25	0.64	0.16	0.7	-4,223,805	-4,225,806	58157
#733	0.02	0.64	0.22	31.33	0.11	-59.74	1.94	0.66	0.17	0.75	-478,808	-480,809	60588
#734	0.07	1.21	0.41	-25.02	0.26	65.85	1.56	0.62	0.3	0.74	-1,137,792	-1,139,793	200651
#735	0.01	0.37	0.14	-64.98	0.06	23.2	2.17	0.67	0.1	0.71	-2,580,808	-2,582,809	20383
#736	0.01	0.3	0.11	-48.01	0.06	39.81	1.72	0.74	0.08	0.74	-2,527,809	-2,529,810	14586

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#737	0.01	0.55	0.18	50.53	0.1	-38.66	1.72	0.62	0.14	0.77	-3,252,802	-3,254,803	41888
#738	0.07	1.1	0.35	-9.46	0.26	81.12	1.31	0.72	0.3	0.85	-1,208,791	-1,210,792	192610
#739	0.07	1.43	0.53	-40.6	0.15	49.4	3.5	0.41	0.29	0.55	-3,844,787	-3,846,788	188122
#740	0.05	1.16	0.43	-13.24	0.16	78.11	2.7	0.49	0.26	0.6	-2,098,798	-2,100,799	147543
#741	0.49	3.74	1.4	-30.16	0.4	60.26	3.54	0.44	0.79	0.57	-1,377,753	-1,379,754	1379312
#742	0.01	0.4	0.15	-22.38	0.1	65.56	1.52	0.95	0.13	0.83	-3,054,796	-3,056,797	34595
#743	0.05	0.93	0.28	40.24	0.25	-48.99	1.12	0.7	0.25	0.89	-1,794,783	-1,796,784	135762
#744	0.02	0.6	0.24	49.18	0.1	-41.63	2.41	0.68	0.16	0.67	-3,305,786	-3,307,787	55352
#745	0.13	1.51	0.5	33.69	0.39	-55.98	1.27	0.7	0.4	0.81	-3,100,773	-3,102,774	357731
#746	0.05	1.24	0.46	-53.75	0.18	35.84	2.51	0.45	0.26	0.58	-2,938,766	-2,940,767	153153
#747	0.11	1.51	0.55	-54.66	0.29	35.91	1.88	0.62	0.38	0.68	-2,560,763	-2,562,764	311355
#748	0.04	0.91	0.33	-82.87	0.15	6.34	2.23	0.6	0.23	0.69	-281,768	-283,769	112013
#749	0.52	3.79	1.18	-80.8	0.66	9.23	1.77	0.45	0.81	0.69	-4,164,716	-12,103,672	1456730
#750	0.02	0.58	0.24	-49.18	0.08	36.87	2.91	0.59	0.14	0.59	-1,622,771	-1,624,772	43571
#751	0.02	0.66	0.26	-30.65	0.12	58.39	2.06	0.66	0.17	0.67	-3,569,773	-3,571,774	64328
#752	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,931,774	-1,933,775	187
#753	0.18	2.02	0.72	-46.85	0.4	43.36	1.77	0.57	0.48	0.68	-1,902,742	-1,904,743	514998
#754	0.27	2.78	0.91	-18.92	0.42	70.87	2.14	0.45	0.59	0.65	-2,363,738	-2,365,739	768383
#755	0.01	0.45	0.16	-38.66	0.12	53.13	1.28	0.83	0.13	0.82	-3,232,765	-3,234,766	36465
#756	0.08	1.48	0.54	-65.77	0.18	24.23	3	0.45	0.31	0.58	-352,731	-354,732	216920
#757	0.03	0.84	0.31	-66.8	0.11	22.62	2.93	0.45	0.18	0.58	-385,744	-387,745	71808
#758	0.43	3.46	1.34	68.13	0.34	-22.31	3.89	0.45	0.74	0.55	-4,072,677	-512,678	1205963
#759	0.19	1.99	0.79	-20.49	0.34	68.96	2.32	0.59	0.49	0.61	-2,713,739	-2,715,740	520982
#760	0.63	3.92	1.46	-31.29	0.55	58.89	2.64	0.51	0.9	0.61	-1,730,692	(-703,3128)	1763223
#761	0.41	3.64	1.33	-79.03	0.46	11.31	2.91	0.39	0.72	0.54	-2,021,675	(-1701,676)	1152855
#762	0.01	0.52	0.19	61.19	0.09	-26.57	2.04	0.61	0.13	0.69	-312,746	-314,747	36652
#763	0.02	0.57	0.18	-33.69	0.17	54.78	1.04	0.84	0.17	0.94	-3,775,745	-3,777,746	60214
#764	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-3,303,753	-3,305,754	187
#765	0.03	0.88	0.33	63.43	0.14	-25.02	2.43	0.55	0.21	0.63	-3,308,734	-3,310,735	94996
#766	0.33	2.42	0.82	30.67	0.59	-59.86	1.39	0.71	0.65	0.79	-3,378,708	(-1262,709)	925089
#767	0.17	2.37	0.87	-33.09	0.27	57.26	3.19	0.38	0.46	0.54	-2,953,716	-2,955,717	475167
#768	0.05	1.05	0.39	-47.56	0.19	43.26	2.03	0.6	0.26	0.67	-1,604,730	-1,606,731	147169
#769	0.91	5.5	1.91	-71.8	0.63	18.2	3.04	0.38	1.08	0.56	-2,785,634	(-579,2317)	2551241
#770	0.22	2.31	0.9	-61.81	0.28	28.07	3.24	0.52	0.53	0.59	-3,572,695	(-3410,696)	614856
#771	0.04	0.8	0.29	-16.39	0.16	75.26	1.8	0.7	0.21	0.73	-730,734	-732,735	99110
#772	0.09	1.6	0.66	2.12	0.17	92.73	3.86	0.43	0.33	0.5	-483,729	-485,730	241978
#773	0.01	0.35	0.11	-21.04	0.07	69.44	1.63	0.72	0.09	0.83	-2,519,738	-2,521,739	19822
#774	0.04	0.86	0.26	-28.18	0.23	60.75	1.11	0.63	0.22	0.84	-405,723	-407,724	104346
#775	0.03	0.97	0.33	-65.32	0.14	25.02	2.46	0.44	0.2	0.62	-318,716	-320,717	92378
#776	0.19	1.89	0.63	-52.39	0.38	38.09	1.64	0.68	0.5	0.79	-3,263,698	-3,265,699	539495
#777	0.07	1.21	0.45	-37.69	0.19	52.13	2.44	0.63	0.31	0.67	-3,155,712	-3,157,713	206074

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#778	0.24	2.64	0.8	-75.26	0.6	14.98	1.34	0.43	0.55	0.68	-2,625,690	-2,627,691	660671
#779	0.02	0.57	0.19	22.25	0.12	-66.8	1.56	0.76	0.16	0.82	-541,722	-543,723	55726
#780	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-2,639,724	-2,641,725	187
#781	0.09	1.71	0.69	-28.39	0.15	63.43	4.7	0.37	0.33	0.48	-3,880,701	-3,882,702	242165
#782	0.18	2.02	0.79	-76.25	0.28	13.63	2.85	0.55	0.48	0.6	-3,510,675	-3,512,676	501347
#783	0.04	0.91	0.35	-57.43	0.14	32.74	2.57	0.6	0.22	0.64	-732,701	-734,702	109769
#784	0.01	0.49	0.18	15.95	0.07	104.04	2.65	0.62	0.12	0.68	-2,139,715	-2,141,716	32725
#785	0.02	0.85	0.32	66.04	0.09	-21.8	3.66	0.4	0.17	0.53	-4,002,700	-4,004,701	64515
#786	0.06	1.14	0.43	14.3	0.16	104.74	2.68	0.59	0.28	0.65	-222,706	-224,707	170357
#787	0.07	1.16	0.43	-80.18	0.19	9.87	2.26	0.66	0.3	0.7	-1,490,687	-1,492,688	198968
#788	0.24	2.51	0.9	155.3	0.31	65.43	2.86	0.49	0.56	0.62	-1,599,686	-1,601,687	684981
#789	0.04	1.06	0.35	-59.26	0.23	30.26	1.55	0.48	0.24	0.67	-2,743,694	-2,745,695	121924
#790	0.01	0.46	0.15	-36.25	0.09	56.31	1.72	0.7	0.12	0.81	-559,703	-561,704	33473
#791	0.01	0.52	0.2	-40.1	0.06	45	3.51	0.52	0.12	0.59	-1,836,700	-1,838,701	31229
#792	0.1	1.53	0.57	-32.78	0.22	56.89	2.56	0.53	0.35	0.62	-4,236,687	-4,238,688	276947
#793	0.05	1.08	0.42	-82.18	0.15	6.34	2.84	0.53	0.25	0.6	-1,455,678	-1,457,679	137819
#794	0.07	1.22	0.4	81.87	0.27	-8.62	1.48	0.6	0.3	0.75	-3,465,677	-3,467,678	199716
#795	0.03	0.63	0.23	37.69	0.17	-52.59	1.3	0.82	0.18	0.81	-2,151,690	-2,153,691	73865
#796	0.02	0.56	0.21	-33.69	0.12	56.31	1.75	0.7	0.15	0.73	-4,281,690	-4,283,691	49555
#797	0.46	3.06	0.97	-23.77	0.73	66.3	1.33	0.62	0.77	0.79	-1,168,652	-1,170,653	1289178
#798	0.03	0.88	0.29	-55.41	0.16	34.51	1.81	0.53	0.2	0.7	-239,674	-241,675	90321
#799	0.02	0.67	0.27	79.38	0.09	-10.3	2.91	0.58	0.16	0.61	-2,490,676	-2,492,677	58718
#800	0.11	1.69	0.6	-36.71	0.22	52.7	2.79	0.48	0.37	0.62	-1,398,666	-1,400,667	305184
#801	0.02	0.54	0.2	40.1	0.12	-50.71	1.75	0.75	0.15	0.74	-454,677	-456,678	48994
#802	0.06	1.19	0.43	-18.78	0.17	-109.29	2.49	0.5	0.27	0.63	-2,324,669	-2,326,670	160072
#803	0.27	2.99	1.11	-5.5	0.33	84.29	3.37	0.38	0.58	0.53	-3,111,656	(-2596,657)	752114
#804	0.02	0.65	0.24	120.96	0.12	31.61	1.91	0.56	0.16	0.66	-1,245,664	-1,247,665	53856
#805	0.01	0.56	0.22	-55.71	0.07	29.74	3.3	0.46	0.12	0.56	-1,270,662	-1,272,663	32538
#806	0.02	0.46	0.16	36.87	0.14	-54.46	1.16	0.91	0.14	0.86	-2,161,667	-2,163,668	43758
#807	0.16	1.99	0.74	-41.42	0.26	48.81	2.84	0.51	0.45	0.61	-787,641	-789,642	455345
#808	0.05	0.97	0.37	49.54	0.21	-41.82	1.75	0.72	0.26	0.72	-4,289,652	-4,291,653	151657
#809	0.02	0.73	0.22	37.3	0.17	-52.59	1.23	0.59	0.18	0.82	-621,654	-623,655	69190
#810	0.43	3.6	1.35	16.14	0.51	-74.18	2.65	0.42	0.74	0.55	-2,962,633	(-585,634)	1209890
#811	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-248,663	-250,664	187
#812	1.45	6.55	2.3	-10.43	1.01	79.78	2.27	0.42	1.36	0.59	-903,586	(-152,2701)	4061266
#813	0.1	2.16	0.87	40.43	0.15	-49.4	5.77	0.26	0.35	0.41	-2,136,617	-2,138,618	274703
#814	0.02	0.58	0.2	58.24	0.12	-33.69	1.71	0.67	0.15	0.75	-3,868,644	-3,870,645	49742
#815	0.01	0.38	0.12	-66.8	0.09	21.8	1.41	0.77	0.11	0.85	-1,292,647	-1,294,648	24497
#816	0.6	4.22	1.26	-19.73	0.75	-109.82	1.69	0.42	0.87	0.69	-3,794,606	-12,403,162	1680943
#817	0.03	0.67	0.2	-66.5	0.19	23.2	1.1	0.73	0.18	0.89	-3,950,644	-3,952,645	73117
#818	0.06	1.29	0.53	-41.27	0.13	50.19	4.17	0.45	0.27	0.52	-819,628	-821,629	165682

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#819	0.02	0.53	0.18	71.57	0.13	-18.43	1.4	0.78	0.15	0.82	-4,238,641	-4,240,642	48807
#820	0.06	1.04	0.38	-59.04	0.21	30.58	1.83	0.7	0.28	0.73	-3,263,627	-3,265,628	168861
#821	0.01	0.38	0.12	-61.7	0.08	29.05	1.43	0.71	0.1	0.85	-1,248,638	-1,250,639	23001
#822	0.04	0.96	0.39	-36.38	0.11	53.97	3.47	0.52	0.22	0.57	-3,176,627	-3,178,628	106590
#823	0.59	3.76	1.43	-8.55	0.55	81.51	2.58	0.52	0.87	0.61	-3,377,608	-7,853,202	1655698
#824	0.01	0.45	0.16	51.34	0.12	-39.29	1.35	0.78	0.13	0.81	-1,836,634	-1,838,635	35530
#825	0.03	0.7	0.24	50.44	0.14	-40.24	1.75	0.69	0.18	0.75	-2,172,629	-2,174,630	74239
#826	0.19	2.38	0.92	-62.53	0.24	26.57	3.88	0.41	0.49	0.53	-1,073,588	-1,075,589	518925
#827	0.01	0.42	0.16	-62.1	0.07	29.74	2.39	0.69	0.11	0.7	-1,725,630	-1,727,631	26741
#828	0.11	1.64	0.57	-21.04	0.21	69.44	2.72	0.5	0.37	0.65	-1,375,612	-1,377,613	298452
#829	0.04	0.89	0.3	-67.62	0.16	21.25	1.9	0.61	0.22	0.74	-612,606	-614,607	108273
#830	0.09	1.57	0.53	-39.35	0.29	49.57	1.82	0.44	0.33	0.63	-1,531,599	-1,533,600	244222
#831	0.12	1.56	0.49	-51.04	0.36	39.47	1.37	0.6	0.38	0.78	-2,482,591	-2,484,592	322388
#832	0.01	0.44	0.19	37.87	0.03	-56.31	6.32	0.36	0.08	0.46	-4,022,612	-4,024,613	15895
#833	0.03	0.81	0.28	-35.54	0.15	53.75	1.85	0.63	0.2	0.73	-4,244,606	-4,246,607	91817
#834	0.02	0.76	0.27	-51.07	0.09	37.87	2.93	0.48	0.17	0.62	-3,072,602	-3,074,603	62084
#835	0.05	1.04	0.37	-31.61	0.15	57.99	2.43	0.54	0.24	0.65	-4,194,592	-4,196,593	130713
#836	0.06	1.13	0.43	-74.65	0.19	15.26	2.32	0.62	0.28	0.65	-1,469,585	-1,471,586	175967
#837	0.03	0.9	0.31	-39.61	0.14	49.76	2.21	0.53	0.21	0.68	-3,888,594	-3,890,595	95744
#838	0.02	0.63	0.26	-39.81	0.09	48.81	2.94	0.58	0.15	0.6	-1,720,598	-1,722,599	51425
#839	0.08	1.21	0.46	-20.67	0.21	69.44	2.21	0.71	0.33	0.7	-3,961,593	-3,963,594	233563
#840	0.04	0.9	0.33	-65.32	0.12	24.78	2.84	0.56	0.21	0.64	-1,143,579	-1,145,580	100419
#841	0.06	1.17	0.41	-18.8	0.19	72.35	2.15	0.59	0.29	0.71	-2,051,584	-2,053,585	181390
#842	0.04	1.02	0.41	-28.61	0.14	61.93	2.95	0.46	0.22	0.54	-1,942,581	-1,944,582	107151
#843	0.21	2.15	0.84	-6.71	0.28	83.29	3	0.57	0.52	0.62	-3,130,573	-3,132,574	589237
#844	0.01	0.37	0.12	50.71	0.09	-41.19	1.34	0.74	0.1	0.88	-2,695,587	-2,697,588	23188
#845	0.12	1.9	0.66	20.89	0.31	-69.62	2.18	0.43	0.4	0.6	-2,900,561	-2,902,562	348194
#846	0.27	2.53	1.01	-67.17	0.31	23.2	3.25	0.53	0.59	0.58	-3,431,531	(-2180,532)	765017
#847	0.07	1.5	0.57	-59.04	0.15	29.36	3.81	0.38	0.29	0.51	-3,232,555	-3,234,556	188870
#848	0.53	3.91	1.4	-44.05	0.43	45.76	3.23	0.43	0.82	0.59	-1,732,518	(-1172,3425)	1477861
#849	0.01	0.39	0.13	37.57	0.09	-52.13	1.44	0.74	0.11	0.79	-4,054,576	-4,056,577	24497
#850	0.05	1.08	0.38	-59.04	0.13	29.74	2.89	0.51	0.24	0.64	-1,889,561	-1,891,562	131461
#851	0.01	0.49	0.17	16.7	0.09	-73.3	2	0.73	0.13	0.78	-4,106,573	-4,108,574	39270
#852	1.08	5.93	2.16	-87.18	0.77	3.04	2.81	0.39	1.17	0.54	-1,572,455	-1,551,874	3027904
#853	0.19	2.28	0.8	-85.33	0.3	4.76	2.72	0.47	0.5	0.62	-3,929,527	-3,931,528	539682
#854	0.37	3.38	1.36	82.41	0.36	-7.77	3.75	0.41	0.69	0.51	-2,637,489	(-1450,490)	1050192
#855	0.34	2.98	1.09	37.39	0.39	-52.65	2.79	0.49	0.66	0.61	-2,242,527	(-2207,528)	964733
#856	0.05	1.28	0.52	-29.41	0.13	60.26	3.92	0.38	0.25	0.49	-1,702,556	-1,704,557	138380
#857	0.01	0.56	0.18	-76.61	0.11	12.99	1.62	0.52	0.13	0.72	-1,956,560	-1,958,561	35717
#858	0.04	0.87	0.32	-57.53	0.15	32.01	2.07	0.7	0.23	0.72	-2,823,552	-2,825,553	117810
#859	0.33	3.34	1.24	3.41	0.43	93.3	2.9	0.37	0.65	0.53	-3,312,542	(-1307,543)	929203

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#860	0.03	0.68	0.24	38.05	0.18	-50.53	1.33	0.81	0.2	0.82	-4,035,555	-4,037,556	84337
#861	0.04	0.92	0.37	-28.81	0.14	59.04	2.61	0.55	0.22	0.58	-2,057,554	-2,059,555	104159
#862	0.02	0.53	0.2	-78.23	0.1	14.04	1.98	0.8	0.15	0.76	-2,672,554	-2,674,555	50490
#863	0.26	2.59	0.94	-29.01	0.38	60.71	2.46	0.49	0.58	0.61	-3,598,533	(-2233,534)	736219
#864	0.08	1.48	0.53	-43.11	0.2	48.37	2.67	0.46	0.32	0.61	-4,097,537	-4,099,538	224774
#865	0.03	0.77	0.28	10.01	0.12	98.13	2.44	0.6	0.19	0.67	-579,552	-581,553	78727
#866	0.02	0.65	0.23	34.82	0.14	-54.46	1.63	0.66	0.17	0.73	-3,535,545	-3,537,546	62271
#867	0.51	4.01	1.59	105.54	0.39	15.78	4.06	0.4	0.8	0.51	-1,406,462	-14,083,480	1423444
#868	0.38	2.95	1.06	-19.27	0.44	70.56	2.41	0.55	0.69	0.65	-2,446,522	(-1603,523)	1060103
#869	0.55	3.26	1.16	-65.42	0.7	24.17	1.66	0.65	0.84	0.72	-4,200,485	(-1334,3254)	1551352
#870	0.12	1.87	0.66	-17.31	0.24	72.18	2.74	0.43	0.39	0.59	-2,332,537	-2,334,538	337348
#871	0.02	0.67	0.24	-54.69	0.13	34.7	1.86	0.61	0.17	0.69	-2,563,540	-2,565,541	60962
#872	0.07	1.52	0.62	-23.2	0.16	66.04	3.87	0.4	0.31	0.49	-1,974,530	-1,976,531	205139
#873	0.06	1.35	0.54	43.78	0.13	-47.49	4.08	0.43	0.28	0.52	-3,870,522	-3,872,523	176528
#874	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,703,543	-1,705,544	187
#875	0.01	0.42	0.14	28.07	0.09	-63.43	1.52	0.75	0.12	0.84	-4,034,535	-4,036,536	29733
#876	0.06	1.11	0.37	11.31	0.23	-77.91	1.6	0.6	0.27	0.73	-2,984,517	-2,986,518	165308
#877	0.1	1.69	0.63	-41.33	0.22	48.01	2.87	0.44	0.36	0.57	-1,814,502	-1,816,503	281248
#878	0.06	1.56	0.61	-62.06	0.14	28.07	4.39	0.33	0.29	0.47	-2,586,489	-2,588,490	180268
#879	0.32	2.4	0.85	16.17	0.56	106.06	1.52	0.69	0.63	0.74	-797,484	-799,485	882640
#880	0.31	2.76	1.05	-22.38	0.37	67.96	2.84	0.5	0.62	0.59	-507,478	-509,479	857582
#881	0.19	2.21	0.75	-4.35	0.33	85.71	2.3	0.48	0.49	0.65	-2,845,482	-2,847,483	528836
#882	0.02	0.58	0.22	-52.7	0.09	37.87	2.32	0.61	0.15	0.68	-3,960,495	-3,962,496	46750
#883	0.06	1.1	0.4	-33.37	0.21	56.31	1.95	0.65	0.28	0.7	-3,234,488	-3,236,489	174845
#884	0.4	3.14	1.13	23.96	0.48	-66.04	2.33	0.51	0.71	0.63	-3,083,473	(-750,474)	1119382
#885	0.03	0.74	0.26	43.73	0.2	-45	1.32	0.75	0.2	0.79	-3,901,485	-3,903,486	92191
#886	0.03	0.83	0.31	-41.76	0.1	48.37	3.12	0.48	0.18	0.6	-2,030,481	-2,032,482	74613
#887	0.44	3.52	1.12	-35.2	0.51	54.78	2.2	0.45	0.75	0.67	-889,458	-8,913,943	1232517
#888	0.23	2.38	0.87	-55.27	0.34	34.08	2.61	0.5	0.54	0.61	-2,068,449	-2,070,450	632060
#889	0.02	0.7	0.28	-41.5	0.08	49.4	3.77	0.47	0.15	0.54	-2,487,478	-2,489,479	51425
#890	0.05	0.86	0.3	-58.5	0.22	31.33	1.35	0.77	0.24	0.81	-3,334,473	-3,336,474	126412
#891	0.15	2	0.76	48.47	0.25	-41.01	3.07	0.46	0.43	0.57	-2,349,451	-2,351,452	410652
#892	0.61	3.7	1.42	-82.71	0.54	6.91	2.61	0.56	0.88	0.62	-623,398	-6,252,906	1712546
#893	0.11	1.73	0.68	2.76	0.26	93.58	2.59	0.45	0.37	0.54	-3,573,468	-3,575,469	300509
#894	0.05	1.18	0.48	33.15	0.14	-57.26	3.52	0.45	0.25	0.53	-4,029,466	-4,031,467	139315
#895	0.03	0.73	0.25	-60.95	0.12	28.3	2.09	0.62	0.18	0.72	-3,524,471	-3,526,472	73491
#896	0.03	0.74	0.27	-30.38	0.15	60.64	1.83	0.64	0.19	0.68	-3,367,473	-3,369,474	76670
#897	0.03	0.8	0.33	85.71	0.11	-4.4	3.08	0.55	0.19	0.58	-2,704,457	-2,706,458	78914
#898	0.02	0.79	0.29	23.63	0.11	-67.38	2.69	0.49	0.18	0.62	-1,213,462	-1,215,463	68442
#899	0.04	0.88	0.32	78.11	0.15	-12.53	2.11	0.59	0.21	0.68	-1,153,454	-1,155,455	101354
#900	0.29	2.66	0.89	-4.72	0.48	85.16	1.85	0.51	0.61	0.68	-1,838,436	-1,840,437	810458

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#819	0.02	0.53	0.18	71.57	0.13	-18.43	1.4	0.78	0.15	0.82	-4,238,641	-4,240,642	48807
#820	0.06	1.04	0.38	-59.04	0.21	30.58	1.83	0.7	0.28	0.73	-3,263,627	-3,265,628	168861
#821	0.01	0.38	0.12	-61.7	0.08	29.05	1.43	0.71	0.1	0.85	-1,248,638	-1,250,639	23001
#822	0.04	0.96	0.39	-36.38	0.11	53.97	3.47	0.52	0.22	0.57	-3,176,627	-3,178,628	106590
#823	0.59	3.76	1.43	-8.55	0.55	81.51	2.58	0.52	0.87	0.61	-3,377,608	-7,853,202	1655698
#824	0.01	0.45	0.16	51.34	0.12	-39.29	1.35	0.78	0.13	0.81	-1,836,634	-1,838,635	35530
#825	0.03	0.7	0.24	50.44	0.14	-40.24	1.75	0.69	0.18	0.75	-2,172,629	-2,174,630	74239
#826	0.19	2.38	0.92	-62.53	0.24	26.57	3.88	0.41	0.49	0.53	-1,073,588	-1,075,589	518925
#827	0.01	0.42	0.16	-62.1	0.07	29.74	2.39	0.69	0.11	0.7	-1,725,630	-1,727,631	26741
#828	0.11	1.64	0.57	-21.04	0.21	69.44	2.72	0.5	0.37	0.65	-1,375,612	-1,377,613	298452
#829	0.04	0.89	0.3	-67.62	0.16	21.25	1.9	0.61	0.22	0.74	-612,606	-614,607	108273
#830	0.09	1.57	0.53	-39.35	0.29	49.57	1.82	0.44	0.33	0.63	-1,531,599	-1,533,600	244222
#831	0.12	1.56	0.49	-51.04	0.36	39.47	1.37	0.6	0.38	0.78	-2,482,591	-2,484,592	322388
#832	0.01	0.44	0.19	37.87	0.03	-56.31	6.32	0.36	0.08	0.46	-4,022,612	-4,024,613	15895
#833	0.03	0.81	0.28	-35.54	0.15	53.75	1.85	0.63	0.2	0.73	-4,244,606	-4,246,607	91817
#834	0.02	0.76	0.27	-51.07	0.09	37.87	2.93	0.48	0.17	0.62	-3,072,602	-3,074,603	62084
#835	0.05	1.04	0.37	-31.61	0.15	57.99	2.43	0.54	0.24	0.65	-4,194,592	-4,196,593	130713
#836	0.06	1.13	0.43	-74.65	0.19	15.26	2.32	0.62	0.28	0.65	-1,469,585	-1,471,586	175967
#837	0.03	0.9	0.31	-39.61	0.14	49.76	2.21	0.53	0.21	0.68	-3,888,594	-3,890,595	95744
#838	0.02	0.63	0.26	-39.81	0.09	48.81	2.94	0.58	0.15	0.6	-1,720,598	-1,722,599	51425
#839	0.08	1.21	0.46	-20.67	0.21	69.44	2.21	0.71	0.33	0.7	-3,961,593	-3,963,594	233563
#840	0.04	0.9	0.33	-65.32	0.12	24.78	2.84	0.56	0.21	0.64	-1,143,579	-1,145,580	100419
#841	0.06	1.17	0.41	-18.8	0.19	72.35	2.15	0.59	0.29	0.71	-2,051,584	-2,053,585	181390
#842	0.04	1.02	0.41	-28.61	0.14	61.93	2.95	0.46	0.22	0.54	-1,942,581	-1,944,582	107151
#843	0.21	2.15	0.84	-6.71	0.28	83.29	3	0.57	0.52	0.62	-3,130,573	-3,132,574	589237
#844	0.01	0.37	0.12	50.71	0.09	-41.19	1.34	0.74	0.1	0.88	-2,695,587	-2,697,588	23188
#845	0.12	1.9	0.66	20.89	0.31	-69.62	2.18	0.43	0.4	0.6	-2,900,561	-2,902,562	348194
#846	0.27	2.53	1.01	-67.17	0.31	23.2	3.25	0.53	0.59	0.58	-3,431,531	(-2180,532)	765017
#847	0.07	1.5	0.57	-59.04	0.15	29.36	3.81	0.38	0.29	0.51	-3,232,555	-3,234,556	188870
#848	0.53	3.91	1.4	-44.05	0.43	45.76	3.23	0.43	0.82	0.59	-1,732,518	(-1172,3425)	1477861
#849	0.01	0.39	0.13	37.57	0.09	-52.13	1.44	0.74	0.11	0.79	-4,054,576	-4,056,577	24497
#850	0.05	1.08	0.38	-59.04	0.13	29.74	2.89	0.51	0.24	0.64	-1,889,561	-1,891,562	131461
#851	0.01	0.49	0.17	16.7	0.09	-73.3	2	0.73	0.13	0.78	-4,106,573	-4,108,574	39270
#852	1.08	5.93	2.16	-87.18	0.77	3.04	2.81	0.39	1.17	0.54	-1,572,455	-1,551,874	3027904
#853	0.19	2.28	0.8	-85.33	0.3	4.76	2.72	0.47	0.5	0.62	-3,929,527	-3,931,528	539682
#854	0.37	3.38	1.36	82.41	0.36	-7.77	3.75	0.41	0.69	0.51	-2,637,489	(-1450,490)	1050192
#855	0.34	2.98	1.09	37.39	0.39	-52.65	2.79	0.49	0.66	0.61	-2,242,527	(-2207,528)	964733
#856	0.05	1.28	0.52	-29.41	0.13	60.26	3.92	0.38	0.25	0.49	-1,702,556	-1,704,557	138380
#857	0.01	0.56	0.18	-76.61	0.11	12.99	1.62	0.52	0.13	0.72	-1,956,560	-1,958,561	35717
#858	0.04	0.87	0.32	-57.53	0.15	32.01	2.07	0.7	0.23	0.72	-2,823,552	-2,825,553	117810
#859	0.33	3.34	1.24	3.41	0.43	93.3	2.9	0.37	0.65	0.53	-3,312,542	(-1307,543)	929203

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#860	0.03	0.68	0.24	38.05	0.18	-50.53	1.33	0.81	0.2	0.82	-4,035,555	-4,037,556	84337
#861	0.04	0.92	0.37	-28.81	0.14	59.04	2.61	0.55	0.22	0.58	-2,057,554	-2,059,555	104159
#862	0.02	0.53	0.2	-78.23	0.1	14.04	1.98	0.8	0.15	0.76	-2,672,554	-2,674,555	50490
#863	0.26	2.59	0.94	-29.01	0.38	60.71	2.46	0.49	0.58	0.61	-3,598,533	(-2233,534)	736219
#864	0.08	1.48	0.53	-43.11	0.2	48.37	2.67	0.46	0.32	0.61	-4,097,537	-4,099,538	224774
#865	0.03	0.77	0.28	10.01	0.12	98.13	2.44	0.6	0.19	0.67	-579,552	-581,553	78727
#866	0.02	0.65	0.23	34.82	0.14	-54.46	1.63	0.66	0.17	0.73	-3,535,545	-3,537,546	62271
#867	0.51	4.01	1.59	105.54	0.39	15.78	4.06	0.4	0.8	0.51	-1,406,462	-14,083,480	1423444
#868	0.38	2.95	1.06	-19.27	0.44	70.56	2.41	0.55	0.69	0.65	-2,446,522	(-1603,523)	1060103
#869	0.55	3.26	1.16	-65.42	0.7	24.17	1.66	0.65	0.84	0.72	-4,200,485	(-1334,3254)	1551352
#870	0.12	1.87	0.66	-17.31	0.24	72.18	2.74	0.43	0.39	0.59	-2,332,537	-2,334,538	337348
#871	0.02	0.67	0.24	-54.69	0.13	34.7	1.86	0.61	0.17	0.69	-2,563,540	-2,565,541	60962
#872	0.07	1.52	0.62	-23.2	0.16	66.04	3.87	0.4	0.31	0.49	-1,974,530	-1,976,531	205139
#873	0.06	1.35	0.54	43.78	0.13	-47.49	4.08	0.43	0.28	0.52	-3,870,522	-3,872,523	176528
#874	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,703,543	-1,705,544	187
#875	0.01	0.42	0.14	28.07	0.09	-63.43	1.52	0.75	0.12	0.84	-4,034,535	-4,036,536	29733
#876	0.06	1.11	0.37	11.31	0.23	-77.91	1.6	0.6	0.27	0.73	-2,984,517	-2,986,518	165308
#877	0.1	1.69	0.63	-41.33	0.22	48.01	2.87	0.44	0.36	0.57	-1,814,502	-1,816,503	281248
#878	0.06	1.56	0.61	-62.06	0.14	28.07	4.39	0.33	0.29	0.47	-2,586,489	-2,588,490	180268
#879	0.32	2.4	0.85	16.17	0.56	106.06	1.52	0.69	0.63	0.74	-797,484	-799,485	882640
#880	0.31	2.76	1.05	-22.38	0.37	67.96	2.84	0.5	0.62	0.59	-507,478	-509,479	857582
#881	0.19	2.21	0.75	-4.35	0.33	85.71	2.3	0.48	0.49	0.65	-2,845,482	-2,847,483	528836
#882	0.02	0.58	0.22	-52.7	0.09	37.87	2.32	0.61	0.15	0.68	-3,960,495	-3,962,496	46750
#883	0.06	1.1	0.4	-33.37	0.21	56.31	1.95	0.65	0.28	0.7	-3,234,488	-3,236,489	174845
#884	0.4	3.14	1.13	23.96	0.48	-66.04	2.33	0.51	0.71	0.63	-3,083,473	(-750,474)	1119382
#885	0.03	0.74	0.26	43.73	0.2	-45	1.32	0.75	0.2	0.79	-3,901,485	-3,903,486	92191
#886	0.03	0.83	0.31	-41.76	0.1	48.37	3.12	0.48	0.18	0.6	-2,030,481	-2,032,482	74613
#887	0.44	3.52	1.12	-35.2	0.51	54.78	2.2	0.45	0.75	0.67	-889,458	-8,913,943	1232517
#888	0.23	2.38	0.87	-55.27	0.34	34.08	2.61	0.5	0.54	0.61	-2,068,449	-2,070,450	632060
#889	0.02	0.7	0.28	-41.5	0.08	49.4	3.77	0.47	0.15	0.54	-2,487,478	-2,489,479	51425
#890	0.05	0.86	0.3	-58.5	0.22	31.33	1.35	0.77	0.24	0.81	-3,334,473	-3,336,474	126412
#891	0.15	2	0.76	48.47	0.25	-41.01	3.07	0.46	0.43	0.57	-2,349,451	-2,351,452	410652
#892	0.61	3.7	1.42	-82.71	0.54	6.91	2.61	0.56	0.88	0.62	-623,398	-6,252,906	1712546
#893	0.11	1.73	0.68	2.76	0.26	93.58	2.59	0.45	0.37	0.54	-3,573,468	-3,575,469	300509
#894	0.05	1.18	0.48	33.15	0.14	-57.26	3.52	0.45	0.25	0.53	-4,029,466	-4,031,467	139315
#895	0.03	0.73	0.25	-60.95	0.12	28.3	2.09	0.62	0.18	0.72	-3,524,471	-3,526,472	73491
#896	0.03	0.74	0.27	-30.38	0.15	60.64	1.83	0.64	0.19	0.68	-3,367,473	-3,369,474	76670
#897	0.03	0.8	0.33	85.71	0.11	-4.4	3.08	0.55	0.19	0.58	-2,704,457	-2,706,458	78914
#898	0.02	0.79	0.29	23.63	0.11	-67.38	2.69	0.49	0.18	0.62	-1,213,462	-1,215,463	68442
#899	0.04	0.88	0.32	78.11	0.15	-12.53	2.11	0.59	0.21	0.68	-1,153,454	-1,155,455	101354
#900	0.29	2.66	0.89	-4.72	0.48	85.16	1.85	0.51	0.61	0.68	-1,838,436	-1,840,437	810458

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#901	0.26	2.65	0.94	67.46	0.42	-23.05	2.25	0.46	0.57	0.61	-2,542,419	-2,544,420	724812
#902	0.09	1.23	0.46	53.75	0.3	-36.25	1.5	0.72	0.33	0.73	-2,412,445	-2,414,446	245157
#903	0.03	0.8	0.26	-82.65	0.22	6.34	1.15	0.67	0.21	0.81	-2,499,451	-2,501,452	94248
#904	1.65	8.24	2.2	-56.07	1.37	33.79	1.61	0.31	1.45	0.66	-2,887,334	-992,194	4619274
#905	0.41	3.33	0.93	-74.26	0.82	15.55	1.14	0.47	0.72	0.78	-3,240,412	(-481,413)	1153229
#906	0.32	2.55	0.87	-35.04	0.53	55.08	1.64	0.61	0.63	0.73	-541,428	-543,429	882827
#907	0.09	1.4	0.51	-77.97	0.21	11.31	2.45	0.57	0.34	0.66	-2,590,431	-2,592,432	250580
#908	0.16	2.03	0.69	-79.76	0.37	10.3	1.89	0.5	0.46	0.66	-2,731,420	-2,733,421	455719
#909	0.02	0.55	0.18	35.84	0.15	-53.75	1.19	0.77	0.15	0.85	-2,769,454	-2,771,455	51799
#910	0.03	0.98	0.41	-72.65	0.08	18.43	5.3	0.34	0.18	0.45	-2,675,439	-2,677,440	73678
#911	0.01	0.51	0.17	58.57	0.09	-33.69	1.95	0.58	0.12	0.72	-2,987,448	-2,989,449	33847
#912	0.42	3.68	1.1	2.14	0.56	92.49	1.94	0.39	0.73	0.67	-3,372,425	(-260,4060)	1181466
#913	0.06	1.24	0.44	5.29	0.23	-83.88	1.93	0.48	0.27	0.61	-2,142,445	-2,144,446	163251
#914	0.02	0.6	0.22	34.29	0.1	-55.01	2.18	0.61	0.15	0.69	-2,870,437	-2,872,438	48994
#915	0.21	2.23	0.87	-12.99	0.32	76.68	2.73	0.52	0.51	0.59	-3,987,419	(-3424,420)	579326
#916	0.03	0.82	0.32	31.22	0.1	-59.04	3.31	0.54	0.19	0.61	-3,475,428	-3,477,429	80971
#917	0.04	0.99	0.33	-24.68	0.19	64.54	1.75	0.47	0.21	0.65	-2,256,424	-2,258,425	101354
#918	0	0.32	0.12	66.8	0.03	-14.04	3.69	0.46	0.07	0.56	-2,830,431	-2,832,432	10659
#919	0.01	0.57	0.2	73.74	0.09	-16.7	2.39	0.54	0.13	0.65	-1,190,421	-1,192,422	39083
#920	0.01	0.32	0.12	-65.22	0.06	23.2	1.88	0.77	0.09	0.77	-2,807,427	-2,809,428	17765
#921	0.9	5.58	1.66	-63.94	1.1	25.99	1.5	0.36	1.07	0.65	-1,931,321	-2,242,031	2513280
#922	0.02	0.53	0.17	-64.65	0.16	26.57	1.04	0.81	0.15	0.89	-1,909,422	-1,911,423	51799
#923	0.01	0.46	0.17	-11.31	0.1	80.54	1.68	0.74	0.12	0.75	-2,303,422	-2,305,423	34221
#924	0.57	3.62	1.33	-28.3	0.69	61.61	1.93	0.55	0.85	0.64	-3,708,385	-10,213,074	1596980
#925	0.02	0.52	0.17	-73.3	0.11	17.1	1.54	0.73	0.14	0.82	-4,290,418	-4,292,419	43571
#926	0.28	2.79	1.04	-9.98	0.35	80.54	2.98	0.46	0.6	0.58	-977,391	-979,392	795498
#927	0.04	1.18	0.49	-8.67	0.09	79.7	5.34	0.33	0.22	0.44	-923,416	-925,417	102850
#928	0.34	2.52	0.83	-67.99	0.56	22.11	1.47	0.68	0.66	0.8	-4,224,374	(-221,375)	965668
#929	0.07	1.38	0.53	-64.61	0.16	26.57	3.25	0.46	0.3	0.56	-2,767,390	-2,769,391	194854
#930	0.47	3.29	1.15	-36.06	0.58	53.62	1.99	0.55	0.78	0.67	-735,356	-7,373,596	1325456
#931	0.01	0.37	0.13	-37.57	0.08	53.13	1.64	0.78	0.11	0.79	-858,405	-860,406	24497
#932	0.08	1.62	0.62	-40.19	0.16	49.09	3.83	0.39	0.32	0.52	-681,382	-683,383	229449
#933	0.03	0.83	0.34	-19.75	0.09	68.2	3.85	0.5	0.19	0.55	-2,201,400	-2,203,401	75922
#934	0.01	0.64	0.27	-10.3	0.04	78.69	6.58	0.33	0.12	0.43	-2,369,400	-2,371,401	29920
#935	0.01	0.57	0.18	-69.15	0.08	18.43	2.37	0.44	0.12	0.66	-1,890,392	-1,892,393	31977
#936	0.01	0.48	0.18	-35.84	0.04	53.13	4.44	0.36	0.09	0.5	-2,053,390	-2,055,391	18139
#937	0.01	0.46	0.17	22.83	0.09	111.8	1.91	0.8	0.13	0.78	-880,392	-882,393	38335
#938	0.02	0.58	0.19	23.2	0.17	-67.17	1.11	0.74	0.16	0.85	-565,385	-567,386	55352
#939	0.07	1.34	0.5	-13.13	0.17	75.96	2.99	0.51	0.31	0.61	-3,501,376	-3,503,377	204765
#940	0.07	1.33	0.51	-28.61	0.15	60.64	3.41	0.48	0.29	0.57	-1,800,375	-1,802,376	187748
#941	0.11	1.8	0.76	42.81	0.17	-48.81	4.36	0.44	0.38	0.5	-3,839,356	-3,841,357	321266

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#942	0.06	1.17	0.44	-20.43	0.16	68.75	2.82	0.54	0.27	0.62	-2,195,376	-2,197,377	165869
#943	0.05	1.28	0.52	-34.19	0.11	53.97	4.71	0.38	0.25	0.48	-1,132,364	-1,134,365	139502
#944	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-3,343,382	-3,345,383	187
#945	0.05	1.02	0.36	41.31	0.2	-48.37	1.82	0.59	0.25	0.7	-3,338,366	-3,340,367	139128
#946	0.01	0.48	0.15	33.69	0.12	-56.31	1.25	0.58	0.12	0.79	-887,373	-889,374	30107
#947	0.05	0.93	0.31	-47.12	0.27	42.51	1.17	0.76	0.26	0.83	-2,089,359	-2,091,360	146608
#948	0.04	0.94	0.36	-74.41	0.12	15.95	3.07	0.56	0.22	0.61	-2,234,352	-2,236,353	110517
#949	0.01	0.56	0.2	-38.29	0.08	49.4	2.63	0.42	0.12	0.58	-3,376,366	-3,378,367	29172
#950	0.26	2.7	1.04	-74.98	0.28	15.26	3.72	0.45	0.57	0.55	-3,015,308	(-2906,309)	724999
#951	0.93	5.15	1.51	-47.41	1.04	42.46	1.45	0.44	1.09	0.72	-3,525,297	-2,371,943	2611455
#952	0.02	0.67	0.23	32.01	0.12	-58.39	1.85	0.69	0.18	0.77	-2,008,358	-2,010,359	69003
#953	0.03	0.79	0.3	-53.75	0.1	34.99	3.05	0.55	0.19	0.61	-786,352	-788,353	76483
#954	0.11	1.92	0.69	-38.23	0.24	51.95	2.88	0.37	0.37	0.54	-1,686,333	-1,688,334	302566
#955	0.06	1.28	0.5	-43.03	0.14	45	3.63	0.43	0.27	0.53	-1,829,341	-1,831,342	157641
#956	0.09	1.2	0.41	-84.29	0.3	6.17	1.35	0.77	0.33	0.81	-3,301,342	-3,303,343	244409
#957	0.03	0.94	0.35	-68.2	0.13	21.8	2.67	0.5	0.21	0.6	-3,611,348	-3,613,349	97427
#958	0.02	0.74	0.29	-77.12	0.08	11.31	3.52	0.53	0.17	0.59	-569,347	-571,348	65637
#959	0.12	1.58	0.5	-52.37	0.48	38.05	1.04	0.6	0.39	0.79	-2,567,335	-2,569,336	334543
#960	0.19	1.96	0.7	-66.71	0.35	23.55	2.02	0.61	0.49	0.7	-3,160,320	-3,162,321	525096
#961	0.03	0.76	0.25	-41.01	0.16	49.09	1.54	0.64	0.2	0.78	-2,650,344	-2,652,345	83776
#962	0.01	0.5	0.18	-62.24	0.07	29.74	2.66	0.48	0.11	0.63	-2,506,345	-2,508,346	26928
#963	0.59	4.88	1.54	-20.16	0.55	69.94	2.81	0.31	0.87	0.56	-2,108,301	(-485,2897)	1654576
#964	0.02	0.67	0.26	-26.57	0.12	61.7	2.12	0.62	0.17	0.66	-1,408,346	-1,410,347	62832
#965	0.01	0.42	0.16	-63.43	0.06	23.2	2.64	0.65	0.11	0.65	-2,737,340	-2,739,341	25245
#966	0.01	0.48	0.16	-55.49	0.1	34.99	1.59	0.75	0.13	0.84	-4,062,339	-4,064,340	38896
#967	0.07	1.2	0.42	55.38	0.24	-35.31	1.74	0.64	0.31	0.73	-3,268,320	-3,270,321	205513
#968	0.02	0.65	0.22	-23.75	0.12	66.8	1.79	0.7	0.17	0.78	-2,699,331	-2,701,332	66198
#969	0.01	0.4	0.15	-56.31	0.05	38.66	2.82	0.58	0.1	0.65	-1,851,331	-1,853,332	20196
#970	0.05	1.02	0.34	62.82	0.24	-26.57	1.43	0.6	0.25	0.75	-1,306,312	-1,308,313	141185
#971	0.03	0.86	0.35	84.69	0.11	-4.4	3.31	0.5	0.19	0.55	-1,467,305	-1,469,306	83589
#972	0.07	1.19	0.45	35.42	0.17	-54.78	2.65	0.58	0.29	0.64	-4,012,308	-4,014,309	183821
#973	0.03	0.7	0.25	-34.22	0.16	55.49	1.56	0.67	0.18	0.74	-1,395,319	-1,397,320	73865
#974	0.01	0.52	0.19	52.13	0.11	-36.03	1.68	0.7	0.14	0.74	-2,613,314	-2,615,315	41701
#975	0.04	0.92	0.31	74.88	0.19	-15.26	1.68	0.63	0.23	0.74	-3,330,303	-3,332,304	117436
#976	0.05	1.15	0.46	69.33	0.11	-21.04	4.07	0.45	0.25	0.53	-3,092,291	-3,094,292	132583
#977	0.04	0.92	0.33	63.43	0.16	-26.57	2	0.66	0.24	0.72	-2,220,298	-2,222,299	123420
#978	0.06	1.22	0.46	-21.04	0.15	67.62	3.03	0.51	0.28	0.61	-1,338,288	-1,340,289	170918
#979	0.06	1.03	0.37	-69.59	0.18	20.85	2.04	0.69	0.27	0.73	-1,717,287	-1,719,288	164186
#980	0.3	2.84	0.92	-81.29	0.63	8.97	1.46	0.46	0.62	0.67	-2,333,249	-2,335,250	833833
#981	0.02	0.75	0.31	-50.39	0.09	37.87	3.3	0.56	0.18	0.58	-2,668,292	-2,670,293	69751
#982	0.01	0.38	0.13	-68.2	0.08	23.96	1.64	0.82	0.11	0.84	-1,490,298	-1,492,299	27115

Object	Area	Perimeter	Major AL	Major AA	Minor AL	Minor AA	Elongation	Roundness	Feret Diameter	Compactness	Centroid	Gray Centroid	Int. Dens.
#983	0.01	0.37	0.12	33.69	0.08	-57.99	1.53	0.73	0.1	0.84	-1,693,285	-1,695,286	21692
#984	0.01	0.3	0.11	22.62	0.09	-68.2	1.21	1.02	0.1	0.92	-3,299,282	-3,301,283	20944
#985	0.39	2.98	1.05	-55.81	0.52	34.19	2	0.56	0.71	0.68	-1,563,239	-15,654,139	1101430
#986	0.1	1.59	0.61	67.2	0.2	-21.37	3.03	0.5	0.36	0.59	-2,579,251	-2,581,252	283492
#987	0.17	1.83	0.58	-33.47	0.44	57.2	1.32	0.63	0.46	0.8	-2,694,252	-2,696,253	472175
#988	0.07	1.17	0.46	-51.5	0.2	38.29	2.32	0.59	0.29	0.63	-3,266,260	-3,268,261	182325
#989	0.06	0.96	0.33	-30.96	0.22	58.67	1.52	0.78	0.27	0.81	-1,385,267	-1,387,268	158950
#990	0.01	0.47	0.16	38.66	0.12	-50.71	1.35	0.79	0.13	0.85	-3,172,273	-3,174,274	38896
#991	0.03	0.72	0.25	-29.05	0.13	60.26	1.92	0.64	0.19	0.73	-3,966,267	-3,968,268	75361
#992	0.04	0.88	0.35	-63.43	0.12	28.3	2.88	0.57	0.21	0.61	-3,040,257	-3,042,258	99110
#993	0.04	1	0.38	-86.27	0.13	3.58	2.88	0.52	0.23	0.61	-4,010,251	-4,012,252	117997
#994	0.01	0.58	0.23	75.47	0.06	-15.95	3.83	0.53	0.14	0.59	-2,540,257	-2,542,258	40205
#995	0.19	1.95	0.71	-75.32	0.3	14.04	2.34	0.62	0.49	0.69	-3,213,226	-3,215,227	521356
#996	0.01	0.34	0.12	74.05	0.06	-15.95	2	0.72	0.09	0.77	-1,654,253	-1,656,254	18513
#997	0.05	1.06	0.42	-59.42	0.12	31.61	3.35	0.5	0.24	0.57	-3,415,233	-3,417,234	126786
#998	0.1	1.39	0.49	77.57	0.26	-12.72	1.9	0.65	0.36	0.72	-4,251,226	-4,253,227	279191
#999	0.01	0.52	0.19	-46.74	0.06	45	3.3	0.5	0.12	0.62	-3,381,247	-3,383,248	30481
#1000	0.02	0.74	0.25	-80.54	0.11	8.75	2.31	0.52	0.17	0.68	-2,888,240	-2,890,241	63206
#1001	0.17	2.26	0.81	21.91	0.28	-67.89	2.87	0.42	0.47	0.58	-1,380,222	-1,382,223	485078
#1002	0.02	0.68	0.29	8.13	0.08	-84.29	3.52	0.6	0.17	0.58	-3,305,246	-3,307,247	62271
#1003	0	0.34	0.13	-42.51	0.03	56.31	4.51	0.47	0.07	0.56	-3,126,243	-3,128,244	12155
#1004	0.07	1.2	0.44	-54.83	0.22	34.29	2.02	0.64	0.31	0.7	-1,617,217	-1,619,218	206074
#1005	0.23	2.55	1.01	-25.32	0.29	64.89	3.51	0.44	0.54	0.53	-2,026,214	-2,028,215	637670
#1006	0.02	0.67	0.22	52.7	0.12	-39.29	1.86	0.58	0.16	0.76	-1,917,229	-1,919,230	59092
#1007	0.05	0.86	0.29	-68.5	0.2	21.37	1.44	0.79	0.24	0.84	-2,625,222	-2,627,223	130900
#1008	0.09	1.51	0.59	11.15	0.18	-79.7	3.24	0.52	0.35	0.59	-3,011,220	-3,013,221	263296
#1009	0.03	0.68	0.23	-60.75	0.15	29.36	1.56	0.78	0.19	0.81	-3,355,223	-3,357,224	79475
#1010	0.13	1.58	0.57	-16.62	0.36	72.8	1.59	0.64	0.4	0.71	-3,560,212	-3,562,213	360910
#1011	0.04	0.91	0.3	24.44	0.2	114.44	1.5	0.61	0.23	0.77	-3,149,216	-3,151,217	112948
#1012	0.04	0.94	0.37	-61.19	0.13	26.57	2.92	0.6	0.23	0.62	-3,314,206	-3,316,207	118558
#1013	0.05	1.17	0.4	8.3	0.18	97.77	2.18	0.48	0.26	0.65	-1,708,214	-1,710,215	147730
#1014	0.06	1.24	0.46	-16.5	0.15	74.48	3.01	0.48	0.27	0.59	-1,770,206	-1,772,207	164373
#1015	0.02	0.63	0.19	22.25	0.17	-67.17	1.15	0.62	0.16	0.81	-2,524,198	-2,526,199	54791
#1016	0	0.03	0.01	45	0.01	135	1	0.79	0.01	0.8	-1,751,187	-1,753,188	187

APPENDIX F

Carbon isotope data from Troll *et al.* (*In Prep.*).

Appendix F. Carbon Isotope ratios of rock and gas samples after Troll et al. (*In Prep*).

Sample Type	$\delta^{13}\text{C}_{\text{CO}_2}$
Basaltic-andesites	
SCL-02	-21.1 (± 0.25)
SCL-26-1	-27.5 (± 0.25)
SCL-26-2	-26.3 (± 0.25)
SCL-29-2	-27.0 (± 0.25)
SCL-29-2	-26.1 (± 0.25)
LMS-6	-26.5 (± 0.25)
Calc-silicate inclusions	
M-XCS-1C	-22.4 (± 0.25)
M-XCS-1R	-24.9 (± 0.25)
M-XCS-7C	-22.2 (± 0.25)
M-XCS-7R	-21.4 (± 0.25)
M-XCS-3	-25.0 (± 0.25)
Chalk sediments (local crust)	
MX99-1	-2.16 (± 0.25)
MX99-2	-1.64 (± 0.25)
JC-1 (carb. Mudst.)	-0.79 (± 0.15)
JC-2 (carbonate)	-0.92 (± 0.15)
JC-3 (carbonate)	-0.86 (± 0.15)
JC-3 (carbonate)	-0.79 (± 0.15)
Fumarole gases	
Allard (1984)	-3.9 (± 0.3)
LMS-2002-1	-4.1 (± 0.3)
LMS-2002-2	-4.1 (± 0.3)
LMS-2003-4	-4.4 (± 0.3)
LMS-2005-1	-3.5 (± 0.3)

APPENDIX G

Diffusion modelling results for Sr in feldspar using the equations of Giletti & Casserly (1994). A maximum crystal residence age can be calculated using these equations assuming that diffusion of Sr acts to eliminate isotopic disequilibrium within crystals and their host melt at magmatic temperatures (950-1050°C for Merapi; Gertisser, 2001).

APPENDIX G

		Sr isotope data									
		Rim		Outer Zone		Inner Zone		Inner Zone		Core	
		Distance	⁸⁷ Sr/ ⁸⁶ Sr	Distance	⁸⁷ Sr/ ⁸⁶ Sr	Distance	⁸⁷ Sr/ ⁸⁶ Sr	Distance	⁸⁷ Sr/ ⁸⁶ Sr	Distance	⁸⁷ Sr/ ⁸⁶ Sr
Calculation of diffusion coefficient		0.00	0.7058	0.2	0.70574	0.28	0.70569	0.54	0.70569	0.80	0.7057
For plagioclase of X _{An} content		0.02	0.7058	0.22	0.70574	0.30	0.70569	0.56	0.70569	0.82	0.7057
Giletti & Casserly, 1994		0.04	0.7058	0.24	0.70574	0.32	0.70569	0.58	0.70569	0.84	0.7057
An = 80		0.06	0.7058	0.26	0.70574	0.34	0.70569	0.60	0.70569	0.86	0.7057
D(0) = 4.4E-08		0.08	0.7058	0.28	0.70574	0.36	0.70569	0.62	0.70569	0.88	0.7057
Enter T = 950 degrees C		0.10	0.7058			0.38	0.70569	0.64	0.70569	0.90	0.7057
ln D -44.0909		0.12	0.7058			0.40	0.70569	0.66	0.70569	0.92	0.7057
D (m2s ⁻¹) 7.1E-20		0.14	0.7058			0.42	0.70569	0.68	0.70569	0.94	0.7057
Calculation of diffusion profiles		0.16	0.7058			0.44	0.70569	0.70	0.70569	0.96	0.7057
Initial ⁸⁷ Sr/ ⁸⁶ Sr = 0.70569		0.18	0.7058			0.46	0.70569	0.72	0.70569	0.98	0.7057
Final ⁸⁷ Sr/ ⁸⁶ Sr = 0.70579		0.20	0.7058			0.48	0.70569	0.74	0.70569	1.00	0.7057
						0.50	0.70569	0.76	0.70569		
						0.52	0.70569	0.78	0.70569		
								0.80	0.70569		

t (years) =	1	5	10	20	25	50	100	125	150	200	250	500
x, mm												
0.00	0.705790	0.705790	0.705790	0.705790	0.705790	0.705790	0.705790	0.705790	0.705790	0.705790	0.705790	0.705790
0.05	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705692	0.705693	0.705695	0.705699	0.705704	0.705719
0.10		0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705693
0.15		0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.20			0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.25			0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.30				0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.35				0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.40					0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.45						0.705690	0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.50							0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.55							0.705690	0.705690	0.705690	0.705690	0.705690	0.705690
0.60								0.705690	0.705690	0.705690	0.705690	0.705690
0.65								0.705690	0.705690	0.705690	0.705690	0.705690
0.70								0.705690	0.705690	0.705690	0.705690	0.705690
0.75								0.705690	0.705690	0.705690	0.705690	0.705690
0.80								0.705690	0.705690	0.705690	0.705690	0.705690