# Volatile Controls on Eruption Style

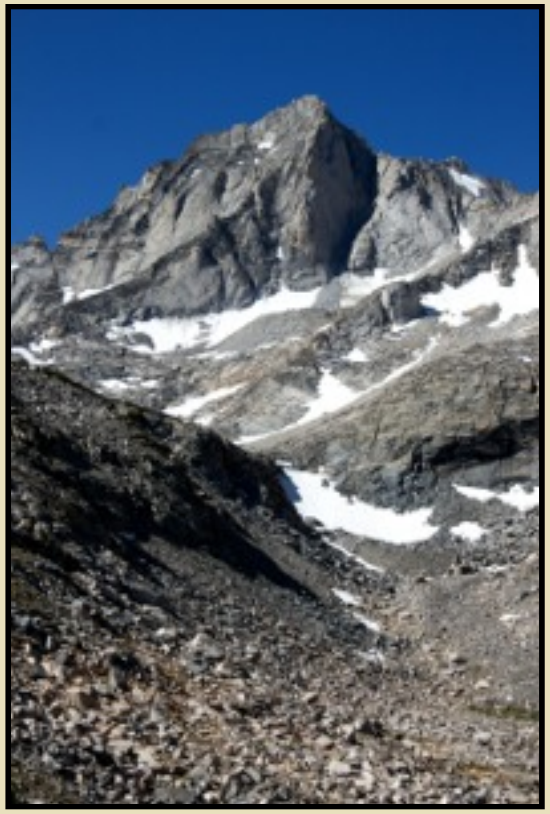
Kathy Cashman
University of Bristol

with help from Alison Rust, Julie Oppenheimer, Jenny Suckale, Isolde Belien, Emma Nicholson & Ariana Soldati

# Overview - the role of volatiles

The behavior of volatiles, in large part, determines whether or not magma reaches the Earth's surface

*Intrusive*



*Extrusive*

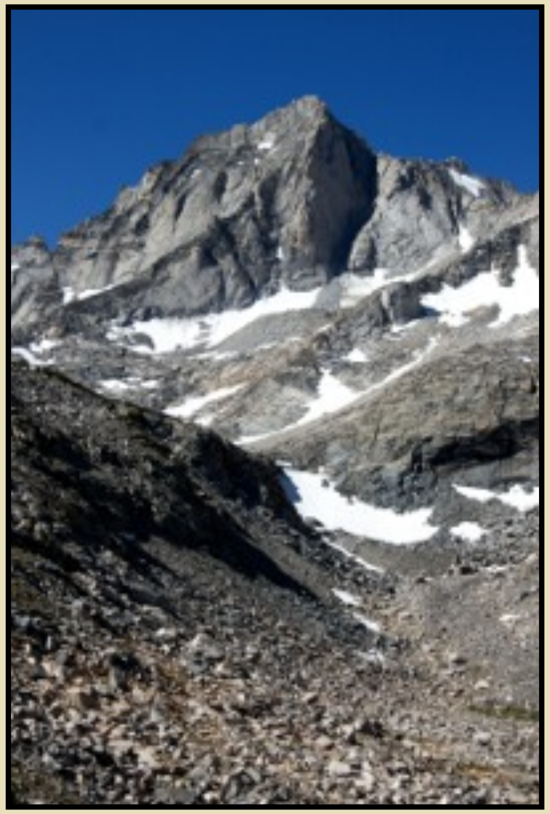
*Effusive*

*Explosive*

# Overview - the role of volatiles

The behavior of volatiles, in large part, determines whether or not magma reaches the Earth's surface

*Intrusive*



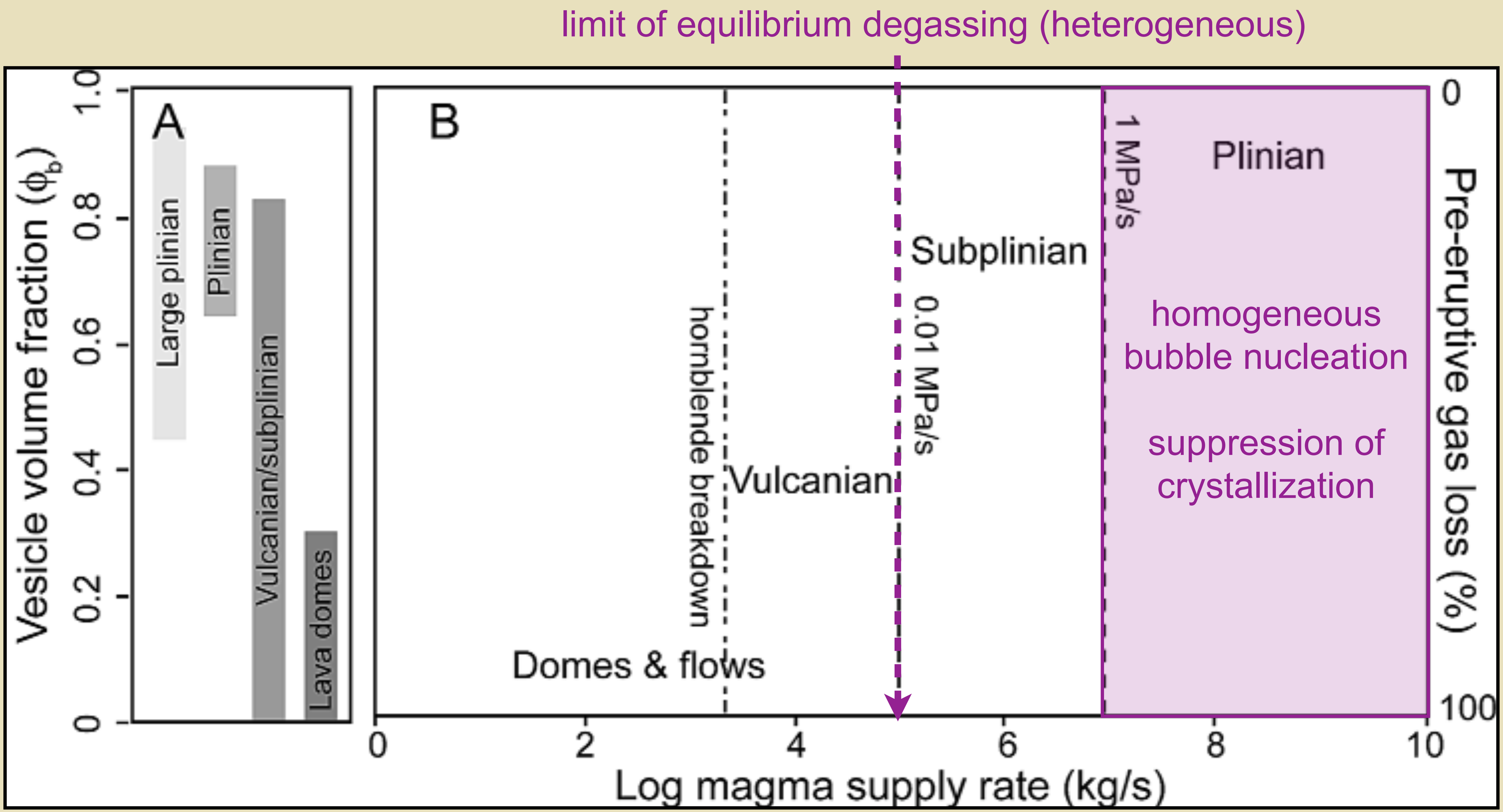
*Extrusive*

*Effusive*

*Explosive*

**HOW, WHERE AND WHEN DOES GAS GET OUT?**

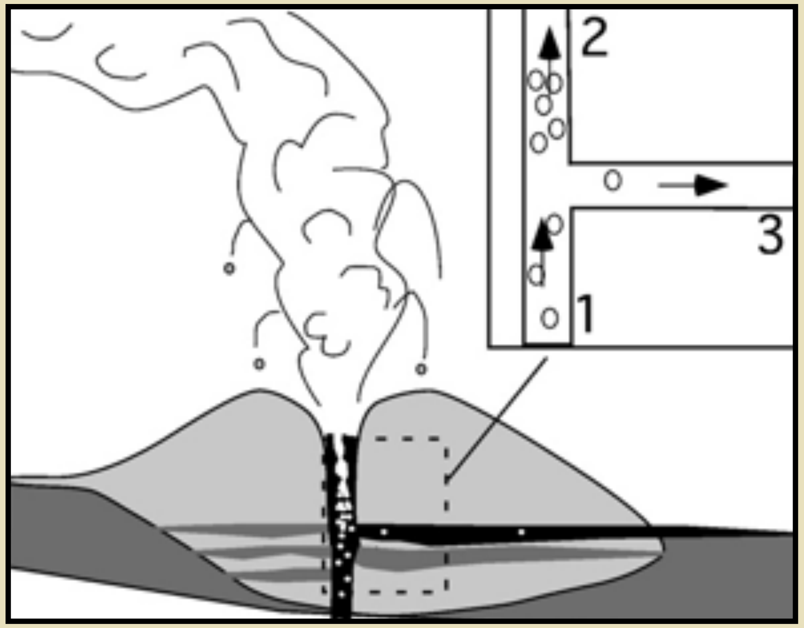
# Ten years ago - silicic systems



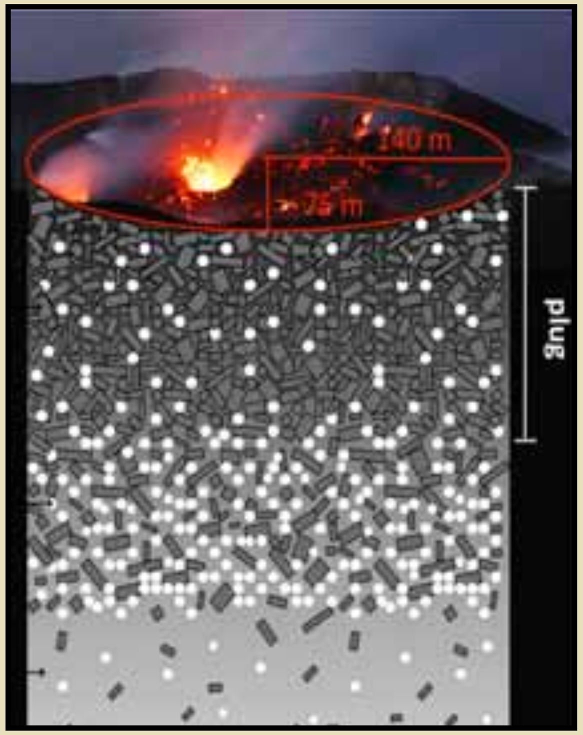

*"Volatile Controls on Magma Ascent and Eruption"* Cashman (2004)

# Now - more data on mafic systems


Bubbles rise through melt
***2-phase flow***




Gas separation allows ***simultaneous explosive and effusive activity at different vents***

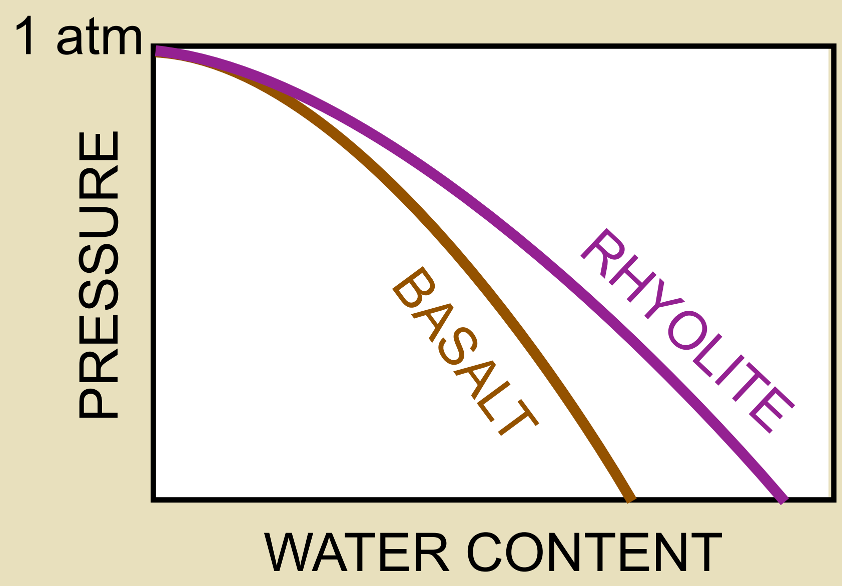



Rapid and extensive shallow crystallization ***can modulate shallow degassing***

# Volatile Behavior

**_Move with magma_**
*CLOSED SYSTEM*

*Dissolved*




*Exsolved*

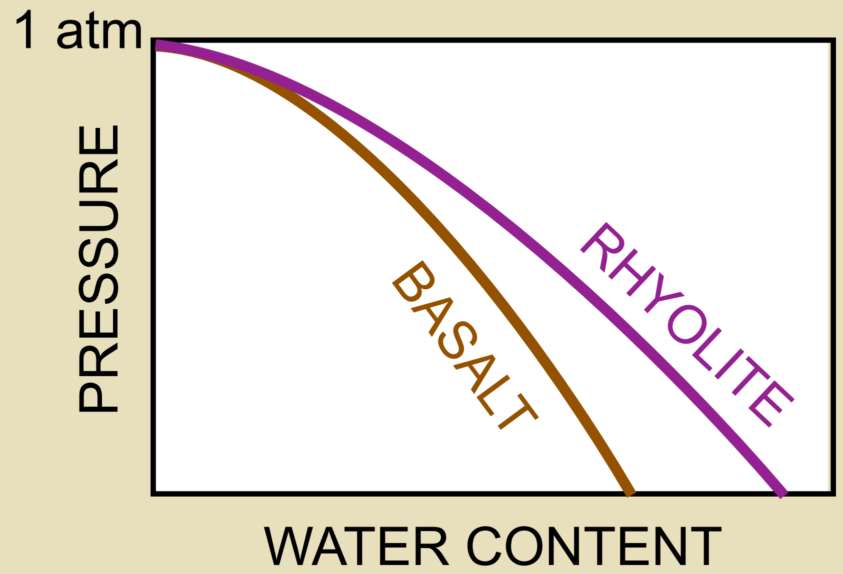
Requires magma rise rate >>
- bubble rise rate
- permeable flow
- diffusion

# Volatile Behavior

**_Move with magma_**
_CLOSED SYSTEM_

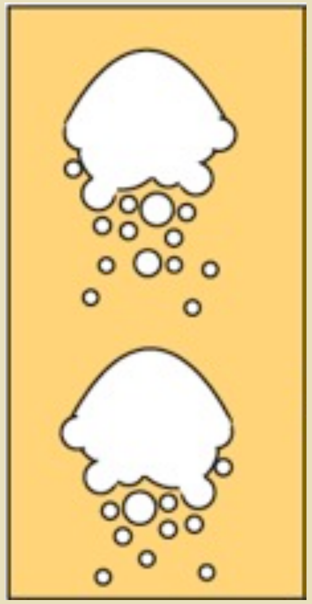
**_Move through magma_**
_OPEN SYSTEM_

_Dissolved_




_Bubble rise_

restricted to crystal-poor mafic systems

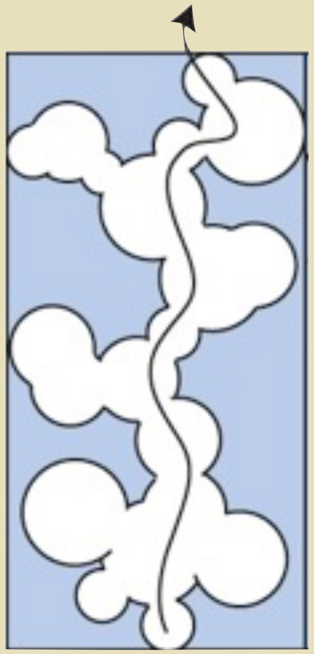


_Exsolved_

Requires magma rise rate >>
- bubble rise rate
- permeable flow
- diffusion

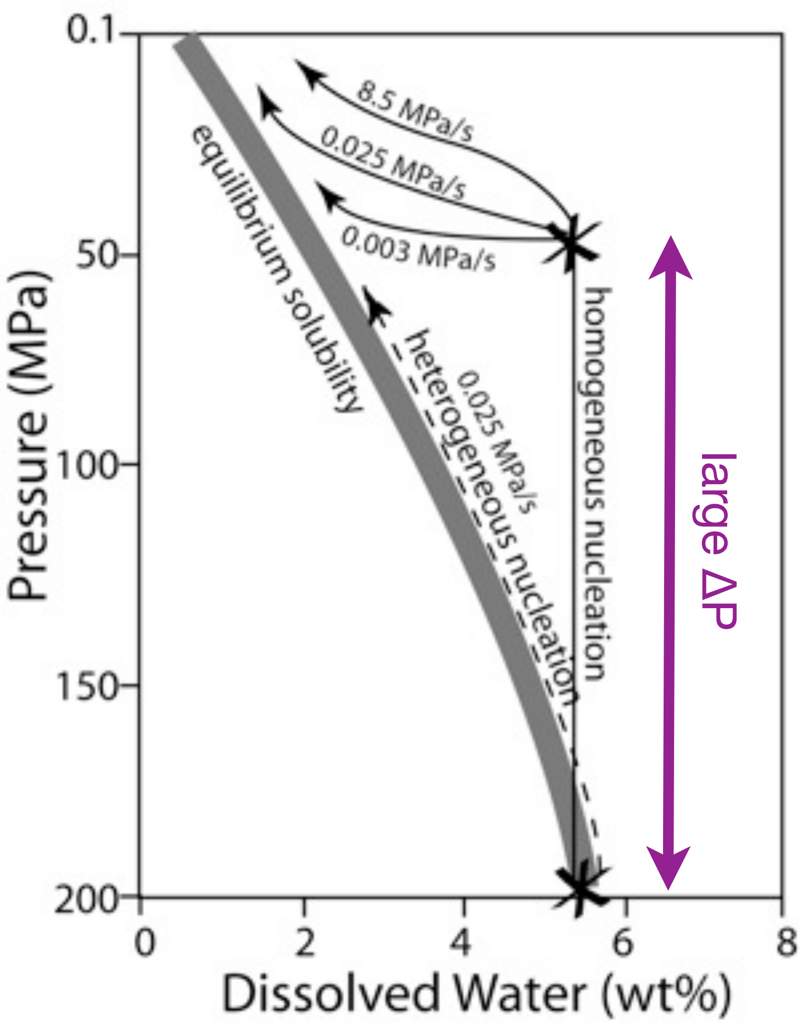
_Permeable flow_

silicic and crystal-rich magmas



# Volatiles move with magma

*Volatile exsolution*
*Equilibrium or dis-equilibrium?*



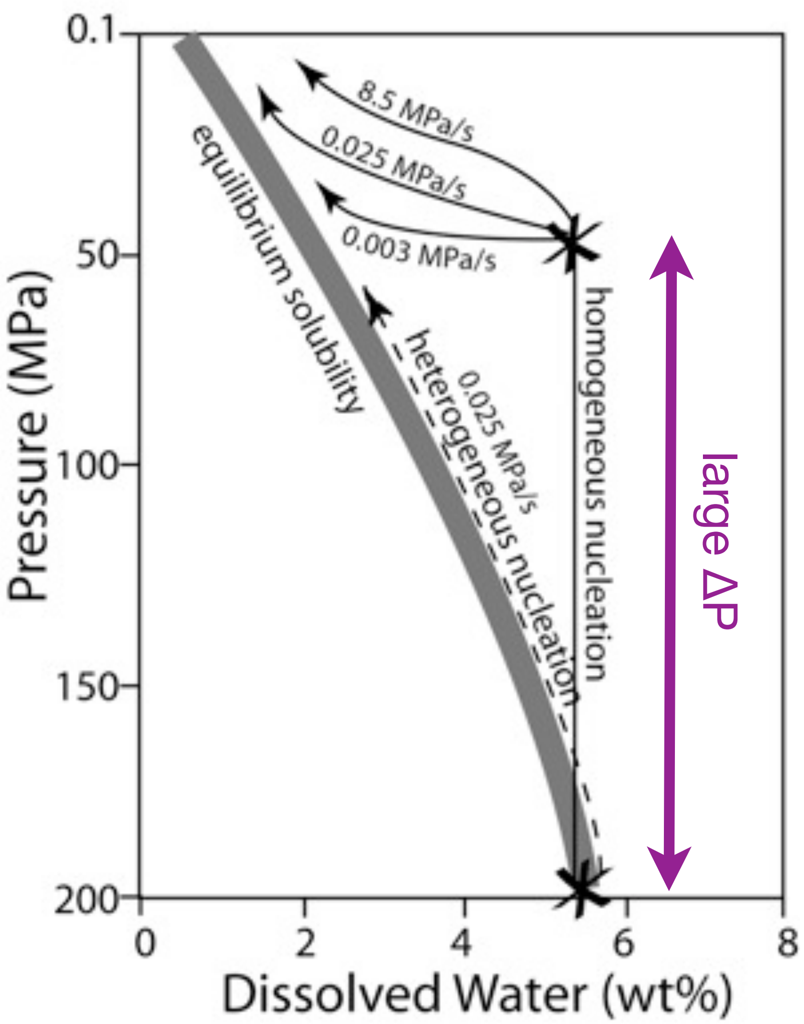

**Rhyolite:**

- homogeneous bubble nucleation commonly occurs at high ΔP
- heterogeneous bubble nucleation can follow equilibrium paths

Gardner et al. (1999); Mangan and Sisson (2000)

# Volatiles move with magma

*Volatile exsolution*
*Equilibrium or dis-equilibrium?*

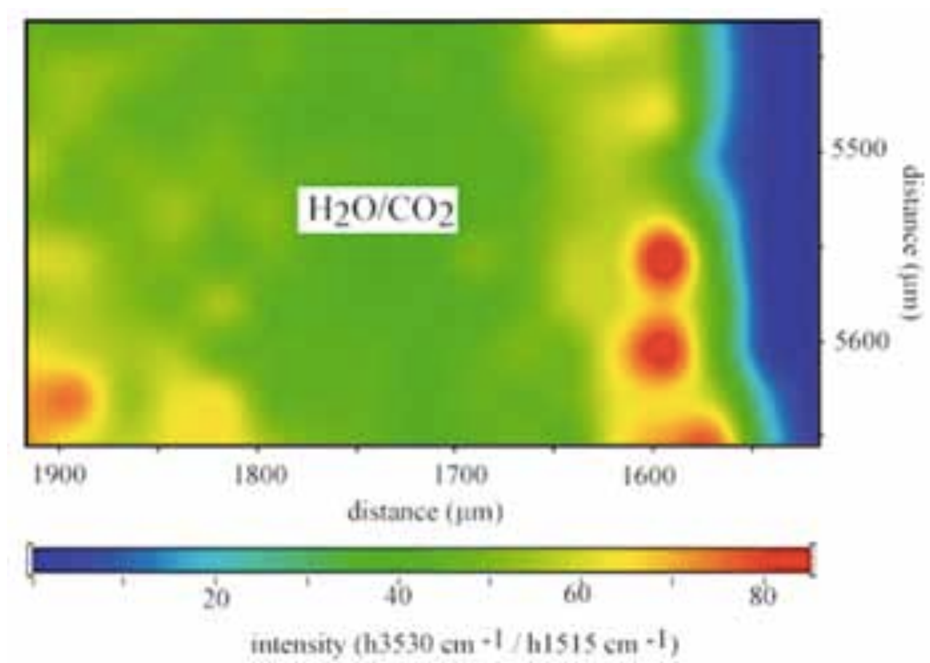



**Rhyolite:**

- homogeneous bubble nucleation commonly occurs at high ΔP
- heterogeneous bubble nucleation can follow equilibrium paths

**Basalt:**

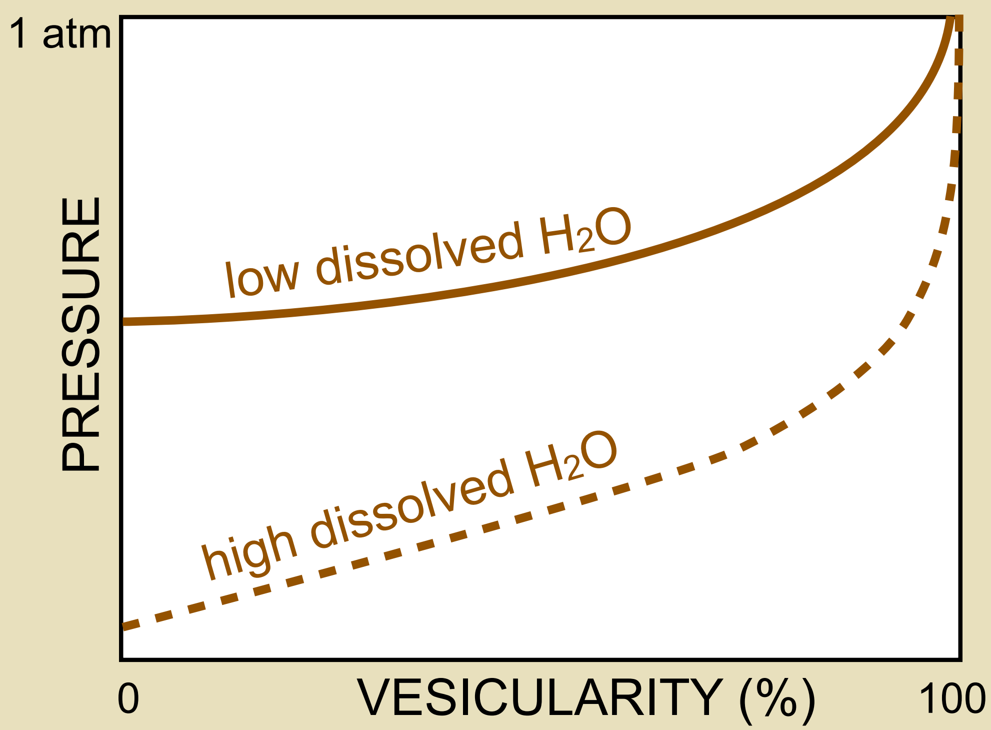
- $H_2O$ exsolution occurs under equilibrium conditions
- $CO_2$ exsolution can be kinetically limited




Gardner et al. (1999); Mangan and Sisson (2000)

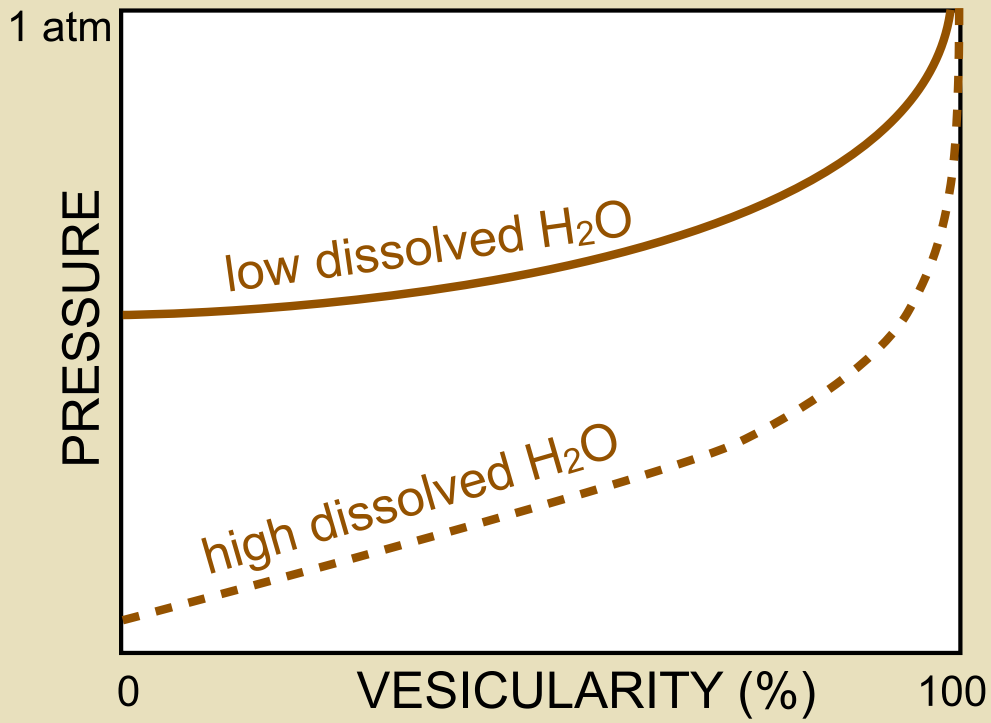
Pichavant et al. (2013)

# Volatiles move with magma



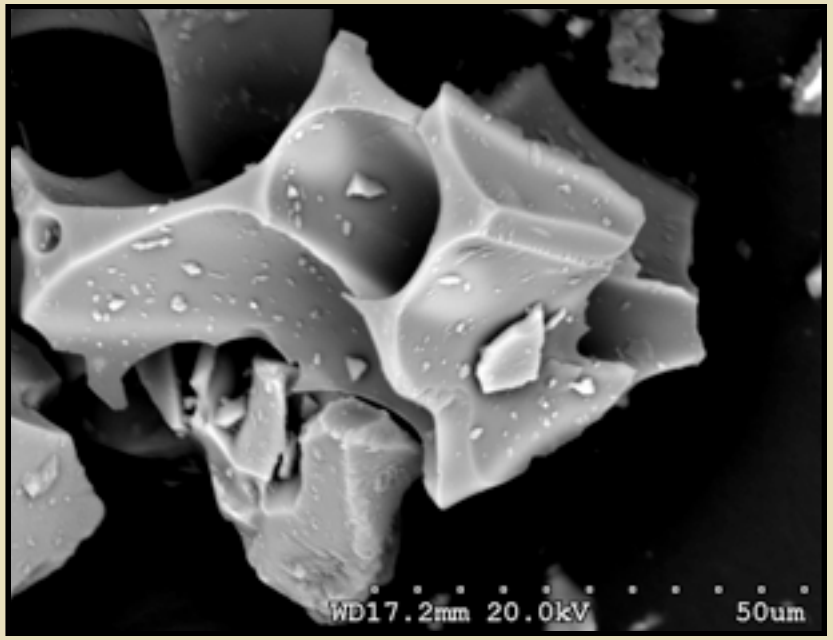

Even small amounts of exsolved water will expand to >>99% when decompressed to surface pressures

# Volatiles move with magma

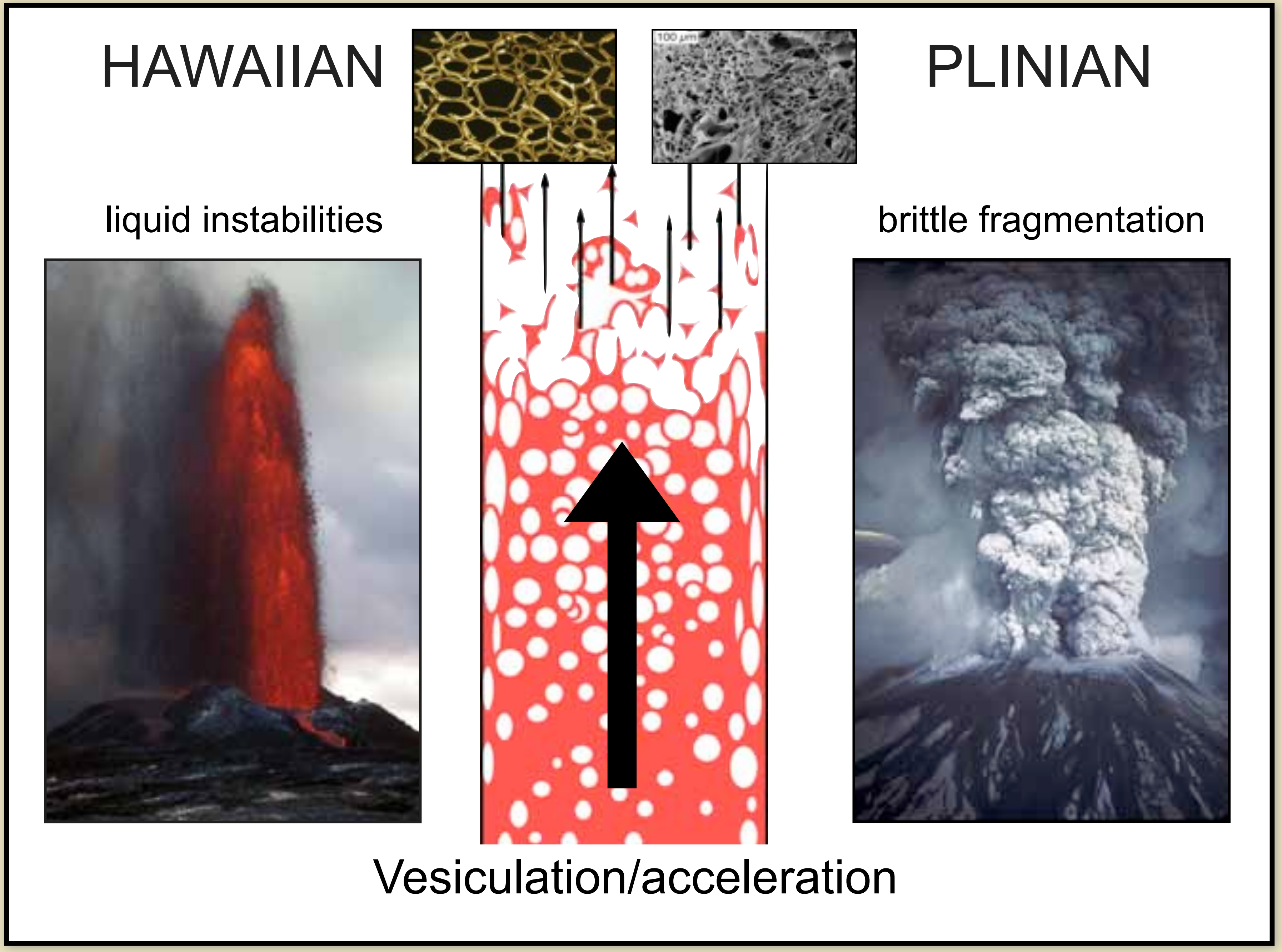



Even small amounts of exsolved water will expand to >>99% when decompressed to surface pressures

Evidence for expansion can be found in the particles formed by magma disruption



# Volatiles move with magma

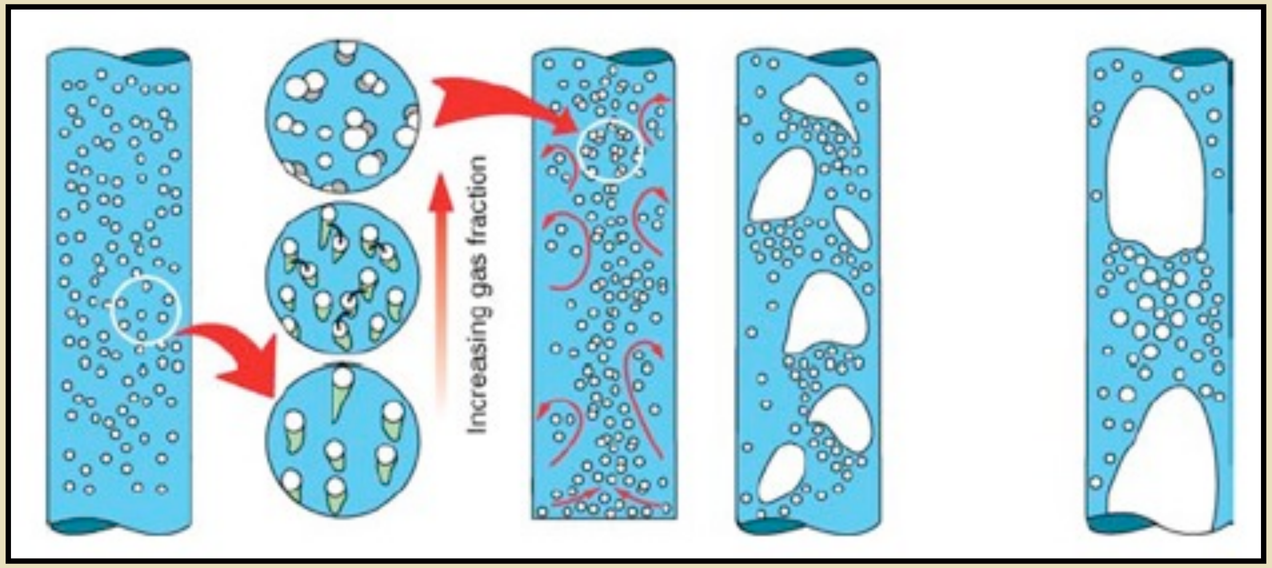



Gas expansion rate
>>

- rise of individual bubbles
- permeable gas flow

# Transitions from closed to open system behavior

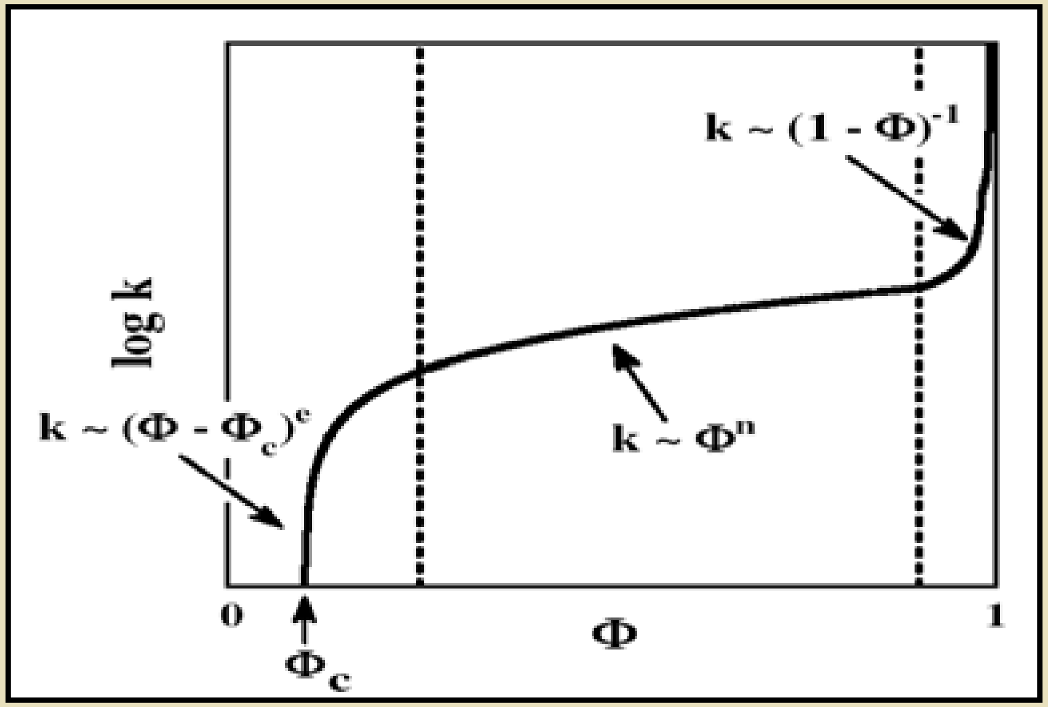
*1. EXCEED CRITICAL BUBBLE RISE VELOCITY*



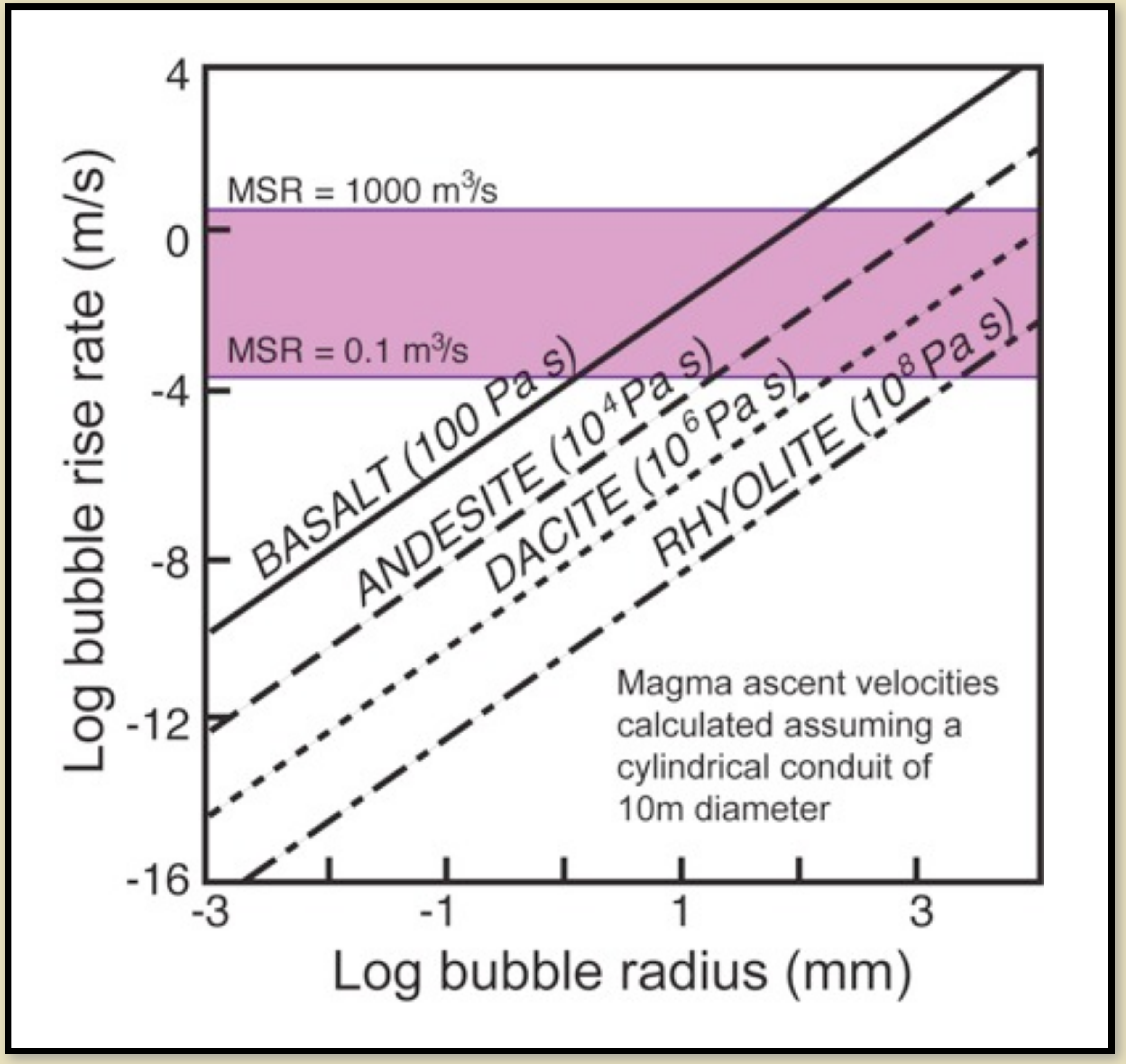

**two-phase flow**

*2. EXCEED CRITICAL PERMEABILITY*

**permeable flow**



# Critical bubble rise rate?

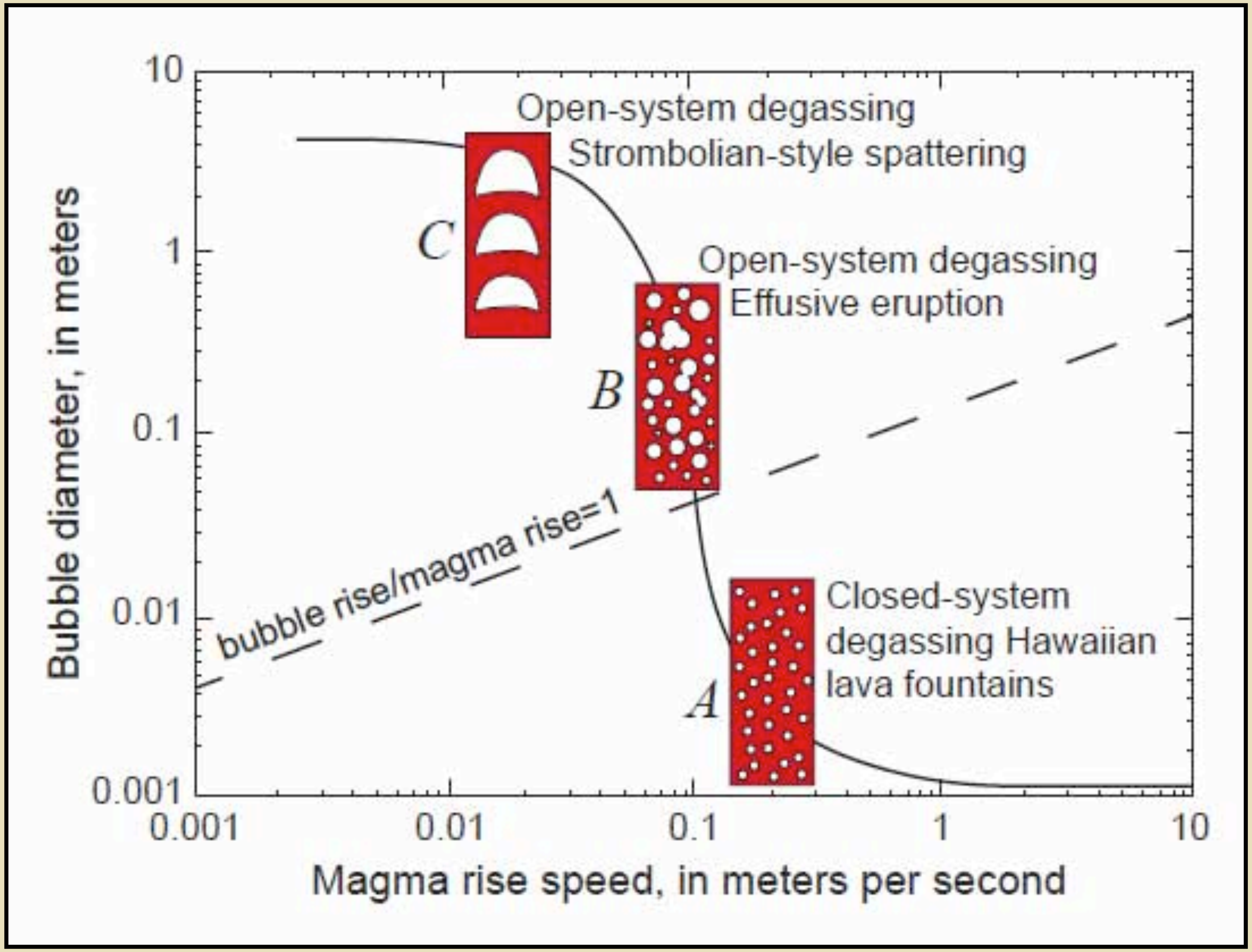



PRIMARY CONTROLS

- melt viscosity
- magma rheology (includes effects of other bubbles and crystals)
- bubble radius

# Transitions in eruption style

## *BUBBLE RISE*

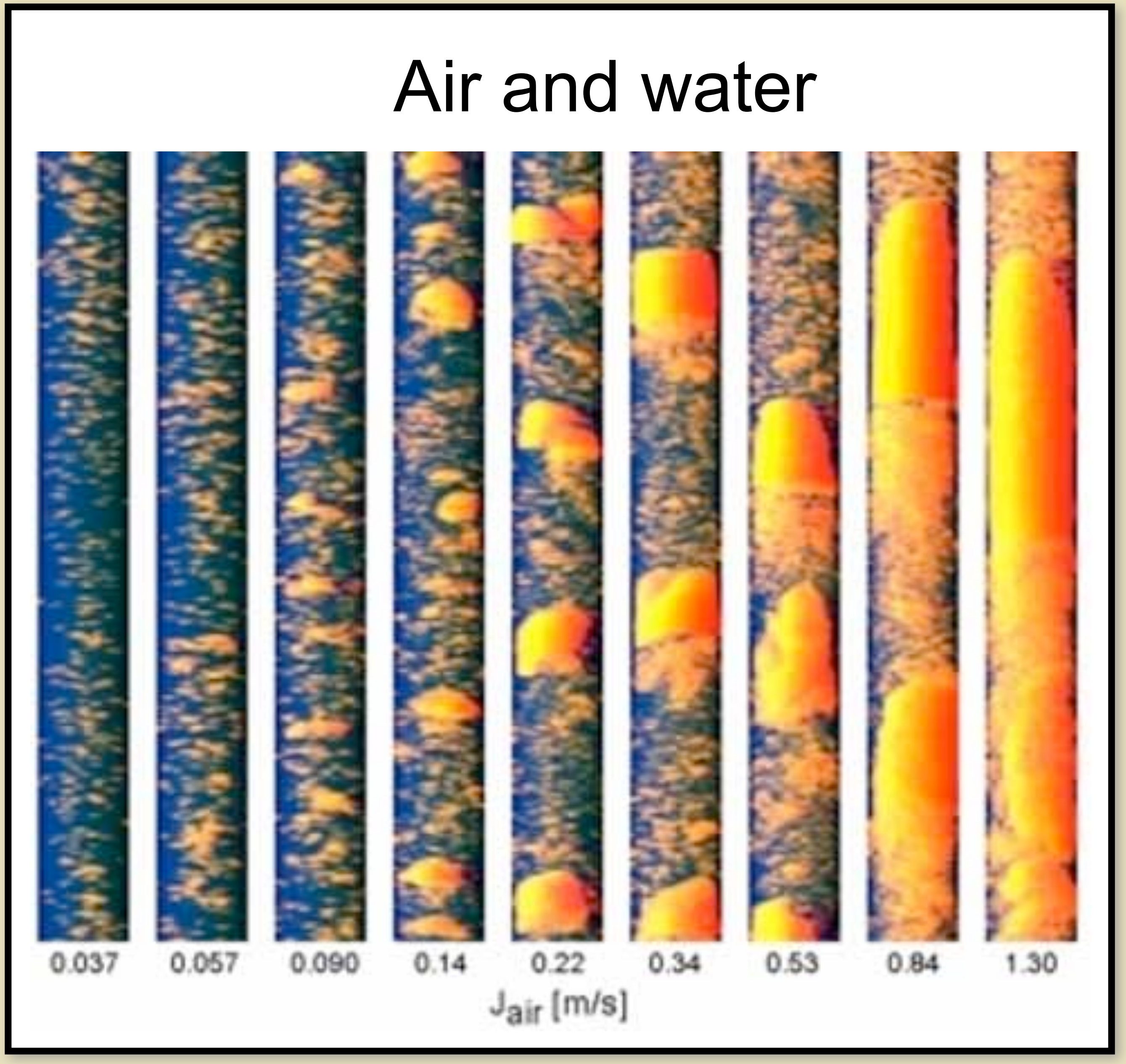


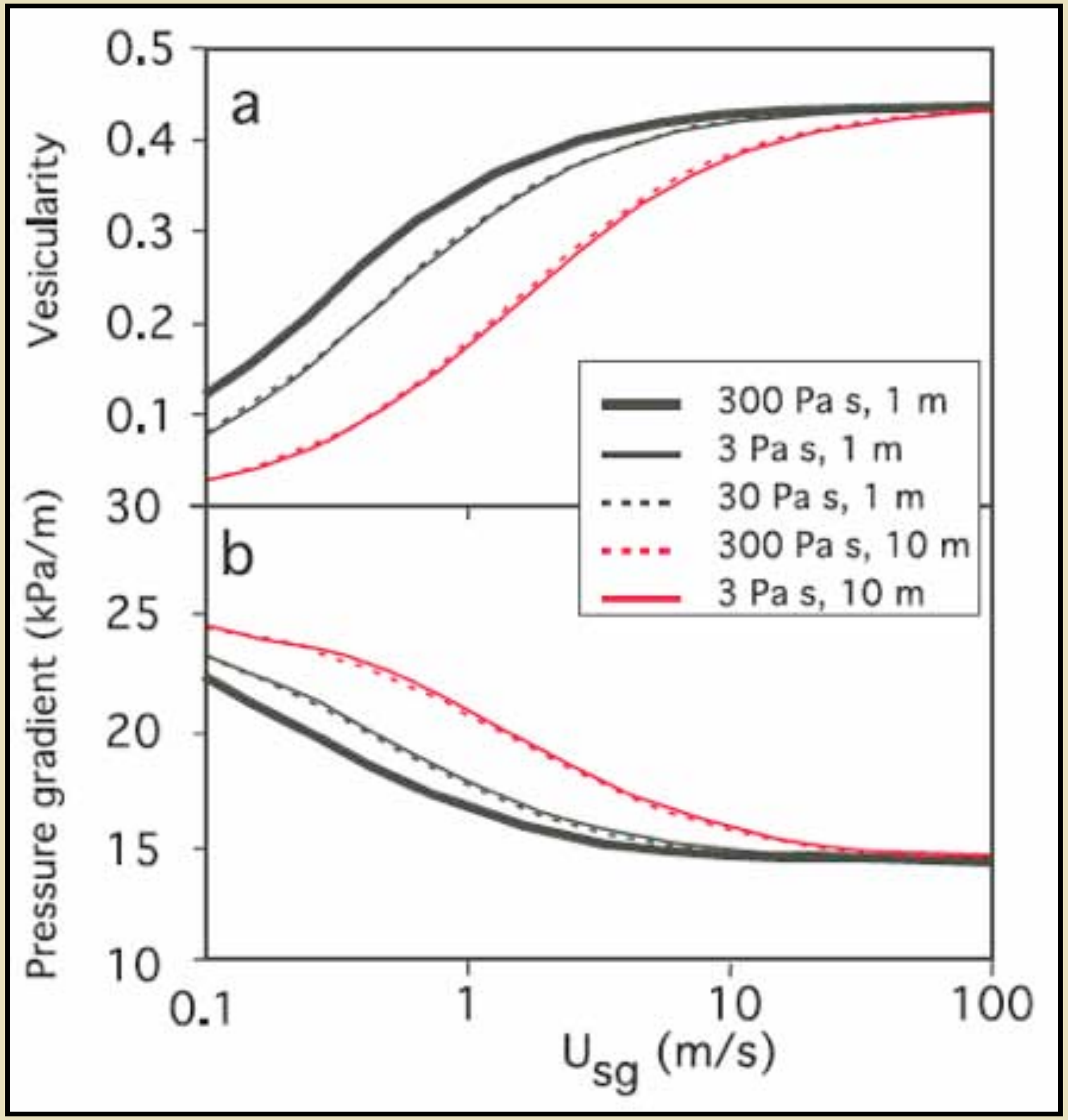

Mangan et al. (*in press*)

Individual bubble rise most likely for low viscosity melts, large bubbles and low magma rise rates

# Bubble rise

***TWO-PHASE FLOW***



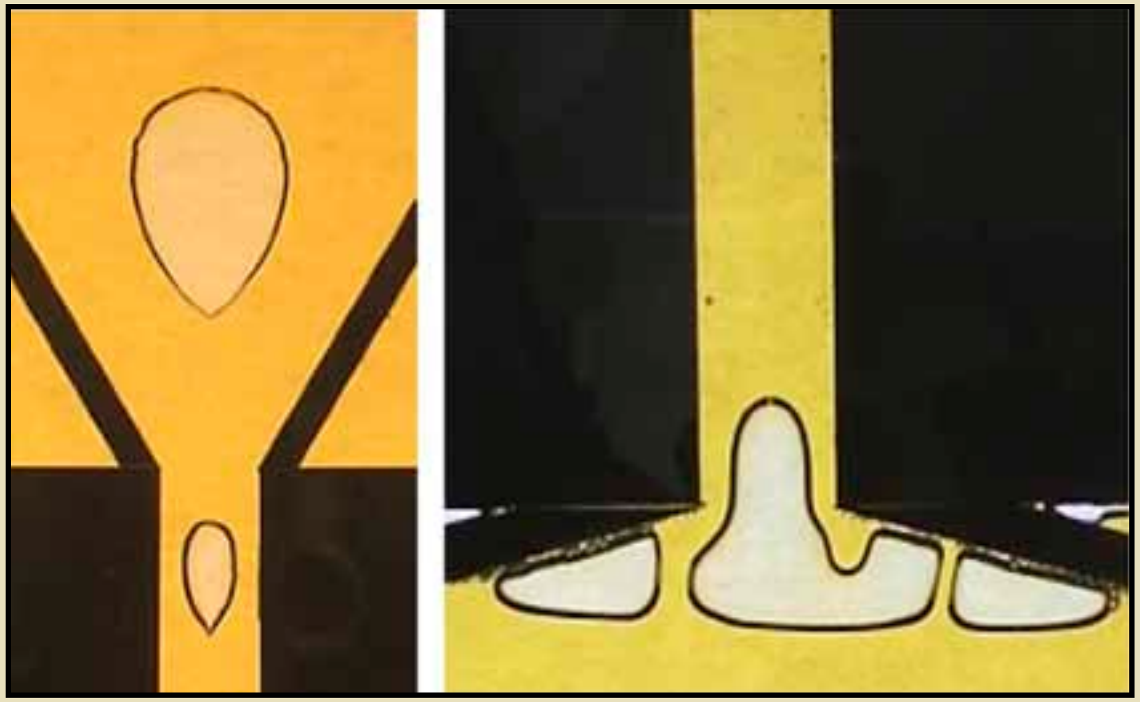

http://www.hzdr.de/db/Cms?pOid=24991&pNid=3016

Pioli et al. (2011)

# Bubble break up

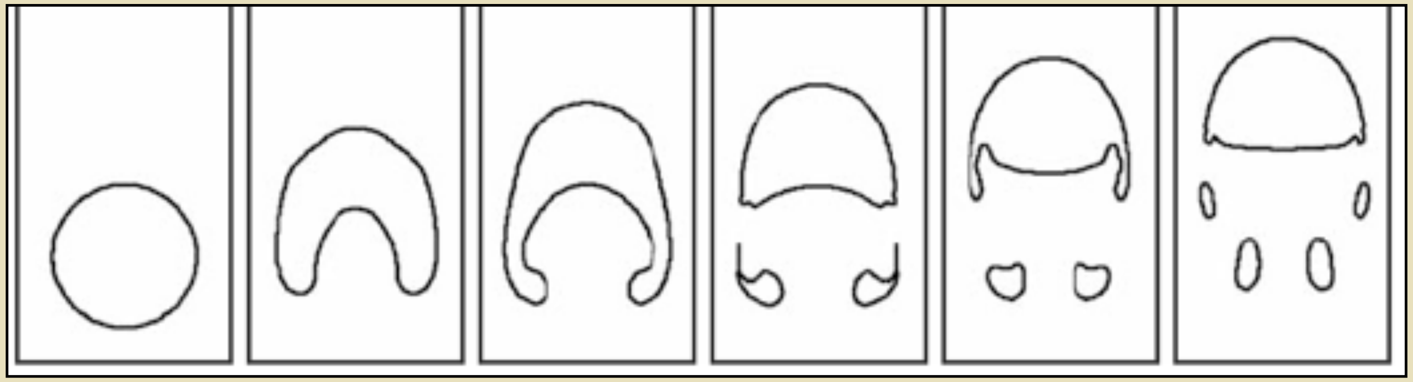
## *BUBBLES CAN ALSO BREAK UP*

**changes in geometry**

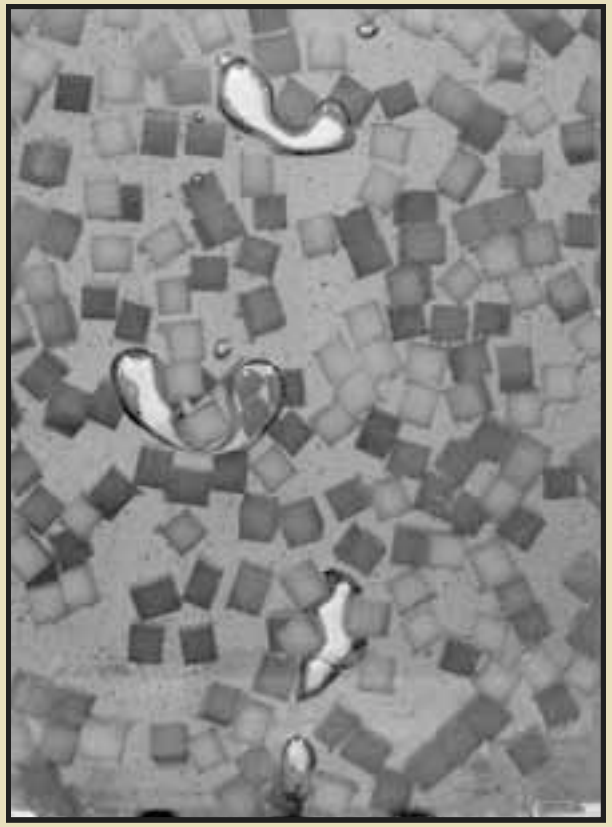


Hele-Shaw cell

**dynamical effects**



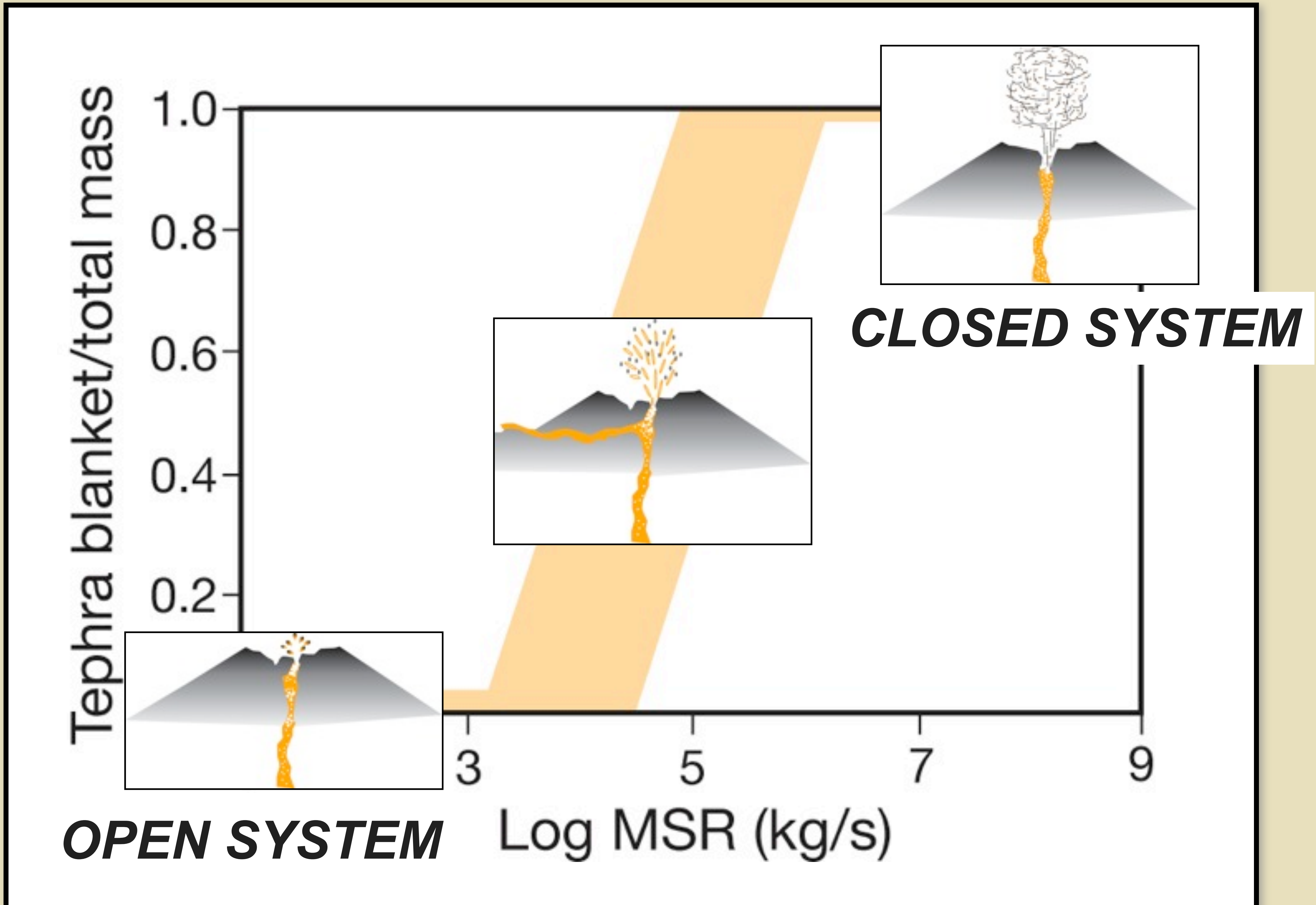
Suckale et al. (2010)



Belien et al. (2010)

**interaction with solid particles**

# Mafic eruption styles



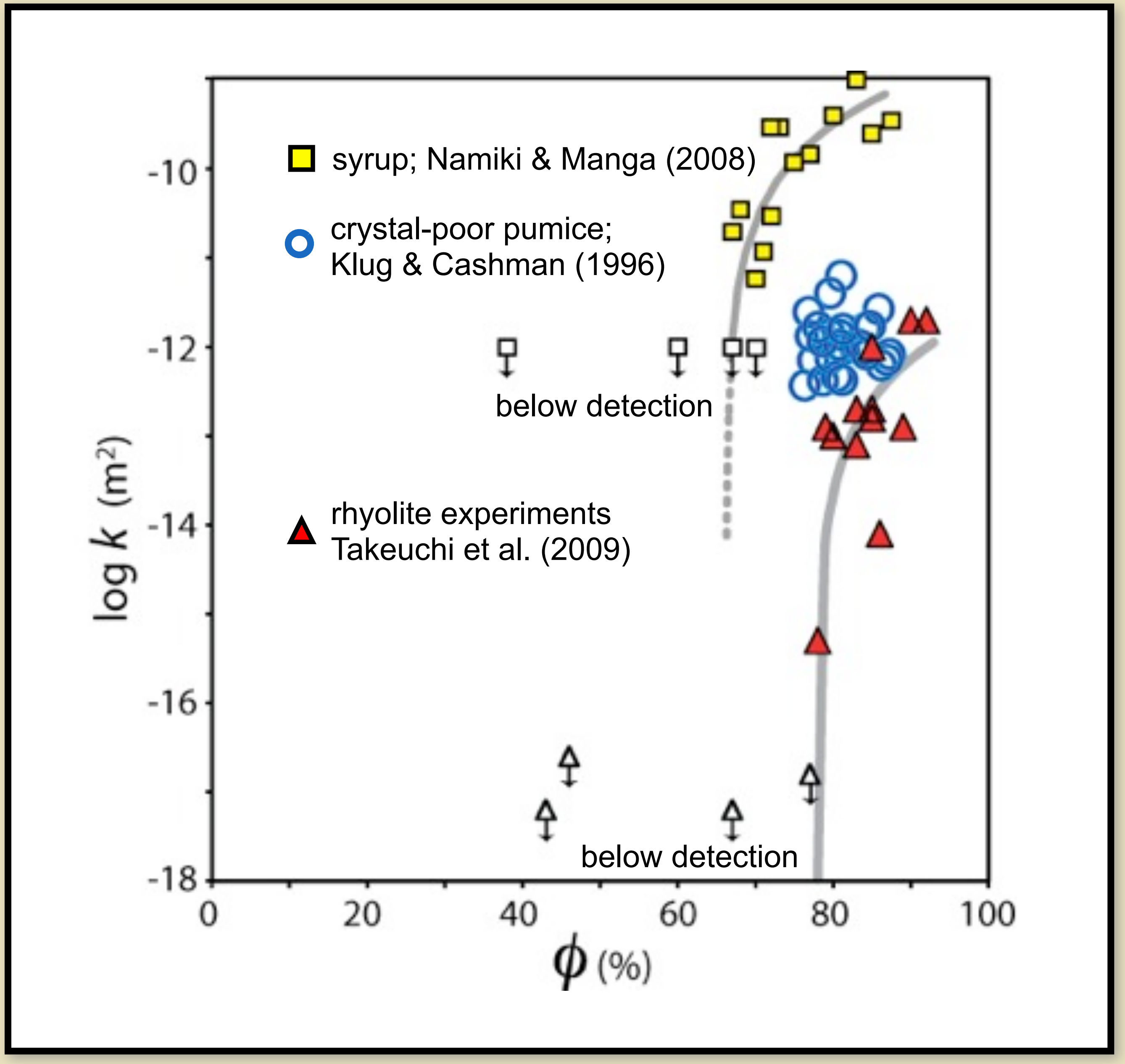

modified from Pioli et al. (2009)

# Critical permeability?

Bubbles coalesce to form permeable gas pathways

PRIMARY CONTROLS

- bubble volume fraction
- time (viscosity, expansion rate)
- role of crystals?

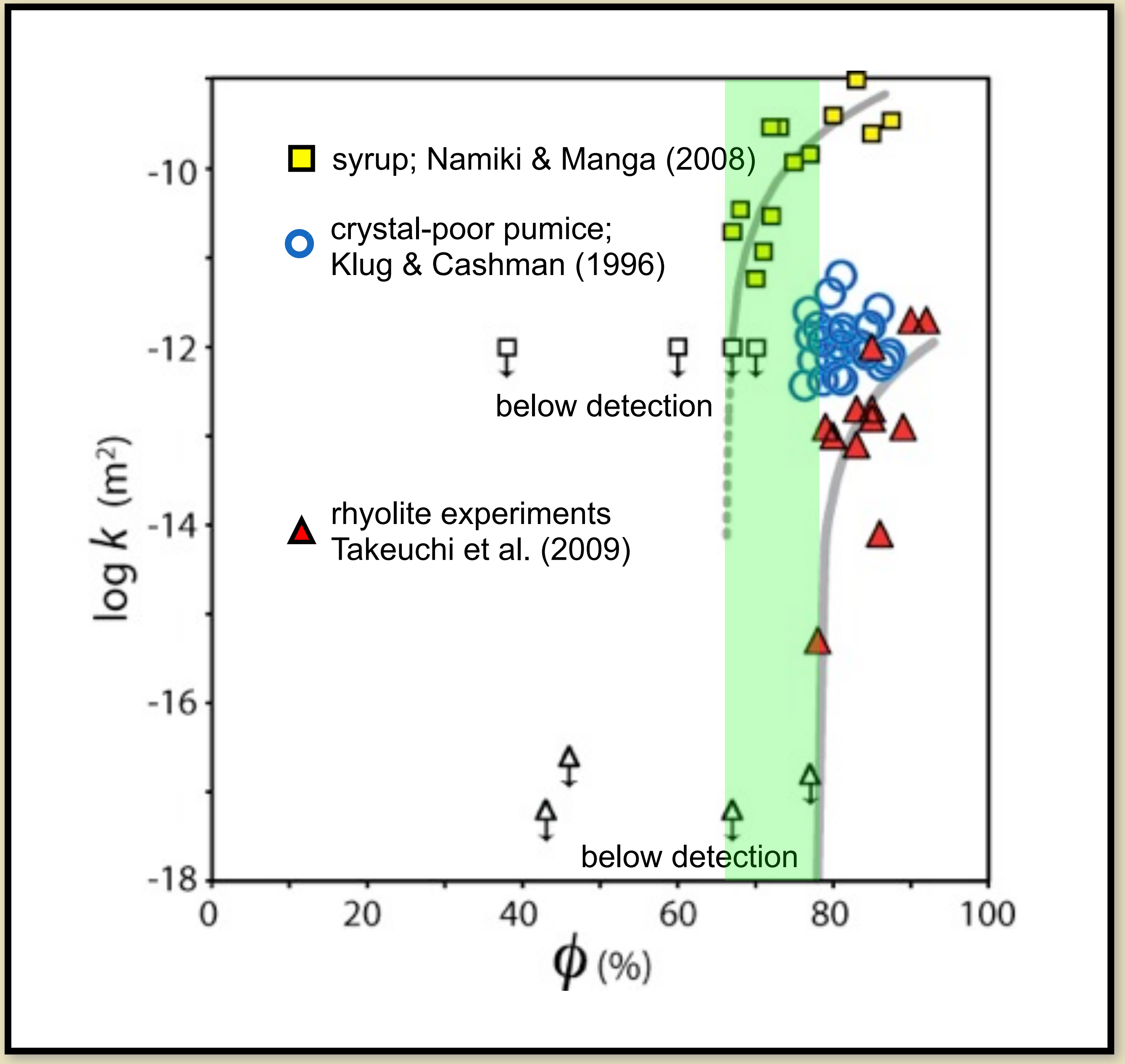



Rust & Cashman (2011)

# Critical permeability?

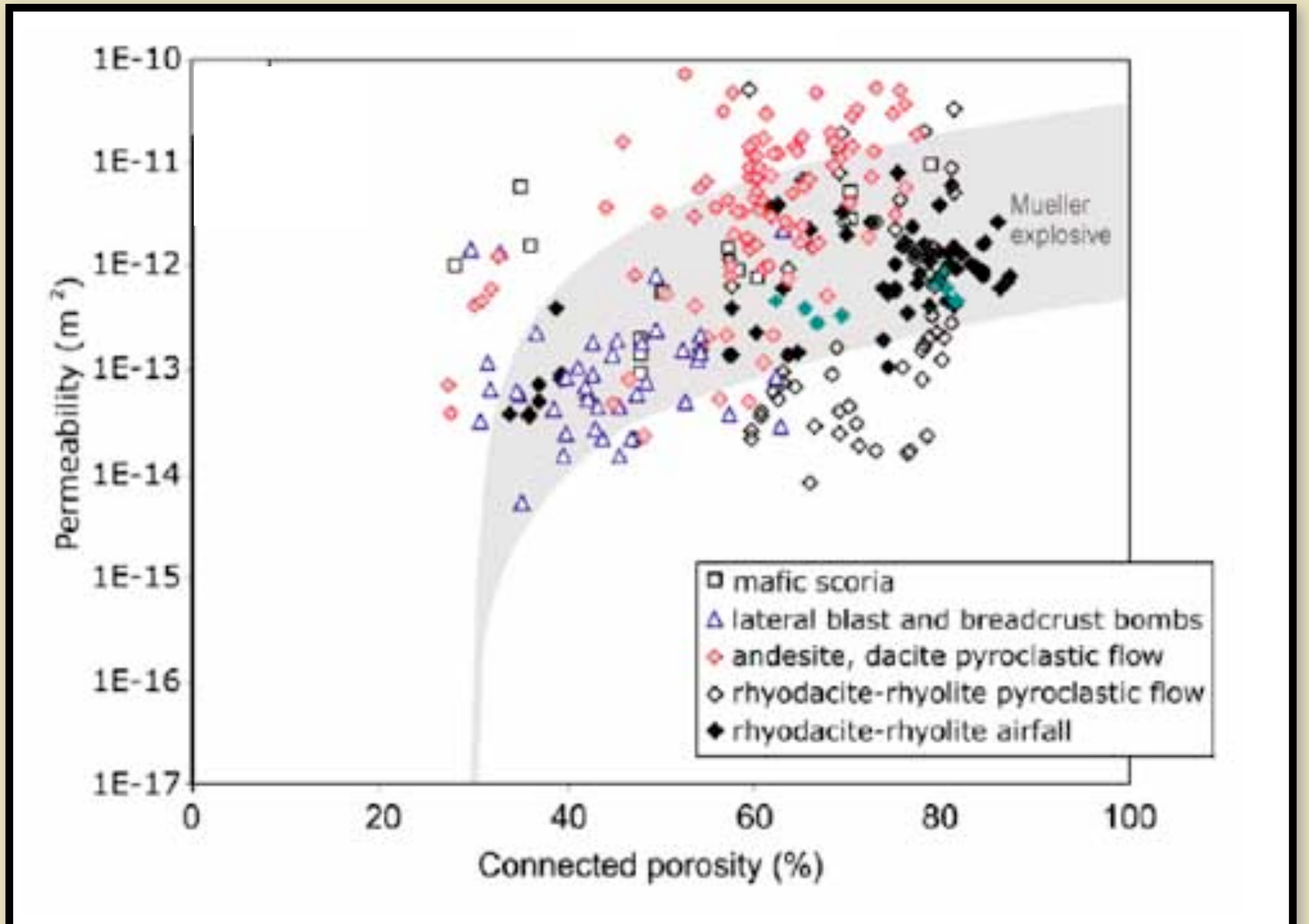
Expanding melts reach the percolation (permeability) threshold only after reaching porosities of 65-75%

*this reflects the time required to thin bubble walls*




Rust & Cashman (2011)

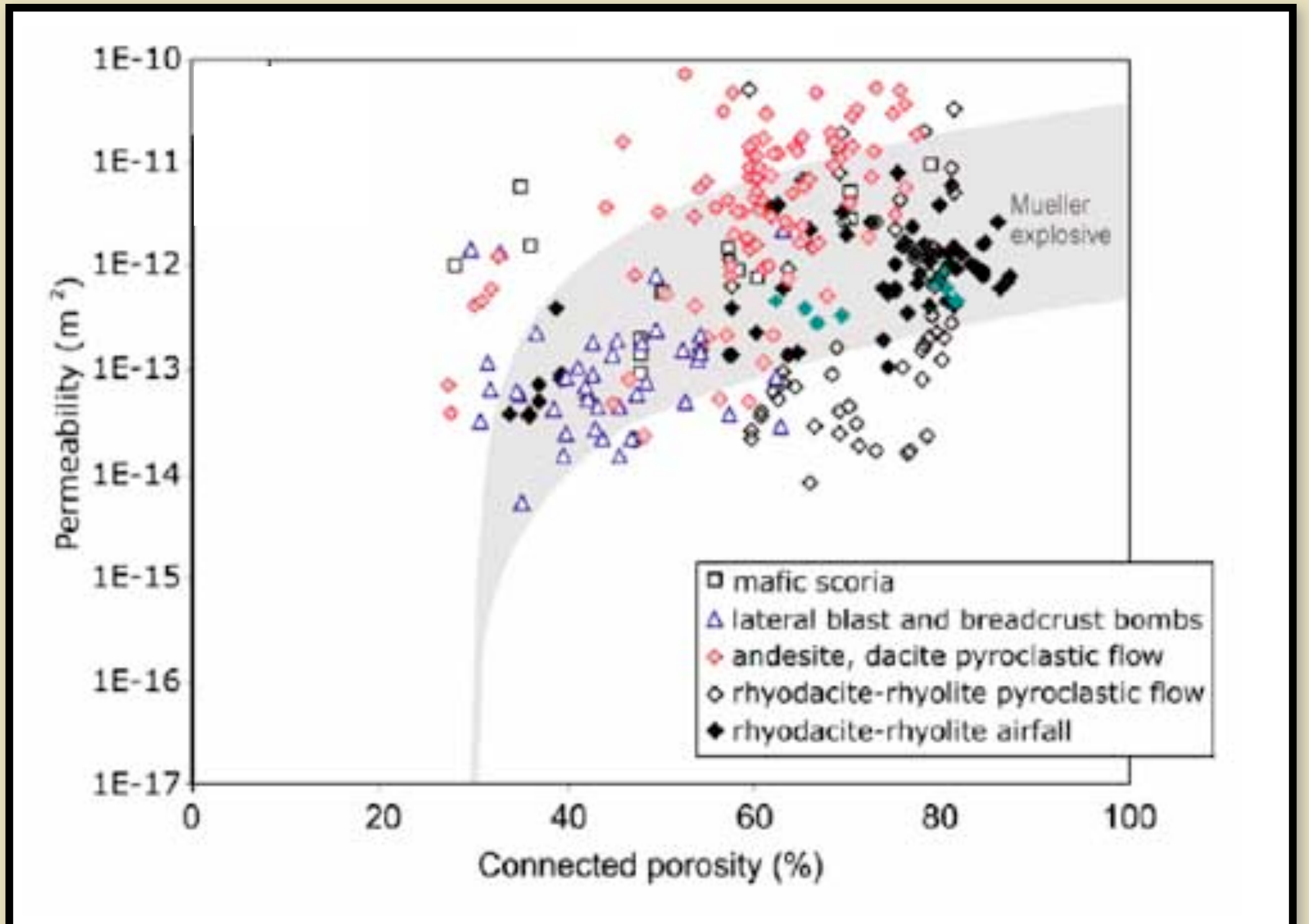
# Permeable flow




Wright et al. (2009)

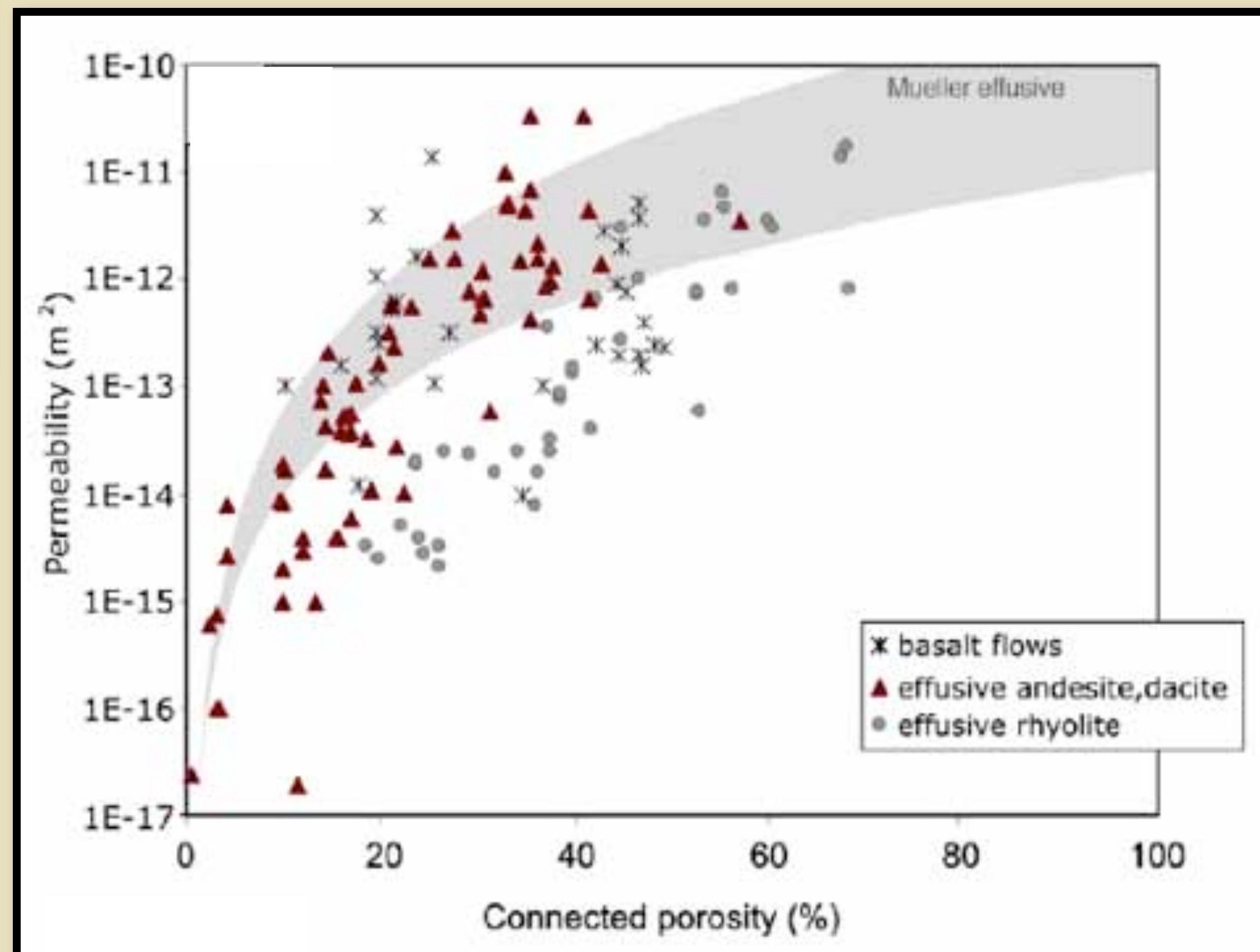
Explosively generated pyroclasts may exceed permeability threshold at lower bulk porosities if they are (1) crystal-rich or (2) have experienced deformation in the conduit

# Permeable flow



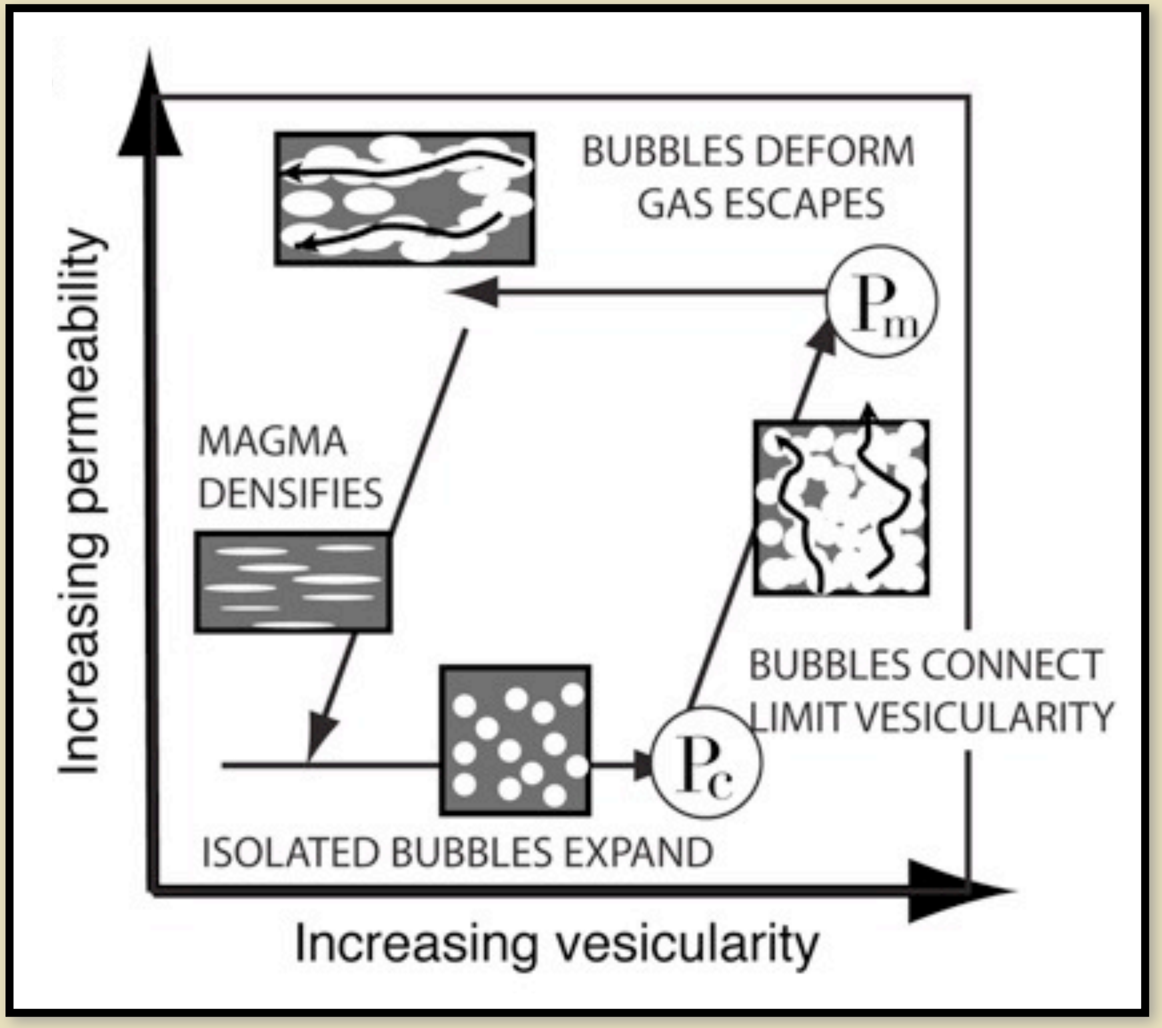

Wright et al. (2009)

Explosively generated pyroclasts may exceed permeability threshold at lower bulk porosities if they are (1) crystal-rich or (2) have experienced deformation in the conduit




Uniformly low bulk porosities of lava flows and domes requires gas loss

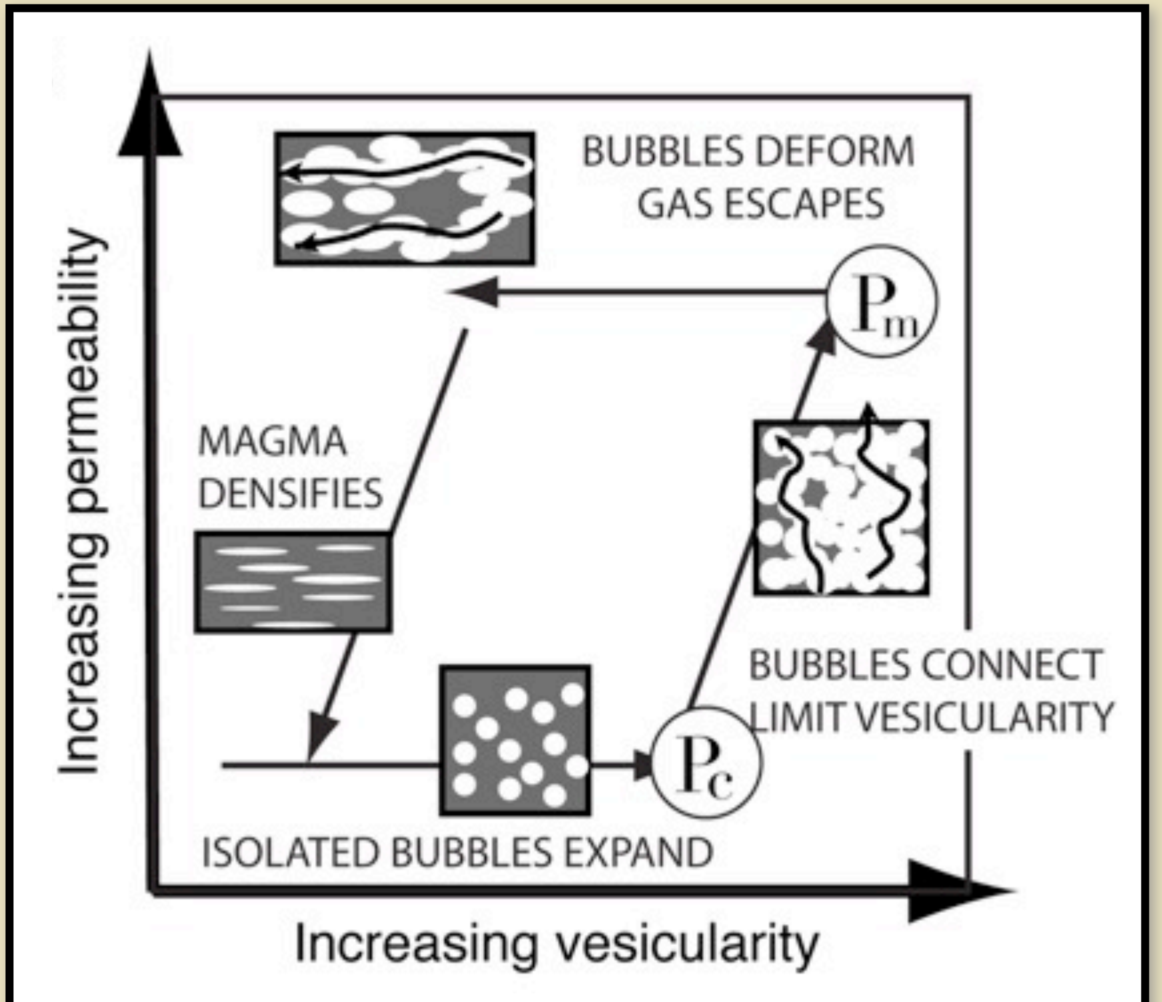
# Permeability hysteresis



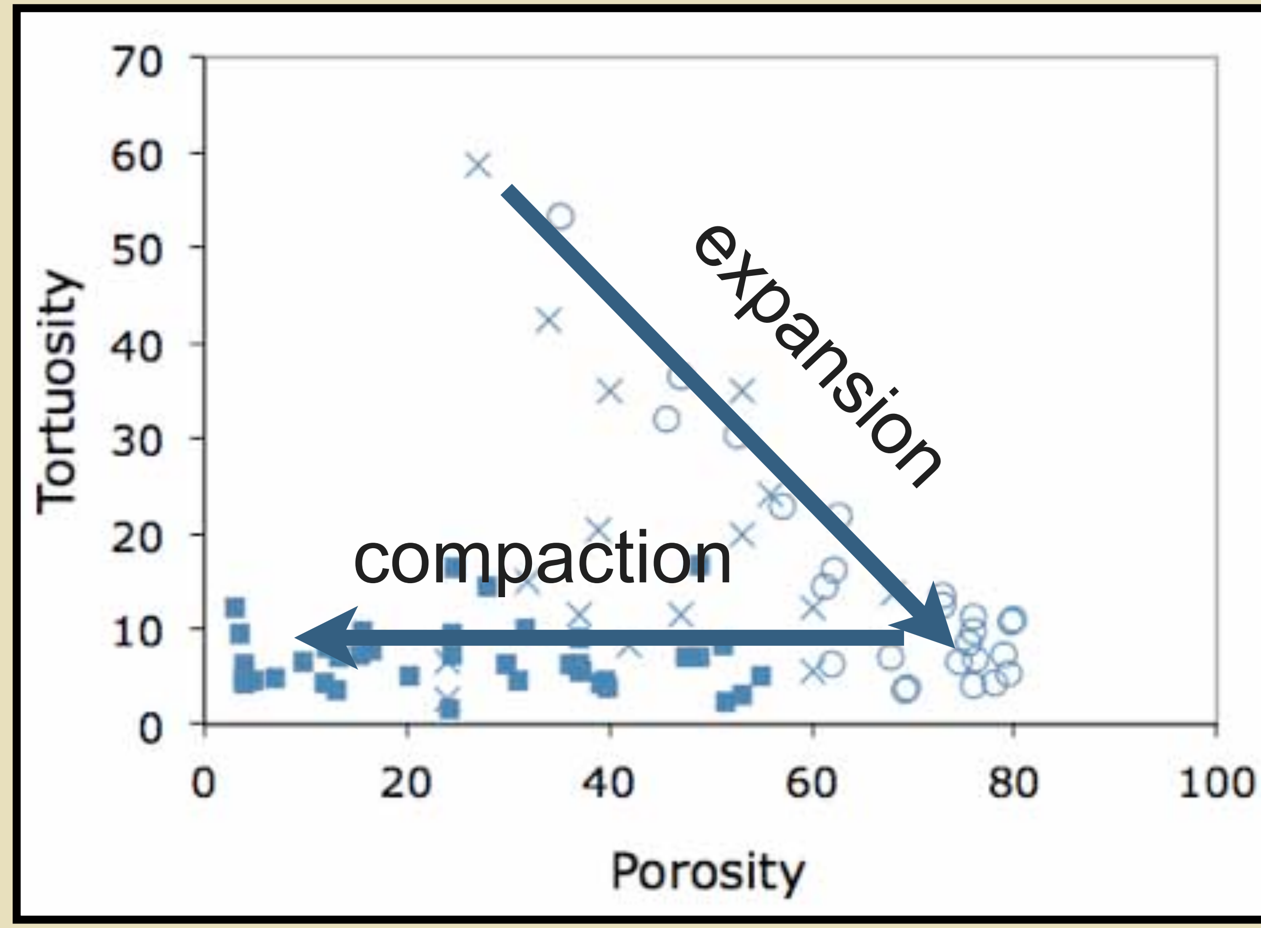

Cashman & Sparks (2013)

The pore structure (and resulting permeability) evolves as magma expands and deforms

# Permeability hysteresis




Cashman & Sparks (2013)



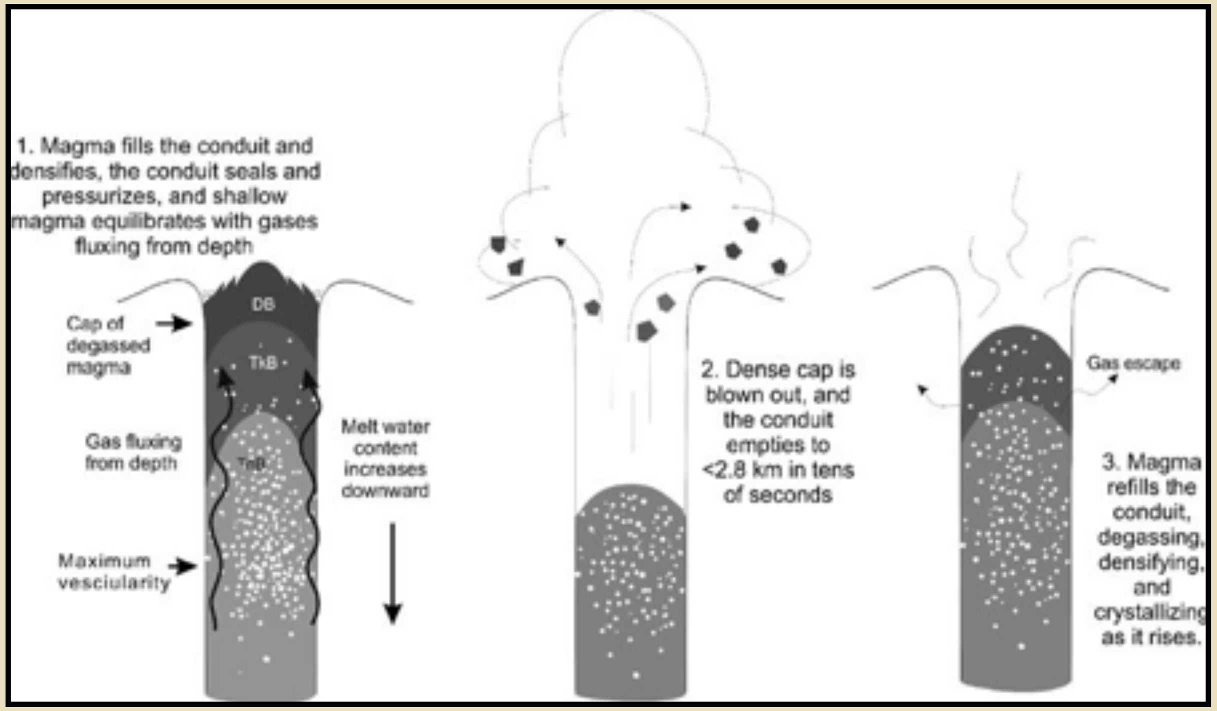

data from LePennec et al. (2001), Bernard et al. (2007), Wright et al. (2007; 2009), Wright & Cashman (2014)

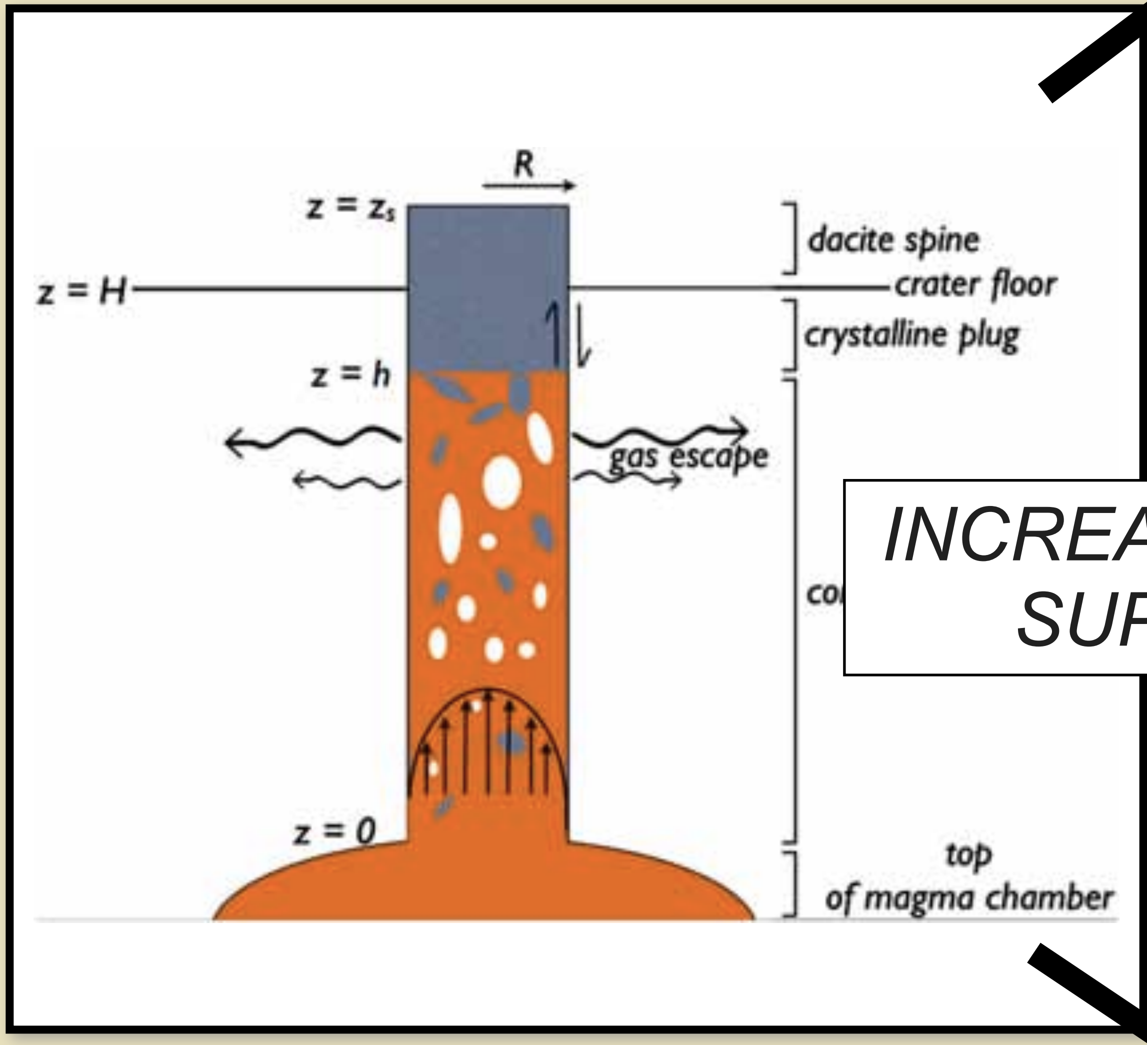
The pore structure (and resulting permeability) evolves as magma expands and deforms

Electrical conductivity measurements confirm systematic changes in the pore structure with compaction

# Shallow conduit degassing

Vulcanian explosions

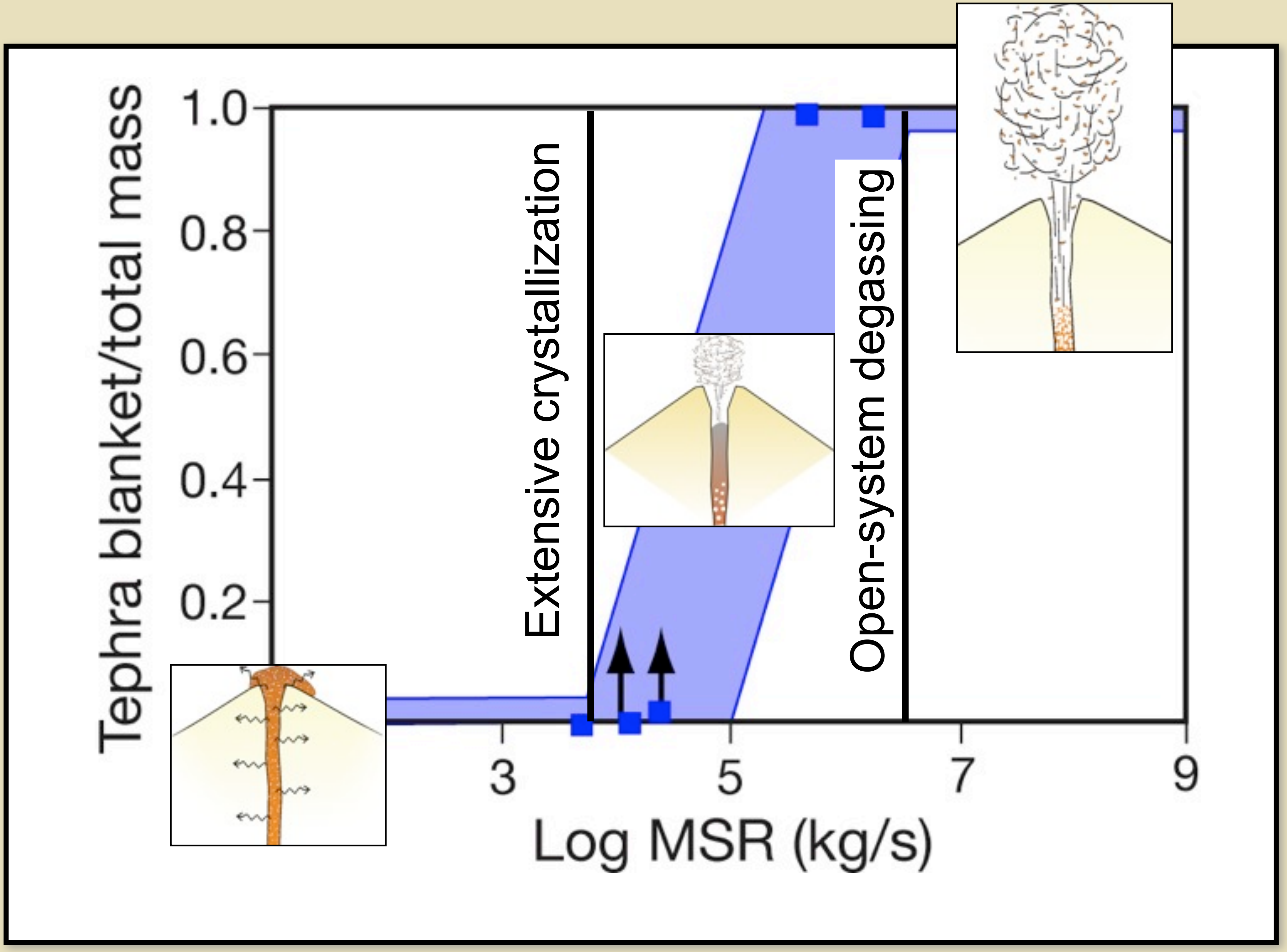


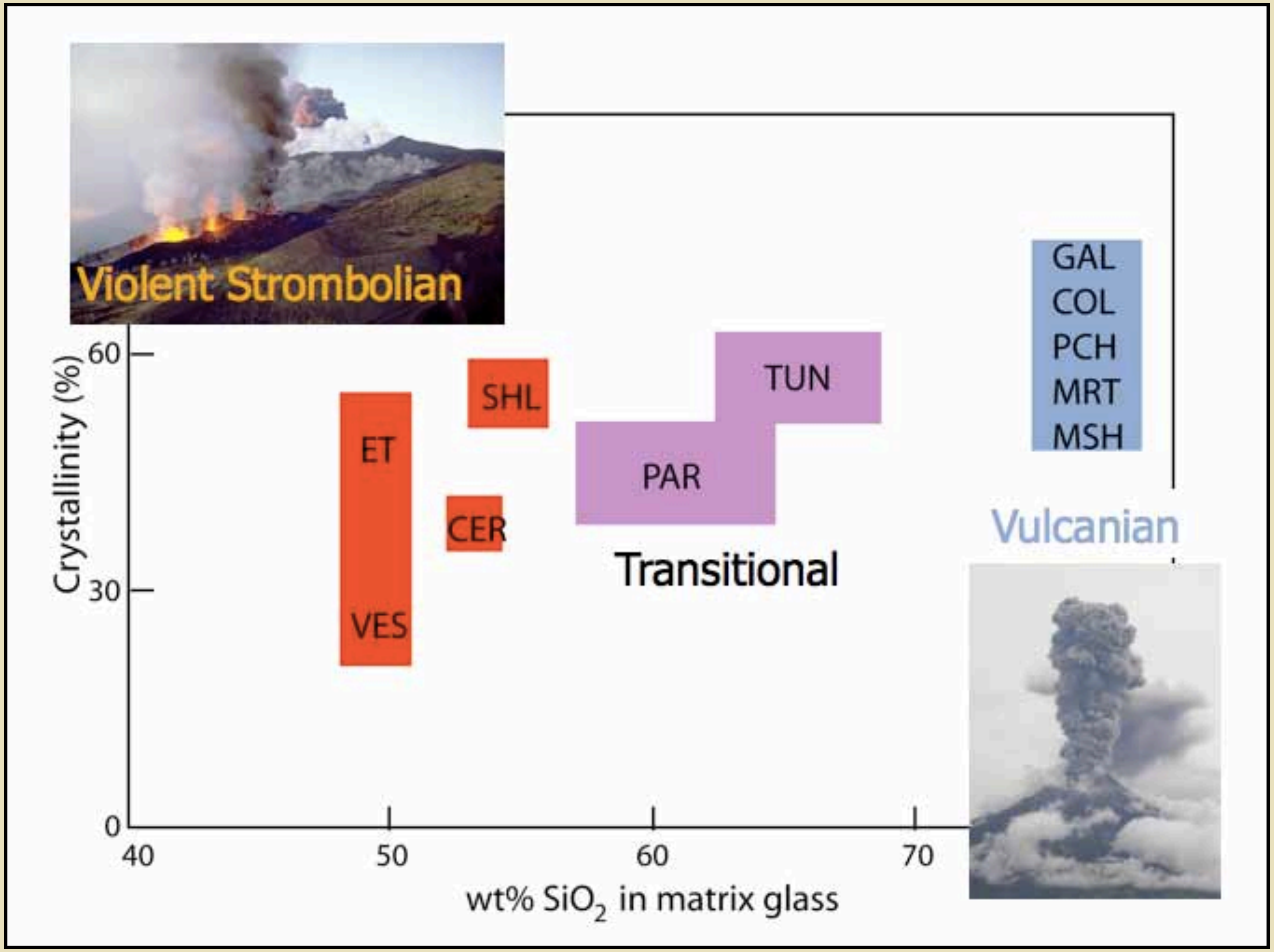

INCREASING MAGMA SUPPLY RATE

domes & spines

# Silicic eruption styles

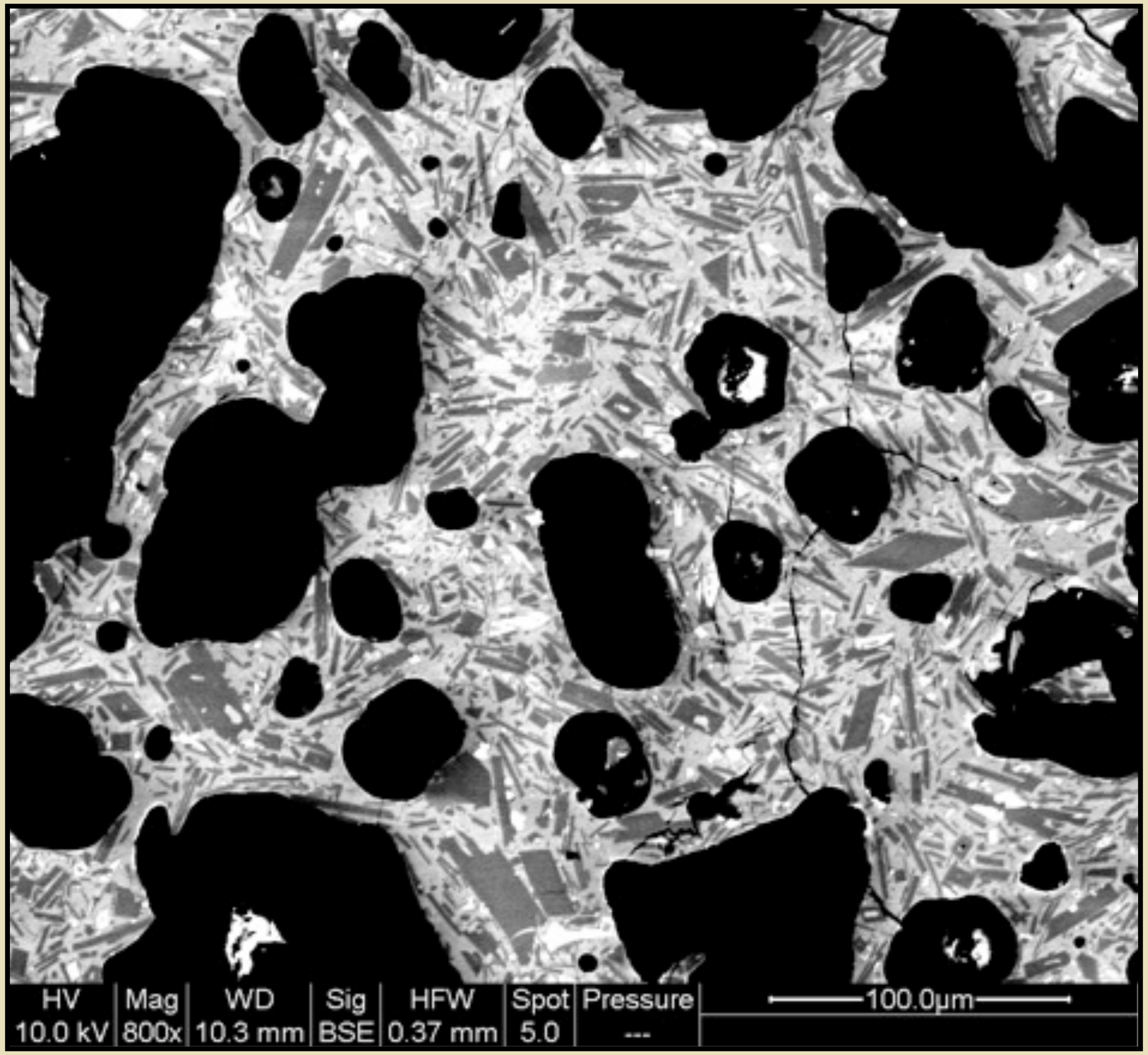


# Transitional eruption styles

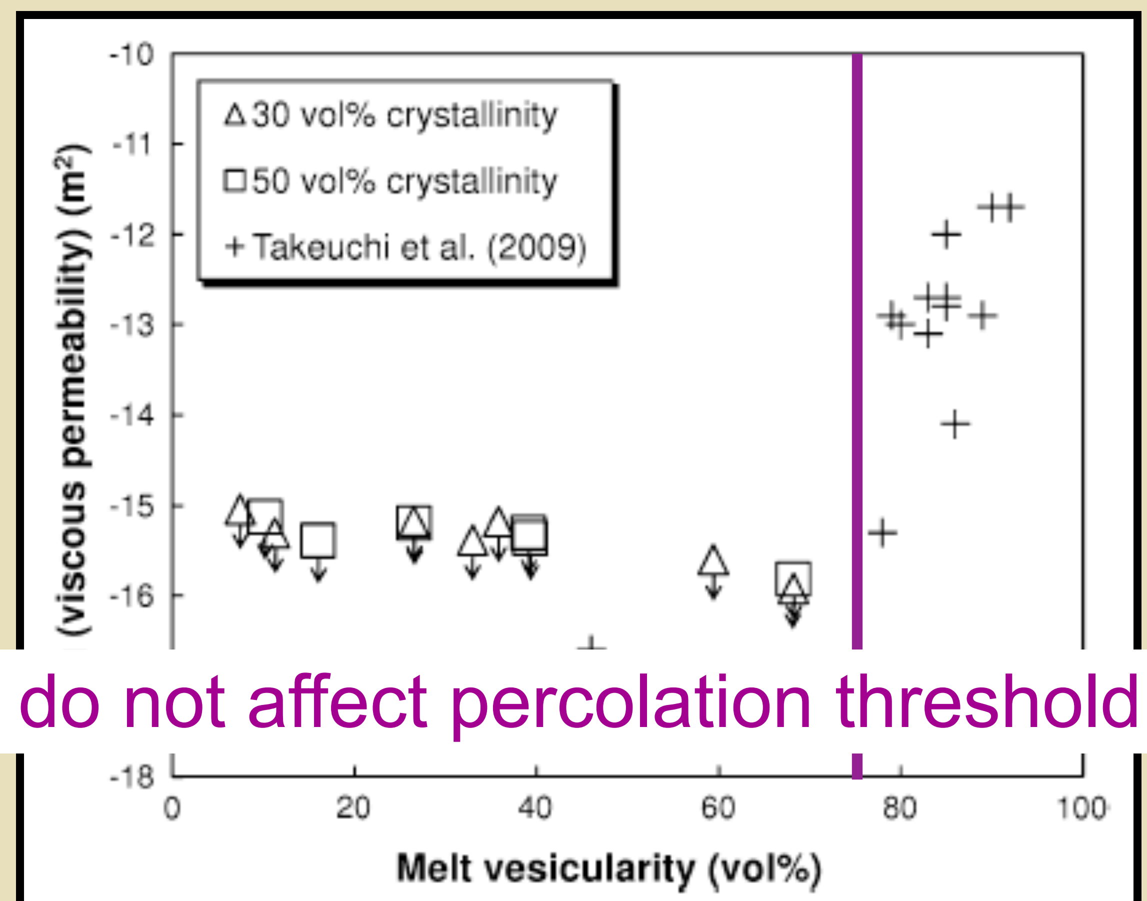



Cashman & Sparks (2013)

# Degassing of multiphase magma



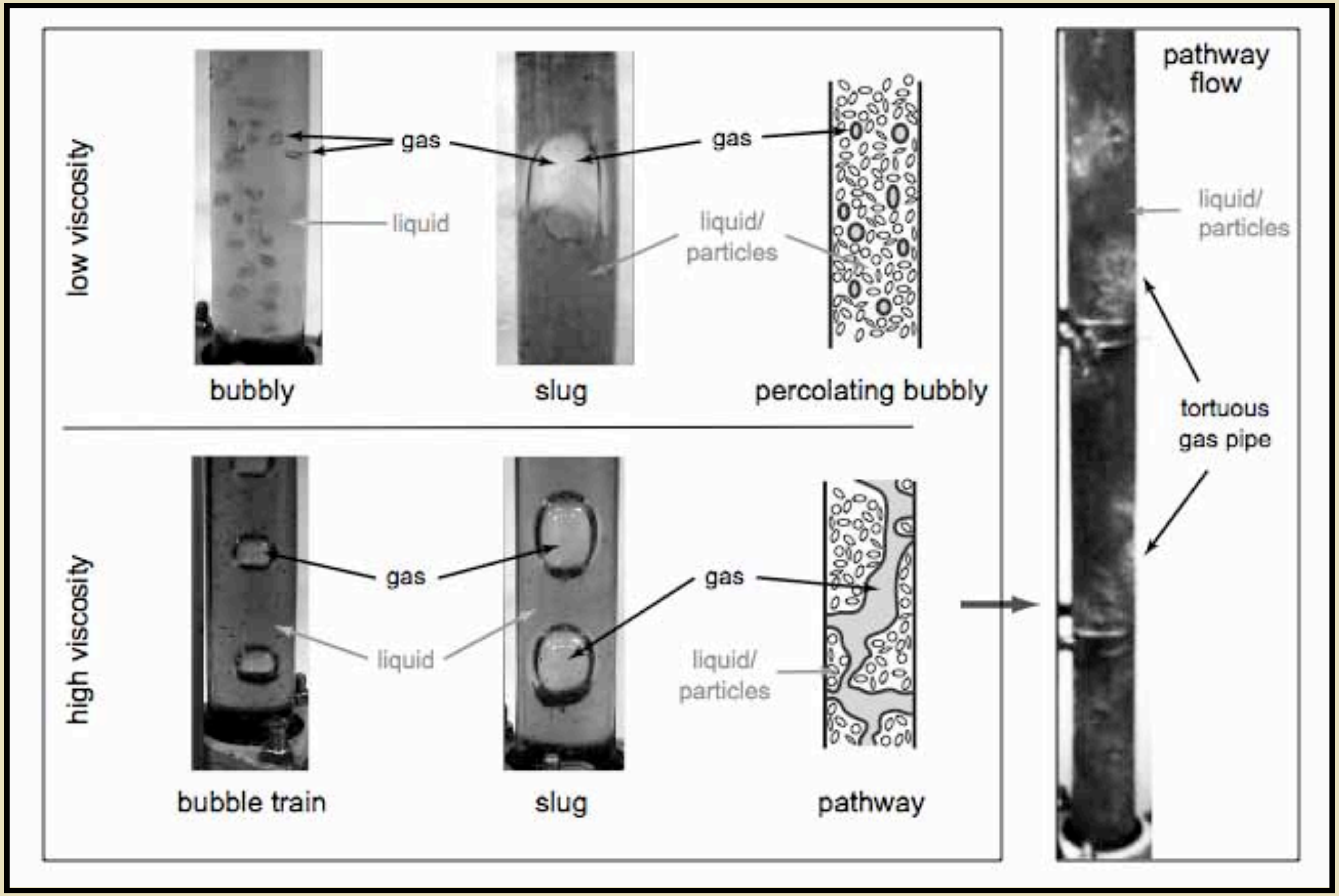

Most erupted pyroclasts have crystals... which leads to the question of the role of crystals on the development of gas pathways




Okamura et al. (2012)

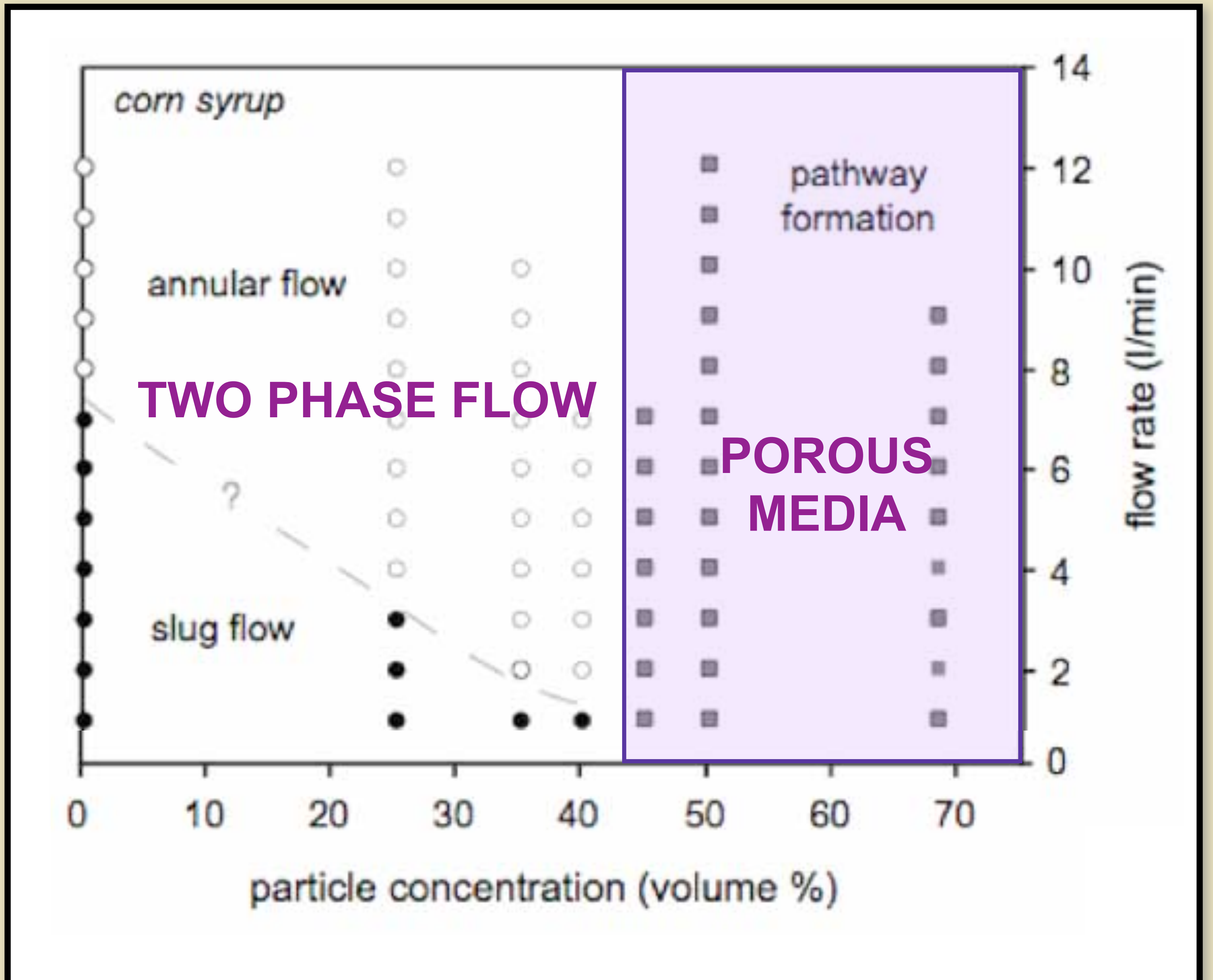
# Multiphase flow

## *THE EFFECT OF PARTICLES ON FLOW REGIMES*



# Multiphase flow

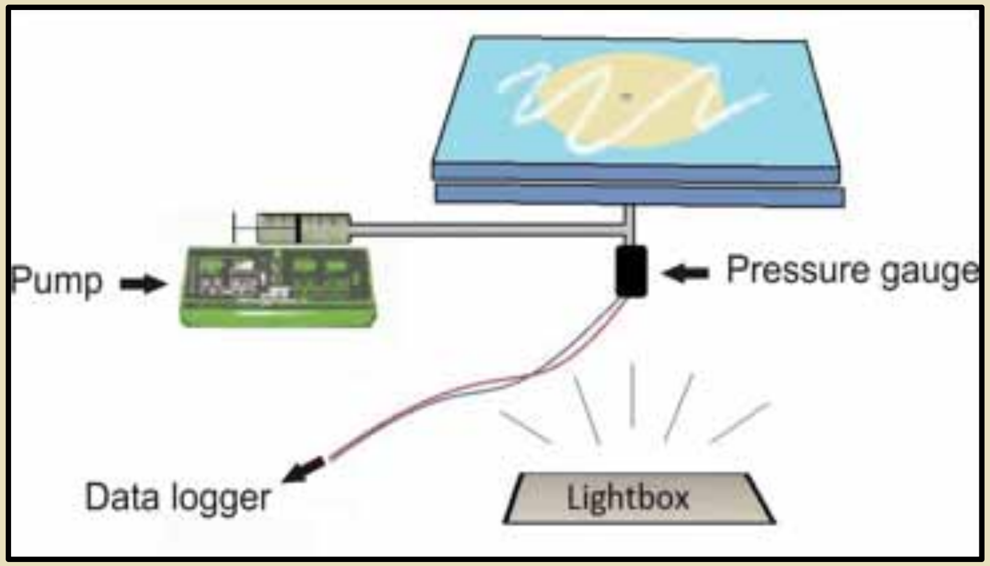
## *THE EFFECT OF PARTICLES ON FLOW REGIMES*




There is an abrupt change in gas behavior close to the point of loose maximum particle packing (the *jamming point*)

# A closer look at the jamming point

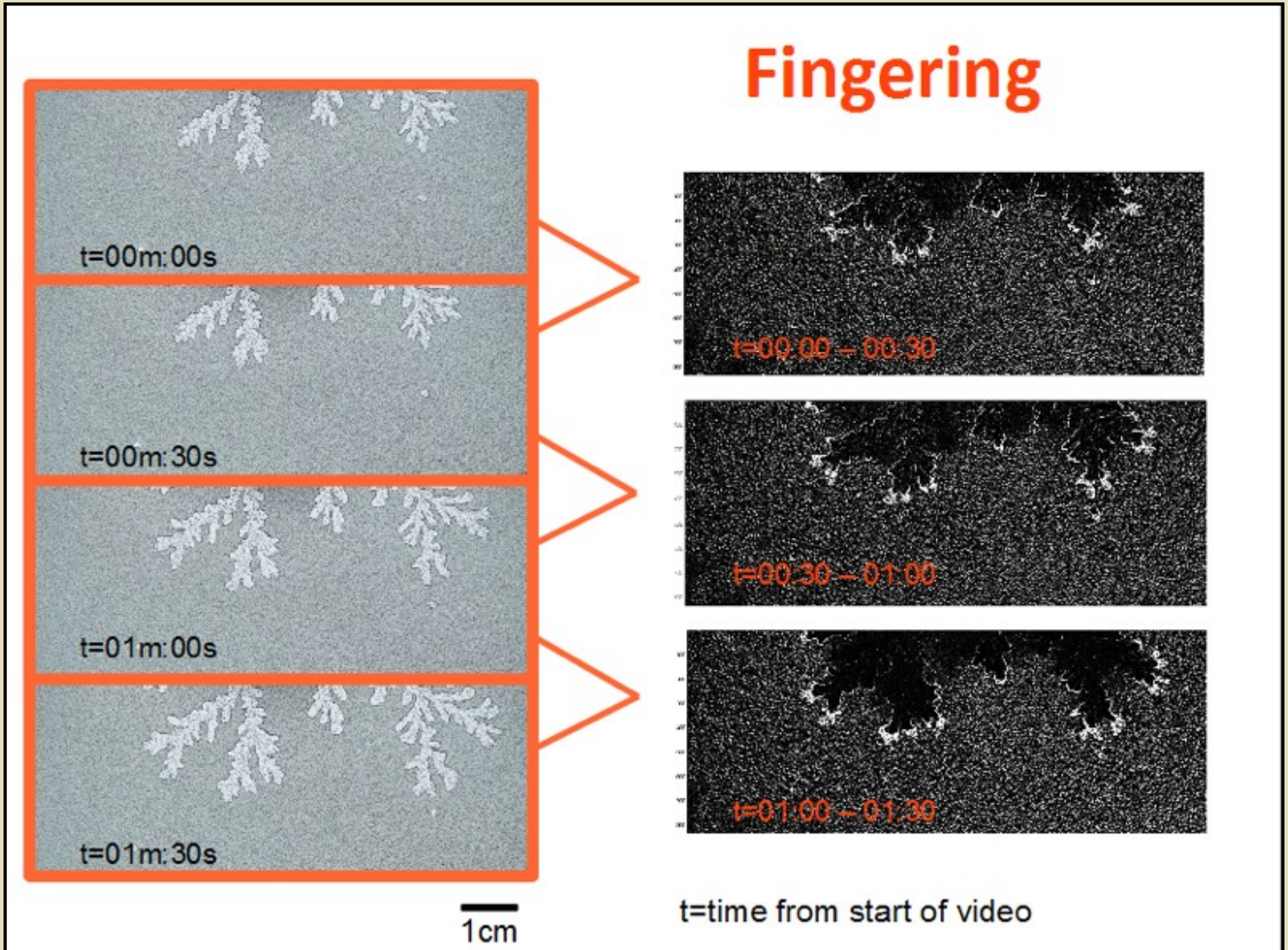
## *GAS INJECTED INTO PARTICLE-RICH SUSPENSION*



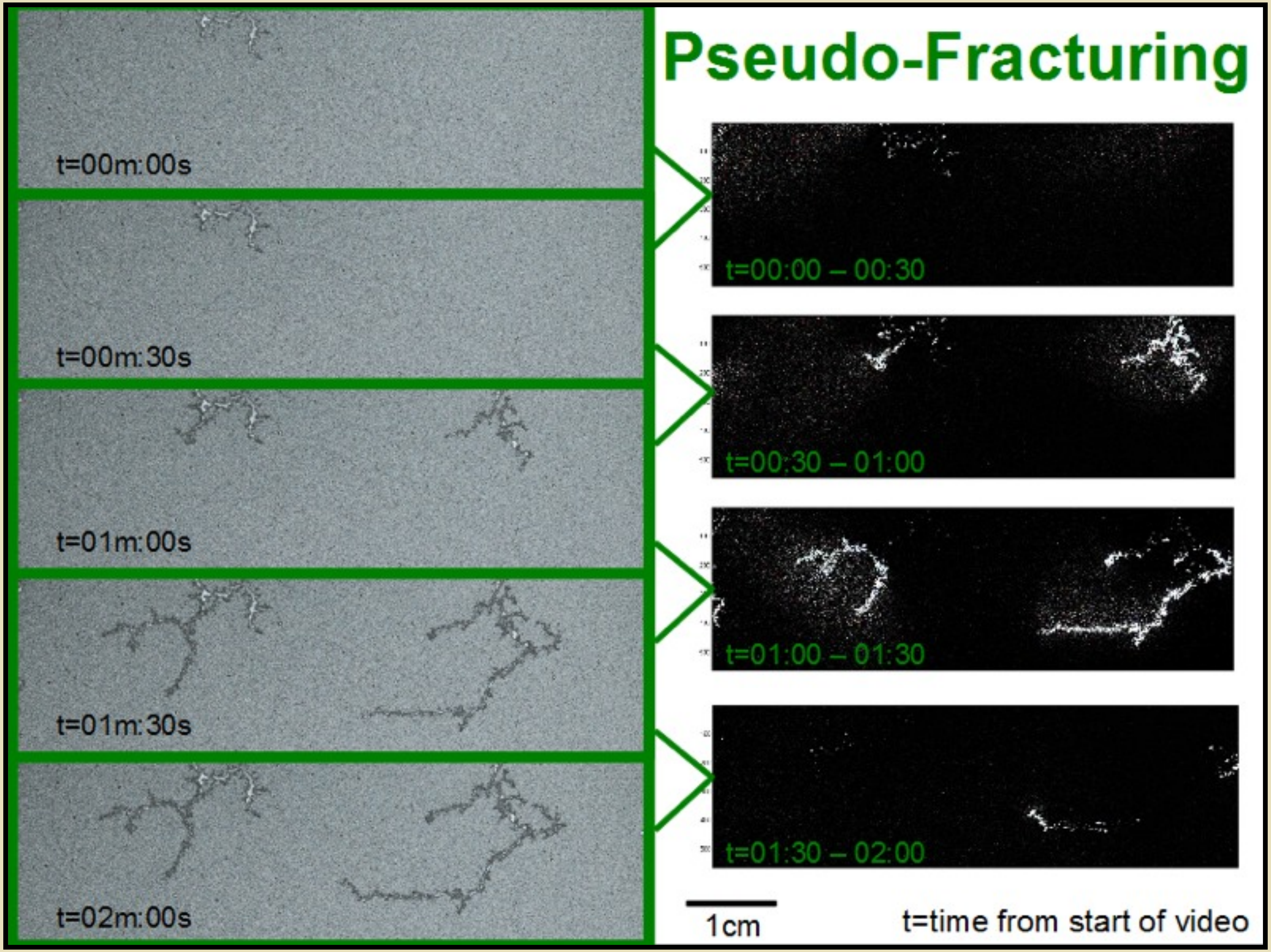

Hele-Shaw cell with golden syrup and glass spheres


increasing particle volume fraction

# A closer look at the jamming point

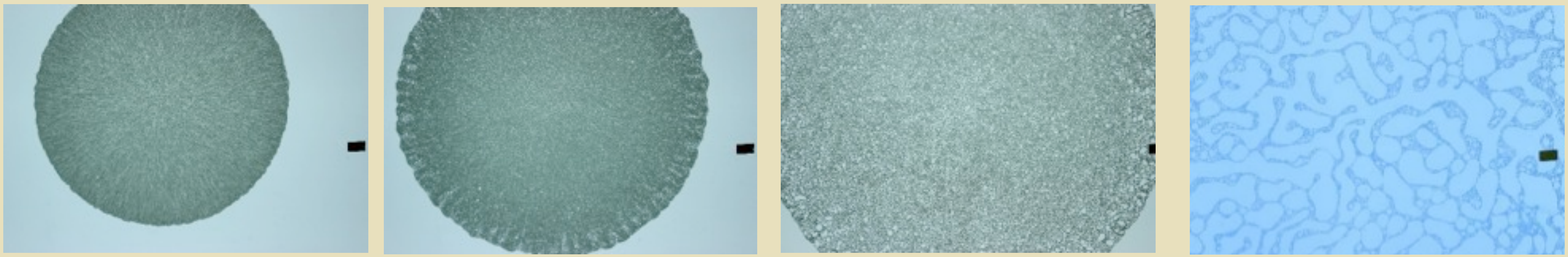


# A closer look at the jamming point

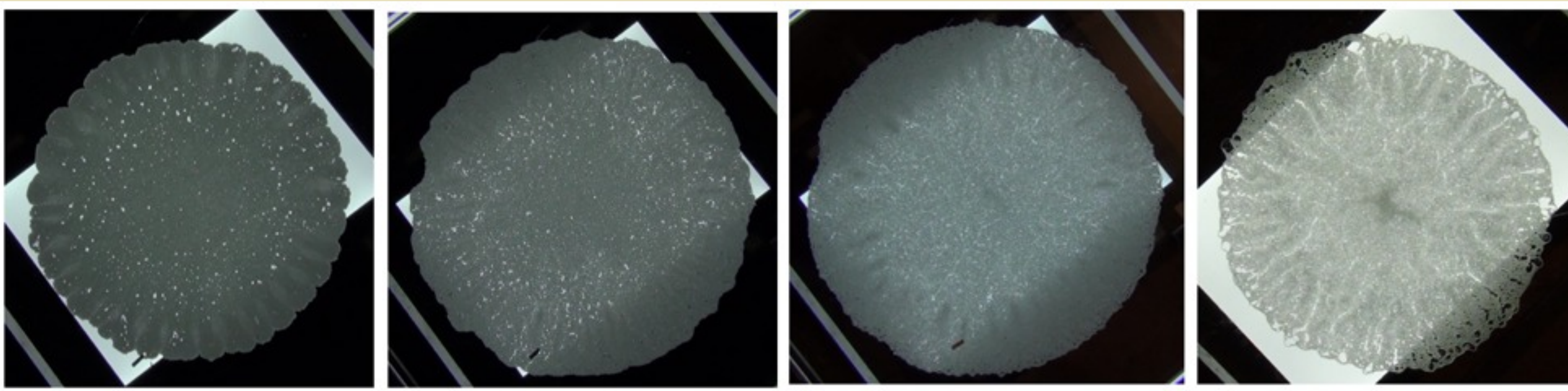


# Internal vesiculation

*Pure syrup (+ baking soda + citric acid)*

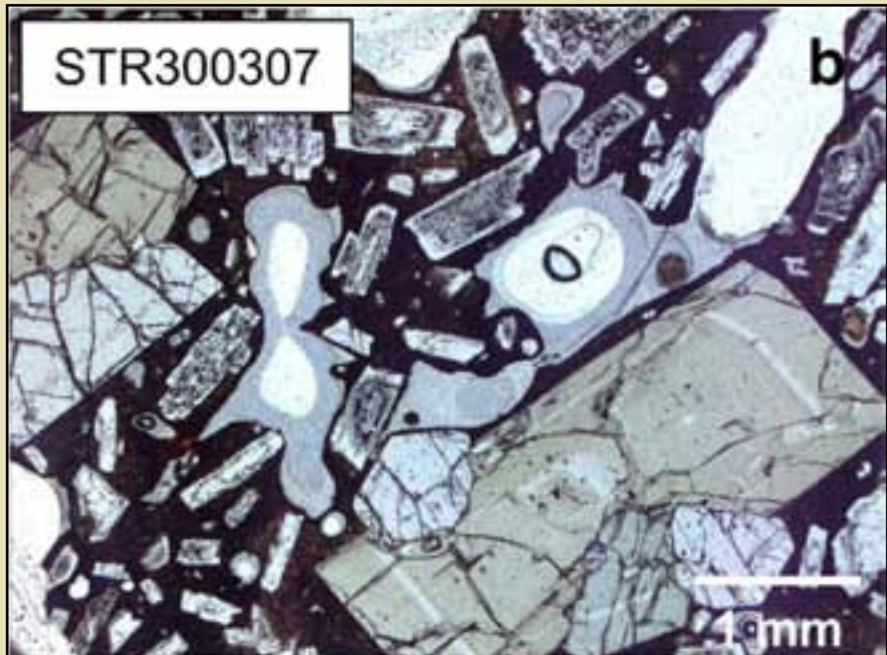


*58% particles*



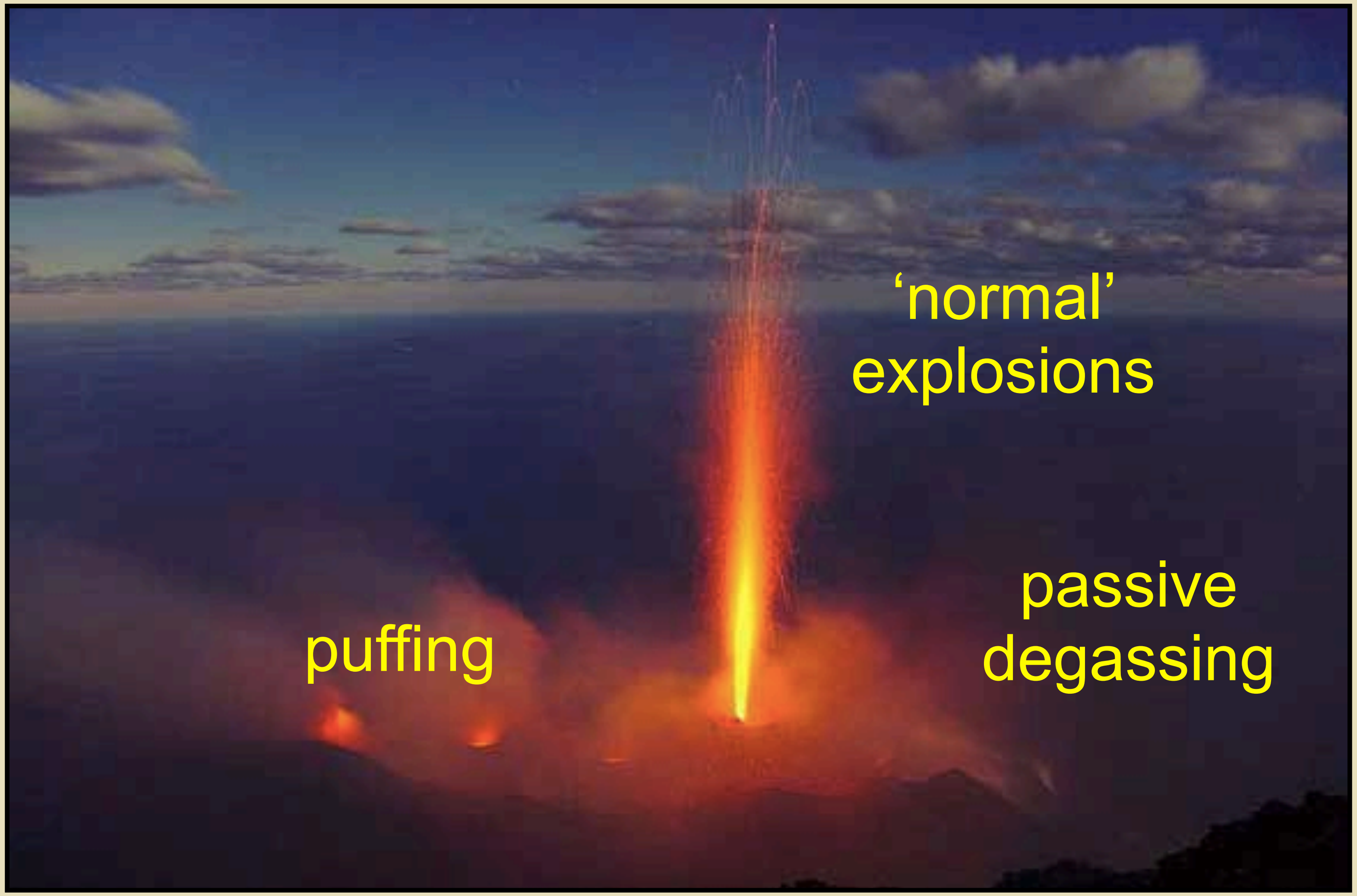
(1) Isolated bubbles (2) First connections (3) Bursting foam (4) Channelling

# Applications?




Landi et al. (2009)

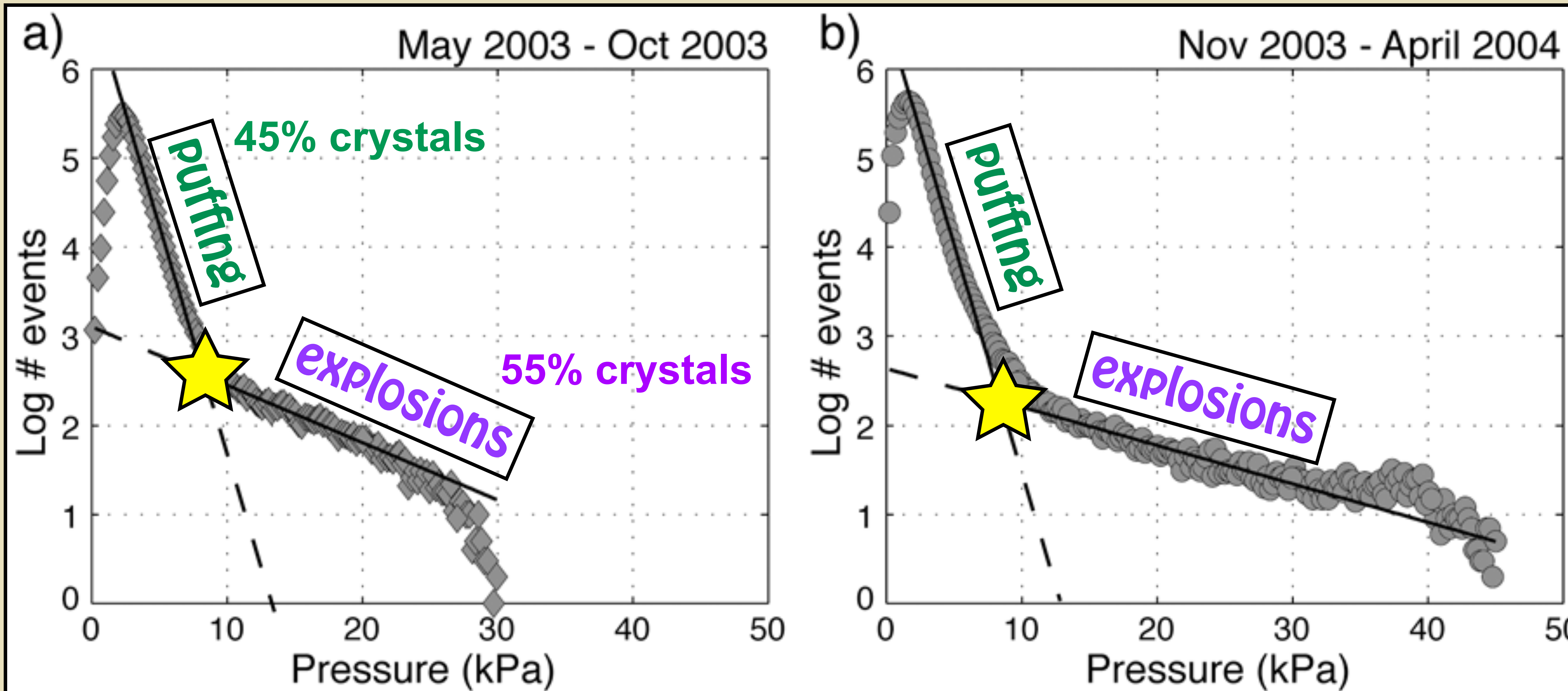
**Stromboli erupts highly crystalline magma**




*Degassing is accomplished by distributed passive degassing (45%), puffing in the central crater (45%) and 'normal' explosions at the ends of the crater terrace (10%)*

# Applications?

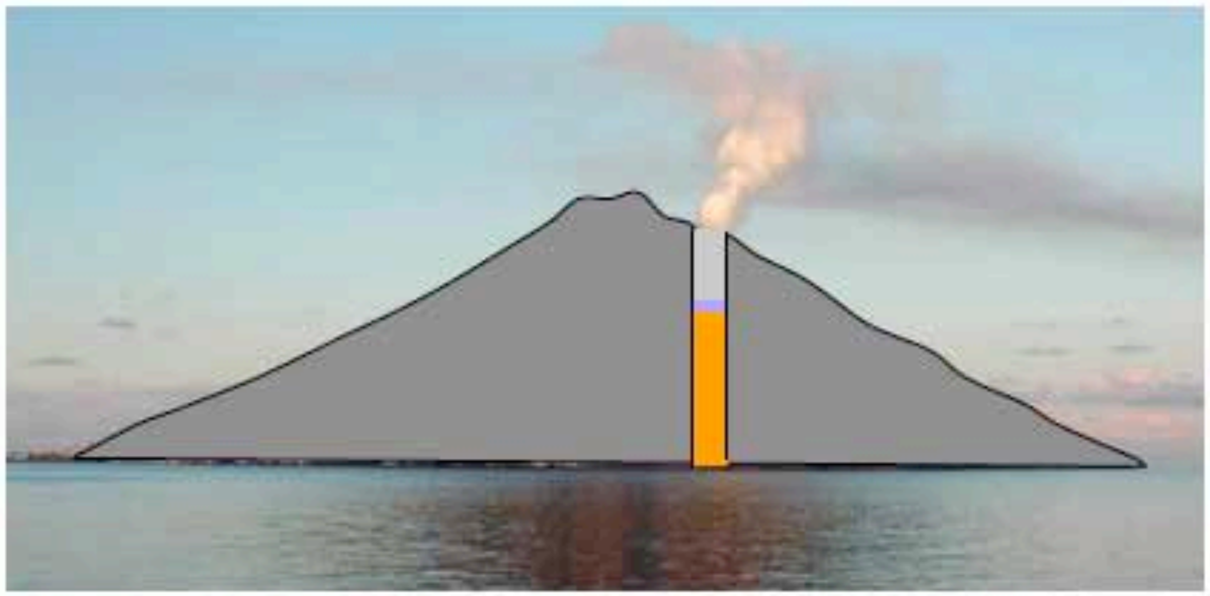
*PUFFING AND EXPLOSIONS HAVE DIFFERENT SOURCES*



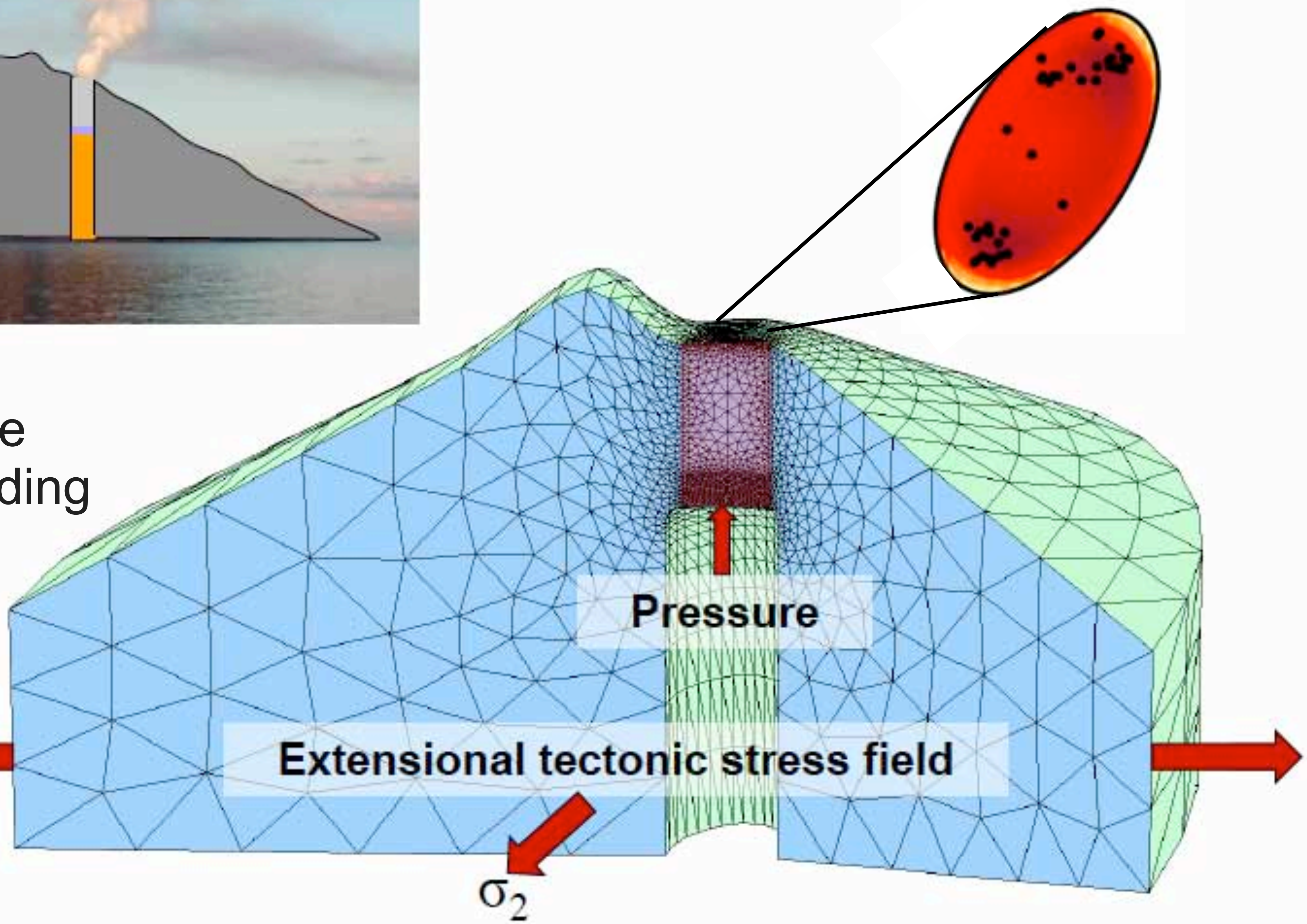

Ripepe et al. (2007)

 = 8kPa *Is this the yield stress at the jamming point?*

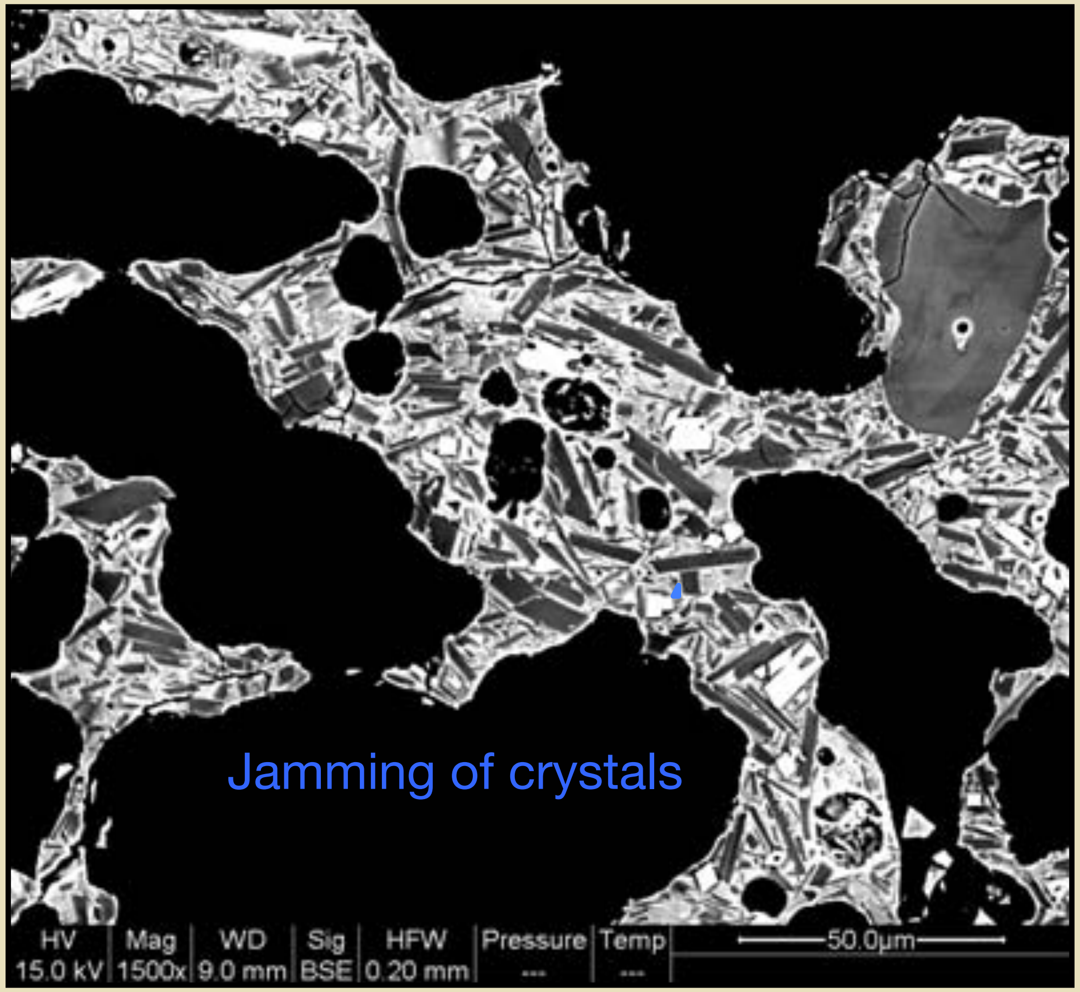
# Applications?



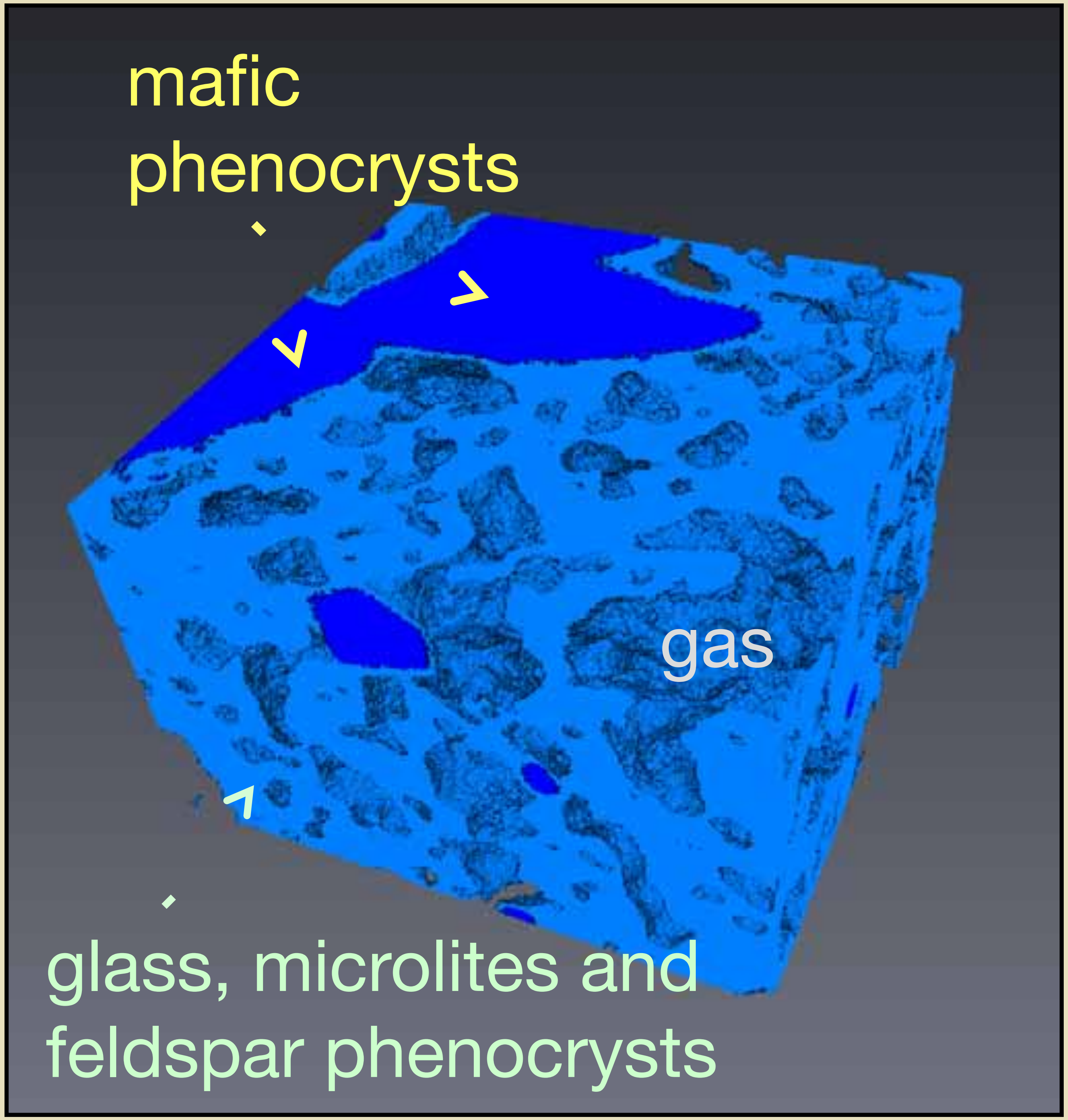
Locations of explosions can be explained by yielding of a ductile plug influenced by tectonic stress



# Mafic scoria




**What is the effect of complex interconnected gas pathways on magma fragmentation?**



# Summary

GAS EXPANDS WITHIN MAGMA:   Magma expansion >> either individual bubble rise or permeable flow

BUBBLE RISE:     Most effective in low viscosity, low crystallinity, near-static melt

PERMEABLE FLOW:    Applicable to high viscosity and high crystallinity magma; requires initial exceedence of porosity threshold but may be maintained during deformation

MULTICOMPONENT SYSTEMS:  crystals affect bulk rheology
- change flow regimes
- aid gas pathway development