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PERSPECTIVES

Large silicic magma bodies and very large magnitude explosive eruptions

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Abstract
Over the last 20 years, new concepts have emerged into understanding the processes that lead to build up to large silicic explosive eruptions based on integration of geophysical, geochemical, petrological, geochronological and dynamical modelling. Silicic melts are generated within magma systems extending throughout the crust by segregation from mushy zones. Segregated melt layers become unstable and can assemble into ephemeral upper crustal magma chambers rapidly prior to eruption. In the next 10 years, we can expect major advances in dynamical models as well as in analytical and geophysical methods, which need to be underpinned in field research.

Keywords Silicic magma bodies · Magma eruptions · Magma

Introduction

An enduring problem is how to generate very large silicic magma bodies capable of feeding eruptions of tens to thousands of km^3 that produce ignimbrites, tephra fall and large calderas. Such volcanism is highly episodic and invites development of conceptual models that capture this characteristic.

Our focus here is the formation and longevity of large-volume silicic magma chambers that erupt catastrophically in association with caldera formation. Emerging concepts based on geological evidence (from past events) and geophysical evidence (from today) are framed by physical and conceptual models of geodynamics, silicic magma generation, magma chamber assembly, magma ascent and eruption triggers. This is largely a story of processes in the middle and upper crust, whilst acknowledging that basalt input at depth is in most cases a fundamental driving force and that silicic melts can also be generated by melting pre-existing rocks.

We define a *magma reservoir* as a crustal region in which melt is present, *mush* as a region in which melt is distributed within a crystalline framework and a *magma chamber* as a melt-rich region commonly containing suspended crystals and bubbles. A reference list organised into specific topics covering the last 20 years of research is supplied in the Electronic Supplementary Material (ESM).

This paper constitutes part of a topical collection:

Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

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The last 20 years

Ideas developed over the last 20 years, building on earlier studies, have highlighted silicic melt generation and storage in the crust in the form of vertically extensive magma mush reservoirs (Fig. 1; ESM-1). Silicic melts are generated within transcrustal magma systems by processing and differentiation of basaltic magma, mostly in the lower and middle crust, and by partial melting of older crust. Upon intrusion into the crust, the basalt magma crystallises and supplies heat (and volatiles) that also drives partial melting of adjacent older crust. The evolved, silica-rich melts are buoyant and can segregate from crystalline residues by compaction related to buoyancy and by tectonically and magmatically driven deformation or disruption (ESM-2). The result is a vertically extensive region of distributed partial melt and segregation of melt-rich regions (Fig. 1). Melts that ascend through mushy regions and intercalated solid crust can accumulate at shallower crustal levels as bodies of potentially eruptible magma, some of great volume, to feed variable amounts of surface volcanism, whilst remaining magma cools to form plutons.

This picture is supported by geophysical data and imaging of present-day anomalous regions that extend throughout the crust and into the upper mantle beneath major silicic volcanic centres. In some cases, these anomalies are regional in extent (ESM-3). Partial melts (~ 10% by volume), usually of silicic composition, are commonly inferred in the middle and upper crust whilst the lower crust contains either lower melt fractions or no geophysically detectable volumes of melt. Marked S-wave anisotropy in the crust reveals a strongly layered character to many igneous systems, suggesting sill-like bodies. Tectonically exhumed sections through igneous crust provide evidence for processing of basaltic magma within lower crustal hot zones, generation and segregation of differentiated intermediate and silicic melts in the lower and middle crust and accumulation of predominantly silicic magmas in the upper crust (ESM-4).

Critical information on the time scales of silicic magmatic systems comes from major developments involving applications of high precision geochronology, in particular $^{40}Ar/^{39}Ar$ dating and zircon studies (ESM-5). In many ignimbrites and plutonic suites, geochronological data indicate long-lived magmatic systems (~ 10^4 to > 10^6 years), time scales supported by residence times of melts in the crust measured by U-series disequilibria. Zircon ages have been interpreted within the concept of 'cold storage' whereby zircons are held either within mush reservoirs or sub-solidus rock for long periods of time before being liberated by processes that produce

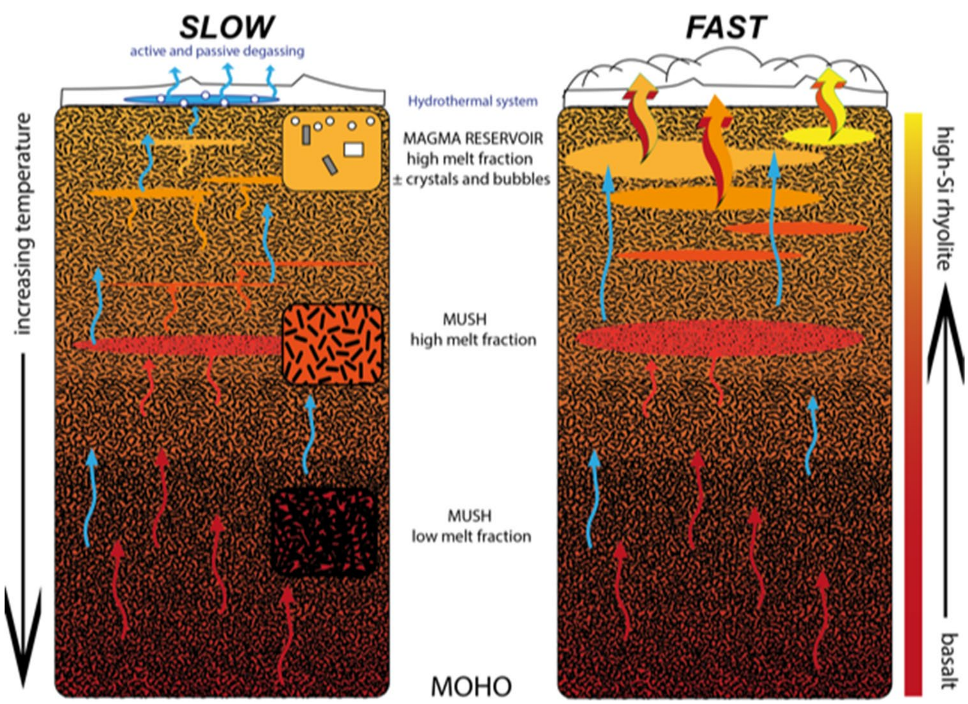

Fig. 1 Schematic example diagrams through a transcrustal silicic magmatic system contrasting slow (left) and fast (right) rates of magma ascent. Multiple high melt fraction magma chambers develop from extraction of melts from mushes and their ascent followed by emplacement at high crustal levels. Mantle-derived basalt emplaced into the lower crust have melt fractions that are generally low due to short time scales of melt extraction governed by high temperatures and low melt viscosities. Evolved basalts and andesites then ascend into the middle crust where further differentiation occurs and generation and extraction of more silicic melts takes place. These silicic melts then ascend into the shallow crust to form magma reservoirs comprising silicic mush and embedded magma chambers. Mushes containing silicic melt have much greater longevity than mush in the deeper crust containing mafic melts due to lower temperatures and high melt viscosities. The diagram does not depict likely occurrence of significant regions of consolidated igneous rock and older crustal rocks which can be remelted, contribute to silicic melt generation and result in discrete separated magma reservoirs at different levels in the crust

eruptible magma. A broadly similar picture has emerged from studies of plutons. These time scales are also consistent with the physical conditions required to form large magma chambers, which develop only in thermally mature systems where large amounts of heat and mass are emplaced into the crust. The resulting vertically extensive regions of mush can store large melt volumes even at low melt fractions.

In contrast to obtaining timescales using radiometric methods, residence times of crystals of the major rock-forming minerals (pyroxenes, amphiboles, feldspars) are increasingly determined using diffusion chronometry. The resulting data are widely interpreted (ESM-6) as evidence of rapid crystallisation and assembly of magma chambers (typically decades to centuries) in the shallow crust (< 10 km) just prior to eruptions (Fig. 2A). Some antecrysts are formed at higher pressures than the host magma. Low pressure rims on higher pressure crystal cores (Fig. 2A) can grow on the timescales of as little as decade or shorter.

Petrological and geochemical studies (ESM-5, ESM-6 and ESM-7) indicate that magma transport and intrusion in transcrustal magma systems is highly dynamic, leading to entrainment of crystals (antecrysts and xenocrysts) from mush, earlier formed plutonic rocks and older crust. There is emerging petrological and geochemical evidence for disruption and intermingling of multiple discrete (and compositionally diverse) magma chambers in the largest eruptions and, sometimes, evidence of significant time gaps between eruption phases (ESM-1, ESM-6 and ESM-7).

Three main explanations for magma chamber formation are as follows: melt segregation from, and melt infiltration into, mush (decompaction); ascent of silicic magma and shallow intrusion; and remobilisation of mush or hot sub-solidus rock by magma recharge with heat and volatile fluxing (ESM-1, ESM-8, ESM-9). Although sometimes framed as rival hypotheses, these mechanisms are not mutually exclusive and likely act in combination. For example, a magma chamber might form by incremental recharge of magma formed by melt segregation and decompaction at greater depths in the system, with contributions from remobilisation of previously consolidated intrusions or mush.

Implicit in incremental growth and recharge models is magma ascent from a deeper source. Thus, a fundamental mechanism of forming magma chambers must include very slow processes of melt segregation from mush to form melt-rich layers (Fig. 3), and decompaction-driven melt segregation and infiltration into mush or adjacent hot rocks (Fig. 2B; ESM-2). Melt accumulations formed

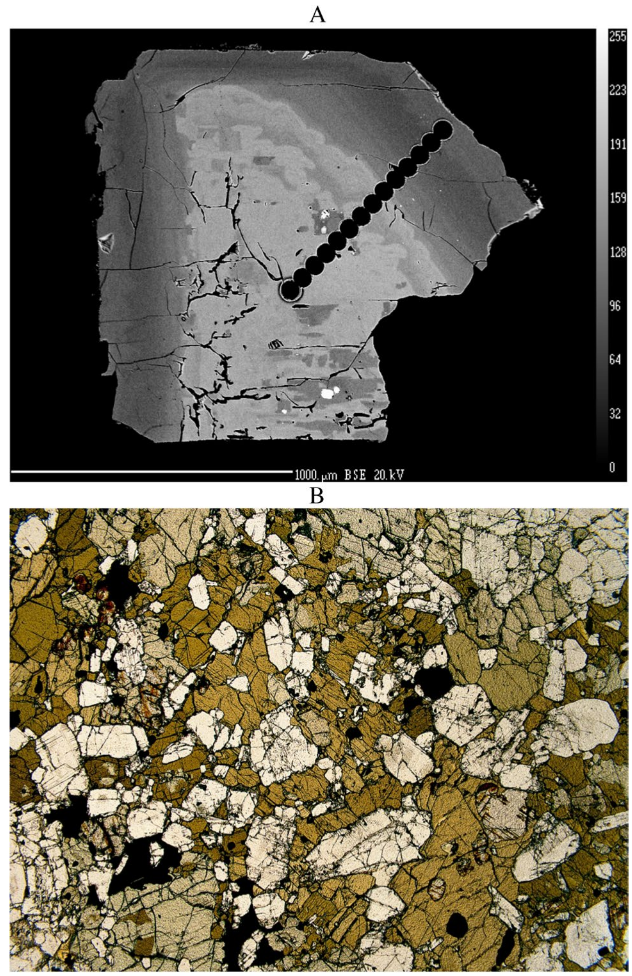

Fig. 2 Examples of the crystal-specific record of crustal magmatic processes. Panel **A**. Back-scattered electron image of a plagioclase feldspar phenocryst (pl6) from the 4 Ma, 1600 km^3 Atana ignimbrite eruption from La Pacana caldera, Chile (ref. 95). The calcic core of the crystal (lighter grey) records magmatic processes occurring within the crustal mush reservoir, whereas the sodic rim (darker grey) grew from the eruptible volume of melt shortly prior to eruption. The black circles are laser-drilled analytical pits for a study of strontium isotope diffusion, which is used to determine the timescales of magmatic processes in the mush and of processes of pre-eruptive melt accumulation. The scale bar is 100 µm. Sample and photograph courtesy of Gregor Weber (University of Oxford). Panel **B**. Photomicrograph in plane-polarised light of a gabbroic plutonic xenolith (DC100) from the volcanic island of Dominica, Eastern Caribbean arc. Dominica has produced several (3 to 5 km^3) ignimbrite eruptions in the past 50 kyr. These eruptions are supplied by silicic melts extracted from a mid-crustal mush system at depths of ≥ 14 km (refs. 98, 122). The plutonic xenolith is a sample of the mush brought to the surface in an eruption. Thermobarometry of similar, olivine-bearing xenoliths from Dominica yield pressures of 1.9 to 3.6 kbar (depths of 7 to 13 km; ref. 122). The xenolith texture testifies to percolative reactive flow of hydrous, silica-rich melt through a mush composed of plagioclase (white), clinopyroxene (pale green) and oxides (black), producing interstitial amphibole (khaki) with a distribution reflecting the original melt. Photograph courtesy of Richard Arculus, Australian National University; field of view is ~ 4 mm across

in this way can ascend to form plutonic rocks, reservoirs of mush and magma chambers by incremental growth and recharge. Further melt extraction from silicic reservoirs emplaced at higher levels can produce high silica rhyolite magma chambers and associated refractory silicic plutonic rock [ESM-4]. Incremental magma chamber growth also allows ductile responses in pre-existing magma reservoirs and hot host rocks, including buoyancy-induced (Rayleigh-Taylor) instabilities and dyke nucleation. High crustal strength and effective viscosity lead to longer time scales for instability development and formation of larger magma chambers.

Both empirical evidence (ESM-8) and numerical modelling (ESM-9) show that magma chamber formation is highly episodic. Volcanic records, combined with petrological, geochronological and geochemical data, highlight alternations of long periods of dormancy, periods of many relatively small eruptions indicating a leaky magmatic system, and finally, in some but not all systems, accumulations of substantial magma volumes preceding large caldera eruptions. Plutonic records likewise indicate pulsatory construction. Erupted magma compositions may change abruptly or remain coherent over long periods of time.

Once a thermally mature, vertically extensive system has developed, mushy magma reservoirs can experience a spectrum of dynamic behaviours from repetitive cycles of very slow processes (melt segregation, accumulation and incremental intrusion) that produce long-lived magma chambers, to very dynamic and disruptive fast processes (tectonic disruption, magma instability, ascent, shallow assembly, magma chamber recharge with remobilisation of mush and older plutons) that form magma chambers rapidly. These processes can be associated with three broad regimes for magma reservoir assembly in the upper crust as follows: magma emplacement with little or no accompanying volcanism; magma emplacement with protracted surface volcanism but individual eruption magnitudes too small for caldera formation; or formation of large magma chambers that erupt catastrophically to form calderas.

Thermal models of magma chamber growth require magma fluxes into the upper crust that are 1–2 orders of magnitude higher than long-term averages. Petrologic evidence of rapid crystallisation of magma chambers in the shallow crust (typically < 10 km) just prior to (~ decades to centuries) large magnitude ignimbrite eruptions comes from diffusion modelling of changes in crystal composition (ESM-6). These observations are also commonly inferred to imply rapid magma reservoir assembly, although the time scales of crystallisation and assembly

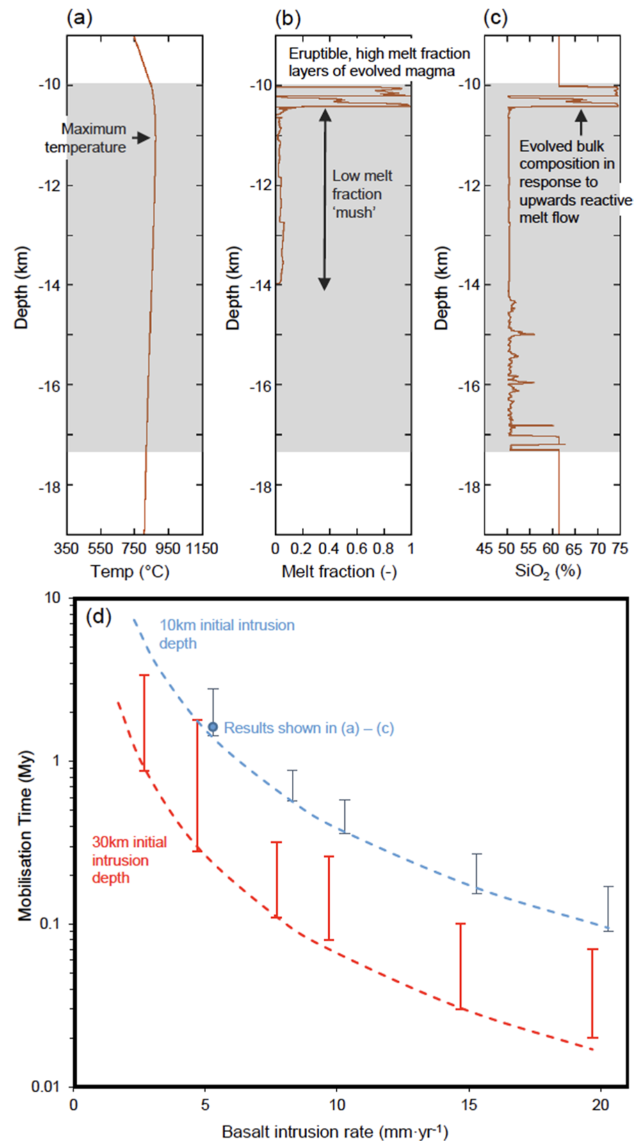

Fig. 3 Examples of insights from numerical modelling approaches. Numerical modelling suggests that the formation of evolved, low crystallinity magma layers in crustal mush reservoirs is an inevitable consequence of reactive percolative melt flow for a broad range of mush reservoir material properties. Panels (**a**)–(**c**) show snapshots of simulated temperature, melt fraction and bulk composition (expressed as SiO_2%), respectively, as a function of depth through a crustal mush reservoir, 1.4 Ma after the onset of basalt sill intrusions that supply the magma reservoir. The time required to form an eruptible magma layer is termed the mobilisation time and is shown in panel (**d**) as a function of the intrusion rate of basalt for two different reservoir depths. Error bars denote the spread of mobilisation times for a broad and reasonable range of mush reservoir material properties, obtained from a large number of numerical simulations in which the material properties were randomly selected from an input range in a simple Monte-Carlo approach. Melt mobilisation timescales are shorter for deeper intrusion depths and with increasing rates of basalt intrusion. Datapoint in panel (d) corresponds to the case shown in plots (a)–(c). Data extracted and replotted from ref. 17

are not necessarily the same. Periods of (non-eruptive) volcanic unrest, which are much more frequent than eruptions, provide indirect evidence for episodic magma recharge.

Once emplaced in the upper crust, magma chambers can fail catastrophically because of magma recharge, decompression caused by large magma transfers from deep to shallow levels in the crust, in situ crystallisation of cooling magma chambers, CO_2 flushing, roof failure caused by deformation of roof rocks from internal magma chamber forces and tectonic triggers (ESM-8). In products of the largest eruptions, there is also emerging petrological and geochemical evidence for disruption of multiple discrete magma bodies, and possibly significant time gaps within eruptive sequences (ESM-6, ESM-7) that suggest a complex interplay of controls on magma release. A major conclusion of studies from the past 20 years is that, although common processes can be discerned from geological evidence or outlined from theoretical modelling, an extraordinary diversity is seen in young, caldera-related magmatic systems.

The next 10 years

Development and quantification of the mush model for silicic magmatism and its relationship with the deeper parts of transcrustal magmatic systems are expected to continue to be centre stage over the next 10 years. This model has now become the paradigm for the generation of silicic melt-dominant bodies and has powerful predictive characteristics.

The realisation that many of the controls on volcanism are due to processes at greater depth will continue to influence research in the next decade. Most observations made at active volcanoes are dominated by shallow phenomena and provide information on the symptoms rather than the fundamental causes of impending or ongoing eruption. Consequently, volcano monitoring efforts are usually focused on the shallow, sub-volcanic regime. However, if the causes of volcanism are deep-seated, they will be much harder to observe and interpret. For example, dynamic behaviours may be largely ductile at depth and therefore not necessarily associated with strong seismicity or marked surface deformation. Much research has focused on magma recharge with associated mush or magma reactivation. Consequently, a major new theme to develop is the causes, rather than the consequences, of recharge. To advance, research into how volcanoes behave will shift from a focus on the shallow parts of the system to modulations of shallow dynamics by deeper processes. A related theme is the recognition that volatiles exsolve and decouple from melt throughout the crust, raising questions about the role of volatiles in the dynamics of silicic magma generation, segregation, ascent and final eruption. Reaction of deep-derived fluids with shallow-stored magmas in the same vertically extensive system may have largely unexplored consequences for eruptive behaviour.

Fieldwork remains a primary tool in studies of large silicic volcanic and magmatic systems and is essential if benchtop and computer-based studies are to be grounded in reality. The major advances of the last 20 years have been underpinned by detailed geological studies augmented by geochronological, petrological and geochemical analysis. The resulting data provide the impetus for developing conceptual models of dynamic processes, constraints on model parameter choices and the evidence to test whether models succeed or fail. Modelling requires these links to observations and inferences from real-life systems.

There is considerable scope for advances in experimental and analytical research (ESM-10). For example, sector zoning in natural zircons renders Ti-in-zircon temperatures subject to uncertainties of 50–100 °C, whilst numerical values for diffusion coefficients vary considerably and many experimental determinations have been obtained under conditions that are inappropriate for the natural systems to which they are applied (e.g. Li diffusion in zircon). There is an acute need for consistent, experimentally determined diffusion coefficients applicable to natural circumstances. Techniques like ID-TIMS for zircons have produced highly precise age data, but there are challenges in interpretation of the consequent whole-grain ages, especially for Quaternary systems.

Whilst many dynamic models have been developed, they are typically specific and bespoke to a particular concept or component of the system rather than addressing the dynamics in a holistic way. The current models are likely too simplified to identify the full diversity of dynamic phenomena, especially if eruptive timing and volume can be shown to be chaotic in its nature. Modelling will move us forward as increasing computing power and coding efficiencies enable 2- and 3- dimensional models to be developed, to include more complex magma, mush and crustal rheologies, and to tackle ever more complex coupled dynamic and commonly non-linear processes. There are other underdeveloped topics too. For example, melt segregation and magma ascent involve volatile exsolution, which changes buoyancy and rheology, whilst decoupling of melts and volatiles increases the likely diversity of dynamical phenomena in highly non-linear systems. Models need to move away from already emplaced magma chambers embedded in elastic media to consider magma emplacement within and around mush reservoirs, characterised by large temperature and rheological gradients. Finally, magmatic systems reside in a crustal envelope subject to external tectonic forces in addition to those forces generated by the presence of a magma chamber itself. Determining interactions between magmatism and tectonism presents an ongoing challenge. Crustal stress states must influence the behaviour of magmatic systems but remain poorly understood.

Another challenge concerns the mechanisms of igneous differentiation. The enduring paradigm has been fractional crystallisation as a consequence of segregating melts from their solid residues. Emerging numerical models and petrological observations emphasise the importance of reactive, percolative flow as an inevitable consequence of buoyancy and compaction-driven melt movement (Fig. 2B). The full range of chemical implications of this mechanism for ignimbrite-forming, silicic magmas remains to be explored and tested against the ignimbrite rock record both for major and trace elements and for isotopes.

One aspiration with great potential to advance this field is deep drilling into large volcanic systems to reach magma and establishing magma observatories. Recent articles (ESM-11) advance compelling cases for such big-picture research exploration.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00445-021-01510-y.

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