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Perspectives

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PERSPECTIVES

The Inner Workings of Crustal Distillation Columns; the Physical Mechanisms and Rates Controlling Phase Separation in Silicic Magma Reservoirs

Olivier Bachmann[1]* and Christian Huber[2]

[1]Department of Earth Sciences, ETH Zürich, Zurich, Switzerland; [2]Department of Earth Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA

*Corresponding author. E-mail: olivier.bachmann@erdw.ethz.ch

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Olivier Bachmann is Professor of volcanology and magmatic petrology at the ETH Zürich. He obtained his PhD at the University of Geneva, and held positions of postdoctoral fellow and professor at the University of Washington (USA) before moving to Zürich in 2012. Olivier has always enjoyed collaborative research focusing on the dynamics of magmatic systems, trying to merge data from different realms, including fieldwork, petrology, geochemistry, geochronology, geophysics, and numerical models. In particular, what happens within magma reservoirs leading to super-eruptions has always been a major drive in his research.

Christian Huber is an associate professor of geophysics at Brown University. He studied Earth sciences and then physics at the University of Geneva, before pursuing a PhD at UC Berkeley, USA. Before moving to Brown University, Chris held a faculty position at the Georgia Institute of Technology. Chris works on dynamical processes associated with multiphase systems, with an emphasis on magmatic systems.

ABSTRACT

Igneous processes have a fundamental impact on how our planet is shaped: they contribute to the growth of continents, control volcanic activity, form ore deposits and supply most volatile elements to our atmosphere. In the course of this igneous differentiation, phase separation plays a key role, as in all distillation processes. How, and how fast, this phase separation occurs are therefore critical questions to address to better understand the inner workings of the Earth (and other planets). In this Perspectives article, we will review some of the most important aspects of the processes that govern igneous distillation, considering the effect of three distinct phases (crystals–melt–fluid, in decreasing order of viscosity and density) on mechanical separation processes in a gravity field. We will also discuss the potential impacts of external factors (e.g. tectonic forces, magma recharge, seismic waves) on phase separation. Regardless of the source of energy driving phase separation in crustal differentiation columns, crystal settling at low crystallinity and compaction at intermediate to high crystallinity play a major role in separating silicate minerals from melts and fluids. We suggest that compaction without any associated deformation of solids (herein referred to as 'crystal repacking') is an important process that can extract up to a few tens of per cent (volume) of melt from its crystalline matrix, particularly in shallow silicic reservoirs. Rates of melt extraction by compaction are probably relatively slow, requiring centuries to millennia to generate large crystal-poor pockets (>10s to 100s of km^3 of silicic melt). Alternative processes, such as gas-driven filter pressing or melt segregation by shear or deformation, can enhance or inhibit phase separation, depending on specific conditions, but they are unlikely to be particularly efficient in silicic systems.

Key words: *magma chamber*; *crust formation*; *phase separation*; *differentiation*

INTRODUCTION

The physical separation of magmatic phases (solids or crystals, silicate melt, and a magmatic volatile phase hereafter referred to as MVP or fluid) controls the chemical differentiation of our planet. Particularly relevant to the discussion here is the presence of volcanic units recording single eruptions with volumes in excess of 100–500 km^3 of crystal-poor high-SiO_2 rhyolites, which testify that crystal–melt separation can be efficient, even for the most viscous melts (Hildreth, 1981; Druitt & Bacon, 1989; Christiansen, 2001; Lipman & Bachmann, 2015; Bachmann & Huber, 2016). In plutonic rocks, this extraction process is recorded and displayed at multiple scales, from centimeter-sized pods or veins of haplogranitic material (probably crystallized rhyolitic melt) visible in outcrop, to high-silica granite bodies that can be mapped at the kilometer scale (see Bachl *et al.*, 2001; Miller & Miller, 2002; Greene *et al.*, 2006; Vernon & Paterson, 2006; Hacker *et al.*, 2008; Jagoutz *et al.*, 2009; Miller *et al.*, 2009, 2011; Otamendi *et al.*, 2009, 2012; Jagoutz, 2010; Memeti *et al.*, 2010; Paterson *et al.*, 2011; Jagoutz & Schmidt, 2012; Coint *et al.*, 2013; Putirka *et al.*, 2014; Lee & Morton, 2015; Lee *et al.*, 2015; Walker *et al.*, 2015; Barnes *et al.*, 2016; Ducea *et al.*, 2017; Hartung *et al.*, 2017; see also Fig. 1 and references therein).

The rate at which the separation between silicate melts and crystals occurs is critical to predicting how and where mobile magmas can accumulate, ascend through the mantle and crust and, ultimately, pool in shallow magmas reservoirs for eruption at the surface (Bachl *et al.*, 2001; Barnes *et al.*, 2001; Coint *et al.*, 2013; Putirka *et al.*, 2014; Gelman *et al.*, 2014; Lee & Morton, 2015; Vigneresse, 2015). Phase separation depends on the thermal state of magmatic systems, and requires the existence of mush zones in which magmas remain above their solidus for significant amounts of time (Marsh, 1981; Koyaguchi & Kaneko, 1999; Huber *et al.*, 2009; Karakas *et al.*, 2017*a*; Szymanowski *et al.*, 2017), whatever the solidus temperature may be (Johannes & Holtz, 1996; Ackerson *et al.*, 2018). Rates of melt extraction and accumulation in melt-rich lenses in upper crustal silicic magma reservoirs form the crux of a continuing debate, in which melt extraction and accumulation are variably argued to be slow (e.g. millennia for large systems; McKenzie, 1985; Wickham, 1987; Bachmann & Bergantz, 2004; Huber *et al.*, 2012) or fast (months to decades or centuries, even for large systems; e.g. Wilson & Charlier, 2009; Druitt *et al.*, 2012; Gualda *et al.*, 2012; Allan *et al.*, 2013; Barker *et al.*, 2016).

In magmas, the physics that governs the separation of phases with different densities involves a continuum of processes from crystal settling at high melt fractions (which rapidly becomes 'hindered' as the crystal content increases; e.g. Koyaguchi *et al.*, 1990; Faroughi & Huber, 2015) to compaction at lower melt fractions (McKenzie, 1985; Shirley, 1986; Miller *et al.*, 1988; Boudreau & Philpotts, 2002; Bachmann & Bergantz, 2004; Vernon & Paterson, 2006; Tegner *et al.*, 2009; Solano *et al.*, 2012; Webber *et al.*, 2015; Riel *et al.*, 2018). Rates for crystal–melt separation can be estimated for both settling and compaction, assuming a composition of the melt (which controls density and viscosity), average densities of the solid phases, and the permeability of the system (which varies as a function of melt fraction and size and shape of solid particles). Additional factors can play a role, such as deformation-induced melt segregation (Rutter & Neumann, 1995; Petford *et al.*, 2000), vibro-agitation of magma chambers (Davis *et al.*, 2007), shearing (Katz *et al.*, 2006; Kohlstedt & Holtzman, 2009), or gas-driven filter pressing (e.g. Anderson *et al.*, 1984; Sisson & Bacon, 1999; Pistone *et al.*, 2015), which have also been suggested as possible phase separation 'enhancers' as they affect the spatial distribution of stresses. The efficiency of these latter processes in upper crustal silicic magma reservoirs remains unfortunately poorly constrained, owing to lack of quantitative assessments, and/or is currently debated (e.g. Bachmann & Bergantz, 2006; Parmigiani *et al.*, 2014; Pistone *et al.*, 2015, 2017; Singer *et al.*, 2016; Cashman *et al.*, 2017; Hildreth, 2017). This contribution focuses on these various processes based on recent findings (see, for example, Costa *et al.*, 2006; Weinberg, 2006; Holness *et al.*, 2007; Bacon *et al.*, 2009; Karlstrom *et al.*, 2009; Tegner *et al.*, 2009; Huber *et al.*, 2011; Schoene *et al.*, 2012; Solano *et al.*, 2012, 2014; Bain *et al.*, 2013; Brown, 2013; Gutierrez *et al.*, 2013; Barboni & Schoene, 2014; Payacán *et al.*, 2014; Faroughi & Huber, 2015; Pistone *et al.*, 2015; Vigneresse, 2015; Webber *et al.*, 2015; Aravena *et al.*, 2017; Samperton *et al.*, 2017; Schaen *et al.*, 2017; Riel *et al.*, 2018) to predict more accurately the separation rates and formation of crystal-poor lenses of evolved magmas in the upper 10–20 km of the Earth's crust. The effect of external factors, such as tectonic stresses and magma recharge, will also be briefly examined.

THE SOURCES OF ENERGY DRIVING CRYSTAL–LIQUID SEPARATION IN SILICIC MAGMA RESERVOIRS

Phase separation in magmas is accompanied by friction and viscous dissipation; it therefore requires an input of

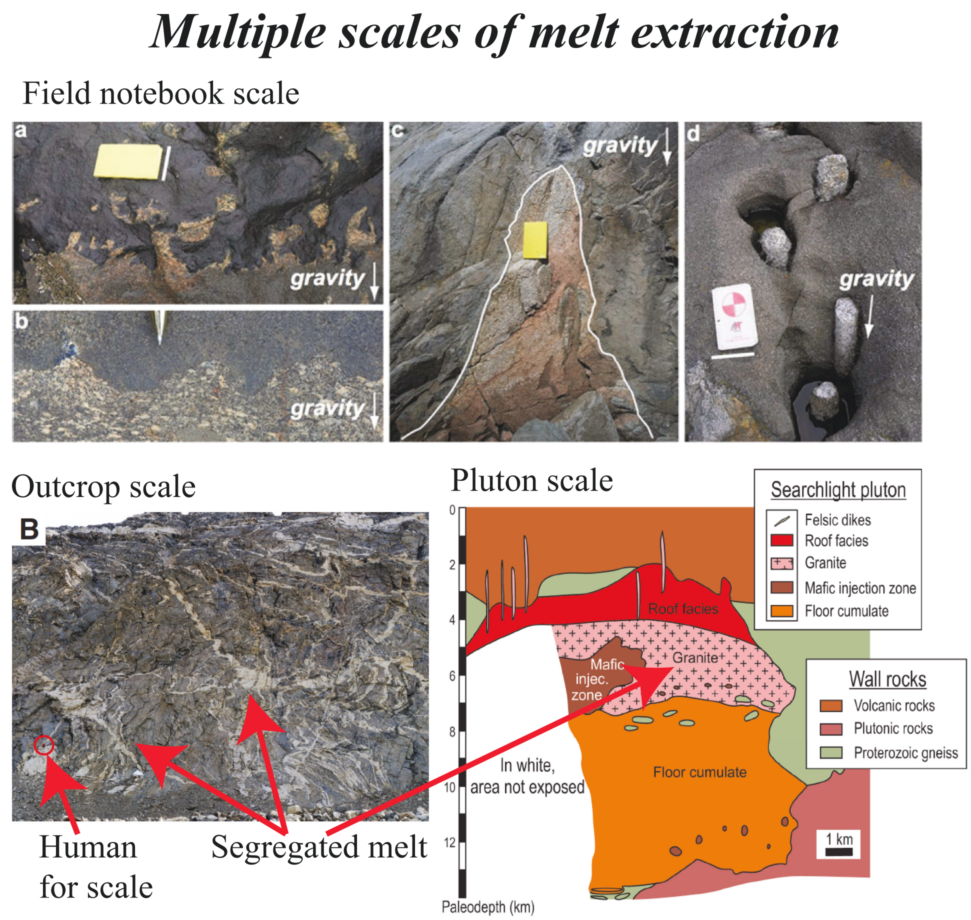

Fig. 1. Field examples of melt extraction in plutonic lithologies at different scales, from the centimeter to the kilometer scale. Photographs for the field notebook scale are from Bain *et al.* (2013), for the outcrop scale from Brown (2013), and for the pluton scale modified from Bachl *et al.* (2001).

energy to take place. The energy sources that drive phase separation in magmatic systems can therefore be broadly classed in two categories: (1) gravitational potential energy caused by density contrasts between phases; (2) mechanical work caused by factors such as tectonic stresses, recharge of magma or earthquakes. As gravitational potential energy is always available for phase separation, especially in silicic magmas where the dominant mineral phases are denser than the melt, buoyancy-driven stresses must play a role. However, as many silicic plutons remain rather homogeneous (with significant amounts of trapped melt component; e.g. Fiedrich *et al.*, 2017), gravity alone is unlikely to be sufficient in many cases, and other sources of energy are required to drive melt–crystal separation.

Magmatic systems are commonly located in tectonically active regions and it is therefore natural to consider the extent to which these stresses can influence the state of shallow magma reservoirs and affect melt extraction processes (e.g. see Petford *et al.*, 2000). There are two generic types of stresses that can be externally imposed on a shallow magma reservoir: dynamic stresses and static stresses. Dynamic stresses, caused by the passing of seismic waves, can be as large as a few MPa in the near to intermediate field (e.g. Luttrell *et al.*, 2011), but decay to 0·01–0·1 MPa in the far field, even for large earthquakes (Manga & Brodsky, 2006). A first possible *ex situ* melt extraction mechanism, proposed by Davis *et al.* (2007) more than a decade ago, is the vibro-agitation of magma reservoirs following large regional earthquakes. Fluidizing beds by mechanical vibration is a well-known industrial process, but it requires vibration frequencies that are comparable with the response timescale of the fluid, which depends both on its viscosity and the permeability of the system. If the viscosity of magmatic fluids is high (as it is for silicic magmas, more than 10^8–10^9 times higher than water), it is unlikely that earthquakes generate sufficient fluidization in the magma reservoir to promote crystal–melt segregation. The major issue with phase separation mediated by dynamic stresses is the short duration over which they actively deform the reservoir (seconds to minutes), a timescale that is probably too short to lead to substantial melt extraction.

On the other hand, static stresses, such as tectonic forces, are more likely to affect phase separation in magma reservoirs as they operate over timescales comparable with the longevity of magmatic systems

(Rutter & Neumann, 1995; Petford *et al.*, 2000). The magnitude and orientation of tectonic stresses are highly variable (Zoback *et al.*, 1989). For depths down to about 8–10 km, they can be as large as a few tens of MPa (e.g. Buck *et al.*, 2006). Tectonic stresses are known to influence the propagation of dikes in the crust and probably influence deformation around, and possibly inside, active magma reservoirs (Nakamura *et al.*, 1977; Petford *et al.*, 2000; Buck *et al.*, 2006). However, if regional tectonic stresses were to exert a first-order control over the efficiency of melt–crystal separation in magma reservoirs, we would not expect large eruptions of crystal-poor rhyolites to occur in all tectonic settings, including extensive, neutral and compressive settings (see Fig. 2 and compilations from Holohan *et al.*, 2005; Hughes & Mahood, 2008). As mentioned by Philpotts & Ague (2009, Chapter 3), tectonic forces may help to deform a magma reservoir (inducing some crystal 'repacking'; see discussion below), but are unlikely to 'squeeze' melt out efficiently if there are no low-pressure environments in the vicinity. Moreover, even when large stresses are applied, extensive melt segregation still appears to require significant time ($>10^3$ years; Rutter & Neumann, 1995; Petford *et al.*, 2000). Hence, although tectonic stresses probably influence the transport and accumulation of magmas in the crust, we argue that, in general, they do not exert a primary control over phase separation, at least in upper crustal mushes.

Magma recharge is ubiquitous in crustal reservoirs (see Bachmann & Huber, 2016, for a review, and references therein), and these episodes can be accompanied by large, but local, stress changes. The stress caused by recharges includes both pressure changes and shear stress. Shearing of parts of the mush can lead to melt segregation, as has been suggested for the mantle (e.g. Kohlstedt & Holtzman, 2009) and crustal reservoirs (Rabinowicz & Vigneresse, 2004; Bergantz *et al.*, 2015). However, as mush zones grow and mature, the recharge volumes tend to be small compared with the size of the mush (e.g. Dufek & Bergantz, 2005; Karakas *et al.*, 2017*a*). Hence, the zones that are actively sheared are likely to involve a minor fraction of the reservoir's volume. Although shear localization can provide efficient pathways for melt transport, it is not clear that large volumes of melt can be mobilized at a faster rate than predicted for *in situ* processes by this process. Indeed, the rate of melt extraction will depend on the distance separating localized melt channels and the permeability of the intervening compacted layers. In addition, silicic mushes from which these rhyolitic melts are derived are often saturated with a volatile phase and it is unclear how shear deformation affects melt–crystal separation in the presence of exsolved volatiles (e.g. Pistone *et al.*, 2012). The importance of magma recharge episodes in driving faster, more efficient, melt extraction from mushes is therefore not fully assessed and should be further studied.

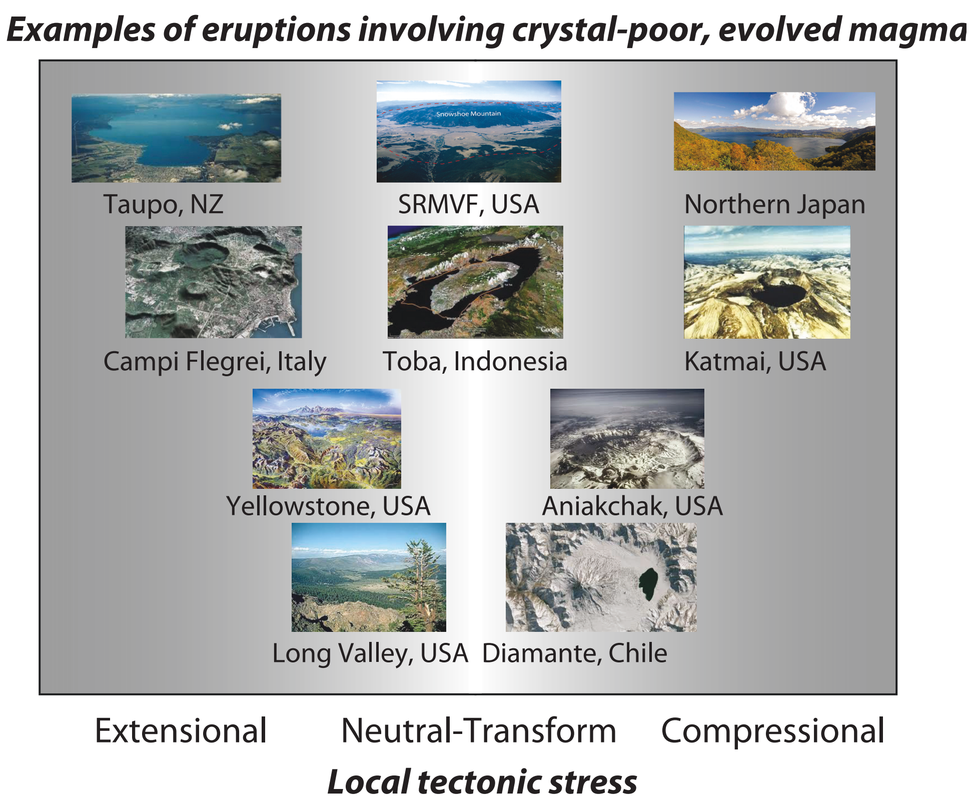

Fig. 2. Examples of caldera-forming eruptions involving crystal-poor deposits in all tectonic settings, from the compilations of Holohan *et al.* (2005) and Hughes & Mahood (2008). SRMVF; Southern Rocky Mountain Volcanic Field.

In summary, it is a combination of energy sources, involving regional tectonics, gravity and mechanical work exerted by magma recharge, that probably drives the process of phase separation in magma reservoirs. The degree to which an individual source of energy contributes to the distillation process depends on each specific system. The diversity of mechanical processes that occur in crustal reservoirs is most probably governed by the volumetric proportions of the phases (crystals, melt and exsolved volatiles) in the system; these are reviewed in the section below.

MECHANISMS AND RATES OF CRYSTAL–MELT SEPARATION IN SILICIC MAGMA RESERVOIRS

Melt-dominated regime: crystallinity lower than rheological lock-up

In silicic magmas, crystals are generally denser than the melt with which they coexist. Naturally, one would expect that the different phases will separate to reduce the excess gravitational potential energy stored in the reservoir. The rate of such separation will then depend on factors such as particle diameter, density contrast, viscous drag, cooling, and phase changes, which will control the development of stable density stratification within the reservoir.

The modes of mechanical separation in a gravity field vary significantly with the proportion of phases considered (see exhaustive summary in Chapter 14 of Philpotts & Ague, 2009). In a fluid-dominated system, settling of particles in the supporting fluid (magmatic crystals in a silicate melt in our case) is commonly assumed to follow Stokes' Law,

$$U_{\mathrm{sed}} = A\left[\frac{g(\rho_{\mathrm{crystal}} - \rho_{\mathrm{melt}})d^2}{\mu}\right]$$

which assumes that a single particle of diameter d exists in the host fluid of viscosity μ considered at rest and infinite in volume (no boundaries between melt and host rocks). Moreover, Stokes' Law implies that the size of the crystal and viscosity of the melt are such that inertial forces are negligible. U_{sed}, the sedimentation velocity, is obtained from matching the drag force exerted by the melt on the crystal with the buoyancy caused by the density difference between particle and melt ($\rho_{\mathrm{crystal}} - \rho_{\mathrm{melt}}$), with A representing a shape factor coming from the calculation of the drag force. This idealized model for crystal–melt separation may provide usefully accurate estimates in some extreme magmatic cases, but it is typically not applicable because (1) the melt is generally not at rest in melt-rich magmas (Martin *et al.*, 1987; Bergantz & Ni, 1999; Dufek & Bachmann, 2010) and (2) there are significant effects caused by the presence of other particles or crystals, even under dilute conditions ('hindered' settling; see Davis & Acrivos, 1985; Koyaguchi *et al.*, 1990; Faroughi & Huber, 2015).

The assumption of a state of rest for the melt limits the application of Stokes' Law for crystals entrained in convective currents as it affects the magnitude and direction of the drag force on the particle or crystal. The dynamics of crystals in melt-rich magmas is further complicated by the fact that crystals interact hydrodynamically, even over distances that extend significantly beyond their sizes. Crystal interactions, even under dilute conditions, have been shown experimentally to affect convective dynamics (e.g. Koyaguchi et al., 1990), an effect that arises not only because of the effect of crystals on magma rheology, but also because velocity perturbations caused by the presence of a crystal have a long range: they decay as $1/r$ whereas stresses decay as $1/r^2$.

To account for crystal interactions during settling, Faroughi & Huber (2015) developed a theoretical model whereby the balance between drag and buoyancy forces is corrected to account both for the reduction in buoyancy associated with the presence of other suspended crystals and for hydrodynamic interactions that either decrease drag when particles are aligned with gravity ('crystal plume' effect) or increase drag when particles are misaligned (increased drag by melt return flow). Using this model, settling velocities are reduced by more than 60% (i.e. the time for phase separation is more than doubled) when considering crystal volume fractions of about 20 vol. %. Assuming this hindered settling to be a lower bound estimate for the duration of phase separation, as it does not include a proper treatment of the drag from convective currents (which retain crystals in suspensions for longer times), we obtain timescales of several millennia to produce large melt-rich bodies capable of erupting $>$100–500 km^3 of crystal-poor rhyolites (see fig. 4b of Faroughi & Huber, 2015).

Crystal-dominated regime: crystallinity higher than rheological lock-up

At the other end of the spectrum, when the solid fraction is intermediate to high, the particle framework (in our case the crystal matrix) can withstand differential stresses (e.g. it has a finite rigidity). Melt–crystal separation can then be driven by either (1) porous flow within a non-deforming mush (e.g. thermal or compositional convection), (2) concurrent immiscible fluid flow between the melt and an exsolved fluid phase, or (3) compaction (see definition below) leading to the expulsion of the melt trapped in collapsing pores. We now briefly discuss the first two processes before focusing on the third, which we expect to be the dominant process controlling melt–crystal separation at high crystal content in magmatic systems.

Thermal or chemical convection in porous media is not spontaneous and variations in buoyancy have to exceed the resistance to the flow exerted by the viscosity of the melt and the limitations of the permeability of the crystal framework. A crude, but useful, first-order approach to the problem is to consider convection in porous media, which, from linear stability analysis, provides the following criterion for the occurrence of convective transport of melt within the mush in terms of the contrast in melt density throughout a mush of thickness H (Nield & Bejan, 2013):

$$\Delta\rho > \frac{4\pi^2 D}{kgH}\mu$$

where D is the diffusion coefficient (thermal or chemical), k is the permeability of the mush and μ is the dynamic viscosity of the melt. For thermal convection, considering a rhyolitic melt within a 1 km thick mush with permeability k of $10^{-12}\,m^2$, we obtain $\Delta\rho$ of $10^8\,kg\,m^{-3}$ (assuming $D = 10^{-6}\,m^2\,s^{-1}$ and $\mu = 10^5\,Pa\,s$), which exceeds by several orders of magnitude the natural $\Delta\rho$ in silicic magma. The situation is similar, yet less extreme, for chemical convection.

The differential flow of immiscible melts and fluids (MVP) within a passive and non-deforming crystal framework is caused by the differences in density between the two fluid phases. Within the pore space, the most buoyant fluids (the MVP) rise, whereas the denser melt sinks to conserve mass. In the absence of porosity change, this process leads to an accumulation of MVP near the top of the mush. Although we will revisit this point when discussing processes occurring within a deforming matrix below, it is not clear that differential flow of immiscible fluids through a non-deformable porous host enhances melt–crystal separation.

In view of the limitations of other processes, compaction-driven melt extraction ('compaction' here defined as involving some sort of matrix deformation; see Supplementary Data lexicon; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org) is expected to control the rate of melt–crystal separation in silicic mushes (see Solano *et al.*, 2014). However, as recently pointed out by Holness *et al.* (2017) and Holness (2018), textural evidence of compaction is scarce in silicic and mafic plutons; microstructures in fully solidified plutonic rocks rarely preserve evidence of extensive syn-magmatic internally generated viscous crystal deformation. Hence, the exact mechanics of compaction, and the rates associated with it, must be explored in more detail.

Once a mush is formed (i.e. the matrix has a finite rigidity), deformation of the matrix, the key for compaction, can be accommodated by two different regimes, which we will term (1) compaction driven by crystal repacking ('mechanical compaction' of Holness *et al.*, 2017) and (2) compaction driven by crystal deformation ('viscous compaction' of Holness *et al.*, 2017; see Fig. 3, Supplementary Data lexicon, and the excellent summary in the textbook of Philpotts & Ague, 2009).

(1) Crystal repacking can occur only over a limited range of crystallinity that starts from the onset of the lock-up [where the matrix develops a yield strength, sometimes referred to as the maximally randomly jammed (MRJ) state; Fig. 3] and ends at the maximum

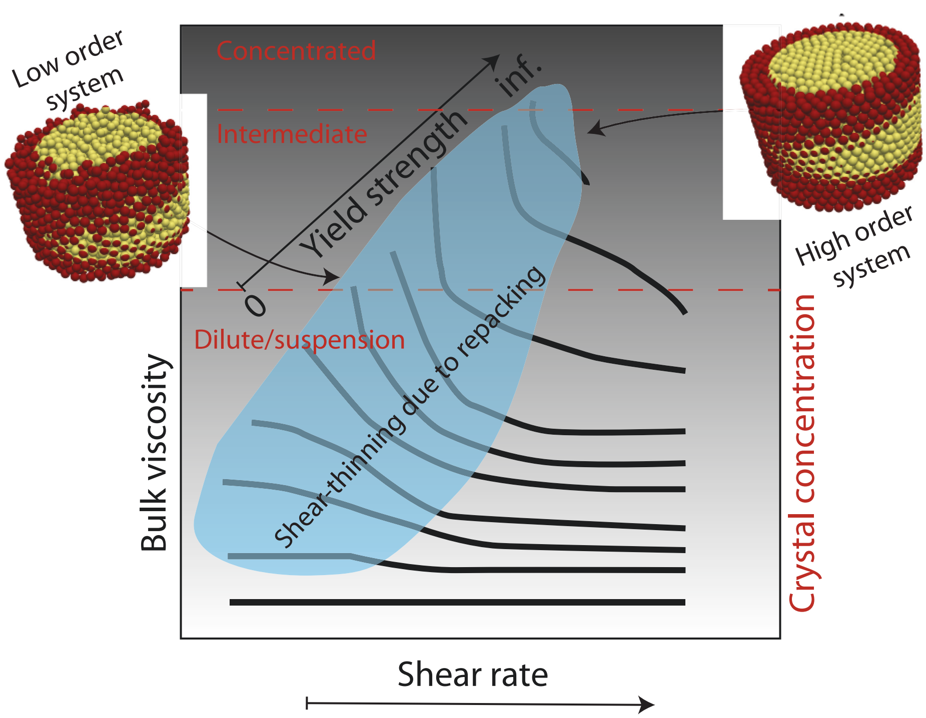

Fig. 3. Schematic diagram showing the evolution of the bulk viscosity as a function of shear rate in a crystal–melt mixture [from dilute to concentrated, modified from S. A. Faroughi (unpublished), with drawings from Roozbahani *et al.* (2017)]. The observed shear-thinning behavior (reduced viscosity as shear rate increases) is due to the development of a preferred orientation for the crystals by repacking of the solid grains. As the yield strength increases, repacking (mechanical compaction of Holness, 2018) is no longer viable, and deformation must occur by crystal deformation or breakage (viscous compaction of Holness, 2018).

packing fraction (the most ordered and highest packing attainable). This range is controlled by the size and shape distribution of the crystals in the mush. Non-sphericity and anisometry greatly increase this range, and polydispersity (variation in grain size; see Supplementary Data lexicon) is known to strongly push the maximum packing fraction to even higher values (Torquato *et al.*, 2000; Donev *et al.*, 2004). For example, the range in packing fraction for monodisperse spheres is small ($\sim$0·64–0·74; see Fig. 4), but can be much larger for networks of aspherical particles (from 0·3 to 0·4 and up to $>$0·9; Philpotts *et al.*, 1998; Torquato *et al.*, 2000; Donev *et al.*, 2004; Torquato & Stillinger, 2010). Repacking is a well-known and very important process that drives compaction in sediments during early diagenesis (Berner, 1980; Boudreau, 1997). Although it is hard to estimate the exact range in the context of silicic mushes, one might expect that repacking alone can accommodate changes in crystal volume fractions that cover several tens of per cent. The important note here is that repacking is caused by differential stresses acting at the reservoir scale (e.g. recharge, tectonic forces, pore pressurization by exsolution) and that as long as the required stresses are smaller than the threshold for plastic deformation of individual crystals, a significant amount of melt segregation in silicic mushes can take place in the absence of crystal deformation. This repacking, which is synonymous with the 'micro-settling' of Bachmann & Bergantz (2004), can therefore be very cryptic in the rock record, but there may be clues associated with the development of fabric or the loss of melt inferred from petrological methods (McNulty *et al.*, 2000; Holness & Isherwood, 2003; Vernon, 2004; Holness *et al.*, 2007; Zak *et al.*, 2007; Holness & Sawyer, 2008; Tegner *et al.*, 2009; Deering & Bachmann, 2010; Turnbull *et al.*, 2010; Miller *et al.*, 2011; Payacán *et al.*, 2014; Putirka *et al.*, 2014; Gelman *et al.*, 2014; Lee & Morton, 2015; Webber *et al.*, 2015; Barnes *et al.*, 2016; Fiedrich *et al.*, 2017).

(2) When considering crystal volume fractions that approach the maximum packing, the mechanical work to repack the matrix more efficiently increases significantly (as crystals lose the ability to rotate and move freely; Fig. 3). At some point, the stresses required to drive repacking can exceed locally the plastic deformation threshold of individual crystals, and subsequent deformation or compaction takes place by crystal deformation. A rough first-order estimate of the stresses required to drive plastic deformation in individual crystals can be retrieved from the experiments of Rybacki & Dresen (2004), although these lack data for more evolved plagioclase and low temperatures $\sim$700–800°C). For a crystal size of 100 μm, flow laws for plagioclase require differential stresses well beyond 10 MPa, even at very low strain rates ($10^{-14}\,s^{-1}$) for magmatic systems. Faster deformation of the crystals would require increasing the required stress differentials even further. In essence, (a) the very large stresses required for significant plastic deformation of individual crystals and (b) the longevity of magma reservoirs at relatively high temperatures (which favors healing of deformation structures; see Karakas *et al.*, 2017*a*; Szymanowski *et al.*, 2017) can both explain why plastic deformation of crystals is generally not conspicuous in thin section (see Vernon, 2004; Vernon & Paterson, 2006; Webber *et al.*, 2015; Fiedrich *et al.*, 2017; Holness *et al.*, 2018). The transition from crystal repacking to crystal deformation is also strongly controlled by the local size and shape distribution of the crystals forming the matrix involved in the compaction process.

In magmas (neglecting the presence of exsolved volatiles), the formation of a rigid crystal framework can

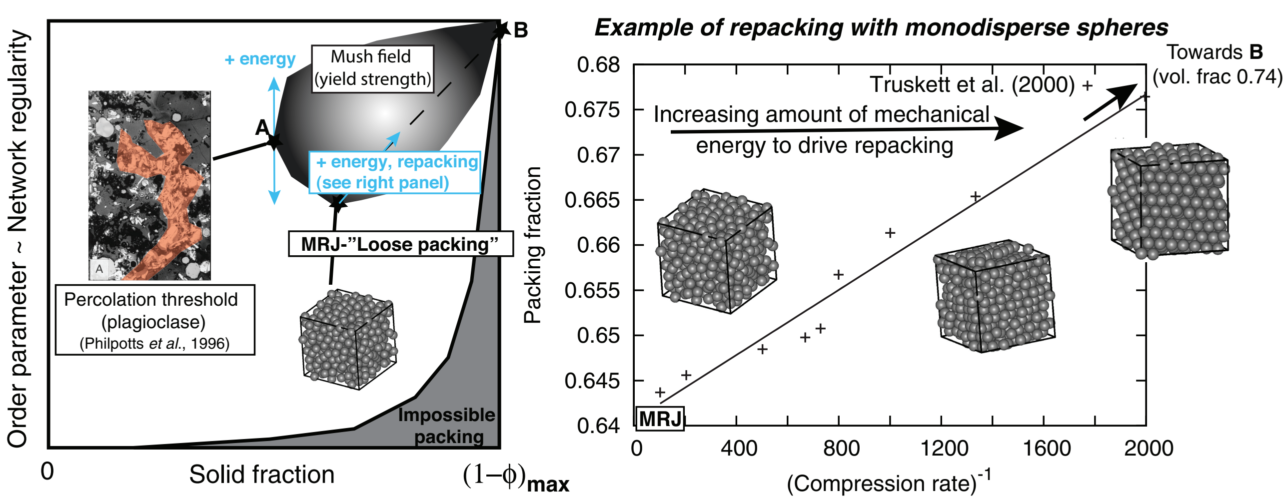

Fig. 4. Repacking of crystalline matrix without crystal deformation. A granular medium can behave rigidly over a wide range of crystal volume fractions, depending on crystal size and shape distributions. According to a random process, the first rigid state that one encounters (packing with the lowest degree of order) is the MRJ (maximally randomly jammed) state; as mechanical work is provided to the matrix, grains can pack with a higher density and order along a trend MRJ–B up to where plastic deformation of crystals becomes more efficient. Data from Philpotts *et al.* (1996), Truskett *et al.* (2000) and Torquato & Stillinger (2010).

take place at relatively low crystal volume fractions, depending on the shape of the crystals and the state of stress of the mixture. The first percolating rigid crystalline frameworks can form at around 30 vol. % of crystals in basaltic magmas (with plagioclase laths) under rest conditions (no forced stress outside gravity; see Philpotts *et al.*, 1996, 1998). Such plagioclase chains would coincide with state A in Fig. 4a; it is a relatively ordered matrix structure (alignment of network-forming crystals) that allows for the lowest rigid packing of crystals. Under finite differential stresses (adding energy to the system; see blue arrows on Fig. 4a), long network chains of crystals that form the first percolating frameworks can be destroyed and only states with higher crystal volume fraction can behave as rigid frameworks. These frameworks are rigid but can nonetheless deform, either at constant volume fraction or most probably forming a denser packing (e.g. MRJ–B trend), where the order and the crystal volume fraction increases. The change in crystal volume fraction along the MRJ–B trend is a proxy for the amount of melt that can be expelled by repacking alone. We expect a transition along the trend from MRJ to B from repacking to compaction that includes plastic deformation of crystals. Interestingly, the actual crystal volume fraction for the states A, MRJ and B are all strongly modulated by the crystal shape and size distributions as discussed above.

Rates of crystal–melt separation are rather difficult to assess for both types of compaction. These rates can be estimated using a parametric approach with matrix flow laws (which do not distinguish between repacking and crystal deformation). The deformation of the matrix is generally modeled through either a linear or a power-law rheology, assuming that material properties (viscosity, permeability) remain isotropic (no fabric development) and neglecting the existence of a yield stress (finite amount of stress required to initiate deformation, as would be expected for crystal deformation or even repacking). Unfortunately, the rheology of the matrix as it undergoes compaction remains one of the most poorly constrained parameters. It is informative, however, to look specifically at the conservation of momentum in the matrix to build an understanding of the various possible stresses that can drive deformation of the matrix

$$\frac{\partial}{\partial x_j}\left[(1-\phi)\sigma_{ij}\right] = -\frac{\mu\phi}{k}(v_i - V_i) + (1-\phi)(\rho_s - \rho_m)g\delta_{i3}$$

where σ is the stress tensor, μ is the dynamic viscosity of the melt, ϕ is the melt fraction or porosity (for two-phase magmas), v_i and V_i are respectively the melt and matrix (solid phase) velocity fields, ρ_s and ρ_m are the solid and melt density, and δ_{i3} is a unit vector along the vertical direction. A useful way to conceptualize this equation is in term of forces driving and resisting the phase separation. The driving force is buoyancy (the last term), whereas the left-hand term acts to decrease spatial variations in stress and melt fraction. If the left-hand term is small compared with the second term (accounting for porous flow of melt), melt can be transported out of the mush with limited mush deformation.

Typical rates of melt extraction for two-phase 'viscous' compacting magma systems (melt + crystals) are up to 0·01–0·05 m a^{-1} [in the vertical direction, using equations derived by McKenzie (1984), assuming high permeabilities at crystal fractions of 0·5–0·6 (Bachmann & Bergantz, 2004)]. These rates are slow, as pointed out more than three decades ago (McKenzie, 1985; Wickham, 1987; Rabinowicz & Vigneresse, 2004). If multiplied by a surface area of 1000 km^2 (a typical area for large calderas, which can therefore be taken to be a typical magma chamber footprint), it will take up to several tens of thousands of years, assuming constant crystallinity conditions, to separate sufficient melt for a VEI 8 eruption. It will take, of course, less time for smaller volumes. Rates of melt extraction considering compaction driven by crystal repacking are likely to be faster, but it is unlikely that those rates will reach values even close to 0·1–1 $km^3\,a^{-1}$, as suggested for some large silicic systems (Flaherty *et al.*, 2018).

Reactive porous flow during compaction (e.g. chemical reaction or phase change by melt migration during compaction) can potentially change the rate of melt extraction, and it is an important factor to consider. Melt extraction through combined reactive transport and compaction has received a lot of attention for the upper mantle (Aharonov *et al.*, 1997; Liang *et al.*, 2010; Weatherley & Katz, 2012), and has been argued to result in dynamic instabilities and the development of structures such as high-porosity channels (e.g. dunite channels; Kelemen *et al.*, 1995) or porosity waves. Reactive porous flow has also been discussed in the context of a crustal setting, but only with one-dimensional simulations (and hence not addressing the possibility of developing melt-rich channels; Solano *et al.*, 2014; Riel *et al.*, 2018). Evidence for melt channels has not yet been identified in silicic upper crustal rocks. Moreover, assuming the melt extracted from a lower crustal or mid-crustal mush is of dacitic to rhyolitic composition, it is not clear that such melt, as it percolates upward, would be sufficiently out of chemical equilibrium with any shallower-seated mush zones to result in channel formation.

Compaction in the presence of a third phase: exsolved fluids

The models discussed above took into account only crystal phases and melt. However, volatiles are commonly abundant in magmatic columns (Candela, 1997; Wallace, 2005; Blundy *et al.*, 2010; Plank *et al.*, 2013), particularly in silicic magmas stored in the upper crust (e.g. Wallace, 2001; Gonnermann & Manga, 2007; Shinohara, 2013; Bachmann & Huber, 2016). As magma crystallizes in shallow reservoirs, volatile elements will accumulate in the residual melt phase, eventually leading to fluid or MVP exsolution (a process called 'second boiling'). Mushy magma reservoirs can also be replenished by recharge from below, bringing additional volatiles to the system. Hence, more realistic mechanical models of phase separation must take into account a low-density and low-viscosity exsolved magmatic volatile phase (MVP) (e.g. Blundy *et al.*, 2010; Mungall, 2015; Boudreau, 2016; Parmigiani *et al.*, 2017).

The influence of a third phase, specifically a more buoyant, compressible and very low viscosity non-wetting fluid has the potential to drastically affect melt–crystal phase separation. Using a newly developed model of three-phase compaction (Fig. 5), we were able to show that the presence of a low-density MVP may not strongly favor melt extraction from its crystalline matrix (Huber & Parmigiani, 2018). Clearly, more work is needed, but preliminary results suggest that in some cases buoyant rise of MVP may even hinder melt extraction (Huber & Parmigiani, 2018).

A postulated effect related to three-phase mush dynamics is gas-driven filter pressing (Anderson *et al.*, 1984; Sisson & Bacon, 1999; Bachmann & Bergantz, 2006; Pistone *et al.*, 2015), a process by which an increase in fluid volume within a mush, caused by either exsolution or fluid migration, leads to the expulsion of an equivalent volume of melt towards an 'accommodation zone' within the reservoir. At the scale of the magma reservoir, gas filter pressing can occur if (see Fig. 6): (1) the volume of the reservoir is increasing; (2) the compressibility of the system accommodates mass addition within the same volume; (3) some mass loss occurs in the reservoir, as a result of either eruption or outgassing.

Two limits are conceivable in such a physical system, as follows.

1. If the surrounding crust hosting the reservoir is rigid, the system behaves isochorically (volume is constant). As the melt and crystals are mostly incompressible, such a situation will lead to bulk reservoir pressurization (e.g. Fowler & Spera, 2010; Tramontano *et al.*, 2017). As the solubility of volatiles is strongly pressure-dependent, exsolution will be limited, and gas filter pressing will probably be inefficient.
2. If the surrounding crust behaves more viscously, it is able to accommodate the space required for the newly exsolved volatiles (volume of reservoir

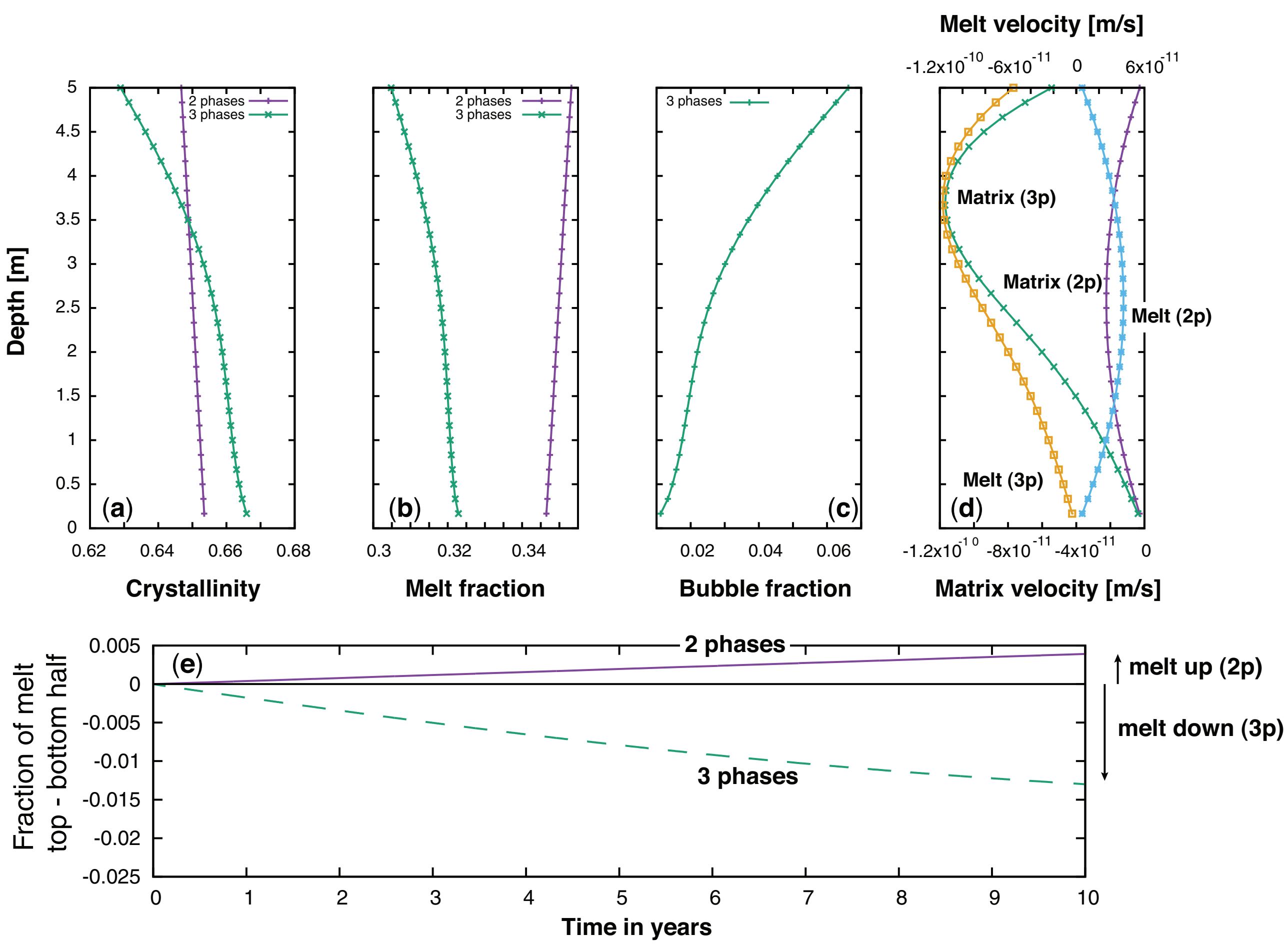

Fig. 5. Example of one-dimensional simulations comparing phase separation (by gravity) between two- and three-phase compaction models. The domain is 5 m thick and initially homogeneous (relative volume of each phase), boundary conditions are no-flux (mass of each phase is conserved). It should be noted that the presence of a buoyant, low-viscosity, volatile phase forces the melt down with the matrix, impeding melt–crystal separation. This is quantified in the last panel, where the relative proportions of melt in the top and bottom halves of the domain are compared (>0 more melt in the top half; <0 more in the bottom half).

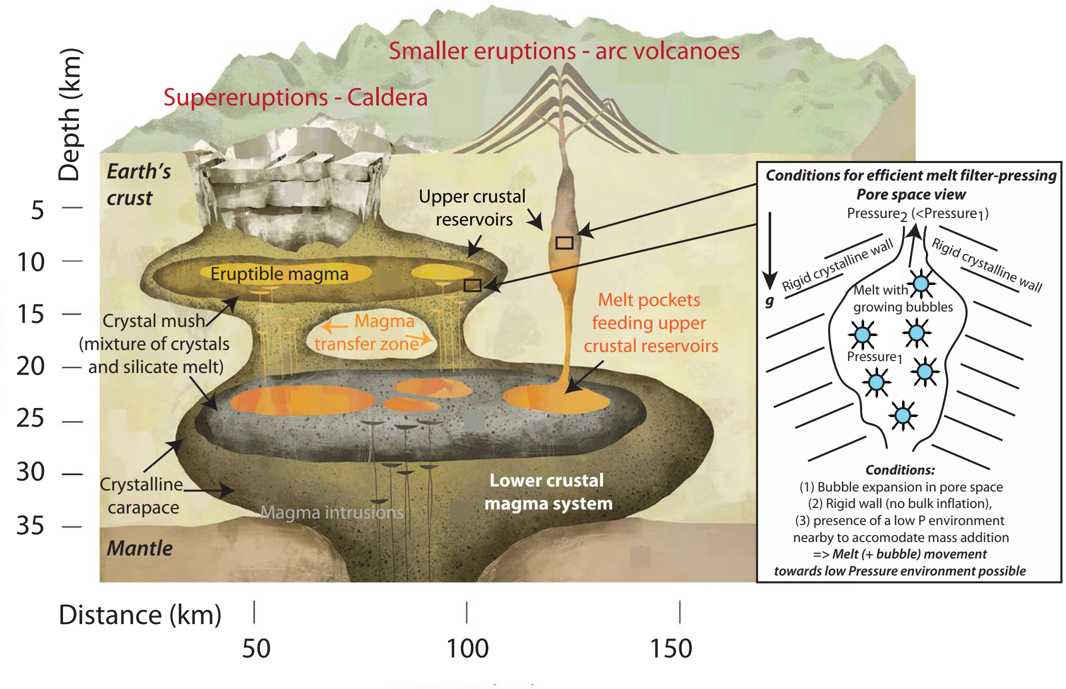

Fig. 6. Schematic diagram showing the conditions necessary for gas filter pressing to occur efficiently in upper crustal mush zones, within the framework of magmatic crustal columns of Bachmann & Huber (2016).

expands), and MVP exsolution and gas filter pressing can potentially proceed. In the most efficient scenario (isobaric conditions permitted by freely deformable wall rocks), and assuming no loss of the MVP phase, a significant amount of melt could be expelled from the mush.

The presence of melt-dominated regions (requiring prior crystal–melt separation), and/or the coupling with phase separation mechanisms (such as hindered settling or compaction) is required to allow melt extraction by gas filter pressing to occur. Melt-rich regions are capable of accumulating MVP (Parmigiani *et al.*, 2016), and are inherently more compressible than higher crystallinity, mushy regions. Hence, melt (and gas) injections from filter-pressed mush below are possible in such pockets, if the gas phase can increase its density.

However, in volatile-rich systems, it is likely that gas filter pressing will be significantly limited, for several reasons.

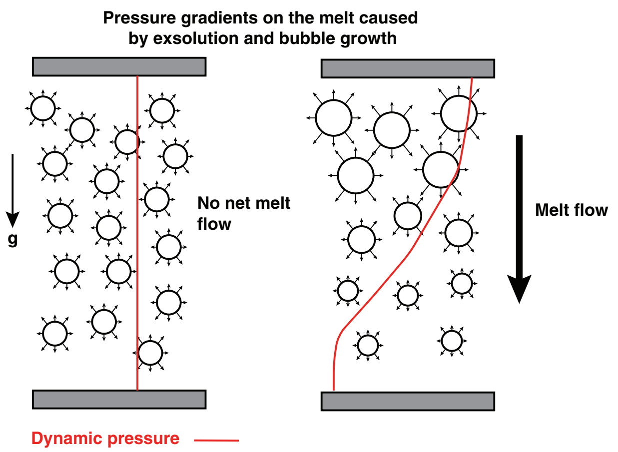

Fig. 7. Schematic diagram representing possible pressure evolution and melt flow during MVP exsolution in a magmatic system.

1. As magma crystallizes, it generates abundant MVP, which will tend to be more voluminous towards the top of the system. Hence, the overpressure caused by exsolution within the pore space is either relatively homogeneous (if the pressure variations within the mush are small) or results in a net downward pore pressure gradient (see Fig. 7).
2. If the quantity of MVP generated is large, gas channels can form in the pore space, allowing rapid outgassing of the reservoir (e.g. Parmigiani *et al.*, 2016). If such degassing pathways exist, then melt displacement (extraction) by further exsolution will not contribute significantly to the extraction of interstitial melt far from the channels.
3. In melt-rich pockets, local overpressurization will probably occur, reducing, or even stopping, the transfer of melt from the mush.

Melt velocities for melt extraction by 'gas-driven filter pressing' calculated by Pistone *et al.* (2015) are of the order of 0·5–10 m a^{-1} ($\sim$1–2 orders of magnitude faster than compaction, and several times faster than hindered settling velocities). Hence, large accumulations of viscous melt could be built in centuries, if such rates are possible. However, the experiments conducted by Pistone *et al.* (2015) are difficult to scale up to magma reservoirs in the Earth's crust, for the following reasons.

1. Expansion of the whole experimental set-up seems to occur, corresponding to the ideal end-member of a fully compliant viscous crust.
2. Cracking occurs within the capsule (probably owing to fast temperature changes).
3. Segregation of melt is not clearly observed.
4. Inflation of the system must be slower than crystallization and gas exsolution for filter pressing to occur. However, those processes are linked, as inflation is actually largely driven by crystallization and gas exsolution. As the kinetics of crystallization and the rate of exsolution are bound to be slow in magma reservoirs, sustaining high separation velocity over decades is not probably feasible in large-scale natural systems.

In summary, according to our present knowledge of the processes that contribute to phase separation, we have failed to find a process that would speed up melt extraction to produce large melt lenses (10–1000 km^3) of the size required for large volcanic eruptions in the order of years to decades. Extraction for such lenses must be a relatively slow process, although it is sufficiently fast to occur before complete solidification of those mushes, even in the cold upper crust. This requires that cooling must be slowed down in some ways, probably by keeping such melt-rich lenses within large long-lived mush zones with massive thermal inertia (Huber *et al.*, 2009; Morse, 2011).

CONCLUSIONS AND PERSPECTIVES

Viscous silicic melt can accumulate in upper crustal reservoirs in large volumes (>100–500 km^3), and must be able to separate from its crystalline matrix on a timescale faster than is required for cooling. There are no obvious physical mechanisms to extract silicic melt rapidly (>0·1–0·01 km^3 of melt per year) from their crystalline matrix. Geochronological data or geospeedometric results that suggest monthly to decadal timescales in large magmatic systems are probably not recording crystal–melt segregation, but other more transient processes, such as post-recharge crystallization shortly prior to eruption. We propose that large melt accumulations must take millennia to form, in agreement with the prolonged survivability of upper crustal magma chambers above the solidus in mature magmatic provinces (>100s kyr; see recent thermal modeling and geochronological results; Karakas *et al.*, 2017*a*; Szymanowski *et al.*, 2017). In contrast to magma source regions in the mantle, intermediate to silicic mushes in the crust can be kept at relatively high melt fractions (~0·2–0·5) for significant amounts of time (potentially >100 000 years for long-lived, mature systems; Huber *et al.*, 2009; Karakas *et al.*, 2017*b*; Szymanowski *et al.*, 2017). Hence, repacking of the crystals (in the absence of intra-crystalline deformation) is likely to be the most efficient way of inducing this phase separation (see Fig. 8). Such repacking is unlikely to leave obvious traces in the plutonic record and its detection will require careful textural examination.

We argue that future research on this topic should focus on better characterizing the physical processes controlling phase separation at intermediate to high crystallinity. In particular, designing experiments in the

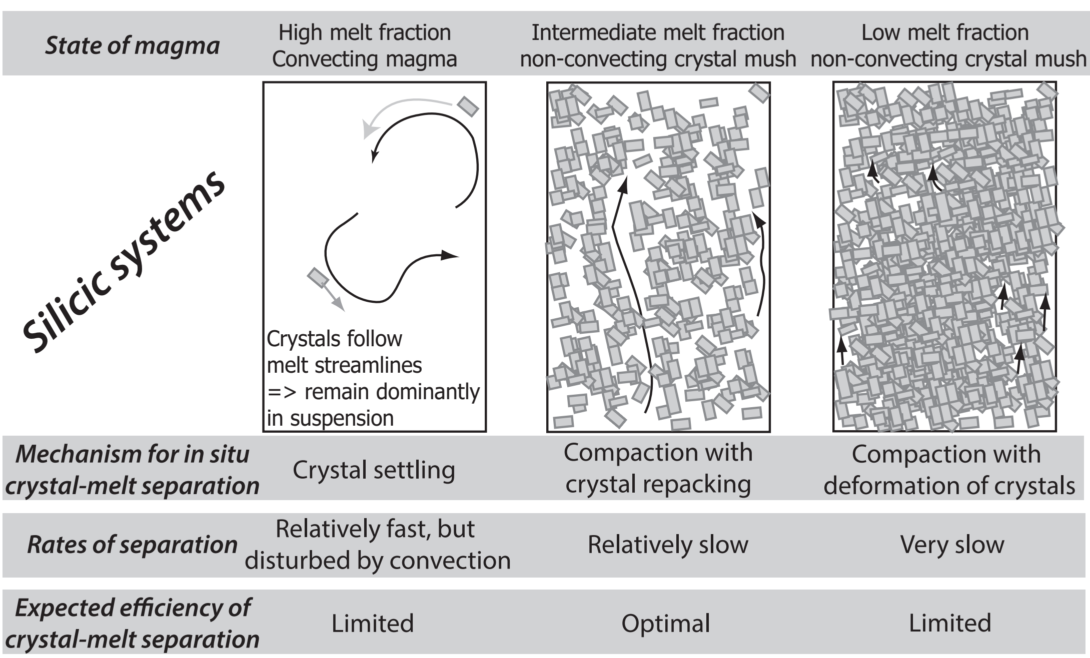

Fig. 8. Summary of mechanisms involved in the separation of melt and crystal in magmatic systems, and their expected efficiency. Modified from Dufek & Bachmann (2010).

laboratory to better assess the importance and rates of crystal repacking, controlling the rheological properties of multiphase mixtures, will be critical. In addition, conducting high-resolution imaging of mush fragments (e.g. Dobson *et al.*, 2016) and conducting numerical simulations at the pore scale (Huber *et al.*, 2008; Llewellin, 2010; Parmigiani *et al.*, 2011) should prove useful in better integrating small-scale processes with the large-scale events that participate in crustal construction, volcanic eruptions, and formation of ore deposits.

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SUPPLEMENTARY DATA

Supplementary data for this paper are available at *Journal of Petrology* online.

REFERENCES

Ackerson, M. R., Mysen, B. O., Tailby, N. D. & Watson, E. B. (2018). Low-temperature crystallization of granites and the implications for crustal magmatism. *Nature* **559**, 94–97.

Aharonov, E., Spiegelman, M. & Kelemen, P. (1997). Three-dimensional flow and reaction in porous media: implications for the Earth's mantle and sedimentary basins. *Journal of Geophysical Research: Solid Earth* **102**, 14821–14833.

Allan, A. S. R., Morgan, D. J., Wilson, C. J. N. & Millet, M.-A. (2013). From mush to eruption in centuries: assembly of the super-sized Oruanui magma body. *Contributions to Mineralogy and Petrology* **166**, 143–164.

Anderson, A. T., Swihart, G. H., Artioli, G. & Geiger, C. A. (1984). Segregation vesicles, gas filter-pressing, and igneous differentiation. *Journal of Geology* **92**, 55–72.

Aravena, A., Gutiérrez, F. J., Parada, M. A., Payacán, Í., Bachmann, O. & Poblete, F. (2017). Compositional zonation of the shallow La Gloria pluton (Central Chile) by late-stage extraction/redistribution of residual melts by channelization: Numerical modeling. *Lithos* **284–285**, 578–587.

Bachl, C. A., Miller, C. F., Miller, J. S. & Faulds, J. E. (2001). Construction of a pluton: evidence from an exposed cross-section of the Searchlight pluton, Eldorado Mountains, Nevada. *Geological Society of America Bulletin* **113**, 1213–1228.

Bachmann, O. & Bergantz, G. W. (2004). On the origin of crystal-poor rhyolites: extracted from batholithic crystal mushes. *Journal of Petrology* **45**, 1565–1582.

Bachmann, O. & Bergantz, G. W. (2006). Gas percolation in upper-crustal silicic crystal mushes as a mechanism for upward heat advection and rejuvenation of near-solidus magma bodies. *Journal of Volcanology and Geothermal Research* **149**, 85–102.

Bachmann, O. & Huber, C. (2016). Silicic magma reservoirs in the Earth's crust. *American Mineralogist* **101**, 2377–2404.

Bacon, C. R., Sisson, T. W. & Mazdab, F. K. (2009). Young cumulate complex beneath Veniaminof caldera, Aleutian arc, dated by zircon in erupted plutonic blocks. *Geology* **35**, 491–494.

Bain, A. A., Jellinek, A. M. & Wiebe, R. A. (2013). Quantitative field constraints on the dynamics of silicic magma chamber rejuvenation and overturn. *Contributions to Mineralogy and Petrology* **165**, 1275–1294.

Barboni, M. & Schoene, B. (2014). Short eruption window revealed by absolute crystal growth rates in a granitic magma. *Nature Geoscience* **7**, 524.

Barker, S. J., Wilson, C. J. N., Morgan, D. J. & Rowland, J. V. (2016). Rapid priming, accumulation, and recharge of magma driving recent eruptions at a hyperactive caldera volcano. *Geology* **44**, 323–326.

Barnes, C. G., Burton, B. R., Burling, T. C., Wright, J. E. & Karlsson, H. R. (2001). Petrology and geochemistry of the late Eocene Harrison Pass pluton, Ruby Mountains core complex, Northeastern Nevada. *Journal of Petrology* **42**, 901–929.

Barnes, C. G., Coint, N. & Yoshinobu, A. (2016). Crystal accumulation in a tilted arc batholith. *American Mineralogist* **101**, 1719–1734.

Bergantz, G. W. & Ni, J. (1999). A numerical study of sedimentation by dripping instabilities in viscous fluids. *International Journal of Multiphase Flow* **25**, 307–320.

Bergantz, G. W., Schleicher, J. M. & Burgisser, A. (2015). Open-system dynamics and mixing in magma mushes. *Nature Geoscience* **8**, 793–796.

Berner, R. (1980). *Early Diagenesis, A Theoretical Approach. Princeton Series in Geochemistry*. Princeton, NJ: Princeton University Press.

Blundy, J., Cashman, K. V., Rust, A. & Witham, F. (2010). A case for CO_2-rich arc magmas. *Earth and Planetary Science Letters* **290**, 289–301.

Boudreau, B. P. (1997). *Diagenetic Models and Their Implementation: Modelling Transport and Reactions in Aquatic Sediments*. Berlin: Springer.

Boudreau, A. (2016). Bubble migration in a compacting crystal--liquid mush. *Contributions to Mineralogy and Petrology* **171**, 1–17.

Boudreau, A. & Philpotts, A. R. (2002). Quantitative modeling of compaction in the Holyoke flood basalt, Hartford Basin, Connecticut. *Contributions to Mineralogy and Petrology* **144**, 176–184.

Brown, M. (2013). Granite: from genesis to emplacement. *Geological Society of America Bulletin* **125**, 1079–1113.

Buck, W. R., Einarsson, P. & Brandsdóttir, B. (2006). Tectonic stress and magma chamber size as controls on dike propagation: constraints from the 1975–1984 Krafla rifting episode. *Journal of Geophysical Research: Solid Earth* **111**, B12404.

Candela, P. A. (1997). A review of shallow, ore-related granites: textures, volatiles, and ore metals. *Journal of Petrology* **38**, 1619–1633.

Cashman, K. V., Sparks, R. S. J. & Blundy, J. D. (2017). Vertically extensive and unstable magmatic systems: a unified view of igneous processes. *Science* **355**, eaag3055.

Christiansen, R. L. (2001). *The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana*. US Geological Survey, Professional Papers 729-G, 145 pp.

Coint, N., Barnes, C. G., Yoshinobu, A. S., Chamberlain, K. R. & Barnes, M. A. (2013). Batch-wise assembly and zoning of a tilted calc-alkaline batholith: field relations, timing, and compositional variation. *Geosphere* **9**, 1729–1746.

Costa, A., Blake, S. & Self, S. (2006). Segregation processes in vesiculating crystallizing magmas. *Journal of Volcanology and Geothermal Research* **153**, 287–300.

Davis, M., Koenders, M. A. & Petford, N. (2007). Vibro-agitation of chambered magma. *Journal of Volcanology and Geothermal Research* **167**, 24–36.

Davis, R. H. & Acrivos, A. (1985). Sedimentation of noncolloidal particles at low Reynolds numbers. *Annual Review of Fluid Mechanics* **17**, 91–118.

Deering, C. D. & Bachmann, O. (2010). Trace element indicators of crystal accumulation in silicic igneous rocks. *Earth and Planetary Science Letters* **297**, 324–331.

Dobson, K. J., Coban, S. B., McDonald, S. A., Walsh, J. N., Atwood, R. C. & Withers, P. J. (2016). 4-D imaging of sub-second dynamics in pore-scale processes using real-time synchrotron X-ray tomography. *Solid Earth* **7**, 1059–1073.

Donev, A., Cisse, I., Sachs, D., Variano, E. A., Stillinger, F. H., Connelly, R., Torquato, S. & Chaikin, P. M. (2004). Improving the density of jammed disordered packings using ellipsoids. *Science* **303**, 990.

Druitt, T. H. & Bacon, C. R. (1989). Petrology of the zoned calc-alkaline magma chamber of Mount Mazama, Crater Lake, Oregon. *Contributions to Mineralogy and Petrology* **101**, 245–259.

Druitt, T. H., Costa, F., Deloule, E., Dungan, M. & Scaillet, B. (2012). Decadal to monthly timescales of magma transfer and reservoir growth at a caldera volcano. *Nature* **482**, 77–80.

Ducea, M. N., Bergantz, G. W., Crowley, J. L. & Otamendi, J. (2017). Ultrafast magmatic buildup and diversification to produce continental crust during subduction. *Geology* **45**, 235–238.

Dufek, J. & Bachmann, O. (2010). Quantum magmatism: magmatic compositional gaps generated by melt–crystal dynamics. *Geology* **38**, 687–690.

Dufek, J. & Bergantz, G. W. (2005). Lower crustal magma genesis and preservation: a stochastic framework for the evaluation of basalt–crust interaction. *Journal of Petrology* **46**, 2167–2195.

Faroughi, S. A. & Huber, C. (2015). Unifying the relative hindered velocity in suspensions and emulsions of nondeformable particles. *Geophysical Research Letters* **42**, 2014 GL062570.

Fiedrich, A., Bachmann, O., Ulmer, P., Deering, C., Kunze, K. & Leuthold, J. (2017). Mineralogical, geochemical, and textural indicators of crystal accumulation in the Adamello Batholith (Northern Italy). *American Mineralogist* **102**, 2467–2483.

Flaherty, T., Druitt, T. H., Tuffen, H., Higgins, M. D., Costa, F. & Cadoux, A. (2018). Multiple timescale constraints for high-flux magma chamber assembly prior to the Late Bronze Age eruption of Santorini (Greece). *Contributions to Mineralogy and Petrology* **173**, 75.

Fowler, S. J. & Spera, F. J. (2010). A metamodel for crustal magmatism: phase equilibria of giant ignimbrites. *Journal of Petrology* **51**, 1783–1830.

Gelman, S. E., Deering, C. D., Bachmann, O., Huber, C. & Gutierrez, F. J. (2014). Identifying the crystal graveyards remaining after large silicic eruptions. *Earth and Planetary Science Letters*, **403**, 299–306.

Gonnermann, H. M. & Manga, M. (2007). The fluid mechanics inside a volcano. *Annual Review of Fluid Mechanics* **39**, 321–356.

Greene, A. R., Debari, S. M., Kelemen, P. B., Blusztajn, J. & Clift, P. D. (2006). A detailed geochemical study of island arc crust: the Talkeetna Arc section, south–central Alaska. *Journal of Petrology* **47**, 1051–1093.

Gualda, G. A. R., Pamukcu, A. S., Ghiorso, M. S., Anderson, A. T., Jr, Sutton, S. R. & Rivers, M. L. (2012). Timescales of quartz crystallization and the longevity of the Bishop Giant Magma Body. *PLoS One* **7**, e37492.

Gutierrez, F., Payacan, I., Gelman, S. E., Bachmann, O. & Parada, M. A. (2013). Late-stage magma flow in a shallow felsic reservoir: merging the anisotropy of magnetic susceptibility record with numerical simulations in La Gloria Pluton, central Chile. *Journal of Geophysical Research: Solid Earth* **118**, 1984–1998.

Hacker, B. R., Mehl, L., Kelemen, P. B., Rioux, M., Behn, M. D. & Luffi, P. (2008). Reconstruction of the Talkeetna intraoceanic arc of Alaska through thermobarometry. *Journal of Geophysical Research* **113**, B03204.

Hartung, E., Caricchi, L., Floess, D., Wallis, S., Harayama, S., Kouzmanov, K. & Chiaradia, M. (2017). Evidence for residual melt extraction in the Takidani Pluton, Central Japan. *Journal of Petrology* **58**, 763–788.

Hildreth, W. (1981). Gradients in silicic magma chambers: implications for lithospheric magmatism. *Journal of Geophysical Research: Solid Earth* **86**, 10153–10192.

Hildreth, W. (2017). Fluid-driven uplift at Long Valley Caldera, California: geologic perspectives. *Journal of Volcanology and Geothermal Research* **341**, 269–286.

Holness, M. B. (2018). Melt segregation from silicic crystal mushes: a critical appraisal of possible mechanisms and their microstructural record. *Contributions to Mineralogy and Petrology* **173**, 48.

Holness, M. B. & Isherwood, C. E. (2003). The aureole of the Rum Tertiary Igneous Complex, Scotland. *Journal of the Geological Society, London* **160**, 15–27.

Holness, M. B. & Sawyer, E. W. (2008). On the pseudomorphing of melt-filled pores during the crystallization of migmatites. *Journal of Petrology* **49**, 1343–1363.

Holness, M. B., Anderson, A. T., Martin, V. M., Maclennan, J., Passmore, E. & Schwindinger, K. (2007). Textures in partially solidified crystalline nodules: a window into the pore structure of slowly cooled mafic intrusions. *Journal of Petrology* **48**, 1243–1264.

Holness, M. B., Vukmanovic, Z. & Mariani, E. (2017). Assessing the role of compaction in the formation of adcumulates: a microstructural perspective. *Journal of Petrology* **58**, 643–673.

Holness, M. B., Clemens, J. D. & Vernon, R. H. (2018). How deceptive are microstructures in granitic rocks? Answers from integrated physical theory, phase equilibrium, and direct observations. *Contributions to Mineralogy and Petrology* **173**, 62.

Holohan, E. P., Troll, V. R., Walter, T. R., Münn, S., McDonnell, S. & Shipton, Z. K. (2005). Elliptical calderas in active tectonic settings: an experimental approach. *Journal of Volcanology and Geothermal Research* **144**, 119–136.

Huber, C. & Parmigiani, A. (2018). A physical model for three phase compaction in silicic magma reservoirs. *Journal of Geophysical Research* **123**, doi:10.1002/2017JB015224.

Huber, C., Parmigiani, A., Chopard, B., Manga, M. & Bachmann, O. (2008). Lattice Boltzmann model for melting with natural convection. *International Journal of Heat and Fluid Flow* **29**, 1469–1480.

Huber, C., Bachmann, O. & Manga, M. (2009). Homogenization processes in silicic magma chambers by stirring and mushification (latent heat buffering). *Earth and Planetary Science Letters* **283**, 38–47.

Huber, C., Bachmann, O. & Dufek, J. (2011). Thermo-mechanical reactivation of locked crystal mushes: Melting-induced internal fracturing and assimilation processes in magmas. *Earth and Planetary Science Letters* **304**, 443–454.

Huber, C., Bachmann, O. & Dufek, J. (2012). Crystal-poor versus crystal-rich ignimbrites: a competition between stirring and reactivation. *Geology* **40**, 115–118.

Hughes, G. R. & Mahood, G. A. (2008). Tectonic controls on the nature of large silicic calderas in volcanic arcs. *Geology* **36**, 627–630.

Jagoutz, O. (2010). Construction of the granitoid crust of an island arc. Part II: a quantitative petrogenetic model. *Contributions to Mineralogy and Petrology* **160**, 359–381.

Jagoutz, O. & Schmidt, M. W. (2012). The formation and bulk composition of modern juvenile continental crust: the Kohistan arc. *Chemical Geology* **298–299**, 79–96.

Jagoutz, O. E., Burg, J. P., Hussain, S., Dawood, H., Pettke, T., Iizuka, T. & Maruyama, S. (2009). Construction of the granitoid crust of an island arc part I: geochronological and geochemical constraints from the plutonic Kohistan (NW Pakistan). *Contributions to Mineralogy and Petrology* **158**, 739.

Johannes, W. & Holtz, F. (1996). *Petrogenesis and Experimental Petrology of Granitic Rocks*. Berlin: Springer.

Karakas, O., Degruyter, W., Bachmann, O. & Dufek, J. (2017a). Lifetime and size of shallow magma bodies controlled by crustal-scale magmatism. *Nature Geoscience* **10**, 446–450.

Karakas, O., Dufek, J., Mangan, M. T., Wright, H. M. & Bachmann, O. (2017b). Thermal and petrologic constraints on lower crustal melt accumulation under the Salton Sea Geothermal Field. *Earth and Planetary Science Letters* **467**, 10–17.

Karlstrom, L., Dufek, J. & Manga, M. (2009). Organization of volcanic plumbing through magmatic lensing by magma chambers and volcanic loads. *Journal of Geophysical Research* **114**, B10204.

Katz, R. F., Spiegelman, M. & Holtzman, B. (2006). The dynamics of melt and shear localization in partially molten aggregates. *Nature* **442**, 676–679.

Kelemen, P. B., Shimizu, N. & Salters, V. J. M. (1995). Extraction of mid-ocean-ridge basalt from the upwelling mantle by focused flow of melt in dunite channels. *Nature* **375**, 747.

Kohlstedt, D. L. & Holtzman, B. K. (2009). Shearing melt out of the Earth: an experimentalist's perspective on the influence of deformation on melt extraction. *Annual Review of Earth and Planetary Sciences* **37**, 561–593.

Koyaguchi, T. & Kaneko, K. (1999). A two-stage thermal evolution model of magmas in continental crust. *Journal of Petrology* **40**, 241–254.

Koyaguchi, T., Hallworth, M. A., Huppert, H. E. & Sparks, R. S. J. (1990). Sedimentation of particles from a convecting fluid. *Nature* **343**, 447–450.

Lee, C.-T. A. & Morton, D. M. (2015). High silica granites: terminal porosity and crystal settling in shallow magma chambers. *Earth and Planetary Science Letters* **409**, 23–31.

Lee, C.-T. A., Morton, D. M., Farner, M. J. & Moitra, P. (2015). Field and model constraints on silicic melt segregation by compaction/hindered settling: The role of water and its effect on latent heat release. *American Mineralogist* **100**, 1762–1777.

Liang, Y., Schiemenz, A., Hesse, M. A., Parmentier, E. M. & Hesthaven, J. S. (2010). High--porosity channels for melt migration in the mantle: Top is the dunite and bottom is the harzburgite and lherzolite. *Geophysical Research Letters* **37**, L15306.

Lipman, P. W. & Bachmann, O. (2015). Ignimbrites to batholiths: integrating perspectives from geological, geophysical, and geochronological data. *Geosphere* **11**, 705–743.

Llewellin, E. W. (2010). LBflow: an extensible lattice Boltzmann framework for the simulation of geophysical flows. Part I: theory and implementation. *Computers and Geosciences* **36**, 115–122.

Luttrell, K. M., Tong, X., Sandwell, D. T., Brooks, B. A. & Bevis, M. G. (2011). Estimates of stress drop and crustal tectonic stress from the 27 February 2010 Maule, Chile, earthquake; *Implications for fault strength: Journal of Geophysical Research: Solid Earth* **116**, B11401.

Manga, M. & Brodsky, E. (2006). Seismic triggering of eruptions in the far field: volcanoes and geysers. *Annual Review of Earth and Planetary Sciences* **34**, 263–291.

Marsh, B. D. (1981). On the crystallinity, probability of occurrence, and rheology of lava and magma. *Contributions to Mineralogy and Petrology* **78**, 85–98.

Martin, D., Griffiths, R. W. & Campbell, I. H. (1987). Compositional and thermal convection in magma chambers. *Contributions to Mineralogy and Petrology* **96**, 465–475.

McKenzie, D. (1984). The generation and compaction of partially molten rock. *Journal of Petrology* **25**, 713–765.

McKenzie, D. P. (1985). The extraction of magma from the crust and mantle. *Earth and Planetary Science Letters* **74**, 81–91.

McNulty, B. A., Tobisch, O. T., Cruden, A. R. & Gilder, S. (2000). Multi-stage emplacement of the Mount Givens pluton, central Sierra Nevada batholith, California. *Geological Society of America Bulletin* **112**, 119–135.

Memeti, V., Paterson, S., Matzel, J., Mundil, R. & Okaya, D. (2010). Magmatic lobes as 'snapshots' of magma chamber growth and evolution in large, composite batholiths: an example from the Tuolumne intrusion, Sierra Nevada, California. *Geological Society of America Bulletin* **122**, 1912–1931.

Miller, C. F. & Miller, J. S. (2002). Contrasting stratified plutons exposed in tilt blocks, Eldorado Mountains, Colorado River Rift, NV, USA. *Lithos* **61**, 209–224.

Miller, C. F., Watson, E. B. & Harrison, T. M. (1988). Perspectives on the source, segregation and transport of granitoid magmas. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 135–156.

Miller, C. F., Furbish, D. J., Walker, B. A., Claiborne, L. L., Koteas, G. C., Bleick, H. A. & Miller, J. S. (2011). Growth of plutons by incremental emplacement of sheets in crystal-rich host: evidence from Miocene intrusions of the Colorado River region, Nevada, USA. *Tectonophysics* **500**, 65–77.

Miller, R. B., Paterson, S. R. & Matzel, J. P. (2009). Plutonism at different crustal levels: insights from the ~5–40 km (paleodepth) North Cascades crustal section, Washington. In: Miller, R. B. & Snoke, A. W. (eds) Crustal Cross-sections from Western North American Cordillera and Elsewhere: Implications for Tectonic and Petrologic Processes. *Geological Society of America, Special Papers* **456**, 1–26.

Morse, S. A. (2011). The fractional latent heat of crystallizing magmas. *American Mineralogist* **96**, 682–689.

Mungall, J. E. (2015). Physical controls of nucleation, growth and migration of vapor bubbles in partially molten cumulates. In: Charlier, B., Namur, O., Latypov, R.& Tegner, C. (eds) *Layered Intrusions*. Dordrecht: Springer, pp. 331–377.

Nakamura, K., Jacob, K. H. & Davies, J. N. (1977). Volcanoes as possible indicators of tectonic stress orientation—Aleutians and Alaska. *Pure and Applied Geophysics, Pageoph* **115**, 87–112.

Nield, D. A. & Bejan, A. (2013). *Convection in Porous Media*. Berlin: Springer.

Otamendi, J. E., Vujovich, G. I., de la Rosa, J. D., Tibaldi, A. M., Castro, A., Martino, R. D. & Pinotti, L. P. (2009). Geology and petrology of a deep crustal zone from the Famatinian paleo-arc, Sierras de Valle Fèrtil and La Huerta, San Juan, Argentina. *Journal of South American Earth Sciences* **27**, 258–279.

Otamendi, J. E., Ducea, M. N. & Bergantz, G. W. (2012). Geological, petrological and geochemical evidence for progressive construction of an arc crustal section, Sierra de Valle Fertil, Famatinian Arc, Argentina. *Journal of Petrology* **53**, 761–800.

Parmigiani, A., Huber, C., Bachmann, O. & Chopard, B. (2011). Pore-scale mass and reactant transport in multiphase porous media flows. *Journal of Fluid Mechanics* **686**, 40–76.

Parmigiani, A., Huber, C. & Bachmann, O. (2014). Mush microphysics and the reactivation of crystal-rich magma reservoirs. *Journal of Geophysical Research: Solid Earth* **119**, 6308–6322.

Parmigiani, A., Faroughi, S., Huber, C., Bachmann, O. & Su, Y. (2016). Bubble accumulation and its role in the evolution of magma reservoirs in the upper crust. *Nature* **532**, 492–495.

Parmigiani, A., Degruyter, W., Leclaire, S., Huber, C. & Bachmann, O. (2017). The mechanics of shallow magma reservoir outgassing. *Geochemistry, Geophysics, Geosystems* **18**, 2887–2905.

Paterson, S. R., Okaya, D., Memeti, V., Economos, R. & Miller, R. B. (2011). Magma addition and flux calculations of incrementally constructed magma chambers in continental margin arcs: combined field, geochronologic, and thermal modeling studies. *Geosphere* **7**, 1439–1468.

Payacán, I., Gutiérrez, F., Gelman, S. E., Bachmann, O. & Parada, M. Á. (2014). Comparing magnetic and magmatic fabrics to constrain the magma flow record in La Gloria pluton, central Chile. *Journal of Structural Geology* **69**, 32–46.

Petford, N., Cruden, A. R., McCaffrey, K. J. W. & Vigneresse, J.-L. (2000). Granite magma formation, transport and emplacement in the Earth's crust. *Nature* **408**, 669–673.

Philpotts, A. R. & Ague, J. J. (2009). *Principles of Igneous and Metamorphic Petrology*. Cambridge: Cambridge University Press.

Philpotts, A. R., Carroll, M. & Hill, J. M. (1996). Crystal-mush compaction and the origin of pegmatitic segregation sheets in a thick flood-basalt flow in the Mesozoic Hartford basin, Connecticut. *Journal of Petrology* **37**, 811–836.

Philpotts, A. R., Shi, J. & Brustman, C. (1998). Role of plagioclase crystal chains in the differentiation of partly crystallized basaltic magma. *Nature* **395**, 343–346.

Pistone, M., Caricchi, L., Ulmer, P., Burlini, L., Ardia, P., Reusser, E., Marone, F. & Arbaret, L. (2012). Deformation experiments of bubble- and crystal-bearing magmas: rheological and microstructural analysis. *Journal of Geophysical Research: Solid Earth* **117**, B05208.

Pistone, M., Arzilli, F., Dobson, K. J., Cordonnier, B., Reusser, E., Ulmer, P., Marone, F., Whittington, A. G., Mancini, L., Fife, J. L. & Blundy, J. D. (2015). Gas-driven filter pressing in magmas: Insights into *in-situ* melt segregation from crystal mushes. *Geology* **3**, 699–702.

Pistone, R., Blundy, J. & Brooker, R. A. (2017). Water transfer during magma mixing events: insights into crystal mush rejuvenation and melt extraction processes. *American Mineralogist* **102**, 766–776.

Plank, T., Kelley, K. A., Zimmer, M. M., Hauri, E. H. & Wallace, P. J. (2013). Why do mafic arc magmas contain $\sim$4 wt% water on average? *Earth and Planetary Science Letters* **364**, 168–179.

Putirka, K. D., Canchola, J., Rash, J., Smith, O., Torrez, G., Paterson, S. R. & Ducea, M. N. (2014). Pluton assembly and the genesis of granitic magmas: insights from the GIC pluton in cross-section, Sierra Nevada Batholith, California. *American Mineralogist* **99**, 1284–1303.

Rabinowicz, M. & Vigneresse, J.-L. (2004). Melt segregation under compaction and shear channeling: application to granitic magma segregation in a continental crust. *Journal of Geophysical Research* **109**, B04407.

Riel, N., Bouilhol, P., Van Hunen, J., Cornet, J., Magni, V., Grigorova, V. & Velic, M. (2018). Interaction between mantle-derived magma and lower arc crust: quantitative reactive melt flow modeling using STyx. In: Ferrero, S., Lanari, P., Goncalves, P. & Grosch, E. G. (eds) *Metamorphic Geology: Microscale to Mountain Belt. Geological Society*, London, Special Publications 478.

Roozbahani, M. M., Borela, R. & Frost, D. J. (2017). Pore size distribution in granular material microstructure. *Materials* **10**.

Rutter, E. H. & Neumann, D. H. K. (1995). Experimental deformation of partially molten Westerly granite under fluid-absent conditions, with implications for the extraction of granitic magmas. *Journal of Geophysical Research: Solid Earth* **100**, 15697–15715.

Rybacki, E. & Dresen, G. (2004). Deformation mechanism maps for feldspar rocks. *Tectonophysics* **382**, 173–187.

Samperton, K. M., Bell, E. A., Barboni, M., Keller, C. B. & Schoene, B. (2017). Zircon age–temperature–compositional spectra in plutonic rocks. *Geology* **45**, 983–986.

Schaen, A. J., Cottle, J. M., Singer, B. S., Keller, C. B., Garibaldi, N. & Schoene, B. (2017). Complementary crystal accumulation and rhyolite melt segregation in a late Miocene Andean pluton. *Geology* **45**, 835–838.

Schoene, B., Schaltegger, U., Brack, P., Latkoczy, C., Stracke, A. & Gunther, D. (2012). Rates of magma differentiation and emplacement in a ballooning pluton recorded by U–Pb TIMS–TEA, Adamello batholith, Italy. *Earth and Planetary Science Letters* **355–356**, 162–173.

Shinohara, H. (2013). Volatile flux from subduction zone volcanoes: insights from a detailed evaluation of the fluxes from volcanoes in Japan. *Journal of Volcanology and Geothermal Research* **268**, 46–63.

Shirley, D. N. (1986). Compaction in igneous cumulates. *Journal of Geology* **94**, 795–809.

Singer, B. S., Costa, F., Herrin, J. S., Hildreth, W. & Fierstein, J. (2016). The timing of compositionally-zoned magma reservoirs and mafic 'priming' weeks before the 1912 Novarupta–Katmai rhyolite eruption. *Earth and Planetary Science Letters* **451**, 125–137.

Sisson, T. W. & Bacon, C. R. (1999). Gas-driven filter pressing in magmas. *Geology* **27**, 613–616.

Solano, J. M. S., Jackson, M. D., Sparks, R. S. J., Blundy, J. D. & Annen, C. (2012). Melt segregation in deep crustal hot zones: a mechanism for chemical differentiation, crustal assimilation and the formation of evolved magmas. *Journal of Petrology* **53**, 1999–2026.

Solano, J. M. S., Jackson, M. D., Sparks, R. S. J. & Blundy, J. (2014). Evolution of major and trace element composition during melt migration through crystalline mush: implications for chemical differentiation in the crust. *American Journal of Science* **314**, 895–939.

Szymanowski, D., Wotzlaw, J.-F., Ellis, B. S., Bachmann, O., Guillong, M. & von Quadt, A. (2017). Protracted near-solidus storage and pre-eruptive rejuvenation of large magma reservoirs. *Nature Geoscience* **10**, 777–782.

Tegner, C., Thy, P., Holness, M. B., Jakobsen, J. K. & Lesher, C. E. (2009). Differentiation and compaction in the Skaergaard intrusion. *Journal of Petrology* **50**, 813–840.

Torquato, S. & Stillinger, F. H. (2010). Jammed hard-particle packings: from Kepler to Bernal and beyond. *Reviews of Modern Physics* **82**, 2633–2672.

Torquato, S., Truskett, T. M. & Debenedetti, P. G. (2000). Is random close packing of spheres well defined? *Physical Review Letters* **84**, 2064–2067.

Tramontano, S., Gualda, G. A. R. & Ghiorso, M. S. (2017). Internal triggering of volcanic eruptions: tracking overpressure regimes for giant magma bodies. *Earth and Planetary Science Letters* **472**, 142–151.

Truskett, T. M., Torquato, S. & Debenedetti, P. G. (2000). Towards a quantification of disorder in materials: Distinguishing equilibrium and glassy sphere packings. *Physical Review E* **62**, 993–1001.

Turnbull, R., Weaver, S., Tulloch, A., Cole, J., Handler, M. & Ireland, T. (2010). Field and geochemical constraints on mafic–felsic interactions, and processes in high-level arc magma chambers: an example from the Halfmoon Pluton, New Zealand. *Journal of Petrology* **51**, 1477–1505.

Vernon, R. H. (2004). *A Practical Guide to Rock Microstructure*. Cambridge: Cambridge University Press.

Vernon, R. H. & Paterson, S. R. (2006). Mesoscopic structures resulting from crystal accumulation and melt movement in granites. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* **97**, 369–381.

Vigneresse, J.-L. (2015). Textures and melt–crystal–gas interactions in granites. *Geoscience Frontiers* **6**, 635–663.

Walker, B. A., Bergantz, G. W., Otamendi, J. E., Ducea, M. N. & Cristofolini, E. A. (2015). A MASH zone revealed: the Mafic Complex of the Sierra Valle Fertil. *Journal of Petrology* **56**, 1863–1896.

Wallace, P. J. (2001). Volcanic SO_2 emissions and the abundance and distribution of exsolved gas in magma bodies. *Journal of Volcanology and Geothermal Research* **108**, 85–106.

Wallace, P. J. (2005). Volatiles in subduction zone magmas: concentrations and fluxes based on melt inclusion and volcanic gas data. *Journal of Volcanology and Geothermal Research* **140**, 217–240.

Weatherley, S. M. & Katz, R. F. (2012). Melting and channelized magmatic flow in chemically heterogeneous, upwelling mantle. *Geochemistry, Geophysics, Geosystems* **13**, Q0AC18.

Webber, J. R., Klepeis, K. A., Webb, L. E., Cembrano, J., Morata, D., Mora-Klepeis, G. & Arancibia, G. (2015). Deformation and magma transport in a crystallizing plutonic complex, Coastal Batholith, central Chile. *Geosphere* **11**, 1401–1426.

Weinberg, R. F. (2006). Melt segregation structures in granitic plutons. *Geology* **34**, 305–308.

Wickham, S. M. (1987). The segregation and emplacement of granitic magmas. *Journal of the Geological Society, London* **144**, 281–297.

Wilson, C. J. N. & Charlier, B. L. A. (2009). Rapid rates of magma generation at contemporaneous magma systems, Taupo Volcano, New Zealand: insights from U–Th model-age spectra in zircons. *Journal of Petrology* **50**, 875–907.

Zak, J., Paterson, S. R. & Memeti, V. (2007). Four magmatic fabrics in the Tuolumne batholith, central Sierra Nevada, California (USA): implications for interpreting fabric patterns in plutons and evolution of magma chambers in the upper crust. *Geological Society of America Bulletin* **119**, 184–201.

Zoback, M. L., Zoback, M. D., Adams, J., et al. (1989). Global patterns of tectonic stress. *Nature* **341**, 291.