The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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2240-4

Advanced School on Scaling Laws in Geophysics: Mechanical and Thermal Processes in Geodynamics

23 May - 3 June, 2011

Mixing and Volcanos

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Berkeley
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Mixing

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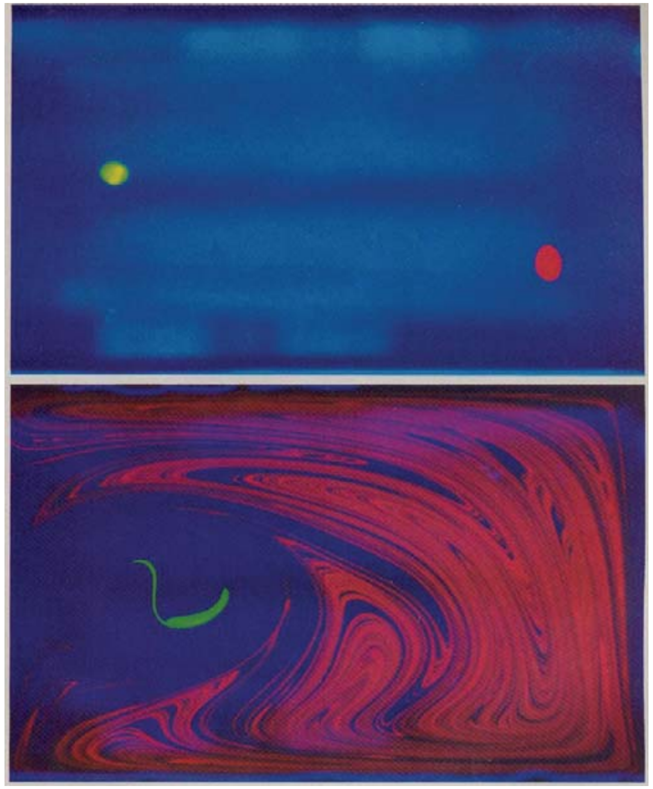
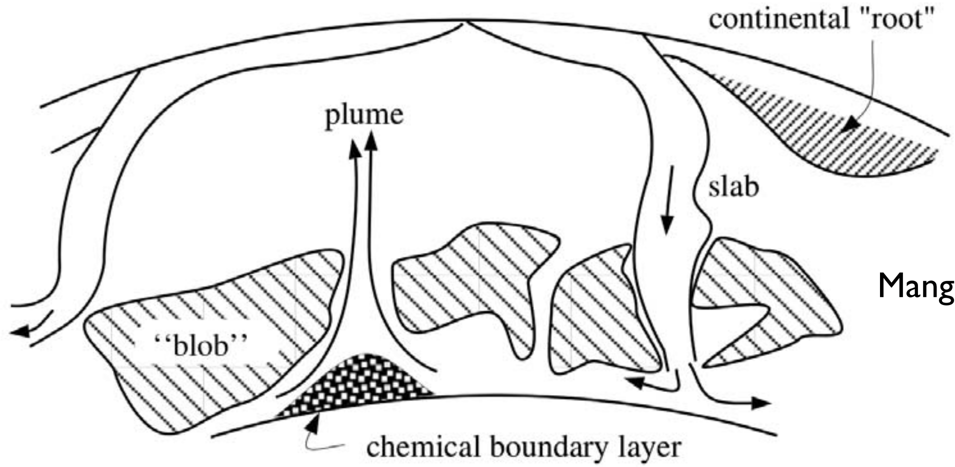


"Virtually everyone agrees that mixing in complicated"
Ottino, Ann Rev Fluid Mech (1990)

Why study mixing?

To provide a quantitative framework to interpret geochemical and isotopic variations in magmas, or structures we image with seismology (present structure and evolution of structures, rates of mass and energy exchange, evolution of mantle composition); magmatic processes within the crust



Manga, *PEPI* (2010)

Outline

- A bit of terminology
- Physics of mixing
- Characterization of mixing
- Mixing in the mantle

Not covered

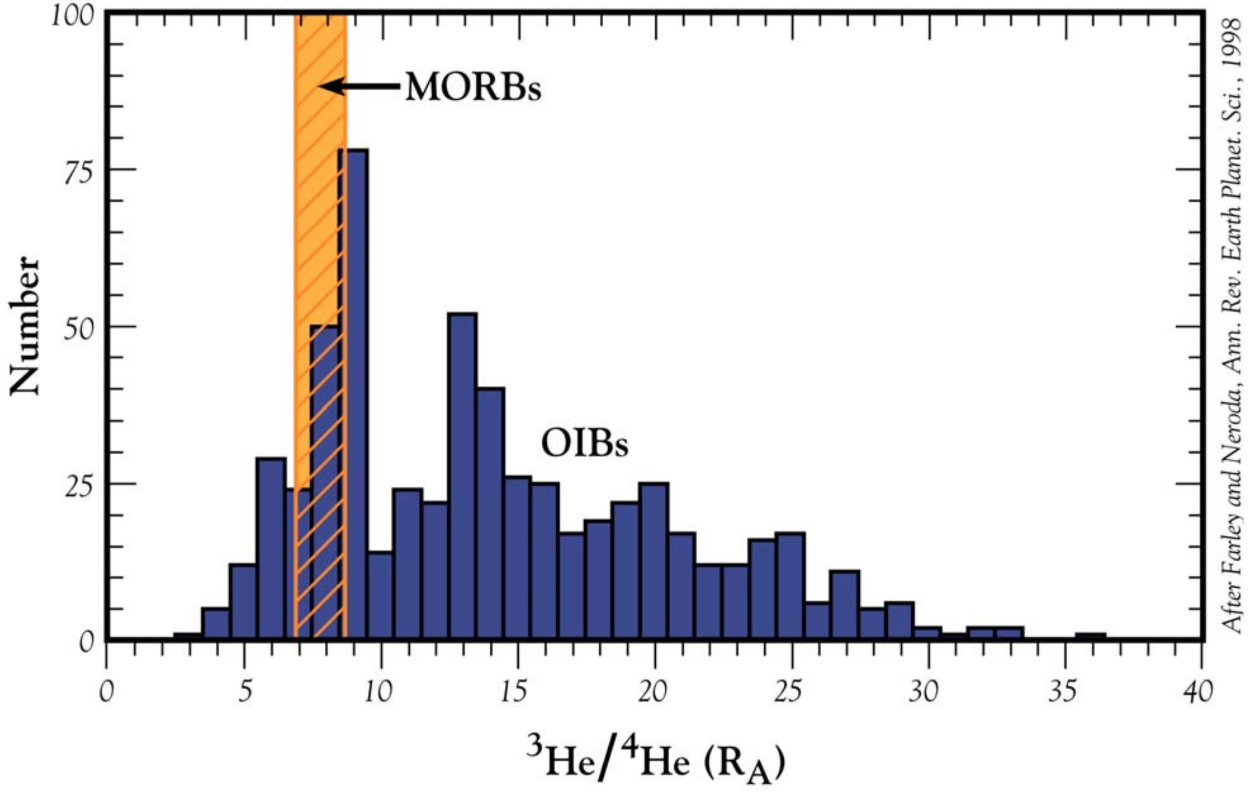
- How convection works (see other lectures)
- The geochemistry we want to interpret
- Numerical and computational challenges (see van Keken et al *JGR* 1997 for a discussion)
- Turbulent mixing (only low Reynolds number, laminar mixing)

Main points

- Flow type matters
- Time dependence matters
- Properties of heterogeneity matter
- Convection both creates and destroys heterogeneity

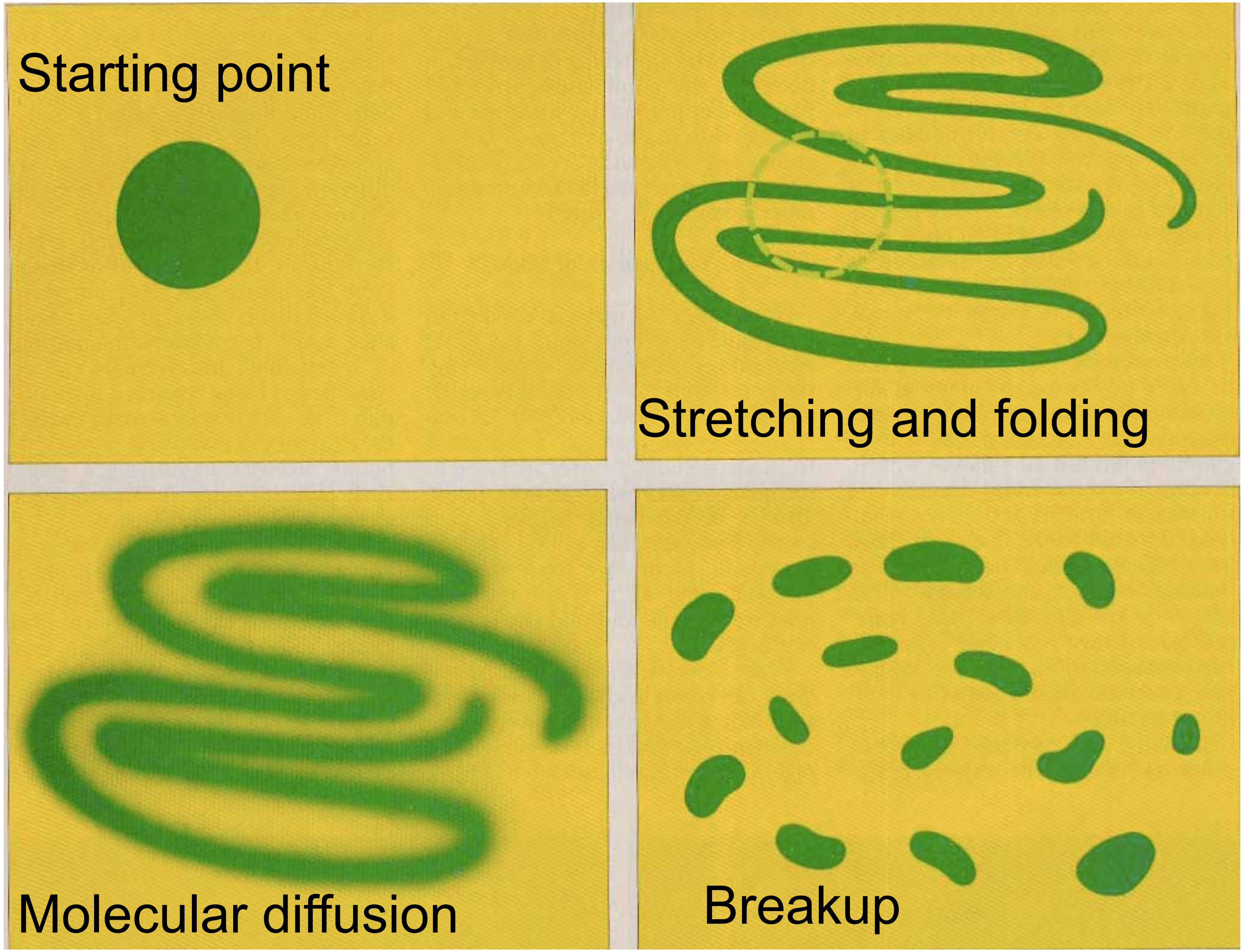
Some observations that we can interpret in the context of mixing

Global scale: mantle contains well-mixed regions and heterogeneity



After Farley and Neroda, Ann. Rev. Earth Planet. Sci., 1998

How does mixing occur?



Ottino, Scientific American 1989

Definitions

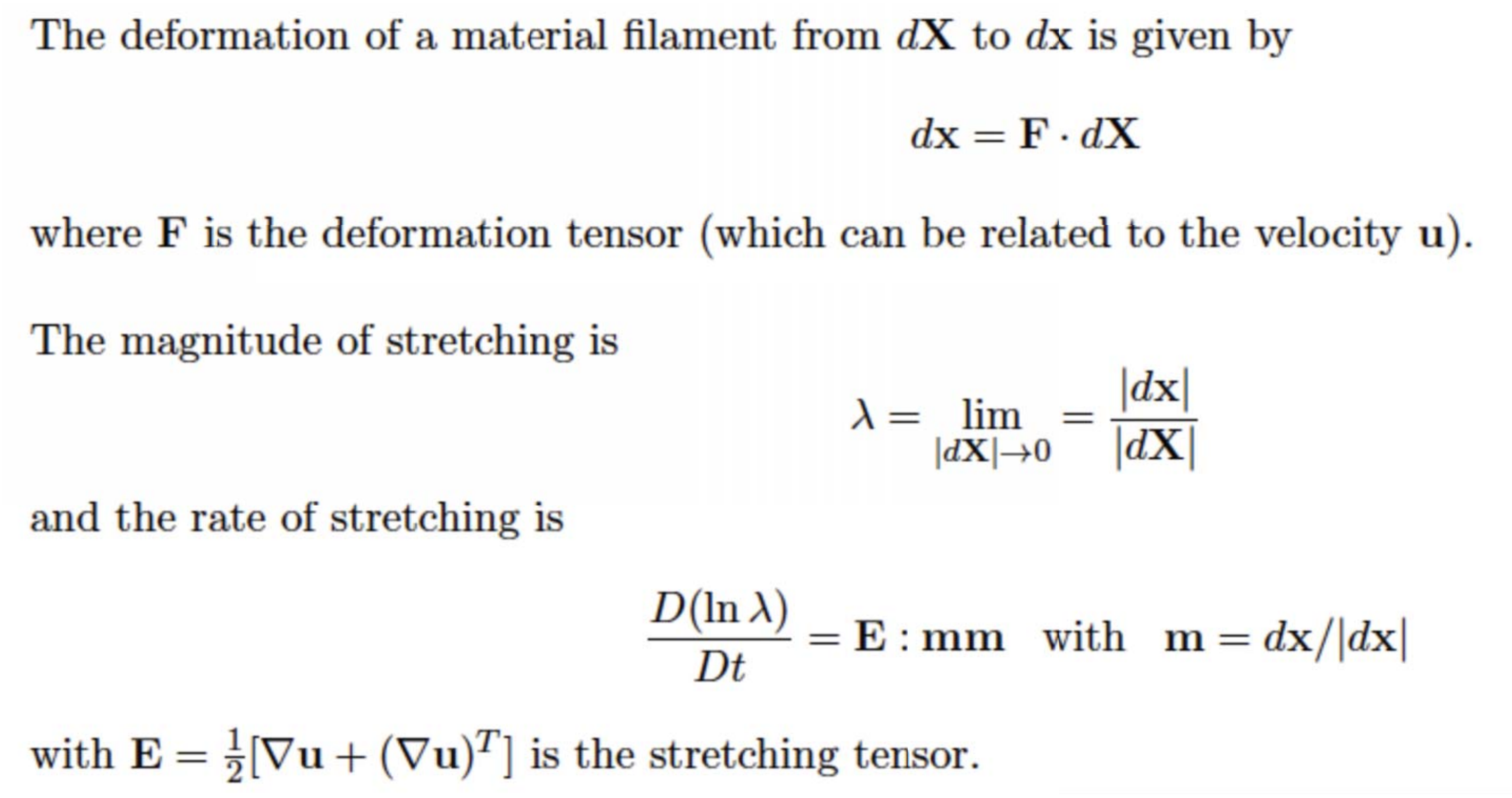
Stirring: *stretching* and *folding* of material surfaces to reduce length scales

Mixing: homogenization by stirring and diffusion

Passive tracer: is convected with the flow $\mathbf{u}(\mathbf{x},t)$ and does not influence the flow

Active heterogeneities: owing to differences in density and/or rheology, modify the flow

Stretching: flow type matters



The deformation of a material filament from $d\mathbf{X}$ to $d\mathbf{x}$ is given by

$$d\mathbf{x} = \mathbf{F} \cdot d\mathbf{X}$$

where $\mathbf{F}$ is the deformation tensor (which can be related to the velocity $\mathbf{u}$).

The magnitude of stretching is

$$\lambda = \lim_{|d\mathbf{X}| \to 0} = \frac{|d\mathbf{x}|}{|d\mathbf{X}|}$$

and the rate of stretching is

$$\frac{D(\ln \lambda)}{Dt} = \mathbf{E} : \mathbf{mm} \quad \text{with} \quad \mathbf{m} = d\mathbf{x}/|d\mathbf{x}|$$

with $\mathbf{E} = \frac{1}{2}[\nabla \mathbf{u} + (\nabla \mathbf{u})^T]$ is the stretching tensor.

Stretching: flow type matters

Lets consider **linear** 2D flows in the x-y plane

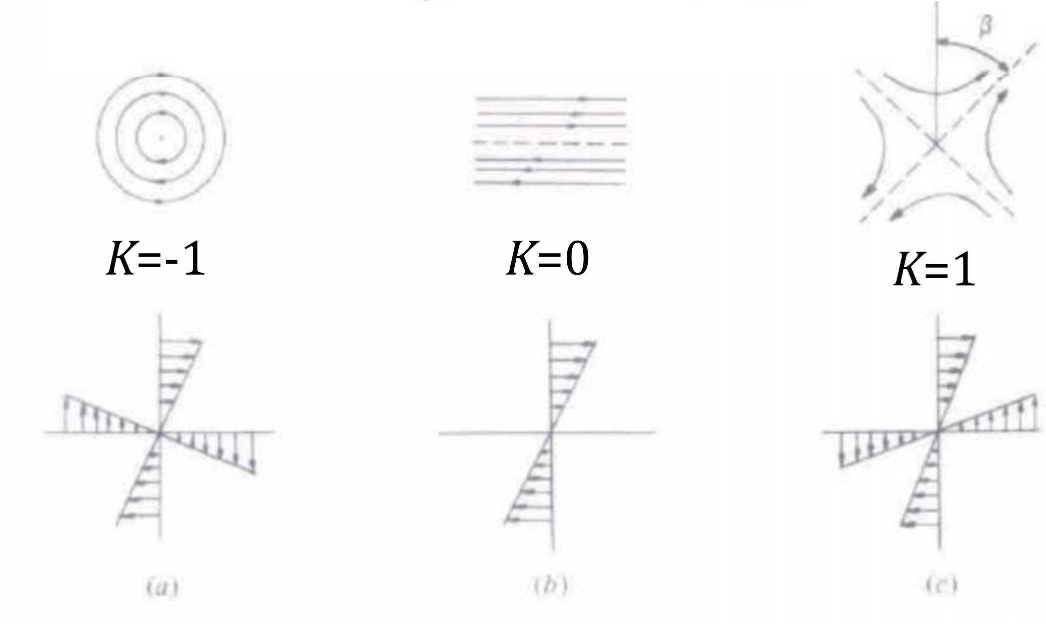
$$v_x = Gy \quad \text{and} \quad v_y = KGx$$

For long times, if $K = 0$ (simple shear)

$$\lambda \sim Gt$$

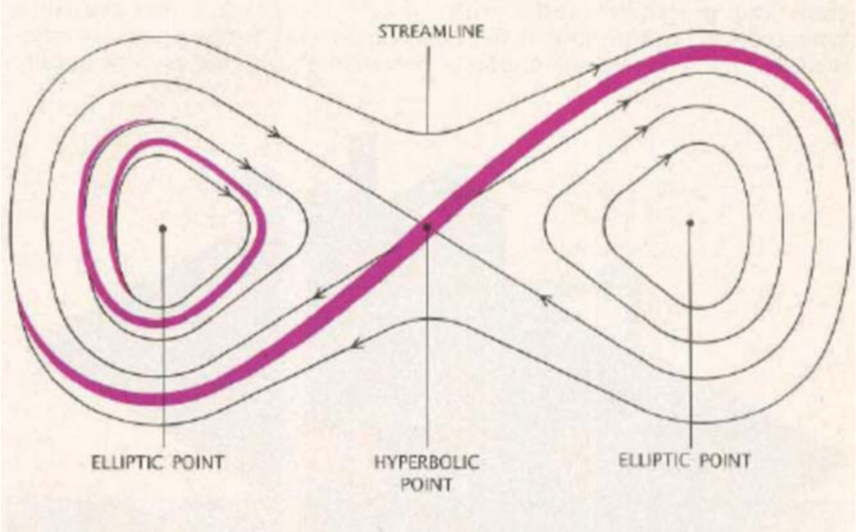
and if $K = 1$ (pure shear, hyperbolic flow)

$$\lambda \sim e^{Gt}$$

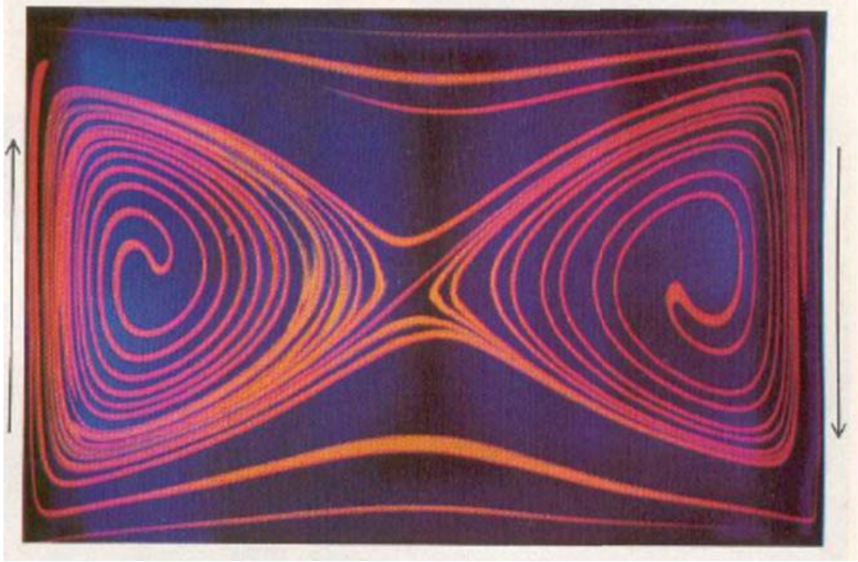


In a more complex flows, regions with pure shear (hyperbolic streamlines) will cause most of the *stretching*

Two types of building blocks for flows: Elliptic and hyperbolic points

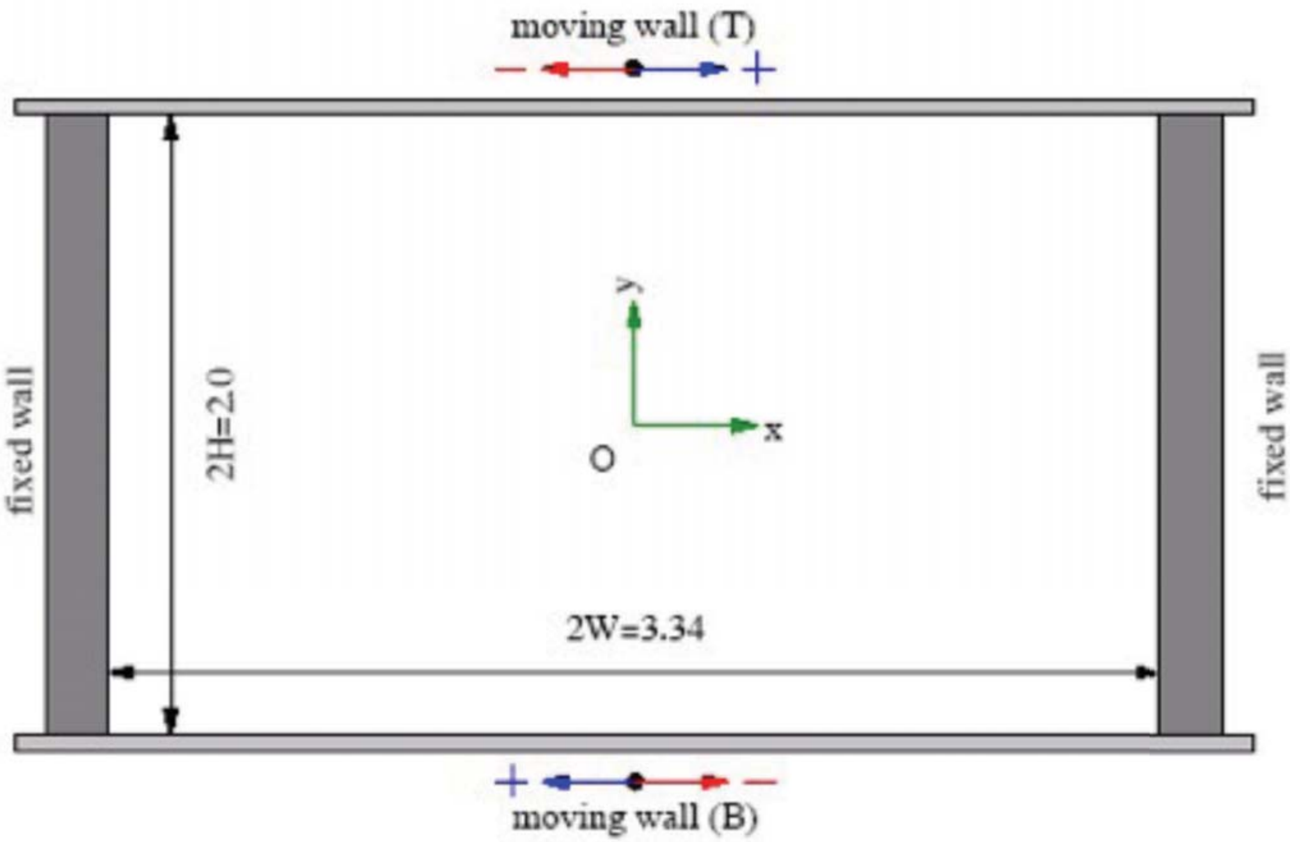


Ottino, *Scientific American* 1989



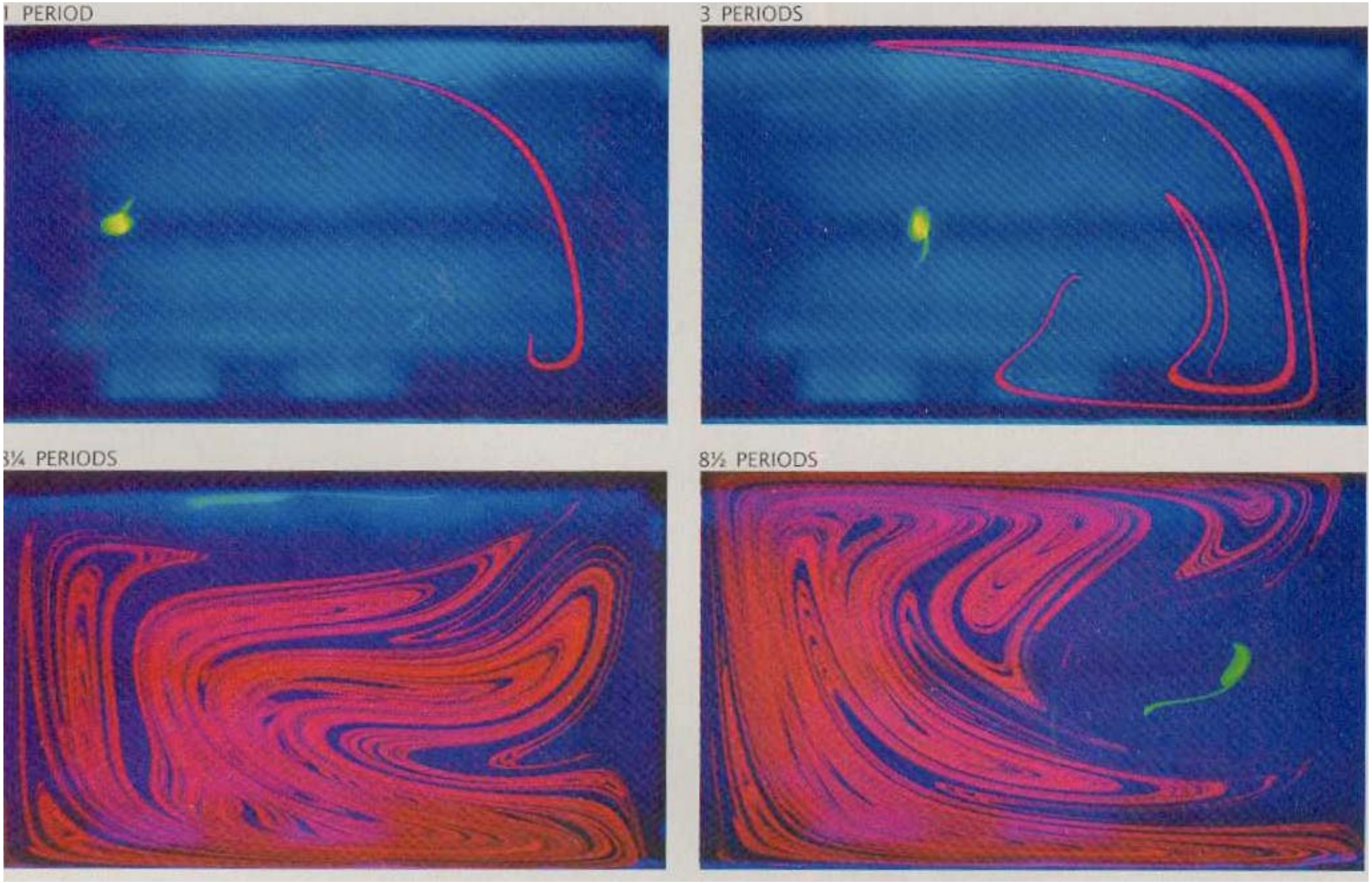
Steady two-dimensional flows are cannot mix well (no way to cross streamlines)

but, Aref (J Fluid Mech 1984) 2D time-periodic flows can mix effectively



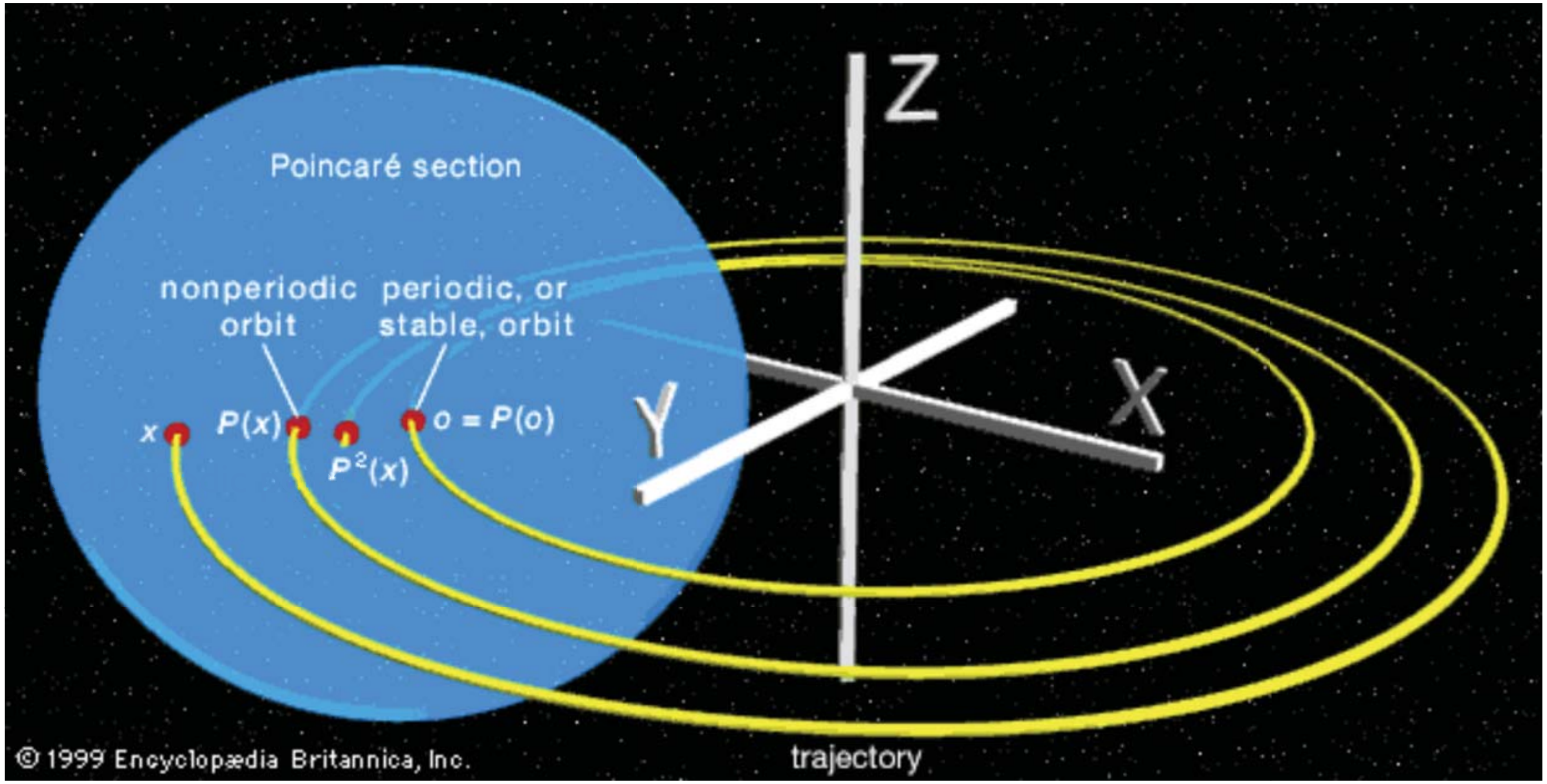
Dimensionless displacement: $D = \frac{VT}{2W}$, T is the duration of a period

Add time-dependence (periodic motion of boundaries) well-mixed and not-well-mixed regions coexist



Poincare sections

(reduces dimensionality by converting flow into a map; convenient way to show the character of solutions for all possible initial conditions)



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Poincare sections

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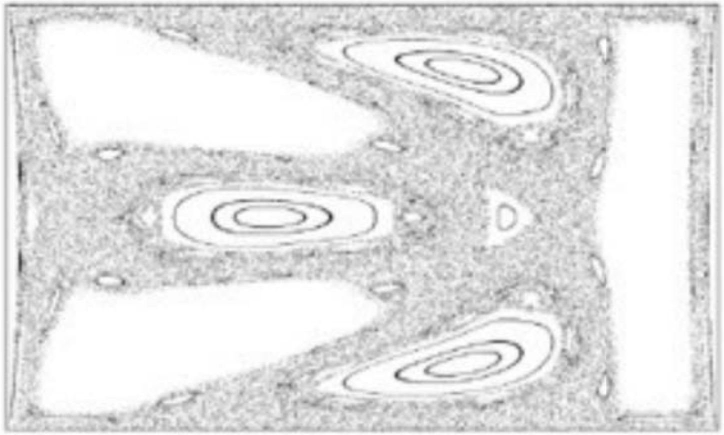
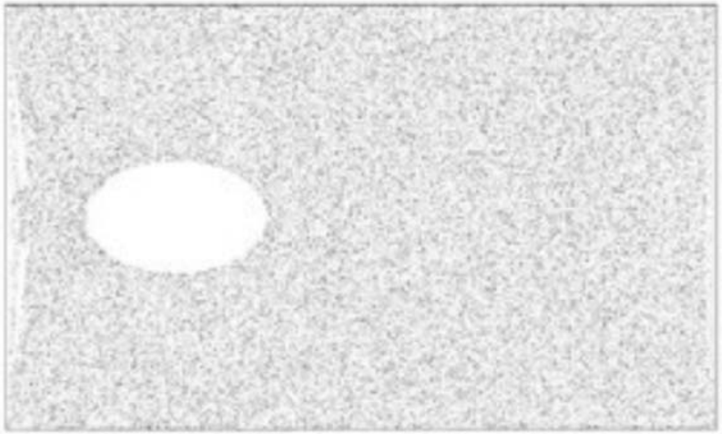
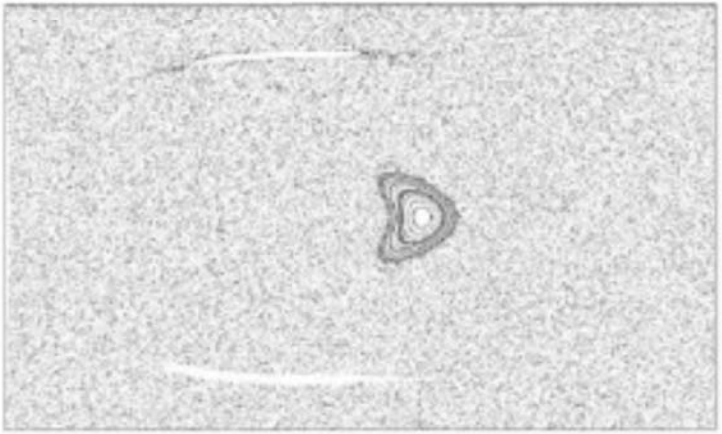


$D = 3$

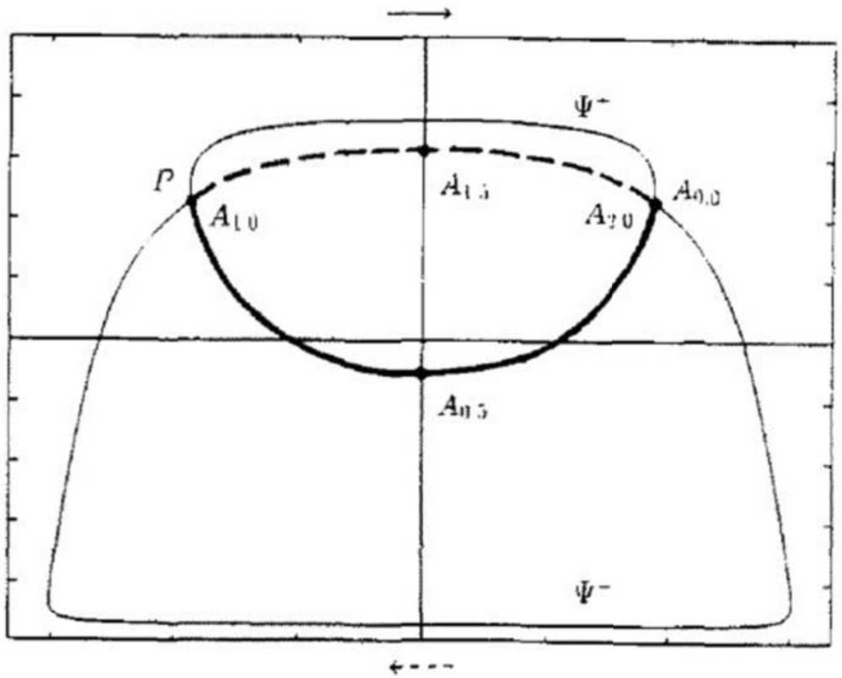


$D = 6.24$

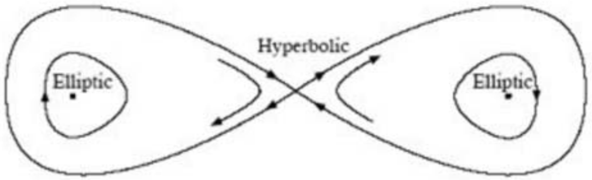
$D = 15$

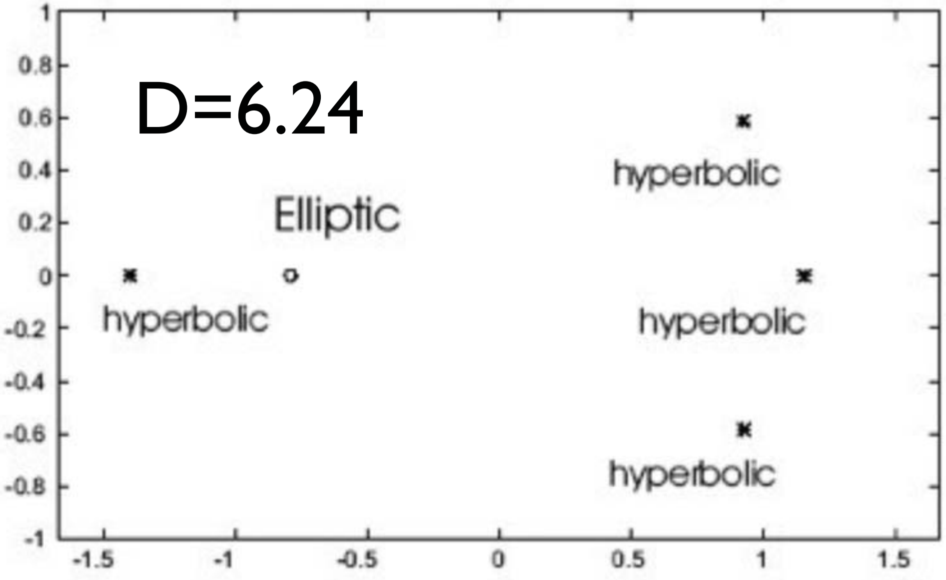


$D = 20$



first-order periodic points





Stirring

Can produce complex structures AND unmixed islands

Under what circumstances does a deterministic flow widespread and efficient stretching of material surfaces (lines in 2D)?

(Mathematical) definition of chaotic flows

- The flow stretches and folds
- The trajectories of tracers are sensitive to initial conditions
- The flow has homoclinic and/or heteroclinic points
- The flow produces horsehoe maps

Mathematical characterization of stretching

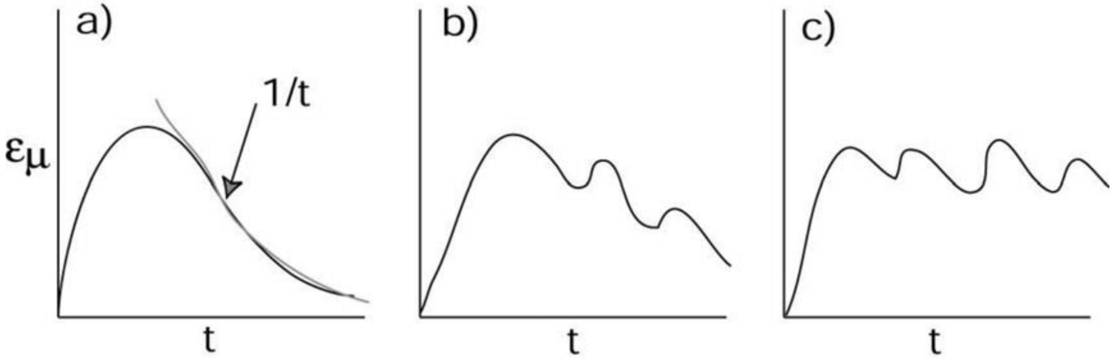
The magnitude of stretching is

$$\lambda = \lim_{|d\mathbf{X}| \to 0} = \frac{|d\mathbf{x}|}{|d\mathbf{X}|}$$

The stretching efficiency is

$$e_\lambda = \frac{D(\ln \lambda)/Dt}{(\mathbf{E} : \mathbf{E})^{1/2}} \leq 1$$

For simple shear, $e \to 0$ for large t (a random sequence of shears has a maximum of $e = 0.28$). For pure shear, $e \to 2/3$, but this requires an unbounded fluid. Hence, for good mixing, we need reorientation.

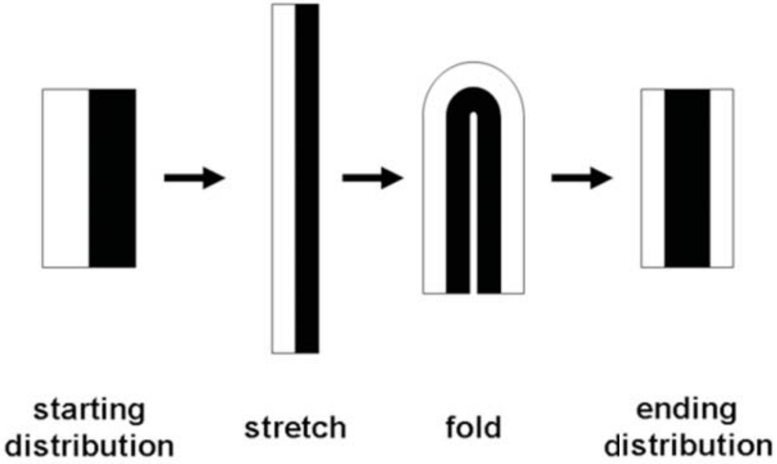


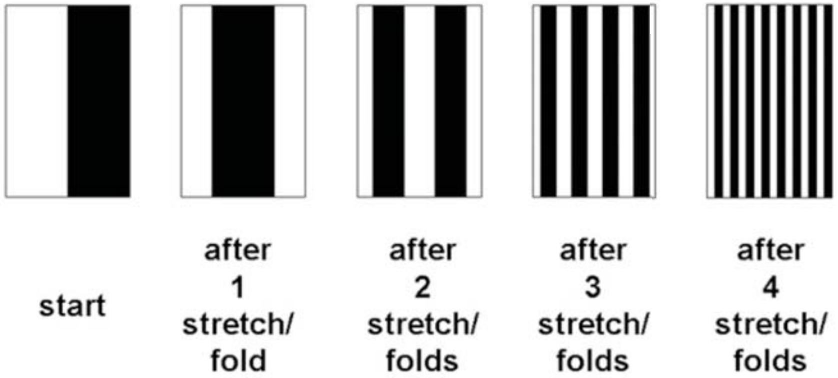
Another way to characterize mixing is with the Lyapunov exponents

$$\sigma = \lim_{|d\mathbf{X}| \to 0; t \to \infty} \left[\frac{1}{t} \ln \lambda \right]$$

(not the same as e because $\mathbf{E} : \mathbf{E}$ varies in space and time). At a given point there is one σ in each direction and the sum is 0. Worry about the largest one.

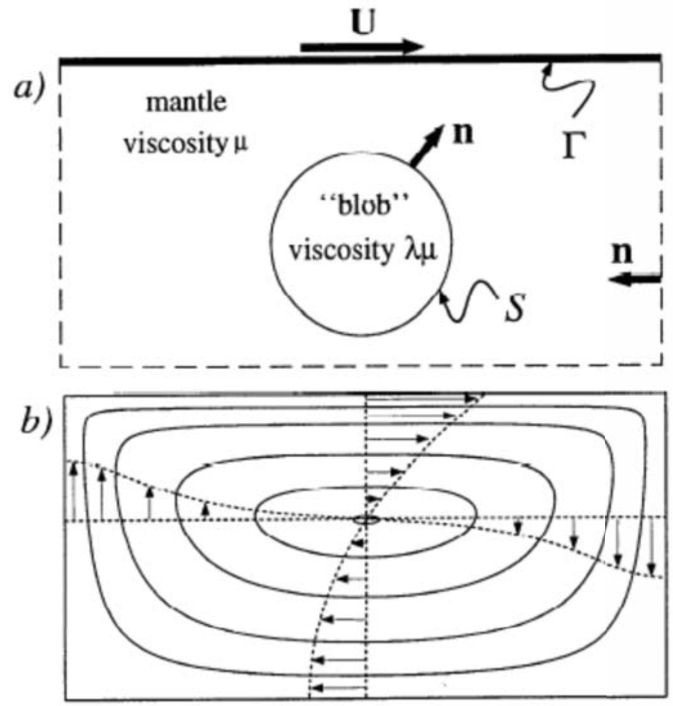
Horseshoe maps



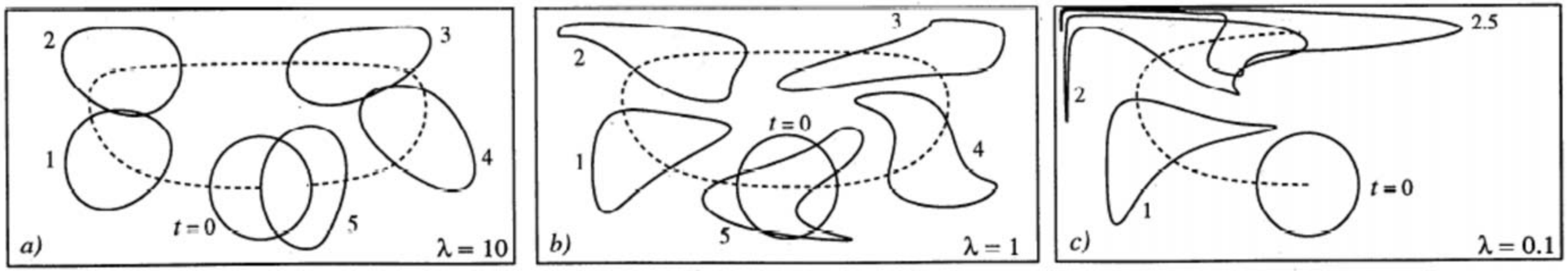


Flow must be capable of stretching and folding and returning it (stretched and folded) to its initial location – called a horseshoe map

Active heterogeneity: viscosity differences affect stretching



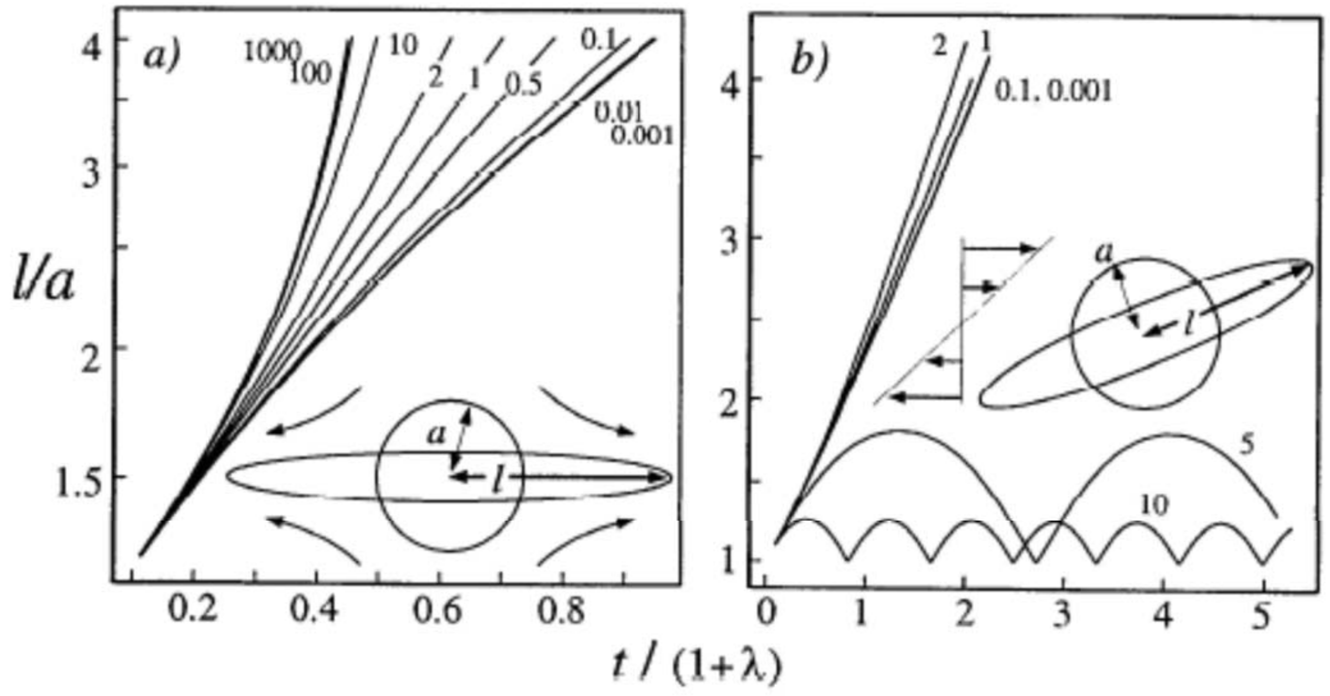
More viscous ⟵ Isoviscous ⟶ Less viscous

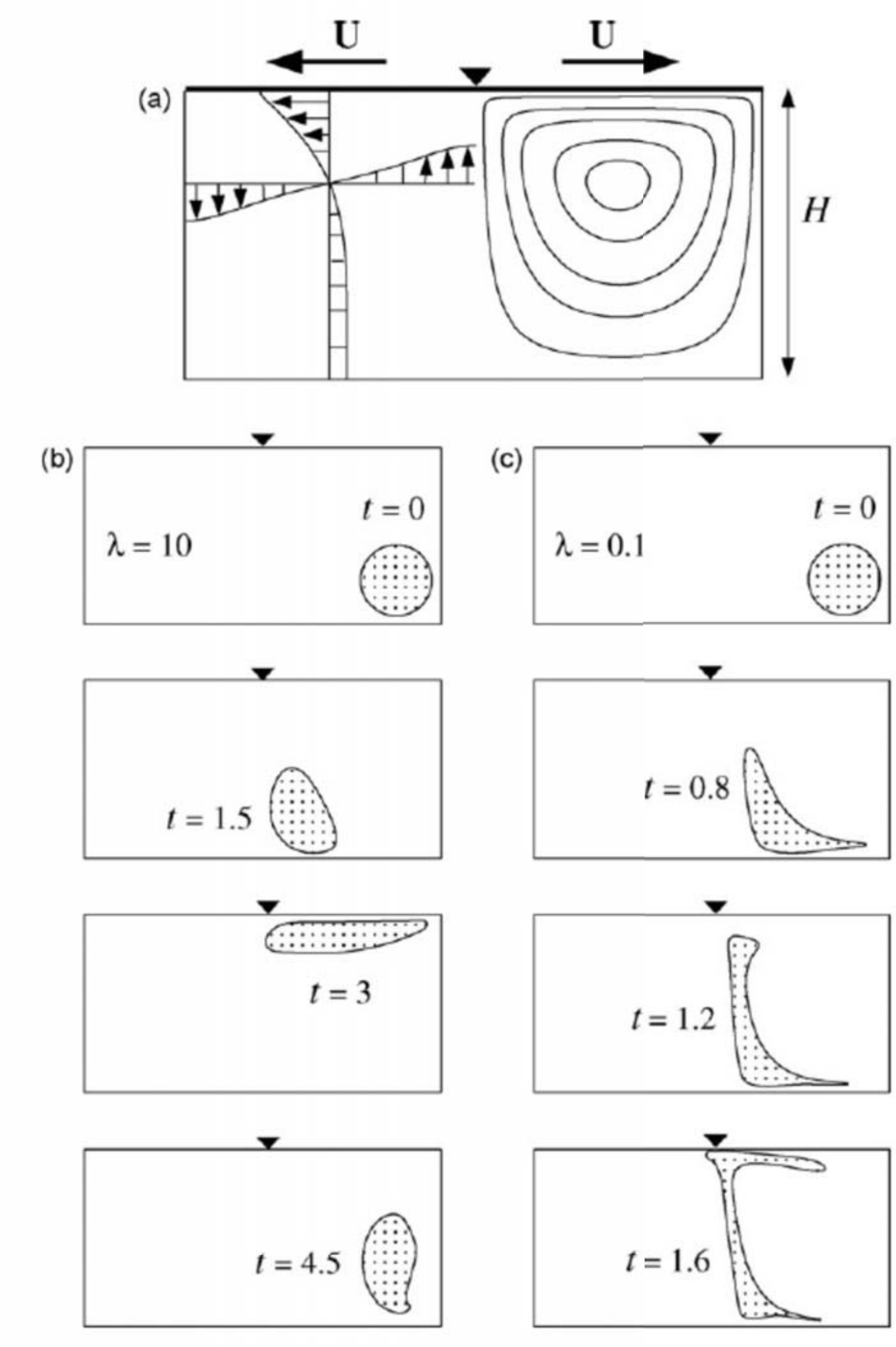


Active heterogeneity: viscosity differences affect stretching

exponential stretching

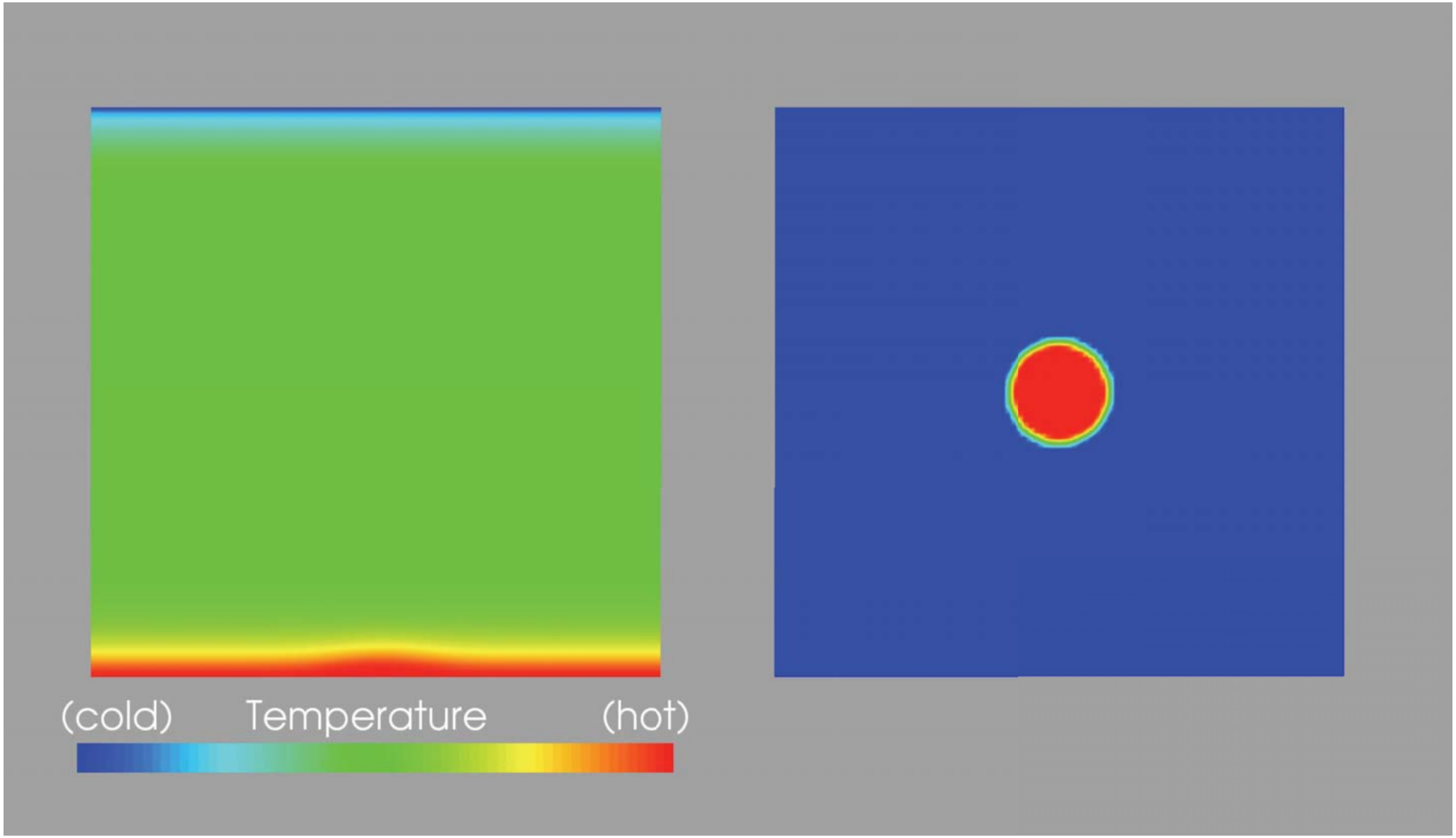
linear stretching





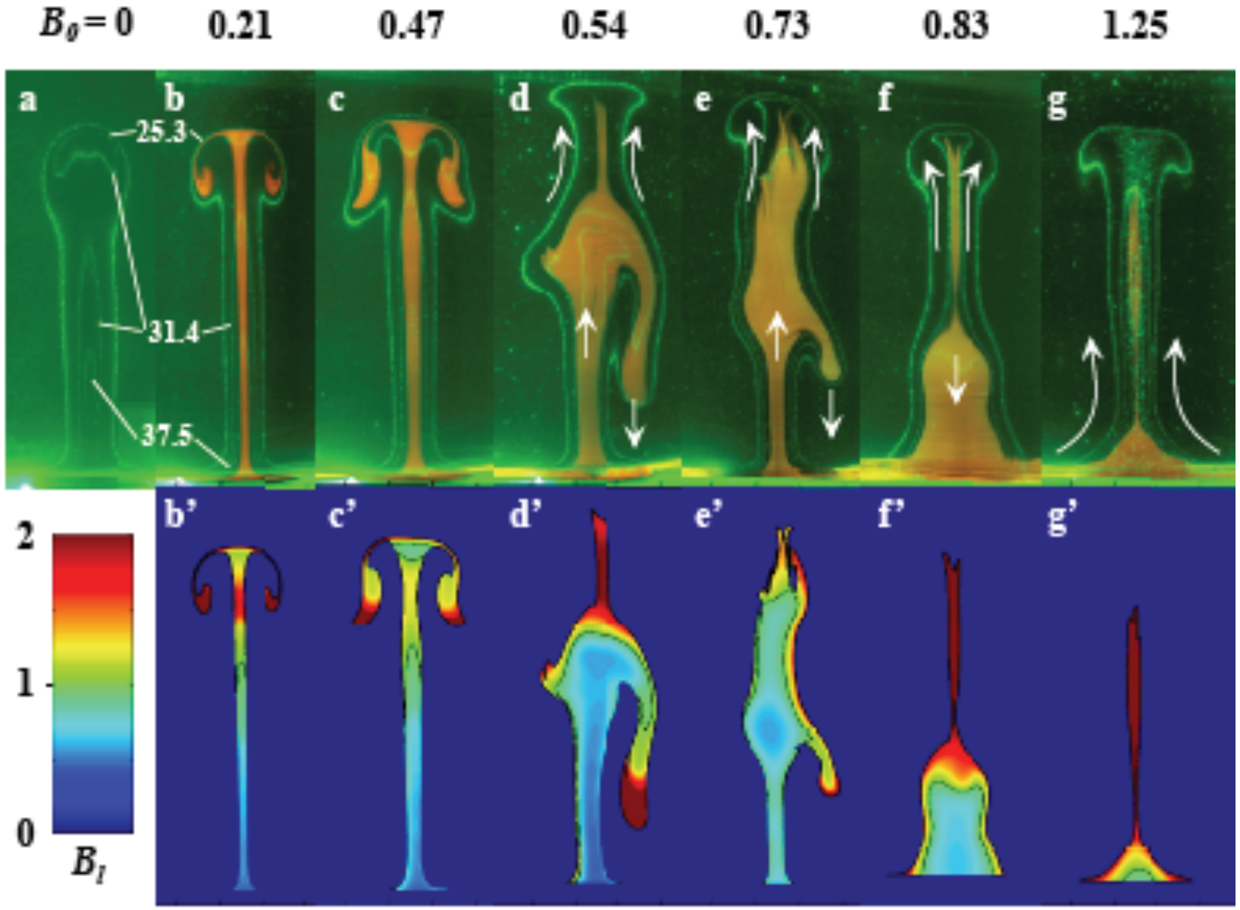
Active heterogeneity: viscosity differences affect stretching and hence flow

Active heterogeneity: viscosity differences affect stretching and hence flow



From Henri Samuel

Active heterogeneity
density differences influences velocity field



$$B_0 = \Delta\rho_{X_{\mathrm{eff}}} / \rho\alpha\Delta T_{\mathrm{eff}}$$

Kumagai et al., *GRL* 2008

Mixing in 3D

- Arnold (C R Acad Sci Paris Ser A 1965) showed that 3D steady flows can have chaotic streamlines)
- Steady, isoviscous thermal convection in a spherical shell, however, is not chaotic (Schmalzl et al. JGR 1996)
- Plate motion changes this story . . .

Mixing associated with plate motion
Poloidal vs toroidal flow

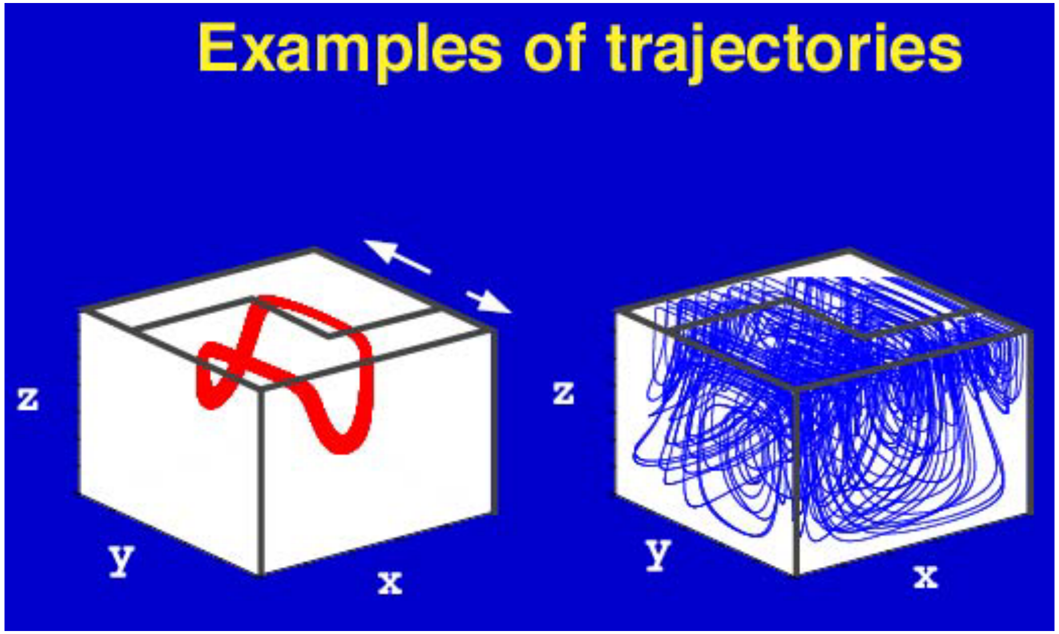
- Poloidal flow: no vertical (radial) vorticity
- Toroidal flow: rotations in horizontal (confined to spherical shells) plane

Surface manifestations

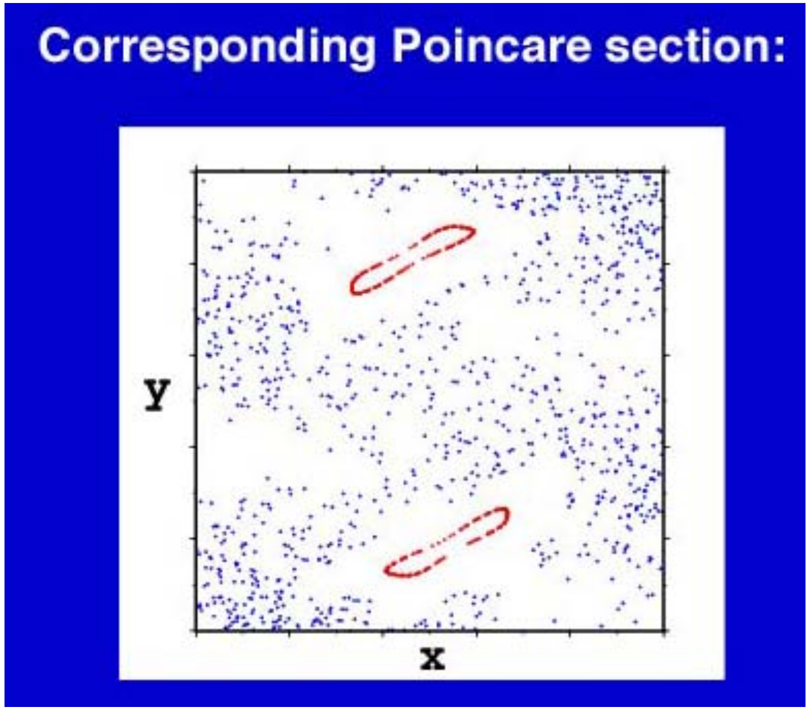
Poloidal motion: ridges and trenches

Toroidal motion: transform boundaries

Roughly equal in magnitude

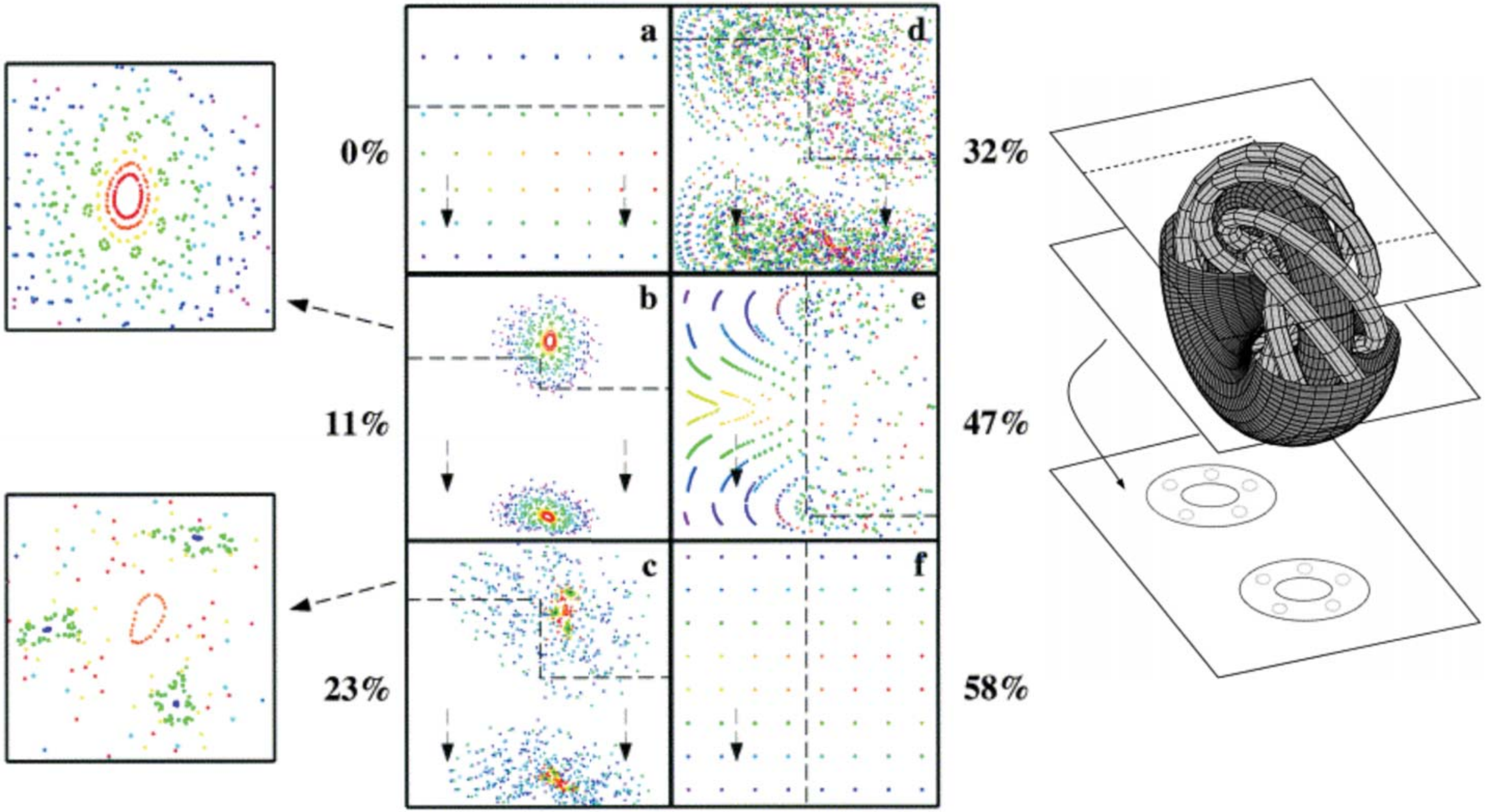


Ferrachat and Ricard, *JGR* 2001

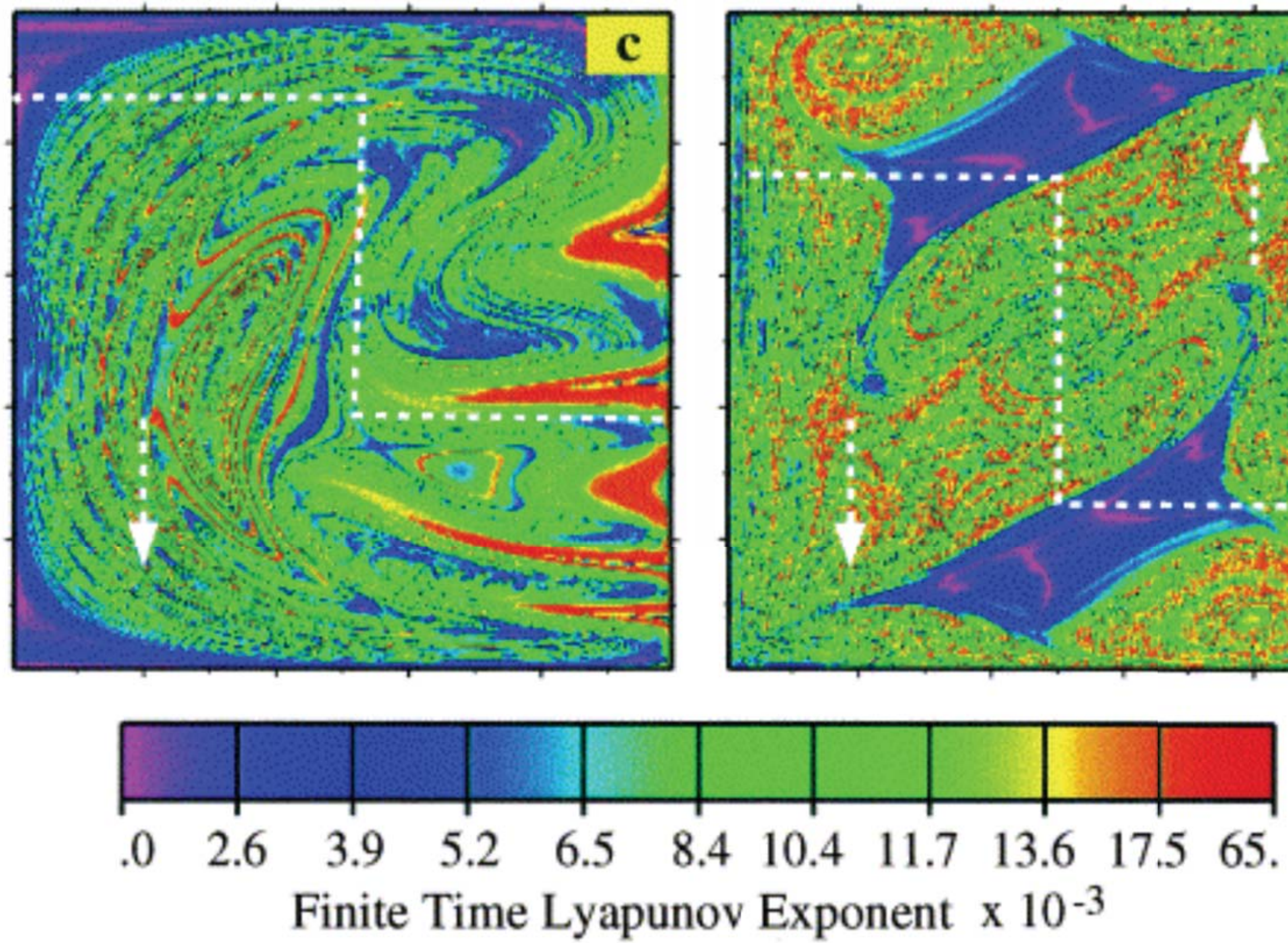


Chaotic trajectories in steady-state plate driven flows

Why? Hyperbolic points do the stretching, toroidal motion does the reorientation

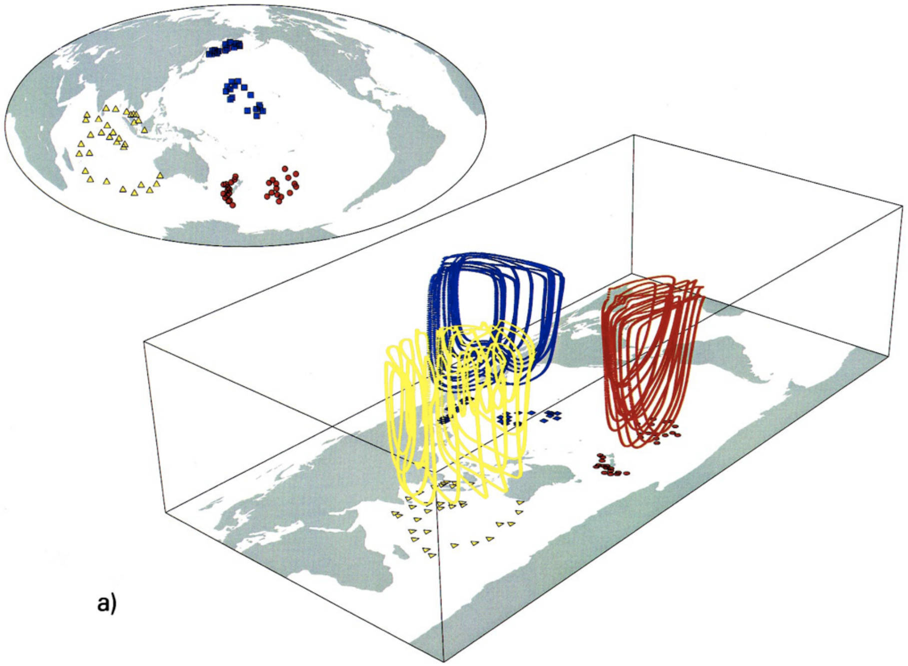


Ferrachat and Ricard, *JGR* 2001



Lyapunov exponents σ estimated by tracking tracers:
Both chaotic and laminar mixing are observed

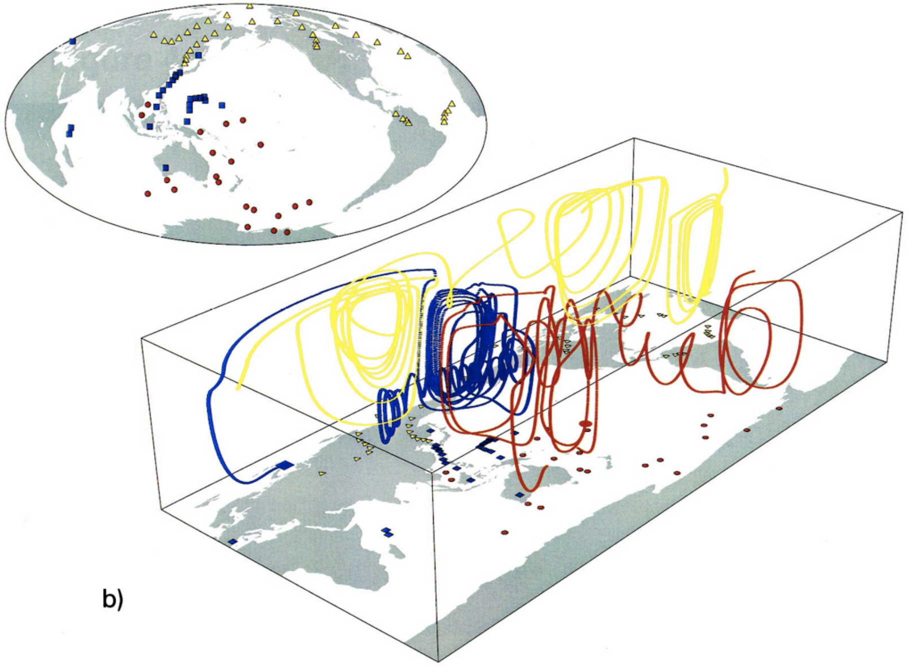
Ferrachat and Ricard, *JGR* 2001



a)

With plate motion, well mixed and poorly mixed regions

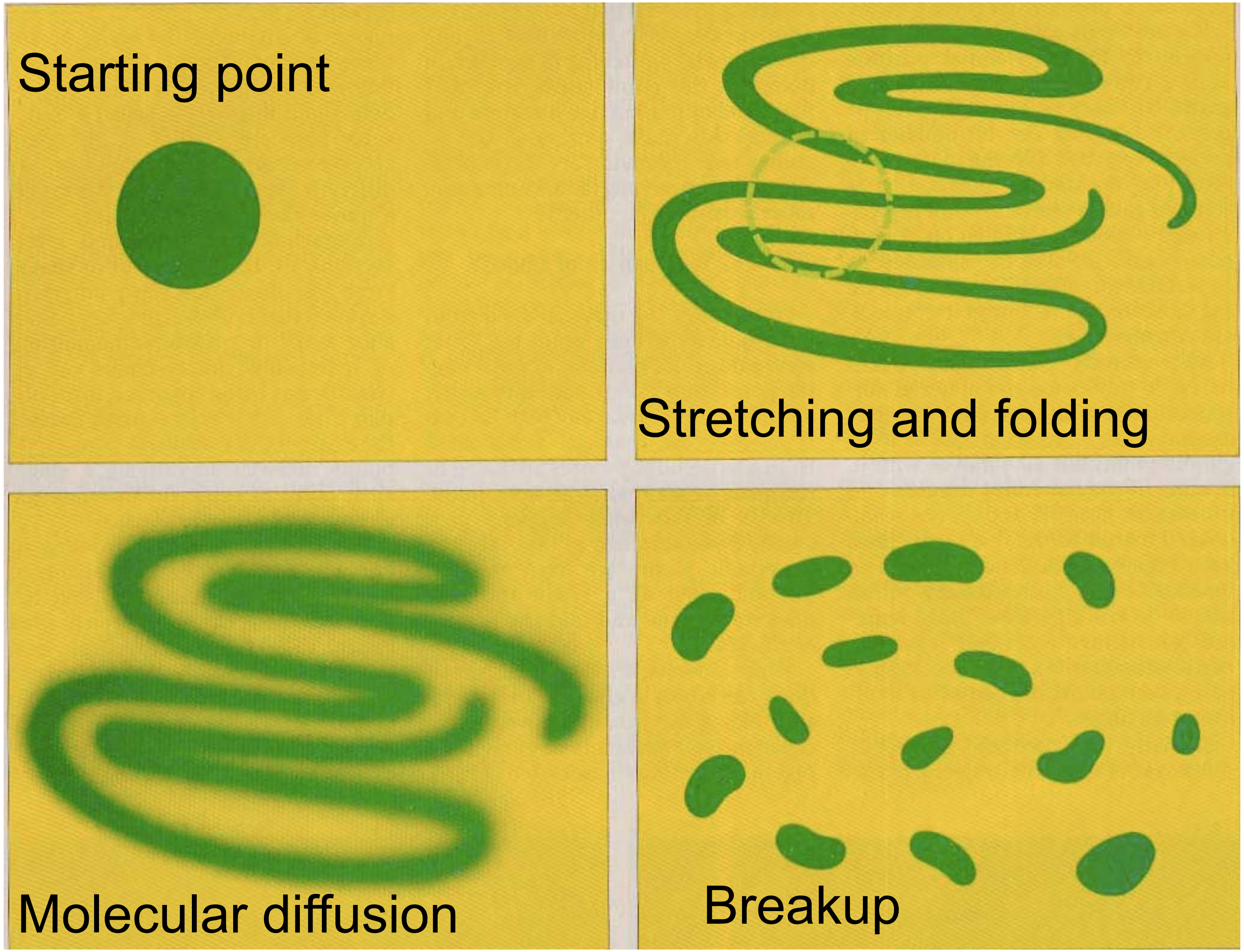
Take steady flow driven present day plate motion and trace particles for 4 Ga



b)

van Keken and Zhong, EPSL 1999

How does mixing occur?



Ottino, Scientific American 1989

What about chemical diffusion?

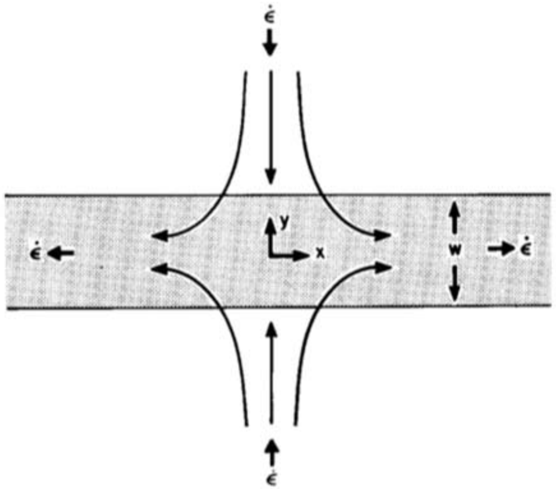
$$\begin{tikzcd} & \frac{DC}{Dt} = \kappa\nabla^2 C \arrow[dl] \arrow[dr] & \\ O(\Delta C/t) & & O(\kappa\Delta C/\delta^2) \end{tikzcd}$$

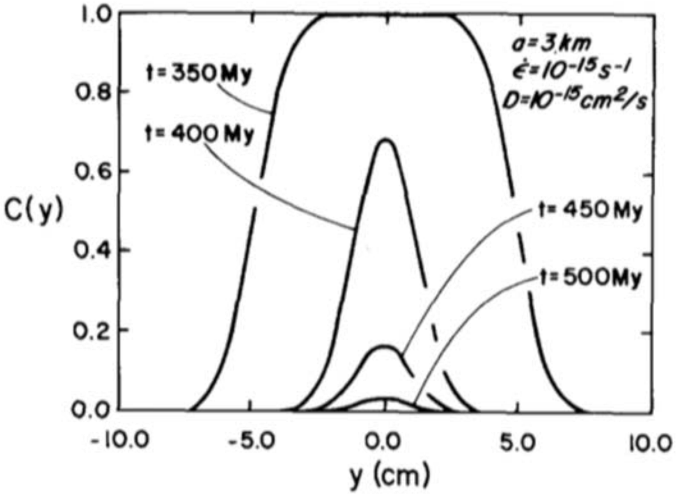
$$\delta \sim \sqrt{\kappa t}$$

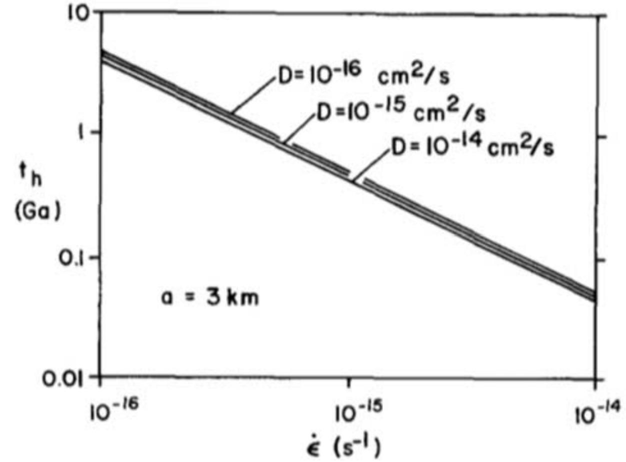
Diffusivities are 10^{-18} – 10^{-20} m^2/s in the mantle
10^{-11} m^2/s in magmas

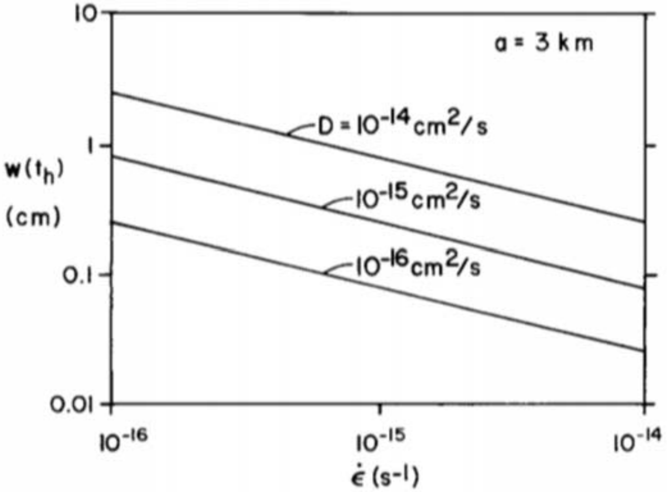
In 4 Ga, diffusion over < 1 m in the mantle
In 30 ka, diffusion over 1 m in magmas

What about chemical diffusion?





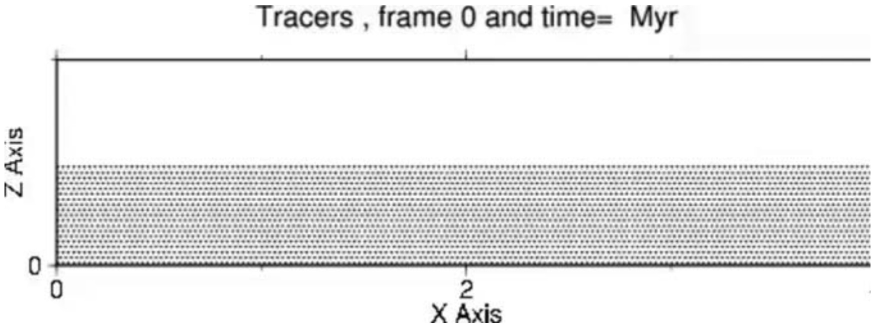




Kellogg and Turcotte, 1987 EPSL

Some ways to analyze mixing in models of the mantle

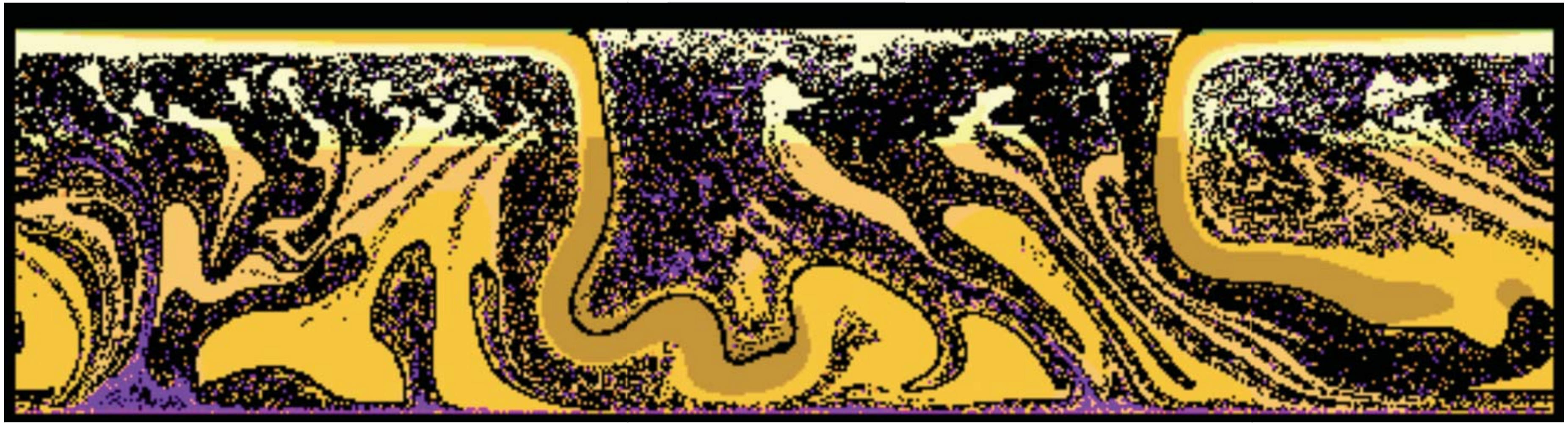
- Dispersal of heterogeneities (visually or using statistical methods)
- Compute derived isotopic signatures



4 Ga of processing mantle at ridges
(Geoff Davies)

250,000 tracer particles (initially orange)
Crust (stuff melted below ridges) in black
Crust that gets within 20 km of the CMB in purple
Darkness scales with viscosity

Stirring and segregation (Geoff Davies)

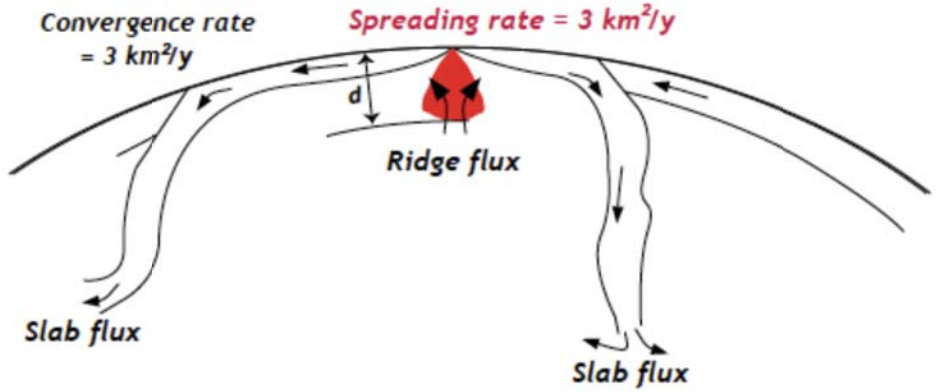


Tracers are more dense than surroundings
Segregation of depleted mantle from crust

Mixing – simplest analysis

(time, no spatial dimensions)

Mid–ocean ridge mass flux



"processing
zone"
depth $\approx$ d

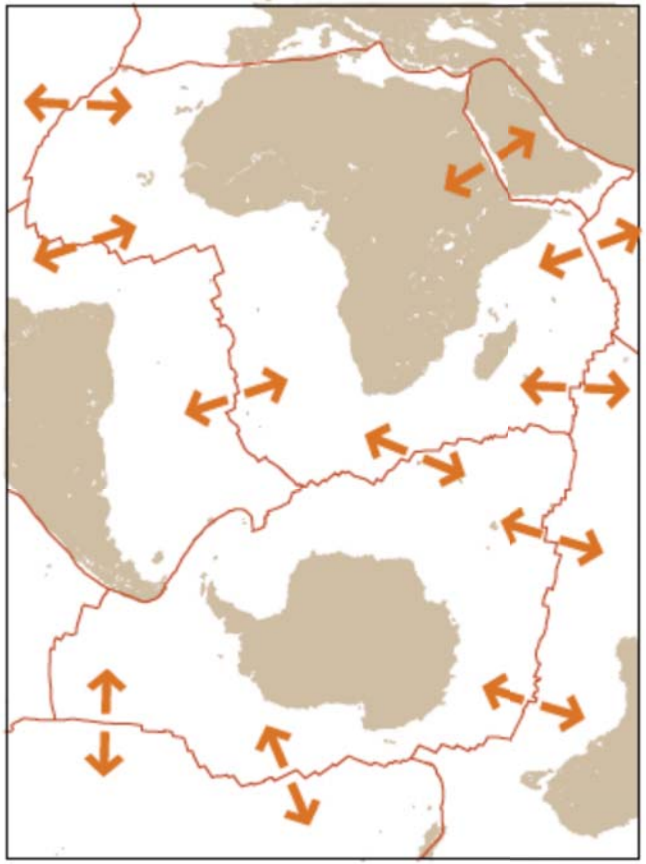
Plate creation rate	$a \approx 3$ km²/y
Mass flux in zone	$\dot{M}_r = ad\rho$
Mass of upper mantle	$M_{um} = 1 \cdot 10^{24}$ kg

"Turnover" time: $\tau_{um} = M_{um}/\dot{M}_r$

depth	τ_{um} (upper mantle)	τ_{em} (entire mantle)
50 km	2 Gy	8 Gy
100 km	1 Gy	4 Gy

From Rick O'Connell, Harvard

Ridge migration over mantle



Ridges move relative to one another

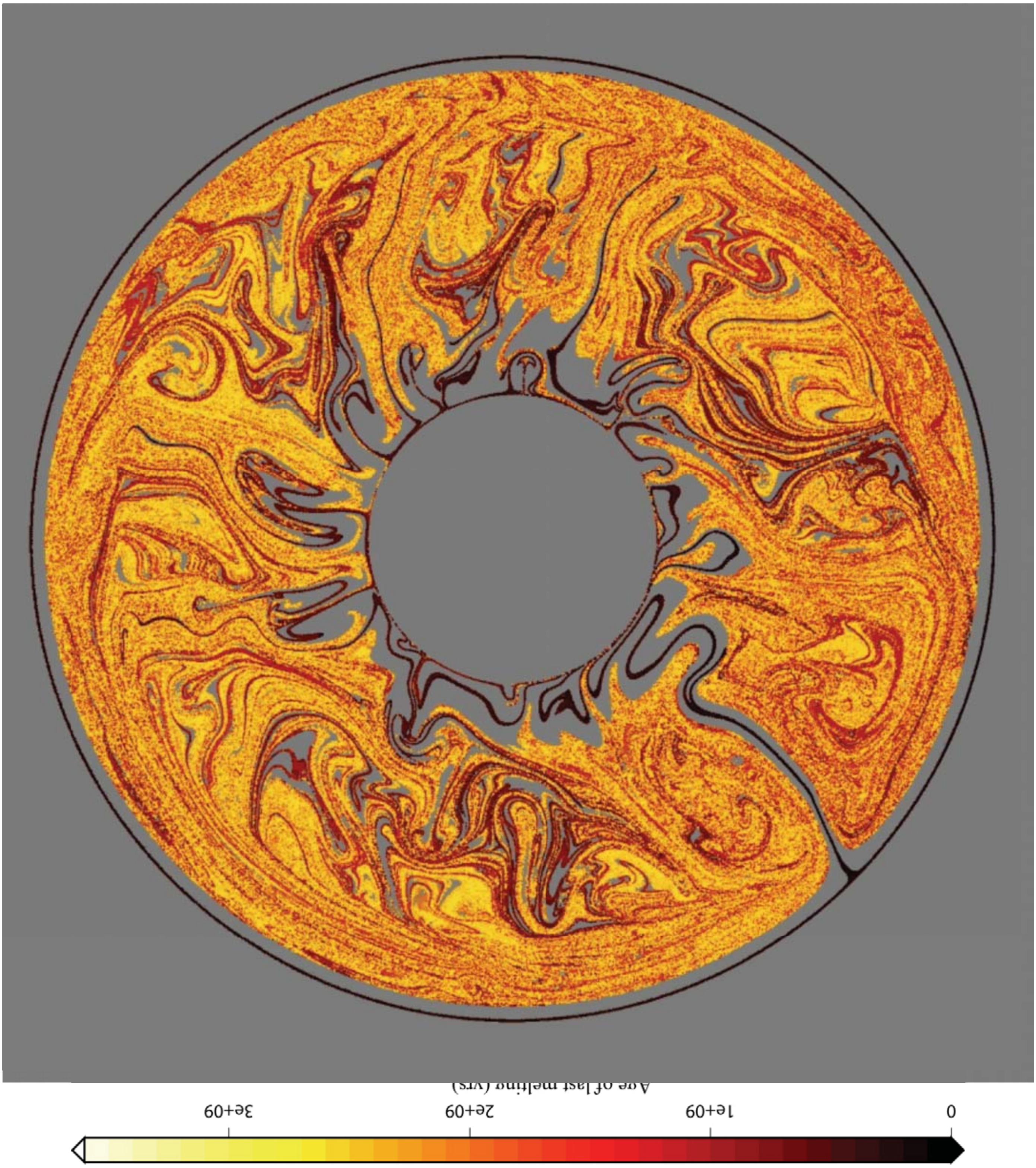
Total ridge length $L \approx 56,000$ km
Ridge migration rate $u \geq 2$ cm/y
Surface area $A = 5 \cdot 10^{14}$m^2

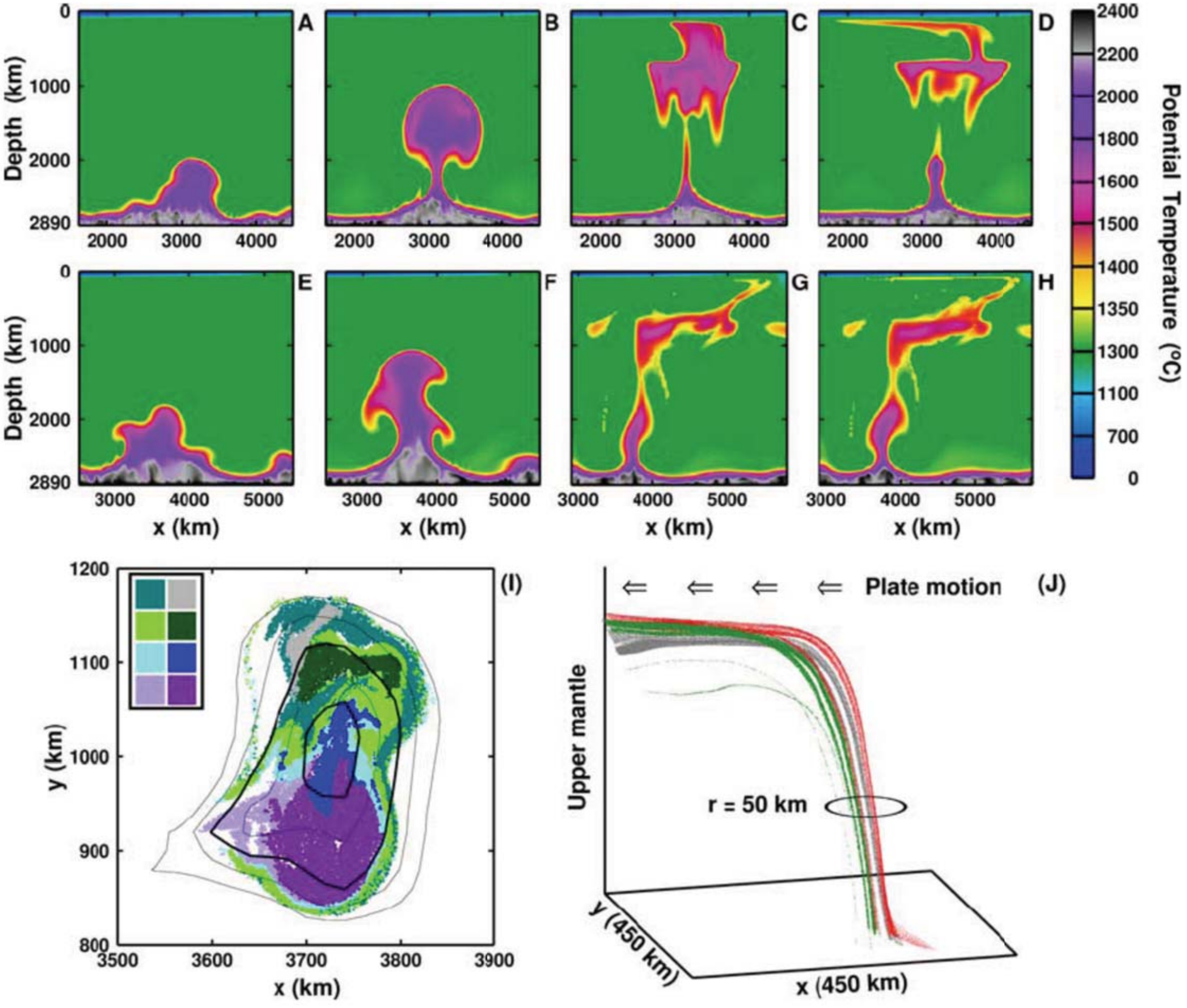
Ridges sweep over Earth's surface with time scale:

"Passover" time, whole Earth $\frac{A}{Lu} \leq 500$ My

From Rick O'Connell, Harvard

Brandenburg et al., *EPSL* 2008





Farnetani and Samuel, *GRL* 2005

Sampling filter

decreasing sampling volume

increasing time

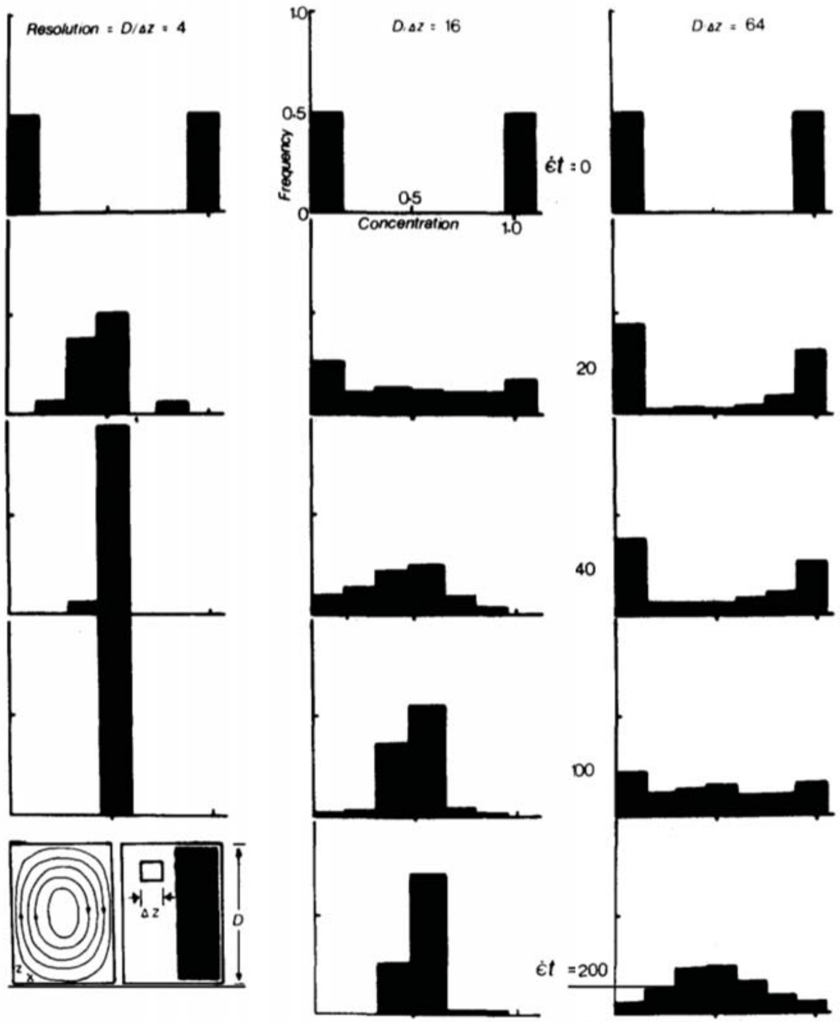


Fig. 7. Histograms of anomalous concentration versus time and sample resolution for a large scale heterogeneity in Bénard convection. The insert shows the initial distribution.

Olson et al., *PEPI* 1984

Characterization of structure

> “Important to distinguish between mixing measure and the process producing mixing . . . The measure should be selected according to the application, and the measurements should be related to the fluid mechanics.” Ottino, *Kinematics of mixing* 1989

- e and σ characterize effectiveness of a given *flow* at stirring
- Other measures can be used to characterize observed *structures* (e.g., spectral analysis, fractal analysis)
- Easiest: striation thickness *s* (1D)
- Use characterization of structure can be used to distinguish between mixing processes

Evidence for length scale reduction in the mantle, recorded in an exposed peridotite

NATURE VOL. 323 11 SEPTEMBER 1986 — ARTICLES — 125

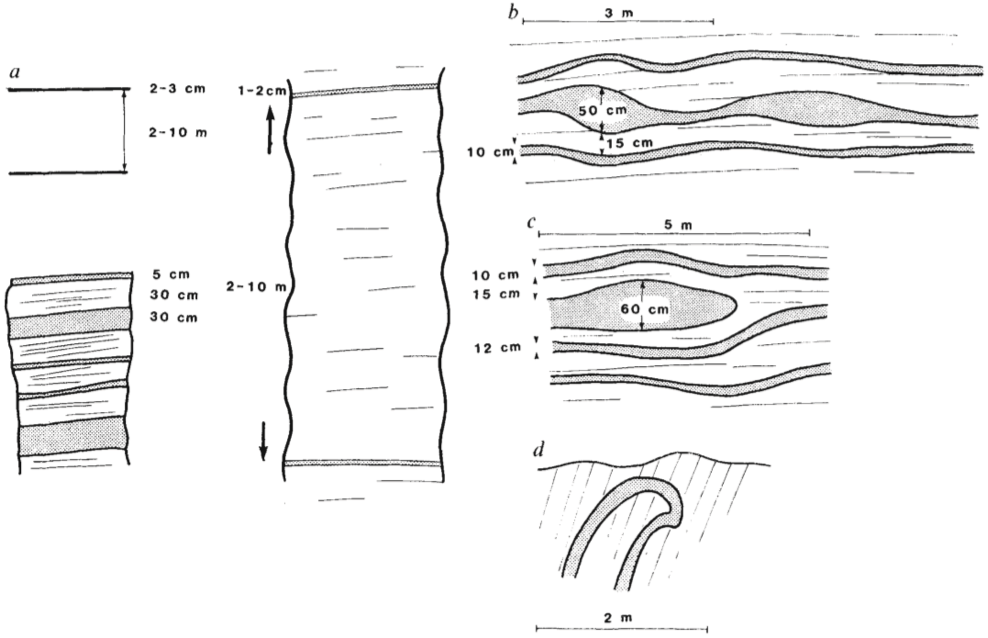


Fig. 2 Occurrences of pyroxenite layers in the Beni Bousera high-temperature peridotite. Grey, pyroxenite; white, lherzolite with foliation. *a*, Occurrences in an outcrop with no folding; *b*–*d*, occurrences with folding and boudinage.

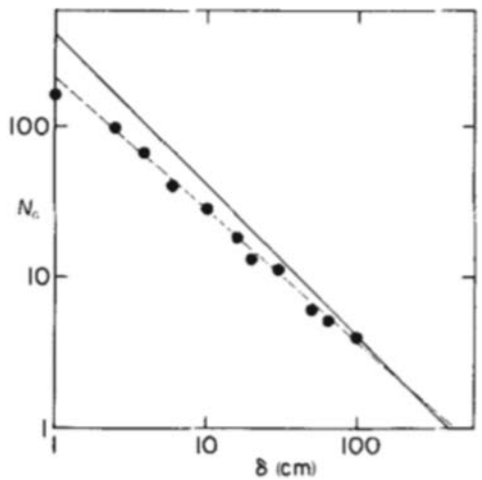


Fig. 3 Number of pyroxenite layers exposed at Beni Bousera with a thickness greater than δ, N_c, as a function of δ. Points, observations; dashed line, $N_c \propto \delta^{-0.87}$; solid line, $N_c \propto \delta^{-1}$.

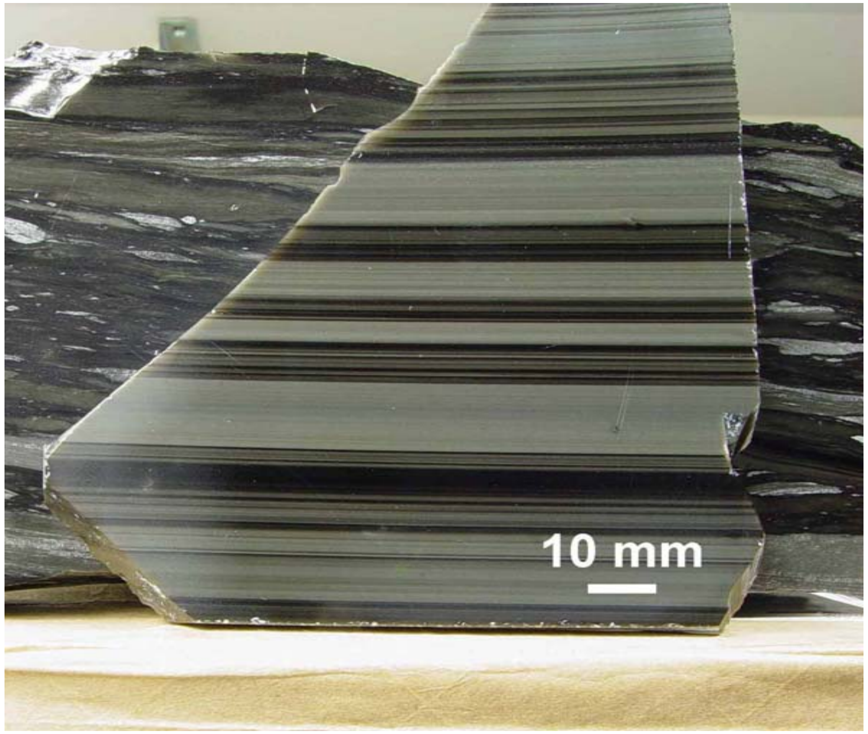
Allègre and Turcotte, *Nature* 1986

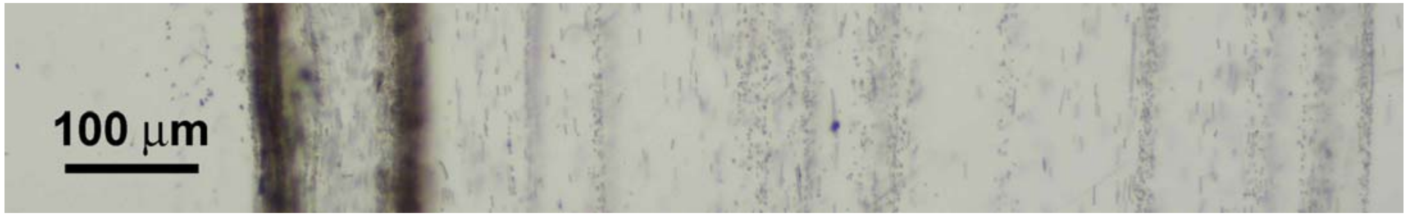
The scale of heterogeneity led Allègre and Turcotte (1986) to support their ‘marble cake’ structure to the mantle

Static.ifood.tv

Easier to see in magmas . .

Obsidian is banded at all scales





Do these bands (in some cases) record how the obsidian deformed?

Terminology

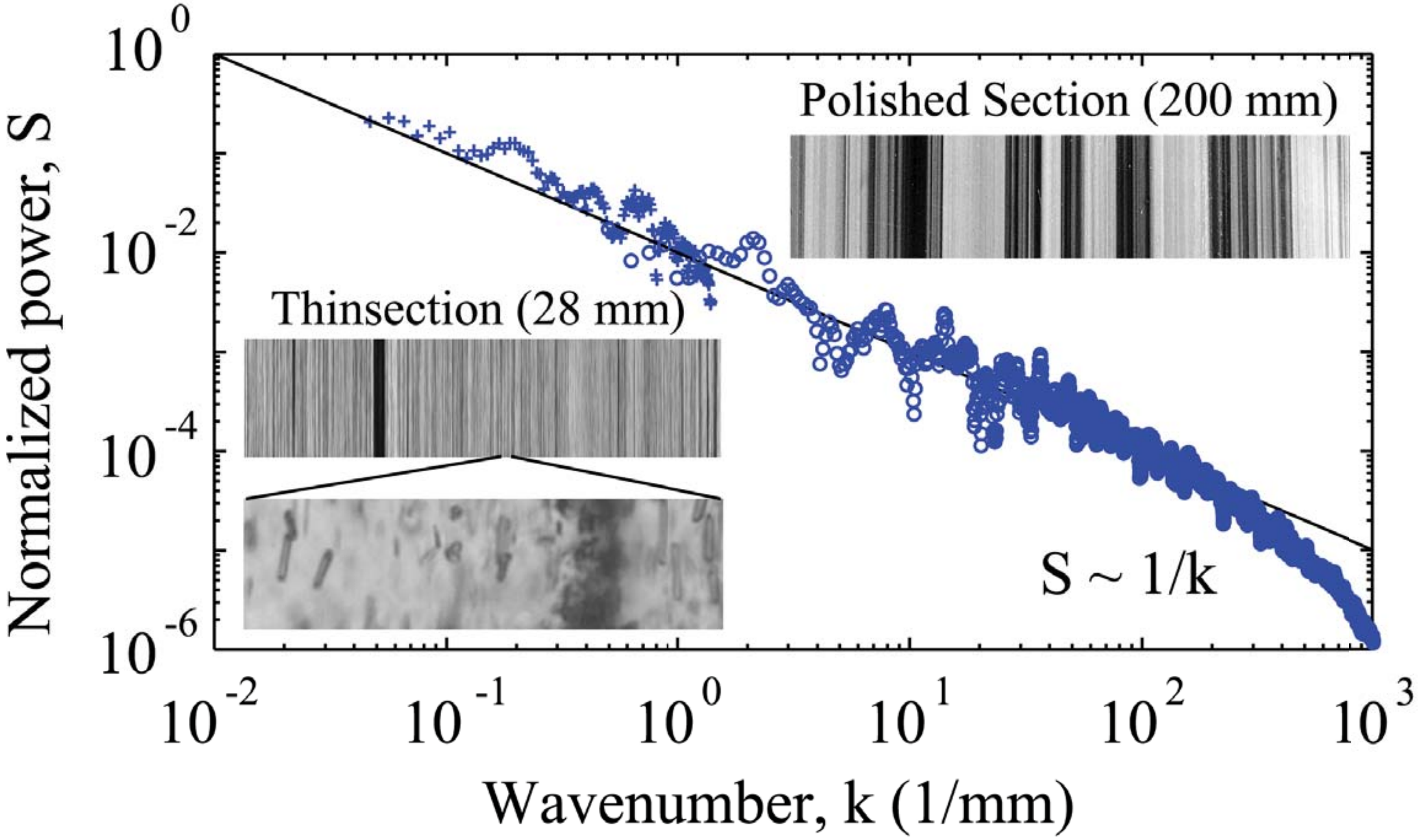
Scale invariance: Attributes do not changes if lengths are changes (no specific scale can be identified - all scales are equally important)

Fractal: A fractal is generally "a rough or fragmented geometric shape that can be split into parts, each of which is (at least approximately) a reduced-size copy of the whole,"[1] a property called self-similarity. Roots of mathematical interest on fractals can be traced back to the late 19th Century, the term however was coined by Benoît Mandelbrot in 1975 and was derived from the Latin fractus meaning "broken" or "fractured."

Multifractal: A single exponent is insufficient, and a continuous spectrum of exponents is needed; around any point, there is a local power law and the “singularity distribution” describes its variation

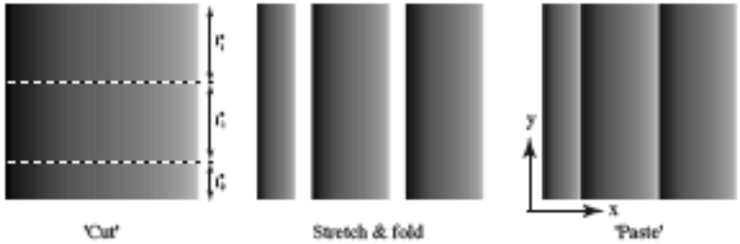
Multiplicative: recursive process that produce interdependencies in different scales, results in multifractal properties

Power spectrum: Scale invariant banding

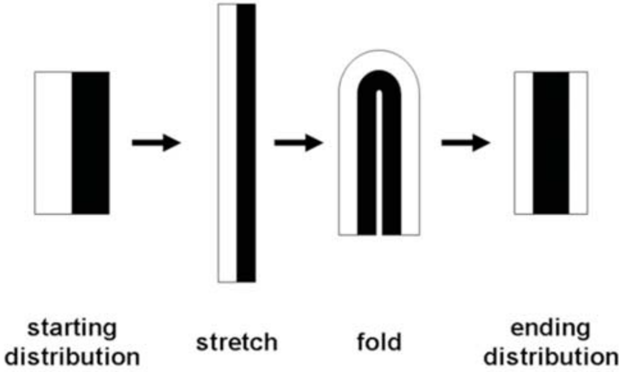


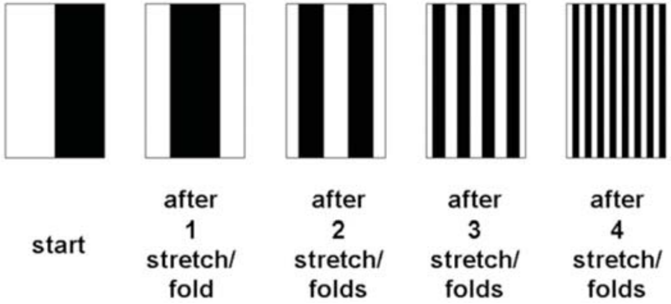
Band widths are scale invarient over 4 orders of magnitude

Baker’s map



Horseshoe maps

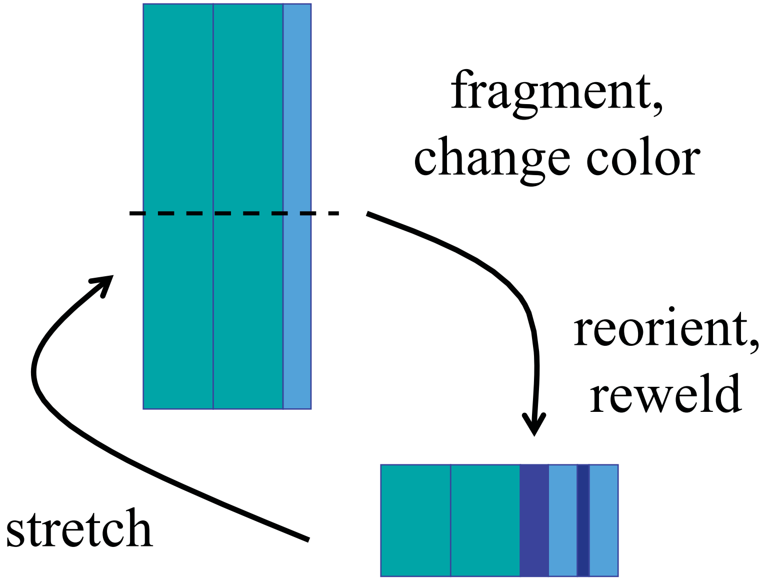




Brecciation, rewelding and deformation

Cantor set

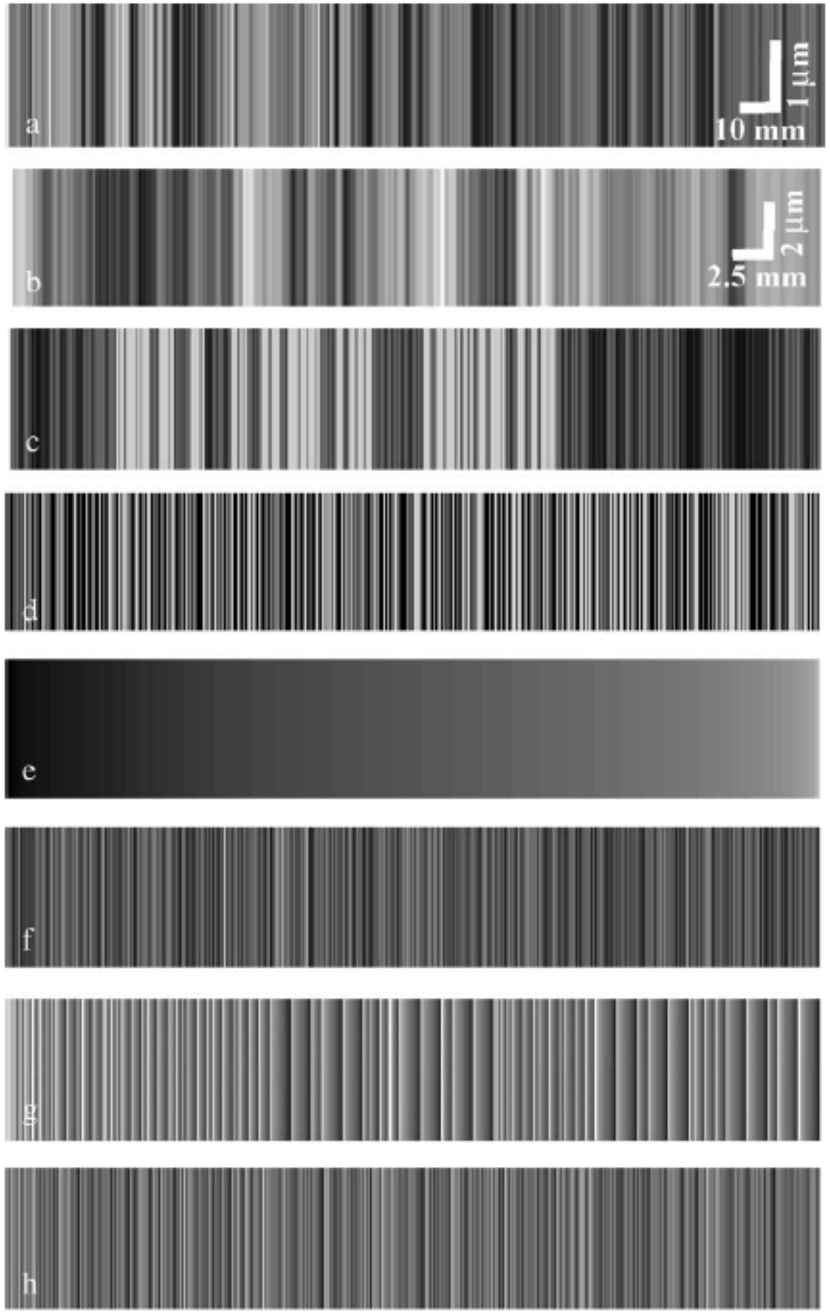
A representative model
Cantor model


fragment,
change color

reorient,
reweld

stretch

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



BGM (200 mm)

MI (55 mm)

Cantor set

B&W Cantor set

BGM color sorted

Random redistribution

4 step Baker

6 step Baker

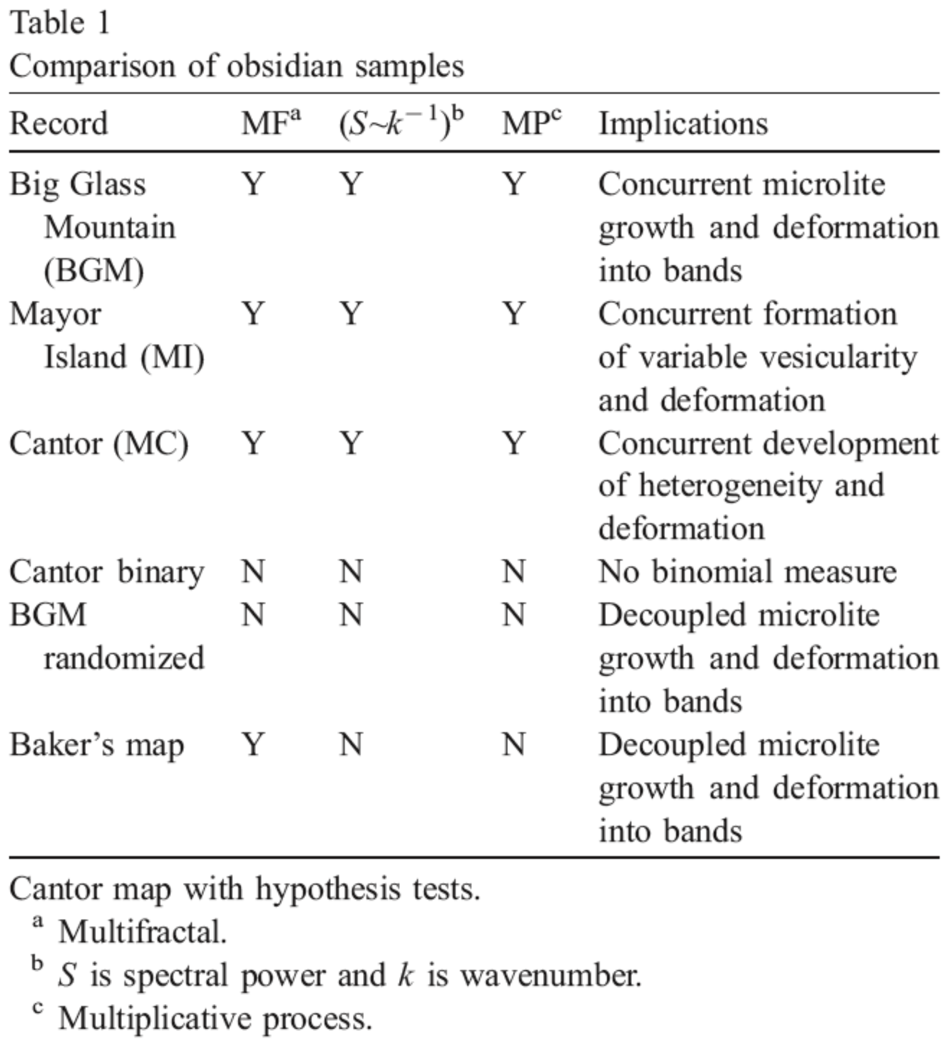


Table 1
Comparison of obsidian samples

Record	MF[a]	$(S\sim k^{-1})$[b]	MP[c]	Implications
Big Glass Mountain (BGM)	Y	Y	Y	Concurrent microlite growth and deformation into bands
Mayor Island (MI)	Y	Y	Y	Concurrent formation of variable vesicularity and deformation
Cantor (MC)	Y	Y	Y	Concurrent development of heterogeneity and deformation
Cantor binary	N	N	N	No binomial measure
BGM randomized	N	N	N	Decoupled microlite growth and deformation into bands
Baker's map	Y	N	N	Decoupled microlite growth and deformation into bands

Cantor map with hypothesis tests.

[a] Multifractal.

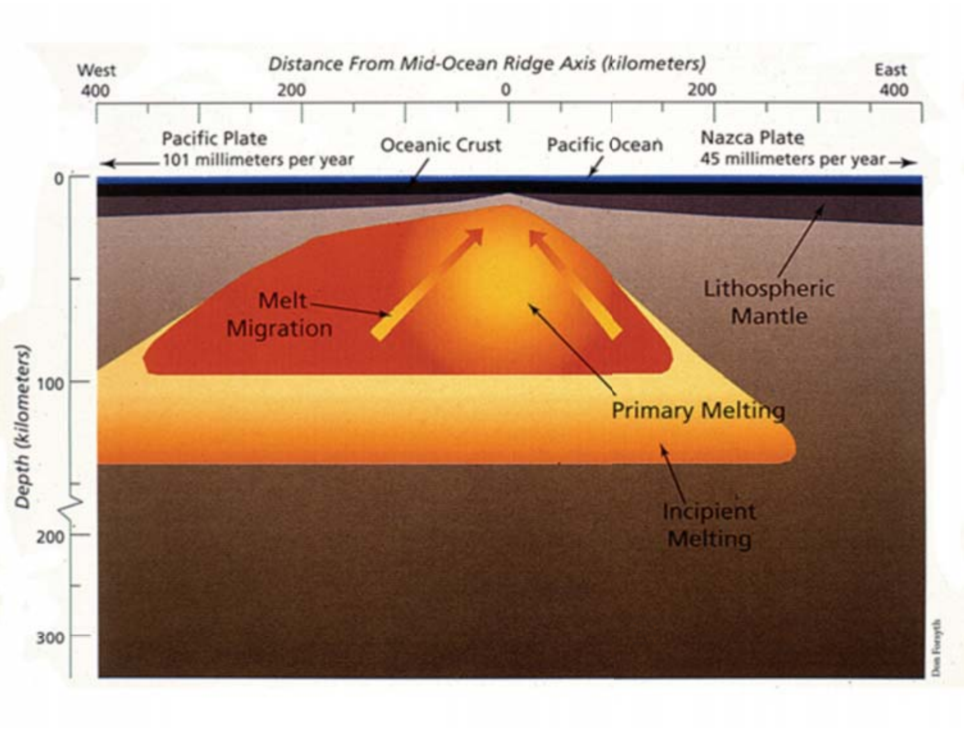
[b] S is spectral power and k is wavenumber.

[c] Multiplicative process.

Baker's map should describe convective stirring

Convection is a source and sink of heterogeneity

- Melting at ridges
- Fluid migration and melting at subduction zones
- Melting at mid mantle phase transitions?
- Melting at the base of the mantle
- Chemical reactions between the mantle and core



Convection is a source and sink of heterogeneity

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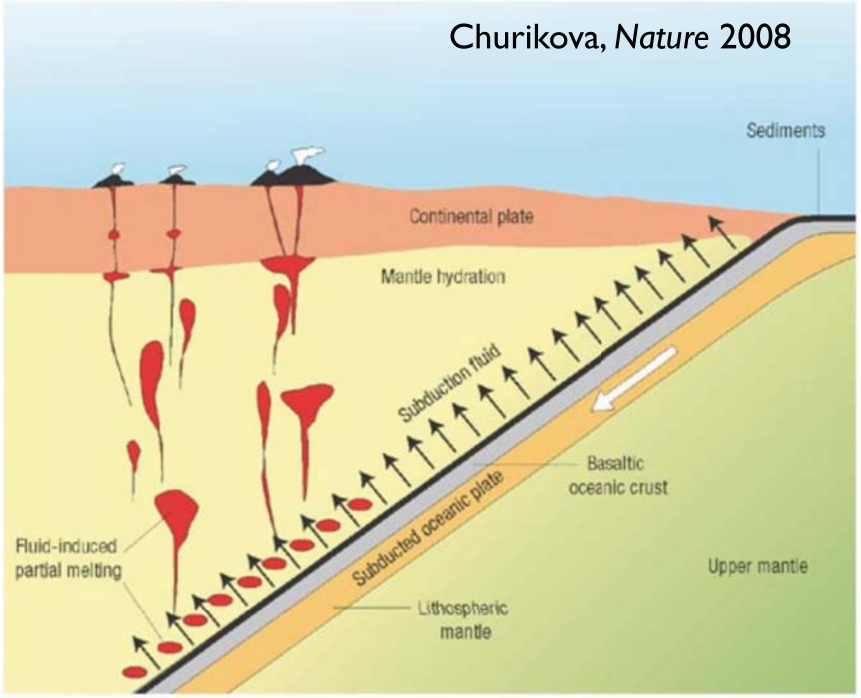
Churikova, *Nature* 2008

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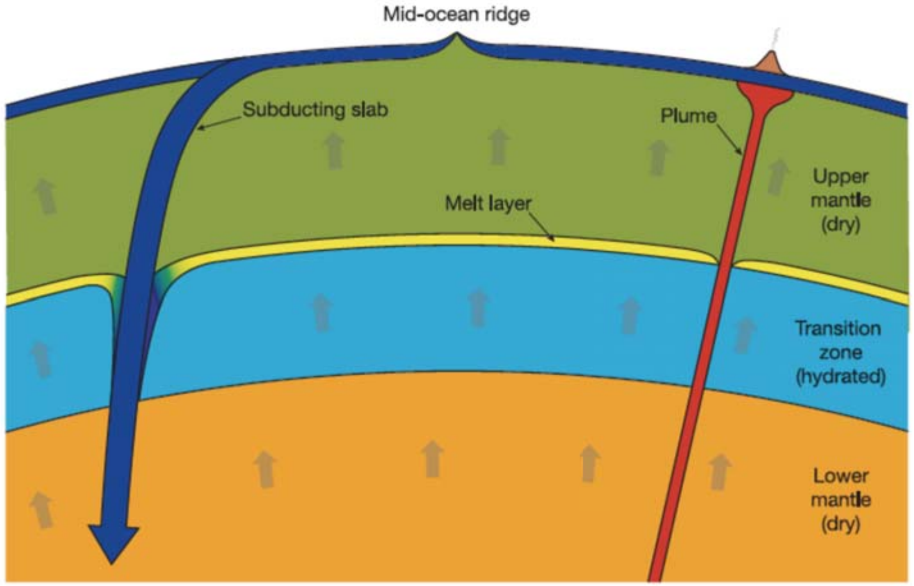
Bercovici and Karato, *Nature* 2003



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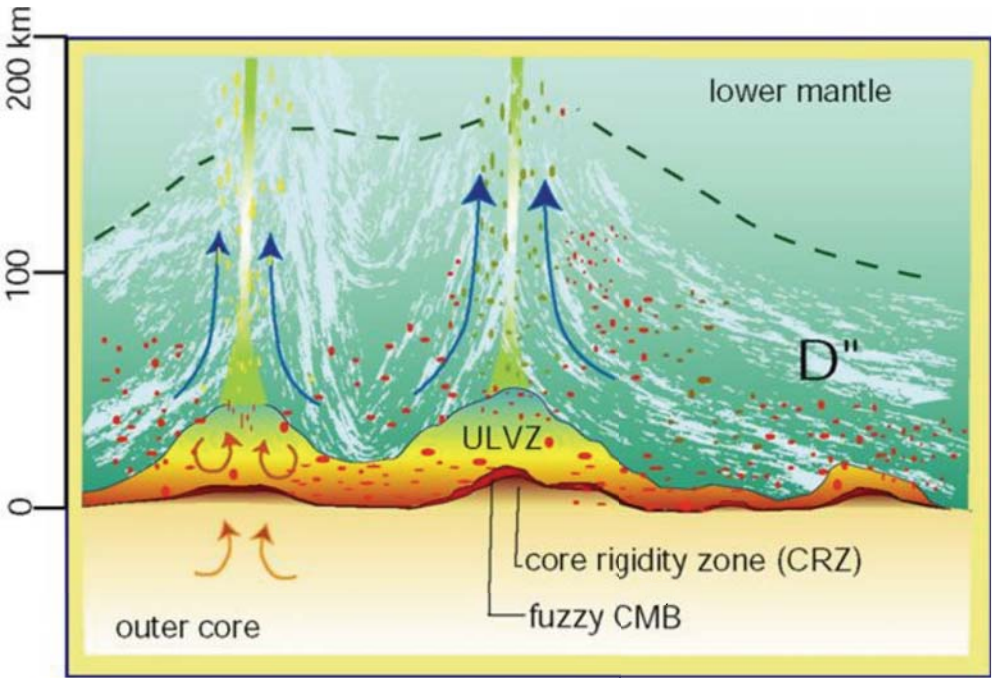

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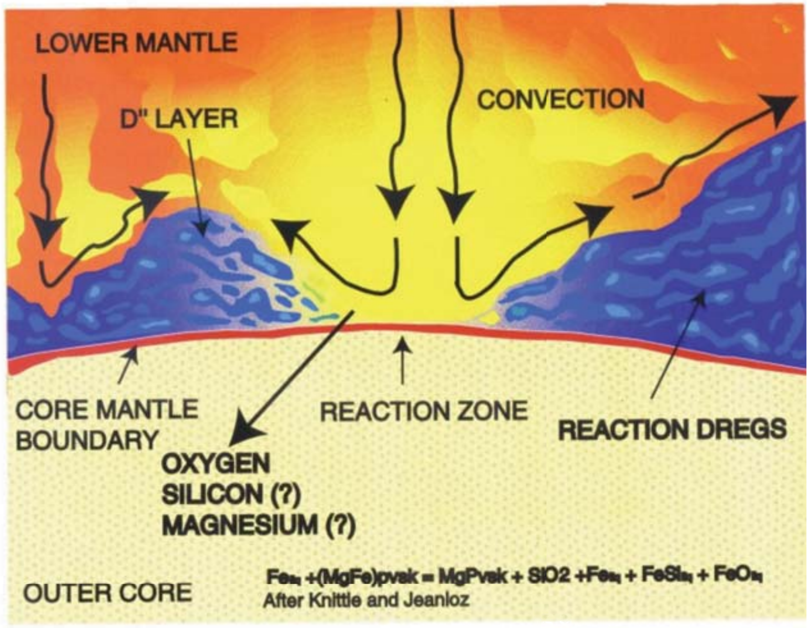
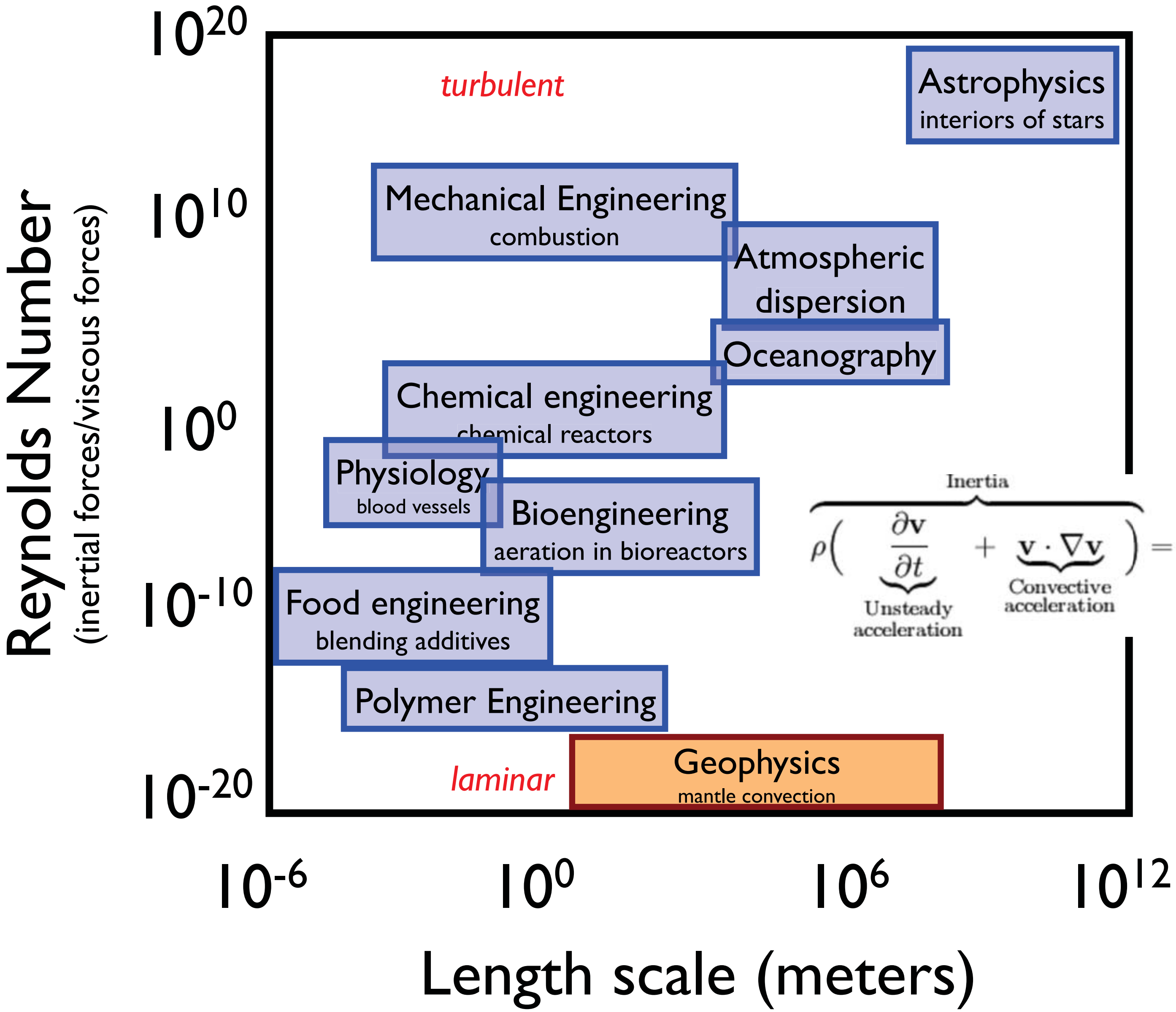


After Knittle and Jeanloz

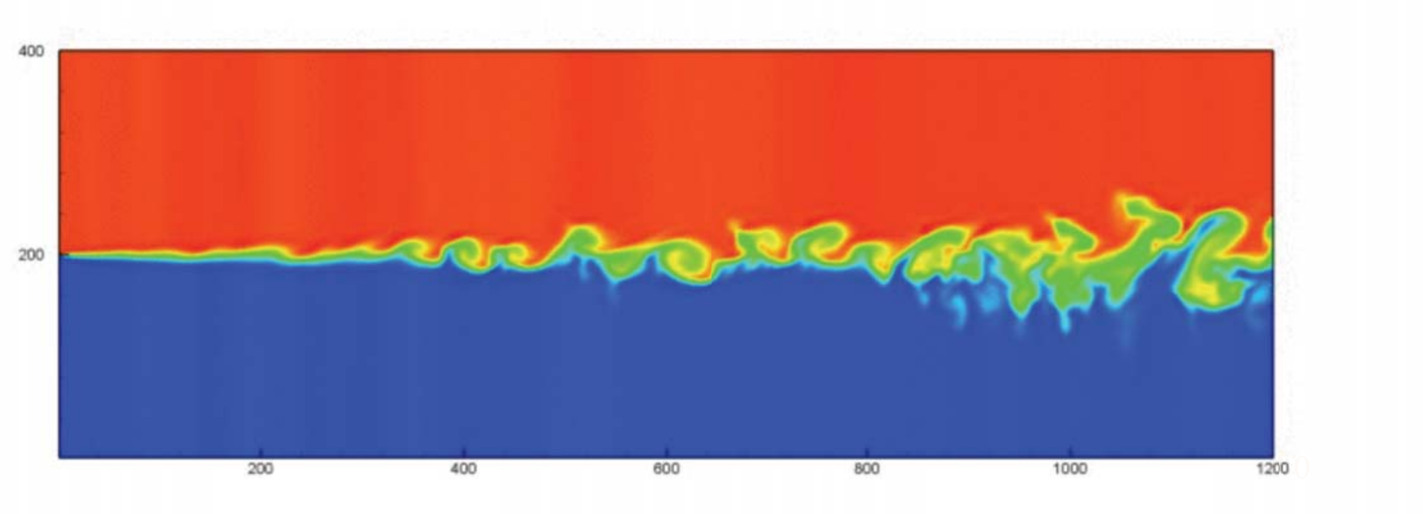
Some mixing scales



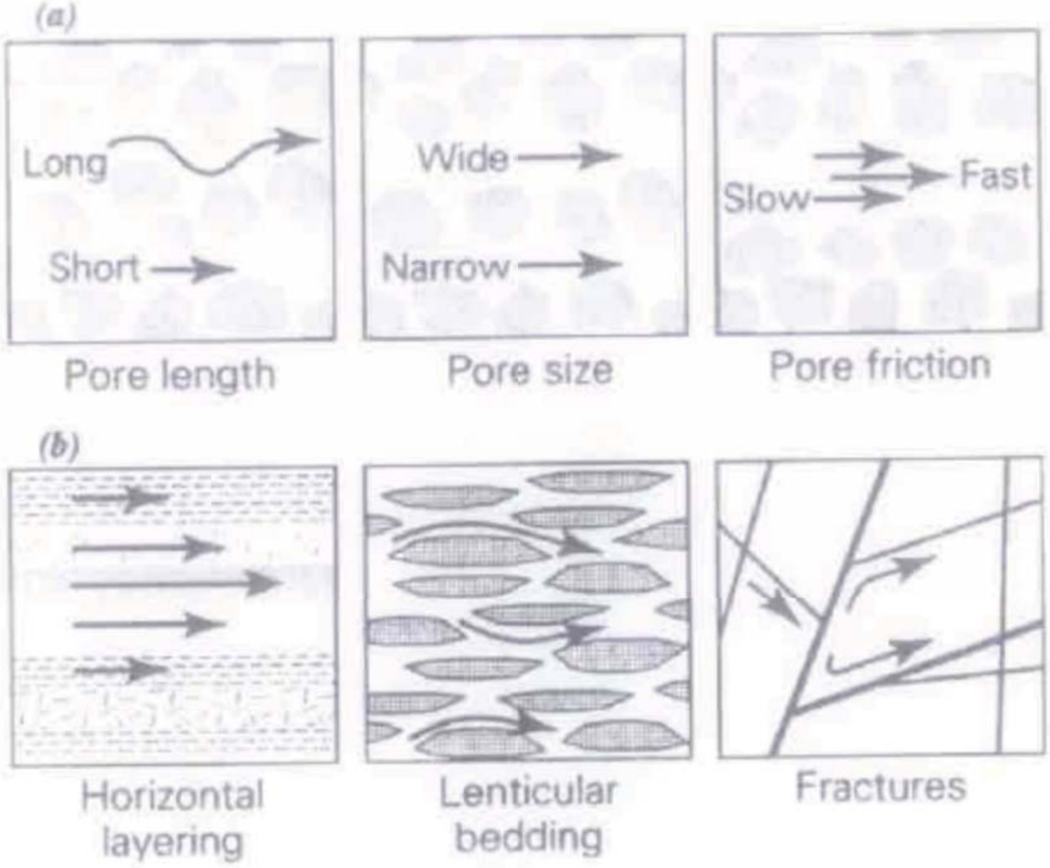
$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{Unsteady acceleration}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\text{Convective acceleration}}\Big)}^{\text{Inertia}} = \underbrace{-\nabla p}_{\text{Pressure gradient}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}} + \underbrace{\mathbf{f}}_{\text{Other forces}}$$

Turbulent mixing

- Energy transfer from large to small scales
- Intermittency in space and time
- Velocity is a complicated function of time



Dispersion in porous materials



From Ingebritsen

- Complexity in flow paths, spatial variation in velocity greatly enhance mixing (dispersion)

“Virtually everyone agrees that mixing is complicated”

“However there is no agreement as to the source of the complications . . . What makes mixing complex? Usually realistic mixing problems have been regarded as nearly intractable from a modeling viewpoint owing to the complexity of the flow fields. Also in many problems of interest the fluids themselves are rheologically complex . . . . .

Mixing problems have been attacked traditionally on a case by case basis. However . . . merging of kinematics with dynamical systems and chaos are providing a paradigm for the analysis of mixing from a rather general viewpoint.”

Ottino, *Ann Rev Fluid Mech* 1990

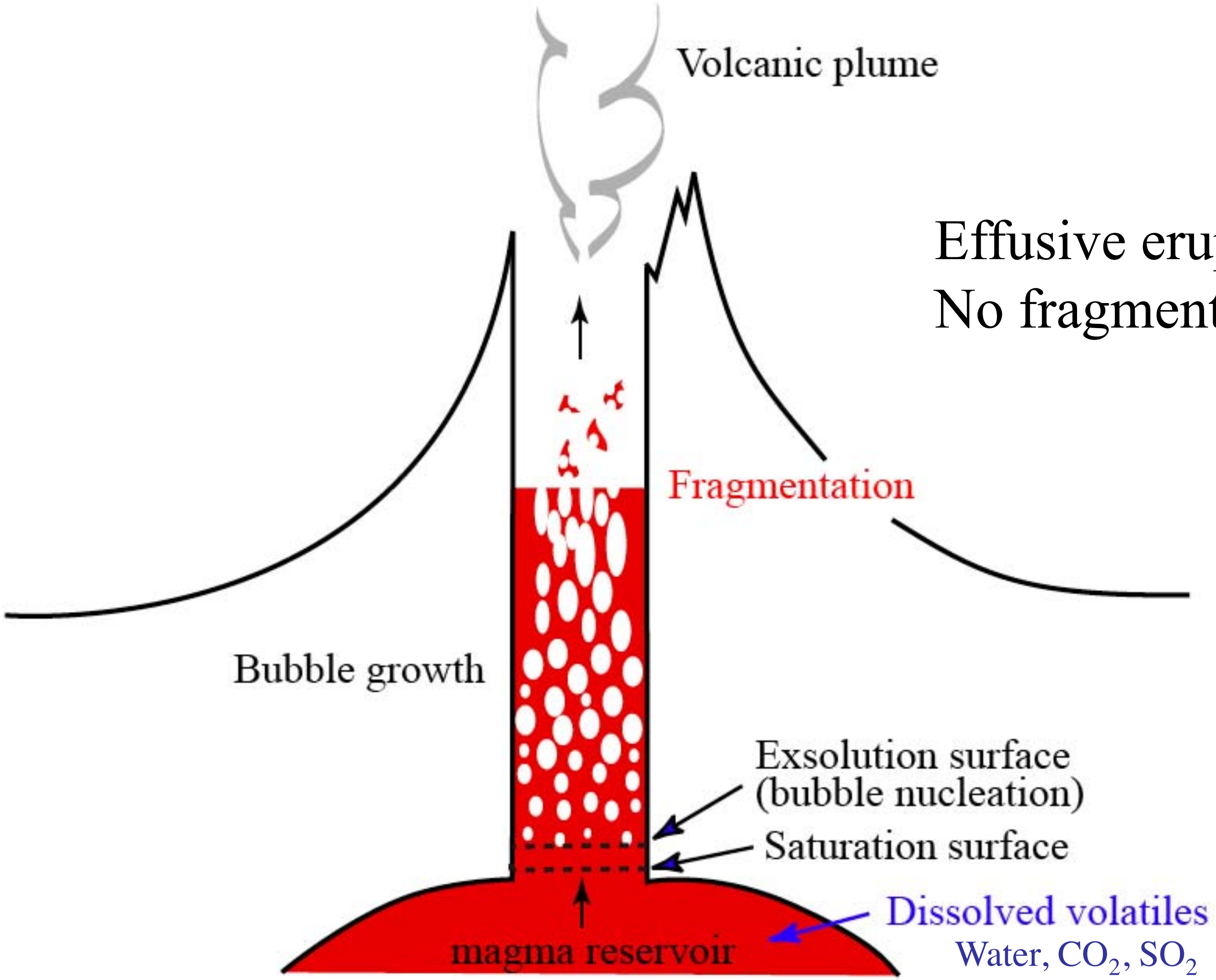
Main points

- Flow type matters
- Time dependence matters
- Properties of heterogeneity matter (active heterogeneity is different from passive tracers)
- Mixing will depend on history of Earth and properties of interior (all of which have uncertainty), hence a stochastic approach may be useful
- Convection both creates and destroys heterogeneity

Why do volcanoes (only sometimes) erupt explosively?

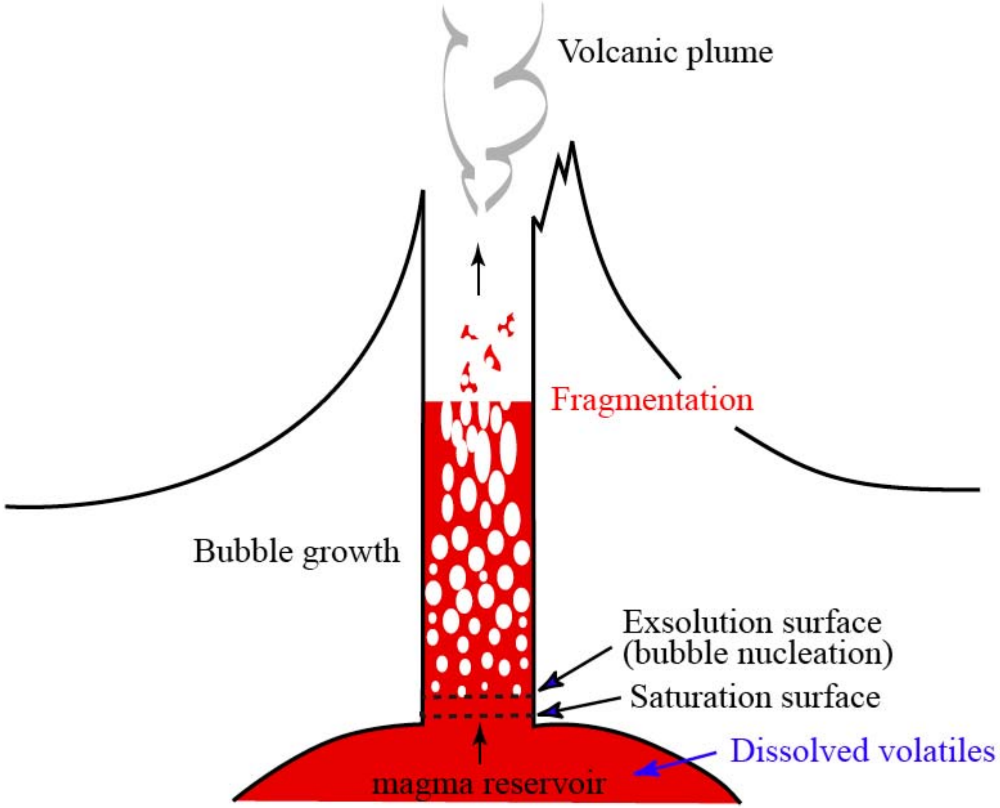
Gonnermann and Manga,
The fluid mechanics inside a volcano,
Annual Reviews of Fluids Mechanics,
2007

Why do volcanoes erupt explosively?
(textbook version)



Effusive eruption:
No fragmentation

Why do volcanoes erupt explosively?

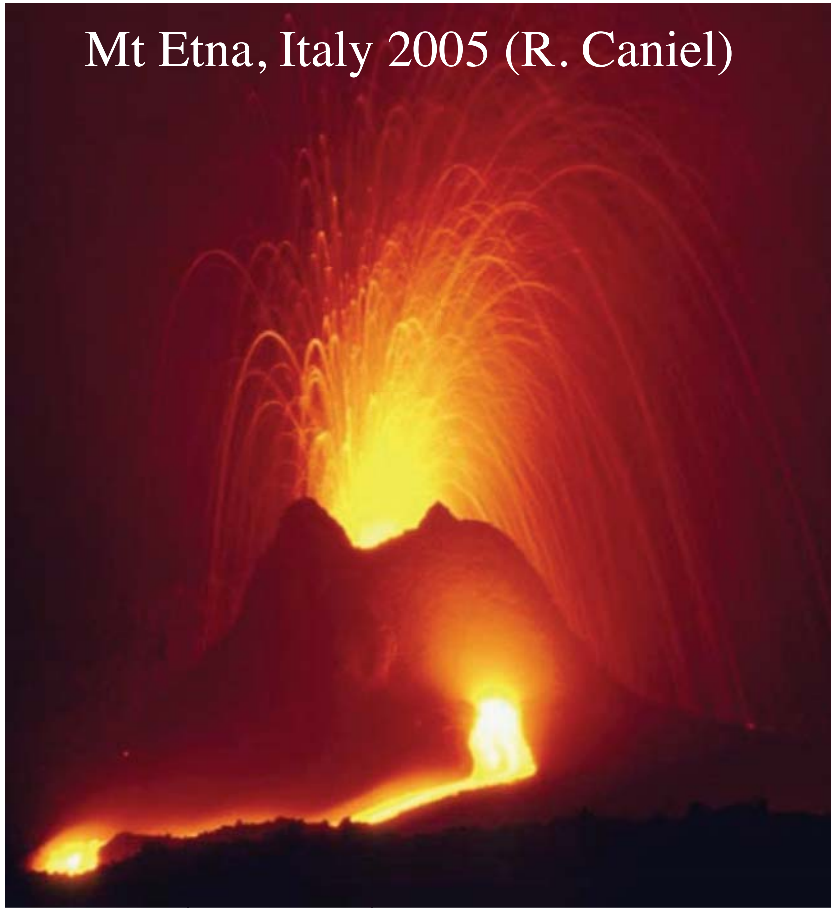


Open questions:

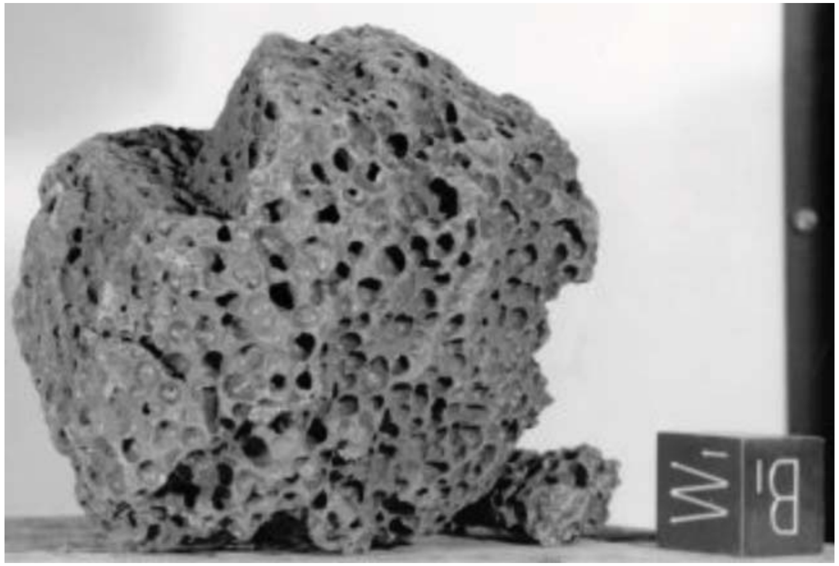
- When, where and how does fragmentation occur?
- Why so much diversity in eruption style?

Three key processes

1. Bubble nucleation, exsolution and bubble growth

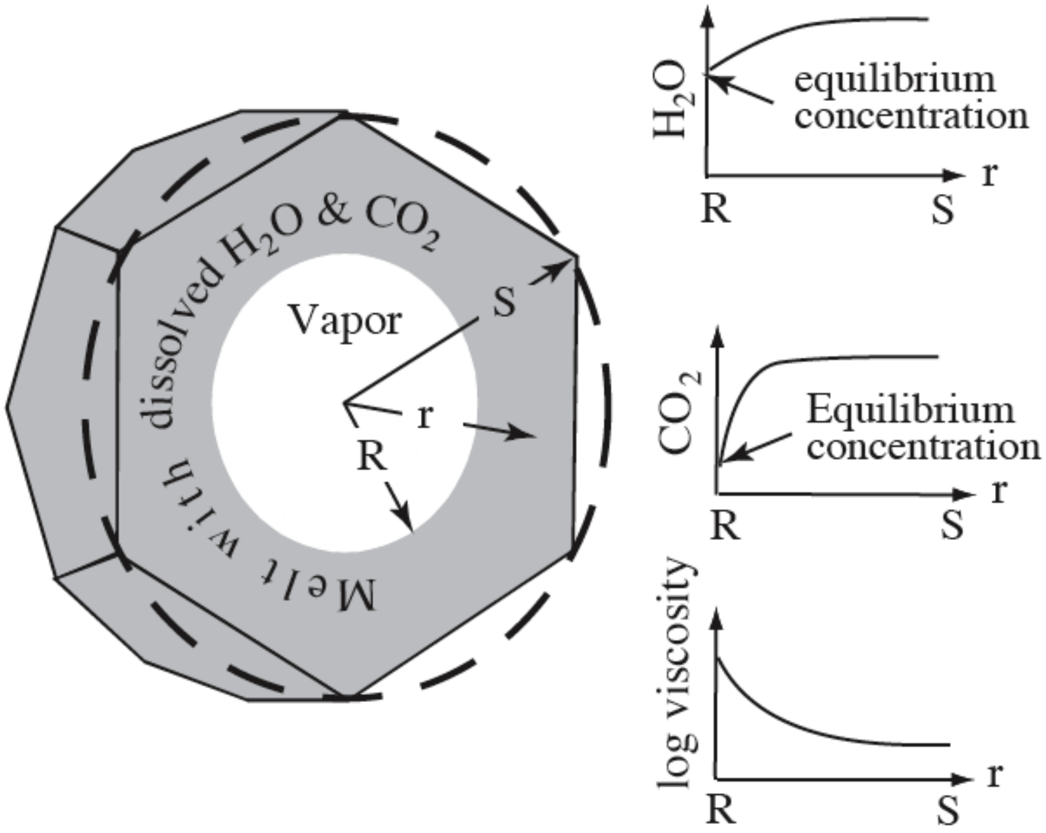


Mt Etna, Italy 2005 (R. Caniel)



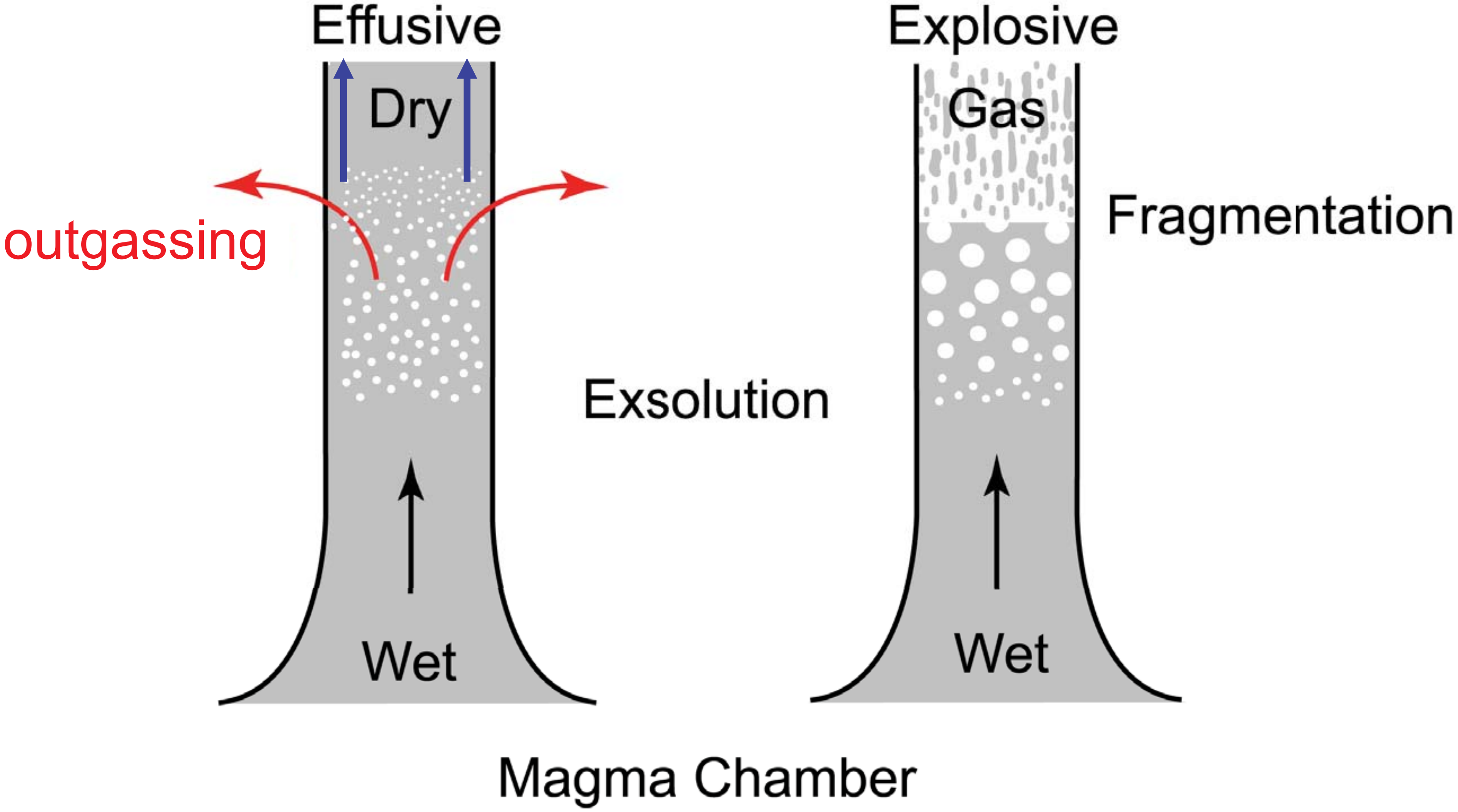
vesicular basalt (from the moon)

Volatile exsolution and bubble growth

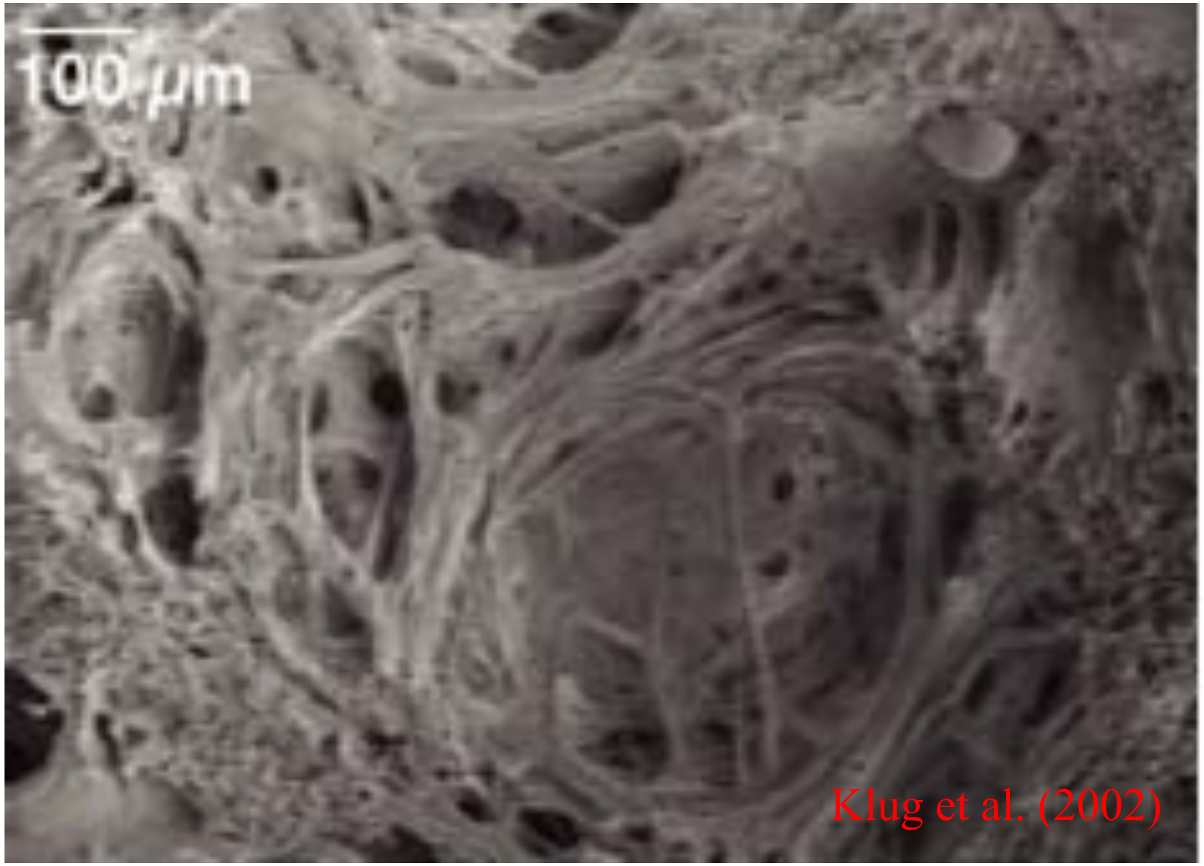


Three key processes

2. Loss of gases, called outgassing, supresses eruption



Vesicular magma is permeable



Klug et al. (2002)

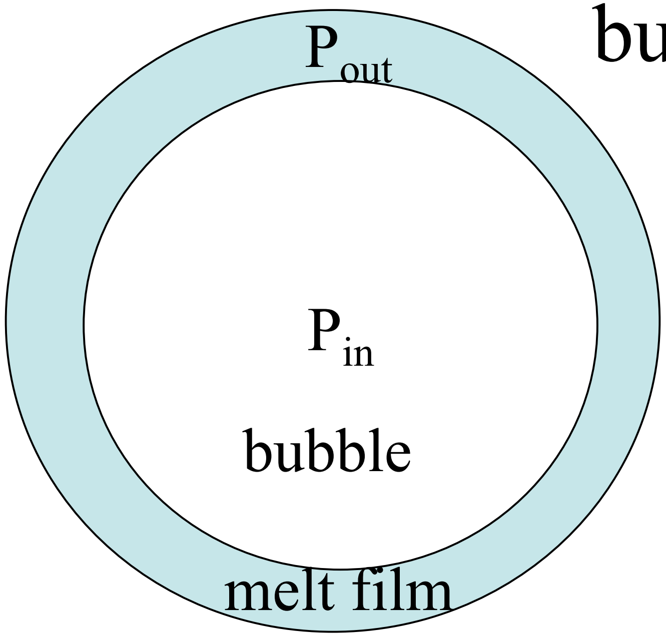
Connections between bubbles allow gases to escape from magma

Permeability depends on vesicularity and bubble size

Three key processes

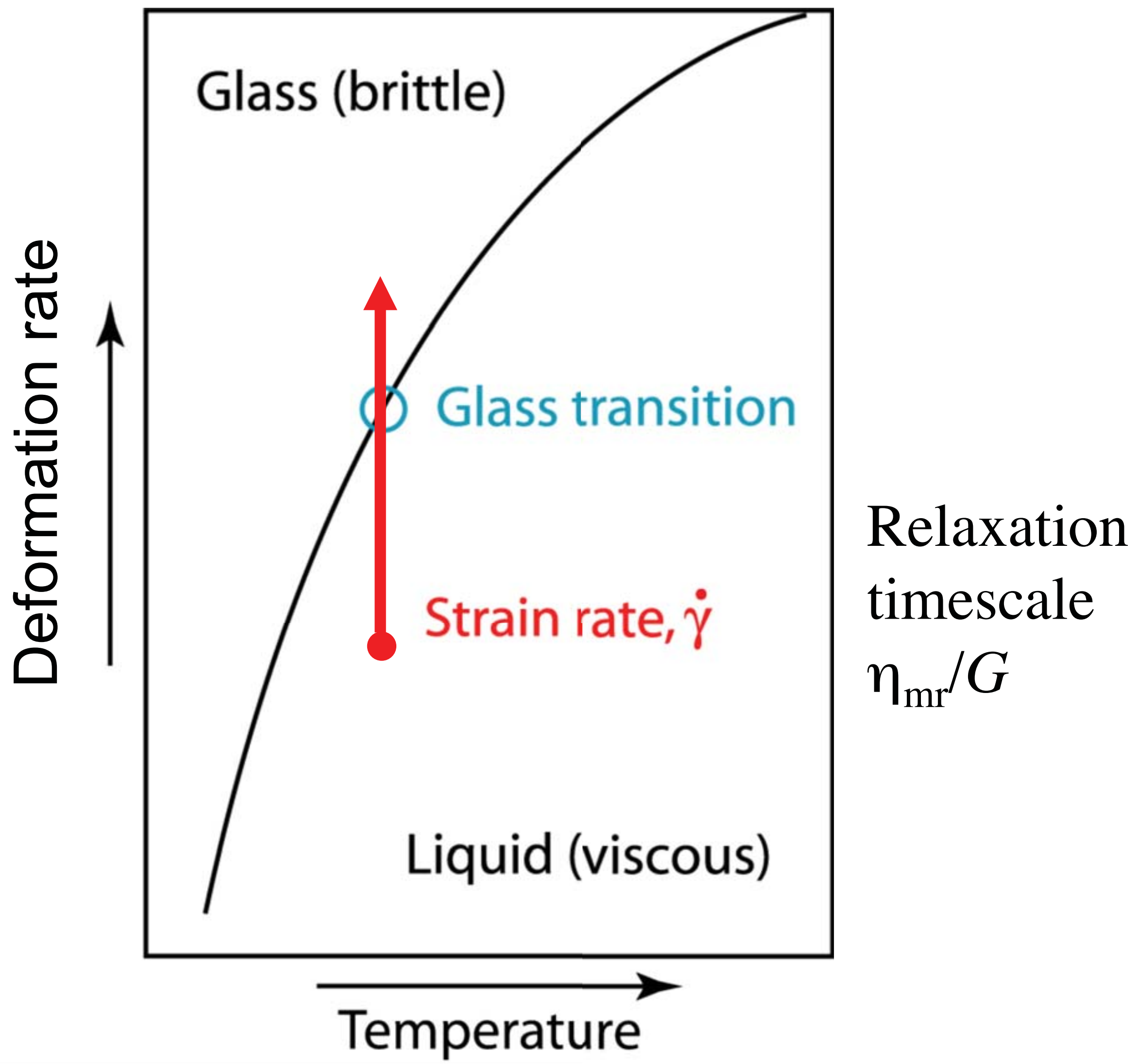
3. Fragmentation

If stresses in film surrounding bubbles too large



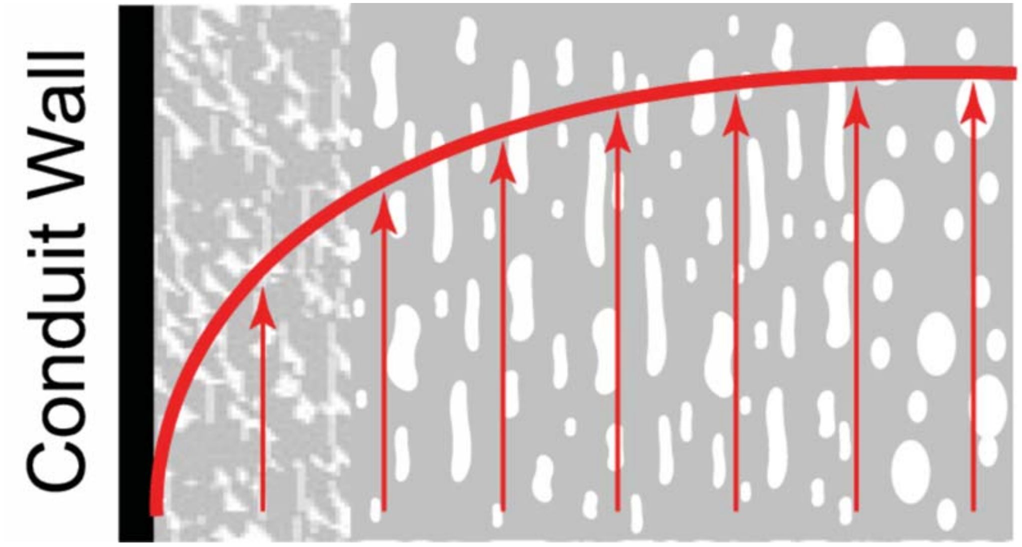
If $P_{in} - P_{out}$ > critical value then film ruptures

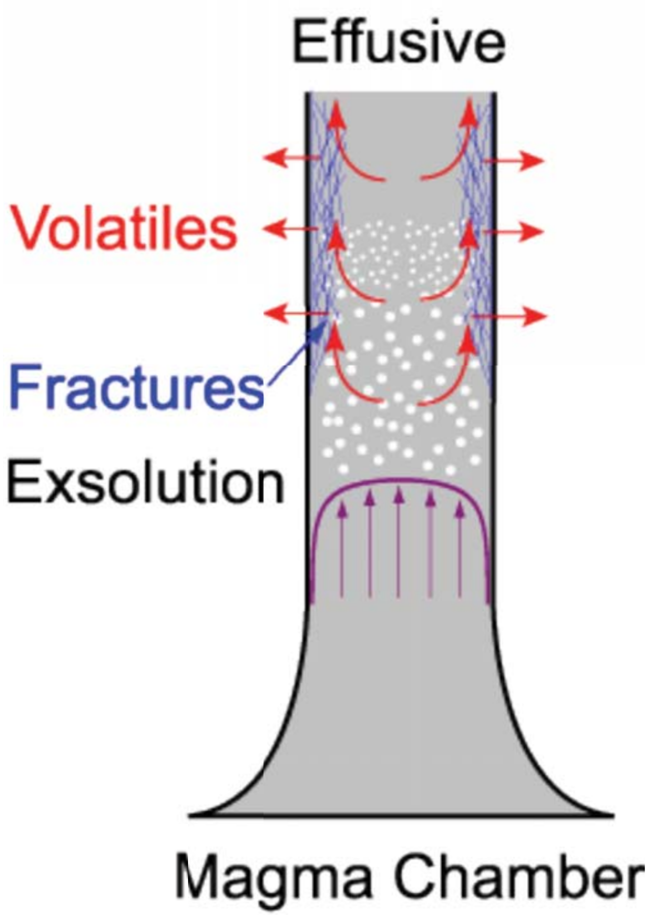
A second way to break magmas . . .



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

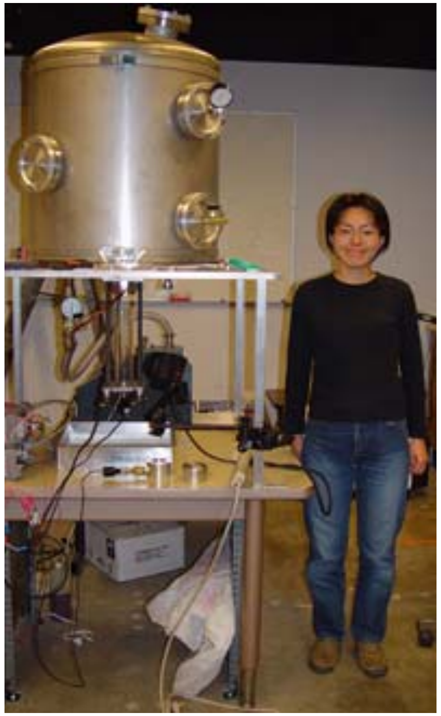
1) Nucleation (forming new) and growth of bubbles
2) Outgassing (loss of gas from the magma)
3) Fragmentation and brecciation (breaking magma into pieces)

Approach

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

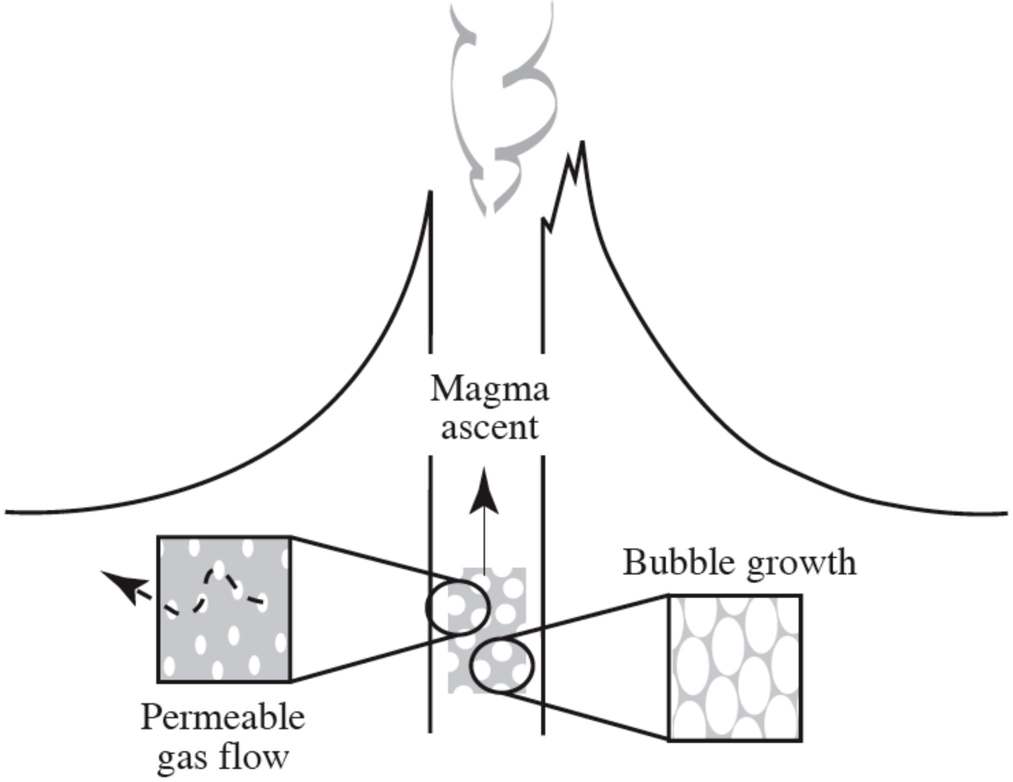
2. Computer simulations

3. Test models with measurements made on rocks



Numerical model

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



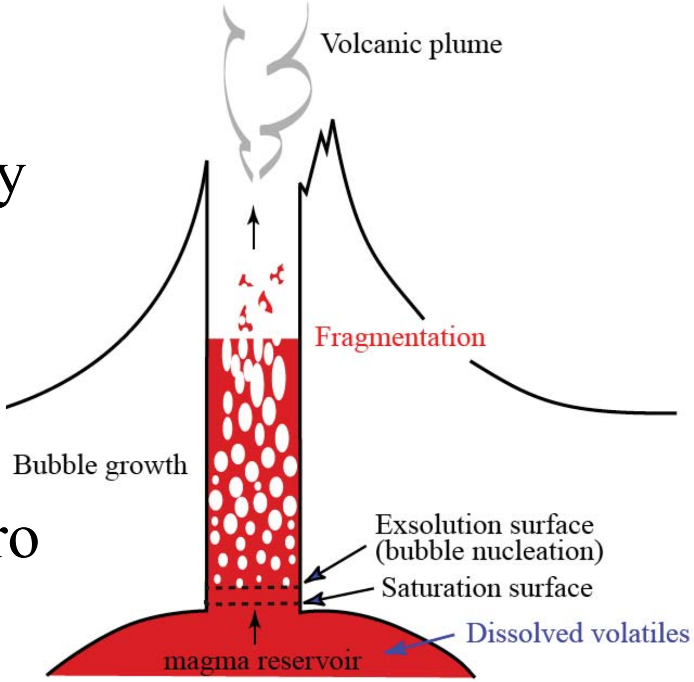
1) Conduit flow:
magma (bubbles+ melt) is locally homogeneous

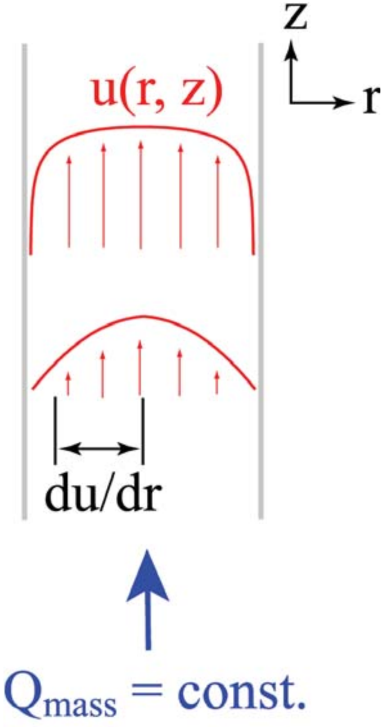
2) Bubble-scale:
Solve for growth of bubbles, determine rheology

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





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

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

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

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- conservation of mass, momentum, energy
  (include viscous dissipation; density, rheology from subgrid model)
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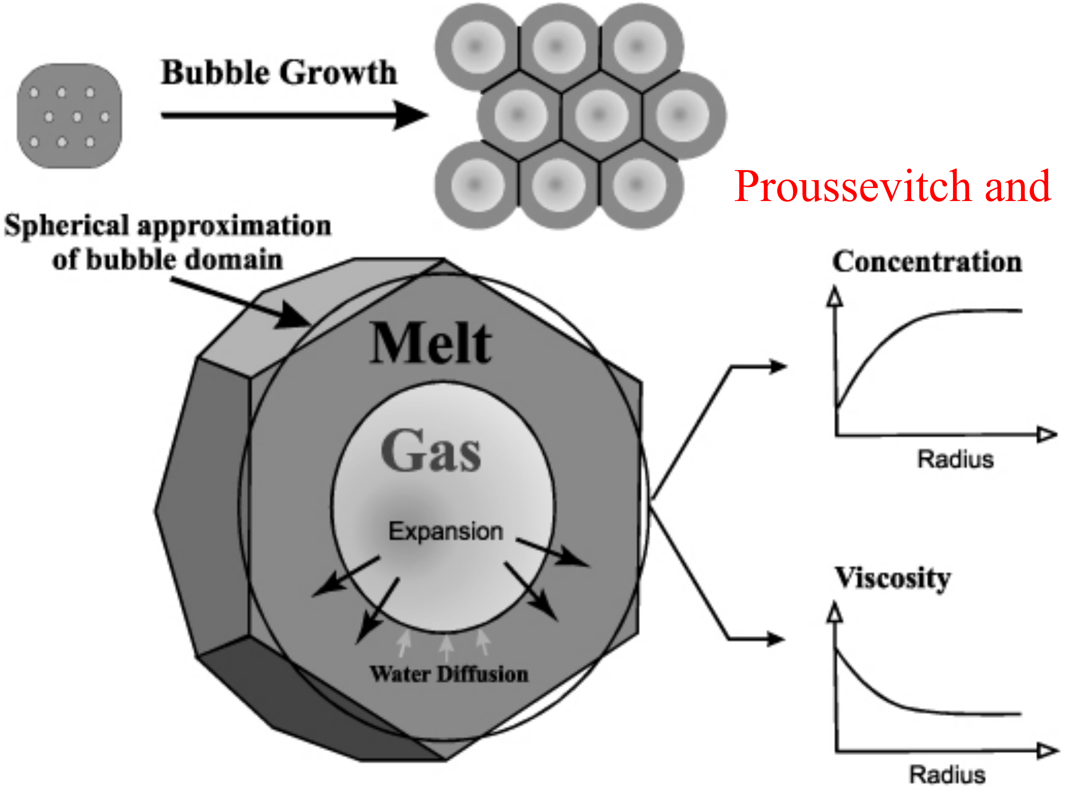
Subgrid model: Volatile exsolution and bubble growth

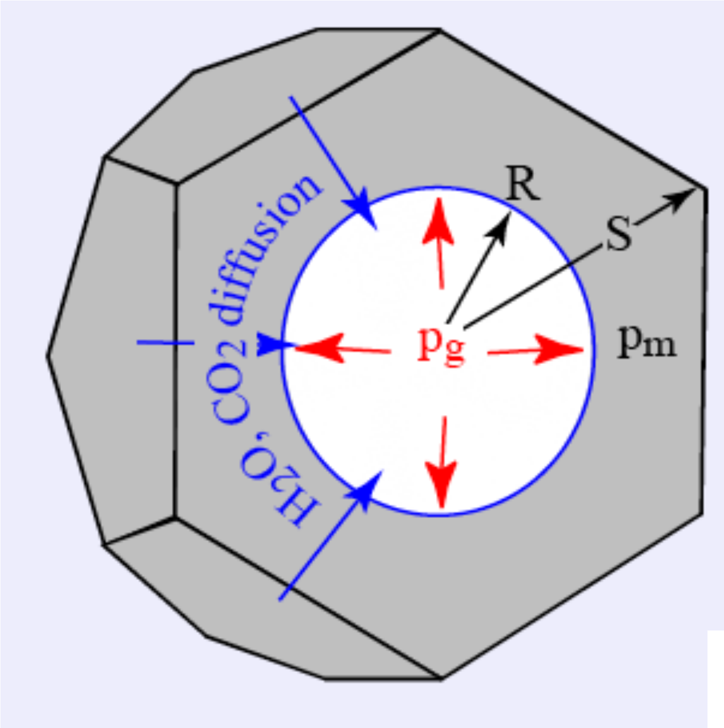


Proussevitch and Sahagian (1998)

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

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

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

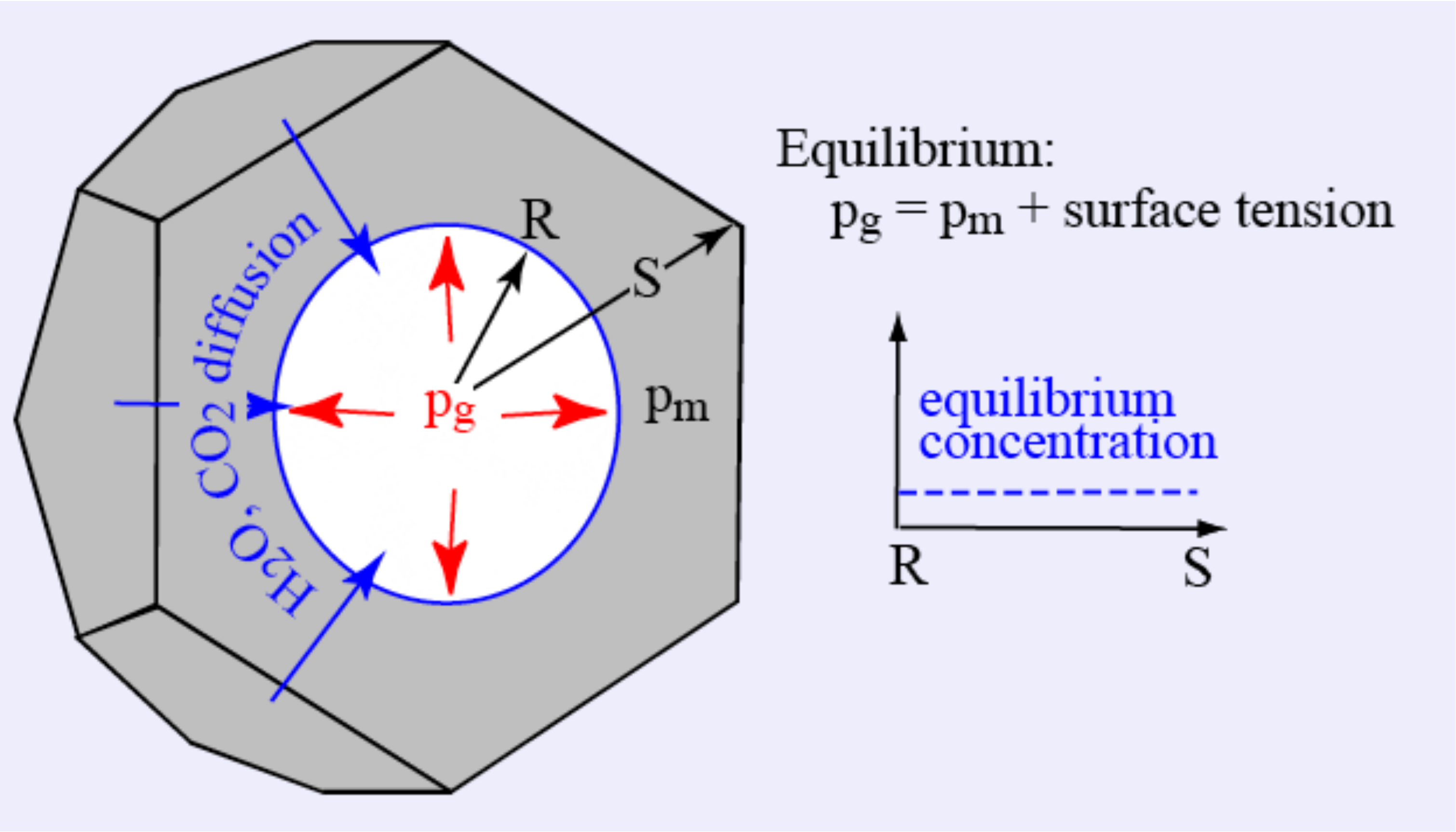
Lensky et al. (2001)

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

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

Bird et al. (1960)

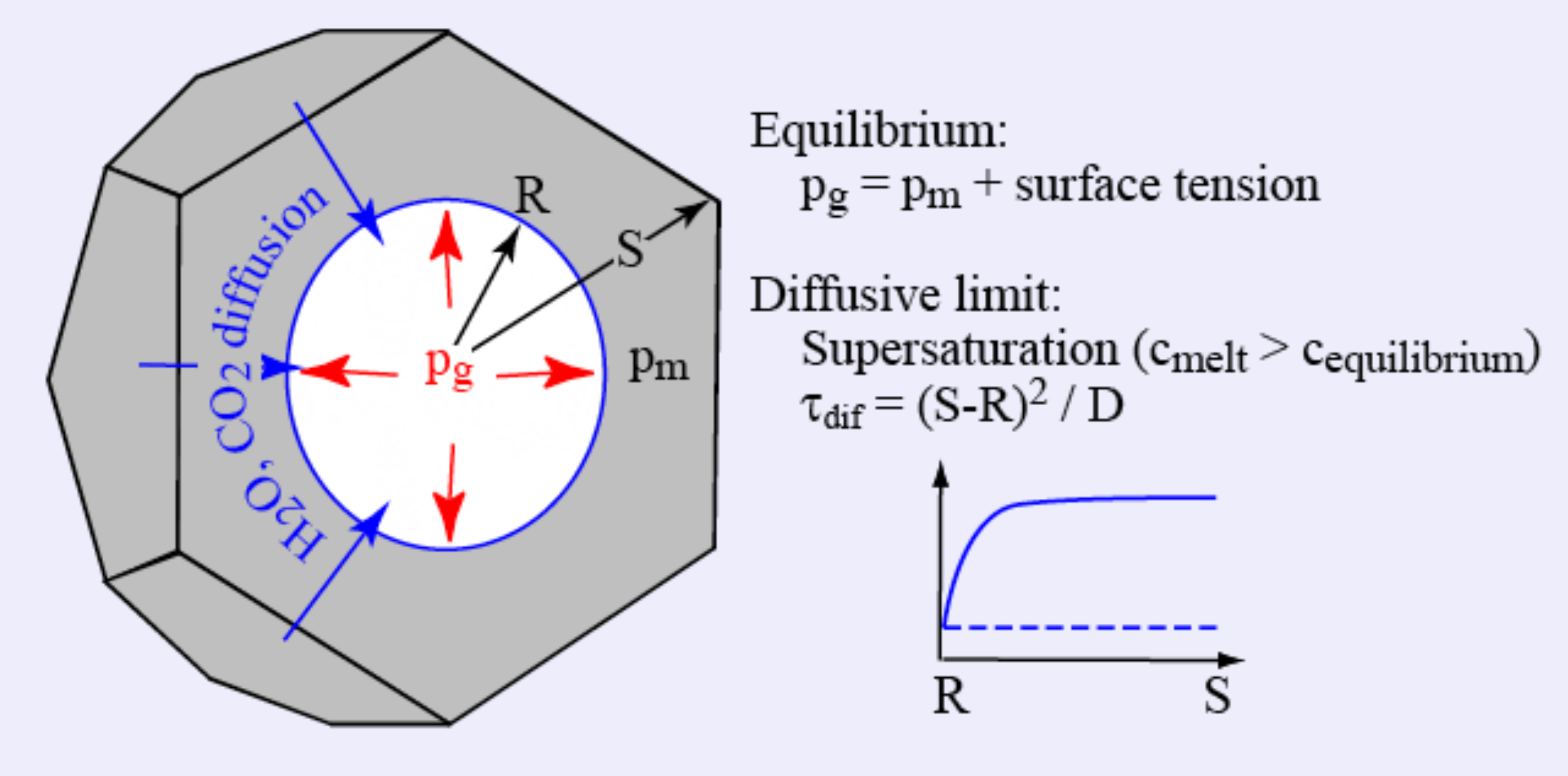
3 Regimes of bubble growth: Equilibrium (solubility-limited)



Growth is governed by changes in solubility

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

3 Regimes of bubble growth: Diffusion-limited



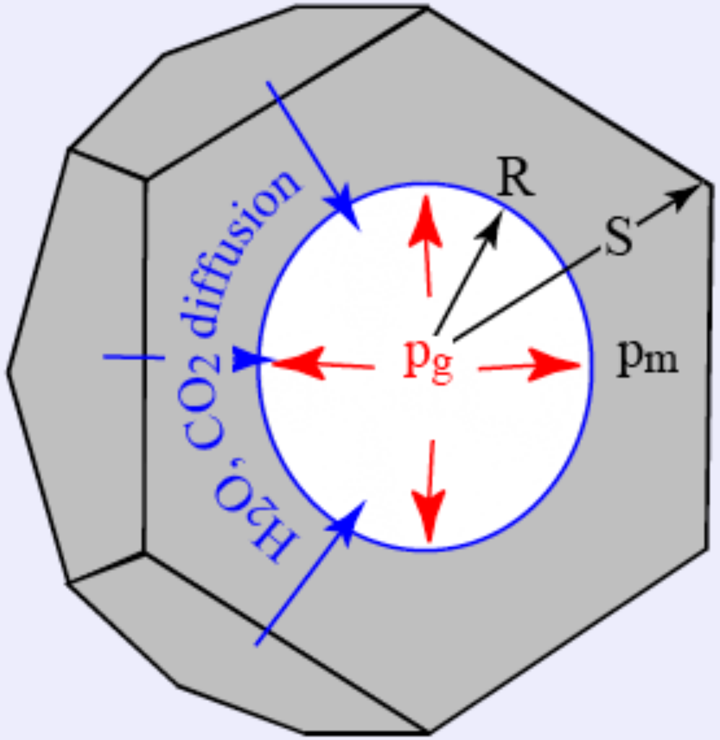
Equilibrium:
$p_g = p_m$ + surface tension

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

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

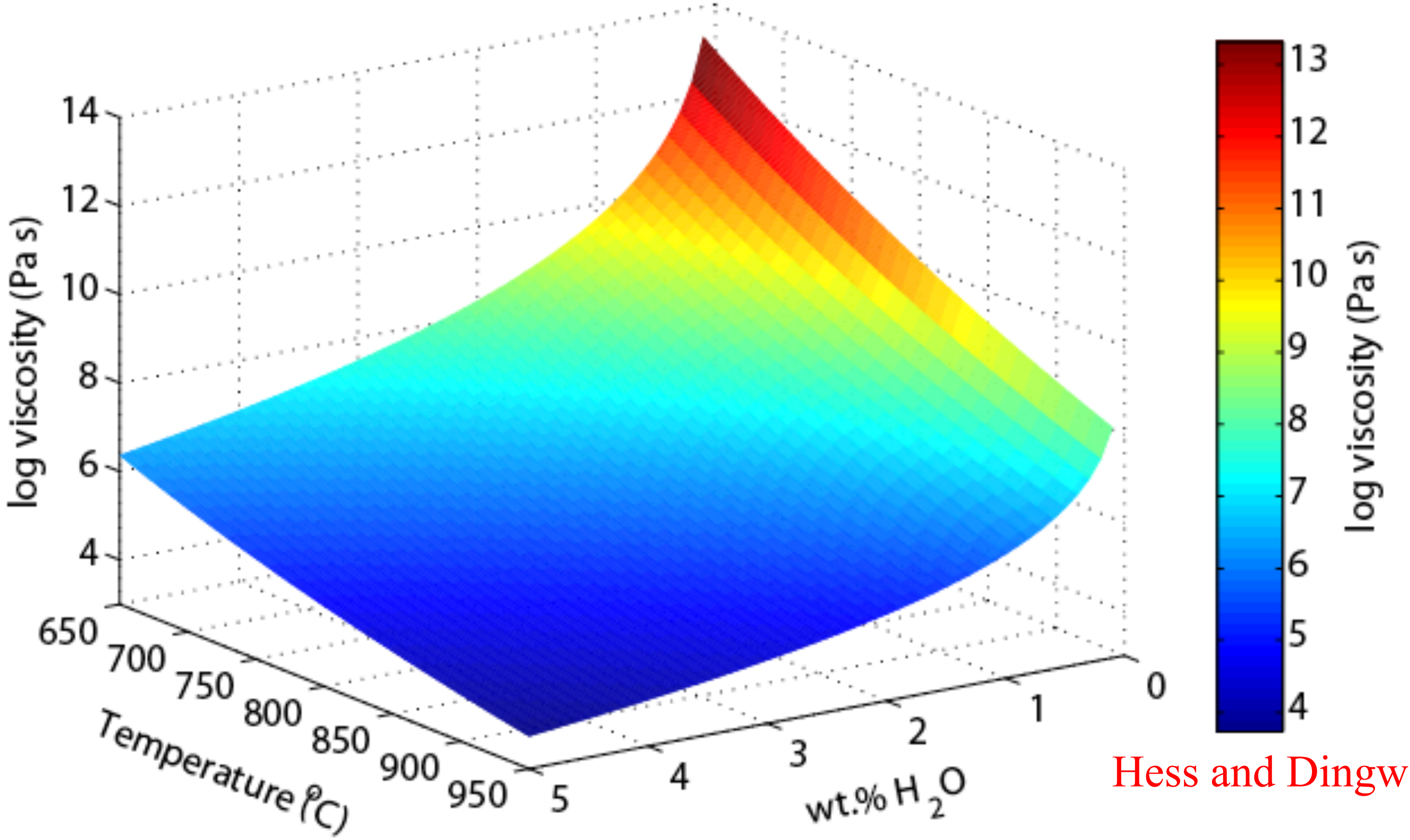
Diffusive limit:
Supersaturation ($c_{melt} > c_{equilibrium}$)
$\tau_{dif} = (S\text{-}R)^2 / D$

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

Growth is by viscosity-limited when

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

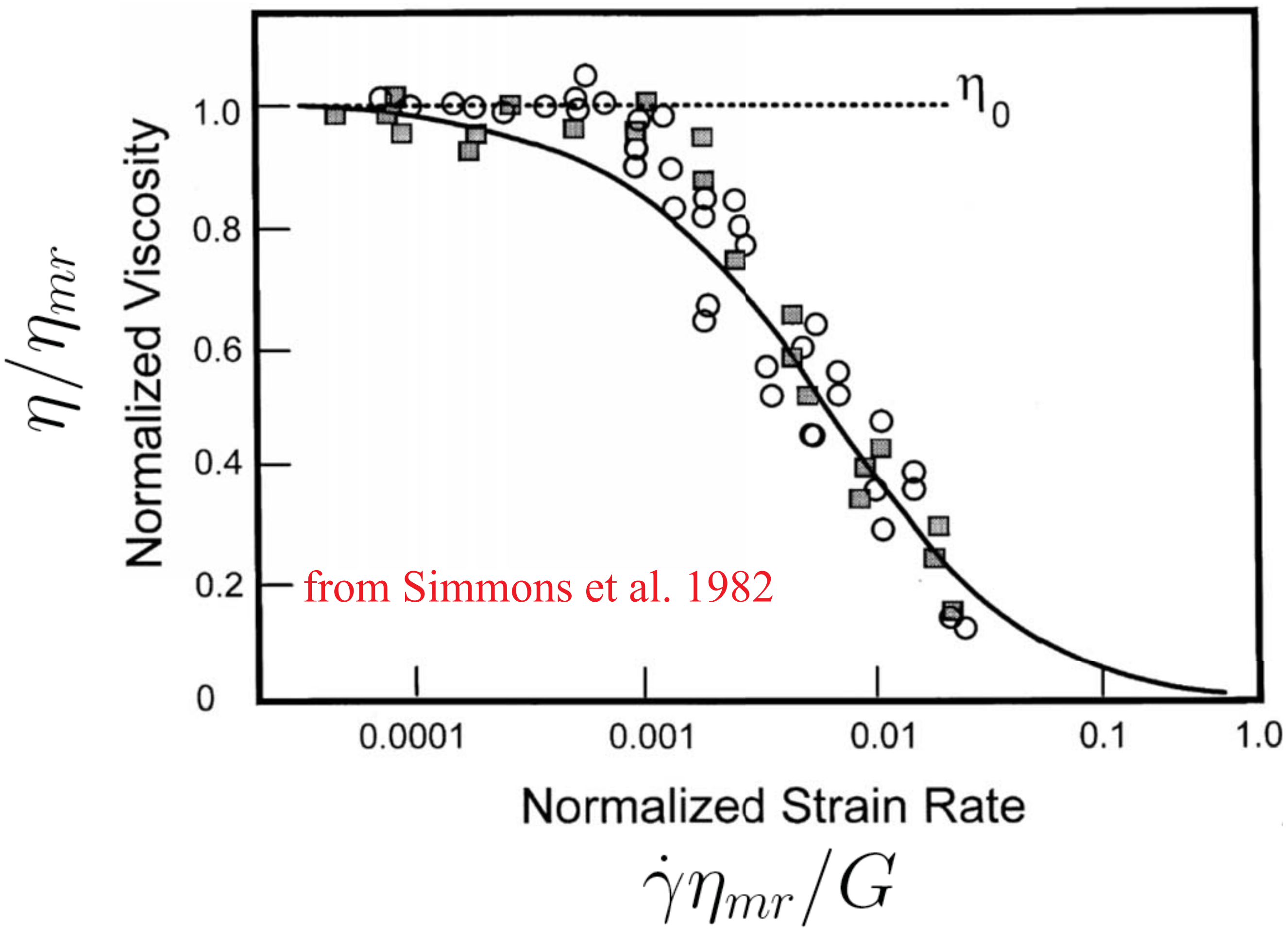
- Melt viscosity depends on amount of dissolved water and temperature (and composition)



Hess and Dingwell (1996)

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

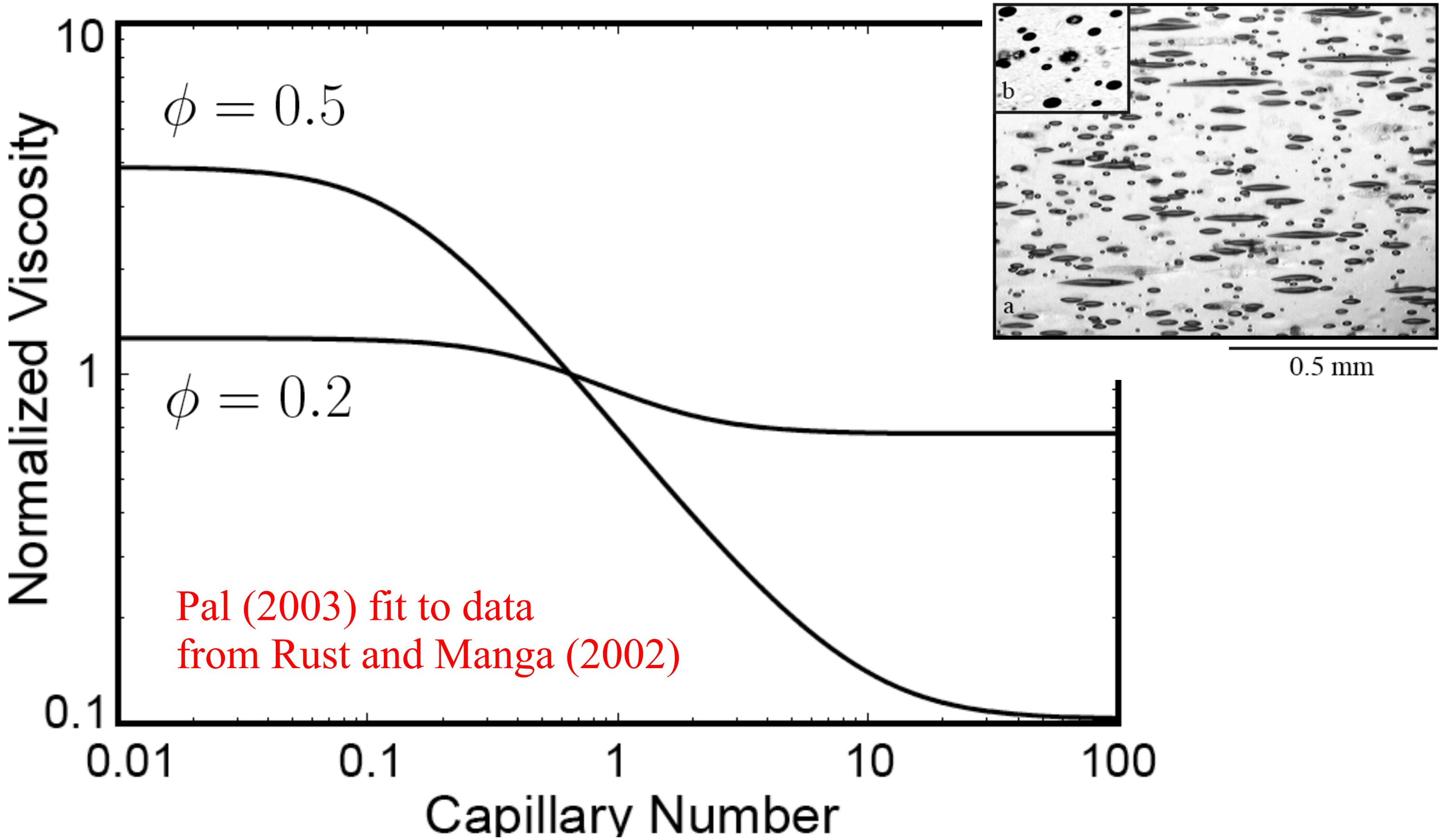
Strain-rate dependent viscosity of melt phase



from Simmons et al. 1982

Silicic magmas are similar (Webb and Dingwell)

Strain-rate dependent viscosity of bubbly suspension

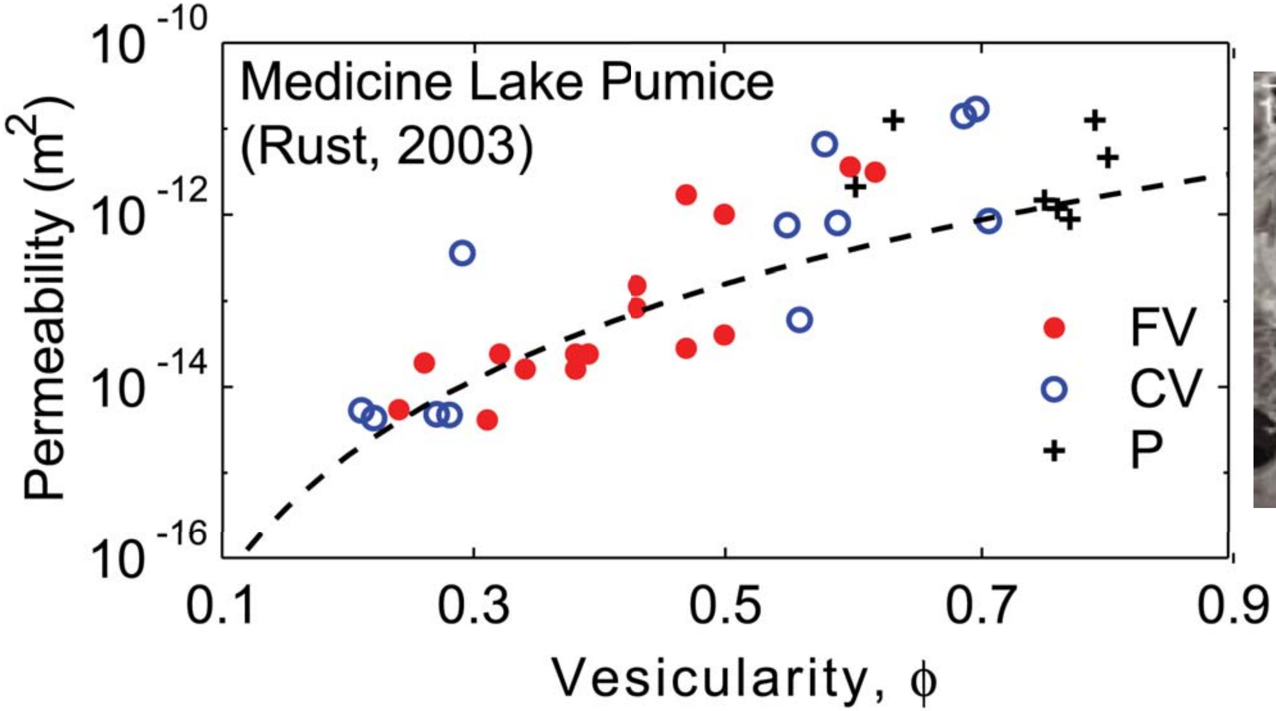


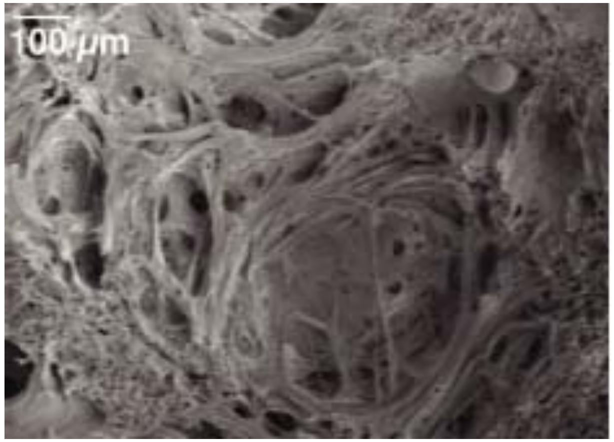
Pal (2003) fit to data
from Rust and Manga (2002)

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

increasing shear rate

Vesicular magma is permeable





Klug et al. (2002)

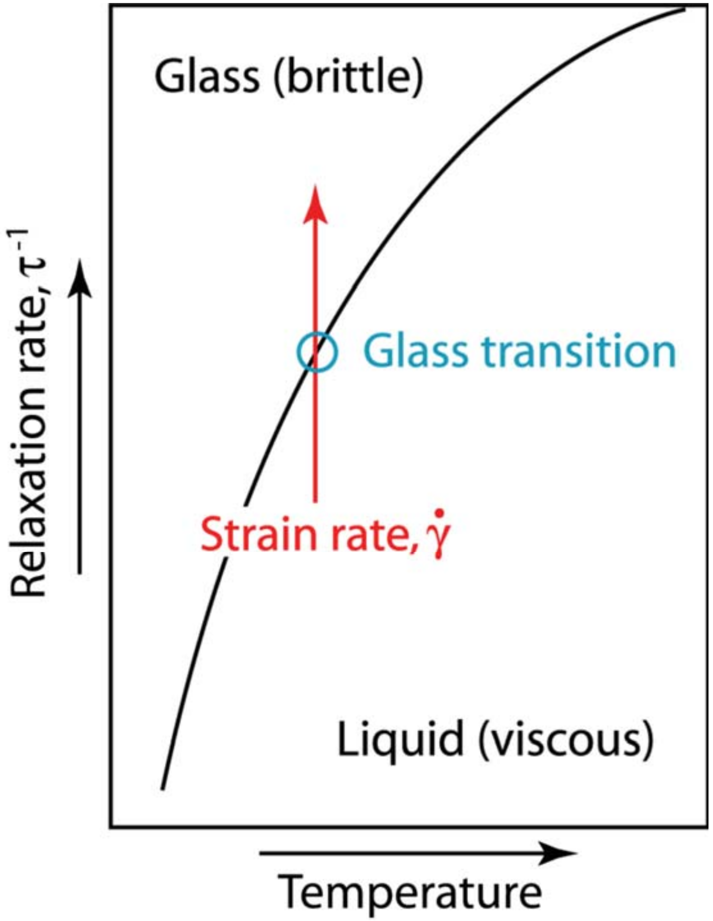
Connections between bubbles allow gases to escape from magma

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

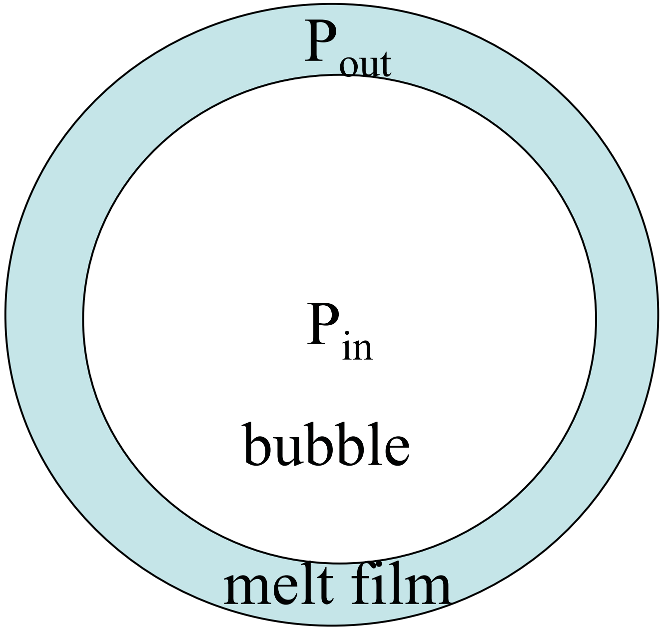
Brecciation



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

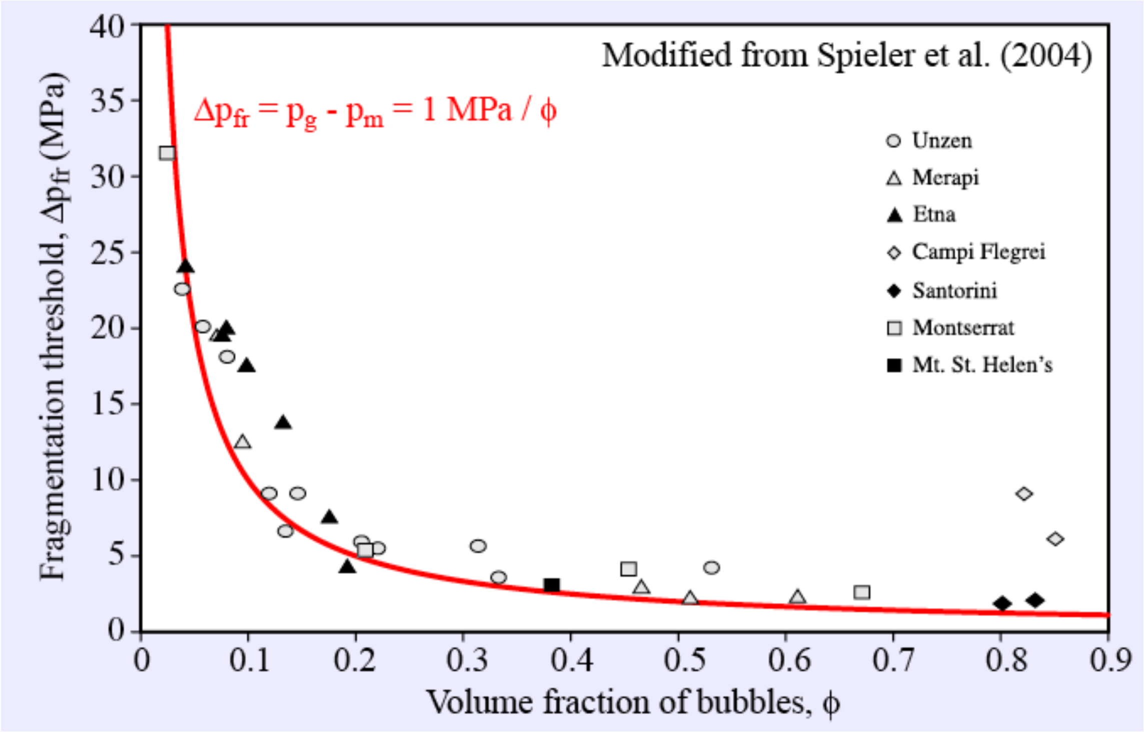
e.g., Webb and Dingwell (1990), Webb (1997), Papale (1998)

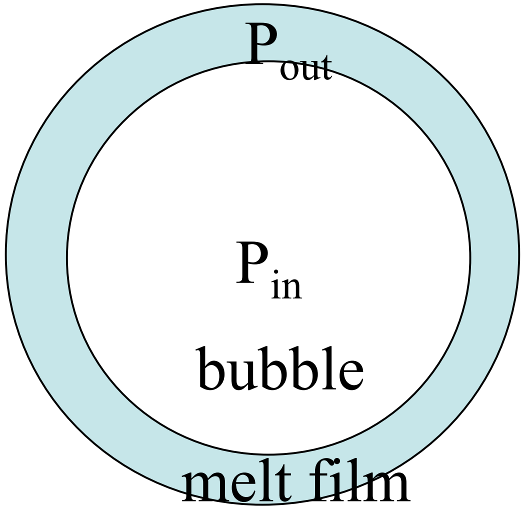
Fragmentation



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

Experiments with real magma





P_{out}

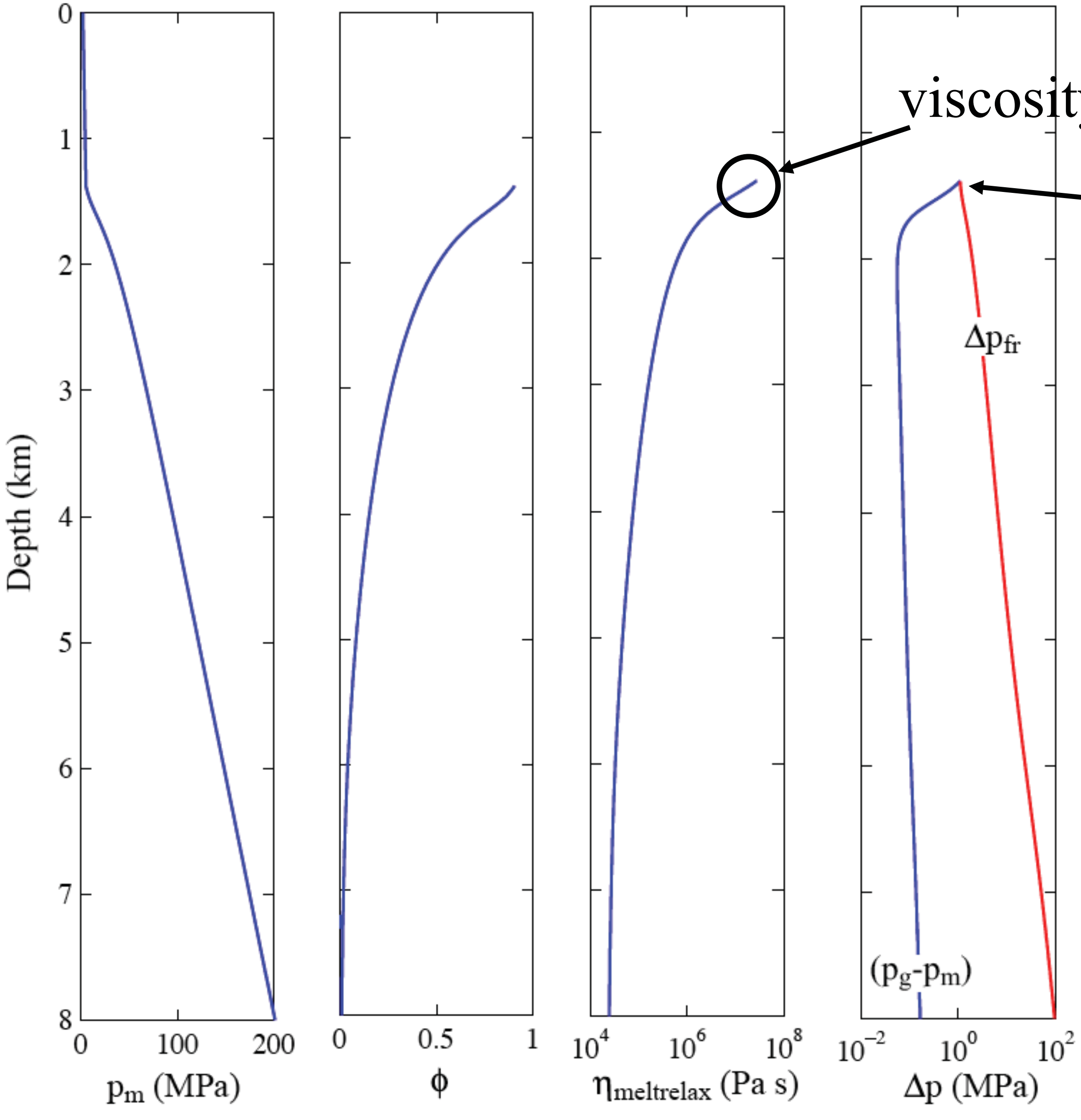
P_{in}

bubble

melt film

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

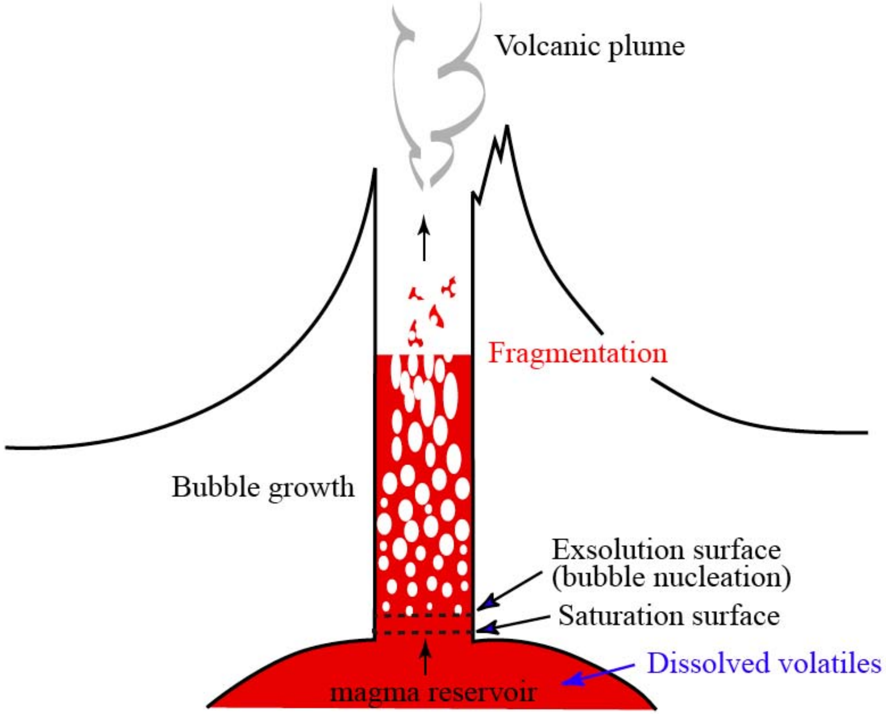
Example: Mount St Helens 1980 conditions



viscosity limits expansion

fragmentation

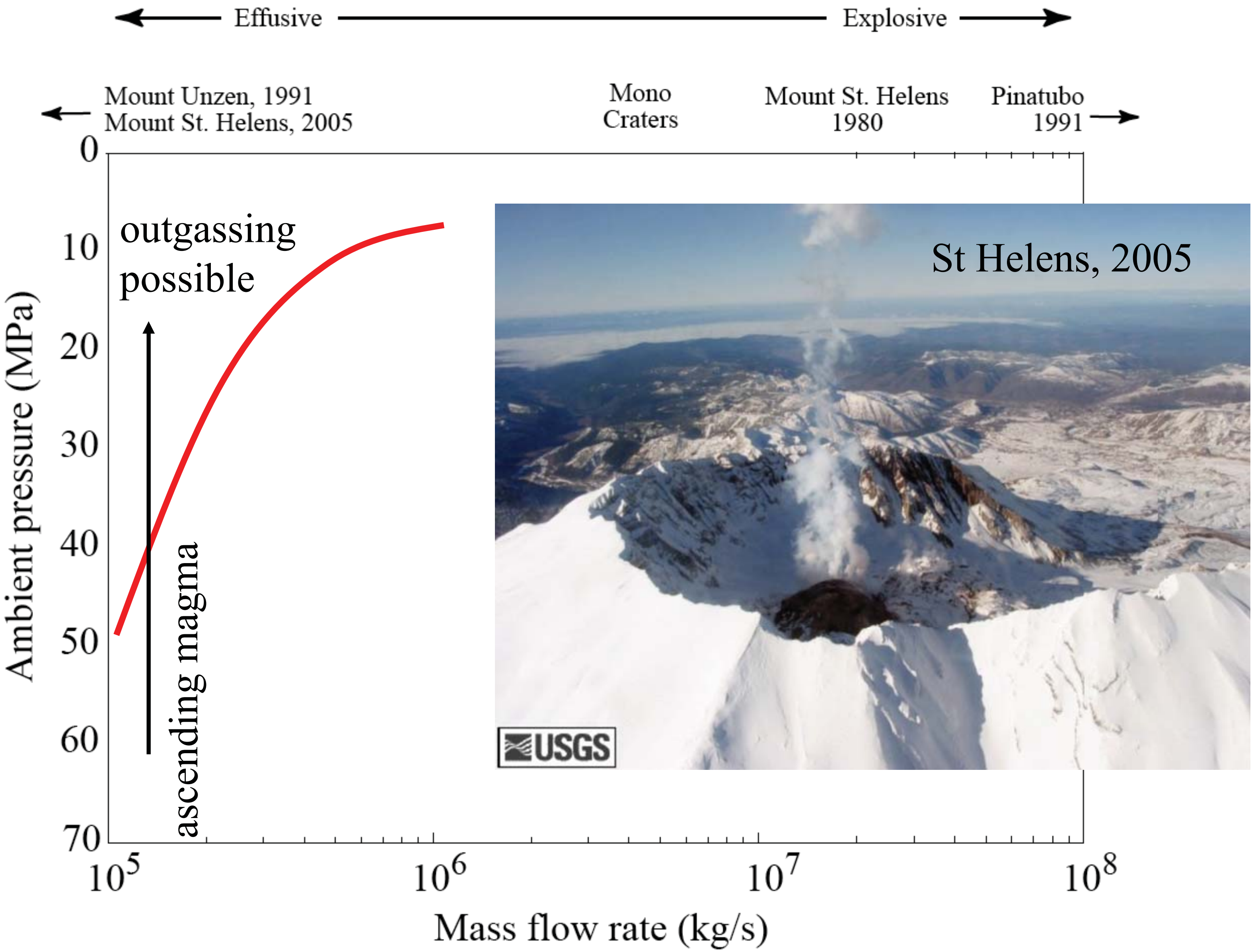
Why do volcanoes erupt explosively?



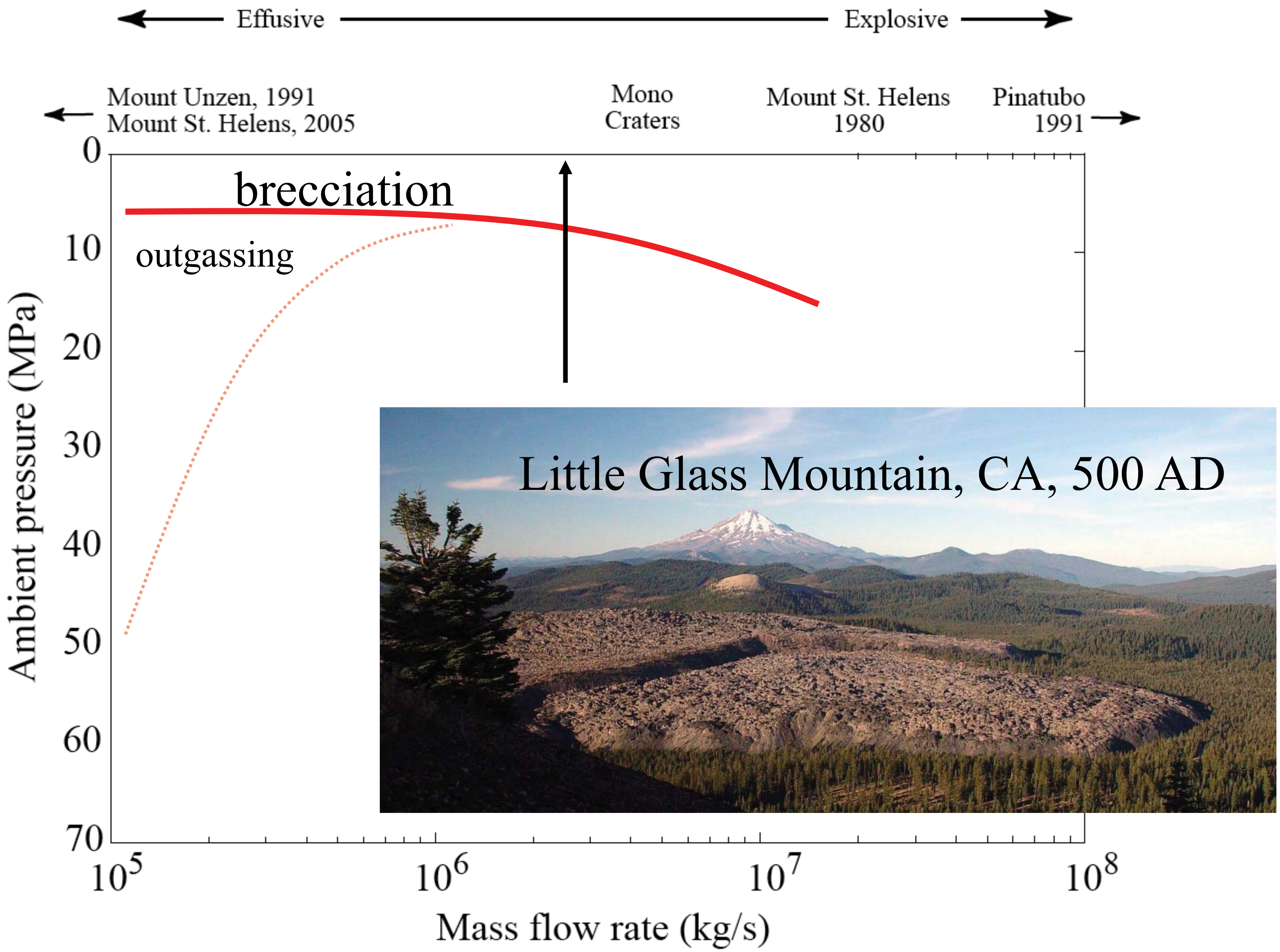
Open questions:

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

Change in eruption style with changing ascent rate



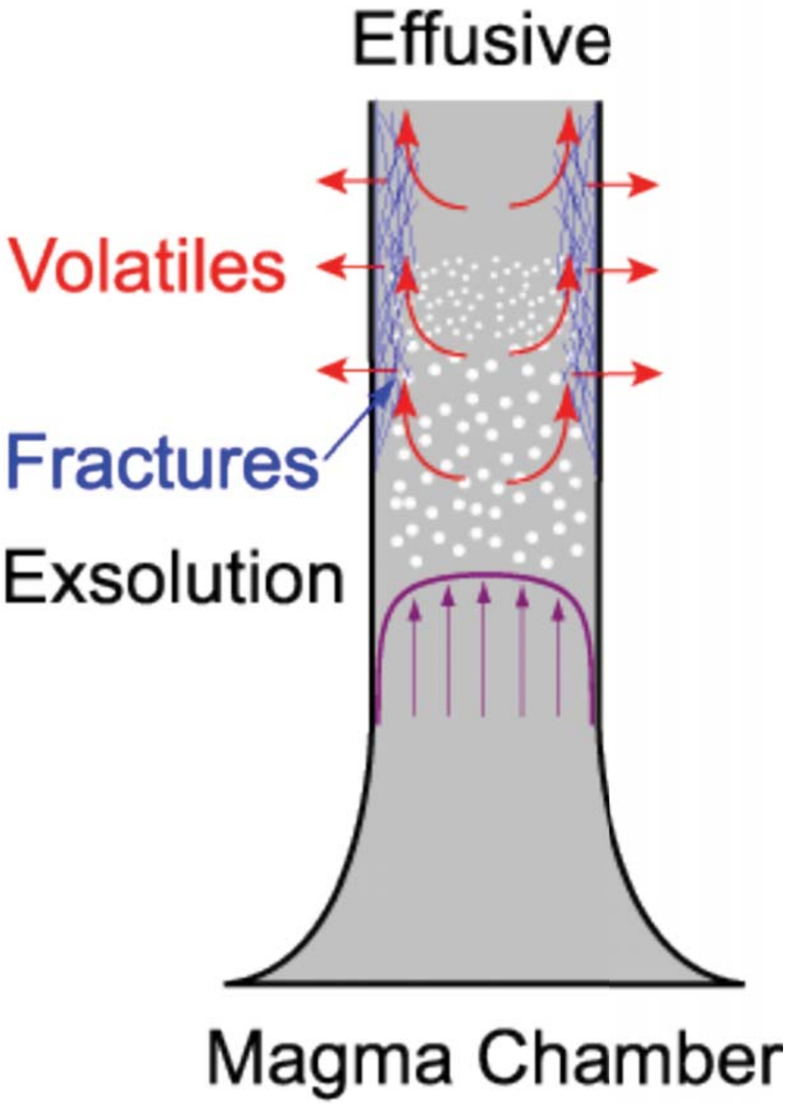
Change in eruption style with changing ascent rate



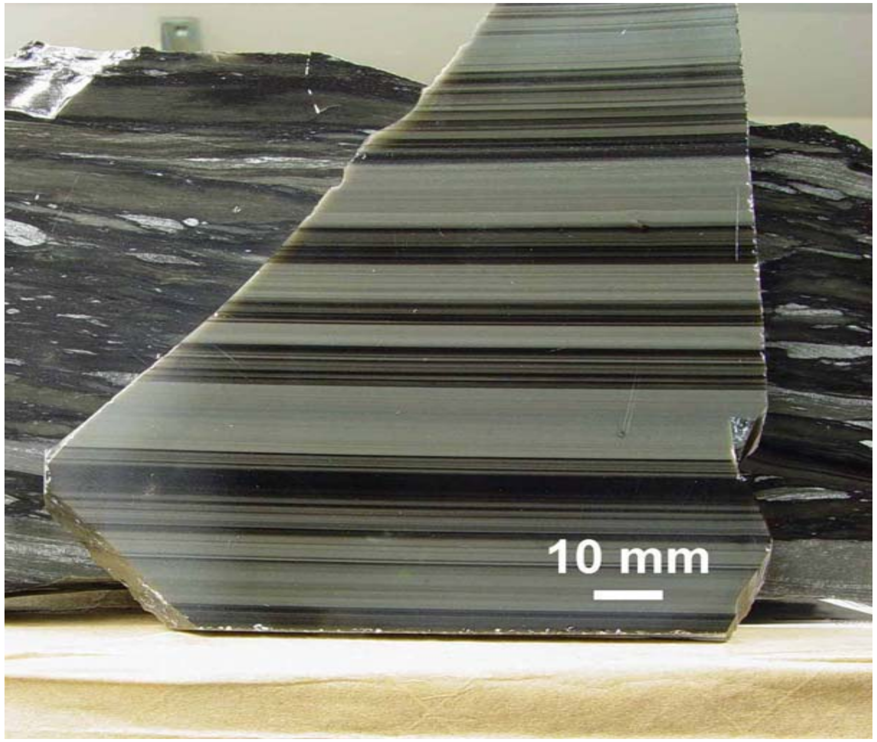
Little Glass Mountain, CA, 500 AD

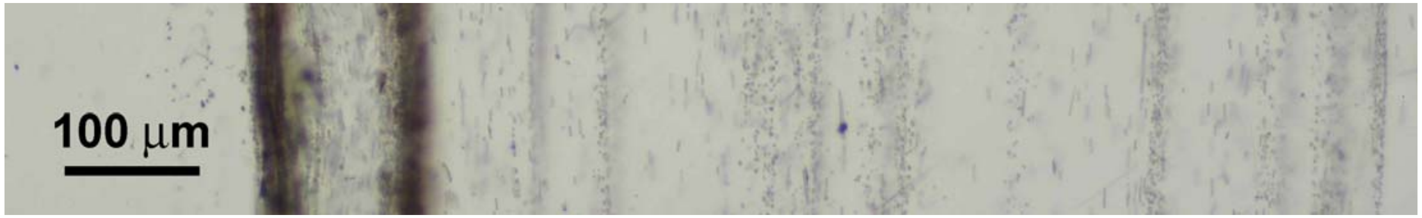
We predict that flow-induced fragmentation (brecciation) occurs at the sides of conduits

Is there any evidence that this occurs?



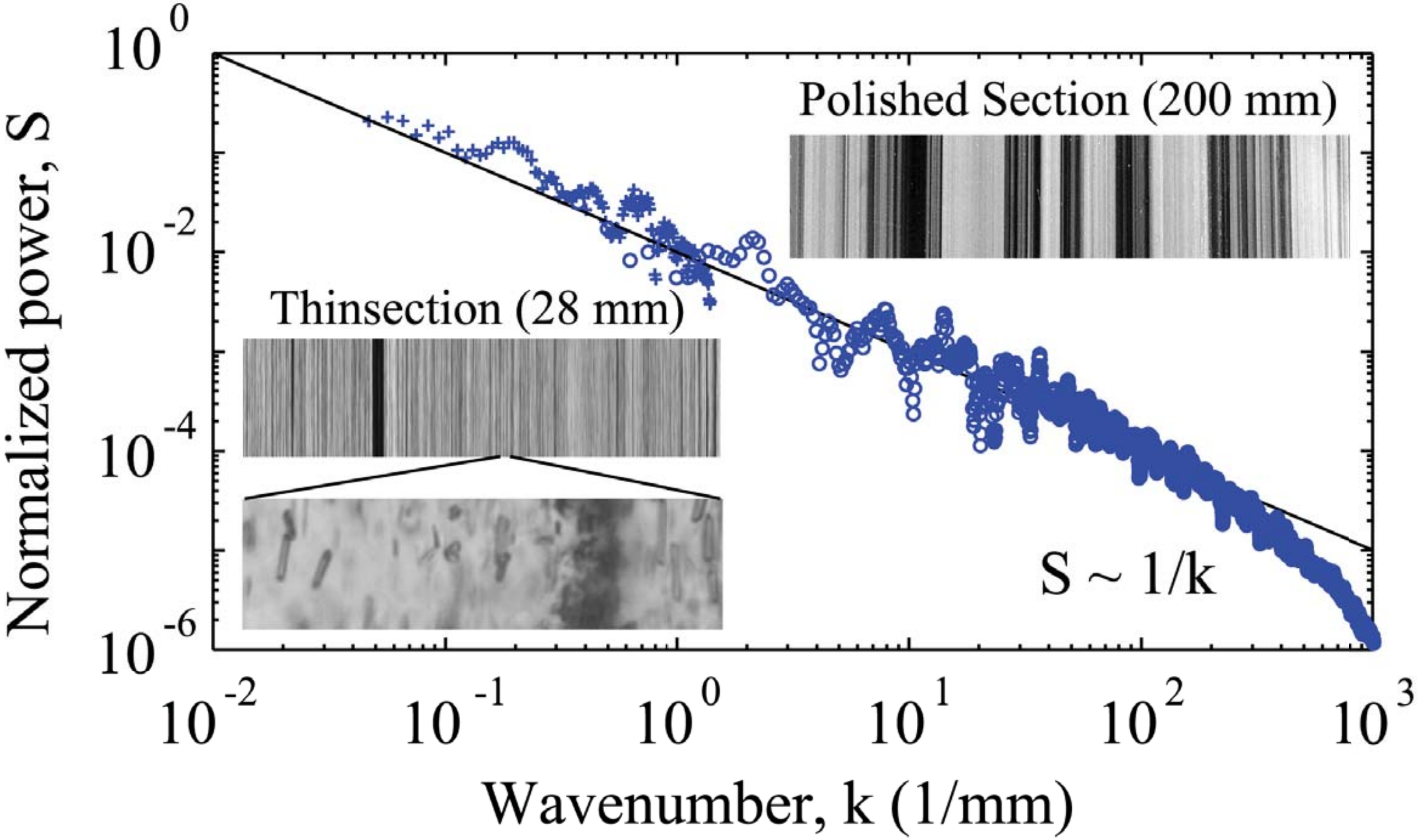
Obsidian is banded at all scales





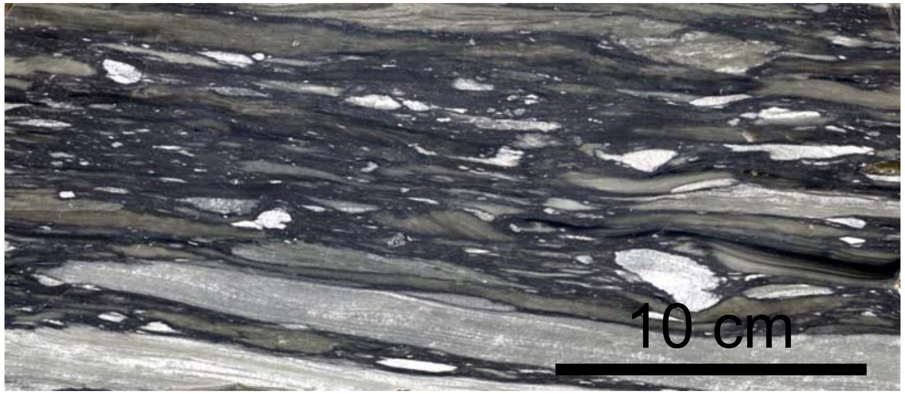
Do these bands (in some cases) record fragmentation?

Power spectrum: Scale invariant banding

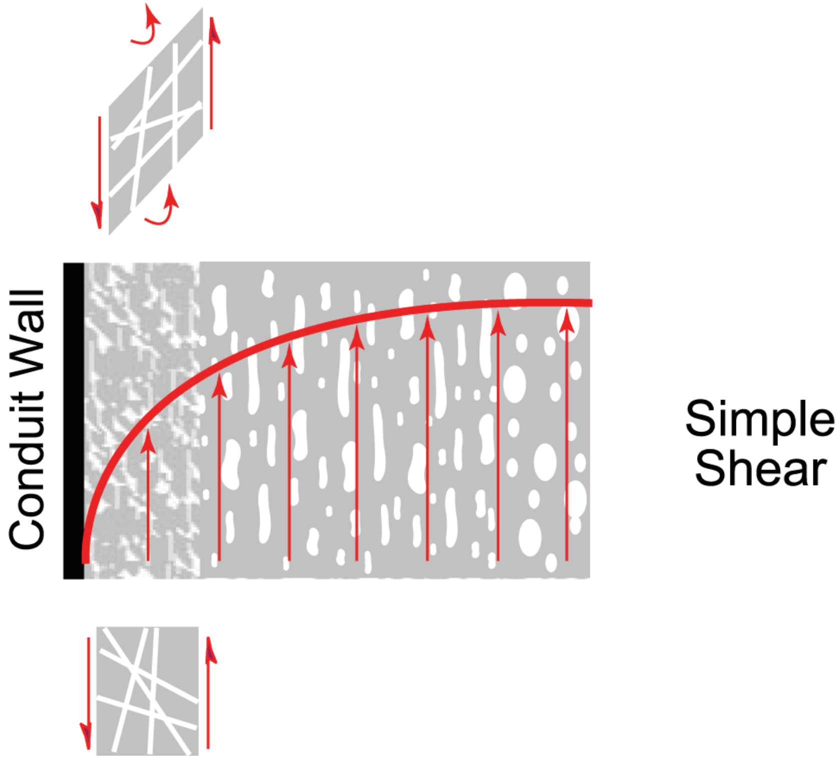


Band widths are scale invarient over 4 orders of magnitude

Brecciation, rewelding and deformation

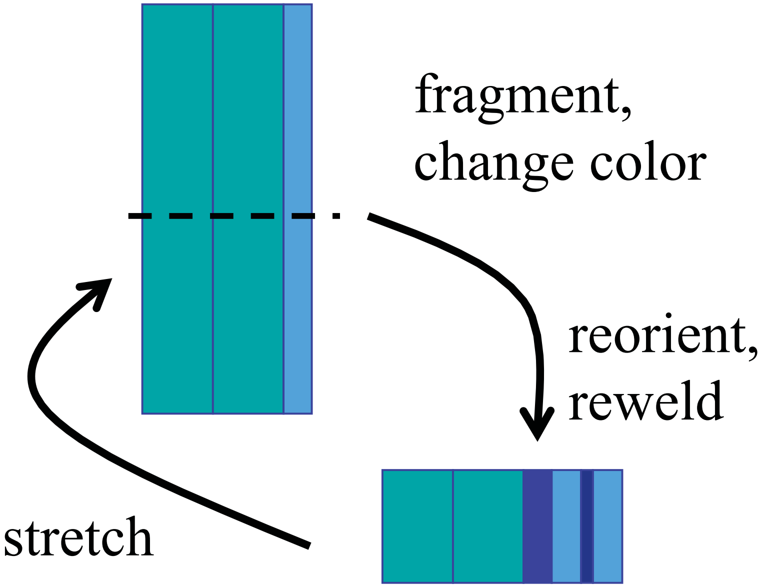


Simple shear . . . .



. . . . rotation and stretching

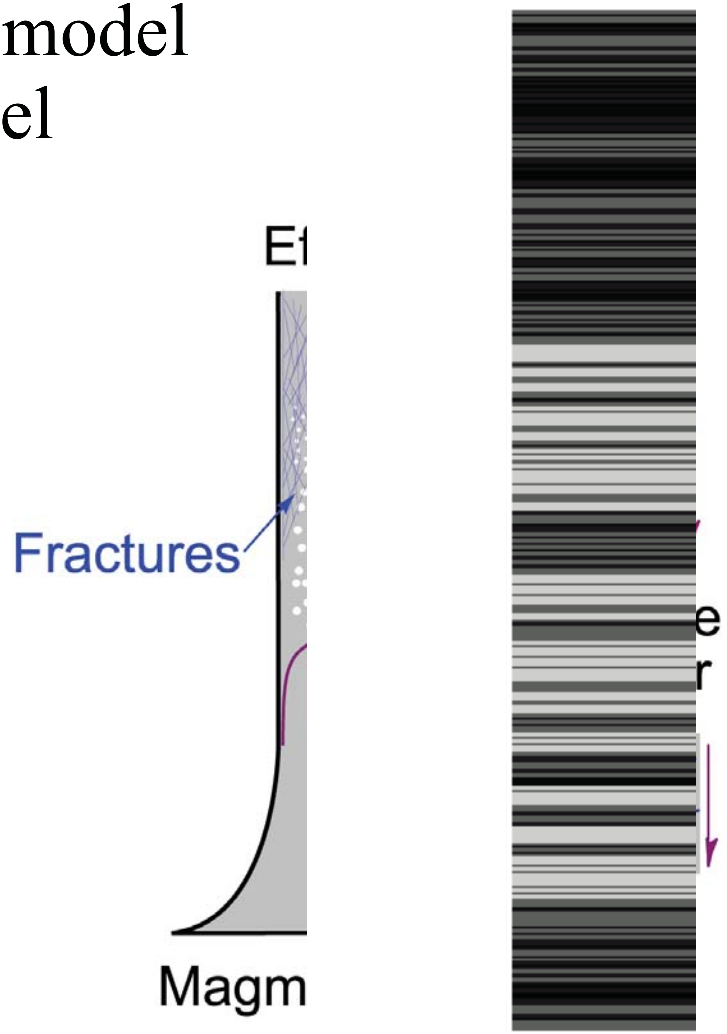
A representative model
Cantor model



fragment,
change color

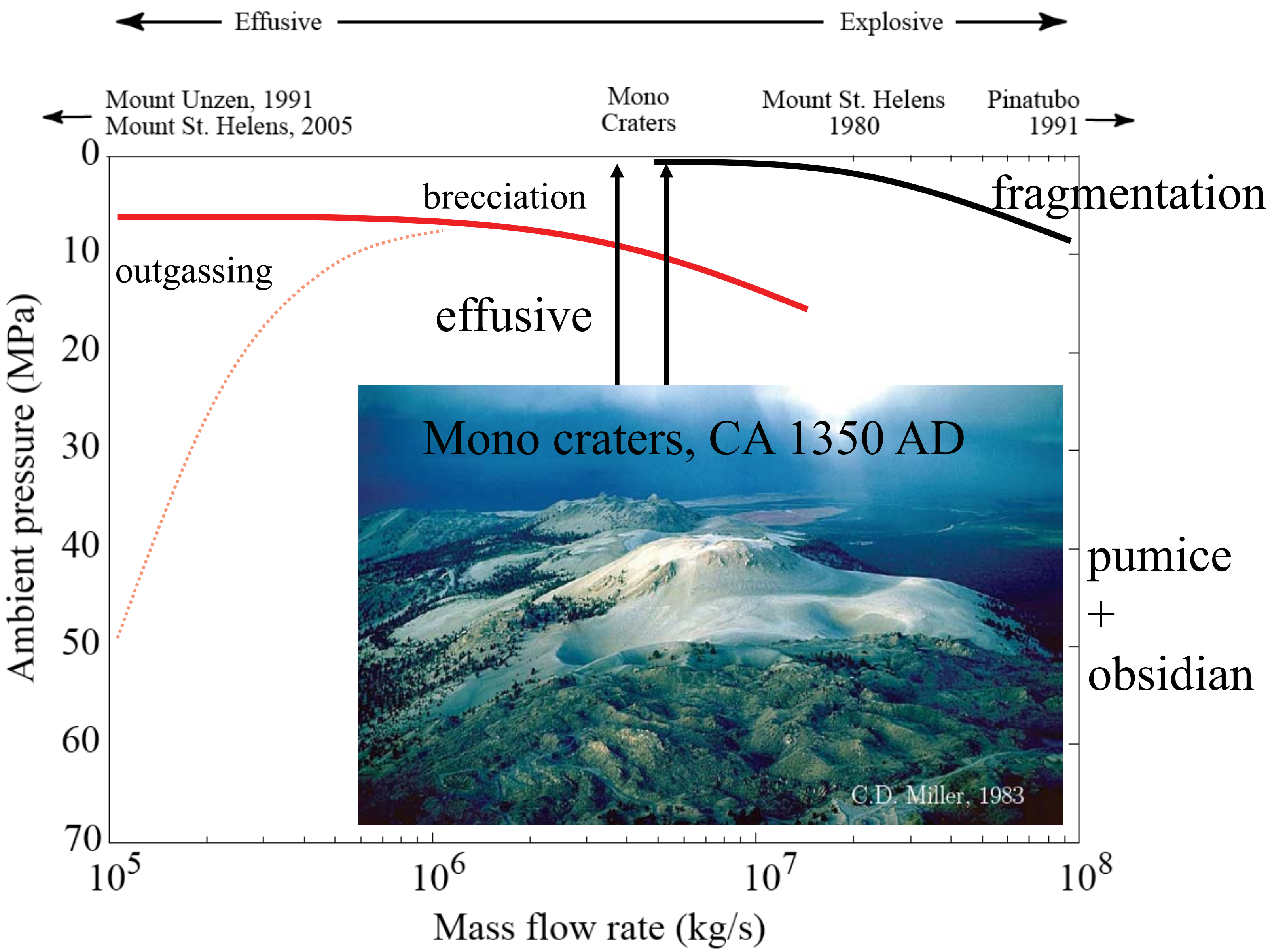
reorient,
reweld

stretch



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

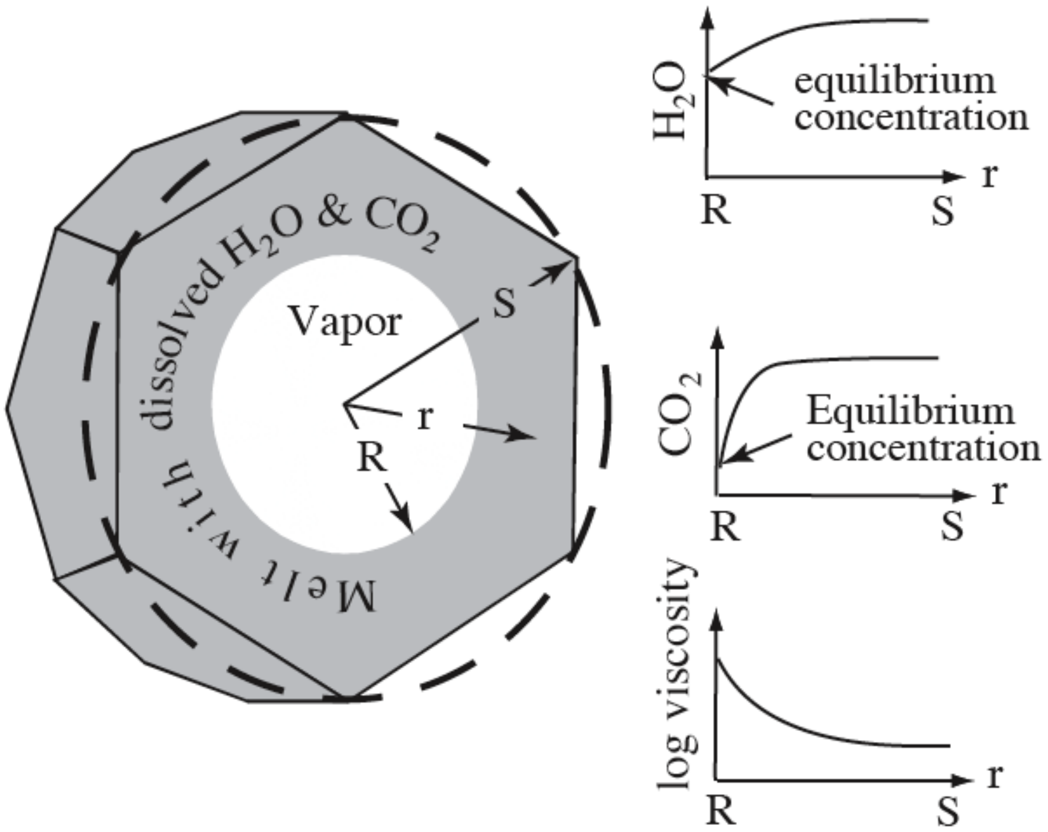
Change in eruption style with changing ascent rate



Mono Crater, CA

Test models using the measured concentration of water and CO_2

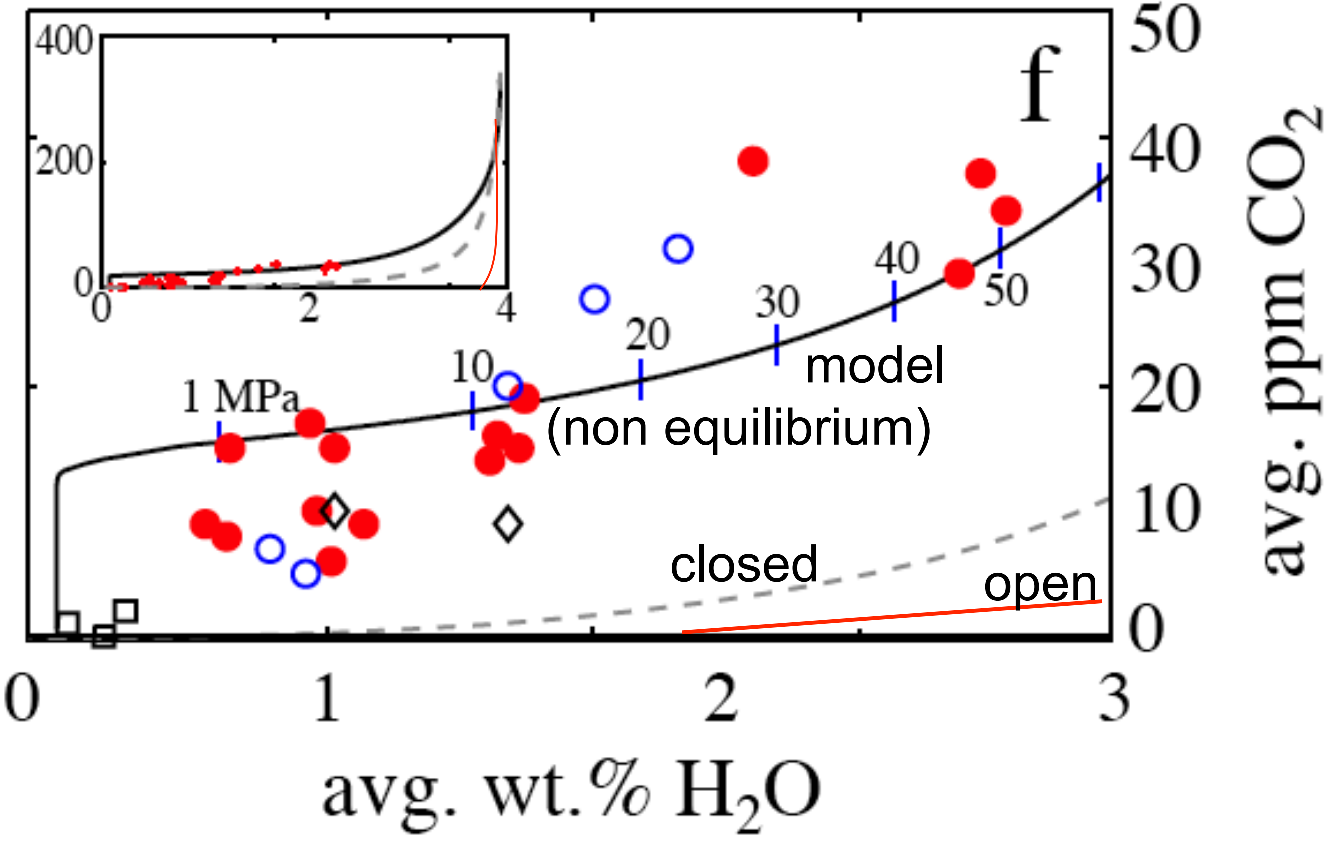
Water diffuses faster than CO_2



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

Water diffuses faster

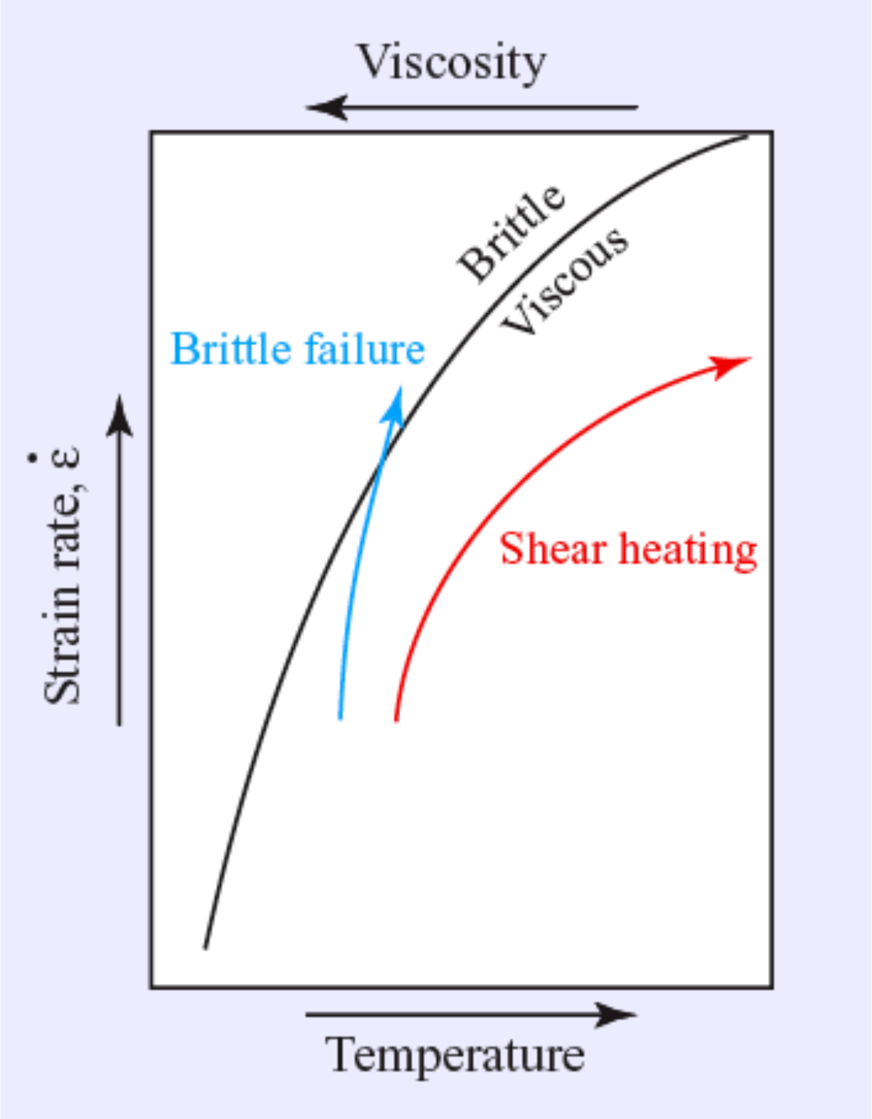
Data from Neuman et al. (1989)



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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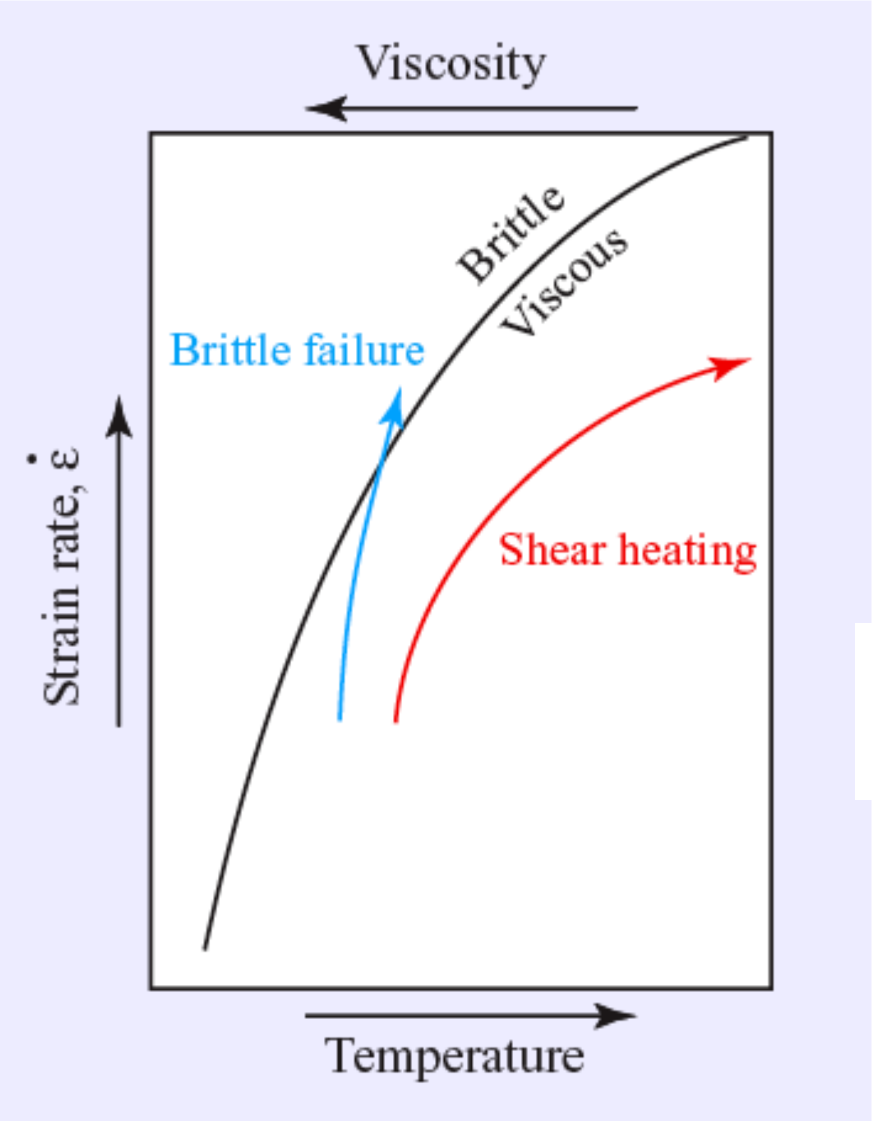
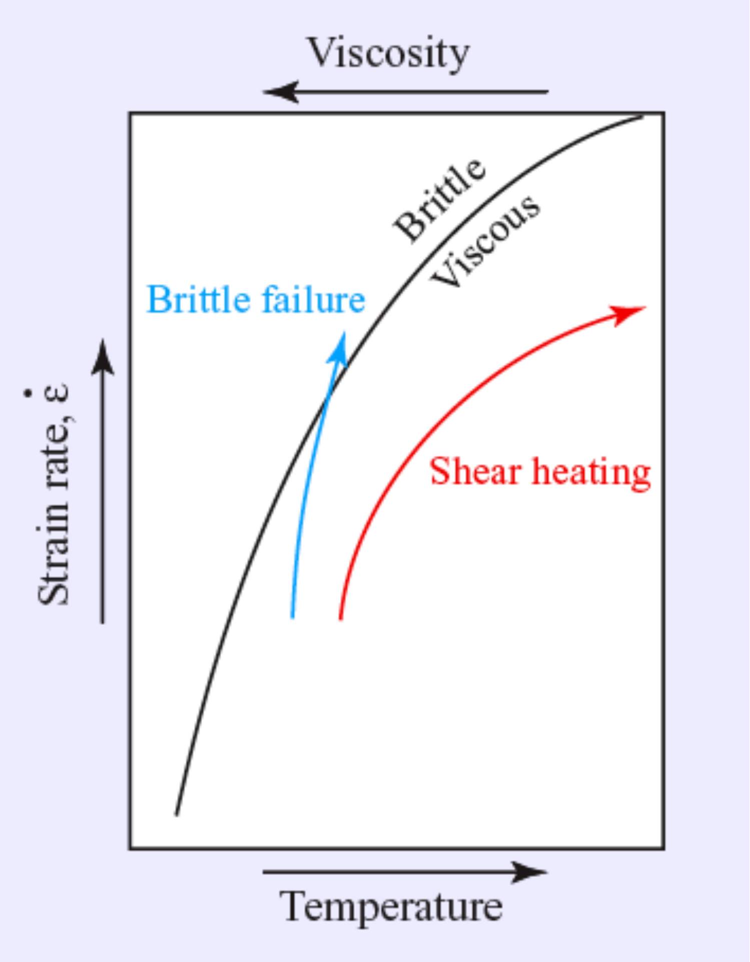


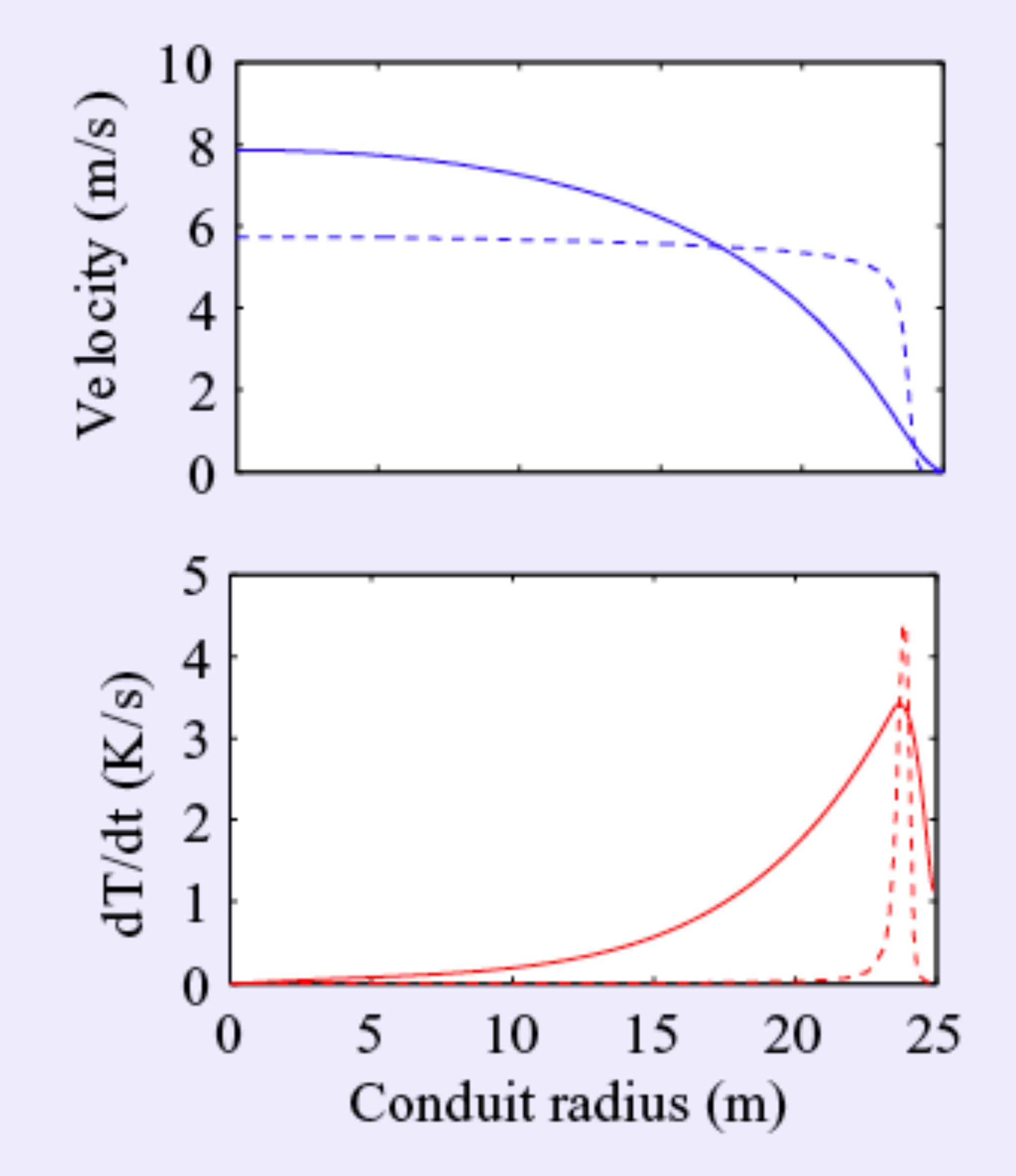
Viscous dissipation important when Brinkman number (viscous dissipation/heat diffusion)

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

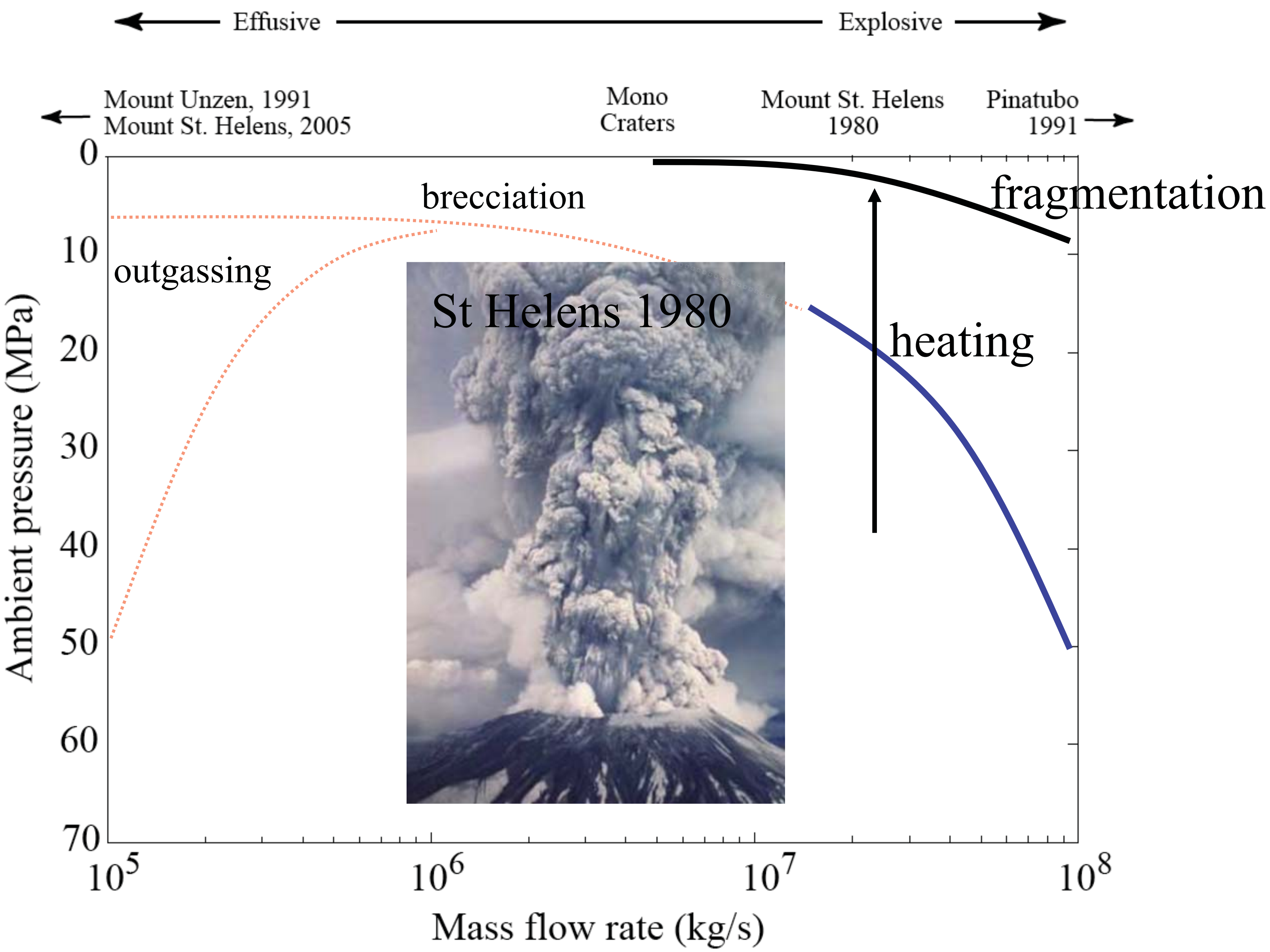
becomes large

Implications:
no brecciation, “blunt” velocity profiles

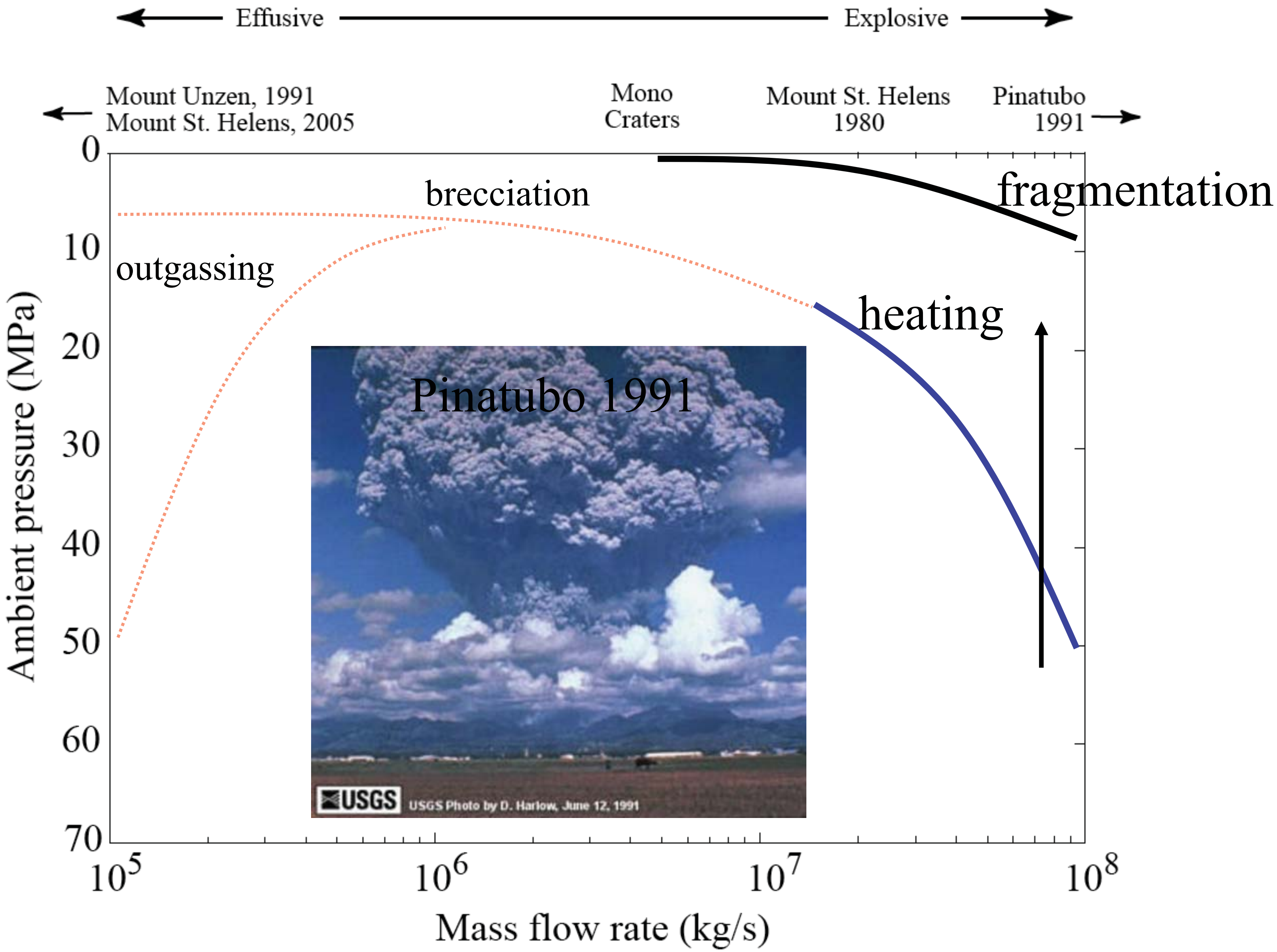




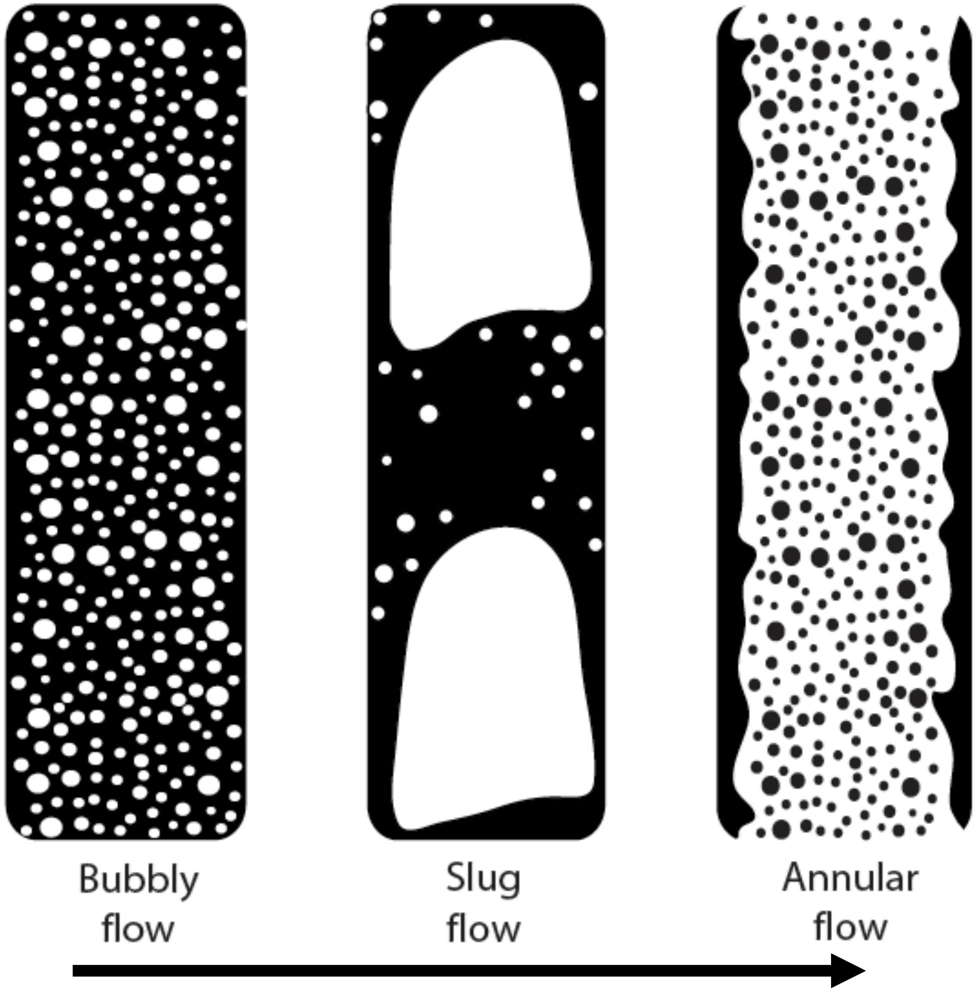
Change in eruption style with changing ascent rate



Change in eruption style with changing ascent rate



Basaltic (low viscosity) eruptions



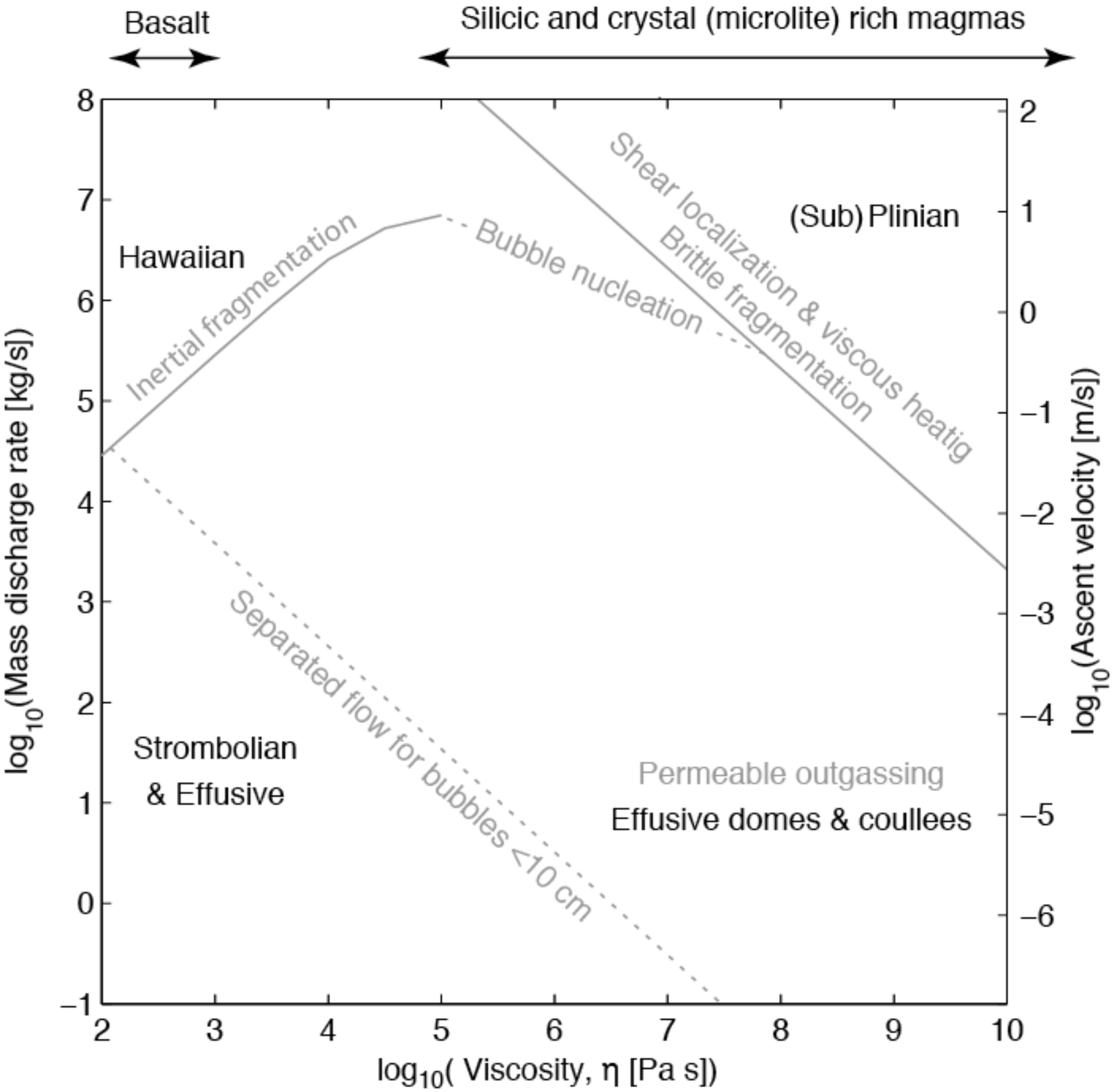
Bubbly flow

Slug flow

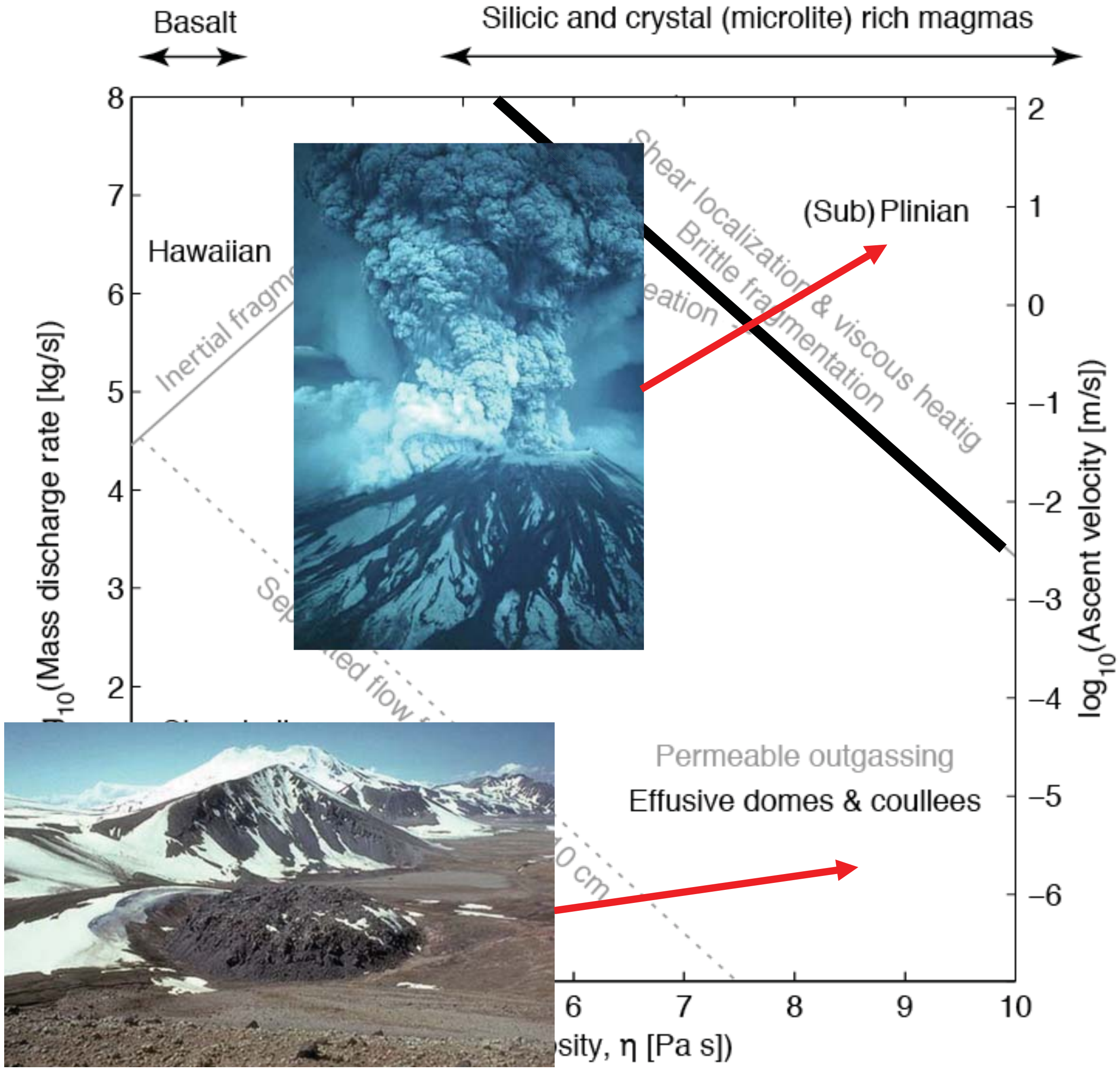
Annular flow

Increasing bubble/melt speed and volume fraction of bubbles

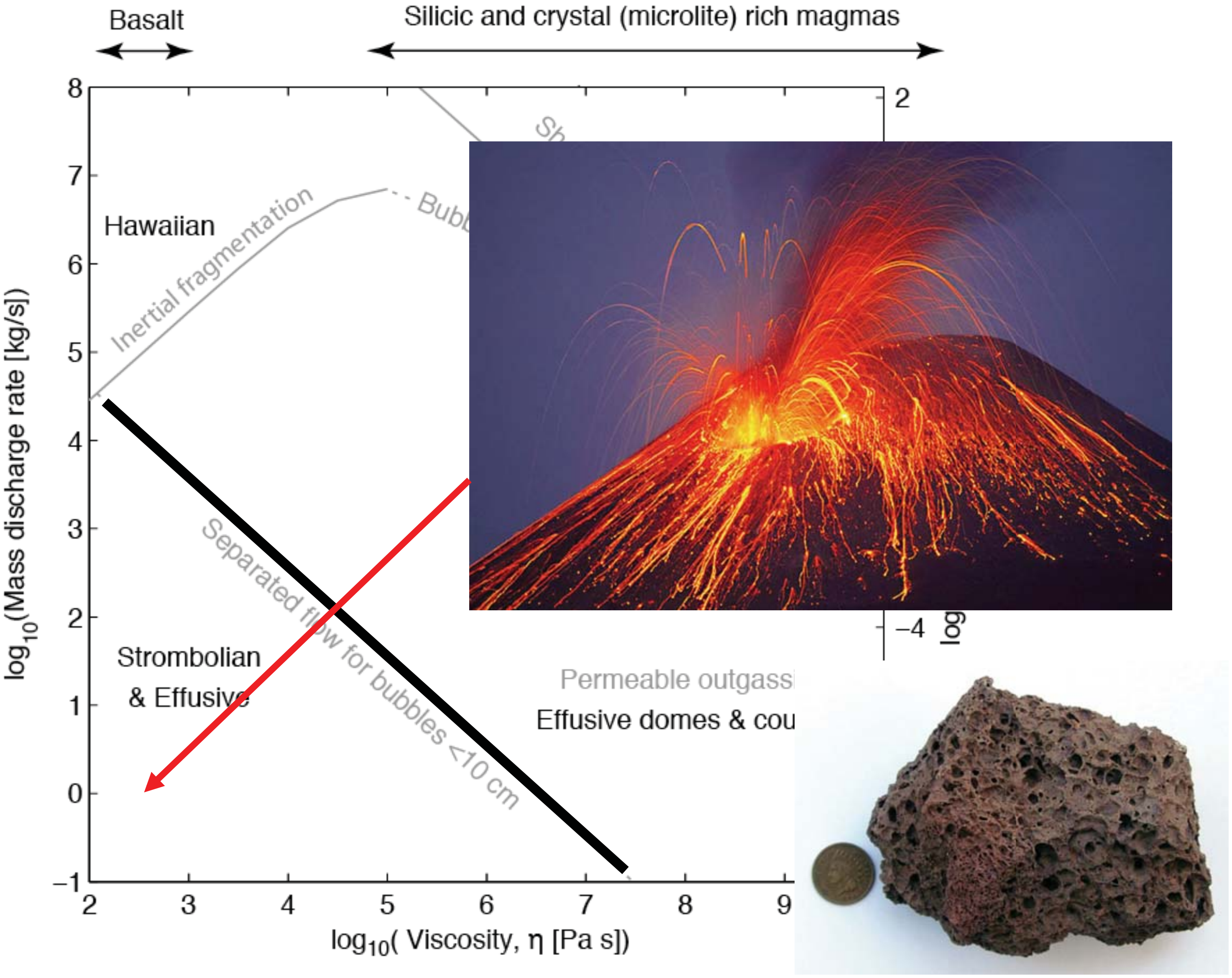
Basaltic eruption styles



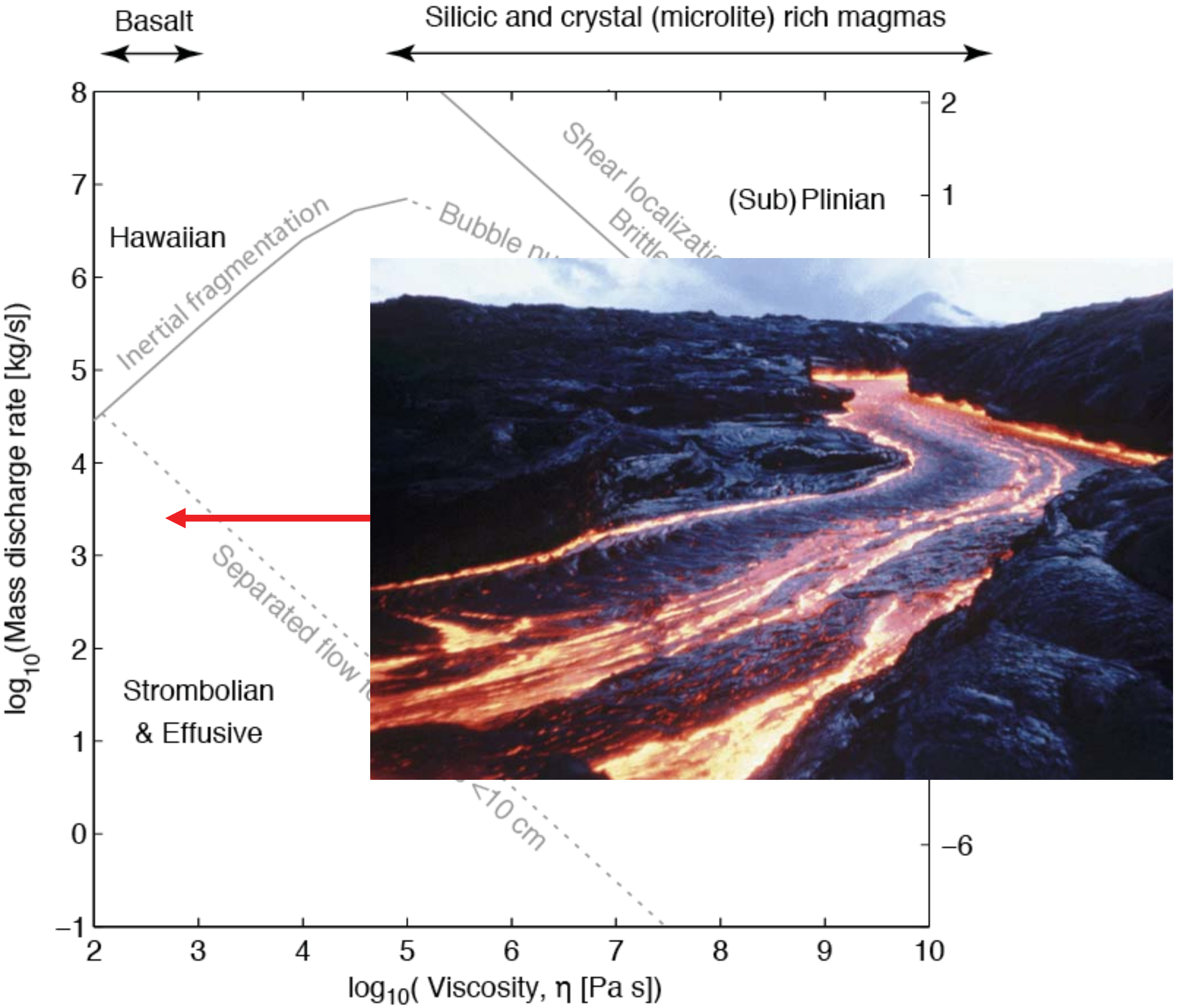
Basaltic eruption styles



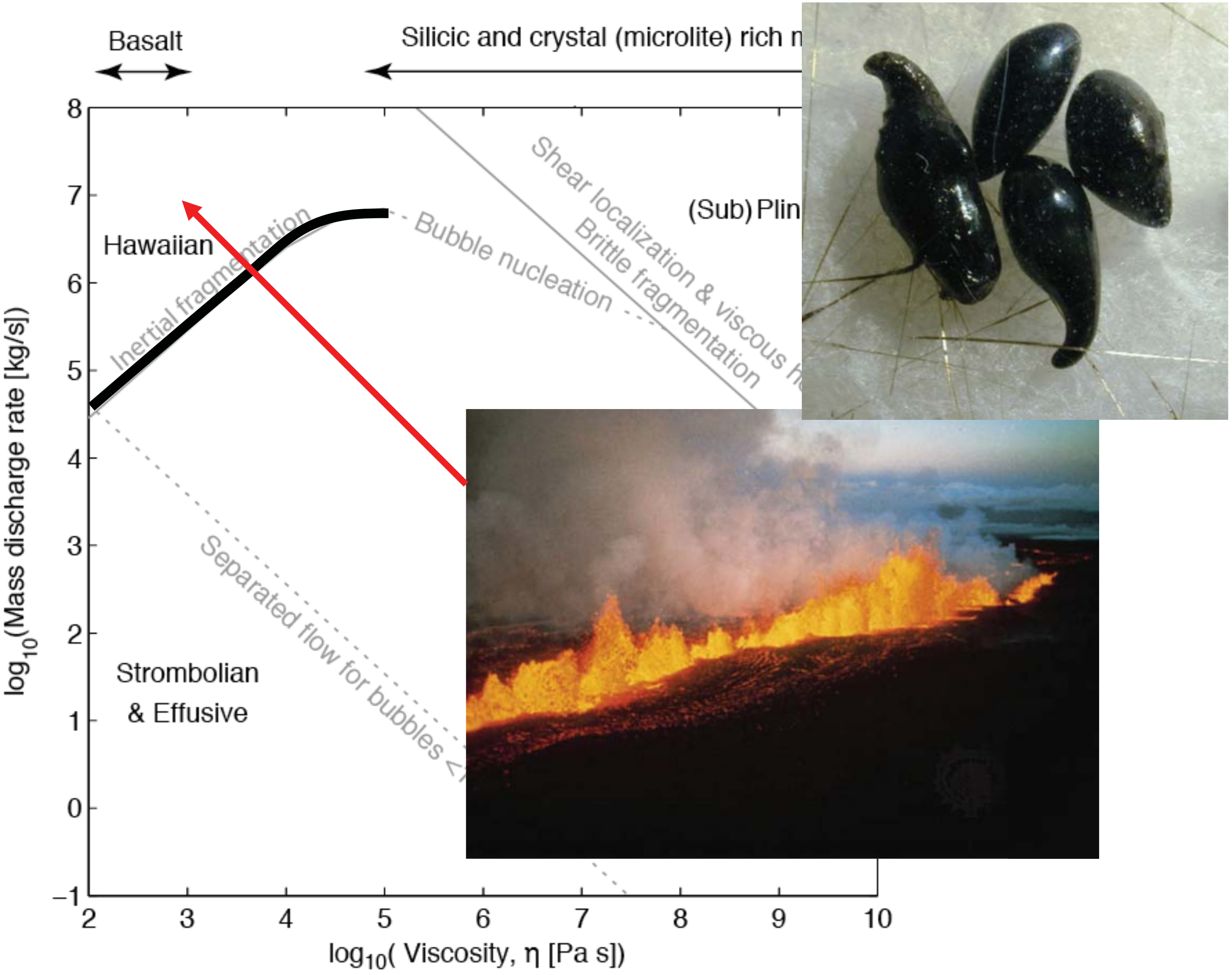
Basaltic eruption styles



Basaltic eruption styles



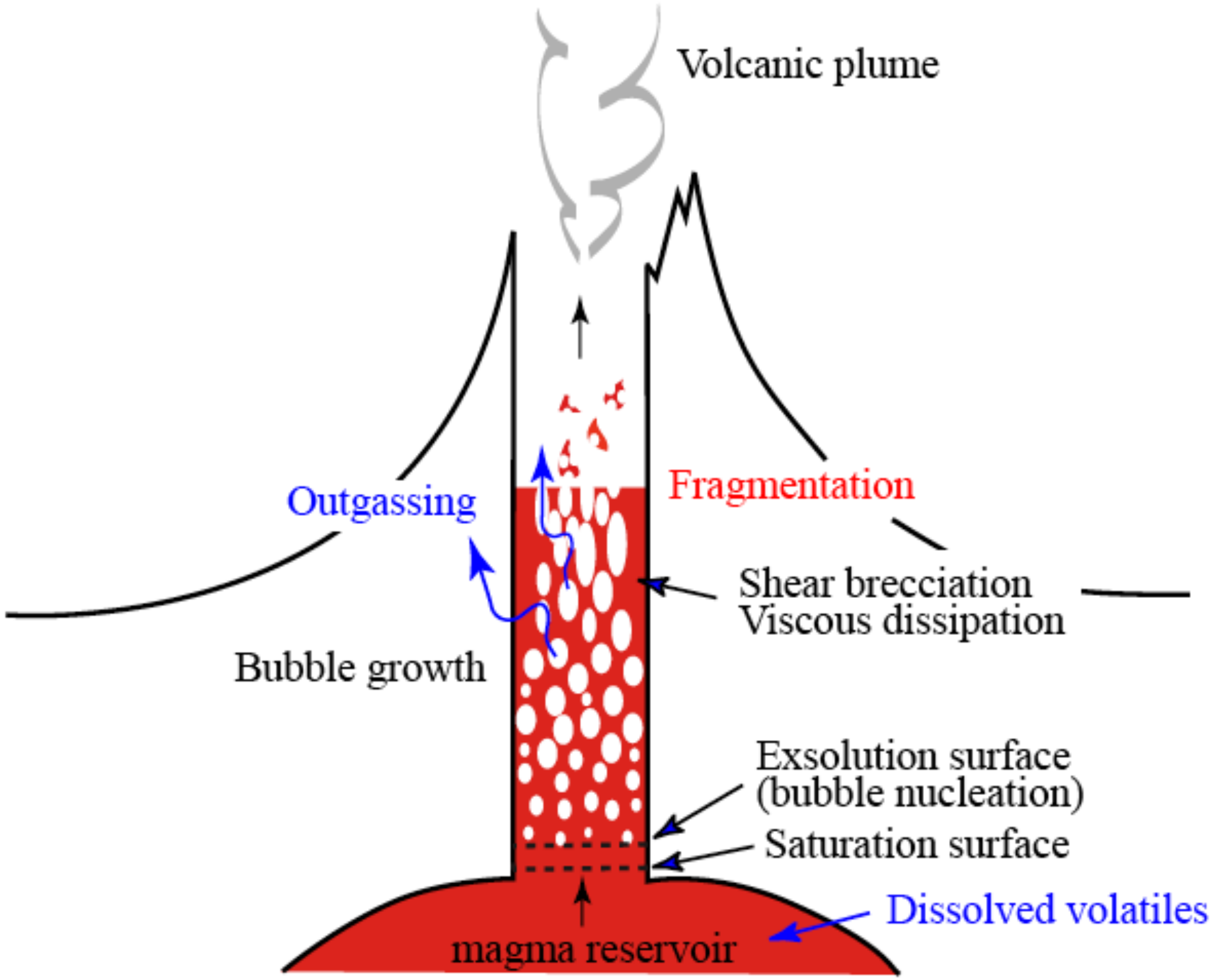
Basaltic eruption styles



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	

Why do volcanoes (only sometimes) erupt explosively?



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

How do bubbly fluids respond to rapid decompression? Experimental model