Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G36766.1

Gas-driven filter pressing in magmas: Insights into in situ melt segregation from crystal mushes

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ABSTRACT

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Gas-driven filter pressing is the process of melt expulsion from a volatile-saturated crystal mush, induced by the buildup and subsequent release of gas pressure. Filter pressing is inferred to play a major role in magma fractionation at shallow depths (< 10 km) by moving melt and gas relative to the solid, crystalline framework. However, the magmatic conditions at which this process operates remain poorly constrained. We present novel experimental data that illustrate how the crystal content of the mush affects the ability of gas-driven filter pressing. Hydrous haplogranitic (2.1 wt.% water in the melt) and dacitic (4.2 wt.% water in the melt) crystal mushes, exhibiting a wide range of crystallinity (34-80 vol.%), were investigated by in situ, high temperature (500-800 °C) synchrotron X-ray tomographic microscopy with high spatial (3 μm/pixel) and temporal resolution (8 sec. per 3D dataset). Our experimental results show that gas-driven filter pressing operates only below the maximum packing of bubbles and crystals (~74 vol.%). Above this threshold, the mush tends to fracture. Therefore, the efficiency of gas-driven filter pressing is promoted close to the percolation threshold and when the mush inflates slowly relative to build-up of pressure and expulsion of melt. Such observations offer a likely explanation for the production of eruptible, crystal-poor magmas within the Earth's crust.

INTRODUCTION

Magmatic differentiation involves the physical separation of crystals from their viscous coexisting melts. The re~~In shallow magma reservoirs re~~latively slow~~, yet poorly constrained,~~ processes of compaction ~~processes (at~~ high crystallinities ~~(,~~ ≥ 70 vol.% crystals; Jackson et al, 2003), and hindered settling ~~at (~~intermediate crystallinities ~~(,~~ 40-50 vol.% crystals; Bachmann and Bergantz, 2004) that drive this separation in shallow magma reservoirs, can be enhanced by the concentration of volatiles in the melt phase and their subsequent exsolution (Sisson and Bacon, 1999).

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Volatile exsolution at low solidification pressures causes the magma to expand, while the high viscosity of the crystallising magma (> 10^5 Pa·s) impedes the bulk inflation of the system. In this scenario, gradients in crystallinity, vesiculation and pressure therefore drive the melt towards regions of lower crystallinity and pressure. SiO_2-rich melts are saturated with 6-8 wt.% H_2O at the depths of < 10 km (Hui et al., 2009) typical of most silicic magma reservoirs, suggesting that this process may be ubiquitous. This ~~G~~gas-driven filter pressing mechanism~~s~~ may drive segregation of compositionally-variable, crystal-poor melts typically forming heterogeneous large ignimbrite deposits (Lipman et al., 1966). The goal of the present study is to quantify the influence of the crystal fraction (ϕ) on melt permeability in order to define the magmatic conditions where gas-driven filter pressing is an efficient mechanism for melt extraction and generation of eruptible, crystal-poor silicic magmas.

METHODS

To capture simulated gas-driven filter pressing, high temperature (T = 500-800 °C) experiments were conducted on a suite of ~~pre-~~synthesised highly differentiated, volatile- and crystal-poor melts (haplogranites, H5; 2.1 wt.% H_2O in the glass, ϕ = 0.34, 0.47 corundum crystals) and less evolved, volatile- and crystal-rich melts (dacites, F; 4.2 wt.% H_2O in the glass, ϕ = 0.5, 0.6, 0.7, 0.8 quartz crystals); using the high spatial (3 µm/pixel) and temporal resolution (~8 sec. ~~per single~~for each 3D dataset) of synchrotron X-ray tomographic microscopy at the TOMCAT beamline~~,~~ (Swiss Light Source), ~~-~~coupled to a laser-based heating system (Fife et al. 2012). Crystal-free samples of both compositions were ~~also~~ used as benchmark during experiments.

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The starting materials have bubble volume fractions (β) ≤ 0.01 and some heterogeneity in the crystal distribution (mean size of 68 μm); however, neither crystallisation nor melting of crystals occurred during heating (i.e. ϕ was constant throughout). We do not simulate ~~Crystallisation~~crystallisation-driven gas exsolution ~~per se was not simulated in our tests~~; rather the different ϕ bracket~~ed~~ the crystallinities occurring in natural gas-saturated mushes. The limited attenuation contrast between crystals and melt was maximised by edge-enhancement and post-acquisition phase retrieval. Technical details are reported in the Data Repository.

The haplogranites and dacites have the same initial melt viscosity (η_{melt} < 1.3 Pa·s). Preferential bubble nucleation on the crystal phases is not expected in either system, as SiO_2-rich melts are the wetting phase (Laporte, 1994, Hurwitz and Navon, 1994). Although both systems should not crystallise during the experiments, c~~C~~hemical differences between the samples (e.g. SiO_2 content, initial H_2O content) ~~could~~ may affect the physical behaviour of bubble nucleation and growth during T increase to 800 °C. ~~, but w~~We do not assume both systems should have the same physi~~c~~o-chemical behaviour: rather we test which allows gas-driven filter pressing.

Sequential 3D images provided a 4D (3D + time) record of bubble growth and microstructure evolution for each T and ϕ as the samples were heated step-wise (25 °C steps with a heating rate of 2 °C/s) between ~~500~~ 475 °C (below the glass transition) and 800 °C~~. Heating steps were initiated at 475 °C (below the glass transition); isothermal~~, and conditions were maintained for 3.5 minutes ~~before heating~~ at each temperature~~to the next T~~. Real-time visual inspection showed negligible bubble growth by the end of each T step~~. S~~, but samples did not achieve ~~perfect~~ textural equilibrium ~~conditions of vesiculation~~ at ~~a given~~ each T~~;~~. ~~however~~However, gas-

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driven filter pressing is a process driven by rapid crystallisation and vesiculation (Sisson and Bacon, 1999), and therefore operate during textural and thermal dis~~which do not necessarily require~~ equilibrium ~~conditions to occur~~.

Karl-Fischer Titration (KFT; Behrens et al., 1996) ~~method~~ was used to quantify H_2O outgassing ~~from the dacites~~ over the same *T*-time path for samples of the same volume to those used in the X-ray tomographic microscopy experiments.

4D MICROSTRUCTURAL EVOLUTION

Time-integrated textural analysis reveals that gas bubbles nucleate and undergo diffusion-limited grow (~~diffusion-limited growth;~~ Data Repository) homogeneously throughout crystal-free haplogranites and dacites~~, but are found predominantly in melt-rich regions within the crystal-bearing samples.~~. Fractures are only generated during vesiculation. No formation or healing of fractures is observed during cooling after experiments.

~~At the spatial resolution of our experiments no heterogeneous bubble nucleation is observed. It is expected that a film of melt is always present between bubbles and crystals, since SiO_2-rich melts are a wetting phase (Laporte, 1994), and corundum and quartz crystals are inefficient sites for bubble nucleation (Hurwitz and Navon, 1994). Fractures are generated during vesiculation, and no formation or healing of fractures is observed during cooling after experiments.~~

In the haplogranitic samples there is no evidence for gas-driven filter pressing. Bubbles increase their volume with minimal coalescence, and form a polygonal network (Figures 1A-D) similar to that found in natural felsic frothy pumices. Despite significant initial intercrystalline porosity, bubble growth in the crystal bearing samples preferentially occurs in melt-rich regions~~,~~. Within the crystal rich regions bubble distribution is homogenous. Bubble growth ~~sharply~~ reduc~~inges~~ the volume of

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the interstitial melt (local $\beta = 0.9$), and generating peripheral compacted crystal clusters (Figures 1A-D). At $T \geq 550$ °C major conchoidal fractures develop (Figures 1C-D, arrows), with smaller fractures up to 200 μm length connecting inflated gas-rich regions (Figure 1D). Fractures are arranged at high angles (70° to 90°) relative to the vertical sample axis along which sample expansion occurs. The fractures radiate out from the inflating gas-rich, crystal-poor regions, passing through both crystals and residual melt (Figures 1C-D, arrows).

In contrast, the dacitic samples show gas-driven filter pressing. The individual bubbles are generally much larger than those ~~generated~~ in the haplogranitic samples (Figures 1E-H). At all temperatures ~~at~~ $\phi \leq 0.5$, ~~,~~ bubbles form and grow by extensive coalescence~~,~~ (predominantly through melt-film attenuation) and no fracture is observed ~~between expanding bubbles. .~~ At $\phi = 0.6$-0.7, bubbles deform around crystals during growth (Figure 1H), and melt concentrates into narrow (20-80 μm-wide) channels within the crystal framework due to the pressure exerted by gas bubbles (Figure 1H, grey arrows from stretched bubbles). At $T \geq 675$ °C, curved fractures form between large bubbles in the melt phase, and jagged fractures are found in the crystal-rich regions (Figure 1H, white arrows). At $\phi = 0.8$, no significant bubble nucleation and growth was observed at any temperature (see insets in Figure 2).

From these behaviours we ~~Here we~~ define ~~a~~ the "ductile regime": ~~-~~when the sample undergoes inflation during vesiculation, and ~~a~~ the "brittle regime": when the sample fractures during vesiculation (with or without inflation). The mechanical evolution ~~of both regimes during vesiculation~~ can be described as a function of ϕ and β. At $\phi = 0.5$-0.7 (the target crystallinities of this study), with the ductile to brittle

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transition ~~clearly~~ occur~~s~~ring at a residual melt fraction ($\mu = 1 - \phi - \beta$) of about 0.25 (Figure 2).

GAS EXTRACTION EFFICIENCY ~~AND MELT VISCOSITY~~

~~The~~ KFT analysis performed on the dacite samples ~~that showed gas-driven~~ filter pressing, supports the microstructural observations. In this system, ~~The~~ H_2O exsolution~~,~~ and ~~therefore~~ η_{melt} ~~in all samples should be the same~~ is constant for a given ~~at each~~ temperature. Comparison of the extraction ~~profiles and bubble~~ and expansion ~~rates~~ profiles therefore reveal ~~s how differences in bulk viscosity and microstructure effect~~ evolving permeability ~~and the filter pressing process~~. ~~The~~ In the crystal free sample, exsolution of isolate bubbles degasses the melt before the formation of a permeable network (~~shows a rapid increase in bubble volume (25% vol.%) from 575 °C followed shortly~~ (at about 15 vol.%) ~~by the rapid release of the majority of H_2O at 600°C~~ (Figure 3A) ~~in the dacitic samples, suggesting a~~,. ~~as bubble volume increase allows interaction and the formation of a permeable network. At~~ After network formation ~~the temperature of network formation (625-650°C)~~ gas exsolution is nearly complete, and bubble volume increases ~~become~~ appear to be thermally controlled.

~~ccelerated H_2O extraction at higher T and with decreasing ϕ (Figure 3A). H_2O extraction begins between 500 °C (high ϕ) and 625 °C (low ϕ) (Figure 3A).~~ The crystal bearing samples show more variable behaviour. At $\phi = 0.5$~~,~~ a first phase of bubble growth results in the formation of a permeable network and gas release. After a short ~~two pulses of bubble growth (or ~20 vol.%) are observed at 575 °C and 625 °C between which~~ period of no growth, a second phase of bubble expansion ~~occurs~~, but accompanied by constant ~~. The early growth is accompanied by extraction of~~

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~1wt.% H_2O, implying a period of coalescence and permeability development. Throughout the hiatus in growth, the second volume expansion and a second hiatus (650 °C and 675–725°C), gas extraction at a is lower than seen in the first release, and the rate; increases gradually with temperature. This suggestsing that no highly efficient pathway is accessible, and the extraction is diffusion controlled until . Above 725 °C, increases in extraction rate occur as fracture is initiated and propagates. (tapping unconnected over-pressured pores).

At higher ϕ, (0.6, 0.7) falling total extraction efficiency highlights the effect of crystals in reducing the ability of the sample to outgas. The begins to fall. $\phi = 0.6$ sample shows near constant bubble growth (40 vol.%) for the majority of the heating schedule, whereas from 575–675 °C, which spans spanning out-gasssing only occurs at the the only period of measureable extraction (~1 vol.%) at 625 °C and the onset of brittle behaviour. While the The total bubble tomography data show volume expansion is efficient, close to that predicted for the melt volume, supporting the microstructural observation that fracture is a minor component of the permeable network and brittle failure is localised with continued bubble growth elsewhere in the sample. The KFT data suggest that the majority of the remaining exsolved gas (~65%) remains trapped in unconnected porosity. The total bubble volume expansion is close to that predicted for the melt volume, supporting the microstructural observation that fracture is a minor component of the permeable network and brittle failure is localised with continued bubble growth elsewhere in the sample. The At $\phi = 0.7$ overall extraction efficiency remains similar, but sample shows a significant reduction in overall bubble volume growth is now reduced (~20% of that possible in the crystal free sample), and pore over-pressures in the unconnected pores will be higher despite

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~~having a similar extraction profile and overall extraction efficiency and the onset of brittle behaviour at a lower temperature. Assuming a similar distribution to that observed in the tomography data, the limited porosity will have significant over pressure after failure.~~. For ϕ ~~=~~ = 0.8, entirely in the brittle regime, ~~the~~ an absence of ~~lack of~~ both bubble ~~growth~~ growth and gas extraction implies significant pore overpressure with volume expansion prevented by the bulk viscosity of the sample. ~~At ϕ = 0.8, no H_2O extraction is detected across the entire T range (Figure 3A), meaning that the exsolved H_2O must remain trapped in a non-permeable bubble network, and/or be released as low-volume "silent" emission. At high ϕ, low permeability is maintained, whereas bubble coalescence allows gas loss at $\phi \leq 0.5$.~~

~~At ϕ = 0.6–0.7, H_2O extraction occurs across a restricted T range (≤ 75 °C), and after the onset of brittle behaviour H_2O extraction is below the limit of detection (~0.02 wt.%) at all temperatures. The onset of brittle behaviour is accompanied by an increase in the KFT uncertainty, which suggests that fracture enhanced permeability is permitting continuous low-volume "silent" emission of gas (see Data Repository). At ϕ = 0.8, no H_2O extraction is detected across the entire T range (Figure 3A), meaning that the exsolved H_2O must remain trapped in a non-permeable bubble network, and/or be released as low-volume "silent" emission. These two processes may be operating simultaneously.~~

DISCUSSION AND CONCLUSIONS

~~Our *in situ* X-ray tomographic microscopy data reveal that gas-driven filter pressing operates only when bulk sample expansion occurs without fracturing or the development of gas permeable pore networks.~~ The gas-driven filter pressing process appears to be most efficient in crystal mushes ($0.5 \leq \phi \leq 0.7$), a minimum of ~ 3 wt.%

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H_2O (Figure 3B), and ~~over a limited window of crystallinity ($0.6 \leq \phi \leq 0.7$) and~~ when bulk sample expansion occurs without fracturing or the development of gas permeable networks. In addition it appear to require $\mu > 0.25$ (Figure 2), ~~i.e.~~ close to the percolation threshold ($\mu = 0.22$-0.29) or maximum packing fraction ($\phi_{max} = 0.66$-0.74 for monodispersed suspensions) (Saar and Manga, 2002). The haplogranitic (2.1 wt.%) sample achieve brittle failure at $\phi \leq 0.47$ without substantial gas-driven filter pressing.

During these experiments

~~Gas exsolution appears to begin shortly after *Tg*, with the initiation of permeable networks~~

~~At s~~ ~~When $\phi \leq 0.5$, permeability via bubble coalescence prevents gas-driven filter pressing. At $\phi = 0.6$-0.7 we see bubble growth driving filter pressing, until μ is driven below the percolation threshold and exsolution only drives pore pressure increase until brittle failure occurs. A wide range of igneous rocks reveals achievement of the critical packing density of bubbles + crystals ($\phi_{max} \sim 0.65$-0.75 in basalts; Marsh, 1981; $\mu \sim 0.3$ in granites; Wickham, 1987), which provides the last "snapshot" of a jammed system below the minimum volumetric proportion of melt to enable flow.~~

$\eta_{~~melt~~ bulk}$ is controlled by ~~evolves as a function of~~ T, ~~and the residual~~ dissolved H_2O, bubble volume fraction and crystal volume fraction ~~(Giordano et al., 2008), and will strongly control the effectiveness of gas-driven filter pressing. The bulk viscosity of the sample will also depend on the local crystal and bubble volume fractions (Pistone et al., 2012)~~. As H_2O exsolves ~~from the melt~~, η_{melt} increases slowly ~~at~~ while H_2O

Comment [A2]: Are we certain we are not seeing it at 0,5 as well. Trapped bubbles mean some pore pressure, and therefore I would suspect the processes is occurring, just maybe not as efficiently as in the 0.6 sample where the instantaneous increase in trapped gas at ~ 1% extraction causes failure? Is it just much slower at 0.5?

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remains ~~contents~~ > 2 wt.%, and more rapidly ~~but more rapidly at H_2O contents~~ at < 2 wt.% (Giordano et al., 2008), and can be estimated using the KFT and tomography data (Pistone et al., 2012) (Figure 3B), up the point of ~~(Giordano et al., 2008). Where bubbles coalescence is the dominant mechanism ($\phi \leq 0.5$), the increase of η_{melt} due to H_2O loss is more important than its decrease due to higher T (Figure 3B). Indeed, η_{melt} increases more distinctly when the residual H_2O dissolved in the melt is < 2 wt.%. The same η_{melt} is expected to occur at $\phi \geq 0.6$; however, the bulk H_2O (i.e. dissolved H_2O in the melt + exsolved gas bubbles) in the system remains in excess of 2 wt.% due to the incapacity of the system to outgas in presence of a continuous crystal network. After the~~ brittle ~~onset~~failure when the ~~,~~ samples enter into the Mohr-Coulomb regime ~~where η_{melt} is meaningless~~ (Figure 3B). The equation:

~~Due to their initial low H_2O content in the melt (2.1 wt.%), the haplogranitic systems reach failure even at $\phi \leq 0.47$ without experiencing substantial gas-driven filter pressing, although it may be possible that with slower heating rates gas-driven filter pressing can be achieved. Conversely, the H_2O-rich (4.2 wt.%) dacitic systems have η_{melt} that allows gas-driven filter pressing. This suggests that, at equivalent rates of volatile exsolution (i.e. relatively fast T-t paths simulating rapid crystallisation and vesiculation in natural systems) as simulated in our experiments, gas-driven filter pressing might only be effective if the residual melt achieves a sufficiently low η_{melt} to prevent fracturing of the mush during gas exsolution, but nonetheless maintains a sufficiently high η_{melt} to allow for gas pressure build-up and to expel melt from the crystal framework. Based on our results, the minimum H_2O content in the silicic melt that allows gas-driven filter pressing to be effective in crystal mushes ($\phi \geq 0.5$) is ~ 3 wt.% (Figure 3B). In addition, elevated pressure (< 1.5 GPa) leads to a reduction in~~

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~~η_{melt} of about 2 orders of magnitude (e.g. Pistone et al., 2012), which may further promotes the efficiency of gas-driven filter pressing. Overall, hydrous dacitic systems probably represent the optimal conditions of efficient gas-driven filter pressing to promote melt segregation from shallow plutonic mushes (< 10 km).~~

~~To assess gas-driven filter pressing as a mechanism of melt extraction from shallow crystal mushes, the operating window controlled by melt permeability (κ) and crystal mush expansion rates that permit inflation without fracture needs to be constrained. Extraction of silicic melts from a mush depends on κ, which is a function of melt fraction (μ) and crystal size (r) (McKenzie, 1984):~~

$$\kappa = \frac{\mu^3 r^2}{A(1-\mu^2)} \quad (1)$$

can be used to assess the range of melt permeability (κ) and crystal mush expansion rates that permit inflation without fracture, where κ is a function of melt fraction (μ) and crystal size (r) (McKenzie, 1984; Jackson et al., 2003). For the crystal sizes (r = 68 μm) and melt fractions in our experiments with 0.25 <~~where A = 50 for μ > 0.1 and r < 1 mm (Jackson et al., 2003). Excluding systems with ϕ ≤ 0.5 due to large gas permeability, the~~ μ ≤ ~~considered ranges from 0.25 (minimum percolation threshold) to~~ 0.4~~. If r = 68 μm,~~, κ ranges from $2.7 \cdot 10^{-12}$ m^2 ~~at~~ (μ = 0.25) ~~-~~to $7.05 \cdot 10^{-12}$ m^2 ~~at~~ (μ = 0.4)~~. in our experiments.~~ The average velocity of melt percolation (v, positive upward within the mush) can then be estimated using Darcy's law:

$$v = \frac{\kappa}{\eta_{melt}} \times \frac{\nabla P}{\mu} \quad (2)$$

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where ∇P is the gas pressure gradient. To maintain a gas pressure gradient (∇P) at a value necessary sufficient to expel melt, the region of magma undergoing gas exsolution must inflateion must be slower than ly relative to the rates at which it crystallises crystallisation and and exsolves gas exsolution (Sisson and Bacon, 1999). From the bubble sizesFollowing the approach of Anderson et al. (1984), and considering that bubbles of 100-200 μm diameter push driving melt the melt through 20-80 μm wide channels within in the crystal framework mush (Figure 1H) and a with a mean gas expansion (~melt expulsion) rate of 0.07 $\mu m^3/s$ of during our experiments we find (~ 45 minutes), the resulting ∇P is on in the order of 0.1-1 MPa/m (after Anderson et al. 1984). Therefore, in a H_2O- (3 wt.%) and SiO_2-rich η_{melt} ~ 10^3 Pa·s at 800 °C, (including the effect of pressure on η_{melt}; Pistone et al., 2012) in the range $0.25 \leq \mu \leq 0.4$, gas-driven filter pressing could therefore expel melt at v of between 0.03-0.3 m/year at (μ = 0.25) and 0.05-0.5 m/year at (μ = 0.4).

In natural silicic systems the mean size of the dominant phenocrysts (feldspar, hornblende, biotite, quartz) is ~ 3 mm (Bachmann and Bergantz, 2004); so for ∇P =0.1-1 PMa, expulsion velocities of 0.6-6 m/year (μ = 0.25) and 1.1-11 m/year (μ = 0.4) are expected. This implies the segregation of crystal-poor melt bodies hundreds of meters thick can occur within a century, and could act as an efficient method of enhancing segregation compared to the Compared to the longevitiesy of crystal mushes (10^4-10^5 years; Bachmann and Bergantz, 2004), provided gas-driven filter pressing could operate efficiently in shallow felsic mushes with ϕ of 0.6-0.7 (Figure 2) resulting in melt segregation and formation of overlying crystal-poor silicic melt caps. However, gas-driven filter pressing in a mush can only be effective where crystallisation and volatile exsolution occur sufficiently rapidly to establish maintain a

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large enough ∇P without between gas bubble pressure and ambient pressure before the reaching the percolation threshold close-packing of phases (~74 vol.%) impedes melt segregation. Despite the complexity of gas exsolution and crystallisation rates, bubble nucleation and growth kinetics, bulk viscosity changes, and build-up of internal pressure (Costa et al., 2006), the results of this study serves as a general guide for the effectiveness of gas-driven filter pressing in particular situations. Compared to the longevities of crystal mushes (10^4–10^5 years; Bachmann and Bergantz, 2004), gas-driven filter pressing could operate efficiently in shallow felsic mushes with ϕ of 0.6–0.7 (Figure 2) resulting in melt segregation and formation of overlying crystal-poor silicic melt caps. However, gas-driven filter pressing in a mush can only be effective where crystallisation and volatile exsolution occur sufficiently rapidly to establish a large enough ∇P between gas bubble pressure and ambient pressure before the close-packing of phases (~74 vol.%) impedes melt segregation.

In natural felsic plutons the mean size of the dominant phenocrysts (feldspar, hornblende, biotite, quartz) is about 3 mm (Bachmann and Bergantz, 2004); thus, at identical ∇P, the v are expected to be 0.6–6 m/year at μ = 0.25 and 1.1–11 m/year at μ = 0.4, with segregation of tens to hundreds meter-thick crystal-poor melts within a century. However, there is little evidence for the presence of large crystal-poor bodies in the present-day crust (10^2–10^3 km^3; Bachmann and Bergantz, 2004). Thus, the expected volumes of silicic melt extracted from a mush via gas-driven filter pressing must be << 10^2 km^3, i.e. not detectable by high resolution local seismic tomography (cell volume of 125 km^3; e.g. Miller and Smith, 1999). If extracted from stagnant mushes, such small volumes of silicic melts may become highly hazardous due to their large volatile content (i.e. H_2O dissolved in the melt + exsolved gas) and low ϕ.

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~~In conclusion, *in situ* observations of magmatic microstructural evolution have shown that gas-driven filter pressing can operate efficiently in shallow felsic crystal mushes with crystal volume fractions of 0.6-0.7 (Figure 2) provided crystallisation and volatile exsolution are rapid enough to establish a gas pressure gradient before the maximum packing fraction of bubbles and crystals is reached (~74 vol.%). Above this threshold, the crystal mush is likely to fracture, restricting melt segregation and hindering the generation of eruptible, crystal-poor magmas.~~ Gas-driven filter pressing is therefore a viable, but highly limited mechanism to rapidly extract large volumes of hazardous gas-rich crystal-poor magmas within the Earth's crust.

ACKNOWLEDGMENTS

CALIPSO Grant (Nr. 312284; FP7/2007-2013) and ERC Advanced Grant CRITMAG supported this research. EXTREMA COST Action MP1207 provided networking support. We acknowledge: C. Clapham, D. Hawley, U. Graber, G. Mikuljan for technical support; G. Robert for assisting with calorimetry; D. Baker, M. Polacci, L. Caricchi, D. Giordano for earlier discussions. Constructive comments by D. Floess and two anonymous reviewers helped improving this manuscript. R. Holdsworth is acknowledged for his editorial handling.

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Publisher: GSA
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FIGURE CAPTIONS

Figure 1. Synchrotron X-ray tomographic microscopy 3D renderings of two representative haplogranitic (H5, ***A-D***) and dacitic samples (F, ***E-H***) with different crystal (***Φ***) and bubble fractions (***β***) at representative temperatures (***T***) and experimental times (***t***, in minutes). Black objects = bubbles and fractures; dark grey field = silicic glass; light grey objects = corundum crystals in H5 glass *and* quartz in F glass. White and dark grey arrows indicate representative fractures and directions of melt expulsion during vesiculation respectively. During experiments gas exsolution mainly consists in: 1) bubble nucleation and growth (white circles), and 2) crystal clustering/compaction (white rectangles).

Figure 2. Crystal fraction (***Φ***) vs. bubble fraction (***β***) diagram reporting all experiments conducted in this study. Squares and circles indicate haplogranitic and dacitic samples respectively. Black and grey colours indicate ductile and brittle regime respectively. Dashed grey lines denote trends of constant melt fraction (***μ***). Grey field indicates impossible physical conditions. 2D reconstructed slices of representative samples display the increase of ***β*** with ***T*** and the increase of sample fracturing with increasing ***Φ***. Each side of the reconstructed slice is 5 mm. White areas in H5 samples are corundum crystals; dark grey areas in F samples are quartz crystals. In all samples black objects are gas bubbles, and light grey matrix is silicic glass. Values reported in each slice are ***T*** in °C.

Figure 3. ***A)*** KFT-measured amounts of H_2O extracted from the melt of dacitic samples (***Φ*** = 0-0.8) at different ***T***. H_2O uncertainties are ±0.07 wt.% in the ductile (solid line) and ±0.14 wt.% in the brittle regime (dashed line). ***B)*** Melt viscosity (η_{melt}) as a function of extracted H_2O, with η_{melt} estimated using the model of Giordano et al. (2008), taking into account the difference between the total H_2O in the melt phase, measured in crystal-free F0 sample in ***A***, and the extracted H_2O at a specific ***T***. At identical exsolution rates (i.e. heating rates applied during KFT measurements), η_{melt} is expected to evolve in the same manner in all dacitic samples; the ***Φ*** increases the incapacity of H_2O extraction from the sample (i.e. the higher ***Φ***, the lower the H_2O extraction). η_{melt} uncertainties are: < 0.4 log units at dissolved H_2O contents < 2 wt.%, and < 0.2 log units at dissolved H_2O contents > 2 wt.%. Further η_{melt} deviations of 0.2 log units must be considered due to limited content of H_2O (< 0.2 wt.%) trapped in the F samples during vesiculation and not measured by KFT.

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G36766.1

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