Magma transport processes

Paul A. Jarvis

paul.jarvis@unige.ch

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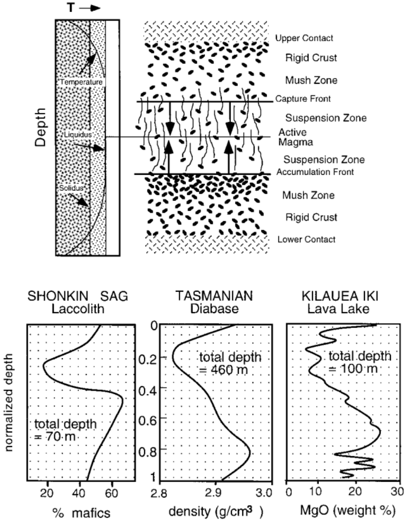
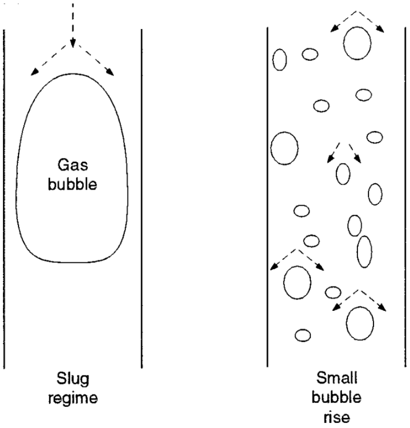
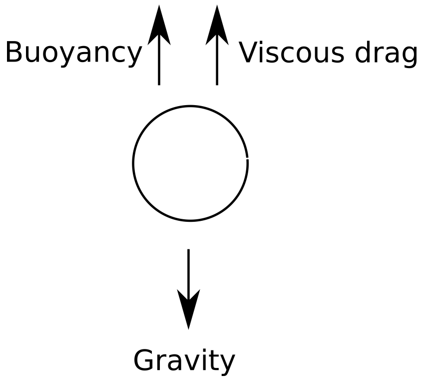
Viscosity and density control how magma is transported within the Earth's crust
Can consider transport of bulk magma, or **fractionation** of individual phases





Crystal settling

Sills can contain **cumulates** - dense regions of crystals which have settled to the base of a chamber



In viscous fluid, three forces act on sphere:

- **Gravity** $F_{\mathrm{g}} = 4\pi\rho_{\mathrm{c}} r^3 g/3$
- **Buoyancy** $F_{\mathrm{b}} = 4\pi\rho_{\mathrm{m}} r^3 g/3$
- **Viscous drag** $F_{\mathrm{v}} = 6\pi\eta_{\mathrm{m}} r v_{\mathrm{s}}$

where r = radius, v_{s} = settling speed

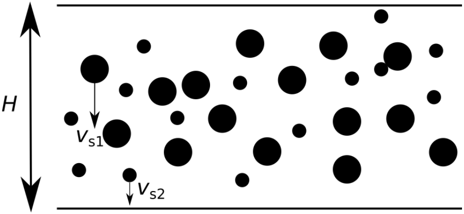
In equilibrium $F_{\mathrm{g}} = F_{\mathrm{b}} + F_{\mathrm{v}} \implies$

$$v_{\mathrm{s}} = \frac{2(\rho_{\mathrm{c}} - \rho_{\mathrm{m}})gr^2}{9\eta_{\mathrm{m}}}$$

Simple models of cumulate formation: Convecting or static magma

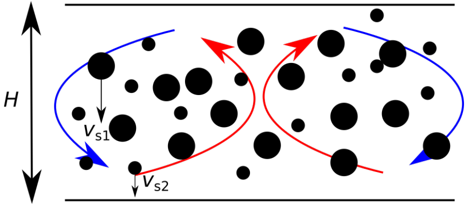
Partially-molten sill, 2 populations of crystals size d_1 and d_2 where $d_1 > d_2$
$\implies v_{s,1} > v_{s,2}$

Static magma



$\phi_1, \phi_2 = \phi_1(\mathbf{x}, t), \phi_2(\mathbf{x}, t)$

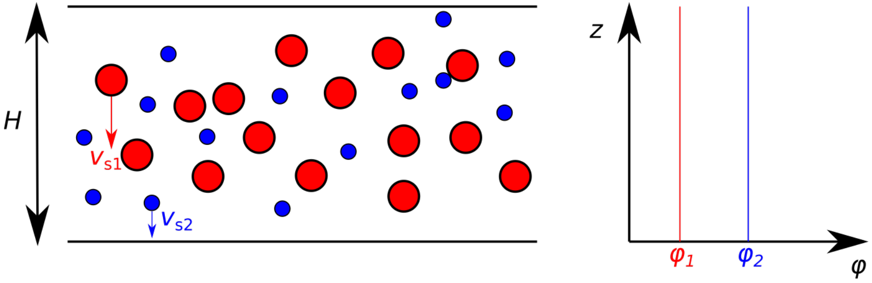
Convecting magma



$\phi_1, \phi_2 = \phi_1(t), \phi_2(t)$

Cumulate crystal size distribution: Static magma

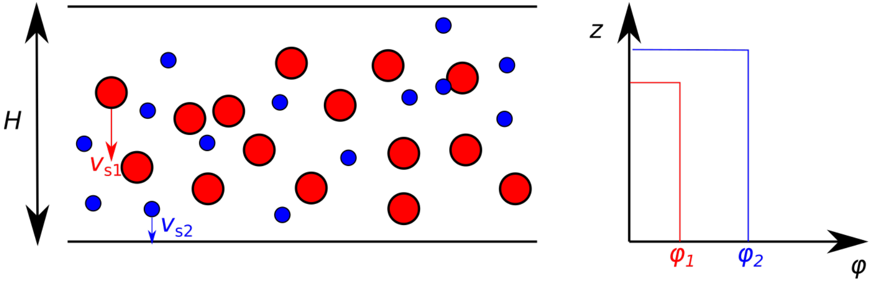
$t = 0$



Both populations are homogeneously dispersed throughout the sill

Cumulate crystal size distribution: Static magma

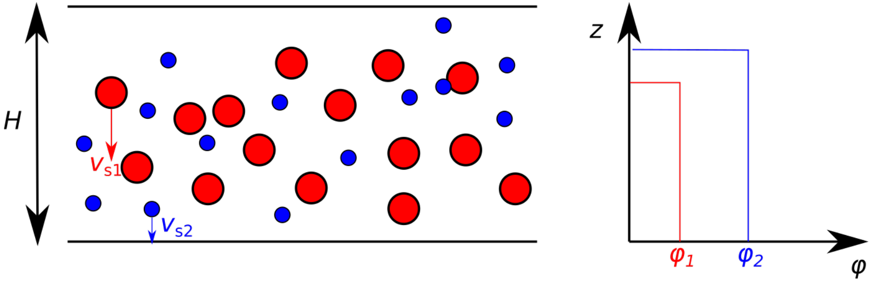
$$t = \mathrm{d}t$$



Populations settle at different speeds

Cumulate crystal size distribution: Static magma

$$t = \mathrm{d}t$$

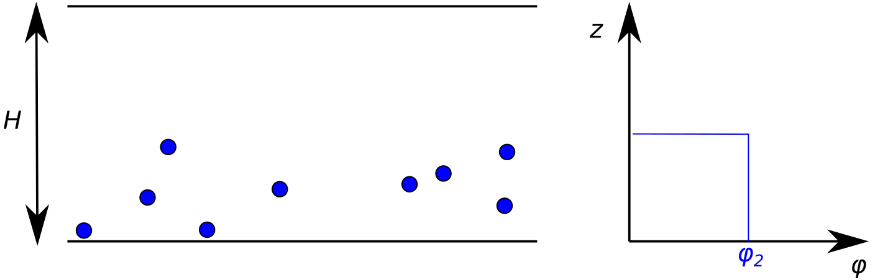


Volume of settling particles per unit area:

$\phi_1 v_{s,1} \mathrm{d}t$ $\qquad$ $\phi_2 v_{s,2} \mathrm{d}t$

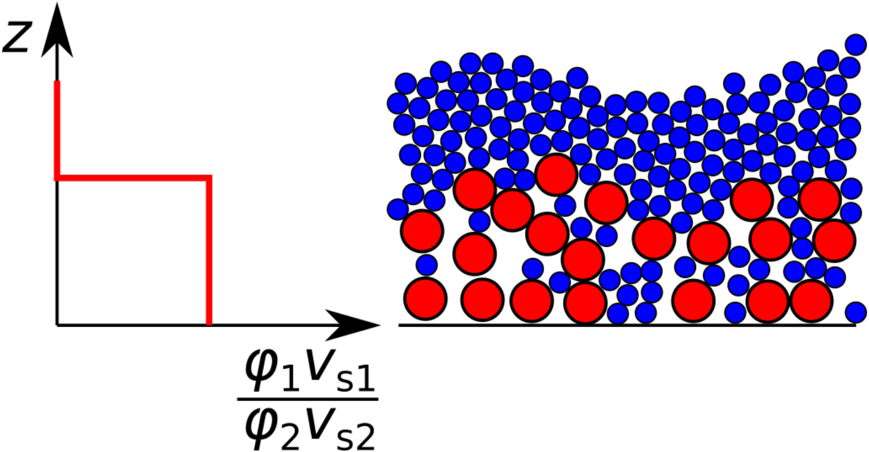
Ratio of population volumes $= \frac{\phi_1 v_{s,1}}{\phi_2 v_{s,2}}$

$$t > H/v_{s,1}$$



All of the coarse population has settled.

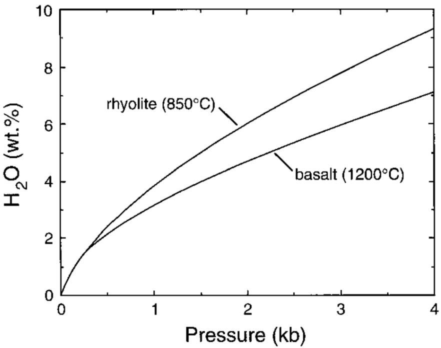
What does the cumulate look like?

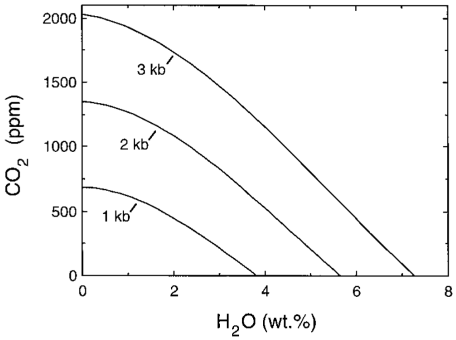


Bubble formation - volatile solubility

As magma rises, pressure falls and bubble solubility decreases

Solubility - Amount of substance that can be dissolved in a mixture

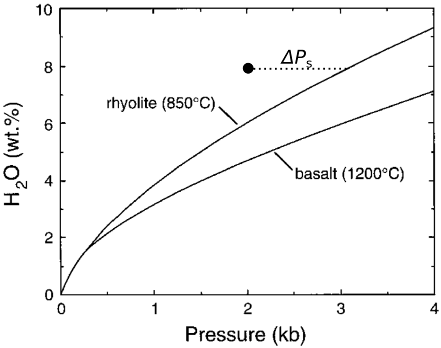




If volatile concentrations exceed solubility, then magma is **supersaturated**

Bubble formation - Supersaturation

Supersaturation - Difference between actual pressure, and that at which concentration of dissolved volatiles would be in equilibrium



Nucleation - Process by which bubbles initially form

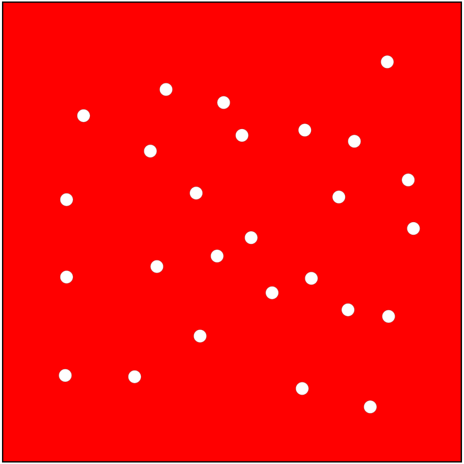
Nucleation creates an interface between melt and volatile

Interfacial tension - Energy created to create an interface between two substances

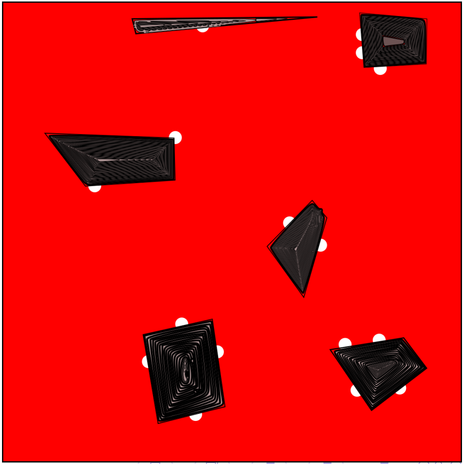
Required amount of supersaturation corresponds to energy needed

Two types of nucleation:

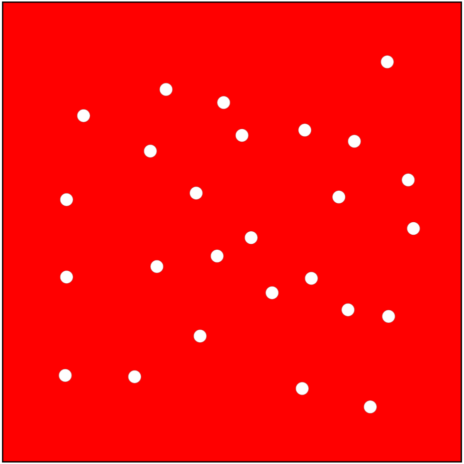
Homogeneous



Heterogeneous



Bubble formation - Homogenous nucleation

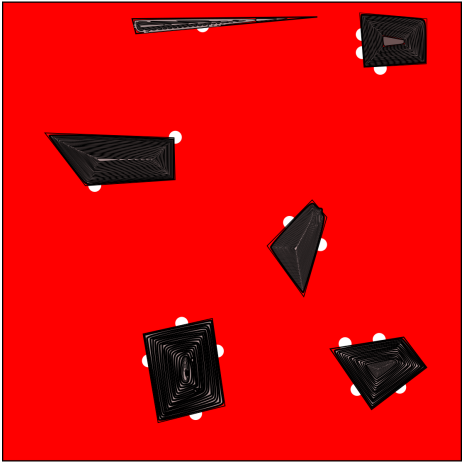


Occurs in the absence of crystals

Bubbles nucleate in the melt

Requires supersaturation of $\sim$ 10-100 MPa

Bubble formation - Heterogeneous nucleation



Interfacial energy between vapour and crystal less than that between vapour and melt

Bubbles nucleate on crystals

Requires supersaturation of $\sim$ 1-10 MPa

$\implies$ in presence of crystals, nucleation will almost always be heterogeneous

Bubble growth

As pressure decreases, bubbles grow due to expansion and increasing amount of exsolved gas
3 regimes of bubble growth:

- Viscosity-limited growth
  - Melt viscosity is sufficiently high to slow down bubble expansion
  - Leads to large supersaturation and build up of over-pressure in bubbles (mechanical disequilibrium)
  - Significant for $\eta_{\mathrm{m}} \geq 10^9$ Pa s (silicic melts at shallow depths and low $X_{\mathrm{H_2O}}$
- Diffusion-limited growth
  - Melt diffusivity is too low for oversaturated volatiles to diffuse to pre-existing bubbles (chemical disequilibrium)
  - Leads to nucleation at the expense of growth
  - Results in many small bubbles
- Solubility-limited growth
  - Diffusivity high, and viscosity low, enough to allow mechanical and chemical equilibrium
  - Bubbles can grow unhindered
  - Favoured for low melt viscosity (hot, mafic) and low ascent rates

Bubble rise speed

Bubble rise speed can be estimated by assuming spherical shape and using Stokes law

$$v_b = \frac{(\rho_m - \rho_b) g d^2}{18 \eta_m}$$

Depends on:

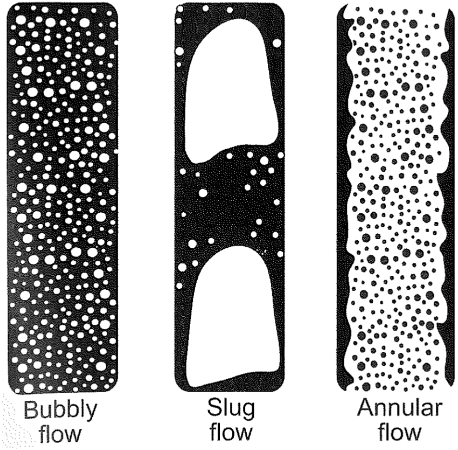
- ρ_m = Melt density
- ρ_b = Bubble density
- d = Bubble diameter
- η_m = Melt viscosity

Other factors:

- Bubble shape
- Bubble concentration ϕ_b
- Crystal fraction ϕ_c

Bubble flow regimes

v_b = Bubble speed, v_m = Melt speed



If $v_b \ll v_m \implies$ **dispersed flow**:

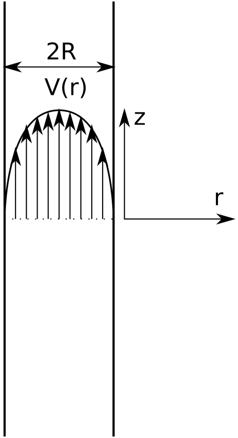
- **Bubbly flow**
- Bubbles dispersed
- Move as passive tracers

If $v_b \gtrsim v_m \implies$ **separated flow**

- $1 \lesssim v_b/v_m \lesssim 10 \implies$ **slug flow**
- $v_b/v_m \gtrsim 10 \implies$ **annular flow**

Flow regimes are observed for gas flow in a vertical pipe
Application to volcanic conduits remains debatable

Conduit flow



Flow driven by pressure gradient $\mathrm{d}P/\mathrm{d}z$
Velocity profile given by

$$\frac{\mathrm{d}V}{\mathrm{d}r} = \frac{r}{2\eta}\frac{\mathrm{d}P}{\mathrm{d}z}$$

Friction with conduit walls means flow is fastest in centre
Model is valid if flow is NOT separated

Fragmentation

Fragmentation - During explosive eruptions, magma fragements to form **pyroclasts** - ash, lapilli, bombs

- Style of fragmentation depends on magma rheology
- In turn depends on $\phi_{\mathsf{c}}, \phi_{\mathsf{b}}, \eta_{\mathsf{m}}, \dot{\epsilon}$
- Controls style of eruption

Magma mixing and mingling - Magmas of different compositions juxtapose and interact

- Viscosity and density contrasts between magmas inhibit mixing
- Heat transfer fromm hot to cold magma associated with rheological changes
- Style of mixing changes with time