An introduction to magma dynamics

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Abstract: A variety of methods have been employed to decipher magmatic systems, including geophysical, petrological, textural and geochemical approaches, and these elucidate a large variety of characteristics of different plumbing systems and magmatic differentiation processes. A common theme to the papers presented in this book is the observation of transport of small volume magma batches with a relatively high frequency, as opposed to less frequent transport of larger magma volumes that would require storage in large crustal reservoirs for long periods of time. The implications of this observation are discussed in the context of a possible tectonic control on crustal magma dynamics.

This book addresses the rapidly developing fields of crustal magma transfer, storage and evolution. During both transfer trough and storage within the crust, magmas are subject to a series of processes that lead to their differentiation. Depths and mechanisms of differentiation, crustal contributions to magma generation through wall-rock assimilation, rates and timescales of magma generation, transfer and storage, and how these link to the thermal state of the crust, are subject to lively debate and controversy. This volume presents a collection of papers that provide a balanced overview of the diverse approaches available to elucidate these topics, and includes both theoretical models and case studies. By integrating petrological, geochemical and geophysical approaches, it provides the reader with new insights to the subject of magmatic processes operating within the Earth’s crust, and reveals important links between subsurface processes and volcanism.

This volume is divided into four sections: ‘Magma transfer: from mantle to surface’ addresses the ascent and evolution of magmas from the zone of melt generation in the mantle to eruption at the surface, forming a backdrop for the detailed studies of distinct parts of magma plumbing systems addressed later. ‘Dynamics of magma transport’ focuses on theoretical and geophysical approaches to understanding magma movement through the crust. ‘Magma reservoir dynamics’ provides insights from petrographic and mineral chemical studies into the processes occurring in crustal magma chambers. Finally, ‘Processes of silicic melt generation’ concludes the book with a dedicated section on the long-standing question of where and how magma differentiation may take place. In nature, these issues are of course intimately related, and some of the papers in this volume address more than one of these aspects. Therefore, the reader may obtain additional insights to a particular theme by referring to the other sections of the book.

With the exception of two contributions (Leeman et al.; Wright & Klein), all case studies presented in this volume deal with subduction zone magmatism. The inferences made here on the dynamics of magma ascent, storage and differentiation are therefore biased towards this tectonic setting. It may be argued that subduction-related magmatic systems are likely to have very different petrogenetic characteristics than ocean ridge and intraplate volcanism. Firstly, the primary magmas are produced at different depths within the mantle, and have different temperatures and compositions, particularly with regard to their volatile contents. Secondly, as a result of these differences, their petrogenetic evolution within crustal magma systems will differ significantly. For example, crystallization of volatile-rich arc magmas may be triggered by rapid decompression-induced degassing during magma ascent through the crust, a process that is not readily applicable for ocean ridge and intraplate magmatic systems. Thirdly, tectonic controls on the geometry of the plumbing systems differ considerably. Ocean ridges are in extension, resulting in rapid magma ascent through dykes and movement...
of newly created crust away from the heat source. In contrast, intraplate magmatism may favour magma storage and differentiation within the crust due to repeated sill intrusion and resulting progressive elevation of the geothermal gradient. Arcs, on the other hand, may be situated within extensional, transtensional or compressional regimes, potentially resulting in differences between the plumbing systems of different arcs (cf. Zellmer). Further work will be required to gain a balanced understanding of the dynamics of magma plumbing systems within different tectonic settings.

Magma transfer: from mantle to surface

Studies of igneous processes often focus on those parts of the crustal plumbing system that are best elucidated by the samples or methods available. It is rare that systems have been studied in sufficient detail to inform the entire process from magma generation in the mantle to eruption at the surface. This book starts with two studies where the amount of data is sufficient to provide such insights, on one hand using global volcanological, geophysical and geochemical datasets to present a broad overview of magma transfer (Zellmer), on the other hand focussing on the single edifice of Stromboli of magma transfer (Zellmer et al.). These papers address the dynamics of igneous processes occurring along the entire plumbing system of Stromboli volcano to gain a detailed understanding of the petrogenetic processes of this volcano (Cigolini et al.). These papers address the dynamics of igneous processes operating at sites of ongoing volcanic activity, and therefore form a backdrop for the detailed studies of the distinct parts of magmatic plumbing systems focused on in the later sections of this book.

From global correlations between eruptive style, surface heat flux and convergence rates of different volcanic arcs, Zellmer infers that the rate of melt production in the mantle wedge ultimately controls the dynamics of magma transfer through the crust, and thereby the chemical and physical properties of magmas and eruption products. It is shown that a deep crustal hot zone (Annen et al. 2006) does not buffer the effects of subduction velocity on melt production, and that the rate of magma generated in and released from the hot zone is proportional to the magma advected to the hot zone from the mantle wedge.

Crystal size distributions, bubble content and magma rheology, petrology and chemistry are a number of parameters that – when studied in combination – may offer a very detailed picture of the processes operating within magma plumbing systems, and can be used to quantify pressures, temperatures and the rates of preeruptive crystallization and gas exsolution. Such a multi-faceted approach is used by Cigolini et al. to elucidate the plumbing system of Stromboli volcano from upper mantle to surface. The data suggest that phenocrysts nucleate within a few days in a magma reservoir that extends vertically from 11 to 5.4 km below the summit of Stromboli. A new model is proposed where the magma chamber takes the shape of a vertically elongated ellipsoid that is penetrated by a feeder dyke sourced from over 30 km depth, i.e. in the mantle. According to this model, the instantaneous elastic rebound of the walls of the depressurizing subvolcanic reservoir explains the occurrence of intermittent paroxysmal eruptions at this volcano.

Dynamics of magma transport

Background

The second section of this book deals with insights that can be gained from theoretical and geophysical research. Direct observations of eruptions along fractures, ground deformation and the distribution of seisms associated with magma intrusion (e.g. Pollard et al. 1983; Rubin & Pollard 1987; Peltier et al. 2005; Yamaoka et al. 2005; Aloisi et al. 2006; Mattia et al. 2007) provide evidence for the role of dykes in magmatic transport (cf. Figs 1a & 2). In the case of andesitic volcanism, effusive or explosive, eruptions are more focused and the conduits are more cylindrical (cf. Fig. 1b). This may be explained through melting of host rocks (Quareni et al. 2001), and may also be related to a sharp increase in magma viscosity close to the surface due to decompression, degassing and crystallization. Rhyolitic magma, when associated with caldera formation, is transported to the surface through ring dykes.

It has also been suggested that interconnected sills could transport magma through the crust (Marsh 2004; Cartwright & Hansen 2006; e.g. Fig. 3a). Interpretation of geochemical and geophysical data suggests that the plumbing system of many volcanoes may be a complex plexus of interconnected sills and dykes (Hildreth 1981; Lahr et al. 1994; Donoghue et al. 1995; La Delfa et al. 2001; Preston 2001; Dawson et al. 2004; Sanchez et al. 2004; cf. Fig. 1c).

For granitic magma, diapirism was thought to be a common mechanism of magma transport and emplacement within the crust (e.g. Whitehead & Luther 1975; White & Chappell 1977; Pitcher 1979; Hildreth 1981; Marsh 1982; cf. Figs 1f & 3b). However, Hot-Stokes diapirism, characterized by ductile flow of host rock around the rising magma mass, is regarded as thermally and mechanically unrealistic within the mid to upper crust, and
Dyking as a magma transfer mechanism is favoured by a number of studies (Clemens & Mawer 1992; Clemens et al. 1997; Petford et al. 2000). Hutton et al. (1990) observed granite intrusion along ductile extensional shear zones and noted that it was solving the room problem posed by pluton emplacement, making diapirism unnecessary. Conversely, Miller & Paterson (1999) introduced

![Diagram](http://sp.lyellcollection.org/)

**Fig. 1.** Summary of possible crustal magma plumbing systems as inferred through studies in this volume. Magmas may have been processed within a lower crustal hot zone (Annen et al. 2006), although some mantle melts may be transferred instantly into and through the crustal section (cf. Straub). (a) Magma transport through dykes (cf. Martin-Del Pozzo et al.; Wright & Klein), at rates of centimetres to tens of kilometres per day. (b) Development of small vertical chambers (cf. Cigolini et al.; Dosseto et al.; Wright & Klein), with storage times between days and a few thousand years. (c) Magma transport through interconnected dykes and sills (cf. Bunger; Leeman et al.), with sill solidification timescales of the order of 10–100 years. (d) Development of small horizontal chambers, e.g. through repeated sill intrusion (cf. Ban et al.; Leeman et al.), with storage times between tens of years and thousands of years. (e) Development of plutons through repeated addition of small magma batches over long timescales of up to $10^7$ years (cf. Burgess & Miller; Gray et al.). Large magma chambers may form through rapid (a few hundred years, e.g. Michaut & Jaupart 2006) large-scale crustal melting when enough thermal energy has accumulated (cf. Leeman et al.). (f) Diapirism as a mechanism to emplace felsic magma reservoirs. For emplacement into the mid to upper crust, visco-elastic diapirism as suggested by Miller and Paterson (1999) would be required. Note that none of the studies in this volume find evidence for diapirism. Although the stalling of magma is not only controlled by the stress field, but also by the rheological properties and densities of crustal lithologies, the studies presented in this volume suggest that (a) and (b) may be favoured in extensional or transtensional settings, while (c)–(e) are more likely to occur in compressional tectonic regimes (see also Zellmer).
the term ‘visco-elastic diapir’ and argued that, if
diapirism is defined as the upwelling of mobile
material through or into overlying rocks (Van den
Eeckhout et al. 1986), then it remains an important
emplacement mechanism of felsic plutons. The fol-
lowing field observations are used to support the
model of visco-elastic diapirism: downward move-
ment of host rocks through multiple processes,
including brittle deformation and stoping; involve-
ment of multiple magma batches; and controls of
regional deformation on pluton emplacement.
Visco-elastic diapirism is called upon in a number
of recent case studies of felsic plutons (e.g.
Cabello et al. 2006; Farris et al. 2006; Zak &
Paterson 2006).

In the case of magma transport through frac-
tures, crustal magma transfer can be very fast on
the order of days to years (Clemens & Mawer
1992; Clemens et al. 1997; Petford 2003; Annen
et al. 2006). Large excesses in $^{226}$Ra in mafic volca-
nic products indicate ascent from source to surface
in the order of 1 ka or less (Turner et al. 2000;
Zellmer et al. 2005). In exceptional cases, magma
ascent rates through the crust can be extremely
fast: $\geq 26$ km per day have been estimated for
some Mexican andesites that carry hornblende–
peridotite xenoliths, which reached the surface so
rapidly that they were not affected by dissolution
in their host magma during ascent from the
mantle (Blatter & Carmichael 1998). In the case
of felsic magma transport through visco-elastic
diapirs, crustal magma transfer rates may be signifi-
cantly slower, of the order of $10^{-2}$ to 1 m year$^{-1}$
(Miller & Paterson 1999).

Contribution of this volume

Independent of storage depth and composition of
the magma, many magma bodies are thought to be
established through repeated sill intrusions (Bridg-
water et al. 1974; Benn et al. 1999; Cruden &
McCaffrey 2001; de Saint-Blanquat et al. 2006;
Pasquare & Tibaldi 2007). The work of Bunger
provides insights into the parameters that govern
sill propagation. It is shown that, during sill
growth, fracture behaviour is strongly influenced
by viscous flow within the near-tip region, and
that the physics of viscous dissipation must there-
fore be taken into account when modelling
sill growth.

Fig. 2. Geophysical observations indicate subvolcanic magma transport through dykes. This example shows modelled
sources obtained from dynamic inversion of Mount Etna tilt data and seismicity recorded during intrusion propagation,
as taken from Aloisi et al., ‘Imaging composite dike propagation (Etna, 2002 case)’, Journal of Geophysical
Union. Reproduced by permission of American Geophysical Union.
Using seismic, geodetic and eruption data from Kilauea volcano, Wright & Klein evaluate the interplay between magma supply and spreading of associated rift zones that provide room for intrusions into the subvolcanic reservoirs. It is shown that the dynamics of magma supply affects spreading rate, intrusion frequency and degree of summit inflation, resulting in varying characteristics of intrusive and eruptive activity at this volcano.

In a case study of the 2006 eruptions of Popocatepetl volcano, Martin-Del Pozzo et al. use varying magnetic anomalies to gain insights into magma ascent and lava dome extrusion. The magnetic signatures of these and associated processes are superimposed, but they can be distinguished on the basis of signal morphology, and correlated with data from other monitoring techniques. It is deduced from magnetic, seismic and petrological data that the plumbing system beneath Popocatepetl is essentially formed by dykes. The stagnation level is constituted from a series of interconnected dykes and does not involve a large magma chamber.
melt from the crystals is mostly by compaction and deformation (McKenzie 1984; Sparks & Huppert 1984; Petford 2003; Bachmann & Bergantz 2004). In a liquid magma this separation can be related to crystal sedimentation or floating, although thermal convection in the magma chamber can prevent crystal settling. In a convecting magma chamber, crystals and liquids can be separated by crystallization on the magma chamber walls and convection of the adjacent fluid (Sparks & Huppert 1984; Sparks et al. 1984).

The shapes and sizes of magma reservoirs are not well known. Many plutons are roughly circular in outcrop with steep sides (Pitcher 1979), and magma chambers and plutons are often represented as spherical bodies. However, geophysical and structural studies show that some plutons are sill-like, low aspect-ratio, tabular bodies (Bridgwater et al. 1974; Lefort 1981; Cruden 1998; Petford et al. 2000), while others are elongate intrusive bodies of a few kilometres vertical extent (e.g. Farris et al. 2006). The Socorro magma body, which can be seen on seismic profiles, is sill-like (Rinehart et al. 1979; Brocher 1981). Further, most igneous bodies may have been emplaced by the incremental assembly of discrete pulses (Coleman et al. 2004; Vigneresse 2004; de Saint-Blanquat et al. 2006). Geochronological data indicate that the assembly of some plutons and batholiths lasted several millions years. For example, according to U–Pb geochronological data, the Tuelume Intrusive Suite of the Sierra Nevada, California, was emplaced over 10 million years (Coleman et al. 2004), and the Mount Stuart batholith and Tenpeak intrusion in the Northern Cascades were emplaced over 5.5 and 2.6 Ma, respectively (Matzel et al. 2006). Long emplacement timescales led Glazner et al. (2004) to question the relationship between plutons and large magma chambers: if plutons are emplaced slowly by amalgamation of discrete pulses of magma, the volume of molten rock during the construction of the pluton might not greatly exceed the volume of a single pulse. However, Matzel et al. (2006) argue that the construction of the Mount Stuart batholith was discontinuous and punctuated by high magma flux intervals that may have led to the formation of large magma reservoirs (cf. Fig. 1e). The existence of calderas, the distribution of vents around these calderas, the large volumes of ignimbrites and the common occurrence of zoning within these ignimbrites support the existence of large and shallow felsic magma chambers (Chapin & Elston 1979; Lipman 1984). In a recent paper, Lipman (2007) provides a series of arguments that support the link between plutons and large-volume ignimbrite volcanism associated with caldera formation, but stresses that large upper crustal magma reservoirs may be short-lived, and that in some arcs the volcanic products may come directly from the mid or lower crust without involving shallow crustal magma chambers. The view that magma reservoirs shallower than 20 km are rare is supported by the absence of detected ground deformation associated with several eruptions in the Andes (Pritchard & Simons 2004), and the view that shallow reservoirs are short-lived is supported by the short residence time of crystals at magmatic temperatures recorded by trace element profiles in zones crystals (e.g. Zellmer et al. 1999, 2003; Costa et al. 2003; Morgan et al. 2004; Morgan & Blake 2005; Zellmer & Clavero 2006).

**Contribution of this volume**

The variety of crystal populations that are found in volcanic products indicate that crustal magma transfer processes may in detail be complicated through uptake of xenocrysts, crystal recycling within the magmatic system of individual volcanoes, and crystal growth and resorption triggered by processes such as magma cooling, recharge, decompression and degassing. **Jerram & Martin** provide a review of how these processes may be deciphered and quantified, and outline avenues for future research, where a combination of textural and microgeochemical techniques may provide an ever more detailed picture of the magma plumbing system beneath individual volcanoes. Santorini, one of the decade volcanoes, is used as a well-studied example.

The evolution of a shallow stratified magma chamber beneath Zao volcano in NE Japan is studied by **Ban et al.**, using the petrology and geochemistry of eruption products within a c. 5.8 ka-old tephra layer. The authors deduce high rates of crystallization and infer that this chamber was short-lived. They also provide evidence for magma mixing due to intrusion of a new pulse of basaltic magma, which ultimately triggered the eruption.

**Processes of silicic melt generation**

**Background**

Since the seminal work of Bowen (1915), it is known that, when magmas crystallize, the separation of crystals from the residual melt leads to a chemical evolution of this melt and to the genesis of evolved magmas. Basalts generated by partial melting of the mantle, when cooling down and crystallizing at the crust-mantle boundary or within the crust, can differentiate and produce intermediate and silicic magmas. However, intermediate and
silicic magmas can also be produced by partial melting of the crust. Experimental petrology shows that partial melting of amphibolites in the lower crust can produce calc-alkaline melts (Rapp & Watson 1995; Sisson et al. 2005). I-type granites are thought to be generated by this mechanism (Chappell & White 2001). The partial melting of crust of granodioritic, pelitic or greywacke composition produces more aluminous melts that are thought to be the origin of S- and some A-type melts (Clemens & Wall 1981; Patiño Douce 1997). Assimilation of crust and fractional crystallization may act concomitantly (APC, DePaolo 1981), and these processes are variably important in the evolution of some silicic magmas.

The generation of evolved magma by differentiation of mafic magma in shallow reservoirs is favoured by many authors (e.g. Sisson & Grove 1993; Grove et al. 1997; Pichavant et al. 2002). However, on the basis of geochemical data, Hildreth & Moorbath (1988) proposed that magma mixing did operate. Recently, more arguments based on petrological, geochemical and thermal data were presented in favour of differentiation in long-lived deep hot zones located in or below the lower crust where multiple sills of basalt are intruded and crystallise (Petford & Gallagher 2001; Bryan et al. 2002; Annen & Sparks 2002; Annen et al. 2006). In these studies, basalt differentiation and partial melting of the crust can happen simultaneously, although this is not necessarily the case. Thermal evolution and differentiation of each successive sill depend on its position on the geotherm, which changes with time as sills transfer heat to their surroundings. The geochemical and petrological characteristics of the melt depend on the time between sill emplacement and melt extraction. If melt segregation and extraction are by compaction, the melt can evolve further during segregation (Jackson et al. 2003).

In recent years, isotopic data have elucidated the timescales of magmatic differentiation processes (cf. Turner & Costa 2007); decrease of $^{226}$Ra excesses during small degrees of differentiation within individual volcanic centres indicate that magmatic evolution may occur in the order of $10^3$ years at some sites (George et al. 2003, and references therein). However, the general decrease of $^{238}$U excesses from mafic towards andesitic compositions in arc lavas suggests that, in order to produce andesitic compositions from less evolved magmas, timescales of the order of $10^5$ years are required, unless open system processes such as magma mixing are involved (Zellmer et al. 2005). Open system processes that involve mixing of young mafic with older more felsic composition do appear to operate in many cases: they are evidenced through macroscopic and microscopic mixing and disequilibrium textures within intermediate volcanic products, and are suggested by the occasional persistence of $^{226}$Ra excesses to dacitic compositions (Zellmer et al. 2005, and references therein). Finally, the generation of some rhyolites has been shown to be associated with large scale rejuvenation of previously intruded felsic magmas from mid to upper crustal levels (Charlier et al. 2005; Lipman 2007). The rates of generation of such felsic magmas are more difficult to constrain, but evidence of assimilation of ancient crustal rocks indicates that thermal incubation times of the order of several hundred ka may be required (Zellmer et al. 2005). However, once the right thermal conditions are attained, rhyolite generation from basaltic magmas may proceed on timescales of the order of $10^4$ years in some systems (Lowenstern et al. 2006).

Contribution of this volume

Using uranium-series isotope constraints, Dosseto et al. show that differentiation from mafic to intermediate and felsic magmas is a rapid process at some arc volcanoes (e.g. <2500 years for Mount St Helens). In contrast to suggestions of a long-lived, deep-crustal hot zone as a key site for magmatic differentiation (Annen et al. 2006), the authors suggest that in the case of Mount St Helens, the magmatic evolution is constrained to the cooler environment of the mid crust.

In their study of the Tuolumne Intrusive Suite of the Sierra Nevada Batholith, California, Gray et al. provide thermobarometric evidence for subsolidus exsolution of crystal phases at depths near 6 km, and argue that the scatter of trace element and isotopic signatures precludes fractional crystallization of a large magma chamber as the dominant process in the generation of the intrusive suite. Instead, the authors suggest a petrogenetic model based on mixing of mantle-derived mafic with granitic melts. Because the Tuolumne Intrusive Suite was emplaced slowly over at least 10 million years (Glazner et al. 2004), successive magma batches that formed the batholith were not molten simultaneously and could not mix after emplacement, which suggests that the magmas mixed at source level or during transport.

In contrast, Burgess & Miller focus their study on the Cathedral Peak granodiorite, which is the largest unit of the Tuolumne Intrusive Suite. It is found that the Cathedral Peak was emplaced rapidly, suggesting that it may have represented a large mushy magma reservoir, where fractional crystallization and magma mixing did operate.
The last two papers of the volume focus on bimodal volcanism. In the Snake River Plain–Yellowstone bimodal magmatic system, Leeman et al. argue that isotopic data on the initially erupted voluminous rhyolites indicate a dominant crustal component. Rhyolite petrogenesis is modelled through massive input of basalts into the mid to upper crust over several million years, leading to partial melting of several kilometres of the upper crust.

Finally, Straub studied the composition of tephra of the central Izu–Bonin volcanic arc (NW Pacific) using mineral chemical data from an ODP drill core. Her work provides evidence for a remarkable constancy in tephra compositions over 42 Ma of eruptive history at this arc and, by inference, constancy in petrogenetic and eruptive processes over this timescale.

Discussion

Integrating the evidence

The processes of crustal magma transfer, storage and differentiation are inherently complex (Marsh 2004): ‘The local size, shape, and age of the system coupled with magma crystallinity, integrated flux, flushing frequency, and nature of wall rock involvement determines the local and system-wide products.’ The papers collected in this volume may serve as a means to move on from that acknowledgment towards an understanding of the dominating characteristics of magmatic systems. Despite the variety of systems addressed (Fig. 1), the overall theme of the papers in this volume is the importance of small volume magma batches that are transported through plumbing systems with a relatively high frequency, as opposed to less frequent transport of larger magma volumes that would have to be stored in larger crustal reservoirs for longer periods of time. This corroborates results from previous work on small volume systems (Bacon et al. 1981; Hildreth 1981; Detrick et al. 1987), and is consistent with studies of magma mixing (e.g. Sparks et al. 1977), and chamber replenishment and inflation (Björnsson et al. 1977; Blake 1981). Frequent transport of small magma batches is directly evident at Popocatepetl, where magma transport to the surface occurs through repeated dyke injection (Martín-Del Pozzo et al.); at Santorini, where crystal size distribution and textural constraints indicate the presence of one or more small reservoirs that repeatedly experience recharge (Jerram & Martin); at Stromboli, where upper crustal magma residence times of a few days are inferred (Cigolini et al.); at Zao volcano and Mount St Helens, where rapid crystallization indicates that the subvolcanic chambers are small and short-lived (Ban et al.; Dosseto et al.); and at Kilauea, where repeated injections into the volcanic edifice can be geophysically observed and correlated with the eruptive behaviour of the volcano (Wright & Klein). High-frequency transport of small magma batches is also evident within the structurally less mature intra-oceanic Izu–Bonin volcanic arc; where Straub argues that the large number of tephra deposits with distinct compositions implies magma transfer processes that do not involve long-term storage within large crustal reservoirs. Further, it is consistent with the global study of Zellmer, which suggests that magma throughput through a lower crustal hot zone is close to steady state, with magma input from the mantle proportional to magma output into the overlying crust. Even the generation of large volumes of evolved melts forming the Snake-River Plain rhyolites (Leeman et al.) is seen as a result of repeated injection of relatively small volume magma batches into mid to upper crustal levels over millions of years. Finally, according to Gray et al., the Tuolumne Intrusive suite was generated by mixing of a number of successive magma batches.

If movement of small volume melt batches is a common phenomenon in the generation and evolution of crustal magmatic systems, critical parameters responsible for variations in magma dynamics are the intrusion frequency and the melt segregation threshold. These will ultimately control the thermal structure of the crust, and therefore the amount and composition of magmas transferred through the plumbing system. Intrusion frequency is dependent on the rate of melt generation within the mantle. Further studies are required to determine the controls on melt segregation, although there is some indication that the local and regional stress regimes are important. These in turn will differ considerably between different tectonic settings.

Considerations regarding the tectonic setting

The tectonic controls on magma ascent and storage, and links to differentiation mechanisms, have not yet been investigated in sufficient detail, and promise to yield many insights into the operation of crustal magma plumbing systems. Future research should therefore include studies that specifically focus on melt differentiation at ocean ridges with variable spreading rates, including on- and off-axis sites of volcanic activity; at intra-plate volcanoes sampled at variable distance from the plume centre; and at arcs situated within contrasting tectonic regimes, e.g. extensional v. compressional. Traditionally, research in ocean ridge and intraplate
settings has focused on the origin of the melts, the melting process, and insights that may be gained into the dynamics and composition of the underlying mantle. Studies of crustal magma evolution may, however, yield many important additional insights. For example, detailed results on oceanic rhyolitic volcanism in Iceland show that differentiation mechanisms range from near-liquidus processes (crystal fractionation ± assimilation, e.g. Carmichael 1964; Macdonald et al. 1990; Nicholson et al. 1991; Lacasse et al. 2007) to near-solidus scenarios (crustal melting, e.g. O’Nions & Grönvold 1973; Sigvaldason 1974; Hémond et al. 1988; Sigmarsson et al. 1991; Jónasson 1994; Lacasse et al. 2007; Martin & Sigmarsson 2007; Zellmer et al. 2008). Future studies of melt evolution at ocean ridge and intraplate settings, as well as above subduction zones, will further refine our understanding of the processes and timescales operating during crustal magma transfer, storage and differentiation, and how they are affected by tectonic controls.

Conclusions

1. Crustal magma plumbing systems are characterized by a variety of processes that include dyke and sill propagation; magma accumulation, segregation, and mixing; crystallization, crystal resorption and recycling; magmatic volatile exsolution and degassing; and various assimilation processes that involve both old and juvenile crust. These can be linked to eruptive behaviour and the chemistry and petrology of erupted or intruded magmatic products.

2. Despite the complexity and variety of crustal magmatic systems, a common theme in the dynamics of magma transfer and storage mechanisms appears to be the high-frequency processing of small melt batches, as opposed to long-term storage of large volumes of melt accumulated in crustal reservoirs. This evidence is mainly based on studies of subduction zone magmatism.

3. Tectonic setting has the potential to exert a strong control on the geometry and evolution of crustal magma plumbing systems, and on the dynamics of magma transfer and storage within these systems. Future studies should address the links between magmatism and tectonism to improve our understanding of the crustal magmatic processes that operate in different tectonic regimes.

4. The length and timescales governing the development of crustal magma reservoirs remain key to the understanding of the petrogenetic processes operating in crustal magmatic systems.

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