How does magma reach the surface?

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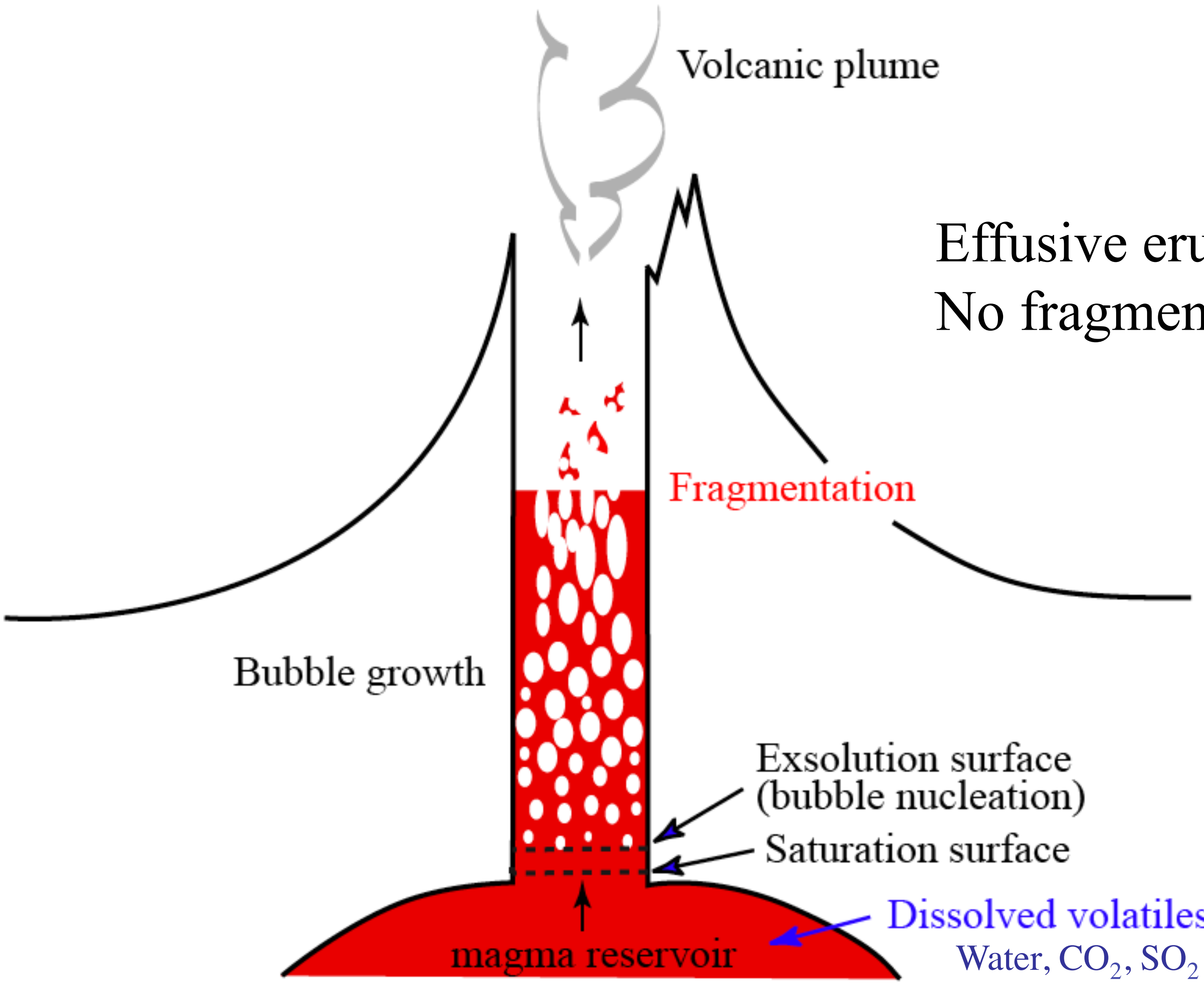
Why do volcanoes (only sometimes) erupt explosively?

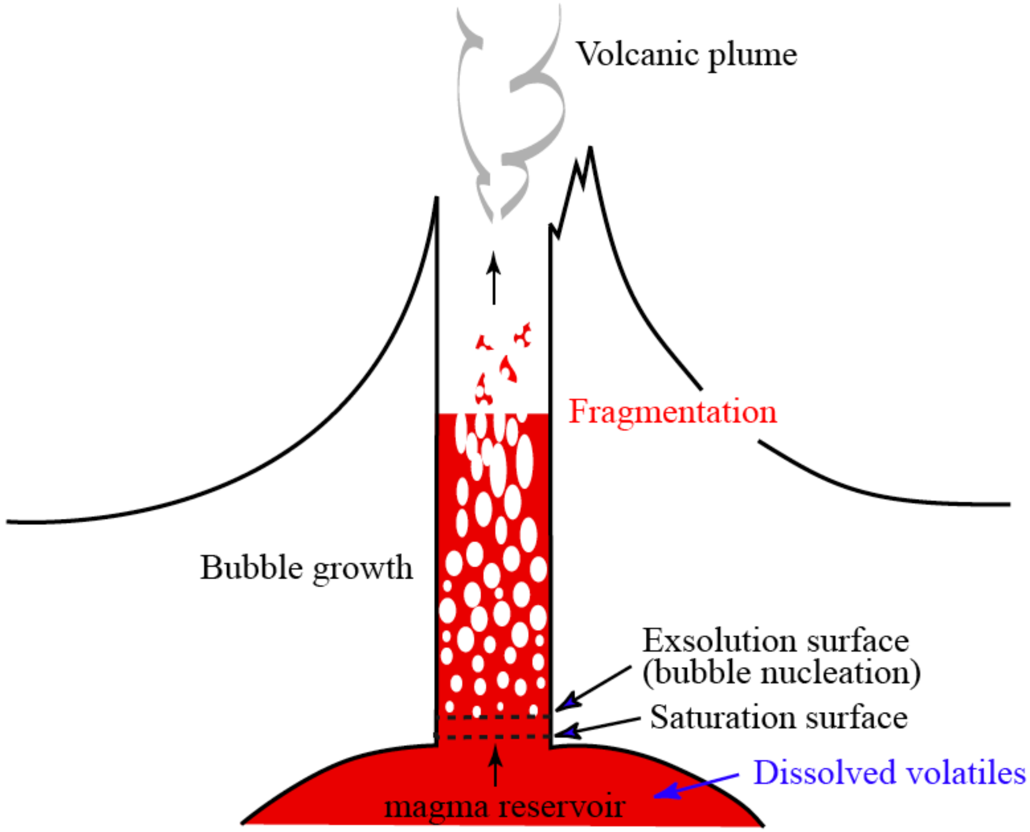
Gonnermann and Manga,
Magma ascent in the volcanic conduit,
Cambridge Univ Press, 2013

Why do volcanoes erupt explosively? (textbook version)

Effusive eruption:
No fragmentation



Why do volcanoes erupt explosively?

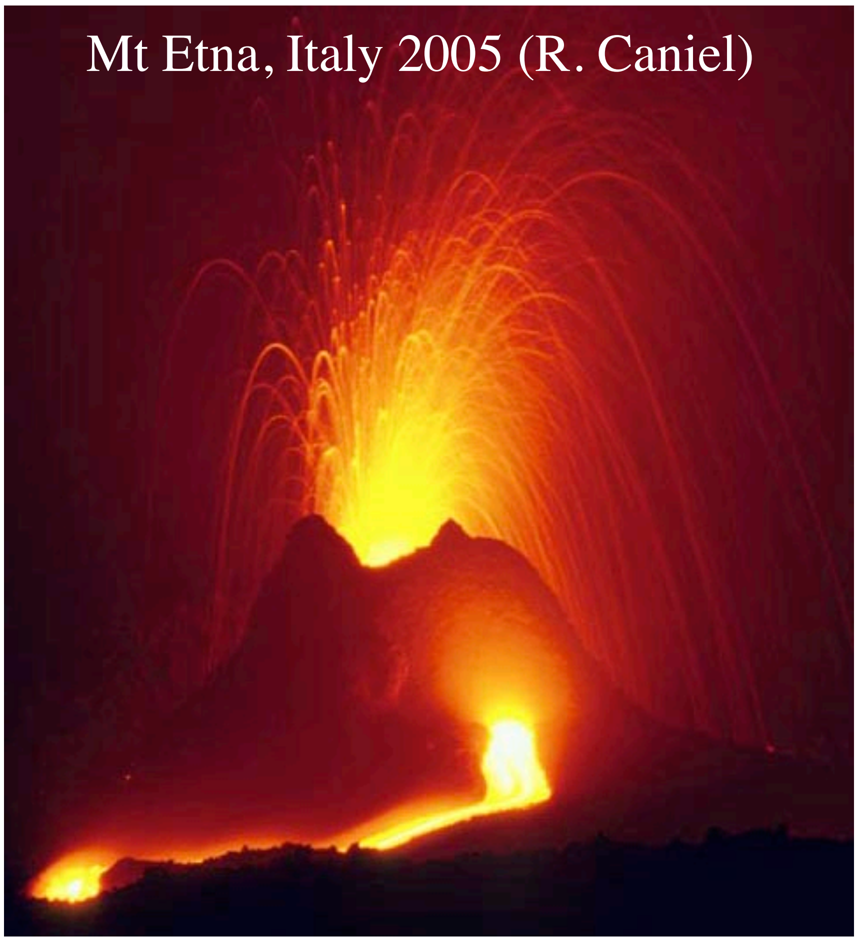


Open questions:

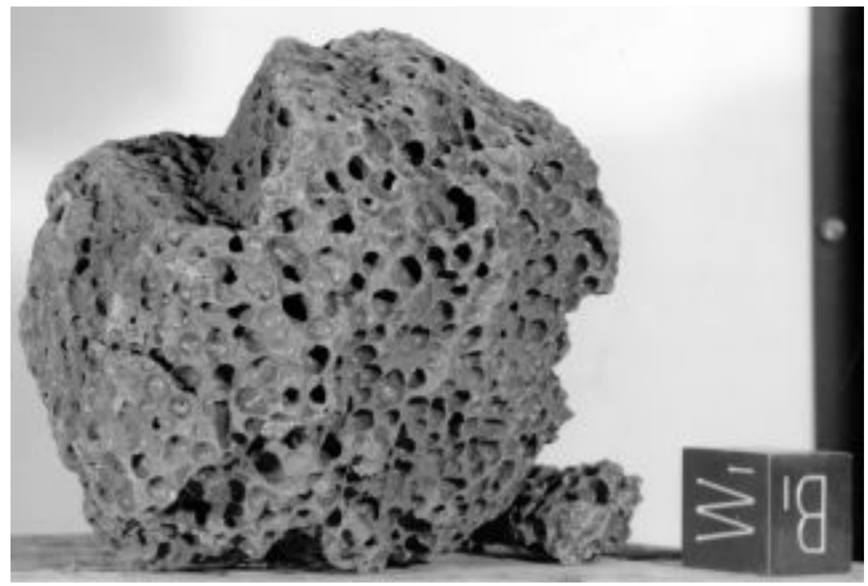
- When, where and how does fragmentation occur?
- Why so much diversity in eruption style?

Three key processes

1. Bubble nucleation, exsolution and bubble growth

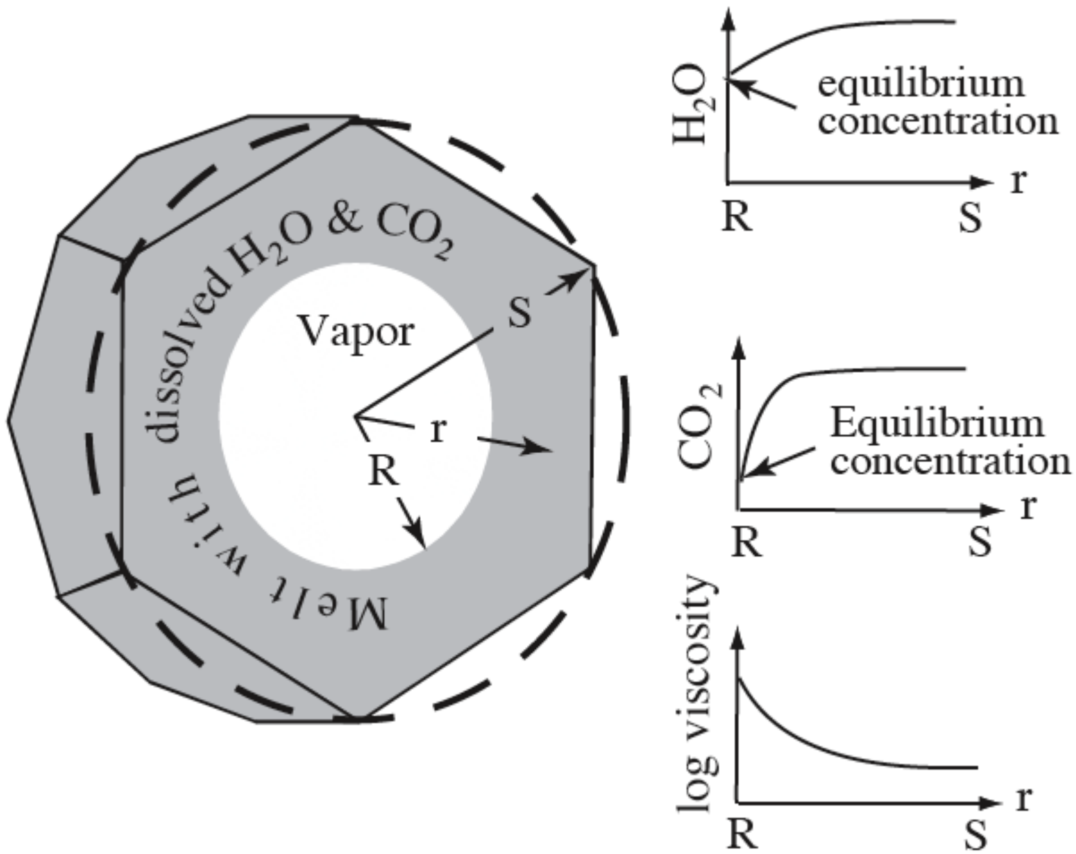


Mt Etna, Italy 2005 (R. Caniel)



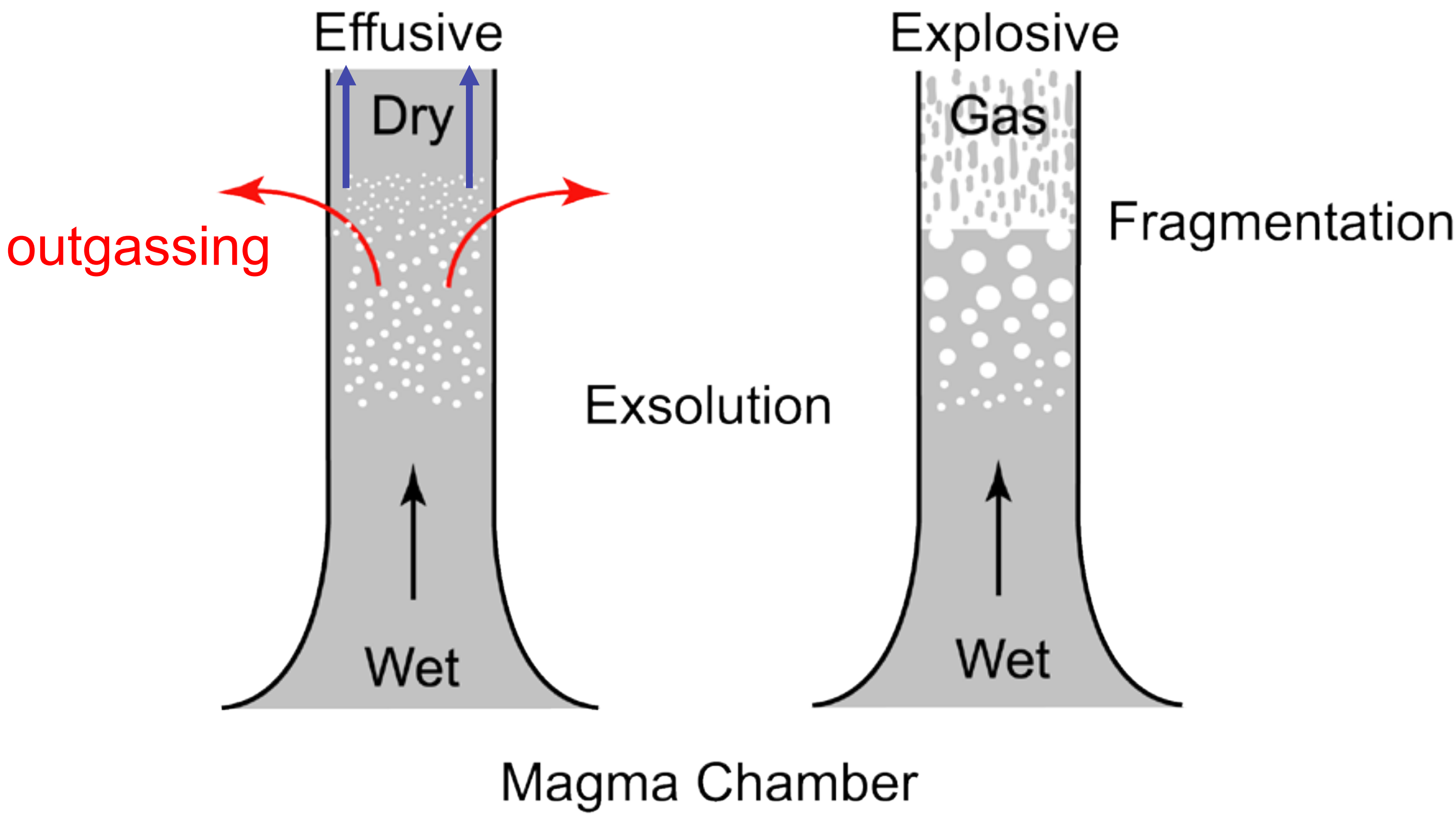
vesicular basalt (from the moon)

Volatile exsolution and bubble growth

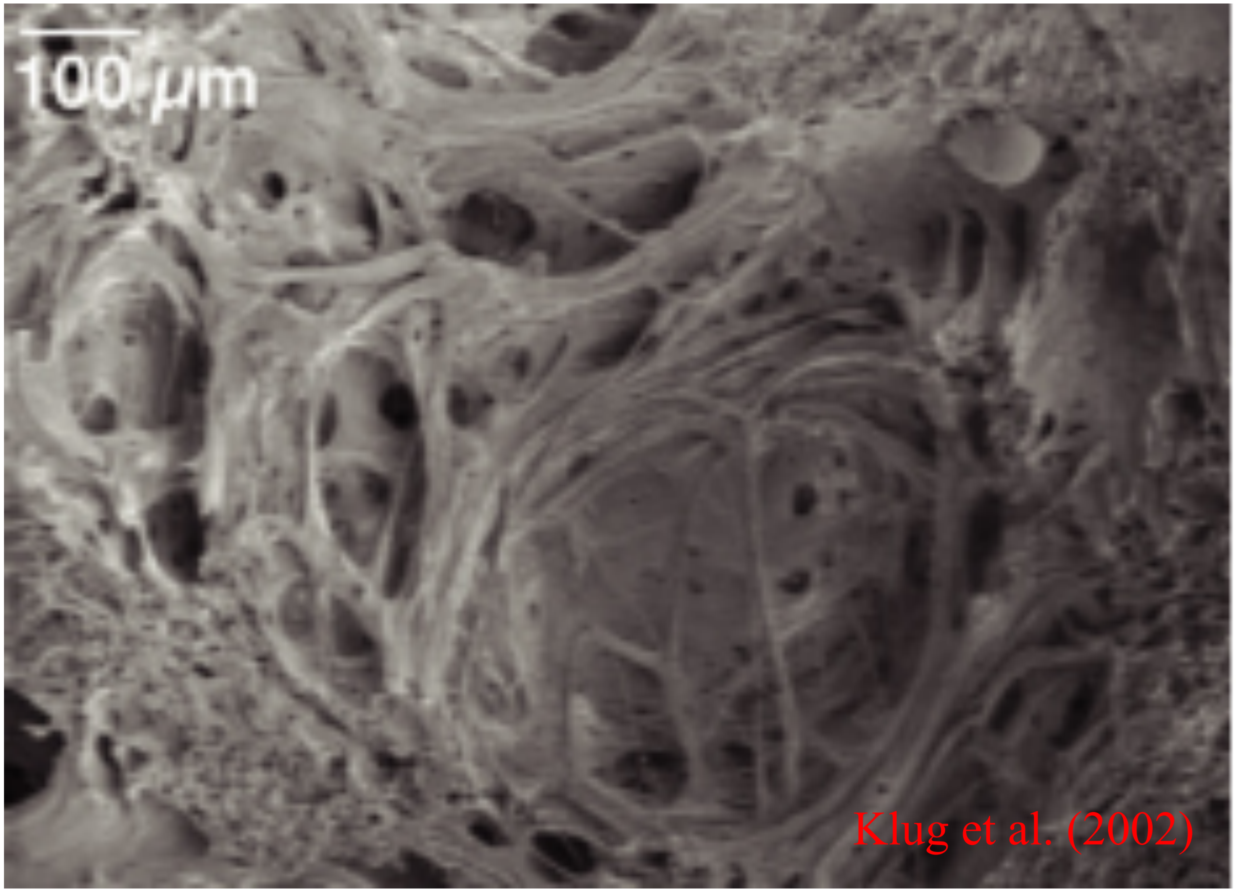


Three key processes

2. Loss of gases, called outgassing, supresses eruption



Vesicular magma is permeable



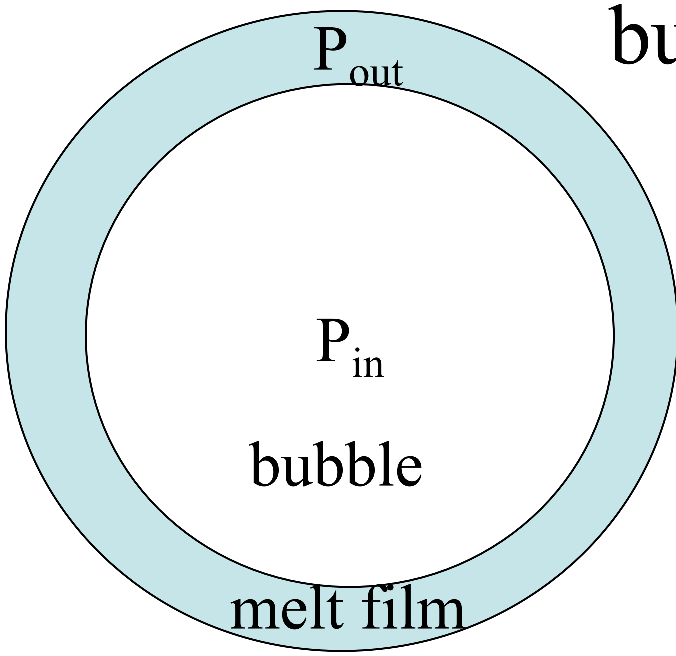
Connections between bubbles allow gases to escape from magma

Permeability depends on vesicularity and bubble size

Three key processes

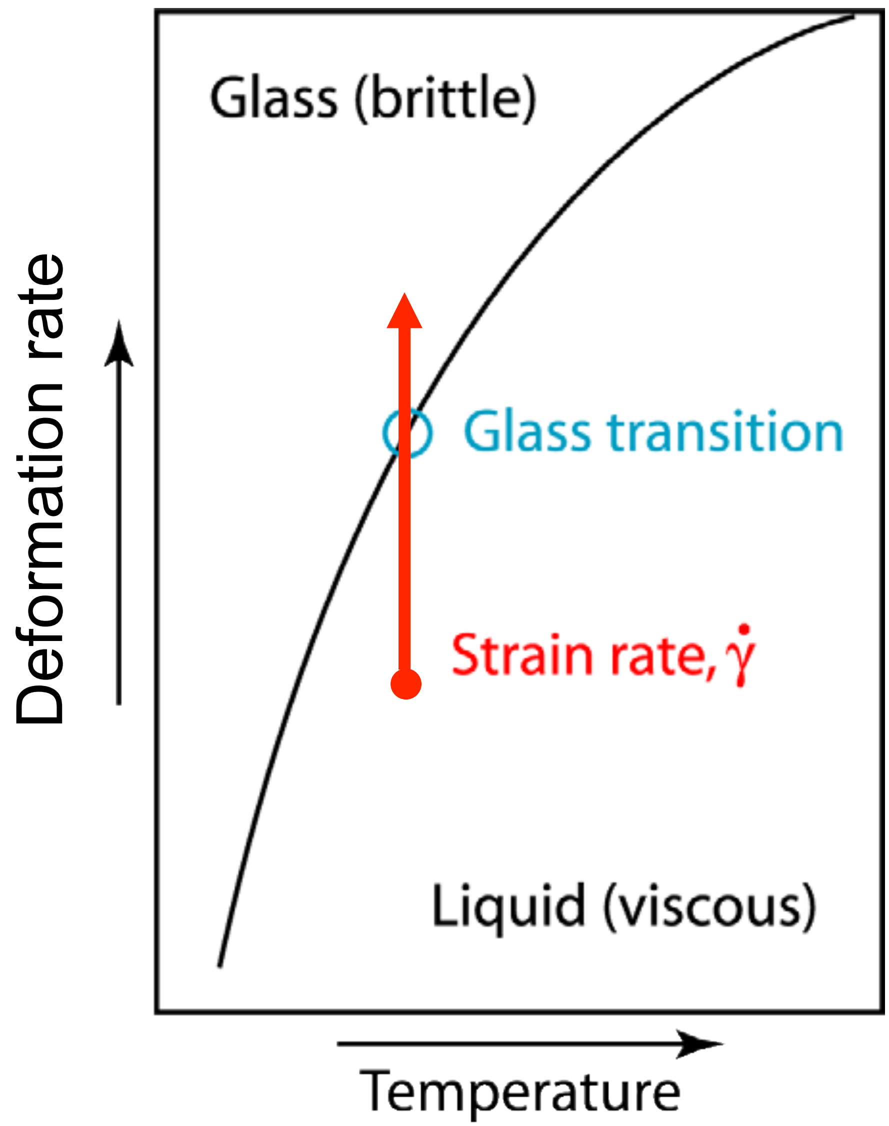
3. Fragmentation

If stresses in film surrounding bubbles too large



If $P_{in} - P_{out} >$ critical value then film ruptures

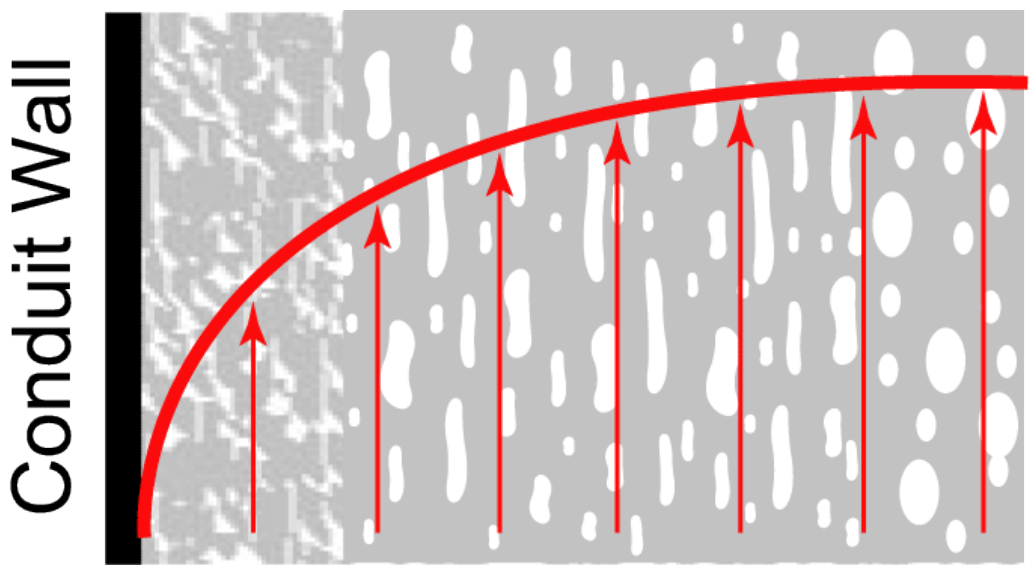
A second way to break magmas . . .

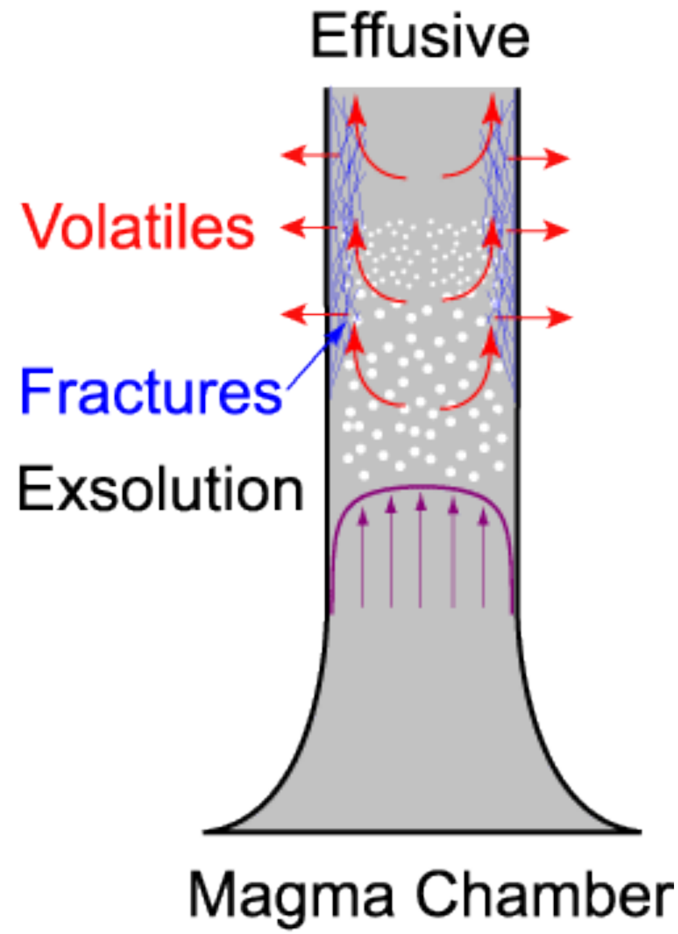


Relaxation timescale η_{mr}/G

Condition: strain rate > CG/η_{mr} with $C \sim 0.01$

Are deformation rates high enough to fragment ascending magma?





we will refer to this brecciation

Three key processes

1) Nucleation (forming new) and growth of bubbles
2) Outgassing (loss of gas from the magma)
3) Fragmentation and brecciation (breaking magma into pieces)

Approach

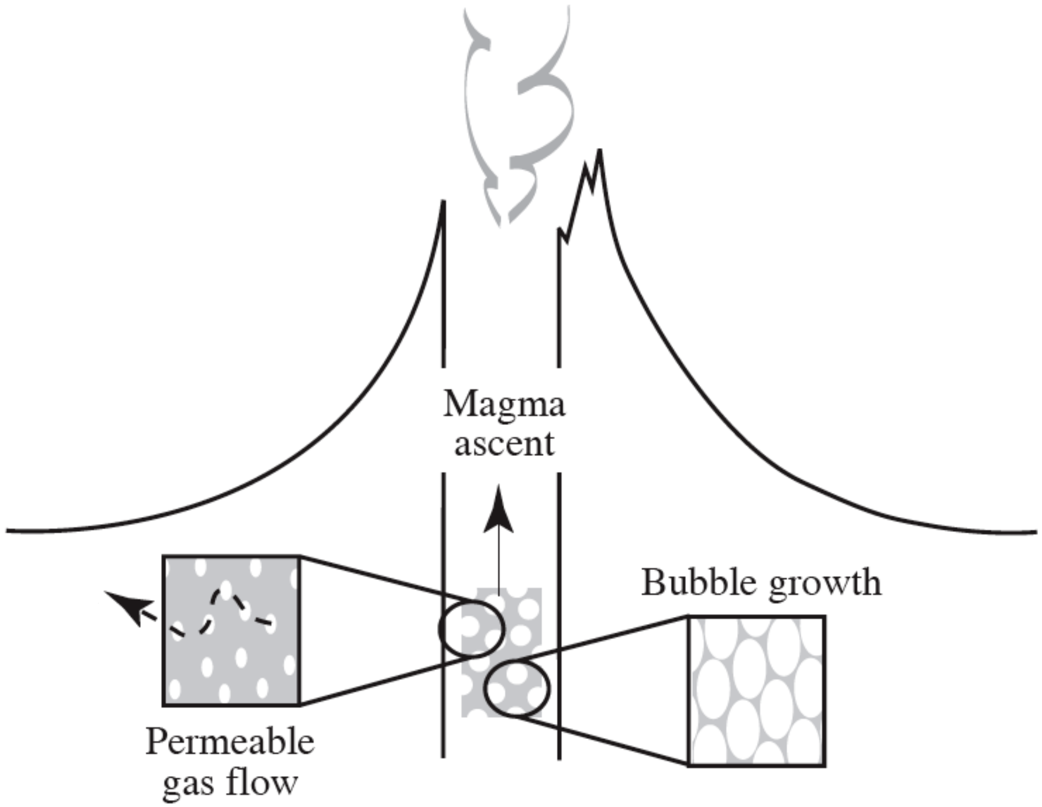
1. Lab experiments and theoretical models to study individual processes and properties

2. Computer simulations

3. Test models with measurements made on rocks

Numerical model

Solve equations for conservation of mass, momentum, energy at two scales

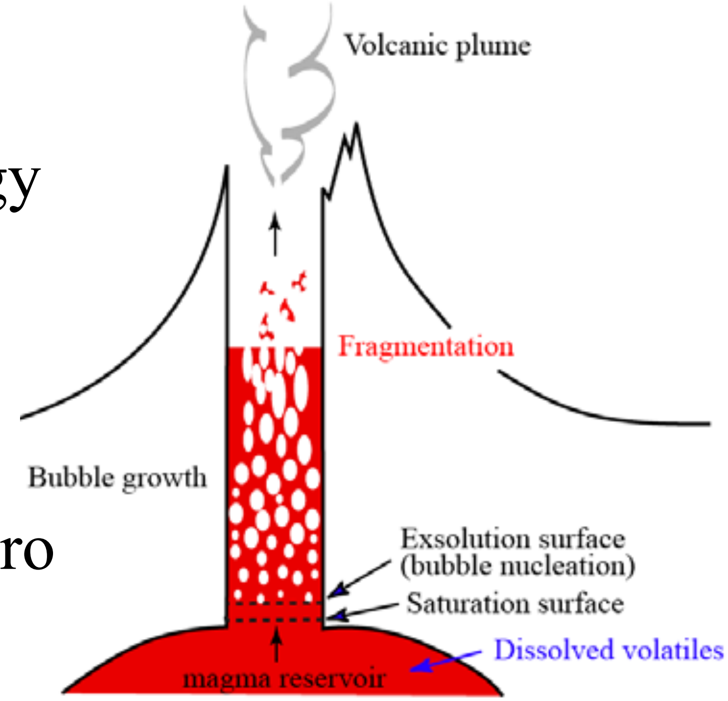


1) Conduit flow:
magma (bubbles+ melt) is locally homogeneous

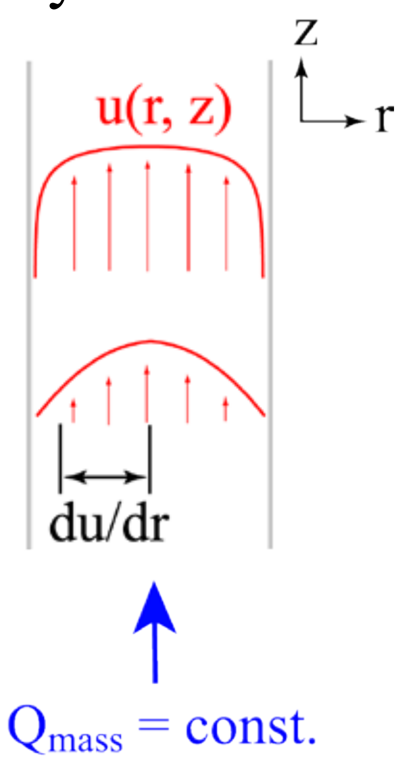
2) Bubble-scale:
Solve for growth of bubbles, determine rheology

Feedbacks between scales through temperature, pressure

Conduit flow



- conservation of mass, momentum, energy (include viscous dissipation; density, rheology from subgrid model)
- non-turbulent, no fragmentation,
- “single” phase magma (melt + bubbles)
- cylindrical conduit , radial velocity is zero
- steady flow



$$-\frac{r}{2}\left(\frac{\partial p_m}{\partial z}+\rho g\right)=-\eta\frac{du_z}{dr}$$

$$\eta=\eta(\dot{\gamma},T_m,\phi,R,c_w)$$

$$\frac{DT_m}{Dt}=\left[D_T\left(\frac{\partial^2 T_m}{\partial r^2}+\frac{1}{r}\frac{\partial T_m}{\partial r}\right)-\frac{1}{\rho_m c_{pm}}\left(\sigma_{rz}\frac{\partial u_z}{\partial r}\right)\right]$$

Conduit flow

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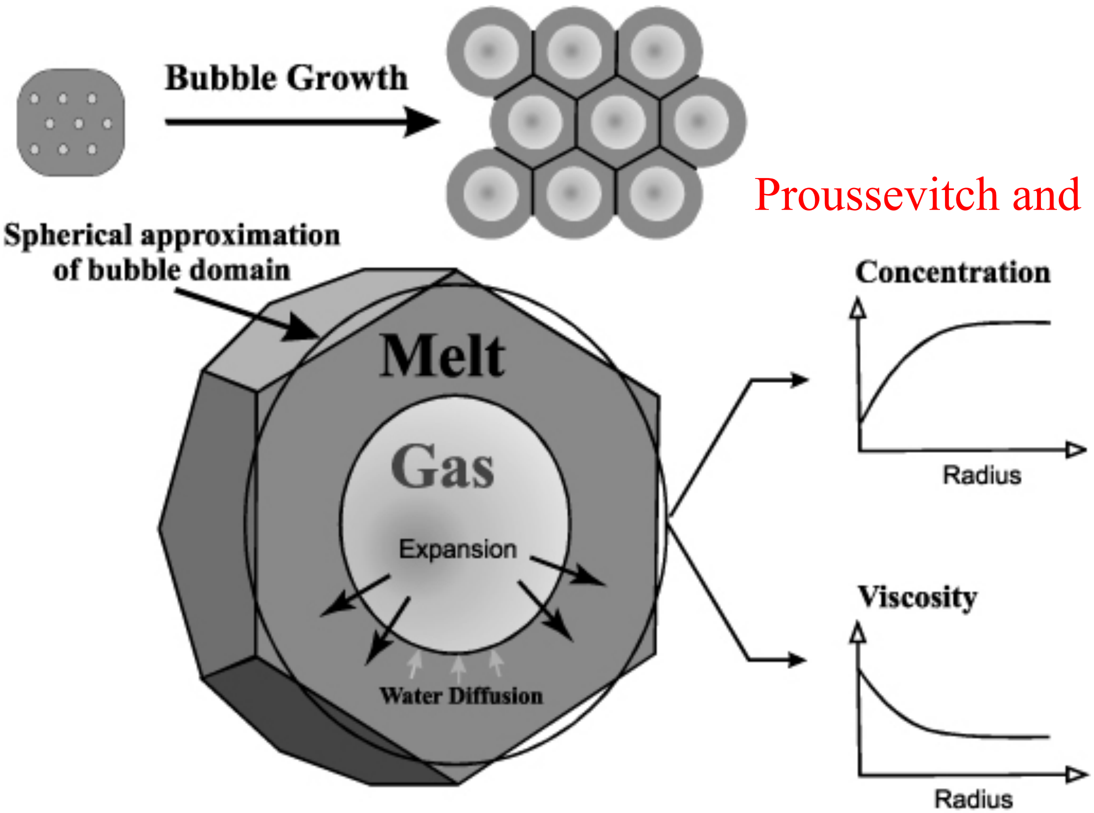
Subgrid model: Volatile exsolution and bubble growth

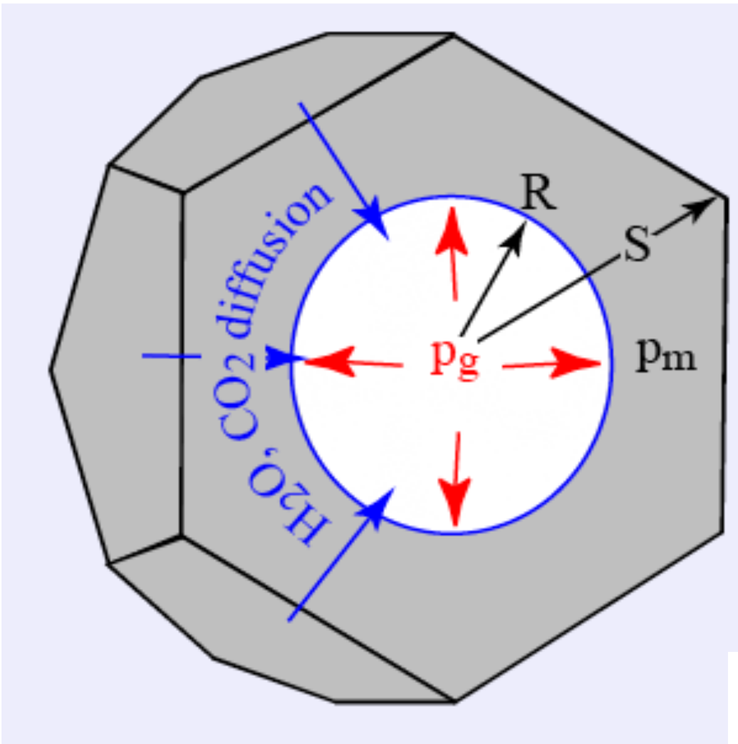


Proussevitch and Sahagian (1998)

Solubility of H_20, CO_2 from Liu et al. (2005)

Diffusivity of H_20, CO_2 from Zhang and Behrens (2000)

Subgrid model: Volatile exsolution and bubble growth



Conservation of mass, momentum and energy, coupled with solubility model and modified Redlich-Kwong equation of state for water-CO_2 mixtures

$$\frac{d}{dt}\left(\rho_g R^3\right) = 3R^2 \rho_m \sum_i D_i \left(\frac{\partial c_i}{\partial r}\right)_{r=R}$$

$$p_g - p_m = \frac{2\gamma}{R} + 12 v_R R^2 \int_R^S \frac{\eta_{melt}(r)}{r^4} dr$$

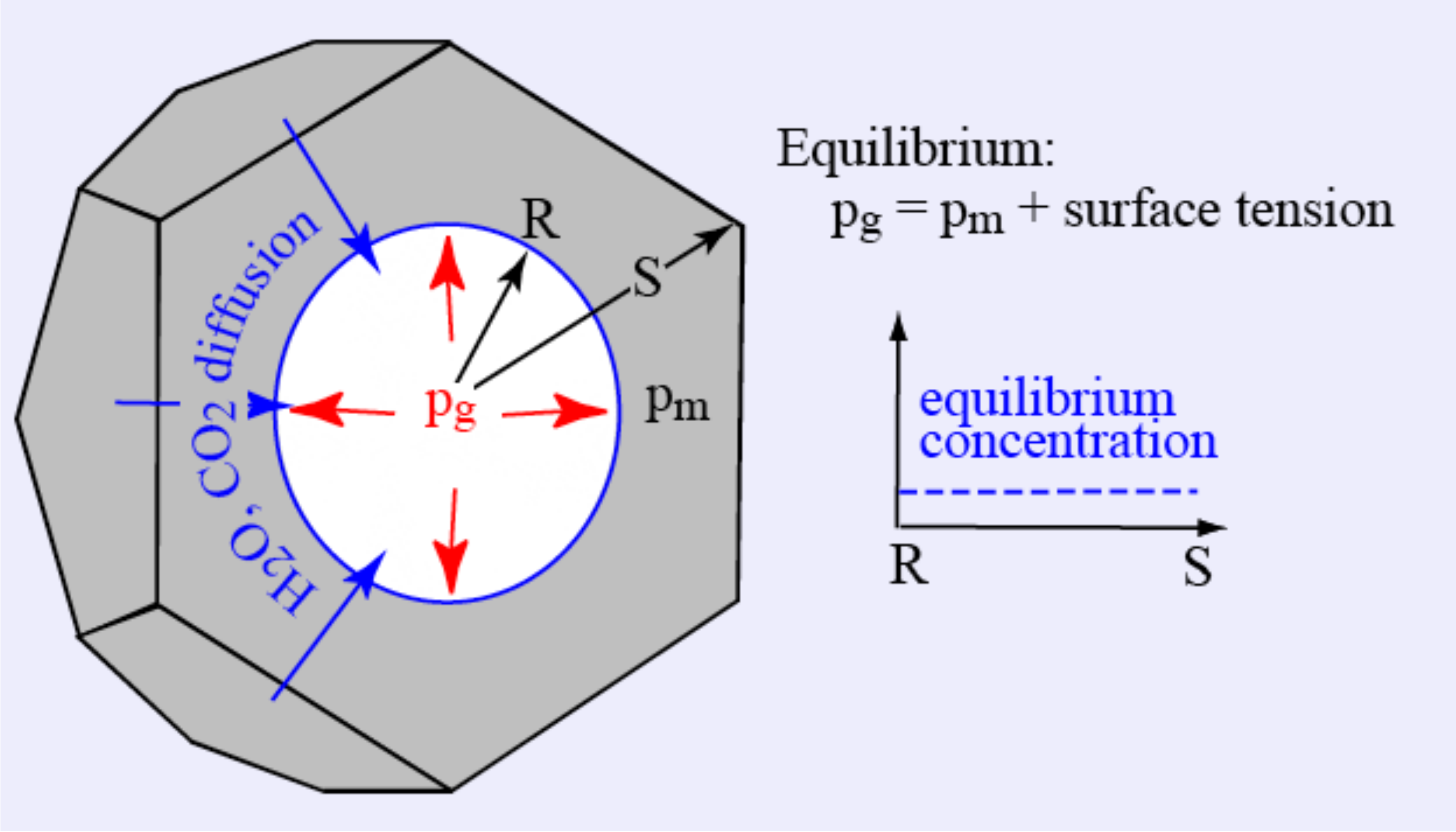
Lensky et al. (2001)

$$\frac{dT_g}{dt} = \Pi \left[\rho_m c_{pm} D_T \left(\frac{\partial T_m}{\partial r}\right)_{r=R} - \sum_i \Delta H_{ev} D_i \rho_m \left(\frac{\partial c_i}{\partial r}\right)_{r=R} + \frac{R}{3}\frac{dp_g}{dt}\right] \quad \Pi = 4\pi R^2 / \left(n\ c_{pg} M_g\right)$$

$$\frac{\partial T_m}{\partial t} + v_r \frac{\partial T_m}{\partial r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_T\ r^2 \frac{\partial T_m}{\partial r}\right) + \frac{2\ \eta}{\rho_m c_{pm}}\left[\left(\frac{\partial v_r}{\partial r}\right)^2 + 2\left(\frac{v_r}{r}\right)^2 - \frac{1}{3}\left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 v_r\right)\right)^2\right]$$

Bird et al. (1960)

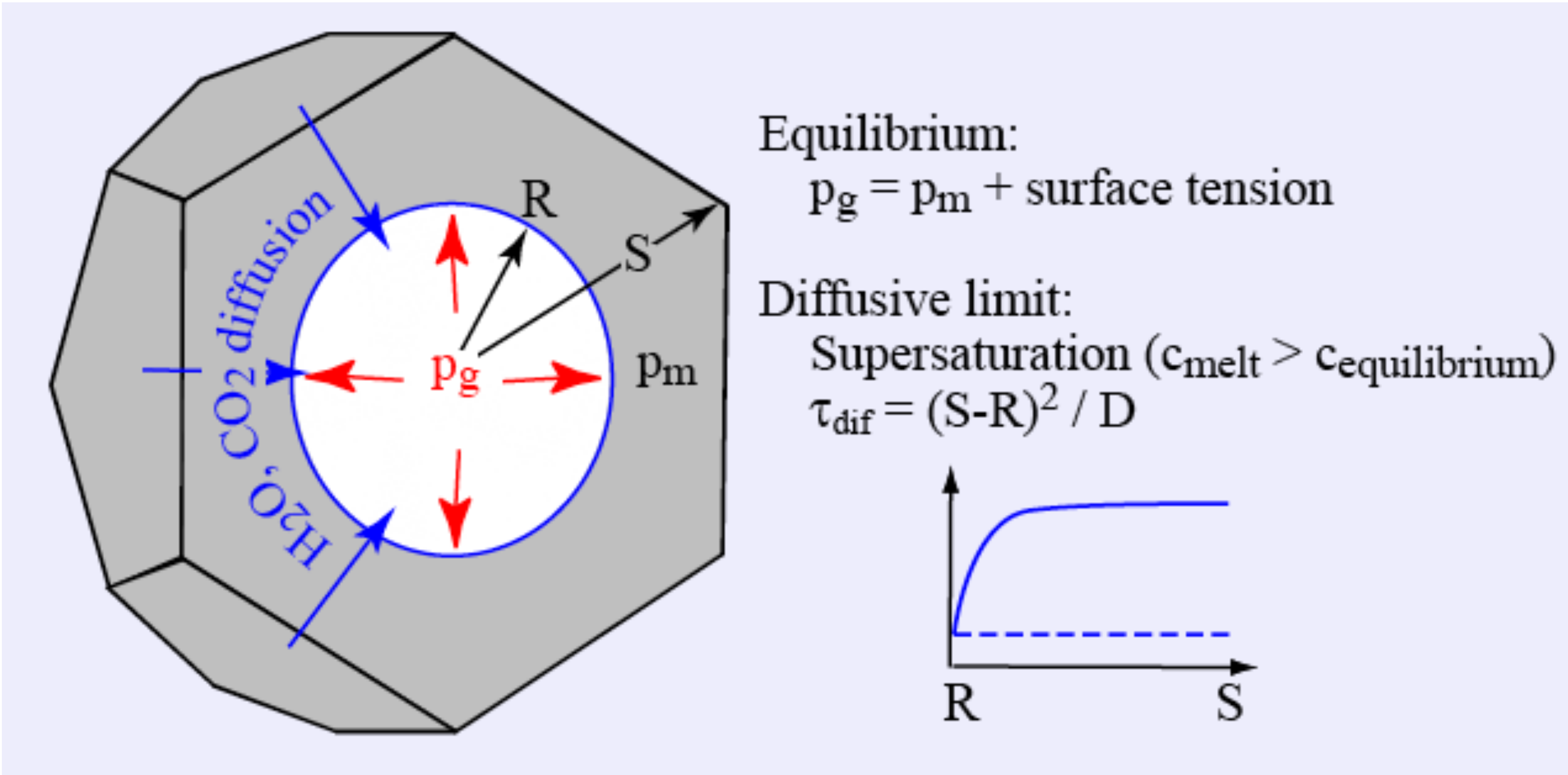
3 Regimes of bubble growth: Equilibrium (solubility-limited)



Growth is governed by changes in solubility

Decompression time scale $\tau_{dec} = p_m/\dot{p}_m$

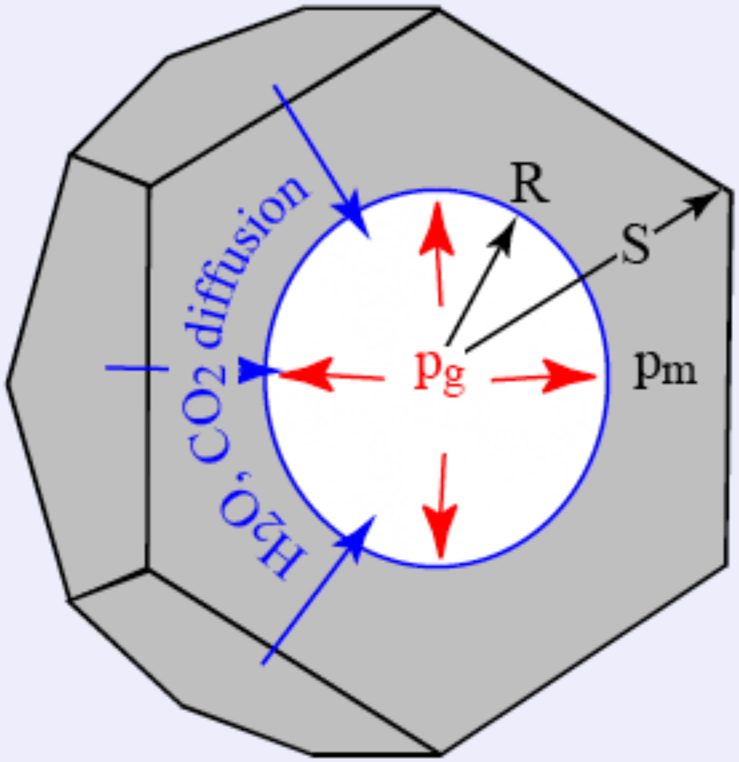
3 Regimes of bubble growth: Diffusion-limited



Growth is by diffusion-limited when $\mathrm{Pe}_{dif} = \frac{\tau_{dif}}{\tau_{dec}} \gg 1$

S-R determined by number density of bubbles N_d

3 Regimes of bubble growth: Viscosity-limited



Equilibrium:

$p_g = p_m$ + surface tension

Diffusive limit:

Supersaturation ($c_{melt} > c_{equilibrium}$)

$\tau_{dif} = (S-R)^2 / D$

Viscous limit:

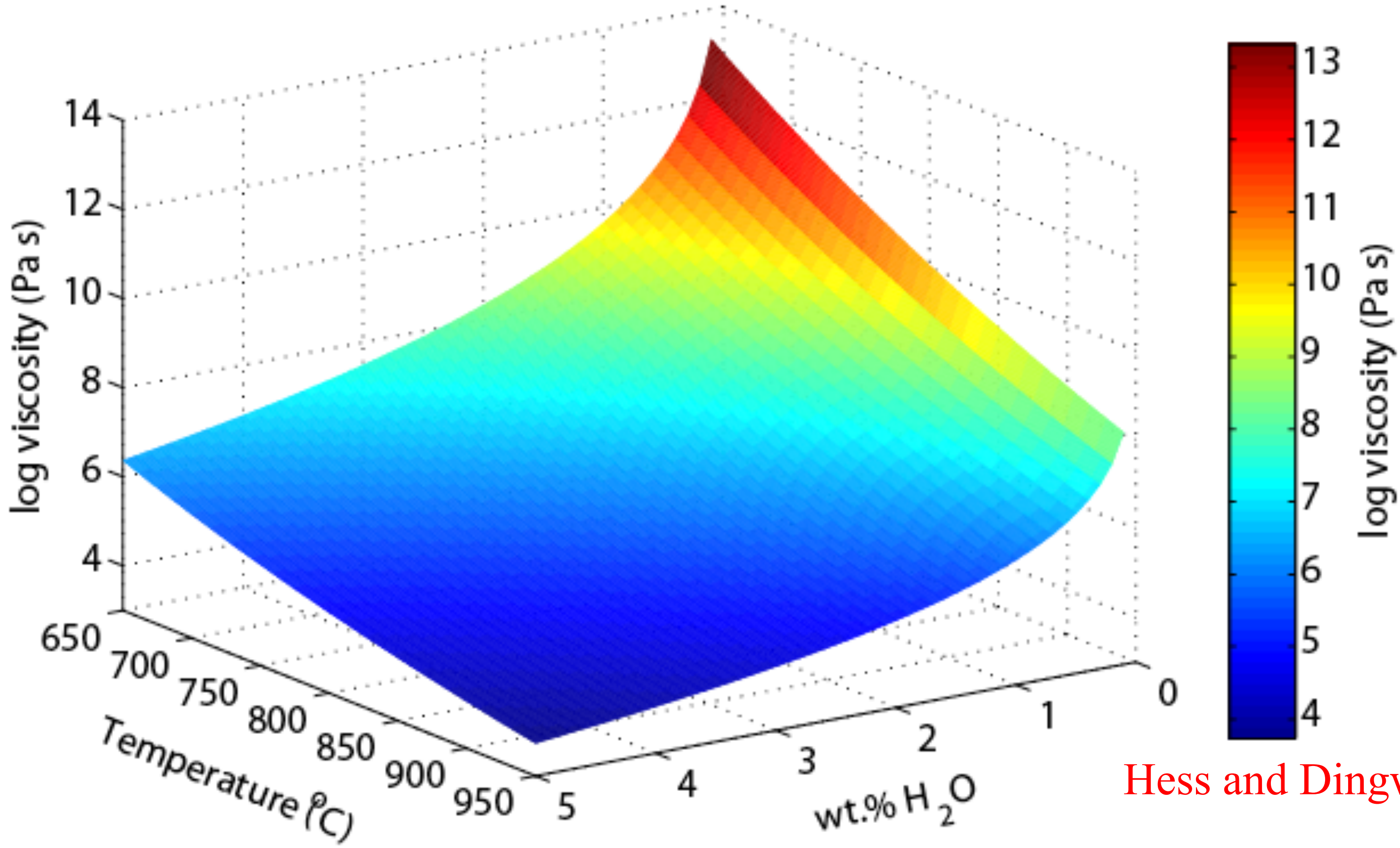
Overpressure ($p_g >> p_m$ + surf. ten.)

$\tau_{vis} = \eta / \Delta p$

Growth is by viscosity-limited when

$$\mathrm{Pe}_{vis} = \frac{\tau_{vis}}{\tau_{dec}} \gg 1$$

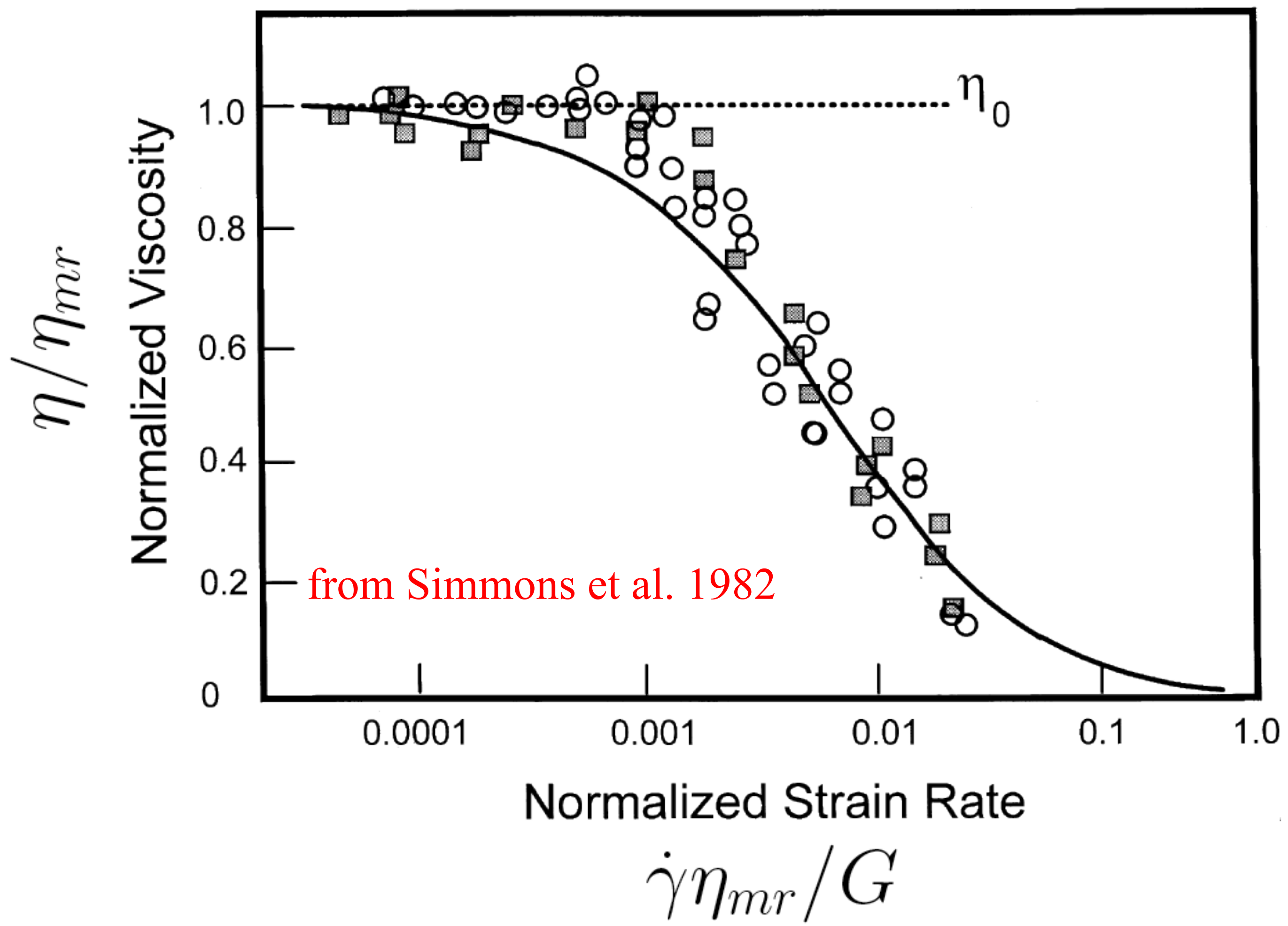
- Melt viscosity depends on amount of dissolved water and temperature (and composition)



Hess and Dingwell (1996)

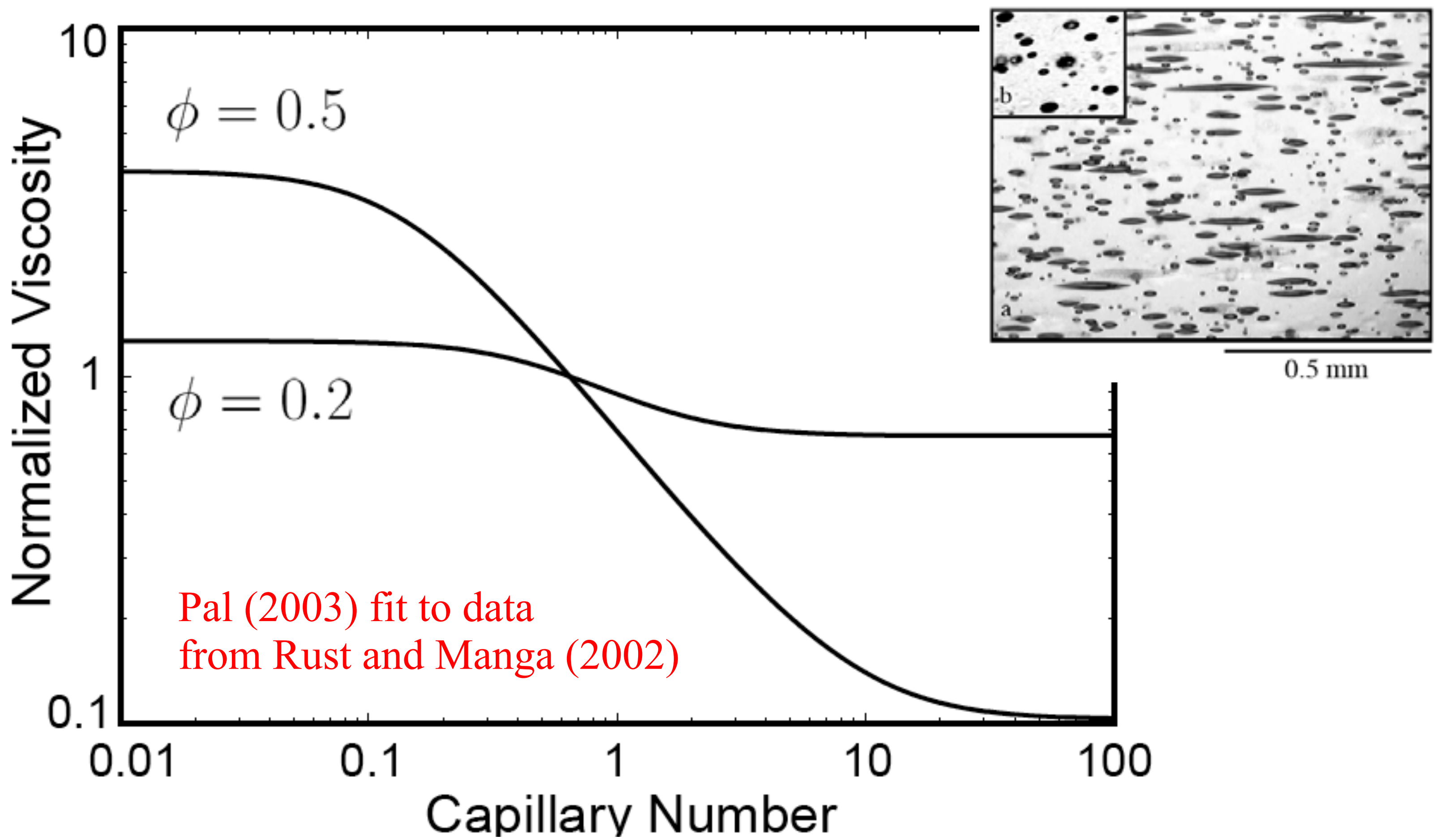
- Melt viscosity depends on deformation rate
- Magma viscosity affected by presence and properties of bubbles and crystals

Strain-rate dependent viscosity of melt phase



Silicic magmas are similar (Webb and Dingwell)

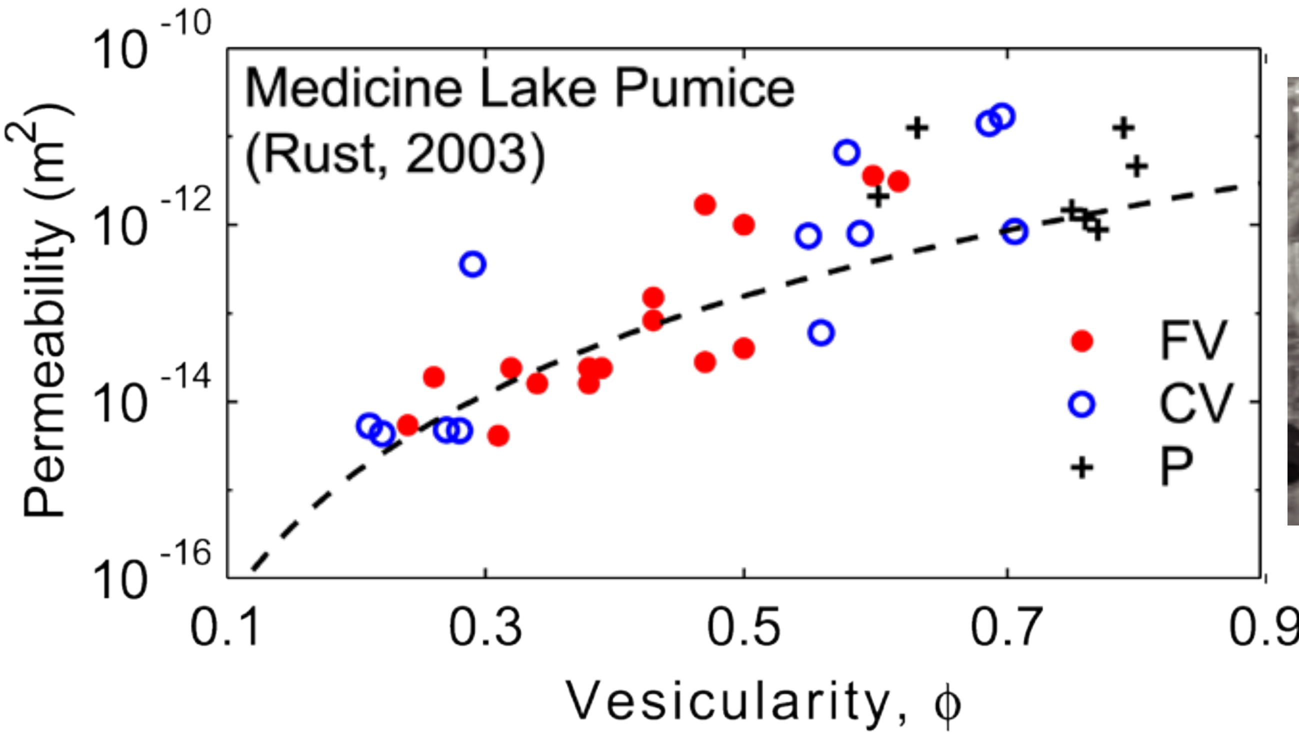
Strain-rate dependent viscosity of bubbly suspension

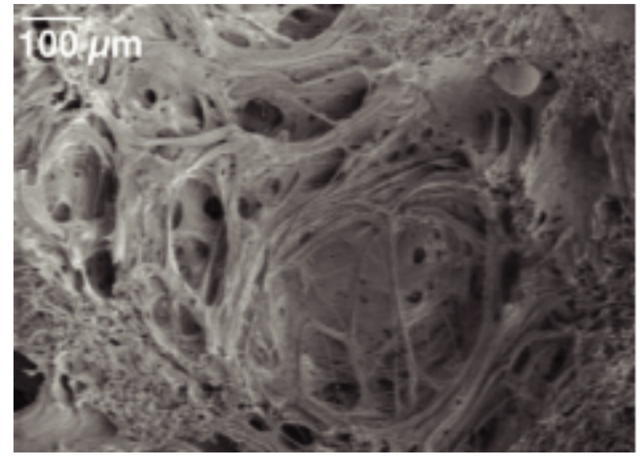


$$\mathrm{Ca} = \eta \dot{\gamma} R / \sigma$$

increasing shear rate

Vesicular magma is permeable





Klug et al. (2002)

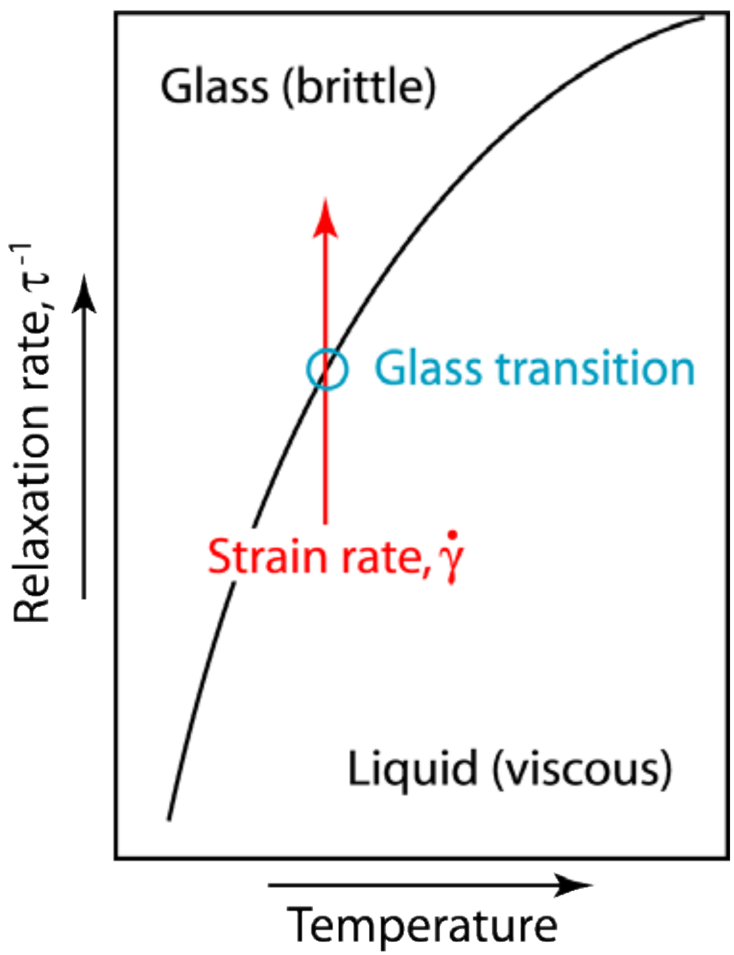
Connections between bubbles allow gases to escape from magma

Permeability depends on vesicularity and bubble size $k \propto \phi^{\beta}$

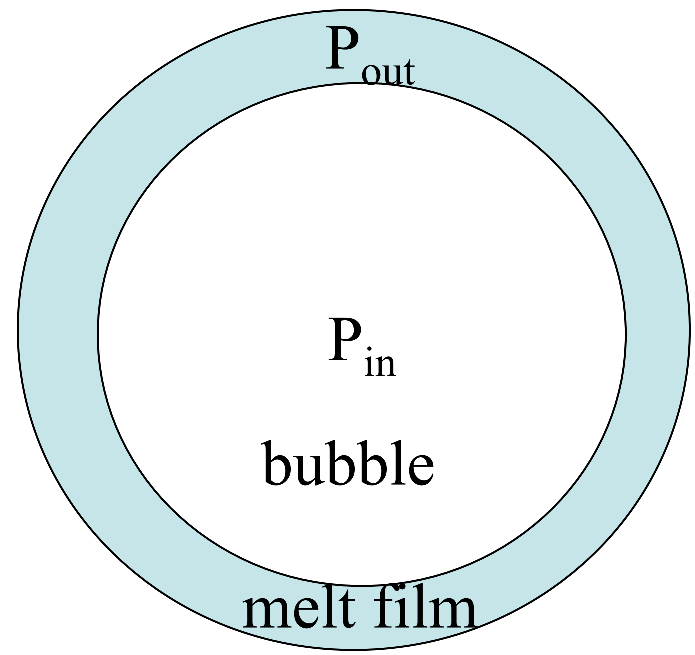
Outgassing efficient when $-\dfrac{\rho_g k}{\eta_g}\dfrac{dp_g}{dz}$ exceeds rate of gas exsolution

Fragmentation criteria: thresholds determined experimentally

Brecciation



Fragmentation

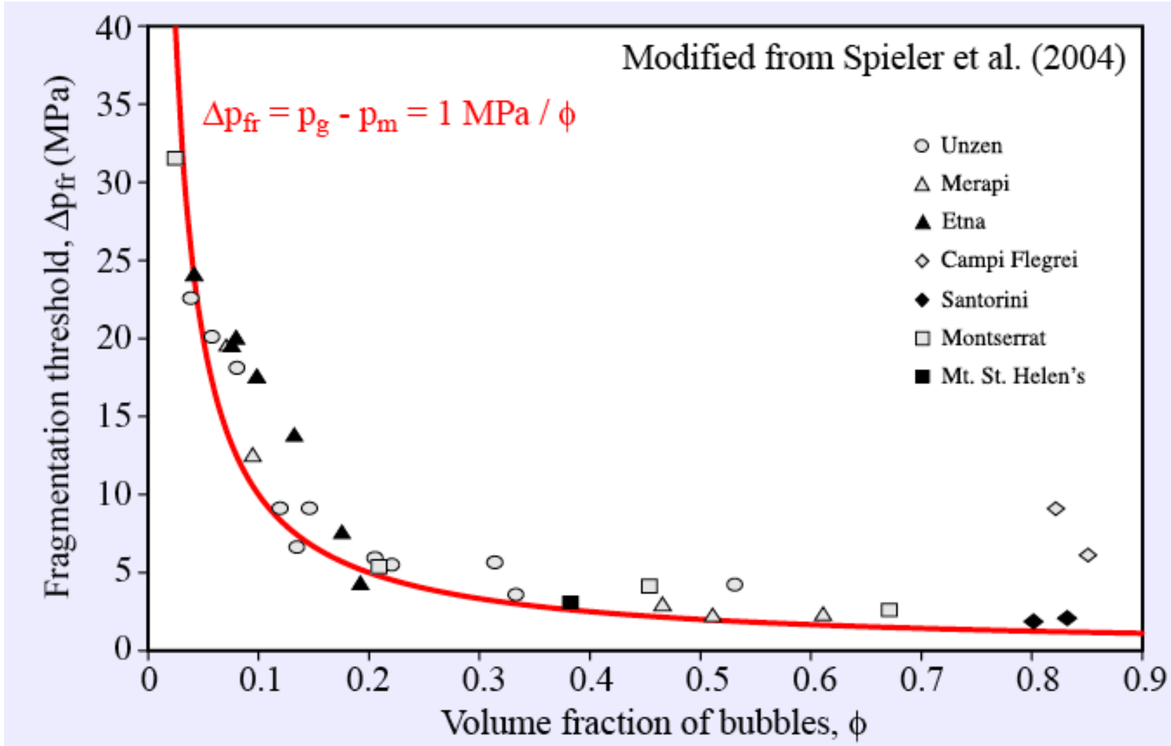


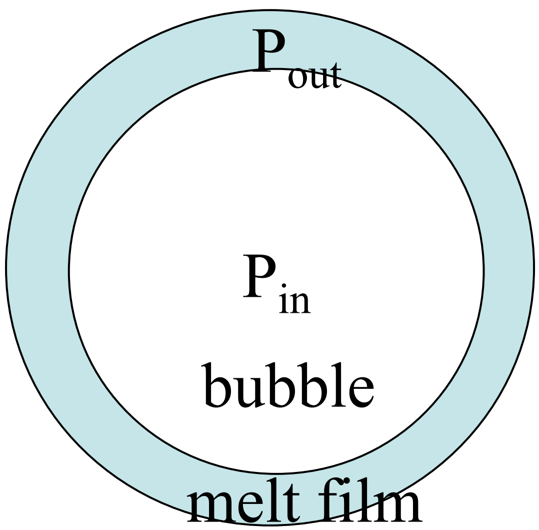
If P_{in} - P_{out} > critical value then film ruptures

Condition: strain rate > CG/η_{mr} with $C \sim 0.01$

e.g., Webb and Dingwell (1990), Webb (1997), Papale (1998)

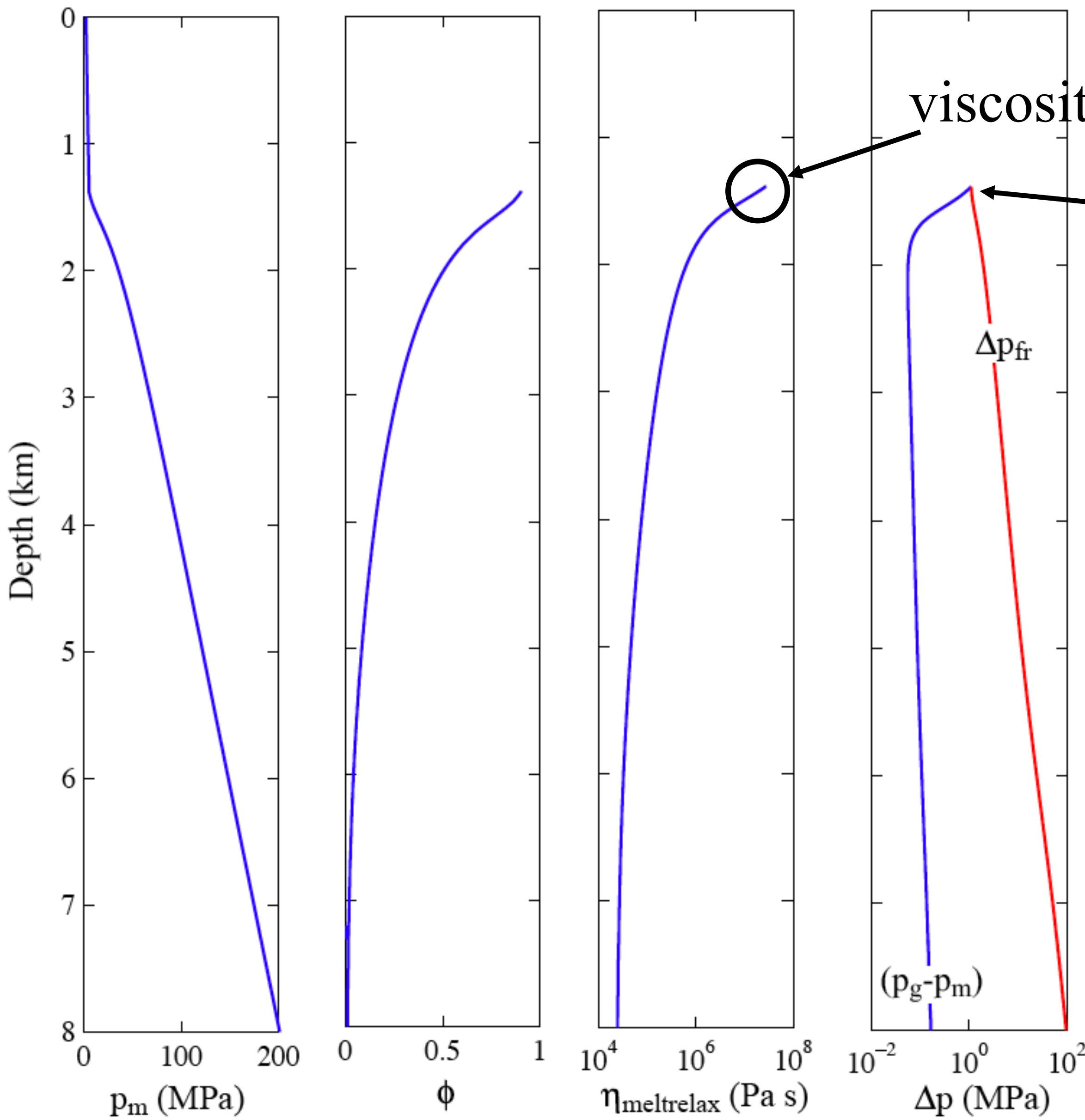
Experiments with real magma



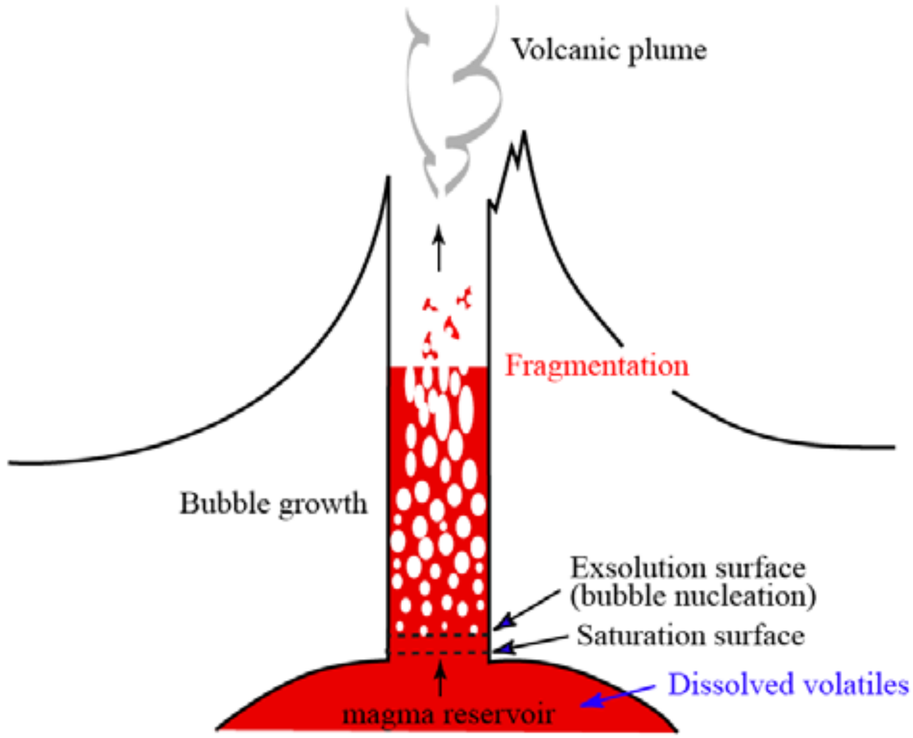


If $P_{in} - P_{out} > 1$ Mpa/ϕ then film ruptures

Example: Mount St Helens 1980 conditions



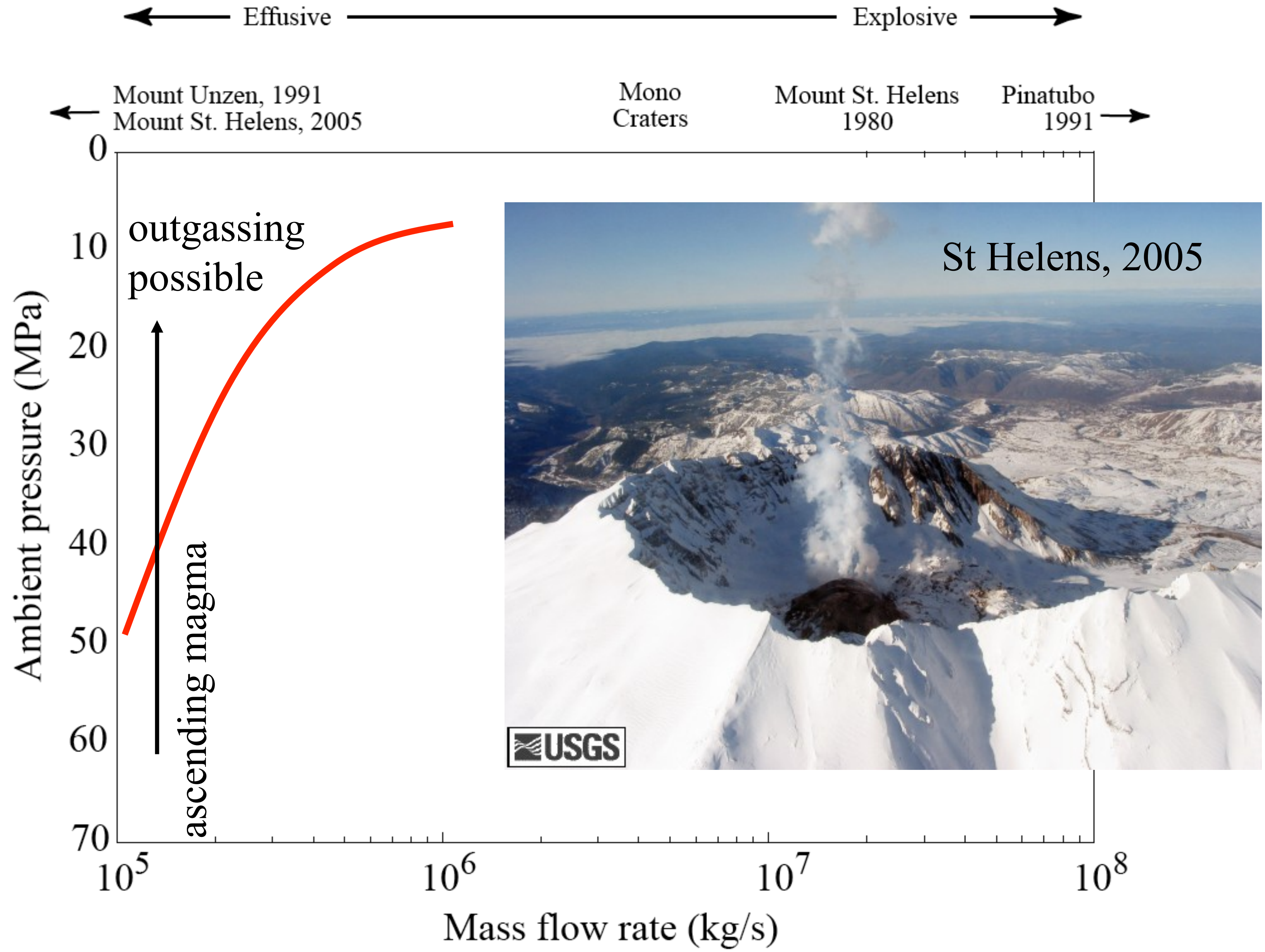
Why do volcanoes erupt explosively?



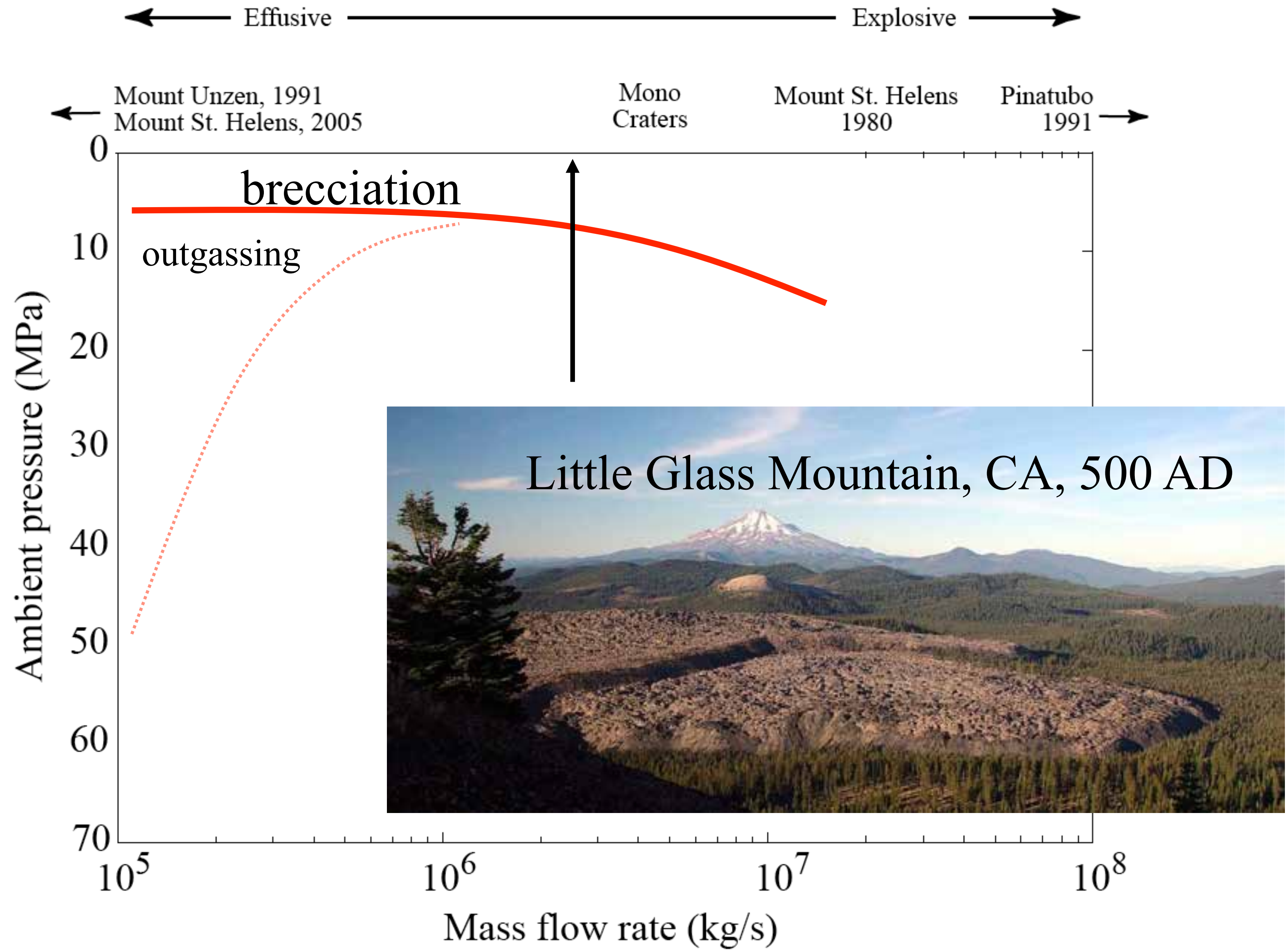
Open questions:

- When, where and how does fragmentation occur?
- Why so much diversity in eruption style?

Change in eruption style with changing ascent rate

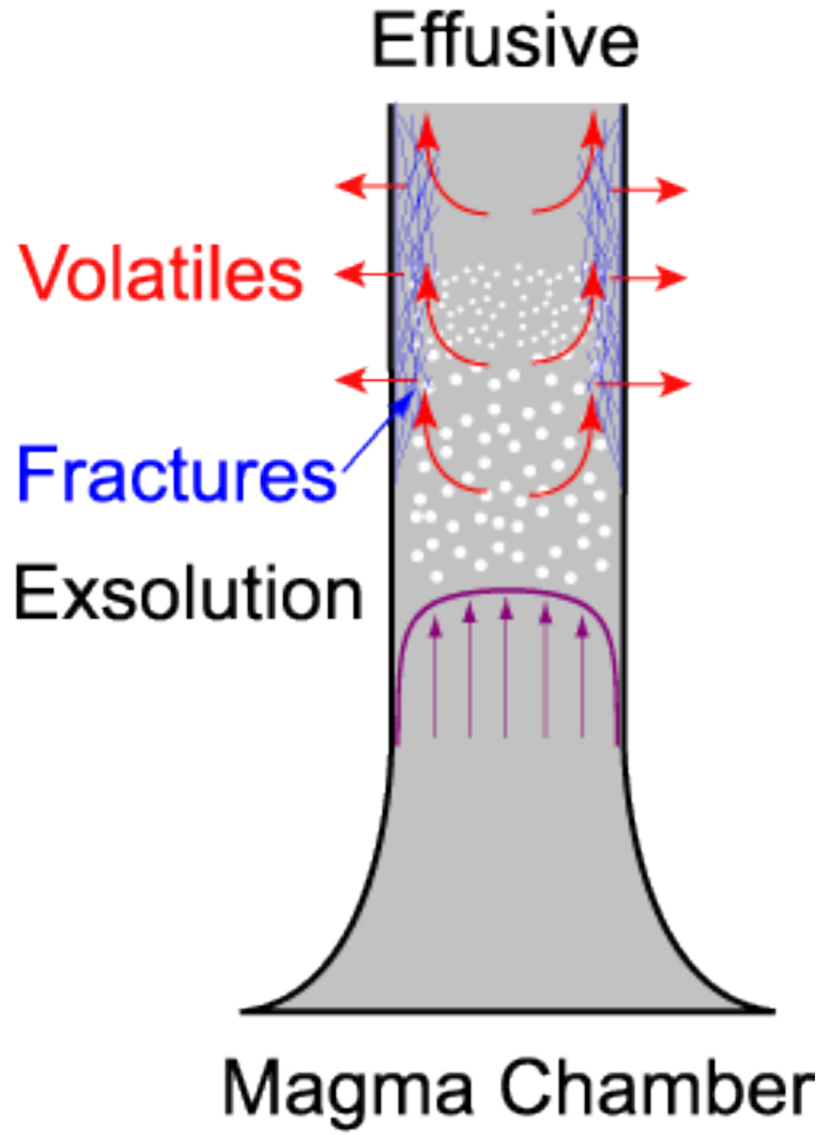


Change in eruption style with changing ascent rate

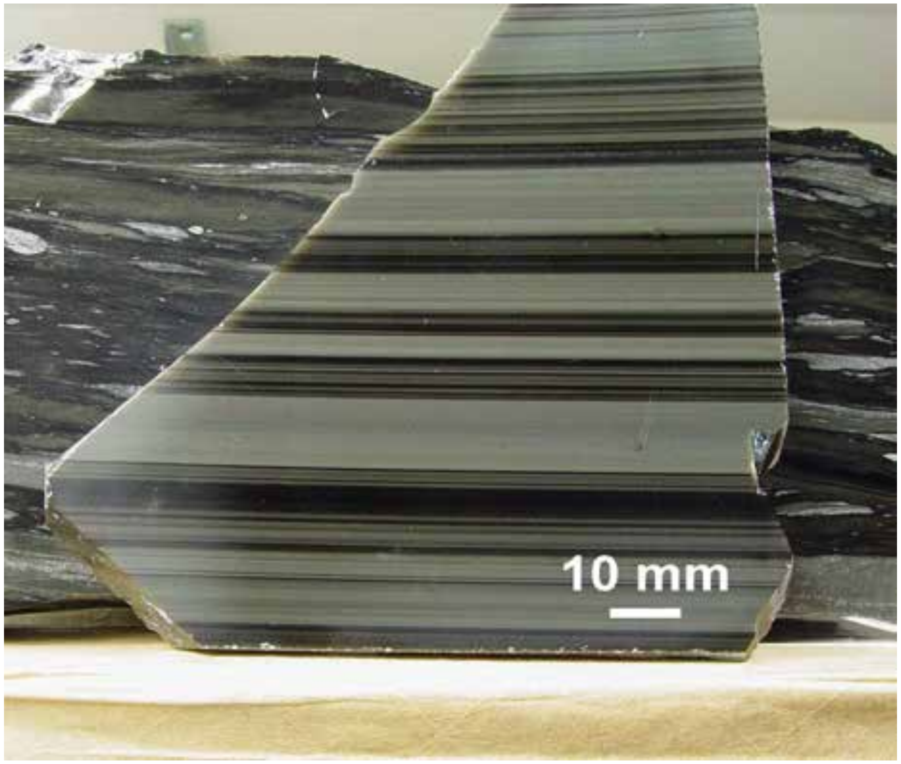


We predict that flow-induced fragmentation (brecciation) occurs at the sides of conduits

Is there any evidence that this occurs?

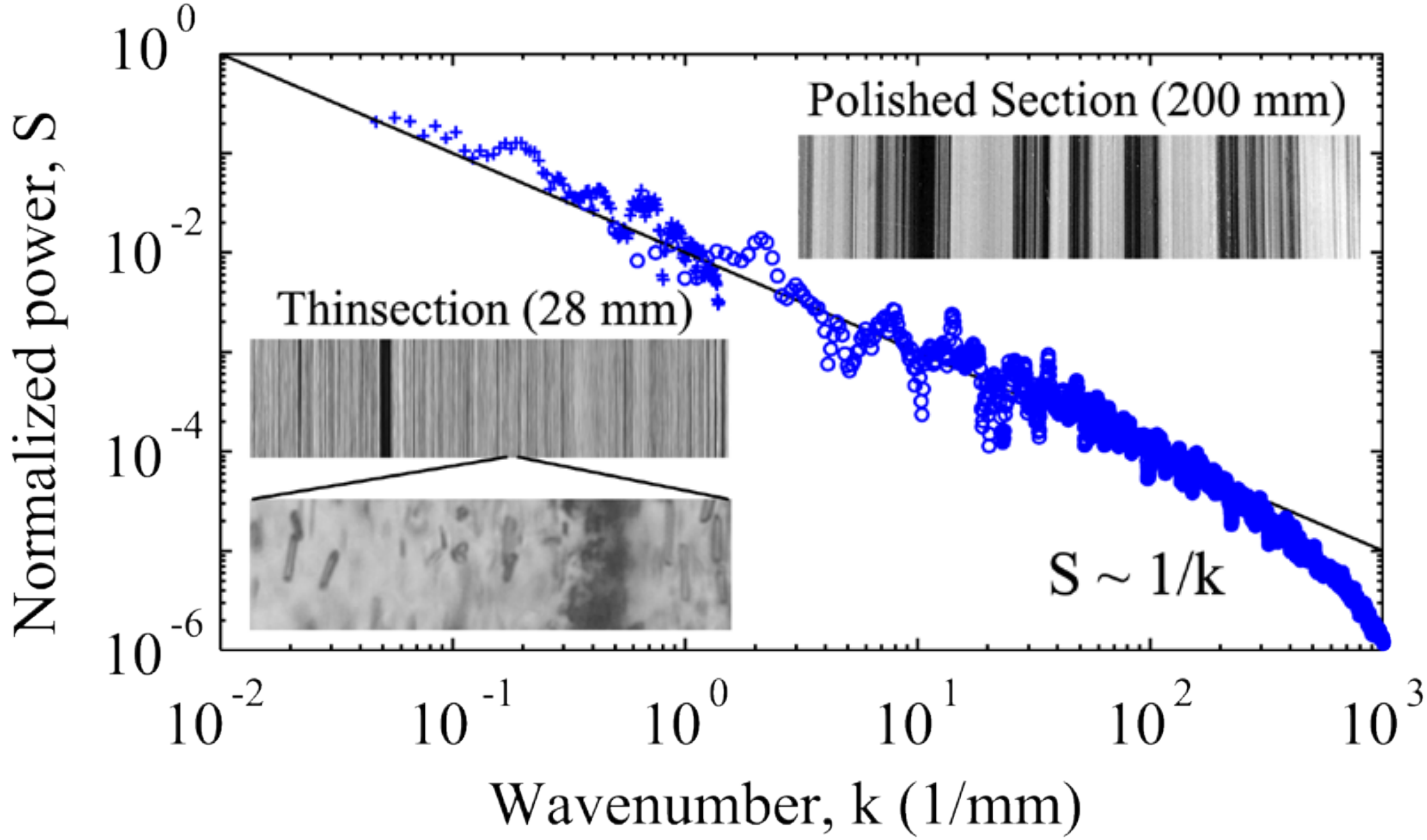


Obsidian is banded at all scales



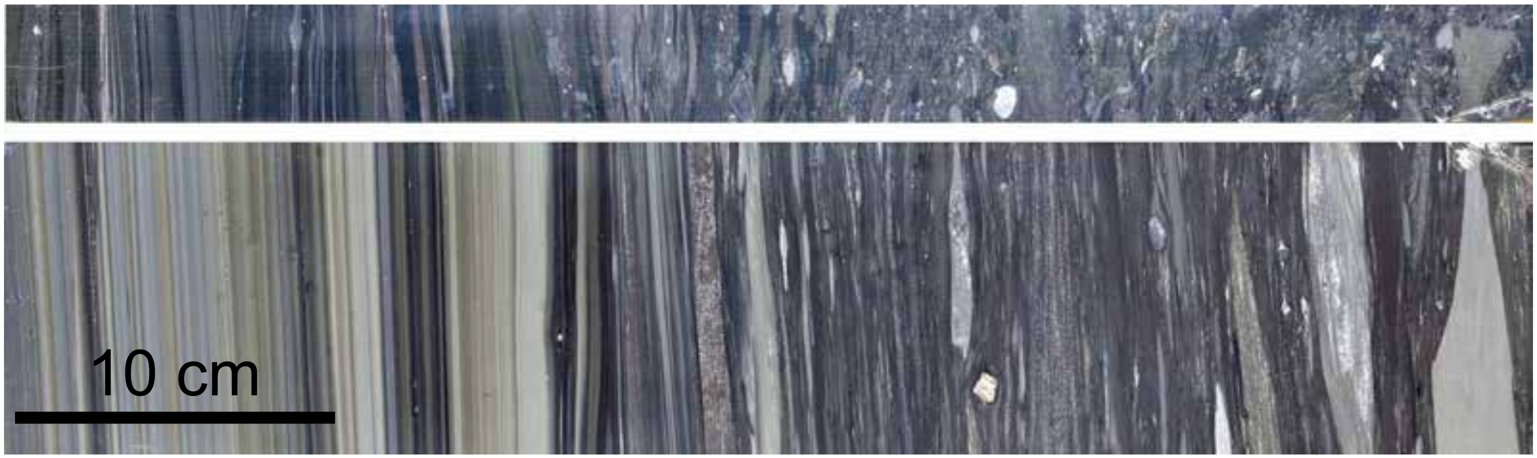
Do these bands (in some cases) record fragmentation?

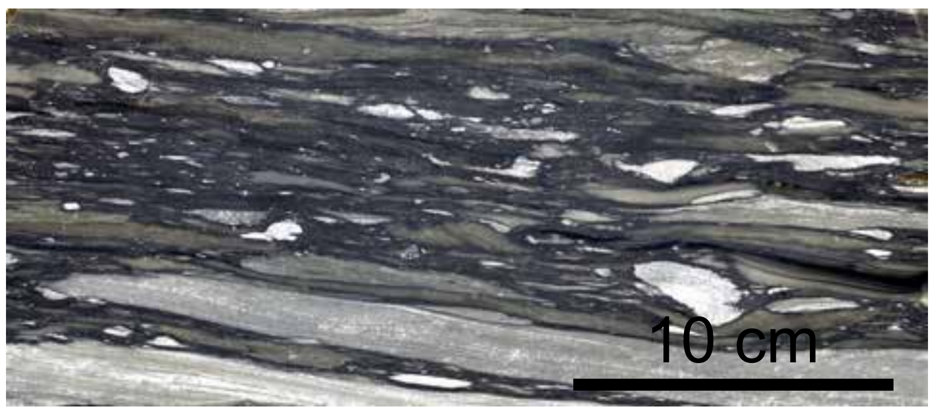
Power spectrum: Scale invariant banding



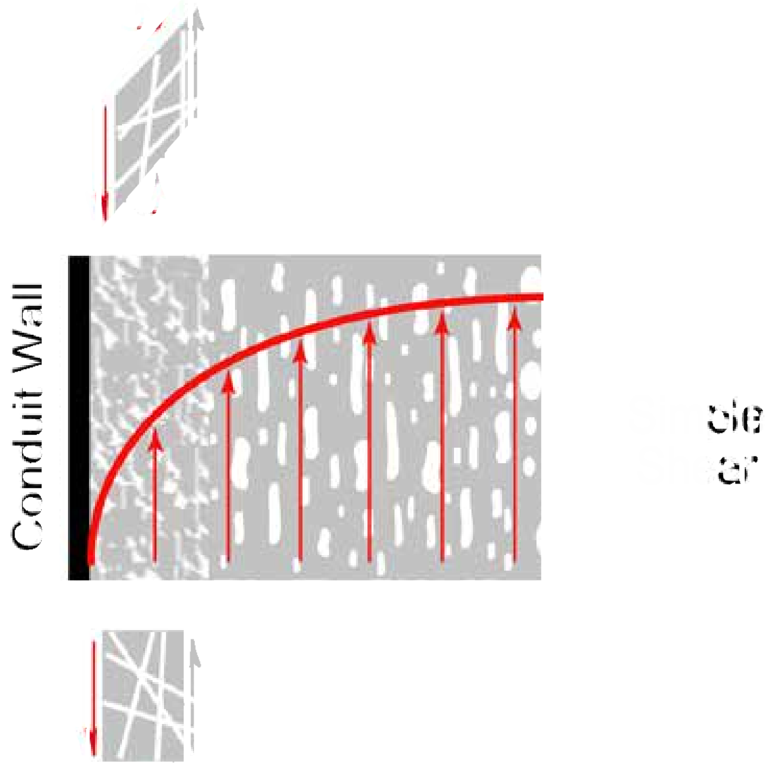
Band widths are scale invarient over 4 orders of magnitude

Brecciation, rewelding and deformation



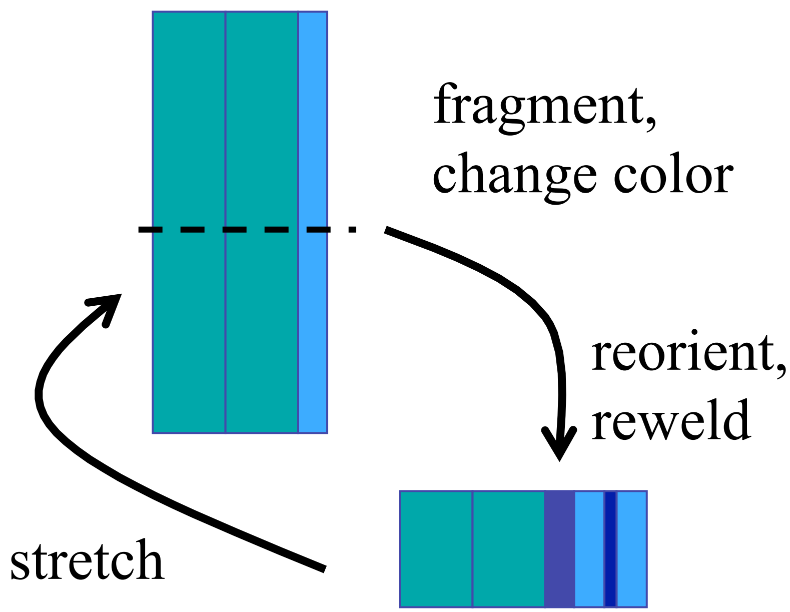


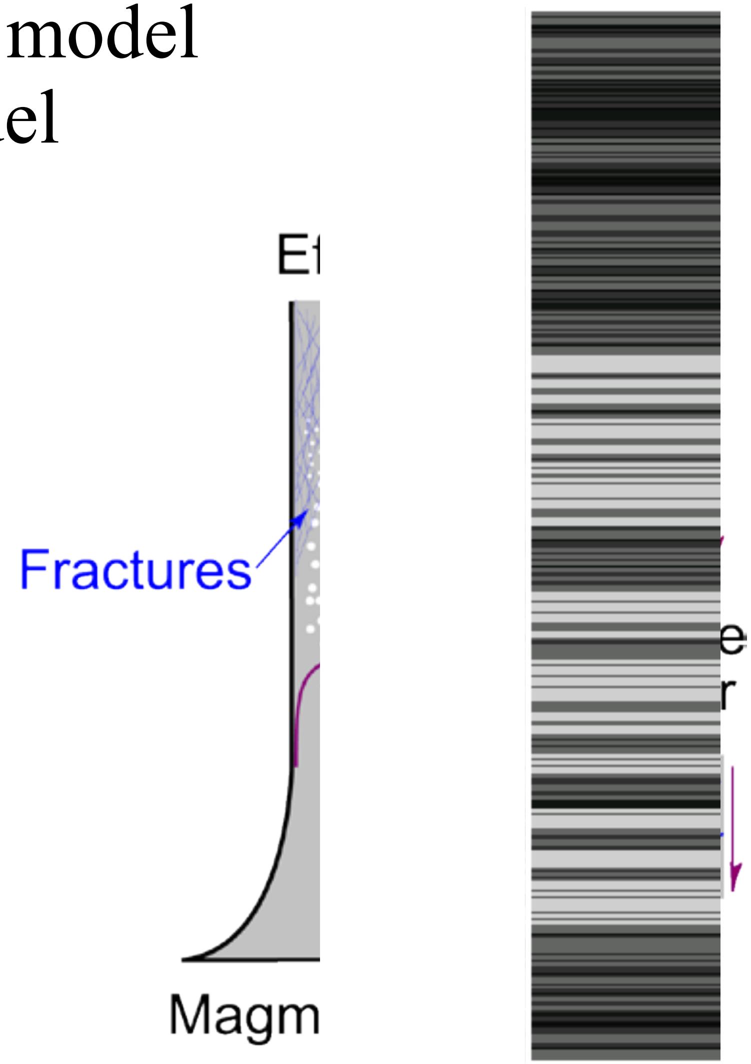
Simple shear . . . .



. . . . rotation and stretching

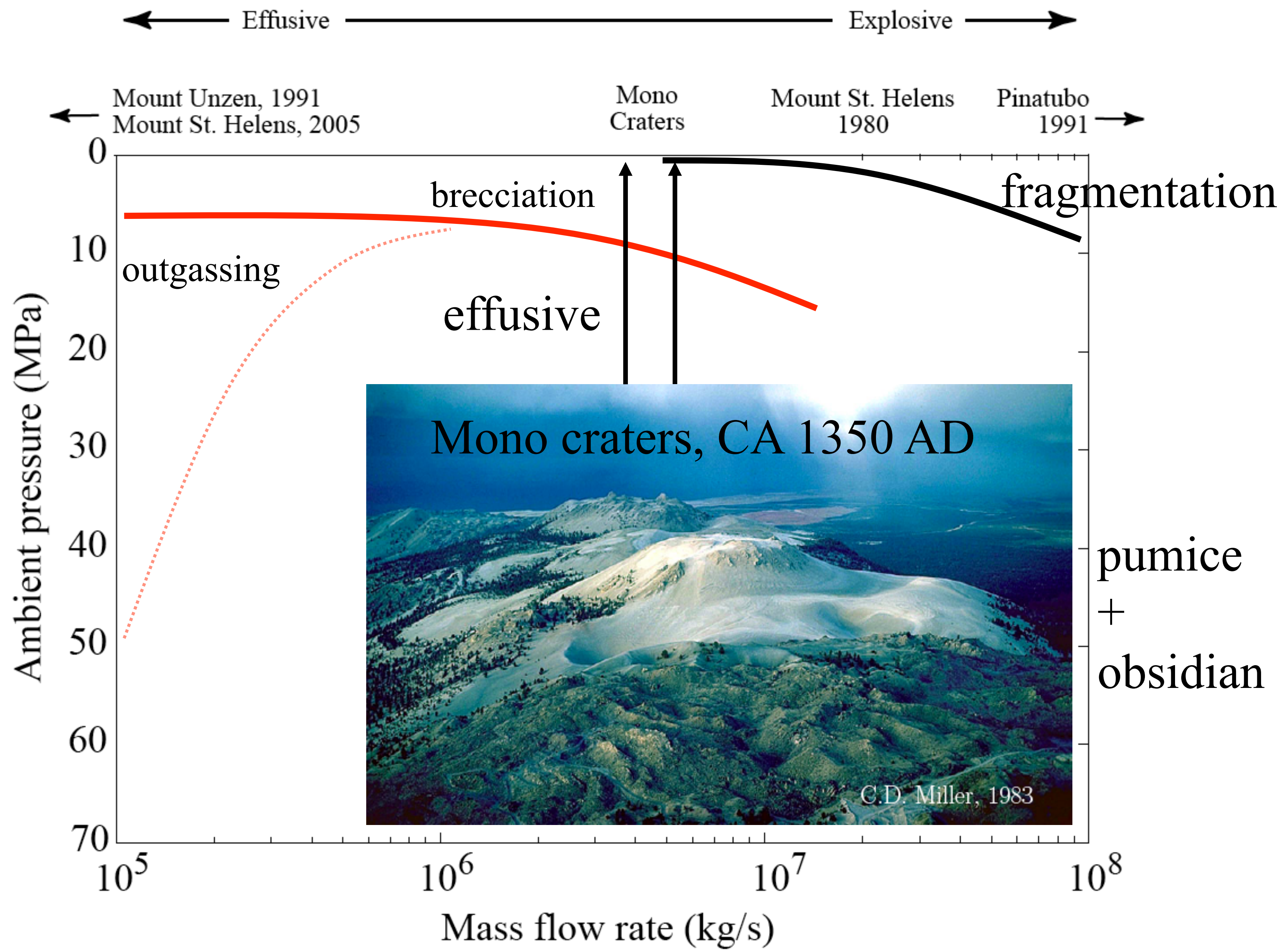
A representative model
Cantor model





Bands consistent with repeated brecciation, reorientation of fragments, welding (stick back together) and stretching (reproduce power law and multifractal characteristic of bands)

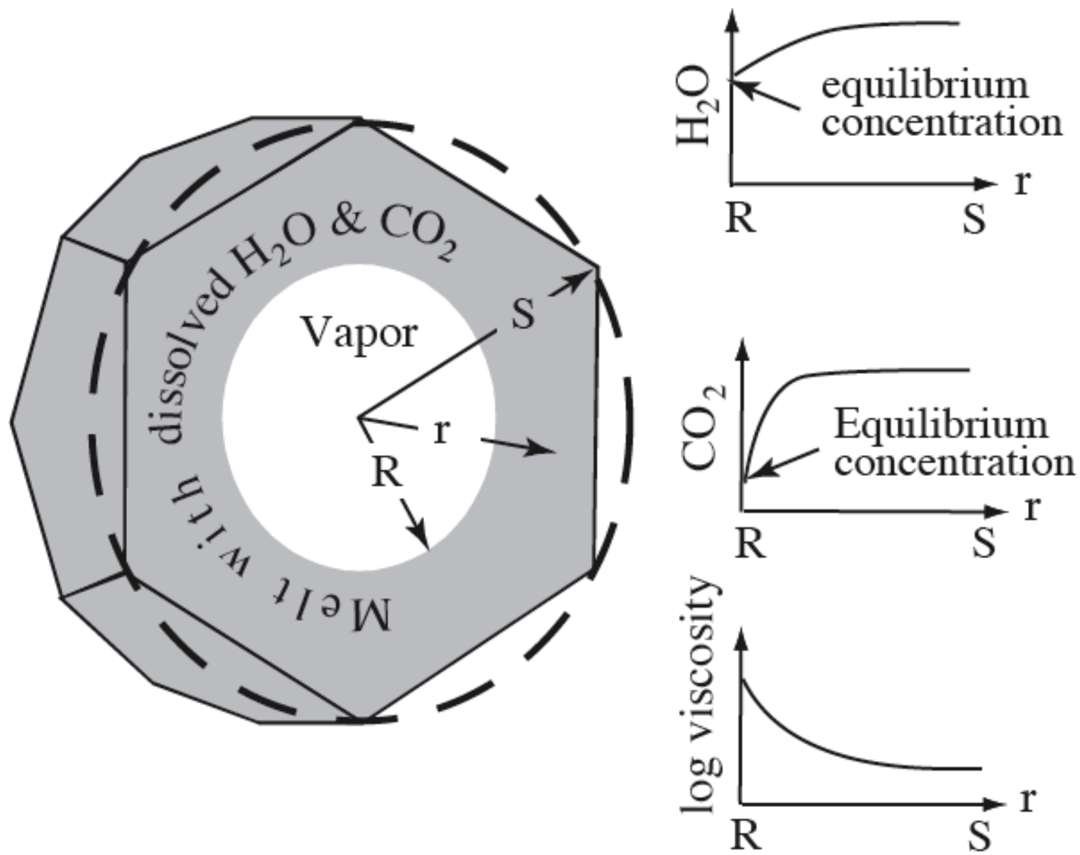
Change in eruption style with changing ascent rate



Mono Crater, CA

Test models using the measured concentration of water and CO_2

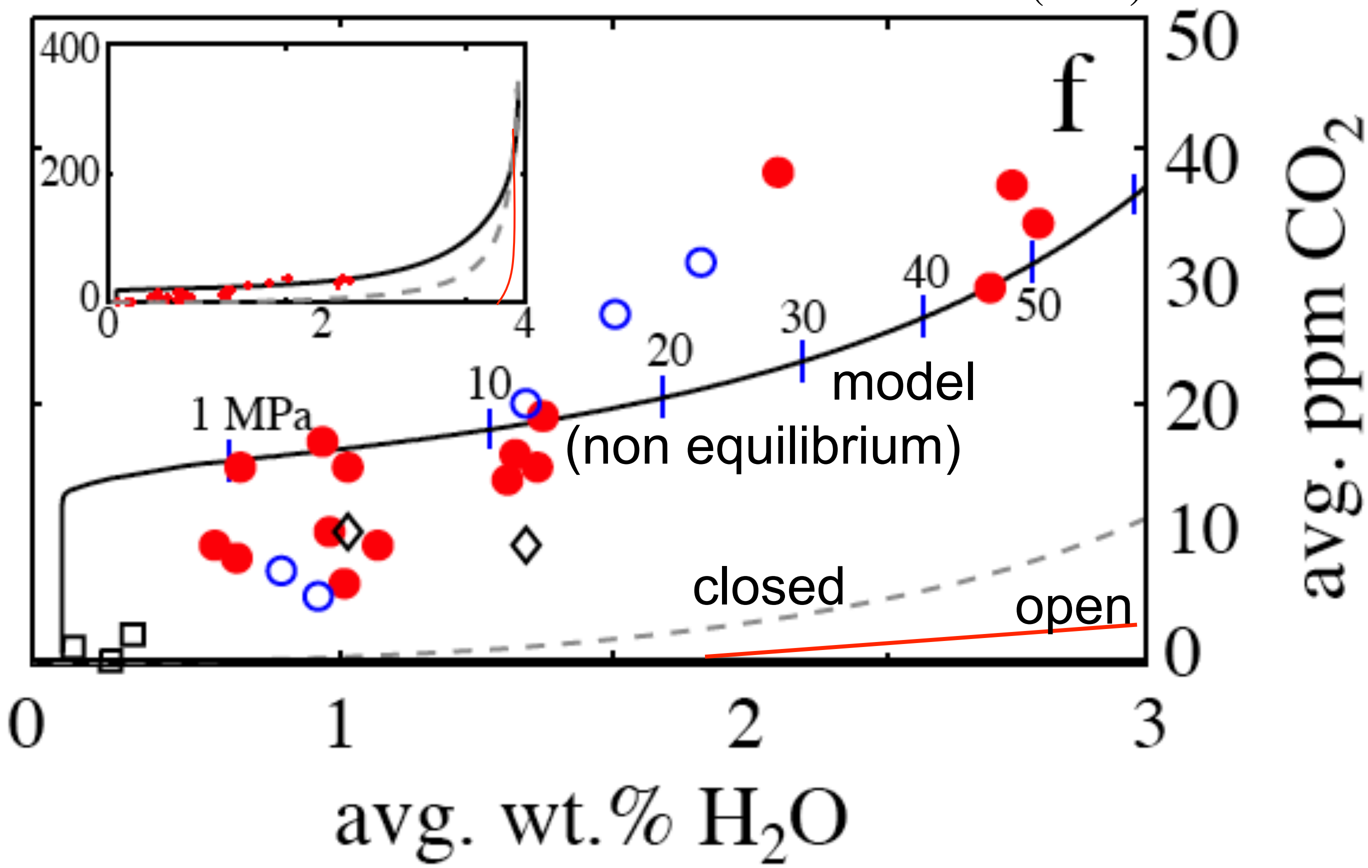
Water diffuses faster than CO_2



Concentration of gases in bubbles is not necessarily
in equilibrium with that in the melt (diffusion limited growth)

Water diffuses faster

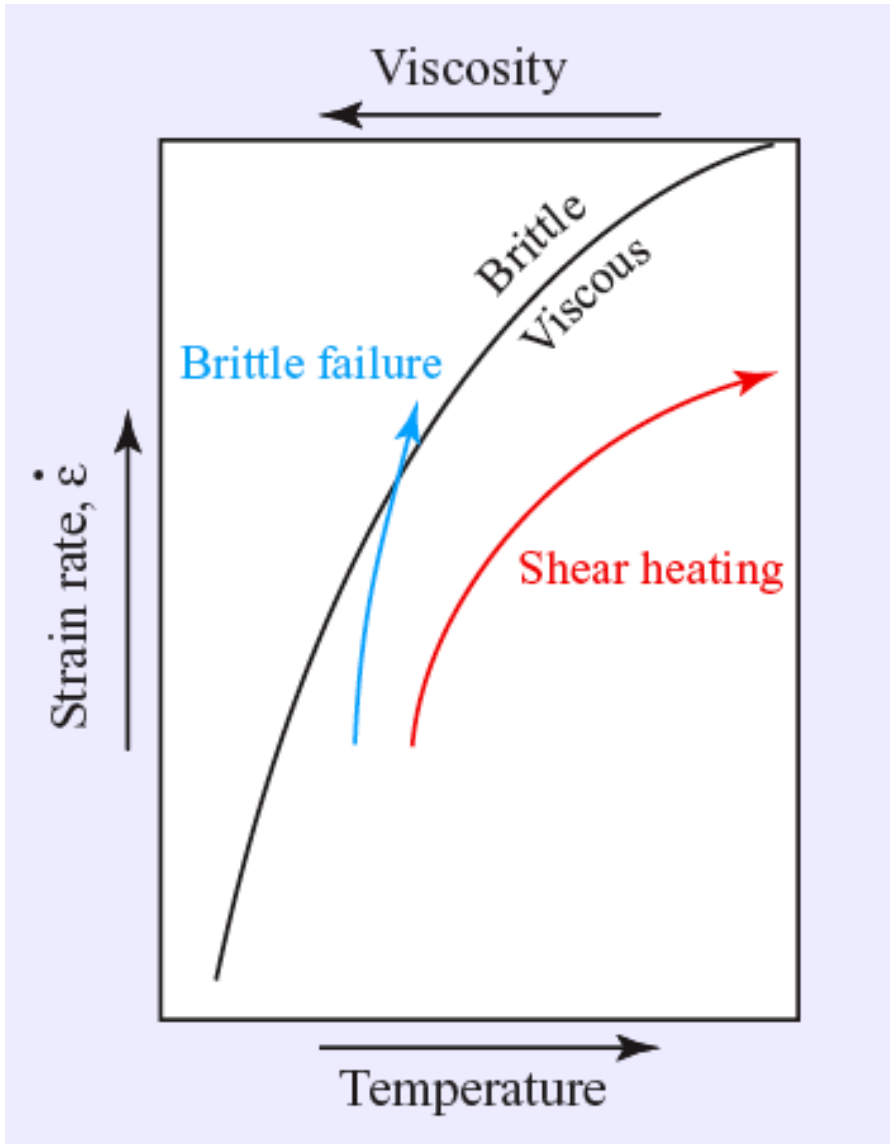
Data from Neuman et al. (1989)



Ascent rate to match data similar to other estimates

Does brecciation always happen?

Not if the magma rises fast enough



Does brecciation always happen?

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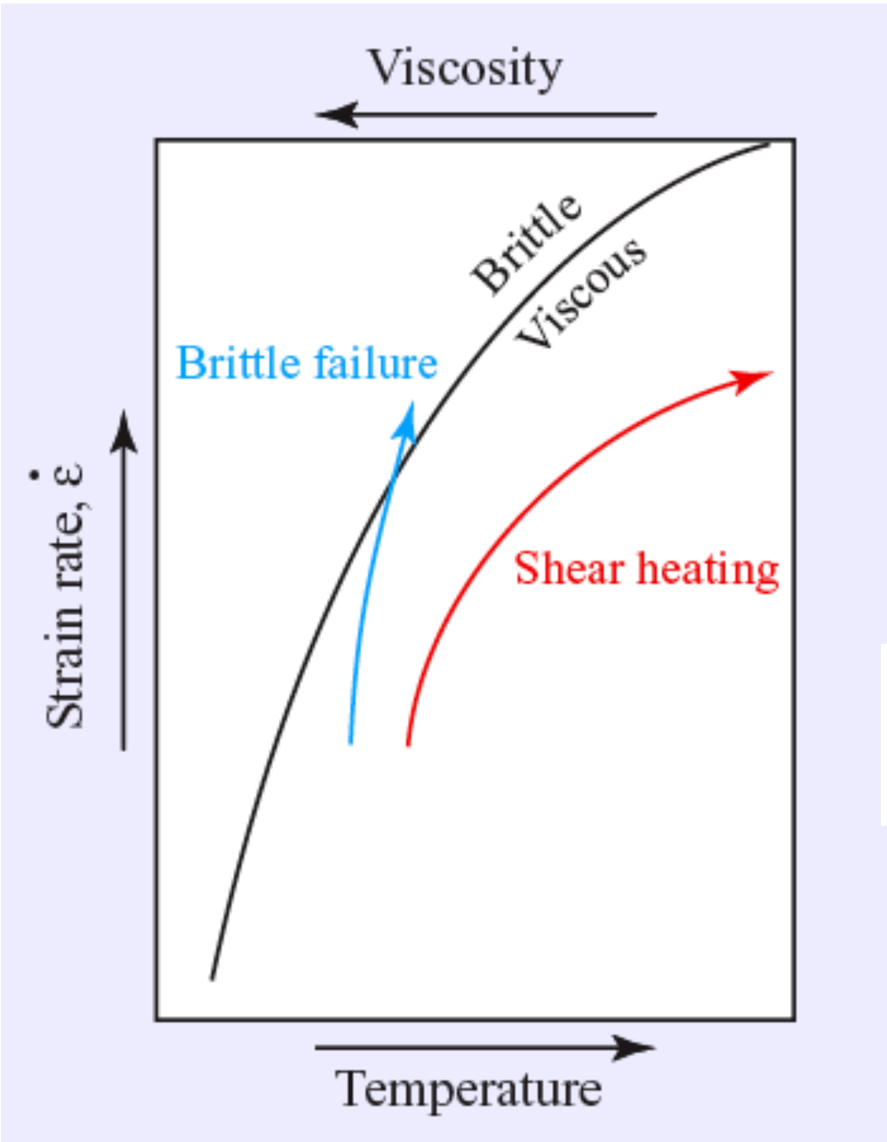
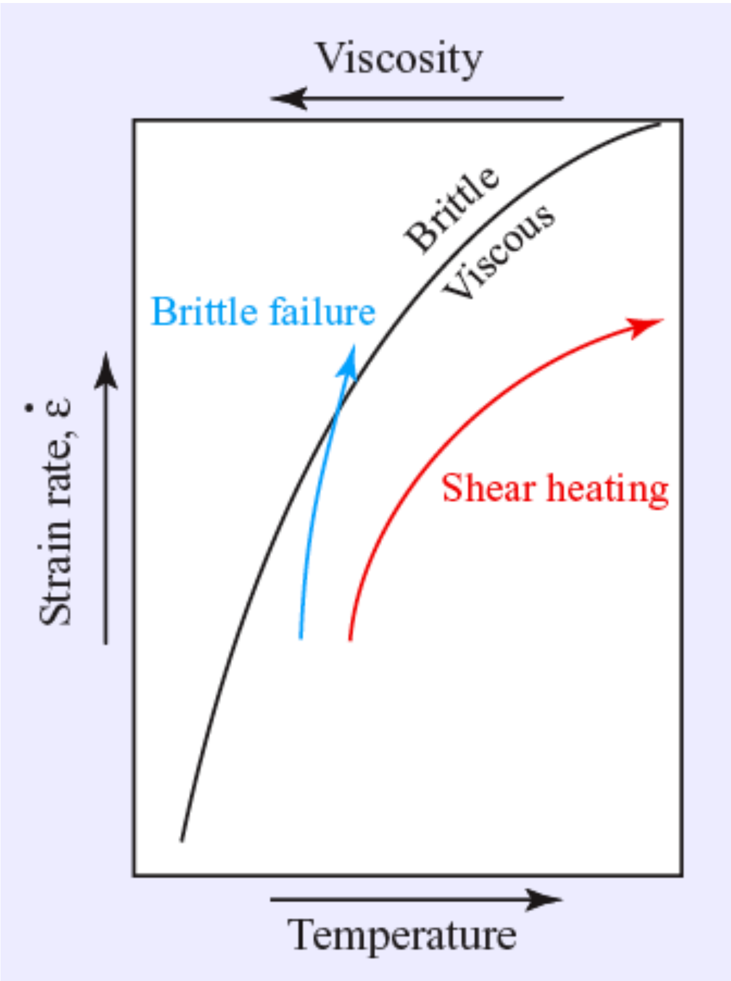


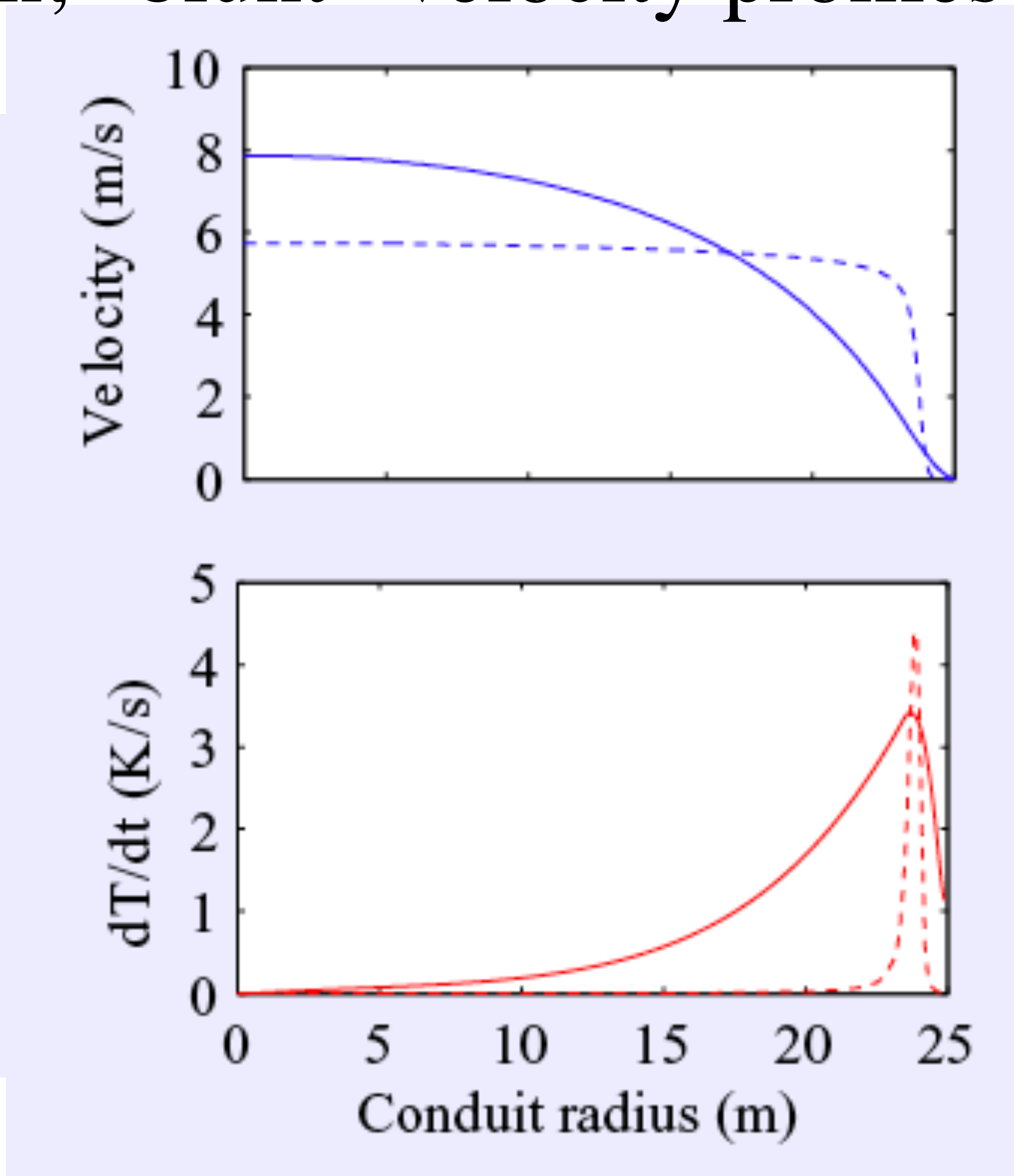
Viscous dissipation important when Brinkman number (viscous dissipation/heat diffusion)

$$\mathrm{Br} = \frac{\eta\ \dot{Q}_m^2}{c_{pm}\ \rho_m^3\ D_T\ \Delta T\ a^4\,(1-\phi)^2}$$

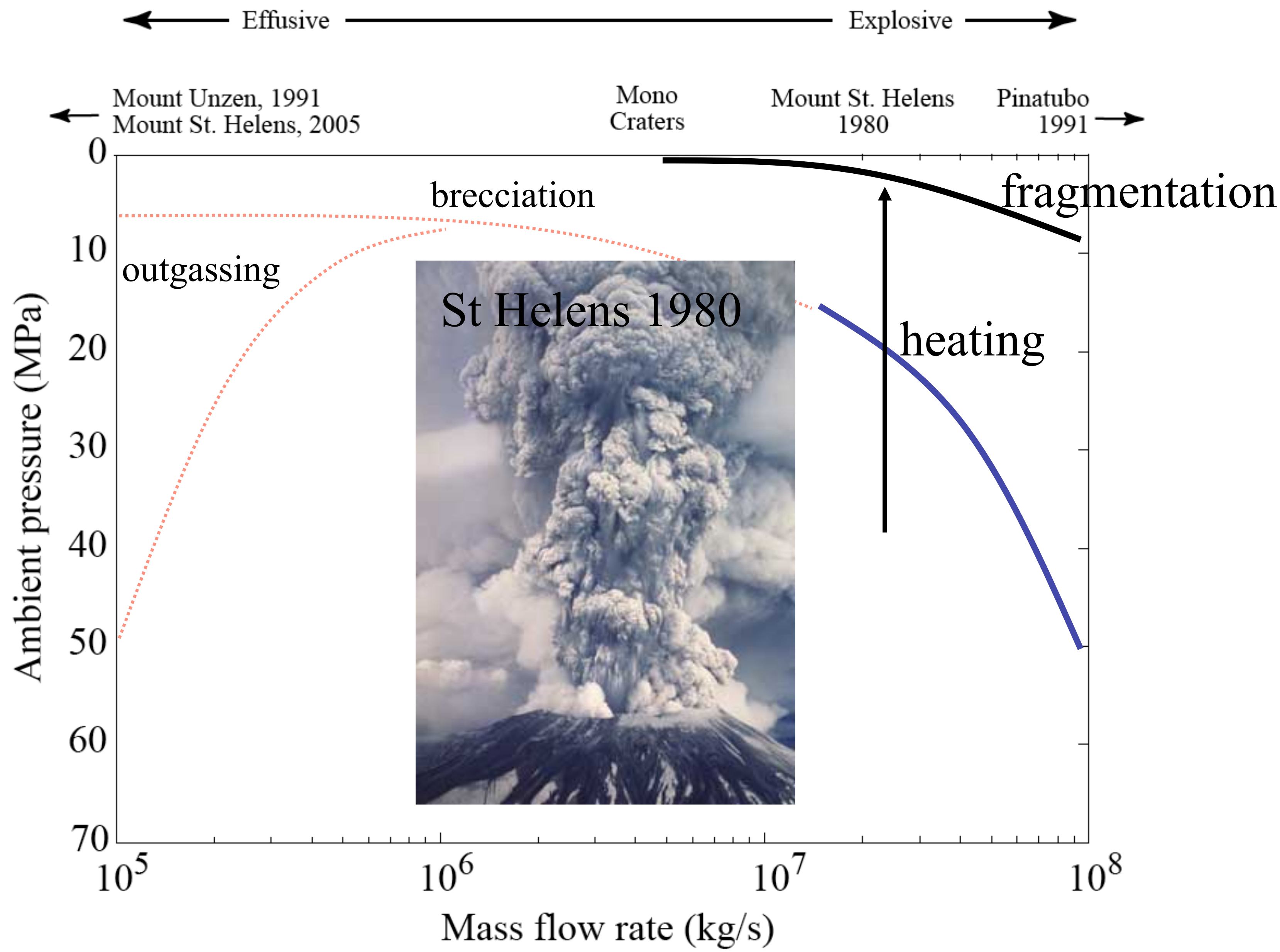
becomes large

Implications:
no brecciation, “blunt” velocity profiles





Change in eruption style with changing ascent rate



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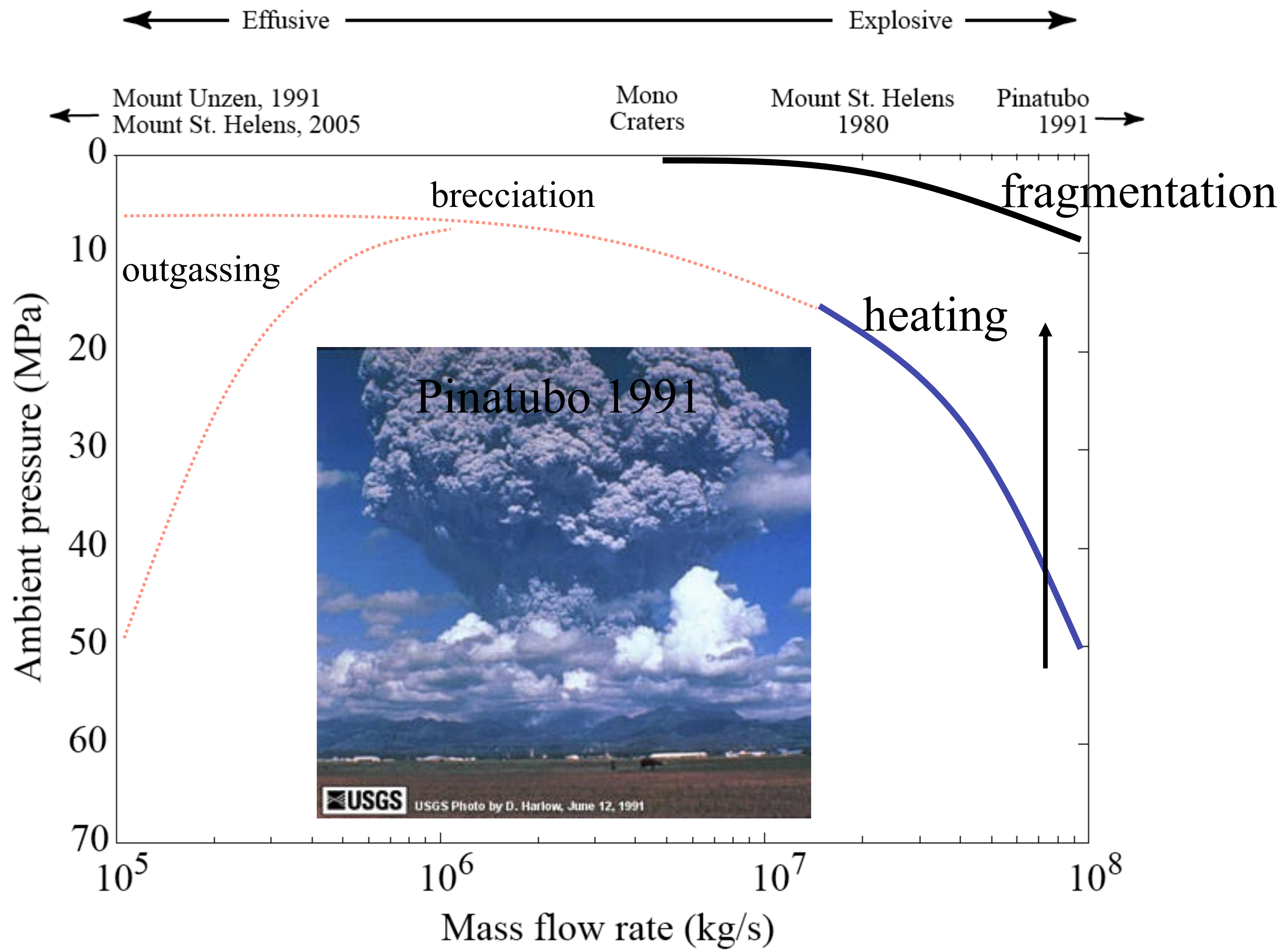
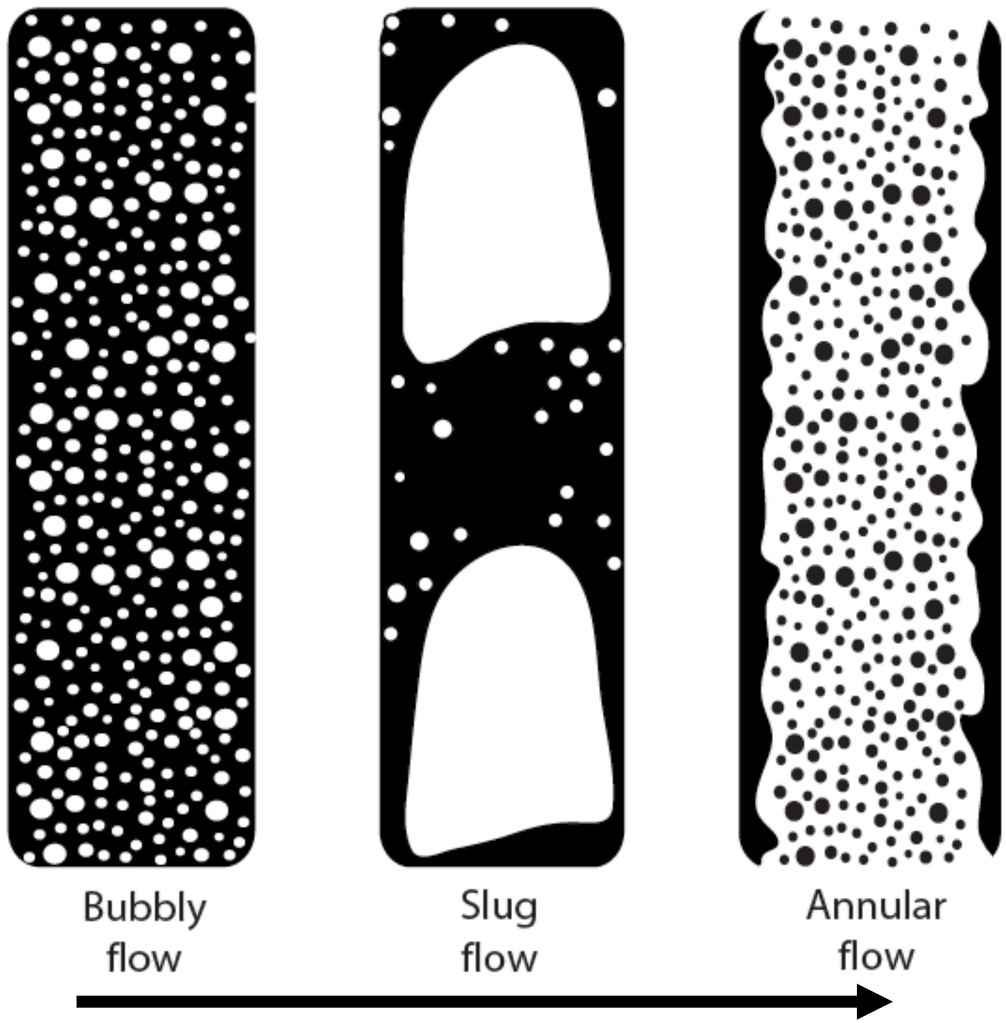
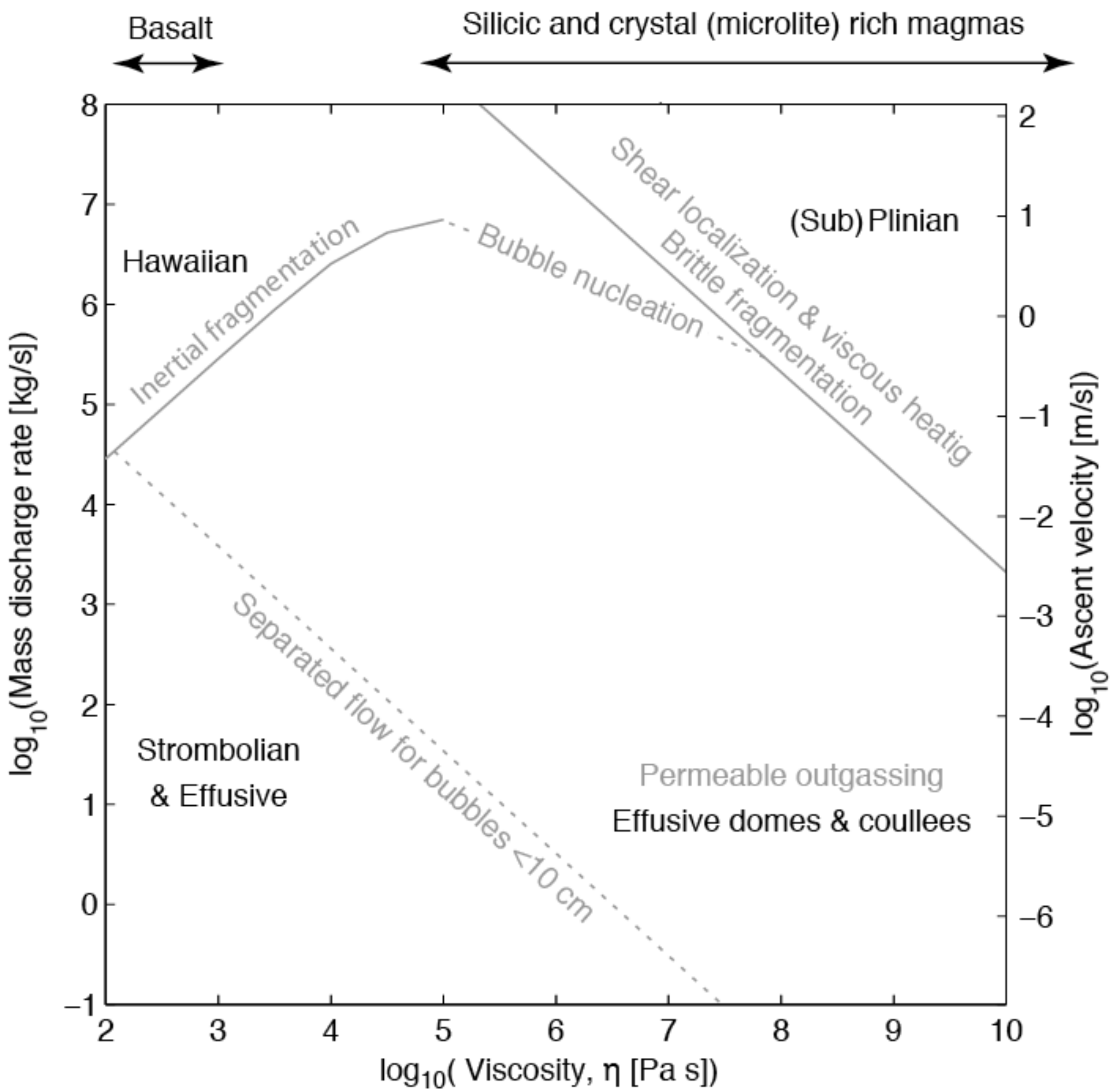


Basaltic (low viscosity) eruptions

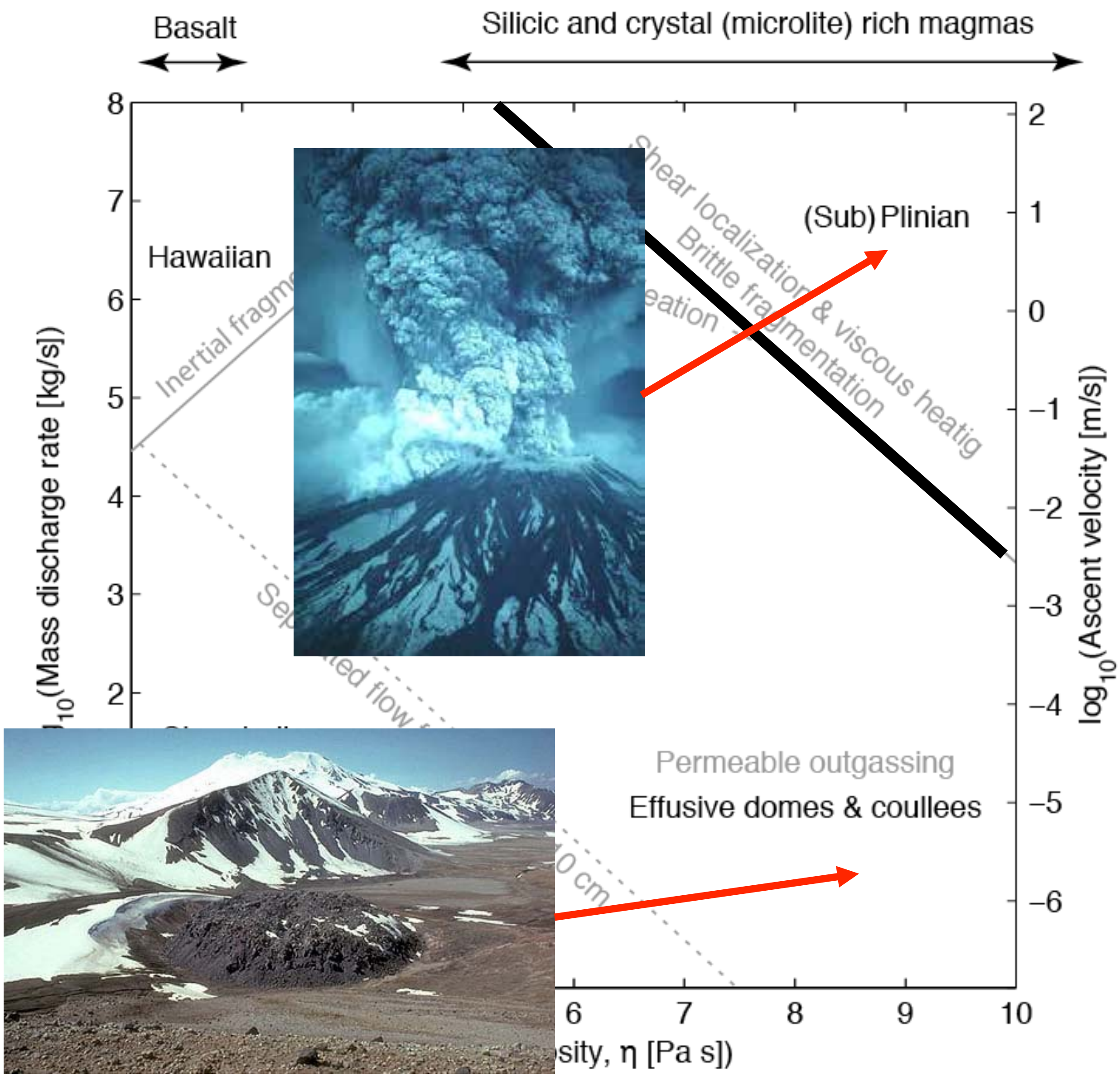


Increasing bubble/melt speed and volume fraction of bubbles

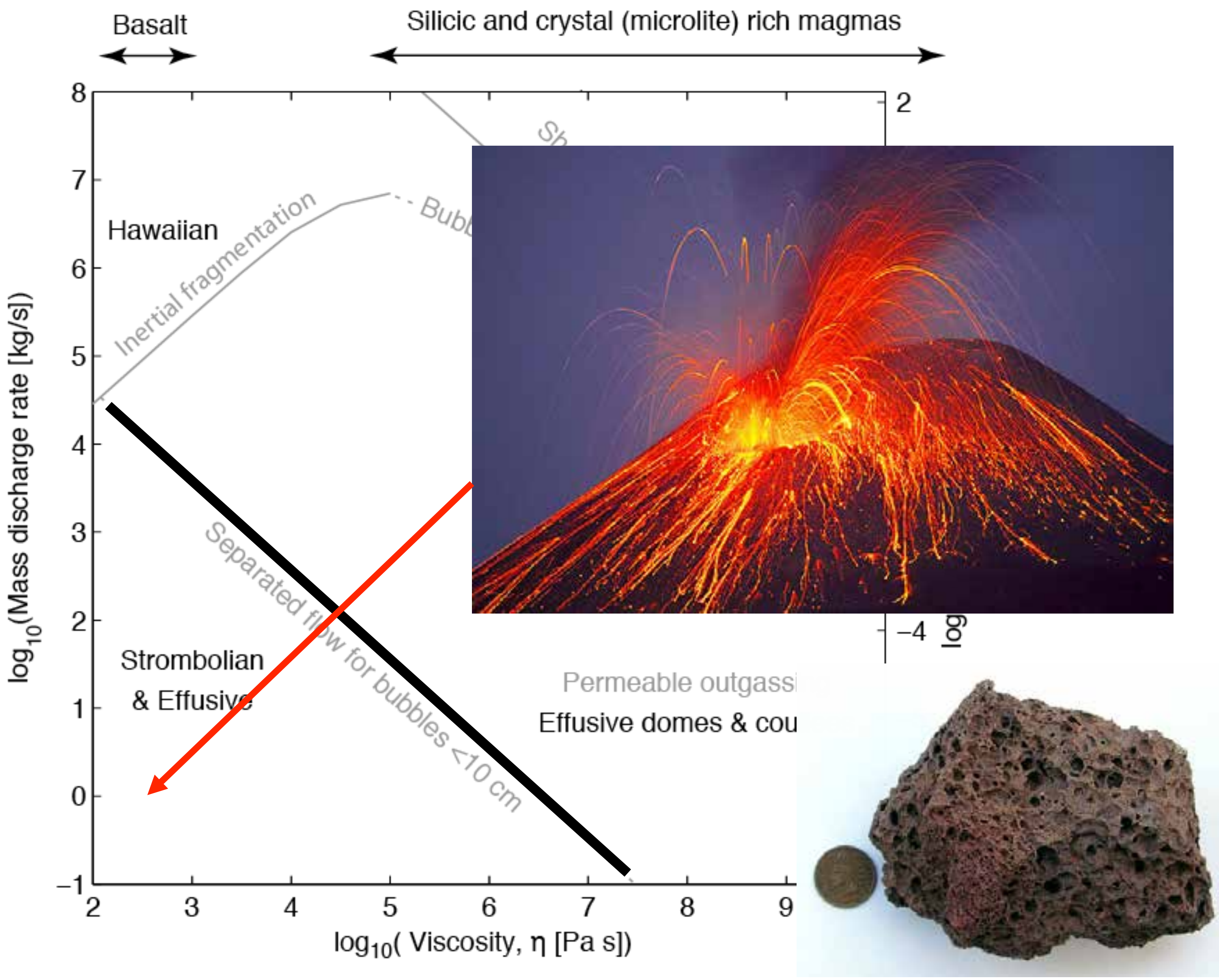
Basaltic eruption styles



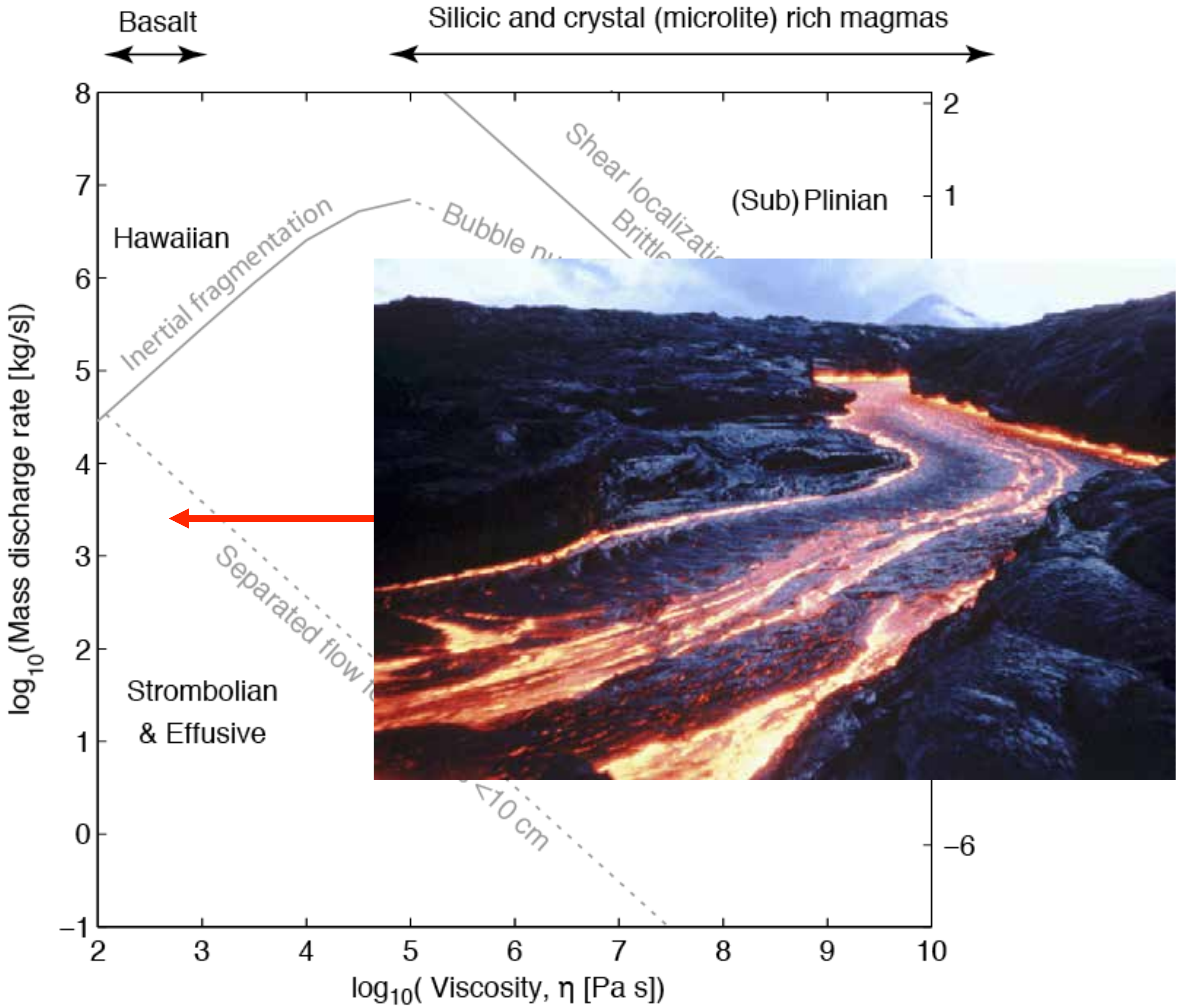
Basaltic eruption styles



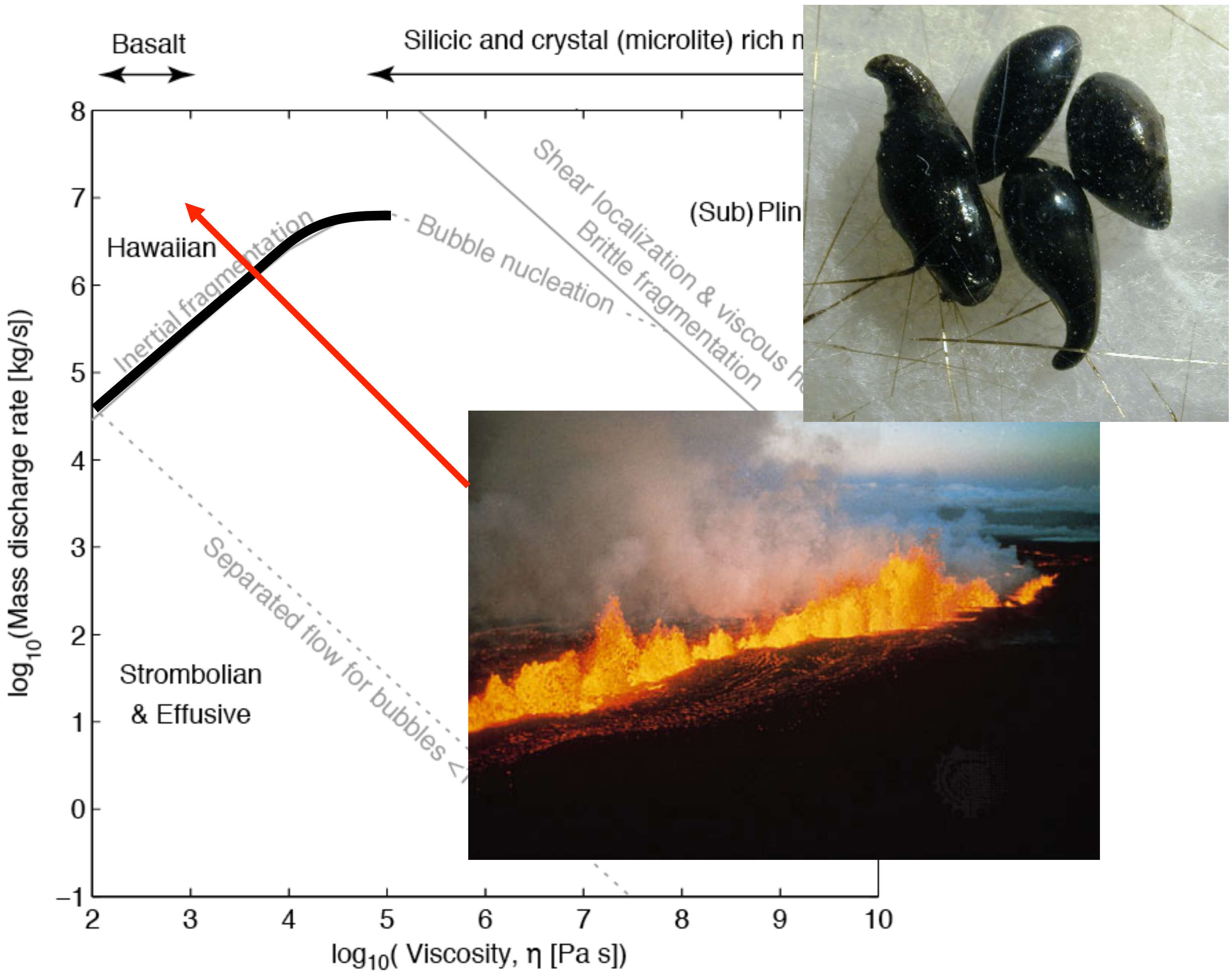
Basaltic eruption styles



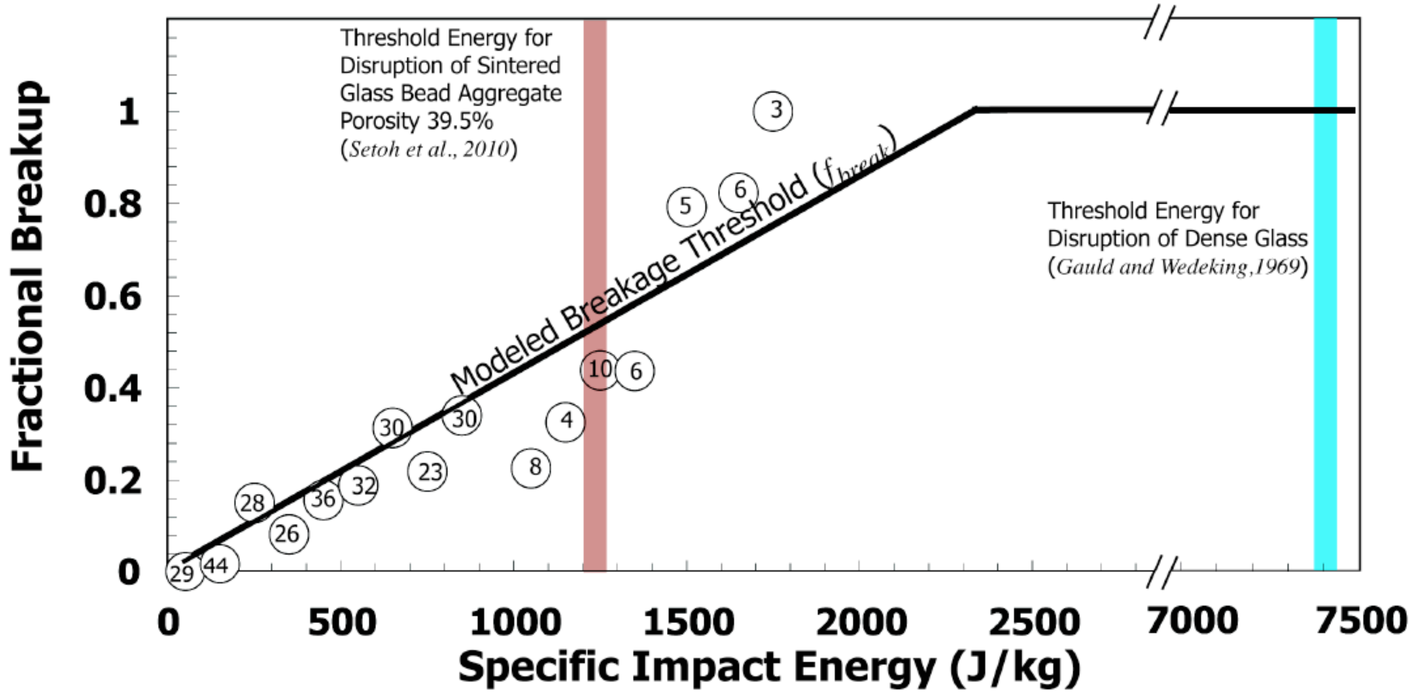
Basaltic eruption styles



Basaltic eruption styles



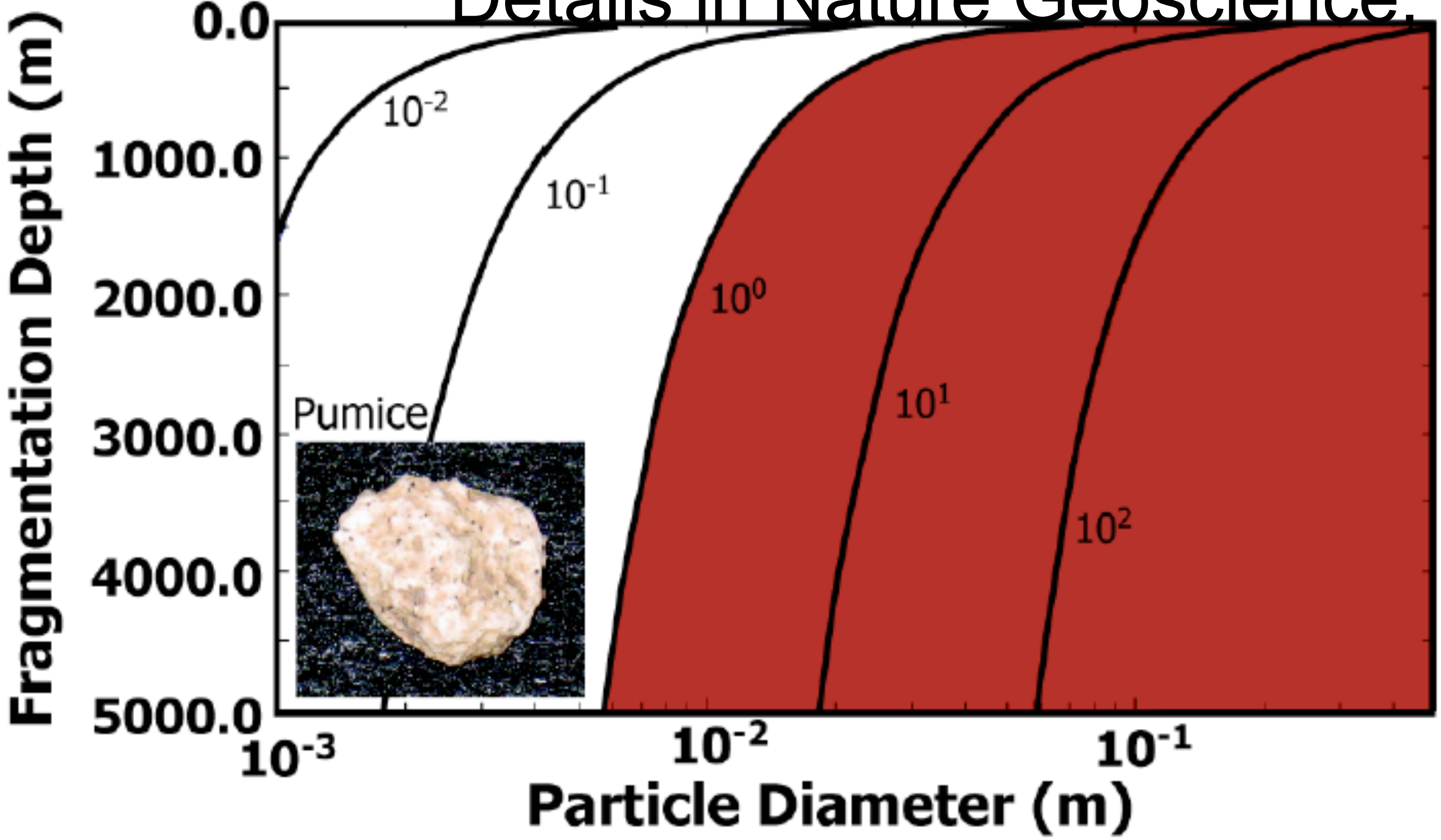
Pumice clasts can break if collisions are energetic enough



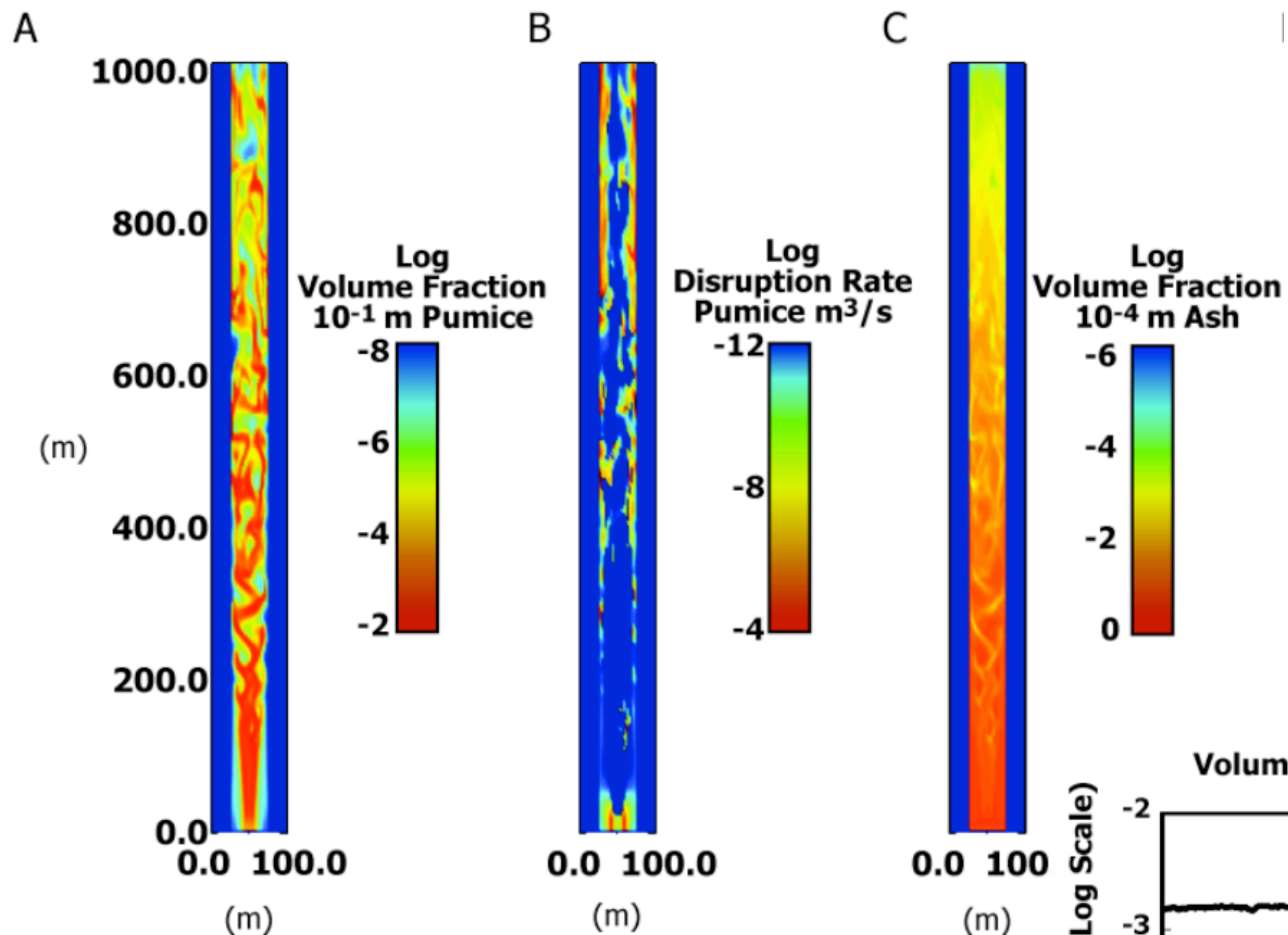
Will large pumice clasts breakup before exiting volcanic conduits?

Analytical model

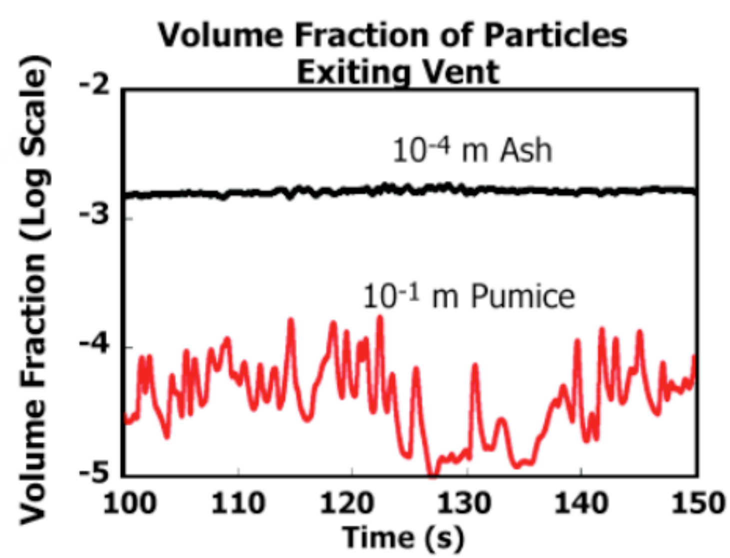
Details in Nature Geoscience, 2012



- Assumptions: choked flow (exit velocity is the speed of sound in a dusty gas)
- Dissipation of granular energy balanced by production owing to shear



Numerical simulations



Lagrangian particles

Equation of motion of particle

$$\frac{du_i^p}{dt} = F_g + F_s + g\left(\frac{2\rho_p - 2\rho_g}{2\rho_p + \rho_g}\right)\delta_i$$

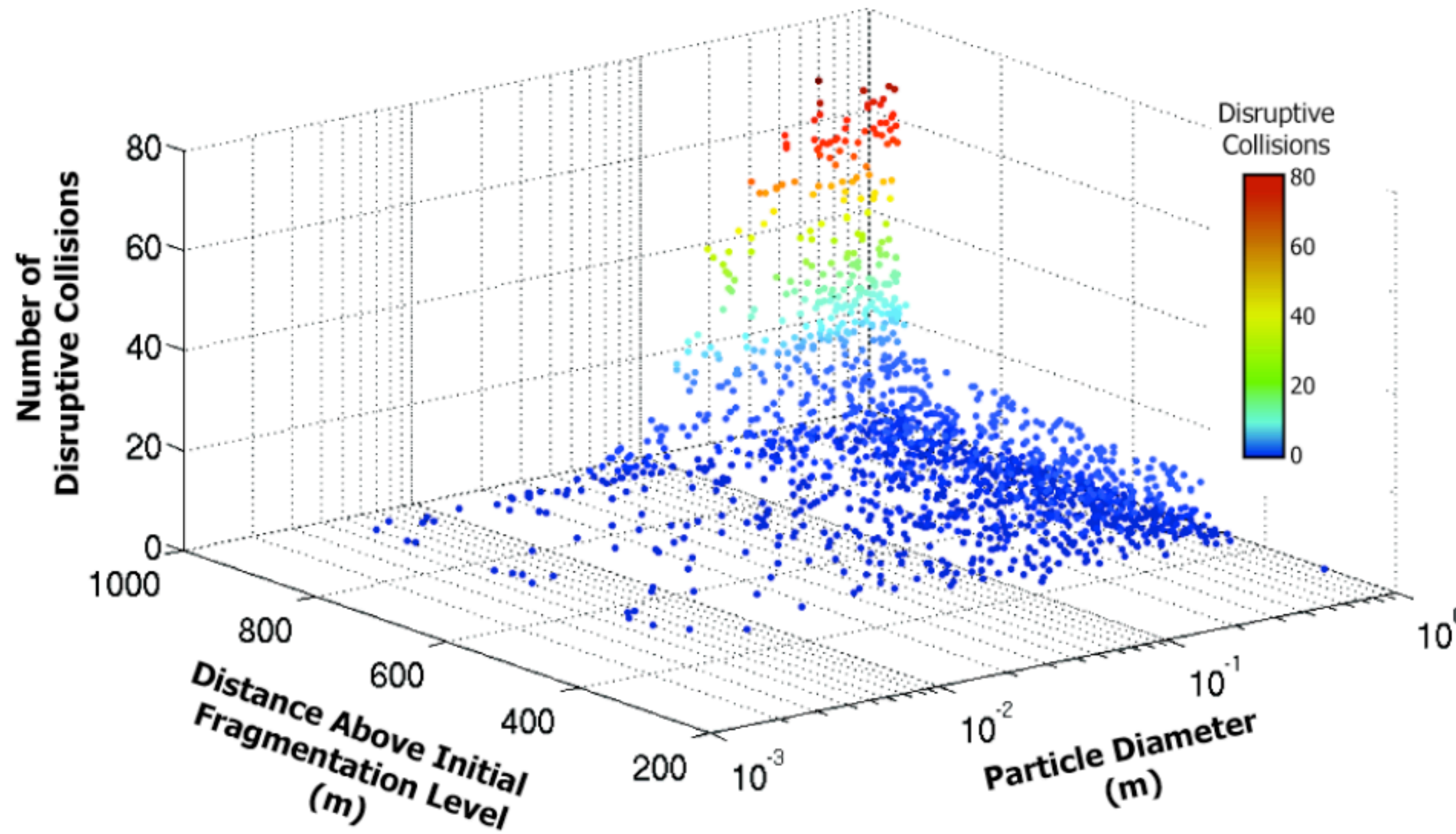
drag from gas

effects of collisions

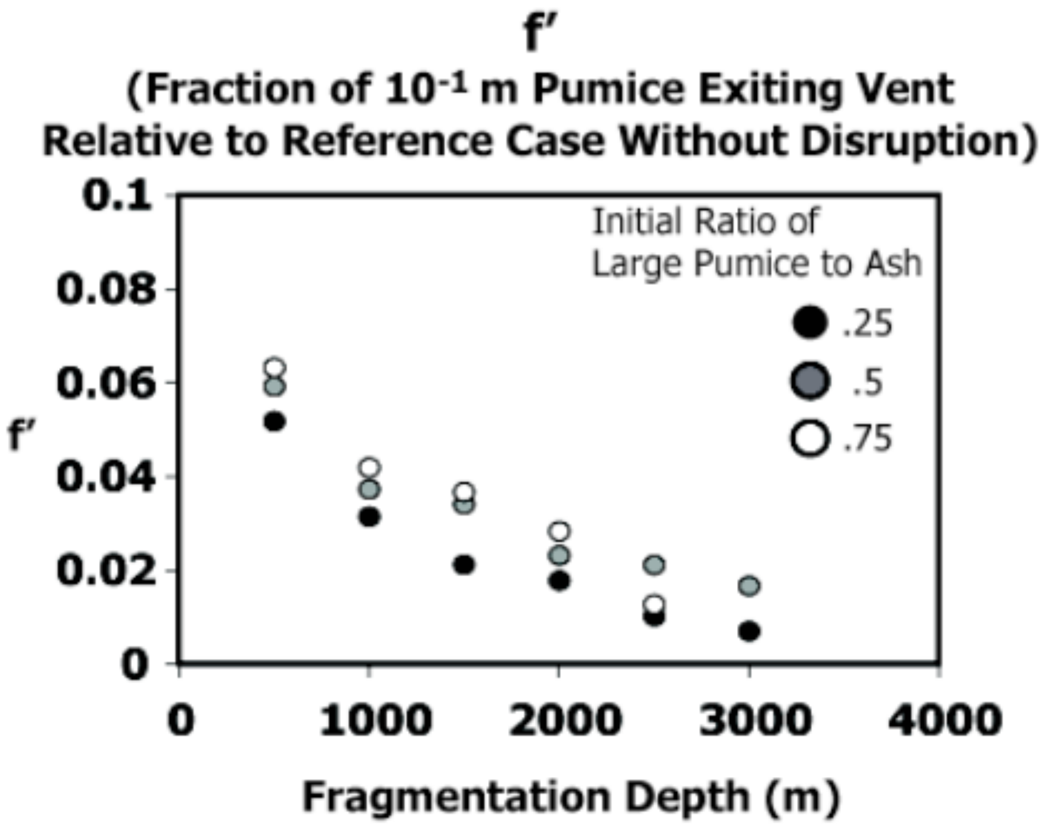
buoyancy force

Detailed expressions in Dufek, Wexler and Manga, *J Geophys Res* (2009)

Lagrangian analysis



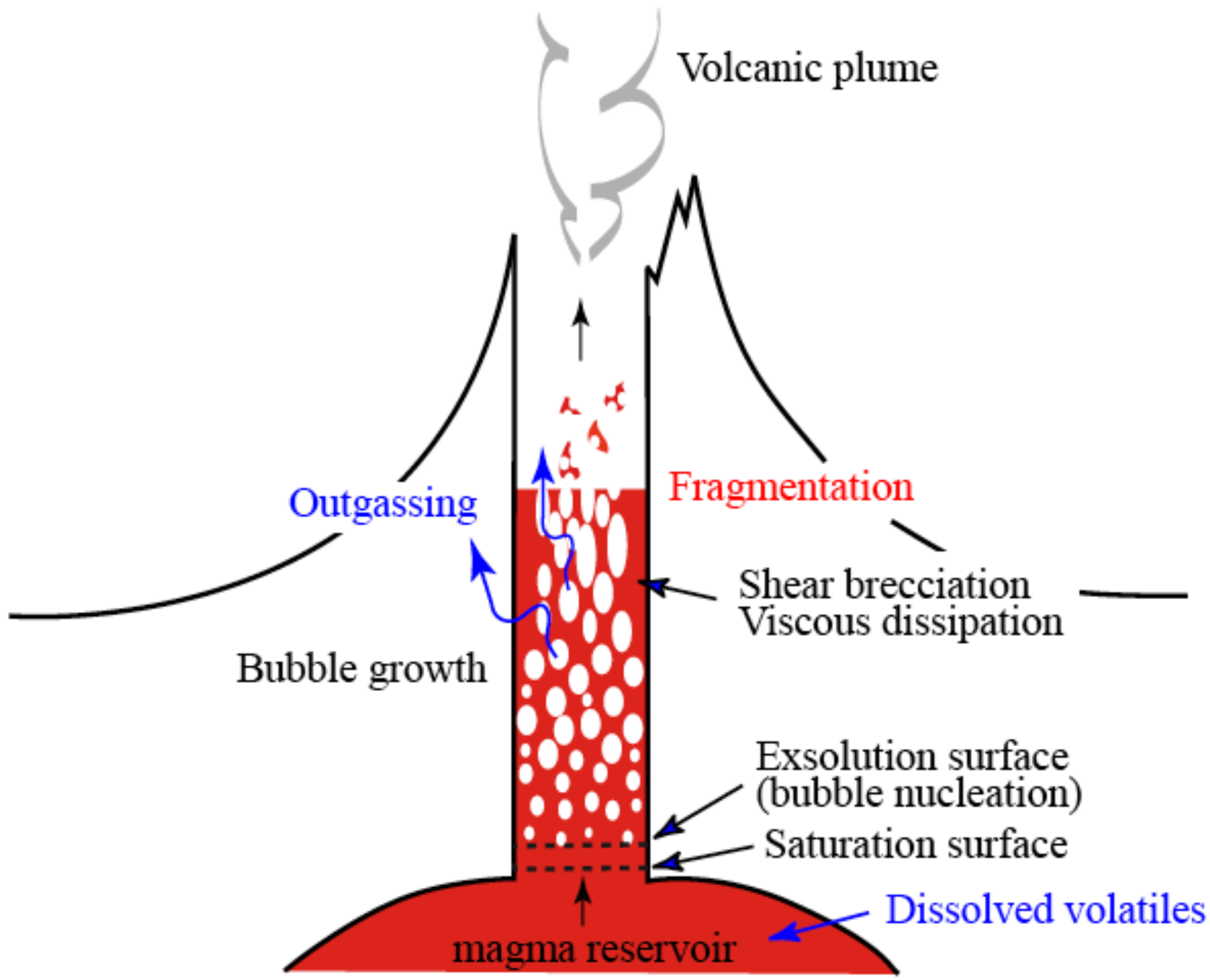
Most large clasts are disrupted for fragmentation > few 100 m



Governing physical processes: summary

Dimensionless number	Process	Value and effect
Reynolds number (inertia/viscous forces)	Bubble growth Magma ascent	<< 1 $<10^3$; laminar flow prior to fragmentation
Peclet number (diffusion/decompression timescale)	Diffusive growth	>> 1 for low N_d; supersaturation, nucleation new bubbles
Peclet number (viscous/decompression timescale)	Bubble expansion	>> 1 is viscosity high enough; overpressure, fragmentation
Brinkman number (viscous dissipation/diffusion of heat)	Viscous heating at conduit walls	if large enough, lowers viscous and prevents shear brecciation
Dimensionless shear rates (shear stress/surface tension or shear rate x relaxation time of melt)	Magma ascent	if large enough, shear thinning and blunt velocity profiles; larger still, becciation
Ascent rate bubbles/magma	Bubble separation	

Why do volcanoes (only sometimes) erupt explosively?



- Interplay between bubble growth, brecciation, outgassing, and fragmentation governs eruption style