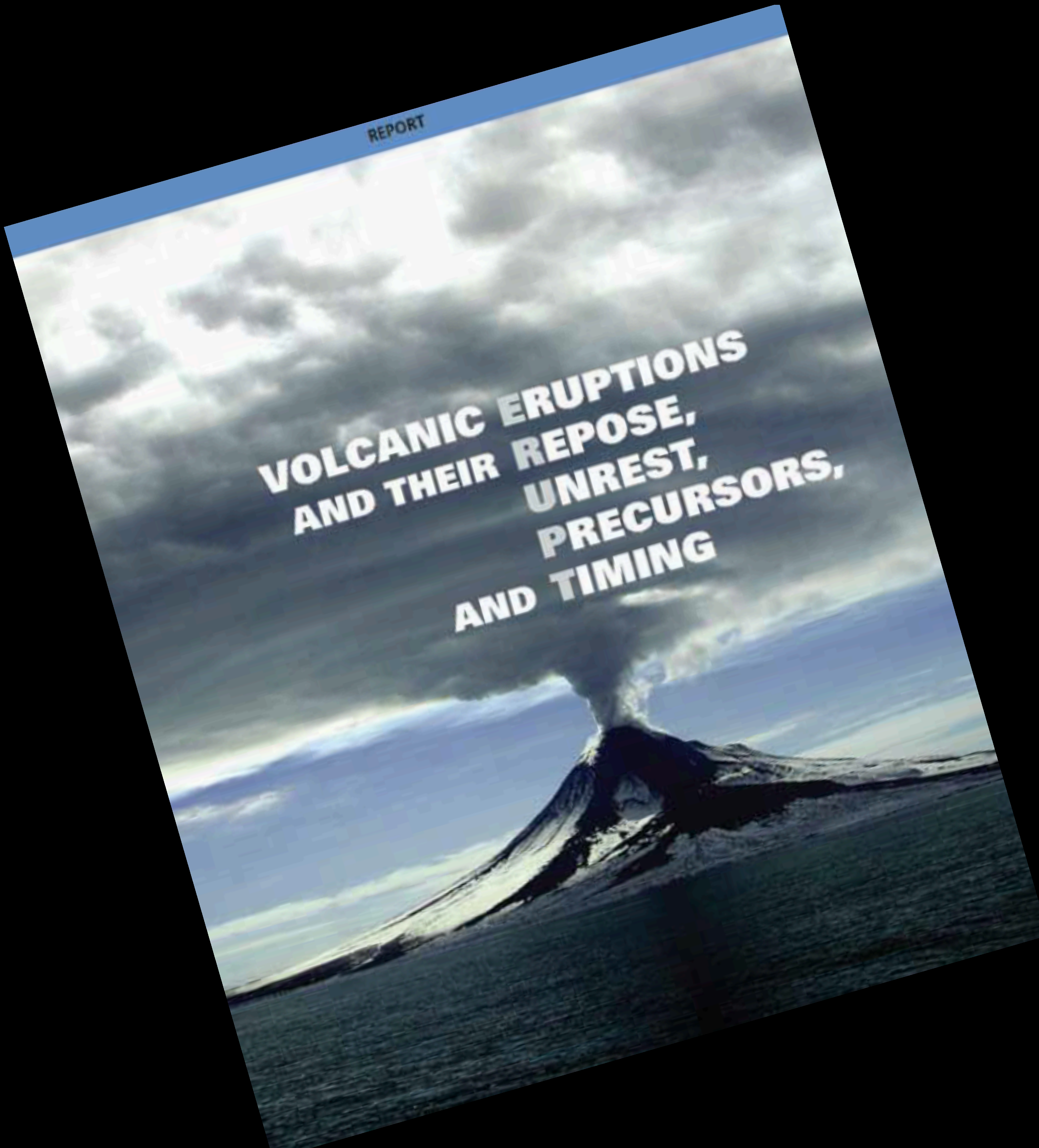
Volcanoes

Kathy Cashman
Univ of Bristol

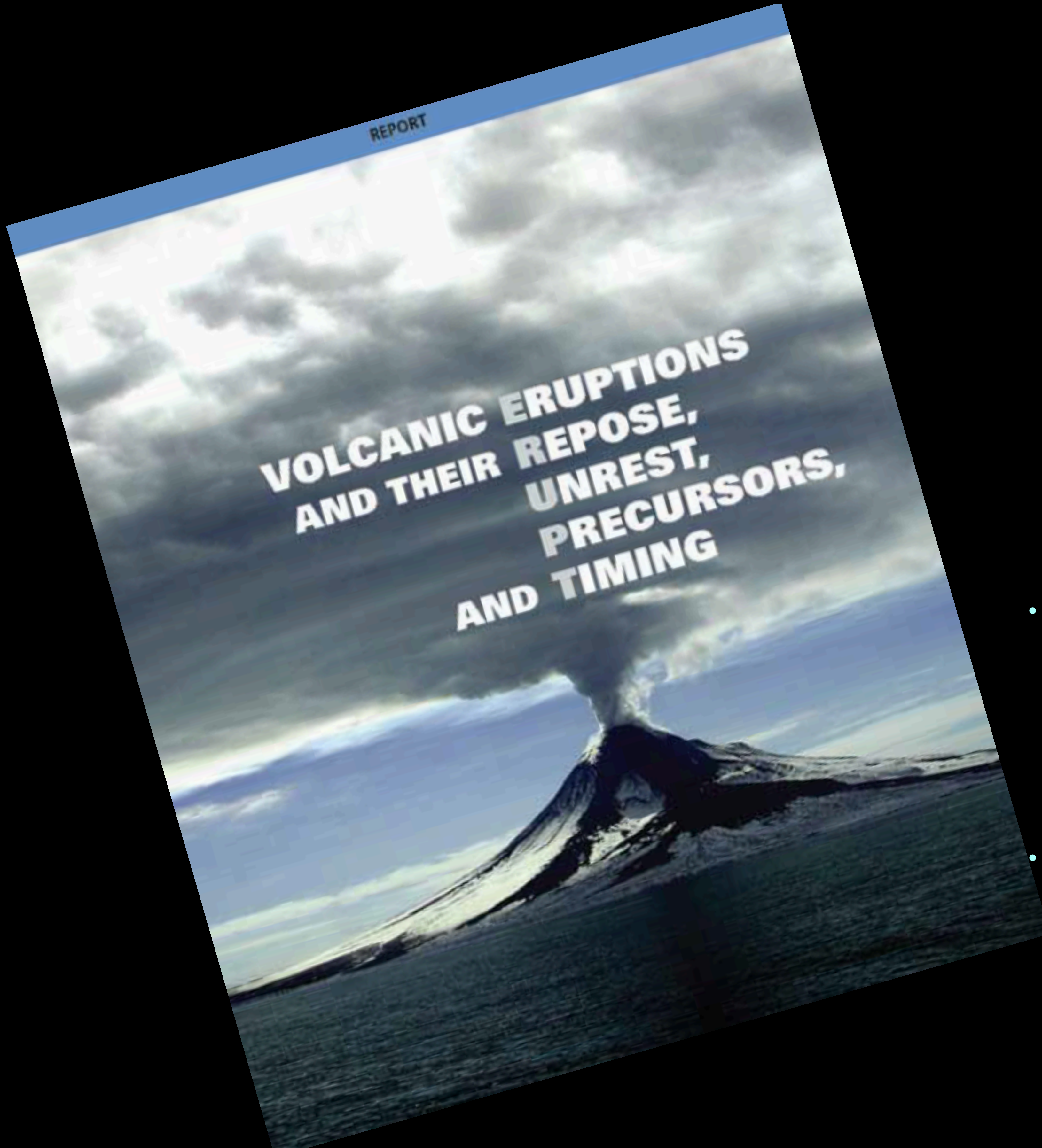
'Blast' by Emma Stibbon



Grand Challenges

Eruption forecasting

Life cycles of volcanoes



Grand Challenges

Eruption forecasting

↕

Life cycles of volcanoes

- *Short-term* forecasts require understanding of shallow magmatic systems and eruption processes
- *Long-term forecasts* require understanding of the larger magmatic system

Overview

Volcano basics & conceptual models
Eruption styles and processes

Case studies
Beyond theory

Magmatic systems
Some deep controls on volcanic processes

Volcano unrest and eruption forecasts

painting by John Jackson

Variations in time scales of eruptive activity

1st order question

Incessant eruption | *Tranquil effusion* | *Paroxysms with long repose*

Stromboli

Kīlauea

Cordon Caulle

Scrope (1862)

Variations in eruption styles within individual volcanoes and/or eruptive episodes

Santa Maria 1902

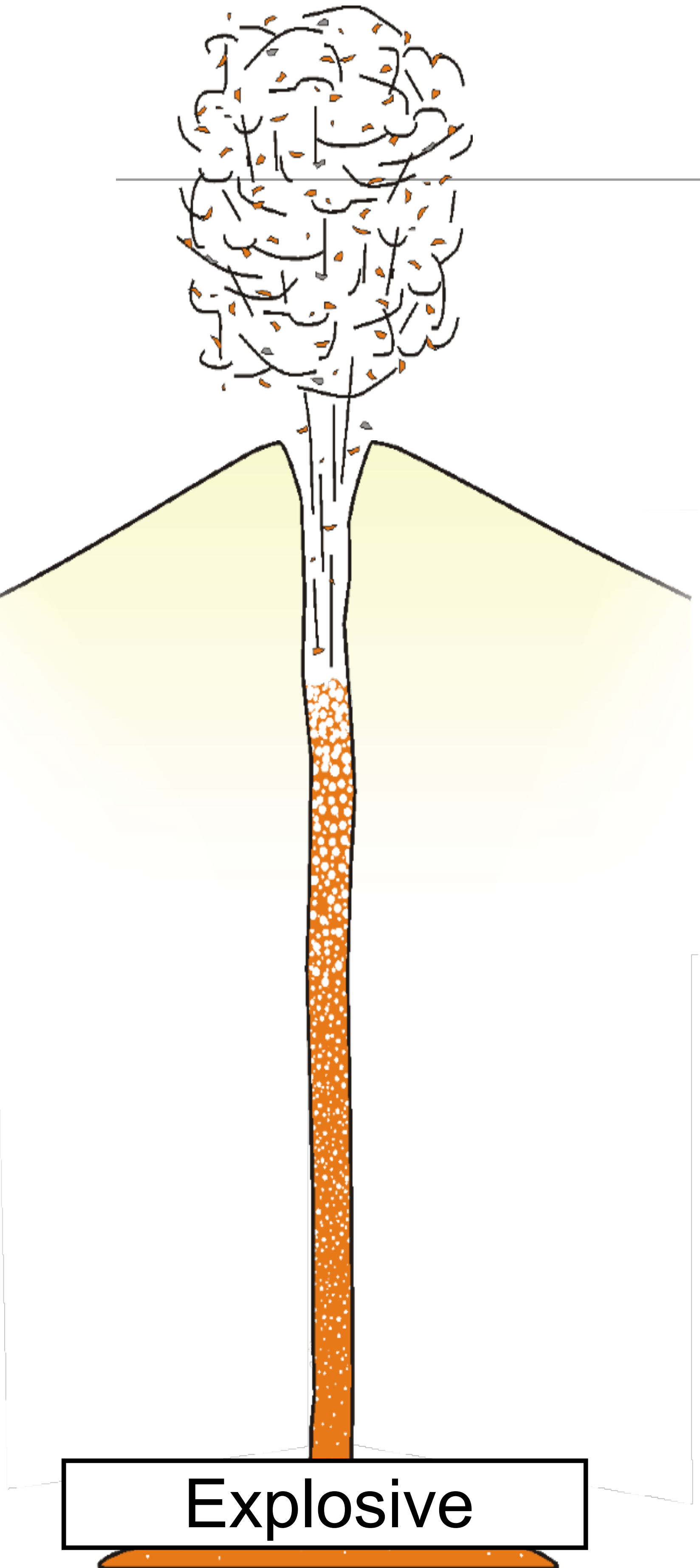
eruption occurred after ~25ka dormancy

Volume: >6.4 km^3 (DRE; Berry 2018)

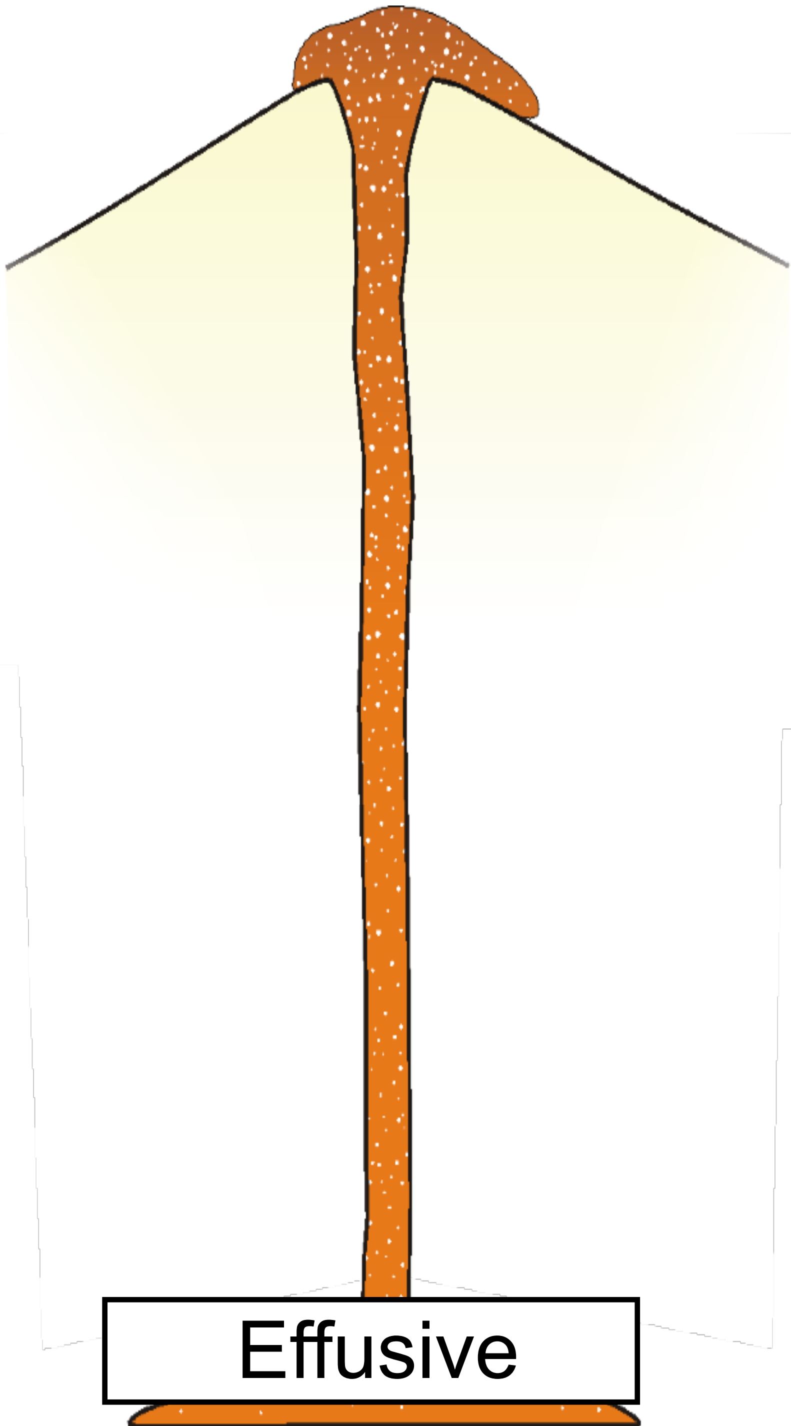
Santiaguito 1922—present

Volume: ~ 1.75 km^3 (1922-2002; Durst, 2008)
~0.02 km^3/yr, or 2 km^3/kyr

Styles of Eruption



At the most fundamental level, we can classify volcanic eruptions as **explosive** or **effusive**, and **pulsatory** or **steady**



Explosive eruption styles

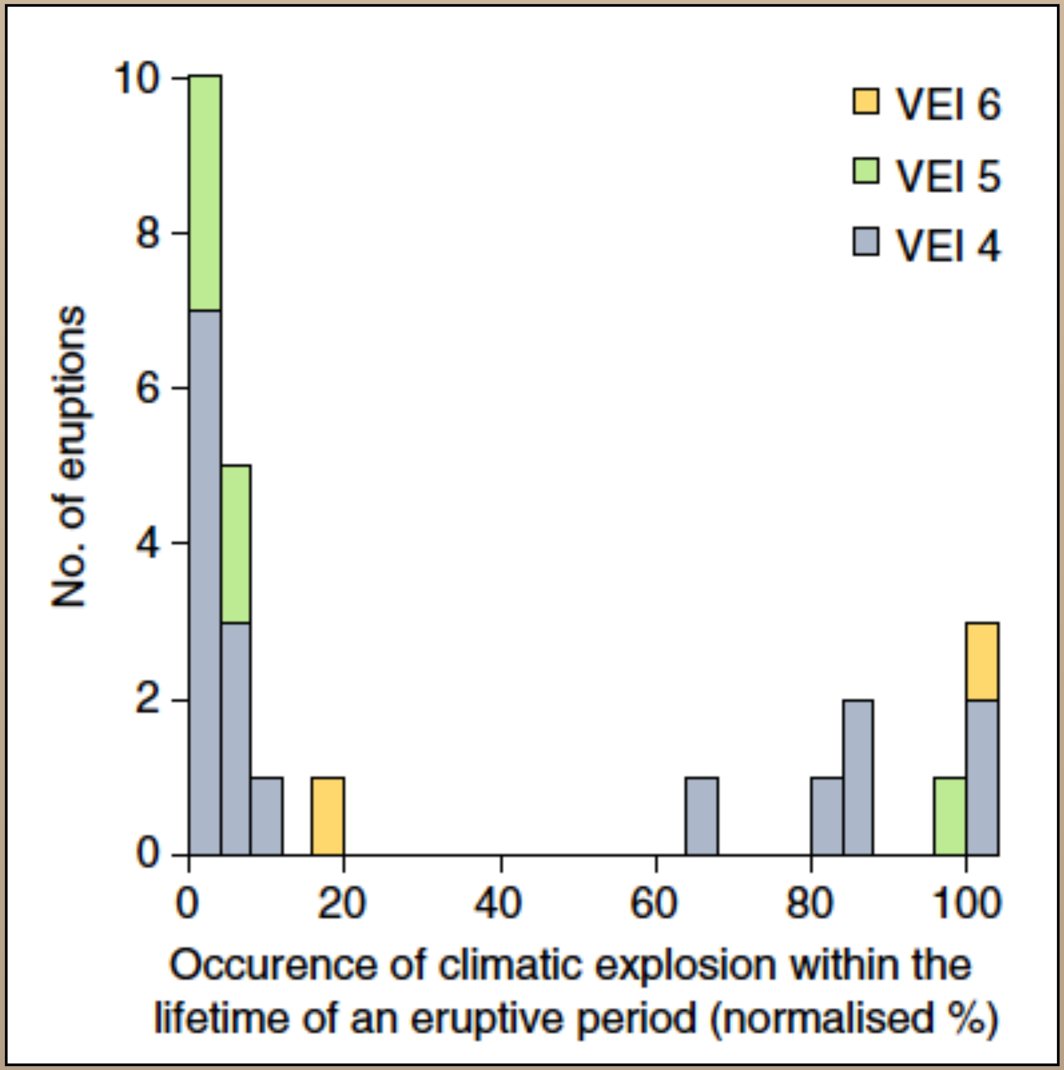
Effusive eruptions produce lava flows, domes and spines, and secondary cones

Littoral explosions

BASALT → *RHYOLITE*

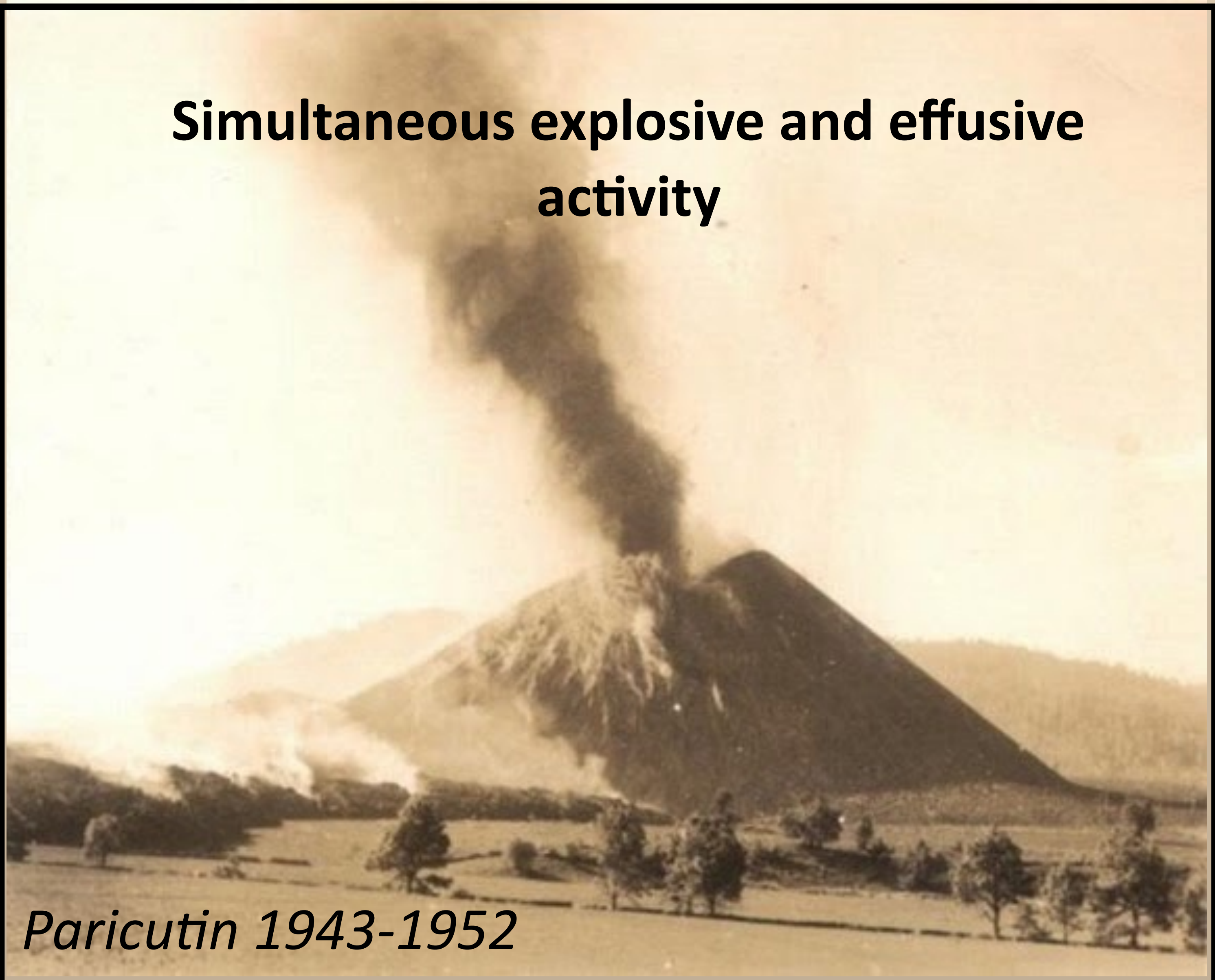
Compound eruption styles

Sequential changes between explosive and effusive activity: *characteristic of dome-building eruptions*



Cassidy et al. (2018)

Simultaneous explosive and effusive activity



Explosive eruptions also occur when magma encounters external water

Magmatic eruptions

Hydromagmatic eruptions

Phreatic eruptions

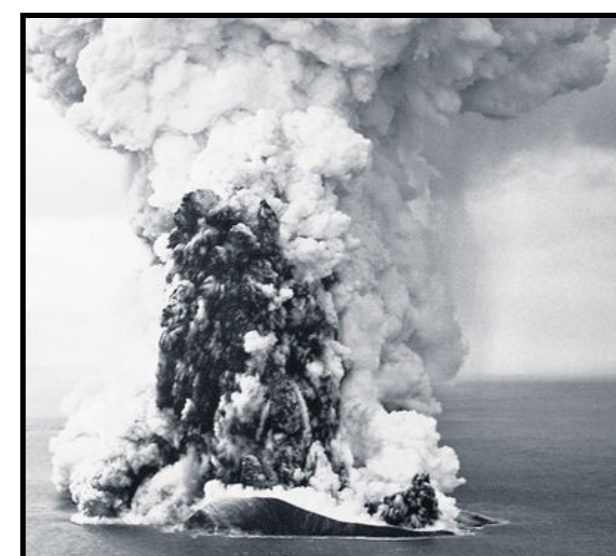
Submarine

Groundwater

Surface water

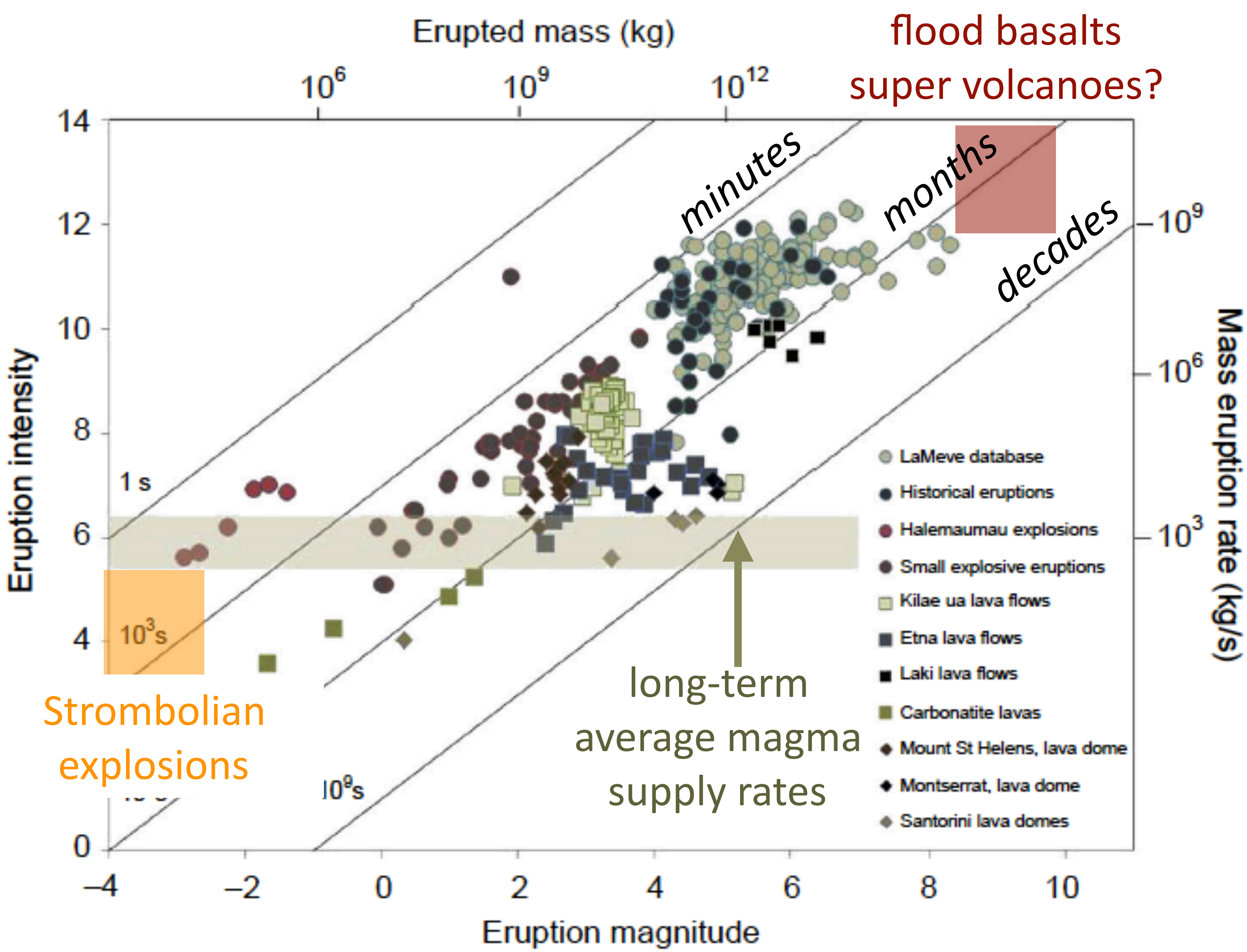
West Mata, Pacific (2009)

Ukinrek Maars, Alaska (1977)



Surtsey, Iceland (1963)

Magnitude-Intensity scale



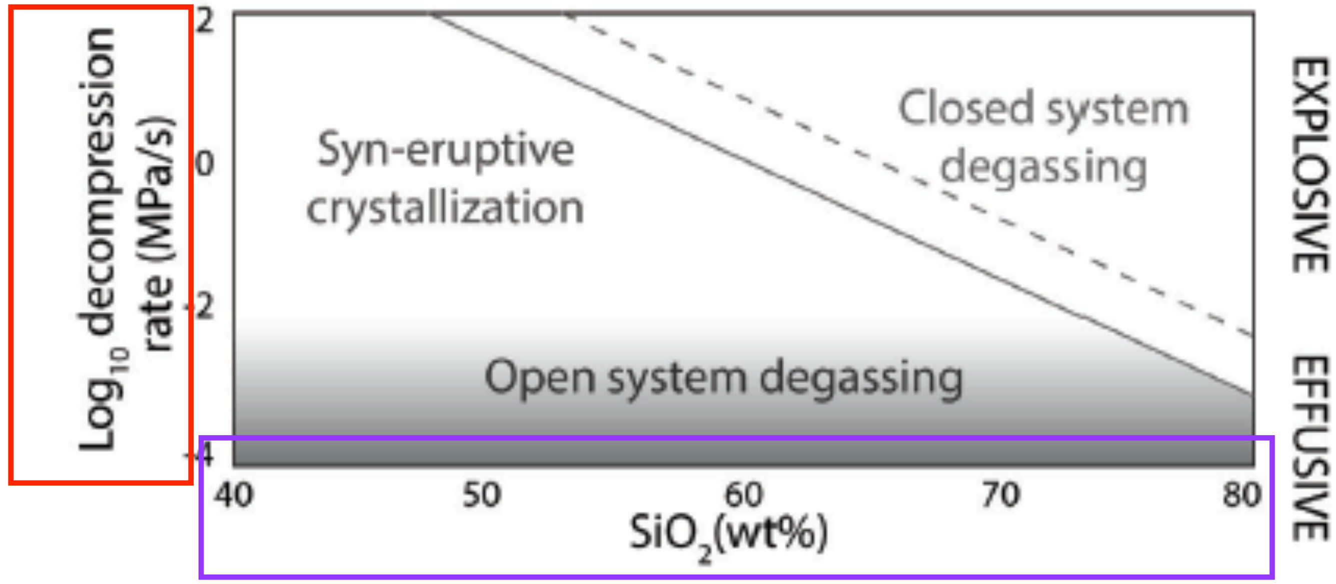
Pyle (2015)

M = $\log_{10}$ (erupted mass, kg) - 7

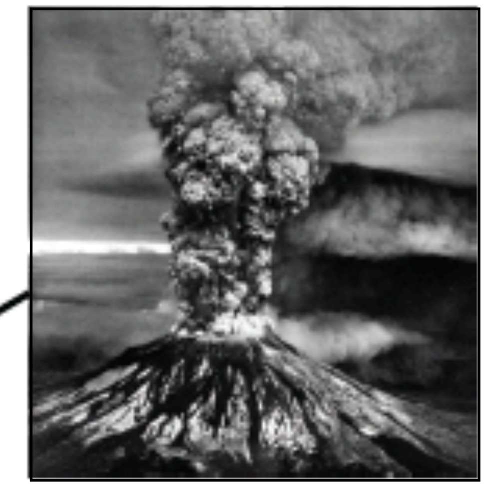
I = $\log_{10}$ (mass eruption rate, kg/s) + 3

This descriptive classification can accommodate all forms of eruptive activity, as long as magnitude and time are constrained

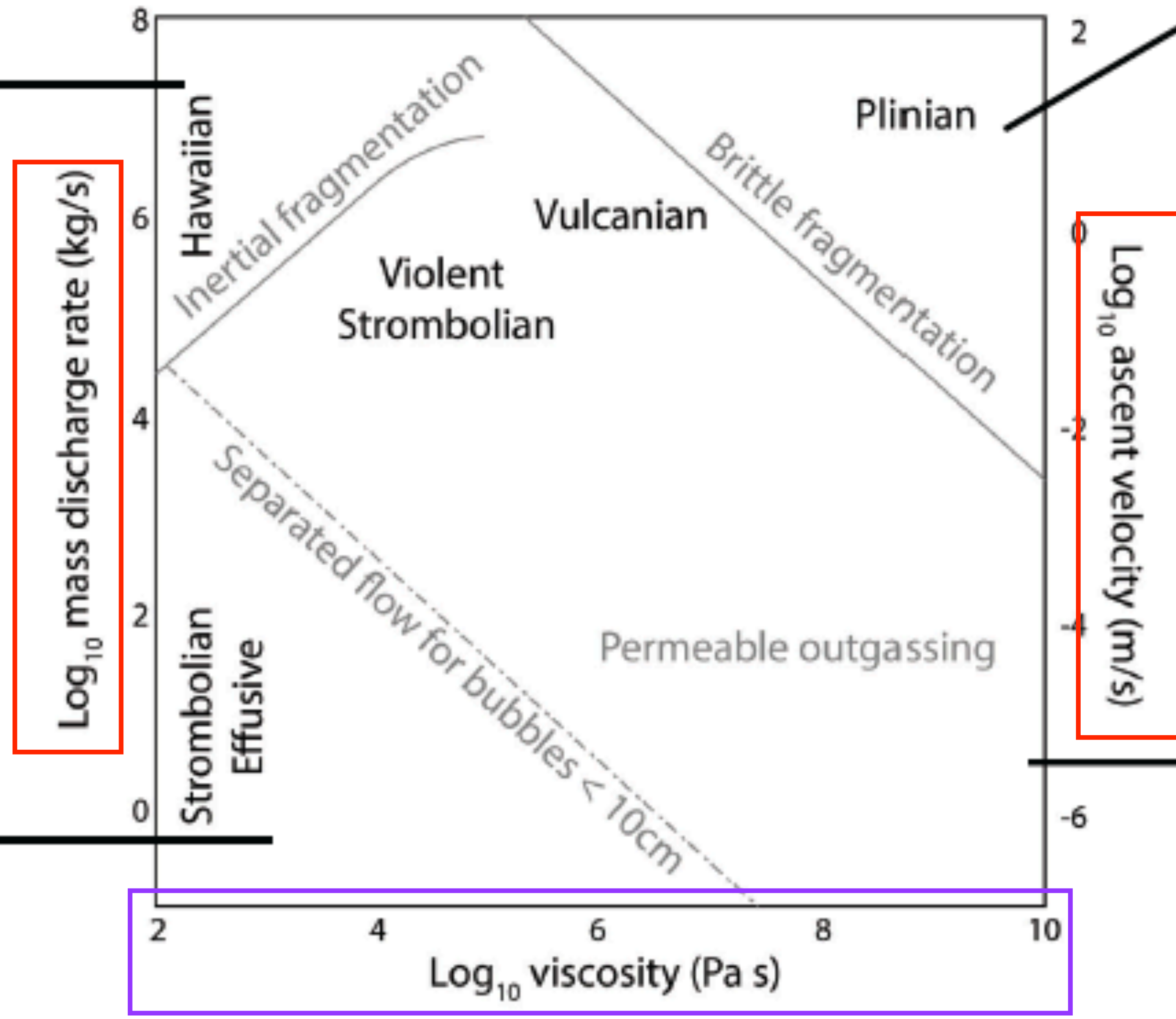
Process-based classification scheme



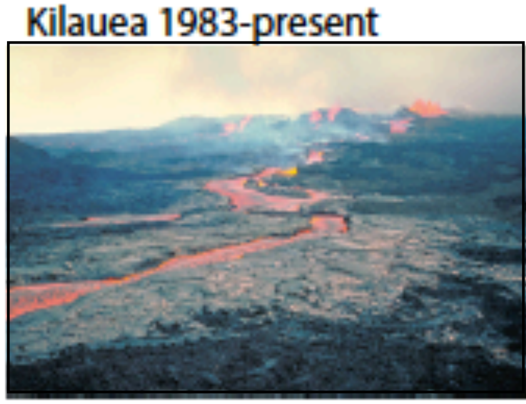
Kilauea Iki 1959



St Helens 1980



Kilauea 1983-present

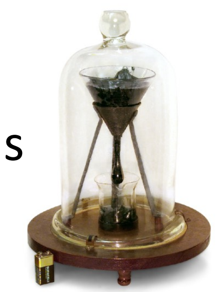


St Helens 2004-2008

NAS report

Compositional controls on viscosity

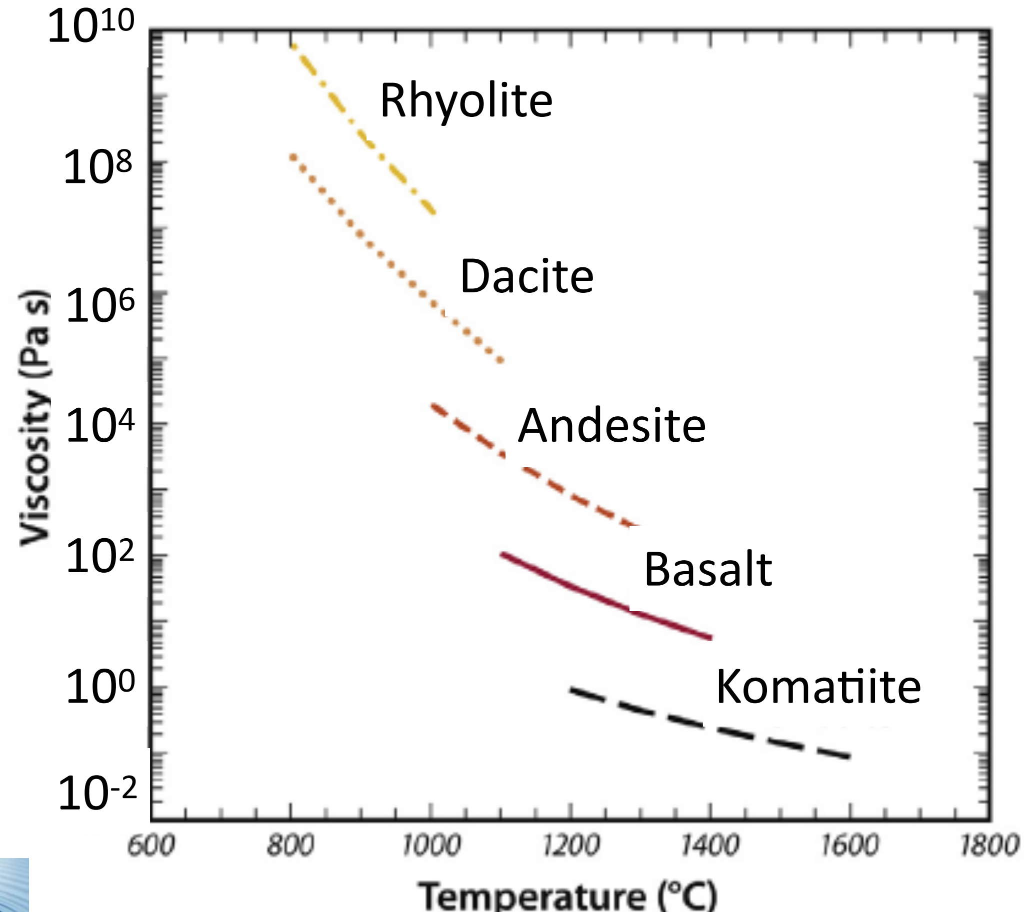
10^7 Pa s

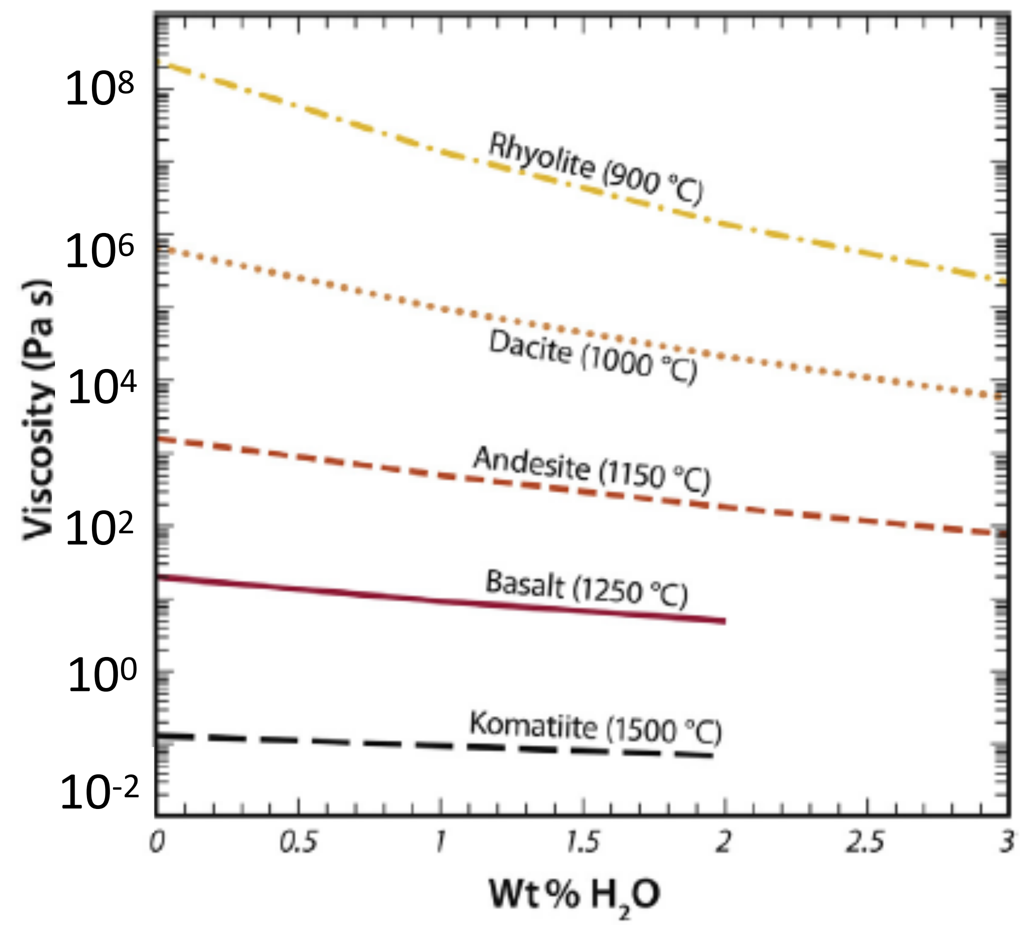


10 Pa s

0.1 Pa s

0.001 Pa s

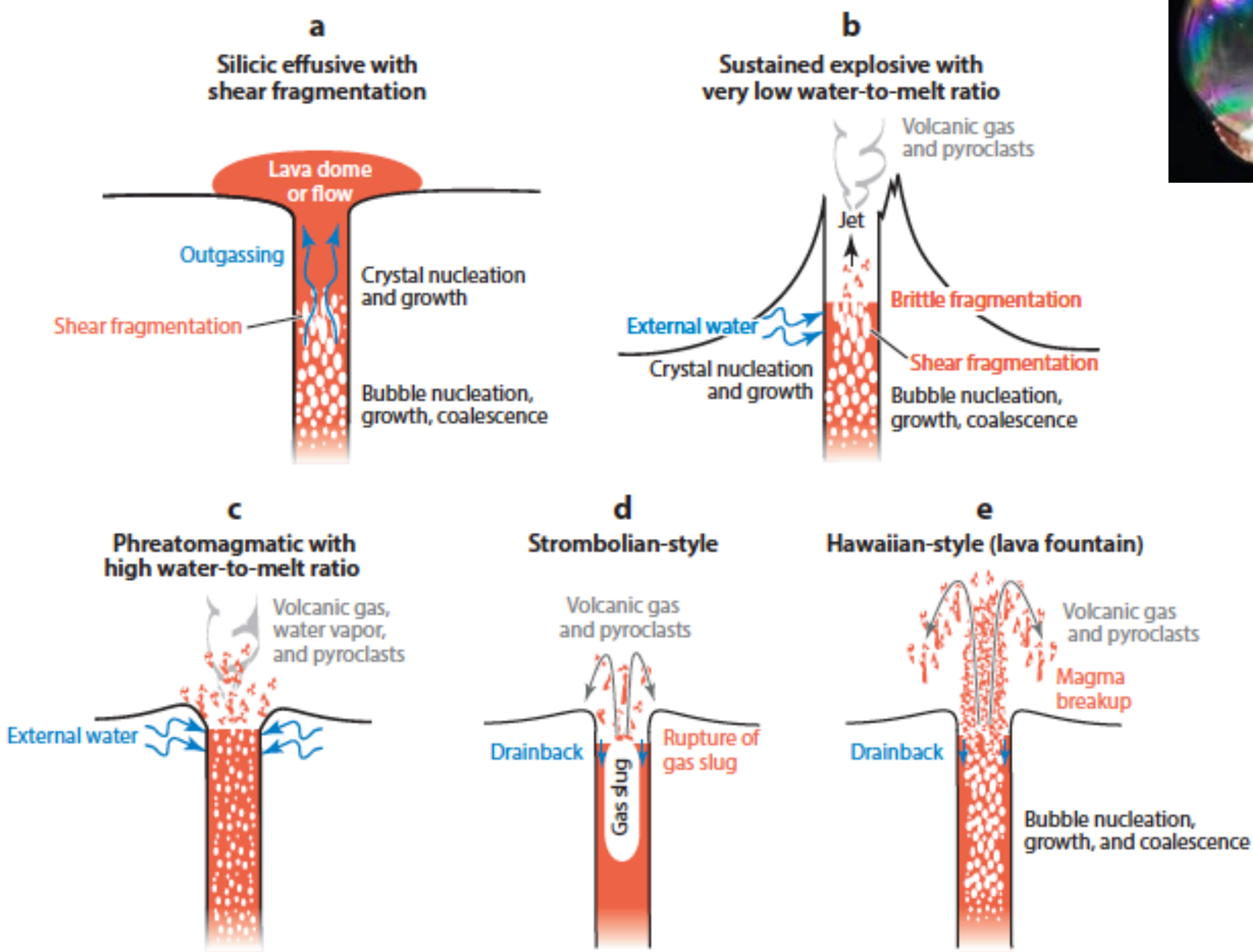




Lesher and Spera (2015)

Pitch Tar Drop experiment

Decompression rate (volatile exsolution)

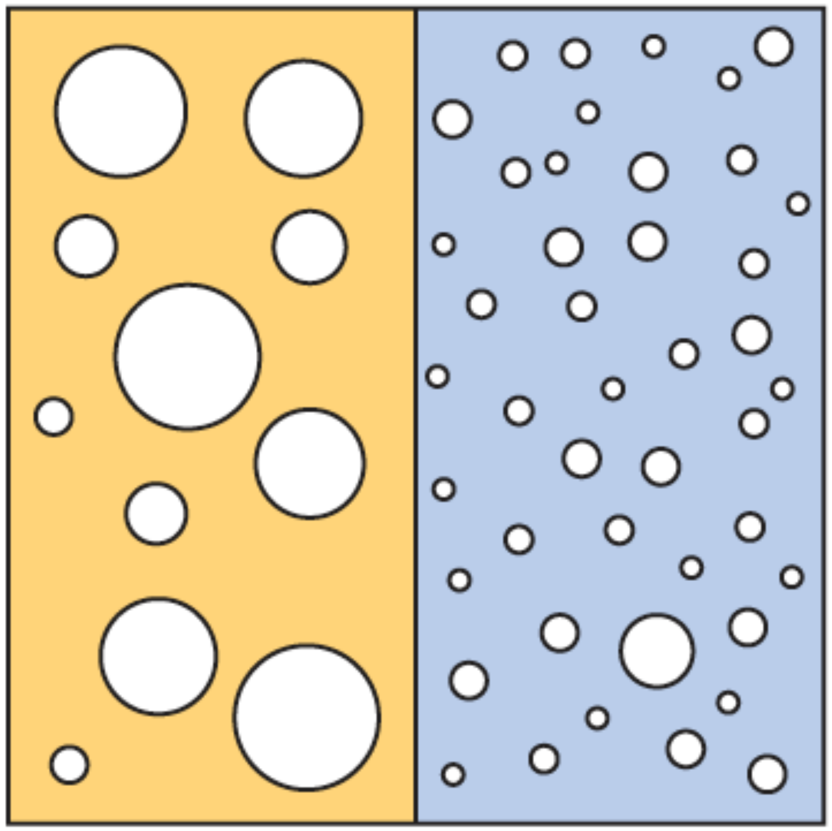


Gonnermann (2015)

Berkeley bubble man

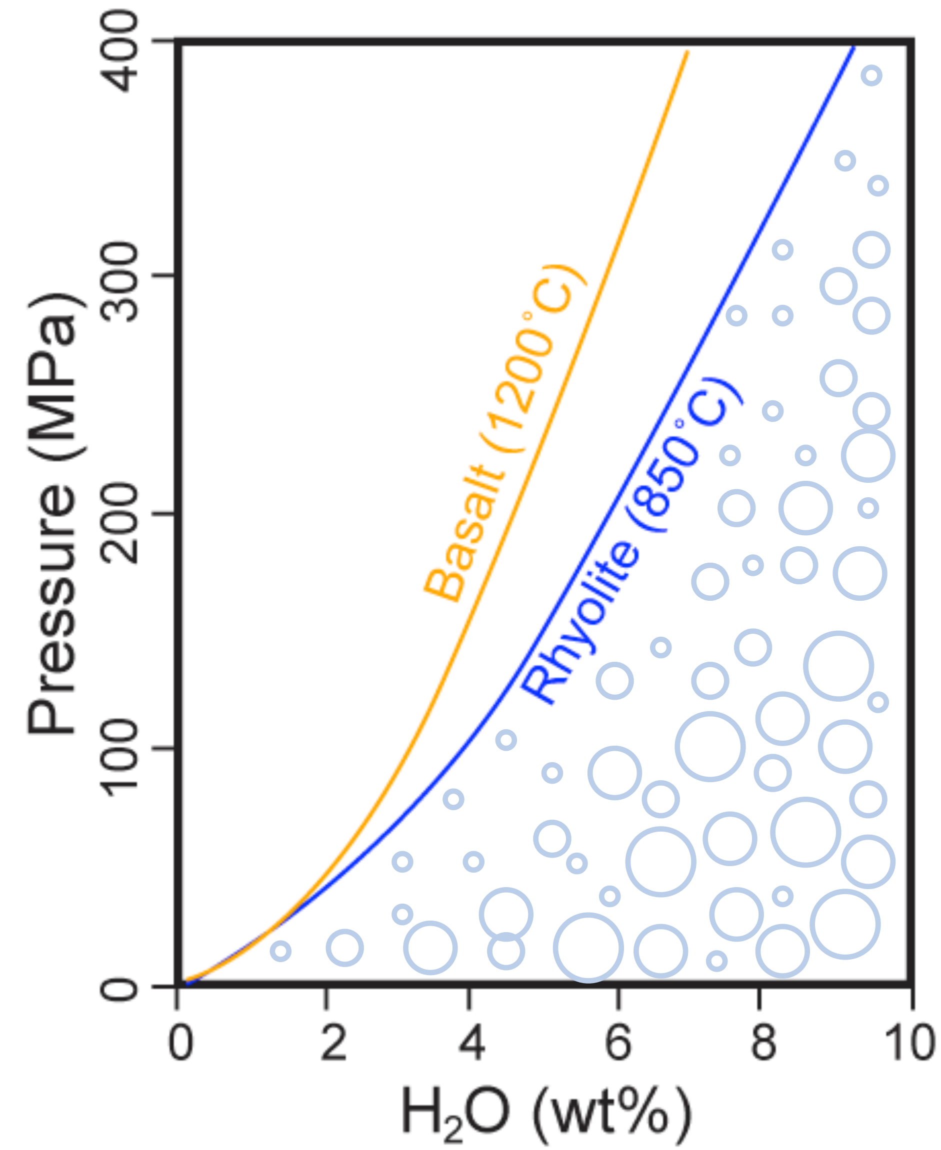
Bubble behavior modulates eruption style

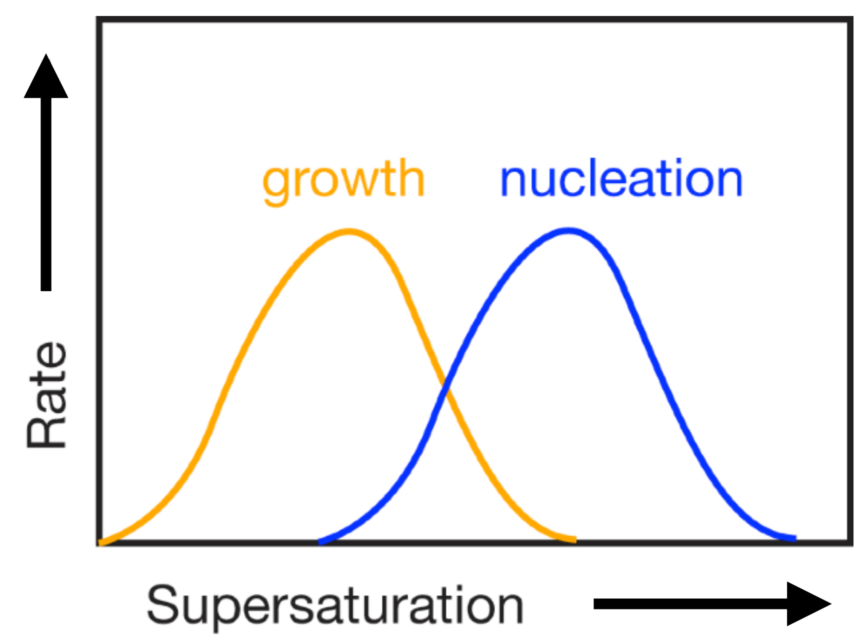
Bubble formation



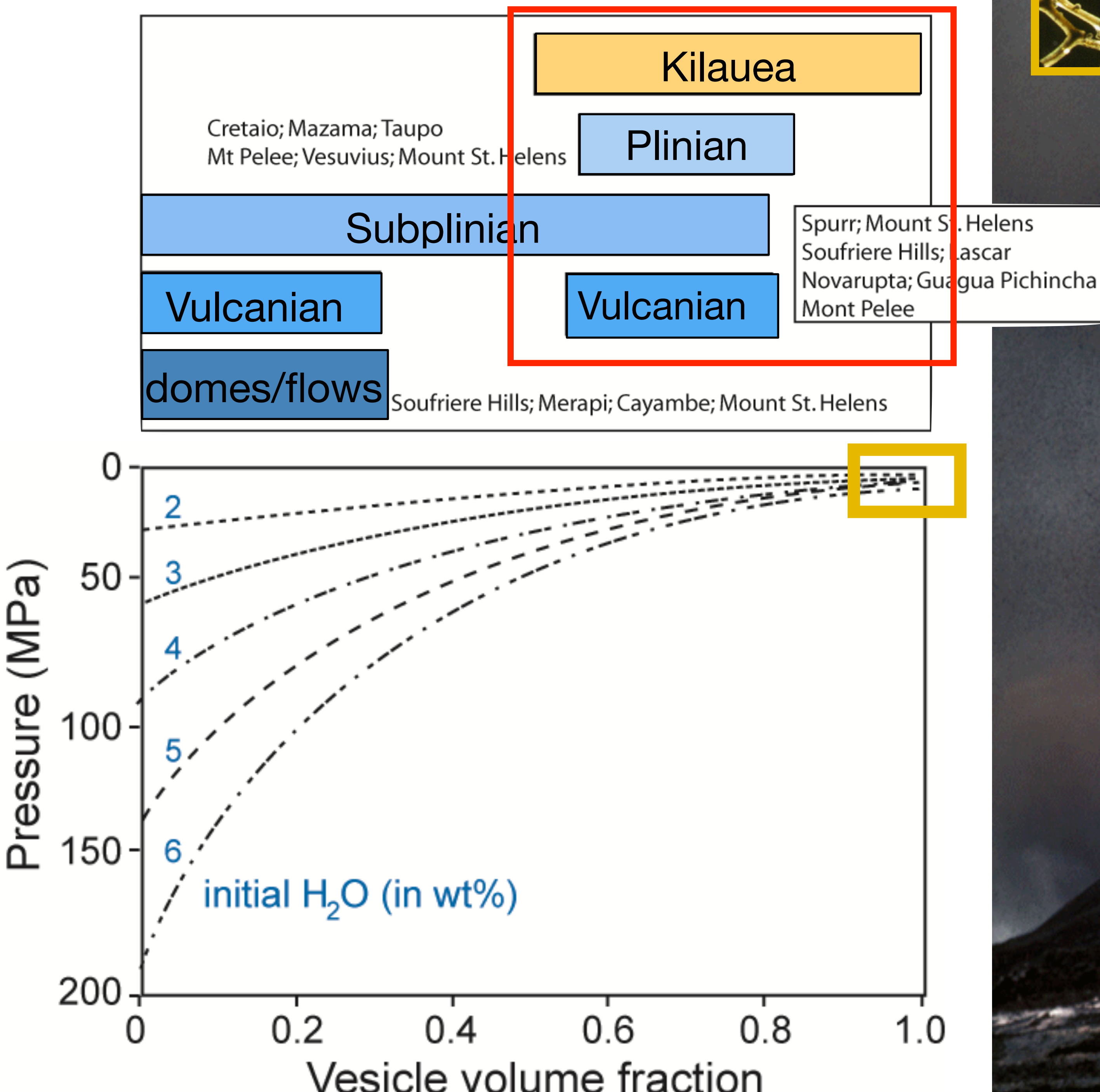
Vesiculation is the inevitable consequence of decompression (magma ascent)

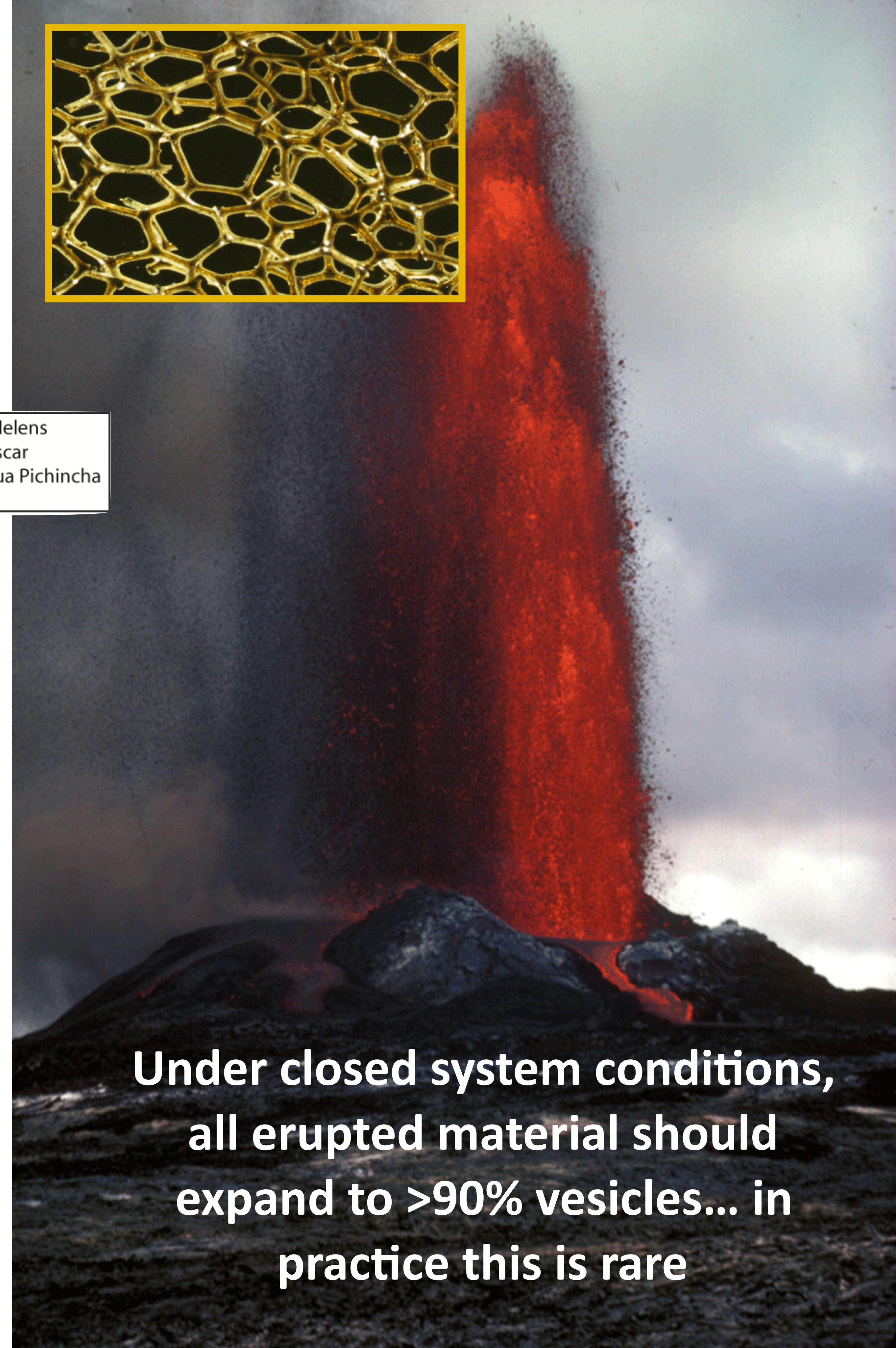
Decompression rate (dP/dt) controls kinetics
(relative importance of bubble nucleation and growth)



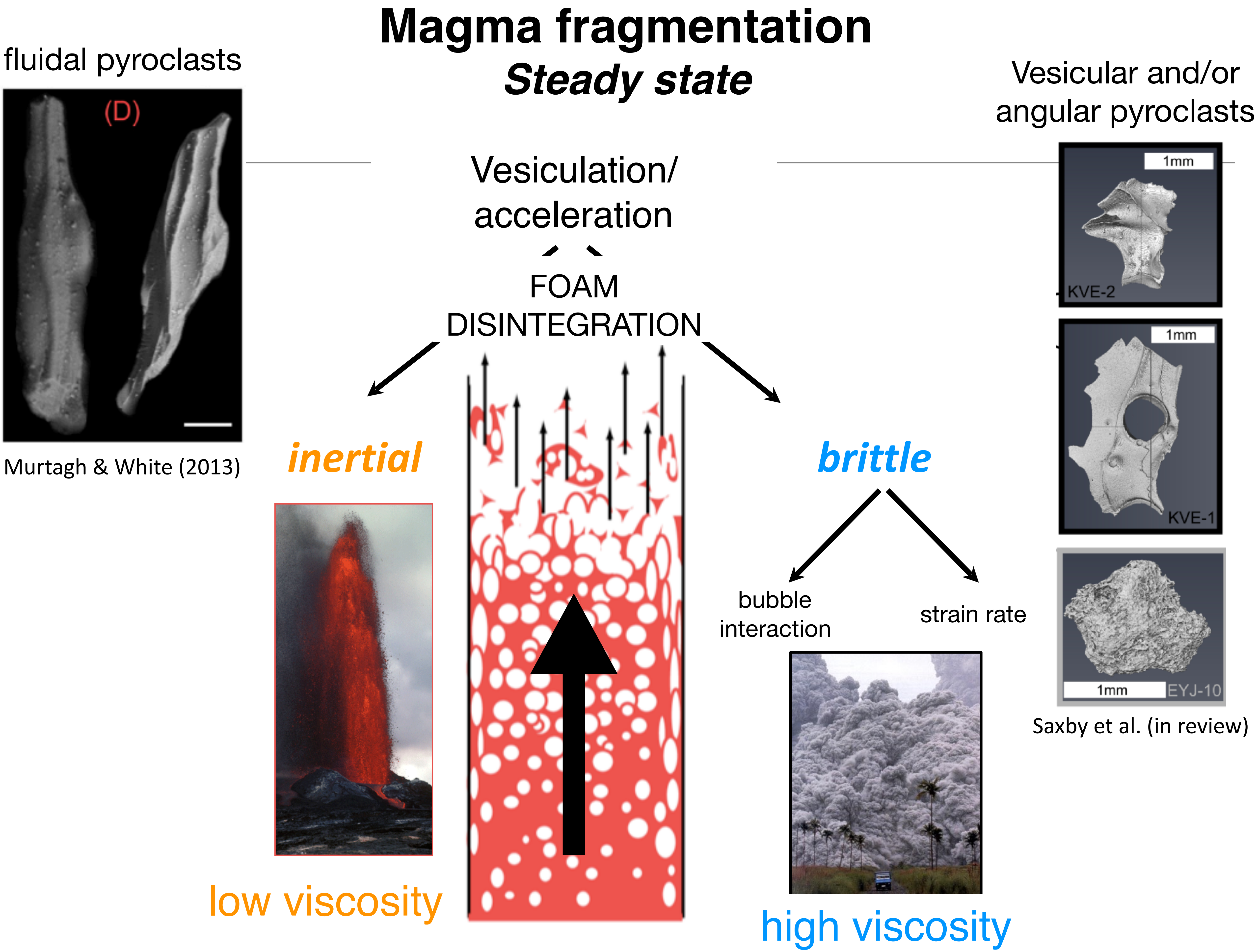


Bubble expansion

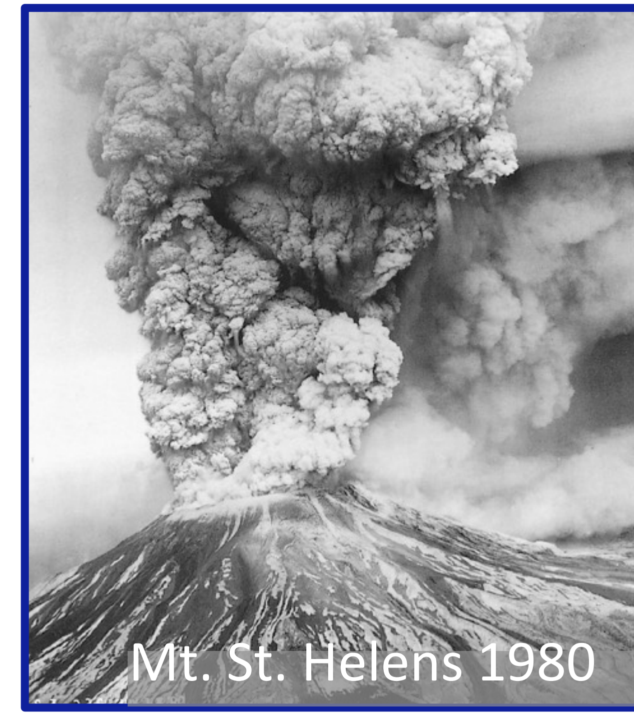




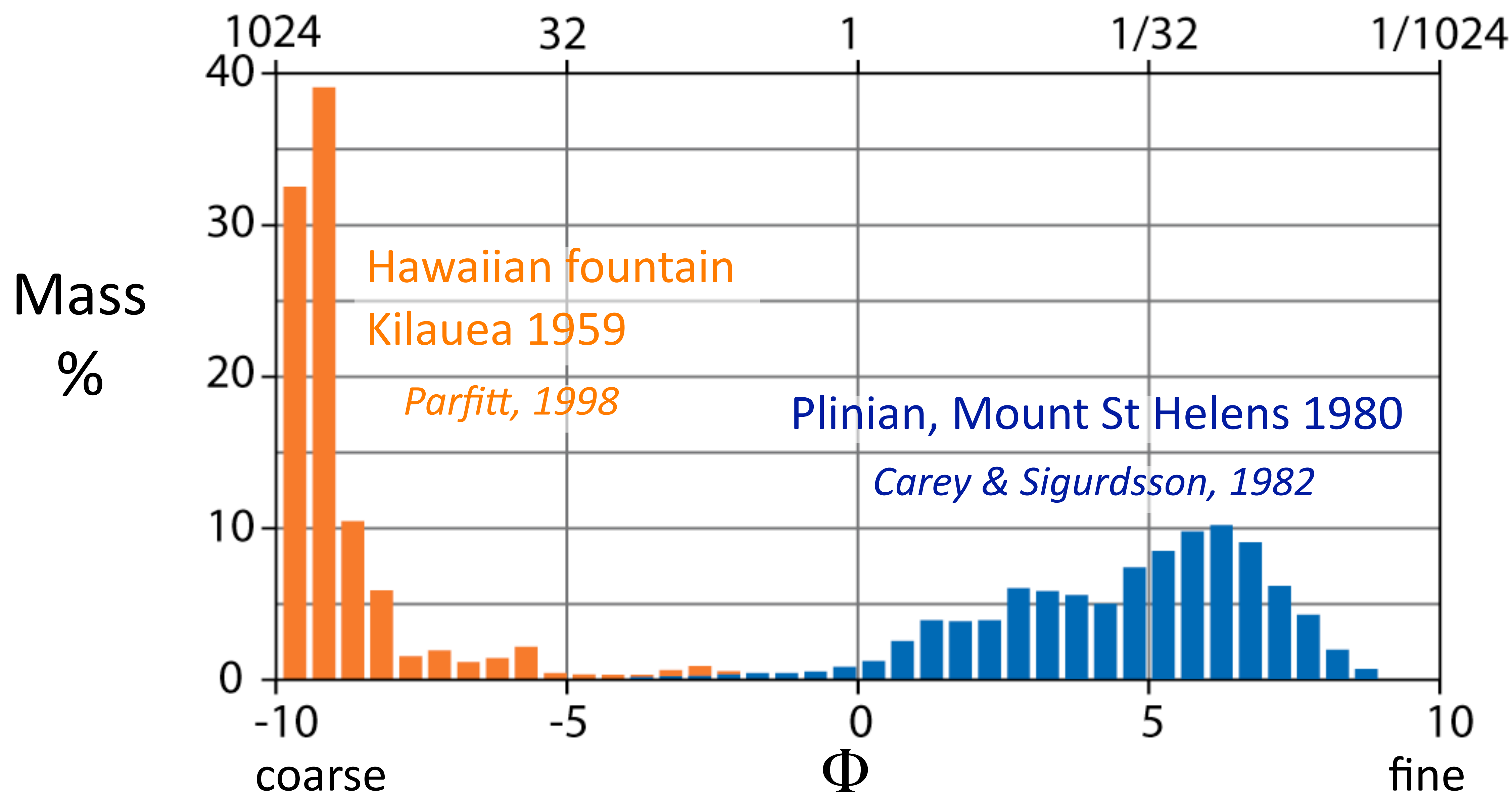
Under closed system conditions, all erupted material should expand to >90% vesicles… in practice this is rare


Magma fragmentation
Steady state
fluidal pyroclasts
(D)
Murtagh & White (2013)
Vesicular and/or angular pyroclasts
1mm
KVE-2
1mm
KVE-1
1mm
EYJ-10
Saxby et al. (in review)
Vesiculation/ acceleration
FOAM DISINTEGRATION
inertial
brittle
bubble interaction
strain rate
low viscosity
high viscosity

Fragmentation style affects the size distribution of pyroclasts

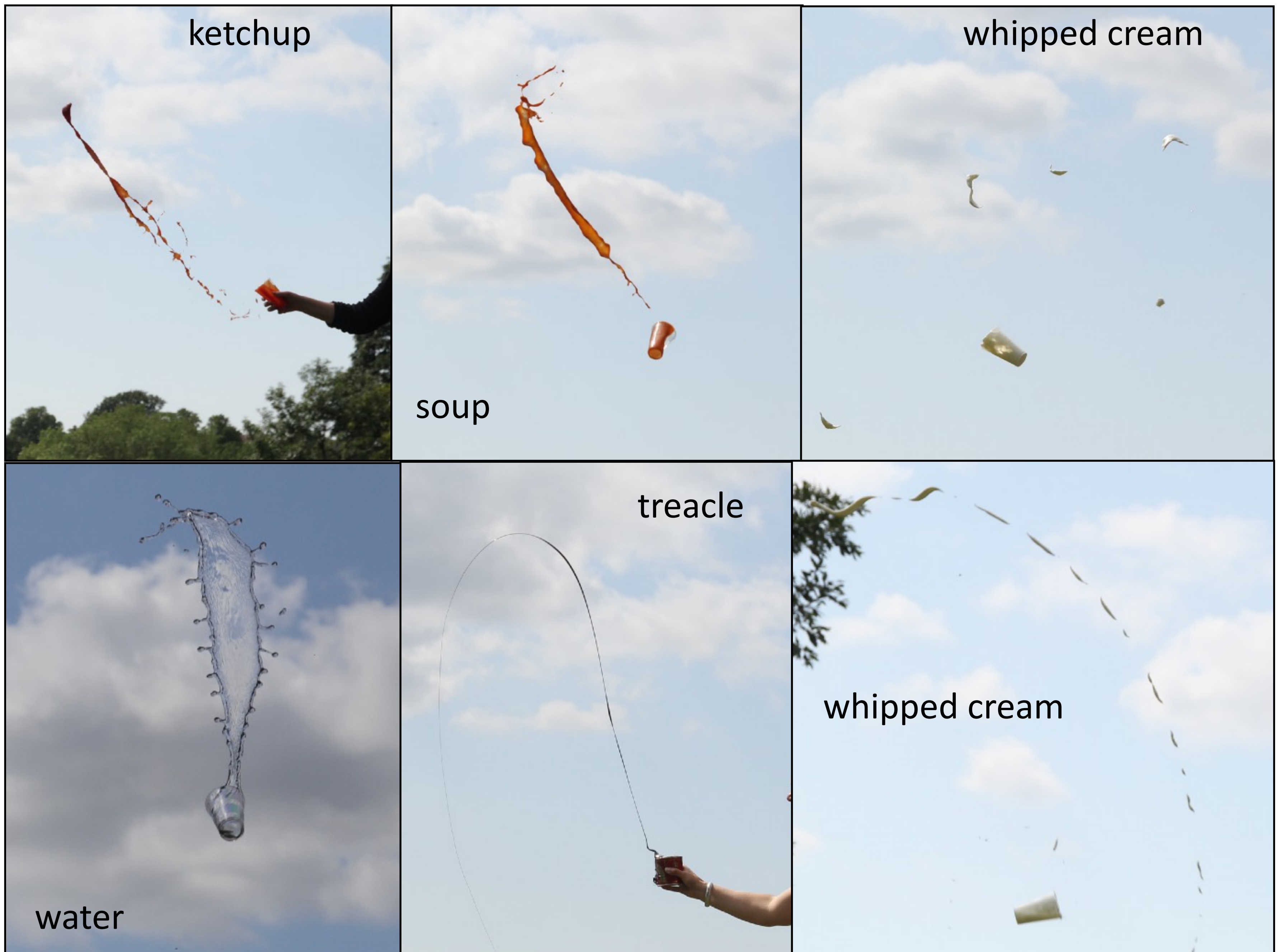


Diameter in mm = $2^{-\Phi}$



Inertial fragmentation

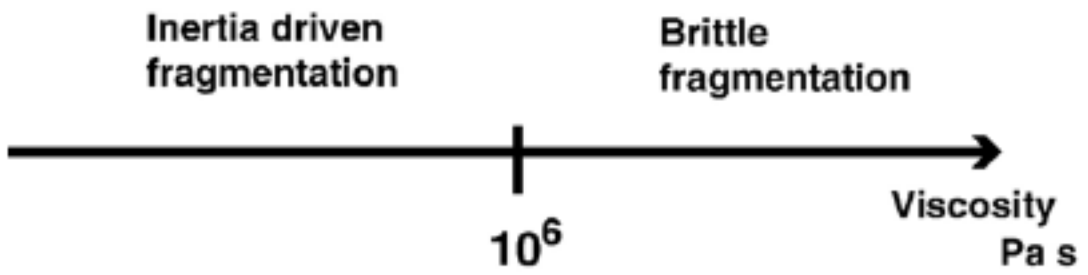
Photo by Bruce Omori



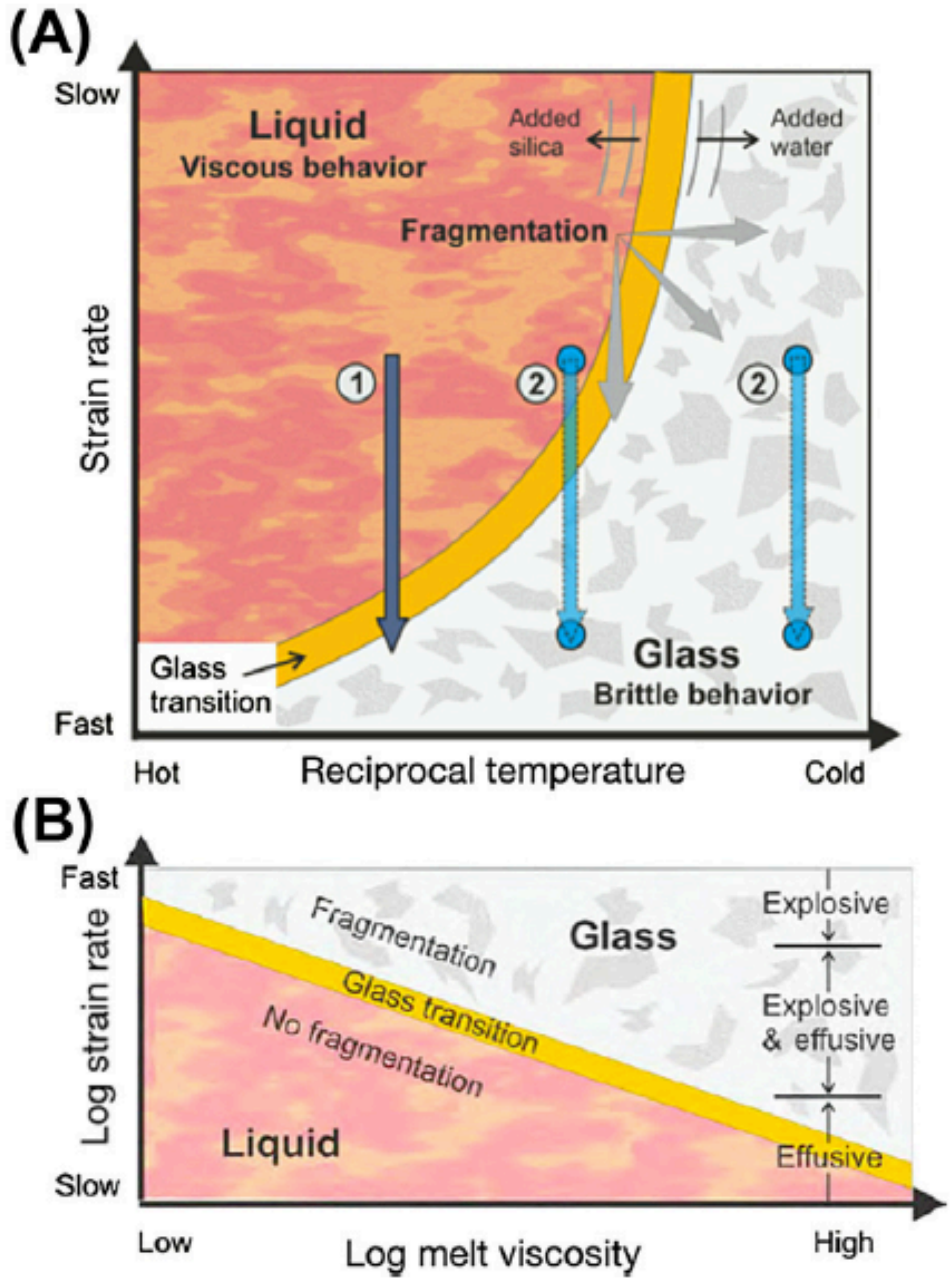
Fragmentation process and products are not well understood for complex fluids

Lunchtime activity?

Brittle fragmentation



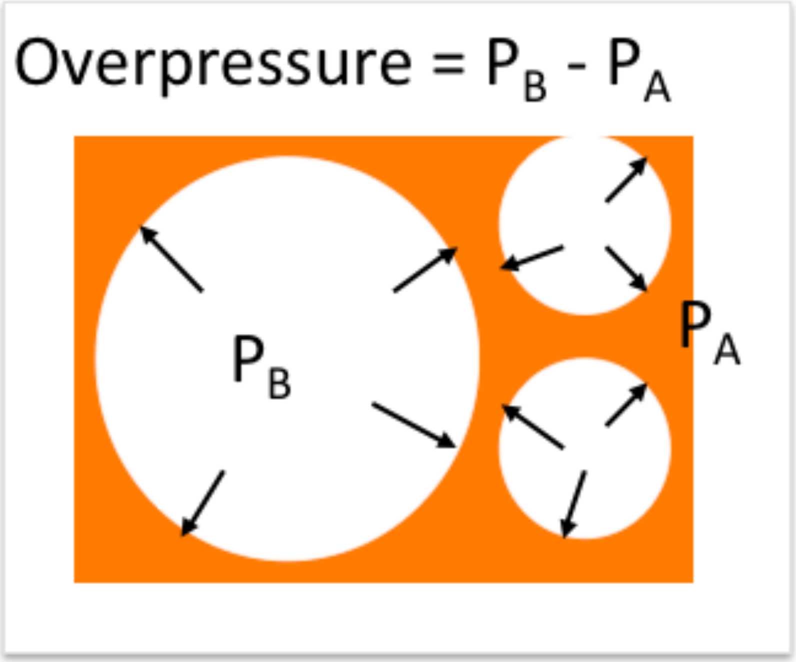
Namiki and Manga (2008)



Cashman and Scheu (2015)

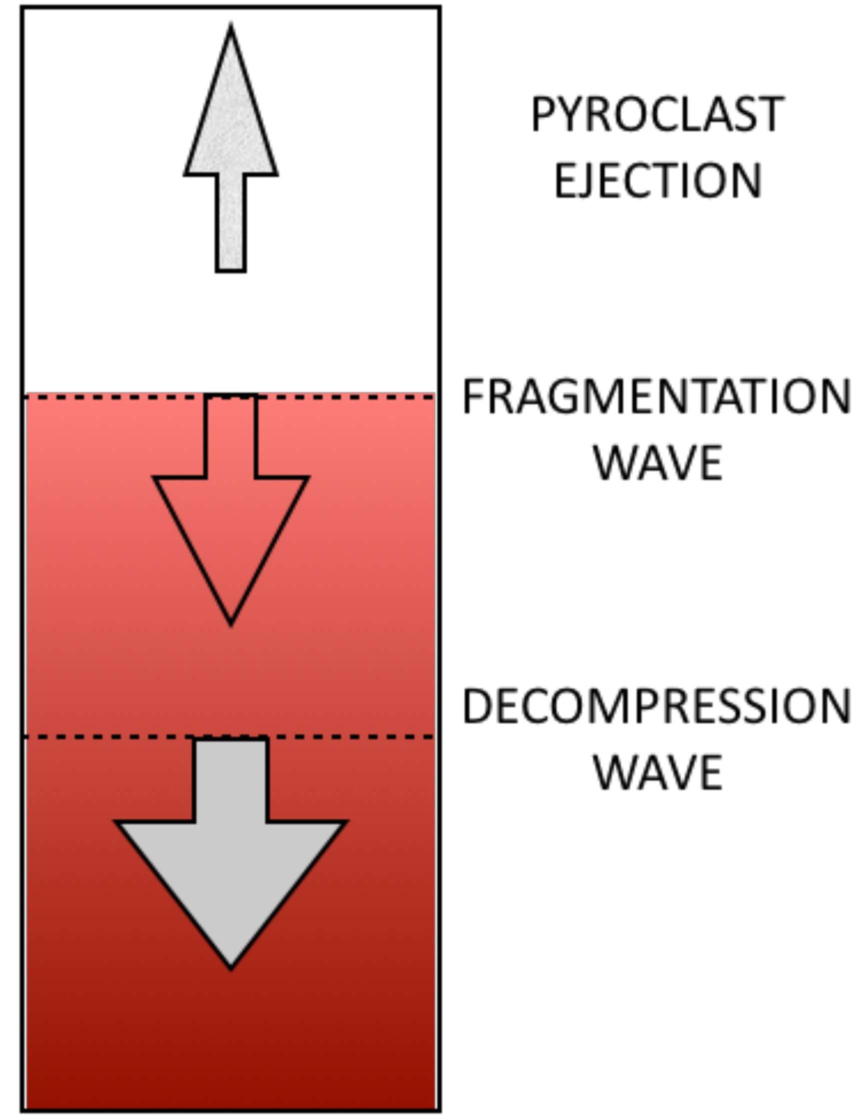
Transition from inertial to brittle fragmentation occurs when melt crosses the glass transition

Decompression-driven bubble expansion is one cause of high strain rates



Fragmentation can also be "top-down"

dP/dt ≠ magma ascent rate



Associated with unsteady conditions during eruption initiation, Vulcanian explosions and flank failures

Fragmentation by thermal stresses

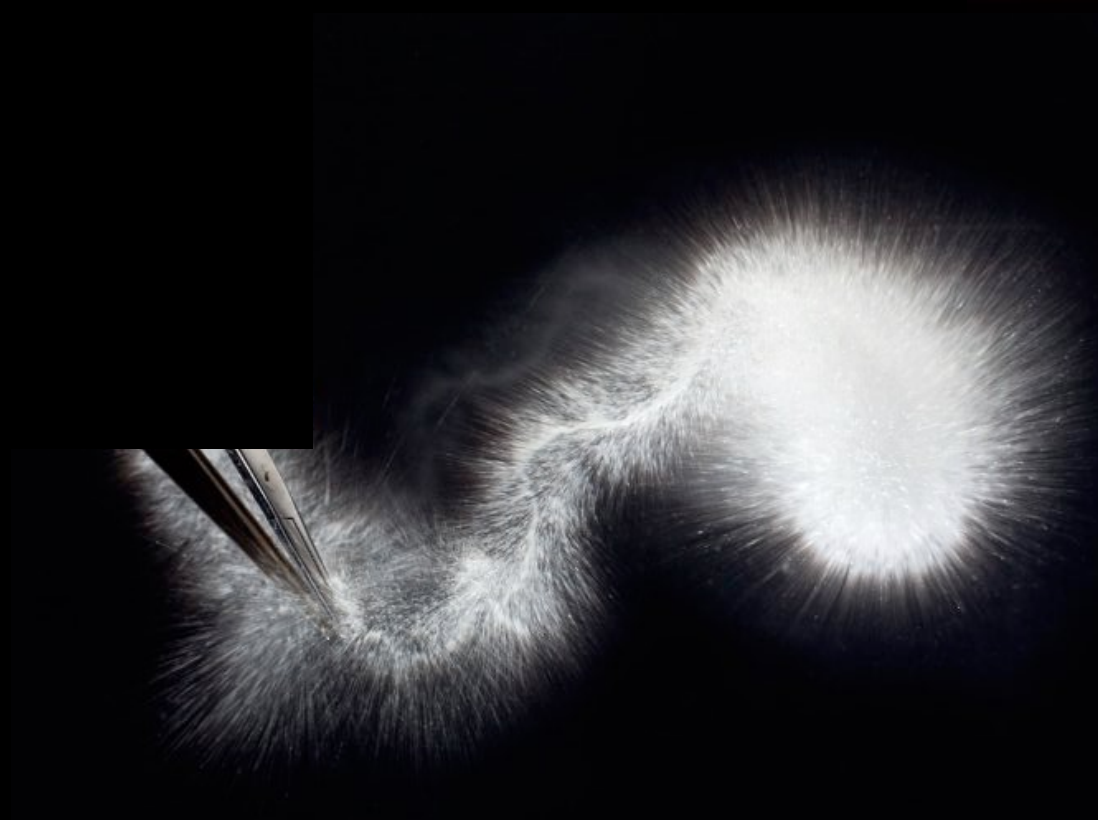
Rapid quenching in water: residual stresses are quenched into the glass

PRINCE RUPERT'S DROPS

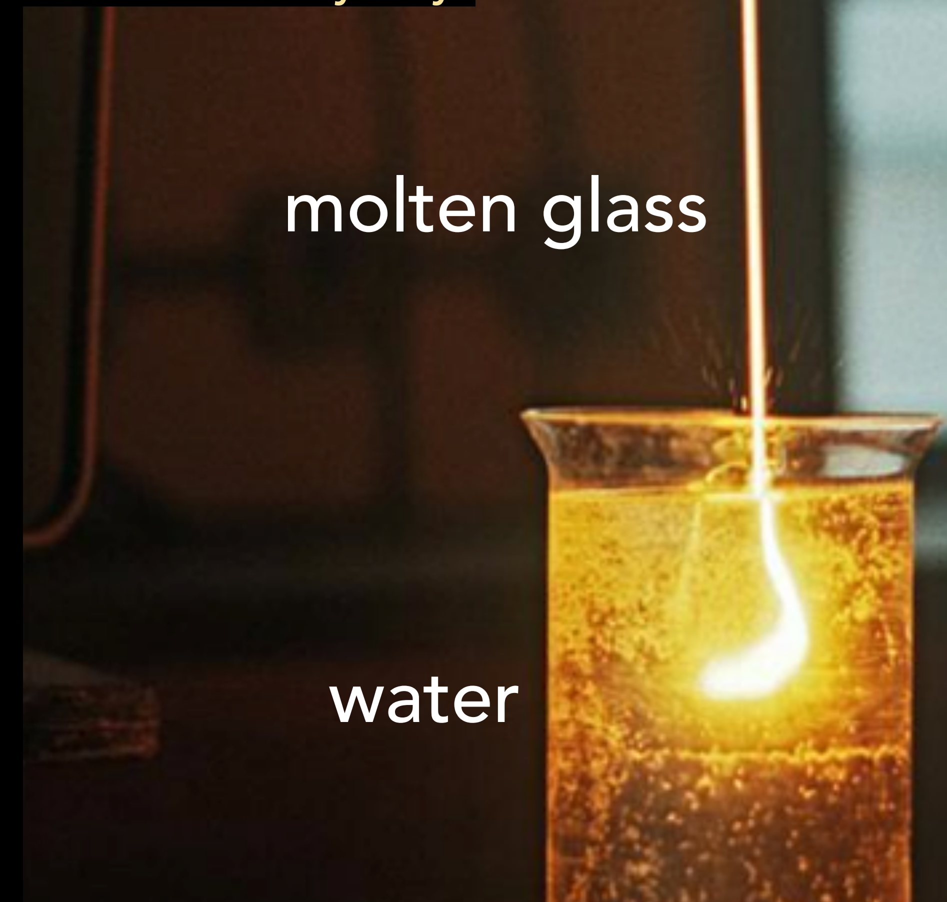
PRINCE RUPERT'S DROPS

These large stresses cause explosive fragmentation when released

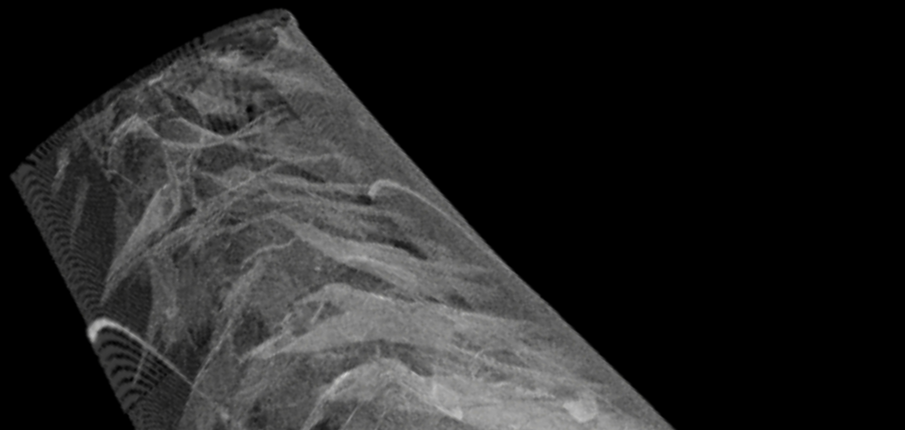
from “Smarter Every Day”

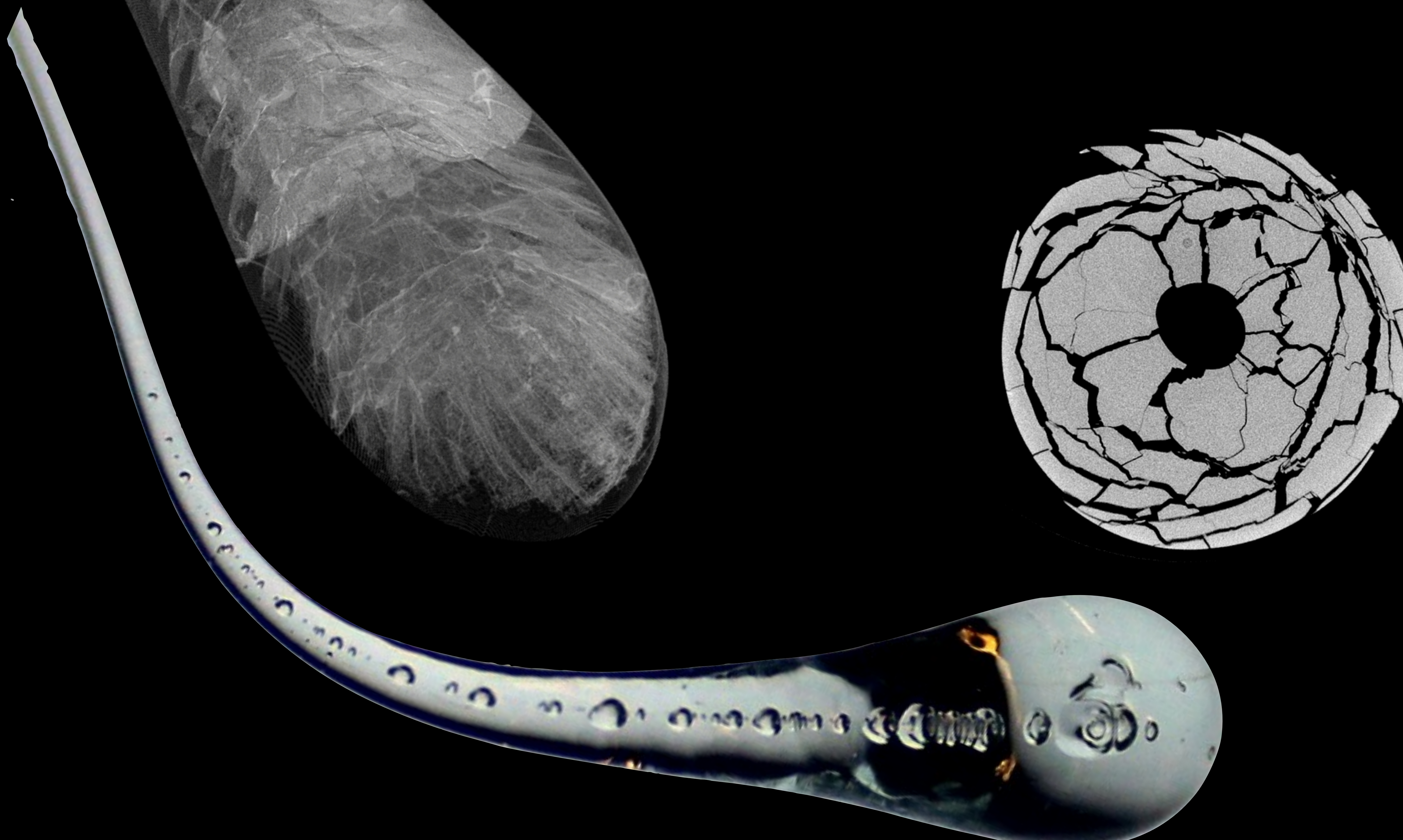


another fun video

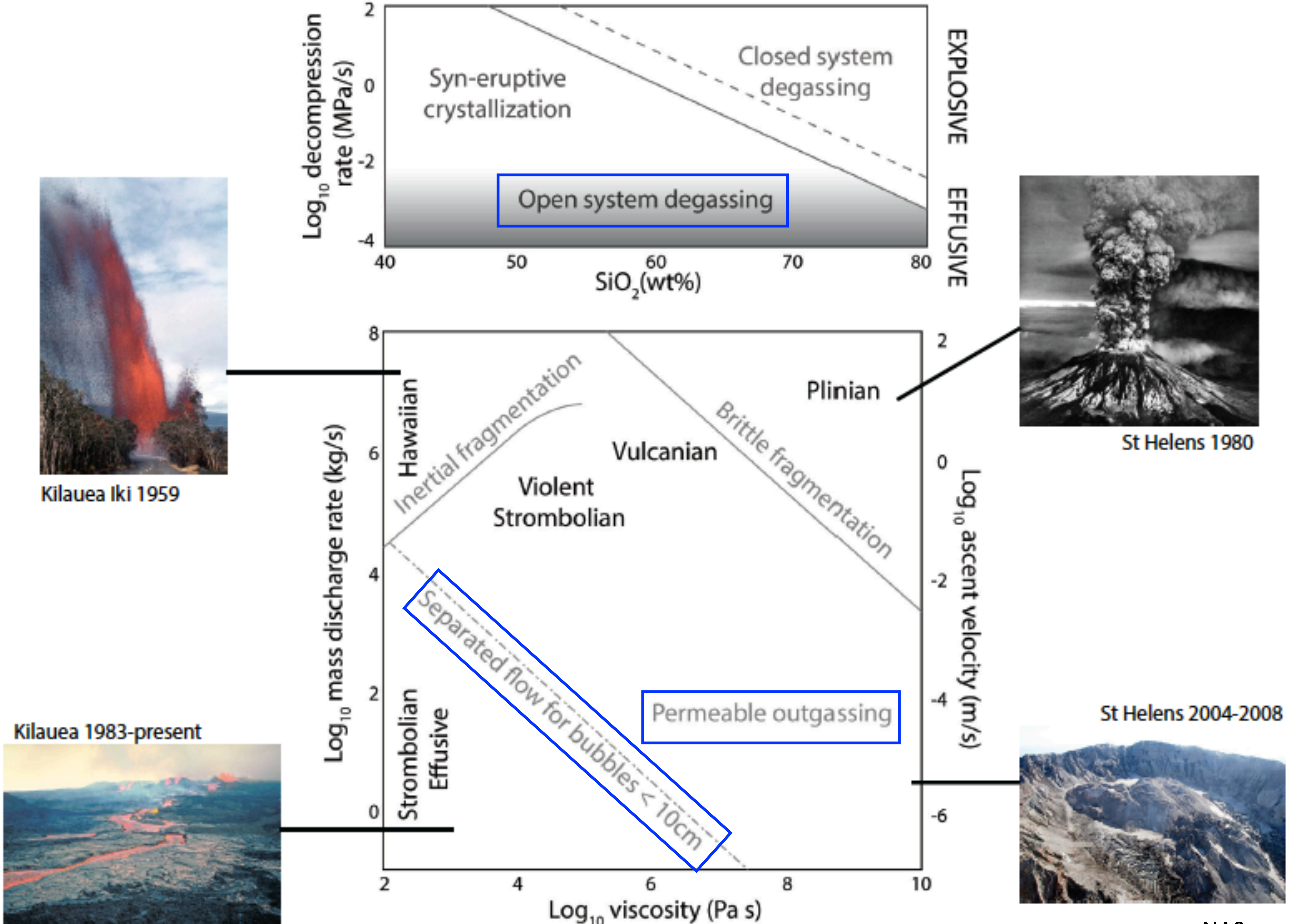


Fragmented particle shapes reflect the complex stress field caused by outer quenching and internal bubbles



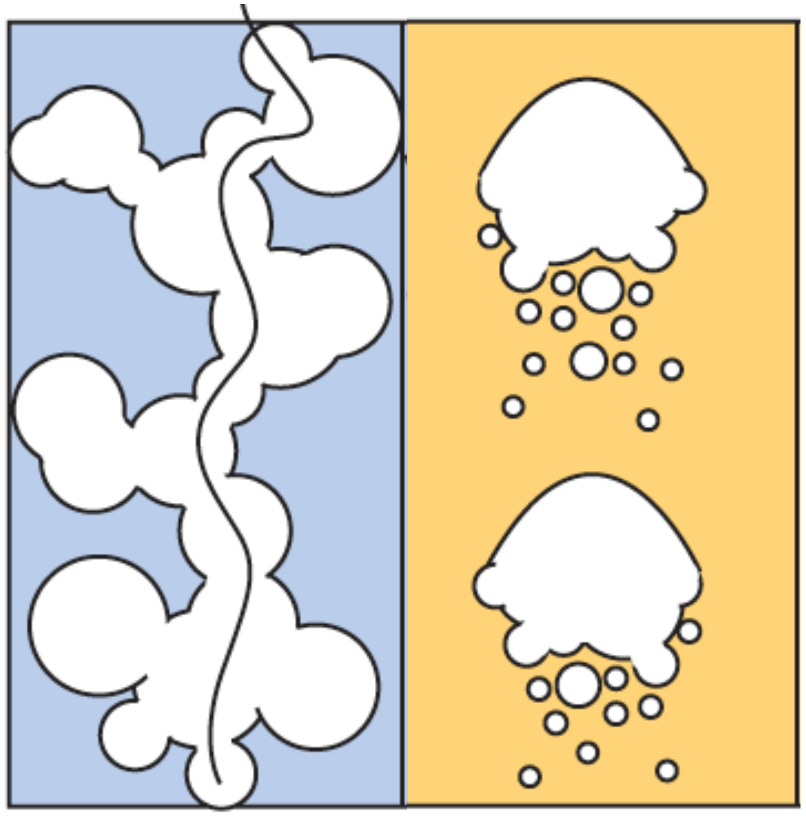


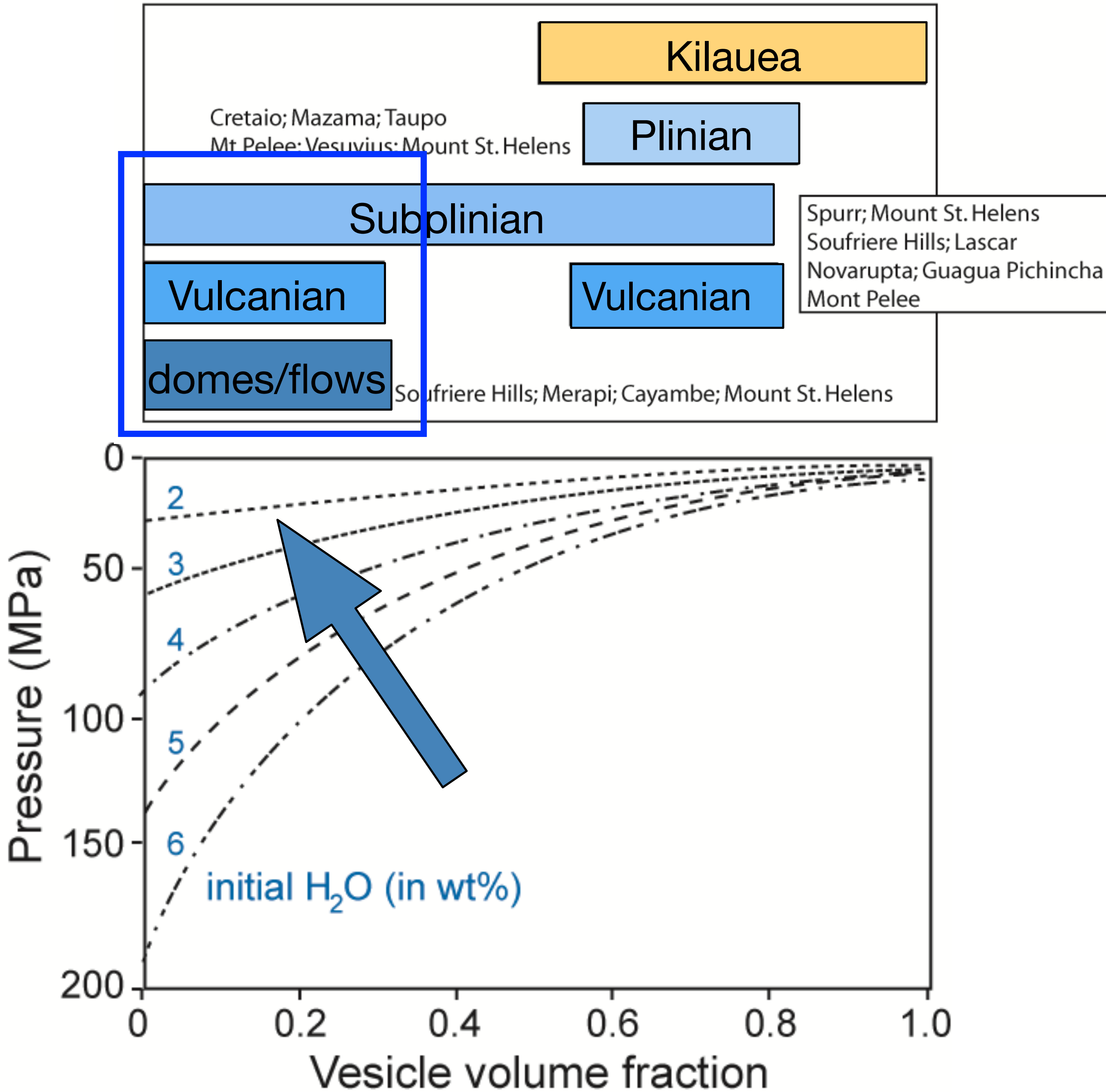
Degassing



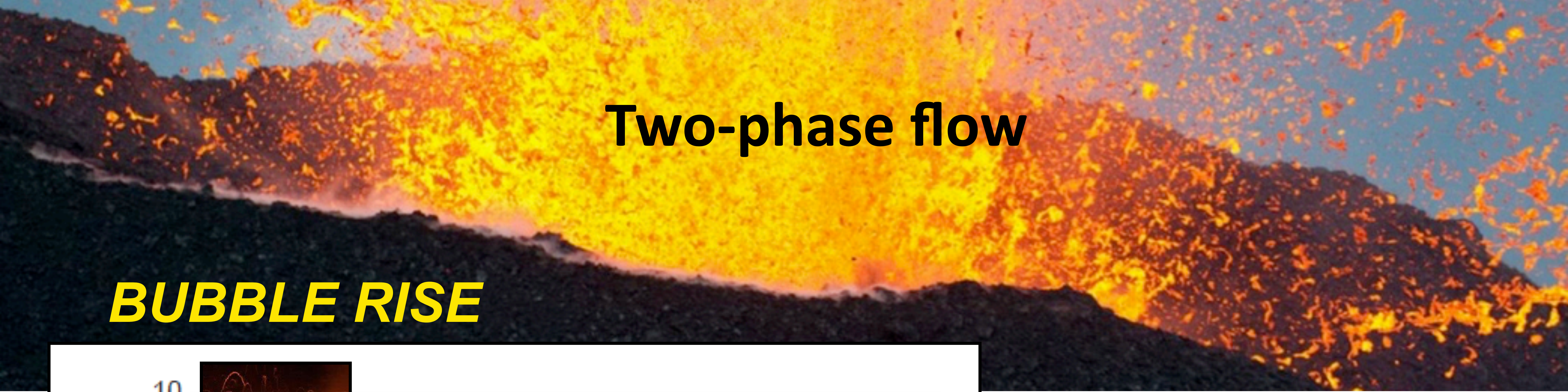
NAS report

Degassing



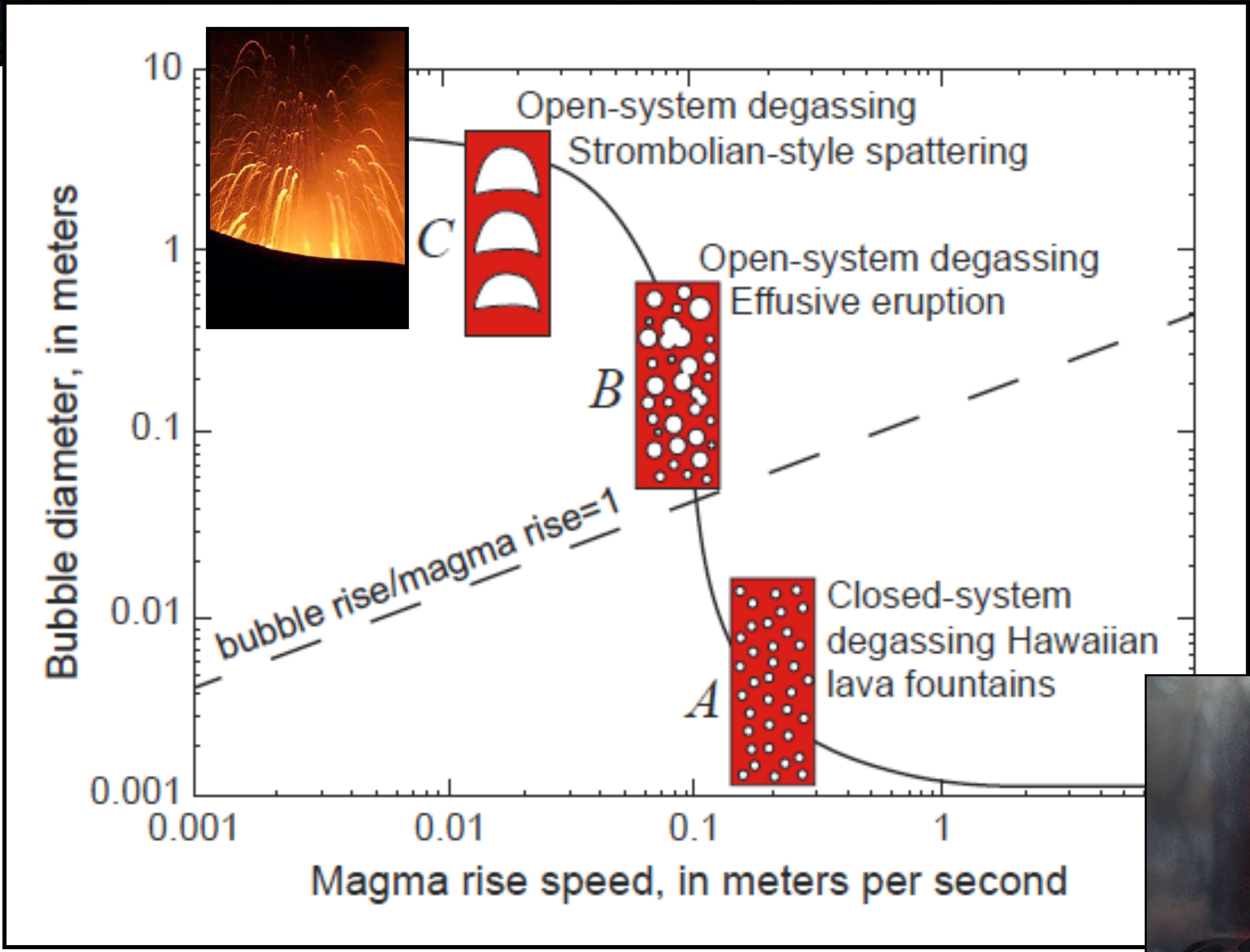


Products of lower intensity or intermittent eruptive activity have a wide vesicularity range; this requires pre- or syn-eruptive gas loss



Two-phase flow

BUBBLE RISE

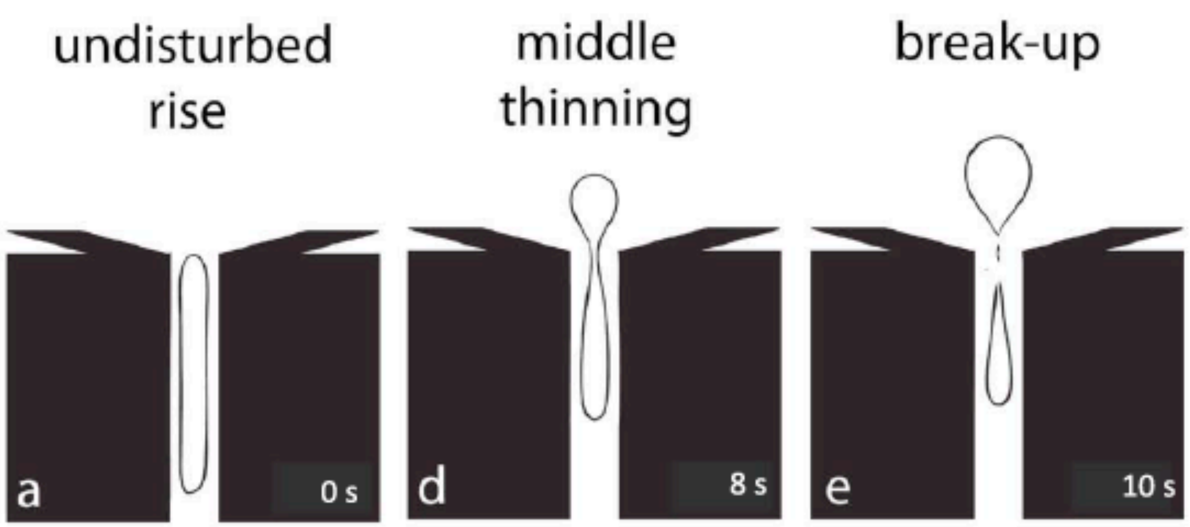


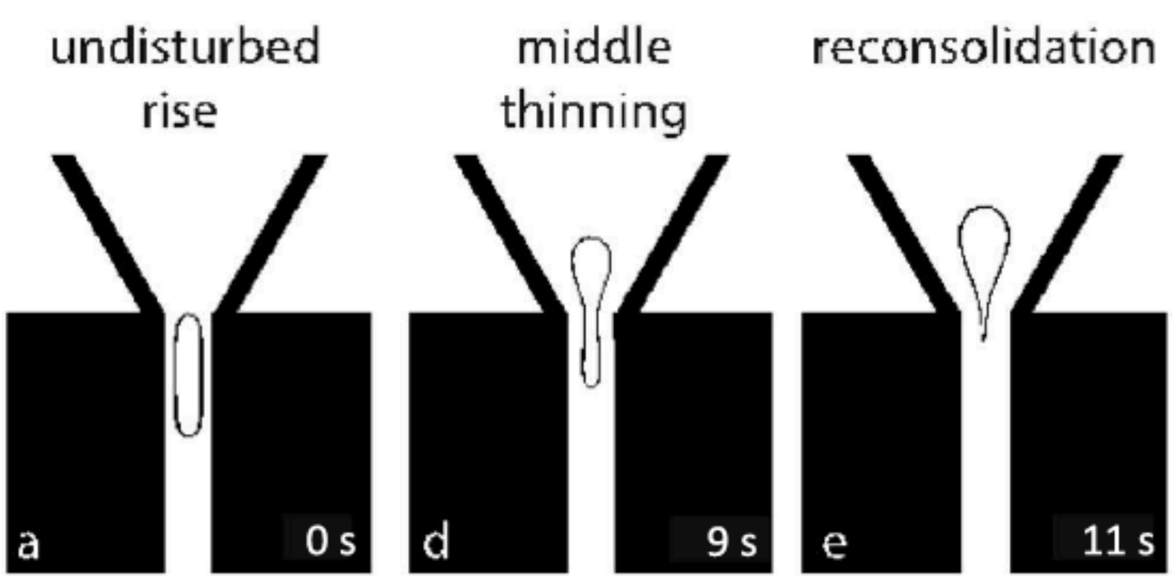
Mangan et al. (*2014*)

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

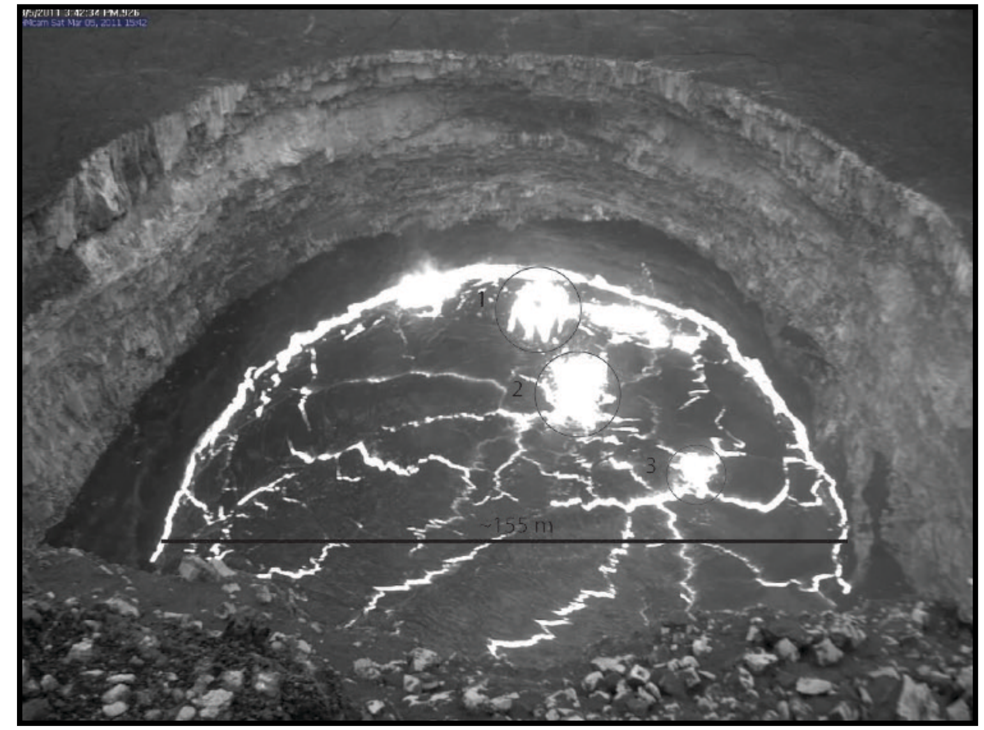
CLOSED SYSTEM

Stability of large (conduit-filling) bubbles depends on geometry

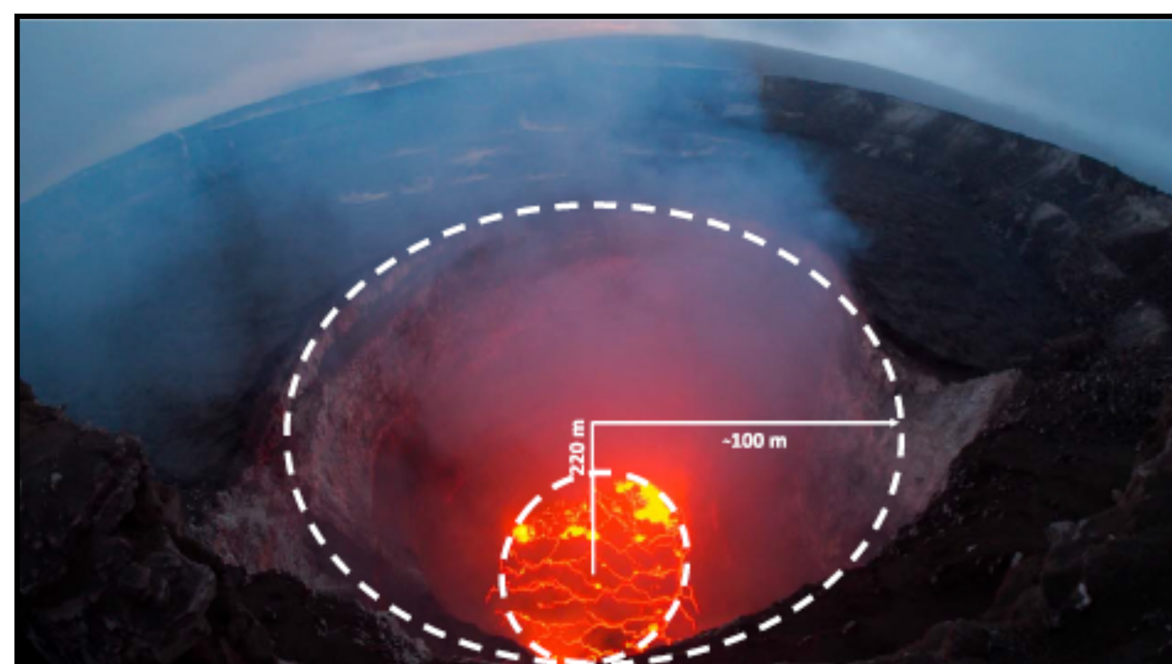


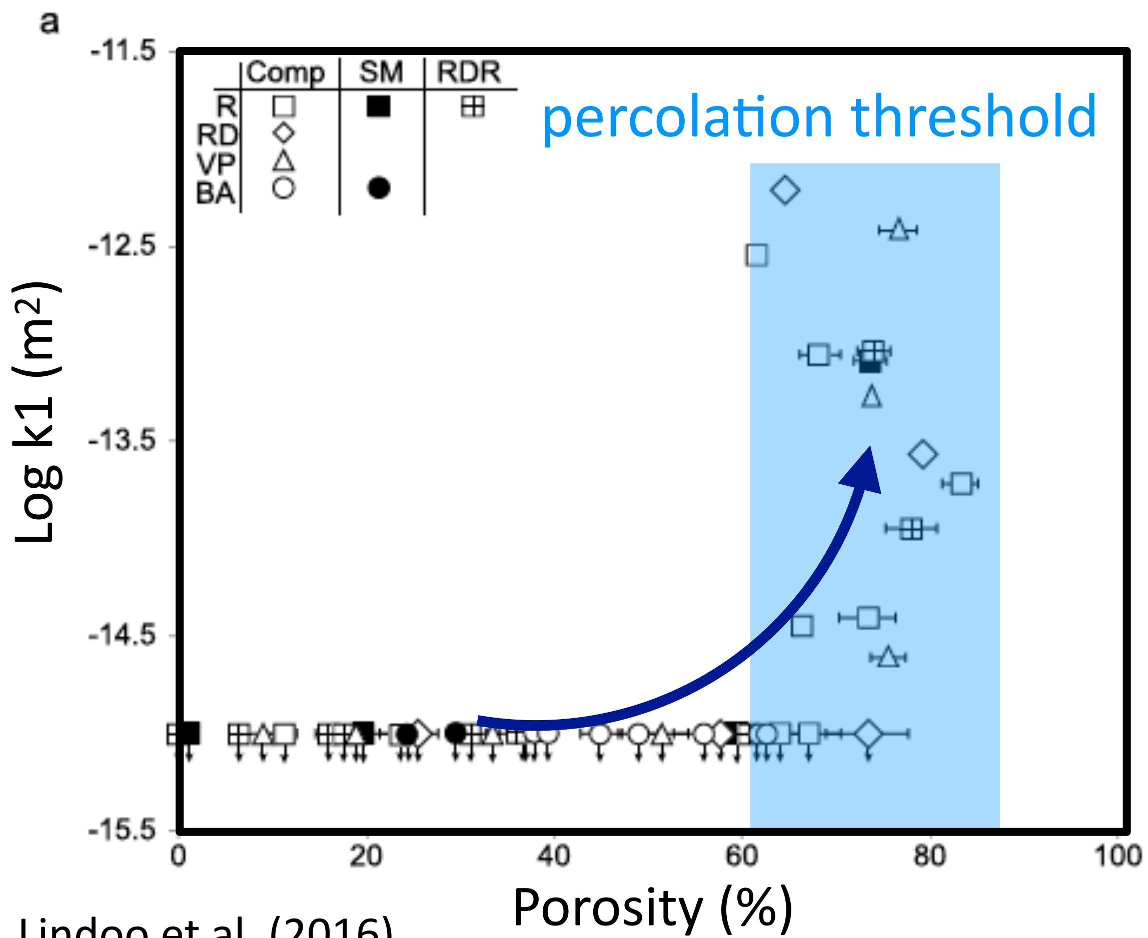


Qin et al. (2018)



Controlled by viscosity and flare angle





Lindoo et al. (2016)

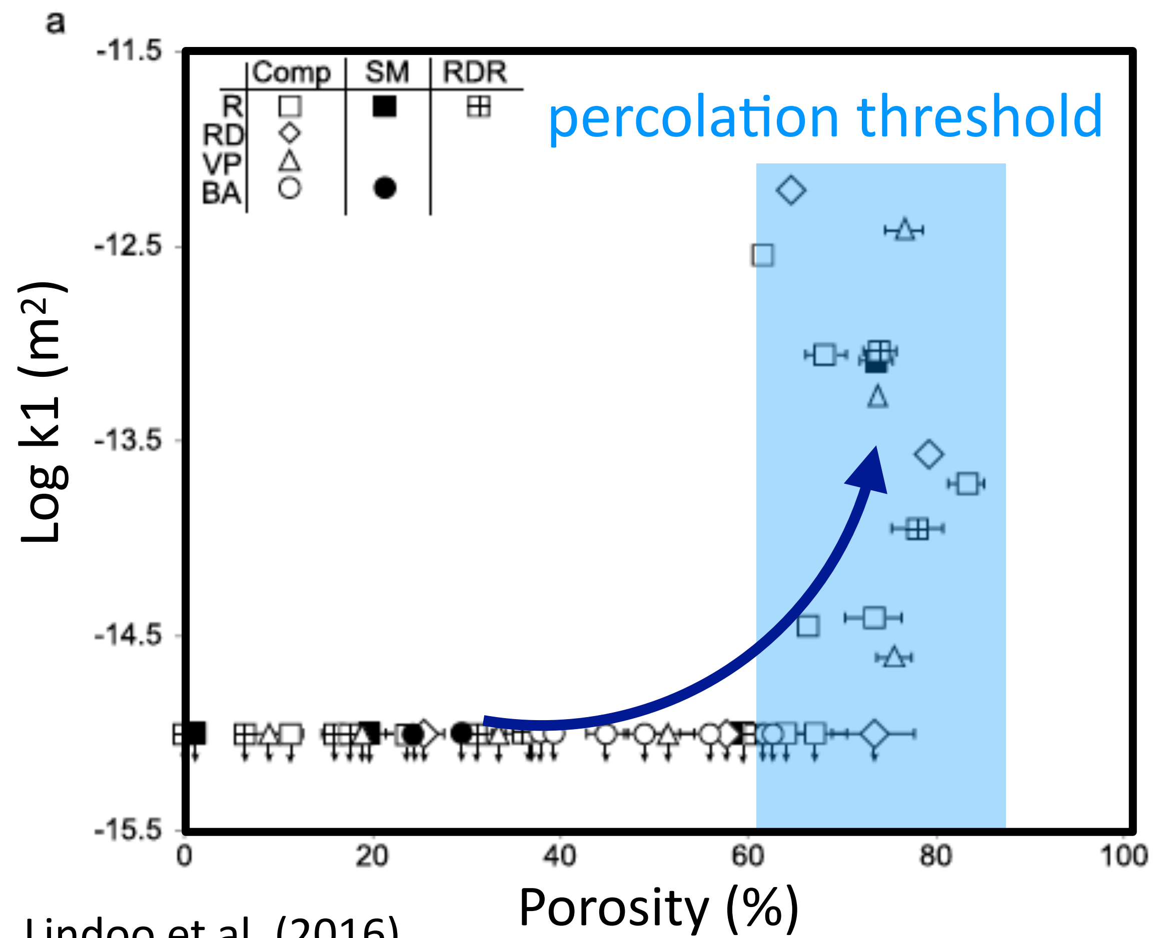
Permeable flow

Melt viscosity does not permit bubble rise

Bubbles expand and coalesce

***Requires melt film thinning and rupture (*time*)**

Permeable flow



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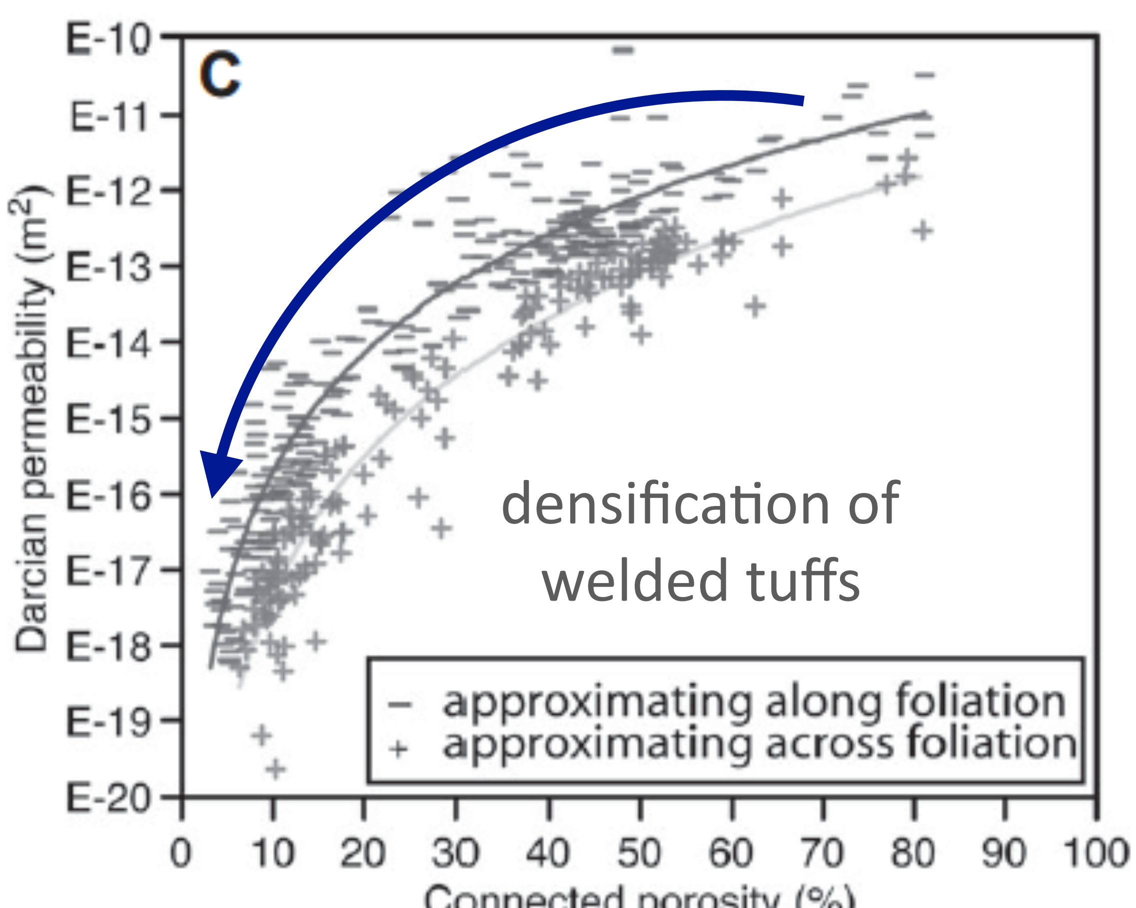
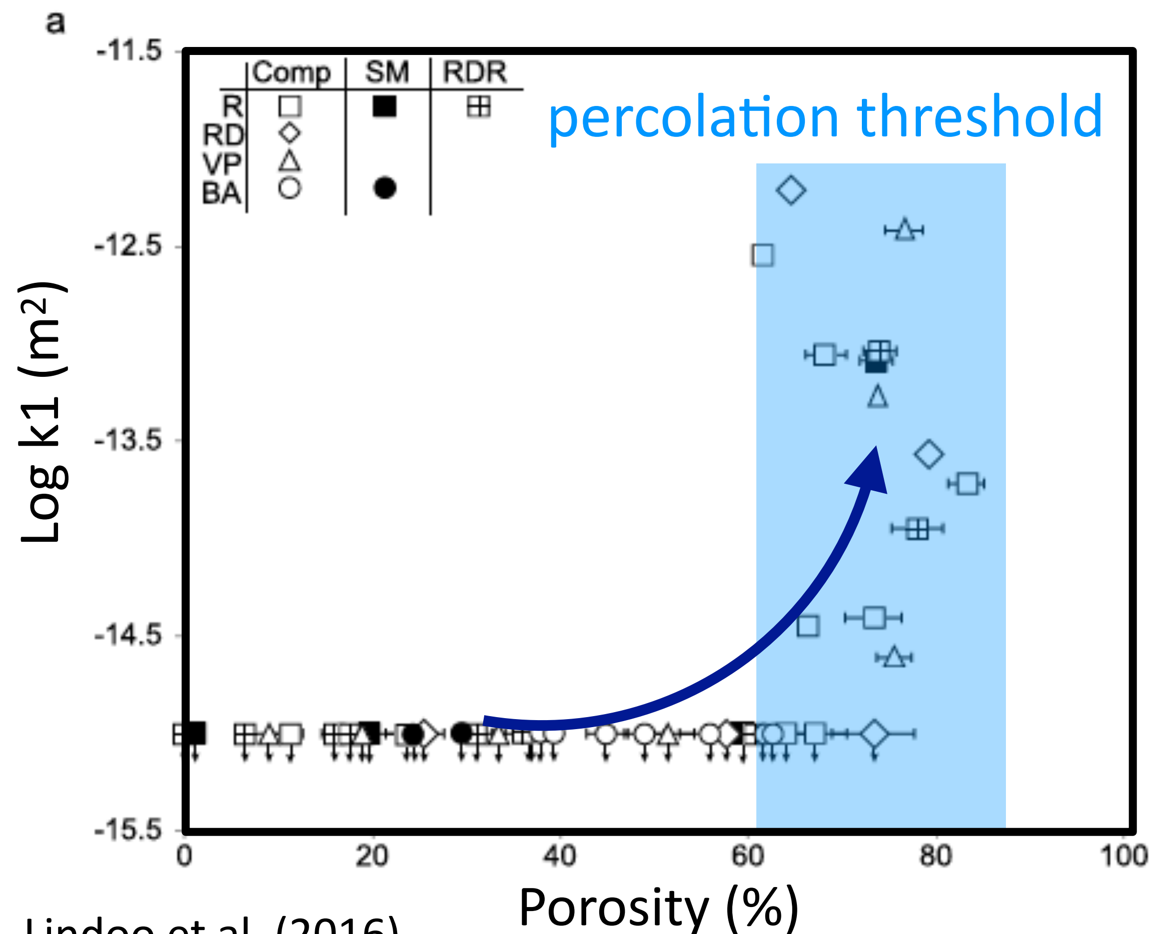


Wright et al. (2014)

Once connections formed, magma (lava) can remain permeable as it loses pore space (densifies)

Permeable flow

Leads to hysteresis vesiculating ≠ densifying



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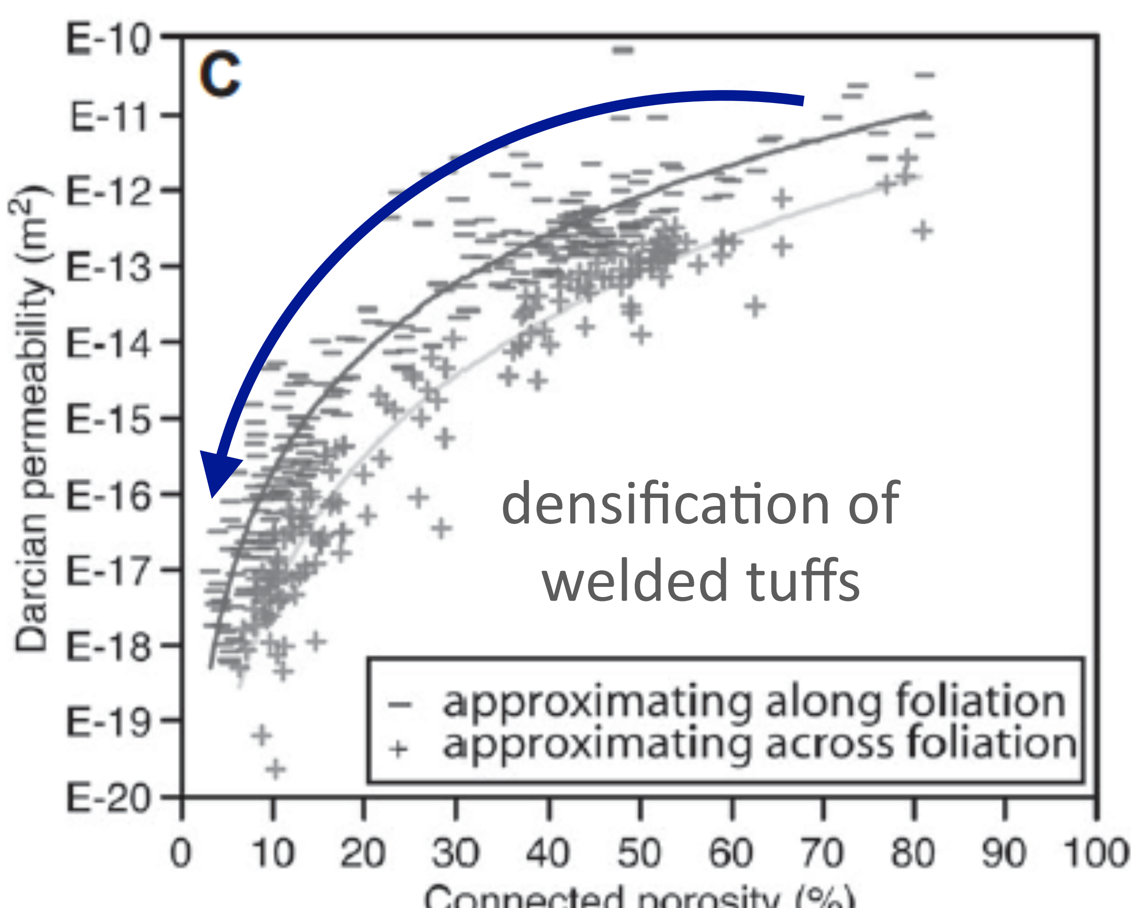

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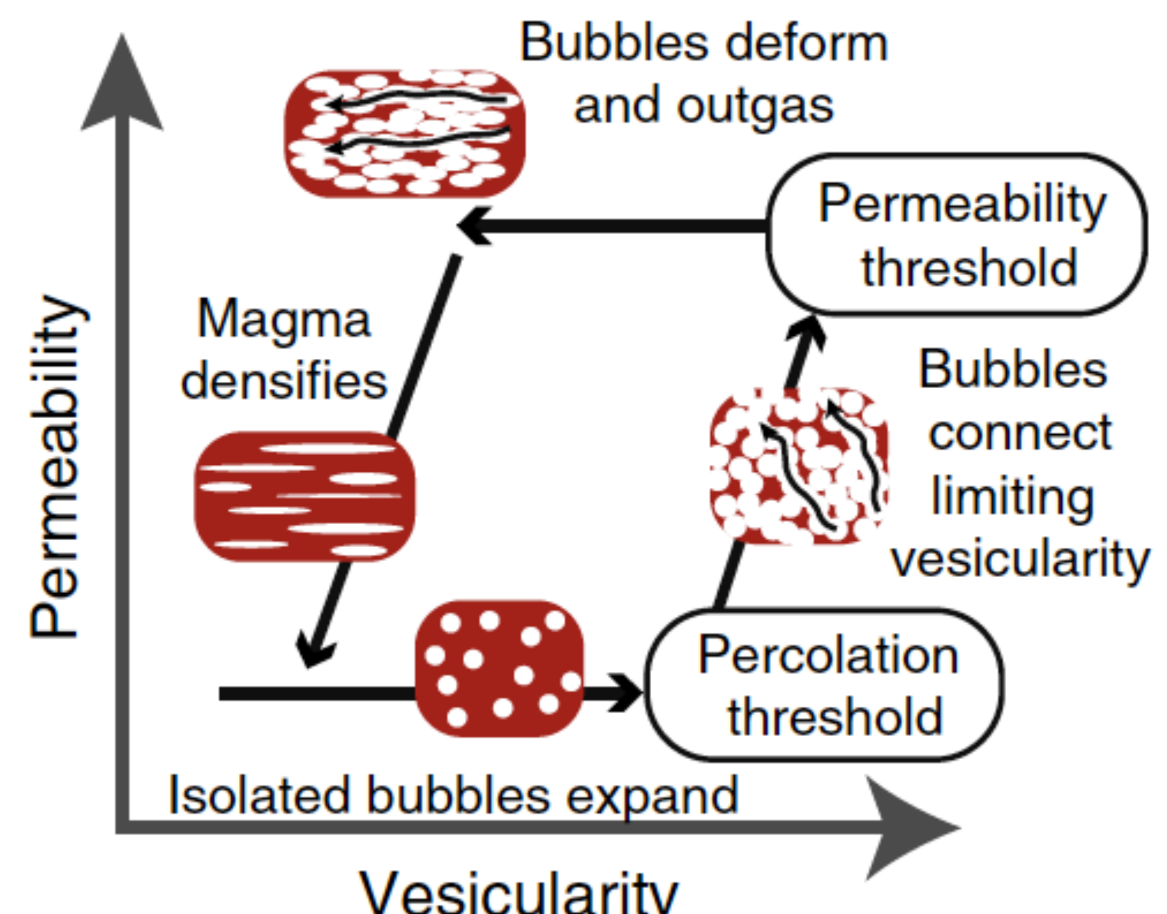
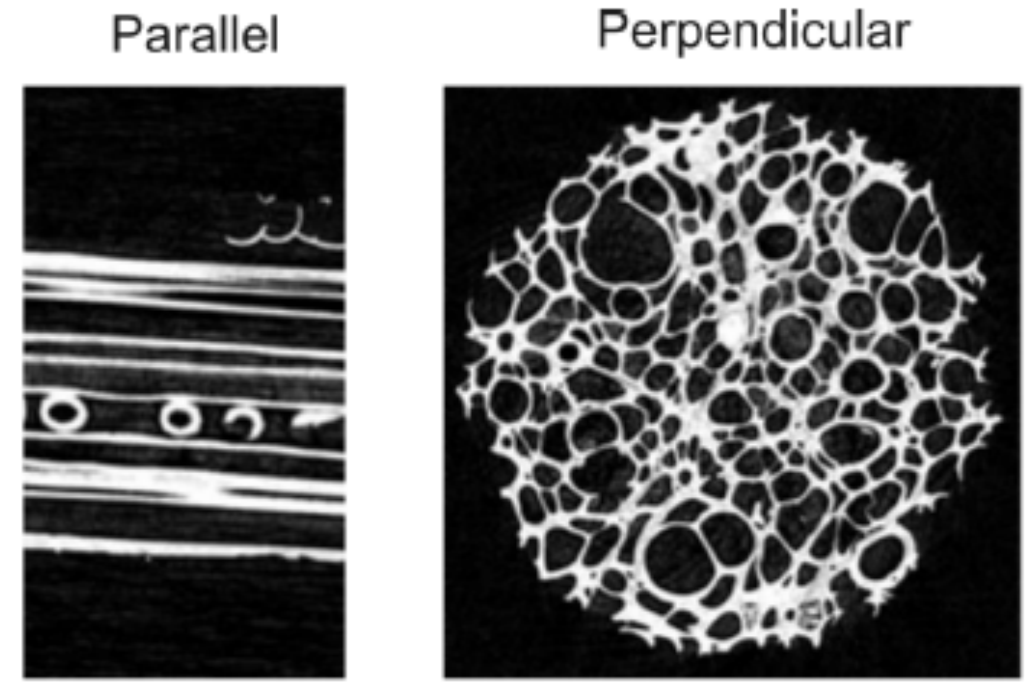
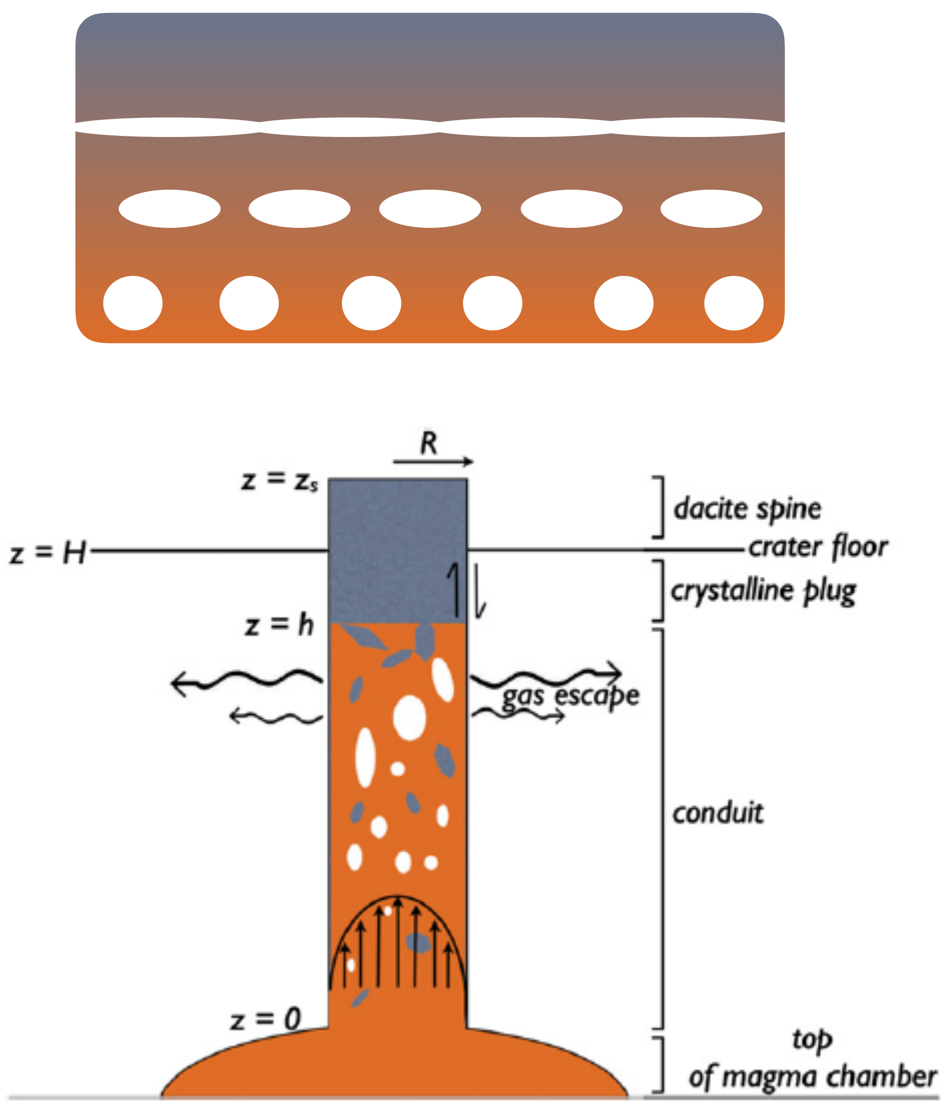


Cassidy et al. (2018)

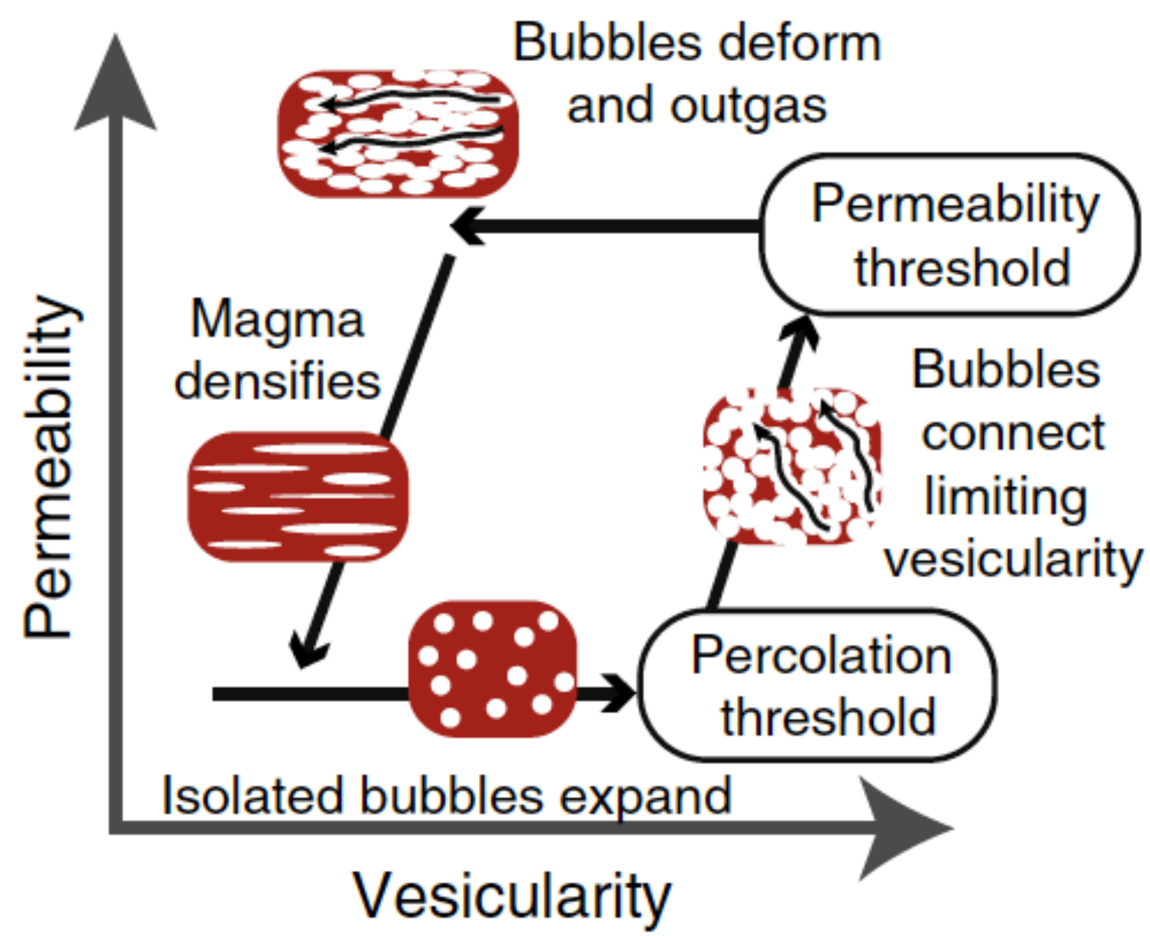
Permeability anisotropy can be large, and will cause anisotropic patterns of gas escape



Wright et al. (2006)

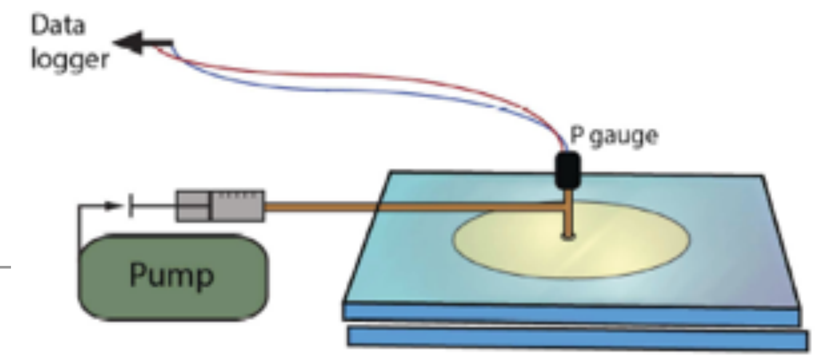


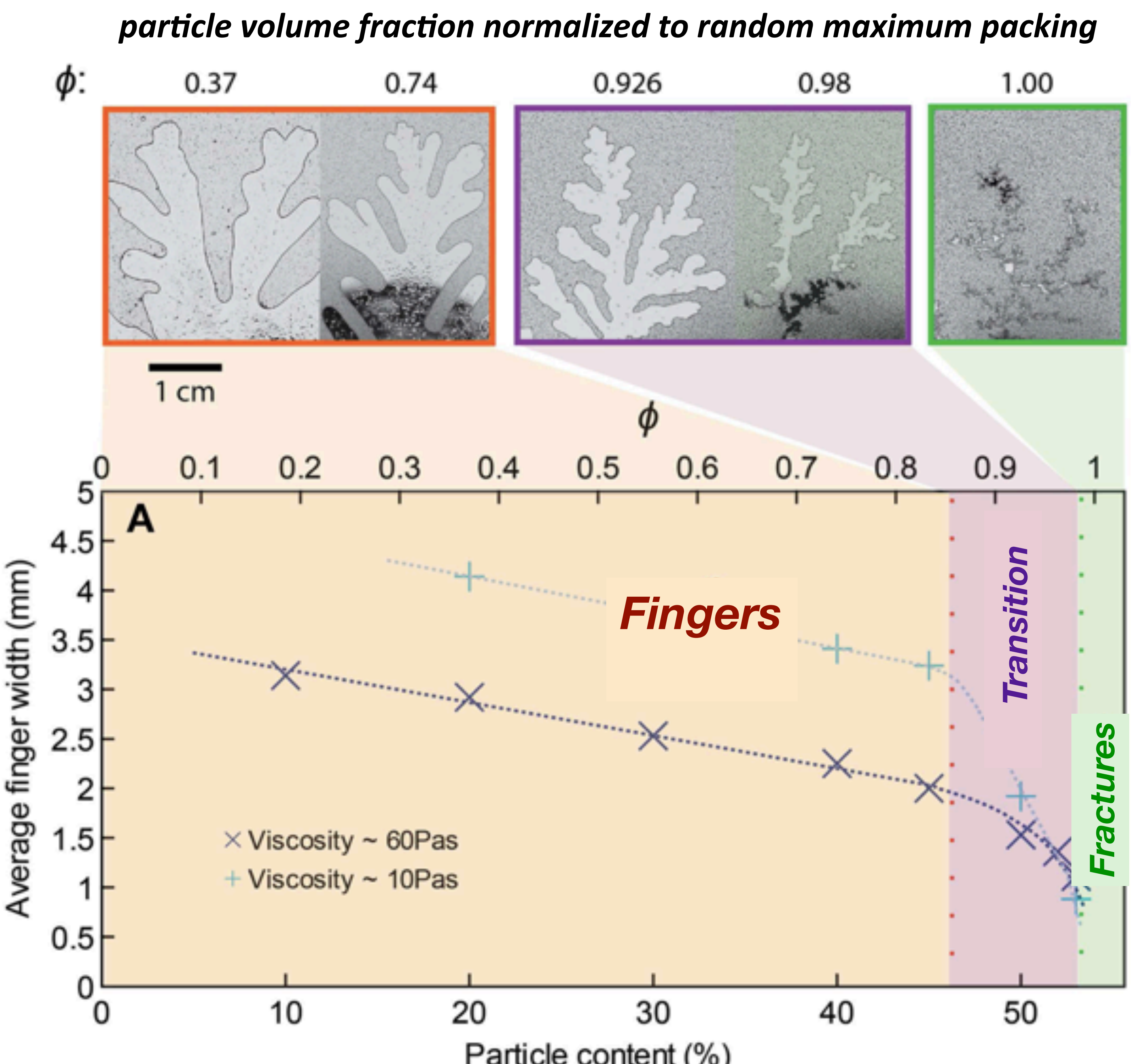
Schneider et al. (2012)



Cassidy et al. (2018)

Crystals also affect permeable pathways





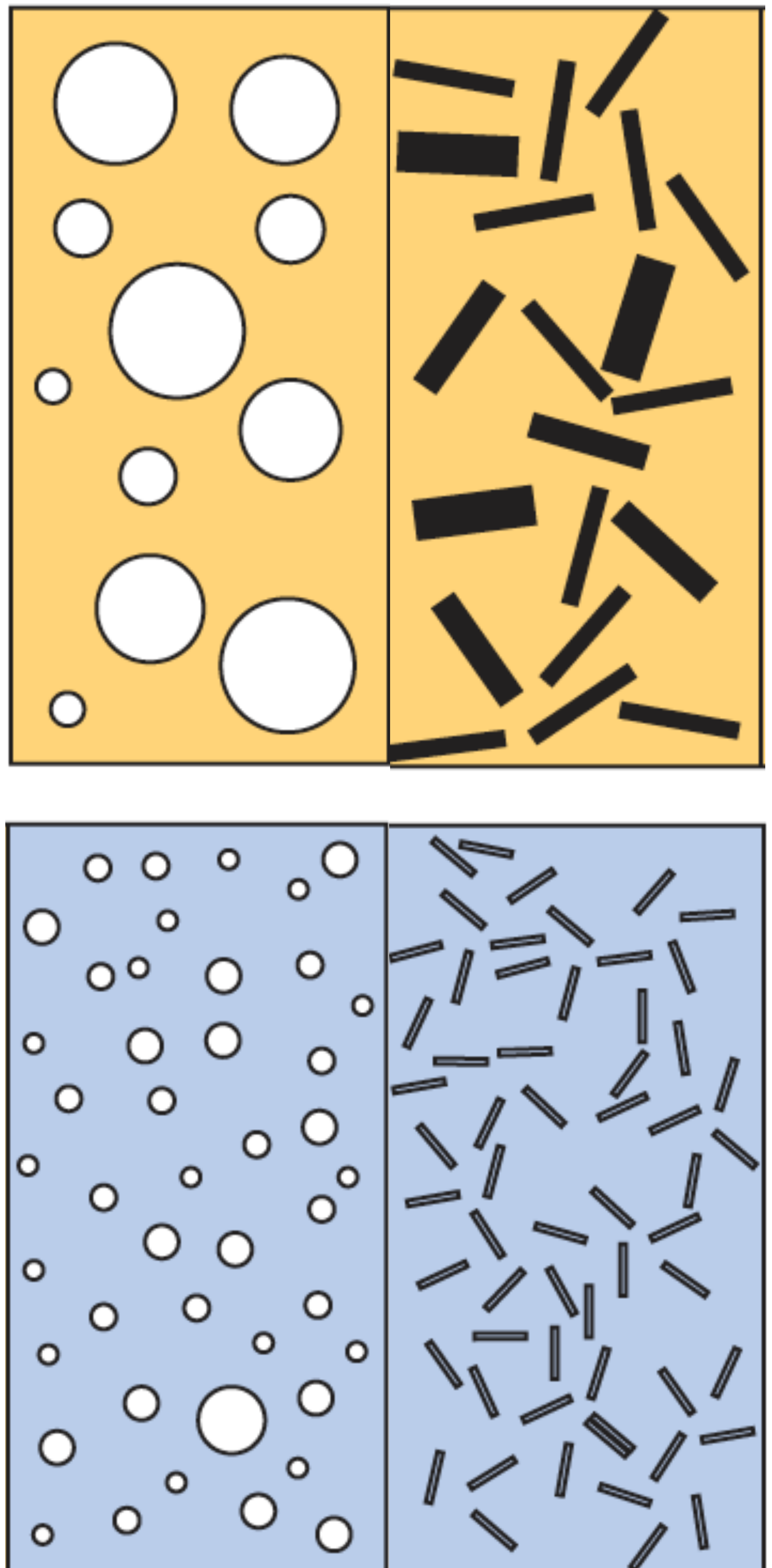
Oppenheimer et al. (2015)

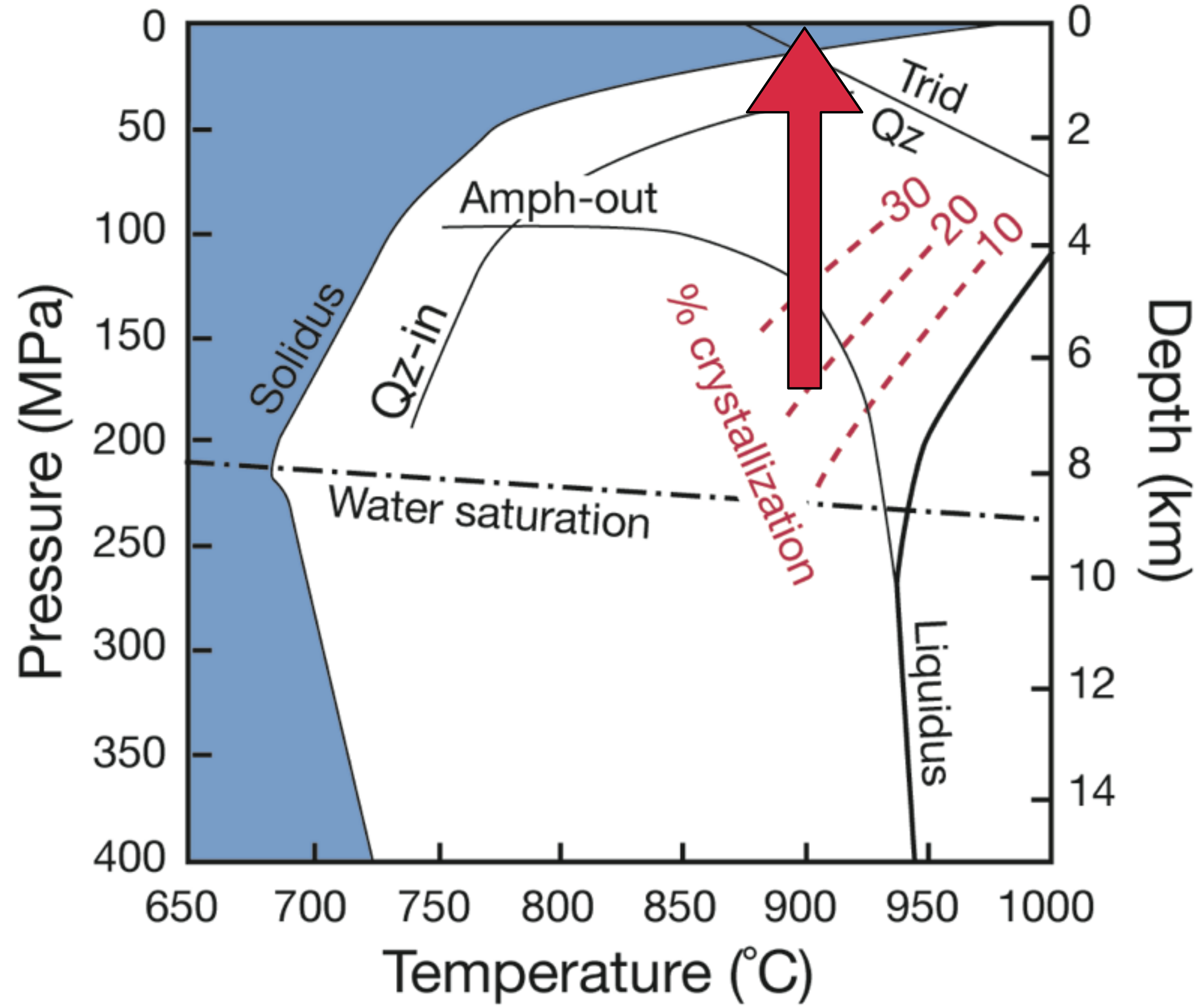
Gas intrusion into particle-liquid suspensions

Behavior changes from fingering to 'fracturing' as the particle concentration approaches random maximum packing

Gas loss is most efficient in the fracture regime

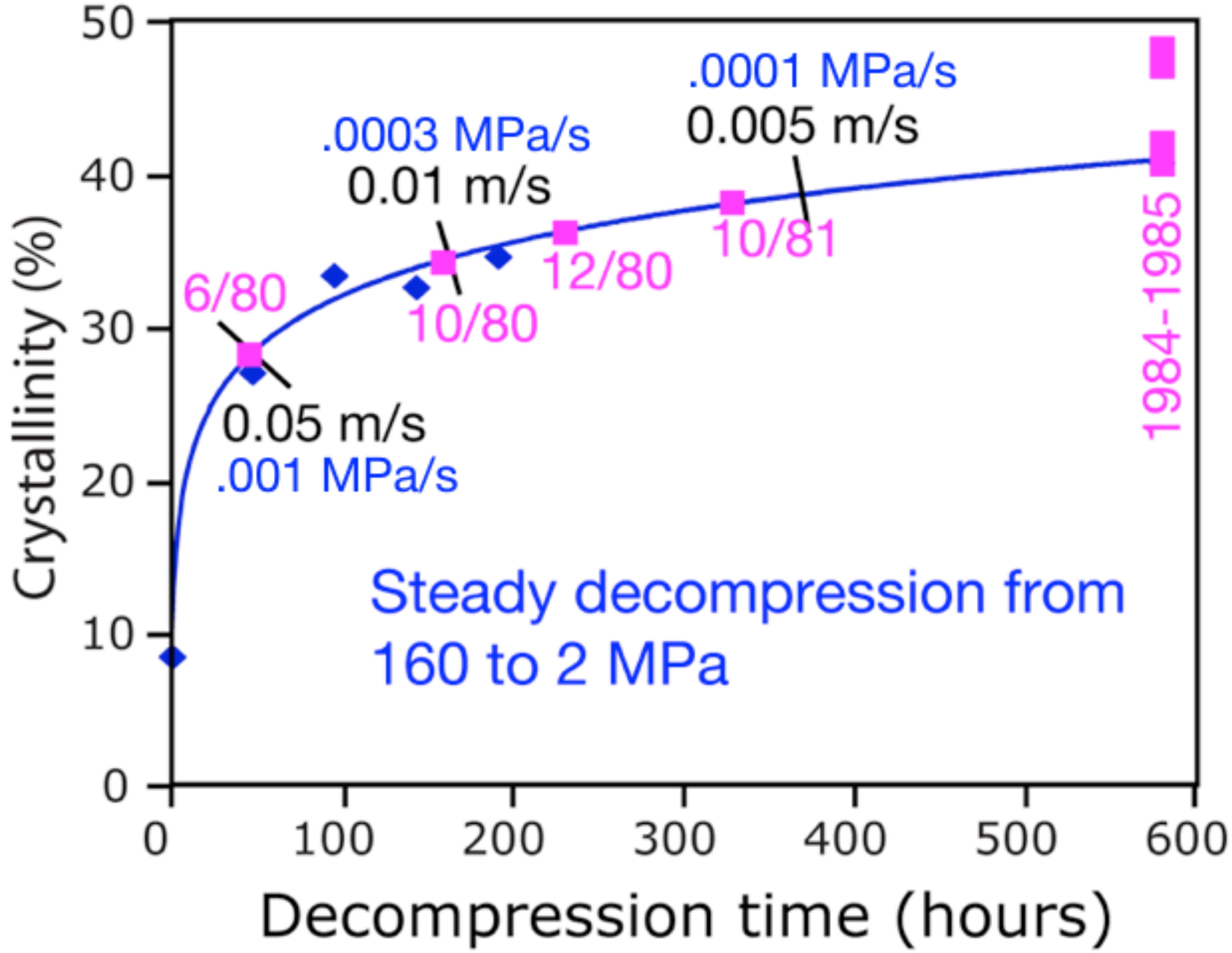
Syn-eruptive changes in crystal content caused by degassing





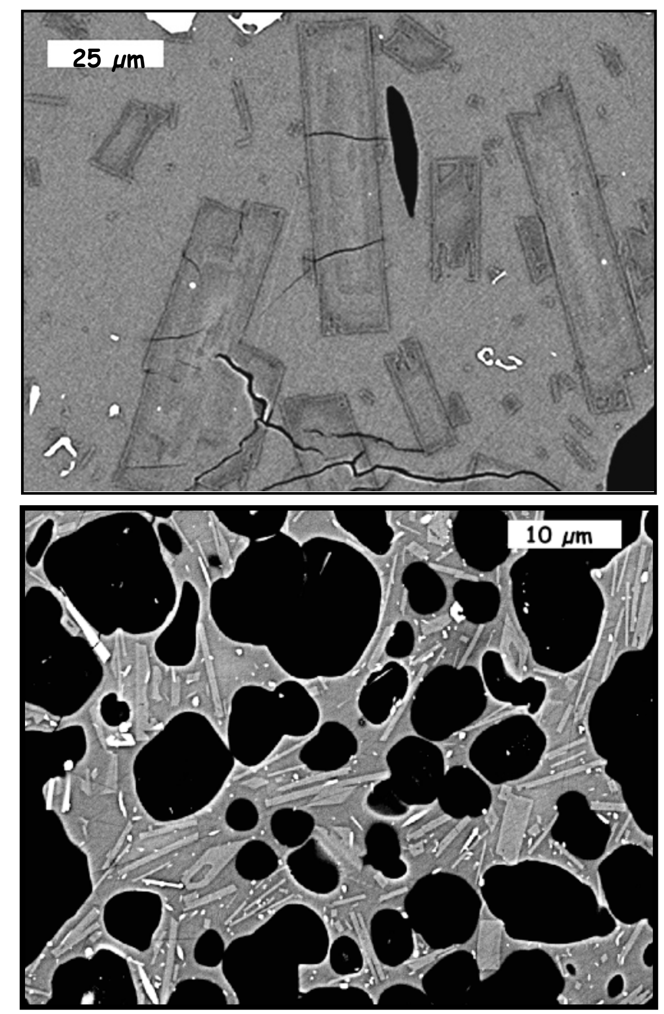
As with vesiculation, balance of nucleation and growth determined by melt viscosity and rate of decompression

Extent of crystallisation depends on decompression time



Cashman and Blundy (2000); Geschwind and Rutherford (1995)

Slow decompression



Fast decompression

Case studies

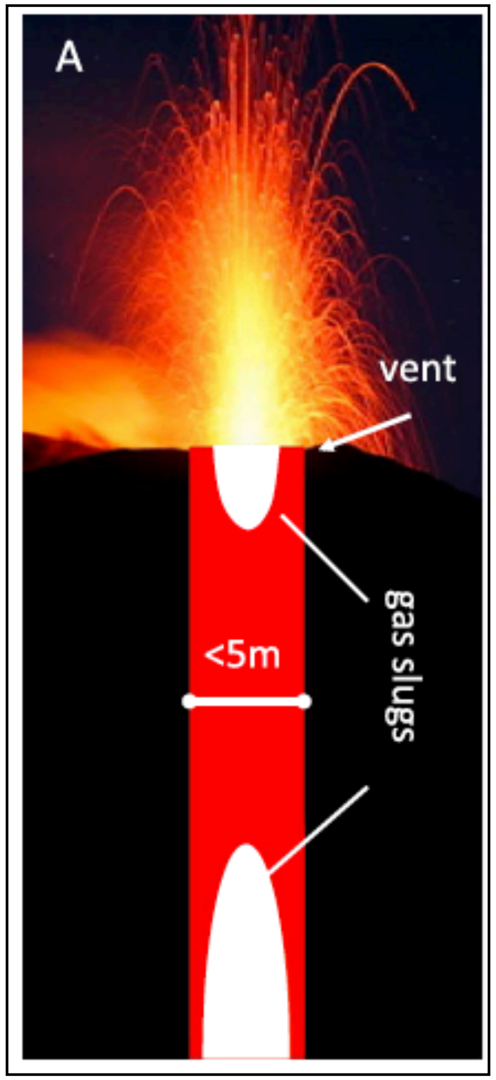
In a lab you're in near-control; you're the giant puppet master making your subject dance to your tune.

In the field you're inside your subject matter and the power relationship is totally different.

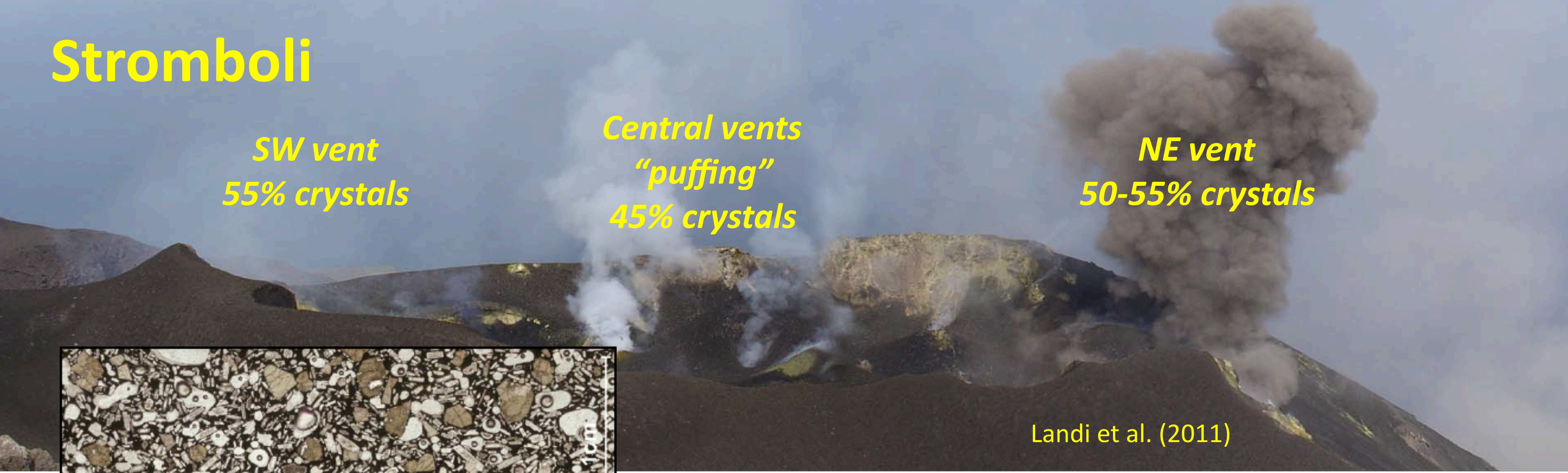
paraphrased from Underland, Robert Macfarland (2019)

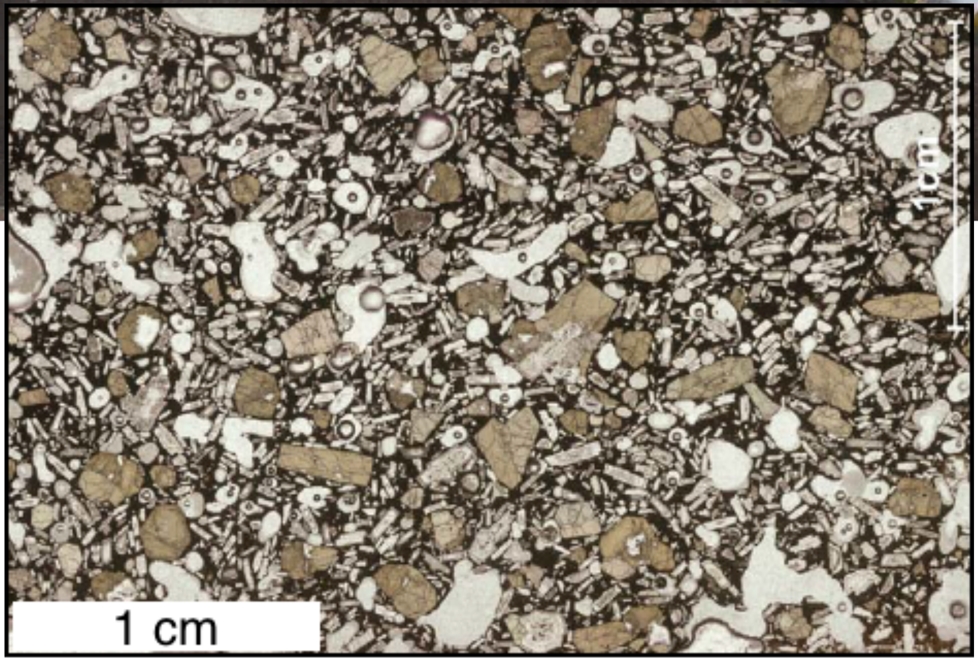
painting by John Jackson

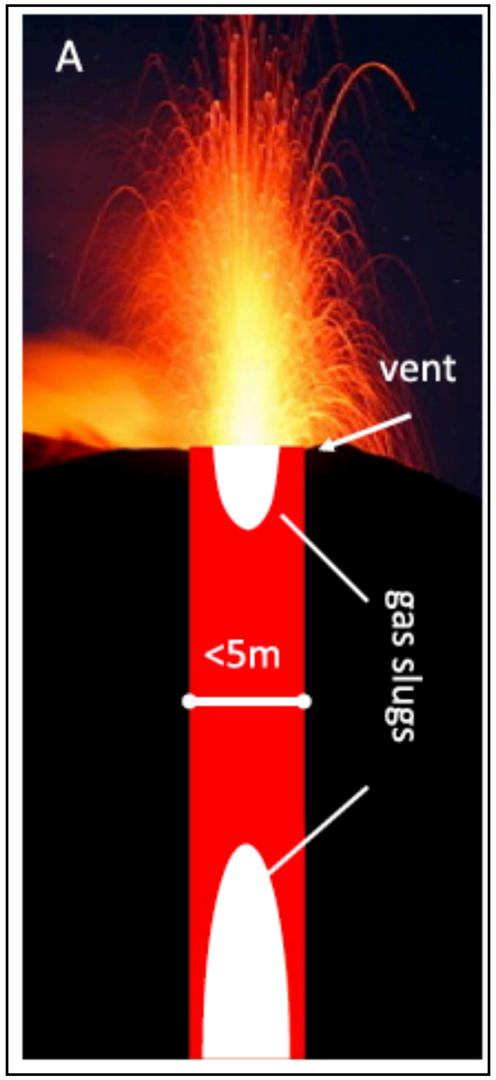

Stromboli


A
vent
gas slugs
<5m

Stromboli

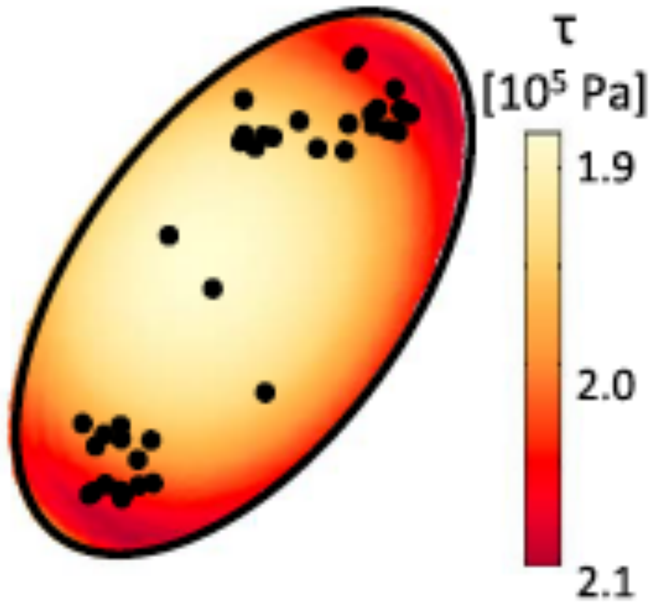


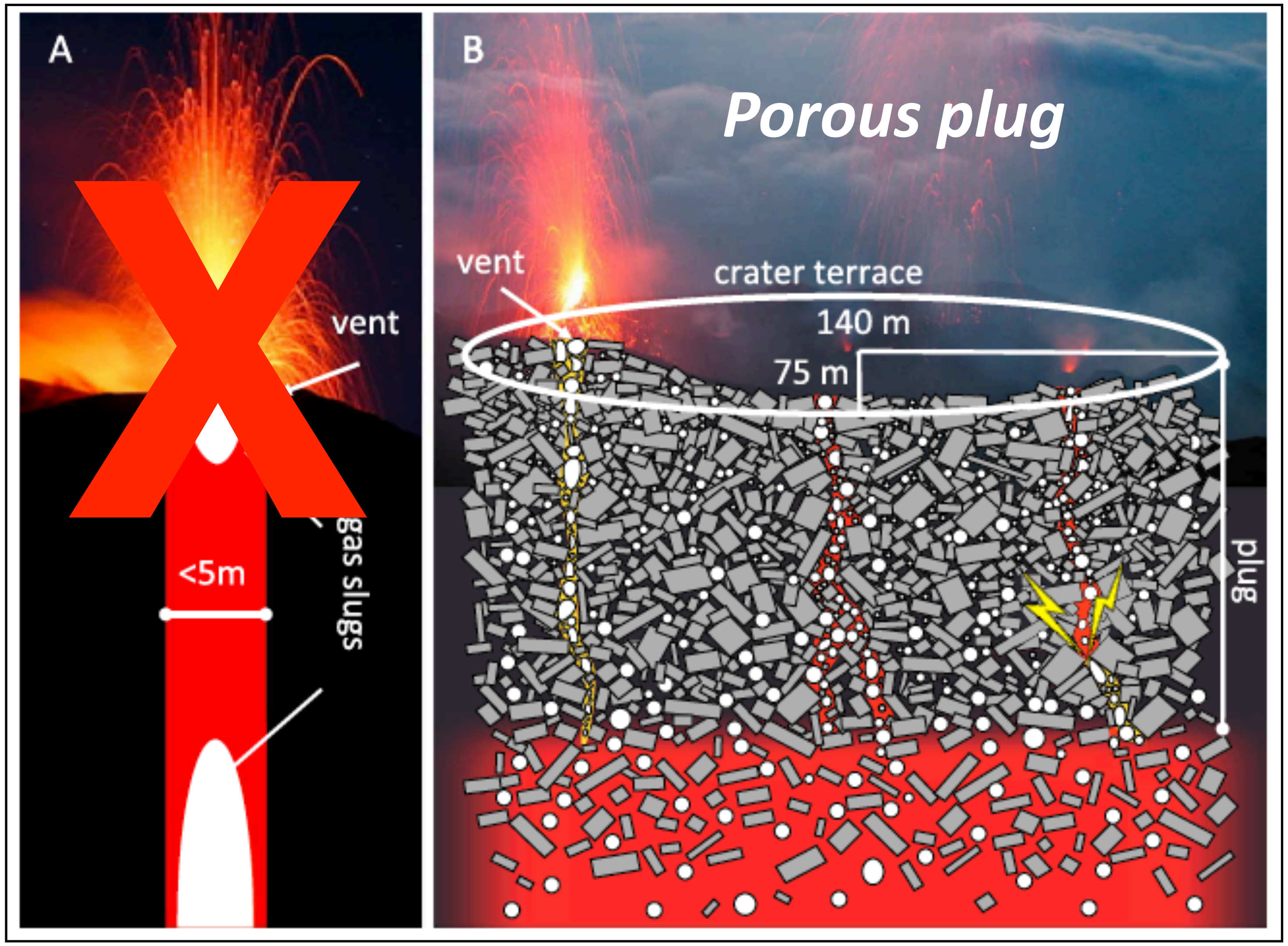




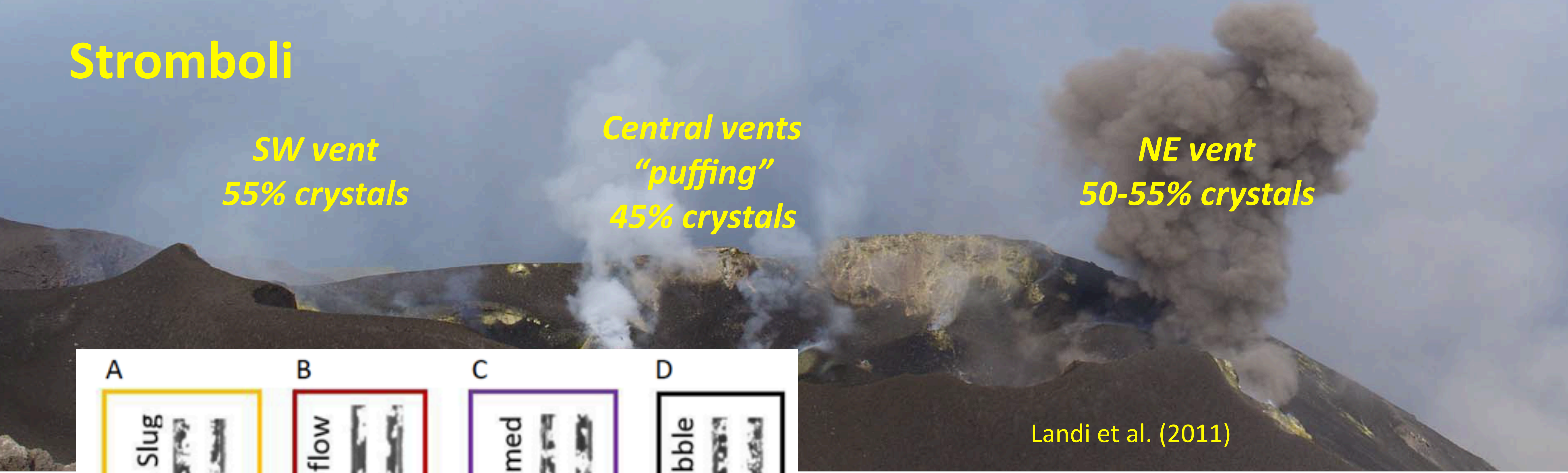
Magma erupted during ‘normal’ Strombolian activity has a high crystallinity

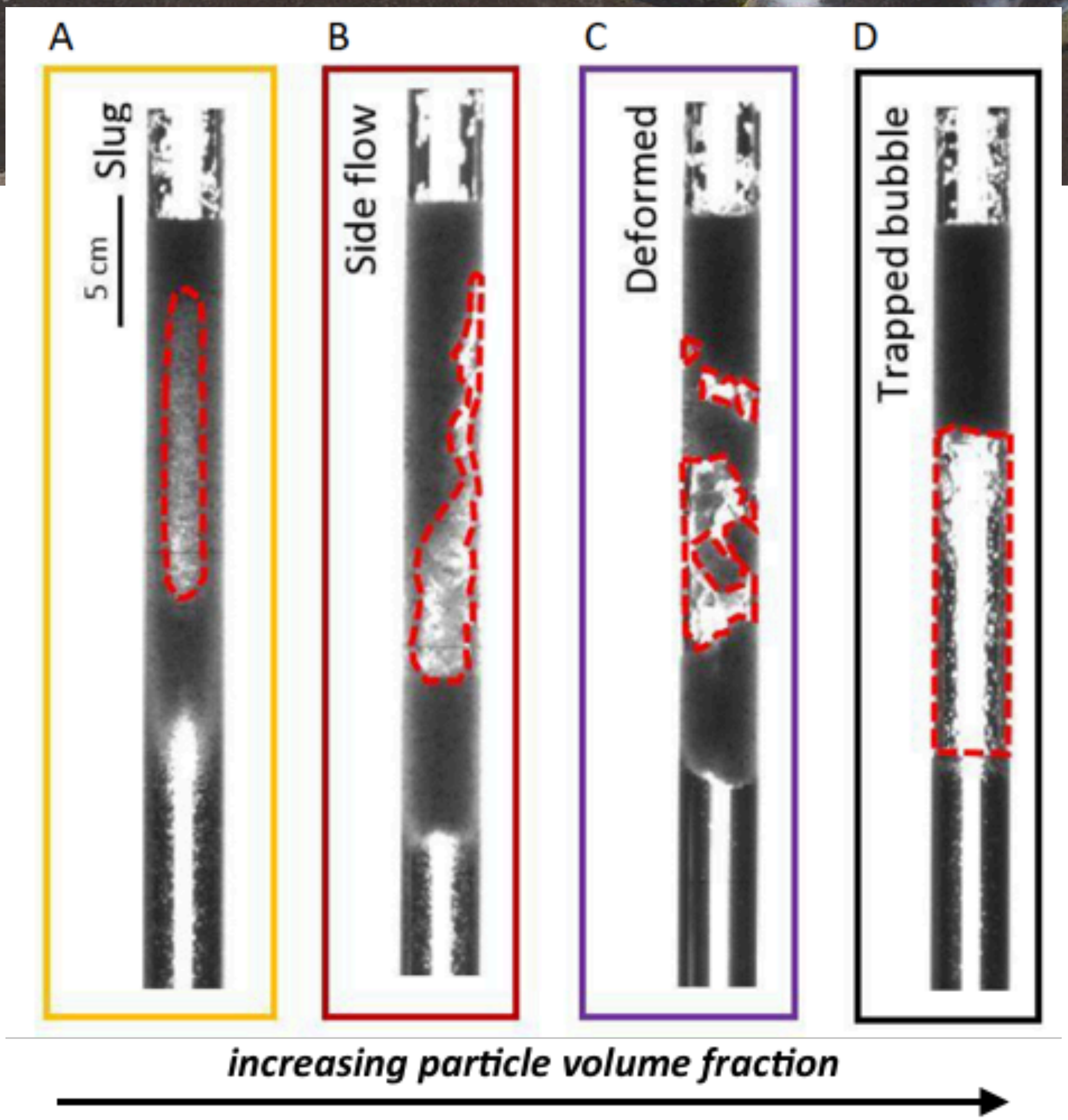
Suggests that fracture mechanism may apply





Suckale et al. (2016)



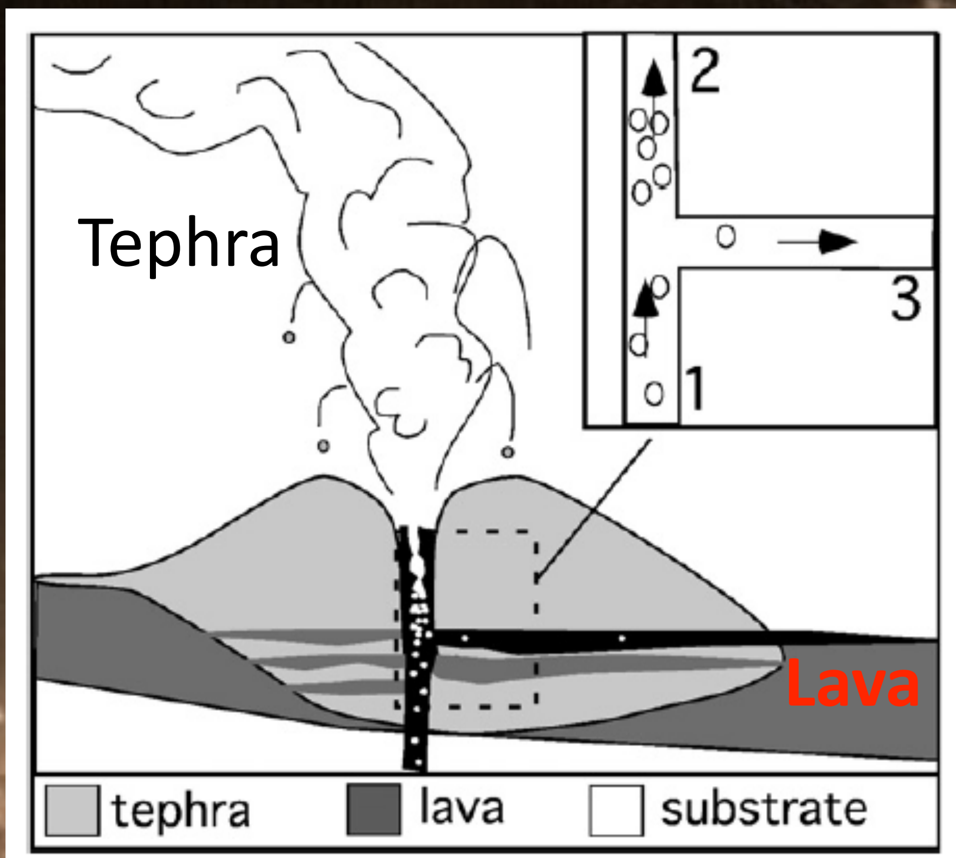


Oppenheimer et al. (in revision)

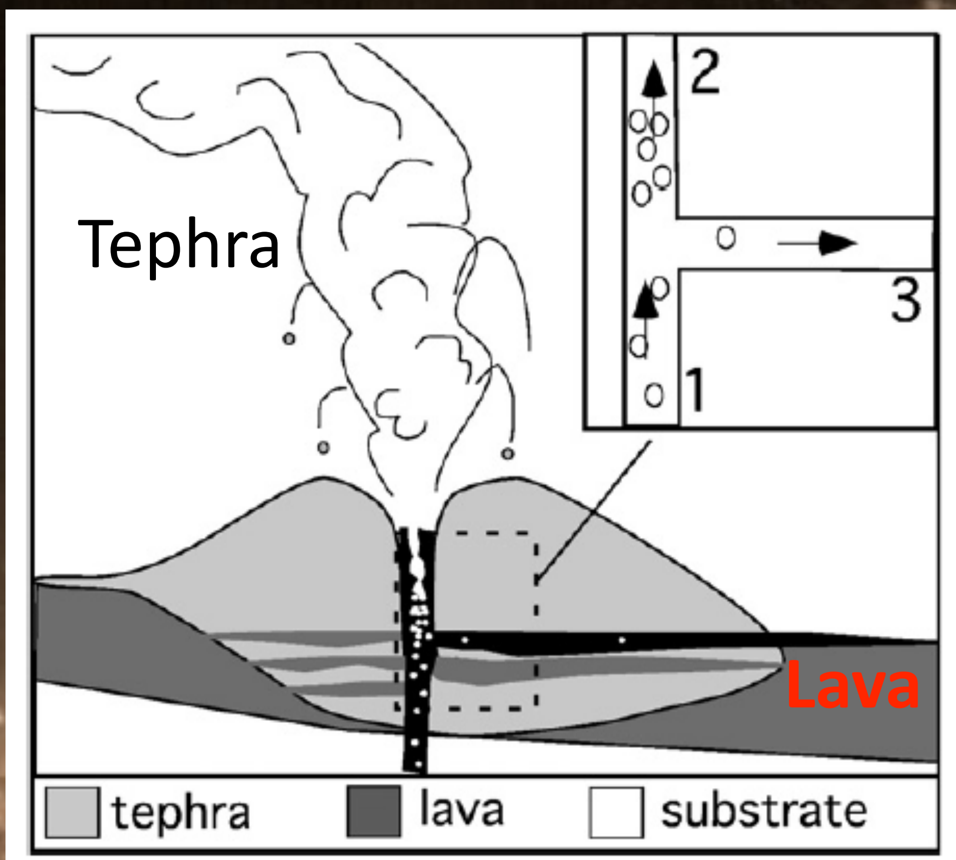
Analogue experiments show that addition of particles generates asymmetric and pulsatory bubble bursts, as well as trapping of bubbles within the particle-rich cap


Parícutin, Mexico
1943-1952
Tephra
Lava

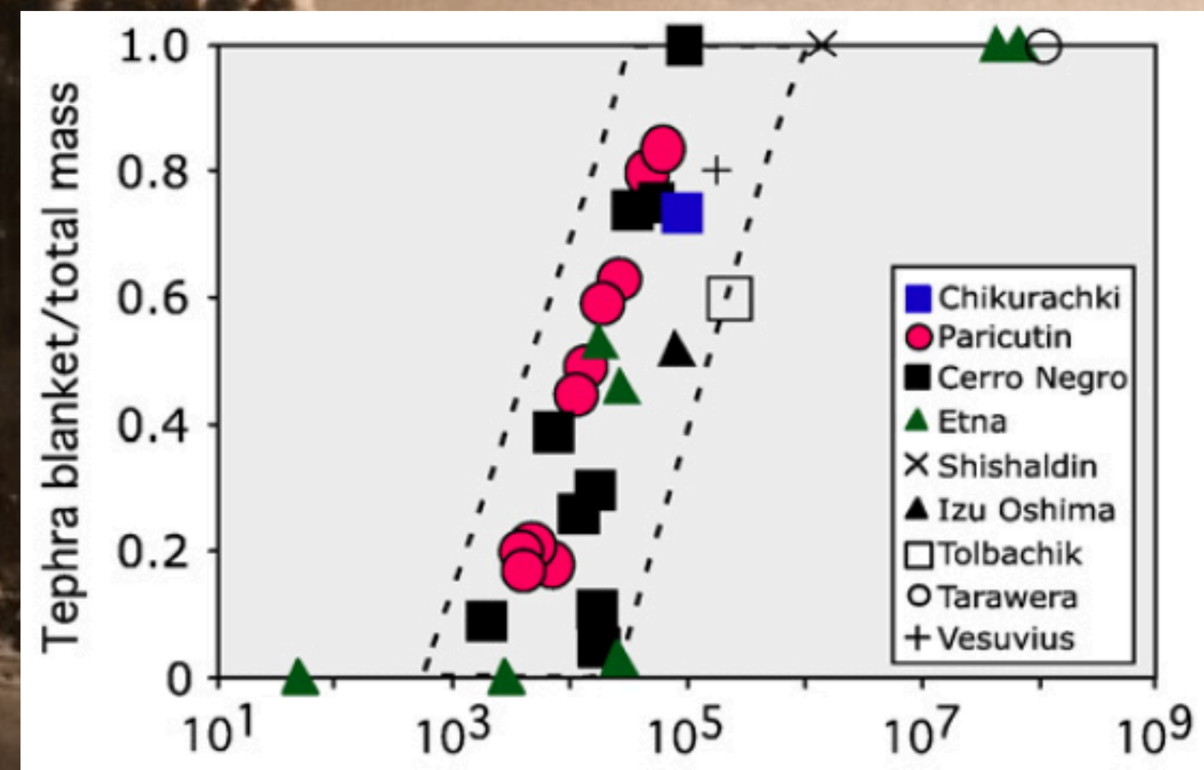
A different mode of two phase flow



A different mode of two phase flow

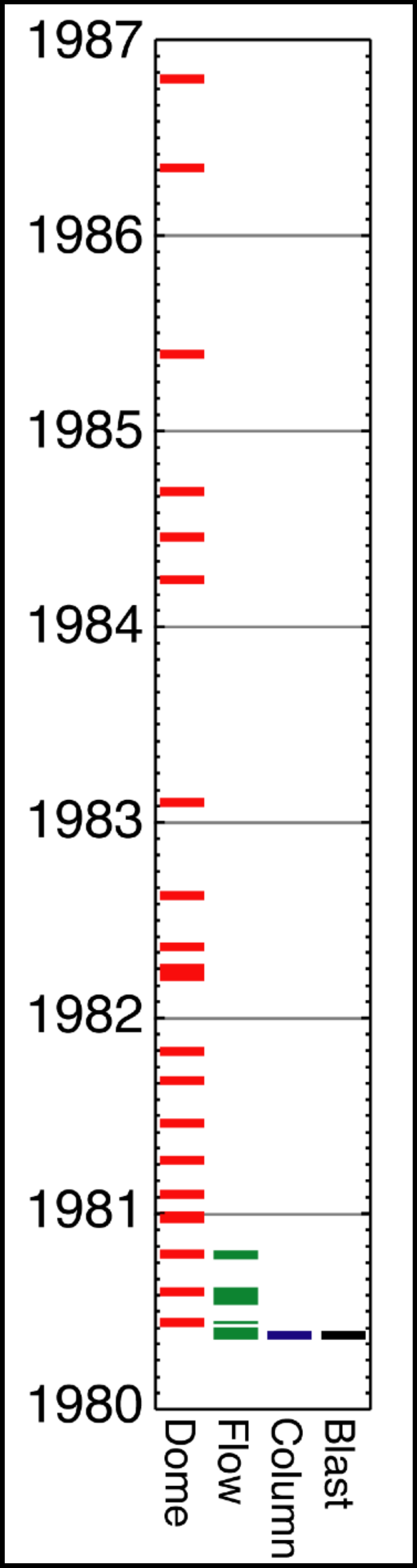


Partitioning of gas (tephra) and lava depends on flow rate

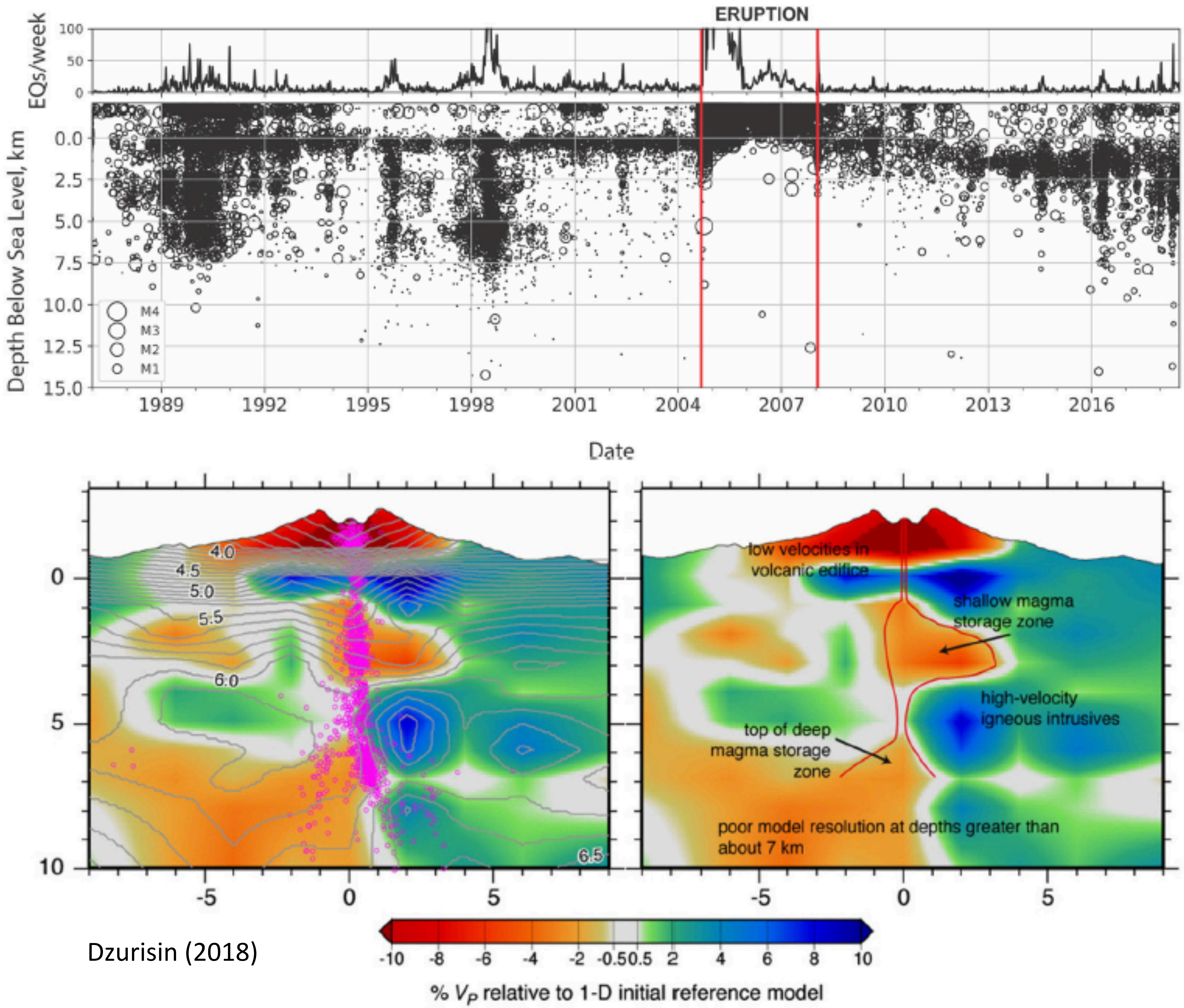


Pioli et al. (2009)

Mount St. Helens 1980-1986

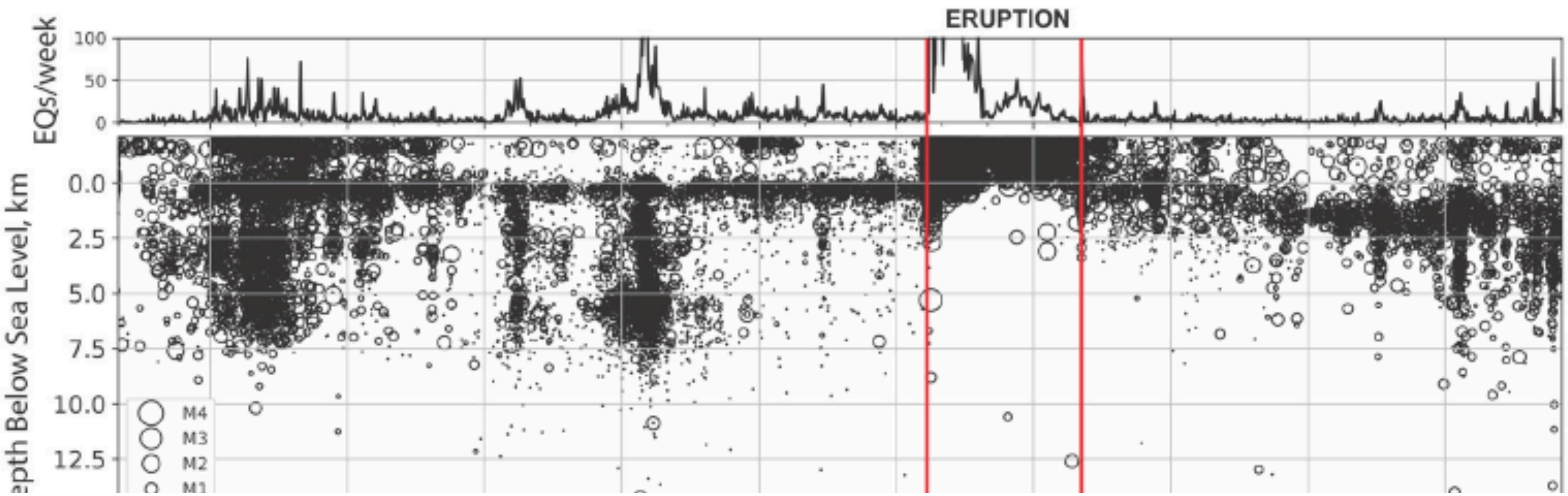


Mount St. Helens 1988-2017

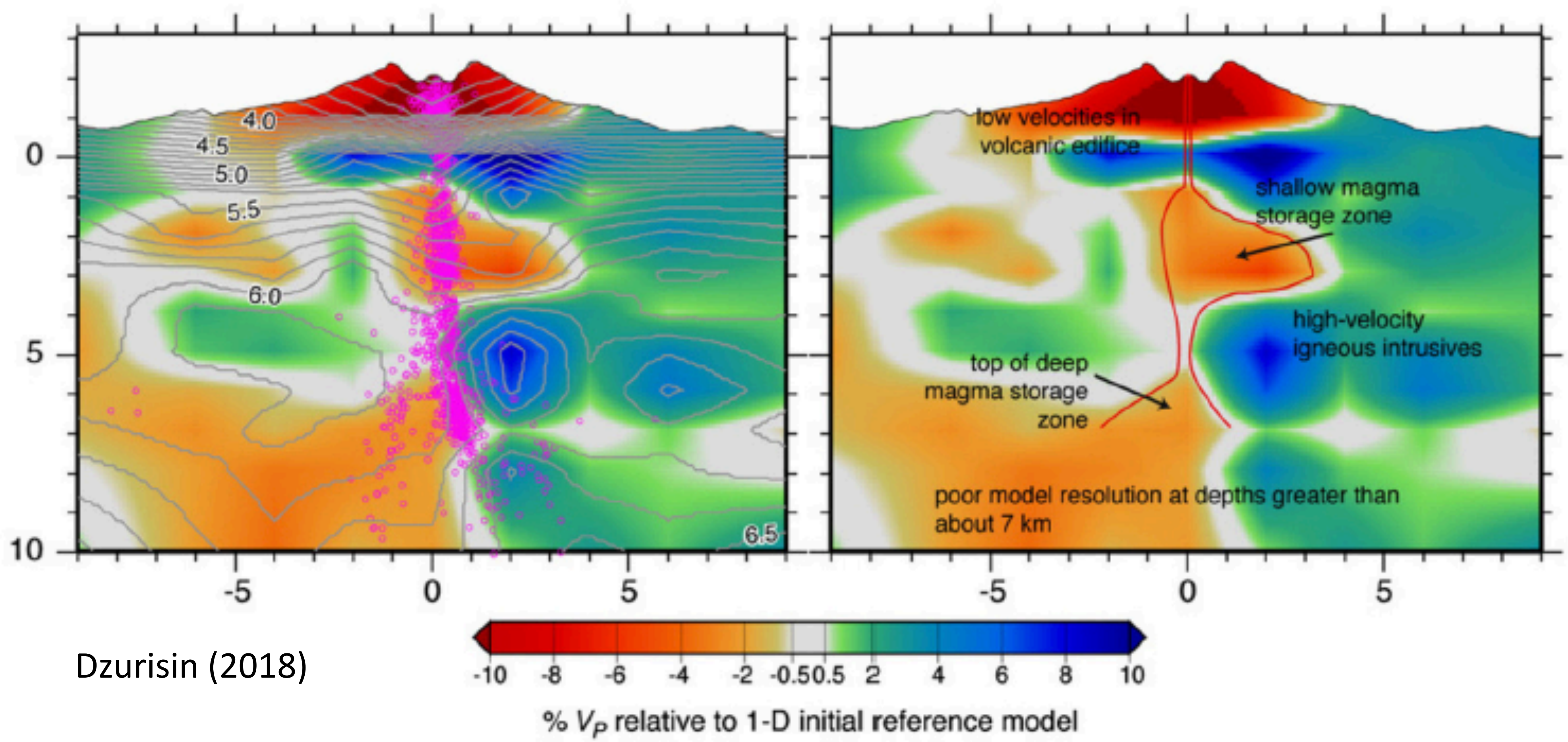


Dzurisin (2018)

Mount St. Helens 1988-2017

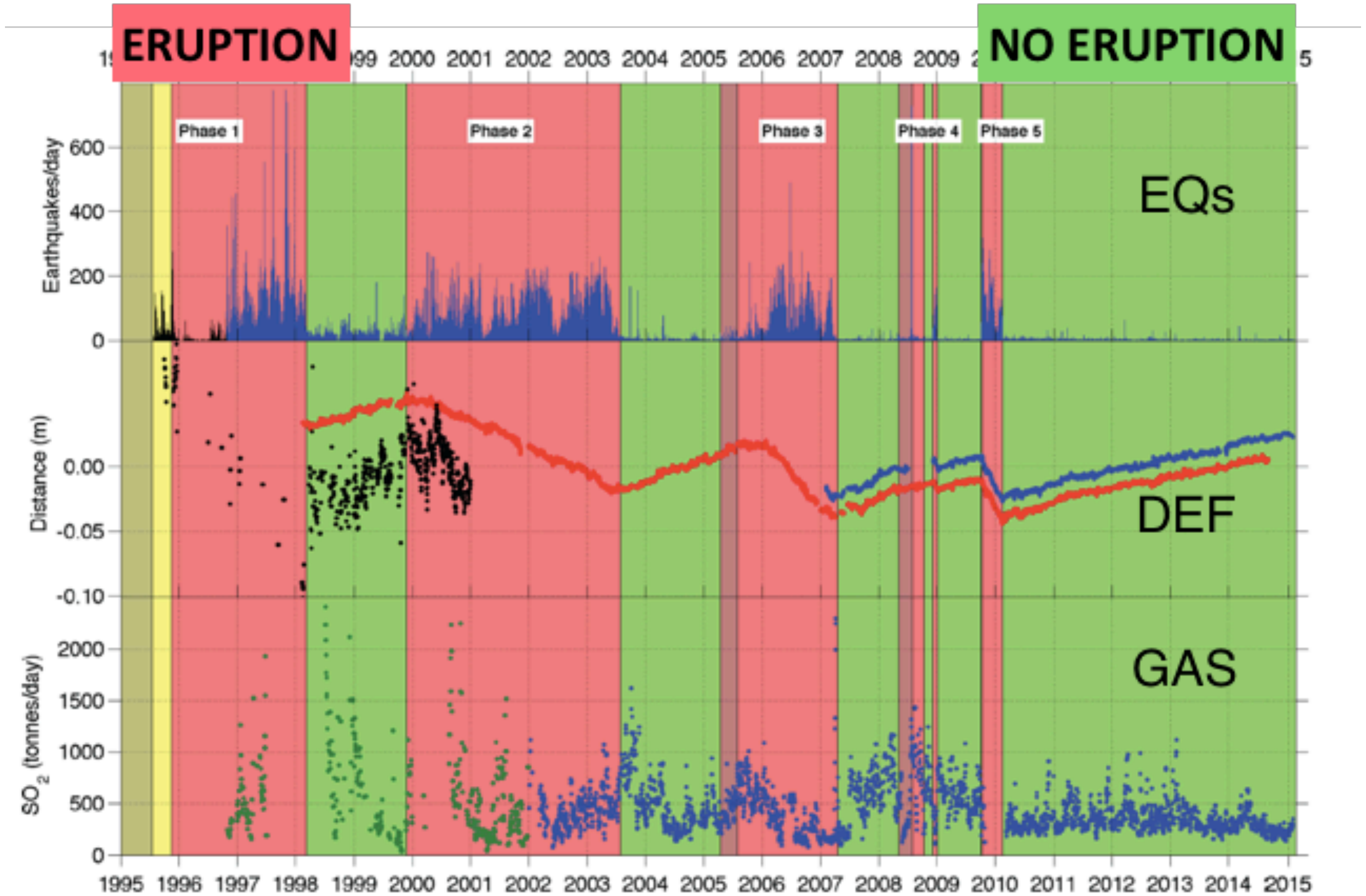


What controls magma accumulation/release?



Dzurisin (2018)

Soufriere Hills, Montserrat 1995-2010

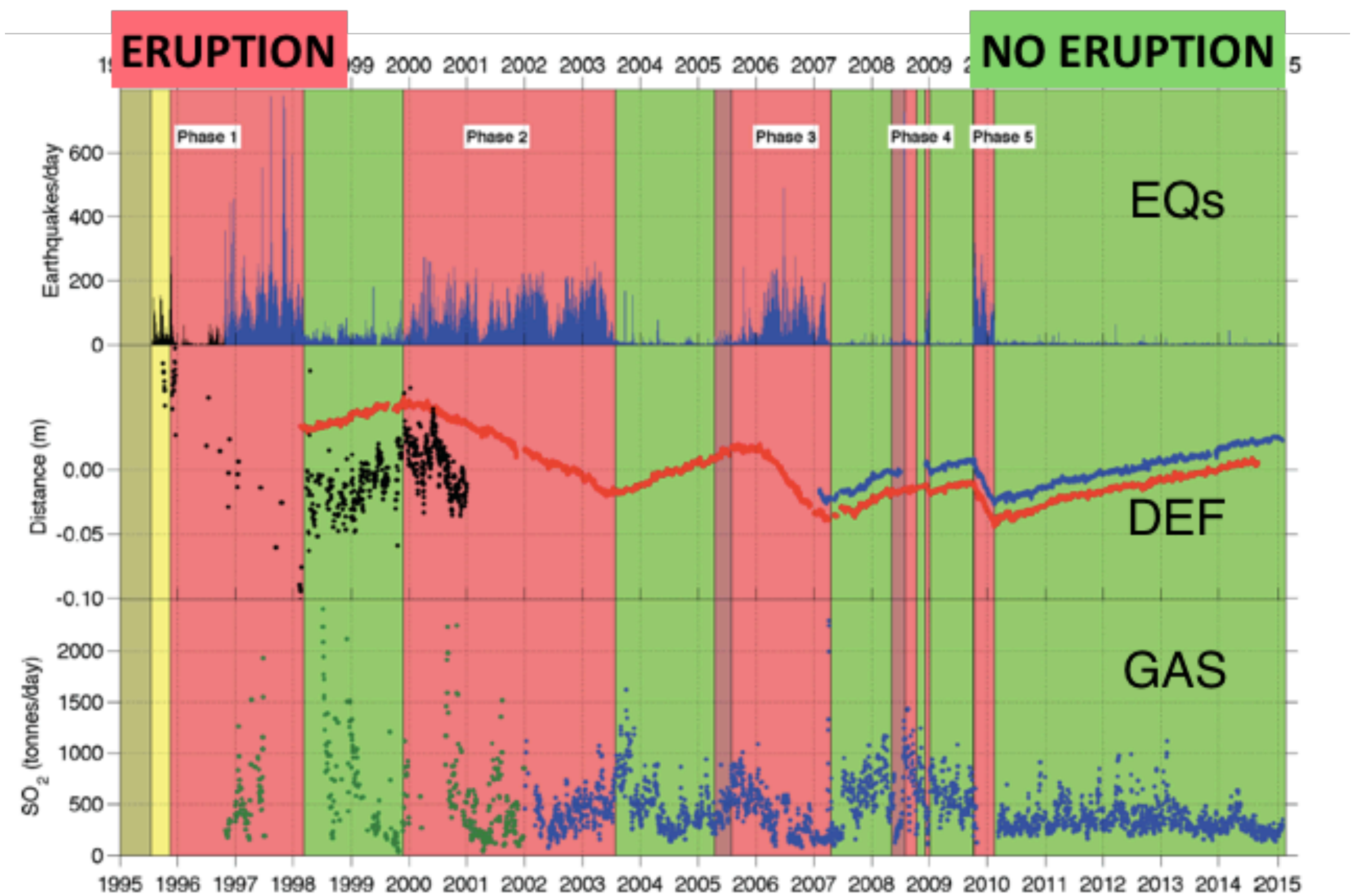


Christopher et al. (2015)

Alternating eruptive and non-eruptive phases

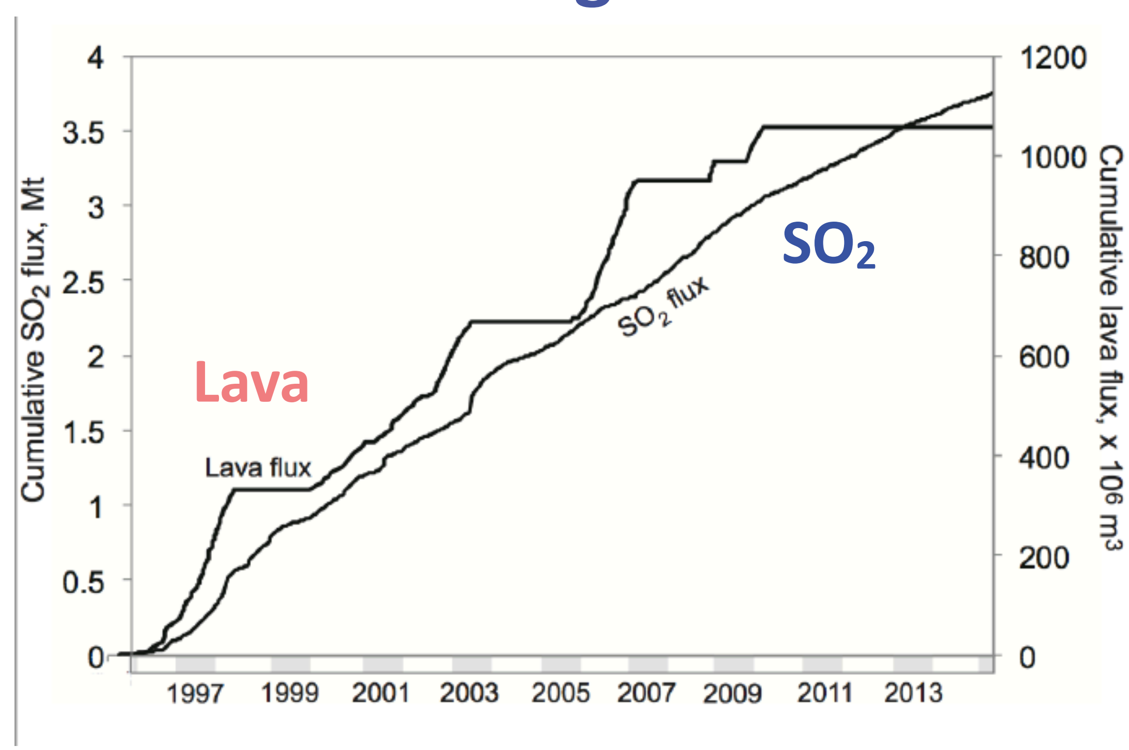
Mirrored by deformation signal

Soufriere Hills, Montserrat 1995-2010



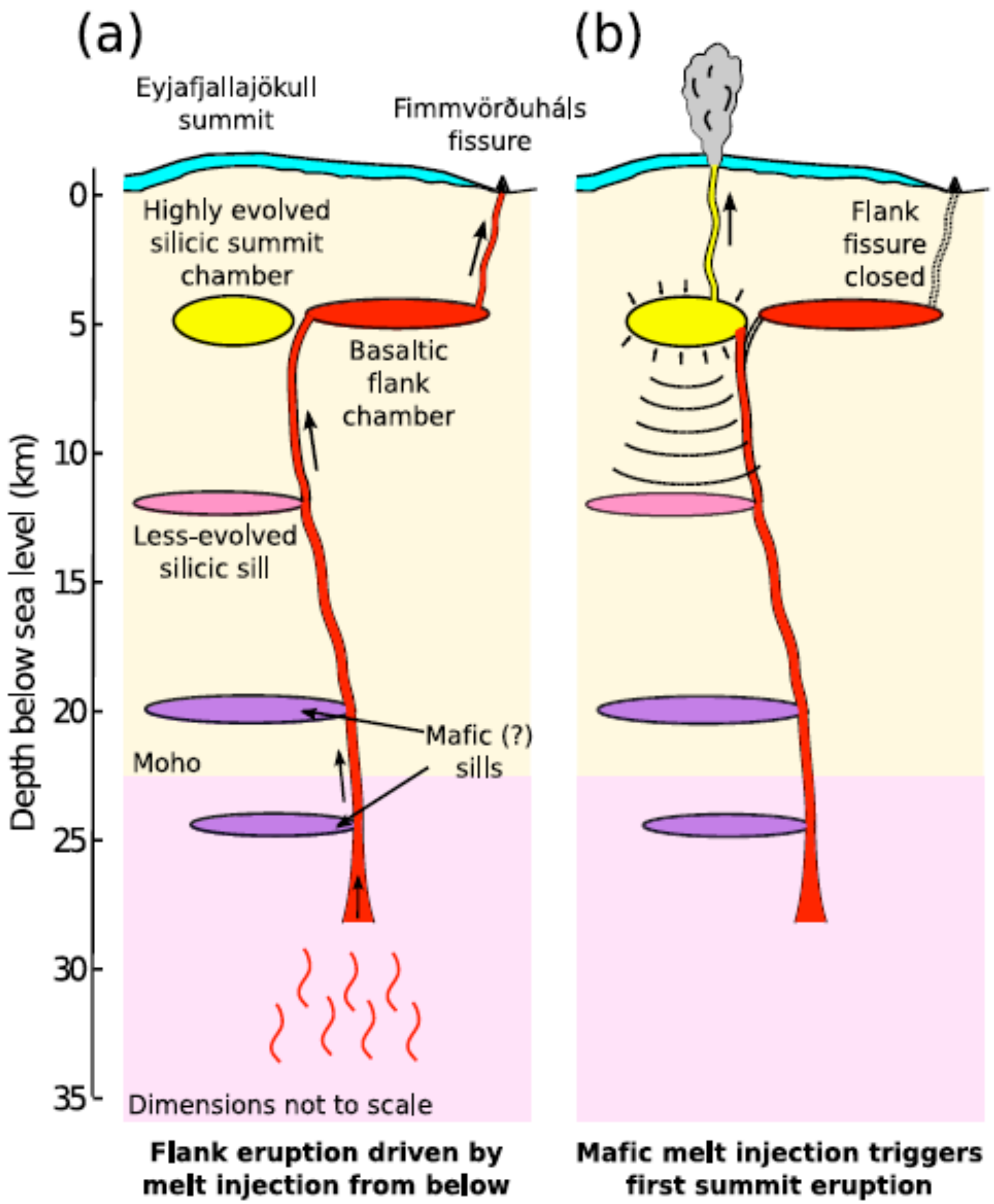
Christopher et al. (2015)

Gas emissions are decoupled from magma flux



How are volatiles stored at depth, and transported to the Earth's surface?

Fimmvörðuháls-Eyjafjallajökull

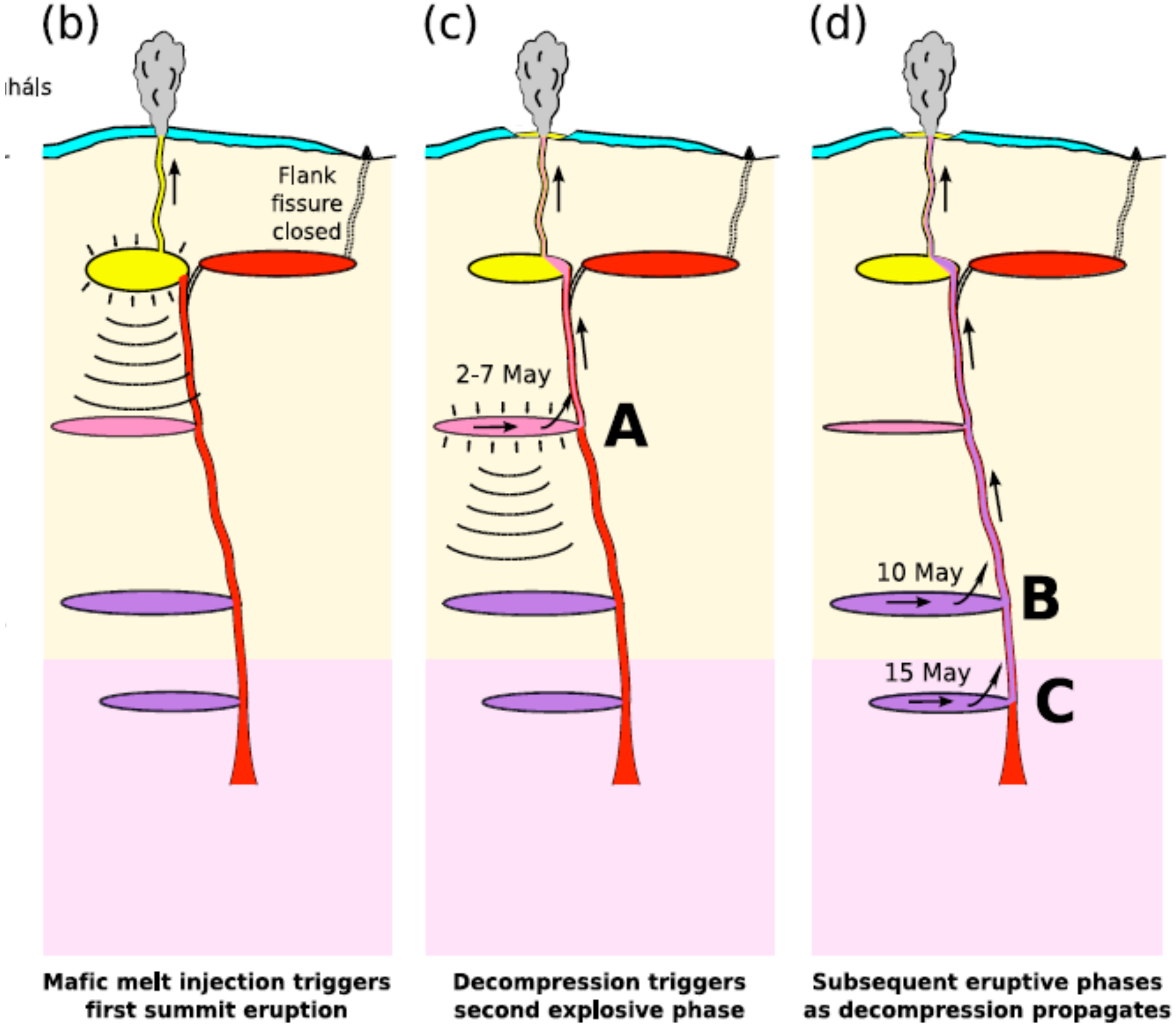


Tarasewicz et al. (2012)

Eyjafjallajökull eruption was triggered by a basaltic fissure eruption on the flank of the volcano

Under what conditions do neighboring melt lenses interact (critical stress threshold)?

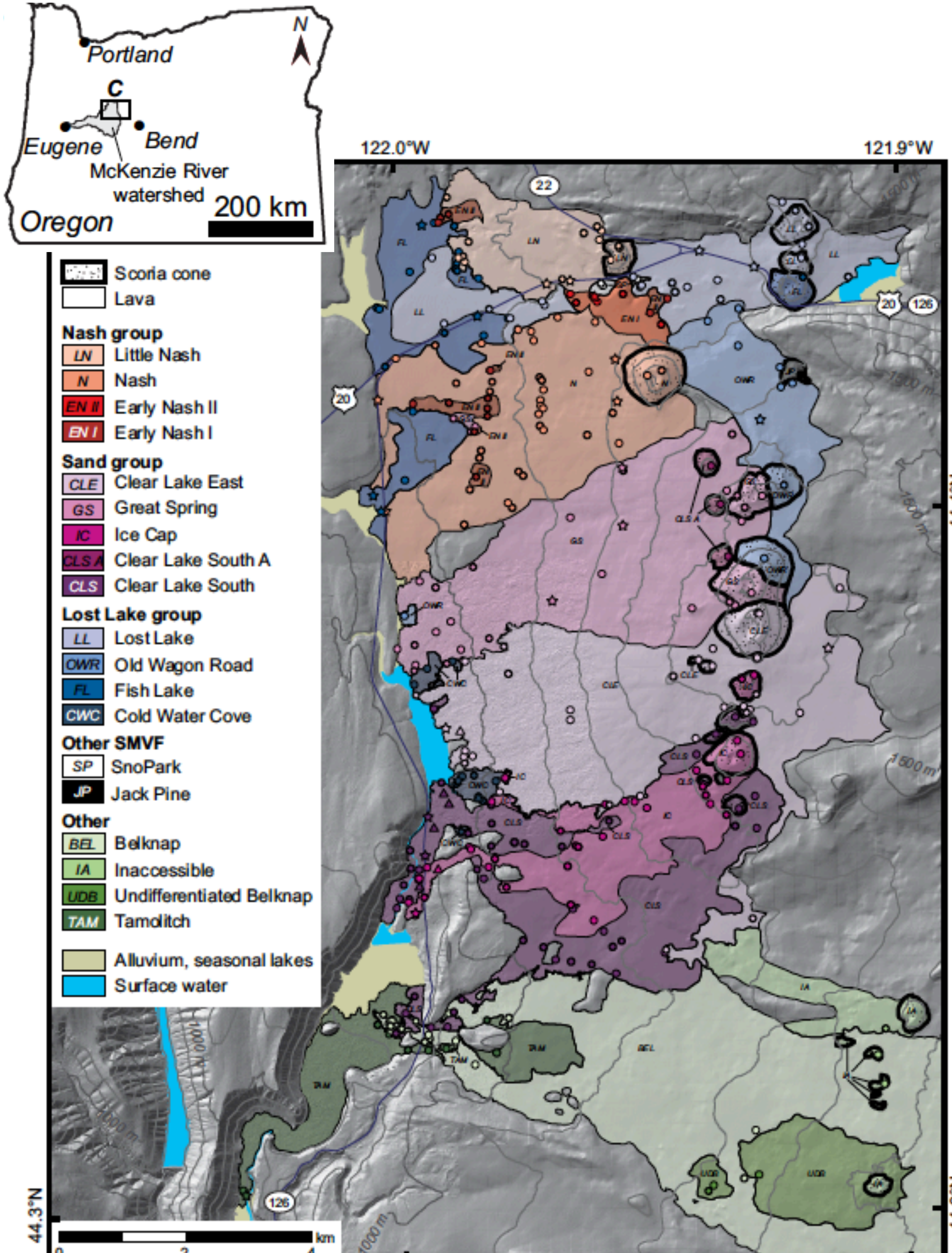
Eyjafjallajökull



Tarasewicz et al. (2012)

Subsequent downward propagation of decompression wave triggered a new explosive eruption each time it encountered a sill

SUGGESTS THAT INDIVIDUAL MELT LENSES ARE ISOLATED AND PRESSURIZED

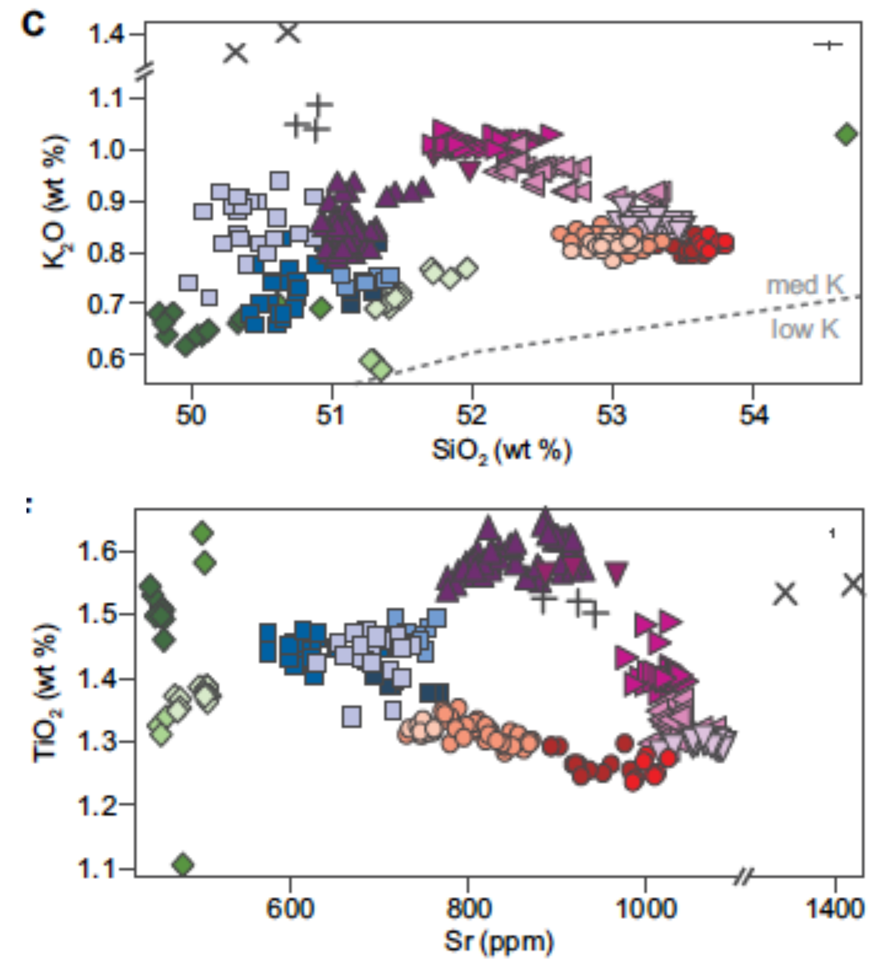


Deligne et al. (2016)

Sand Mtn. Volcanic Field, OR

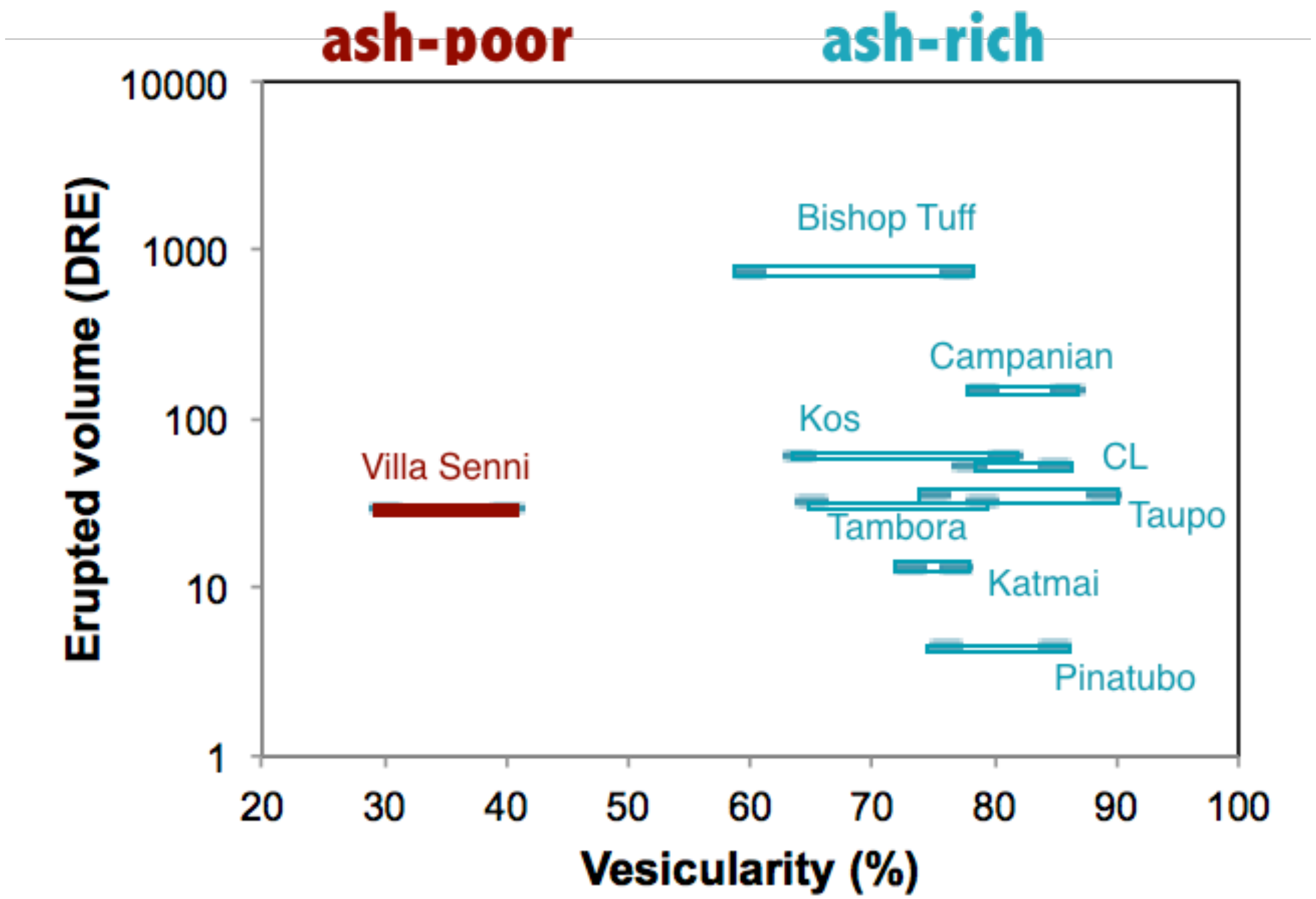
c. 3000ybp

Why the wide compositional range in a single eruptive episode?



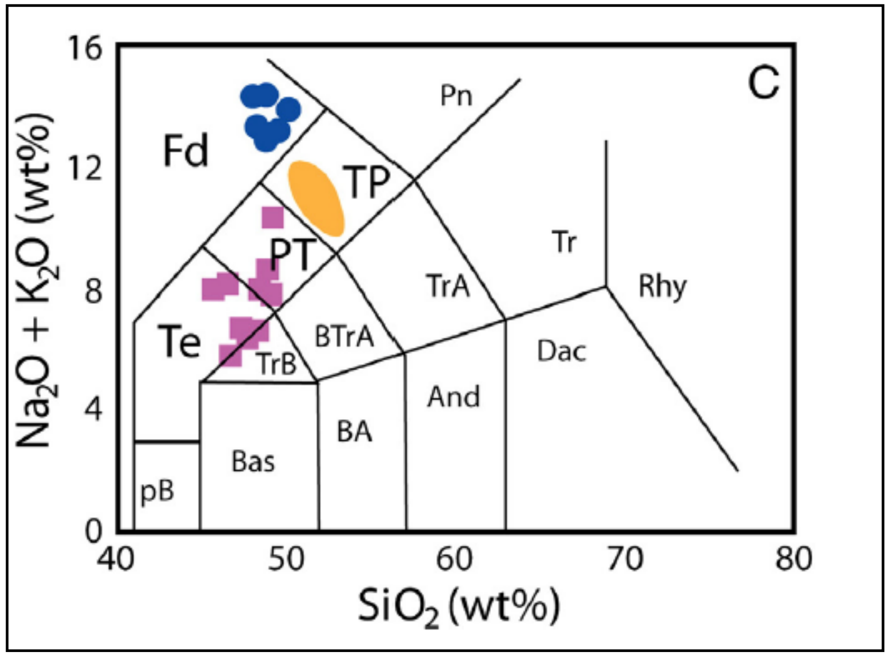
Role of crustal extension?

Colli Albani 355ka
Villa Senni eruption



Cashman and Giordano (2014)

Explosive eruption of ~30-40 km³ of mafic alkalic magma produced scoria-rich ignimbrites

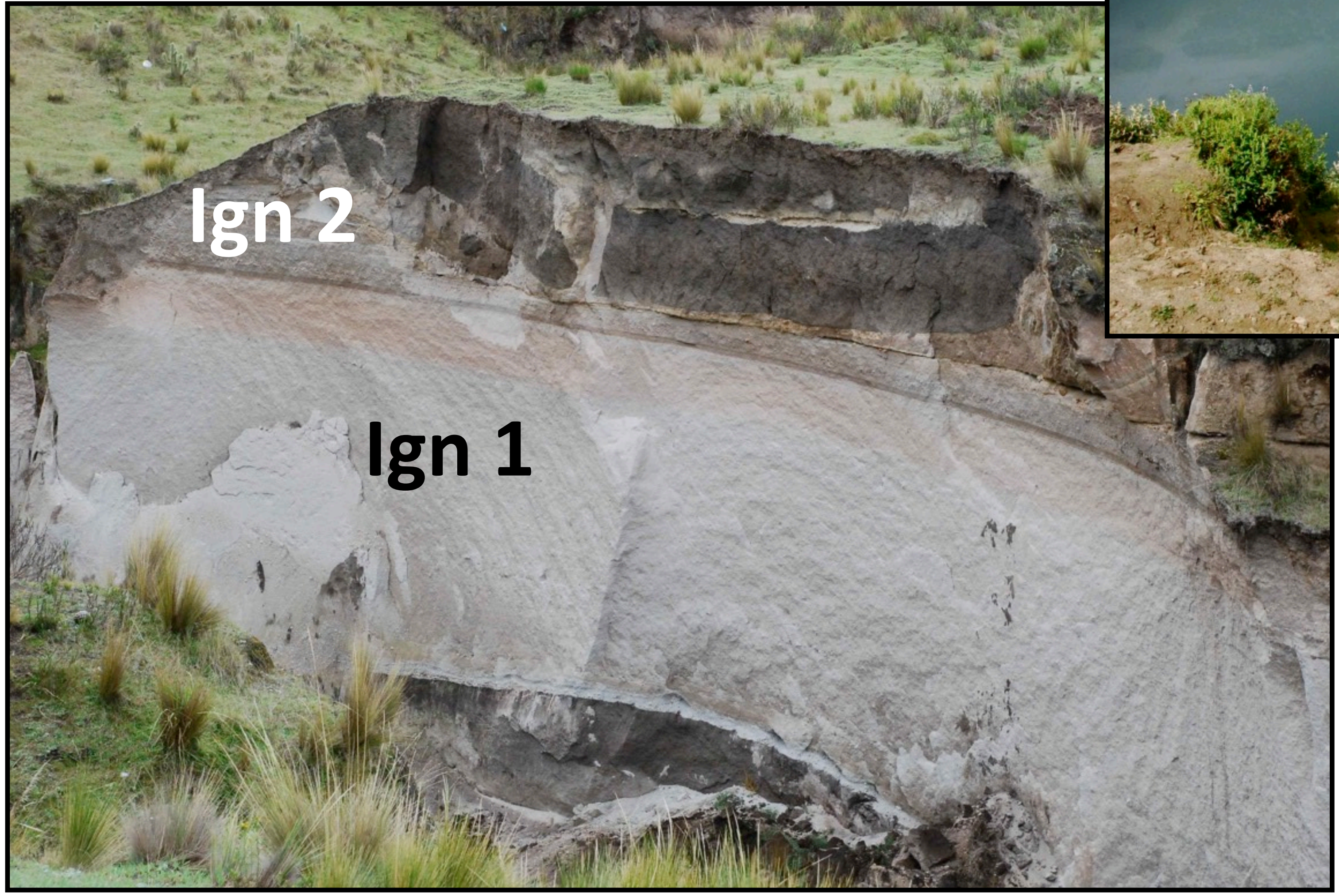


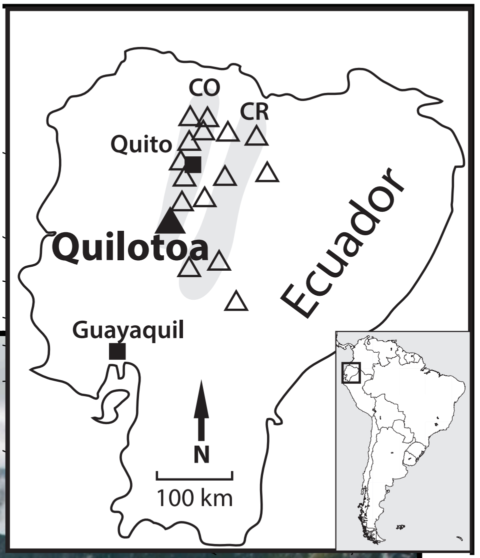
Another example of tapping multiple isolated melt lenses?

Quilotoa, Ecuador

800ybp

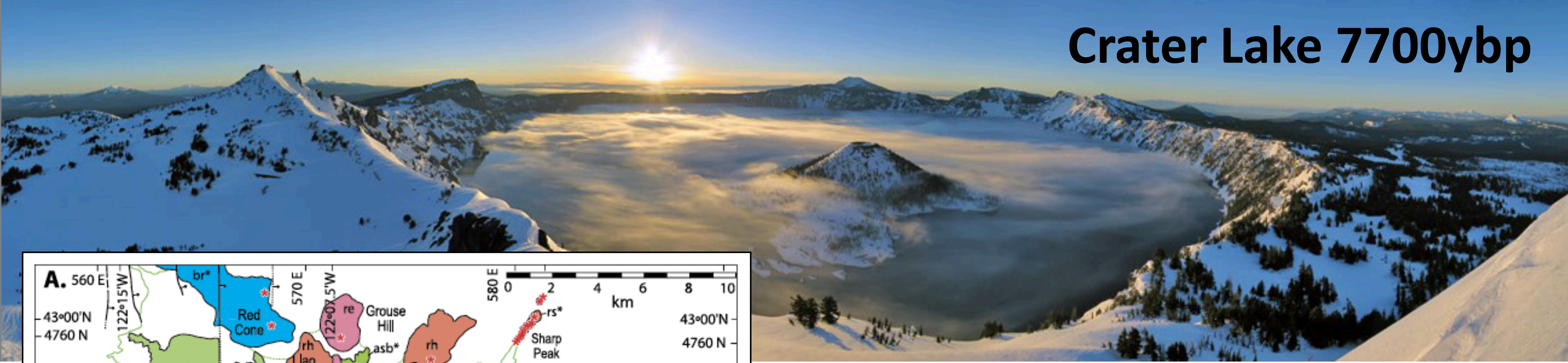
Volcano has shown a repeated pattern of producing back-to-back ignimbrite eruptions

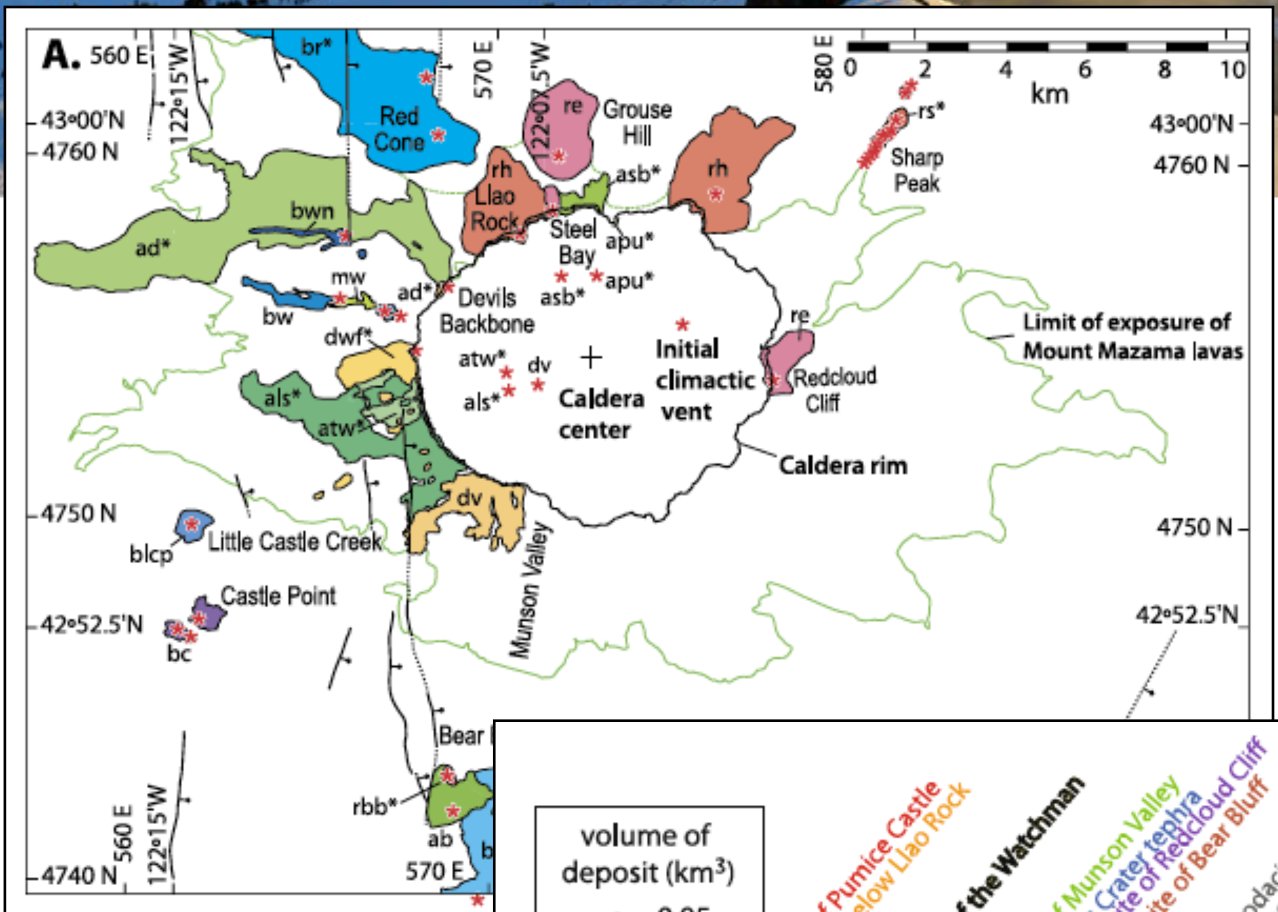




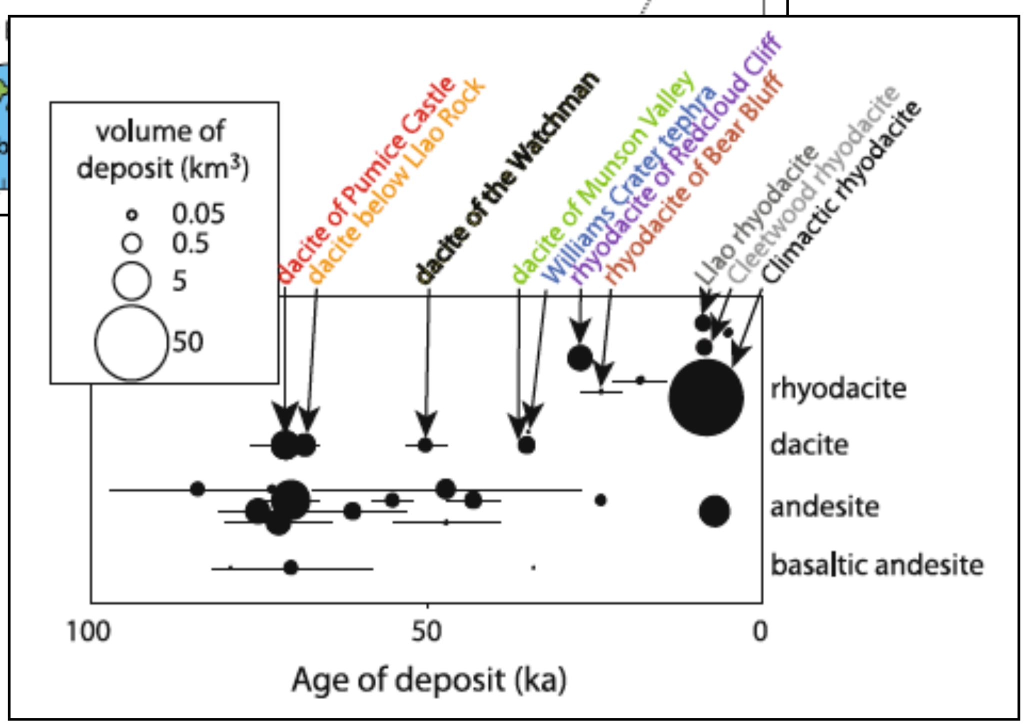
Influence of magma storage depth?

Crater Lake 7700ybp





Karlstrom et al. (2015)



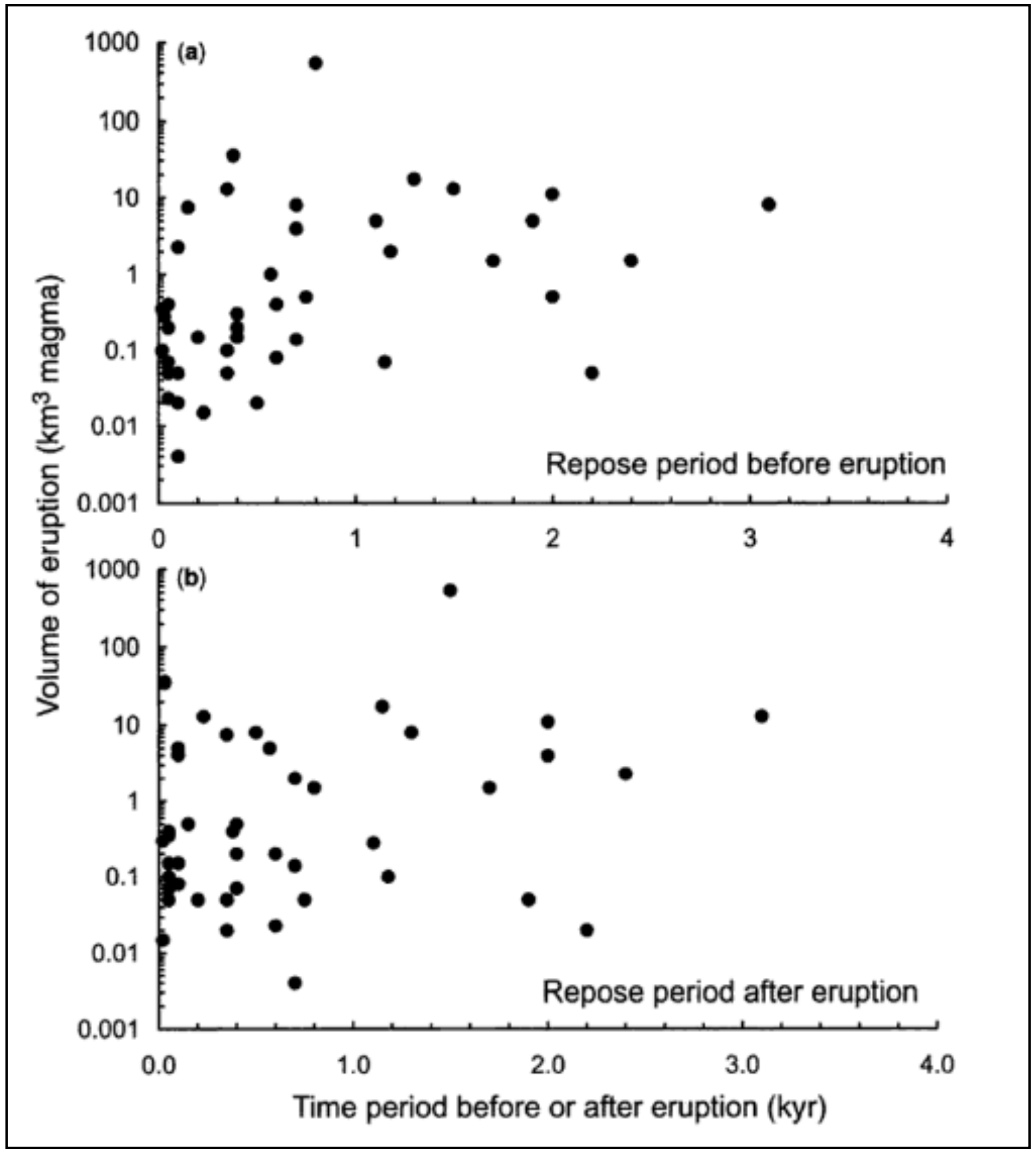
Wright et al. (2012)

LLao Rock rhyodacite [≤ 5km³ fall; 0.5 km³ flow]
200 yrs before climactic eruption

Cleetwood rhyodacite [~ 0.5 km³ fall; 0.6 km³ flow]
months before climactic eruption

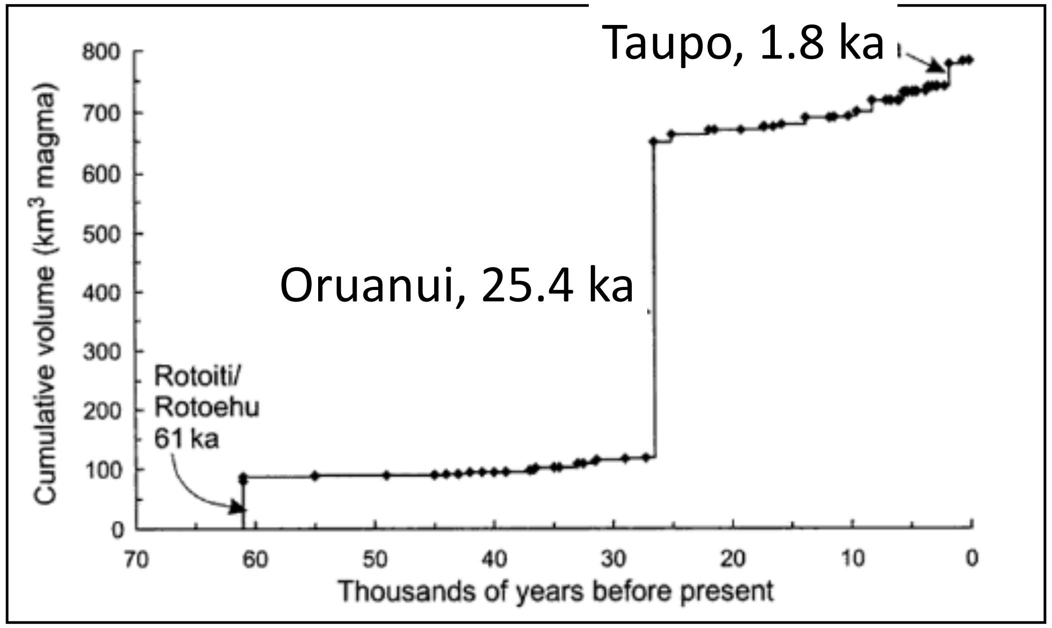
What triggered the main event?

Taupo Volcanic Zone



Wilson et al. (2009)

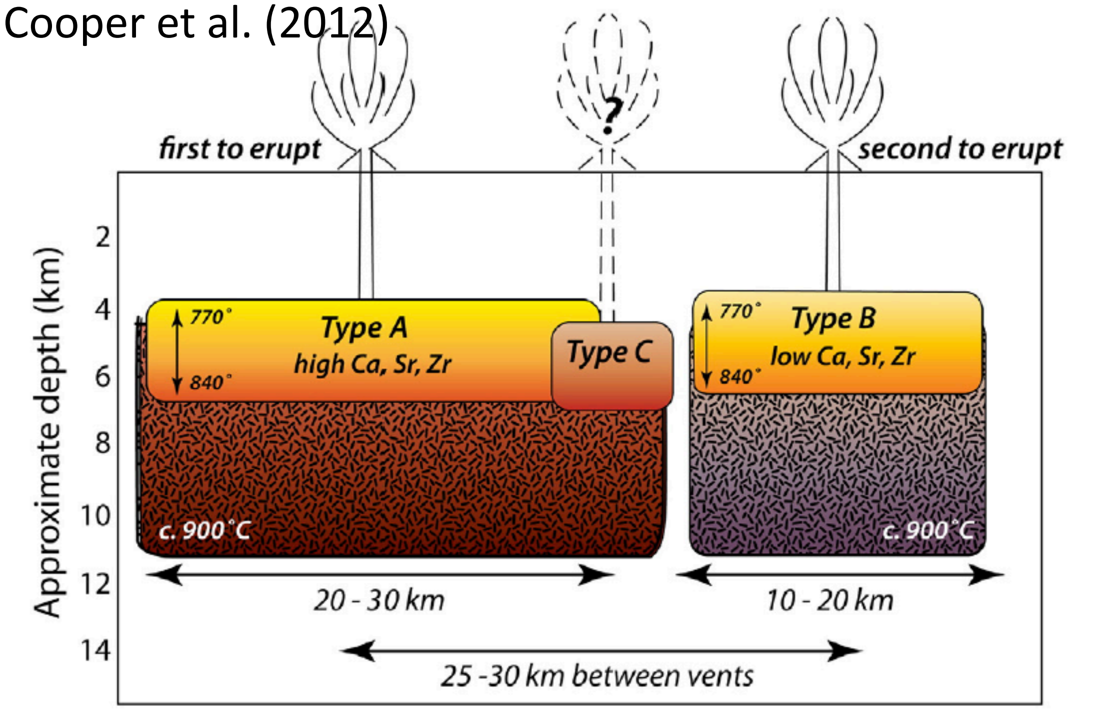
No apparent relation between repose time and erupted volume



What determines the volume of individual eruptions?

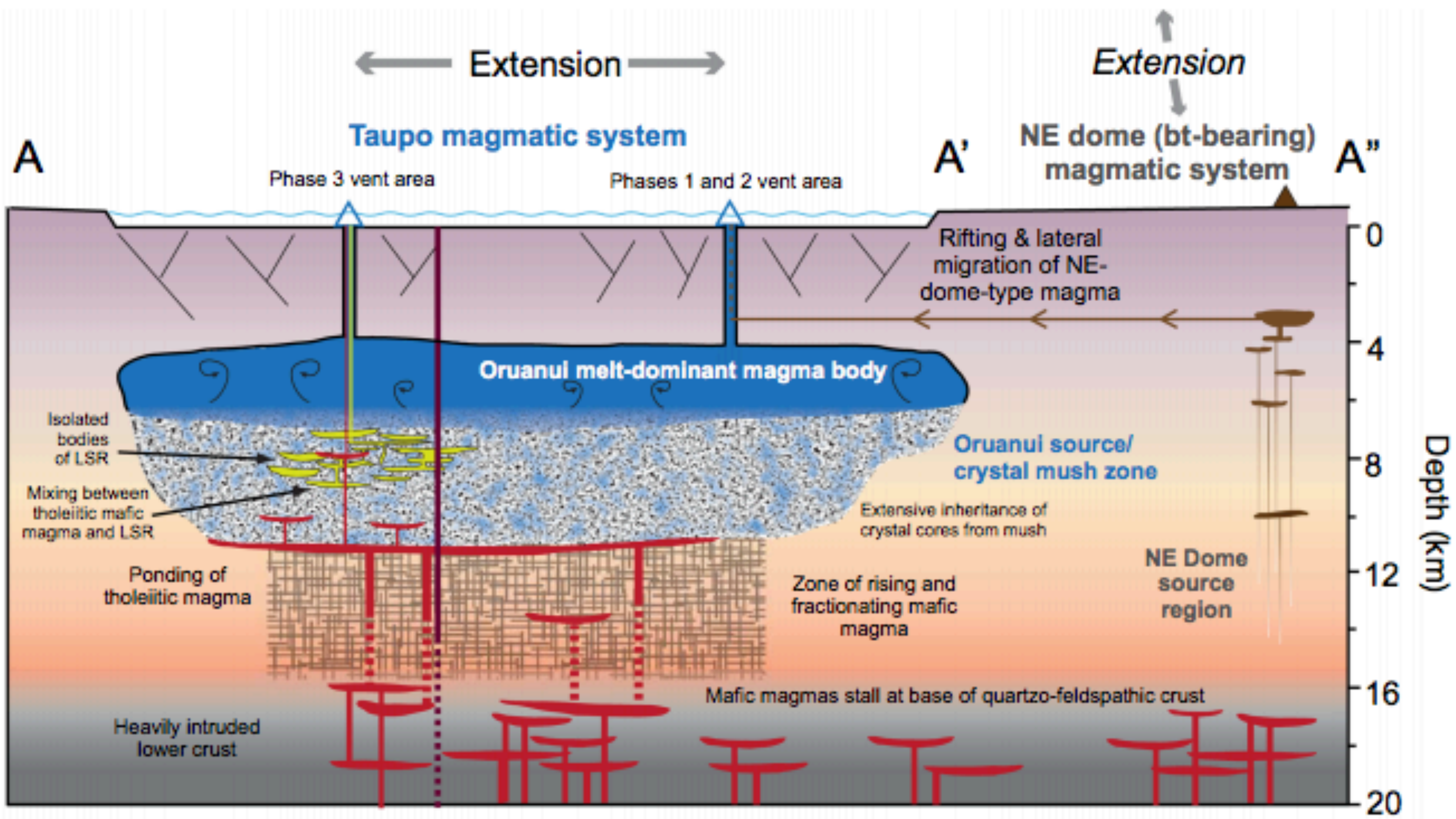
Taupo Volcanic Zone

Cooper et al. (2012)



Kidnappers supereruption
(1 Ma; 1200 km³)

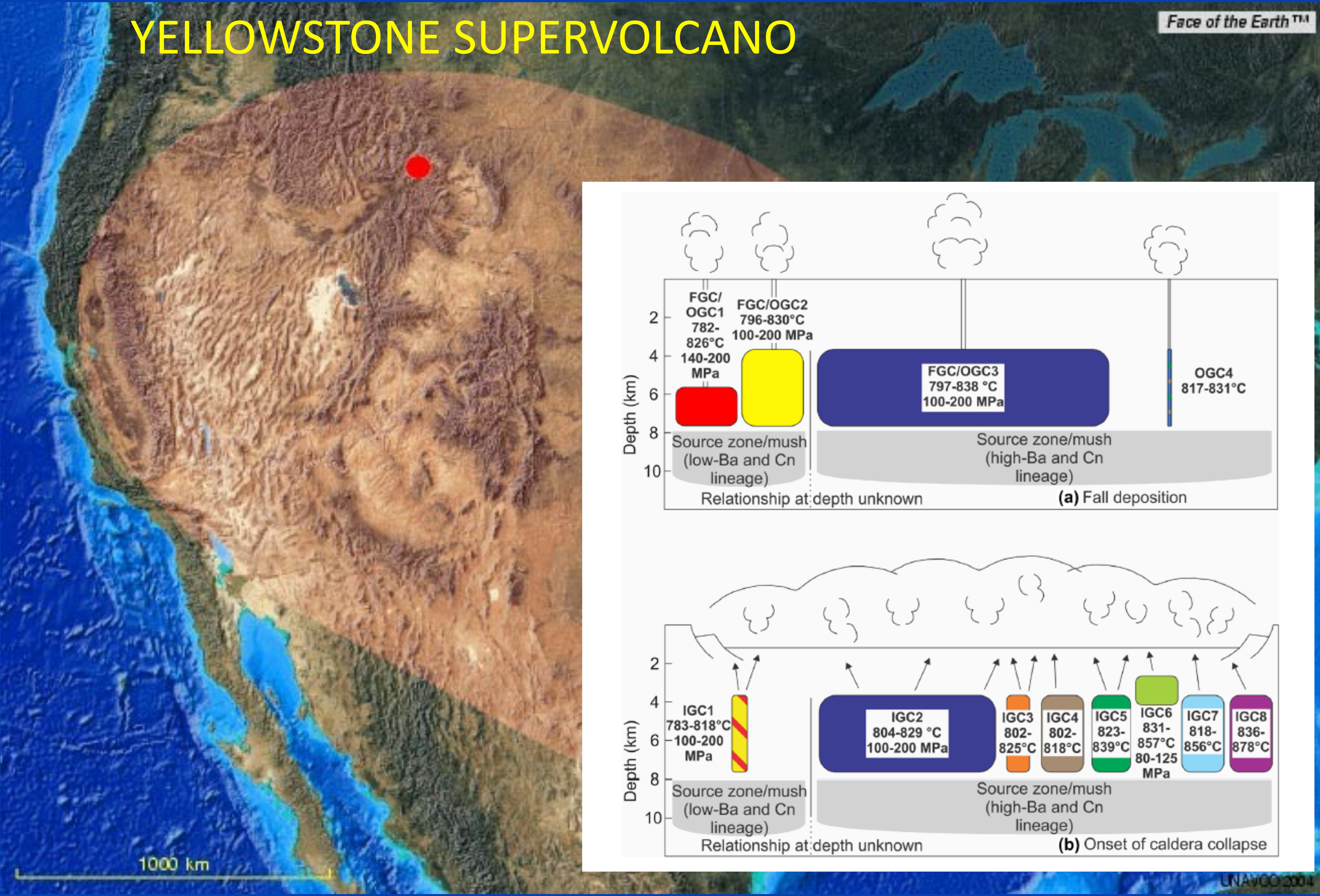
Oruanui supereruption
(25.4 ka; 530 km³)



Allan et al. (2017)

Is there a maximum size for single magmatic systems?

YELLOWSTONE SUPERVOLCANO



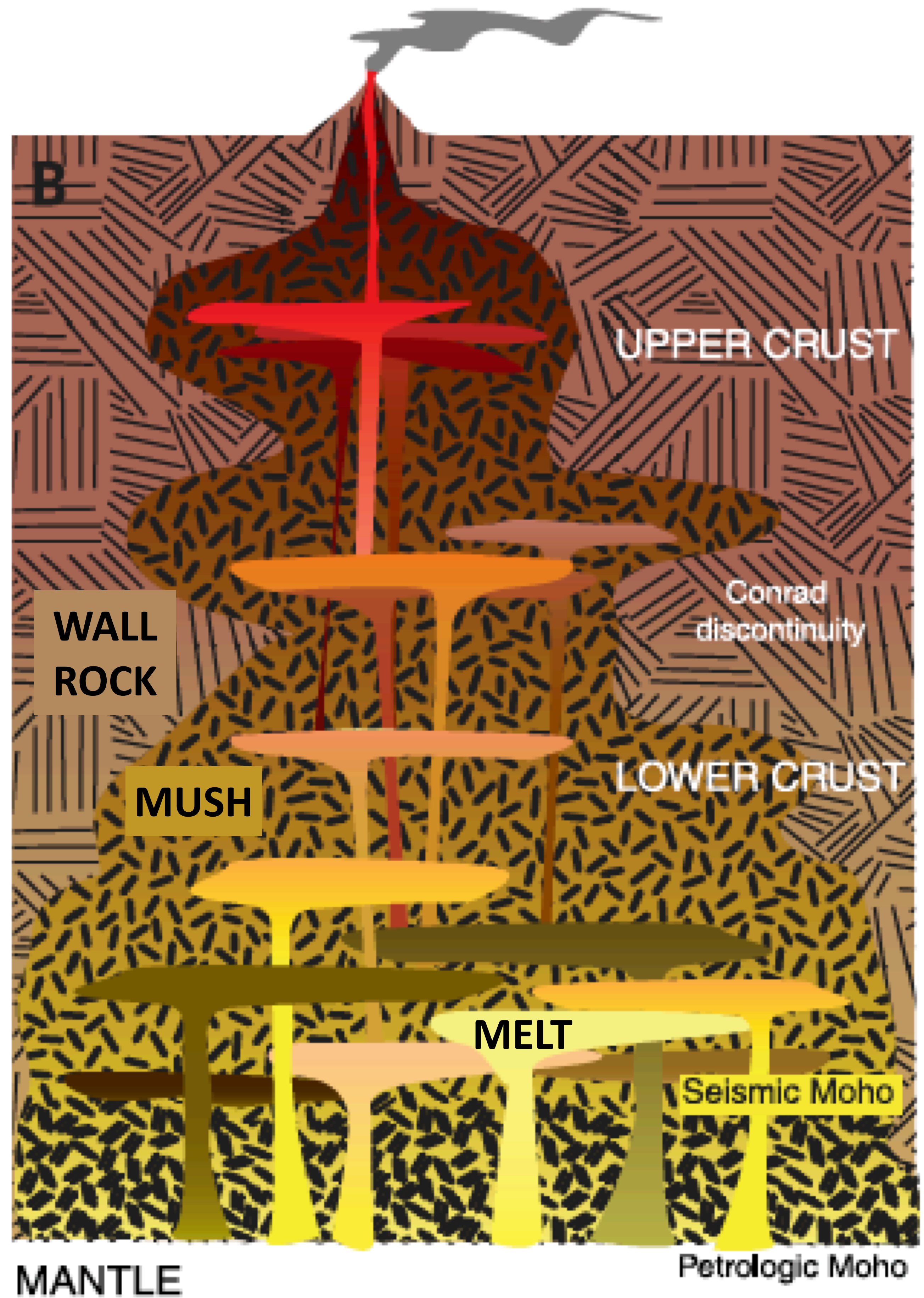
Swallow et al. (2018)

TCMS
Trans-crustal magmatic systems

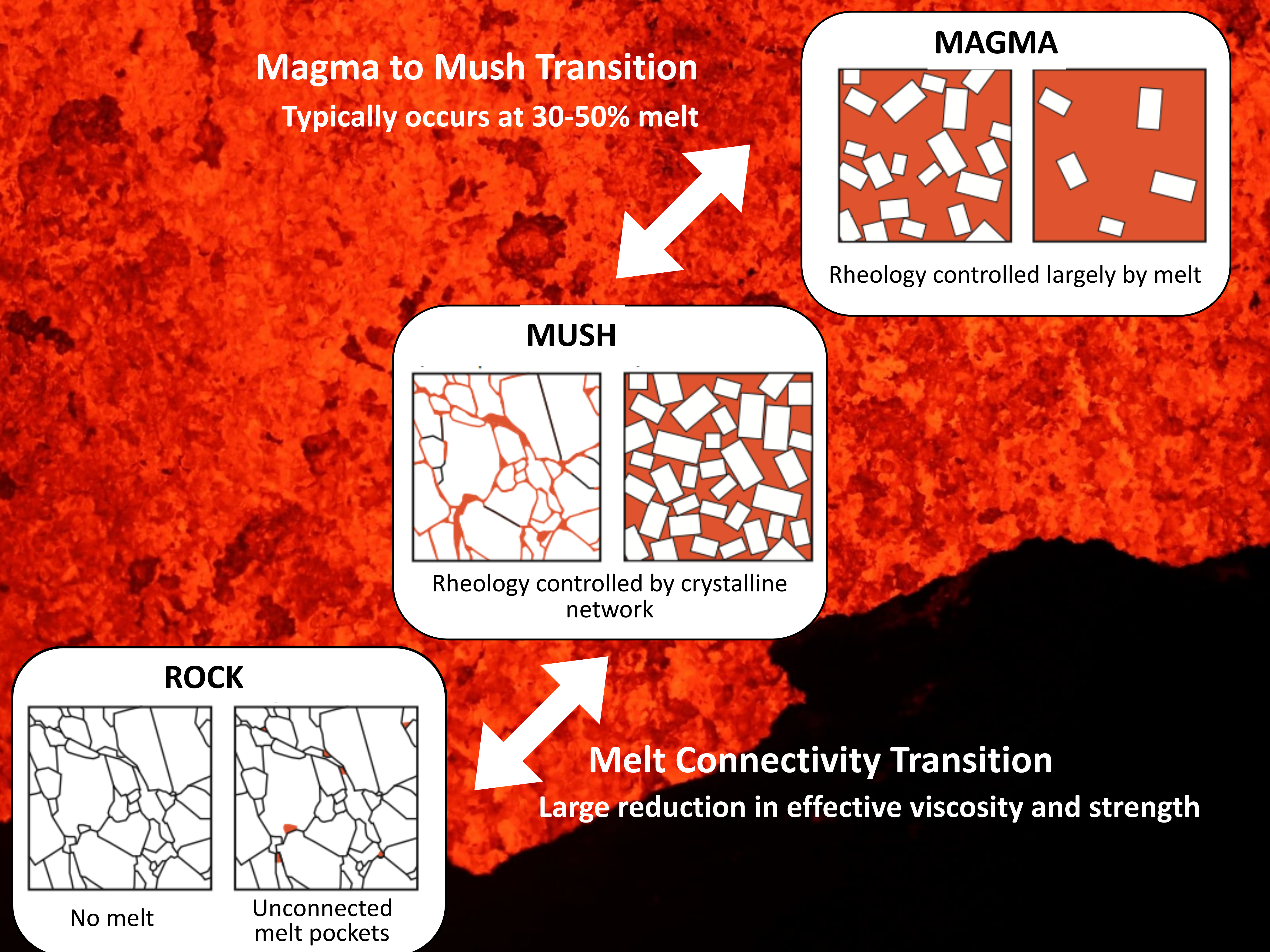
Combined evidence from geophysics and petrology/geochemistry provides abundant evidence for magmatic systems that traverse the crust

Changing the ways in which we think about

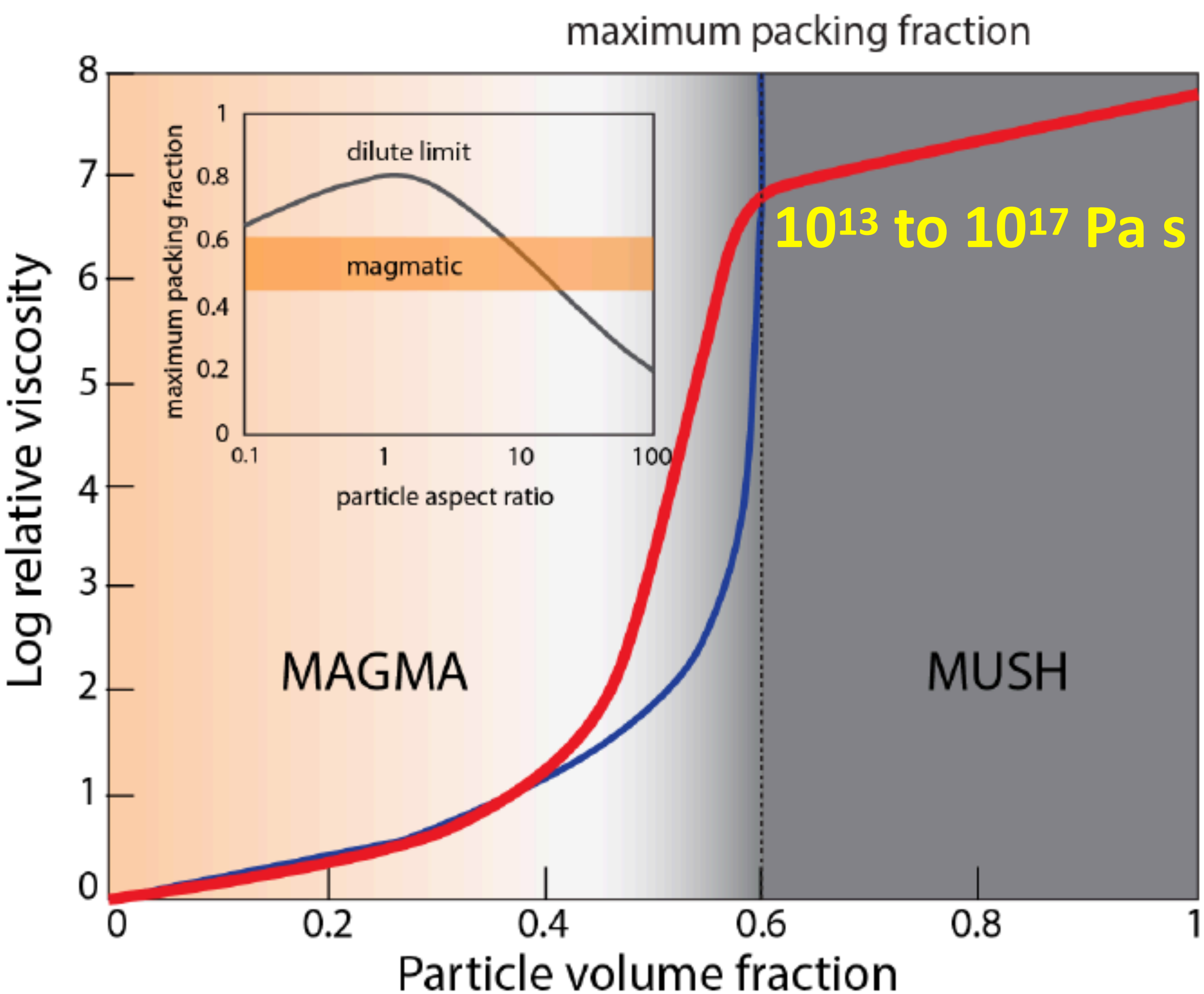
magma evolution
melt accumulation and volcanic eruptions
life cycles of volcanoes

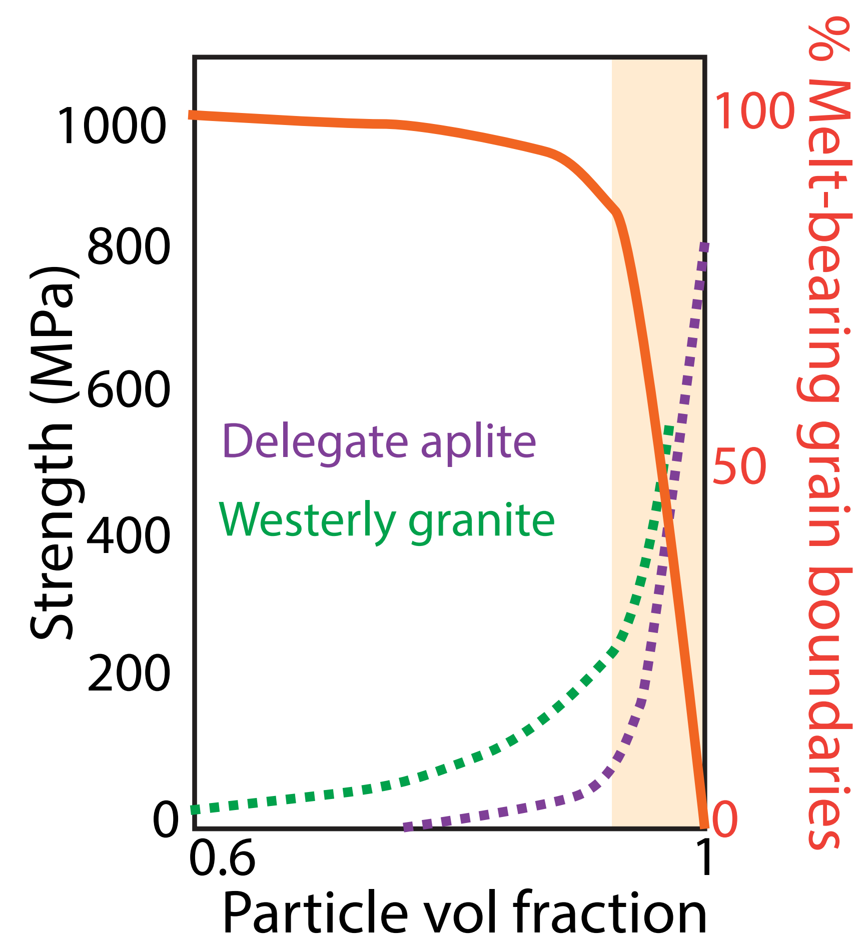


Cashman et al. (2017)


Magma to Mush Transition
Typically occurs at 30-50% melt
MAGMA
Rheology controlled largely by melt
MUSH
Rheology controlled by crystalline network
ROCK
No melt
Unconnected melt pockets
Melt Connectivity Transition
Large reduction in effective viscosity and strength

Melt content controls rheology
Melt distribution controls permeability

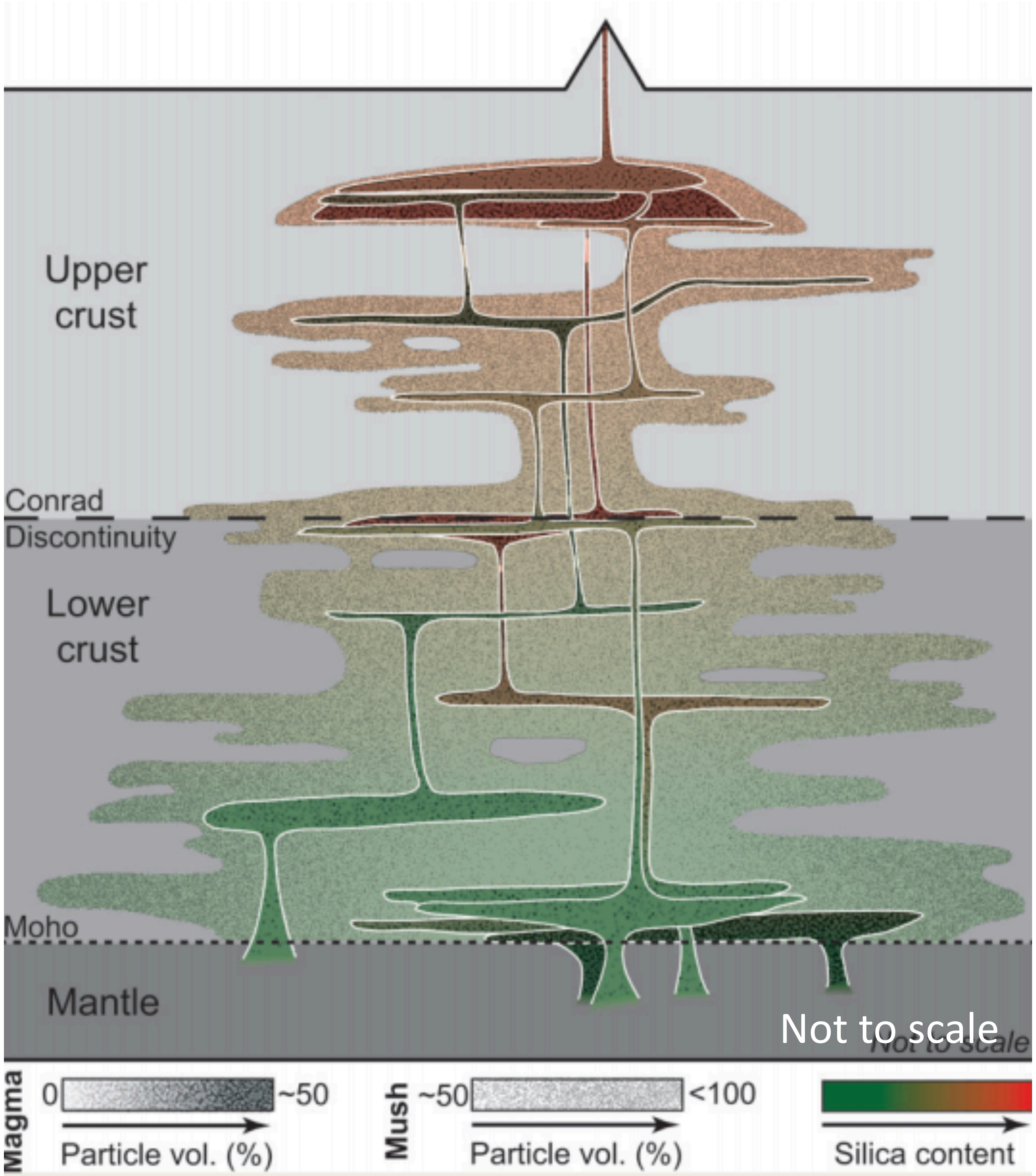




ERUPTIBLE NON-ERUPTIBLE

Cashman et al. (2017)

Stability of melt lenses



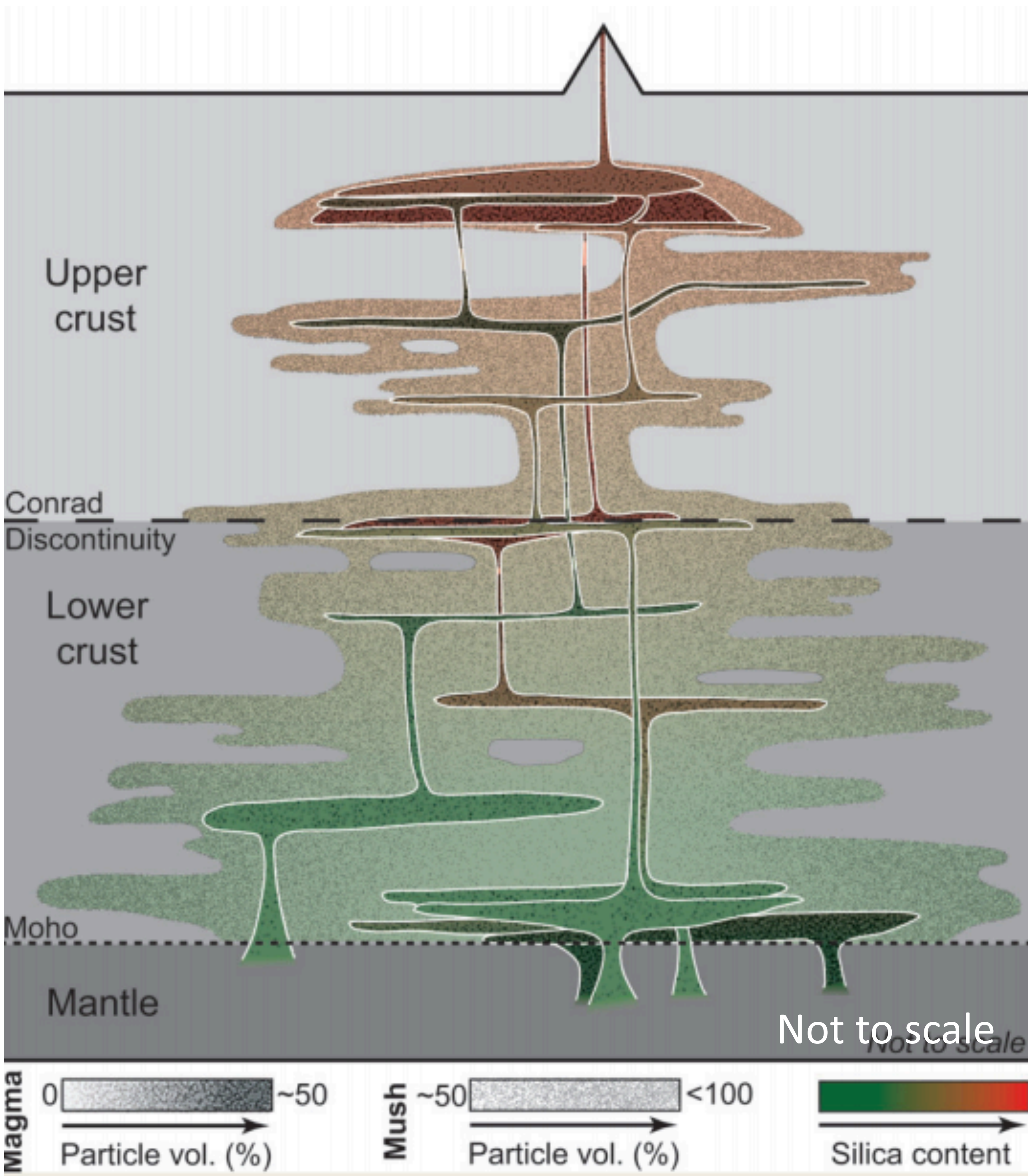
Magee et al (2018)

What conditions allow:

Rapid transfer to shallow reservoirs the upper crust?

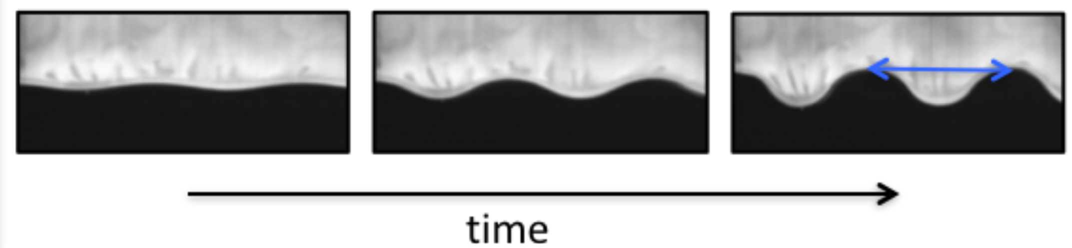
Storage of buoyant magmas in deep crustal regions?

Stability of melt lenses

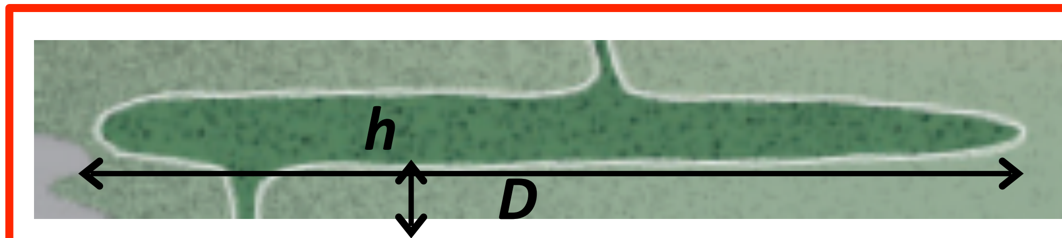


Magee et al (2018)

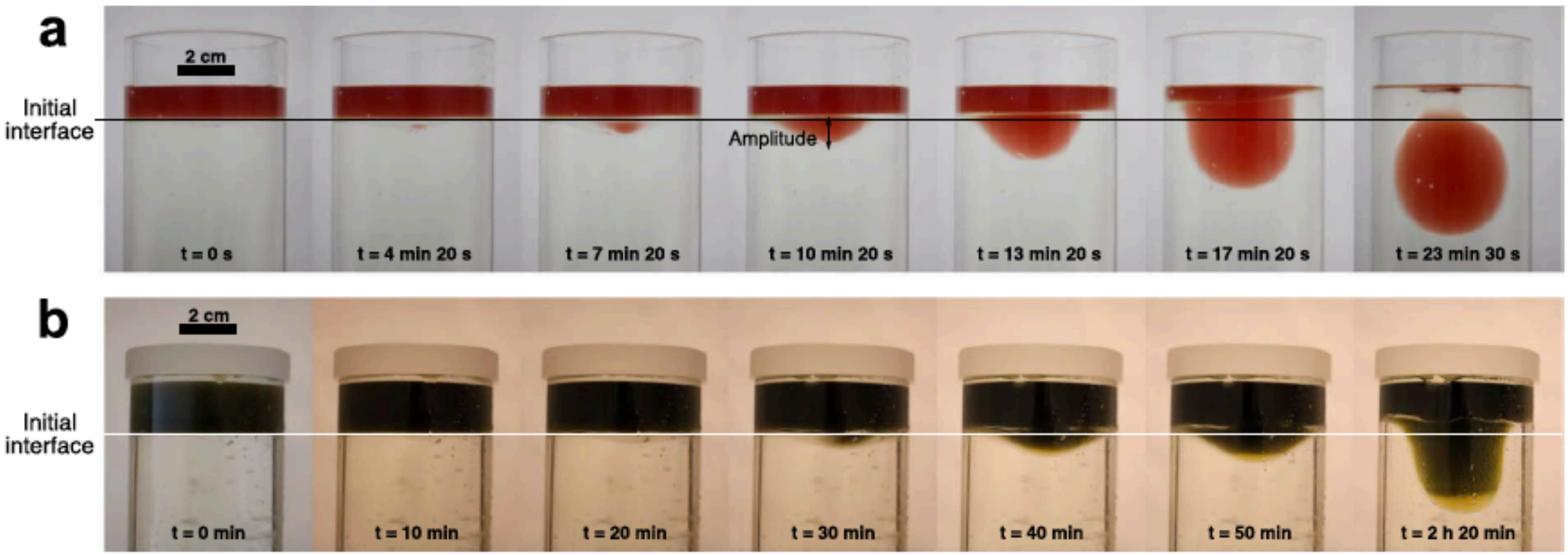
Rayleigh-Taylor instability:



Theory: For an infinite fluid layer, instability wavelength is proportional to the viscosity contrast



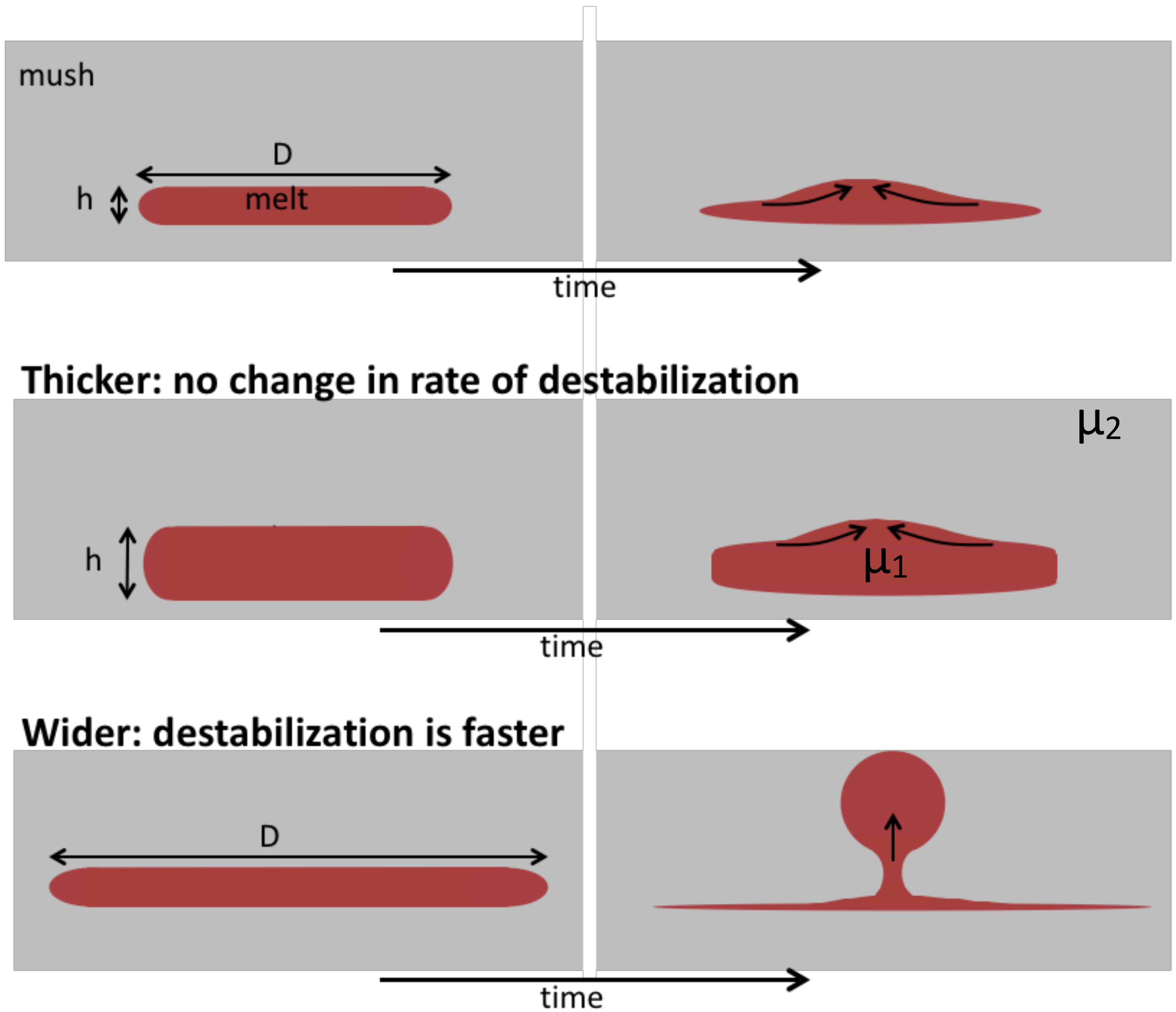
What is the stability of melt lenses of finite length?



Seropian et al. (2018)

For β>1, $\frac{\text{Growth rate unconfined}}{\text{Growth rate confined}} \approx \beta = \frac{\text{Wavelength unconfined}}{\text{Wavelength confined}}$

Timescale depends on mush strength and D



Seropian et al. (2018)

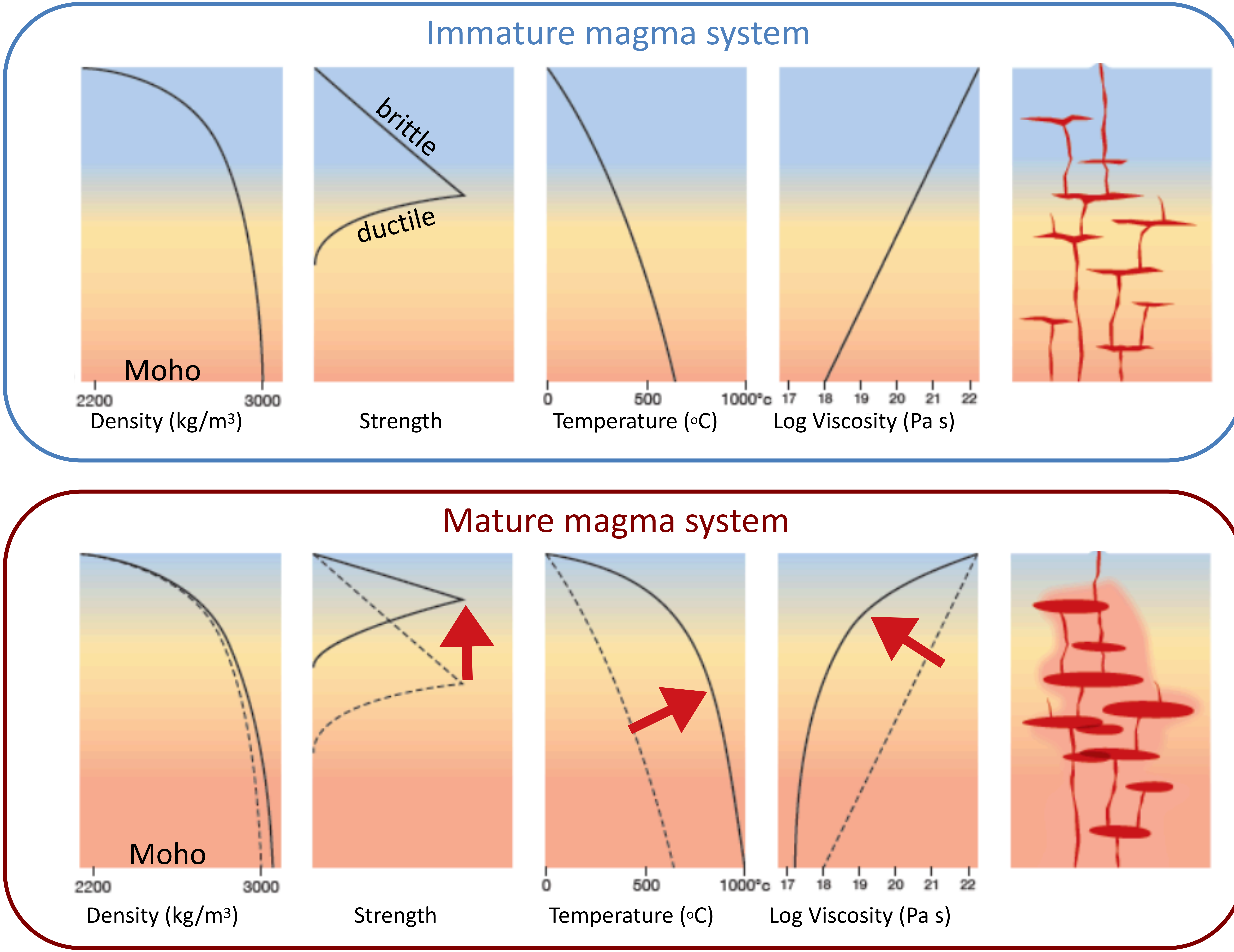
Increase in *D* accelerates instability growth if $\beta > 1$

$$\tau_{RTI} = \frac{\beta}{n_c} = \frac{6\pi\mu_2}{\Delta\rho g D}$$

Increase in *h* accelerates instability growth only if $\beta \leq 1$

$$\tau_{RTI} = \frac{1}{n_c} = \frac{\mu_2}{0.232 g\Delta\rho h}\varepsilon^{-1/3}$$

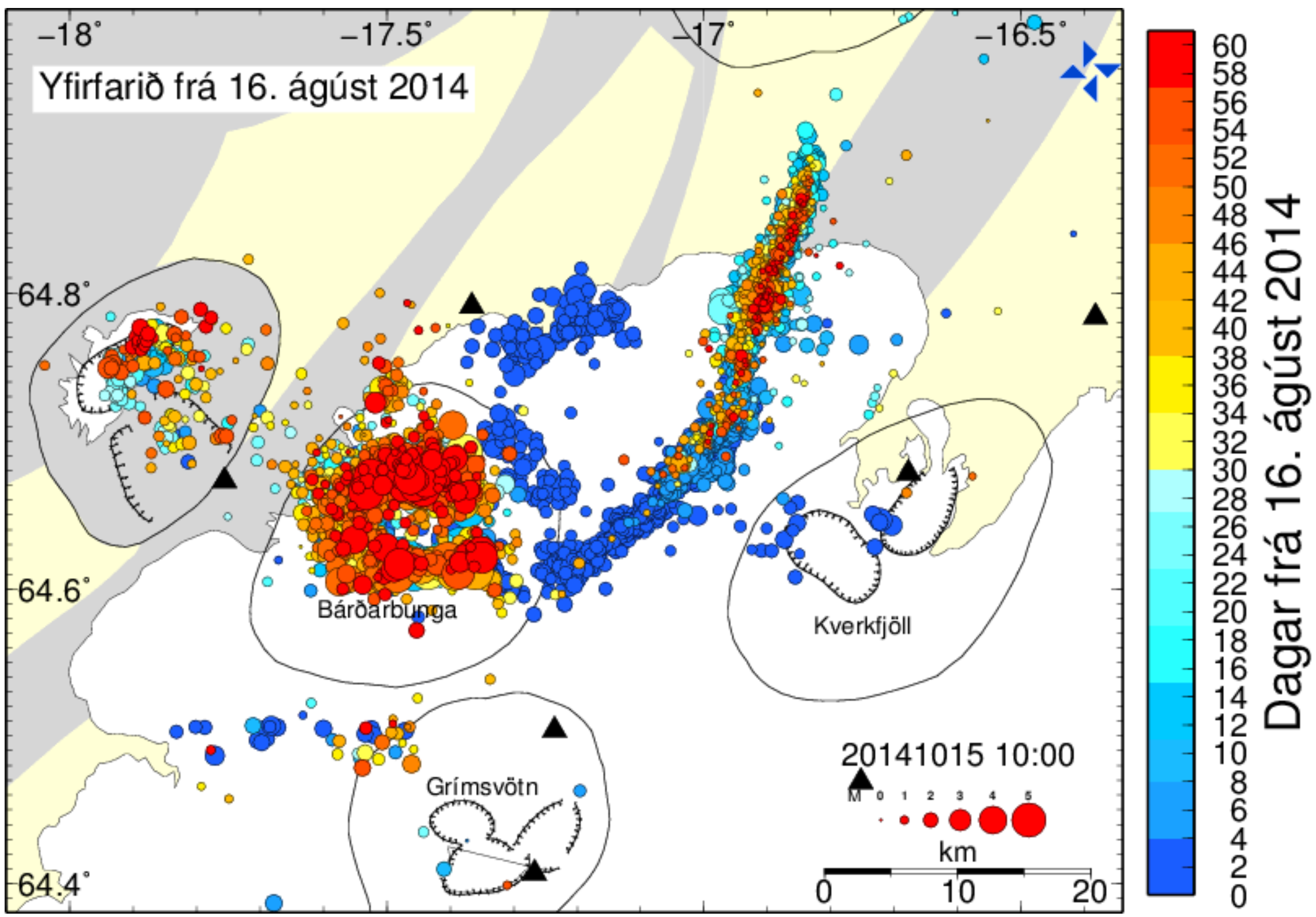
$\varepsilon = \mu_2/\mu_1 >> 1$

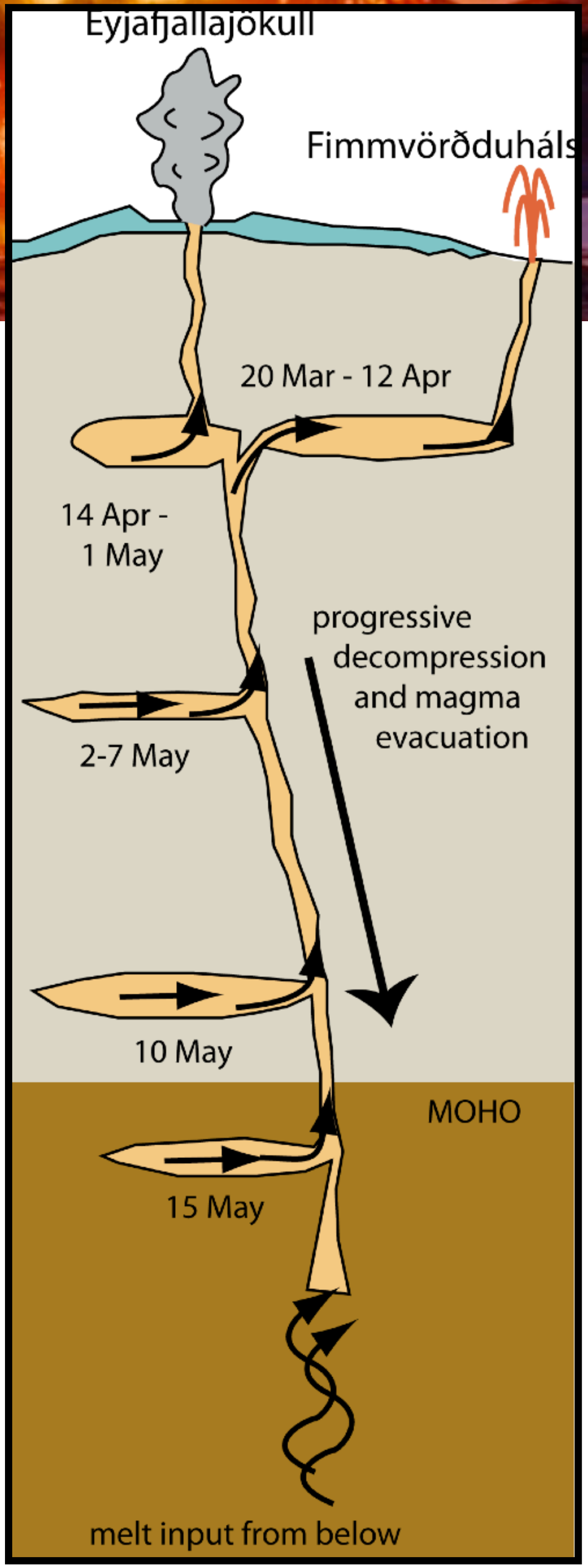


Sparks et al. (2019)

Immature crust: melt transfer via dikes

Bardabunga - Holuhraun 2014-2015

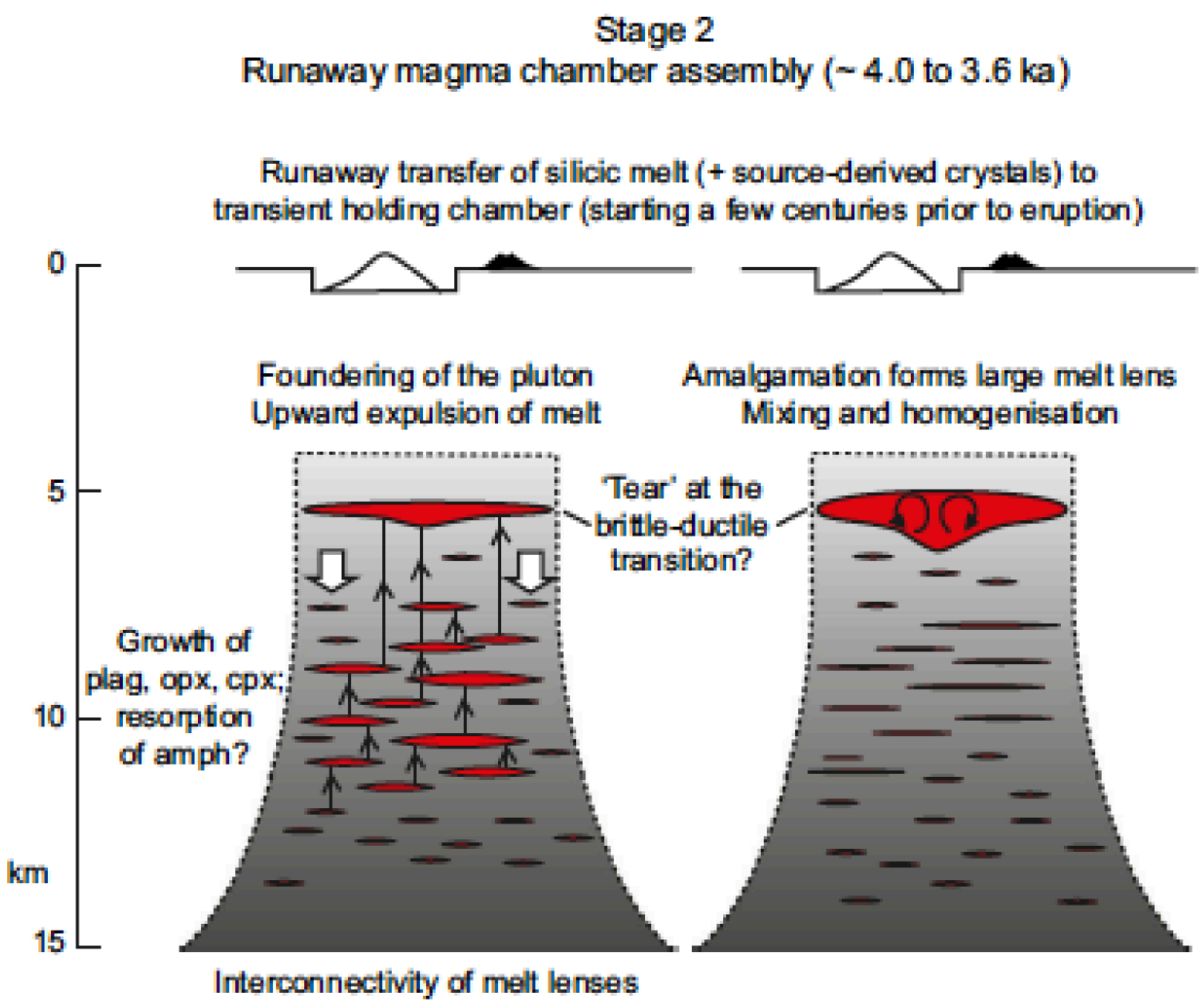




Mature system - Santorini

Multiple timescale constraints for high-flux magma chamber assembly prior to the Late Bronze Age eruption of Santorini (Greece)

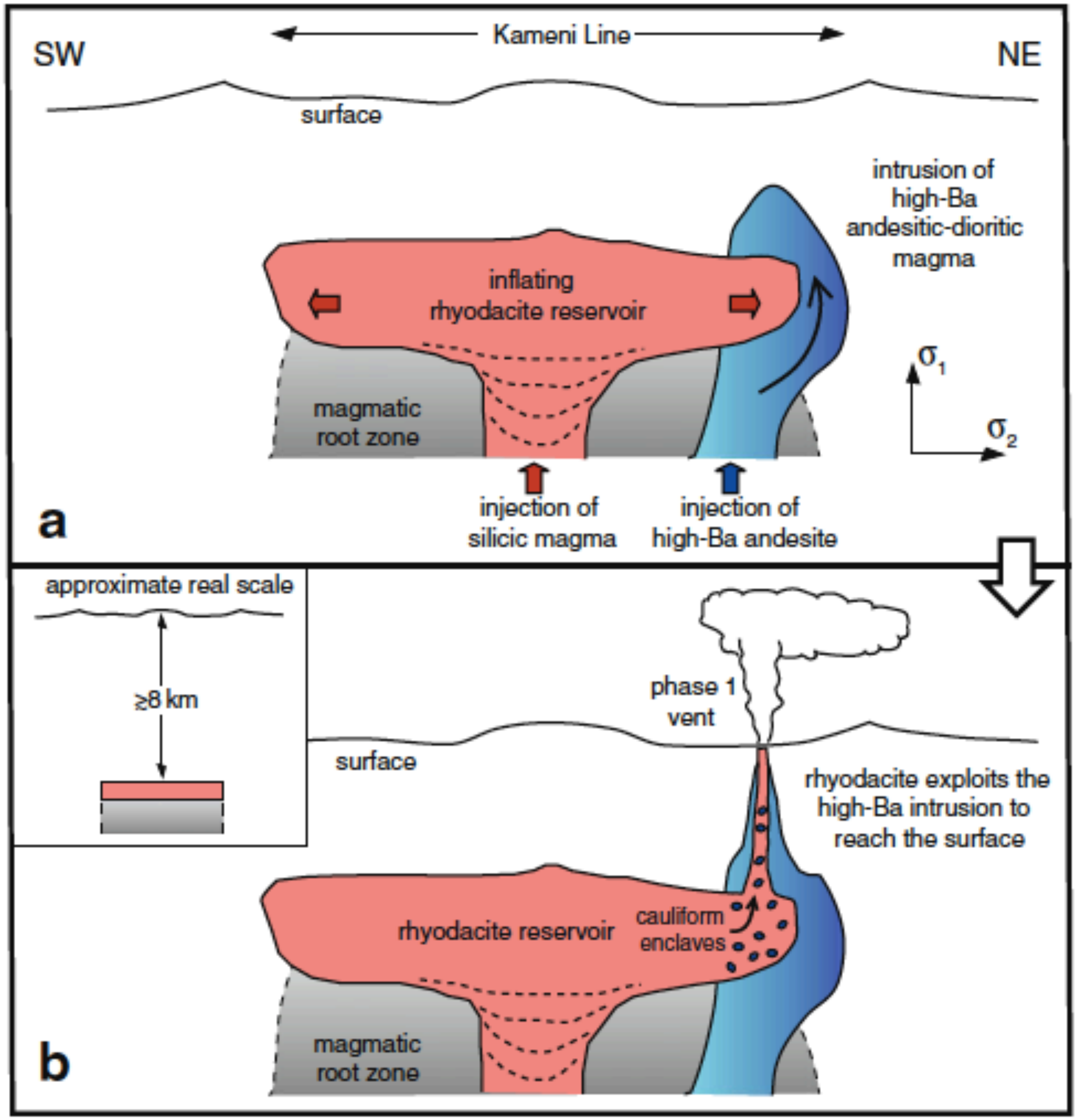
T. Flaherty[1] · T. H. Druitt[1] · H. Tuffen[2] · M. D. Higgins[3] · F. Costa[4] · A. Cadoux[5]



Using a combination of methods, the authors calculated that it took ~400 years to construct the upper crustal magma chamber that fed the Minoan eruption

Flaherty et al. (2018)

Santorini



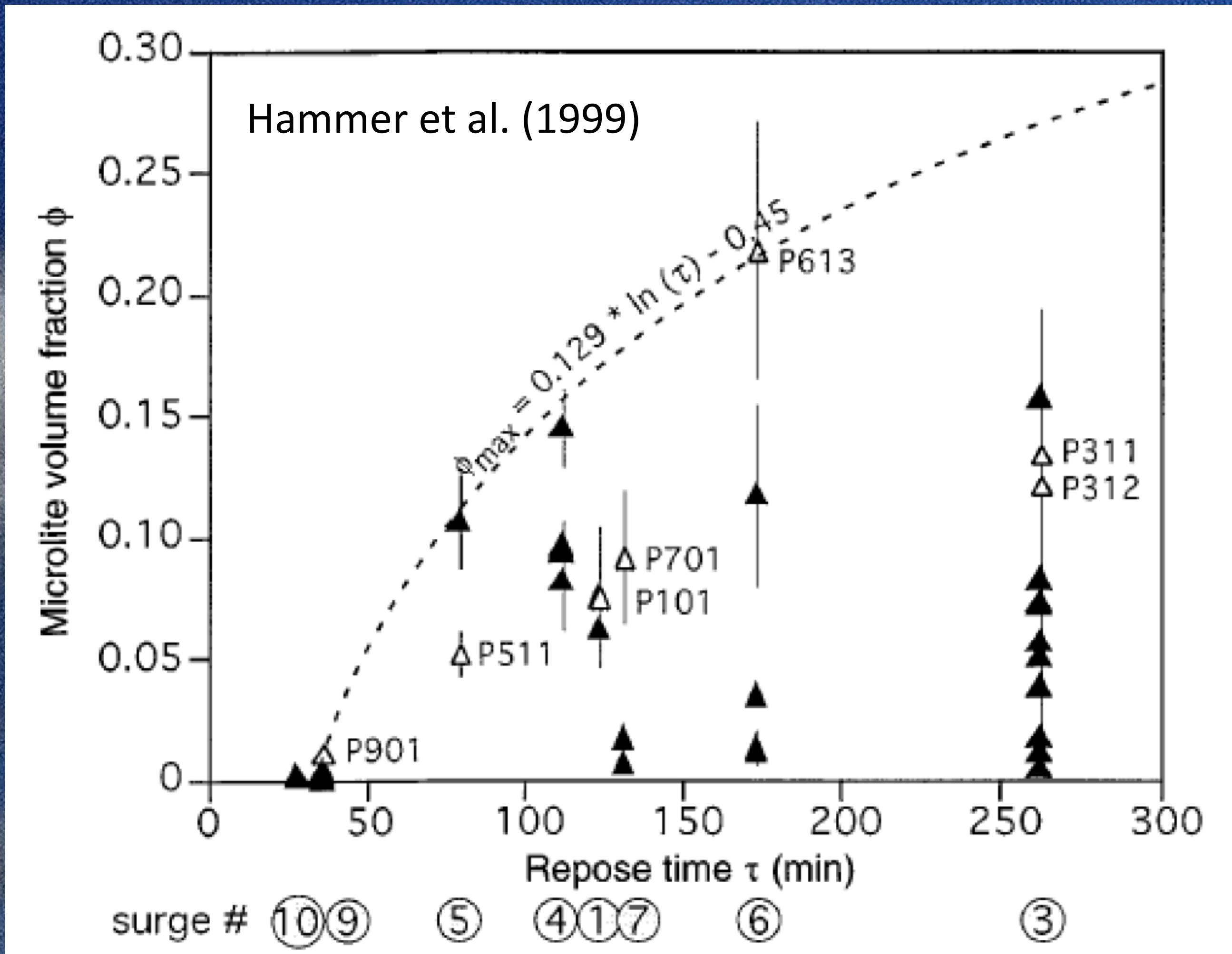
Druitt (2014)

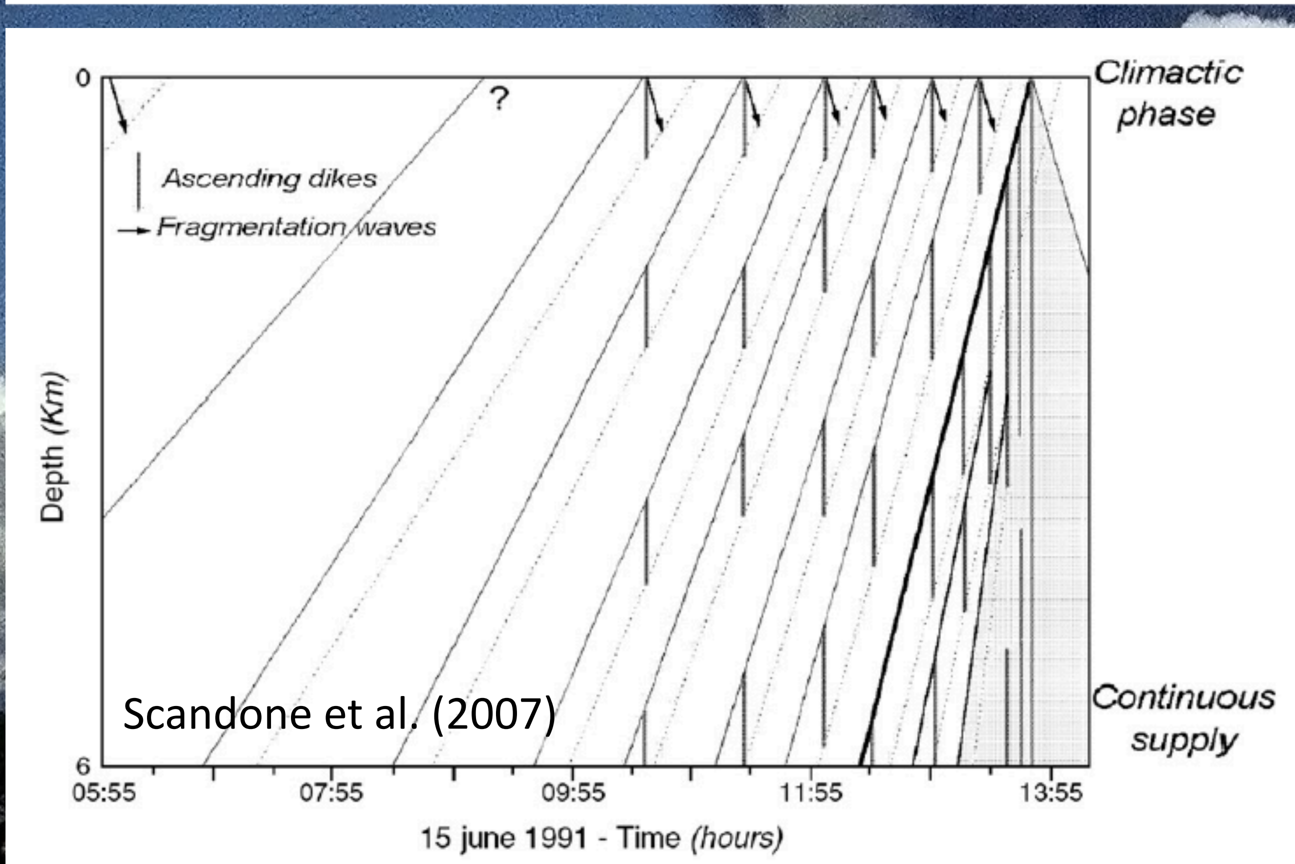
Eruption was triggered by "recharge magma" (the final lens destabilisation?) that created a path to the surface

How to construct a conduit?

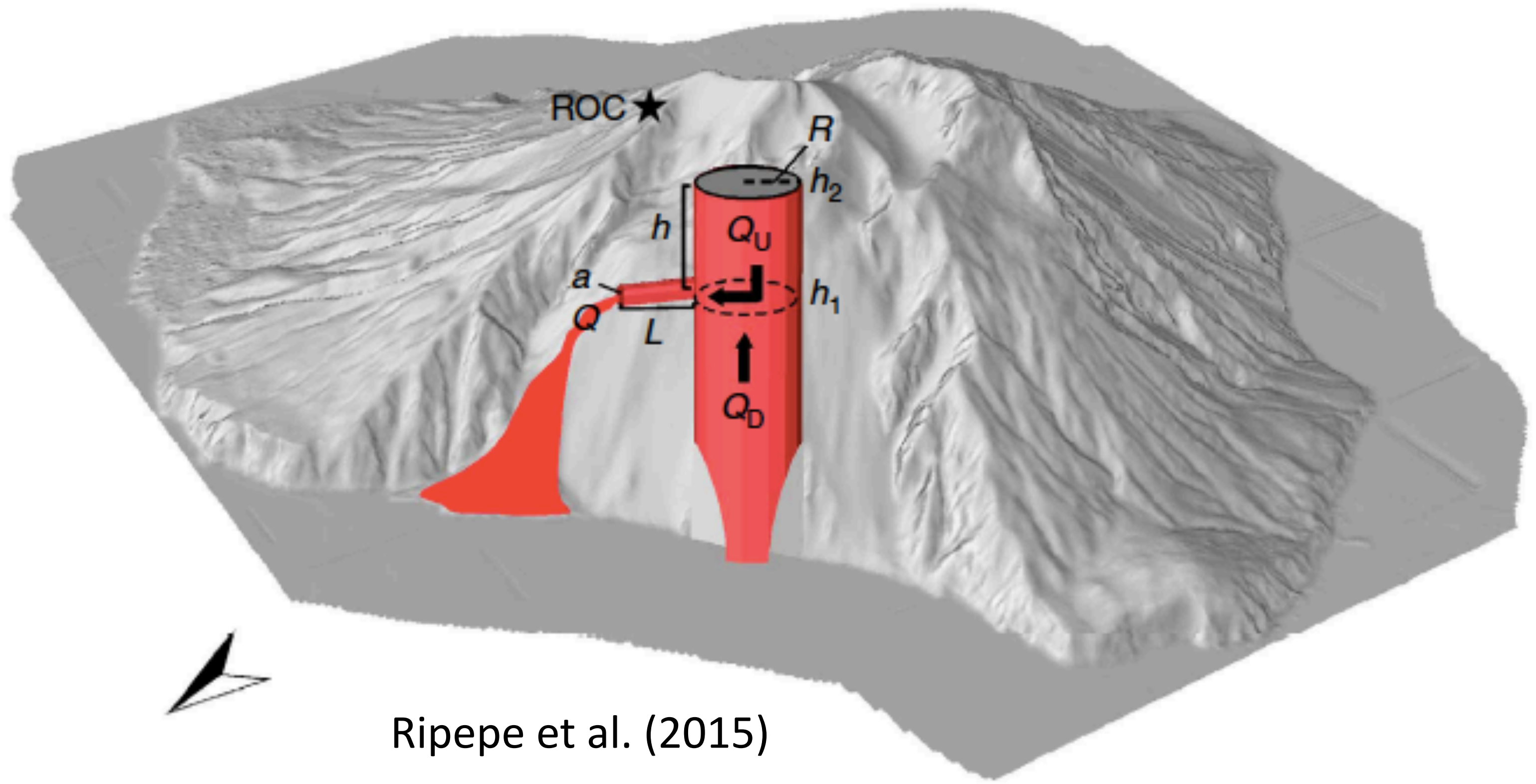
et al. (2007)

Pinatubo 1991





Progression of precursor eruptions suggests that the conduit was constructed by a succession of magma inputs over days prior to the climactic event

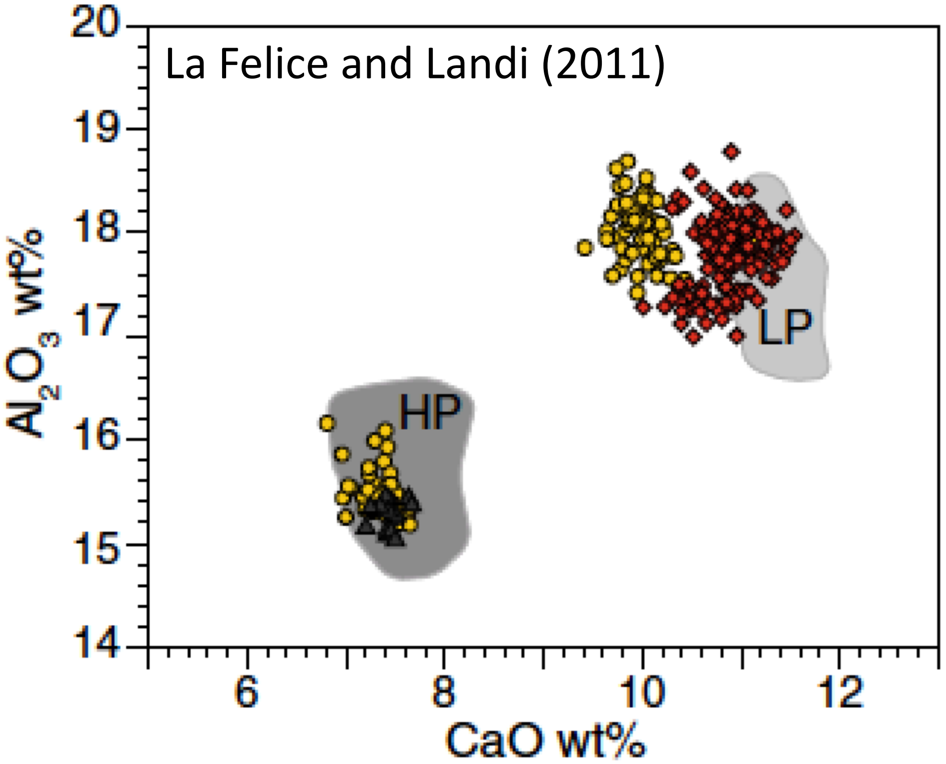


Ripepe et al. (2015)

Downward-propagating decompression wave triggers influx of volatile-rich magma from separate reservoir at 7-10 km

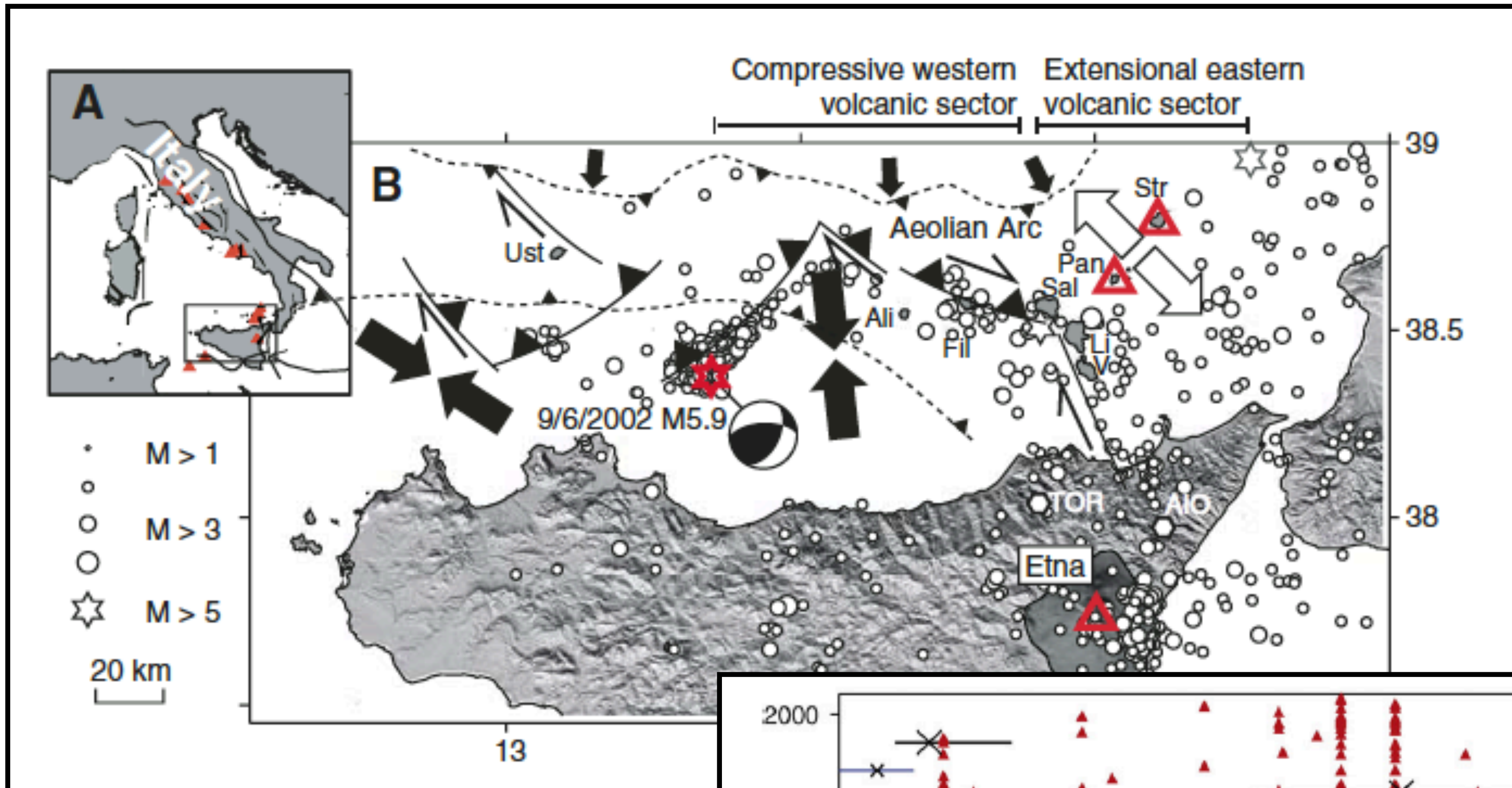
Conduits are transient

Lava drainage causes magmastatic head change
ΔP = 4.3-6.7 MPa

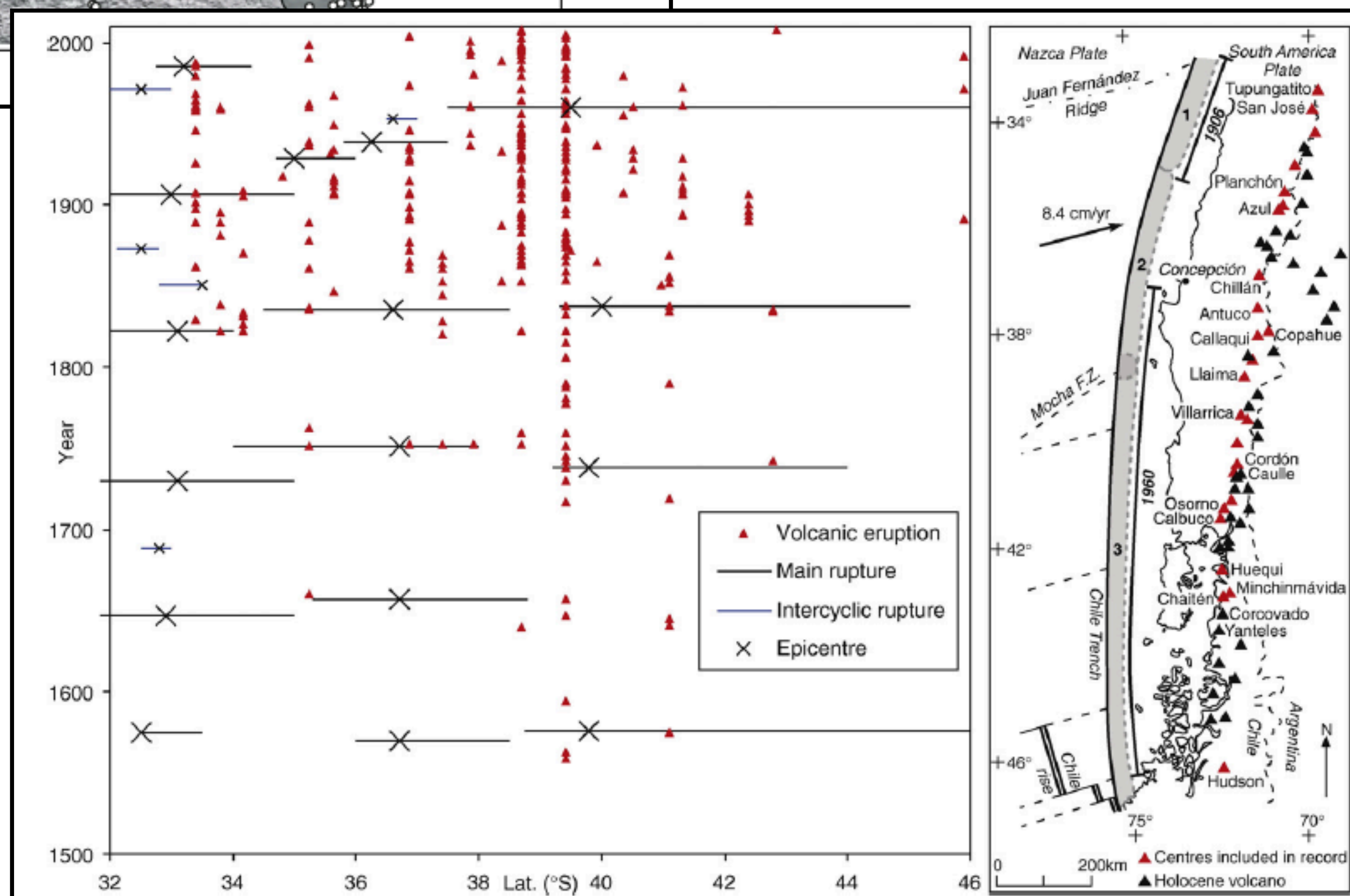


Earthquake triggers?

Triggering of eruptions by earthquakes has long been a topic of discussion



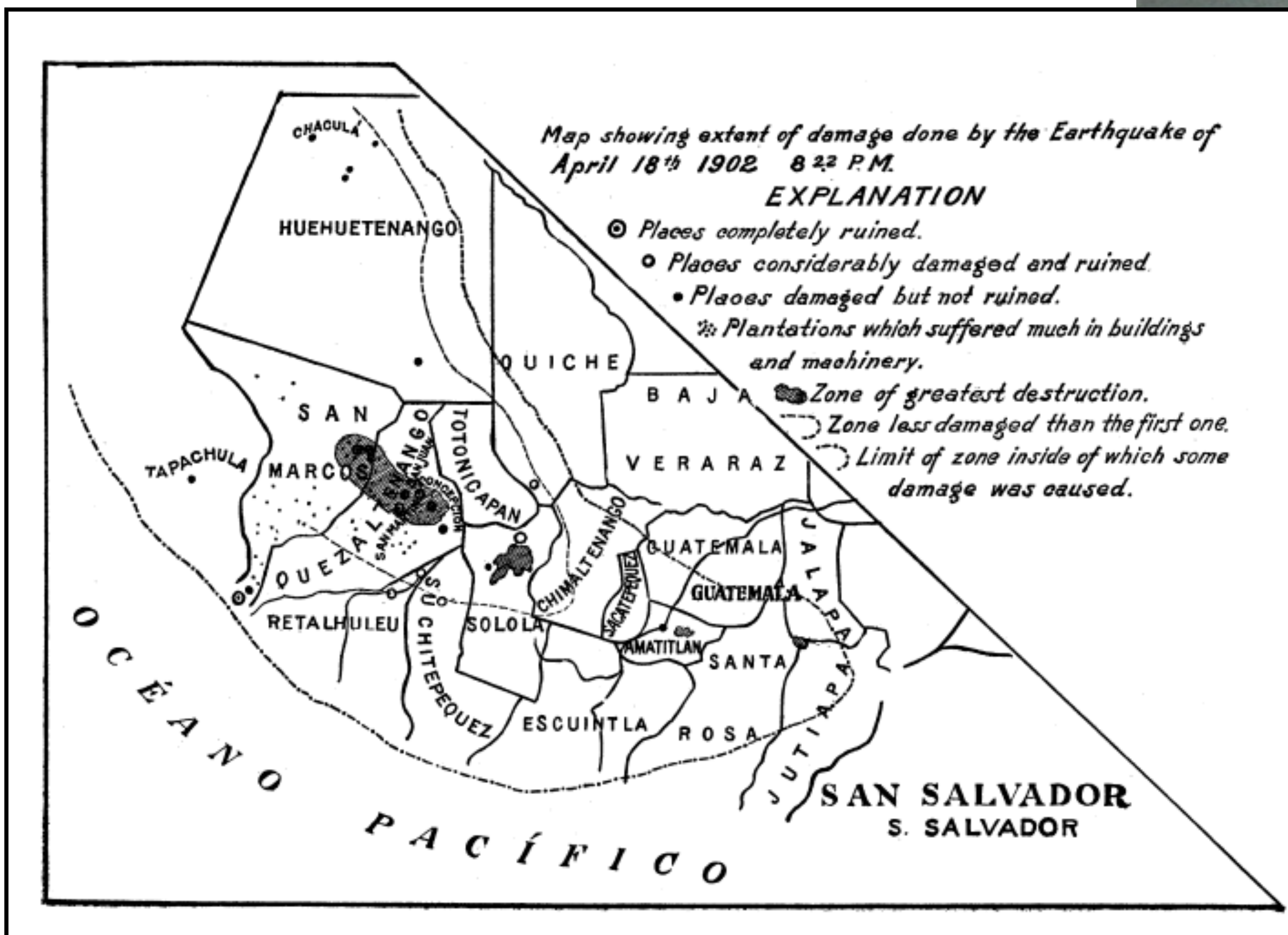
Walter et al. (2009)



Watt et al. (2009)

Questions remain about mechanisms, distance of influence and timing of earthquake triggers

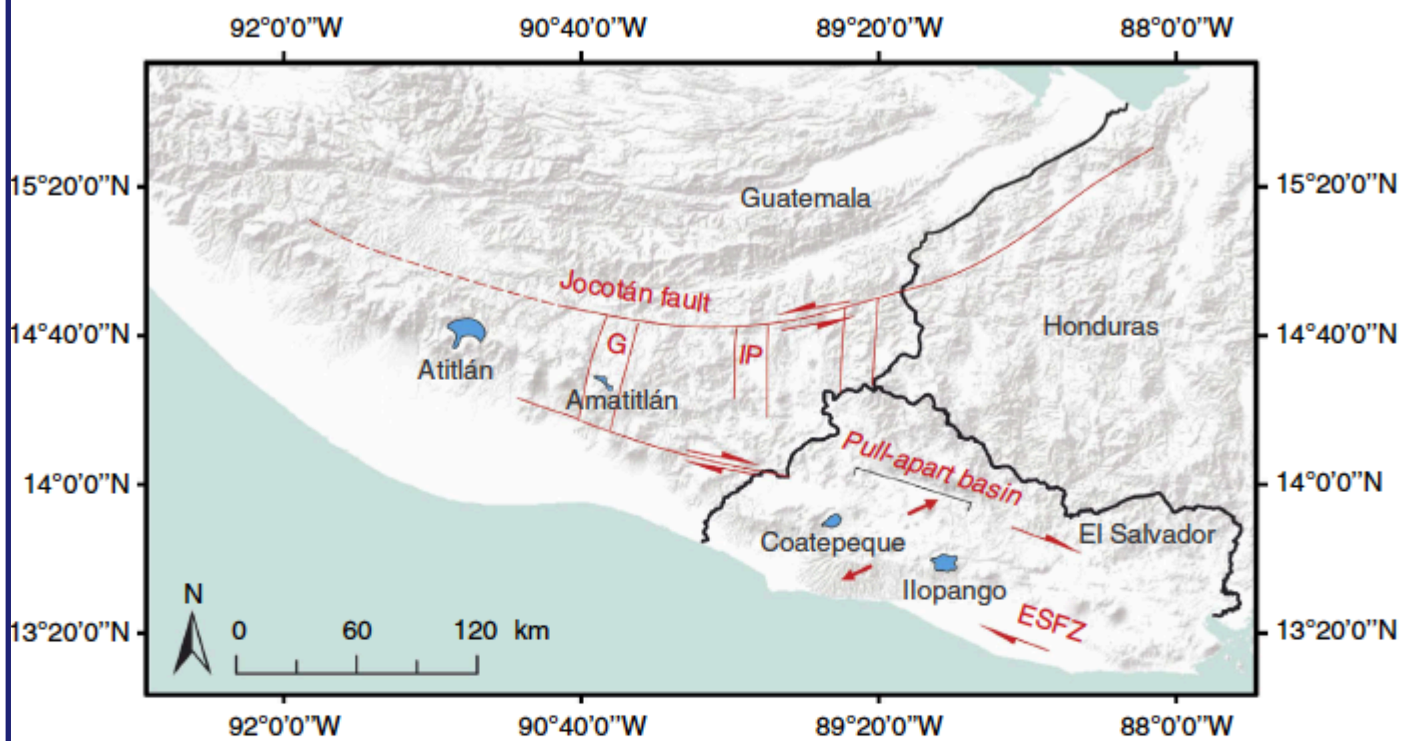
A magnitude 7.5 earthquake preceded the 1902 eruption of Santa Maria by 6 months… is this a coincidence?



[Zu S. 106.]

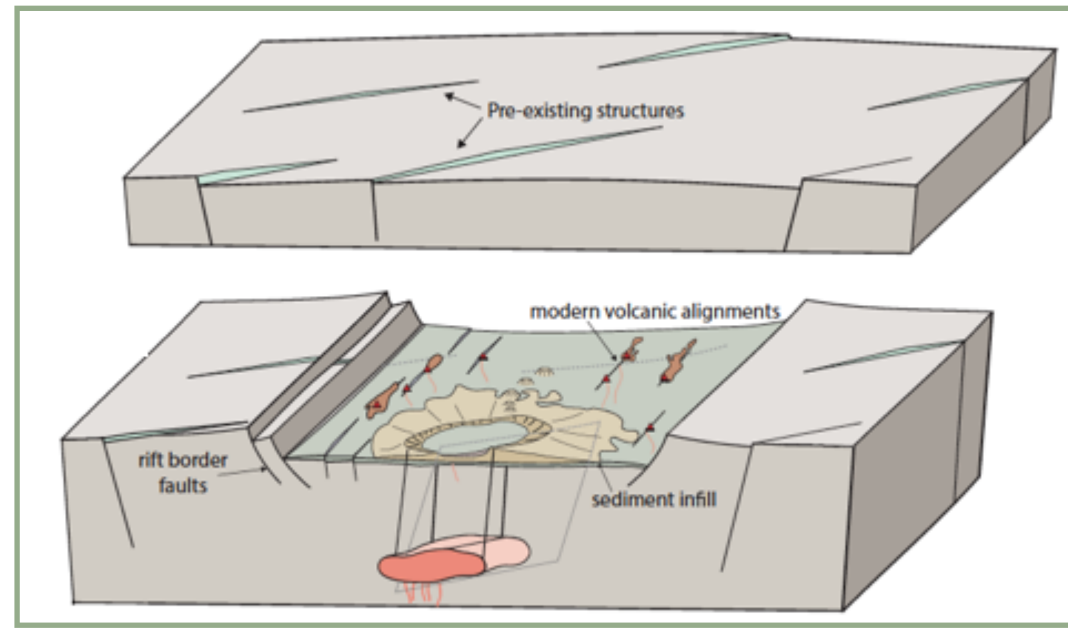
Abb. 31. Ausbruchswolke des Santa Maria (mit STREIT'scher Wolke rechts). (Aufgenommen von FERNANDEZ y VALDEAVELLANO, von Quezaltenango aus.)

Influence of tectonics?



Saxby et al. (2015)

Calderas commonly form in extensional or trans-tensional settings



Robertson et al. (2015)

and may take advantage of pre-existing structures

Forecasting

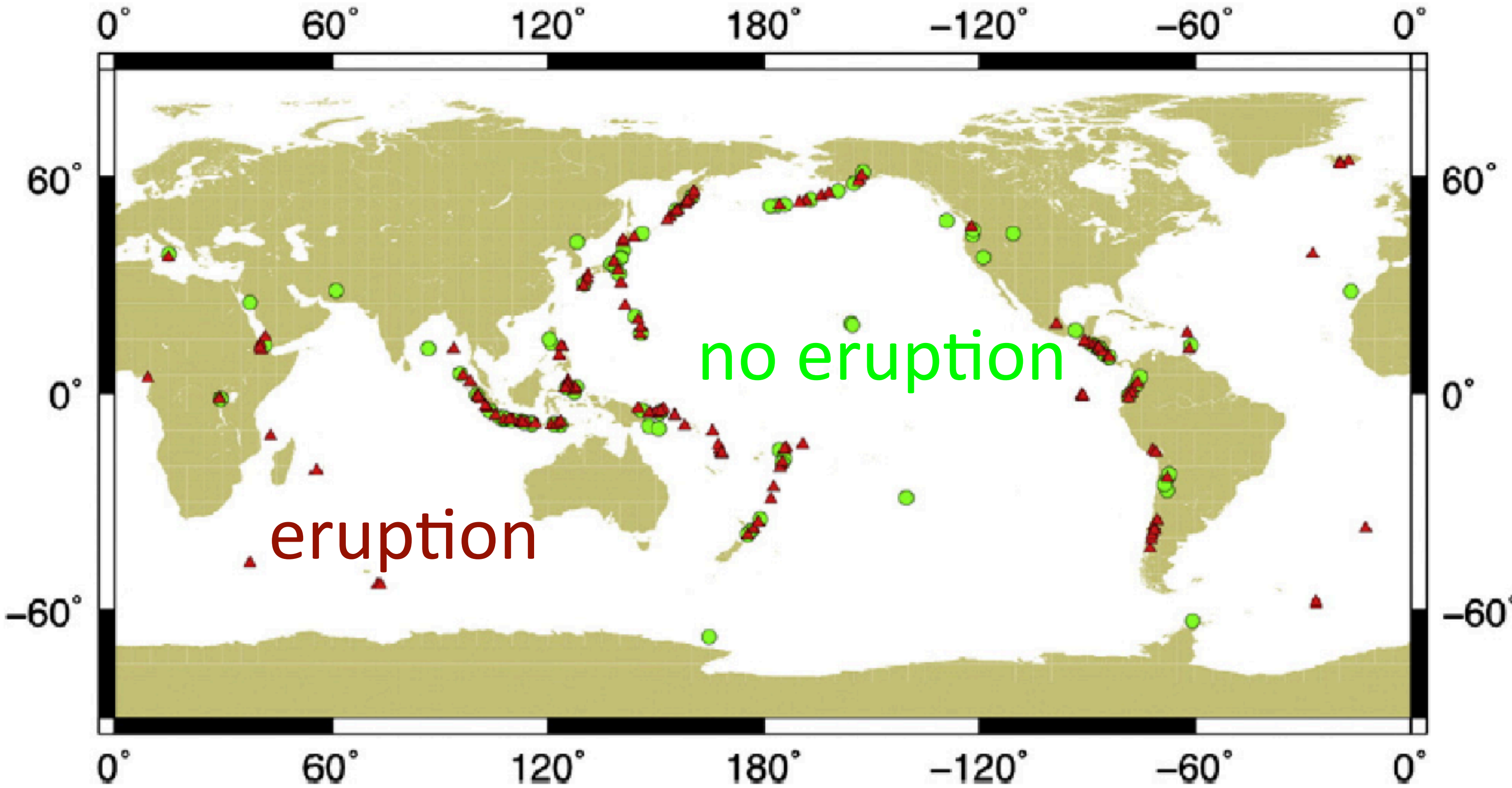
Short-term forecasting is based on interpreting signals of volcanic unrest

Probabilistic assessments
Physics-based models

Need forecasts for:

- eruption initiation
- eruption evolution
- eruption termination

painting by John Jackson



Phillipson et al. (2013)

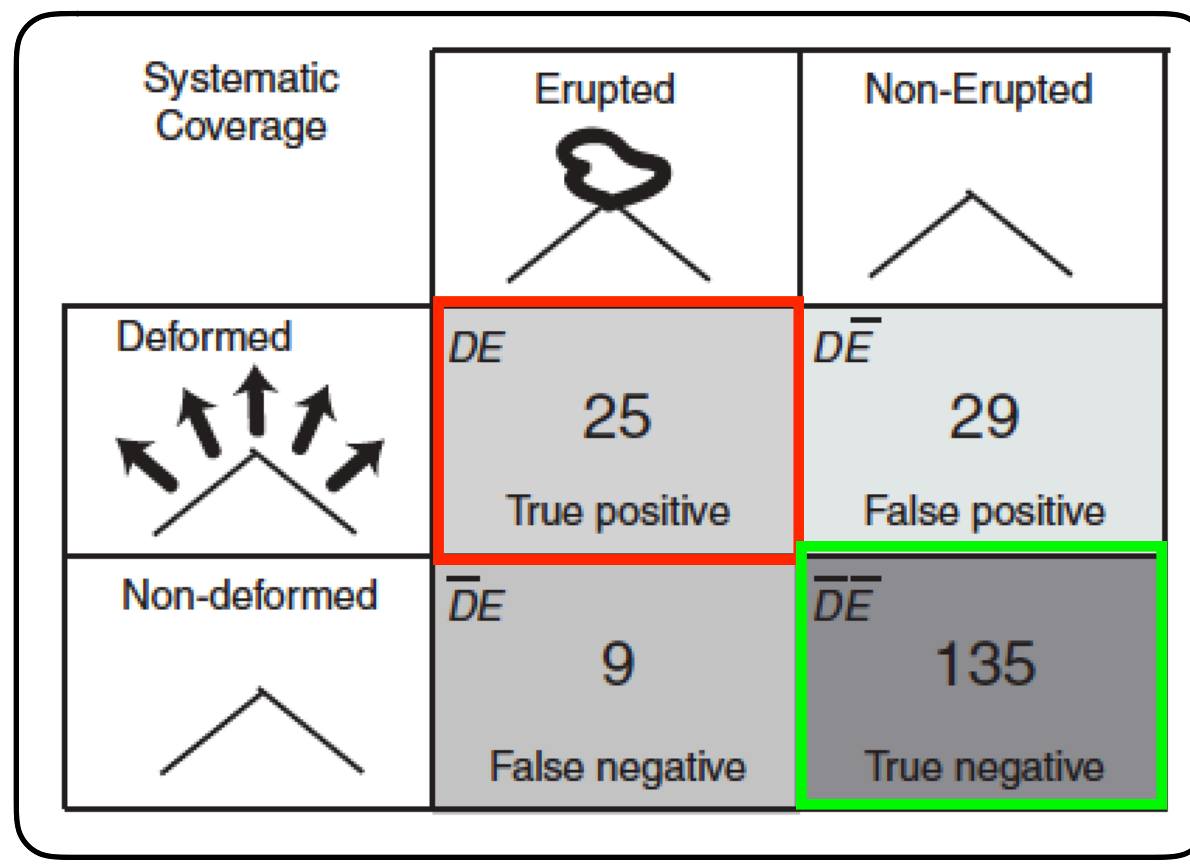
Global Volcanic Unrest 2001-2011

47% of restless volcanoes eventually erupted

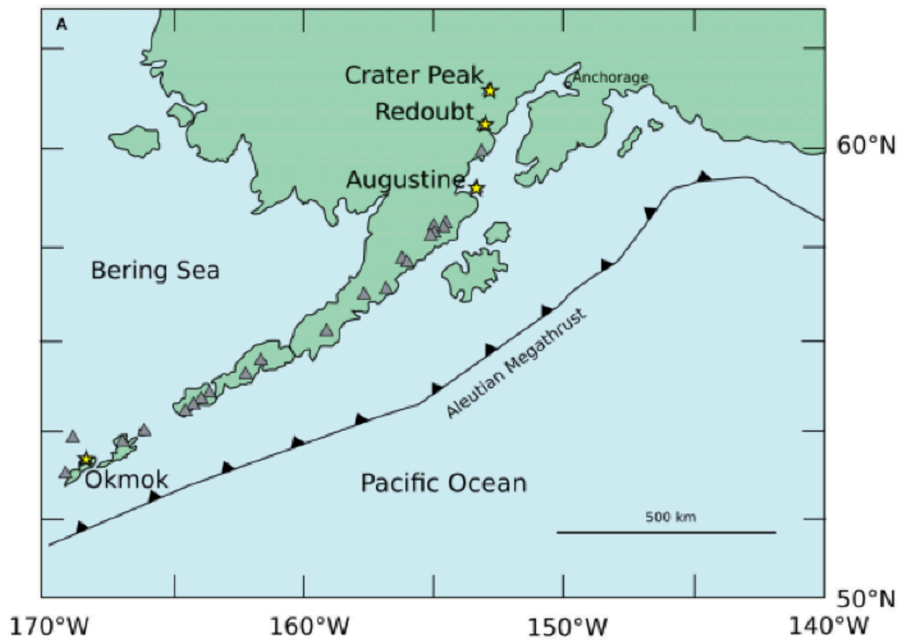
A similar conclusion can be drawn from 18 years of InSAR analysis

BUT

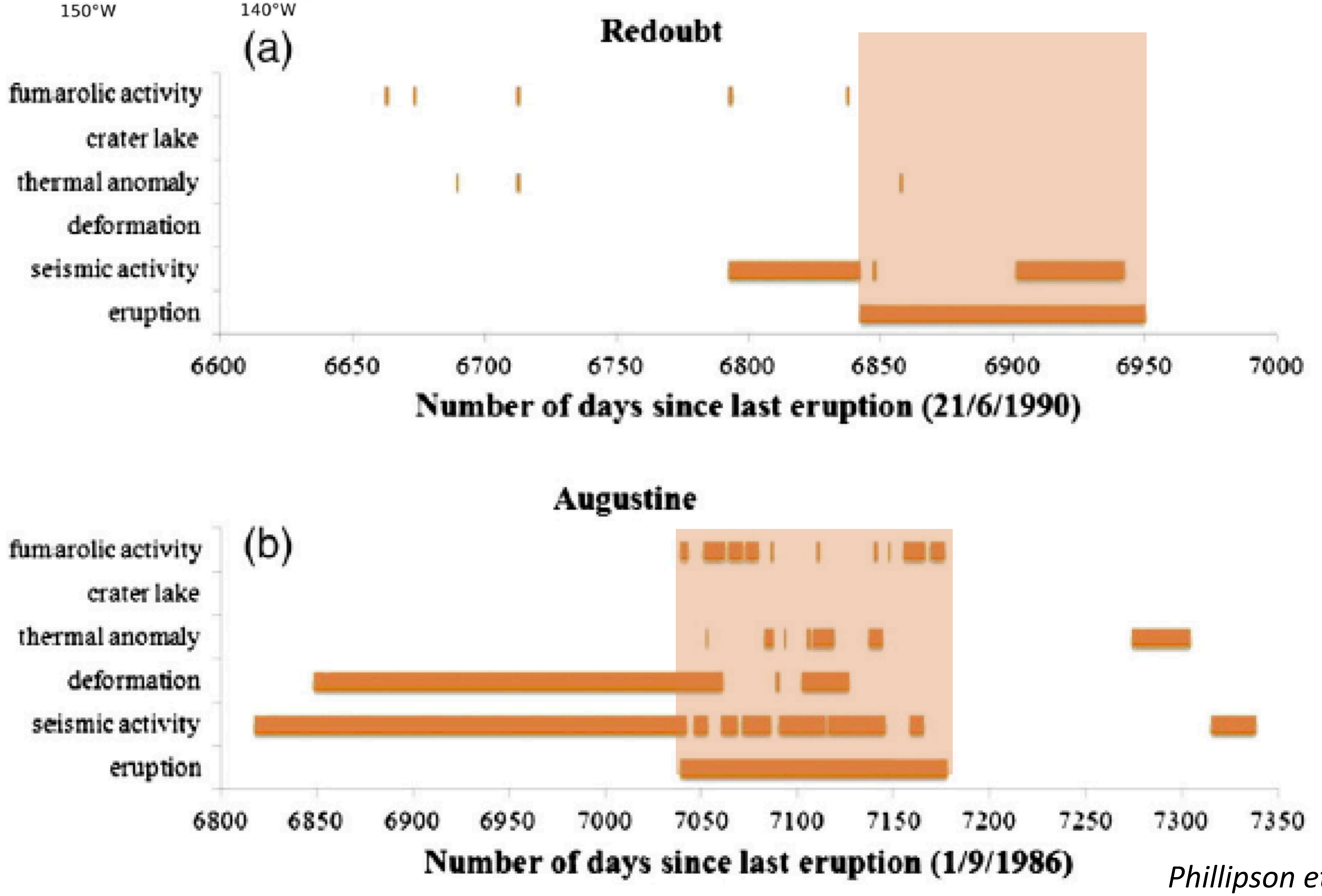
more important for forecasting is the confirmation that most quiet volcanoes did not erupt



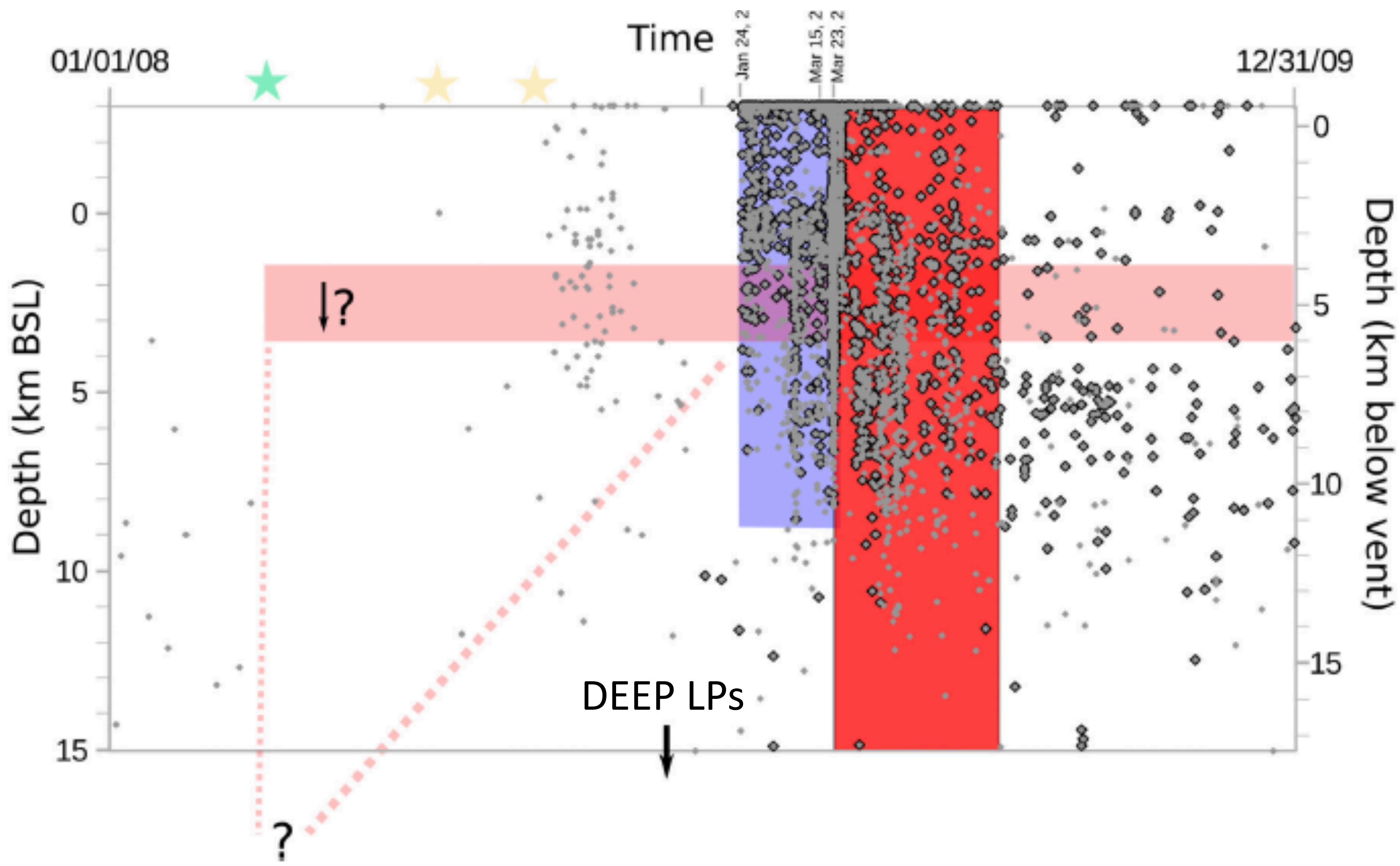
Biggs et al. (2014)



Patterns of unrest vary, even for nearby volcanoes with similar repose intervals

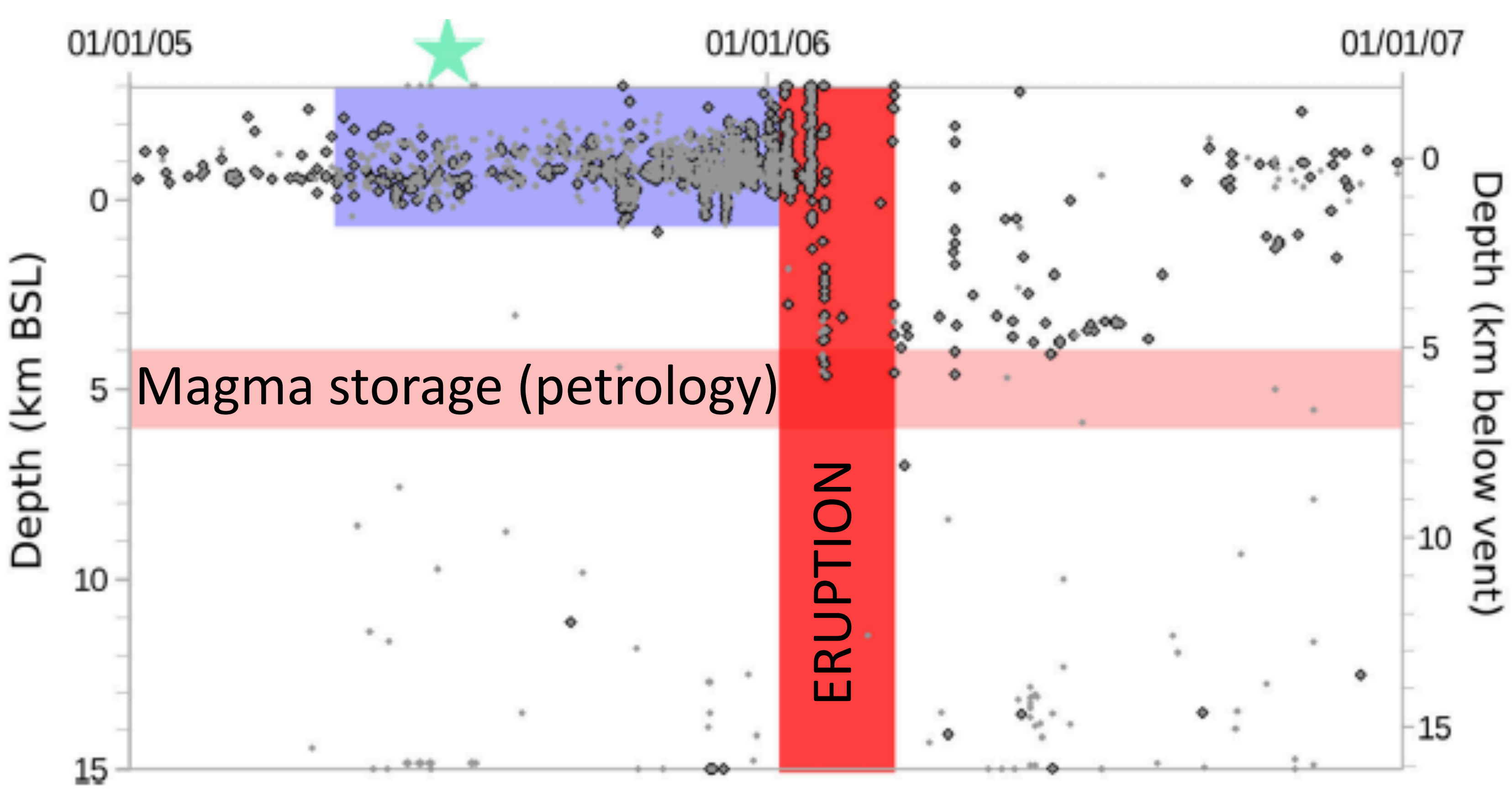


Phillipson et al. (2013)



Redoubt

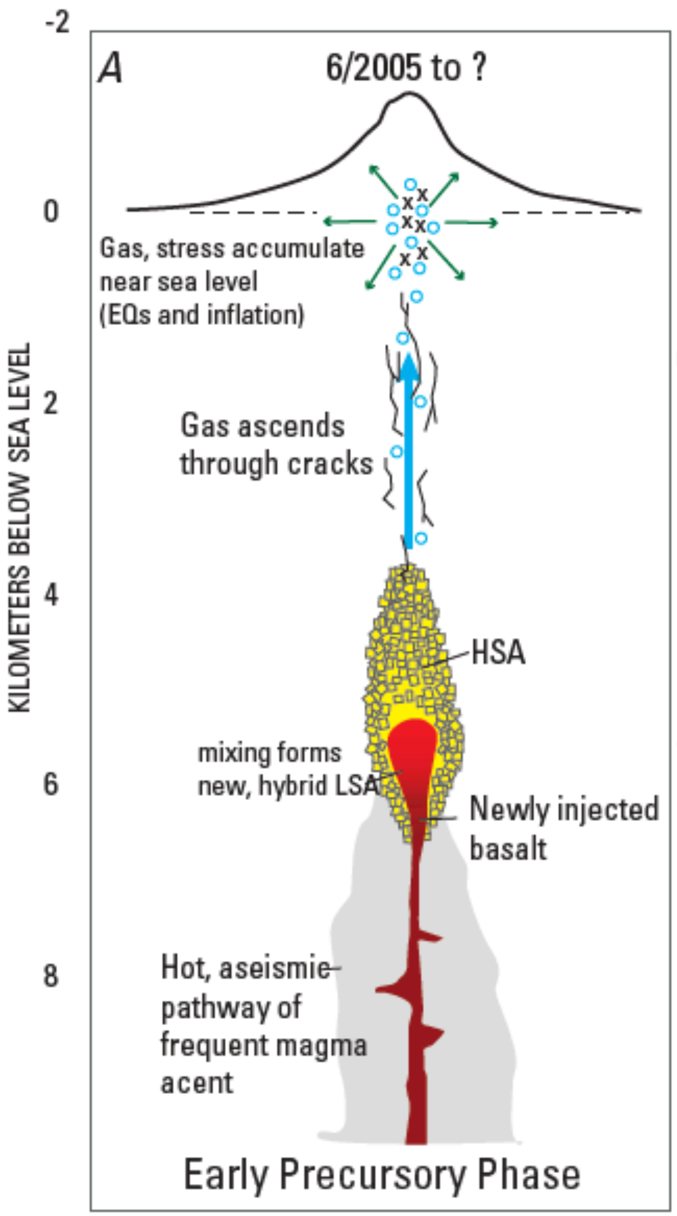
Precursory deformation and gas emissions prior to 2 months of precursory seismicity over large depth range



Roman and Cashman (2015)

Augustine

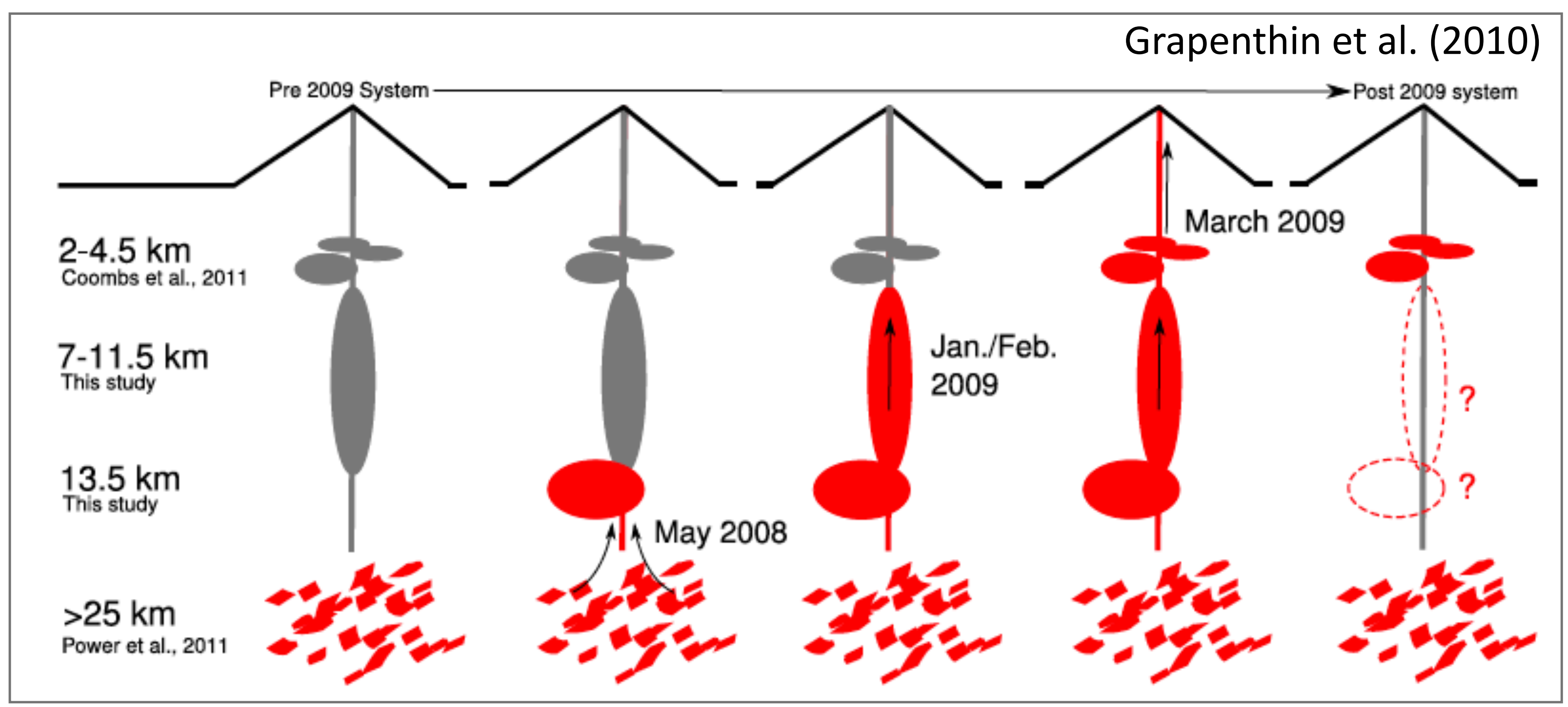
Precursory seismicity is shallower than inferred magma storage and precedes deformation



Larsen et al. (2010)

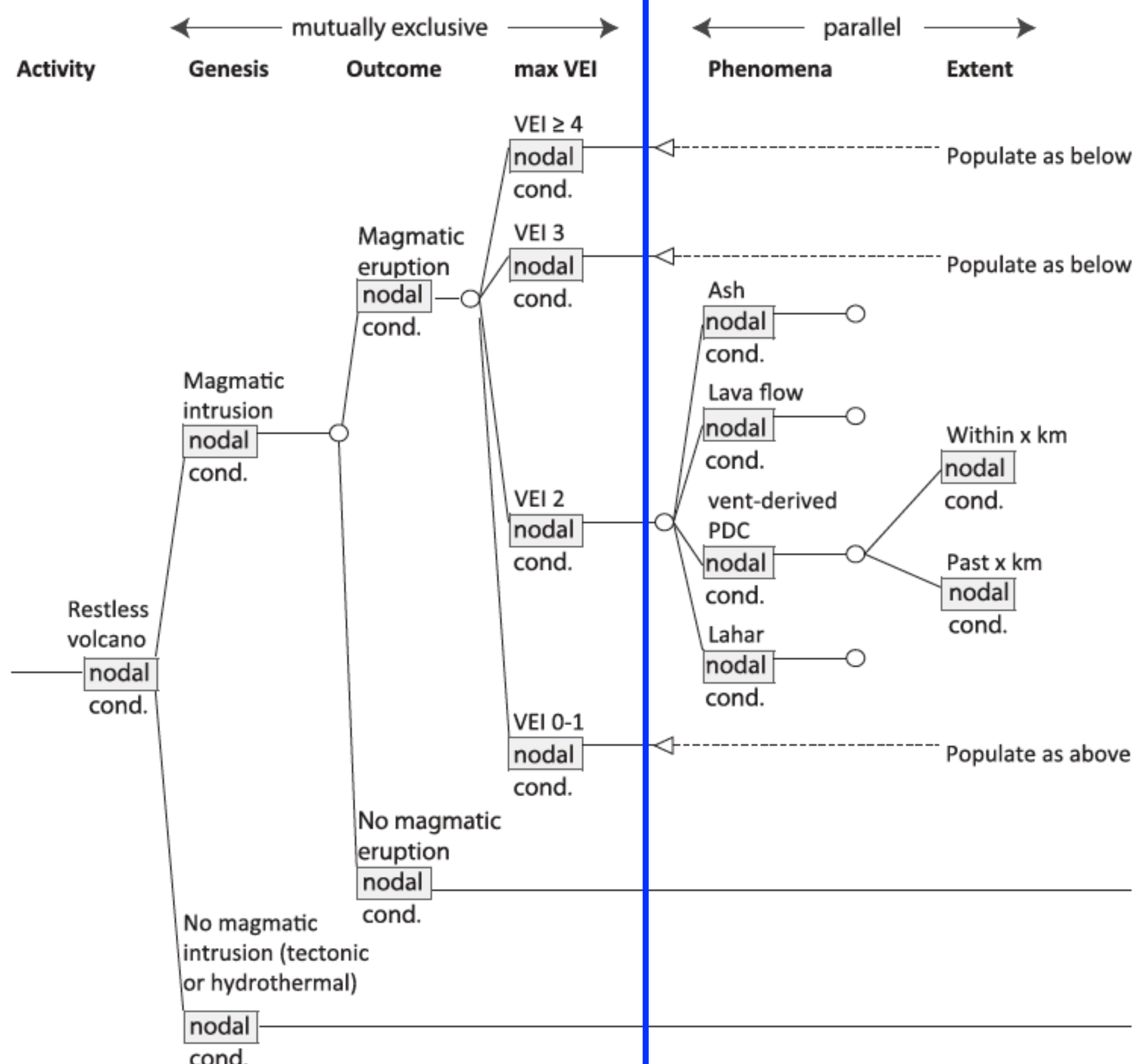
Difference between Augustine and Redoubt attributed, in part to the role of gas (and the presence/extent of a hydrothermal system?)

Role of the magmatic-hydrothermal interface?



Forecasts - Probabilistic Event Trees

Probabilities sum to 0



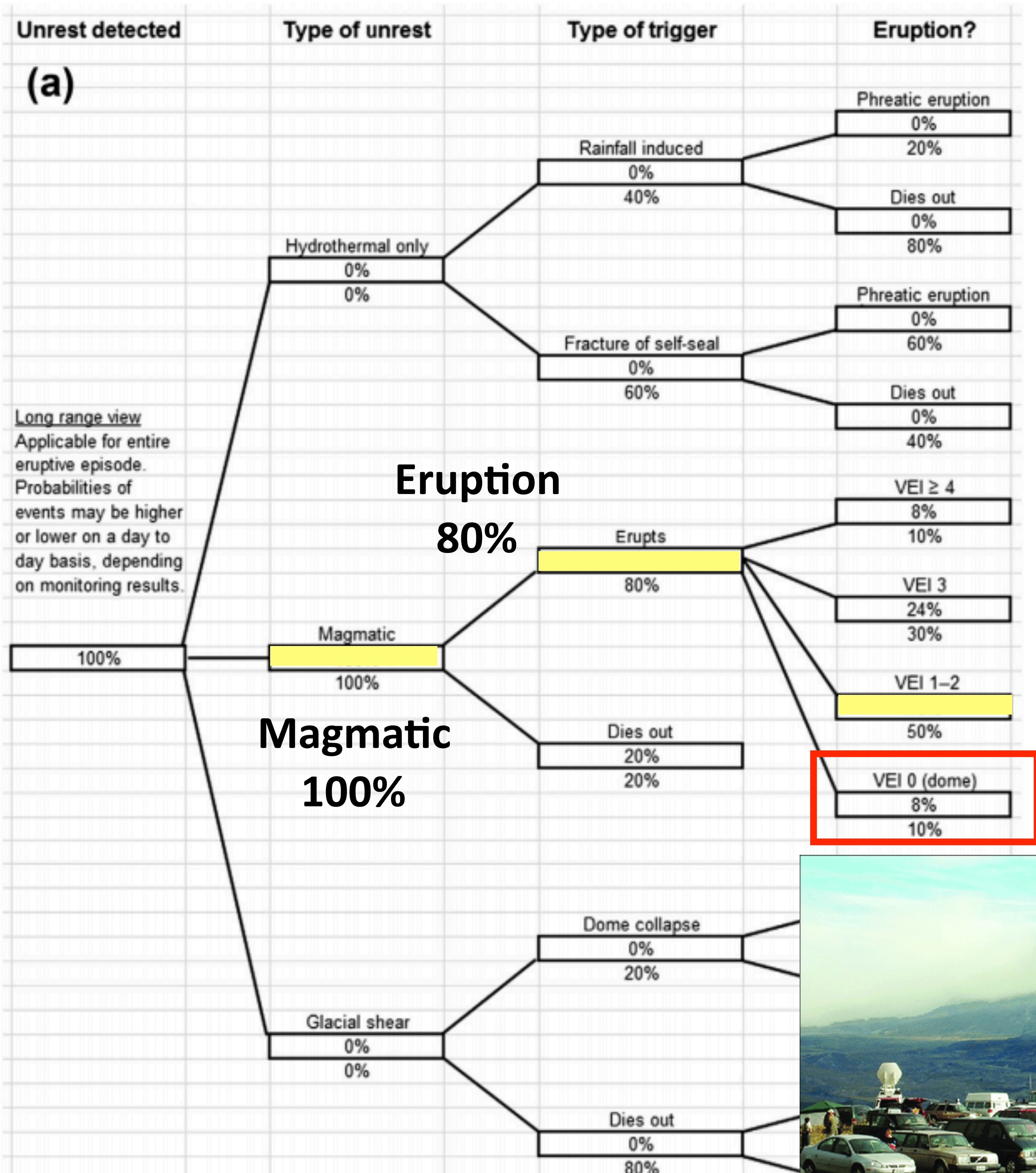
Probabilities of each branch determined by

past activity
analogue volcanoes
expert elicitation

Wright et al. (2018)

Example: Mount St. Helens 2004

Important because of the media frenzy and memories of 1980 eruption



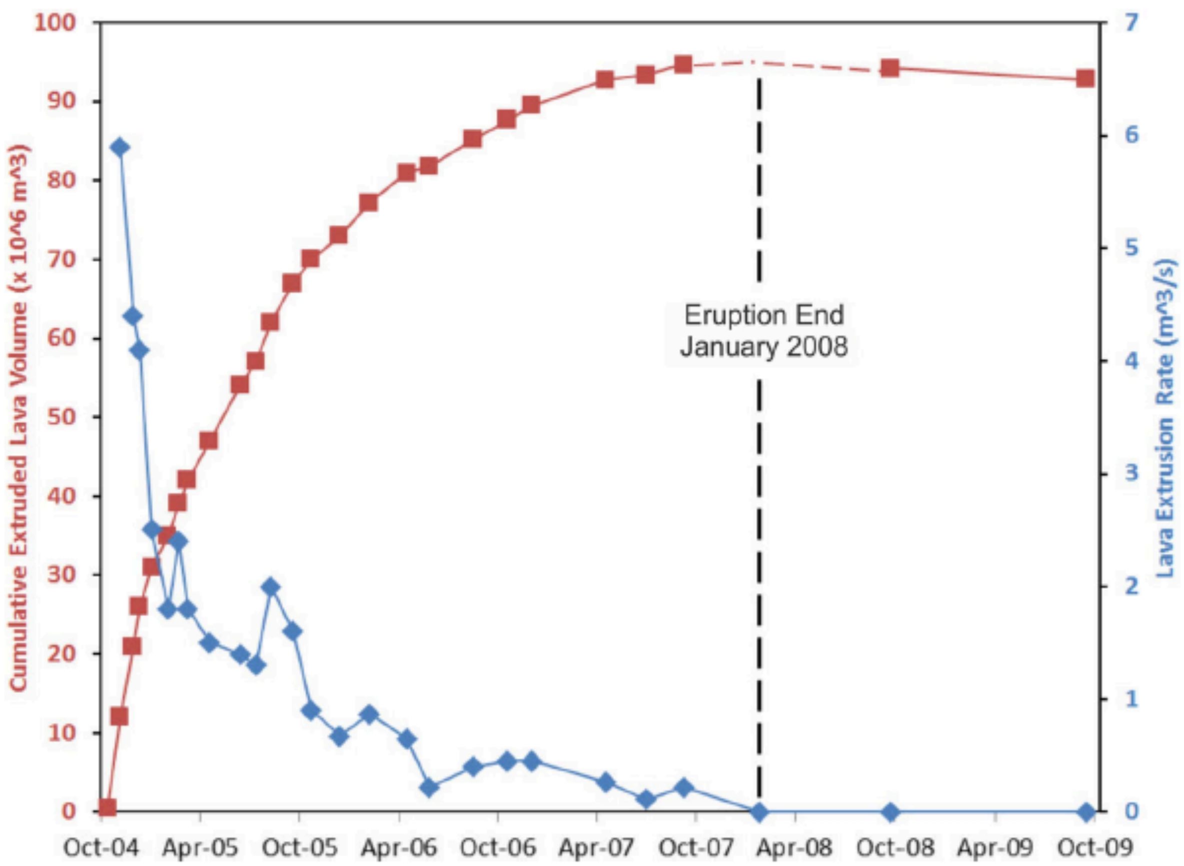
Newhall and Pallister (2015)

VEI 1-2 most likely (50%)

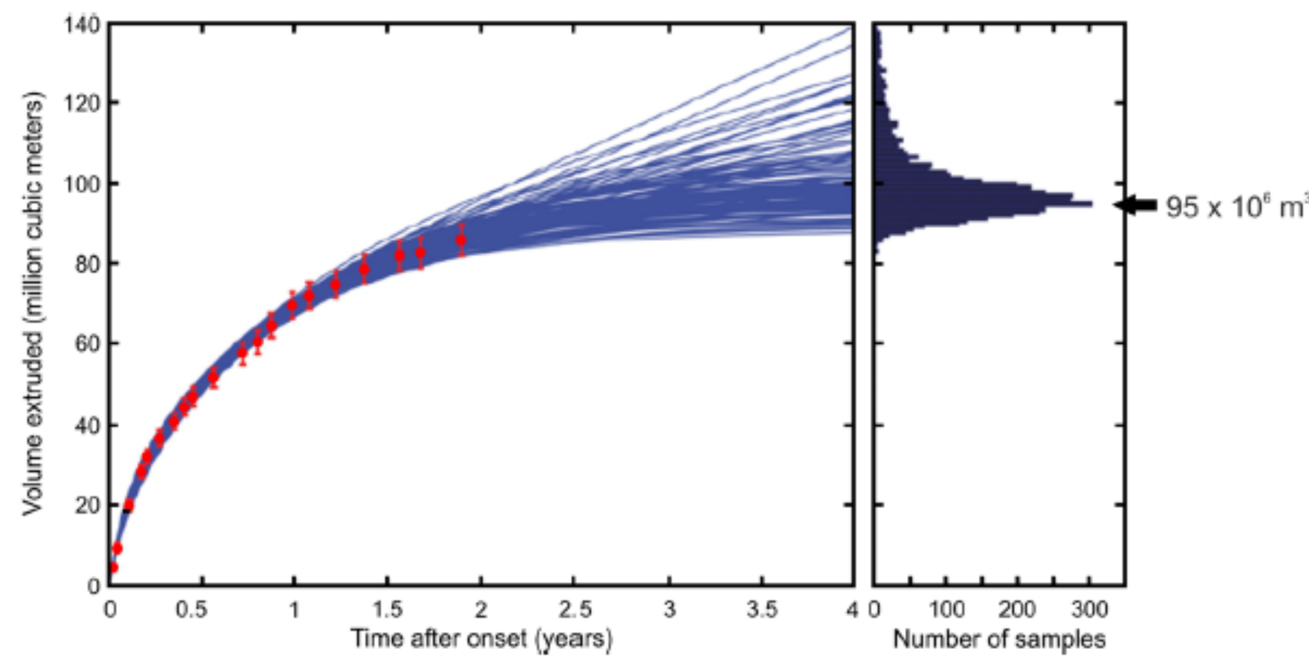
Actual outcome (dome) 8%

End of the eruption?
Physics-based hind casting

Bayesian, physics-based assessment of volume predictions

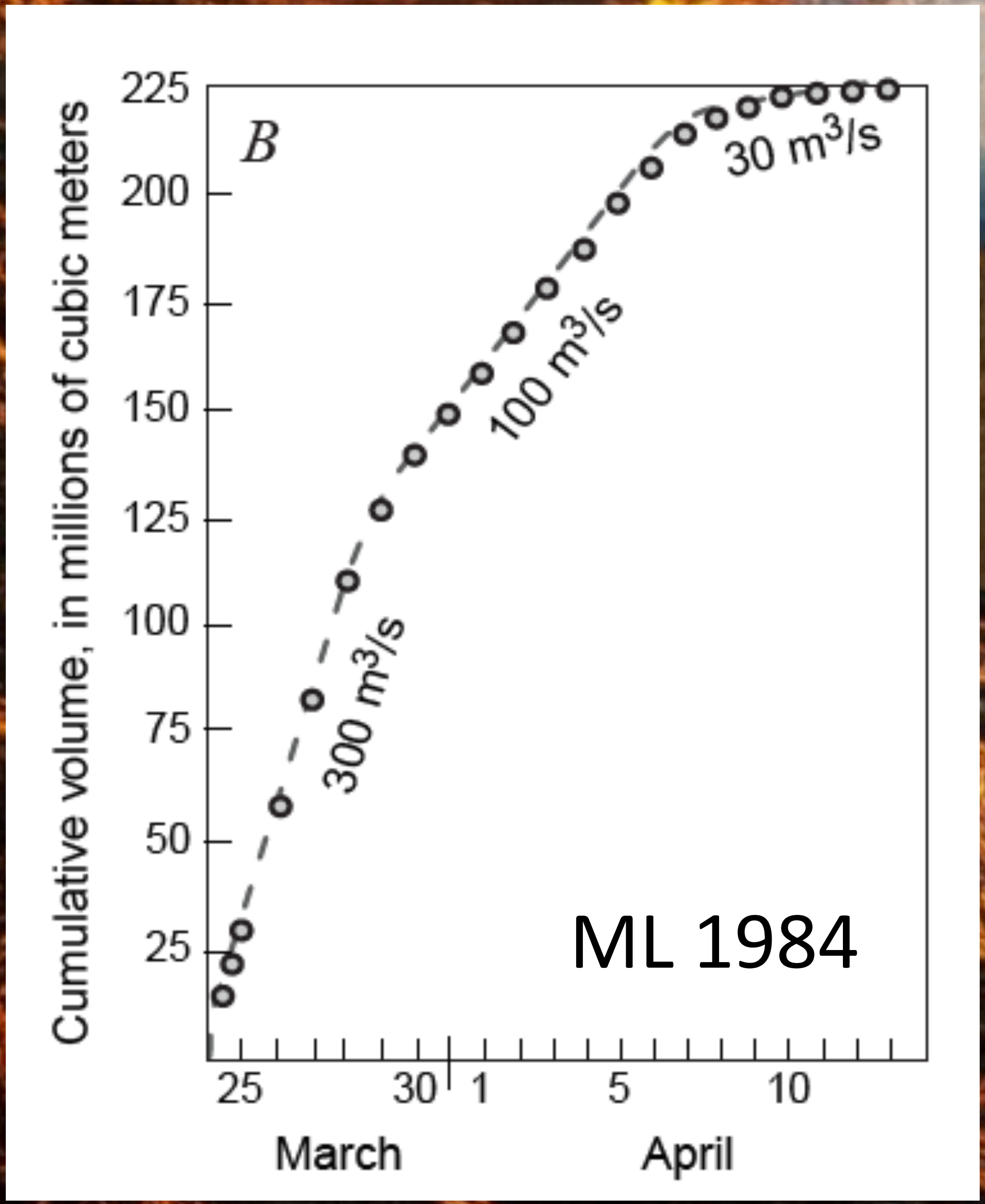


Dzurisin et al. (2015)



Dzurisin et al. (2015) after Segall (2013)

Patterns of eruptive behavior

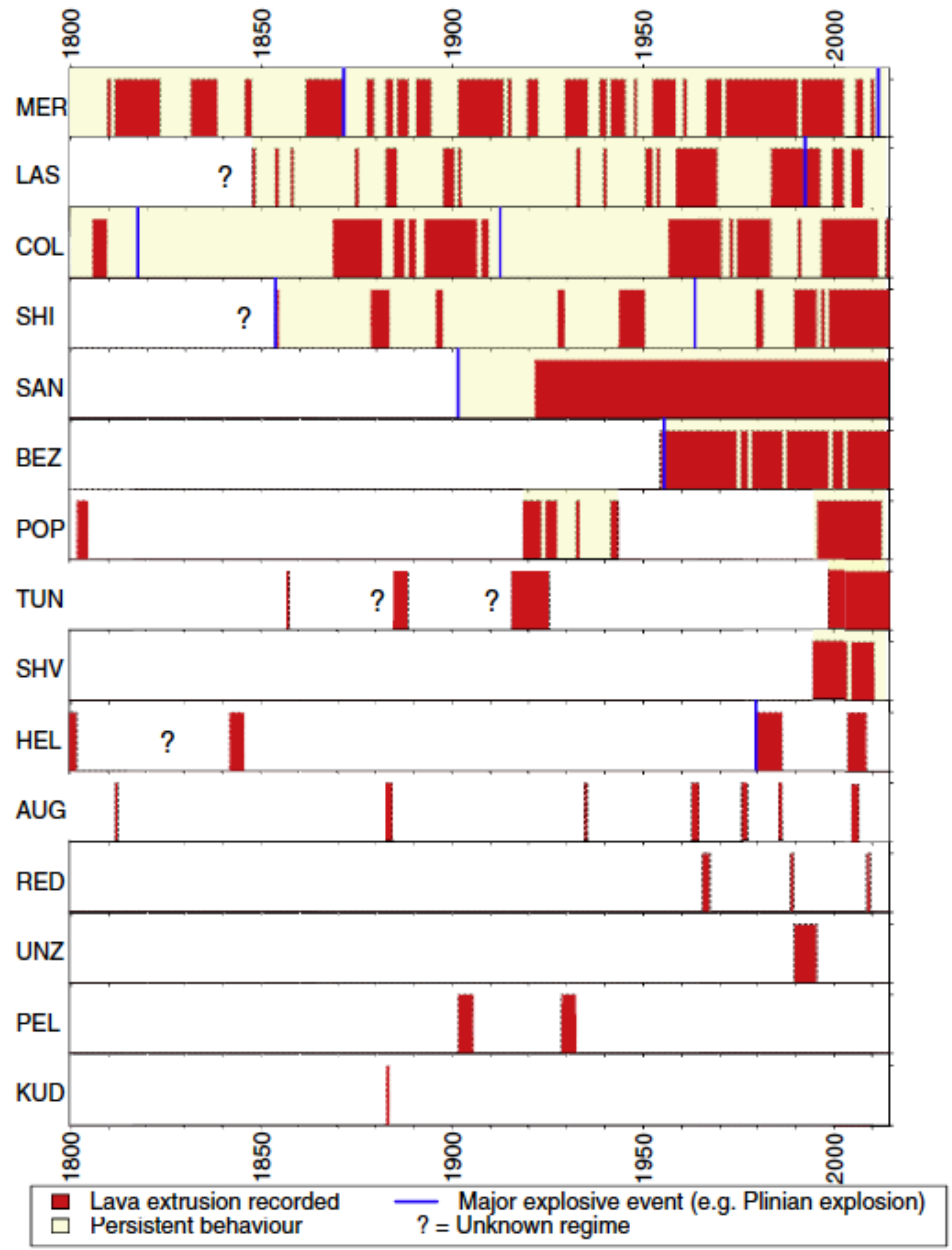


Eruptions fed by a single pressurised melt source show an exponential decay in eruption rate

Many volcanoes, however, are not that well behaved

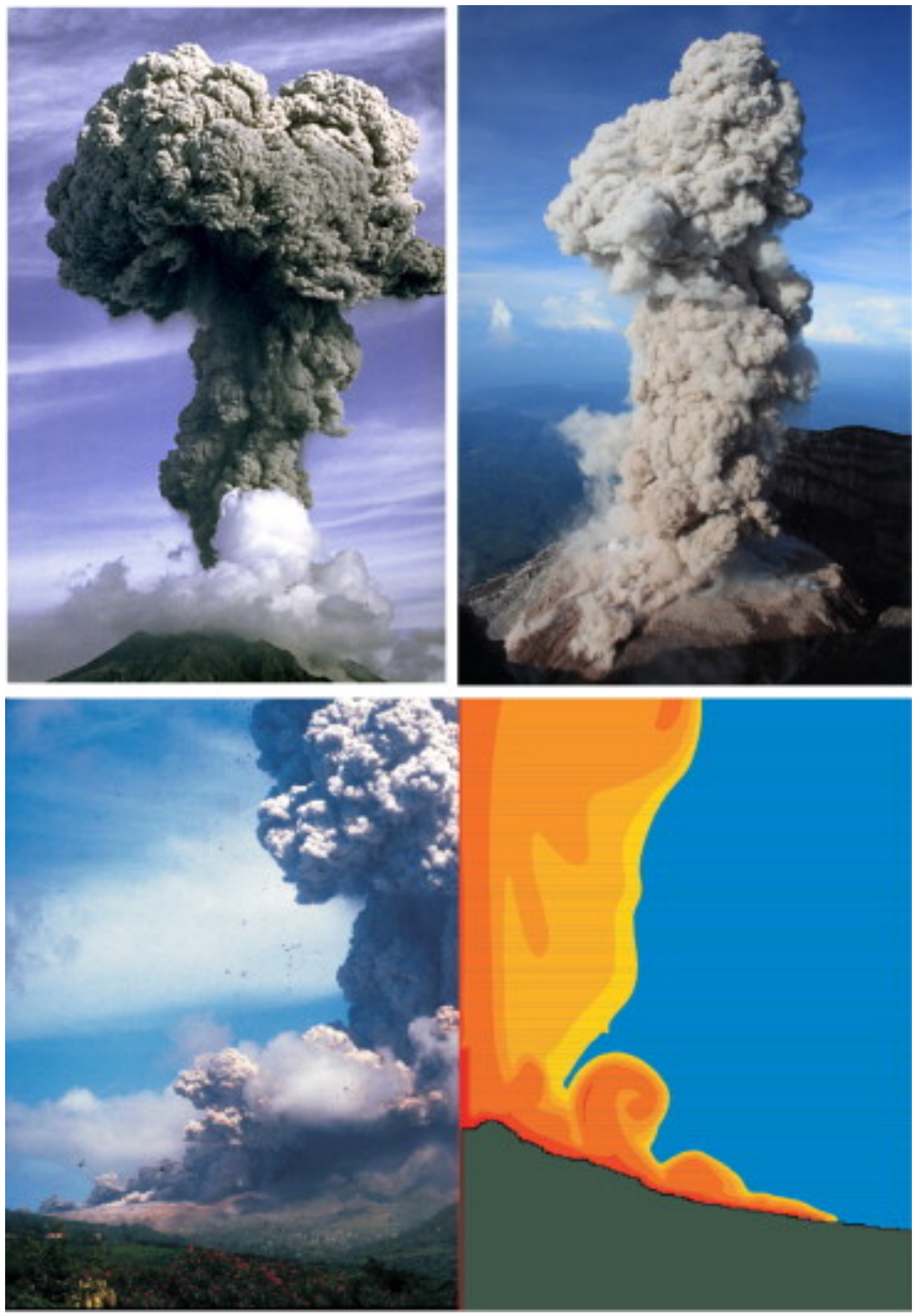
Some reasons for complex time histories:

Vent migration
Conduit/source control
Compositional variations
External influences



Sheldrake et al. (2016)

How to forecast transitions in eruptive behavior?

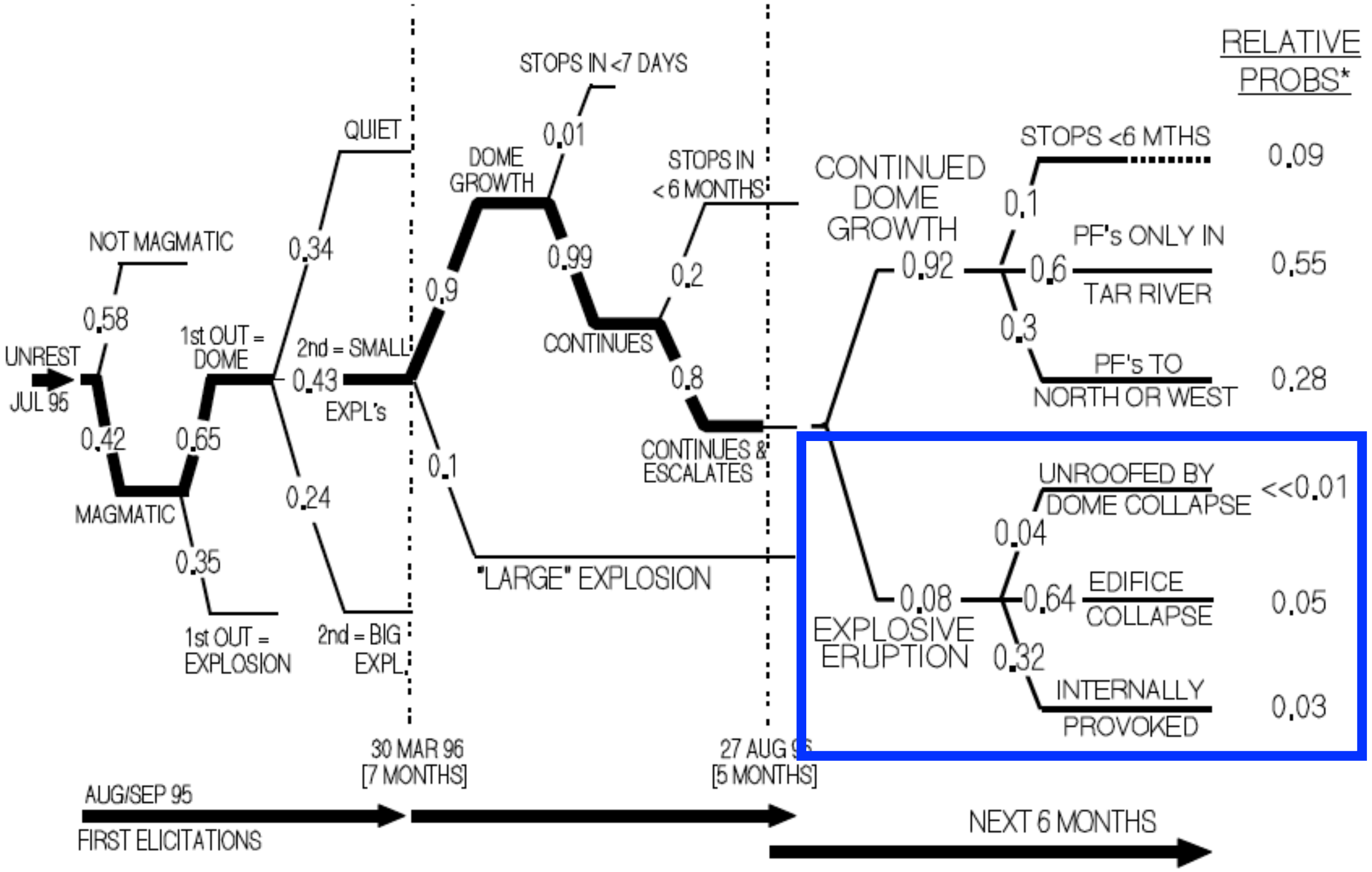


Clarke et al. (2015)

Example: Montserrat

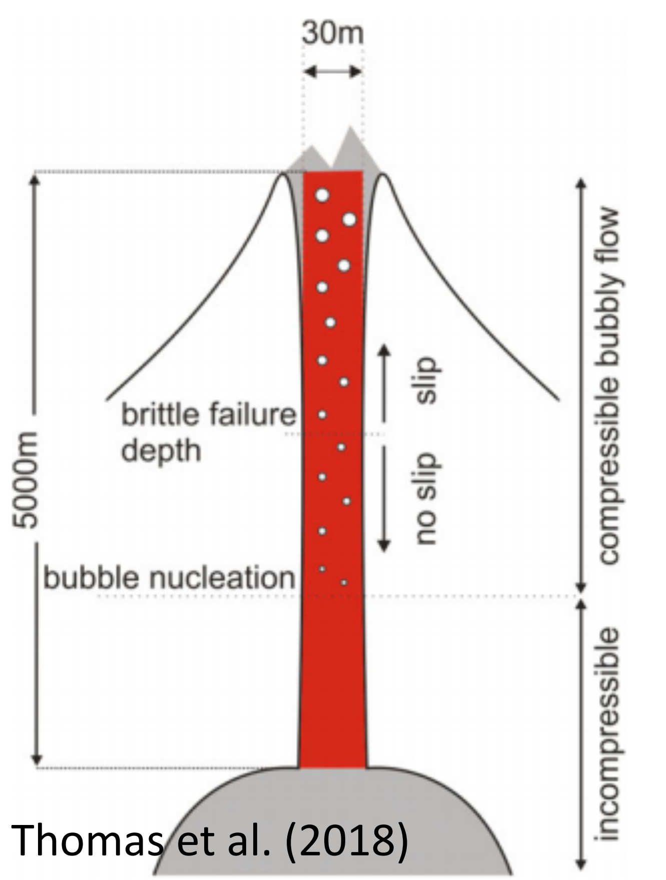
Event trees updated every six months

Biggest concern was possibility of a major eruption



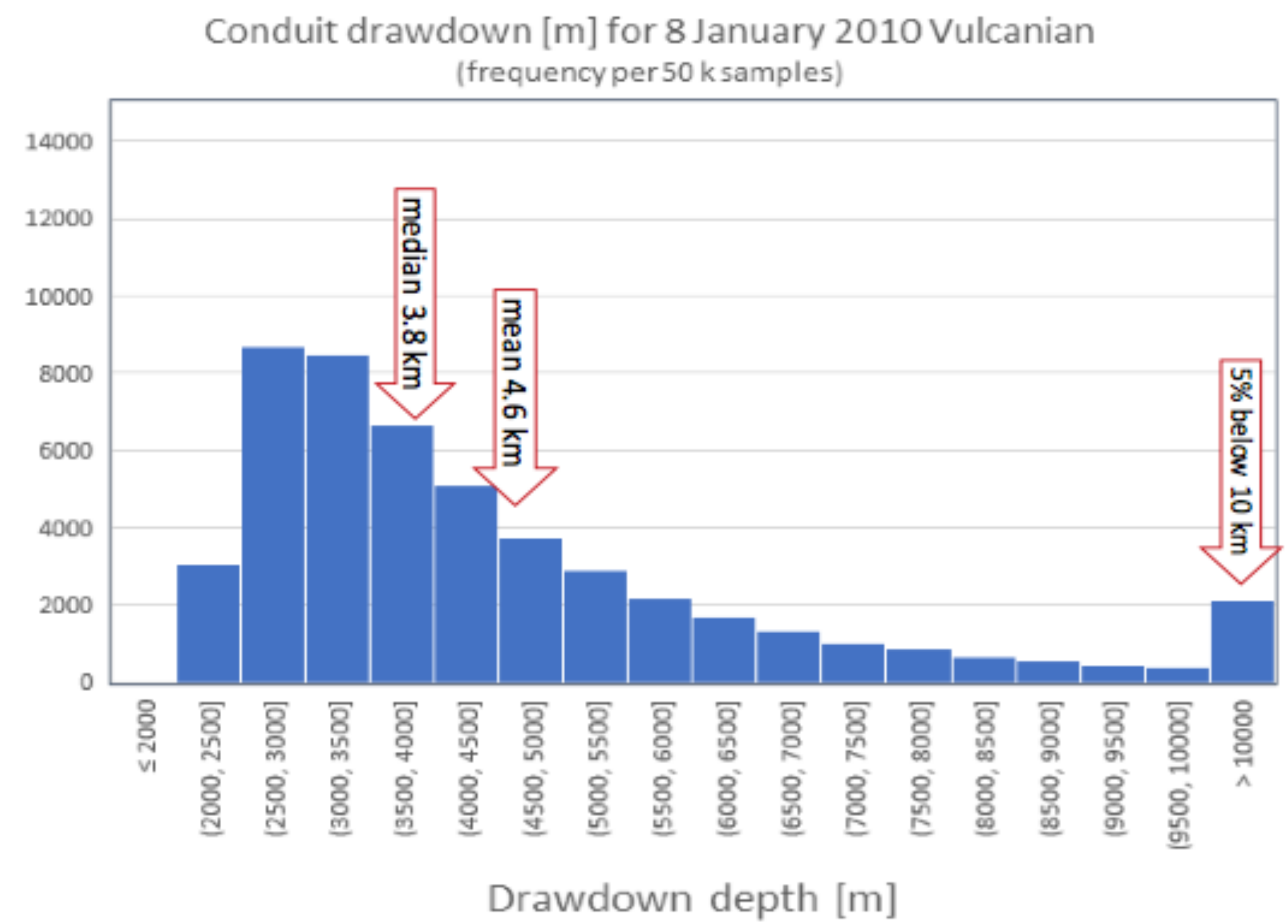
Aspinall and Cooke (1998)

Downward counterfactual analysis: Runaway eruption at SHV



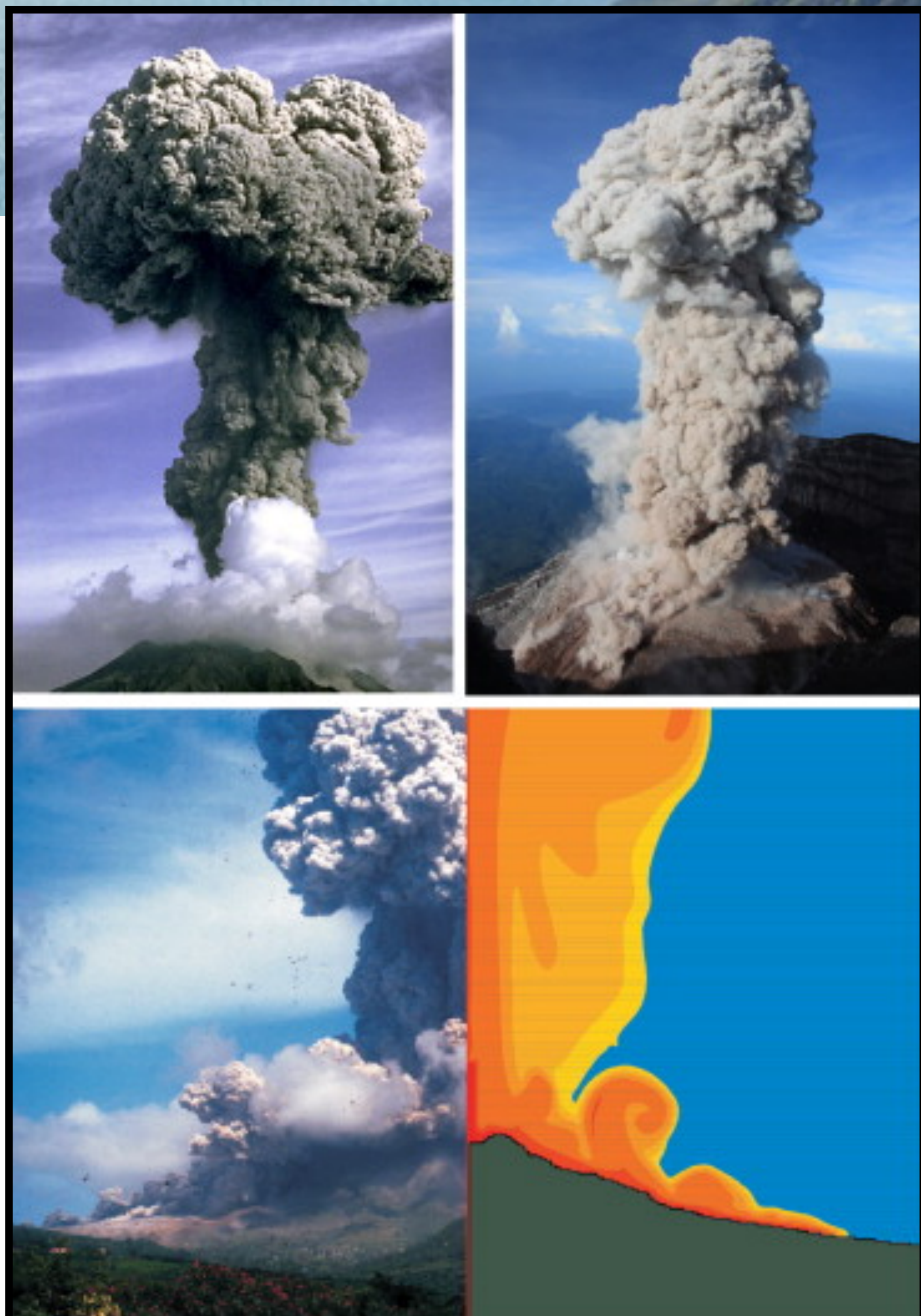
Thomas et al. (2018)

Bayesian Belief Network Monte Carlo sampling
Vary conduit dimensions (h,r) for different volumes
Calculate probability of evacuating conduit to reservoir depth



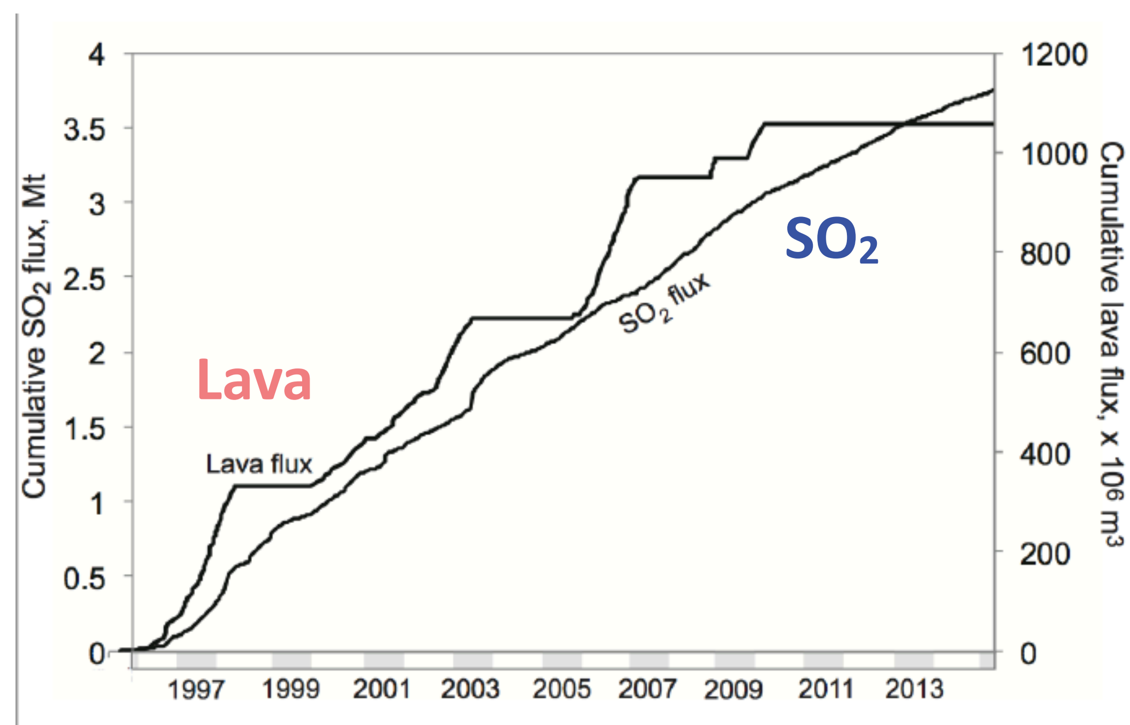
Aspinall and Woo (in review)

Downward counterfactual analysis:
Runaway eruption at SHV



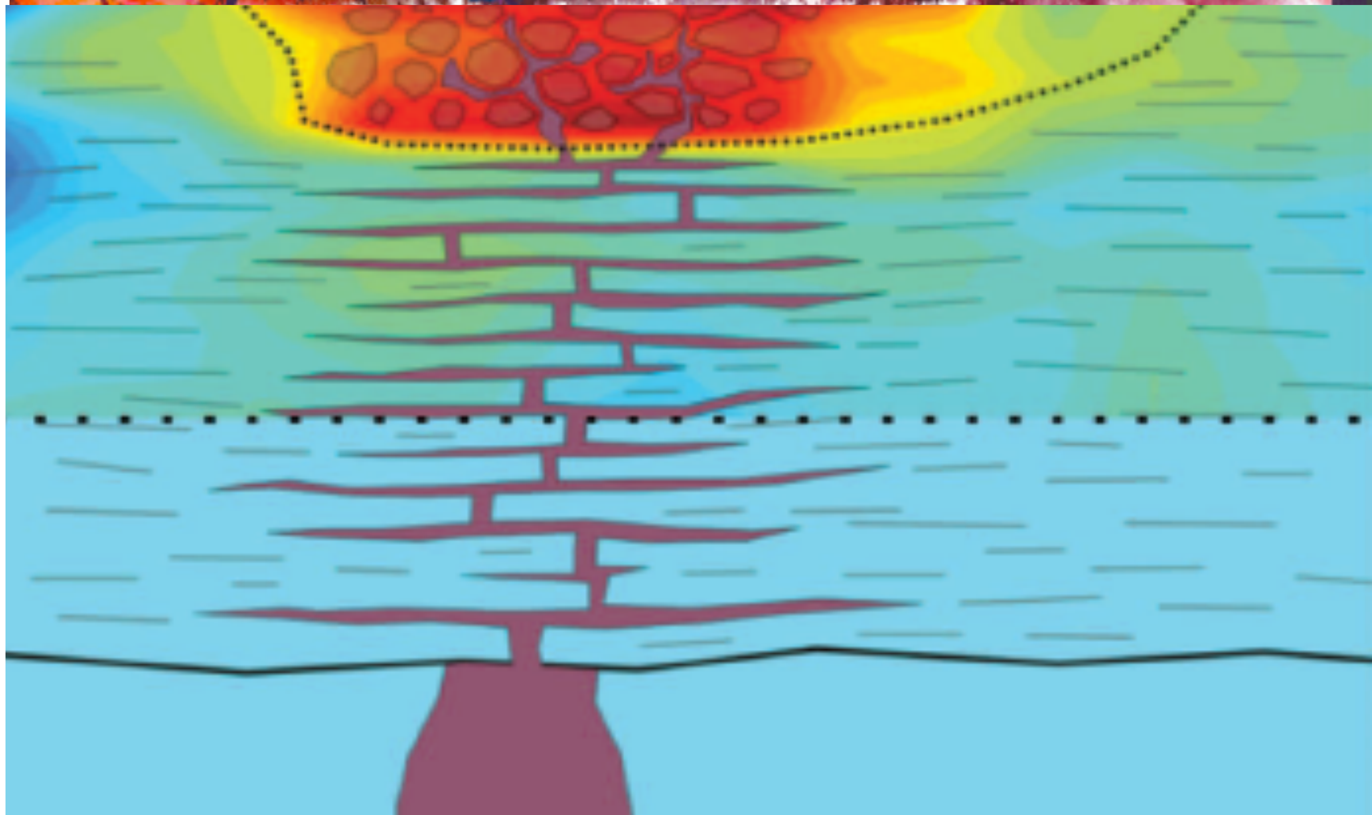
Clarke et al. (2015)

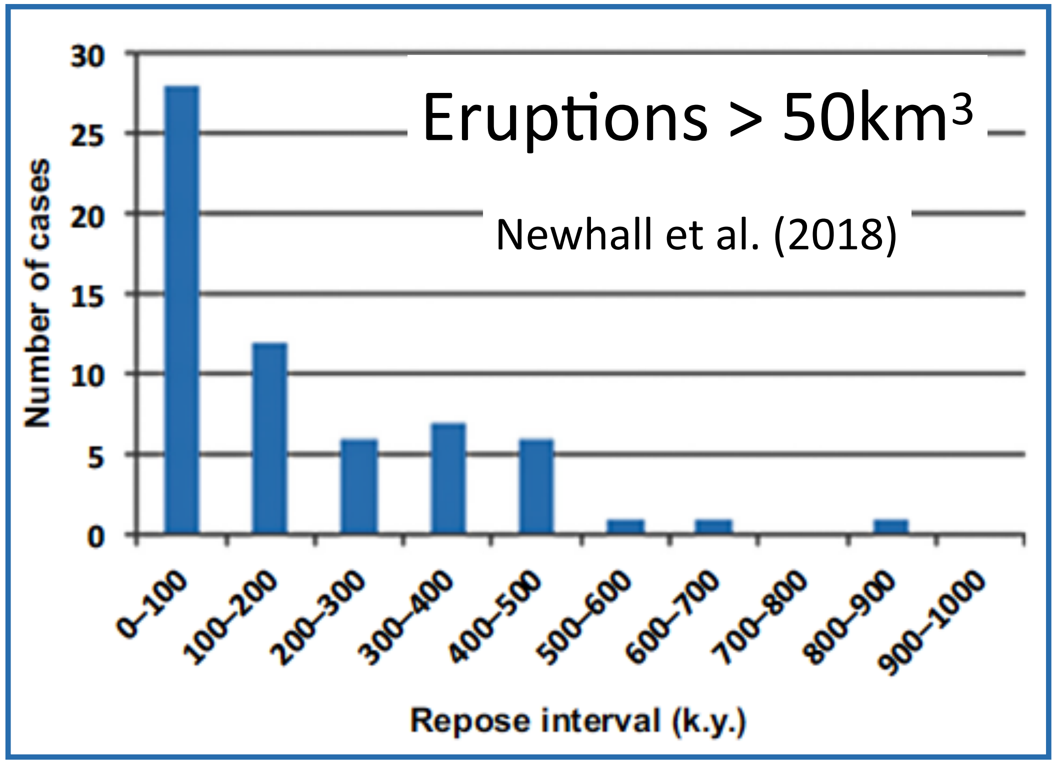
High probability of sustained eruption if use the total volume erupted during the 1997 Vulcanian episodes



How to forecast the next M7+ eruption?

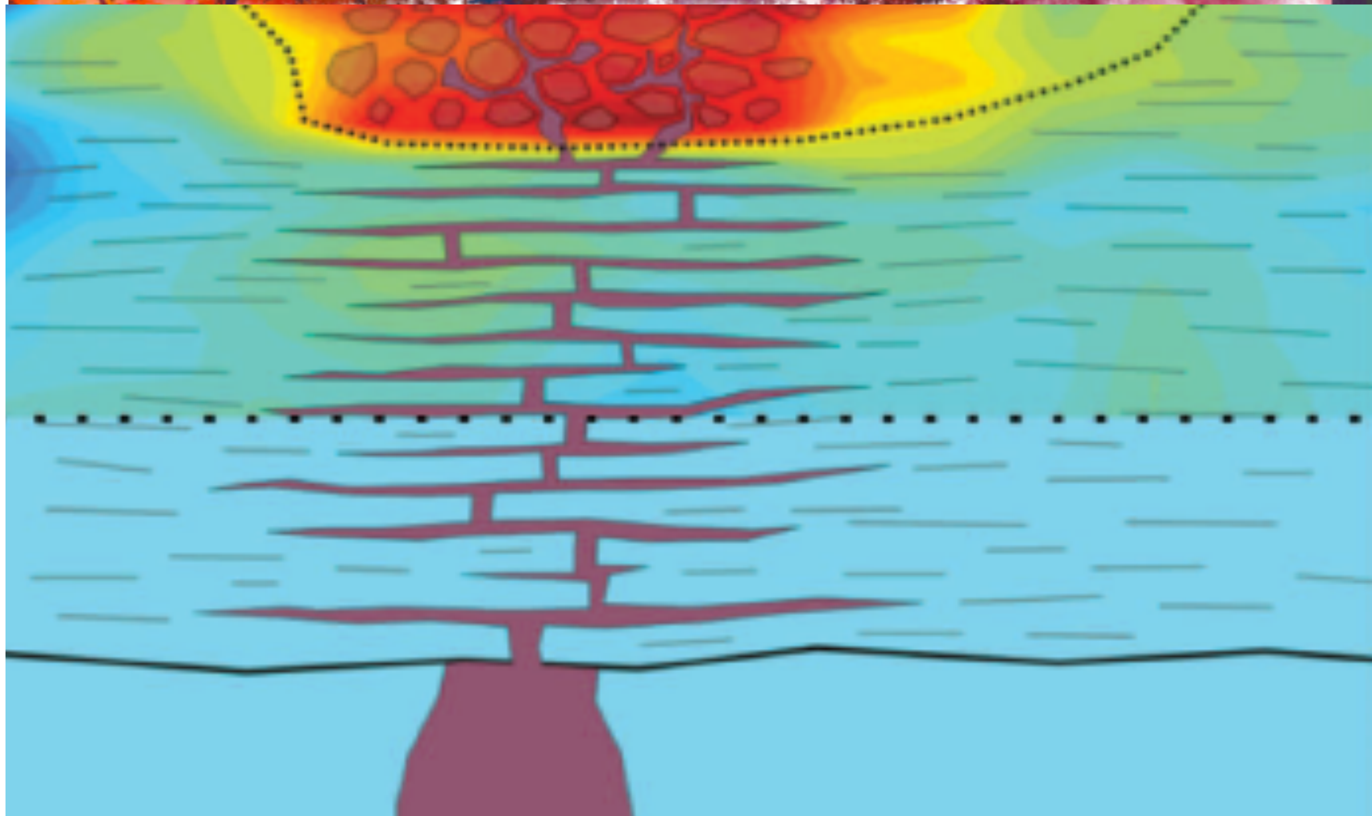
Location
Timing

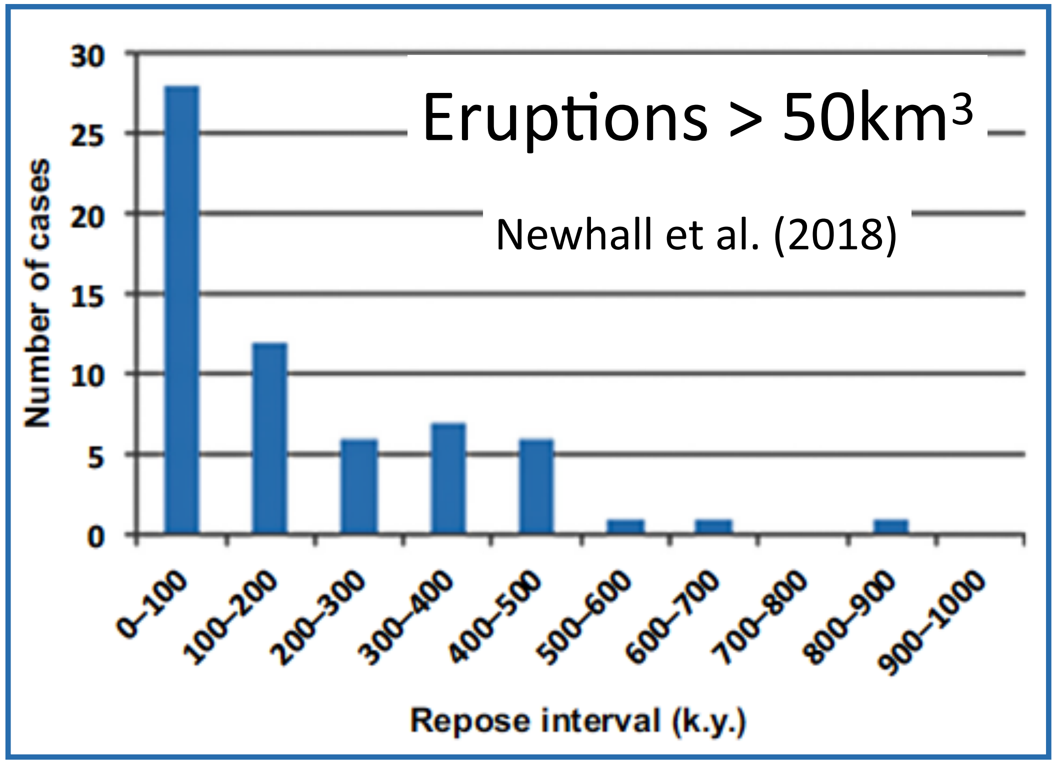




Eruptions > 50km3
Newhall et al. (2018)
Number of cases
30
25
20
15
10
5
0
0–100
100–200
200–300
300–400
400–500
500–600
600–700
700–800
800–900
900–1000
Repose interval (k.y.)

IT COULD HAPPEN
ONE NIGHT

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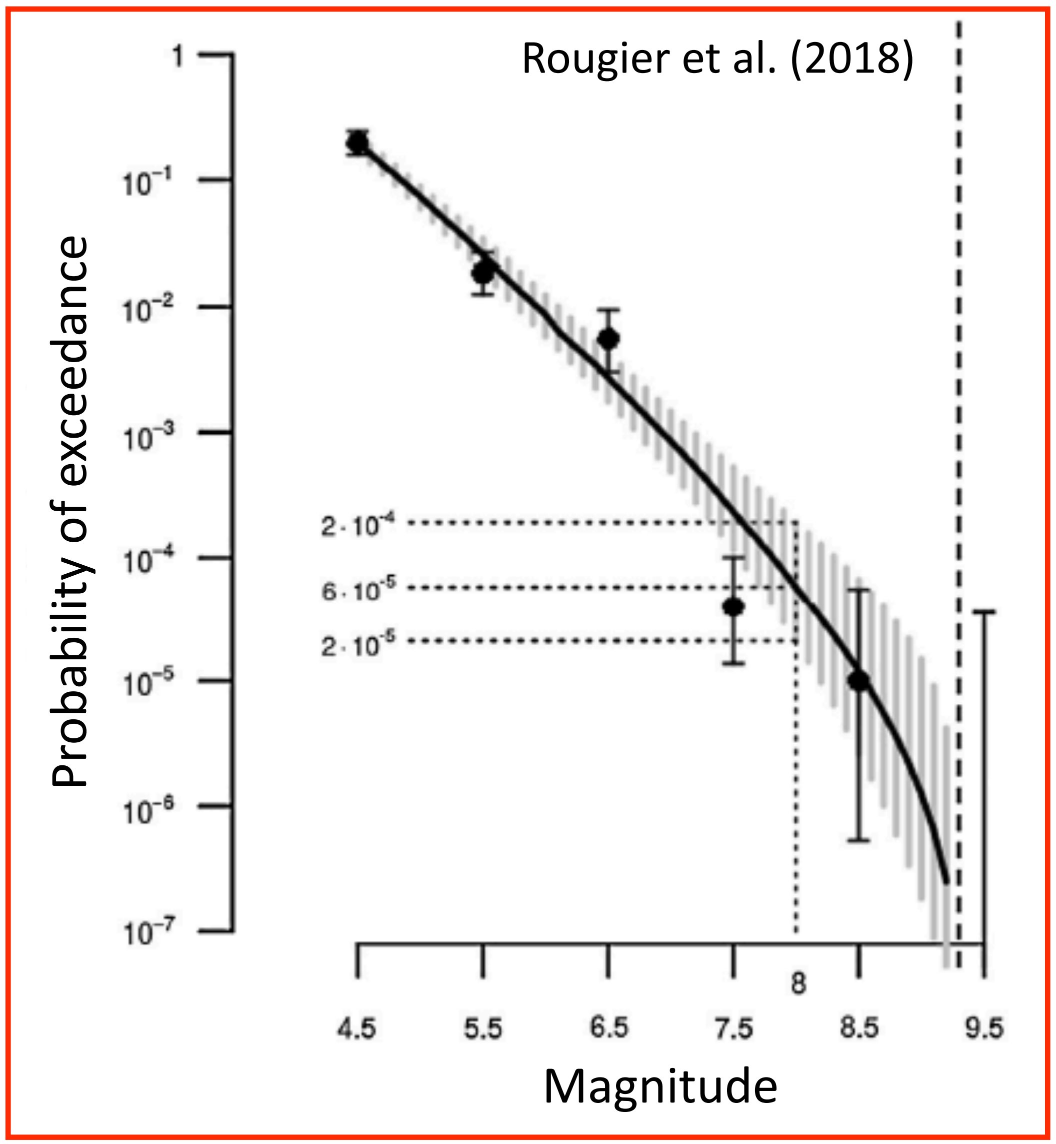
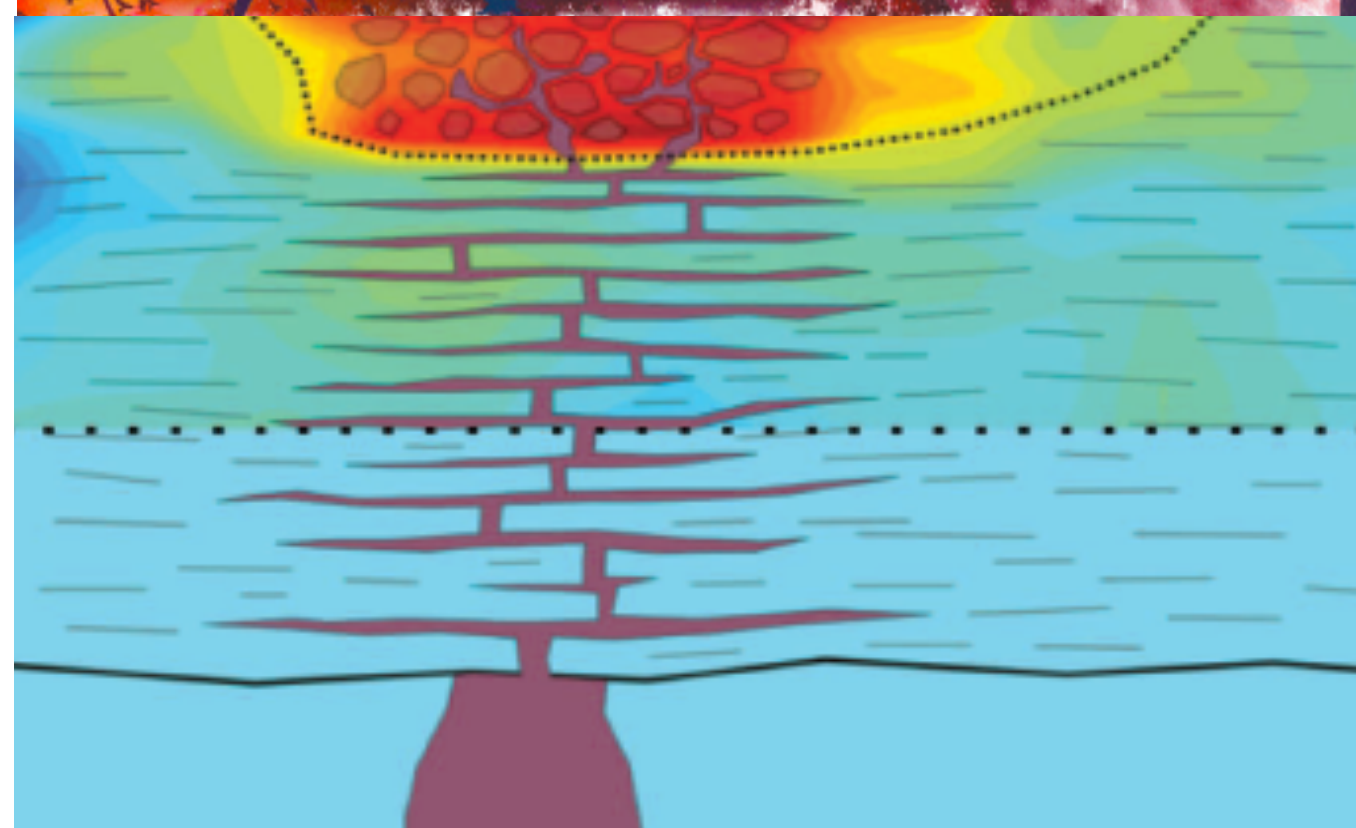
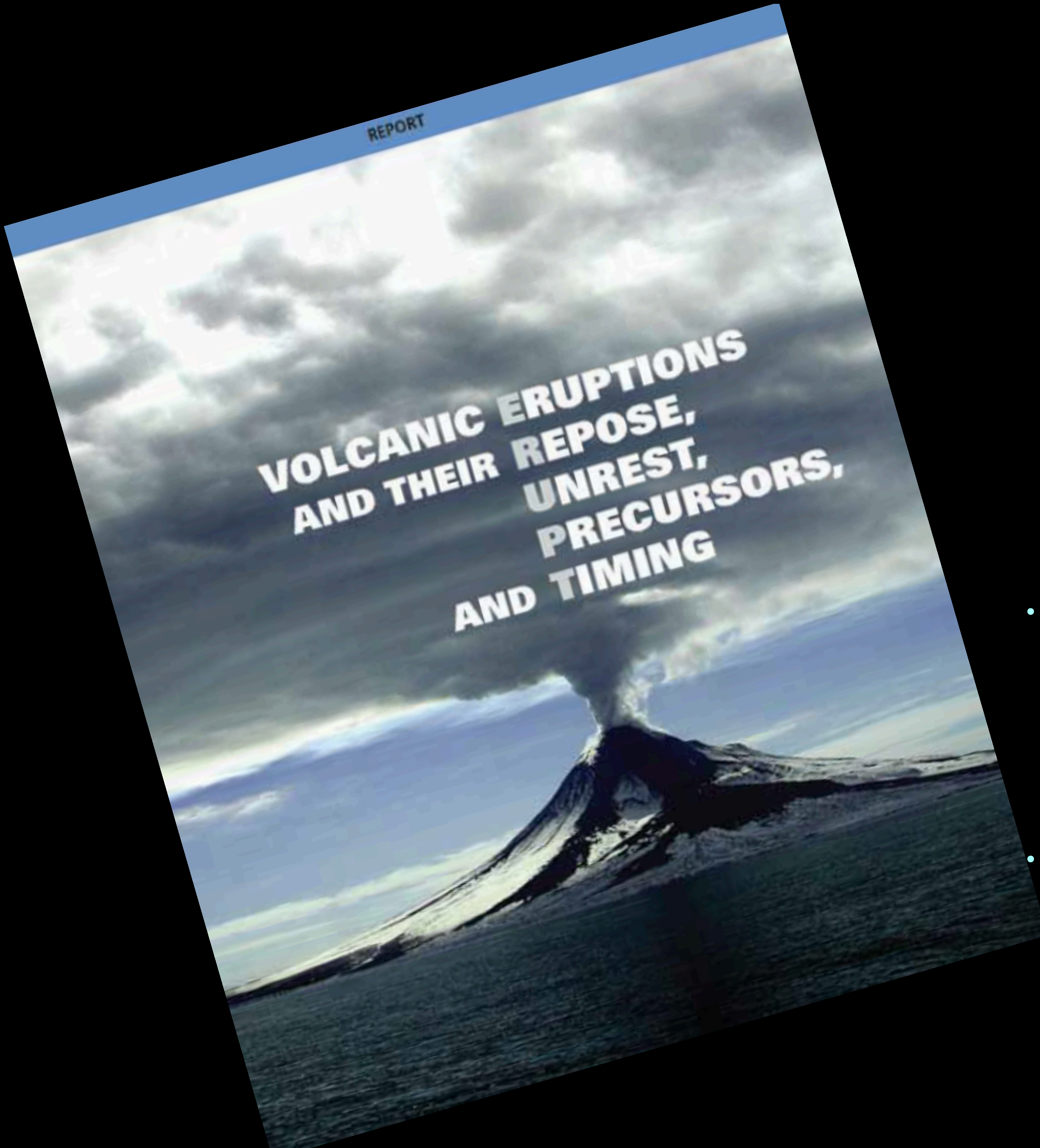

Rougier et al. (2018)
Probability of exceedance
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
2·10⁻⁴
6·10⁻⁵
2·10⁻⁵
4.5
5.5
6.5
7.5
8
8.5
9.5
Magnitude


IT COULD HAPPEN
ONE NIGHT





Grand Challenges

Eruption forecasting

↕

Life cycles of volcanoes

- *Short-term* forecasts require understanding of shallow magmatic systems and eruption processes
- *Long-term forecasts* require understanding of the larger magmatic system

"It was the human contacts, not field adventures which inspired me. Gradually I realized that the killing of thousands of persons by subterranean machinery totally unknown to geologists and then unexplainable was worthy of a life's work."

Thomas Jaggar, quoted in *The Last Volcano* by John Dvorak (2015)

Magma chamber - Mark Rothko

Thanks to all of my collaborators, especially Bristol colleagues
Willy Aspinall, Juliet Biggs, Jon Blundy, Alison Rust & Steve Sparks

AXA Research Fund

EXCELLENCE IN SCIENCE THE ROYAL SOCIETY

University of BRISTOL