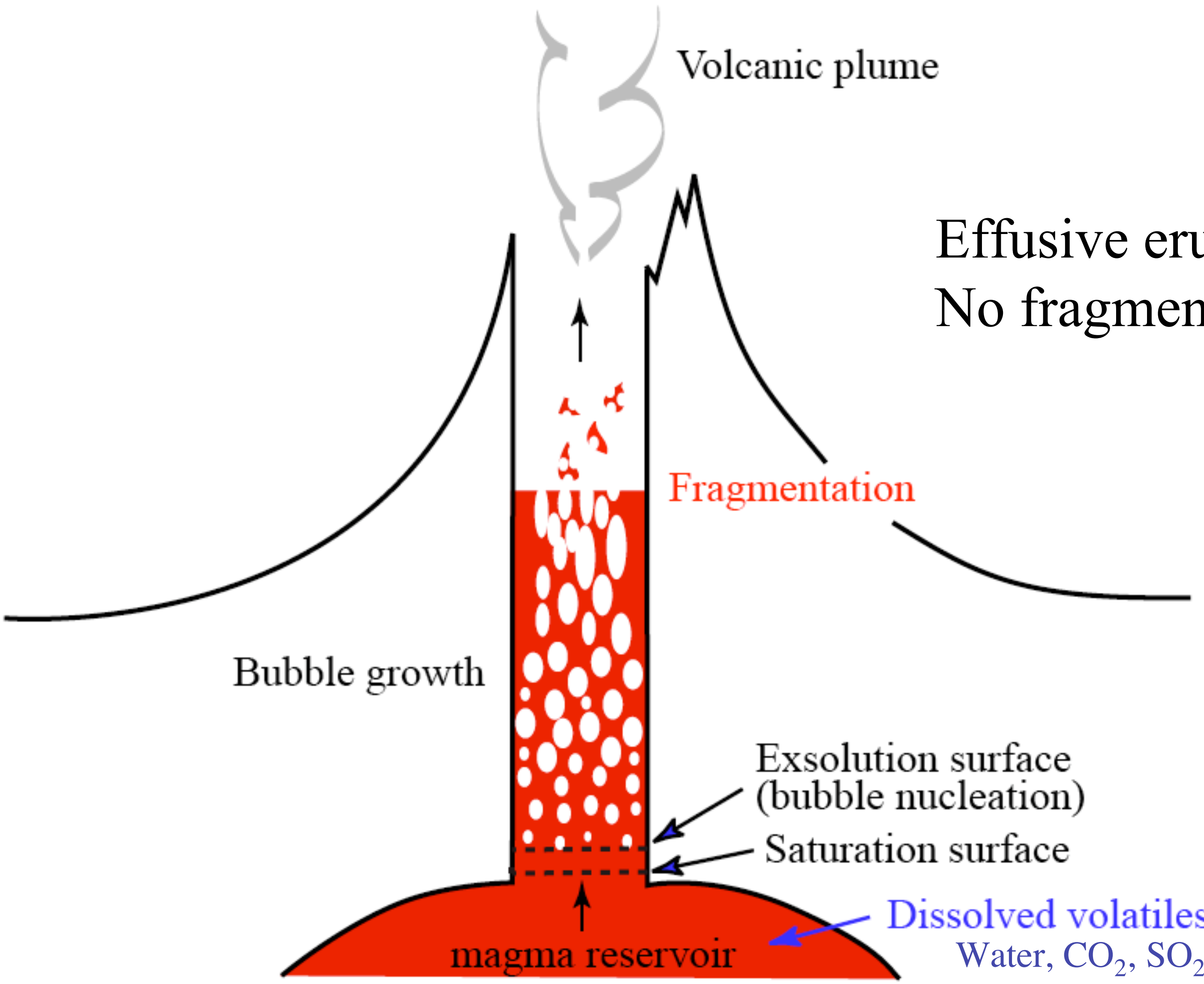
Why do volcanoes (only sometimes) erupt explosively?

Gonnermann and Manga,
The fluid mechanics inside a volcano,
Annual Reviews of Fluids Mechanics,
2007

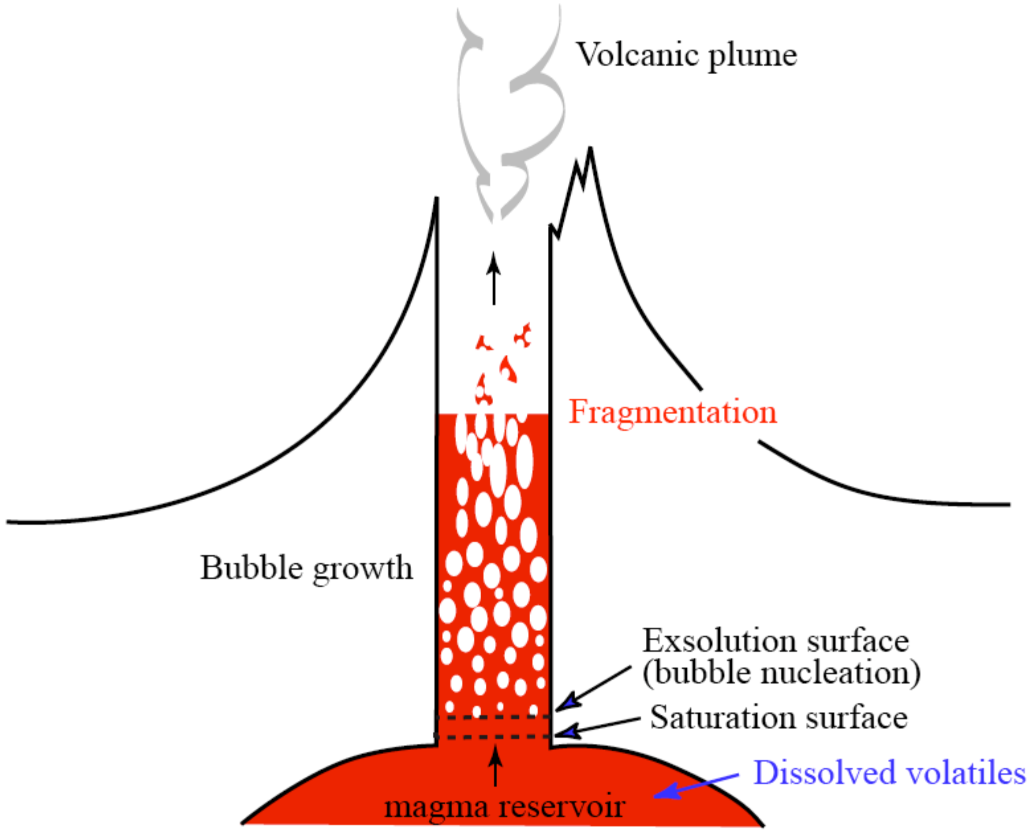
Magma = molten rock

Why do volcanoes erupt explosively?
(textbook version)



Effusive eruption:
No fragmentation

Why do volcanoes erupt explosively?

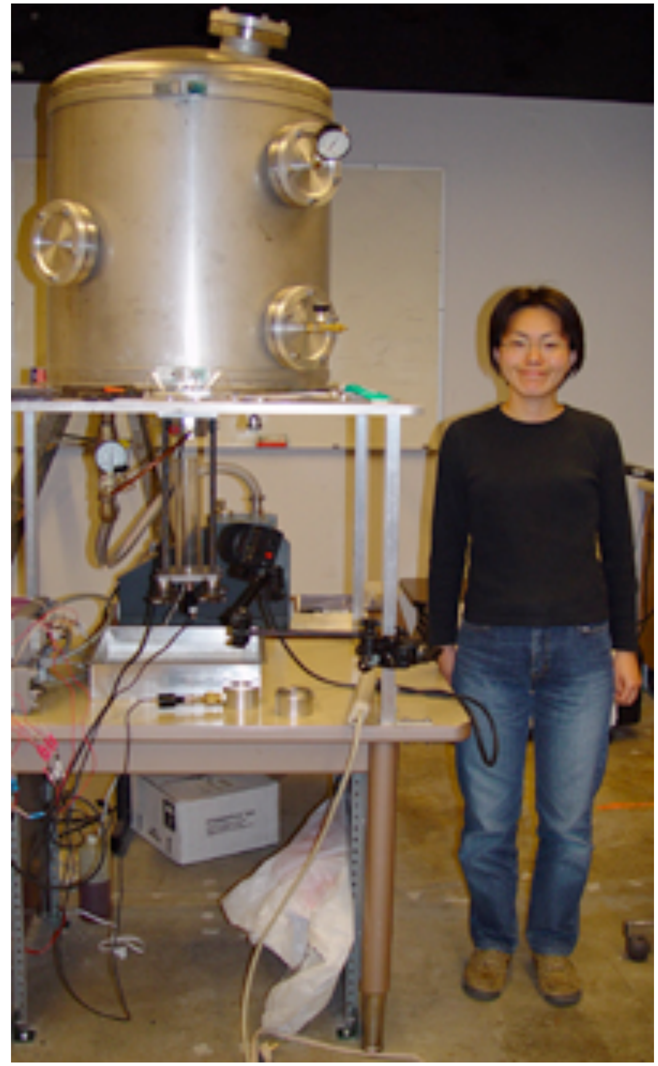


Open questions:

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

Who did the work?

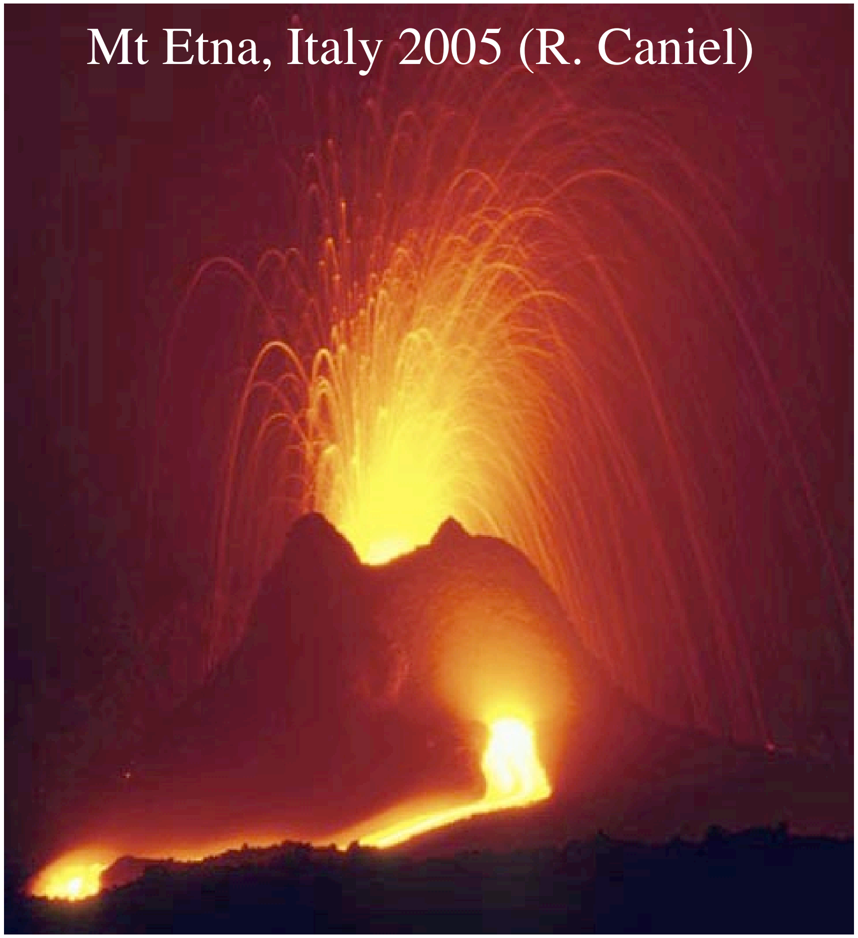
Helge Gonnermann
(conduit modeling)

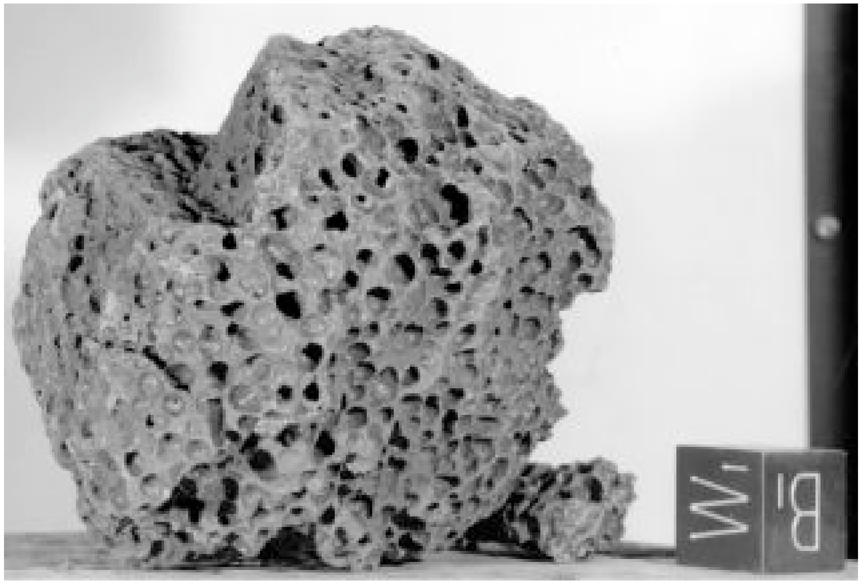


Atsuko Namiki
(decompression experiments)

Three key processes

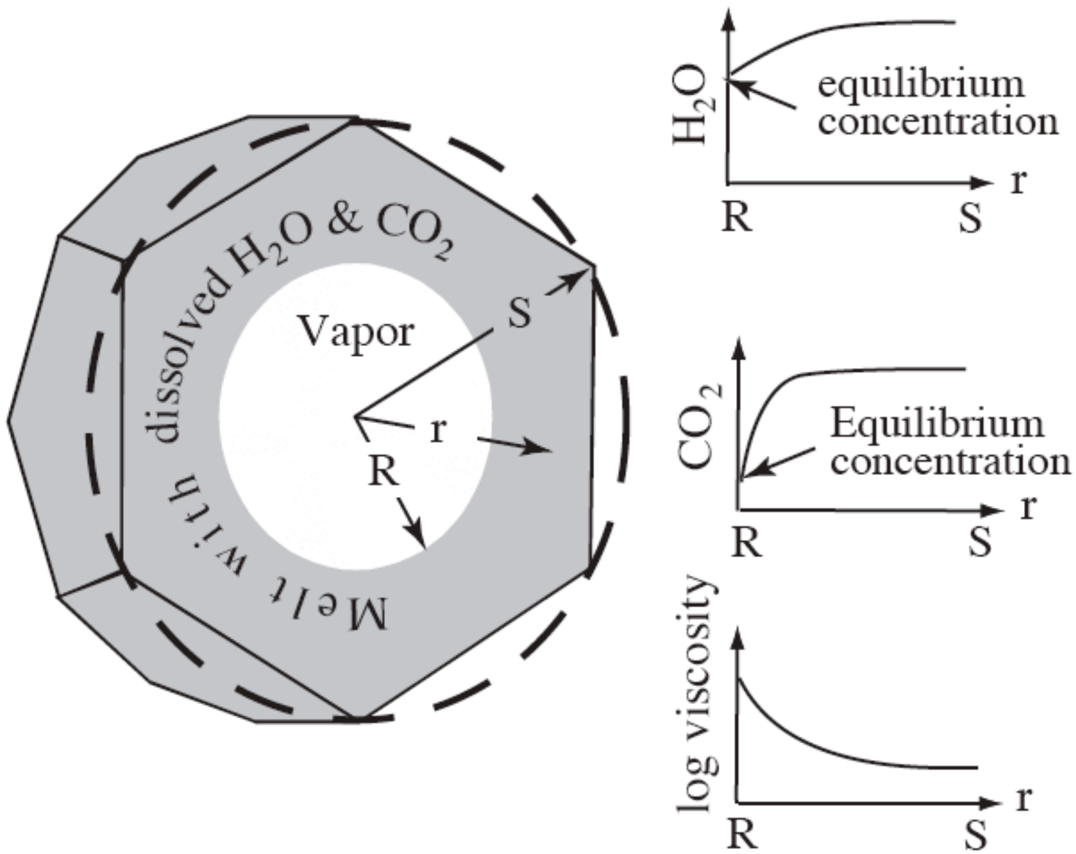
1. Bubble nucleation, exsolution and bubble growth





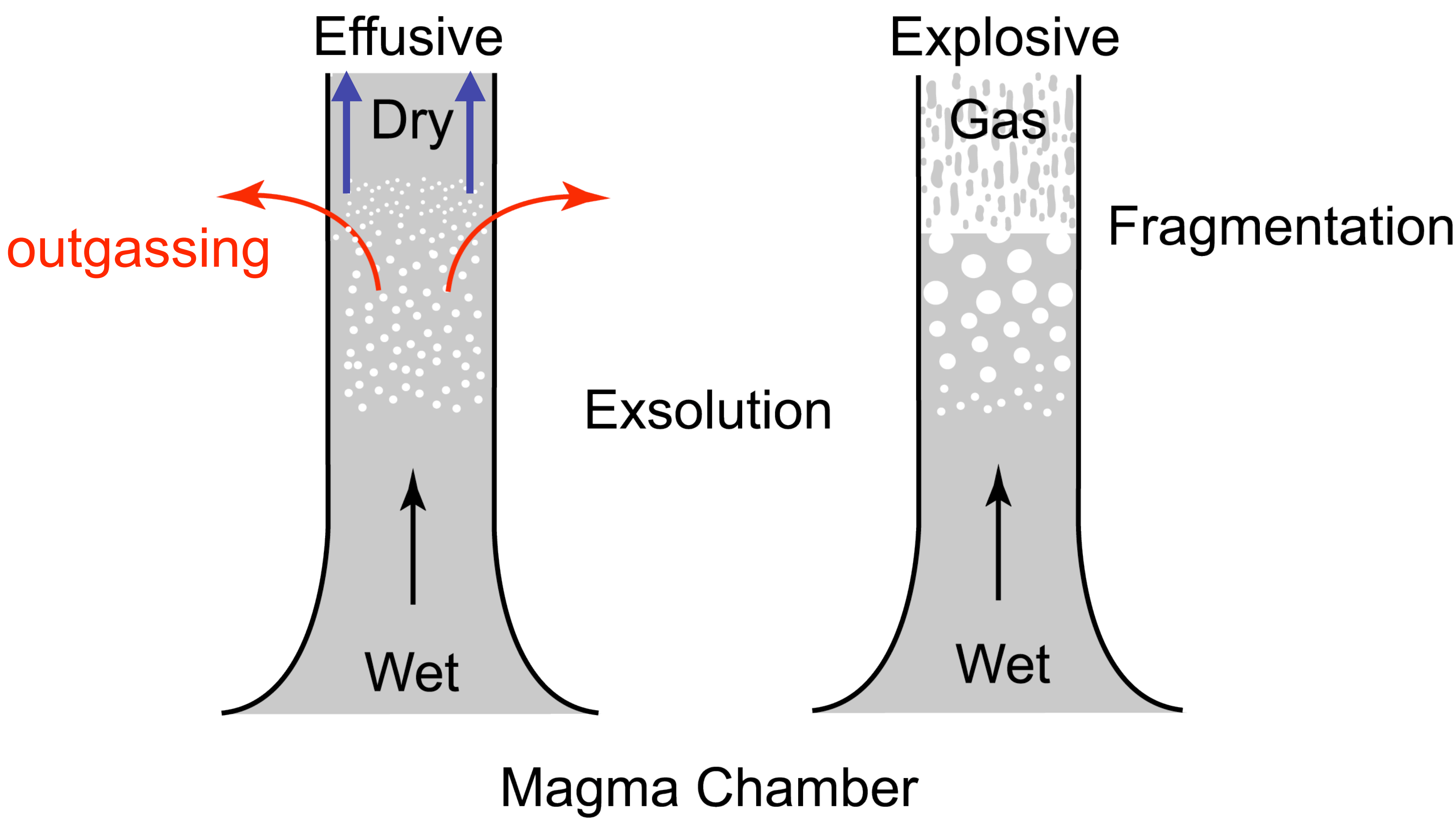
vesicular basalt (from the moon)

Volatile exsolution and bubble growth

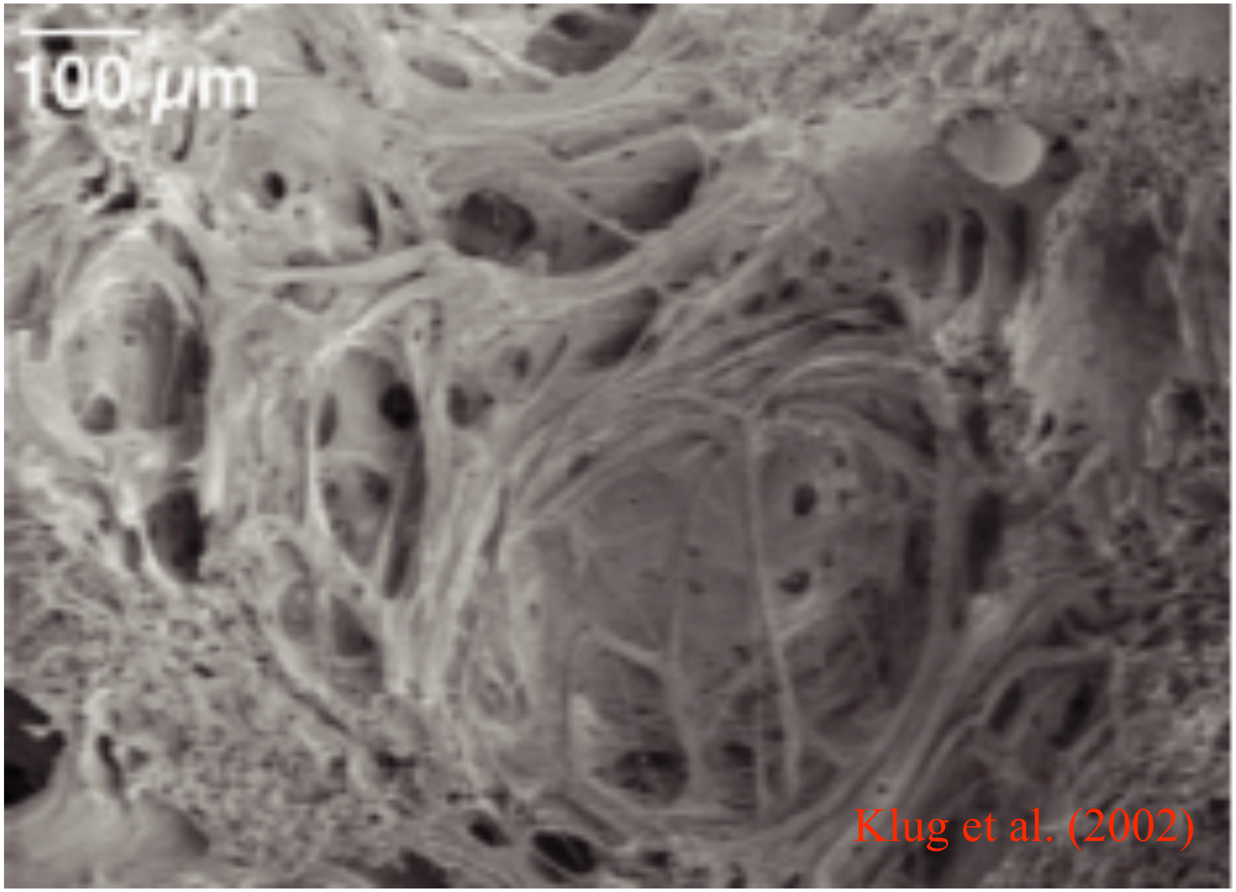


Three key processes

2. Loss of gases, called outgassing, supresses eruption



Vesicular magma is permeable



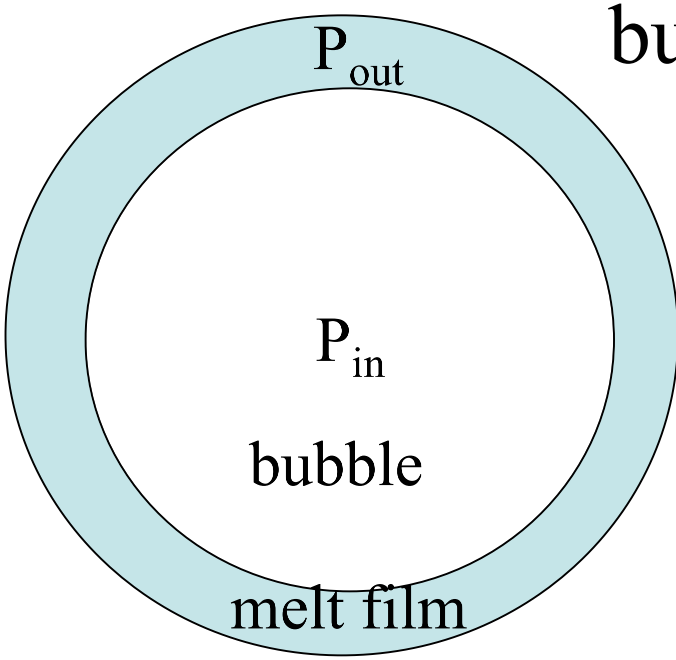
Connections between bubbles allow gases to escape from magma

Permeability depends on vesicularity and bubble size

Three key processes

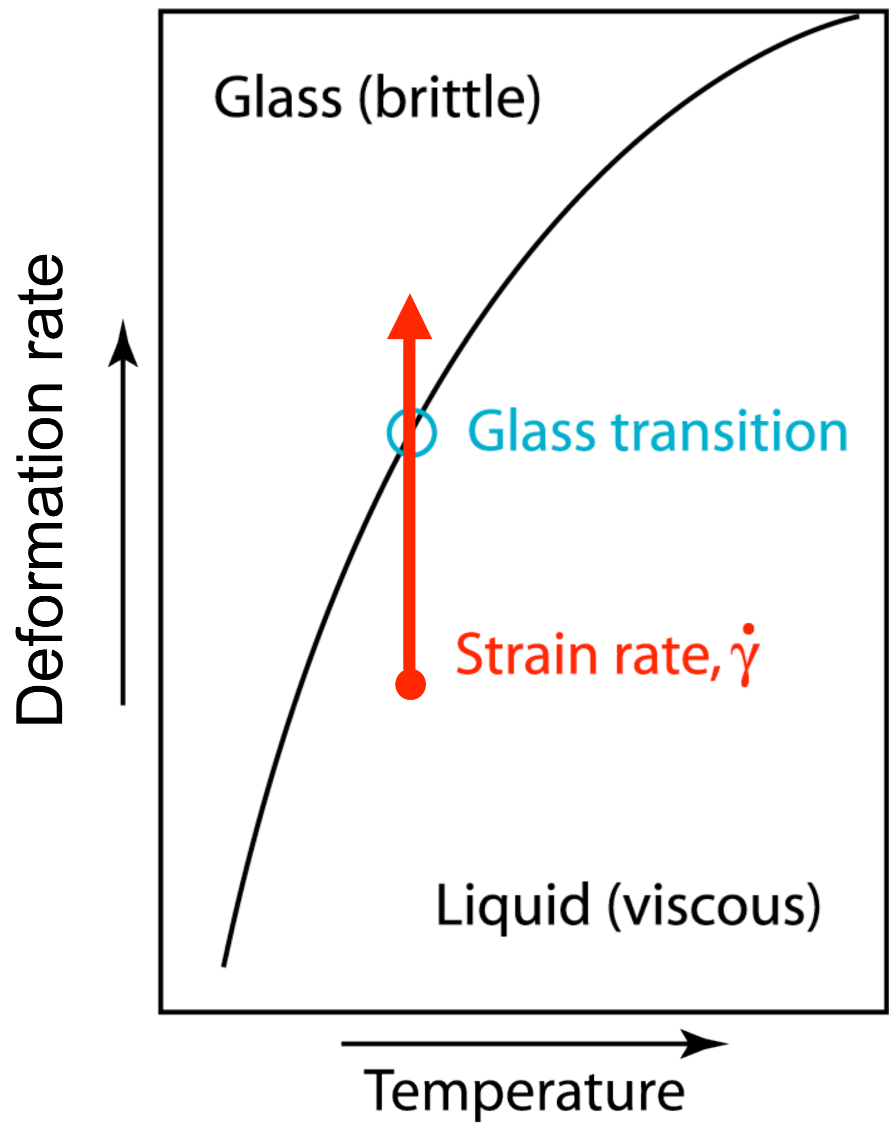
3. Fragmentation

If stresses in film surrounding bubbles too large



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

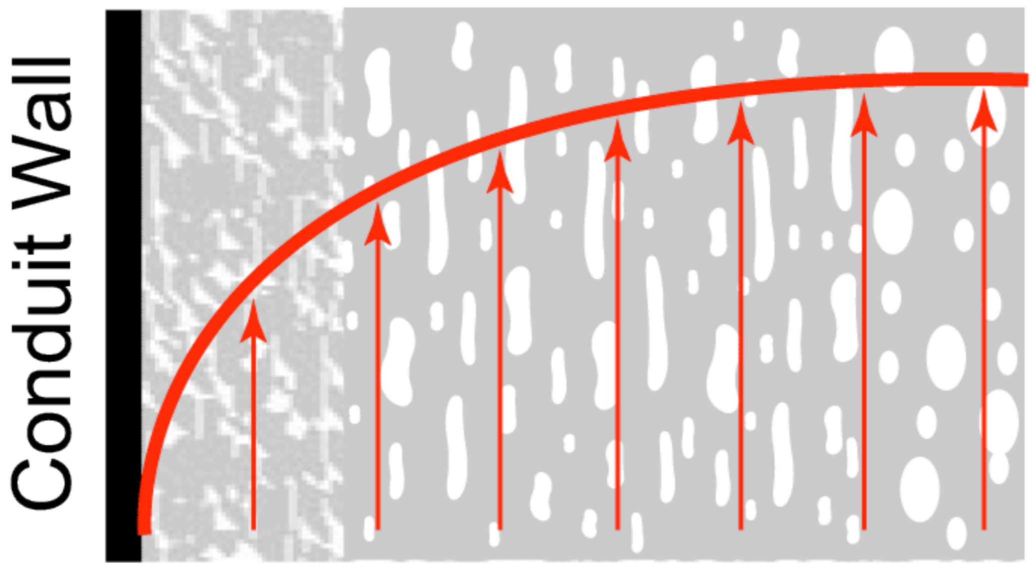
A second way to break magmas . . .

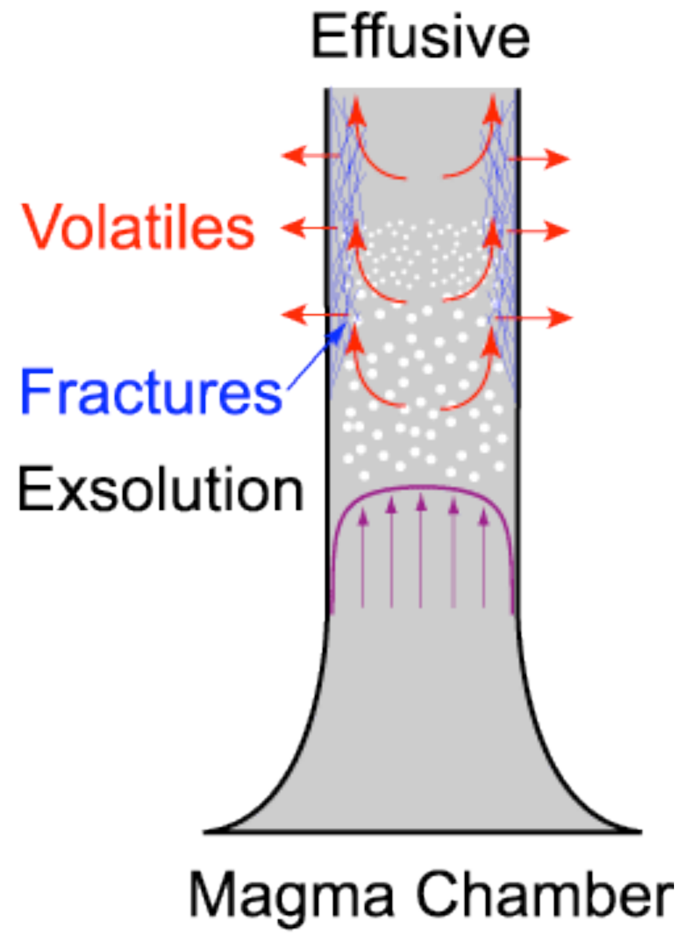


Relaxation timescale η_{mr}/G

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

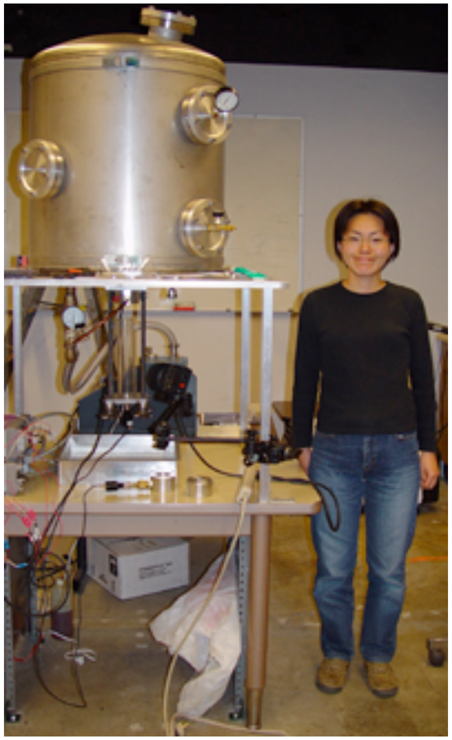
1) Nucleation (forming new) and growth of bubbles
2) Outgassing (loss of gas from the magma)
3) Fragmentation and brecciation (breaking magma into pieces)

Approach

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

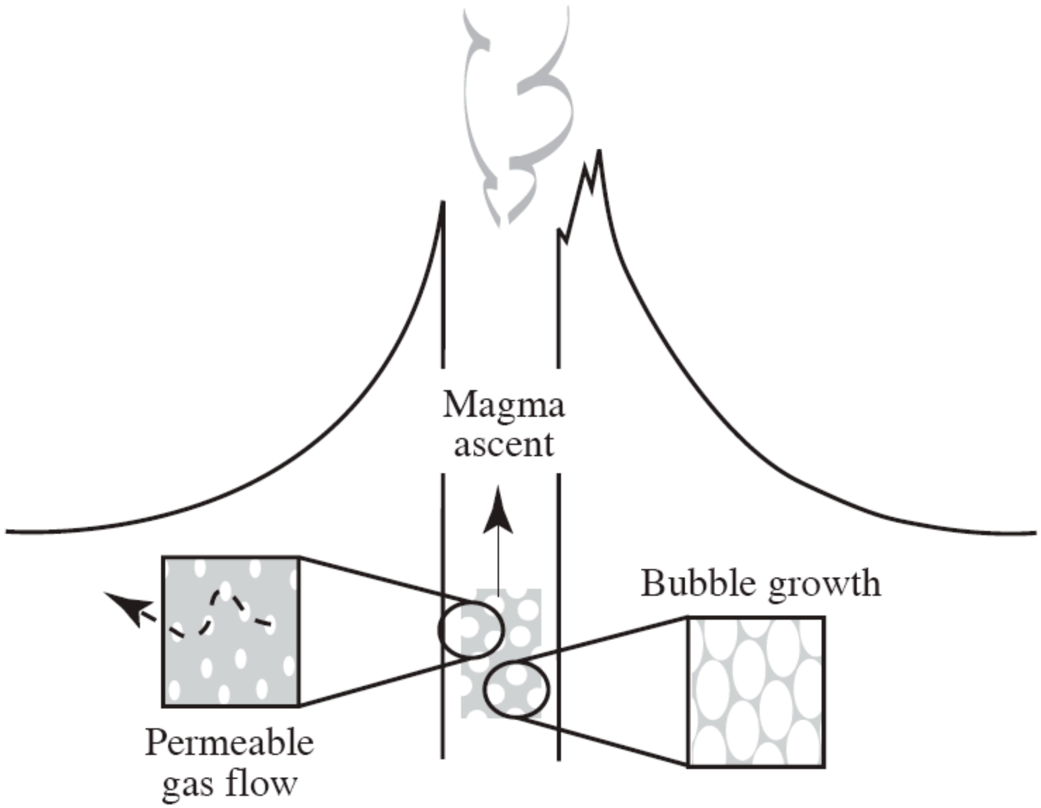
2. Computer simulations

3. Test models with measurements made on rocks



Numerical model

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



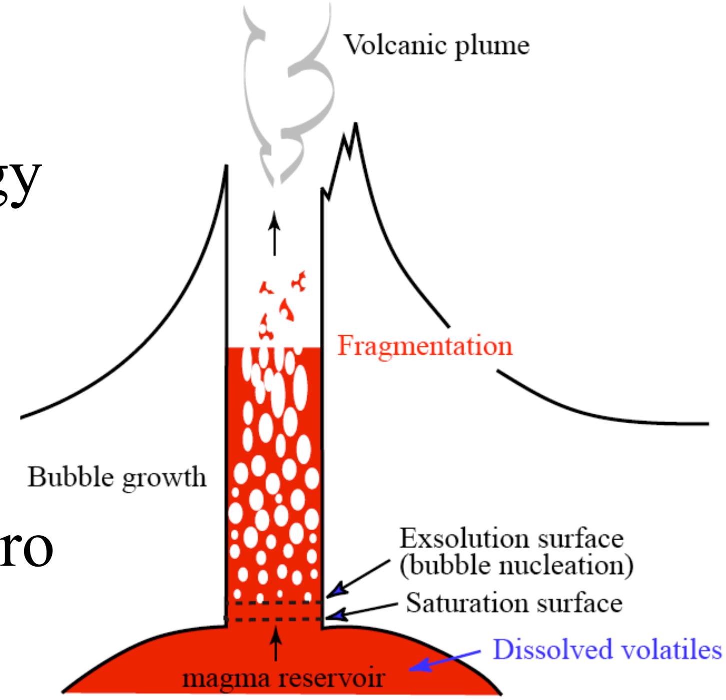
1) Conduit flow:
magma (bubbles+ melt) is locally homogeneous

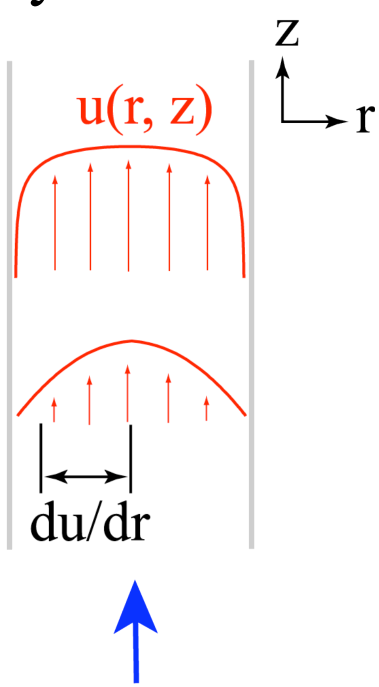
2) Bubble-scale:
Solve for growth of bubbles, determine rheology

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





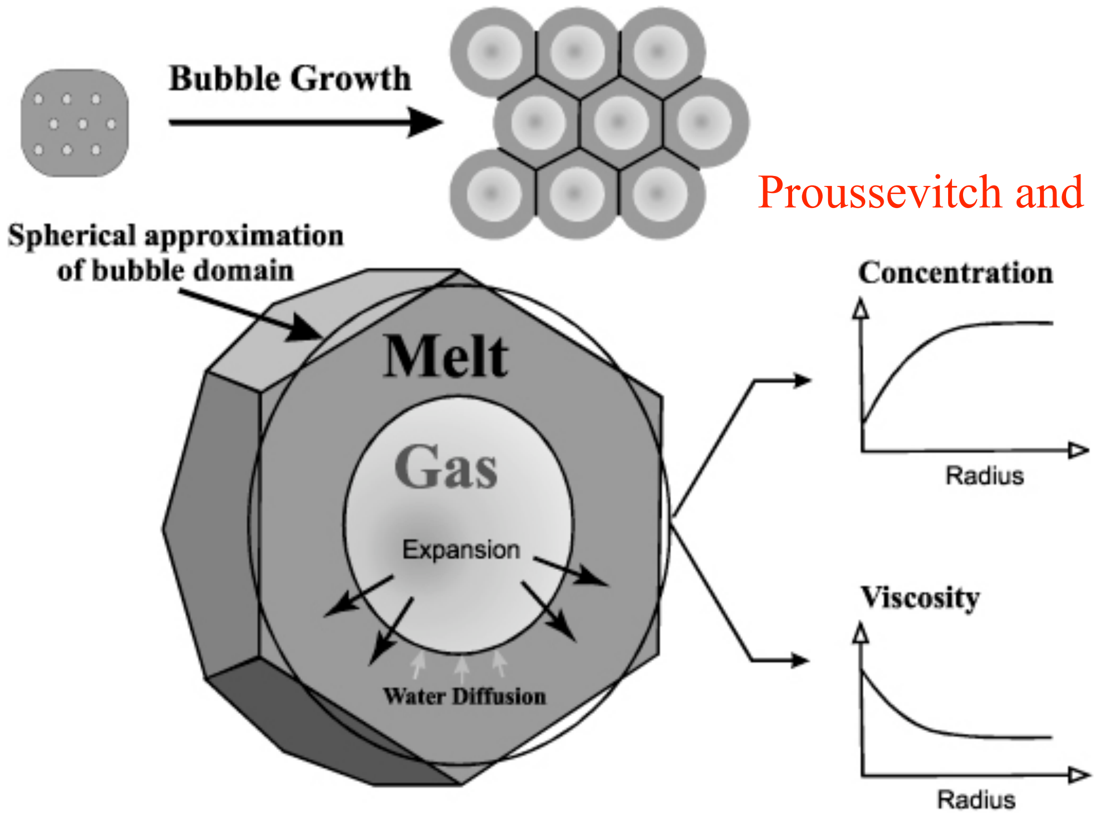
Q_{mass} = const.

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

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

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

Subgrid model: Volatile exsolution and bubble growth

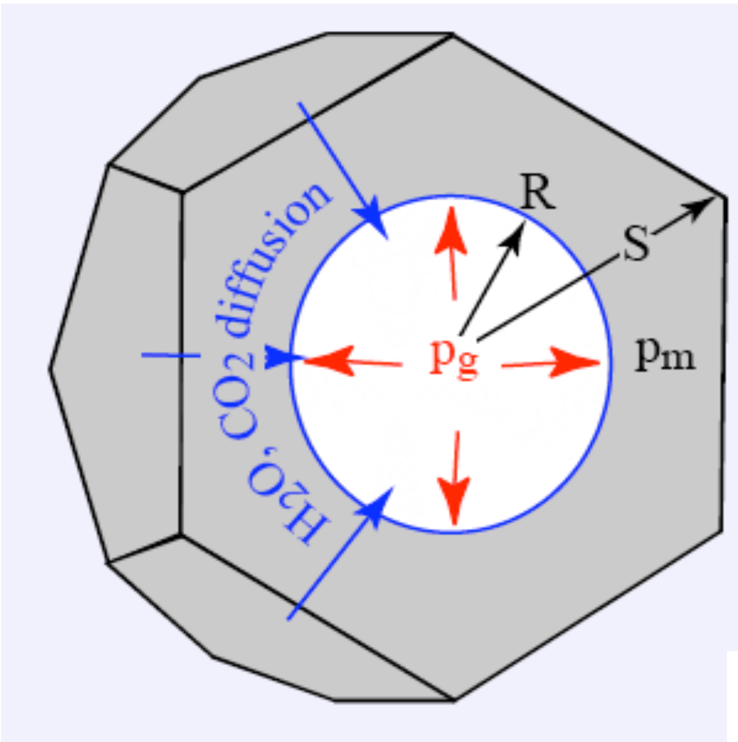


Proussevitch and Sahagian (1998)

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

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

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

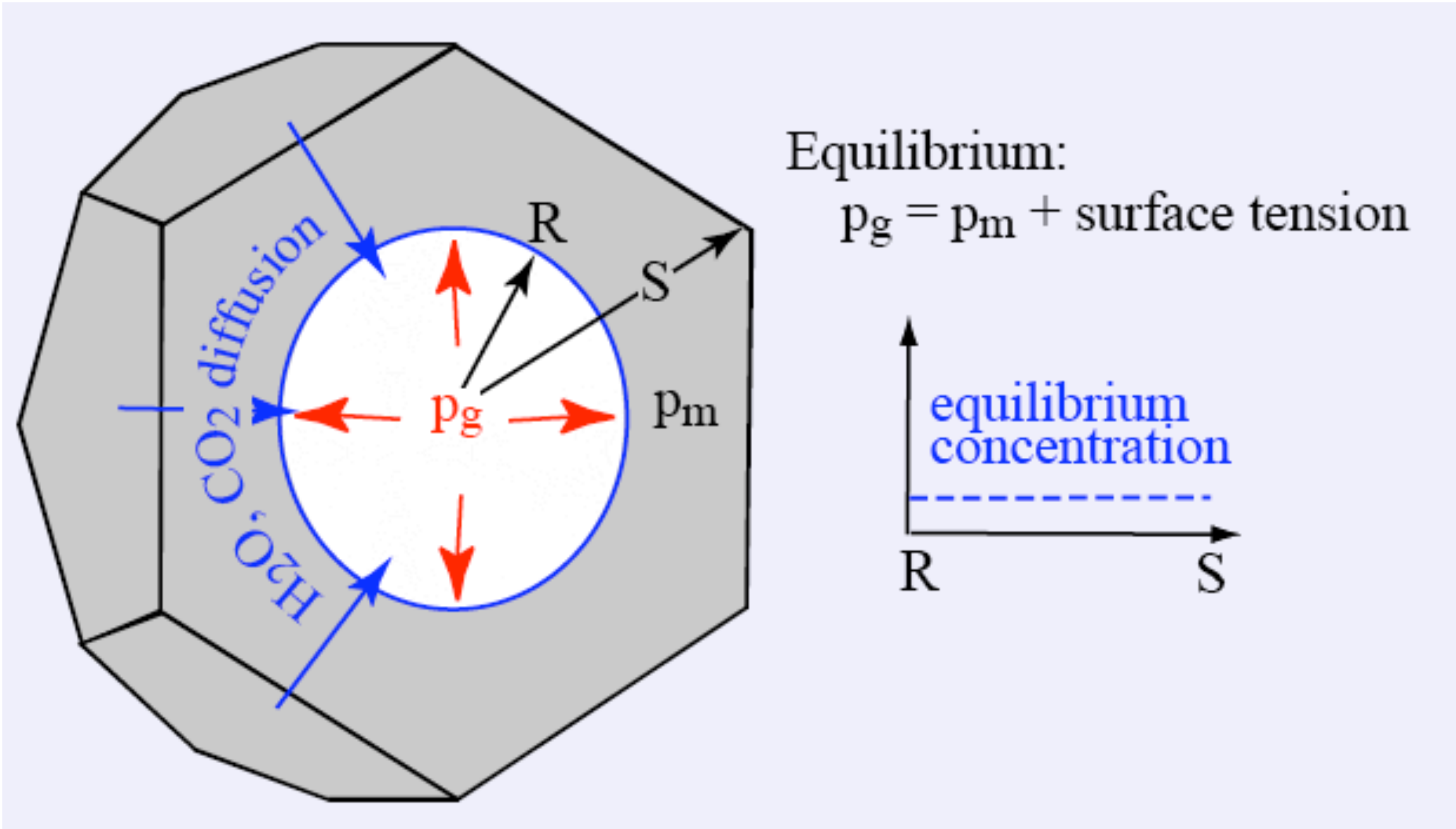
Lensky et al. (2001)

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

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

Bird et al. (1960)

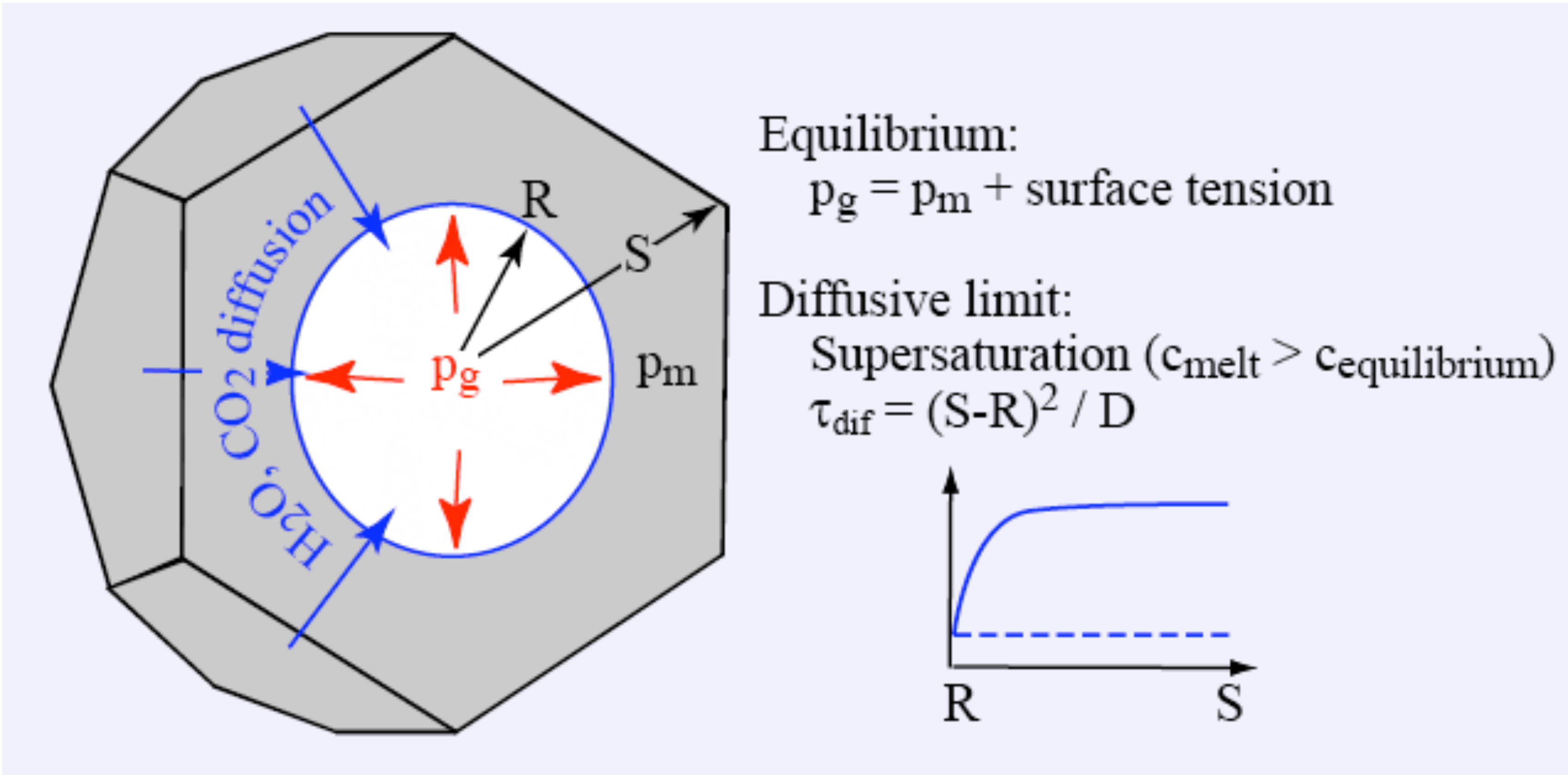
3 Regimes of bubble growth: Equilibrium (solubility-limited)



Growth is governed by changes in solubility

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

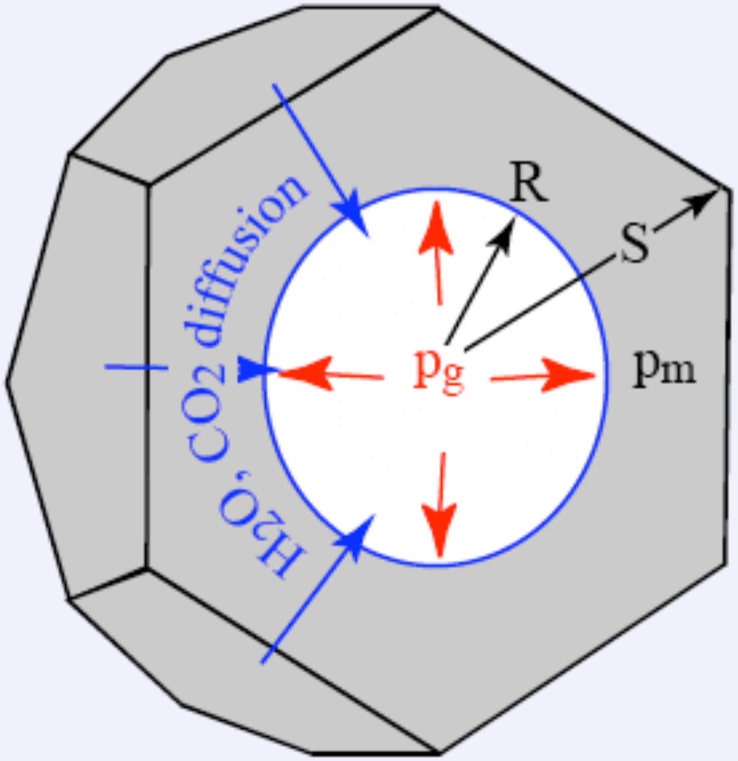
3 Regimes of bubble growth: Diffusion-limited



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

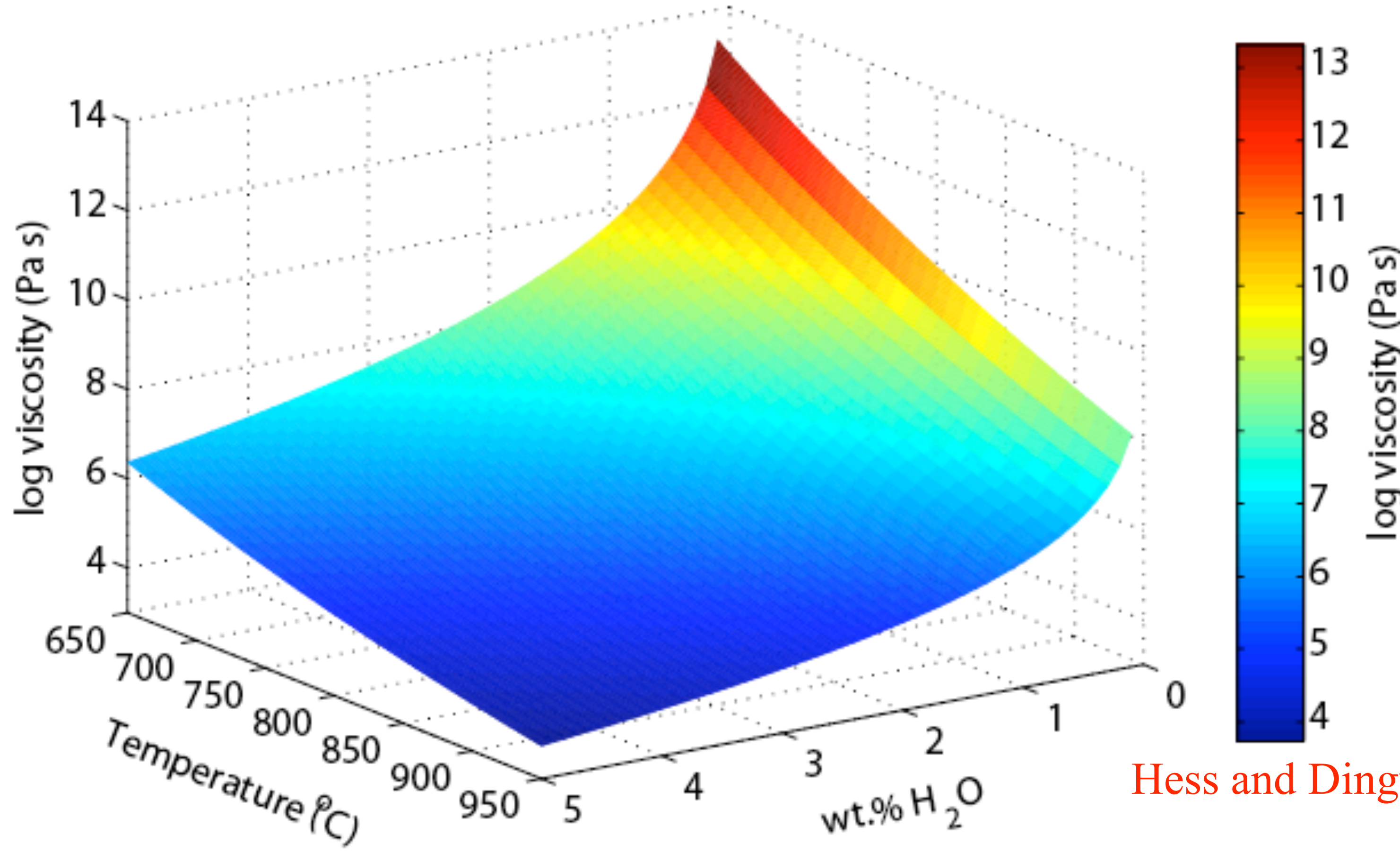
Diffusive limit:
Supersaturation ($c_{melt} > c_{equilibrium}$)
$\tau_{dif} = (S-R)^2 / D$

Viscous limit:
Overpressure ($p_g >> p_m$ + surf. ten.)
$\tau_{vis} = \eta / \Delta p$

Growth is by viscosity-limited when

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

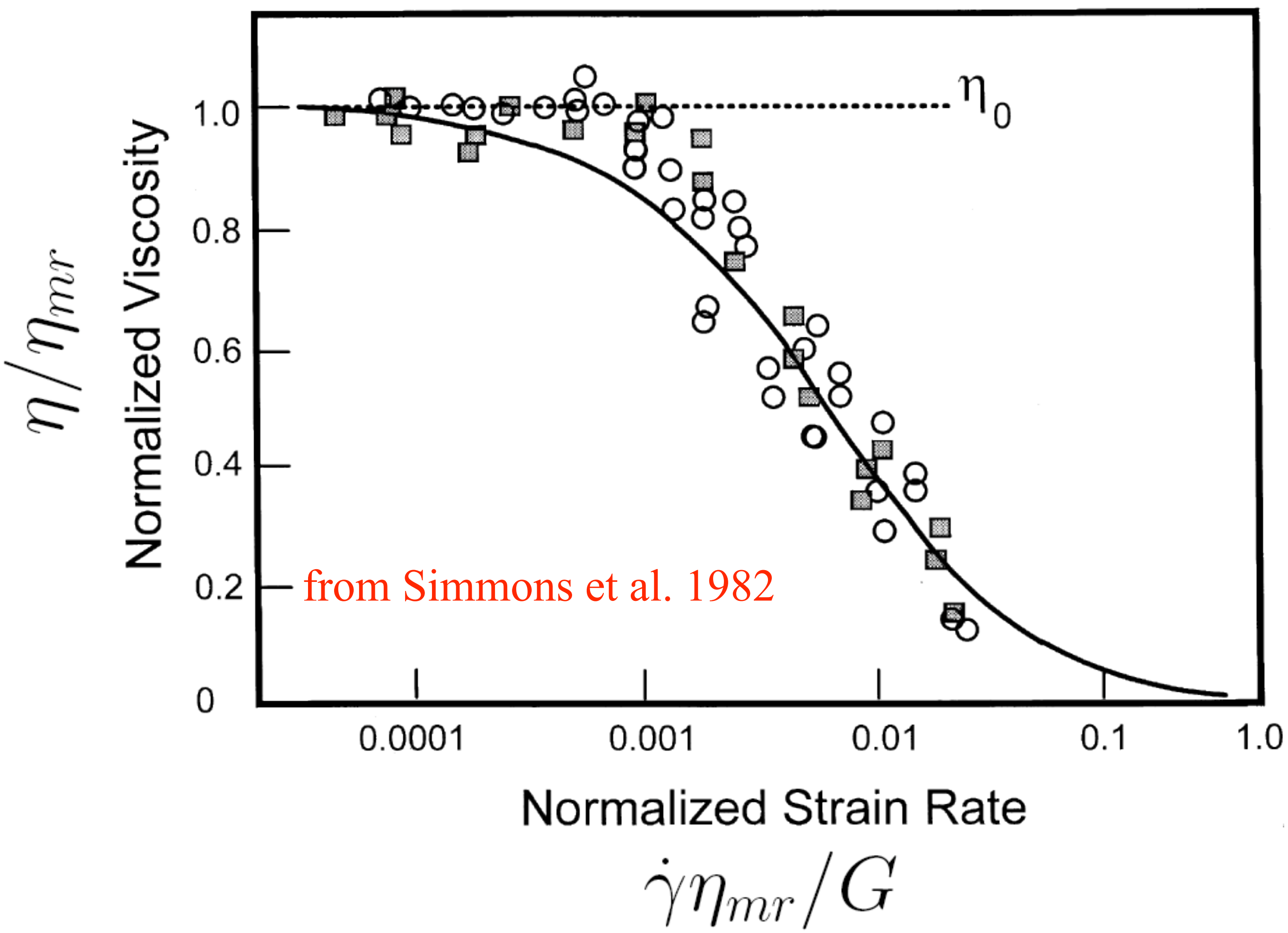
- Melt viscosity depends on amount of dissolved water and temperature (and composition)



Hess and Dingwell (1996)

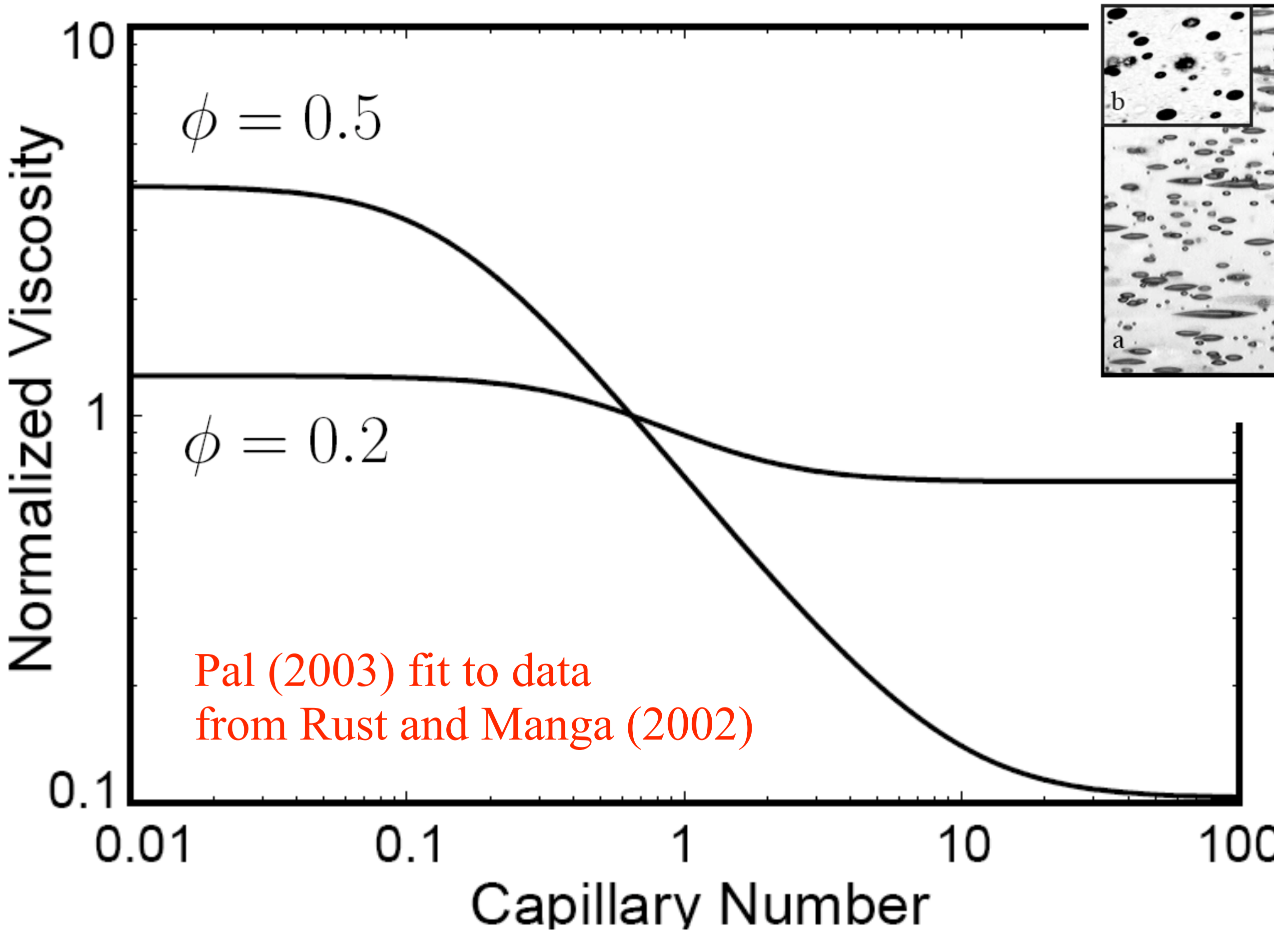
- Melt viscosity depends on deformation rate
- Magma viscosity affected by presence and properties of bubbles and crystals

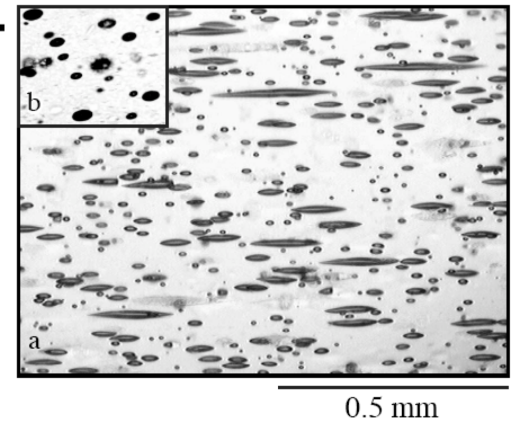
Strain-rate dependent viscosity of melt phase



Silicic magmas are similar (Webb and Dingwell)

Strain-rate dependent viscosity of bubbly suspension

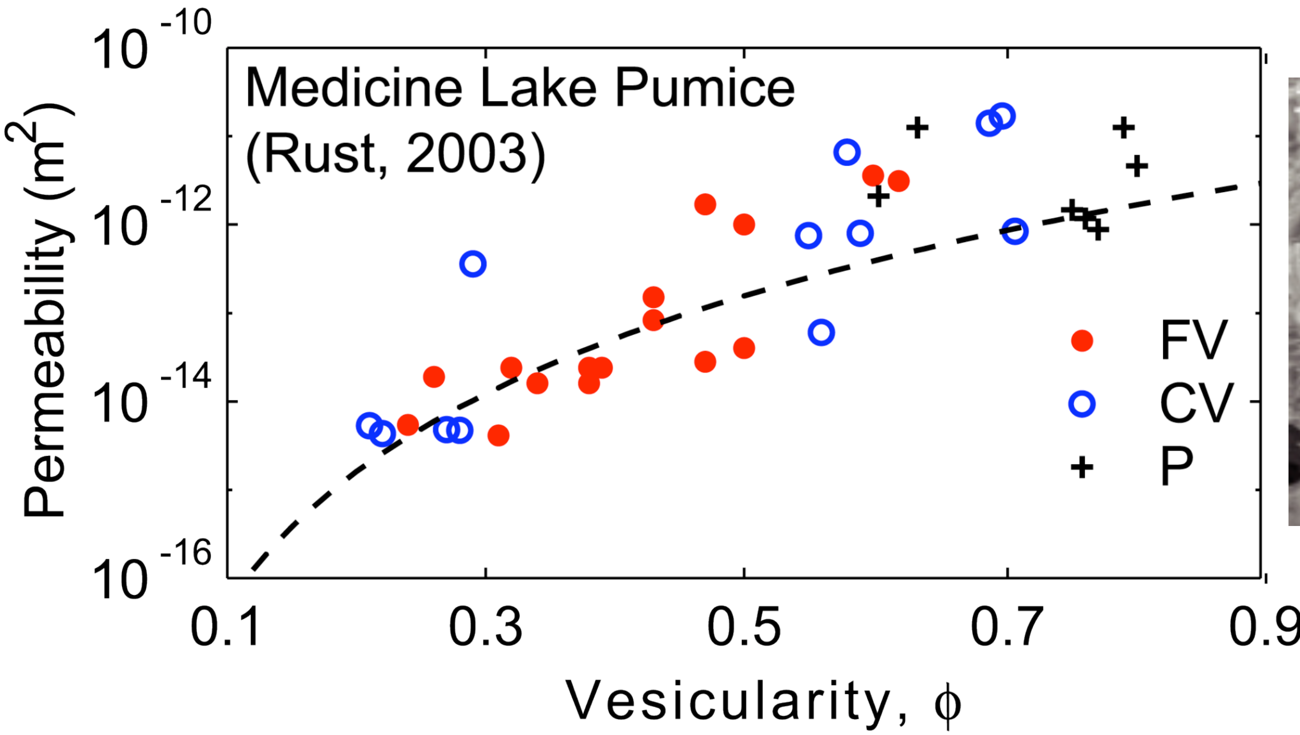


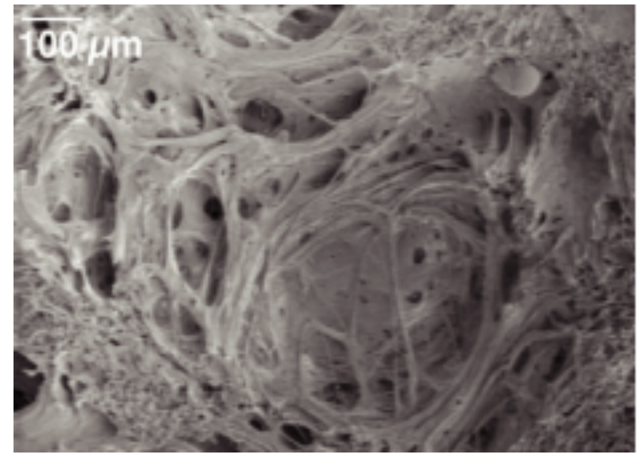


$$\mathrm{Ca} = \eta\dot{\gamma}R/\sigma$$

increasing shear rate

Vesicular magma is permeable





Klug et al. (2002)

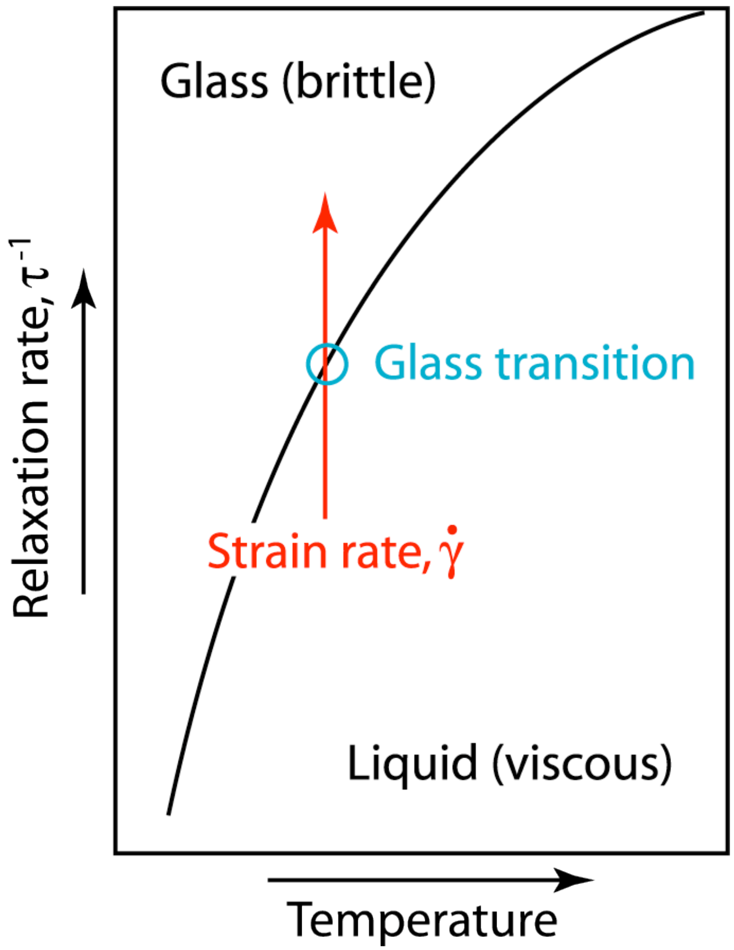
Connections between bubbles allow gases to escape from magma

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

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

Fragmentation criteria: thresholds determined experimentally

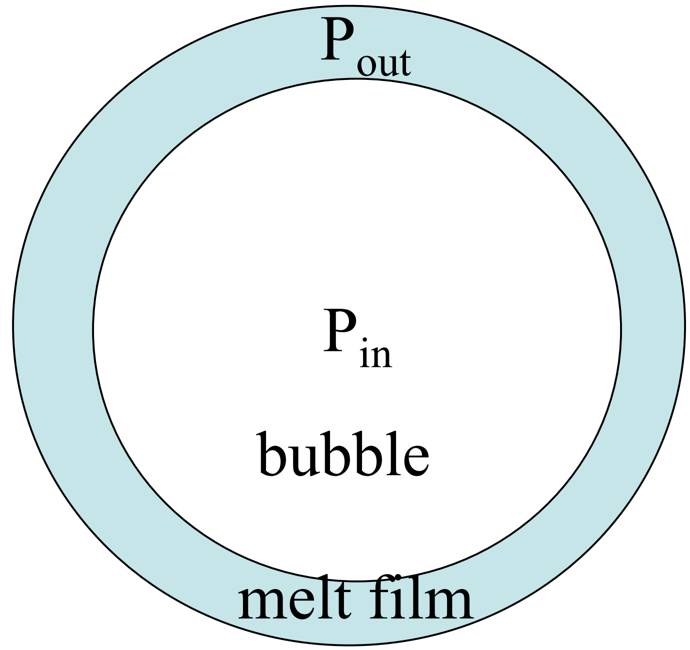
Brecciation



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

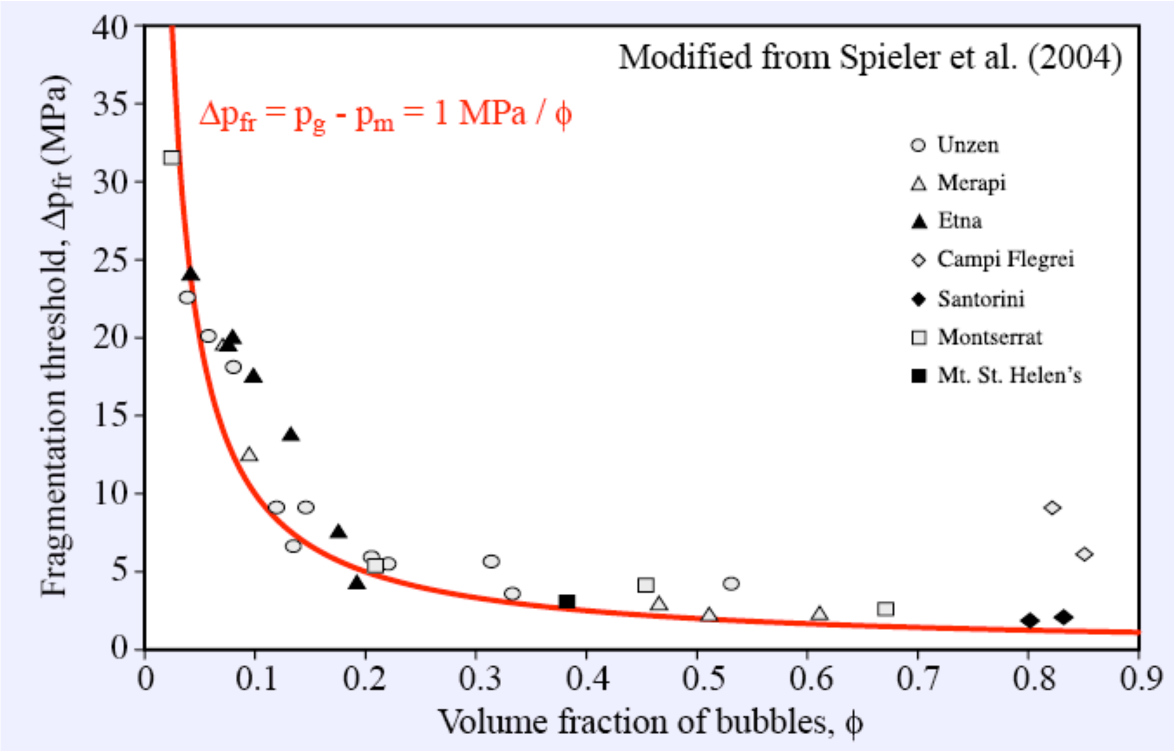
e.g., Webb and Dingwell (1990), Webb (1997), Papale (1998)

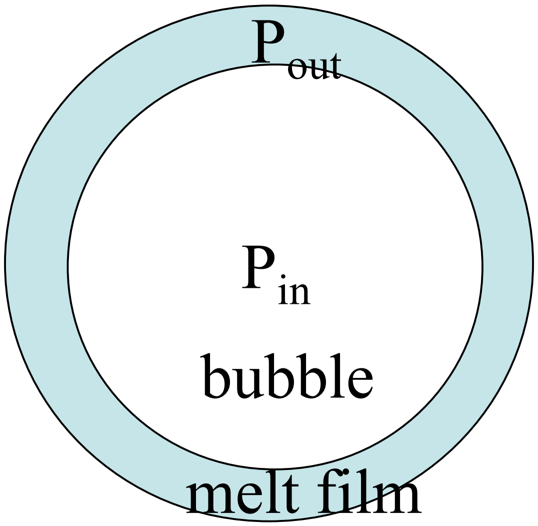
Fragmentation



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

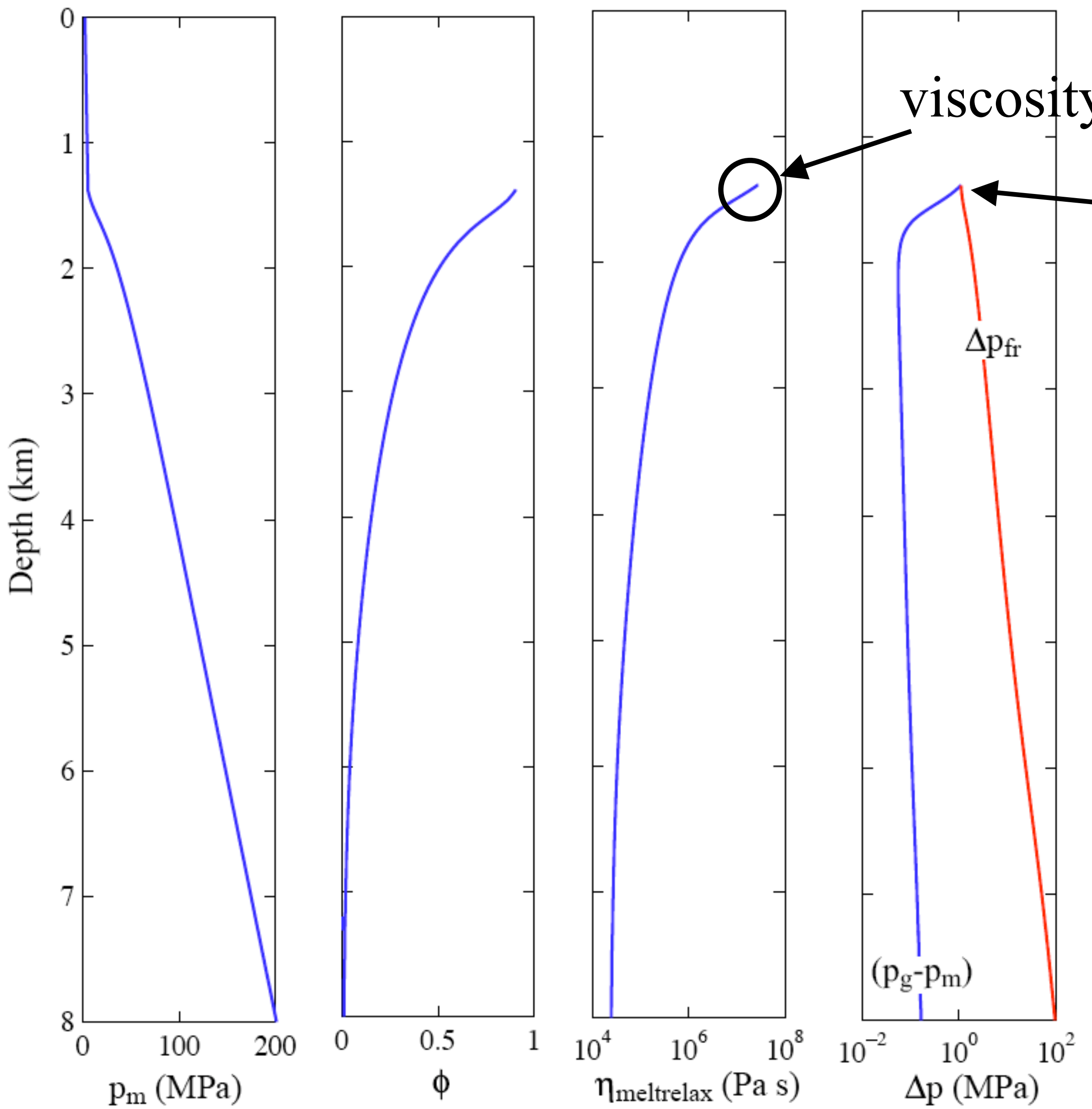
Experiments with real magma

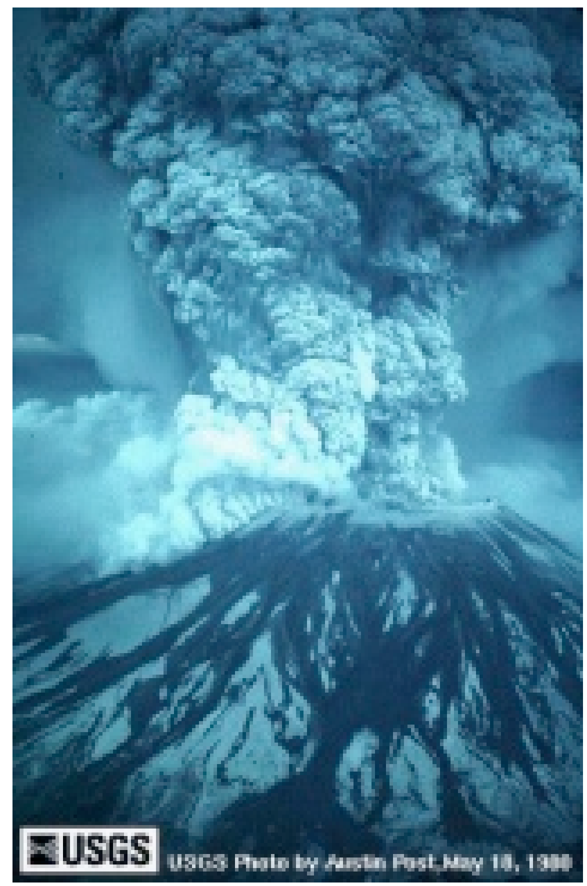




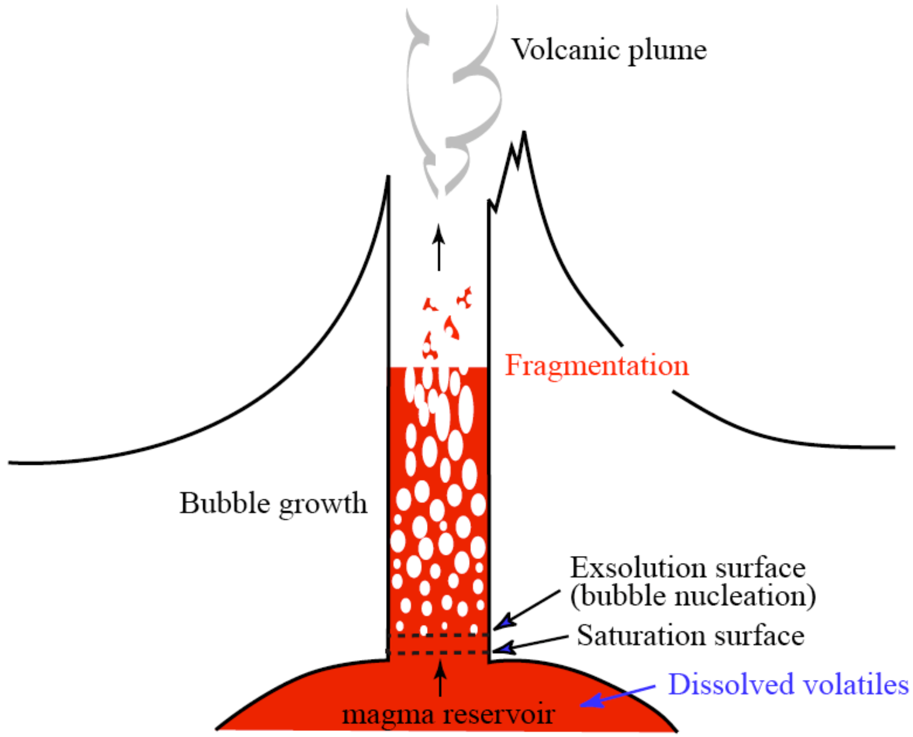
If P_{in} - P_{out} > 1 Mpa/ϕ then film ruptures

Example: Mount St Helens 1980 conditions





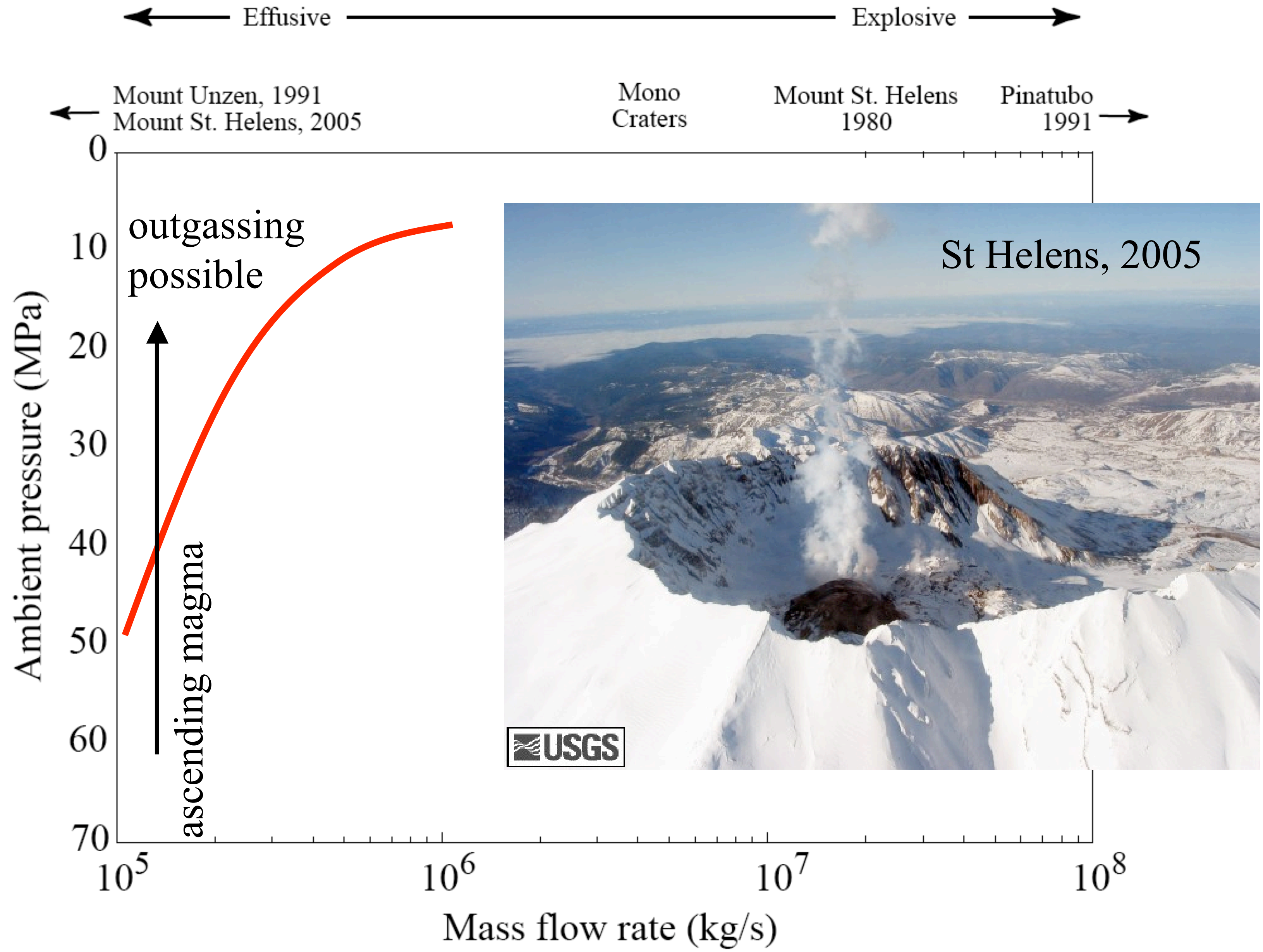
Why do volcanoes erupt explosively?



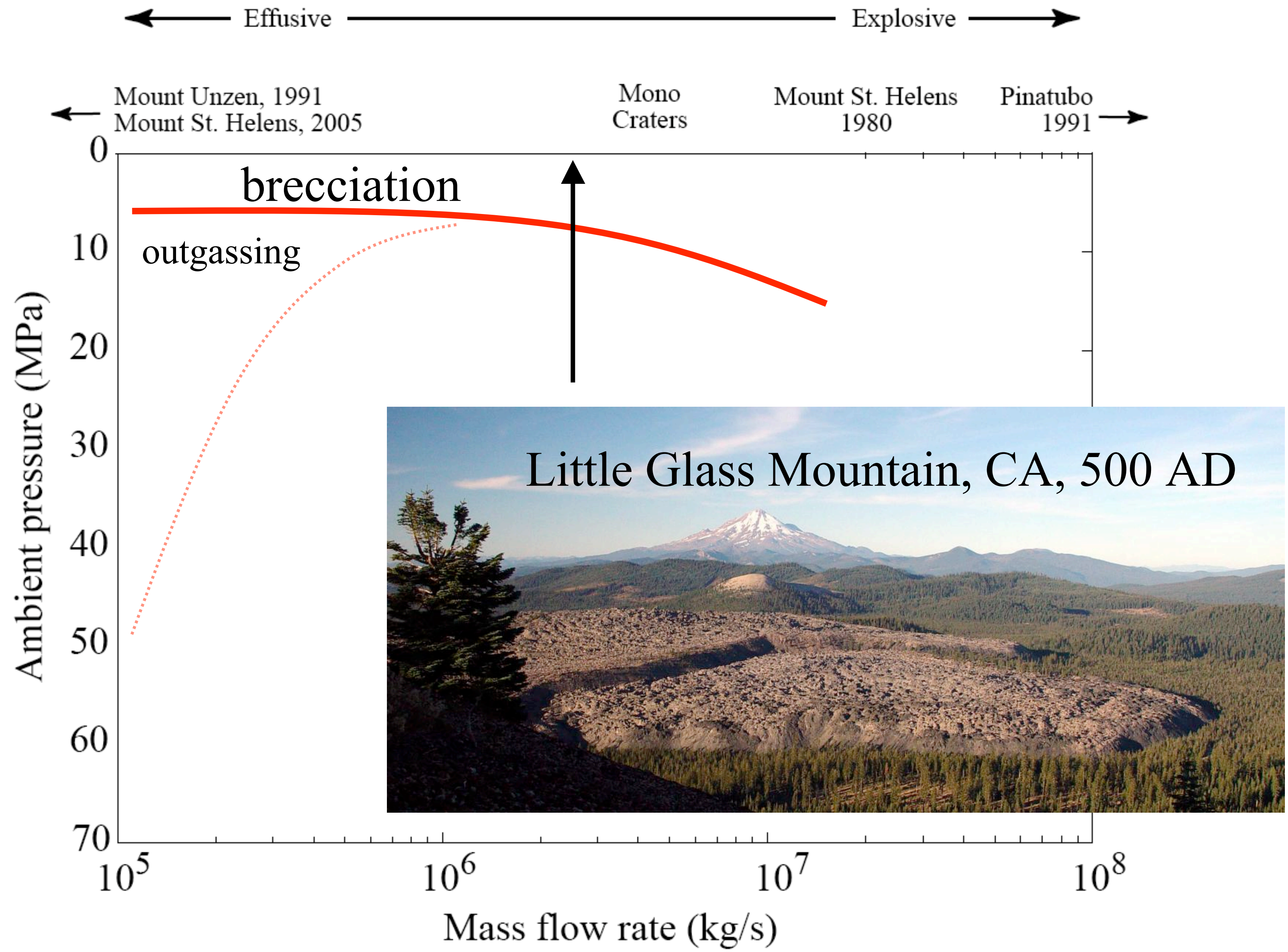
Open questions:

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

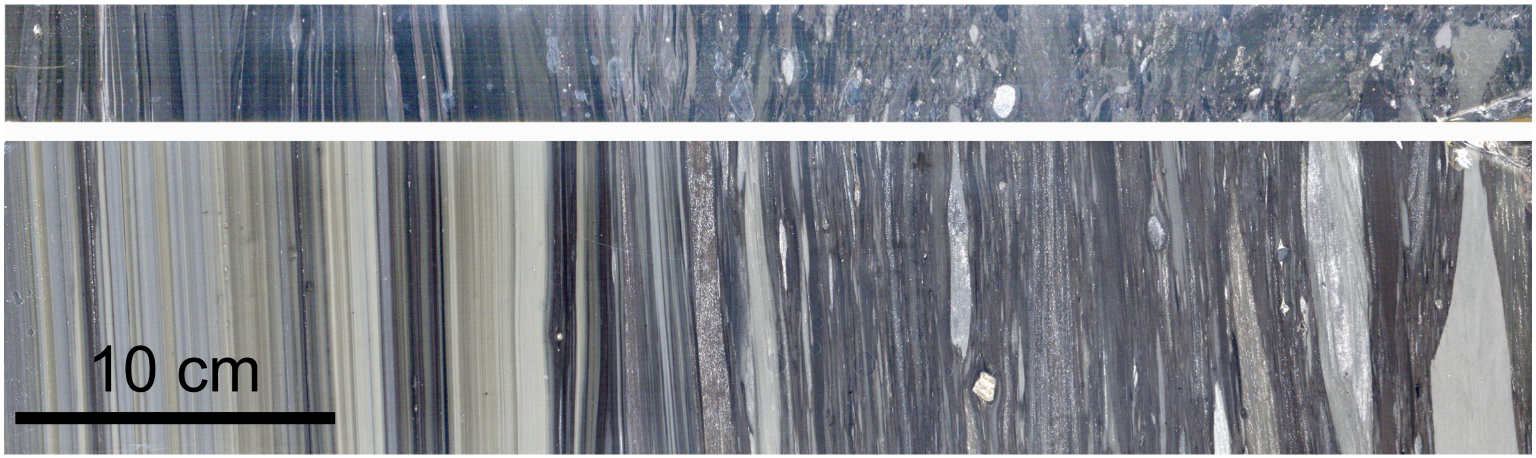
Change in eruption style with changing ascent rate

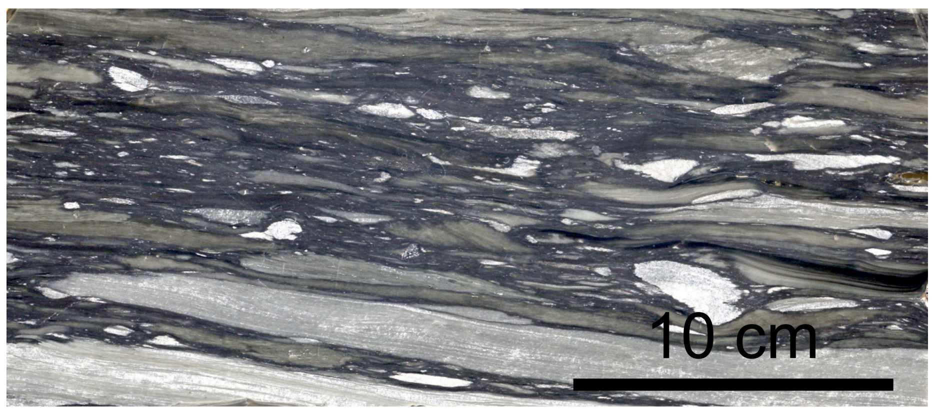


Change in eruption style with changing ascent rate

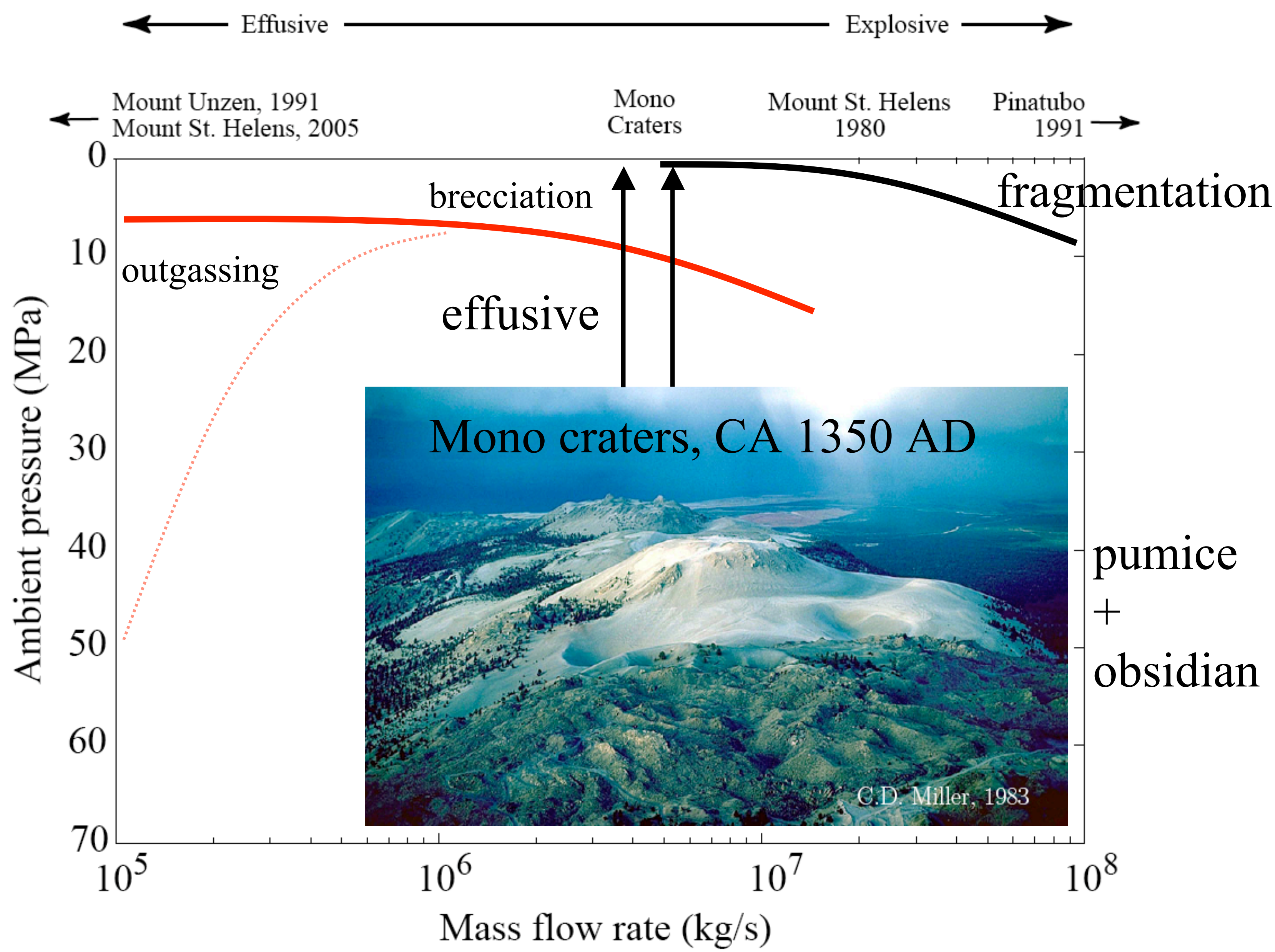


Brecciation, rewelding and deformation



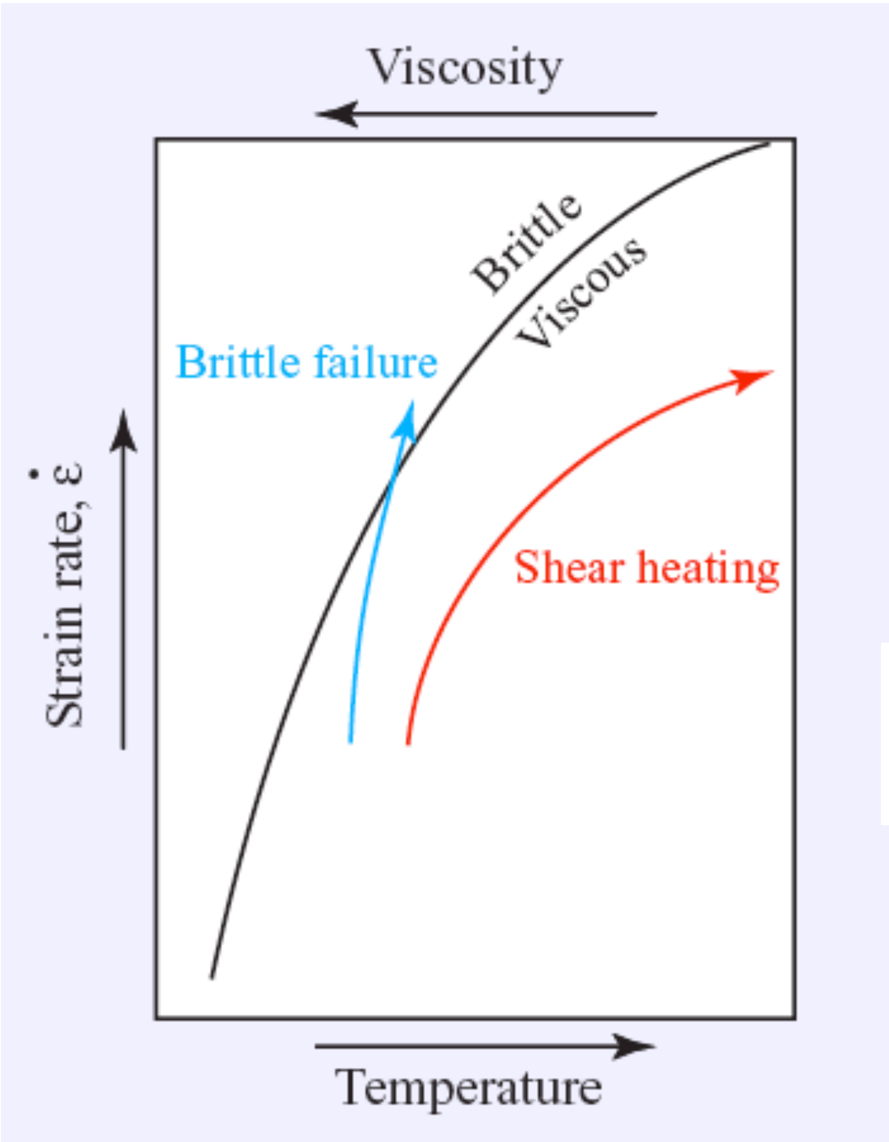


Change in eruption style with changing ascent rate



Does brecciation always happen?

Not if the magma rises fast enough

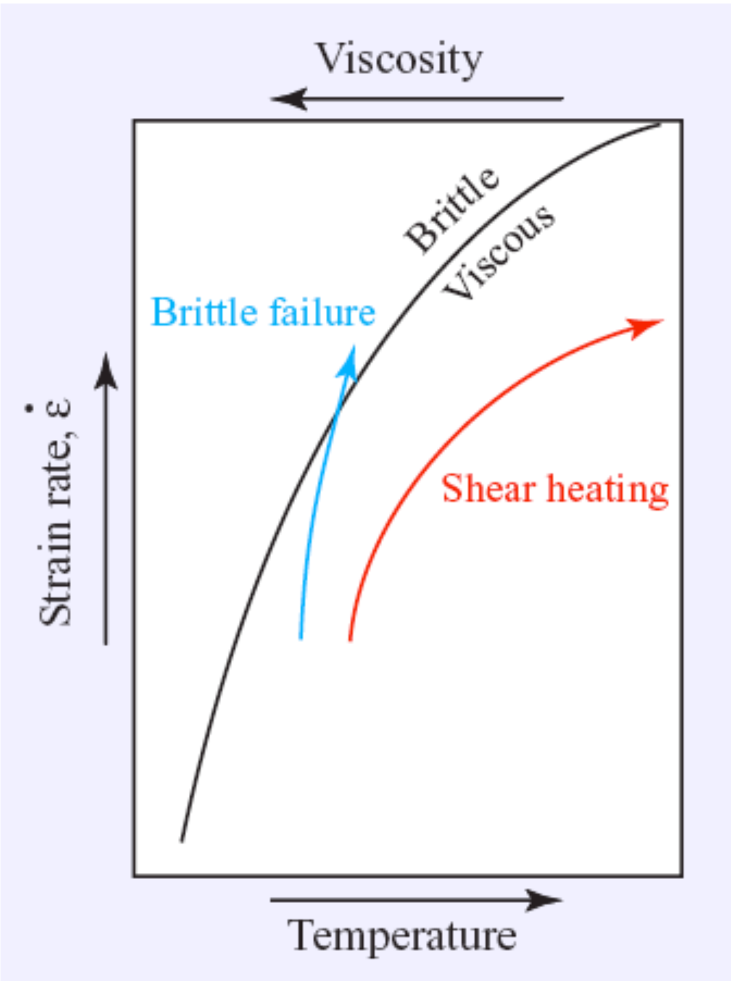


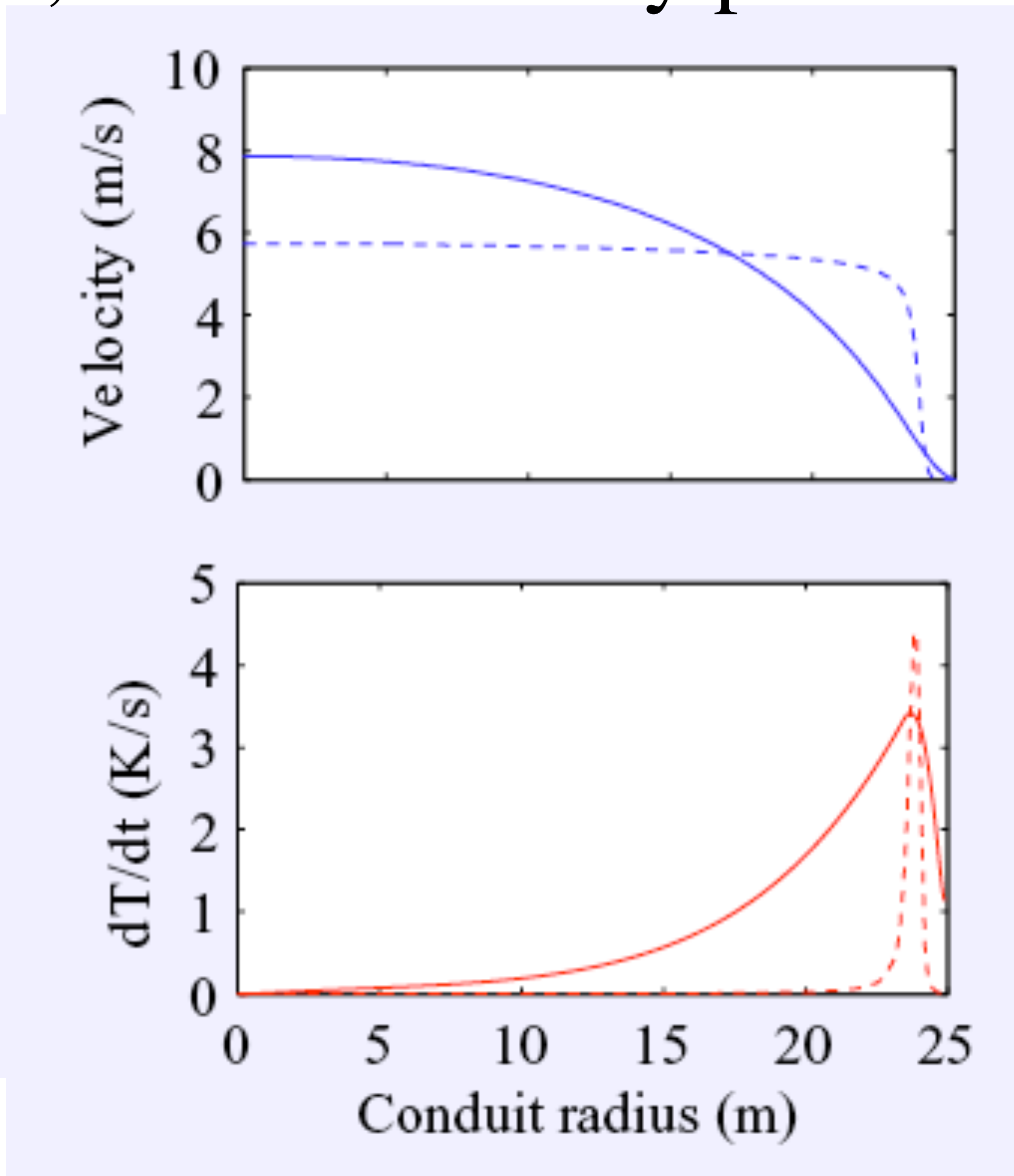
Viscous dissipation important when Brinkman number (viscous dissipation/heat diffusion)

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

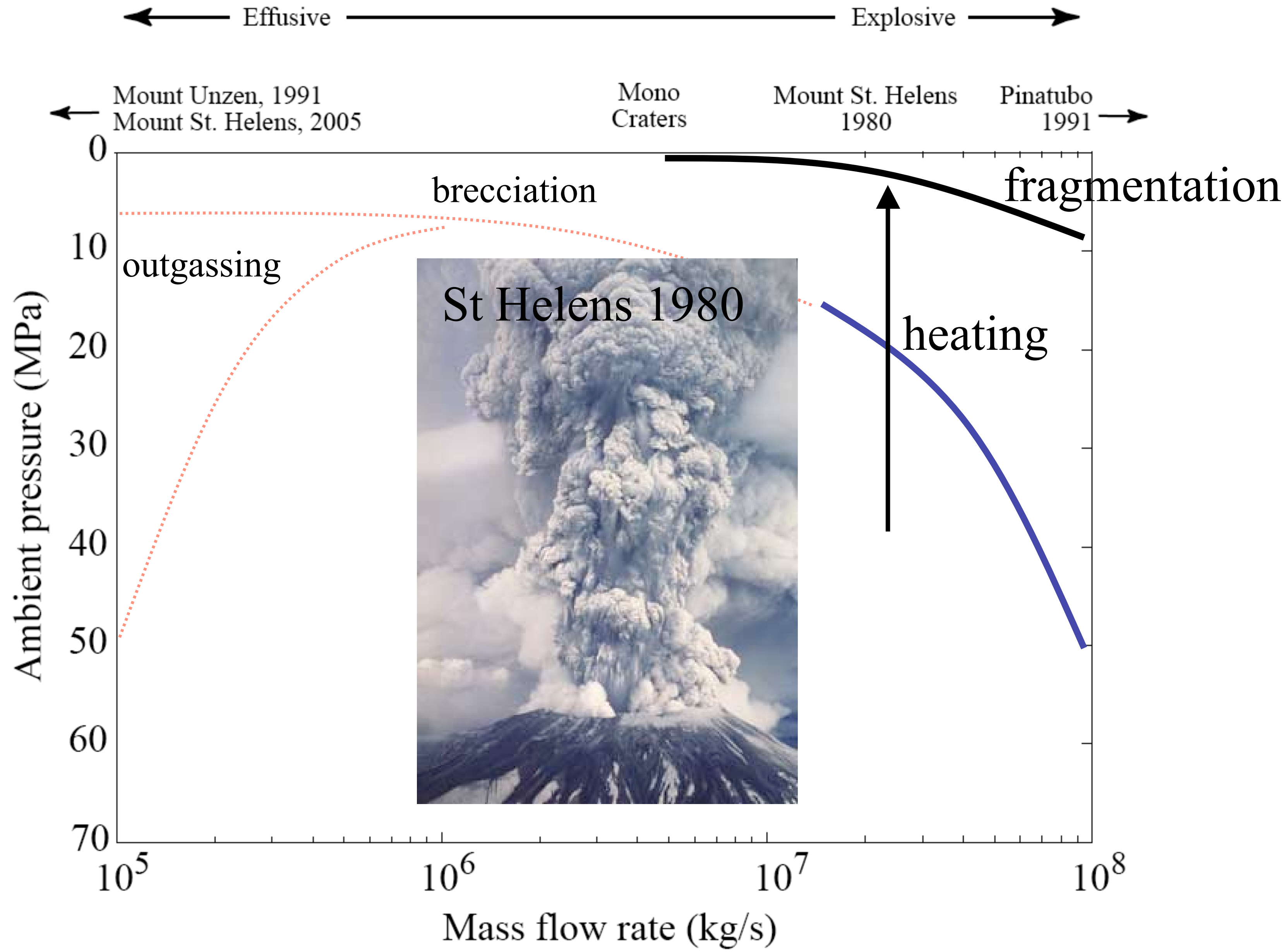
becomes large

Implications:
no brecciation, “blunt” velocity profiles

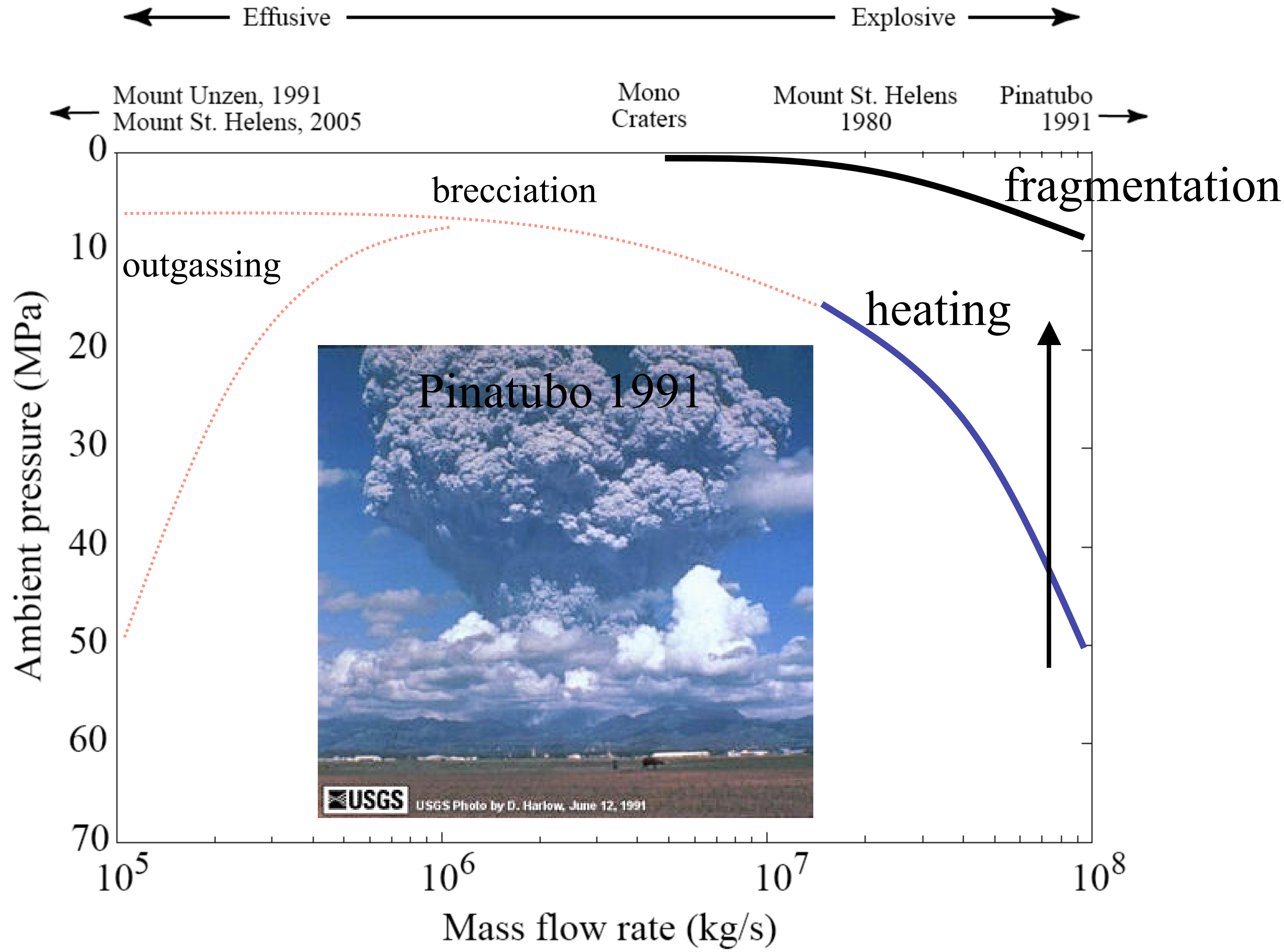




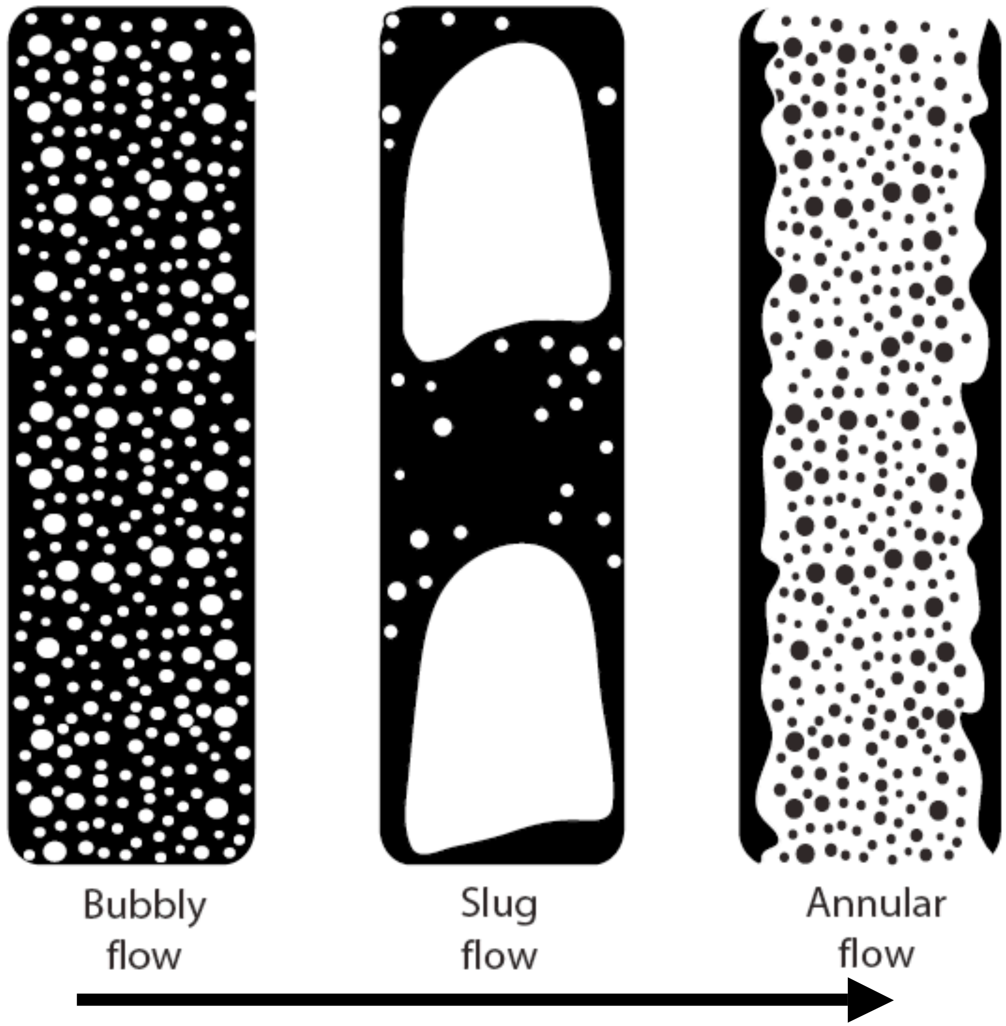
Change in eruption style with changing ascent rate



Change in eruption style with changing ascent rate

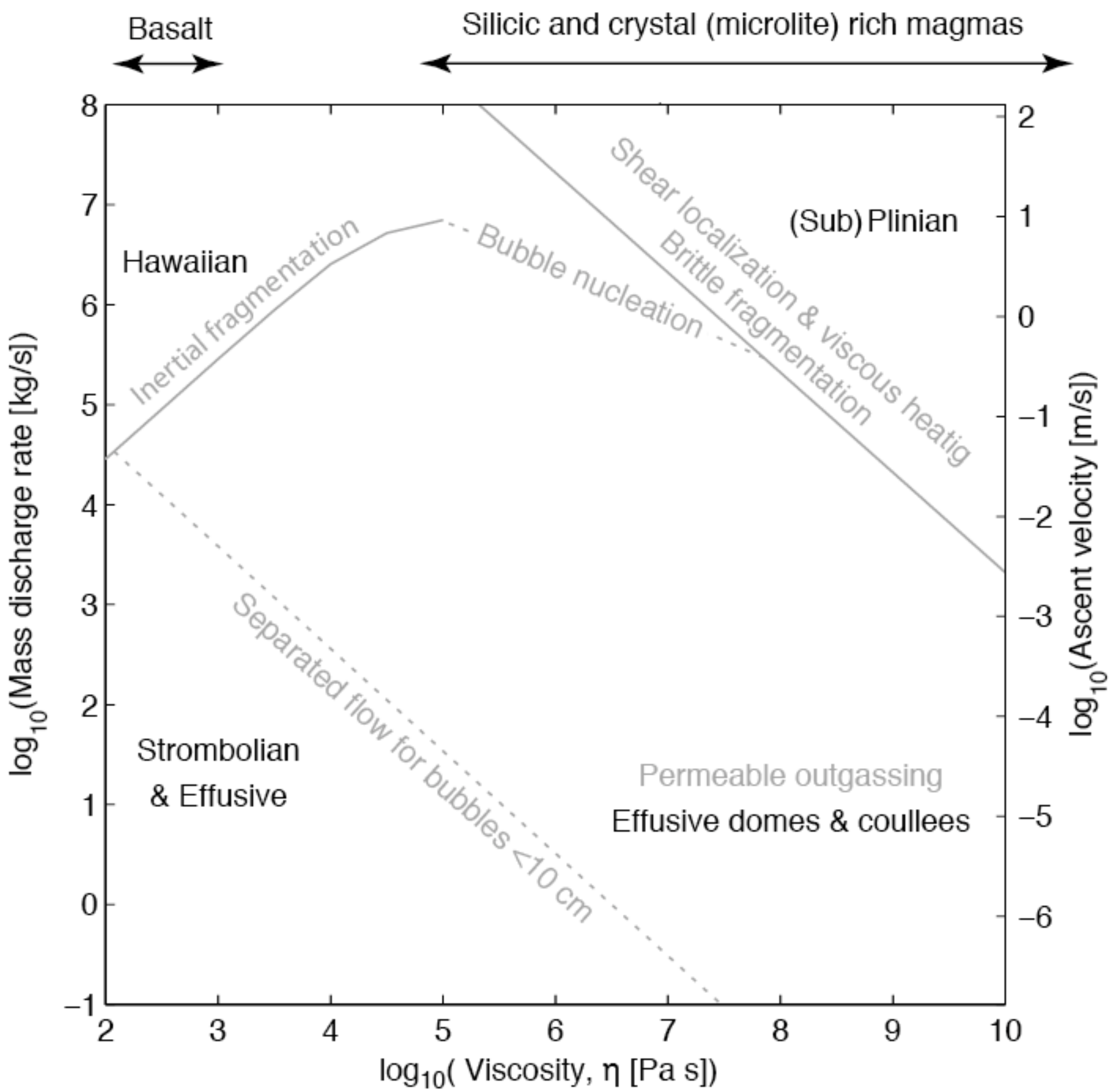


Basaltic (low viscosity) eruptions

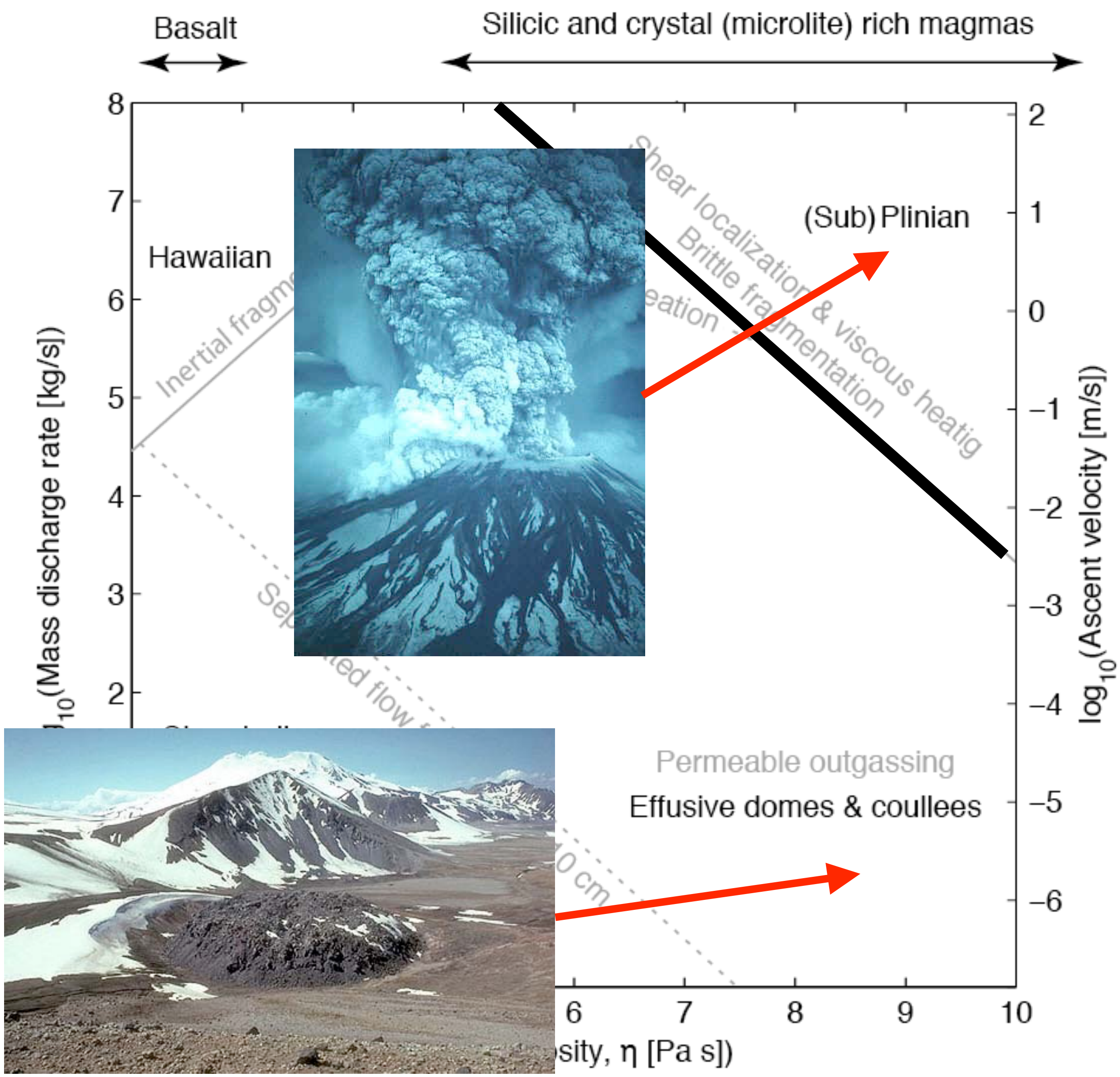


Increasing bubble/melt speed and volume fraction of bubbles

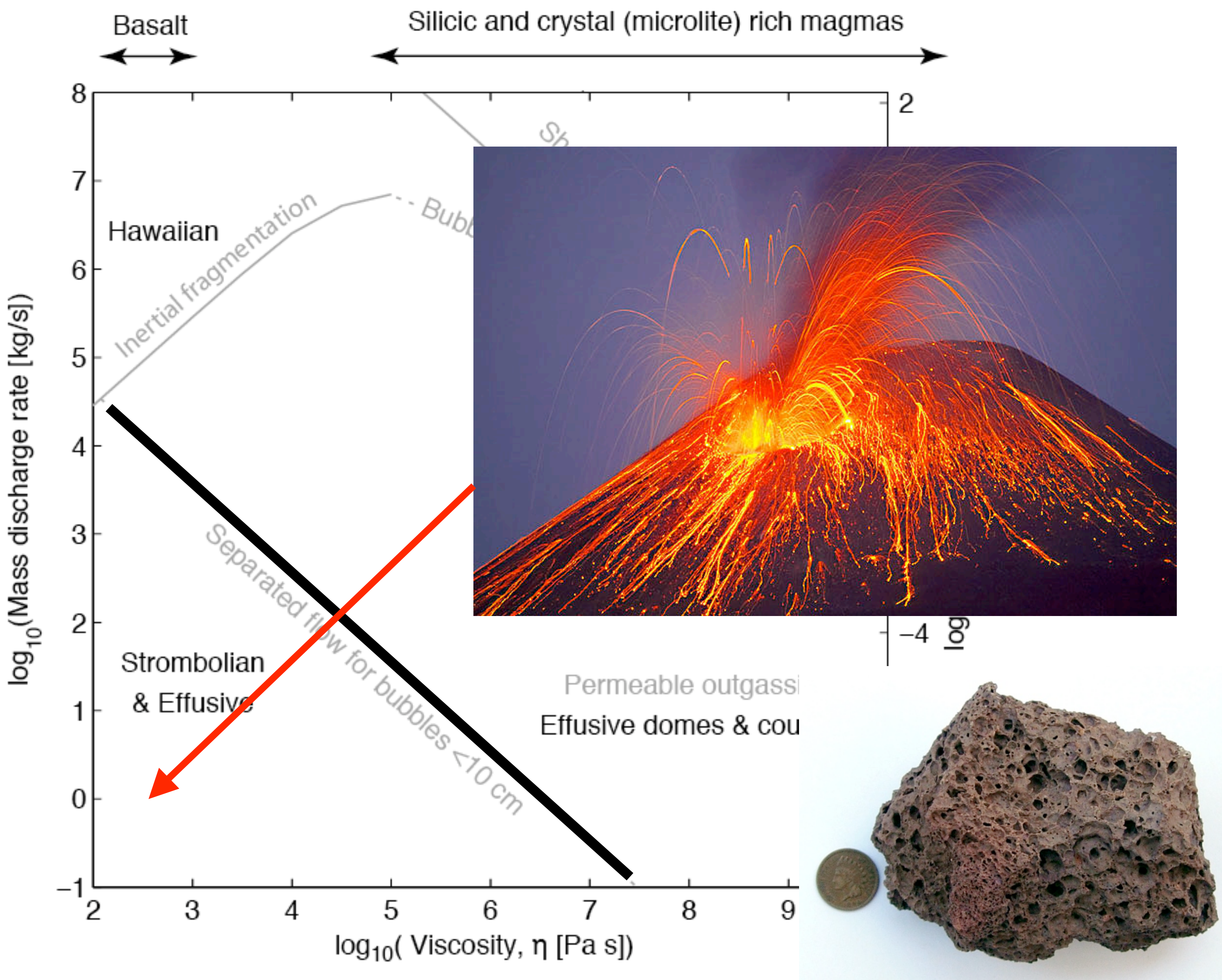
Basaltic eruption styles



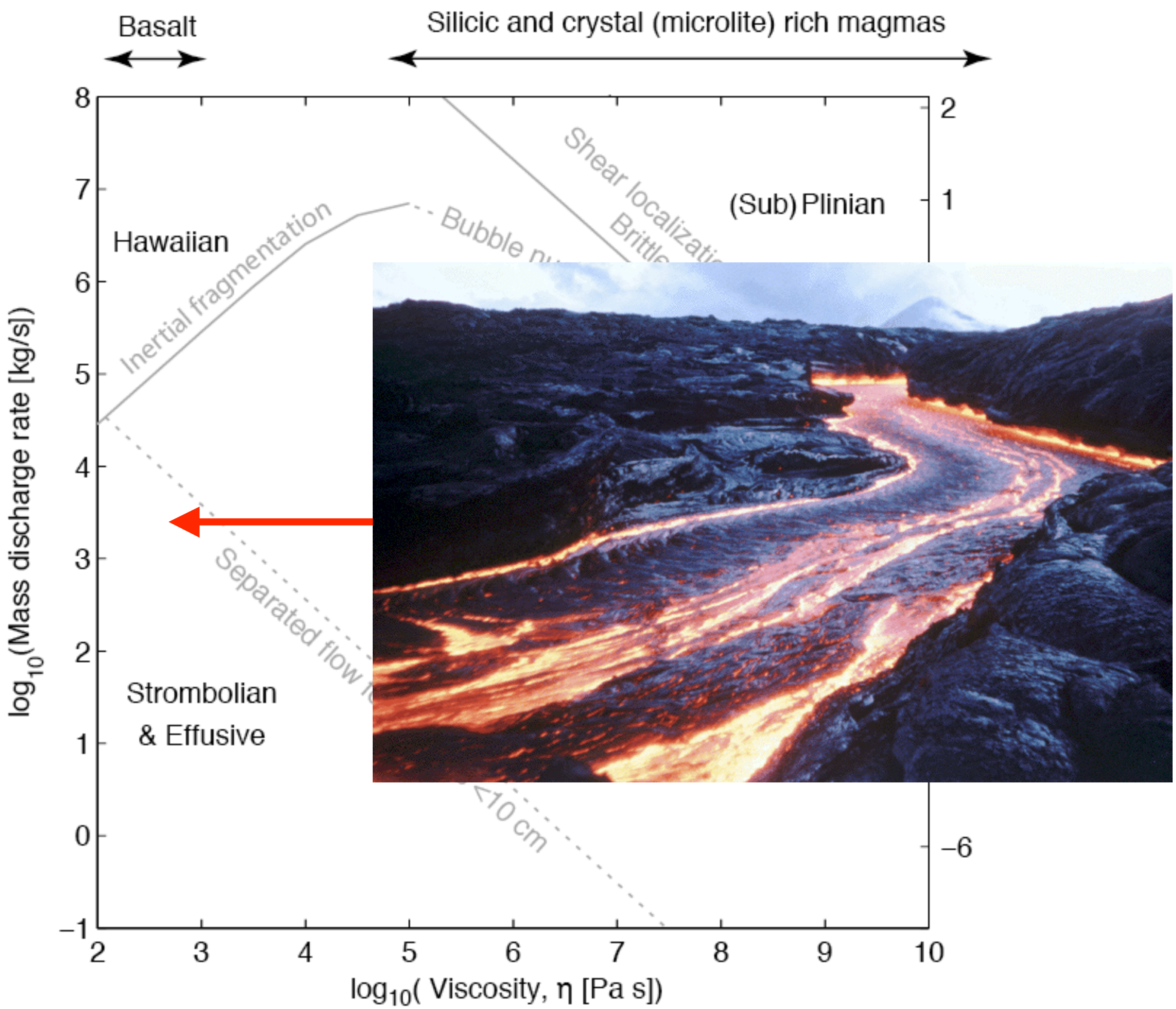
Basaltic eruption styles



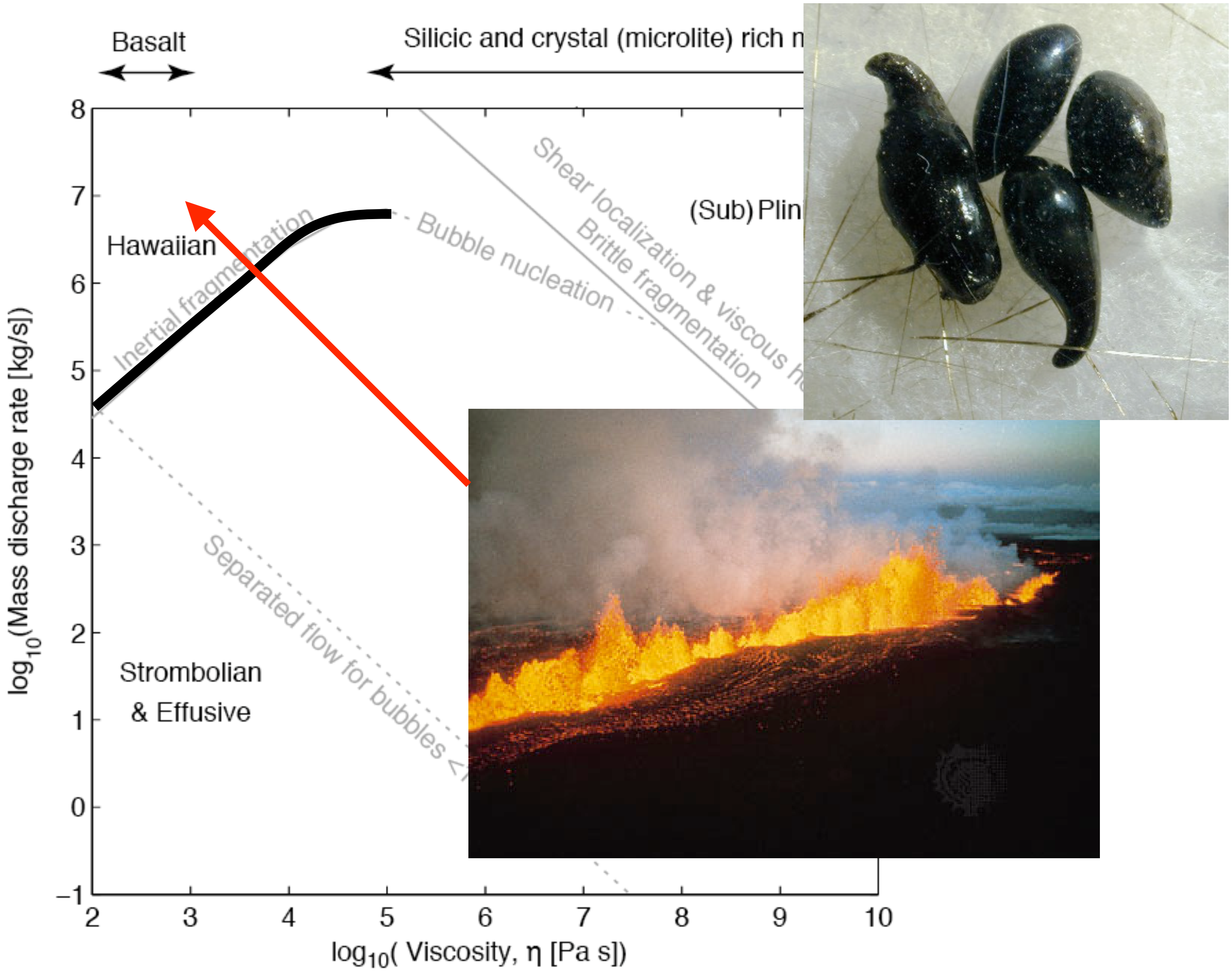
Basaltic eruption styles



Basaltic eruption styles



Basaltic eruption styles



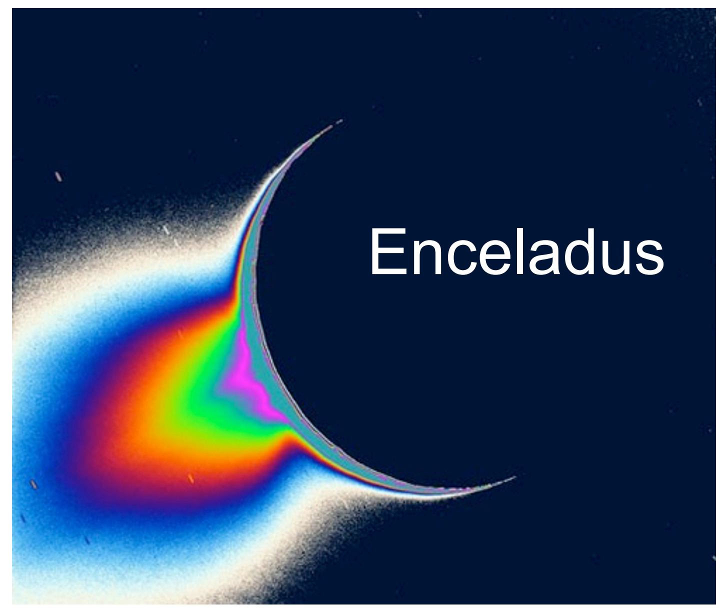
Governing physical processes: summary

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	

Ongoing volcano projects

- Why conduits?
- Why do eruptions stop?
- Huge (>1000 km^3) caldera forming eruptions
- Effects of external water
- Mobility of pyroclastic flows
- Cryovolcanism (icy moons)

Reuters



Porco et al., Science 2006

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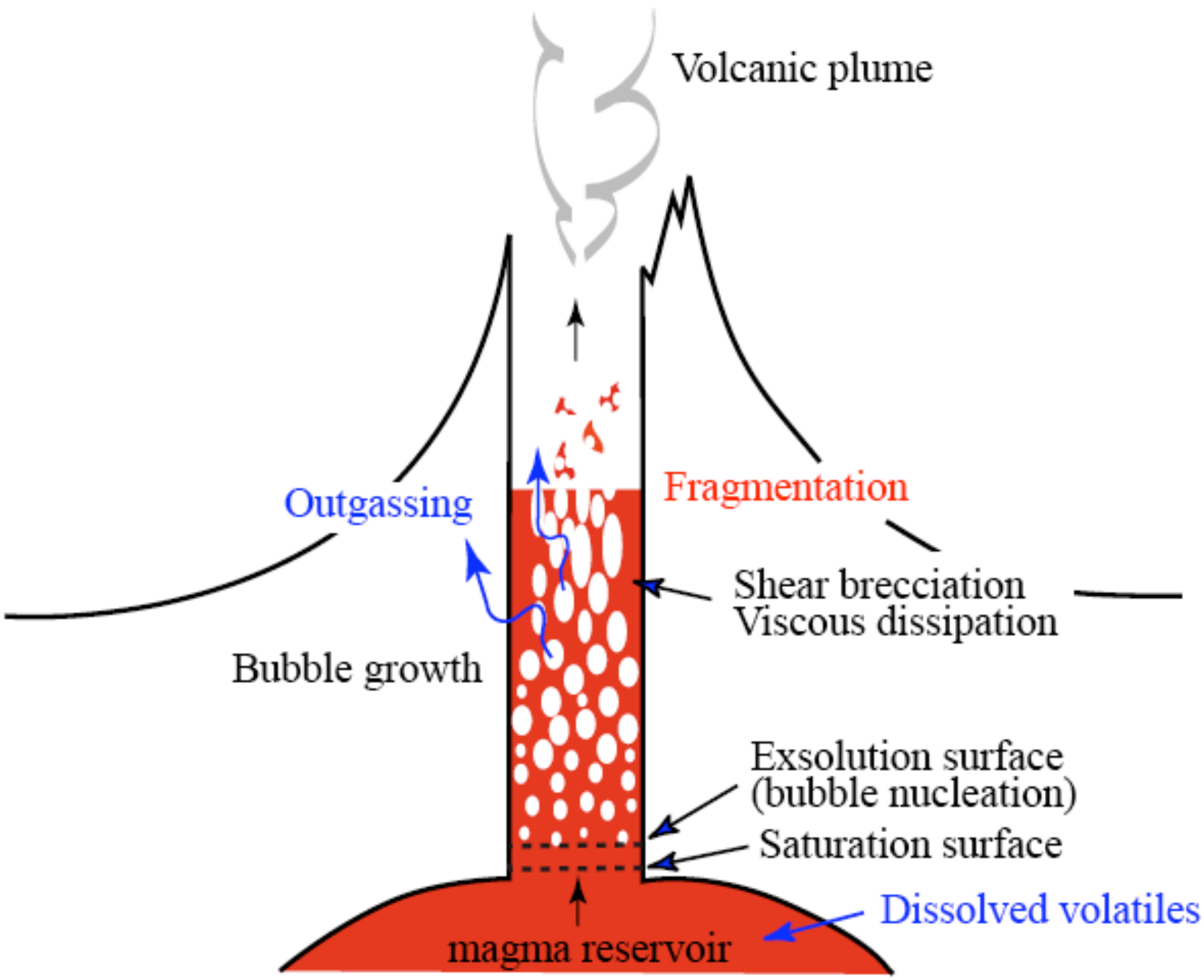

- Interplay between bubble growth, brecciation, outgassing, and fragmentation governs eruption style