Designing and Using Decompression Experiments to Investigate Magma Ascent Rates

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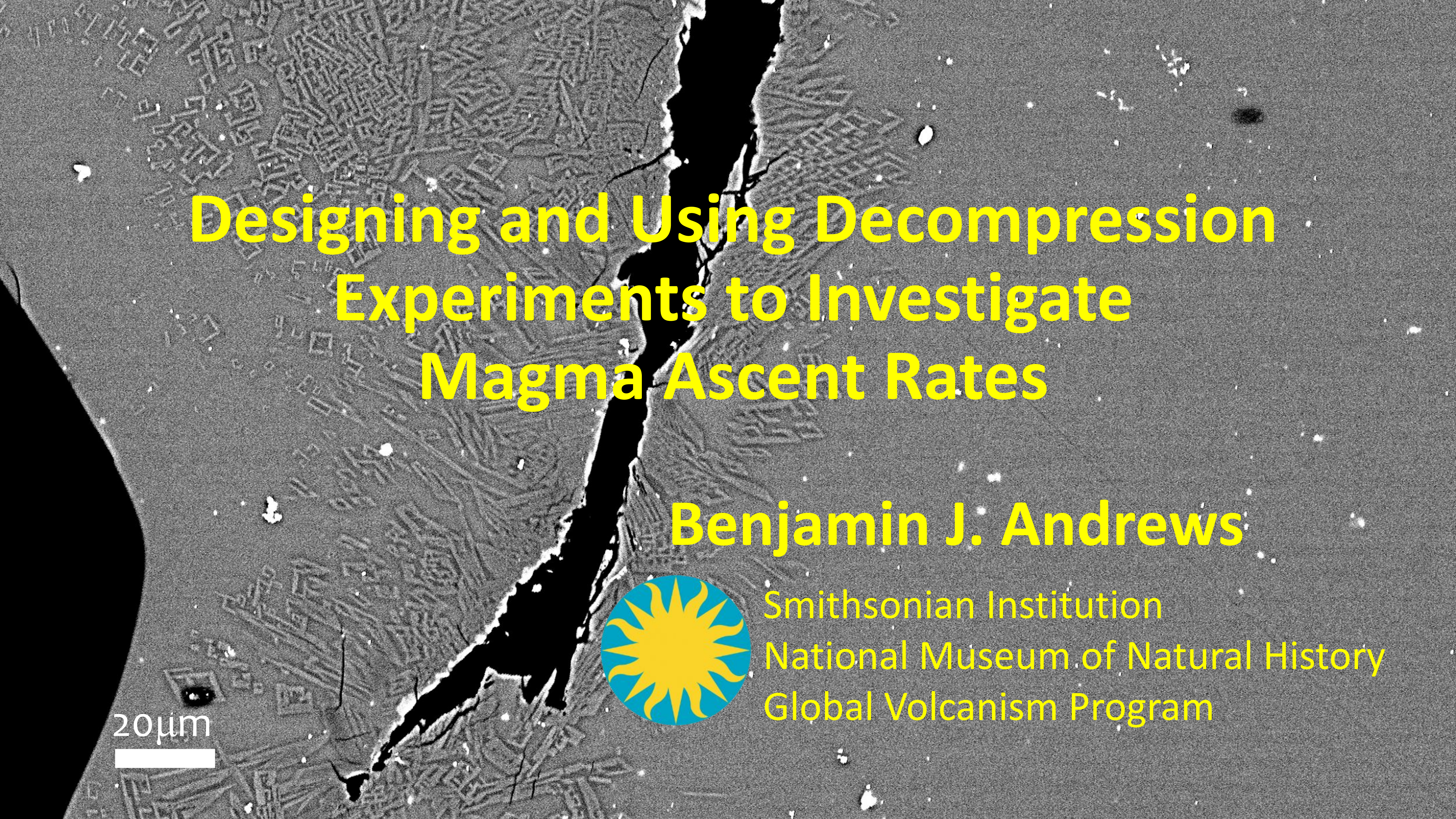
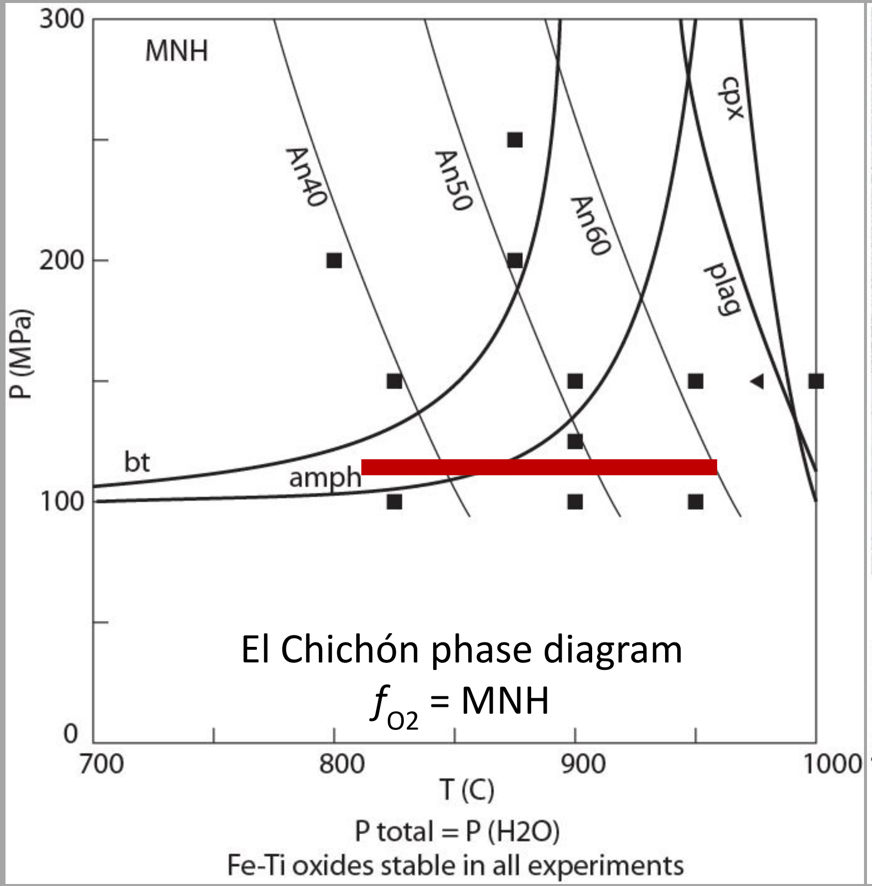
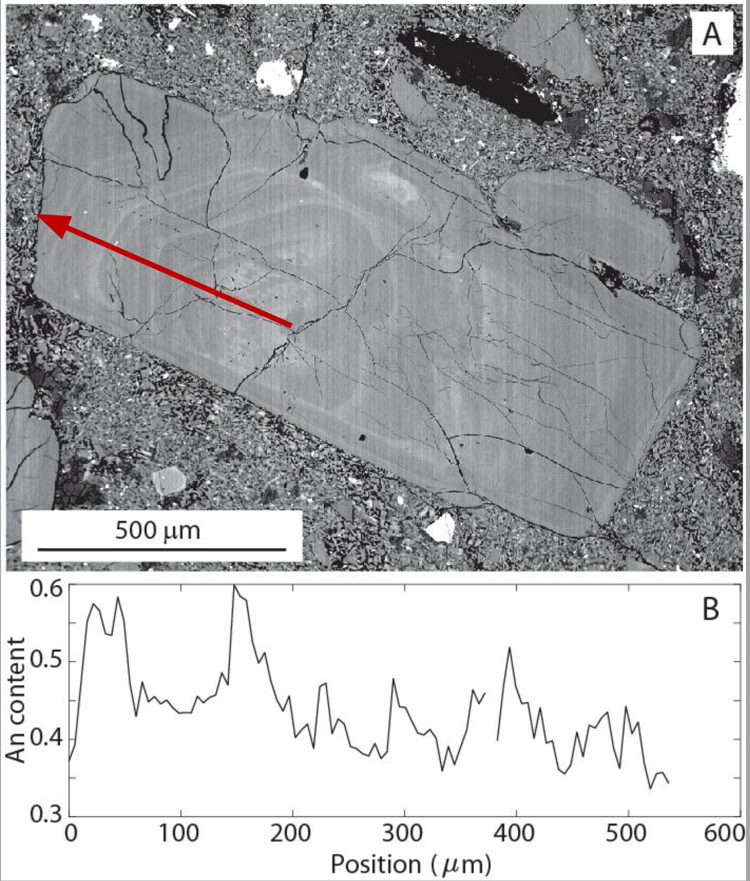


Equilibrium Experiments





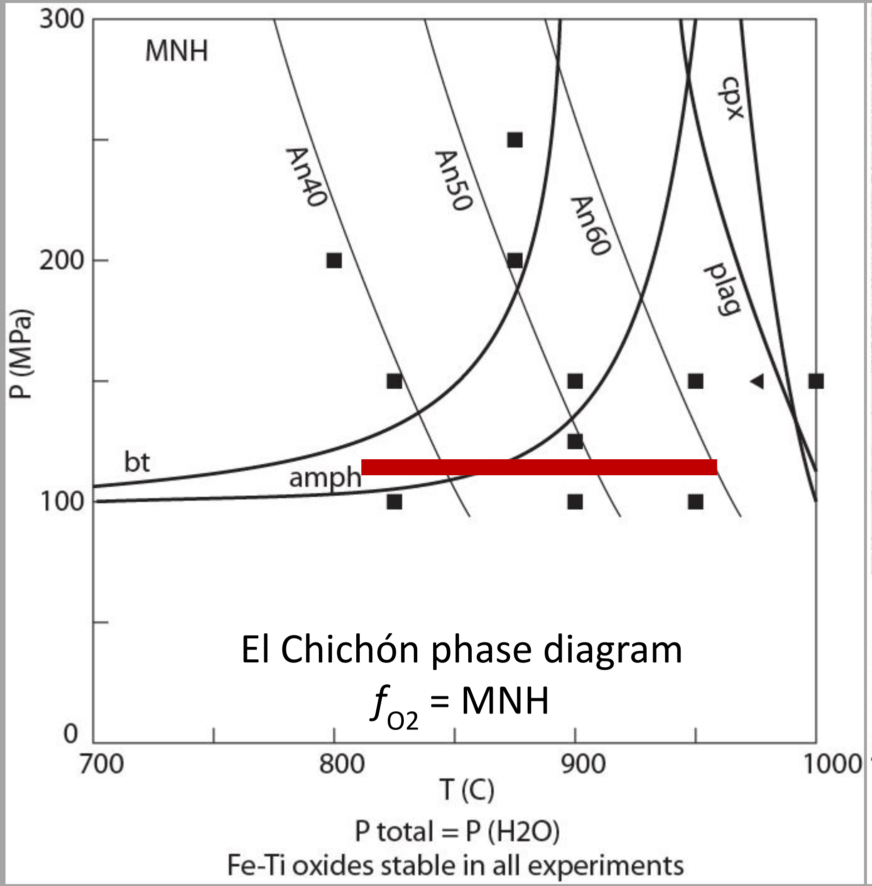
Determine phase assemblage and compositions as f(P,T,f_{O2})

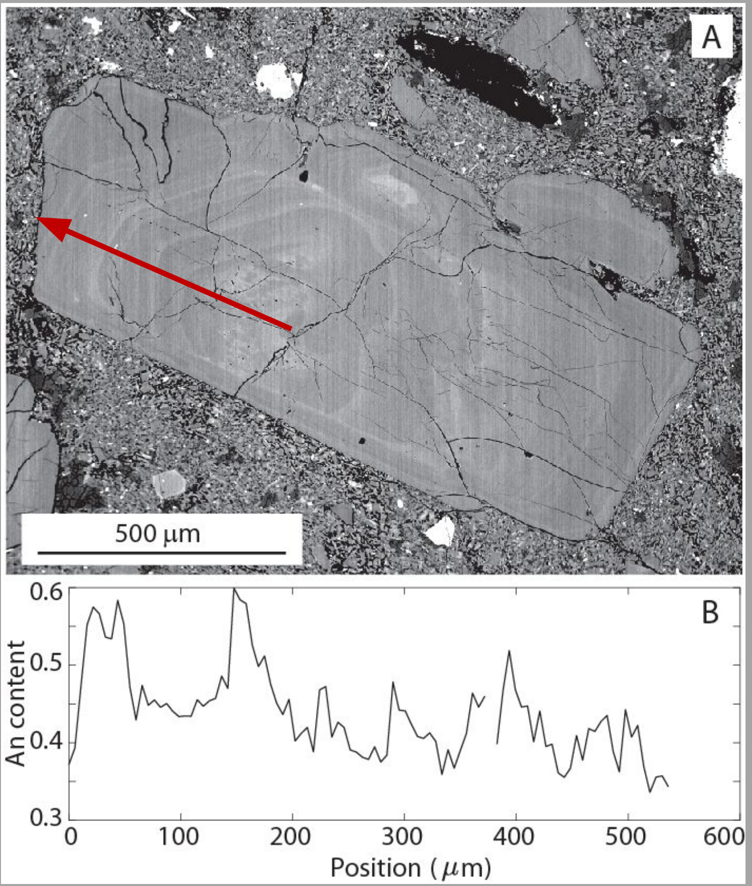
Experiments form foundation of programs like MELTS

Gualda et al., 2012;
Ghiorso and Gualda, 2015

(Andrews and Gardner, 2007;
Andrews, 2021)

Equilibrium Experiments





Determine phase assemblage and compositions as f(P,T,f_{O2})

Experiments form foundation of programs like MELTS

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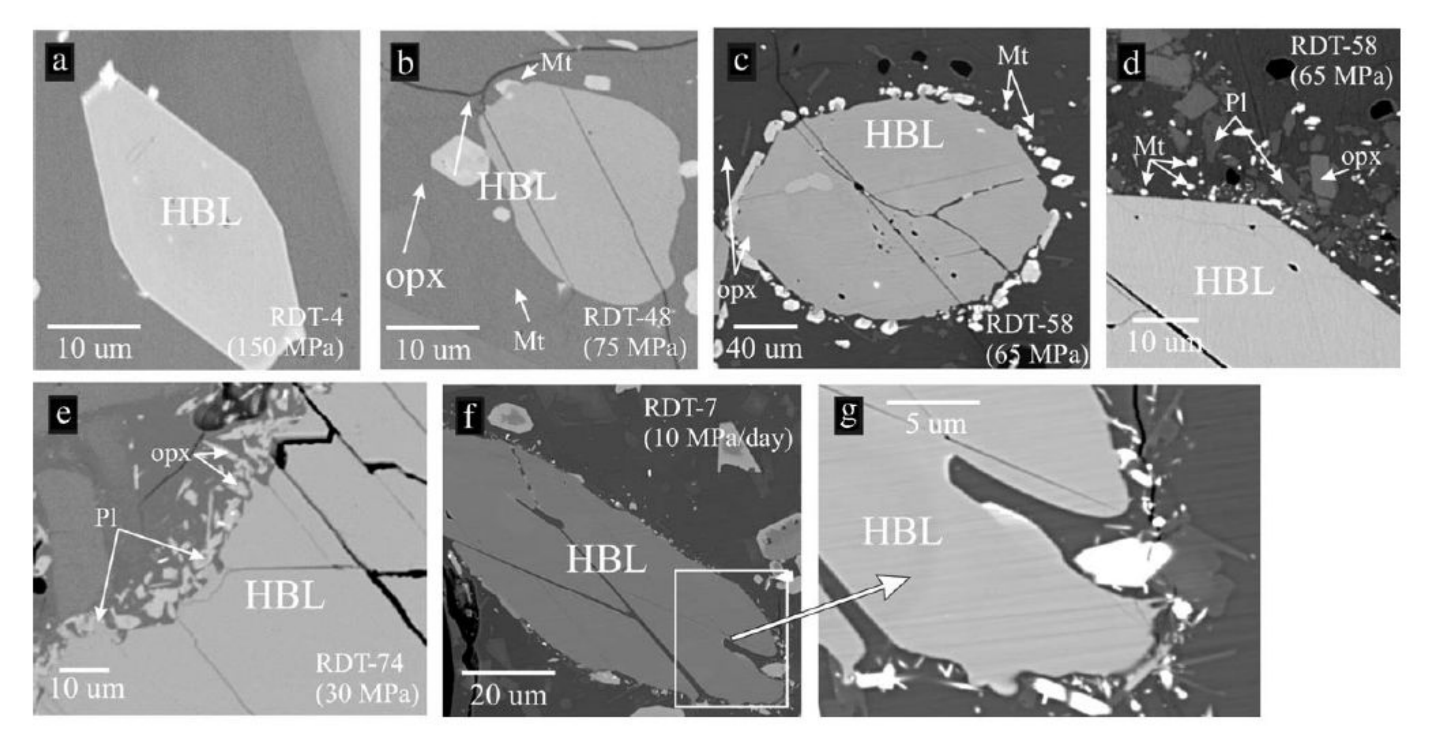
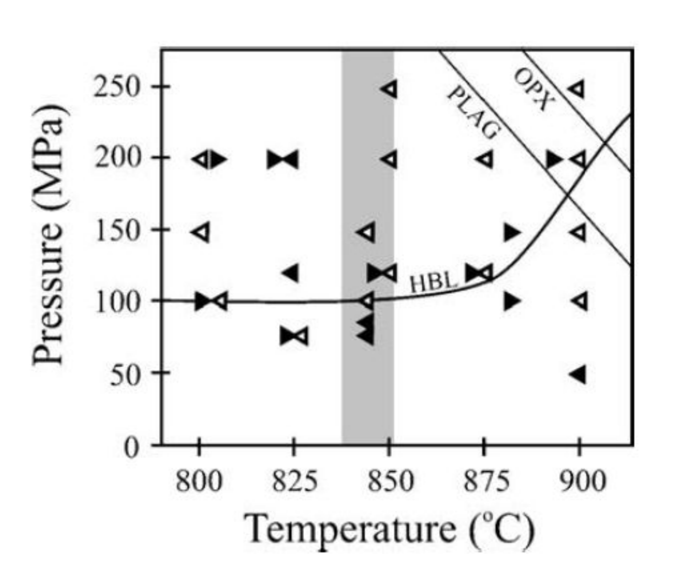
Thermodynamic equilibrium is an aspirational state.

Decompression experiments





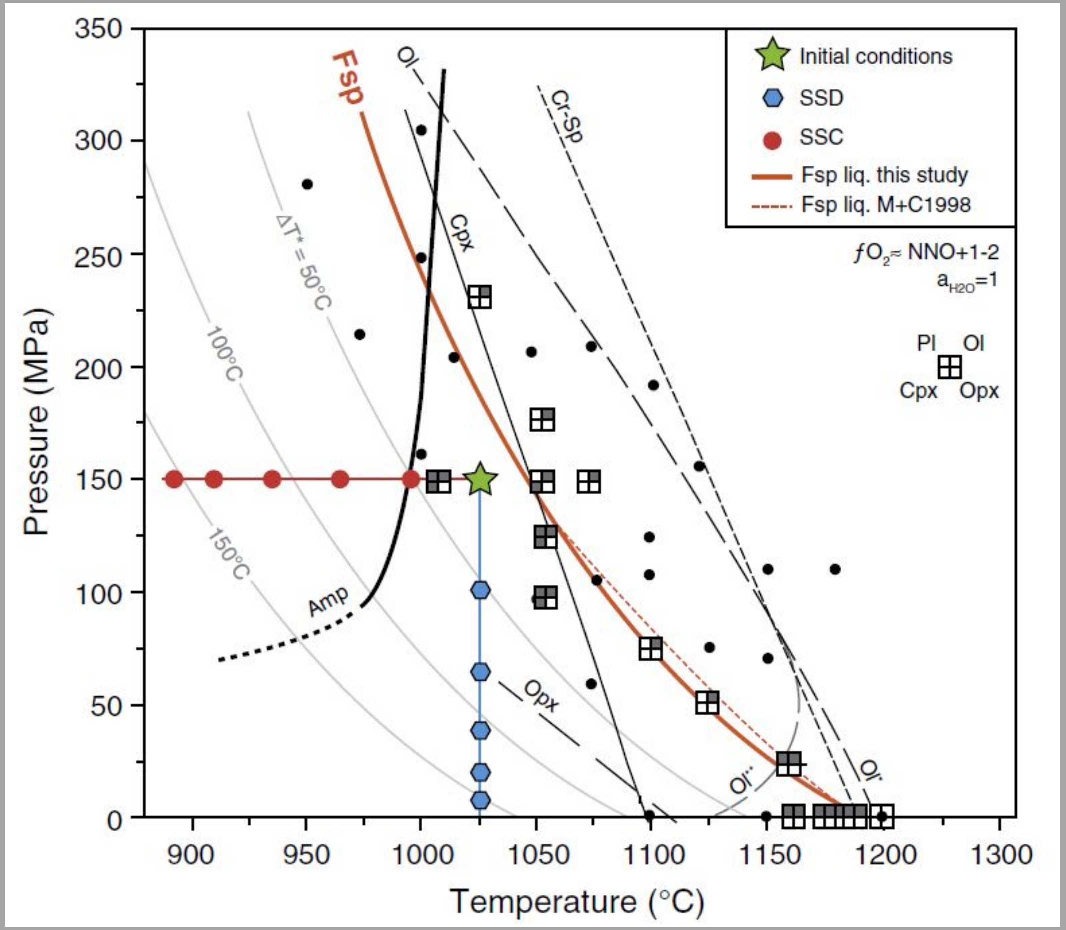
Redoubt 1989 Dacite
Amphibole breakdown
Browne and Gardner, 2006

Many rocks show disequilibrium textures.

Use experiments to determine the rates of processes.

Decompression experiments

1) Begin at some "EQB" state
2) Decompress the system
3) Quench at different times
4) Measure textural changes to obtain rates



Mascota Basaltic Andesite
Shea and Hammer, 2013

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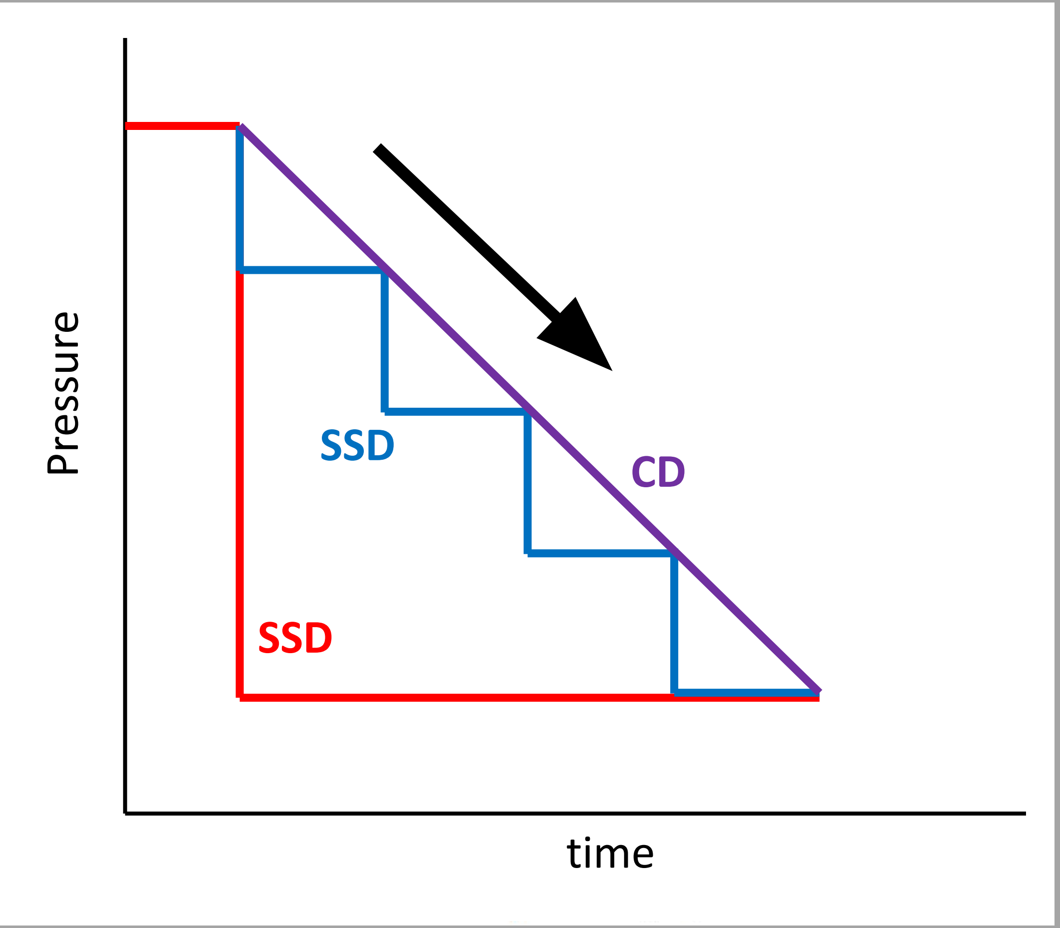

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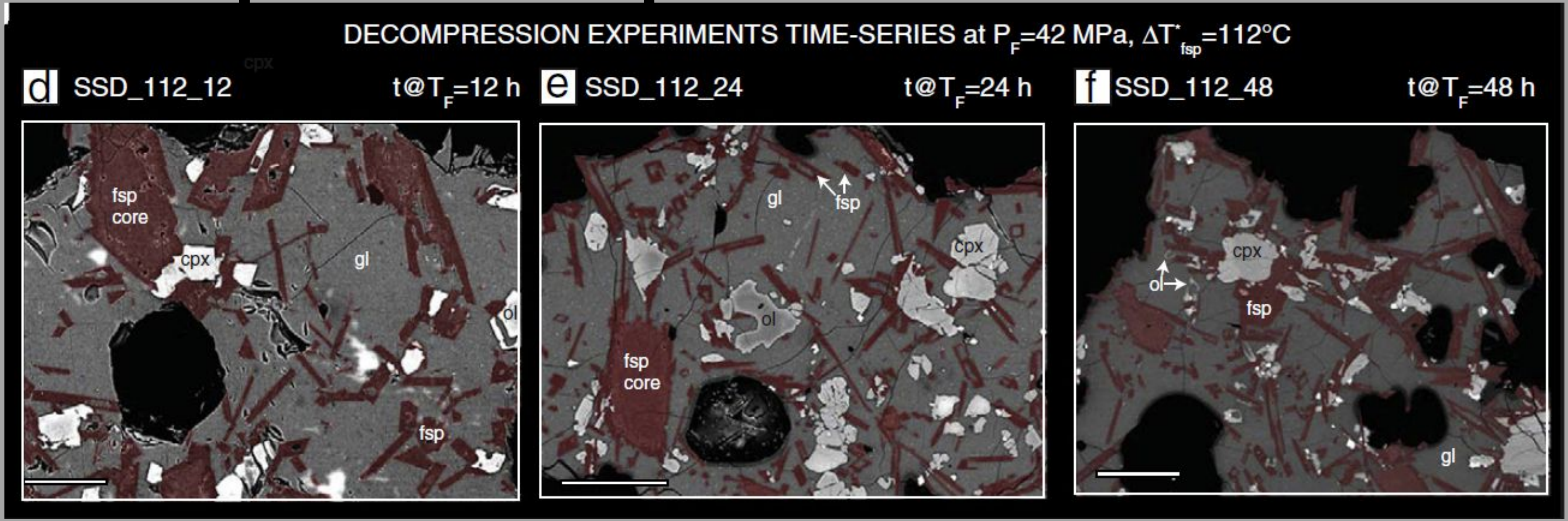

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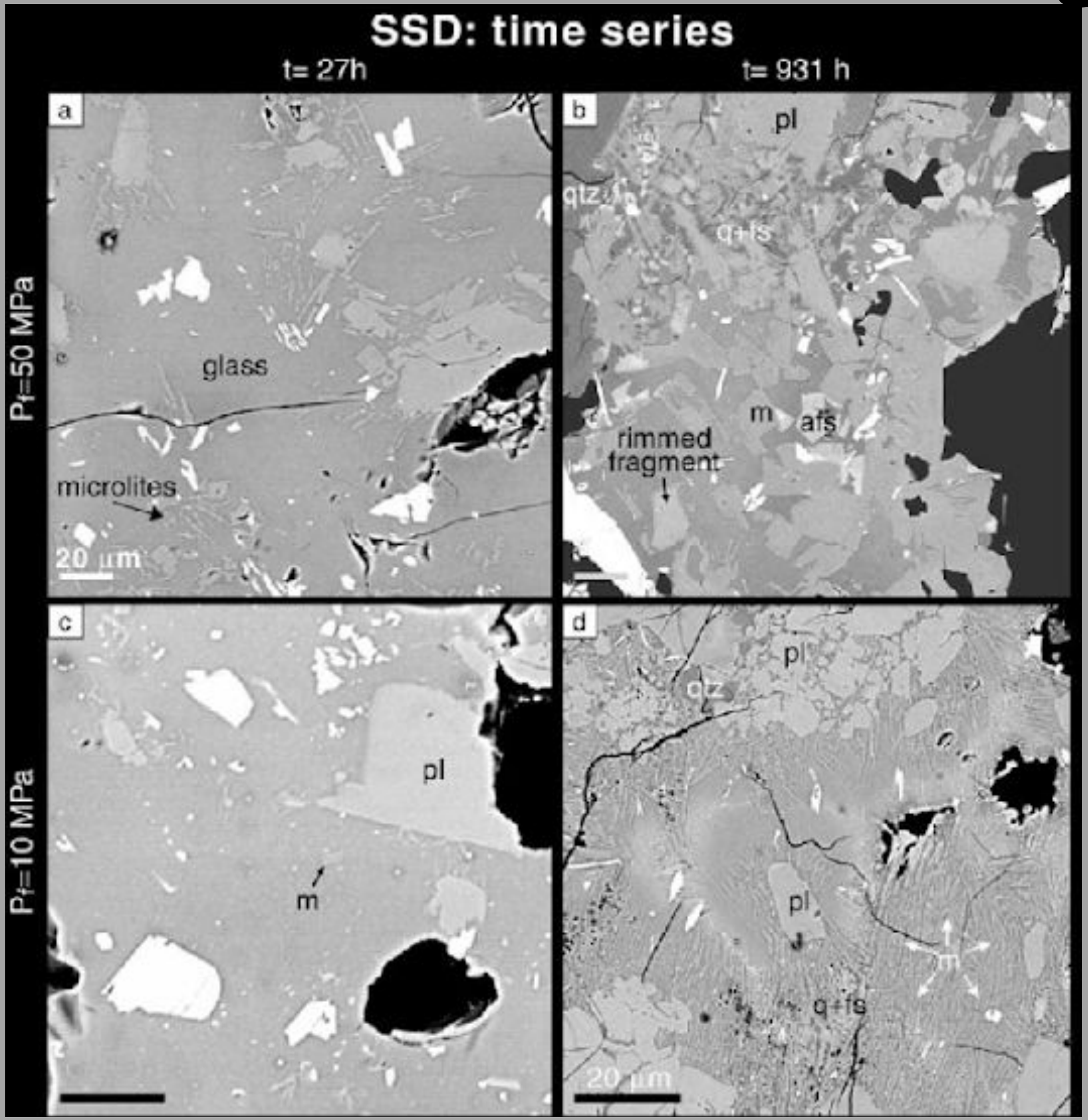
Measure textural changes to obtain rates



Changes with time in:

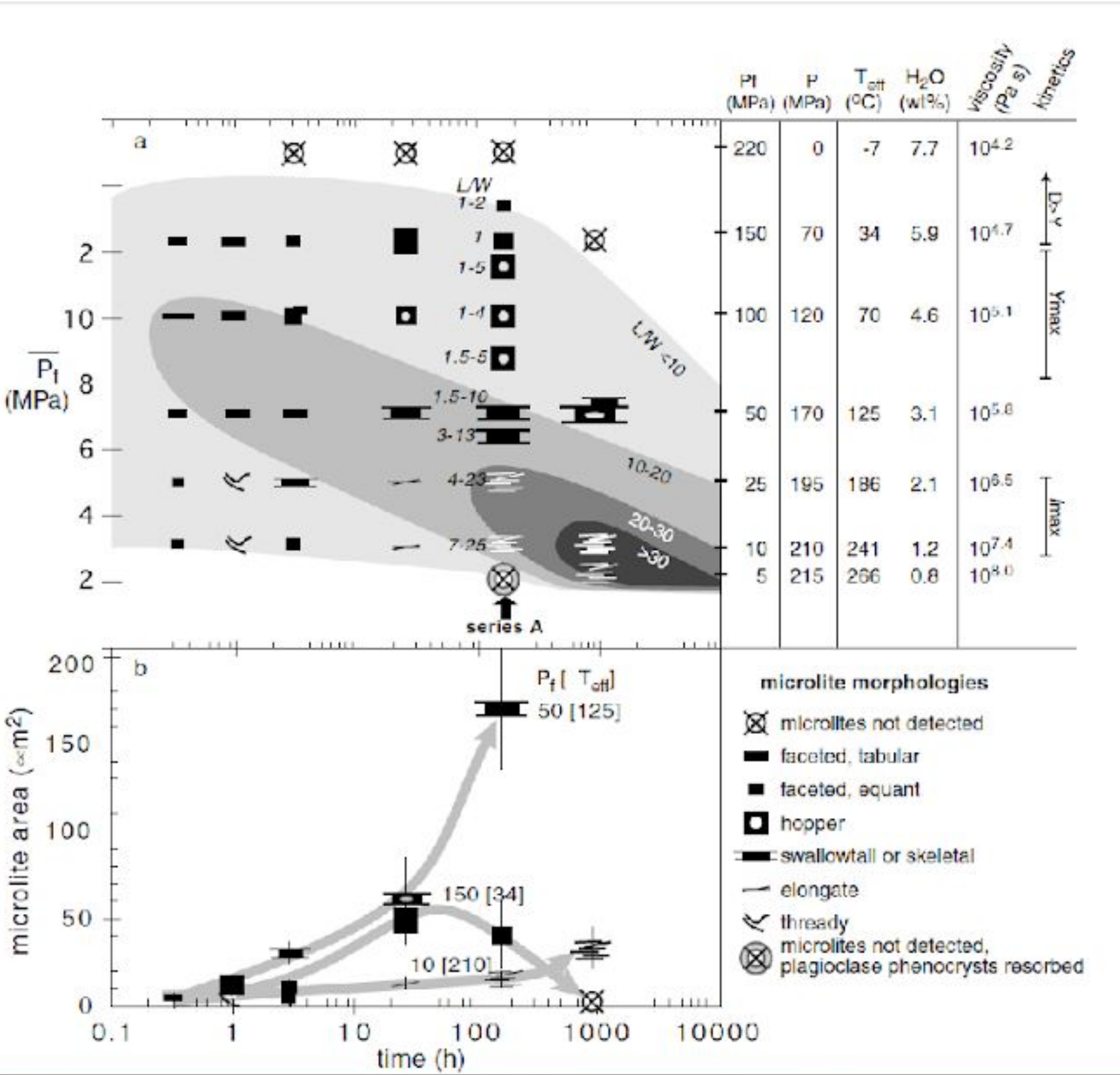
Numbers Nucleation

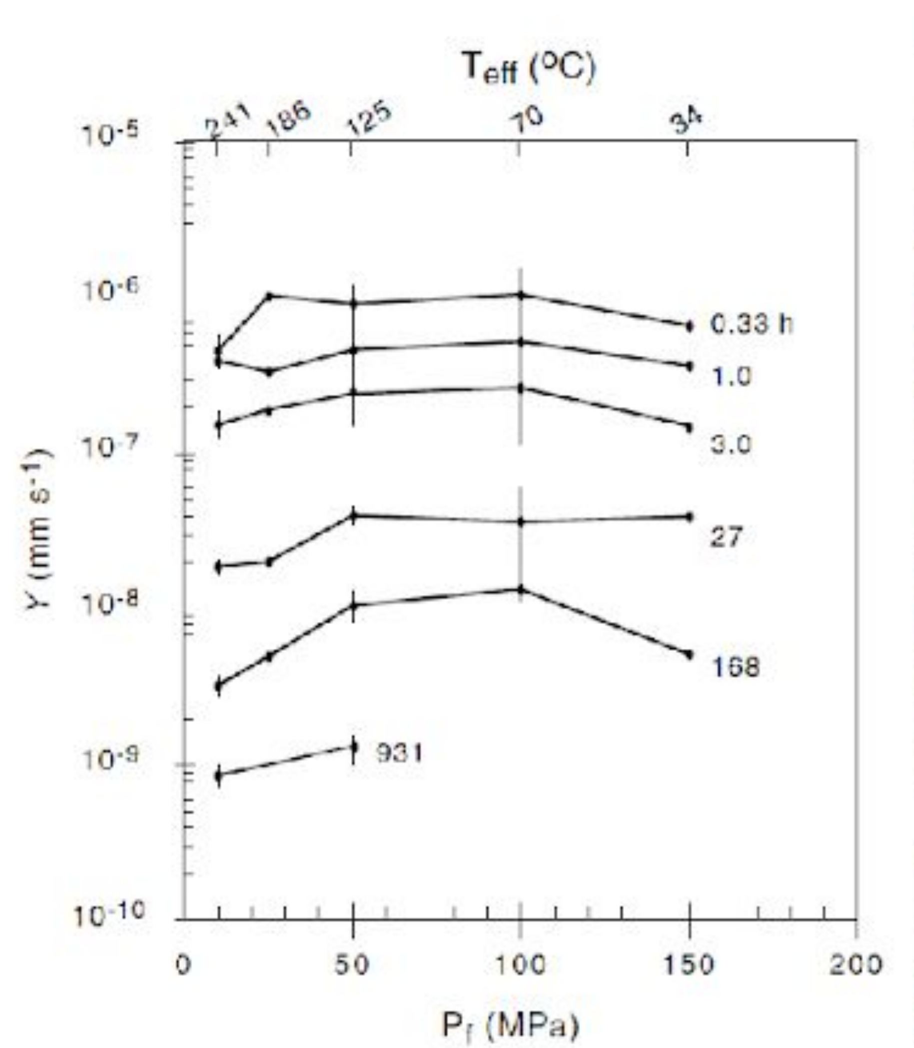
Sizes Growth

Composition

Crystal habit

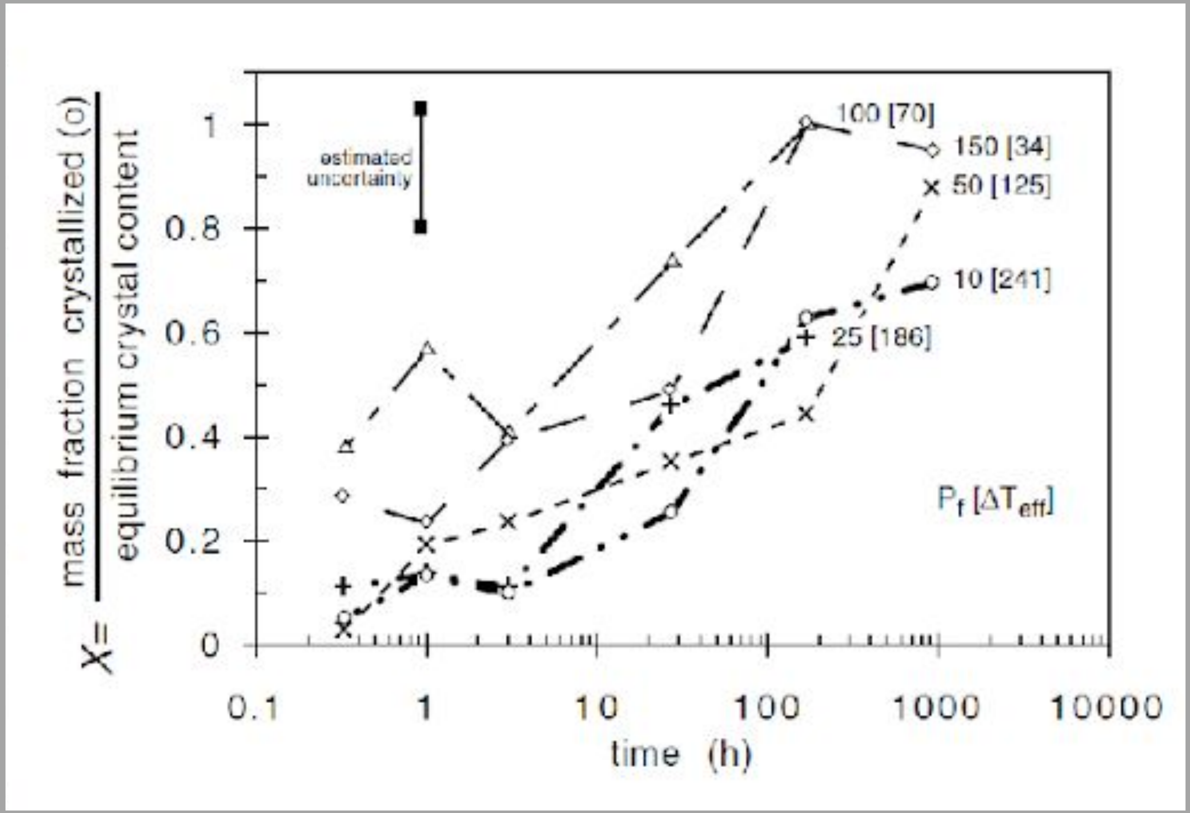
Hammer and Rutherford, 2002; Figure 5

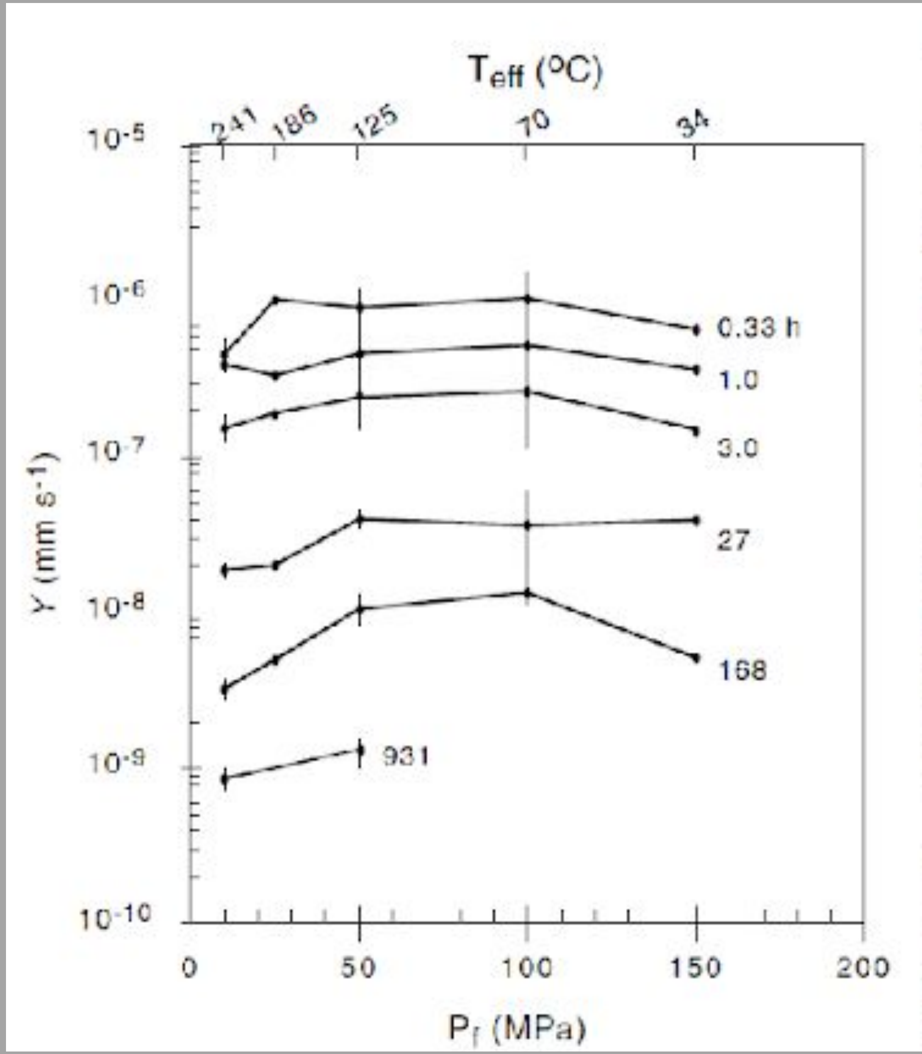




Hammer and Rutherford, 2002;
Figure 12 and 13

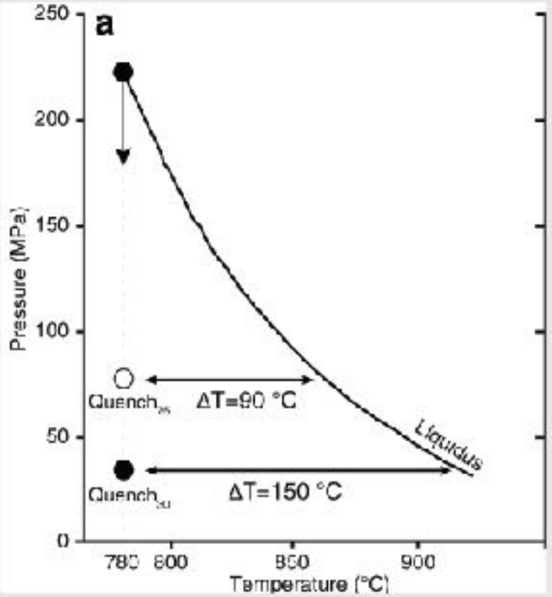
Time-averaged rates slow with time…





Hammer and Rutherford, 2002;
Figures 9 and 13

Supersaturation controls Nucleation and Growth Rates

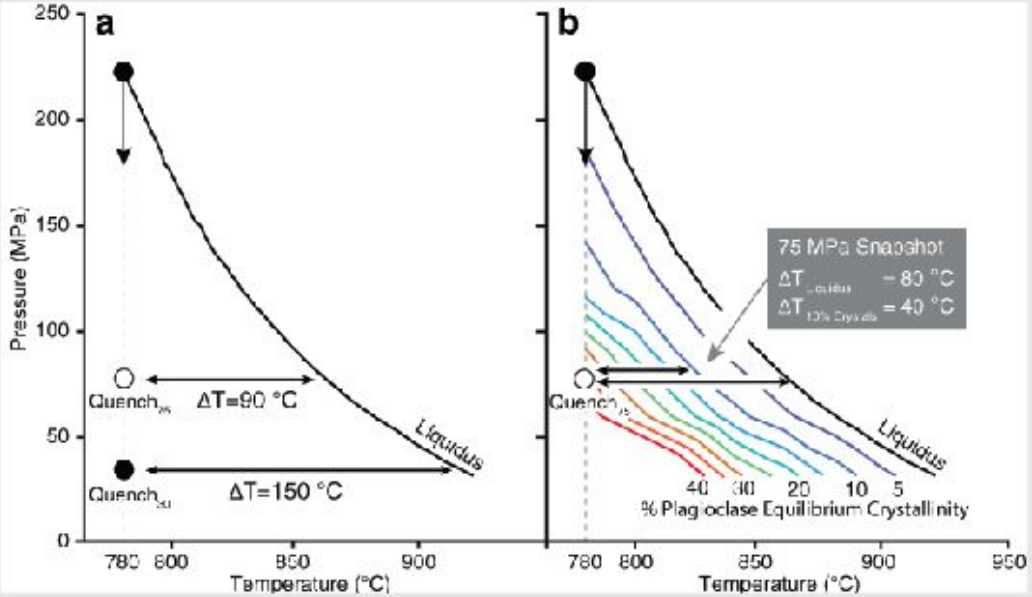


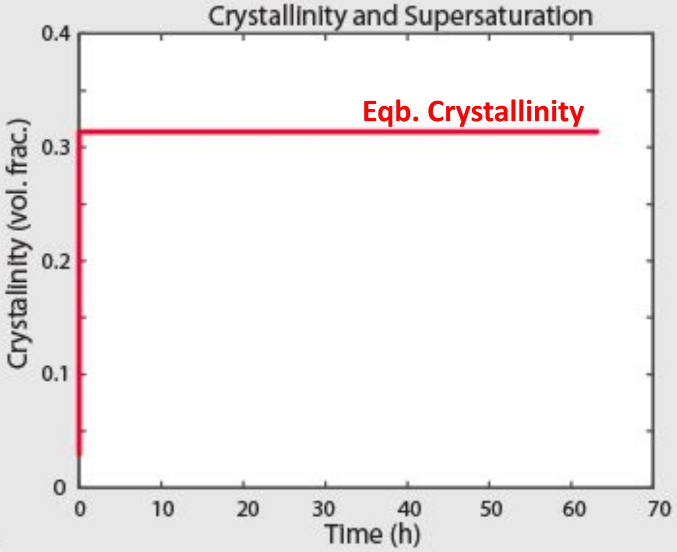
- Amount of disequilibrium commonly quantified as "Undercooling" (ΔT)
- Find Nuc./Growth rates as f(ΔT) through experiments
- ΔT is not constant, but evolves in response to crystallization, thus *effective* ΔT is often used
- ΔT cannot be directly measured

Hammer and Rutherford, 2002; Befus and Andrews, 2018

Hammer and Rutherford, 2002

Supersaturation controls Nucleation and Growth Rates

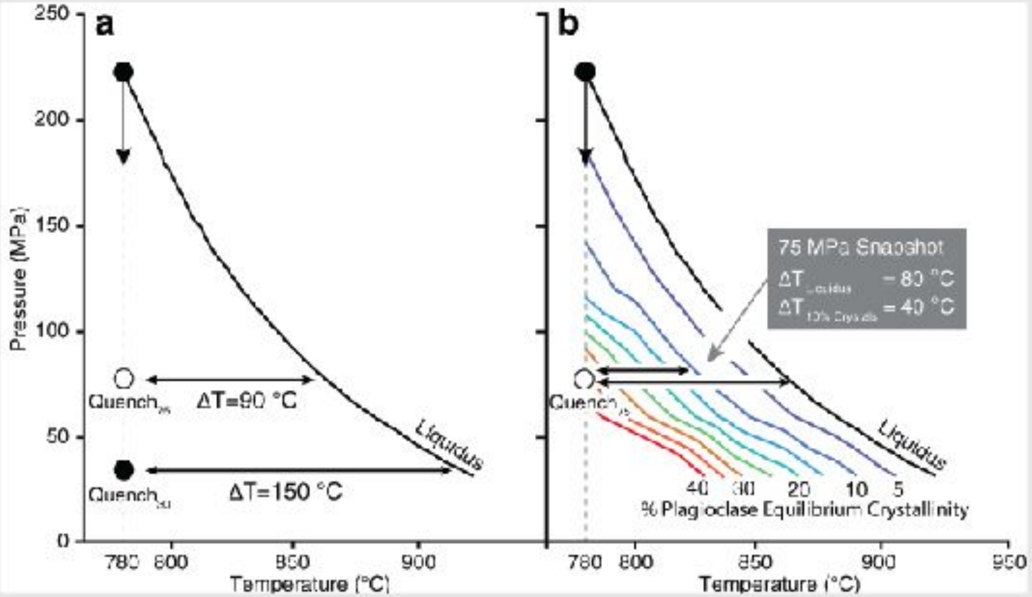


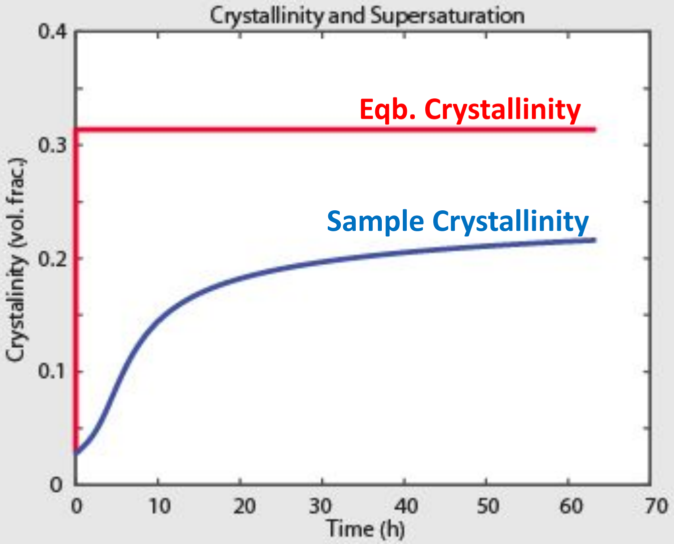


- Equilibrium crystallinity can be calculated (from experiments or MELTS)

Befus and Andrews, 2018

Supersaturation controls Nucleation and Growth Rates

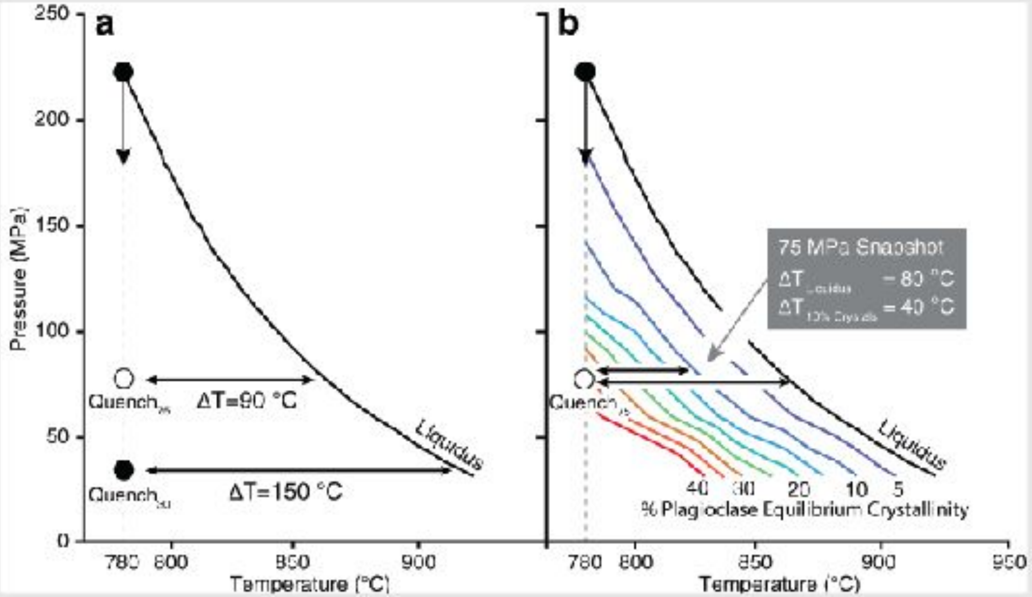


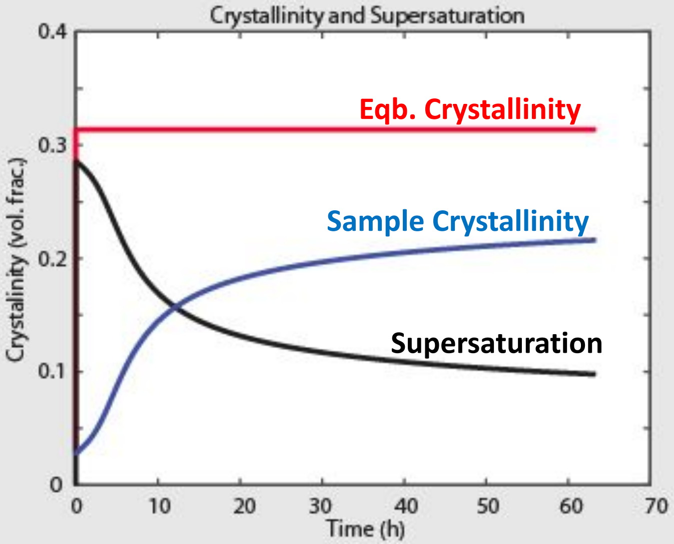


- Equilibrium crystallinity can be calculated (from experiments or MELTS)
- Sample crystallinity (φ) can be measured

Befus and Andrews, 2018

Supersaturation controls Nucleation and Growth Rates

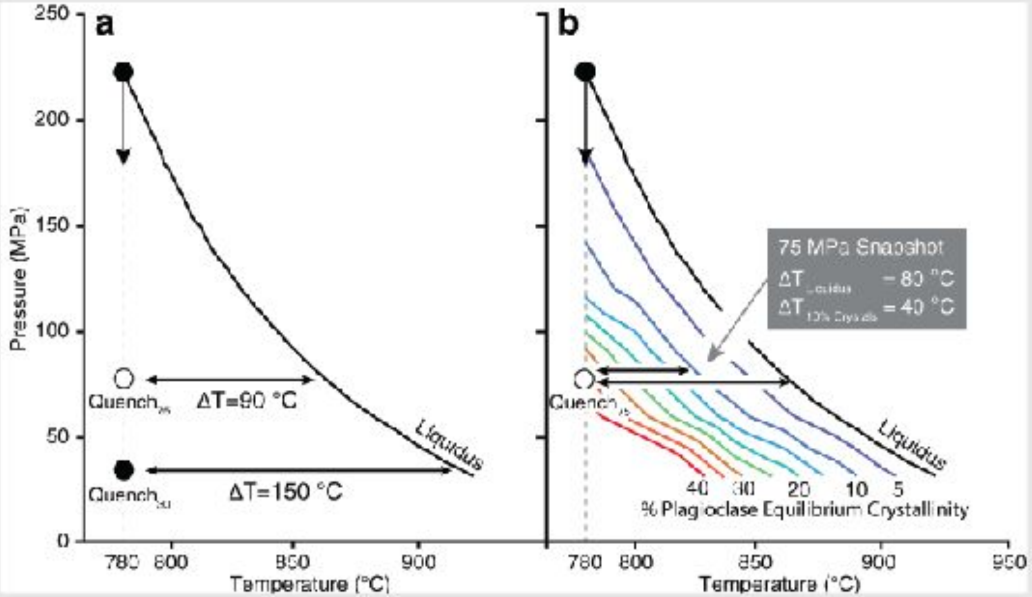


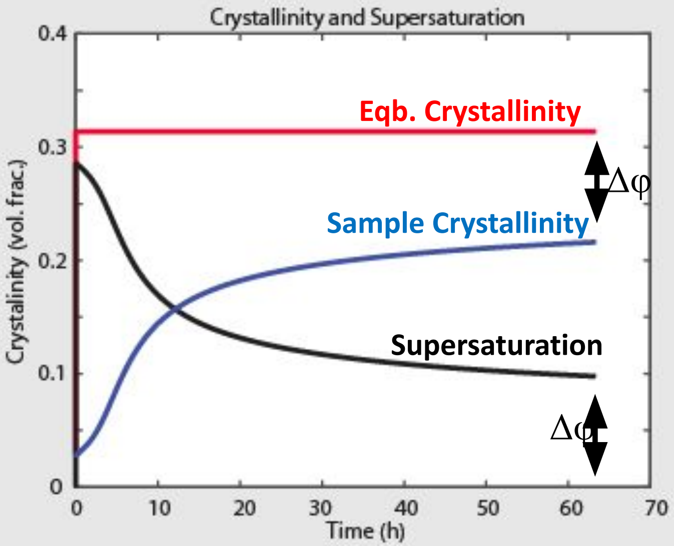


- Equilibrium crystallinity can be calculated
- Sample crystallinity (φ) can be measured
- Supersaturation (Δφ) can thus be quantified

Brugger and Hammer, 2010; Riker et al., 2015; Befus and Andrews, 2018

Supersaturation controls Nucleation and Growth Rates





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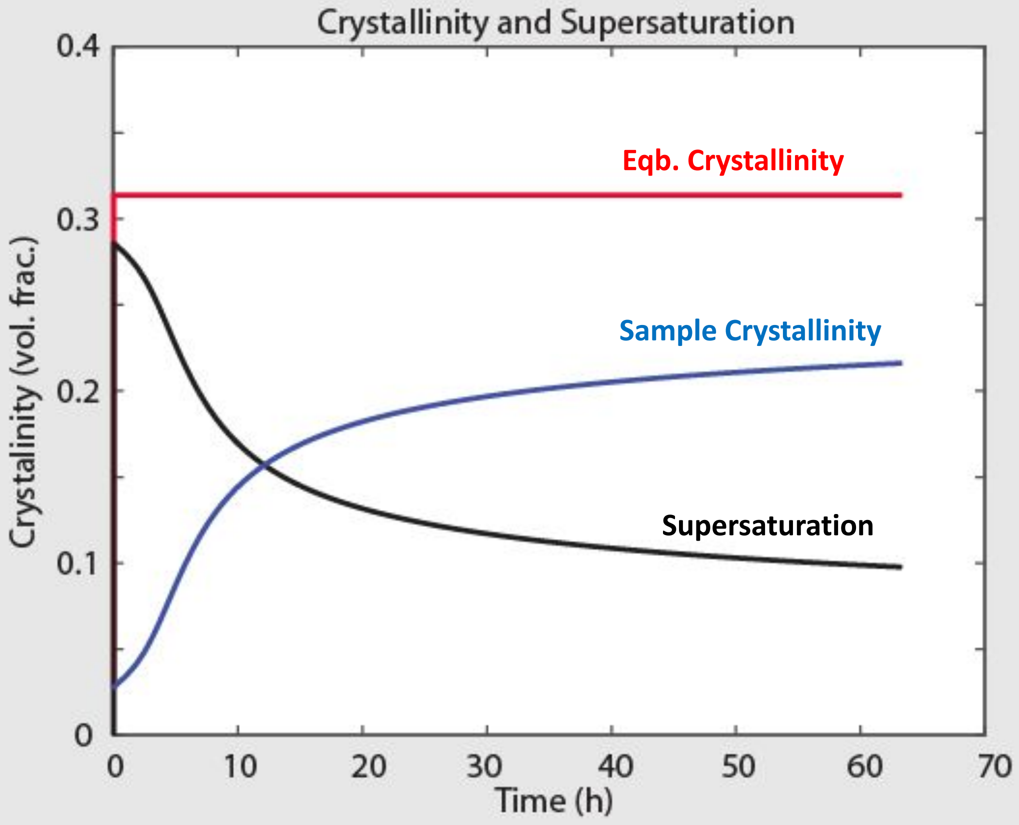
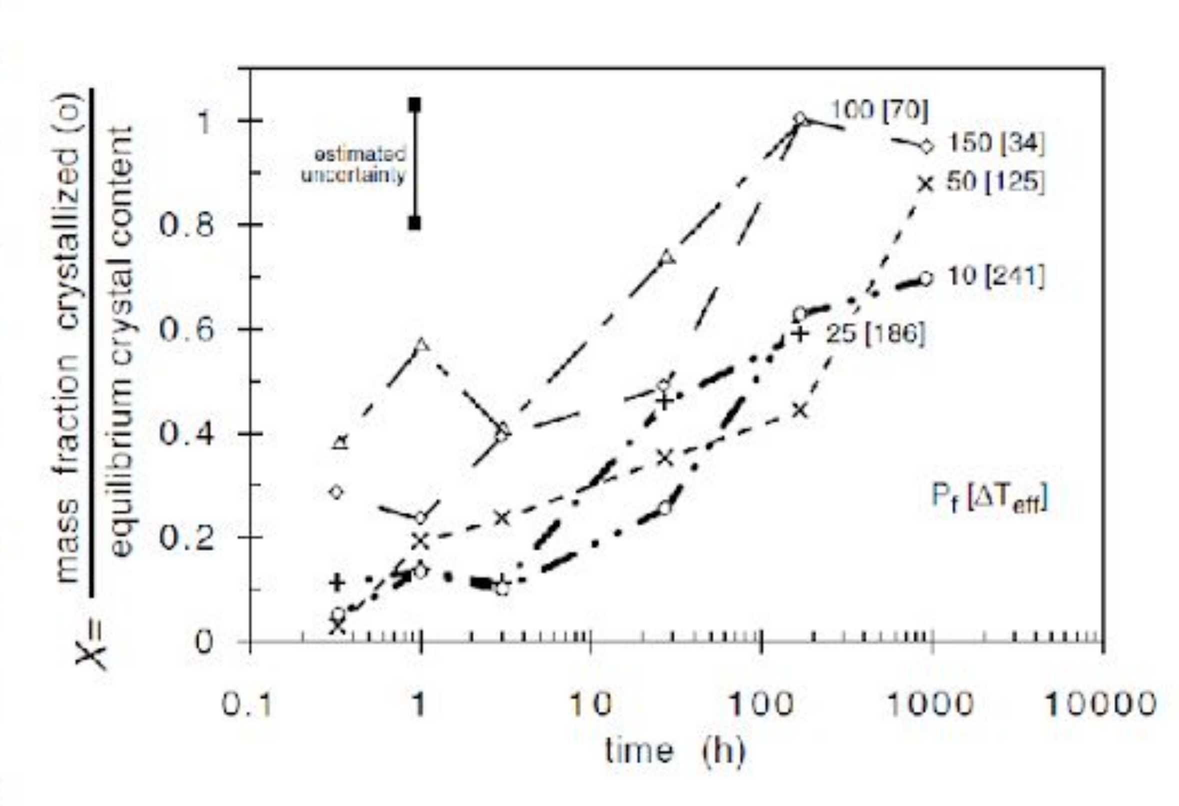
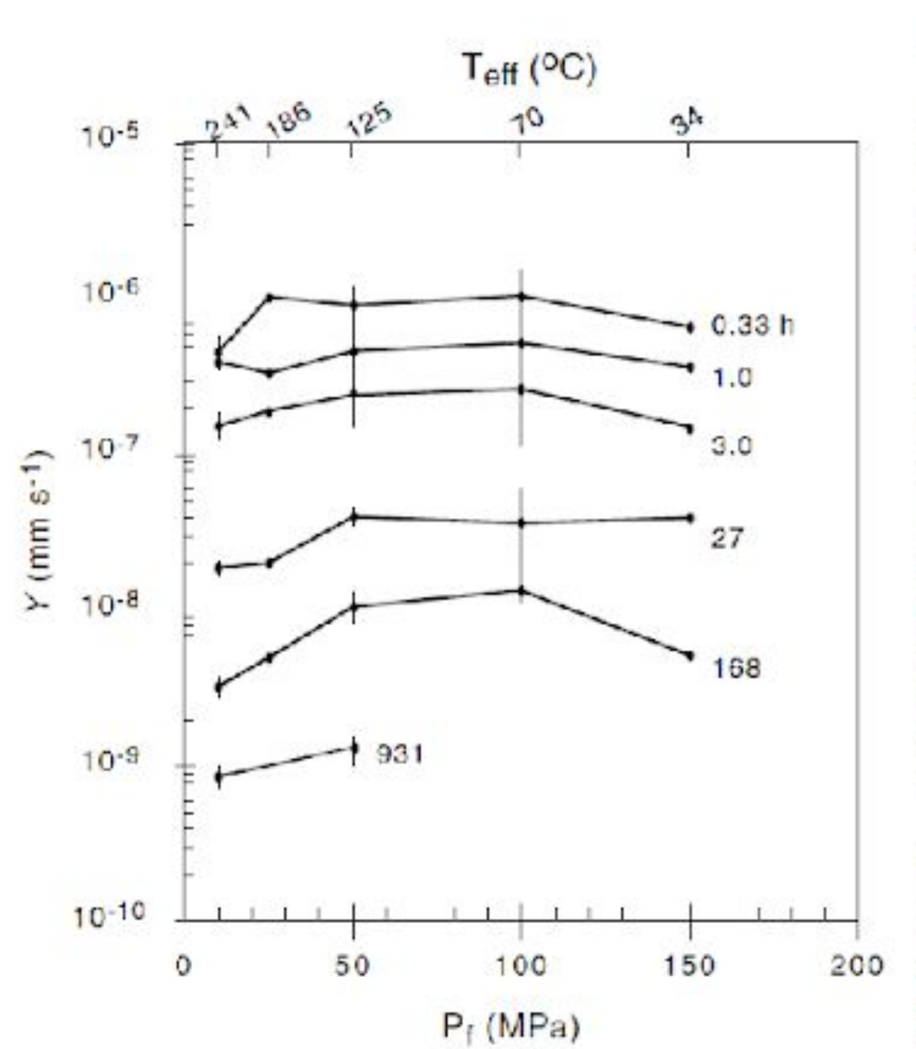
Crystallization changes amount of Supersaturation



- Supersaturation (Δφ) evolves through time
- Nucleation and Growth rates assuming constant values of ΔT do not account for crystallization and thus reduction in Δφ

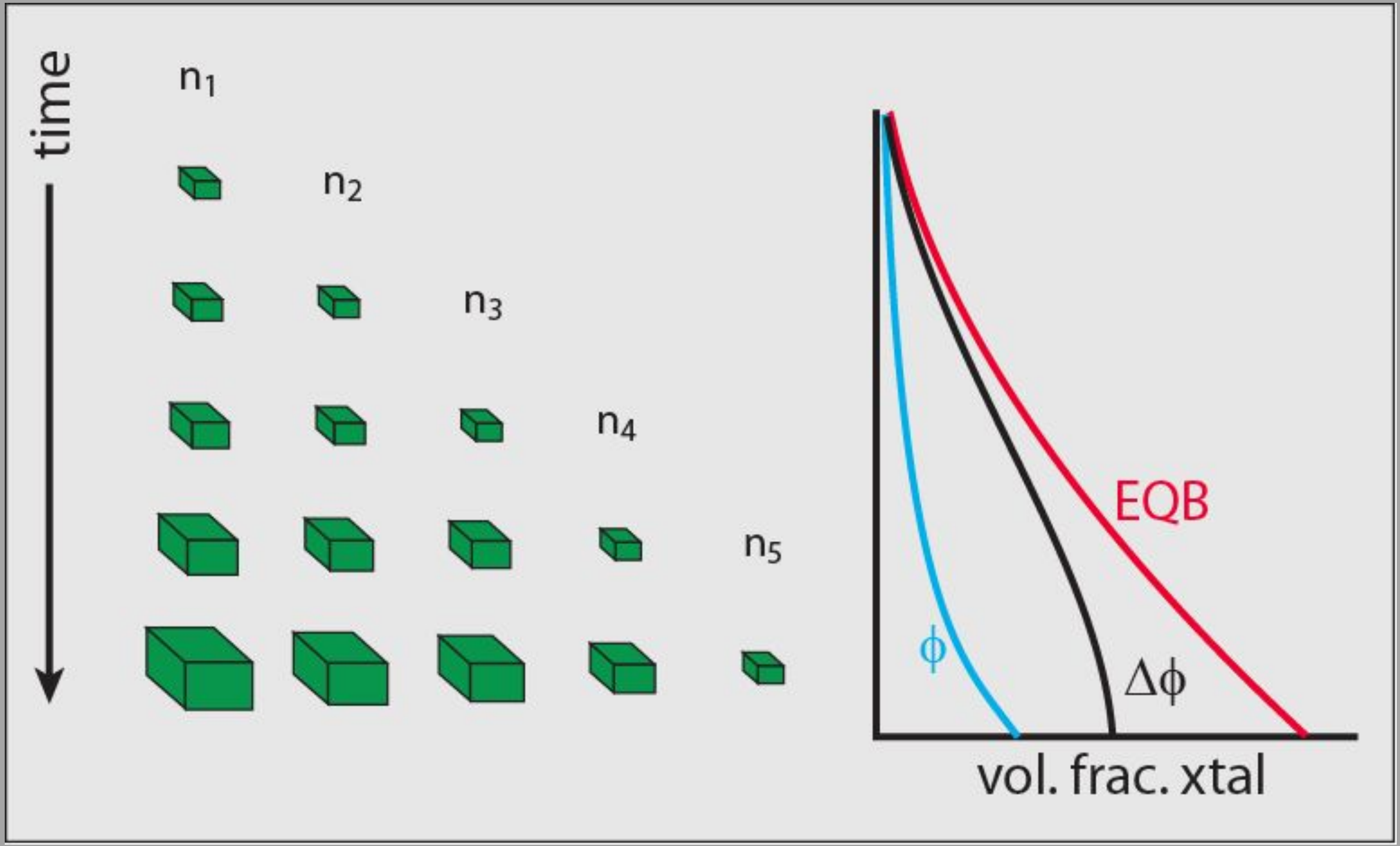
Crystallization changes with amount of Supersaturation





Hammer and Rutherford, 2002;
Figures 9 and 13

Quantifying crystallization rates



Andrews and Befus, 2020; Andrews, 2021; Marshall and Andrews, 2023

Magmas crystallize (or dissolve) in response to thermodynamic disequilibrium (Δφ)

Crystallization is the sum of the product of crystal numbers (n1, n2, n3, …) with corresponding volumes (V1, V2, V3, …)

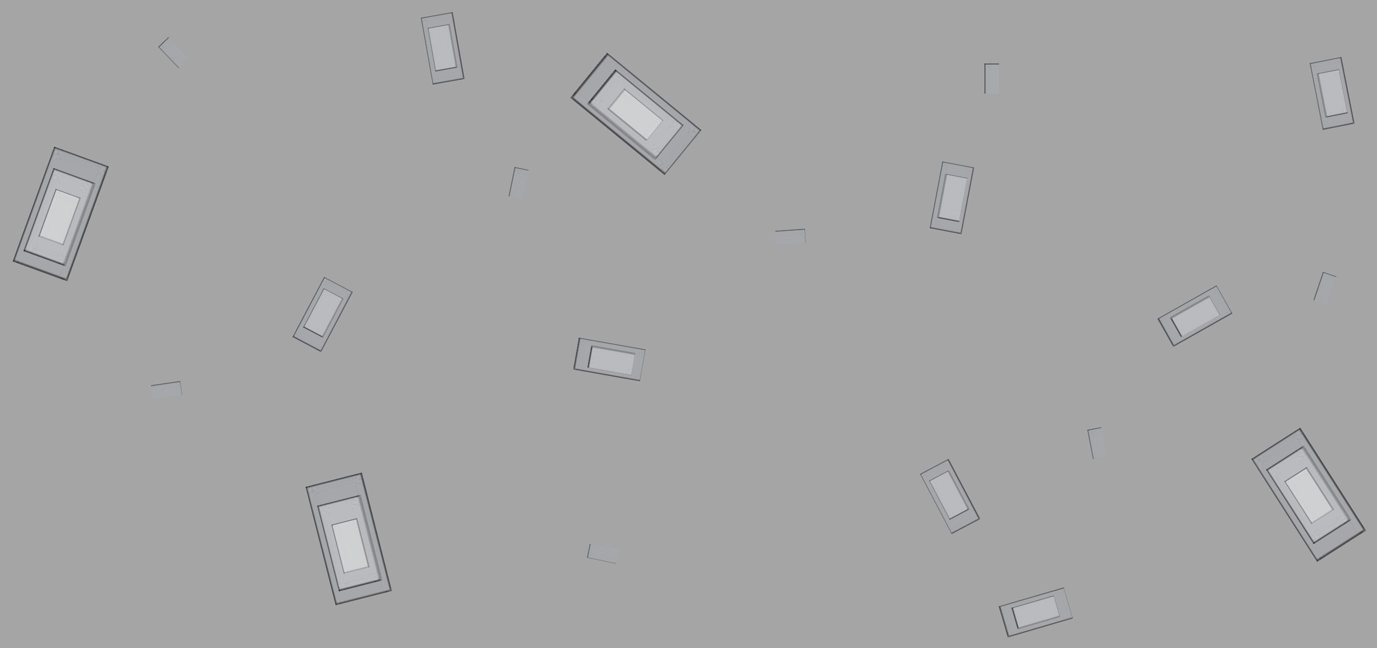
Crystallization rate at any moment is a function of the instantaneous growth rate and the crystal population (CSD) *at that moment*

Nucleation and Growth Rates

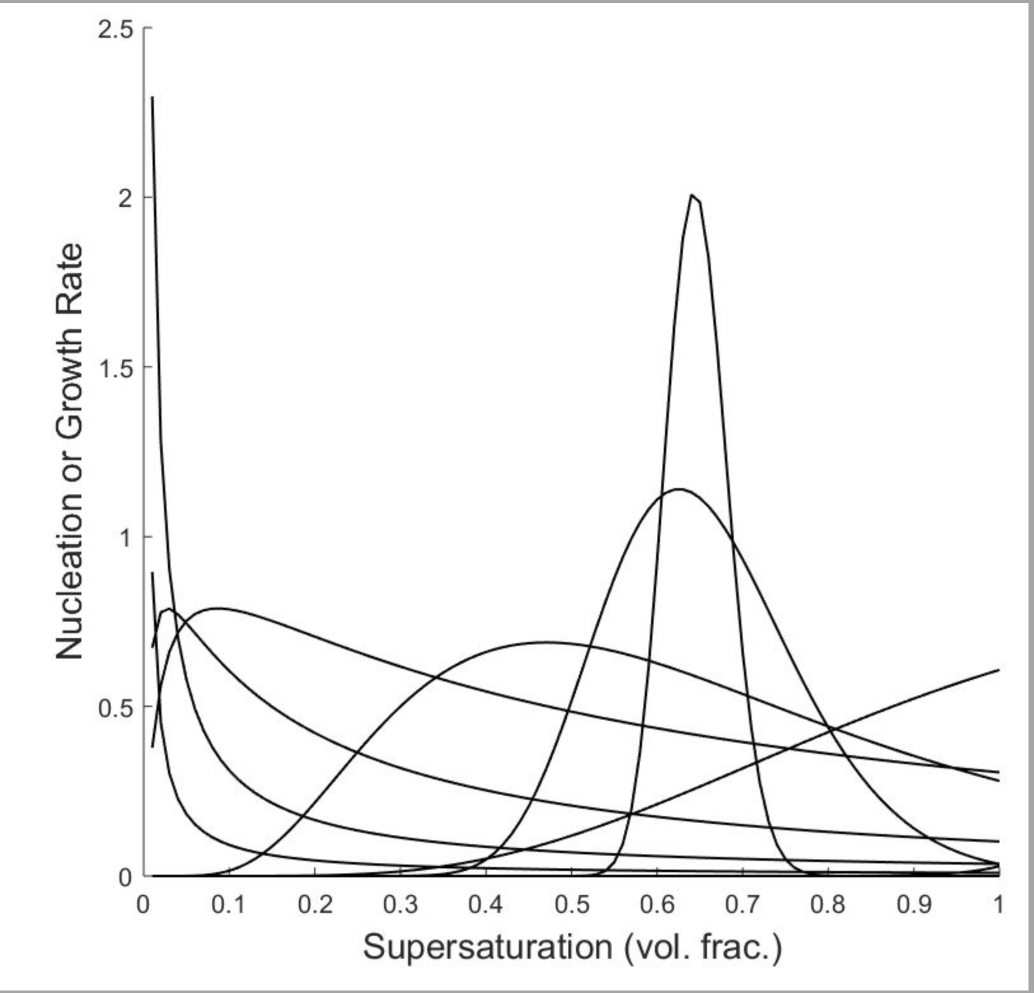
Crystallinity φ is $\sum N_i V_i \big/ V_{sys}$ □function of rates

How fast do new crystals appear?

How fast do existing crystals grow?



Quantifying crystallization rates



Befus and Andrews, 2018; Andrews and Befus, 2020; Marshall and Andrews, 2023

The shape of Nucleation and Growth rate functions is not specified *a priori*

Rates can be described with log-normal functions

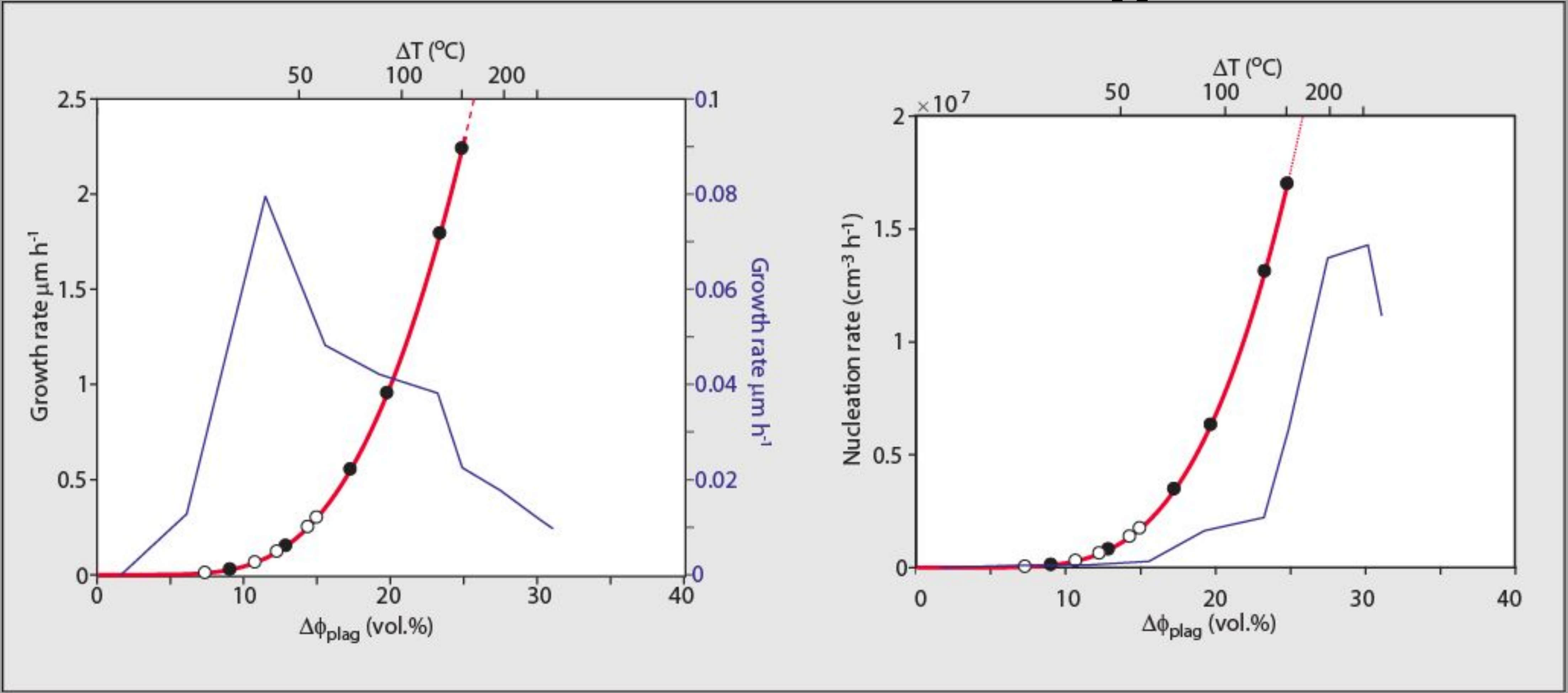
$$Rate(x) = \frac{k}{x\sqrt{2\pi}} exp^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$$

$$x = b\ exp^1 \Delta\phi_{plag}$$

Monte Carlo search of parameters μ, σ, b, and k; N=200,000

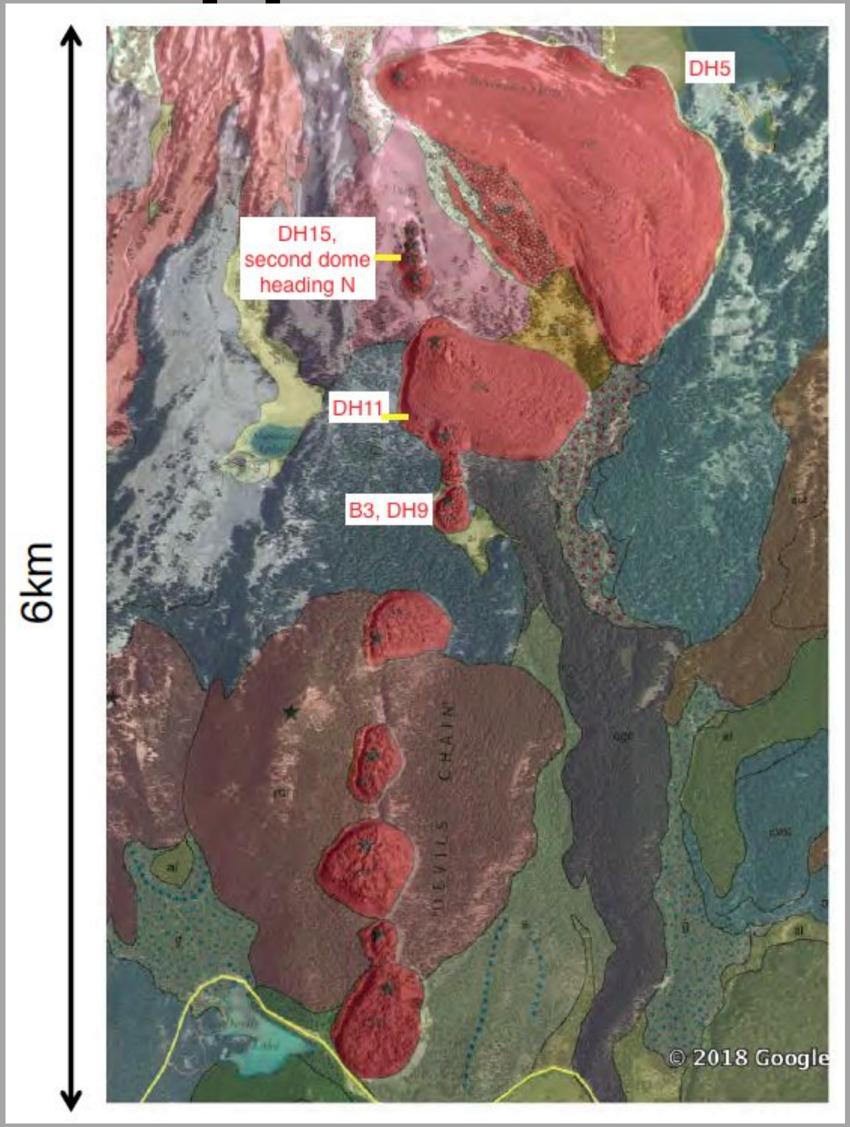
Find functional forms that best fit observed (experimental) crystal sizes, number densities, and final crystallinities

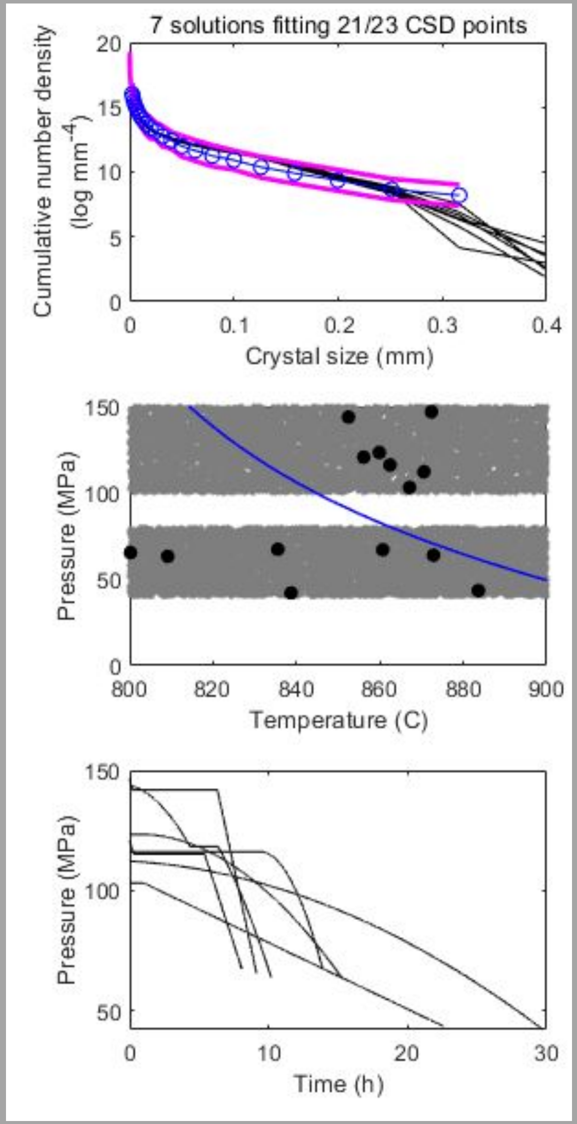
Pinatubo dacite nucleation and growth rates



Hammer and Rutherford, 2002
Befus and Andrews, 2018

Application of Pinatubo rates to South Sister





Initial Pressures (P_i):

103 – 146 MPa

Final Pressures (P_f):

42 – 67 MPa

- Agree with petrologic estimates

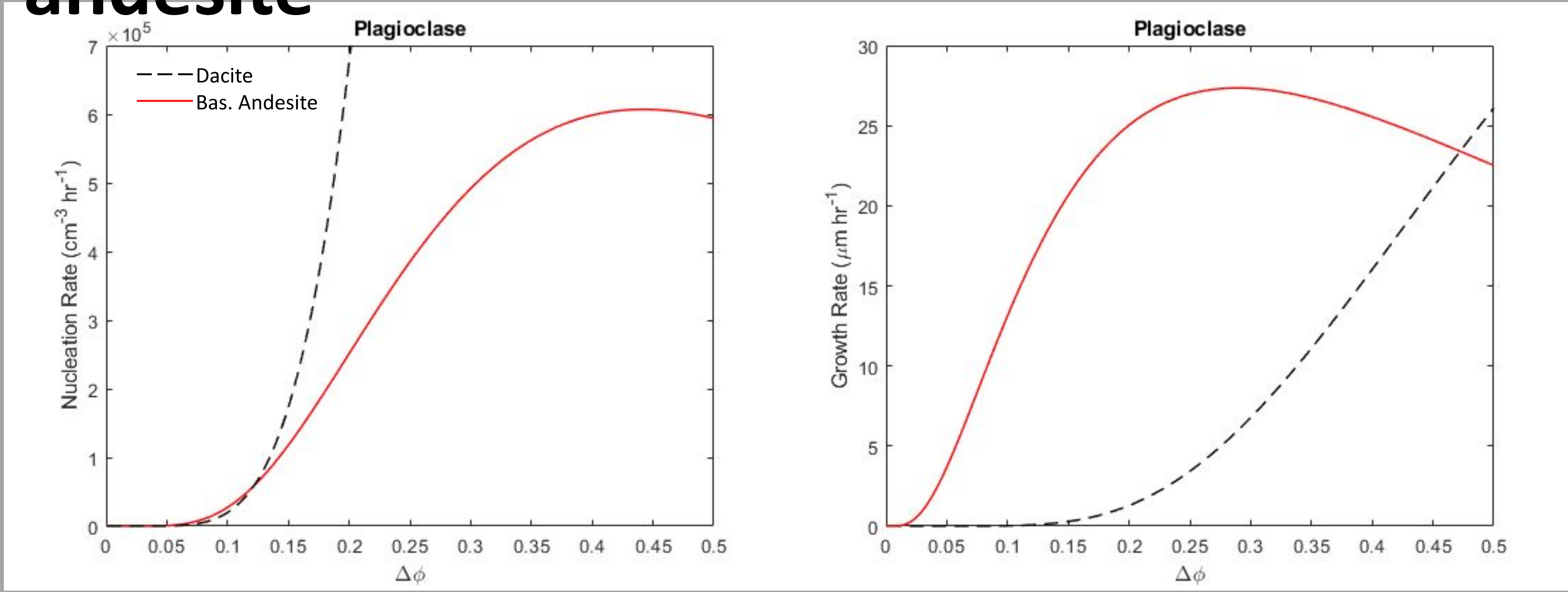
Average decompression rates:

2.3 – 9 MPa/h

Total times (to P_f): 8 – 30 h

- Extrapolating to surface (0.1 MPa): 16 – 40 h

Plagioclase Rates in Mascota basaltic andesite

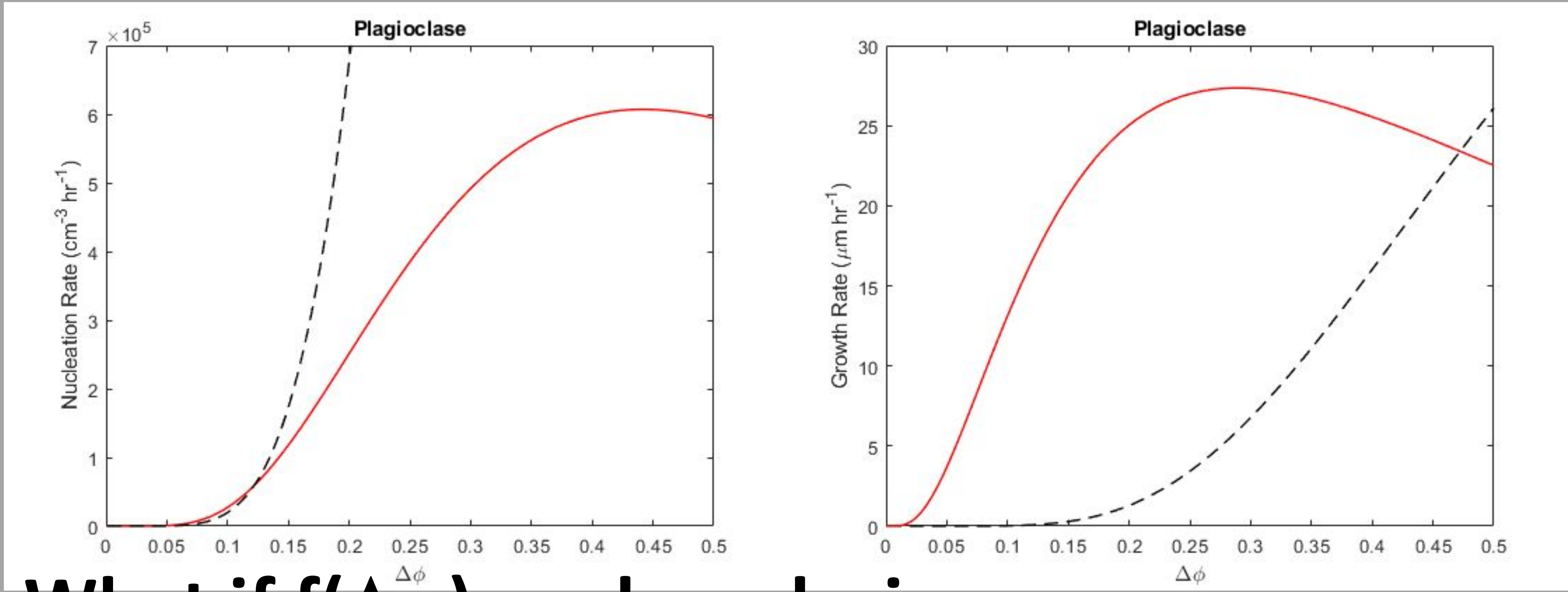


Nucleation rates are 10x lower in basaltic andesite…

…*Linear* Growth rates are >10x greater in basaltic andesite, *volumetric* rates are ~1000x faster

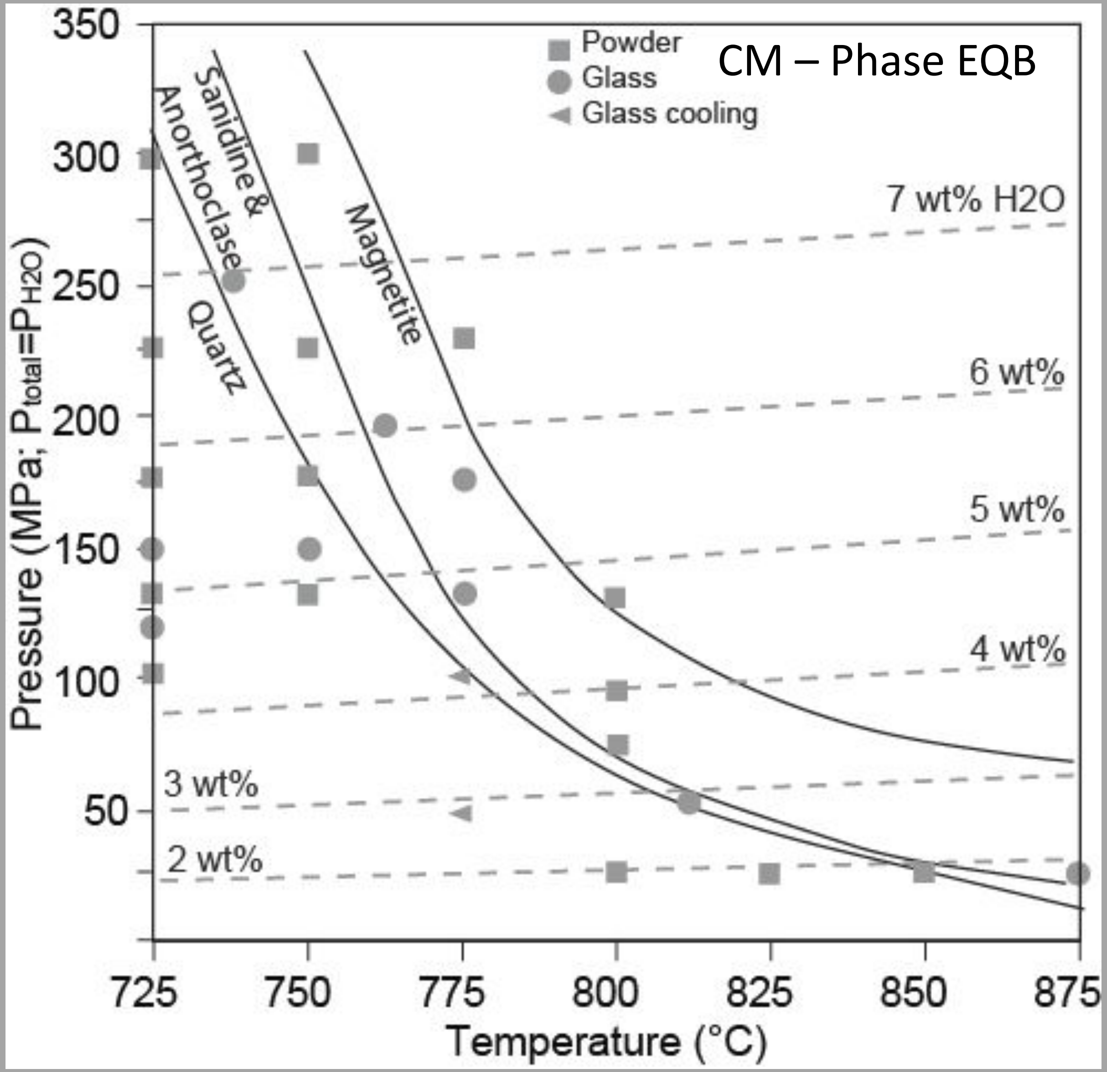
Shea and Hammer, 2013; Befus and Andrews, 2020; Marshall and Andrews, 2023

What if rates are not only a function of $\Delta\varphi$?



What if $f(\Delta\varphi)$ evolves during decompression?

Crystallization rates from experiments

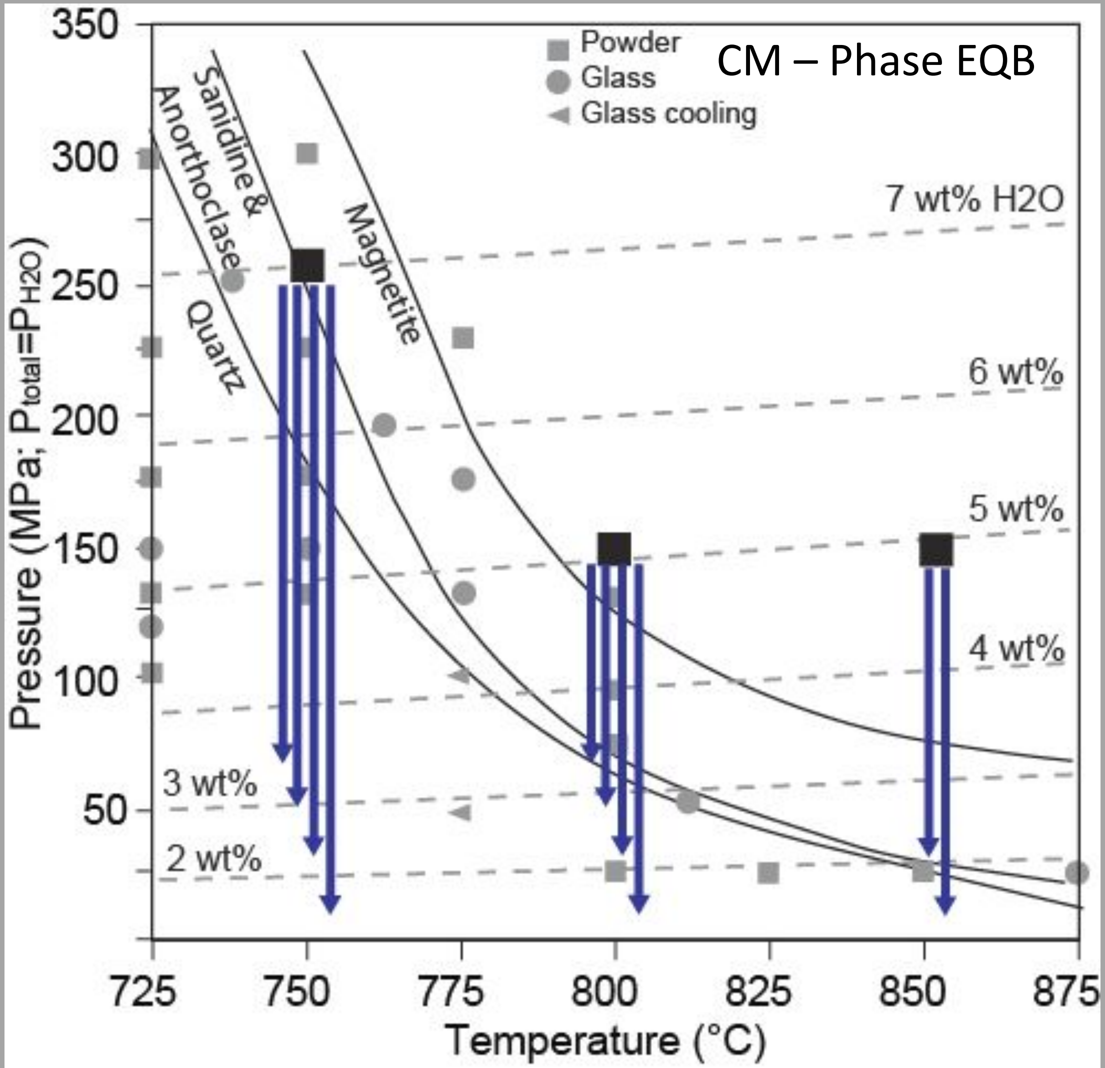


Decompression experiments in cold-seal Waspaloy Vessels ($log_{10}f_{O2}$ = NNO+1)

Crushed and annealed starting material:
Valles Caldera (NM) – Cerro Del Medio
South Sister (OR) – Devil's Chain

Magdalen Grismer's work! V34A-04, Wed. 1630
Phase EQB experiments at NMT, Decompressions at SI

Crystallization rates from experiments



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Single-step decompressions from P_i to P_f=[70, 50, 30, 10 MPa]

Hold times of 8-504 hours at each P_f

Bucket quench (cool below T_{glass} <30s)

Magdalen Grismer's work! V34A-04, Wed. 1630
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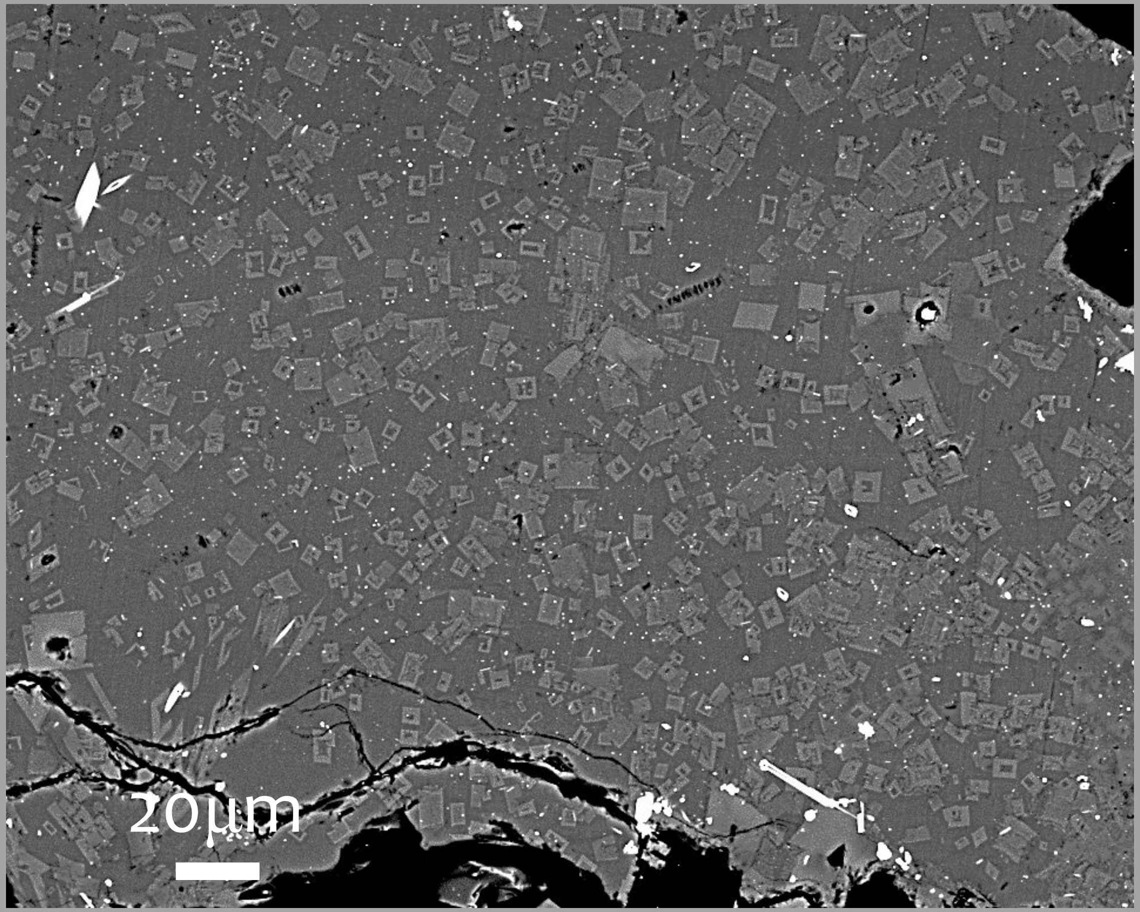
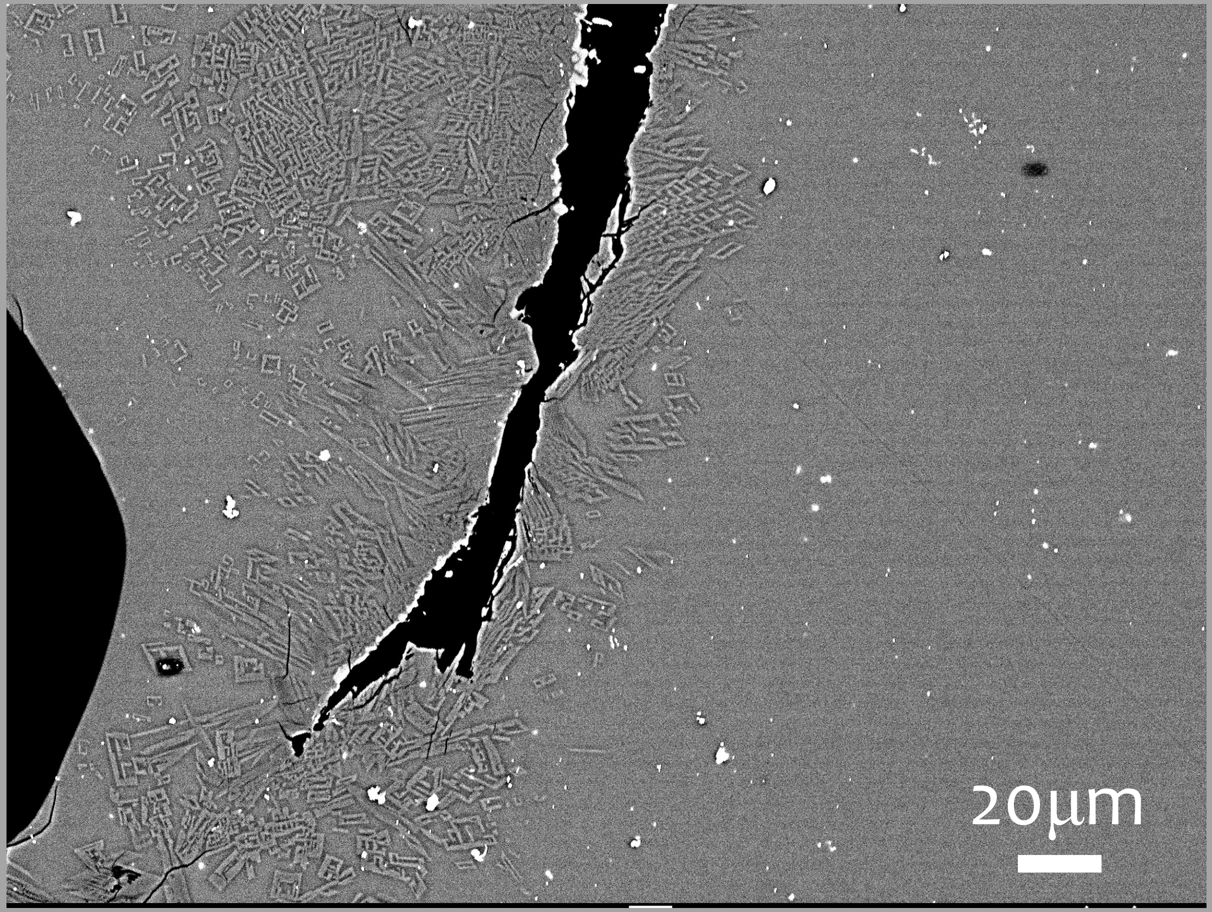
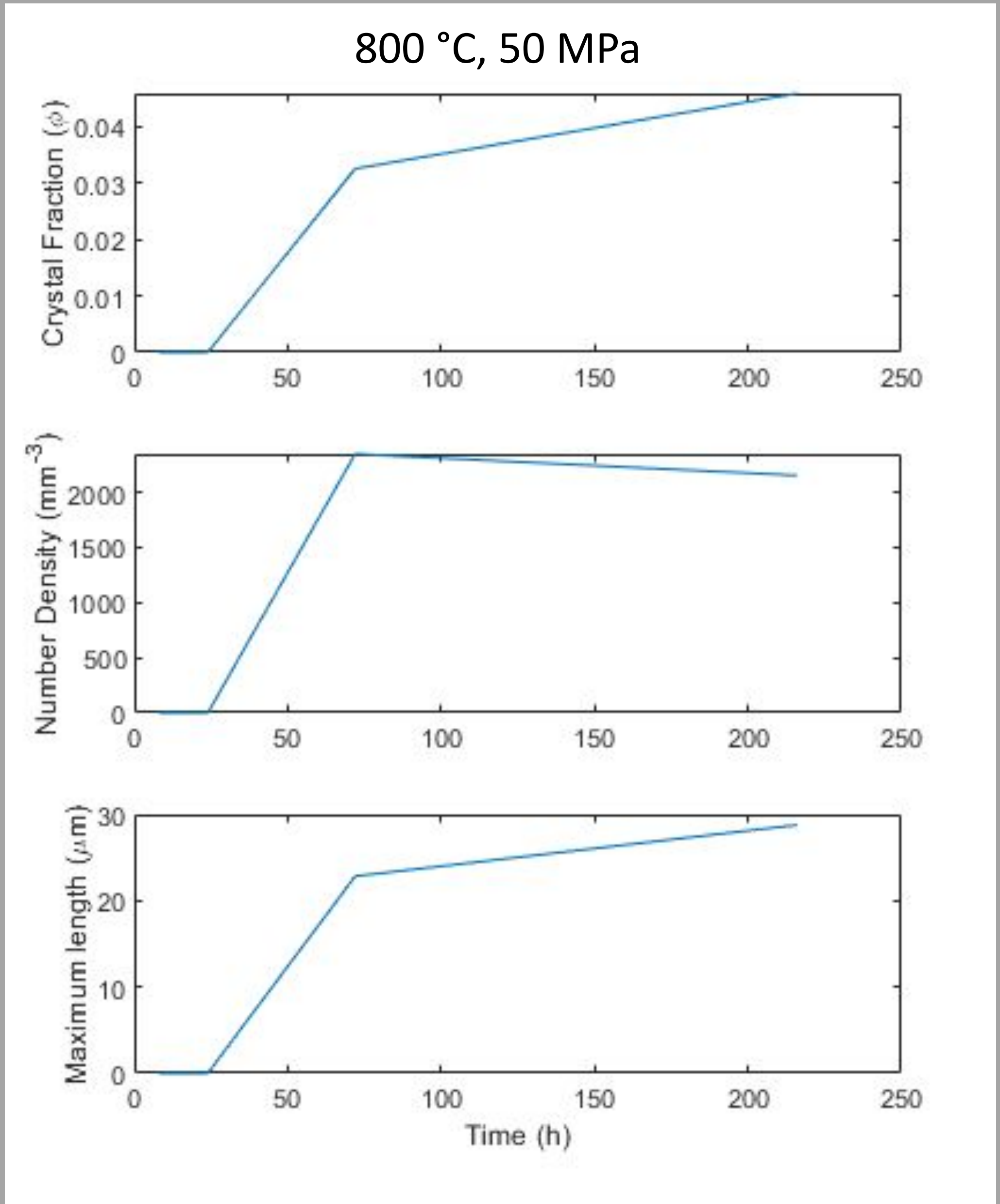
Example experimental results



750°C 50MPa 504h



800°C 10MPa 210 h



Experimental results

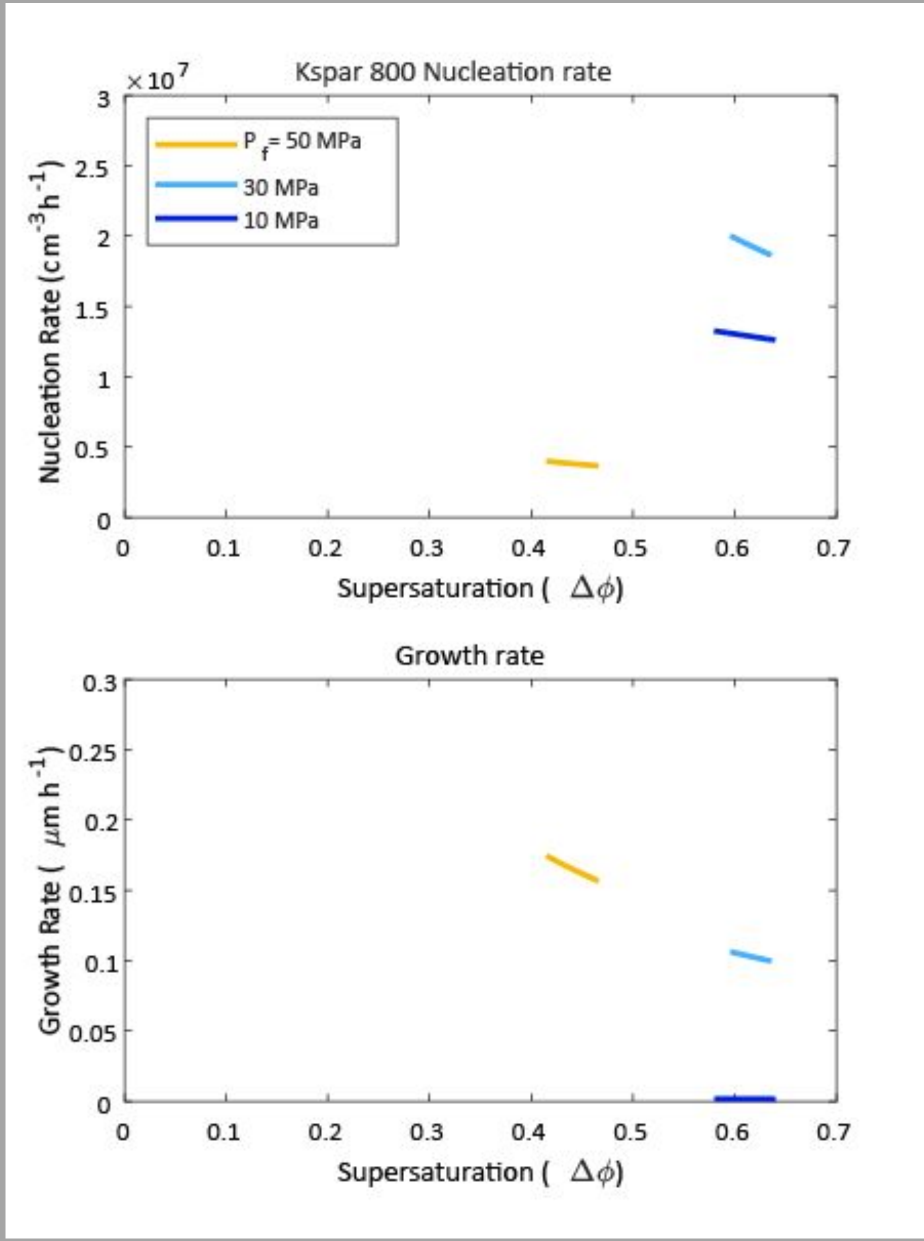
Crystal textures from BSE images

Analysis performed in ImageJ and Matlab

N_A to N_V conversion and characteristic size following methods of Hammer et al., 1999

Each T-P_f suite of experiments provides a timeseries of crystal growth

 Instantaneous Nucleation and Growth rates as a function of T and P_f

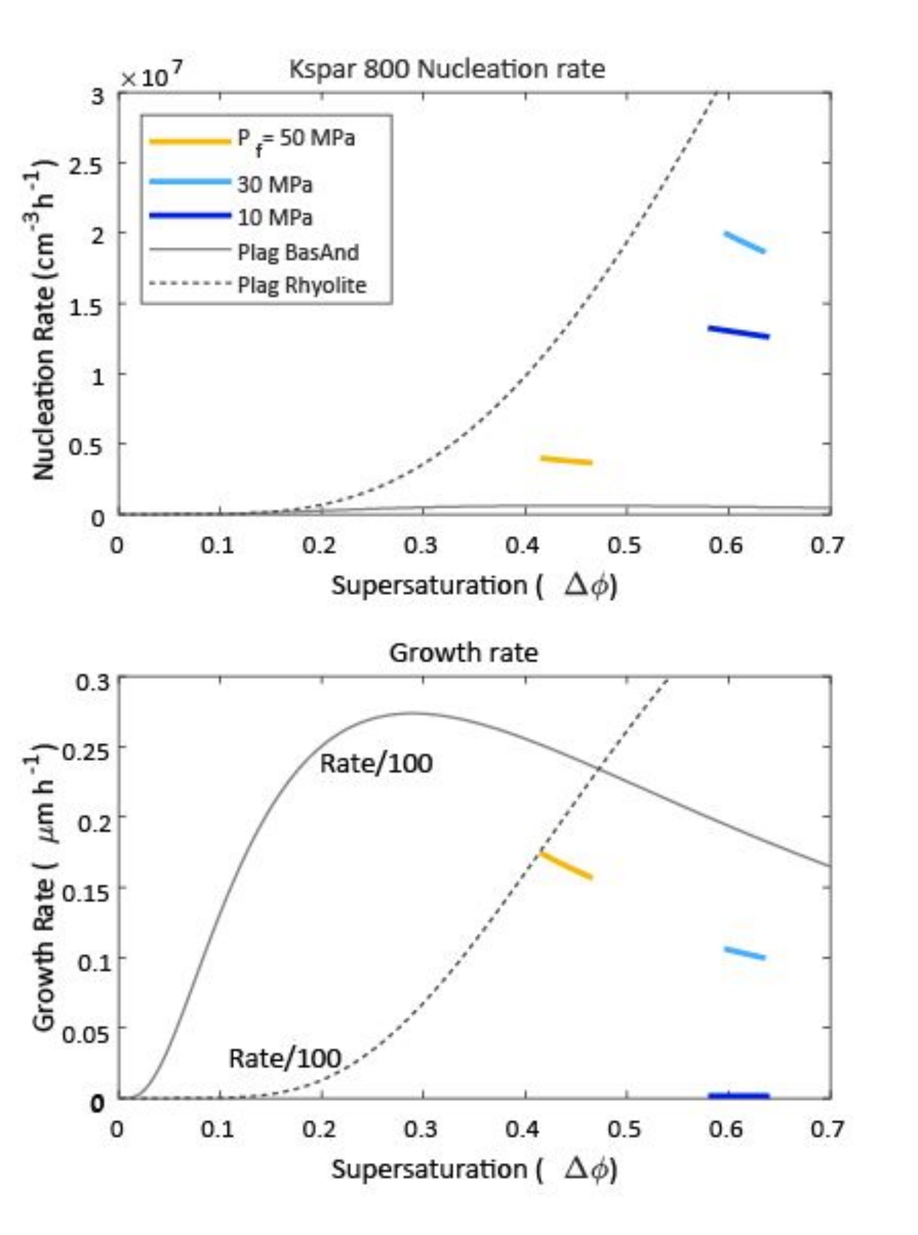


Nucleation and growth rates

K-spar nucleation on order of 10^7 $cm^{-1}h^{-1}$

K-spar growth at <<1 μm h^{-1}

Crystallization sufficiently slow that system remained highly supersaturated



Befus and Andrews, 2018; Marshall and Andrews, 2023

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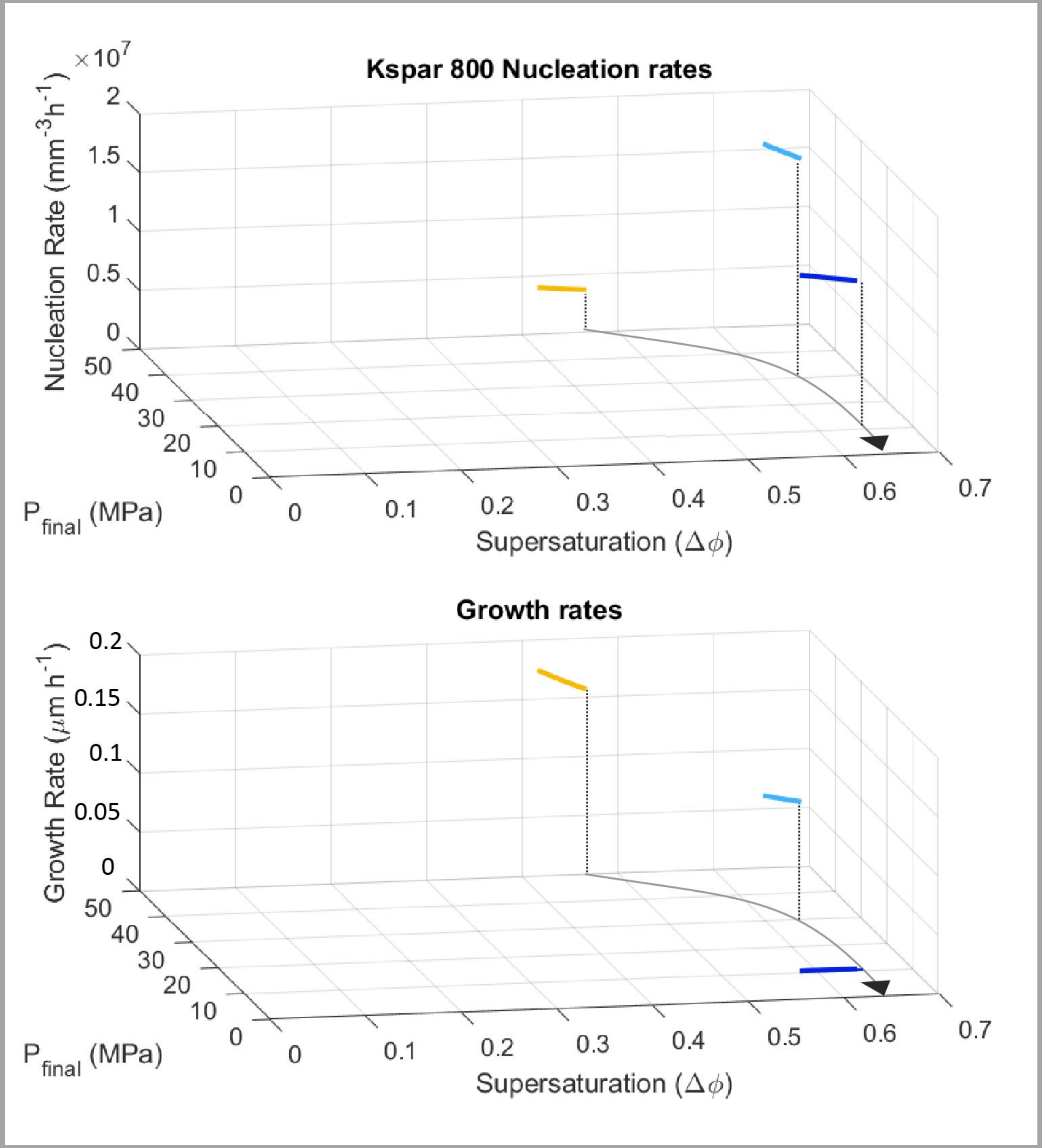
Nucleation rates are between *integrated* rates for plagioclase in rhyolite and basaltic andesite

Growth rates are less than *integrated* rates for plagioclase in rhyolite and basaltic andesite



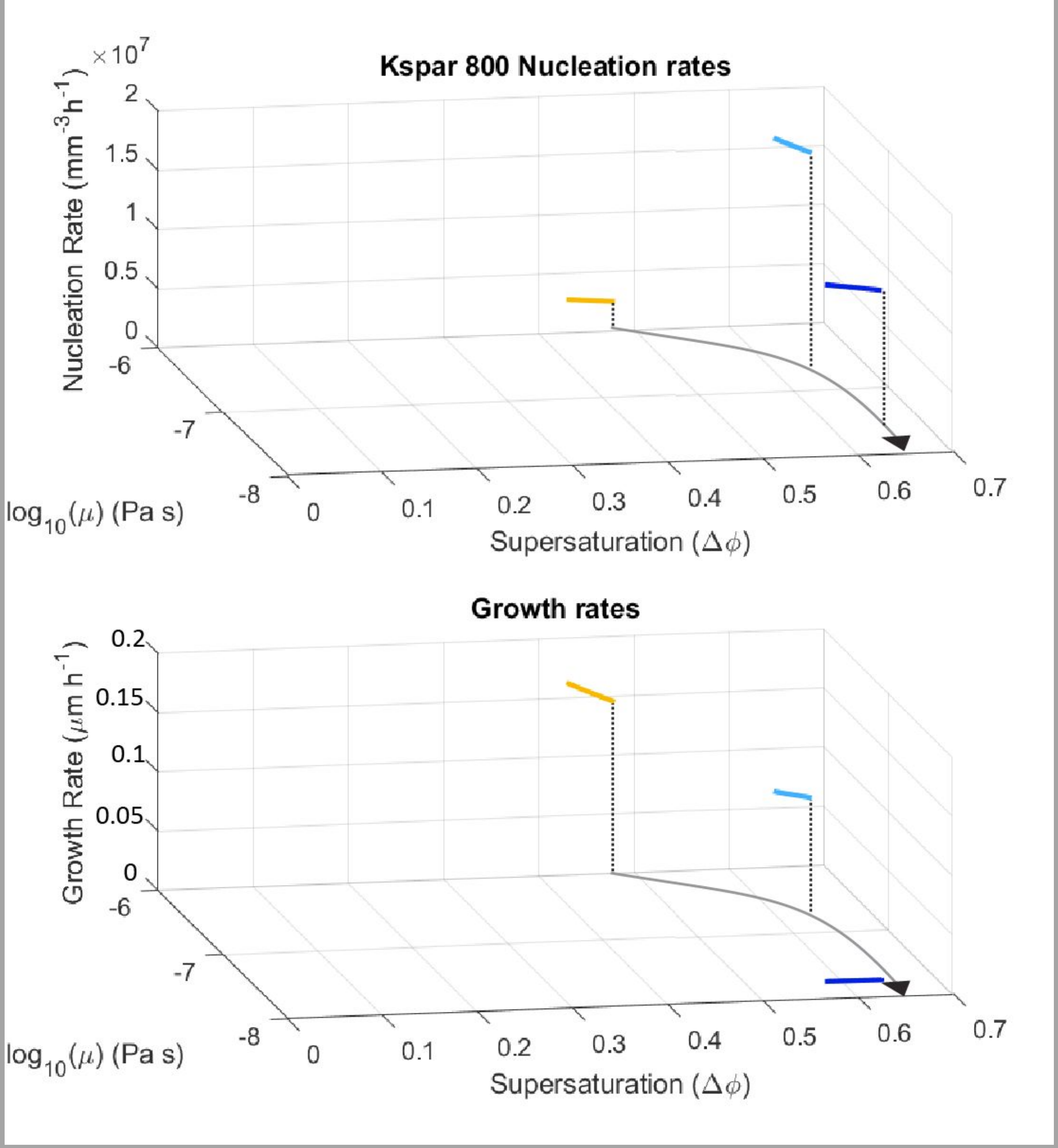
Crystallization rates depend on pressure

As pressure decreases:

- Nucleation rate increases
- Growth rate decreases

- Supersaturation increases

Crystallization rates depend on viscosity



Moore et al., 1998; Giordano et al., 2008

As pressure decreases:

- Nucleation rate increases
- Growth rate decreases

- Supersaturation increases
- Viscosity increases

Nucleation and growth are effectively terminated when viscosity exceeds $10^{7.5}$ Pas

Decompression Experiment Strategy

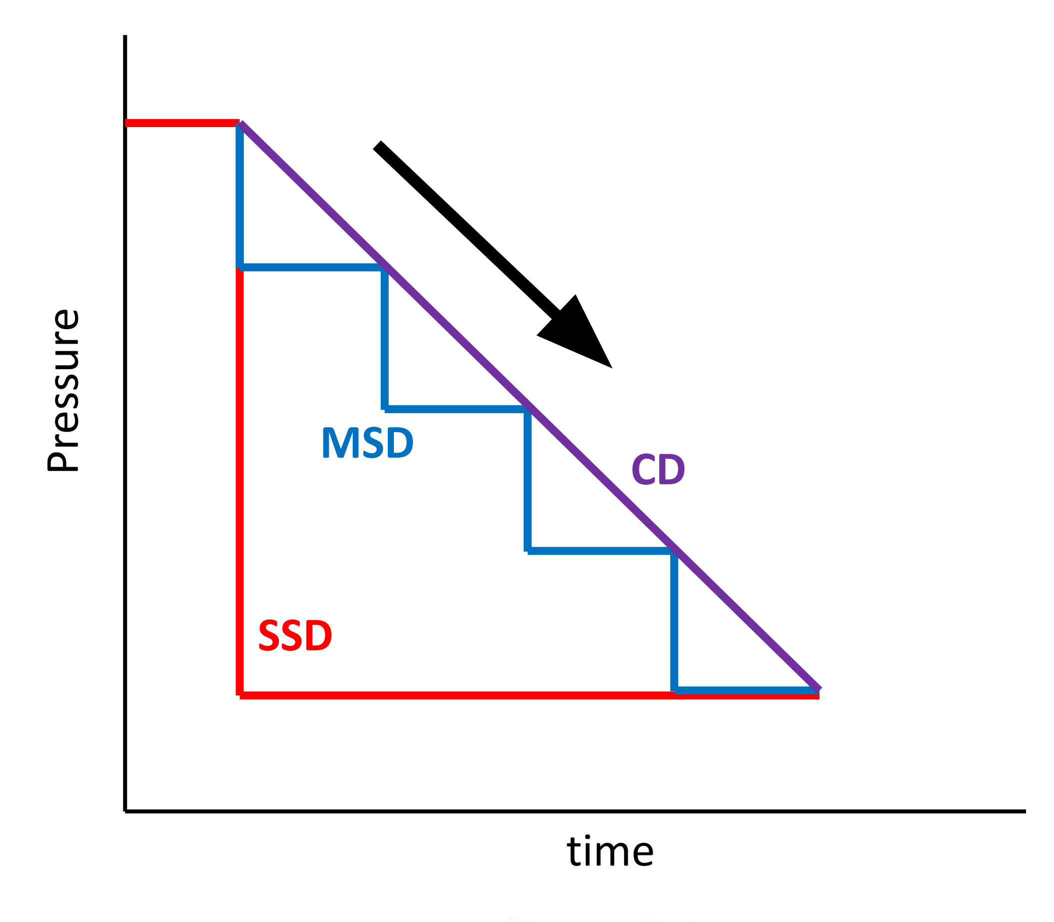
Nature follows a "continuous" path

Crystallization rates change during decompression as:

- Melt degasses (*increase rates*)
- Crystallization occurs (*decrease rates*)
- Viscosity increases (*decrease rates*)

Single-step decompressions allow determination of rates with minimal syn-experiment variation in dissolved volatiles and viscosity

Use Multi-step or Continuous experiments as a validation or test



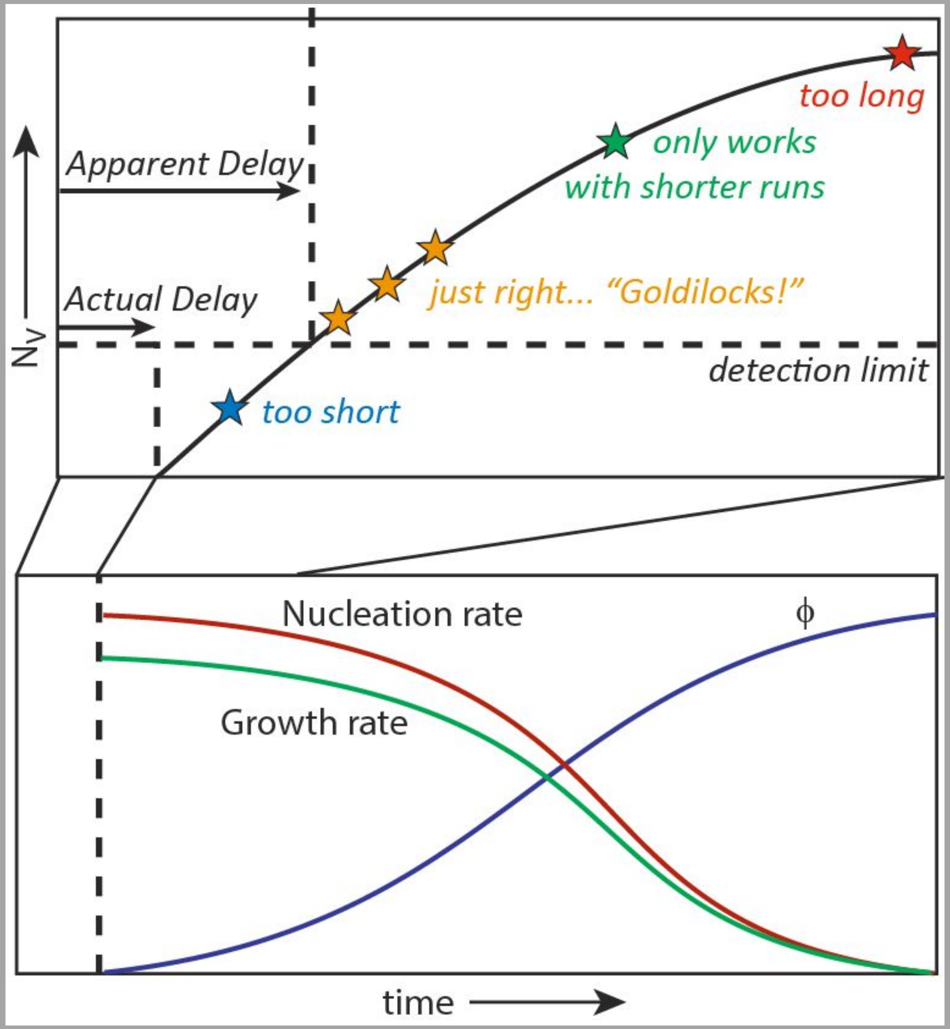
Measuring small numbers of small things in small volumes with often ~~low~~ small contrast

Quantitative measurements are hard

- Numbers and sizes of small crystals
- Compositions (small crystals or thin rims)

SEM images can be fantastic, but are 2D

XRCT data can be… low contrast, low resolution, and high frustration

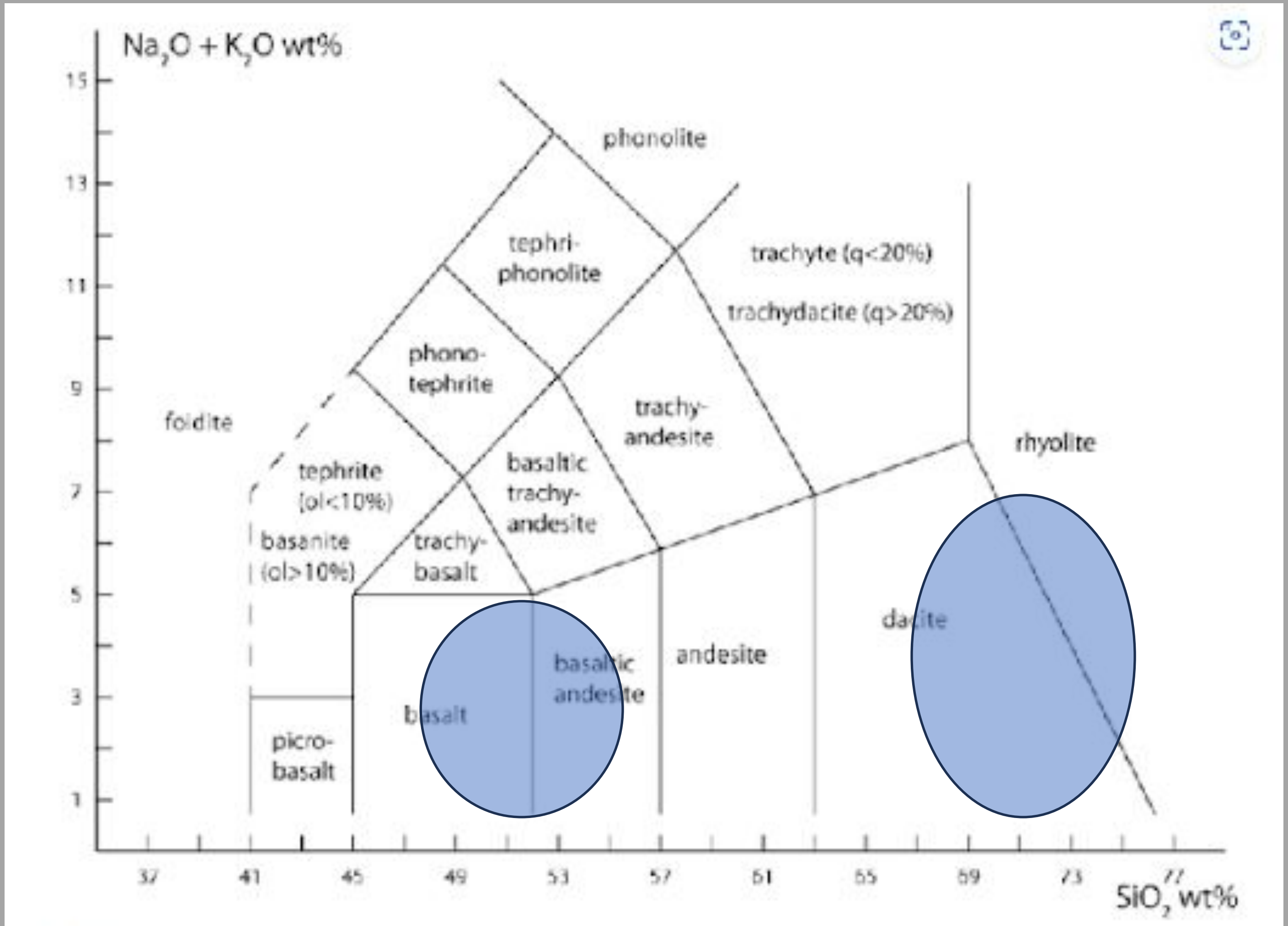


Future goals…

Move beyond plagioclase…

Examine intermediate compositions and more alkalic magmas

Waters, Walker, Tsuchiyama, Toramaru, Swanson, Suzuki, Sisson, Shea, Rutherford, Mollo, Martel, Mangan, Larsen, James, Hammer, Grove, Grismer, Gardner, Fenn, Devine, Couch, Coombs, Cichy, Browne, Befus, Andrews… … …



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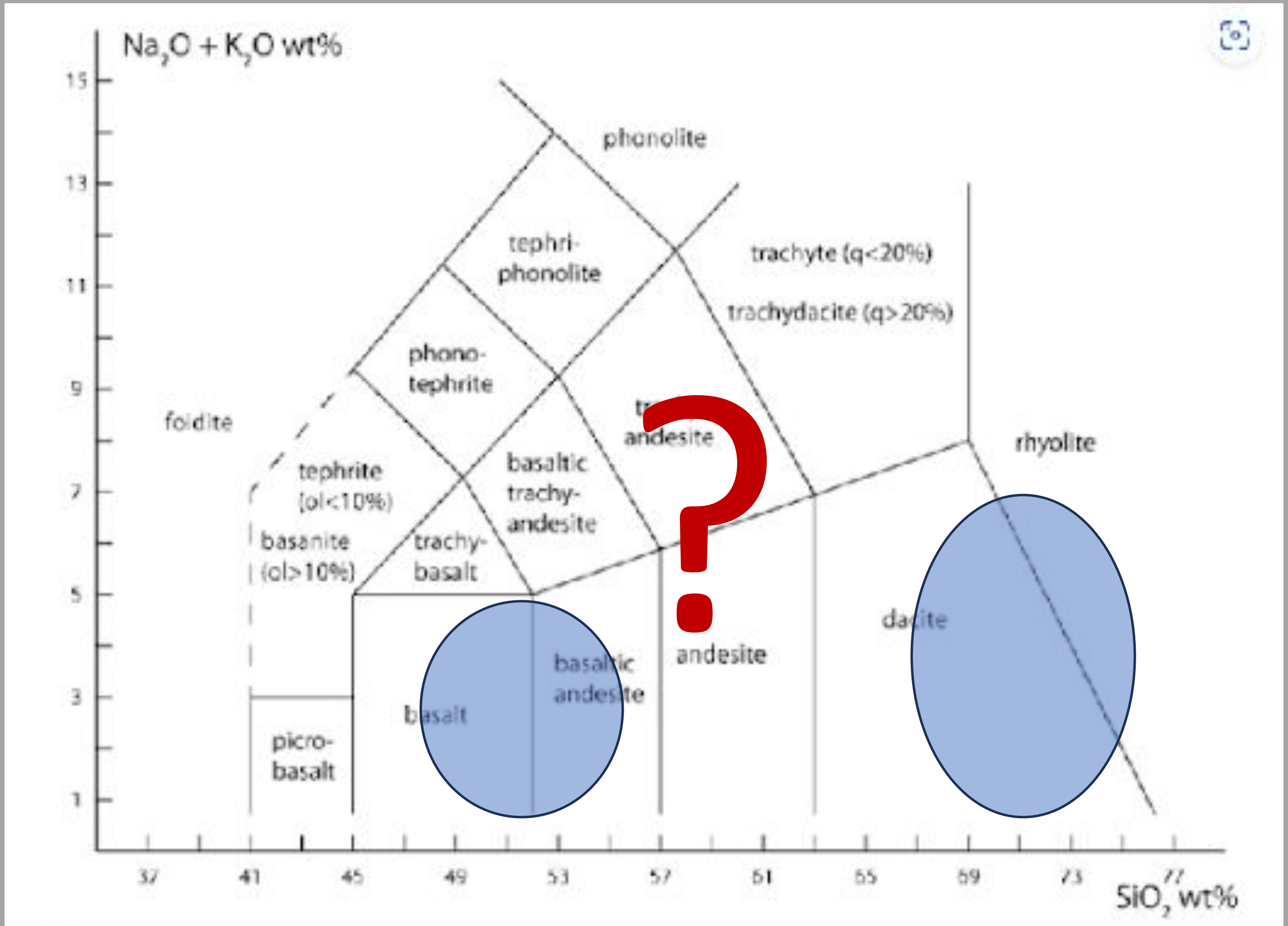

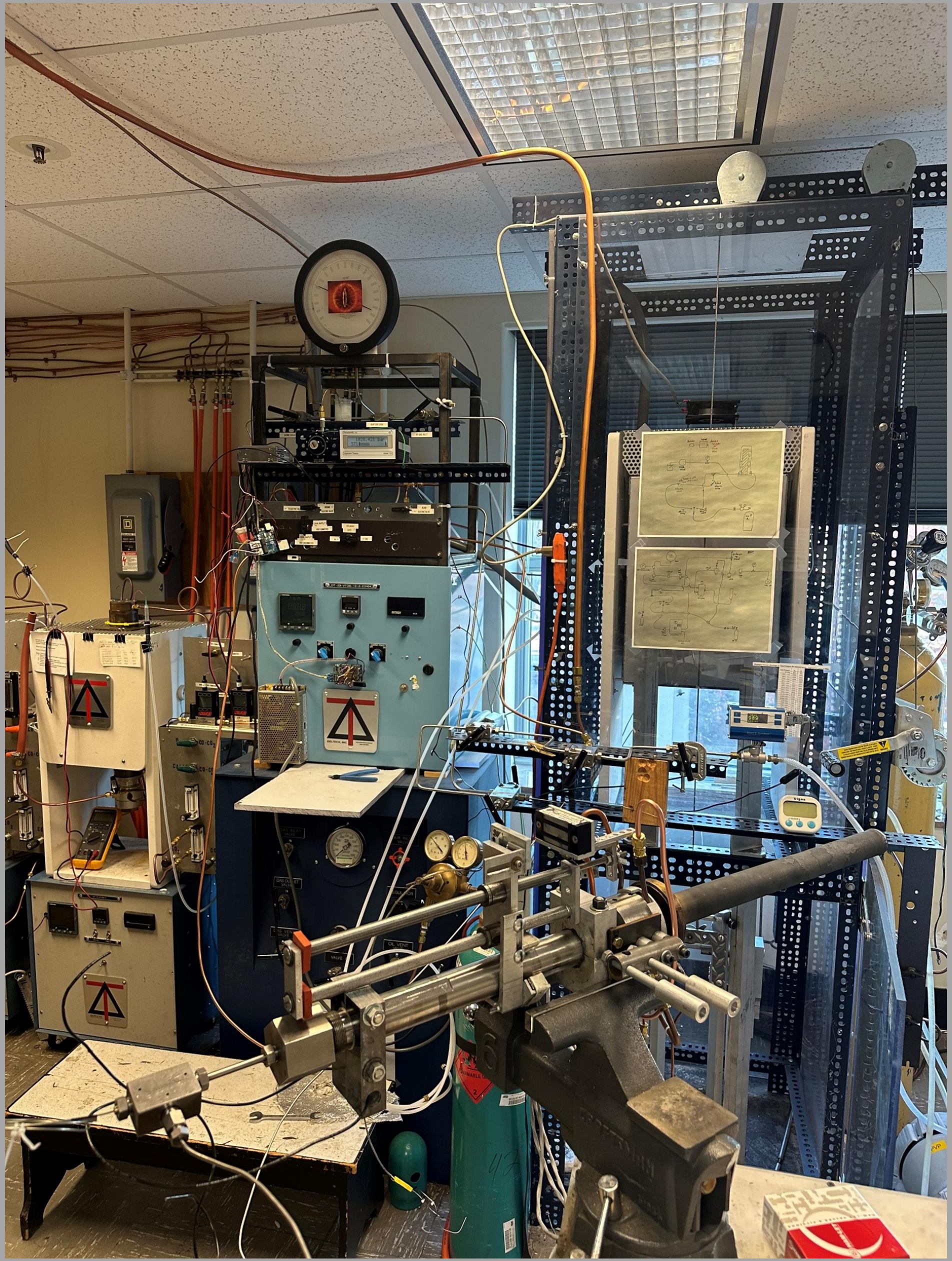


Thermo
LINDBERG/BLUE M
LINDBERG/BLUE M
LINDBERG/BLUE M
H2
CLOSED
H3
CLOSED