Plumbing Systems of Shallow Level Intrusive Complexes

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Abstract

We have come a long way from simple straw and balloon models of magma plumbing systems to a more detailed picture of shallow level intrusive complexes. In this chapter, the sub-volcanic plumbing system is considered in terms of how we can define the types and styles of magma networks from the deep to the shallow subsurface. We look at the plumbing system from large igneous provinces, through rifted systems to polygenetic volcanoes, with a view to characterising some of the key conceptual models. There is a focus on how ancient magmatic centres can help us better understand magmatic plumbing. New innovative ways to consider and quantify magma plumbing are also highlighted including 3D seismic, and using the crystal cargo to help fingerprint key magma plumbing events. Conclusions are drawn to our understanding of the 3D plumbing system and how these recent advances can be helpful when exploring the other chapters of this contribution.

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1 Introduction

Traditionally, shallow magma systems have been conceived as relatively simple, direct pathways allowing magma to rise from a holding chamber to the surface (cf. magma conduit). The plumbing system at this shallow level (<5 km) is often simply depicted as a vertical cylindrical conduit leading from a simple magma chamber where magma passes through (the straw and balloon model; Fig. 1) but does not really reside or stagnate (except as indicated by solidified plugs, volcanic necks etc). Deeper plumbing systems that feed the shallow level chambers, are

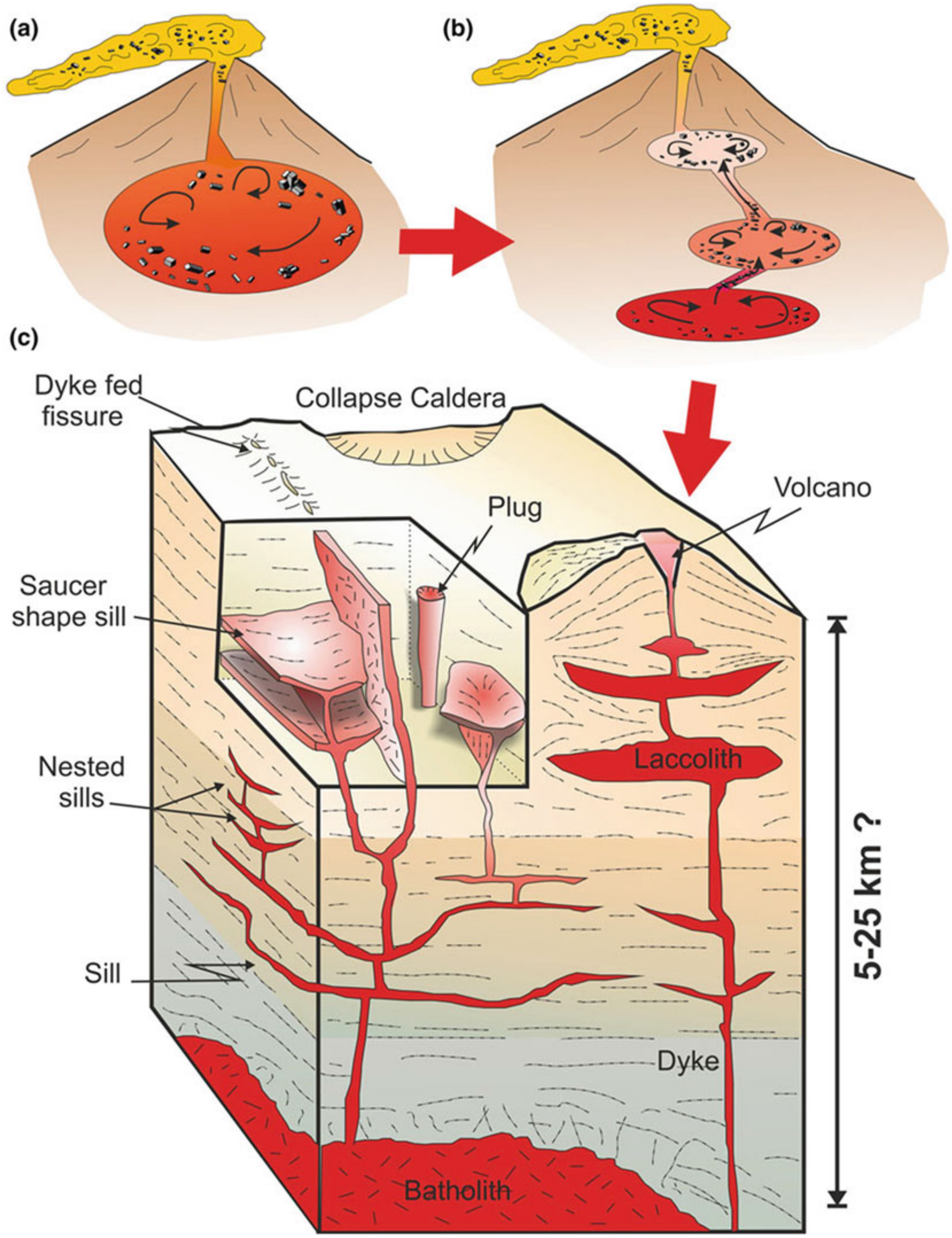


Fig. 1 Conceptual evolution of our understanding of the complexities of the subvolcanic plumbing system. **a** The classic 'Balloon and Straw' model, with a balloon-like magma chamber feeding a volcano; **b** realisation of multiple magma storage zones and a complex plumbing system; **c** 3D distribution network of magma plumbing from deep to shallow levels in the crust feeding a variety of volcanoes

somewhat more enigmatic, with often little physical linkage made from the sources of melting, to the volcanic system near the surface, and particularly confused for granitic magma ascent that was viewed early on as slow-rising, hot Stokes diapirs from their source (see Petford 1996). Recent studies (some of which will be touched on here) have illustrated the variability in dimensions and geometry of shallow systems and the possible way in which they are linked at depth. Fissures are increasingly recognised as important pathways and vents for many mafic and even silicic eruptions. Magma may pond at shallow depths (<1–5 km) before eruption in sill complexes of variable size and complexity, or as more circular central complexes. Sill intrusion can be observed to be at shallow depths within the volcanic sequences themselves and the disaggregation and direction of flow of the magma plumbing system is strongly affected by the nature of lithologies the magma passes through e.g., syn-sedimentary (stratified and sometimes poorly lithified) versus old metamorphosed or igneous basement hosts. Volcanic centres can appear, when exposed at the surface or imaged in gravity data, as relatively discrete sub-circular bodies, or as a more complex amalgam of multiple centres with linked feeding systems, replenished and reused several times in their evolution. Once melt has been segregated and extracted from source rocks, many processes can then operate within the plumbing network, the magma chamber(s) and on eruption at the surface that combine to define the final chemistry, crystallinity, eruptive style and even aerosol injections into the atmosphere.

In this short overview, the sub-volcanic plumbing system is considered in terms of how we can define the types and styles of magma networks from the deep to the shallow, their common settings, innovative ways in which we can image and capture the complexities of magma systems, and new techniques using volcanic eruptive products as a proxy for recording information from depth. The closing remarks point to our current knowledge, and a way forward to better understand shallow level intrusions. The aim here is not to provide an exhaustive review, but to touch on some of the key points that will be emphasised by the other studies within this book.

2 What is the Magma Plumbing System?

How we define the shallow-level magma system and how it relates to the overall journey that magma makes from deep within the lithosphere, or even the asthenosphere, to the sub-volcanic domain, is a non-trivial task. One person's shallow magma chamber is another person's deep magma storage zone, and the scales and depths involved can range from a few meter thick dykes to km^3 sized magma batches, and from a few 100s of meters to a few to several 10s of km, respectively. We have advanced significantly from the classic text book views of simple balloon and stick-type magma chambers depicted in the introduction (e.g., Fig. 1a) to a realisation of much more complexity in the subvolcanic system linking several subvolcanic chambers (Fig. 1b), and finally to a conceptual 3D model linking the sub-surface system to volcanoes at the surface (Fig. 1c) (e.g., Jerram and Davidson 2007; Jerram and Martin 2008; Thomson and Schofield 2008; Cashman and Sparks 2013). This progression of understanding has resulted from numerous research programs and published bodies of work, but how do we build a detailed picture of the types and variation that we may find in the subvolcanic system?

Generally speaking, the way in which magma can journey through the crust is through dykes, sills and variably shaped magma chambers, the latter being also areas where magma may reside for some time. Dykes mainly represent the vertical transport component of the system with typical widths of meters to a few 10s of meters with commonly observed continuous strike extents of 100s of meters to 10s of km's; discontinuous dyke swarms can laterally extend for >1000 km on Earth (e.g., 1270 Ma Mackenzie dyke swarm; LeCheminant and Heaman 1989; Ernst and Baragar 1992). All magma compositions can form dykes, but by far the most common and volumetrically significant dykes are basaltic in composition. Dykes are observed to form over a wide range of depths from deep crustal examples such as the Scourie Dykes (at mid to lower crust e.g., O'Hara 1961; Tarney 1973), through sedimentary basins (e.g., NAIP dyke swarms, Macdonald et al. 2010) to very shallow systems feeding lavas (e.g., fissure fed lava systems, as evidenced by chains of scoria cones; e.g., Iceland, Thordarson and Self 1993).

Sills provide potential storage zones of some significant magma volumes particularly when found in nested sill complexes (e.g., Marsh 2004) or in large igneous provinces (e.g., Bryan et al. 2010 and references therein). Sill thicknesses vary in a similar manner to dykes, but tend to have a larger average thickness, 10s of meters is common with sills over 100 m in thickness commonly found in continental flood basalt provinces (e.g., Peneplain Sill, Jerram et al. 2010). This thickness requires inflation and accommodation space, and often the overburden can be faulted and folded (White et al. 2009). The potential for contemporaneous eruption and sill intrusion may be particularly important to help feed large lava sequences in flood basalts.

In both sills and dykes, evidence for lateral flow as well as vertical (upwards flow) in the system can be observed. Magma can flow significant distances laterally in sub-volcanic plumbing systems (>1000 km) such as the Mackenzie dyke swarm (e.g., Ernst and Baragar 1992), and the Dry Valleys sill complex, Antarctica (e.g., the Peneplain sill and Basement sill; e.g., Marsh 2004) both showing major along strike extent, and significant lateral injection and flow. Magmatic centres represent sites where a magma pathway persists for a relatively long period of time (100,000 years to millions of years), which also include the potential for contemporaneous tapping and eruption of spatially separate chambers within the same complex (e.g., Brown et al. 1998; Smith et al. 2005; Martin et al. 2010).

In terms of tectonic setting, we can broadly consider three major magma generating systems: those at rifted settings (e.g., continental rifts, mid-ocean ridges), those at subduction zones, and those associated with plumes/hot spots, which can occur through both oceanic and continental crust. While tectonic stresses can have important controls on magma pathways at regional scales, it has also been recognised that at the volcano-scale, magma chamber stresses and volcanic evolution that can generate load stresses or new magma pathways to the surface through collapse are also important. It is not so clear then that considering magma plumbing at these separate tectonic settings truly reflect the systems in detail, as often similar volcanic systems can develop irrespective of tectonic setting. It may also be possible to consider the magmatic plumbing system in terms of long-lived versus short lived systems, or by dominant magma composition types. Again, problems arise here in the fact that is difficult to define what maybe meant by short vs long lived, particularly in pulsed systems. Although one magma type might dominate, a compositional diversity can exist with different magma types utilising the plumbing system either during one eruption or over time, blurring such a definition.

To help simplify the approach of considering magma plumbing systems, in this contribution we will consider the magma plumbing in terms of three types of scenarios (which are partly determined by scale, tectonic setting and by time/longevity) which are not mutually exclusive: Large Igneous provinces, predominantly rifted settings, and polygenetic volcanoes where magma plumbing systems can persist for long periods. Within this broad sub-division, a number of the key features of the magma systems are introduced, and we look at how these are manifest in terms of the volcano plumbing that can be observed at the surface, or inferred through innovative ways of imaging or remotely sampling the magma plumbing. More specific case studies and examples showing the plumbing styles from a number of settings will appear throughout the rest of the contributions in this series, and will hopefully build on what we introduce here.

3 Large Igneous Provinces

Here we briefly consider the intrusive component associated with continental flood basalt provinces (CFBPs), as an example of large igneous provinces (LIPs). LIPs are sites of the most frequently recurring, largest volume basaltic and silicic eruptions in Earth history (e.g., Bryan et al. 2010 and references therein), and as such, require the flux of huge amounts of magma from the upper mantle and deep to shallow crust, through multiple pathways to the surface. How is that recorded in the geological record and what can it tell us about what is beneath modern volcanoes?

There are many locations where CFBPs are preserved on the planet at differing degrees of erosion which partly exposes the plumbing system, and from which we can gain insight into the nature and evolution of the system (e.g., Jerram and Widdowson 2005). Examples such as the Siberian Traps, Paranã-Etendeka province, North Atlantic igneous province, Antarctic Ferrar-South African Karoo provinces, Columbia River and Deccan Traps, are some of the more well-known and studied examples. Due to differing levels of erosion and combined with geochemical variations that occur, we are able to construct a general idea of the regional plumbing systems for CFBPs. These systems are vast and in practice, any investigation of them starts to identify almost all possible types of intrusion, from complex forms in volcanic centres, plugs, laccoliths/lopoliths, through dyke swarms, to nested sill complexes (e.g., Ernst and Baragar 1992; Marsh 2004; Jerram and Widdowson 2005; Macdonald et al. 2010; amongst many examples). By looking at the resultant ways in which mantle-derived melts make it from depth to surface, it is possible to produce a schematic picture of the styles of magma plumbing. Bryan et al. (2010), considered the largest known eruptions that have occurred on Earth, and constructed a simplified end-member diagram to highlight the relative journey that magmas of all volumes can have from the mantle to the surface (Fig. 2). The general plumbing under CFBPs is normally characterised by that depicted in Fig. 2a, b. Here, sometimes magma plumbing

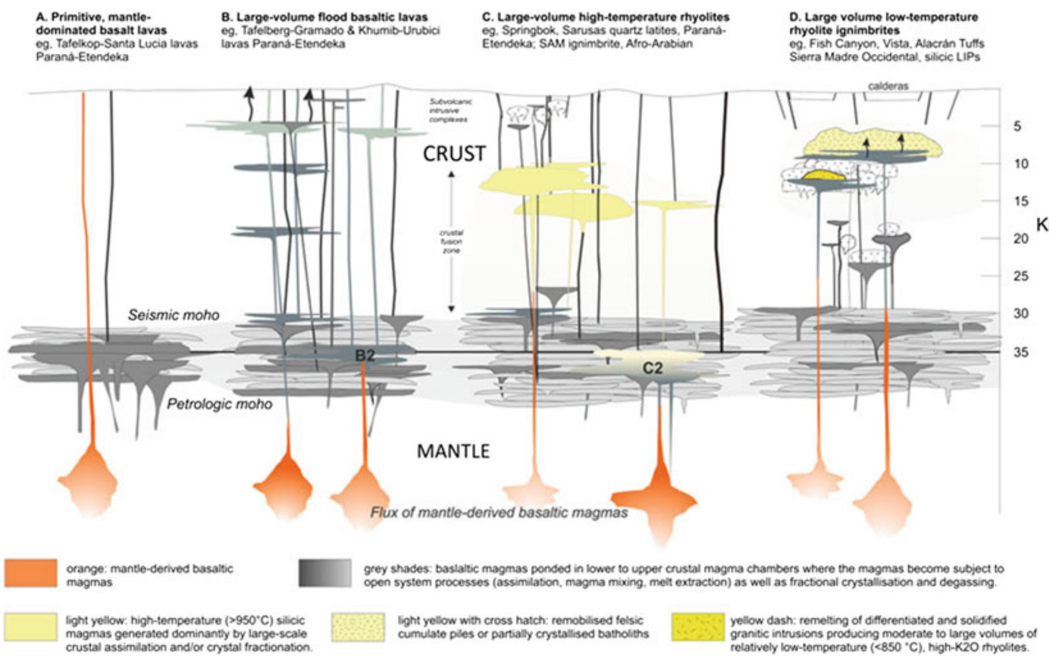


Fig. 2 Types of plumbing and magma pathways present at Large Igneous Provinces (modified from Bryan et al 2010). The figure text highlights the main styles of pathway from simple eruption of primitive melt at the surface to more complex batches of magma with varying degrees of complexity in terms of composition, volumes, and crystal loads

can be simple and deep, leading to very primitive 'mantle-like' melts making it to the surface (Fig. 2a). More commonly, magma stalls in chambers and intrusive complexes that occur in the middle to upper crust, producing sill complexes (Fig. 2b). These complexes can be vast and very complex internally (see below). New constraints on eruption rates, particularly for the largest eruptions known, require 10^3–10^4 km^3 of magma available for eruption over decadal (flood basalts) or days to weeks (flood rhyolite) timescales, and thus the existence of substantial magma reservoirs most likely residing within the upper crust, but also a highly efficient transport network allowing magma to readily evacuate from holding chamber (s). This includes the existence of large volume sills as un-erupted examples (see Bryan et al. 2010).

4 Predominantly Rifted Settings

In areas where the Earth's crust is spreading apart, both the generation of melt through decompression as well as the accommodation space for the resultant magma are found in close proximity. One of the most common magma generating systems to consider is that which occurs at mid-ocean ridges. These are very important given their distribution around the globe and that they are responsible for creating the constant conveyor belt of present-day oceanic crust and where ophiolite complexes preserve examples of this process throughout Earth's history. It can also be shown that the latter stages of continental break-up require a transition from continental to oceanic rifting. Recent work on Iceland and in the Afar desert has looked at the shallow plumbing system as measured using shallow geophysics (e.g., Wright et al. 2012a, b). Fig. (3a, b) highlights the generalised model of dynamic spreading at the Dabbahu rift in Ethiopia, along with a picture showing the manifestation of part of this rifting at the Earth's surface, the Dabbahu Fissure (Fig. 3c, d, e). The stresses that build up along the rift are released during rifting episodes, when bursts of magmatic activity lead to the injection of vertical sheets of magma (dykes) into the crust. The magma is supplied to the crust periodically, and is stored at multiple positions and depths. It then laterally intrudes in dykes within the brittle upper crust during the rifting episodes (Wright et al. 2012a, b). This represents the current picture at thinned crust at the stages of continent separation. The dyke swarms that can be found through continental crust in ancient flood basalt settings likely represent the onset of this rifting phase (e.g., Macdonald et al. 2010 and references therein). These rift systems and large fissure type eruptions are present in many of the larger flood basalt settings as discussed above, and in some cases the fissure systems can be linked directly to flood basalt flows such as the Roza flow in the Columbia River (e.g., Thordarson and Self 1998). Where oceanic rifting is concomitant with a plume setting such as in the Iceland example, complex fissure, rift and shallow magma chamber systems develop, as recently imaged during the 2010 Eyjafjallajökull eruption (Sigmundsson et al. 2010).

5 Plumbing at Polygenetic Volcanoes—Persistent Magma Pathways

Some of the more complex plumbing systems we encounter are those where persistent magma pathways exist, which can occur in a variety of different settings. Polygenetic volcanoes, principally lava shields, stratovolcanoes and calderas, characterise many present-day tectonic settings such as subduction zones (both extending and non-extending), continental rifts and 'hotspots' (both continental and oceanic). Despite this variability in tectonic and crustal setting, the construction of polygenetic volcanoes reflect not only persistent magma supply but also the 'centralised' venting of magma over time scales of 10^3–10^7 years. Lava shield volcanoes typically reflect the frequent venting of mafic magmas only, whereas at stratovolcanoes and calderas, a much broader compositional range of magmas are supplied and vented. A fundamental implication then is that a

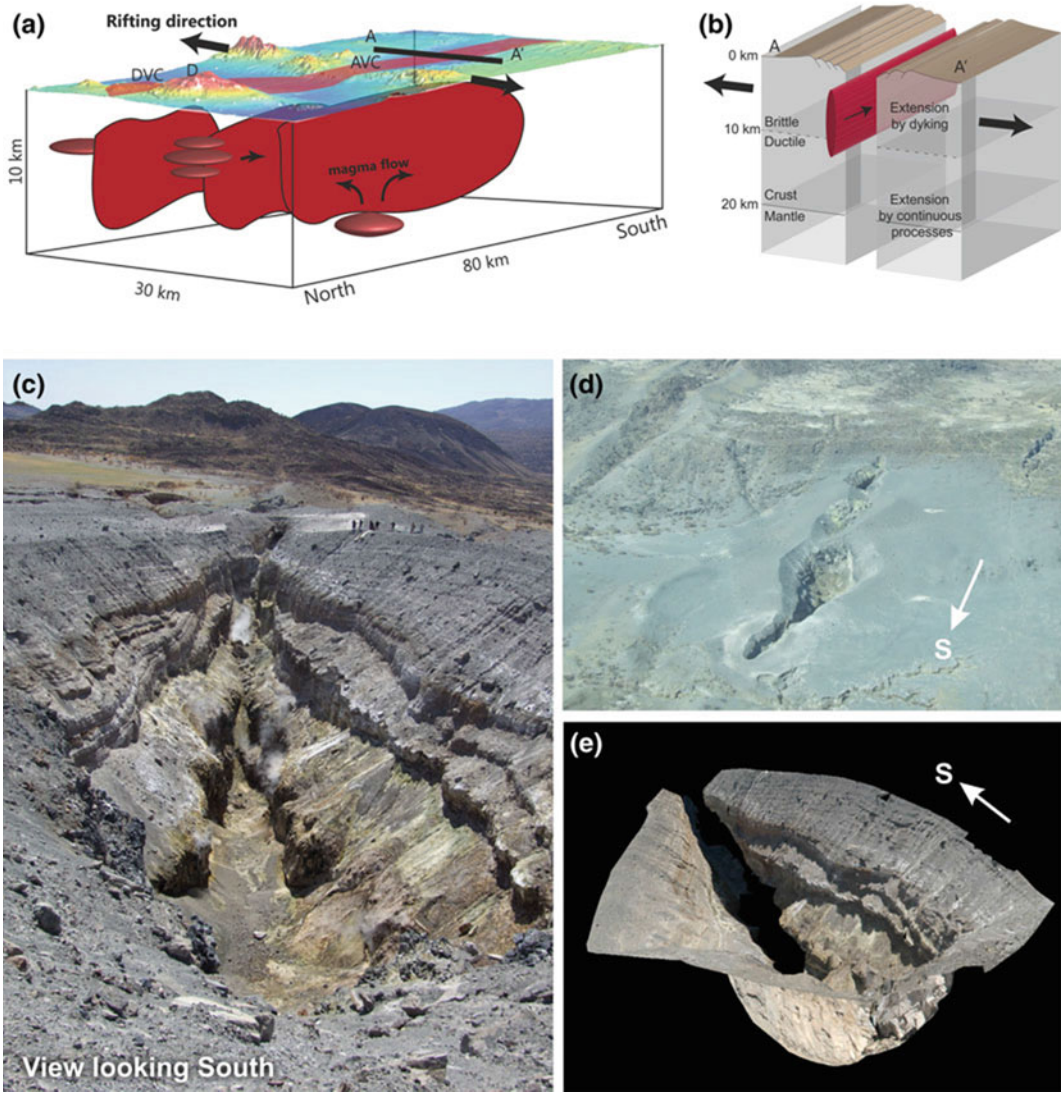


Fig. 3 Magma plumbing in predominantly rifted settings, example from the Afar rift, Ethiopia. **a** schematic model of magma plumbing at Dabahu rift showing schematic locations of magma chambers (*red ellipsoids*). Also labelled are Dabbahu (D), Dabbahu Volcanic Centre (DVC), Ado 'Ale Volcanic Centre (AVC), and location of cross section in b. Coloured map shows topography and also the zone of fissuring and faulting (highlighted in *light red* on map surface); **b** generalised cross-section of a typical slice of crust away from a magmatic centre (**a** and **b** courtesy of T. Wright, see also Wright et al. 2012a, b for details); **c** view of Dadahu fissure; **d** Dadahu fissure from the air; **e** 3D surface map of Dabahu fissure from laser scanning (from Jerram and Smith 2010)

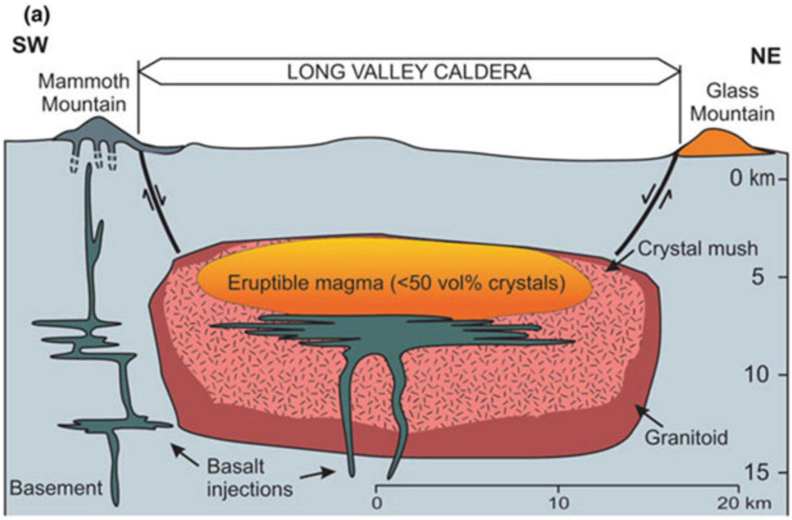
plumbing system, once established from the magma source regions, remains in existence and can essentially be re-used by new magma batches that may be separated by as much as 100,000s years and have no connection to the previous magmatic batch or episode. This is evident for example from the growth history of the andesitic Ngauruhoe cone (New Zealand), which reflects an open magma and plumbing system that supplies small (<0.1 km^3) and short-lived (100–10^3 years) magma batches but which have no simple time–composition relationships between successive batches even when separated by only a few tens of years (Hobden et al. 2002). Another fundamental implication is that it increases the possibility and likelihood of cannibalisation of previous magmatic material transported and stored along that plumbing system as succeeding magma batches attempt to successfully arrive at the surface for eruption. Consequently, magmas erupted from stratovolcanoes and calderas are likely to exhibit "contamination" effects arising simply from prior use of the magma plumbing system. This has been widely recognised in many recent studies of andesites and their crystal cargoes from arc settings (e.g., Dungan and Davidson 2004; Streck et al. 2007; Reubi and Blundy 2009; Kent et al. 2010; Zellmer et al. 2003, 2014). For caldera systems, "contamination" can also be generated by the involvement of spatially separate but contemporaneous magma bodies that are tapped during catastrophic caldera collapse and/or by tectonic faults that become active during eruption (e.g., Brown et al. 1998; Gravley et al. 2007).

Current views then of sub-volcanic magmatic systems is that magma storage can occur at multiple levels in the crust. As principally driven by studies on the origin of crystal-rich magmas, the main magma reservoir may be best represented as a crystal mush zone that can quickly be replenished and rejuvenated through new (mafic) magma injections (e.g., Bachmann and Bergantz 2003, 2004, 2008a, b; Glazner et al. 2004; Bachmann et al. 2007) (see example in Fig. 4a). This is analogous to the view of magmatic systems as "mush columns" (e.g., Marsh 1996, see Fig. 4b) where:

1. a sufficient magnitude and frequency of magma supply exists to sustain supersolidus and permissive zones for magma transport upwards;
2. the local mush state of the plumbing system is important as a source of crystal cargo for new magmas;
3. the tectonic immobility of the magmatic centre allows a sustained supply of magma to promote development of an intrusive, partly mushy underpinning that can be reprocessed through reheating by later magmas; and
4. he magmatic 'strength' of the system affects petrologic and chemical variability of erupted magmas.

The timescales involved in the storage of crystal mushes and their remobilisation are quite variable and somewhat difficult to constrain. In many crystal-rich systems the magma chamber or storage zones in the 'mush column' can reside in the crust for long times (e.g., Gelman et al. 2013; Cooper and Kent 2014). This suggests that the timescales of magma storage can be large, up to hundreds of thousands of years. Yet for the eruption of volcanoes responding to new magma influx in the system, it can be shown to happen quite quickly. Indeed, short residence times have been calculated for some crystal-poor, caldera-forming eruptions (e.g., Santorini) where the erupting magma may only reside for a few thousand years before a caldera forming eruption (e.g., Fabbro et al. 2013). With a complex magmatic plumbing system we can expect elements of the system to have a long-lived nature in terms of some crystal mushes and residence times, with events (particularly eruptive cycles, and largely crystal-free magmas) being short-lived (e.g., Cooper and Kent 2014). The eruptive, short-lived parts of the cycle may be triggered relatively quickly, i.e. rapid responses to new magma batch injections, but there may also be only a limited window in which to get magma through the system to erupt before it becomes locked up in the mush zone of the plumbing system (e.g., Barboni and Schoene 2014).

Shallow level pathways can also develop as a result of magma chamber/volcano growth and evolution. The stresses around magma chambers will change with magma flux, and can act as a vehicle to focus magma-feeding dykes, known as 'magmatic lensing' (e.g., Karlstrom et al. 2009). Key controls on the pathway that magmas take from their holding chambers to reach the surface are any superimposed regional-scale tectonic stresses, and more localised stresses generated by the subvolcanic magma chamber (e.g., Bistacchi et al. 2012) and/or gravitational loading by the edifice (e.g., Muller et al. 2001). Recent numerical



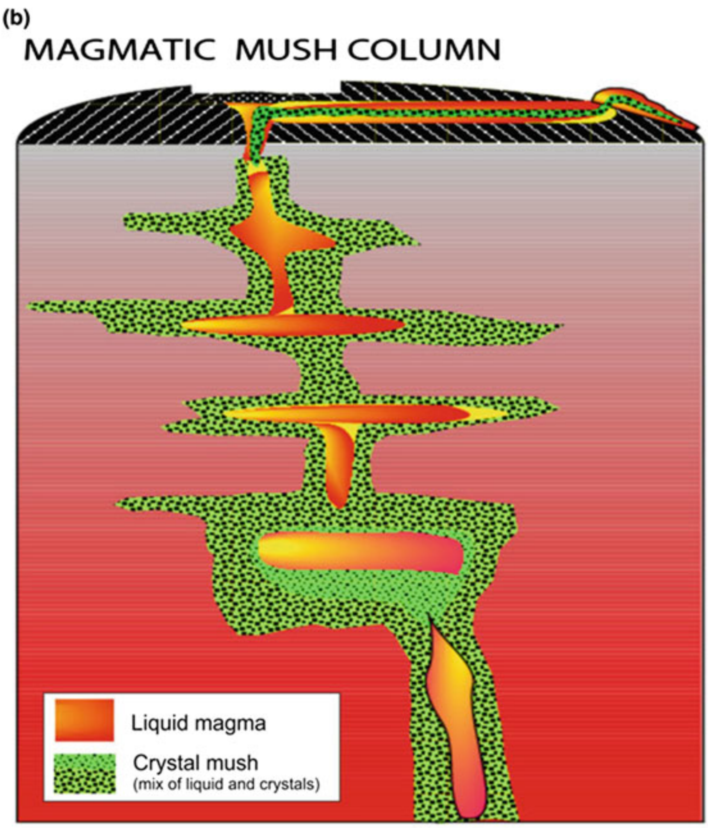


Fig. 4 Examples of magma plumbing in polygenetic systems; **a** schematic plumbing beneath Long Valley Caldera, USA (after Bachmann and Bergantz 2008a, b). In systems like Long Valley, large pools of silicic magma are produced by extracting interstitial liquid from long-lived "crystal mushes" (magmatic sponges containing >50 vol% of crystals) and collecting it in unstable, eruptable liquid-dominated lenses. **b** The magma mush column (after Marsh 2004), where liquid rich lenses and linked plumbing bodies are intricately associated with crustal mushes around the walls and in the chambers within the column. Shallow sills and eruptions from such systems can contain a variety of crystal cargos from crystal-poor to crystal-rich batches (see also Fig. 7)

modelling-based studies indicate the shape of the magma chamber can significantly affect the stress field distribution around the chamber and thus the resulting geometry of the magma plumbing system (Martí and Geyer 2009).

Surrounding polygenetic volcanic centres are three main types of intrusion geometries that are related to shallow magma chambers: (i) radial subvertical intrusions, (ii) vertical to outward-dipping, concentric intrusions or ring dykes, and (iii) inward-dipping concentric swarms (inclined or cone sheets). Magma chamber inflation has been shown experimentally to generate radial fractures that can act as magma pathways and produce radial dyke systems (e.g., Marti et al. 1994), and cone sheets can also develop above the inflating magma system (Bistacchi et al. 2012). Ring dykes, characteristic of many calderas and cauldrons, have classically been interpreted to have formed during piston-like roof subsidence (e.g., the classic study of Smith and Bailey 1968). Recent work has interpreted some classic ring dykes as inflated sheets (e.g., Stevenson et al. 2008) sparking debate about the origin of some of the classic ring-like features surrounding polygenetic volcanic centres (Emeleus et al. 2012). Given these ring fractures are now filled by igneous rock, they must have acted as major magma pathways in initial inflation, and during and after caldera collapse.

Studies of many caldera-forming eruptions have demonstrated that vents, either central or fissure, initially existed within the ensuing area of collapse (e.g., Smith and Houghton 1995; Bryan et al. 2000), and that the eruptions evolved to having multiple vents located along the ring fault system or other collapse-controlling faults (e.g., Bacon 1983; Druitt and Sparks 1984; Hildreth and Mahood 1986; Suzuki-Kamata et al. 1993). The arcuate train of post-collapse rhyolite domes within the Valles Caldera are an example of continued utilisation of the collapse ring fault as these rhyolites were erupted over an $\sim$1 Myr interval from immediately following caldera formation until $\sim$200 ka (Spell and Harrison 1993). The very presence of calderas reflect the prior existence of a relatively large holding chamber at shallow depth (<10 km) of sufficient magma vol (>5 km^3) which, after eruption, allowed roof failure and collapse.

6 Exposed Shallow Volcanic Centres and Complexes

In many instances, sub-volcanic centres and complexes are exposed due to exhumation. These provide a wonderful opportunity to explore the relationships within the intrusive system and in some cases, how they link to surface volcanism. The classic centres from the British and Irish Paleogene province (known by many as the British Tertiary Igneous Province) in Scotland and Ireland, are one such case where the rocks provide a window into 'fossil' volcanoes (e.g., Emeleus and Bell 2005; Jerram et al. 2009a). Two classic centres, Rum and Skye, provide excellent insights into magma dynamics and evolution, as well as the form and complexities of volcanic centres that once fed volcanoes at the surface. Figure 5 highlights some of the features preserved in the Rum intrusion, with a dynamic interpretation of the magma chamber at the time of formation (from Goodenough et al. 2008). Everything from pyroclastic rocks, igneous layering with repeated geochemical cycles, and jumbled up intrusive breccias that remobilise existing rigid as well as ductile layered sequences are testament to a dynamic and open magma chamber (see Emeleus and Troll 2009, and references therein). The Skye volcanic centre (Fig. 6) has a similar level of complexity and is interpreted to be a cone-shaped structure, which was repeatedly in-filled with new batches of magma, forming complex layering and compositional types from peridotites to granites. The intrusion is dissected in such a way that it is possible to view the side contact of the magma chamber (Fig. 6c), which helps to further constrain the lower parts of the chamber structure. Such exposures of the internal structure of these volcanic centres are thus vital to be able to picture how they act as plumbing systems to volcanoes. In more simple closed systems such as the Skaergaard intrusion (e.g., Nielsen 2004), the overall geometry of the preserved intrusion more closely

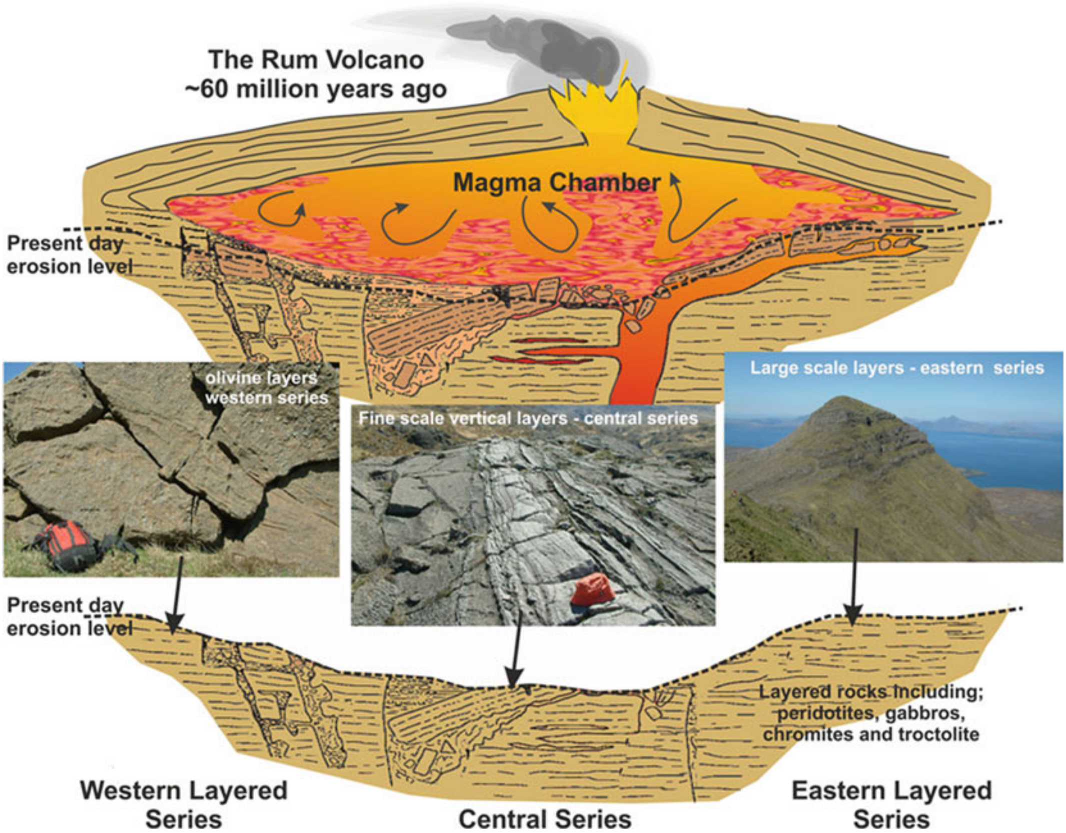


Fig. 5 Internal structures and reconstruction of the Rum volcanic centre (after Goodenough et al. 2008). Evidence for the open-system nature of the Rum Centre is preserved in the complex layering structures seen in the Western, Eastern and Central Layered Series. Repeated injections of new magma have resulted in repetitive cycles of peridotites, gabbros and troctolites, as well as complex slumps, breccias and cross cutting relationships in the now exposed core of the magma chamber

represents that of the original body at depth, and may provide some idea of the extent of systems that do not make it to the surface to erupt. In these cases where the volcanic centres or shallow, closed magma chambers are very well-constrained, the feeding pathways to these 'igneous centres' are somewhat poorly constrained and in some cases hypothetical.

In other examples, extensive sill complexes exist such as those found offshore in the North Atlantic; (e.g., Hansen and Cartwright 2006; Schofield et al. 2012), the Karoo basin (see Svensen et al., this book), offshore West Africa (Rocchi et al. 2007) and Antarctica (Jerram et al. 2010). Many of the sills form classic saucer shapes (see Polteau et al. 2008), and these saucer shapes have been used to help explain their emplacement with layered sedimentary and volcanic sequences (e.g., Goulty and Schofield 2008; Hansen et al. 2011), and many can be traced for several km's laterally. These sill complexes are commonly interlinked and are sometimes nested directly one on top of another, with the magma feeding zone being used repeatedly. Although examples exist where the sills are intruded before the eruption of the lava flows, in most of the examples of flood basalt provinces, significant sill complexes develop after a thick 'lid' of lava material has developed. This can be exidenced by the cross cutting relationships and absolute dating of the emplacement events. In some instances saucer-shaped sill complexes can even be found intruding into the thick flood basalt

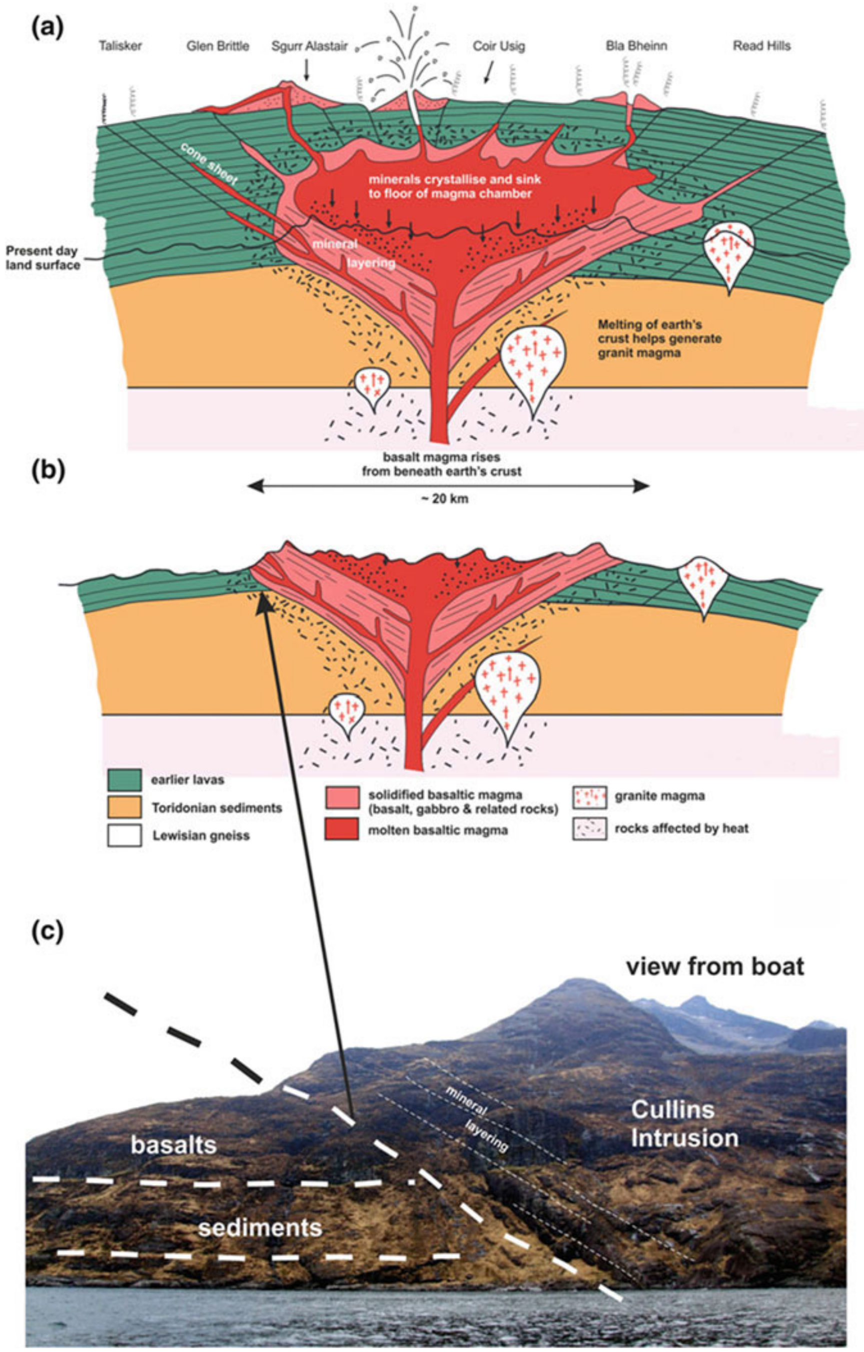


Fig. 6 Internal plumbing of the Skye volcanic centre; **a** artistic impression of the plumbing at the time of eruption, (Reproduced and based on Stephenson and Merritt 2006, with the permission of the British Geological Survey © NERC. All rights reserved' and Scottish Natural Heritage © Scottish Natural Heritage 2006), **b** present-day erosion level removed, **c** edge of the volcanic edifice as seen from the boat trip into the Cullins for Elgol

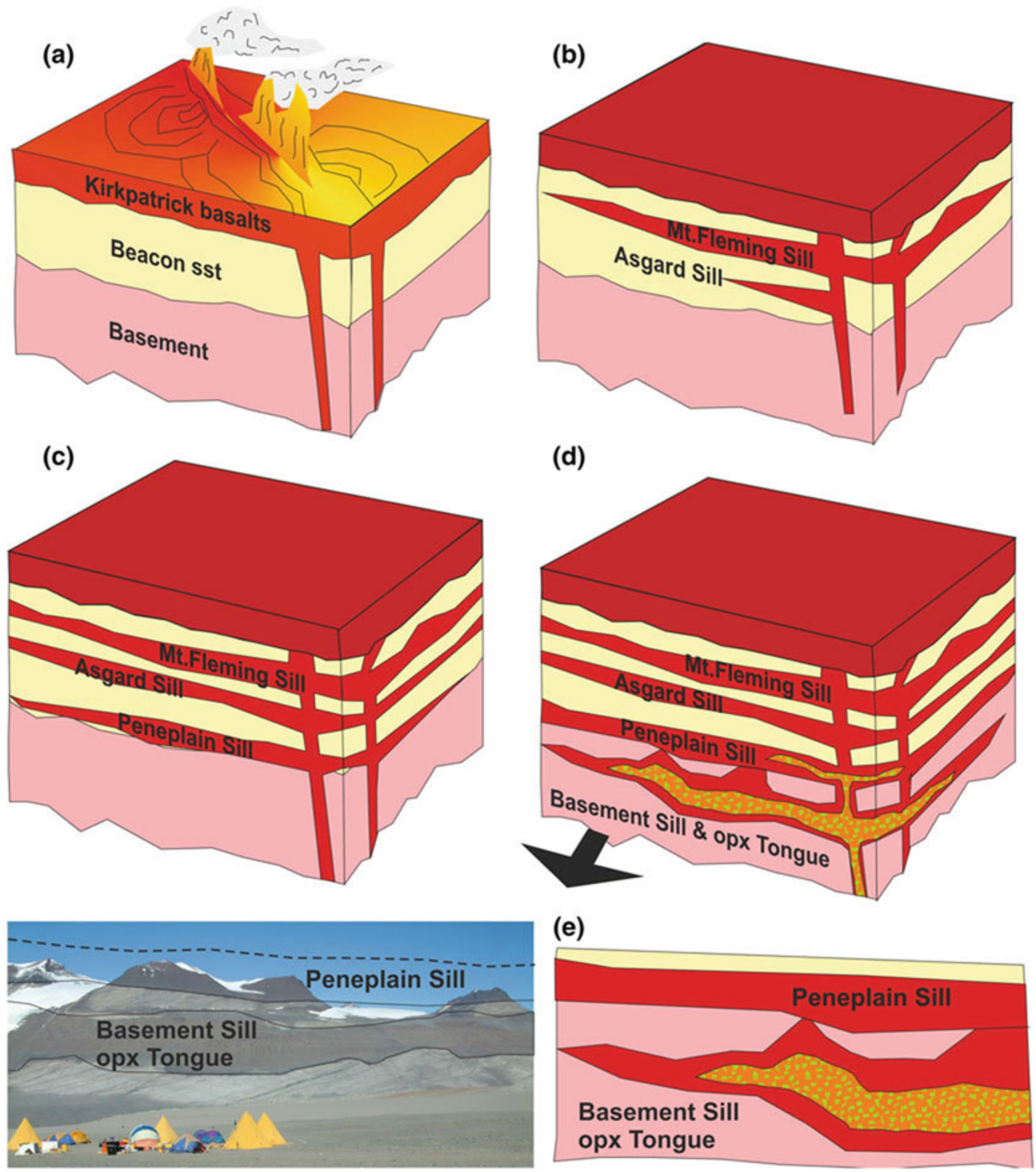


Fig. 7 Schematic representation of how the magma plumbing system developed in the Dry Valleys, Antarctica, ~180 Ma (after Jerram et al. 2005). **a** Onset of flood volcanism with the outpouring of the Kirkpatric Basalts. **b** Initial sills start to form close to the sediment lava contact, first with the Fleming Sill then with the Asgard Sill. **c** The Peneplain Sill follows and intrudes along the Kukri Peneplain between the basement and the Beacon Supergroup. **d** Finally, the Basement Sill is intruded into the basement granites with an irregular contact. During emplacement of the Basement sill, a magma laced with orthopyroxene (opx) crystals, from the magma mush column, invades the base of the plumbing system producing the opx tongue. **e** Present-day erosion levels expose the Basement Sill and Peneplain sill in the Wright Valley

lava sequences themselves (e.g., the Faroe Islands in the North Atlantic Igneous Province, Hansen et al. 2011).

The example given in Fig. 7 highlights the evolution of the nested sill complex from the Dry Valleys, Antarctica (see Jerram et al. 2010, and references therein). Here, the sill complex was part of the plumbing system that fed flood basalts above, and resulted in a series of large-volume sill bodies that stepped down through the Karoo sedimentary sequence and into basement rocks (Fig. 7). Seismic imaging has been instrumental in helping to map out the extent of these sill complexes in offshore settings like the North Atlantic (e.g., Thomson and Schofield 2008; Schofield et al. 2012), and is discussed further below.

7 Innovative Ways to Image and Understand Magma Plumbing

It has long been a goal to attempt to image and map out active and ancient magma systems. Remote sensing techniques have been applied to monitor active volcanoes and volcanic settings, to image where possible, what is happening to magma in shallow systems in the sub surface. With modern volcanoes and active volcanic settings, geophysical methods have long been used to help image the shallow volcanic subsurface (e.g., Miller and Smith 1999). The magma pathway can be mapped out by epicentres of shallow magmatically-induced earthquakes highlighting the route the magma is taking from depth to the surface. Very detailed mapping of ground deformation at active volcanic centres is now possible with very high resolution GPS and ground surveying from satellites that when combined with subsurface imaging, can be used in turn to build an understanding of the subsurface structure, magma pathways and movement (e.g., Sigmundsson et al. 2010; Wright et al. 2012a, b).

Physical models are another method to test 3D geometries and subsurface plumbing structure (e.g., Galland et al., this book). Additionally, where good outcrop and erosion permit (e.g., Figs. 6 and 7), it is possible to map out and interrogate the intrusions directly. These data are vital as it provides case studies to build our understanding on (e.g., Westerman et al., this book; Svensen et al., this book; Gudmundsson et al., this book). Magma flow directions can be inferred from the sill structures (e.g., Schofield et al. 2012) and by using magnetic fabric data (e.g., Stevenson and Grove, this book). Geochemical fingerprinting can also be used to determine the relative emplacement of sill-dyke complexes in eroded sub-volcanic systems (e.g., Galerne et al. 2008; Galerne and Neumann, this book). However, developing a robust 3D picture of ancient plumbing systems can be more difficult as when exposed on the surface and are partly eroded. Examples in the subsurface that can be remotely imaged can provide a window into the geometrical relationships and linkages of the magma pathways to the surface. Additionally, we may be able to use the products from modern eruptions to interrogate the subsurface, where they contain information about the magma migration and evolution through time. These two areas will be briefly elaborated on below.

7.1 Geophysical Imaging of Ancient Magma Plumbing Systems in 3D

One recent innovative way to image and map out the 3D distribution of sub-surface intrusions has actually come from data-sets that have been generated by offshore exploration for oil and gas. 2D and 3D seismic surveys in volcanic rifted margins are providing increasingly complex data sets that image the volcanic and intrusive facies across large areas offshore (e.g., Planke et al. 2000; Cartwright and Hansen, 2006; Jerram et al. 2009a, b; Wright et al. 2012a, b). Where 3D data are available, volume rendering of the high amplitude parts of the surveys can often reveal much detail within the sub-volcanic system at a scale, which is difficult to appreciate at the outcrop level. Saucers, lobes/fingers of magma intrusion can be mapped out invading shallow sedimentary basins (e.g., Thomson and Schofield 2008; Schofield et al. 2012). The examples in Fig. 8 highlights high amplitude reflectors in seismic and how their morphology can be picked out in 3D (Thomson 2005; Goulty and Schofield

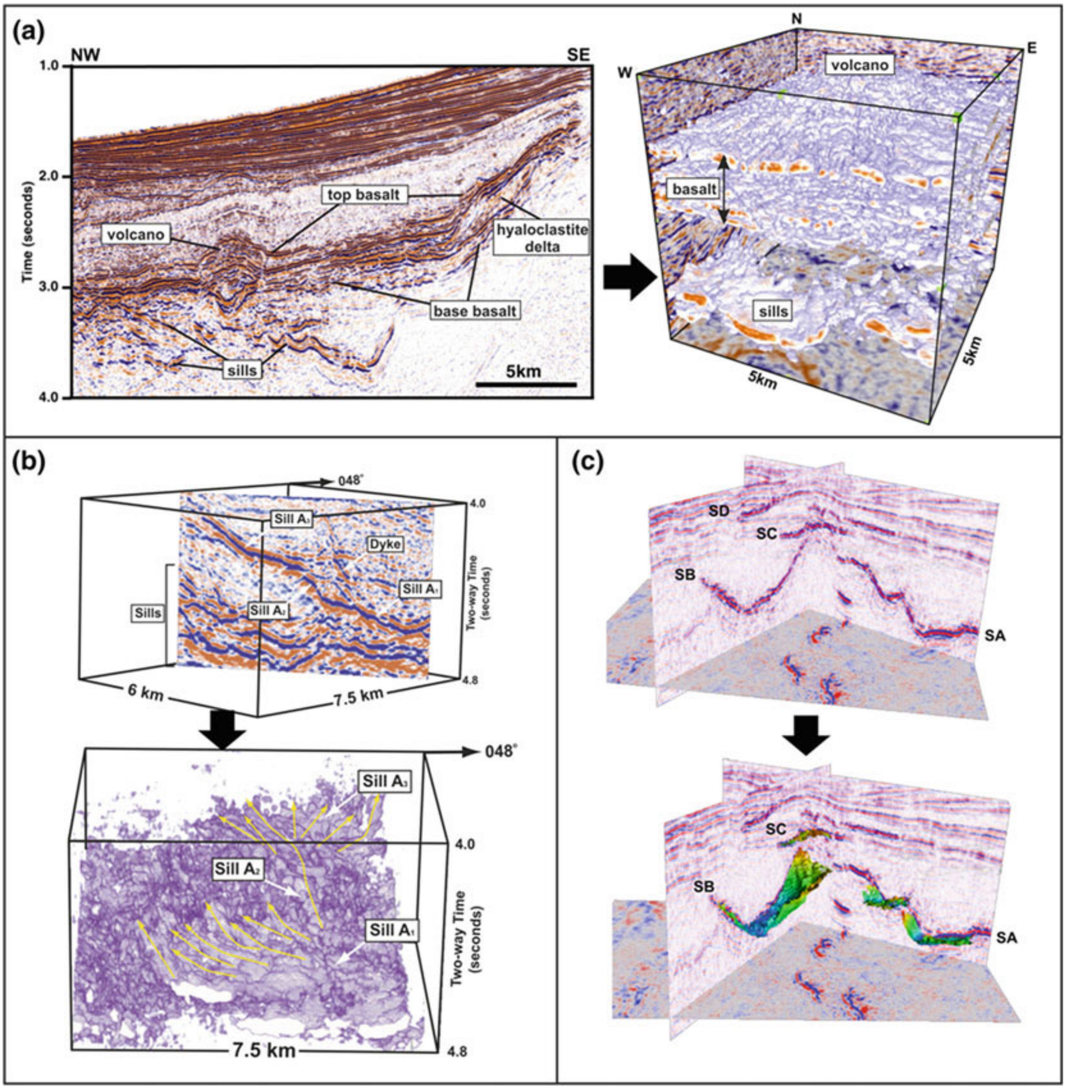


Fig. 8 Intrusions imaged from seismic images in 3D. **a** Volcanic features from seismic highlighted on a 2D seismic line and on a 3D volume rendering of high amplitudes (images courtesy of K. Thomson, see also Thomson 2005). **b** 2D seismic image and 3D rendered image, from a 3D data set, highlighting sill and dyke intrusions in offshore sedimentary units (igneous rocks show up as bright reflectors). The volume-rendered image of the intrusion network that can be used to show magma pathways (image courtesy of Schofield, see Goulty and Schofield 2008). **c** Three cross-cutting seismic lines showing high amplitude saucer shaped sills, the surface of the sills is highlighted in the lower image (see Planke et al. this book)

2008; Planke et al., this volume). In these cases, it is intrusion of material into sedimentary basins that enable their imaging due to the large contrast between the igneous and sedimentary rocks. Further examples of the geophysical imaging of the sub-surface are provided by Planke et al., this volume.

7.2 Using Volcanic Products to Investigate the Sub-volcanic System

When volcanoes erupt with a crystal payload/cargo, it is possible to use the crystal population to help unravel the magma system at depth (e.g., Jerram and Davidson 2007; Cashman and Sparks 2013). As crystals grow, they record the magma around them, and if residency in magma is long-lived, periods of growth and recycling of crystals through different parts of the magma system can occur, and the resultant crystal population records those changes (e.g., Jerram and Davidson 2007; Jerram and Martin 2008). The crystal population can be characterised by examining the crystal size distribution (CSD) (e.g., Jerram and Higgins 2007), and variations that the crystal may have experienced during growth can be characterized by the geochemistry and textures in the growth zones. In some instances, the combination of CSD and geochemical analysis can be used in combination to find out about magma dynamics (e.g., Turner et al. 2003; Morgan et al. 2007). In a sense, the crystals are used as a fingerprint of the magmatic history and residency in the shallow sub-volcanic realm. The final crystal population that is found within the erupted rock may consist of phenocrysts and microlites (autocrysts) that are directly linked to the erupting magma, antecrysts which represent recycled crystals from the plumbing system, and xenocrysts which are alien to the magmatic system incorporated from country rock (Jerram and Martin 2008 and references therein).

The most recent eruptive cycles in Santorini, for example, can be used as a simple case study to highlight the value of interrogating the crystal population to understand the magma plumbing system. The post-caldera islands of Palaea and Nea Kameni, which have been the focus of historic volcanism on Santorini, lie in the centre of the flooded caldera and represent magmatic activity that resumed soon after the Minoan eruption (most recent caldera-forming eruption). The Nea Kameni edifice broke the surface in 197 BC and subsequently, at least nine subaerial episodes of volcanic activity have occurred, the last of which was in AD 1950. The Kameni islands are formed from dacite lava flows, which contain abundant magmatic enclaves, interpreted to be the quenched fragments of replenishing magmas that periodically triggered eruptive events (Martin et al. 2006). Each eruptive triggering event occurred only a few weeks to months before the eruptions themselves (Martin et al. 2008). The disequilibrium phenocryst assemblages found in the lavas and the phenocryst-bearing enclaves provide evidence for the entrainment and recycling of older crystal populations into the lavas and enclave magmas. Martin et al. (2006) showed that by combining the phenocryst portion of the crystal size distribution CSD (a measure of the crystal population) with reasonable plagioclase growth rates, the calculated residence times suggested that recycling from a Minoan, or pre-Minaon source was feasible.

This crystal recycling was further investigated using isotopic geochemical fingerprinting of the crystals within the main volcanic cycles looking at different magma batches (Martin et al. 2010). Figure 9 shows the Sr isotopic ratios recorded from crystal separates and from the background glass for several of the eruptive events on Santorini. This highlights a number of different mixing and mingling episodes occurring between the different eruptions as recorded in the resultant eruptive products (Martin et al. 2010), suggesting a very complex model of mixing and recycling of crystals throughout the evolution of the Santorini volcano. Even focusing on a single eruption, e.g., the Minoan cycle (Fig. 10a), identifies a complex picture of magma mixing and mingling with several identifiable magmatic components residing within the subvolcanic plumbing system (Martin et al. 2010).

A similar pattern of crystal recycling exists at other volcanoes with multiple magma inputs and complex plumbing systems with depth. Shiveluch volcano in Kamchatka, provides another case study where the magma plumbing system can be revealed through its crystal cargo at eruption (Cashman and Sparks 2013). Carefully piecing together the different magma inputs, core and rim differences preserved within antecrysts, and the different mixtures of crystal species, it is possible not only to gain insight into the different contributing components but also some semblance of the depth relationships of these processes within the volcano (e.g., Fig. 10b). Detailed investigations of important minor mineral components such as zircons, also display

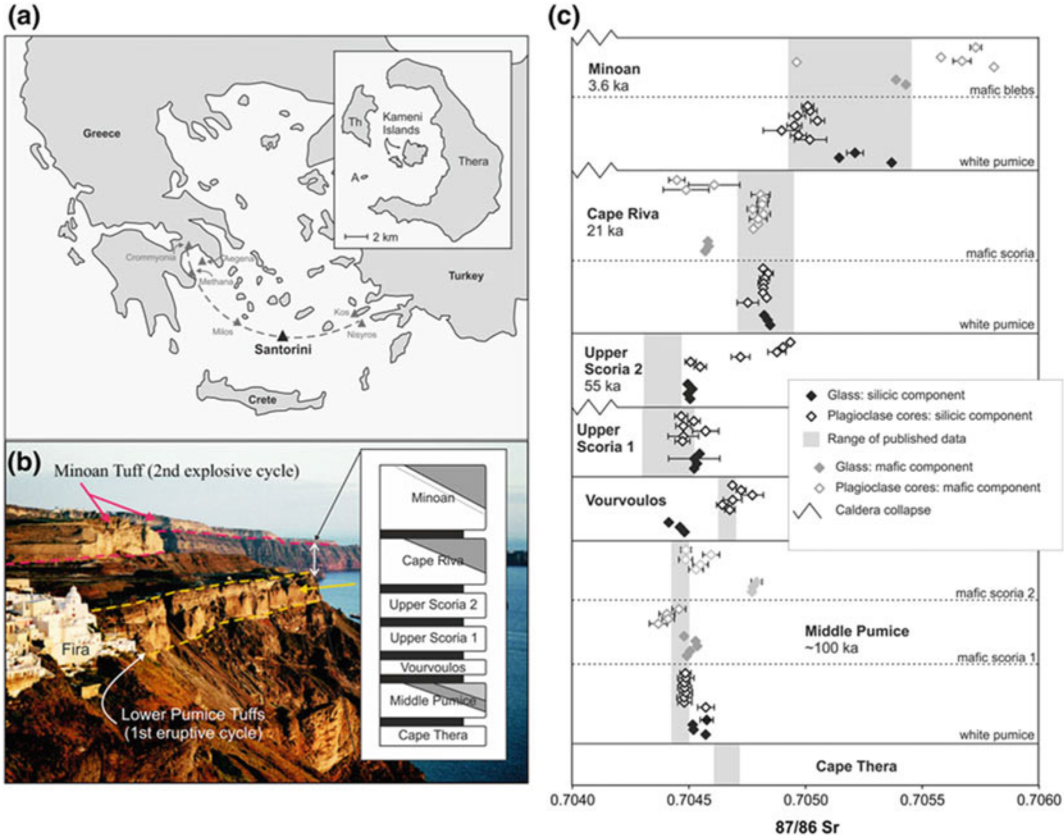


Fig. 9 Detail of volcanic cycles on Santorini (adapted from Martin et al. 2010). **a** Location map of Santorini, **b** Stratigraphy of Minoan cycle (terminology and ages from Druitt et al. 1999), **c** $^{87}Sr/^{86}Sr$ values for the different volcanic events showing whole rock vs separate analysis (crystals + glass). It is clear from these data that the crystal populations and separate melt compositions record far more detail about the isotope variations in the system than by using whole rock data alone (see also Fig. 10a)

crystal population complexities, which highlights the importance of recognising this type of process (e.g., Charlier et al. 2005), particularly as these crystals are often used to provide age constraints on eruptions.

Where volcanic sequences can be very well-constrained in terms of their spatial and temporal relationships, then their crystal populations can potentially provide a valuable link into an understanding of the subsurface complexity and evolution. In some examples such as the Santorini case study presented above, an increase in crystal recycling and complexity is observed at a single volcano, as well as examples which show results where crystal recycling appears to increase over time at a regional scale (e.g., Bryan et al. 2008; Ferrari et al. 2013). In other examples, volcanoes can show a distinct lack of connectivity between eruptive events, with new influxes of magma and absence of any large, active reservoirs that would promote homogenisation (e.g., Hobden et al. 2002). Although the shallow sub-volcanic system cannot be fully realised in its true extent for many volcanic centres, such examples of textural and geochemical analysis of the volcanic products provide valuable insight on the complexities that can exist in subvolcanic plumbing systems (Jerram and Martin 2008).

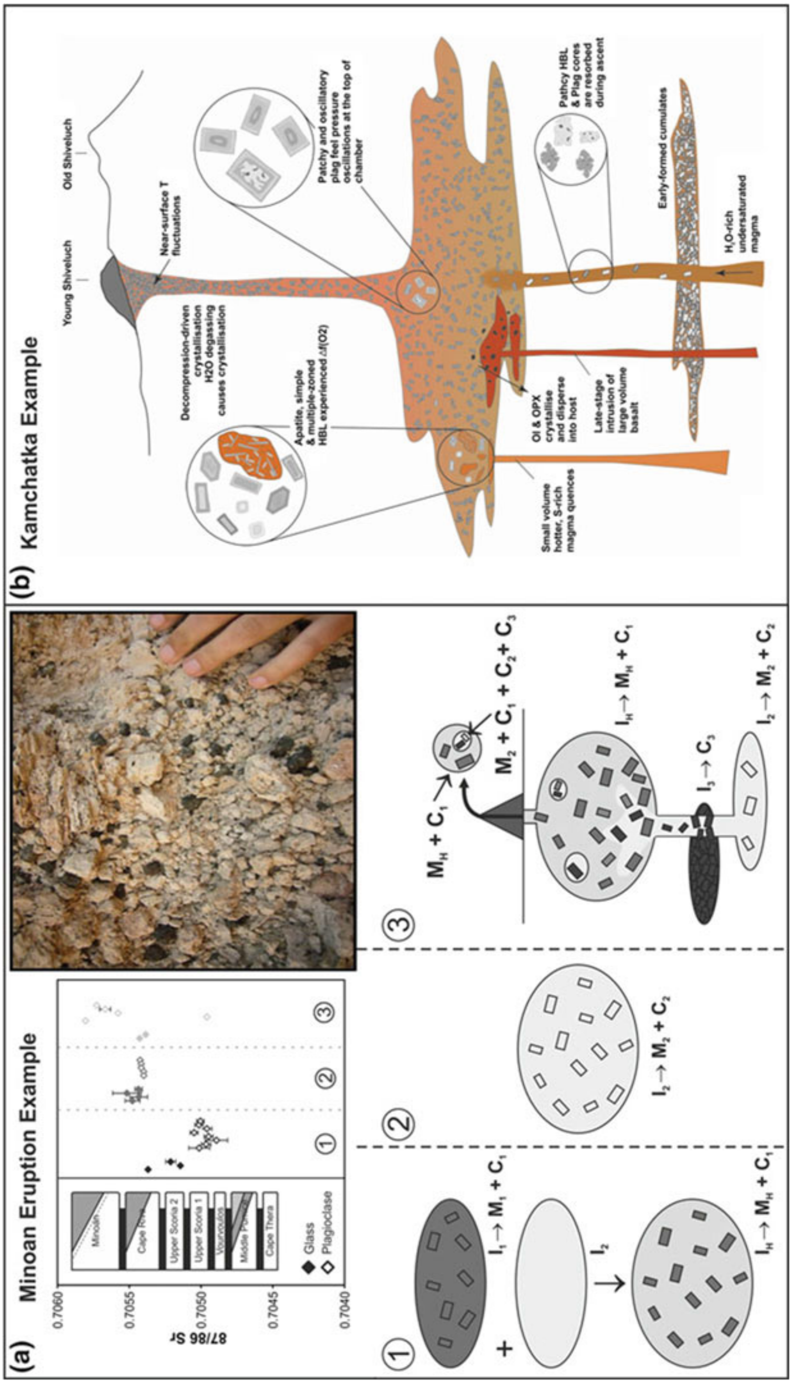


Fig. 10 Examples of complexity locked up within crystal populations as tracers of magma plumbing systems. **a** Highlight of the Minoan eruption showing complex relationships of different magma components that help provide detail of the complex plumbing and recycling of crystals at depth beneath the volcano. **b** Kamchatka example where differing crystal types (phenocrysts/antecrysts) and mixed crystal populations help reveal the complexities of the magma plumbing syatem (adapted from Cashman and Sparks 2013, image curtesy of Kathy Cashman)

8 Closing Remarks

Clearly the styles and types of sub-volcanic plumbing systems are as wide and varied as the volcanism that occurs on the planet today and that which has occurred in the past. It is important as you start to explore the following chapters in this book that complexities exist between different parts of the sub-volcanic system, some of which reflect the historical evolution of the subject, the details available from certain well-constrained studies (or limitations of information where subjects are less well-known), and an ongoing development of types of analysis and imaging that push further our understanding of the subject. In this short contribution, we have touched on some of the key points to consider when looking at shallow intrusive systems with the following main points/conclusions:

1. Although major magma systems on Earth at the first order reflect different styles of magma generation (subduction zones/complex continental, rifting zones and plume/hotpsot), regional to local-scale complexities lead to a mixed plumbing system that is not dependent specifically to these volcano-tectonic variants. Types and styles of volcano (e.g., stratovolcano, calderas, shield volcanoes, fissures) can be found in varied contexts and can be driven by the subsurface complexities, tectonic stresses and magma flux.
2. It may not be exactly clear how to define shallow versus deep magma systems, depending on how complex and linked they may be. As an example, it is wise to consider a fairly deep seated system for kimberlite volcanoes but a very shallow system in rifted zones. In other examples, very large-volume single eruption events, such as the high-Ti silicic eruptions in the Paranã-Etendeka, are thought to be deep as there are a lack of collapse calderas for these suggesting holding chambers may have been deeper.
3. Large igneous provinces display many volcanic types and plumbing architectures encompassing almost all possible types of intrusion, from complex forms in volcanic centres, plugs, laccoliths/lopoliths, through dyke swarms, to nested sill complexes.
4. In predominantly rifted settings, the magma flux through the system has a marked effect on how complex the plumbing system is.
5. Polygenetic volcanoes represent centralised venting of magma over time scales of 10^3–10^7 years, and can develop complex crystal mush pathways to the surface from significant depths in the crust. At shallow levels, intrusion geometries and plumbing are dictated by more localised stresses, and reflect inflation, migration and collapse features close to the volcano surface.
6. The complexities associated with modern volcanic systems and many eroded examples, allow an investigation of magmatism in the upper few 10s of km of the system, but to fully unravel this complexity also requires knowledge and appreciation of the deeper settings and primary magma source regions that can often be lacking.
7 Large-scale magma plumbing networks have been imaged using seismic along volcanic rifted margins as demonstrated by recent 3D seismic exploration data sets, and provide an exciting new methodology in constraining internal complexity and linkages within large-scale plumbing systems.
8. A number of remote sensing techniques are being deployed on active volcanoes to shed light on the very shallow components of the magma system, and revealing magma movement and storage by seismic, GPS and using satellite interferometry.
9. Where well-constrained volcanic products are found on the surface, and particularly where they contain crystal populations, it is becoming increasingly clear that the crystals themselves can be interrogated as a proxy for the magma system at depth. Crystal zoning profiles record changes in the magma system as the crystals grew and this can be a powerful way of fingerprinting key isotopic changes related to contamination, magma mixing and crystal recycling, storage depths and rates of transfer within the shallow magma system.

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References

Bachmann O, Bergantz GW (2003) Rejuvenation of the Fish Canyon magma body: a window into the evolution of largevolume silicic magma systems. Geology 31(9):789–792

Bachmann O, Bergantz GW (2004) On the origin of crystal-poor rhyolites: extracted from batholithic crystal mushes. J Petrol 45(8):1565–1582

Bachmann O, Bergantz GW (2008a) Rhyolites and their source mushes across tectonic settings. J Petrol 49 (12):2277–2285

Bachmann O, Bergantz GW (2008b) The magma reservoirs that feed supereruptions. Elements 4(1):17–21

Bachmann O, Miller CF, de Silva S (2007) The volcanic–plutonic connection as a stage for understanding crustal magmatism. J Volcanol Geoth Res 167:1–23

Bacon CR (1983) Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, USA. J Volcanol Geoth Res 18(1):57–115

Barboni M, Schoene B (2014) Short eruption window revealed by absolute crystal growth rates in a granitic magma. Nat Geosci 7:524–528

Bistacchi A, Tibaldi A, Pasquarè FA, Rust D (2012) The association of cone–sheets and radial dykes: data from the Isle of Skye (UK), numerical modelling, and implications for shallow magma chambers. Earth Planet Sci Lett 339:46–56

Brown SJA, Cole JW, Wilson CJN, Wooden J (1998) The Whakamaru group ignimbrites, Taupo Volcanic Zone, New Zealand: evidence for reverse tapping of a zoned silicic magmatic system. J Volcanol Geoth Res 84:1–37

Bryan SE, Cas RAF, Martí J (2000) The 0.57 Ma plinian eruption of the Granadilla Member, Tenerife (Canary Islands): an example of complexity in eruption dynamics and evolution. J Volcanol Geoth Res 103(1):209–238

Bryan SE, Ferrari L, Reiners PW, Allen CM, Petrone CM, Ramos-Rosique A, Campbell IH (2008) New insights into crustal contributions to large-volume rhyolite generation in the mid-tertiary Sierra Madre occidental province, Mexico, revealed by U-Pb geochronology. J Petrol 49:47–77

Bryan SE, Ukstins Peate I, Peate DW, Self S, Jerram DA, Mawby MR, Marsh JS, Miller JA (2010) The largest volcanic eruptions on Earth. Earthscience Rev 102 (3):207–229

Cartwright J, Hansen DM (2006) Magma transport through the crust via interconnected sill complexes. Geology 34:929–932

Cashman KV, Sparks RSJ (2013) How volcanoes work: a 25 year perspective. Geol Soc Amer Bull 125:664–690

Charlier BLA, Wilson CJN, Lowenstern JB, Blake S, Van Calsteren PW, Davidson JP (2005) Magma generation at a large, hyperactive silicic volcano (Taupo, New Zealand) revealed by U-Th and U-Pb systematics in zircons. J Petrol 46:3–32

Cooper KM, Kent AJR (2014) Rapid remobilization of magmatic crystals kept in cold storage. Nature 506 (7489):480–483

Druitt TH, Edwards L, Mellors RM, Pyle DM, Sparks RSJ, Lanphere M, Davies M, Barreiro B (1999) Santorini Volcano. Geological Society, London, Memoirs, 19

Druitt TH, Sparks RSJ (1984) On the formation of calderas during ignimbrite eruptions. Nature 310 (5979):679–681

Dungan MA, Davidson JP (2004) Partial assimilative recycling of the mafic plutonic roots of arc volcanoes: an example from the Chilean Andes. Geology 32:773–776

Emeleus CH, Bell BR (2005) British regional geology: the Palaeogene Volcanic districts of Scotland, 4th edn. British Geological Survey. 214 p. doi:10.1017/S0016756806213050

Emeleus CH, Troll VR (2009) A geological excursion guide to Rum. The Palaeocene Igneous Rocks of the Isle of Rum, Inner Hebrides. NMSE-Publishing Ltd. The Geological Society of Edinburgh (78 colour plates), 152 p. ISBN: 9781-905267224

Emeleus CH, Troll VR, Chew DM, Meade FC (2012) Lateral versus vertical emplacement in shallow-level intrusions? The Slieve Gullion ring-complex revisited. J Geol Soc London 169:157–171

Ernst RE, Baragar WRA (1992) Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. Nature 356:511–513

Fabbro GN, Druitt TH, Scaillet S (2013) Evolution of the crustal magma plumbing system during the build-up to the 22-ka caldera-forming eruption of Santorini (Greece). Bull Volcanol 75(12):1–22

Ferrari L, López-Martínez M, Orozco-Esquivel T, Bryan SE, Duque-Trujillo J, Lonsdale P, Solari L (2013) Late Oligocene to Middle Miocene rifting and synextensional magmatism in the southwestern Sierra Madre occidental, Mexico: the beginning of the Gulf of California rift. Geosphere 9(5):1161–1200

Galerne CY, Neumann ER, Planke S (2008) Emplacement mechanisms of sill complexes: information from the geochemical architecture of the Golden Valley Sill Complex, South Africa. J Volcanol Geoth Res 177:425–440

Gelman SE, Gutierrez FJ, Bachmann O (2013) The longevity of large upper crustal silicic magma reservoirs. Geology 41:759–762

Glazner AF, Bartley JM, Coleman DS, Gray W, Taylor RZ (2004) Are plutons assembled over millions of years by amalgamation from small magma chambers? GSA today 14(4/5):4–12
Goodenough K, Emeleus CH, Jerram DA, Troll VR (2008) Golden rum: understanding the forbidden isle. Geoscientist 18(3):22–24
Goulty NR, Schofield N (2008) Implications of simple flexure theory for the formation of saucer-shaped sills. J Struct Geol 30:812–817
Gravley DM, Wilson CJN, Leonard GS, Cole JW (2007) Double trouble: paired ignimbrite eruptions and collateral subsidence in the Taupo Volcanic Zone, New Zealand. Geol Soc Amer Bull 119(1–2):18–30
Hansen DM, Cartwright J (2006) Saucer-shaped sill with lobate morphology revealed by 3D seismic data: implications for resolving a shallow-level sill emplacement mechanism. J Geol Soc London 163:509–523
Hansen J, Jerram DA, McCaffrey K, Passey SR (2011) Early cenozoic saucer-shaped sills of the Faroe islands: an example of intrusive styles in basaltic lava piles. J Geol Soc 168(1):159–178
Hildreth W, Mahood GA (1986) Ring-fracture eruption of the Bishop Tuff. Geol Soc Amer Bull 97(4):396–403
Hobden BJN, Houghton BF, Nairn IA (2002) Growth of a young, frequently active composite cone: Ngauruhoe Volcano, New Zealand. Bull Volcanol 64:392–409
Jerram DA, Davidson JP (2007) Frontiers in textural and microgeochemical analysis. Elements 3:235–238
Jerram DA, Higgins DM (2007) 3D analysis of rock textures: quantifying igneous microstructures. Elements 3:239–245
Jerram DA, Martin VM (2008) Understanding crystal populations and their significance through the magma plumbing system. In: Annen C, Zellmer GF (eds) Dynamics of crustal magma transfer, storage and differentiation, vol 304. Geological Society, London, Special Publications, pp 133–148
Jerram DA, Smith S (2010) Earth's hottest place: how to build a 3D volcano. Geoscientist 20(2):12–13
Jerram DA, Widdowson M (2005) The anatomy of continental Flood Basalt provinces: geological constraints on the processes and products of flood volcanism. Lithos 79:385–405
Jerram DA, Davidson JP, Petford N (2005) Hot and cold in the dry valleys. Geoscientist 15(9):4–5, 14–15
Jerram DA, Goodenough K, Troll VR (2009a) From British tertiary into the future: modern perspectives on the British Palaeogene and North Atlantic Igneous provinces. Geol Mag 146:305–308 (North Atlantic Special Issue)
Jerram DA, Single RT, Hobbs RW, Nelson CE (2009b) Understanding the offshore flood basalt sequence using onshore volcanic facies analogues: an example from the Faroe-Shetland basin. Geol Mag 146(3):353–367
Jerram DA, Davis GR, Mock A, Charrier A, Marsh BD (2010) Quantifying 3D crystal populations, packing and layering in shallow intrusions: a case study from the basement sill, dry valleys, Antarctica. Geosphere 6:537–548
Karlstrom L, Dufek J, Manga M (2009) Magma chamber stability in arc and continental crust. J Volcanol Geoth Res 190(3–4):249–270
Kent AJR, Darr C, Koleszar AM, Salisbury MJ, Cooper KM (2010) Preferential eruption of andesitic magmas through recharge filtering. Nat Geosci 3(9):631–636
LeCheminant AN, Heaman LM (1989) Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening. Earth Planet Sci Lett 96(1–2):38–48
Macdonald R, Bagiński B, Upton BGJ, Pinkerton H, MacInnes DA, MacGillivray JC (2010) The Mull Palaeogene dyke swarm: insights into the evolution of the Mull igneous centre and dyke-emplacement mechanisms. Mineral Mag 74:601–622
Marsh BD (1996) Solidification fronts and magmatic evolution. Mineral Mag 60:5–40
Marsh BD (2004) A magmatic mush column Rosetta Stone: the McMurdo dry valleys of Antarctica. EOS Trans Am Geophys Union 85:497
Marti J, Ablay GJ, Redshaw LT, Sparks RSJ (1994) Experimental studies of collapse calderas. J Geol Soc 151:919–929
Martí J, Geyer A (2009) Central vs flank eruptions at Teide-Pico Viejo twin stratovolcanoes (Tenerife, Canary Islands). J Volcanol Geoth Res 181(1):47–60
Martin VM, Holness MB, Pyle DM (2006) Textural analysis of magmatic enclaves from the Kameni Islands, Santorini, Greece. J Volcanol Geoth Res 154:89–102
Martin VM, Morgan DJ, Jerram DA, Cadddick MJ, Prior DJ, Davidson JP (2008) Bang! month scale eruption triggering at Santorini volcano. Science 321:1178
Martin VM, Davidson JP, Morgan DJ, Jerram DA (2010) Using the Sr isotope compositions of feldspars and glass to distinguish magma system components and dynamics. Geology 38:539–542
Miller DS, Smith RB (1999) P and S velocity structure of the yellowstone volcanic field from local earthquake and controlled source tomography. J Geophys Res 104 (B7):15105–15121
Morgan DJ, Jerram DA, Chertkoff DG, Davidson JP, Pearson DG, Kronz A, Nowell GM (2007) Combining CSD and isotopic microanalysis: magma supply and mixing processes at Stromboli volcano, Aeolian islands, Italy. Earth Planet Sci Lett 260:419–431
Muller JR, Ito G, Martel SJ (2001) Effects of volcano loading on dike propagation in an elastic half-space. J Geophys Res Solid Earth 106(B6):11101–11113
Nielsen TFD (2004) The shape and volume of the skaergaard intrusion, Greenland: implications for mass balance and bulk composition. J Petrol 45(3):507–530
O'Hara MJ (1961) Petrology of the Scourie dyke, Sutherlandshire. Mineral Mag 32:848–865
Petford N (1996) Dykes or diapirs? Trans Roy Soc Ed Earth Sci 87:104–114
Planke S, Symonds PA, Alvestad E, Skogseid J (2000) Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins. J Geophys Res [Solid Earth] 105:19335–19351

Polteau S, Mazzini A, Galland O, Planke S, Malthe-Sorenssen A (2008) Saucer-shaped intrusions: occurrences, emplacement and implications. Earth Planet Sci Lett 266(1–2):195–204

Reubi O, Blundy JD (2009) A dearth of intermediate melts at subduction zone volcanoes and petrogenesis of arc andesites. Nature 461:1269–1273

Rocchi S, Mazzotti A, Marroni M, Pandolfi L, Costantini P, Bertozzi G, di Biase D, Federici F, Lô PG (2007) Detection of Miocene saucer-shaped sills (offshore Senegal) via integrated interpretation of seismic, magnetic and gravity data. Terra Nova 19:232–239

Schofield N, Heaton L, Holford S, Archer S, Jackson C, Jolley DW (2012) Seismic imaging of 'Broken-Bridges': linking seismic to outcrop scale investigations of intrusive magma lobes. J Geol Soc 169:421–426

Sigmundsson F, Hreinsdóttir S, Hooper A, Árnadóttir Th, Pedersen R, Roberts MJ, Óskarsson N, Auriac A, Decriem J, Einarsson P, Geirsson H, Hensch M, Ófeigsson BG, Sturkell E, Sveinbjörnsson H, Feigl KL (2010) Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption. Nature 468:426–430

Smith RL, Bailey RA (1968) Resurgent cauldrons. Geol Soc Am Mem 116:613–662

Smith RT, Houghton B (1995) Vent migration and changing eruptive style during the 1800a Taupo eruption: new evidence from the Hatepe and Rotongaio phreatoplinian ashes. Bull Volcanol 57:432–439

Smith VC, Shane P, Nairn IA (2005) Trends in rhyolite geochemistry, mineralogy, and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone, New Zealand. J Volcanol Geoth Res 148(3):372–406

Spell TL, Harrison TM (1993) 40Ar/39Ar geochronology of post-Valles Caldera rhyolites, Jemez volcanic field, New Mexico. J Geophys Res 98:0148–0227

Stephenson D, Merritt J (2006) Skye; a landscape fashioned by geology. Scottish National Heritage publication, p 22

Stevenson CTE, O'Driscoll B, Holohan EP, Couchman R, Reavy RJ, Andrews GMD (2008) The structure, fabrics and AMS of the Slieve Gullion ring-complex, N. Ireland: testing the ring-dyke emplacement model. In: Thompson K, Petford N (eds) Structure and emplacement of high-level magmatic systems: geological society of London special publications, vol 302. Geological Society of London, London, pp 159–184

Streck MJ, Leeman WP, Chesley J (2007) High-magnesian andesite from Mount Shasta: a product of magma mixing and contamination, not a primitive mantle melt. Geology 35:351–354

Suzuki-Kamata K, Kamata H, Bacon CR (1993) Evolution of the caldera-forming eruption at Crater Lake, Oregon, indicated by component analysis of lithic fragments. J Geophys Res 98:0148–0227

Tarney J (1973) The Scourie dyke suite and the nature of the Inverian event in Assynt. In: Park RG, Tarney J (eds) The early precambrian of Scotland and related rocks of Greenland. University of Keele, Keele, pp 105–118

Thomson K (2005) Extrusive and intrusive magmatism in the North Rockall Trough. In: Doré AG, Vining BA (eds) Petroleum geology: north-west Europe and Global Perspectives—proceedings of the 6th Petroleum Geology Conference, pp 1621–1630

Thomson K, Schofield N (2008) Lithological and structural controls on the emplacement and morphology of sills in sedimentary basins, structure and emplacement of high-level magmatic systems. Geol Soc London Spec Publ 302:31–44

Thordarson T, Self S (1993) The Laki (Skaftár Fires) and Grímsvötn eruptions in 1783–1785. Bull Volcanol 55:233–263

Thordarson T, Self S (1998) The Roza member, Columbia River Basalt group: a gigantic pahoehoe lava flow field formed by endogenous processes? J Geophys Res 103:27411–27445

Turner S, George R, Jerram D, Carpenter N, Hawkesworth C (2003) Case studies of plagioclase growth and residence times in island arc lavas from Tonga and the Lesser Antilles, and a model to reconcile discordant age information. Earth Planet Sci Lett 214:279–294

White JDL, Bryan SE, Ross PS, Self S, Thordarson T (2009) Physical volcanology of continental large igneous provinces: update and review. In: Thordarson T, Self S, Larsen G, Rowland SK, Hoskuldsson A (eds) Studies in volcanology: the legacy of George walker. Special Publications of IAVCEI 2, Geological Society of London, pp 291–321

Wright KA, Davies RJ, Jerram DA, Morris J, Fletcher R (2012a) Application of seismic and sequence stratigraphic concepts to a lava-fed delta system in the Faroe-Shetland Basin, UK and Faroes. Basin Res 24:91–106

Wright TJ, Sigmundsson F, Pagli C, Belachew M, Hamling IJ, Brandsdóttir B, Keir D, Pedersen R, Ayele A, Ebinger C, Einarsson P, Lewi E, Calais E (2012b) Geophysical constraints on the dynamics of spreading centres from rifting episodes on land. Nat Geosci 5(4):242–250

Zellmer GF, Sakamoto N, Iizuka Y, Miyoshi M, Tamura Y, Hsieh H-H, Yurimoto H (2014) Crystal uptake into aphyric arc melts; insights from two-pyroxene pseudo-decompression paths, plagioclase hygrometry, and measurement of hydrogen in olivines from mafic volcanics of SW Japan. In: Gómez-Tuena A, Straub SM, Zellmer GF (eds) Orogenic andesites and crustal growth. Special Publication - Geological Society of London 385(1):161–184

Zellmer GF, Sparks RSJ, Hawkesworth CJ, Wiedenbeck M (2003) Magma emplacement and remobilization timescales beneath Montserrat: insights from Sr and Ba zonation in plagioclase phenocrysts. J Petrol 44 (8):1413–1431