Bubble, Bubble, Toil and Trouble!

From Magma to Ash: Analysis of the Causes of Explosive Volcanic Eruptions

Dork Sahagian
Lehigh University

Based on collaboration with

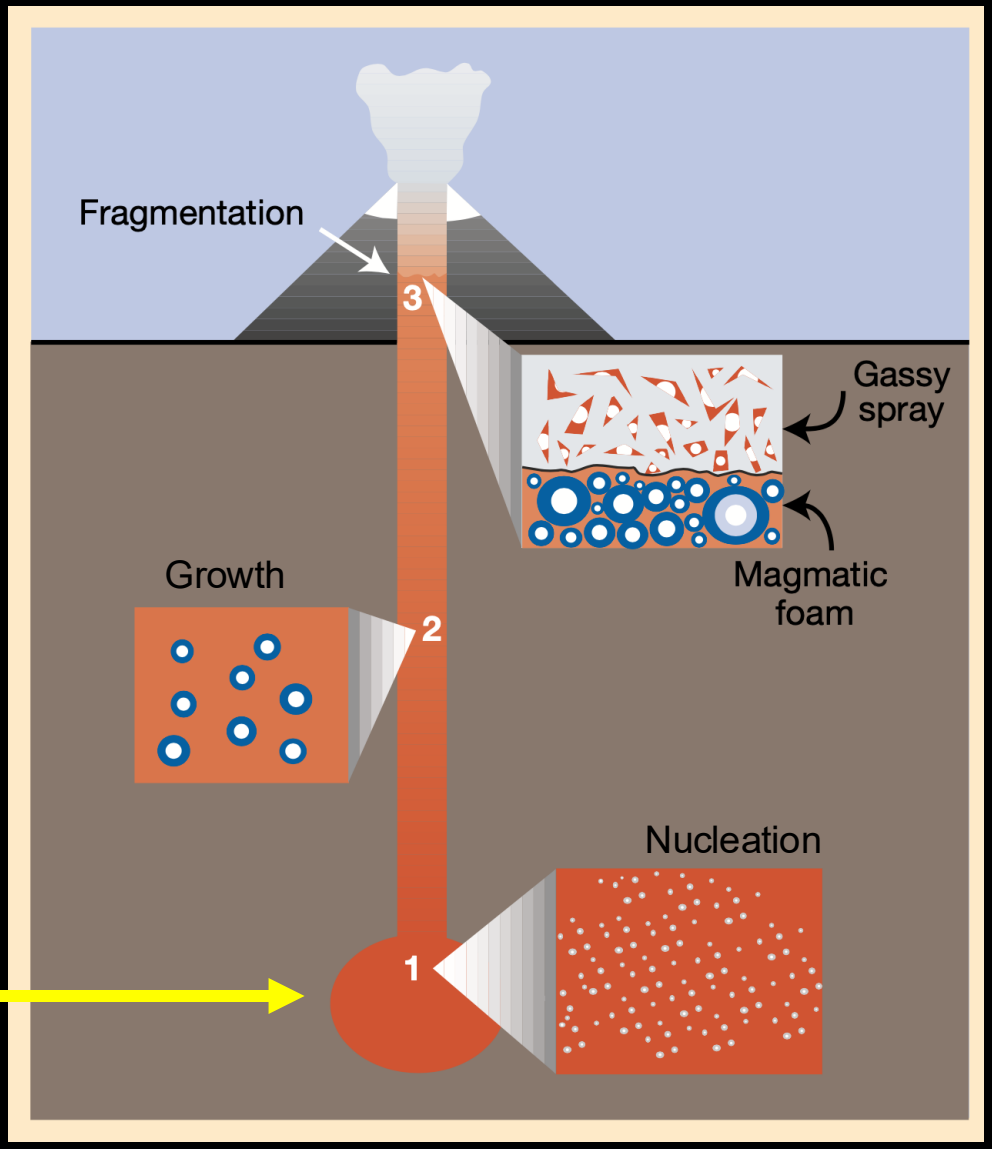
Tamara Carley
Hripsime Gevorgyan
Gianna Greger
Candace Wygel
Leslie Tintle
Megan Clark
Alex Proussevitch
Ed Lewellin
Fabian Wadsworth
Halim Kusamaatmaja
Jim Gardner
Patrick Sullivan

Actually, explosive eruptions look more like this:

And they are driven by BUBBLES!

SO!
We must study bubbles carefully to understand explosive eruptions.

GENERAL SCHEME



All starts with NUCLEATION

It just shouldn't happen!
(but it does…)

- Pressure inside a bubble depends on
    1. Ambient pressure (hydrostatic)
    2. Surface tension pressure
    3. Dynamic pressure (viscous resistance to growth)

- Surface tension depends on 1/r

- Solubility of water depends on Pressure

- So until bubbles reach a certain critical size, they can't exist

- YET THEY DO! TINY BUBBLE PARADOX!!

***Homogeneous* nucleation:** spontaneous formation of bubbles due to supersaturation in homogeneous liquid below solvus (hard to do).

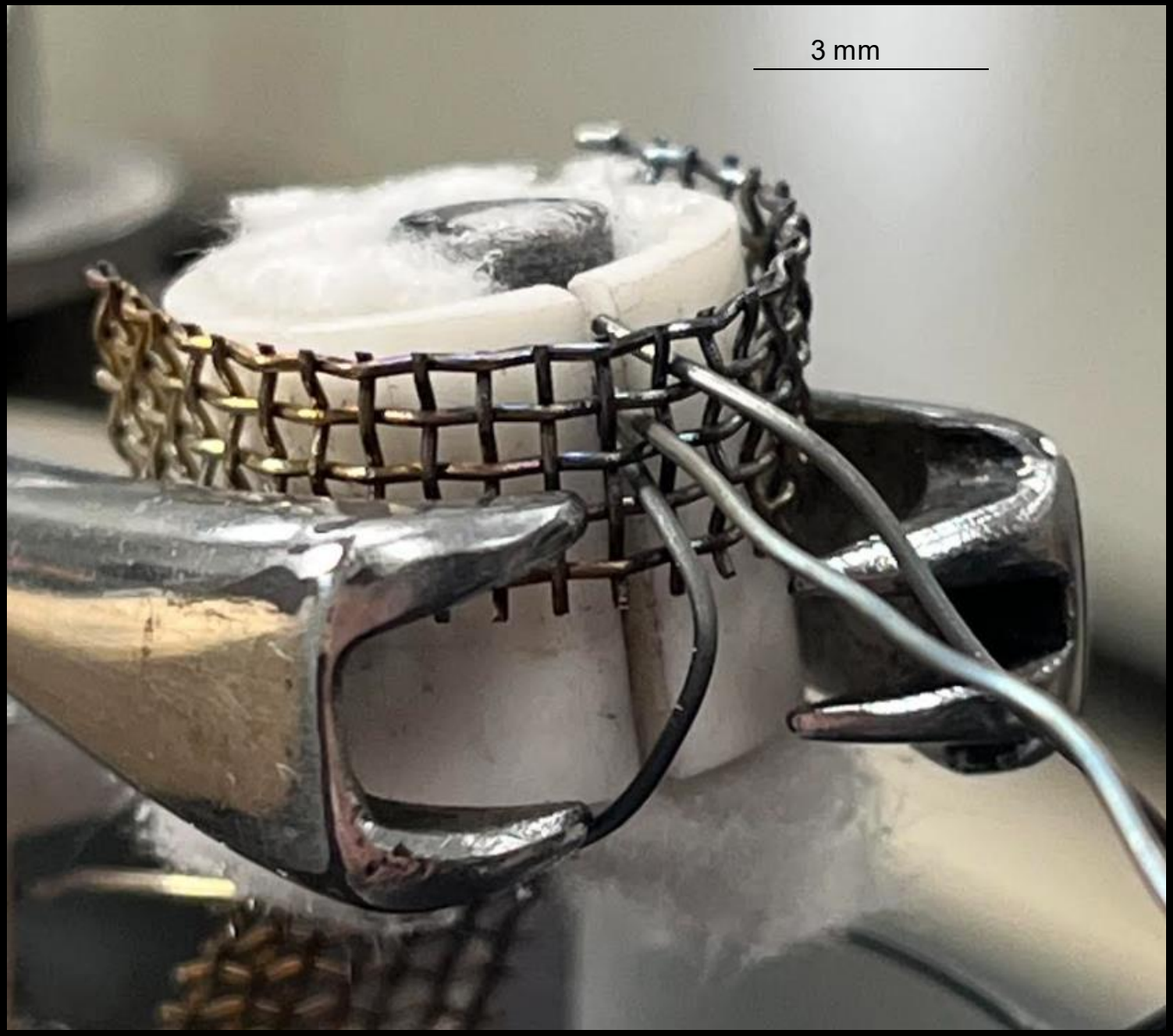
***Heterogeneous* nucleation:** Facilitation by solid surface or melt structure that reduces activation energy required to nucleate bubble (easy to do so more common)

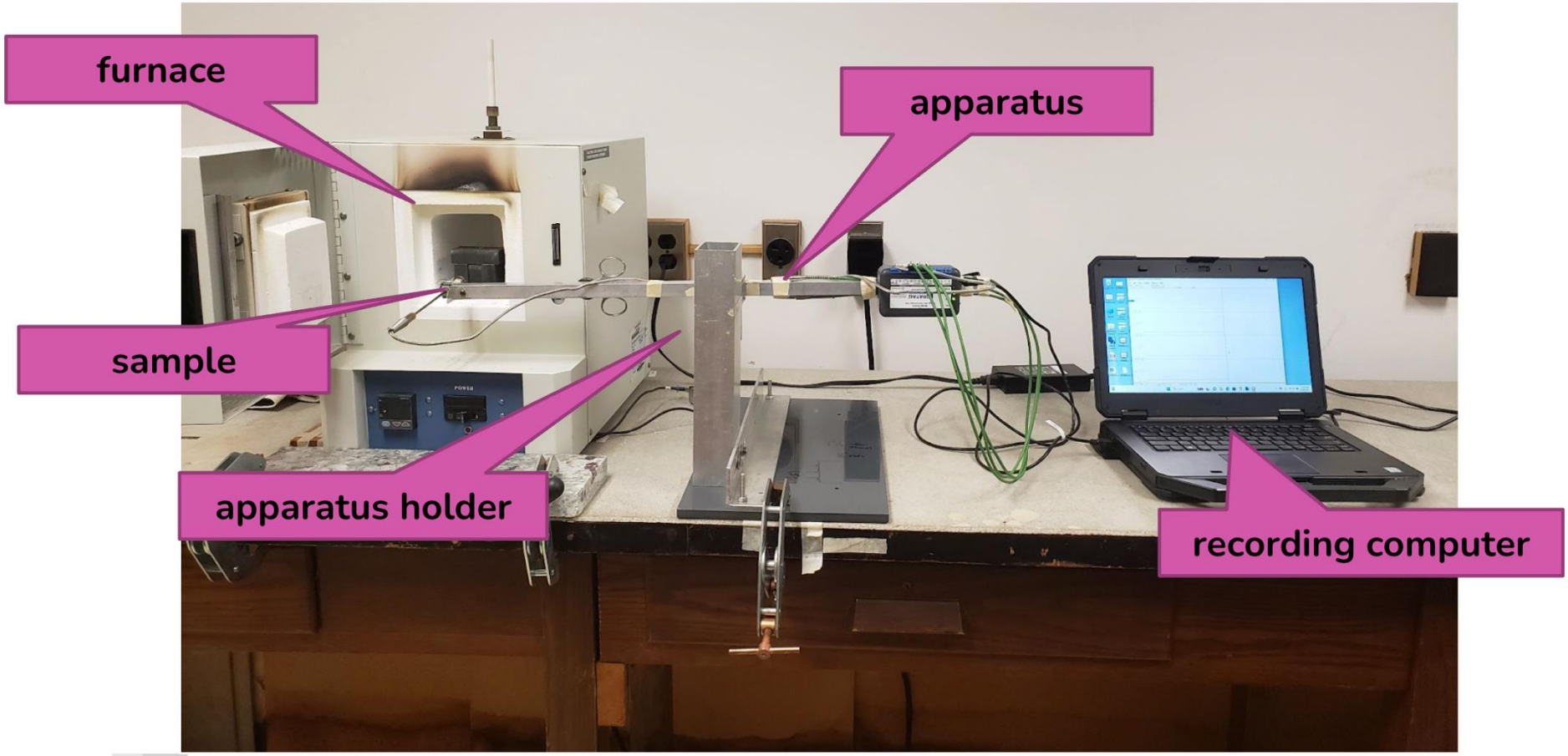
***Spinodal Decomposition*:** Extreme end member of oversaturation involving spontaneous phase separation and uphill diffusion below spinode. (very hard to do and unlikely in most natural systems)

It is all about tiny bubbles…

So How do real bubbles ACTUALLY nucleate?

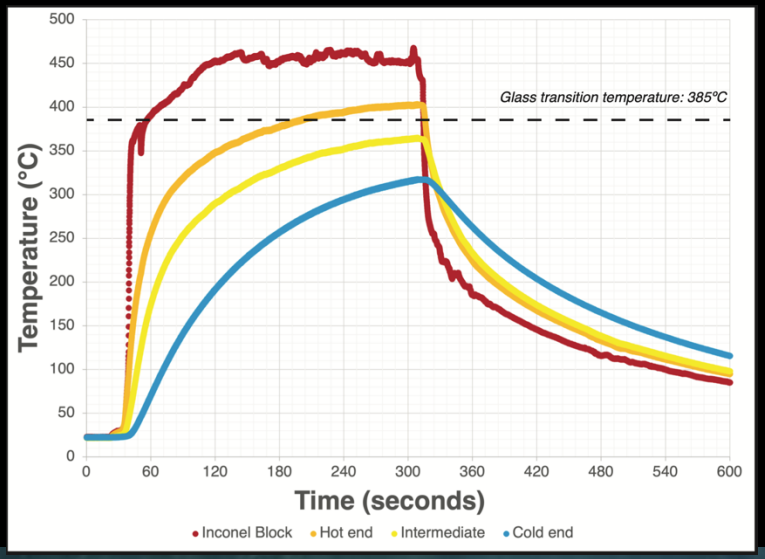
Fabricate an oversaturated sample, hold it carefully, and heat it up!





The experimental setup

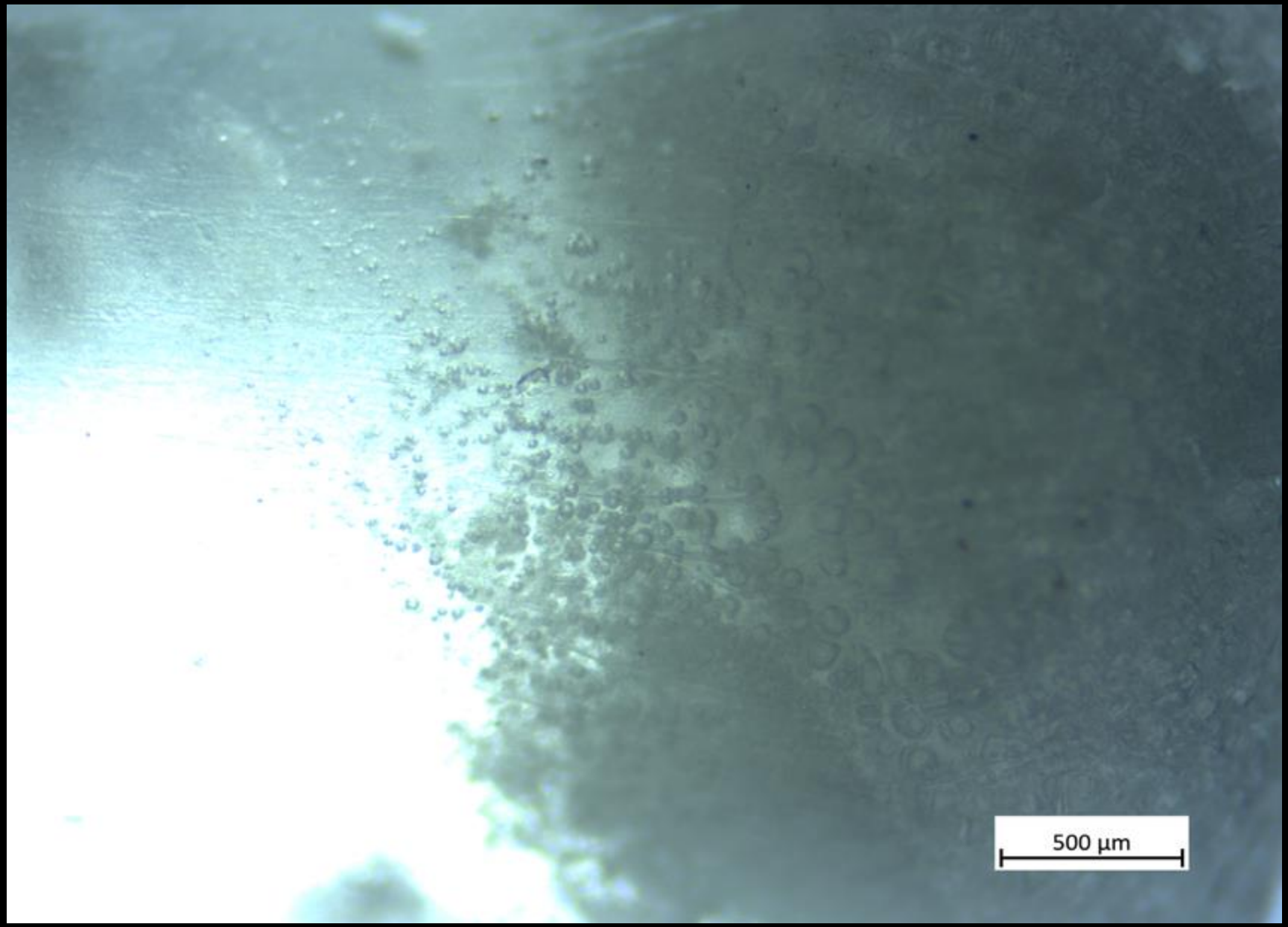
So we cook samples in the furnace …



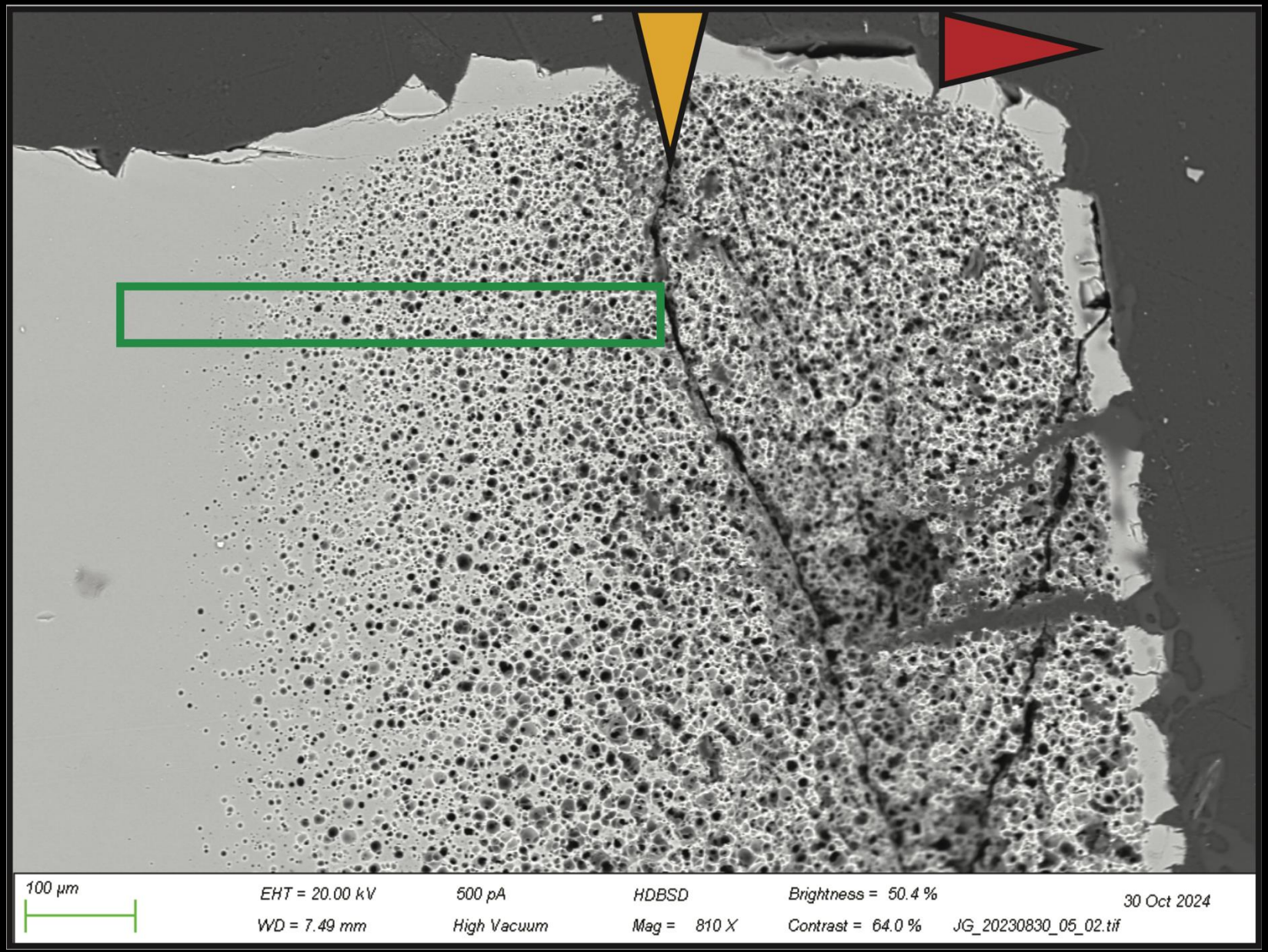
before

after

Close-up look: Catching nucleation in the act!



Close-up look

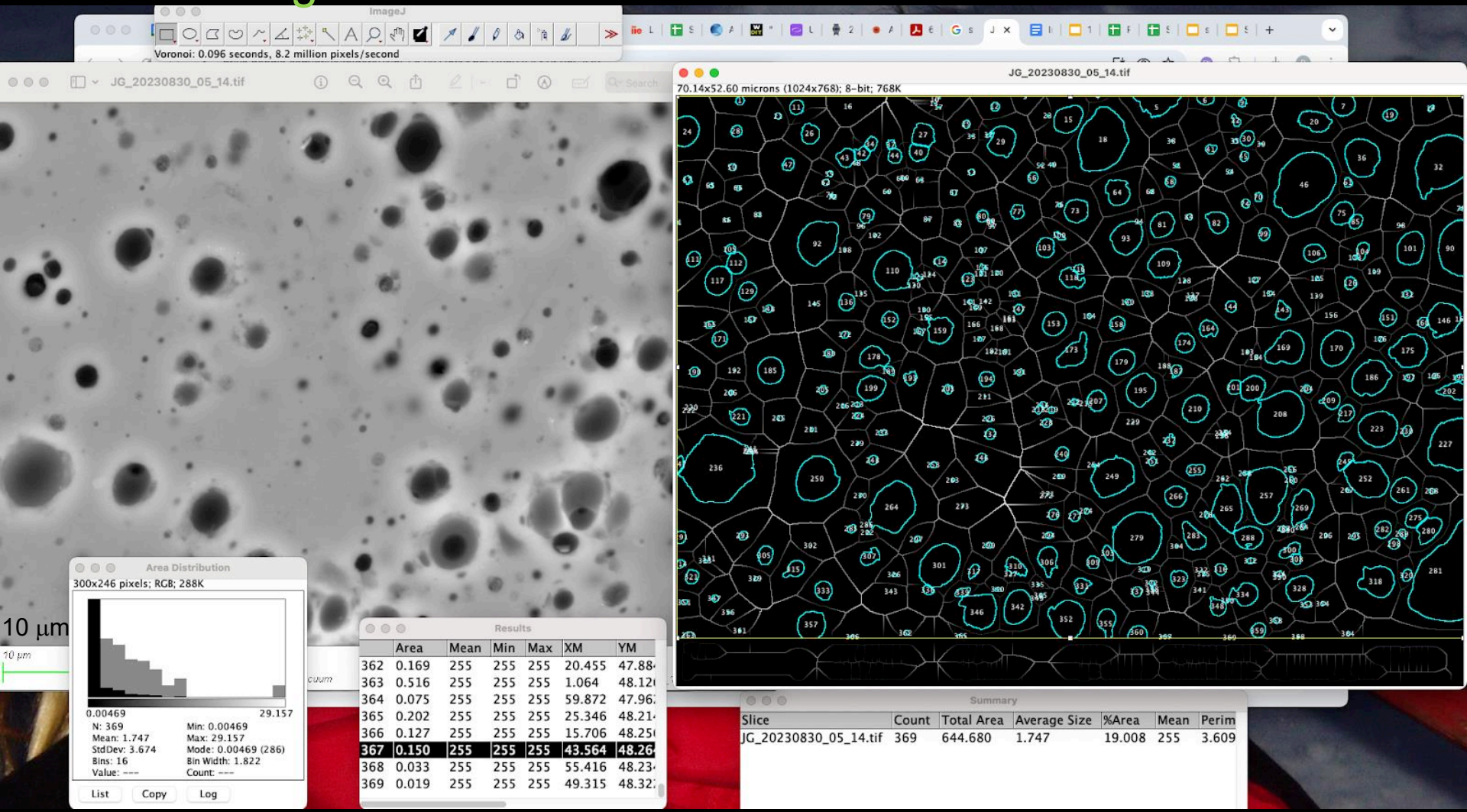


SEM image of polished section

Bubble size and space distribution: Use ImageJ

SEM image

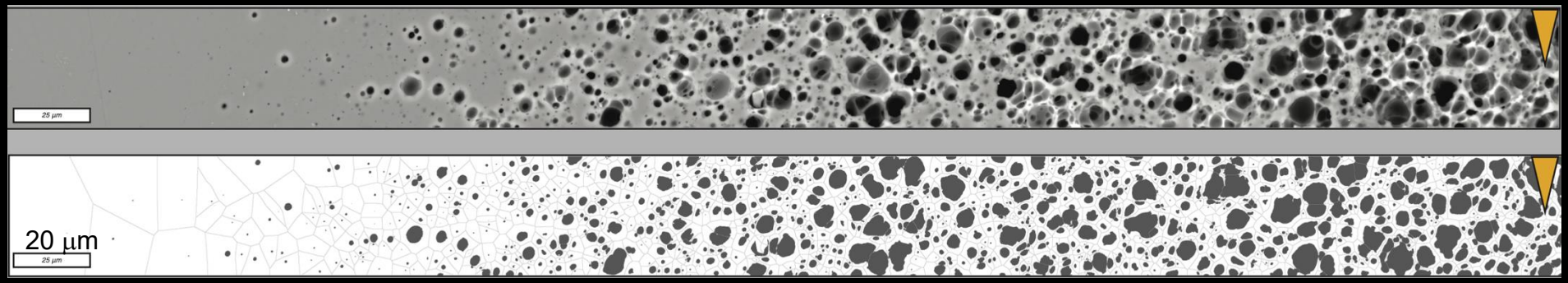
Voronoi distribution



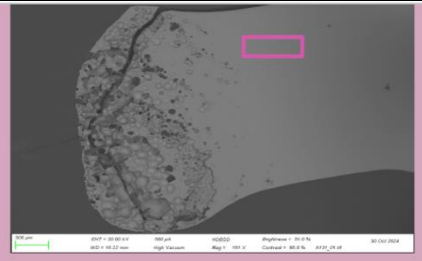
Stitching it all together, we get:

- Vesicularity as a function of position
- Voronoi spacing of nucleation sites
- Nucleation site number density
- Time and amount above glass transition as function of position
- Nucleation rate as a function of position (time above glass trans)

Does NOT give remaining dissolved water concentration- (FTIR)



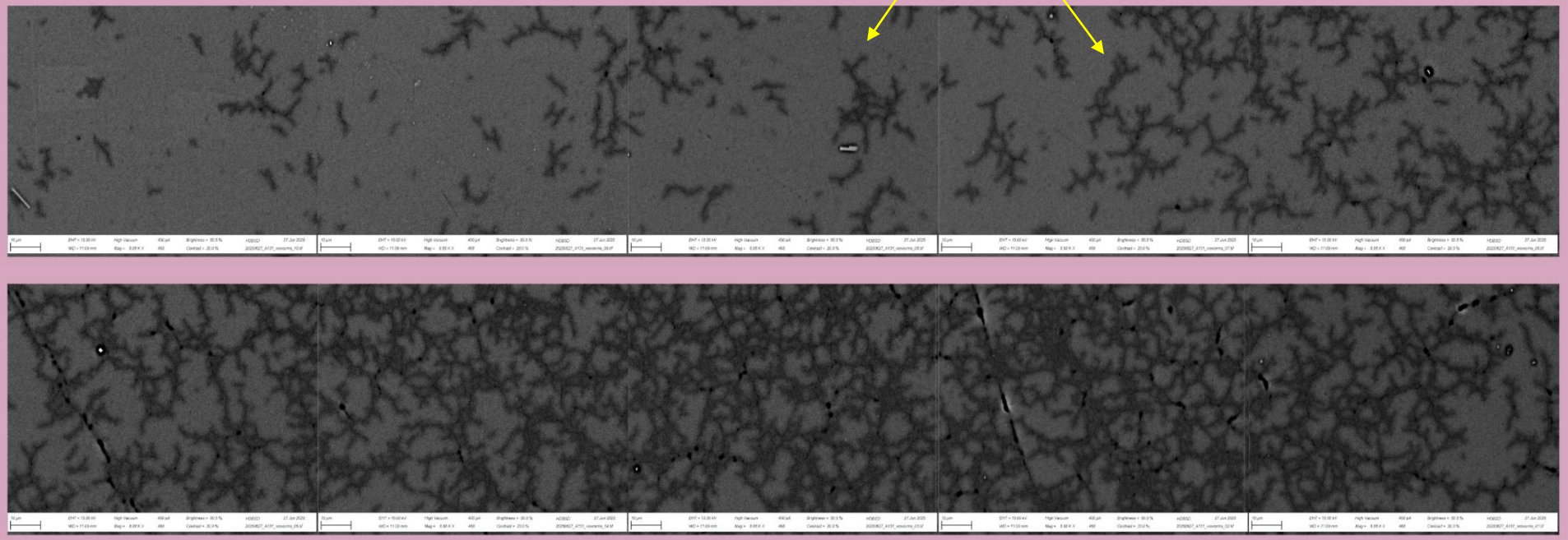
A131



Water gradient?

Hot end

Beginnings of phase separation?



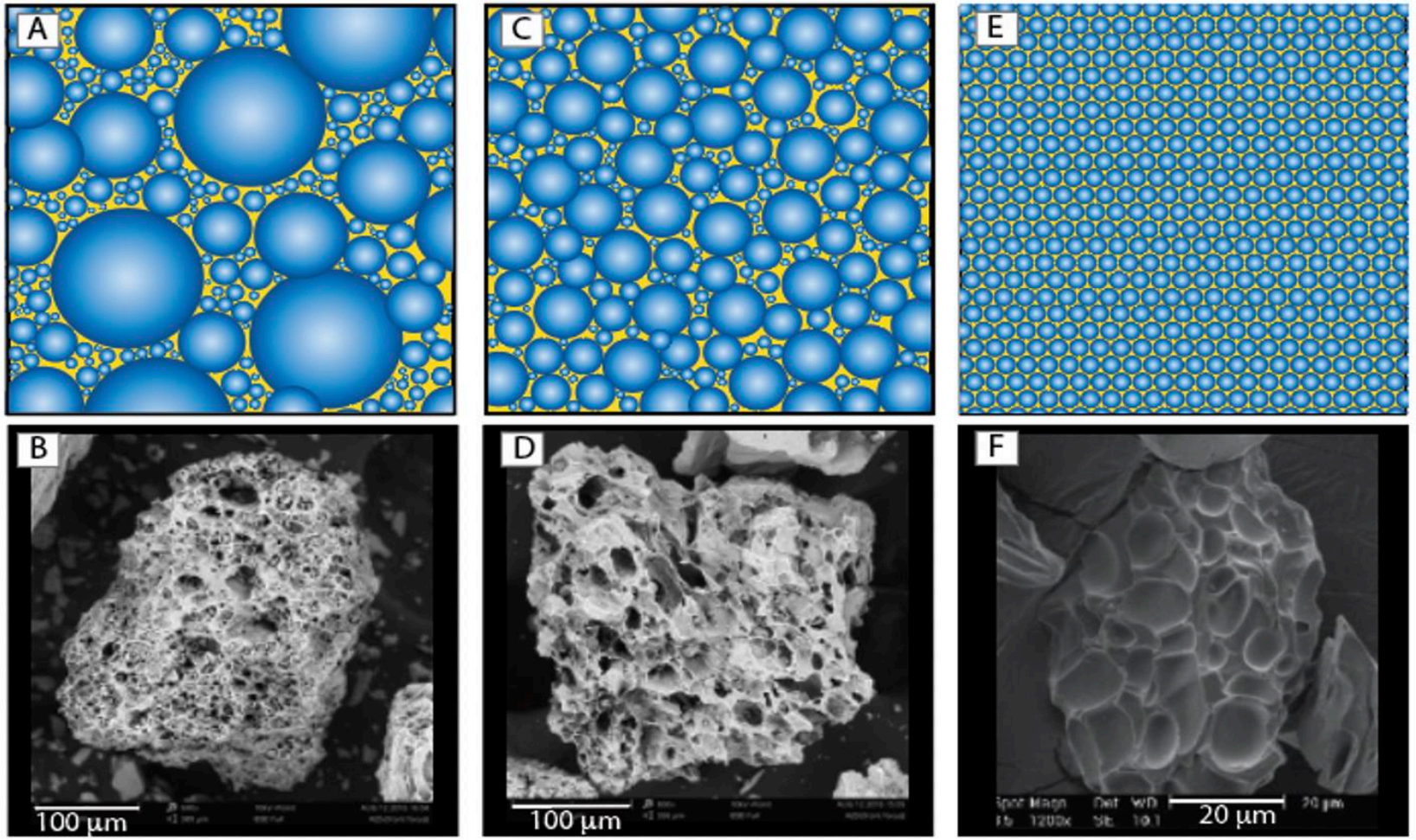
Cold end

So we can nucleate bubbles in a magma…

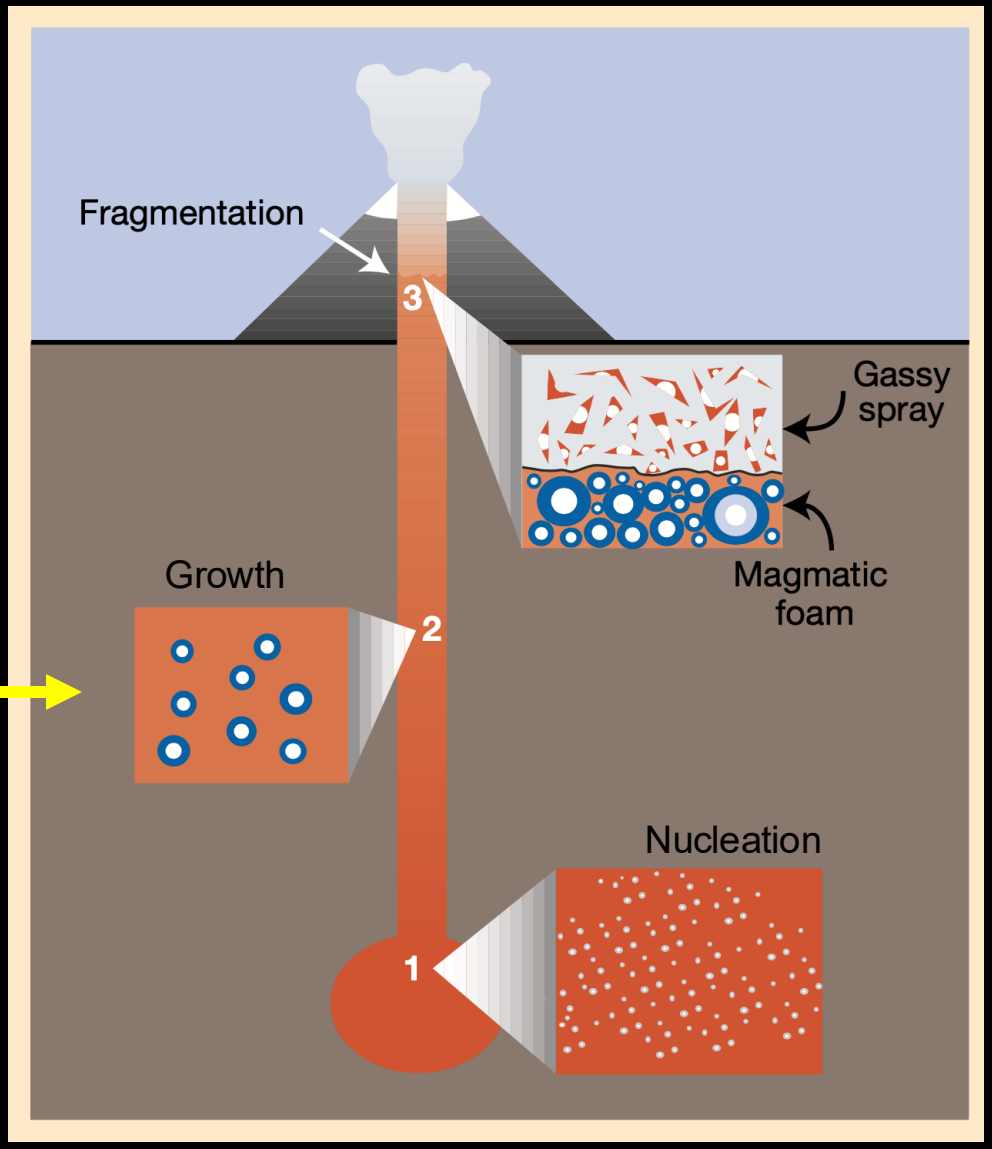
Poorly sorted bubbles make broad bubble size distribution

Better sorted bubbles make narrower bubble size distribution

Perfectly sorted bubbles make identical bubbles



GENERAL SCHEME



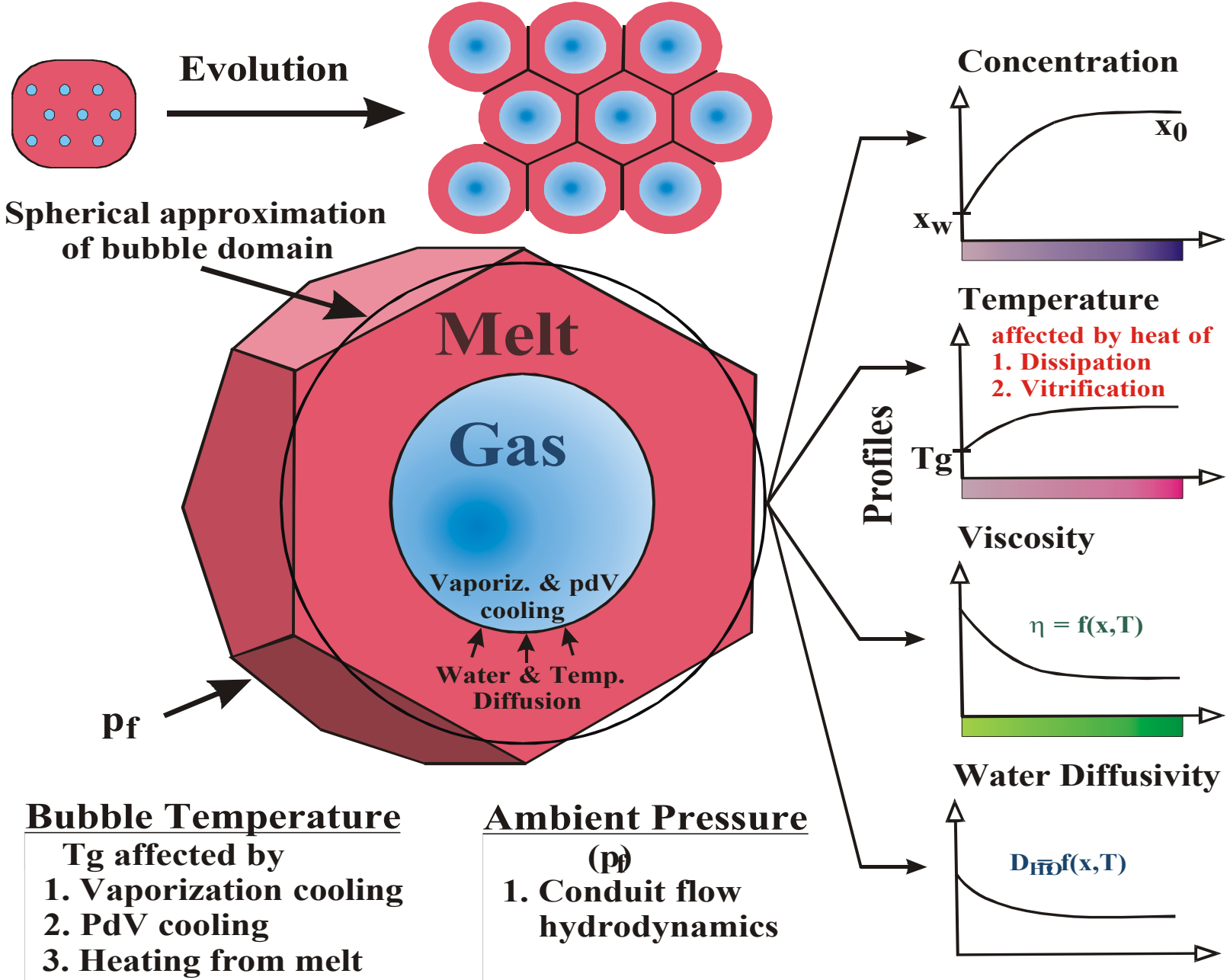
Bubbles must grow!

BUBBLE GROWTH

Once nucleated, bubbles grow by diffusion and decompression

Growth is controlled by diffusion rate, which is controlled by concentration gradient, viscosity, and bubble size

- Magma oversaturates in volatiles (e.g. water) during decompression
- Pressure inside a bubble depends on
    1. Ambient pressure (hydrostatic)
    2. Surface tension pressure
    3. Dynamic pressure (viscous resistance to growth)
- Solubility of water depends on Pressure



Bubble Temperature

Tg affected by

1. Vaporization cooling
2. PdV cooling
3. Heating from melt

Ambient Pressure

(p_f)

1. Conduit flow hydrodynamics

Bubble Pressure

$p_{gf} = p + p + \sigma p_f$

Interface concentration

$x_{wg} = f(p)$

Bubble Growth during Decompression

Rate of decompression controls oversaturation

As bubbles grow, they accelerate those above them, so decompression rate increases with time

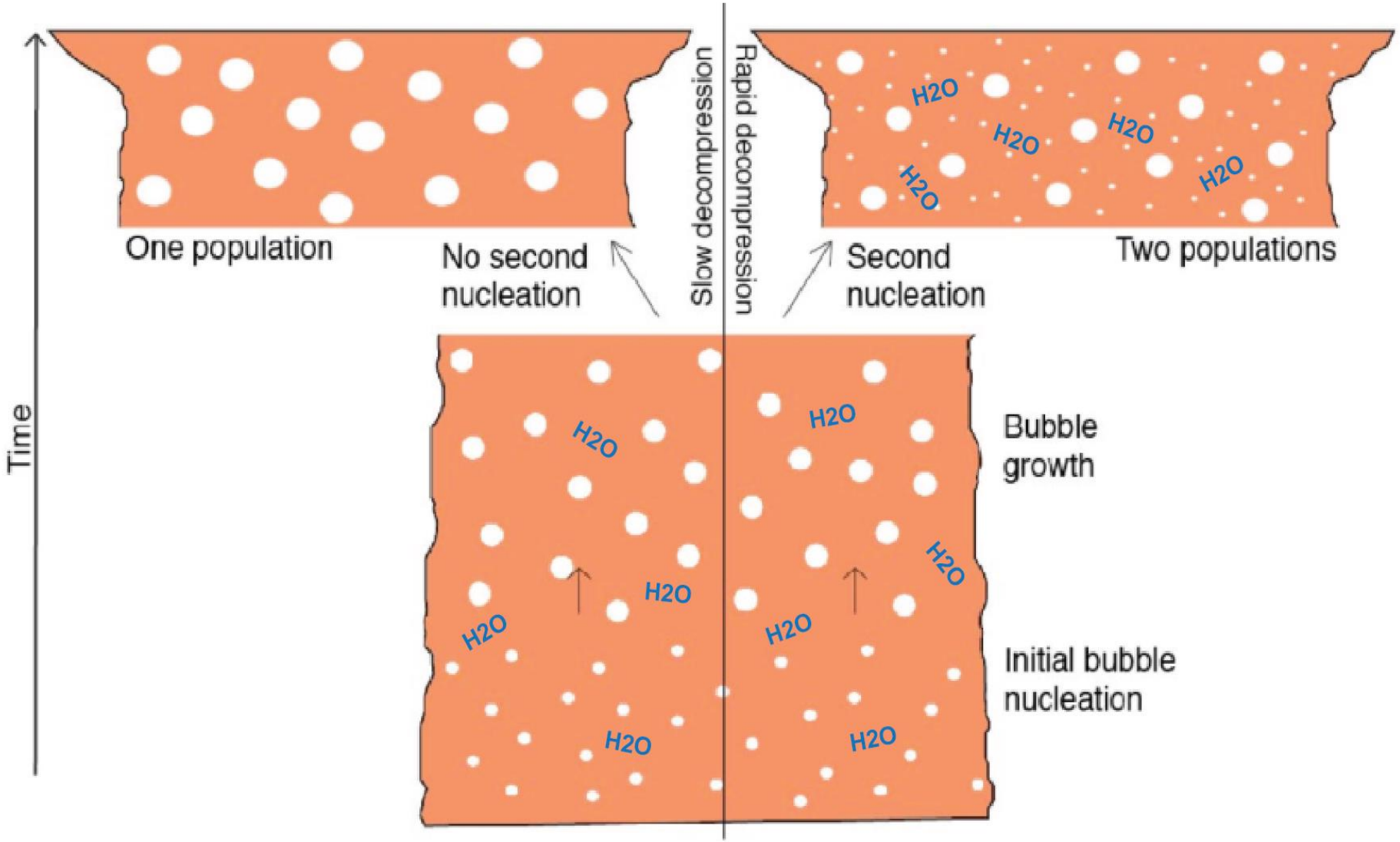
As a bubble rises with its host magma, its growth accelerates due both to accelerating decompression and increasing oversaturation

- So you get an acceleration of acceleration!

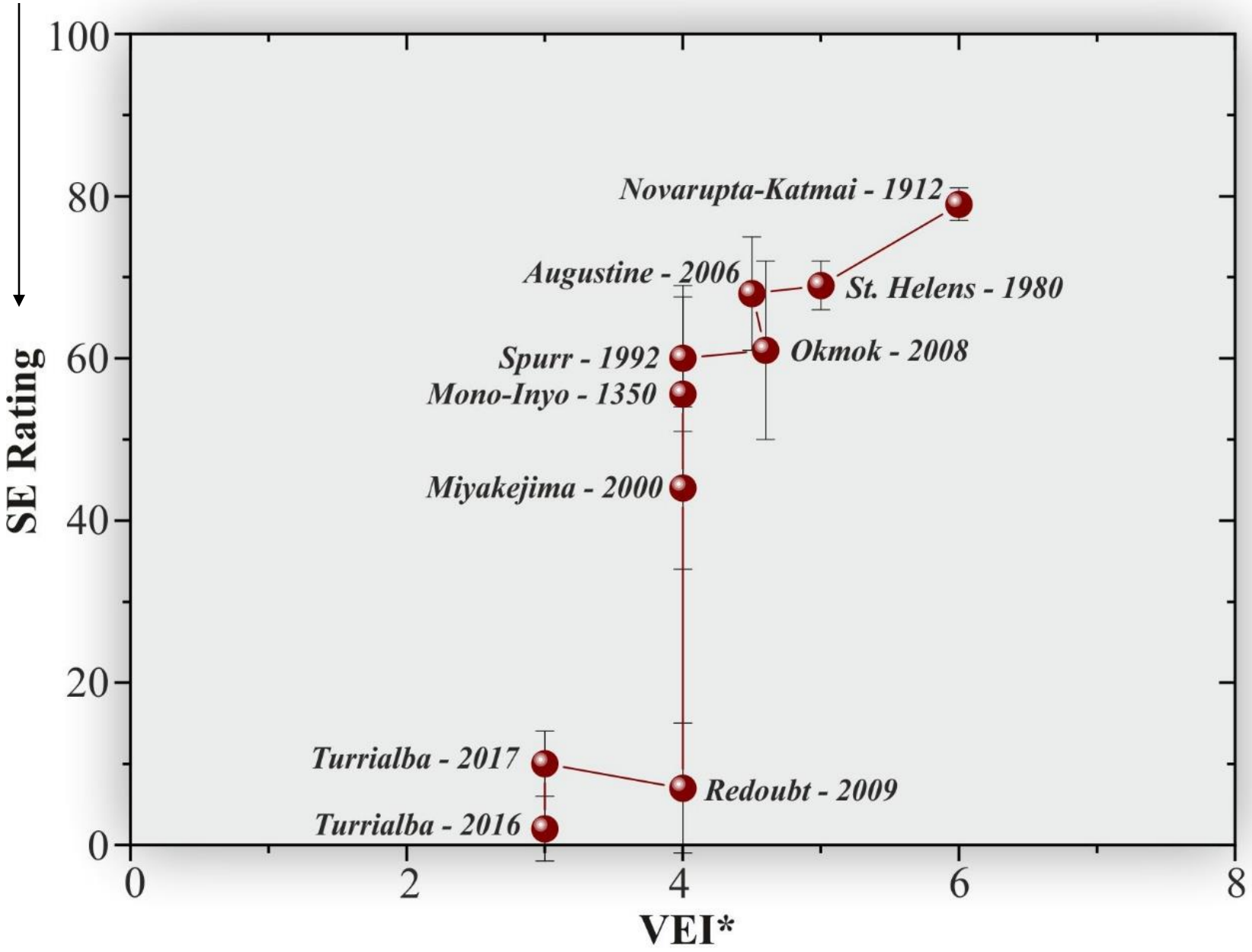
In viscous magmas, viscous resistance becomes limiting and “excess” pressure develops. Pressure inside bubble becomes much greater than ambient.

- Extreme oversaturation leads to syn-eruptive nucleation with high number density.

If ascent and decompression is fast enough, oversaturation in bubble walls makes a second “syn-eruptive” nucleation event.

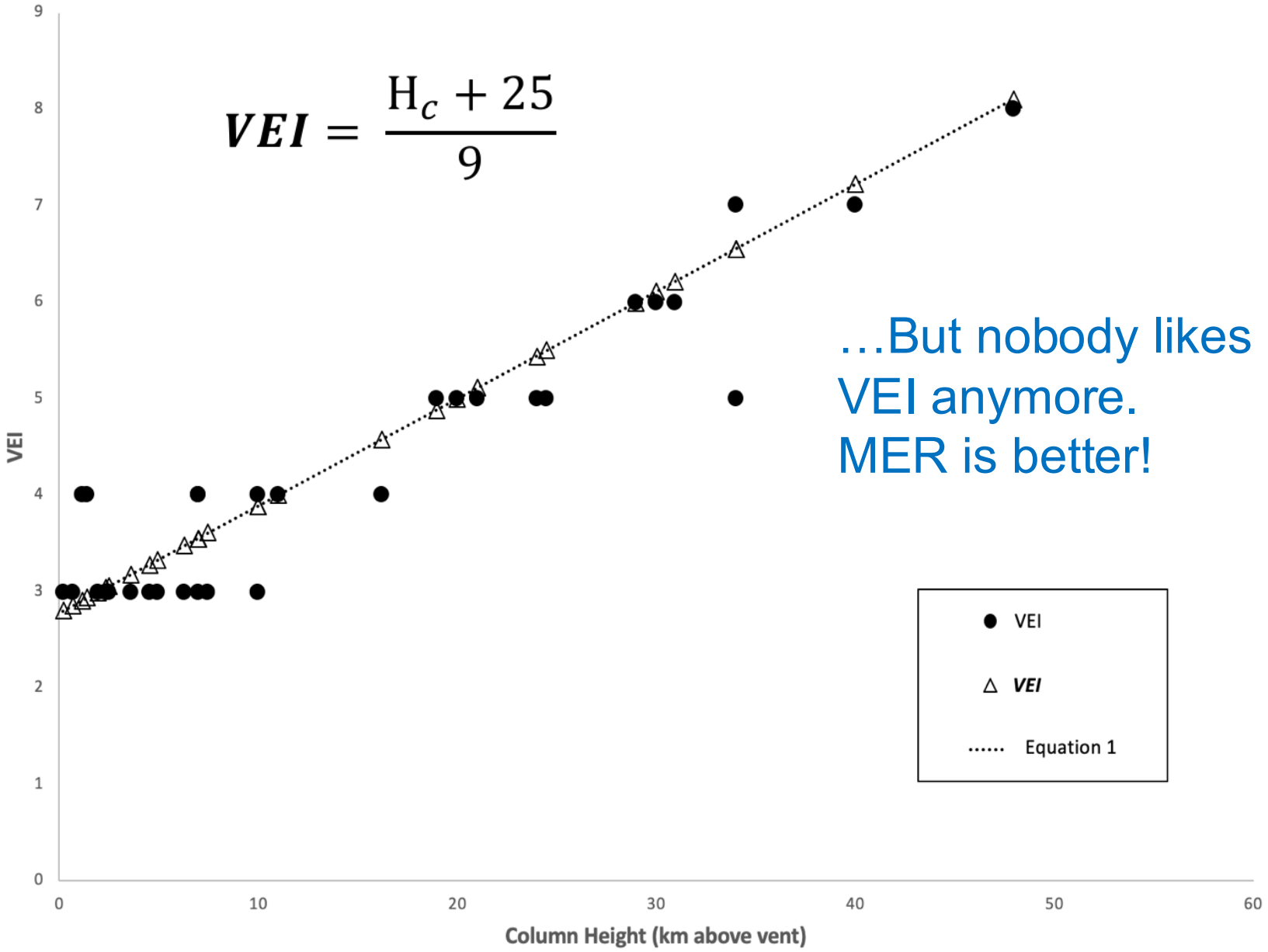


The fraction of ash particles that include syn-eruptive bubbles



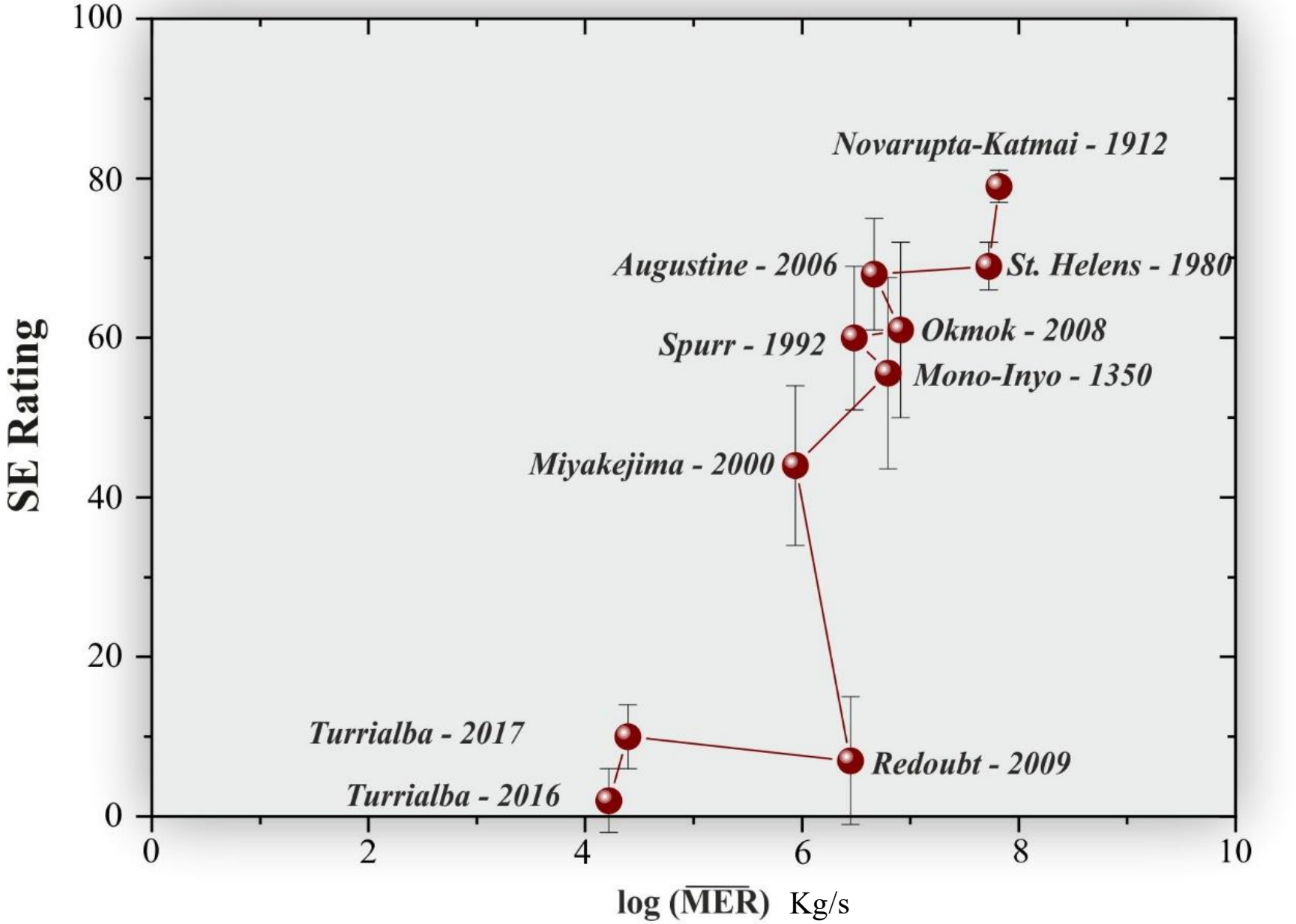
Speaking of VEI… We can calculate VEI in real time!

$$VEI = \frac{H_c + 25}{9}$$



…But nobody likes VEI anymore. MER is better!

Volcanologists do not like VEI anymore- Use MER!

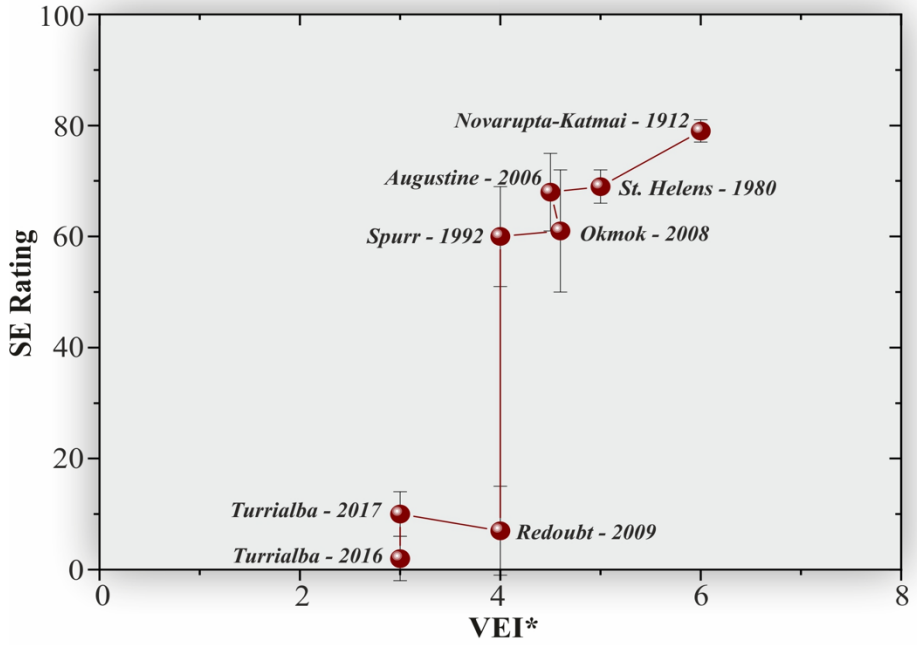


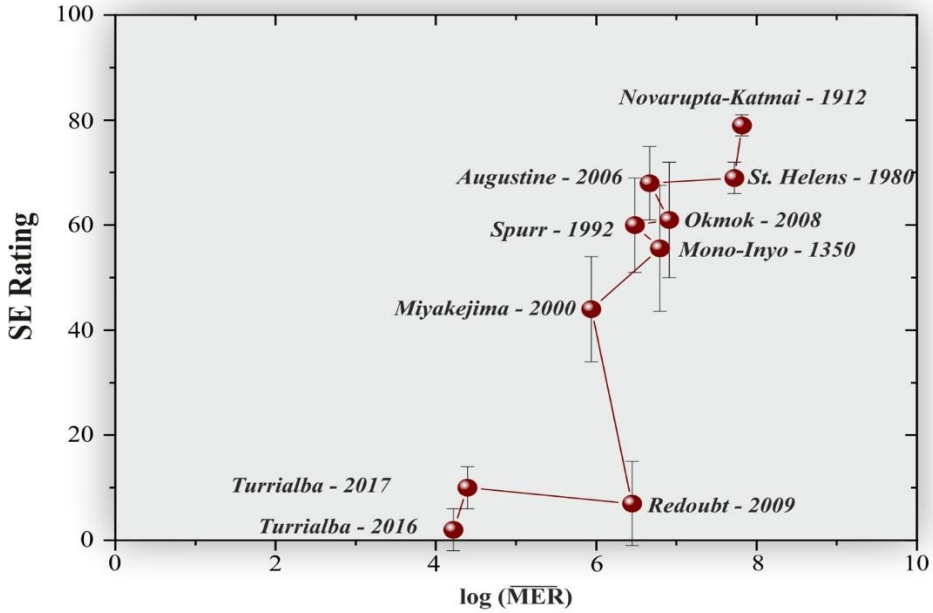
Since MER and VEI can both be found from eruption column height, it is no surprise that they are closely related.

VEI threshold: 4

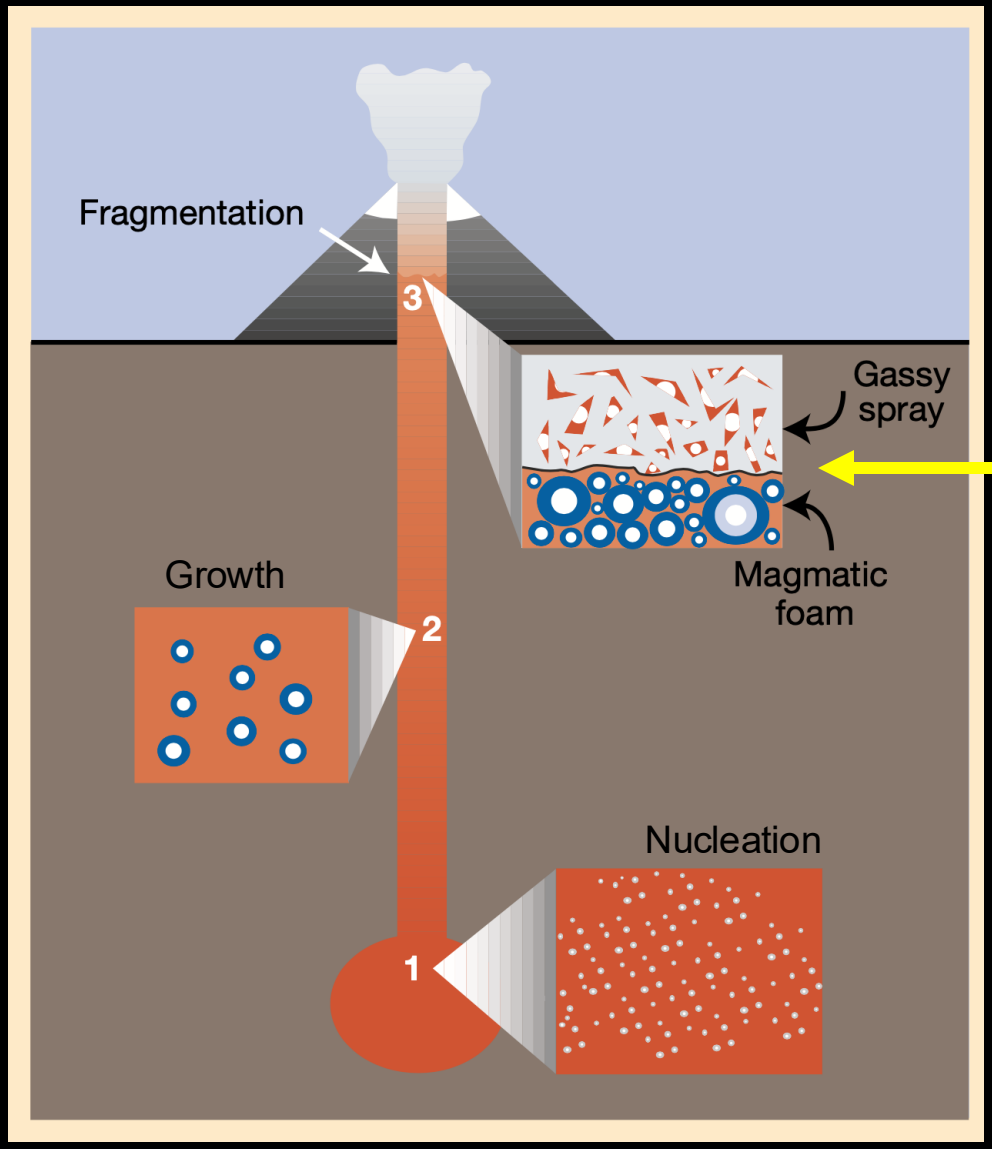
MER threshold: 5×10^6 kg/s

Threshold for explosive eruptions





GENERAL SCHEME



Bubbles pop! (Fragmentation)

Fragmentation

POP THE BUBBLES!

- Bubbles grow to make a magmatic foam
- Inter-bubble films stretch.
  - either strain rate exceeds critical OR
  - tensional stress within film exceeds critical
    (we found that the latter is more likely…)
- Bubbles burst when films and Plateau borders break
- Gas from adjacent bubbles coalesces, makes permeability
- Magma converts from bubbly liquid to gassy spray

MAKES ASH!

Bubbles and Ash
How is nucleation related to ash?
How does ash reflect eruption energy?

Nucleation mechanism controls nature of foam, which controls ash morphology!

SORTED

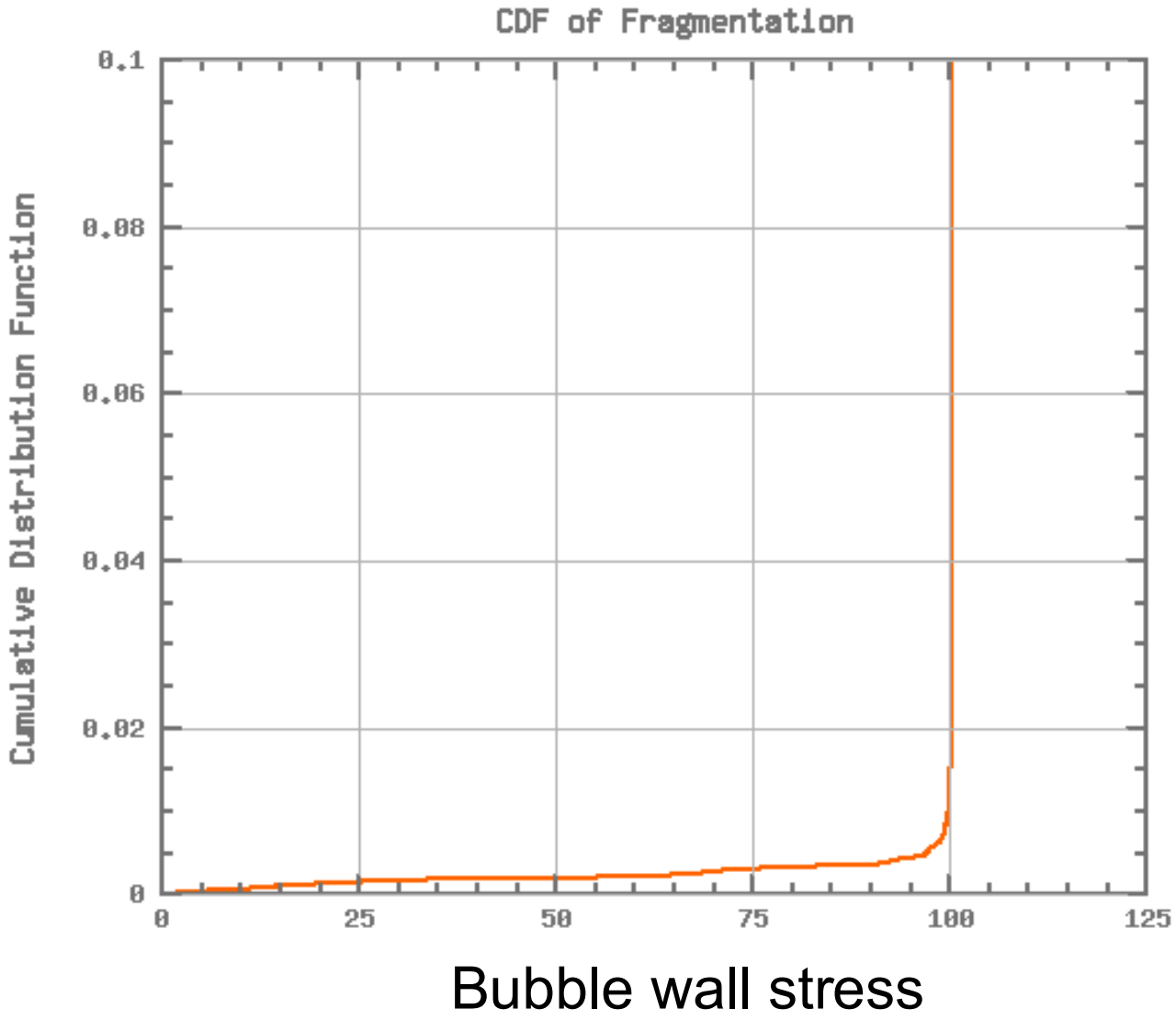
UNSORTED

Spinodal Decomposition

Homogeneous

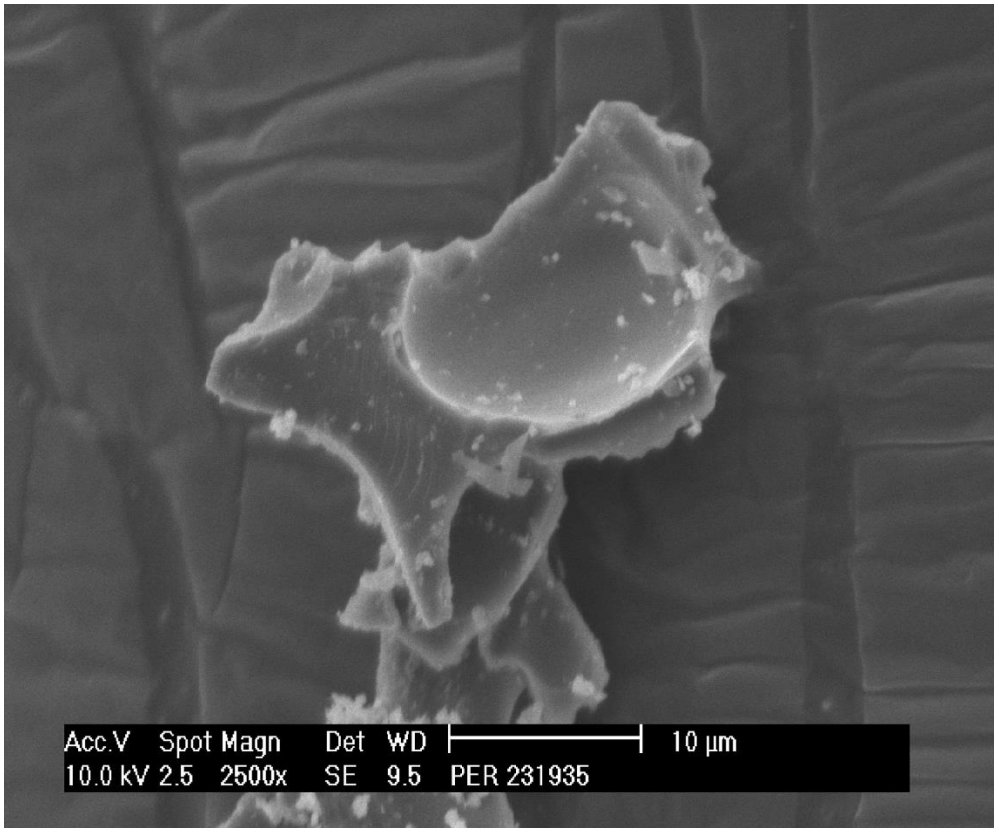
Heterogeneous

Fractional Bubble Wall Failure for Sorted Bubbles in the Voronoi Spacing



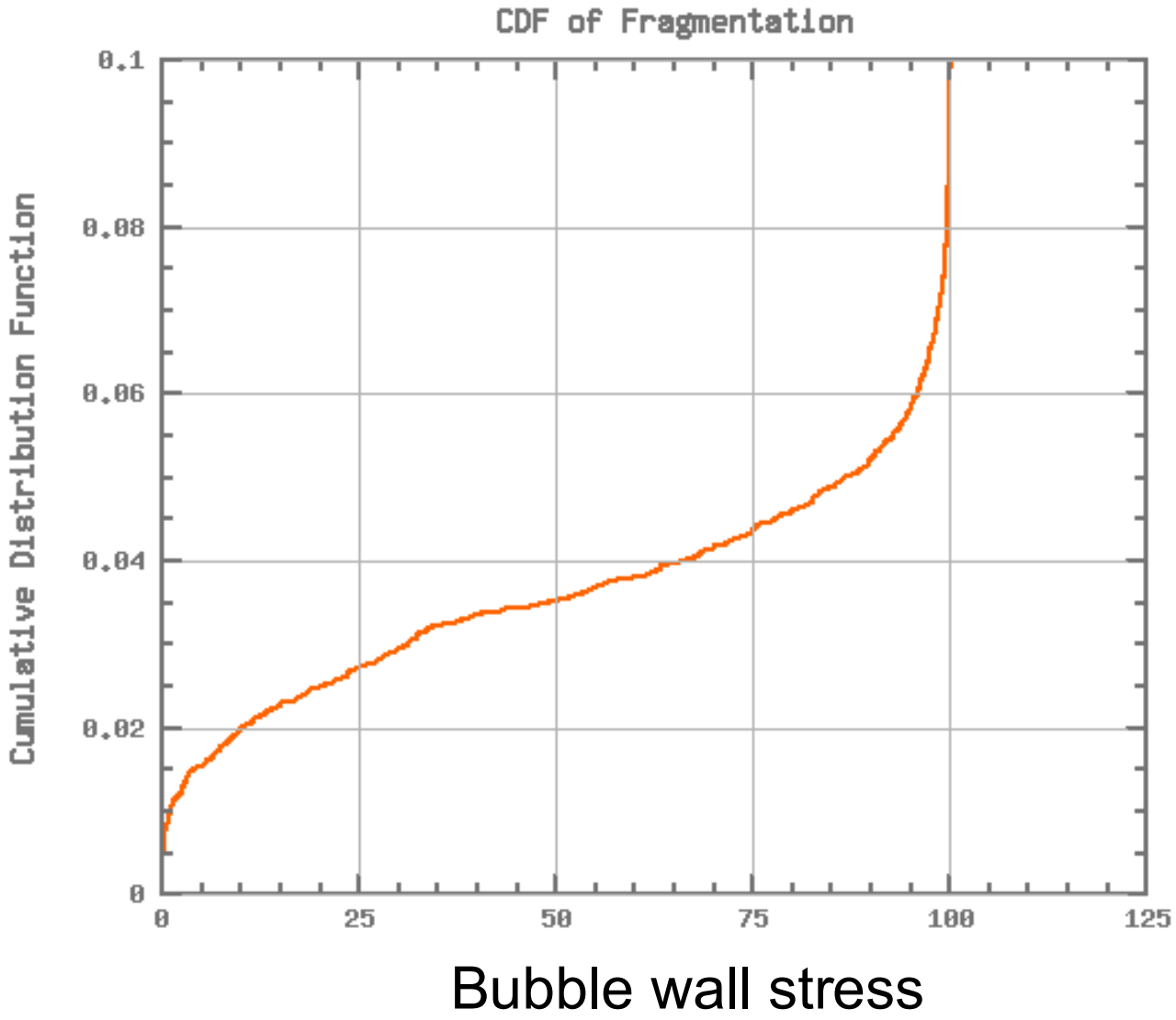
Well sorted bubbles make explosive fragmentation all at once.

And they make simple ash particles, since all bubbles burst

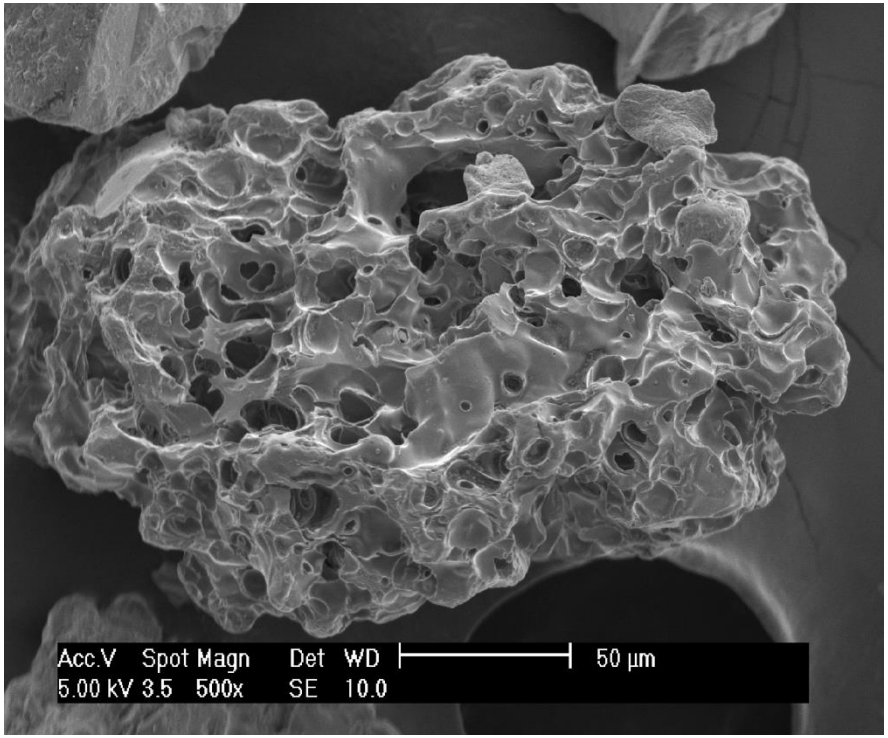


Simple ash particles display a single vesicle imprint or preserve the plateau border between adjacent vesicles that all burst during fragmentation

Poorly sorted bubbles burst over a range of stresses and thus times-less explosive



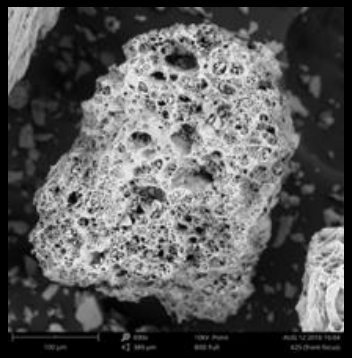
Makes more compound ash particles



Compound ash particles display numerous vesicle imprints on their surfaces and contain complete vesicles in their interiors that did not burst during fragmentation.

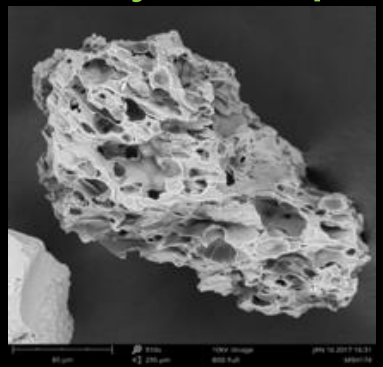
So its all about bubble nucleation!

Nucleated syn-eruptive bubbles

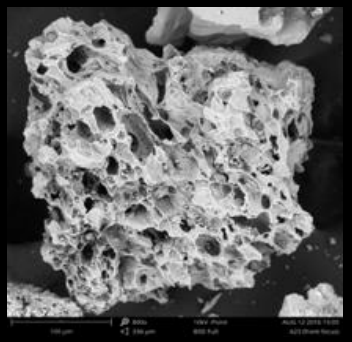


Katmai 6

VEI

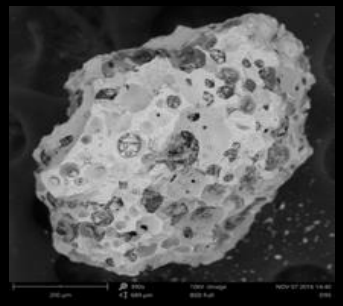


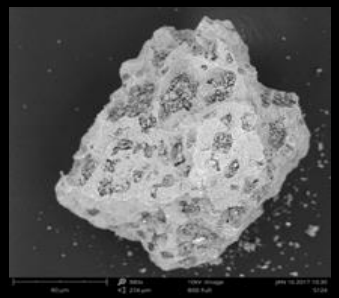
Mt. St. Helens 5



Augustine 4

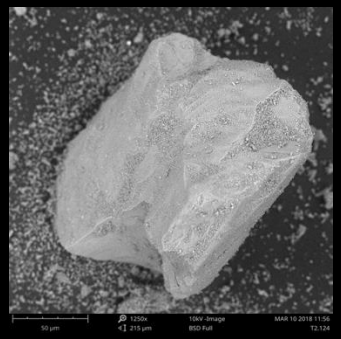
Okmok 4





Spurr 4

Redoubt 3



Turrialba 2

Didn’t nucleate syn-eruptive bubbles

What we think we know –

How bubbles grow

How MER (and VEI) is reflected in ash morphology

Threshold of MER (and VEI) for syn-eruptive bubble nucleation

How to nucleate bubbles in homogeneous and heterogeneous glass

How to determine nucleation density and rate in lab samples

What we know we don't know –

To what extent heterogeneous nucleation inhibits homogeneous

How big crystals need to be to nucleate multiple bubbles

How small a crystal can be to still nucleate a bubble

If spinodal decomposition can occur in natural systems

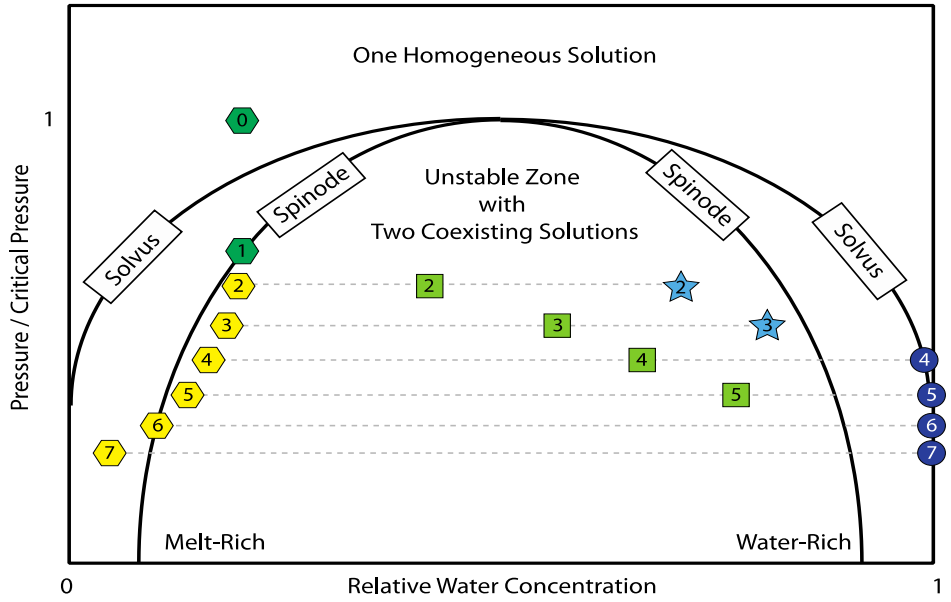
What we don't even know that we don't know…

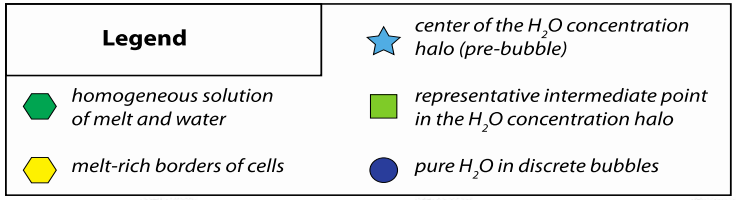
QUESTIONS?

The ash cloud poked through tropopause.
Our models were all full of flaws.
The ash aggregated.
The experts debated
But still couldn't figure the cause.

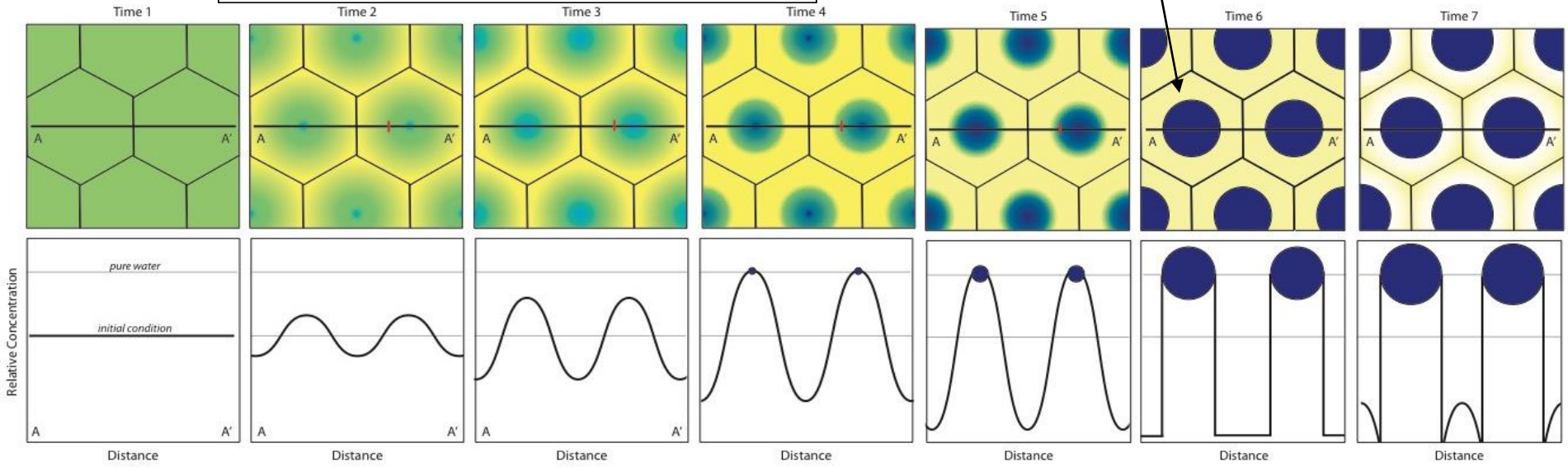
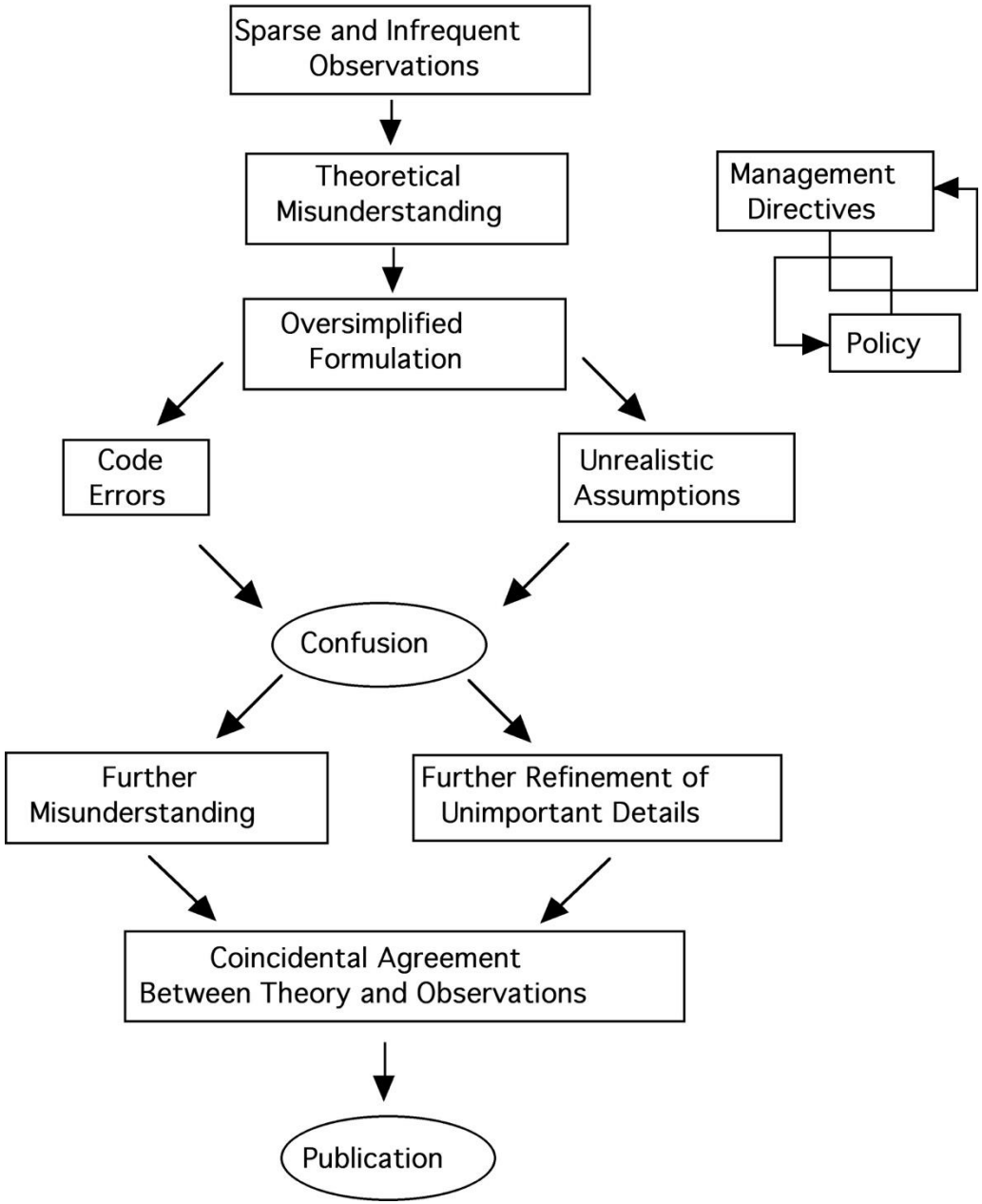
Health Hazards

You thought it was safe to inhale.
Alveoli the ash would impale.
If you don't hold your breath
You'll suffer slow death.
Get away from the ash without fail!





Cells grow with bubbles!



NUMERICAL MODEL DEVELOPMENT