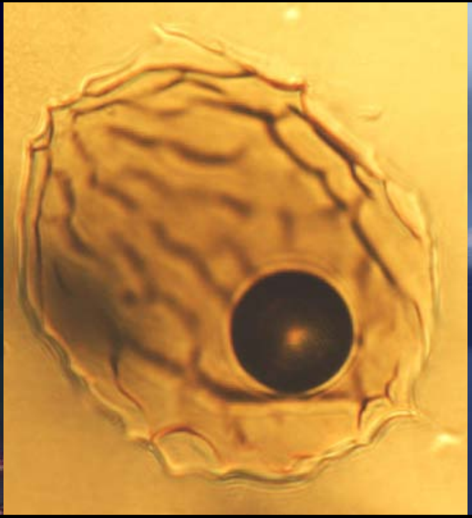
Formation of Melt Inclusions

Adam Kent, Oregon State University

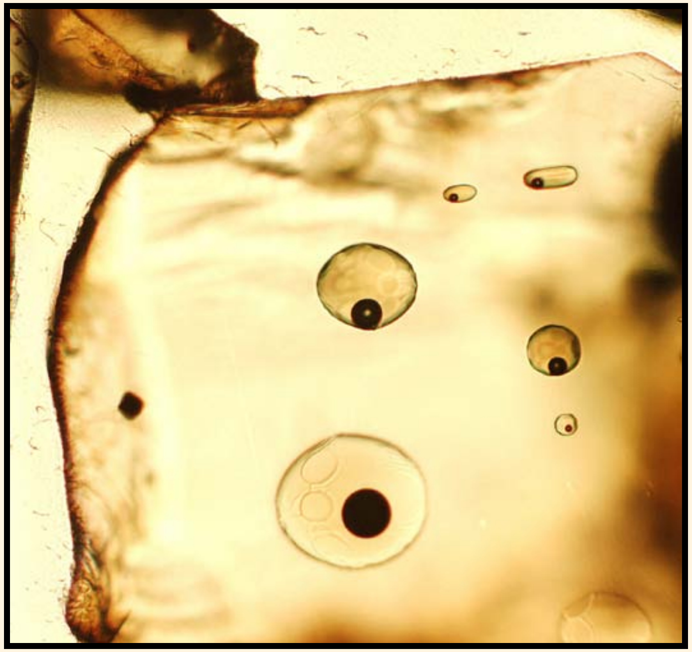




Key Questions

- How do melt inclusions form?
- What are the key processes involved?
- Does the process of formation effect the changed composition?

How do melt inclusions form?

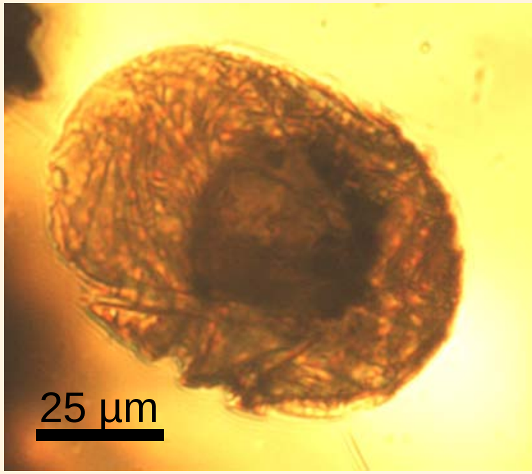
The widespread occurrence of melt inclusions in basaltic rocks shows that their formation is a normal part of the process of crystallization in igneous rocks

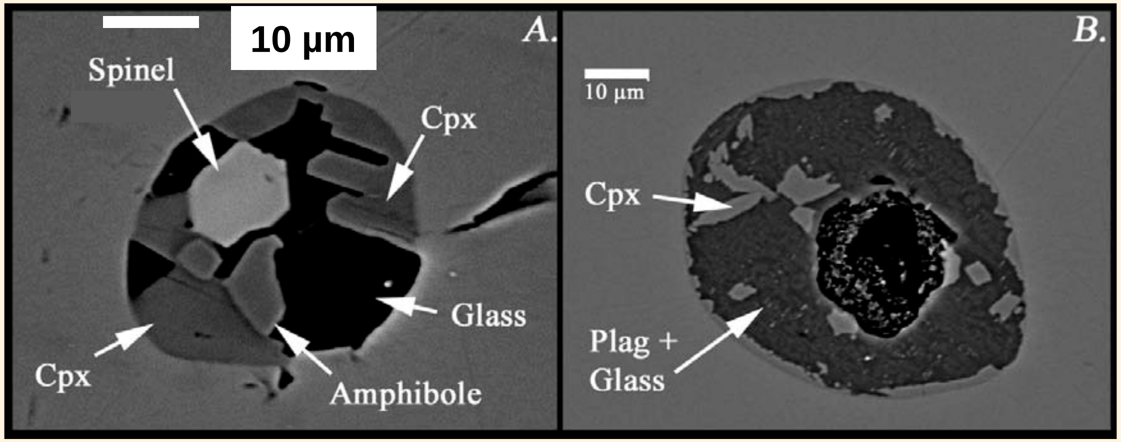


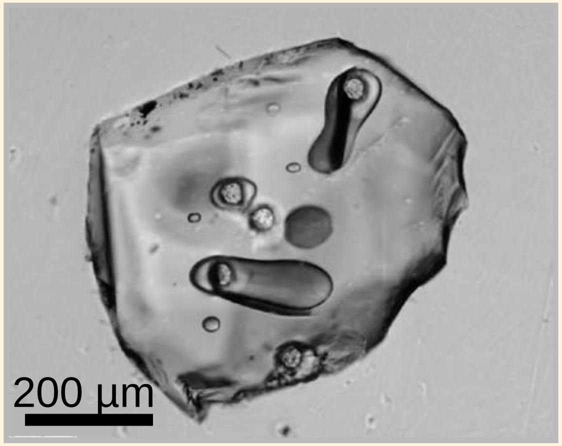
Melt inclusions form in regions of relatively slow crystal growth

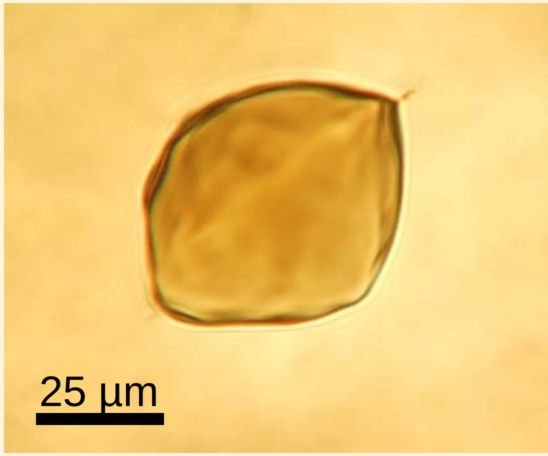
Do the processes that lead to melt inclusion formation alter their compositions?

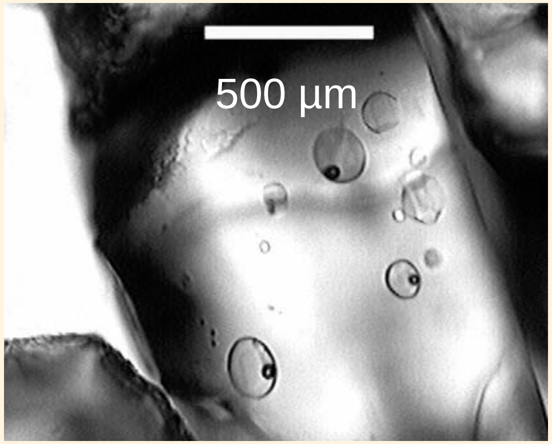
Olivine-hosted melt inclusions











Other common hosts: plagioclase, pyroxene (quartz and alkali feldspar in evolved rocks)

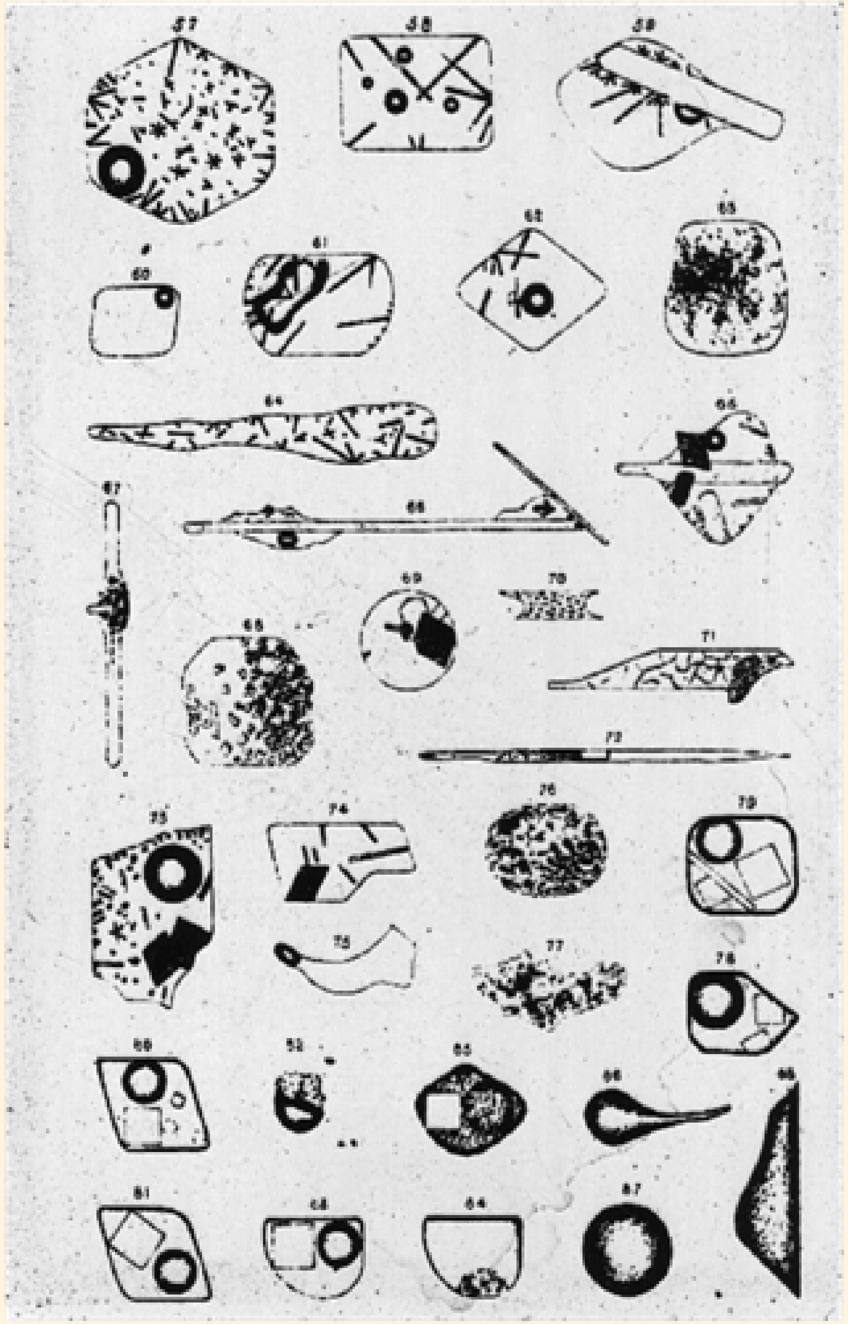


Fig. 1. Photograph showing the original drawings of silicate-melt inclusions in effusive and intrusive rocks by Sorby (1858). Silicate-melt inclusions where mainly studied in phenocrysts from lavas of the Vesuvius and in quartz grains in granites from Cornwall (e.g. St. Austell).

Melt Inclusion Formation

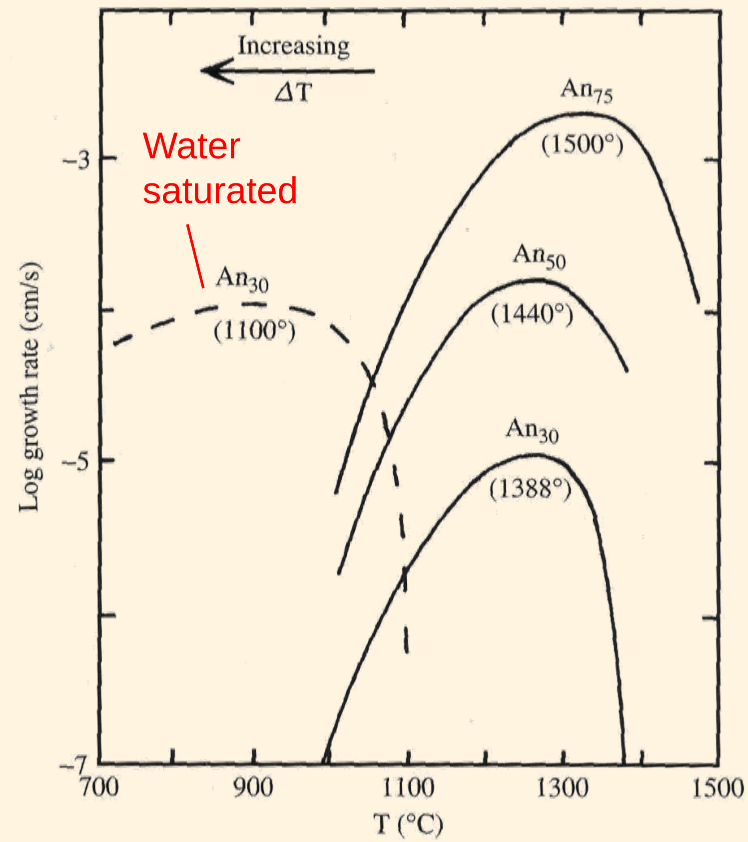
- Melt inclusions occur in regions of relatively low crystal growth

1. Rapid crystal growth followed by textural equilibration
2. Slow equilibrium crystal growth and surface defects
3. Rapid dissolution followed by growth
4. Healing of melt-filled fractures

Crystal Growth

- Occurs after viable nuclei are present
- **Requires diffusion** of crystal components in and latent heat out
- Diffusion depends on:
  - Temperature ($D = D_0 e^{-Ea/RT}$)
  - Melt structure and composition
    - Faster in wet, depolymerized melts
- Crystal growth occurs preferentially in the direction of strongest bonds (Si-O)
  - Amphibole and Pyroxene have elongate crystals
  - Micas form plates

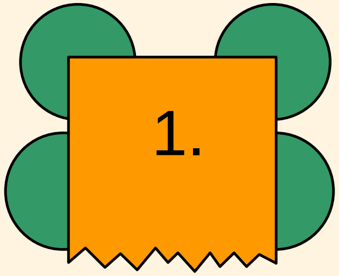
Growth Rates Influence Crystal Shape

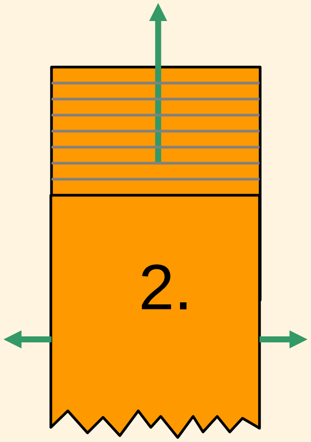


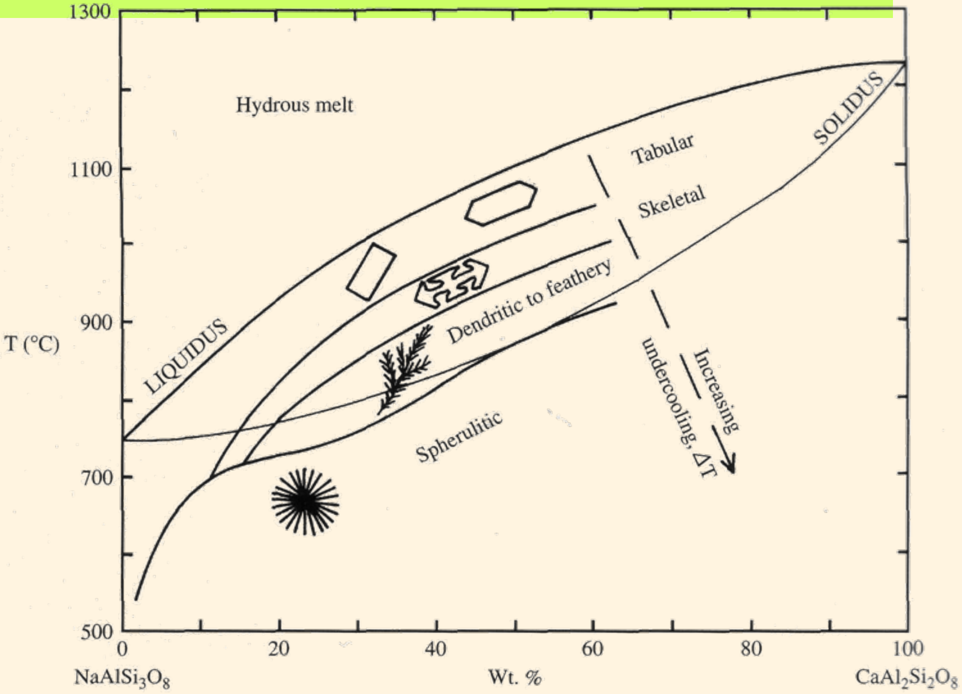
6.13 Experimentally determined plagioclase growth rates as a function of degree of undercooling, ΔT, in their equivalent melts.

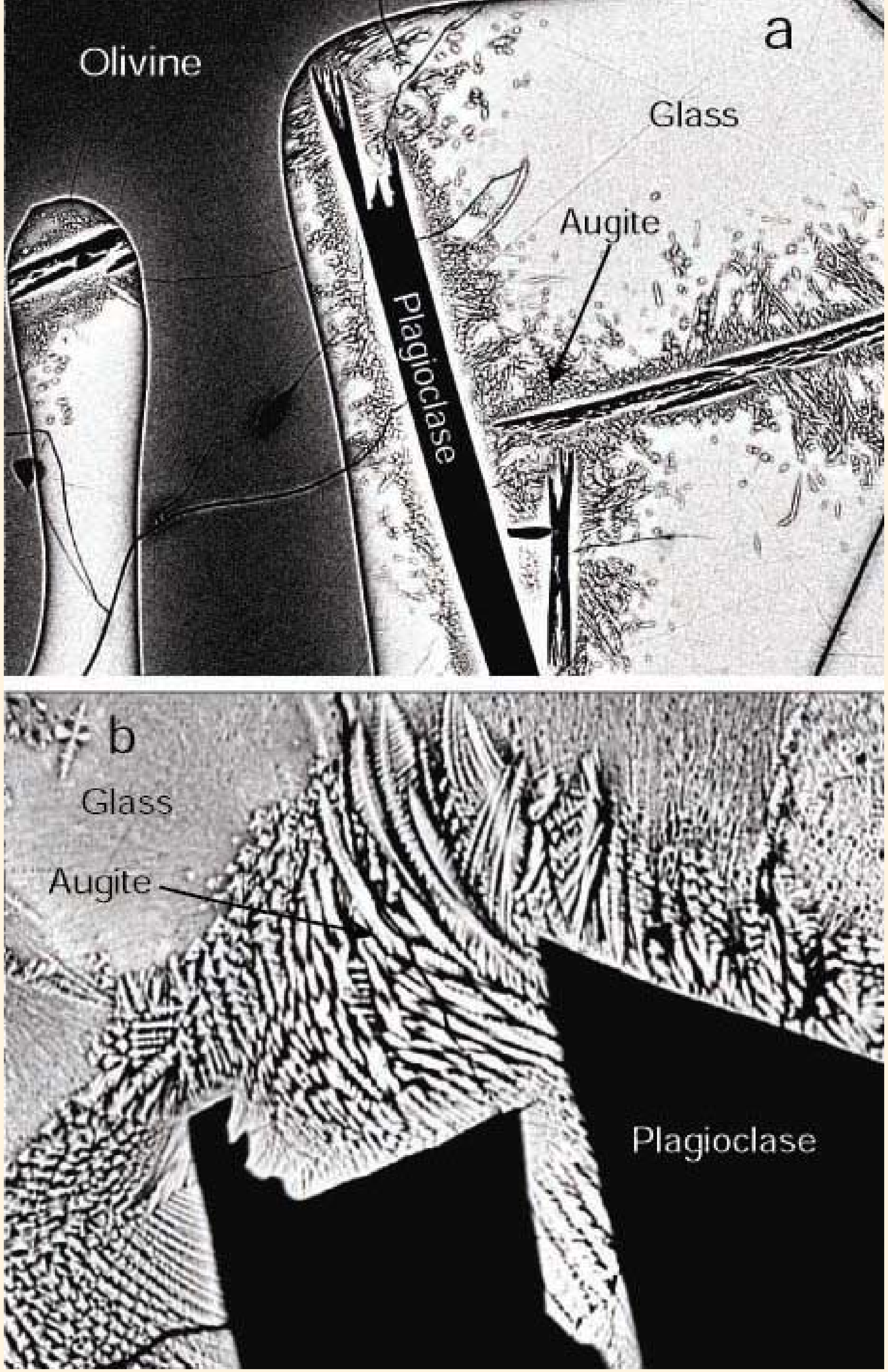
Influence of cooling rate on crystal shape

- At higher rates of crystal growth (ie greater undercooling) crystal shapes increasingly depart from equilibrium
- Rapid growth favors disequilibrium growth along preferential directions
  - Diffusion favors longer crystals

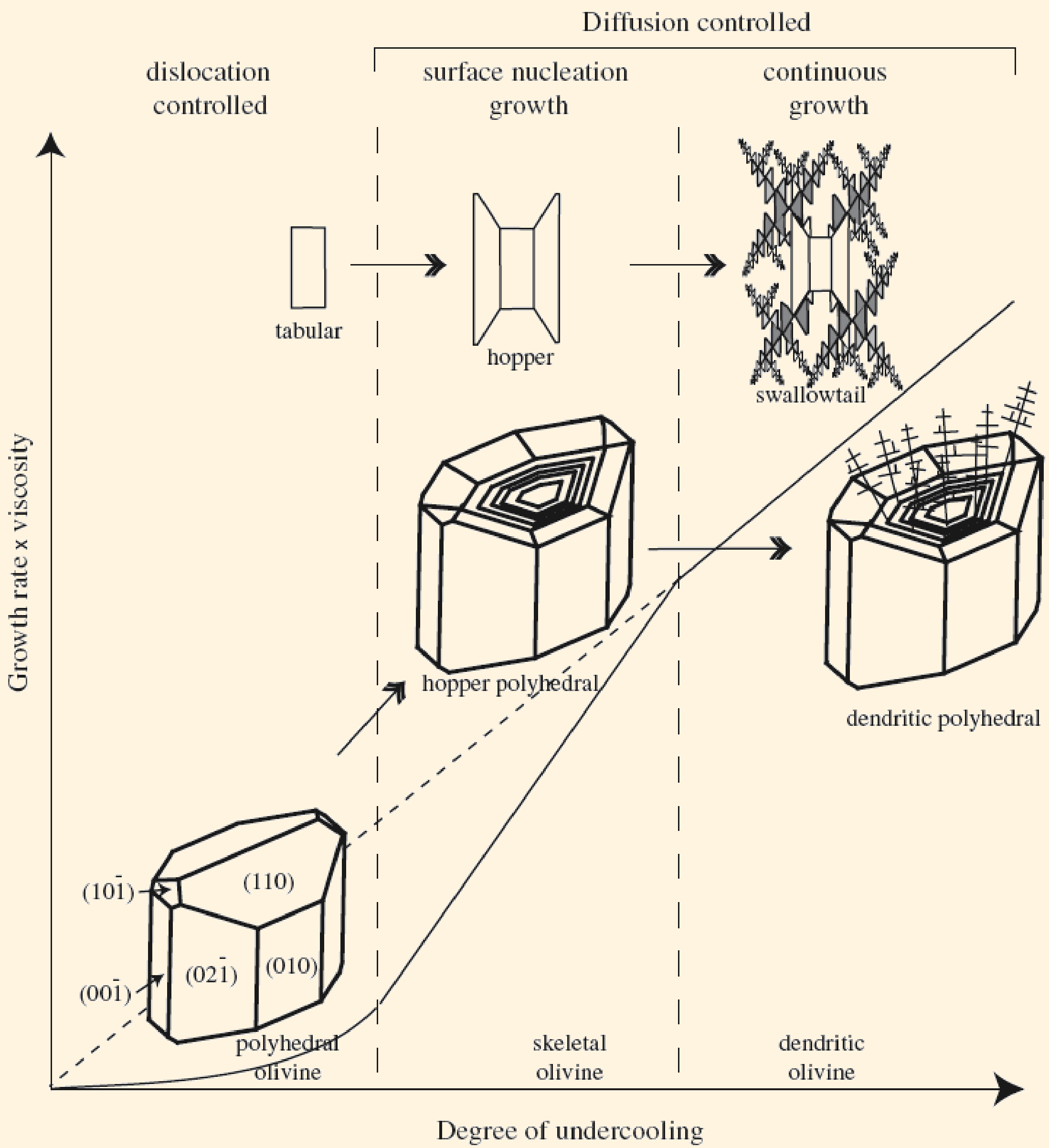


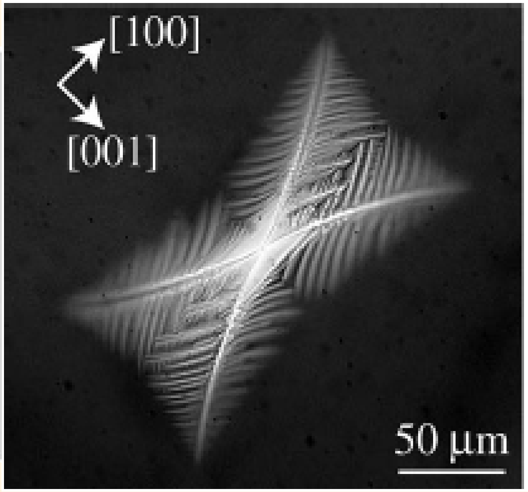


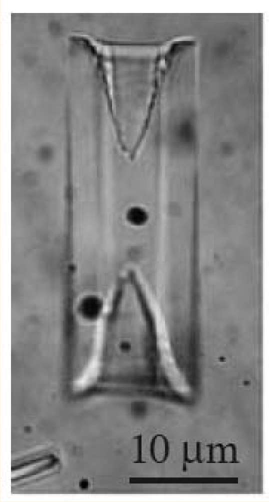


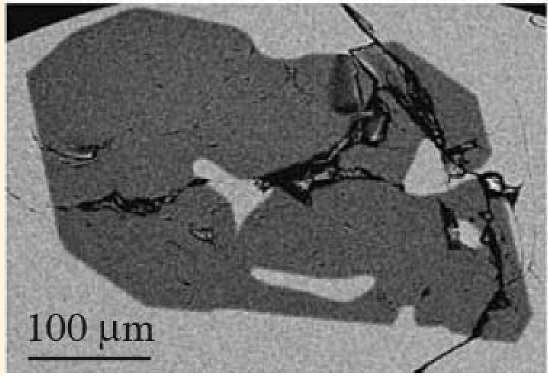


Augite crystallites nucleating on plagioclase in Hawaiian basalt



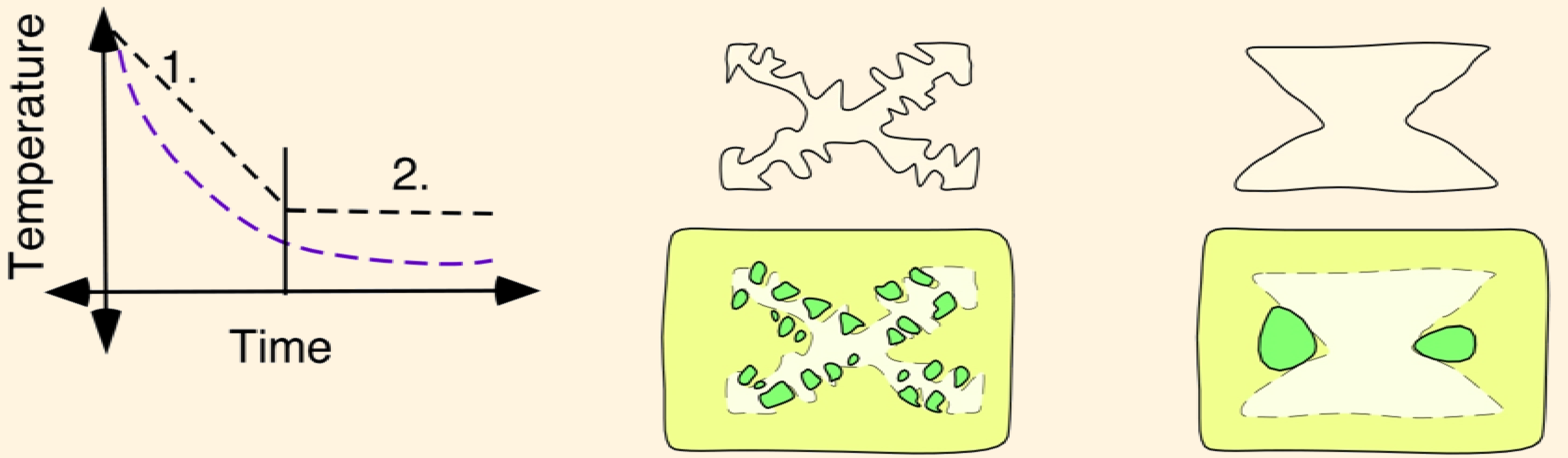






Faure et al. 2006

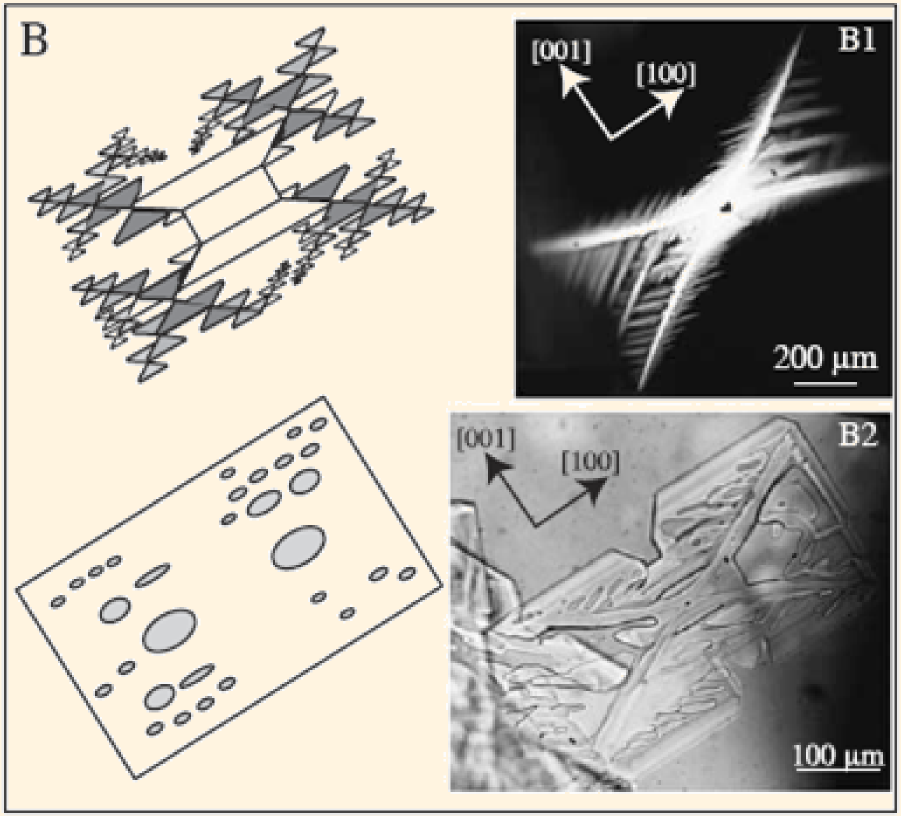
1. Rapid crystal growth followed by textural equilibration

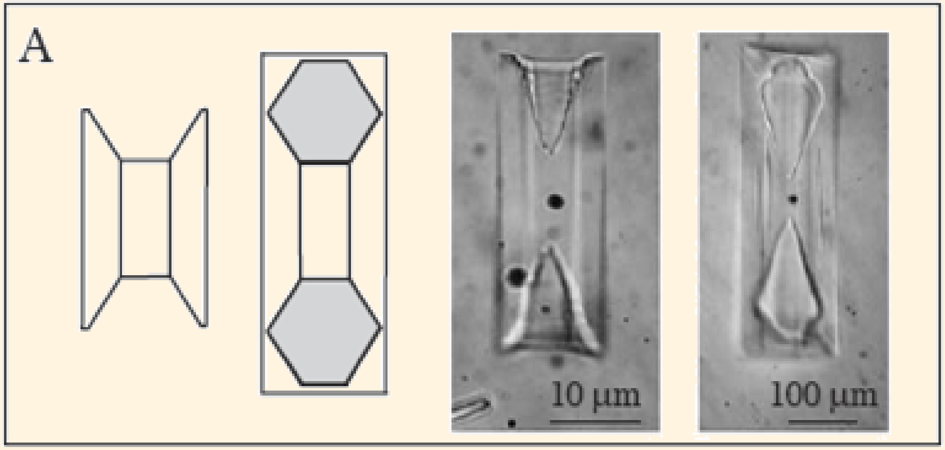


1. Rapid disequilibrium growth (skeletal, hopper, dendritic)

2. Slower equilibrium overgrowth (tabular, equant)

Faure and Schiano, 2005



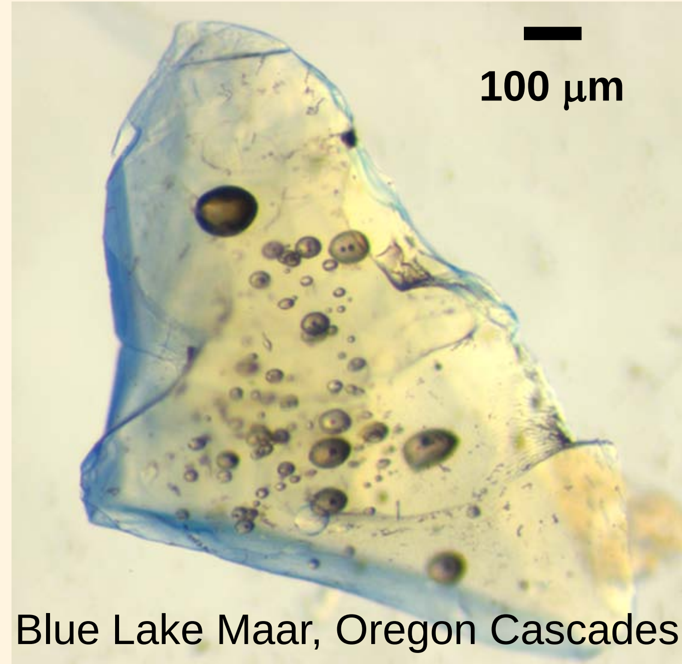


Melt inclusion formation is part of **textural maturation**

Experimental and natural closed dendritic olivine with melt inclusions (very fast cooling)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

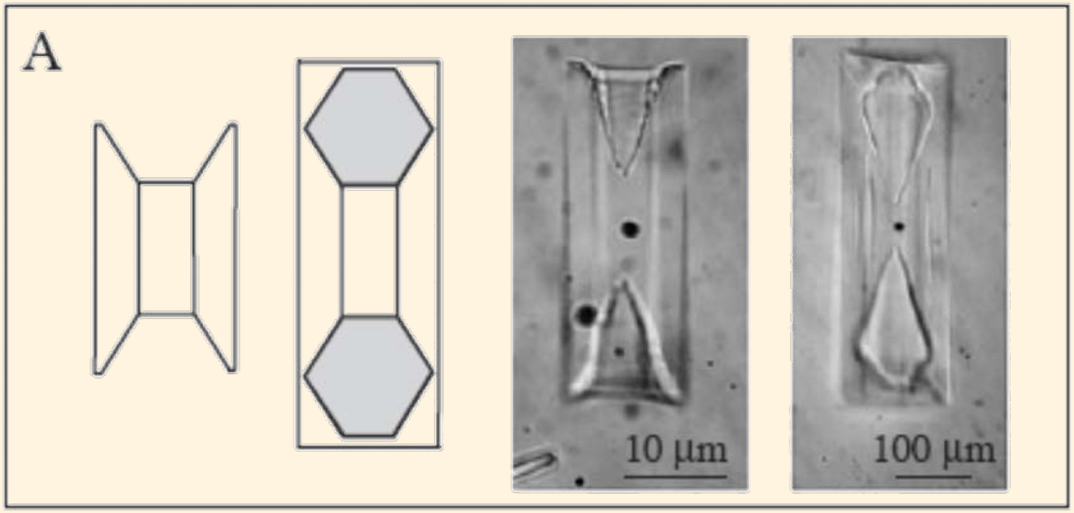
Faure & Schiano (2005)



Blue Lake Maar, Oregon Cascades

Stromboli Volcano
Photo courtesy of N. Metrich

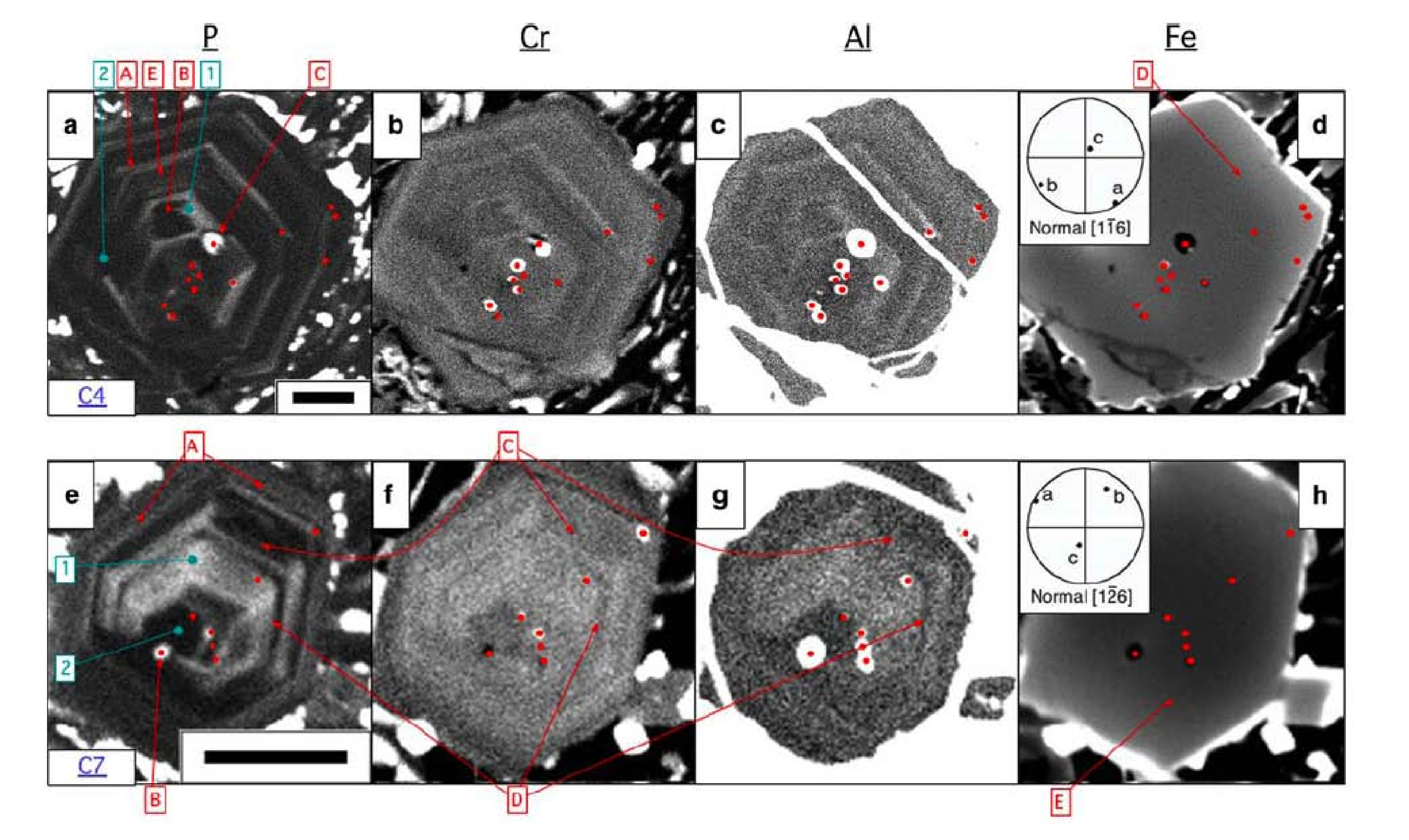
Experimental & natural skeletal (hopper morphology) olivine with melt inclusions (faster cooling)



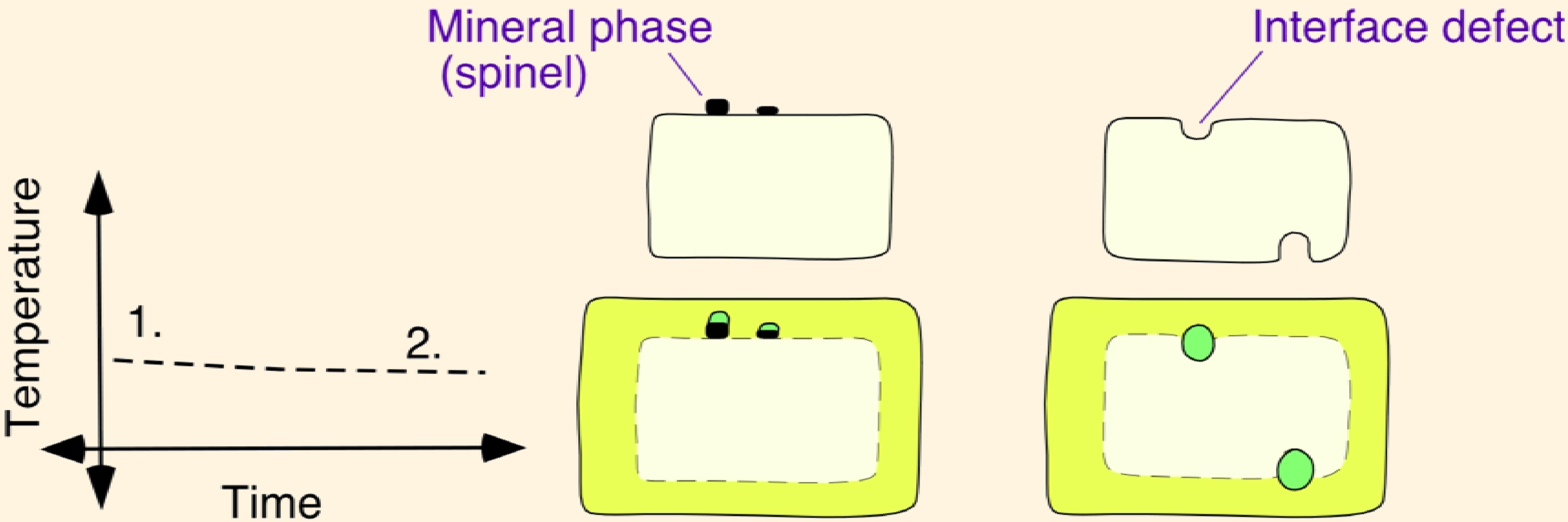
Faure & Schiano (2005)

Keanakakoi Ash

500 μm



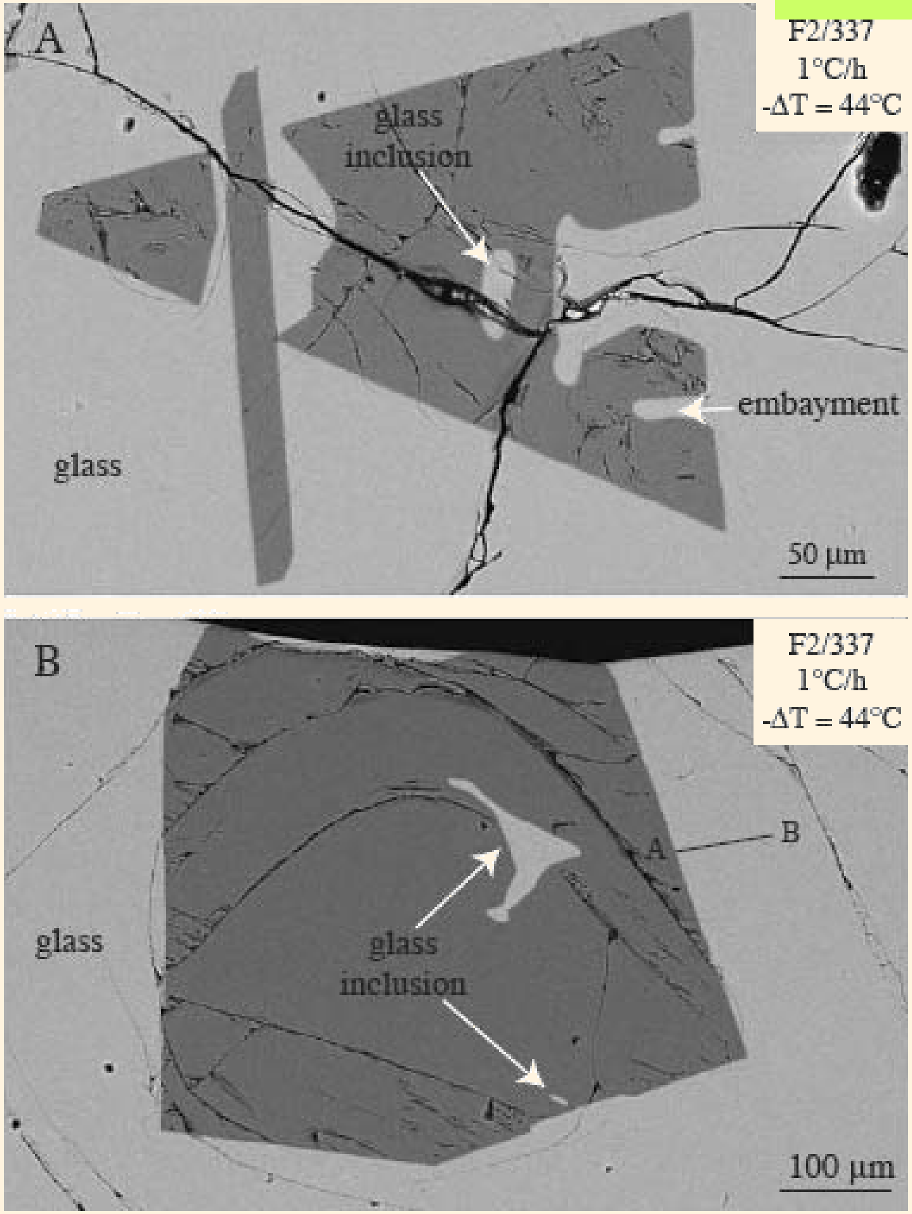
Milman-Barris et al. 2007



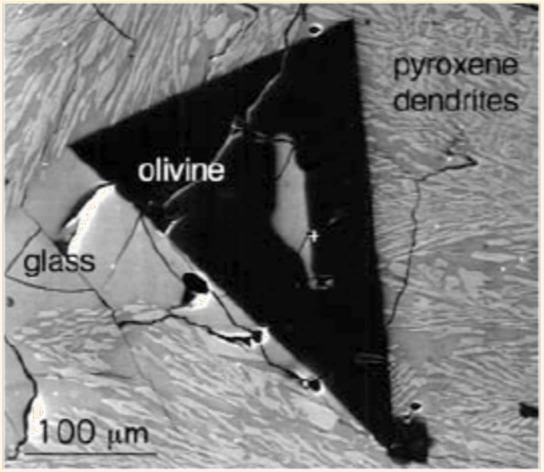
1. **Slow equilibrium growth (local growth defects, minerals)**

2. **Continued slow overgrowth (tabular, equant)**

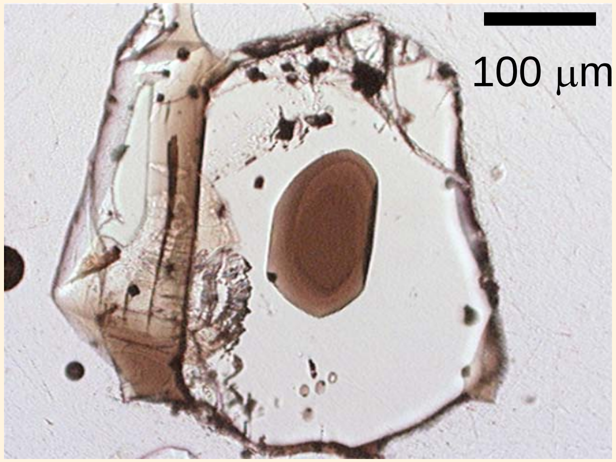
Faure and Schiano, 2005



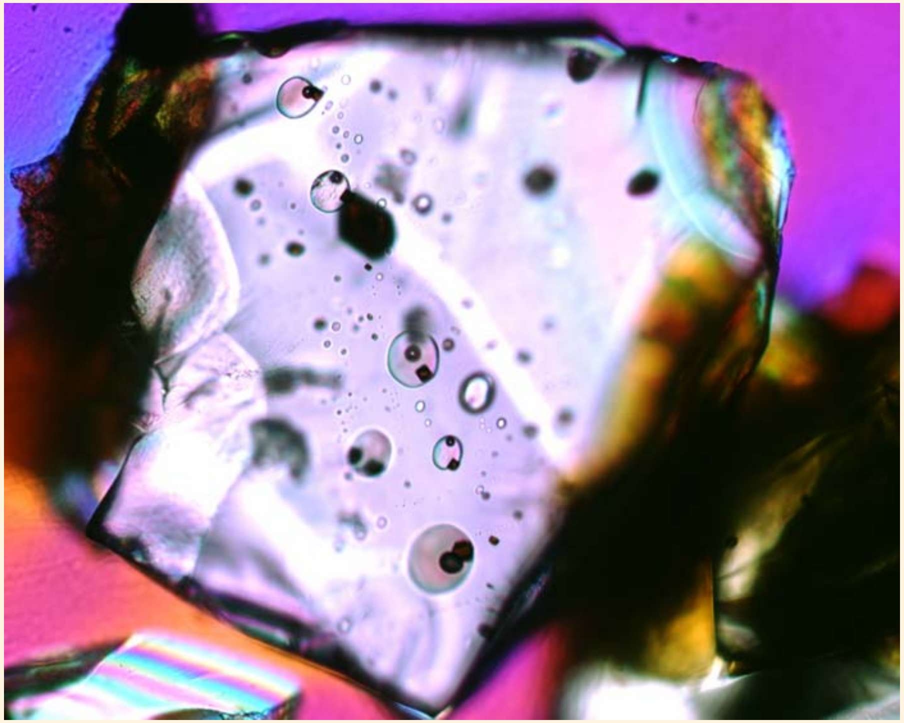
Experimental and natural polyhedral olivine with melt inclusions (slow cooling)

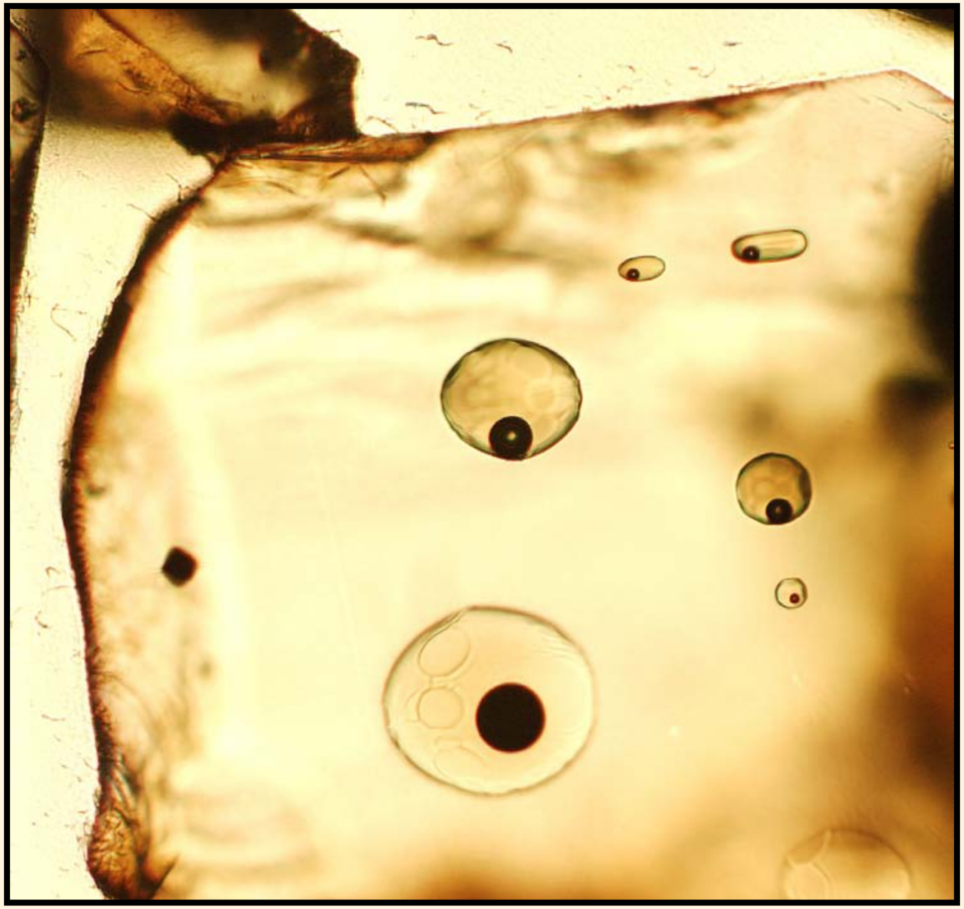


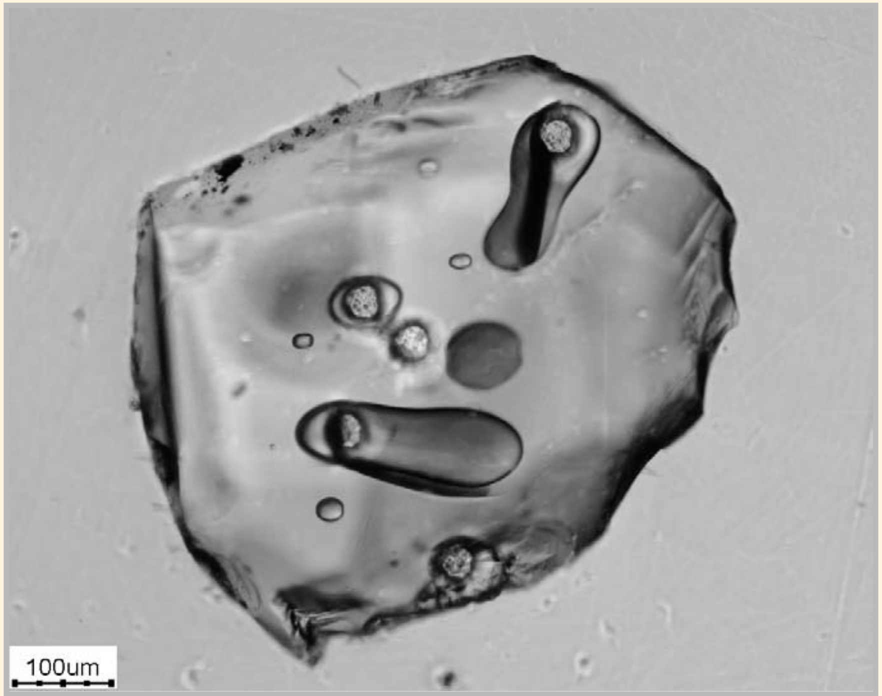
Faure & Schiano (2005)



Keanakakoi Ash, Kilauea, Hawaii

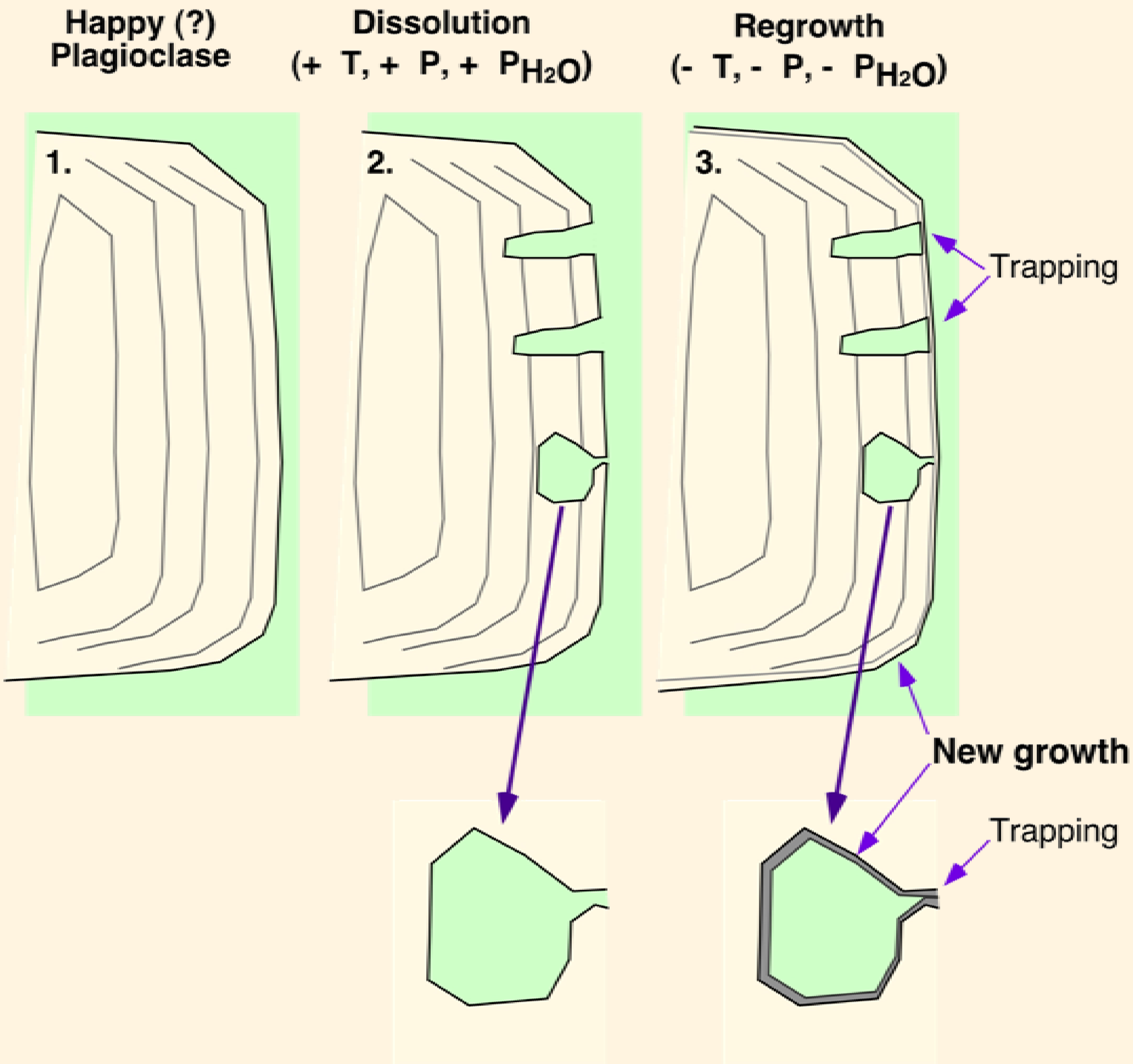






These inclusions probably represent the majority of analyzed melt inclusions

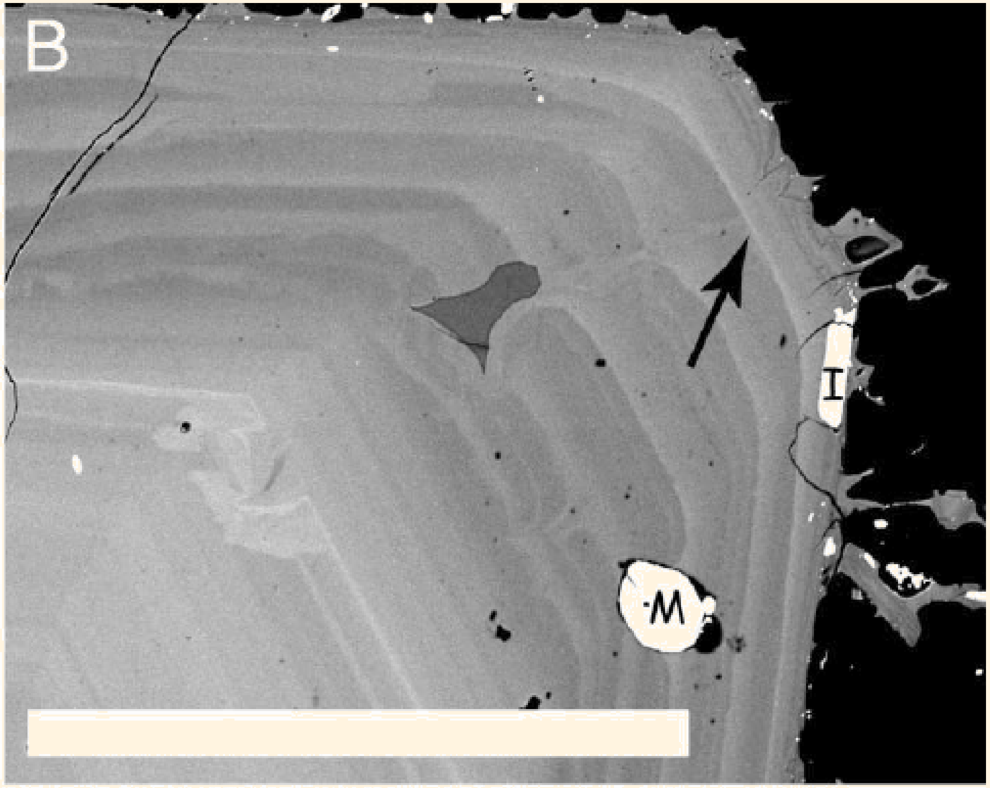
3. Rapid dissolution and growth

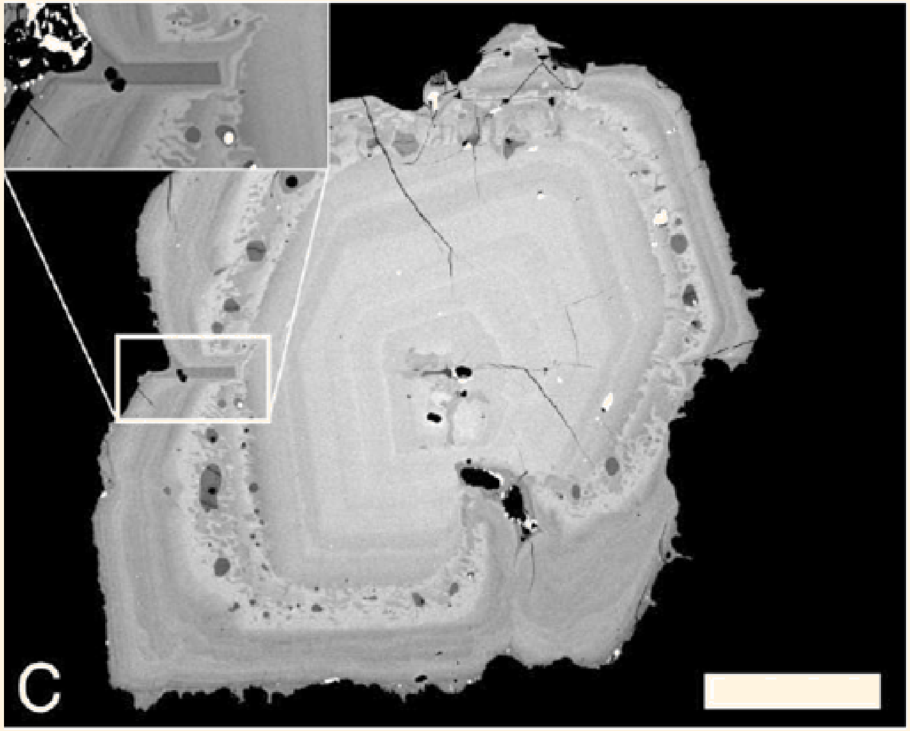


Melt inclusions in Plagioclase

QuickTime™ and a
decompressor
are needed to see this picture.

Melt inclusions in Plagioclase





Blundy and Cashman, 2005 *Geology*

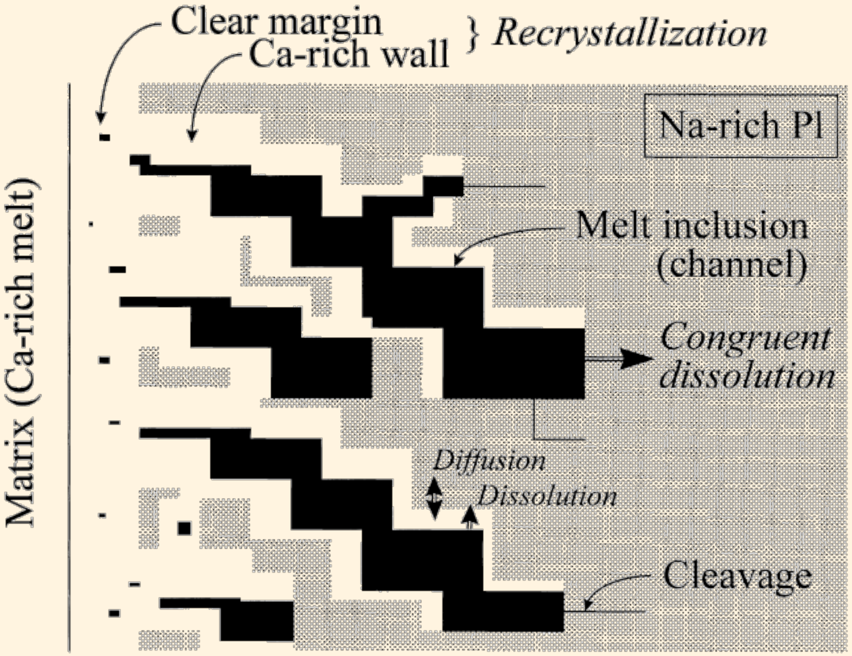
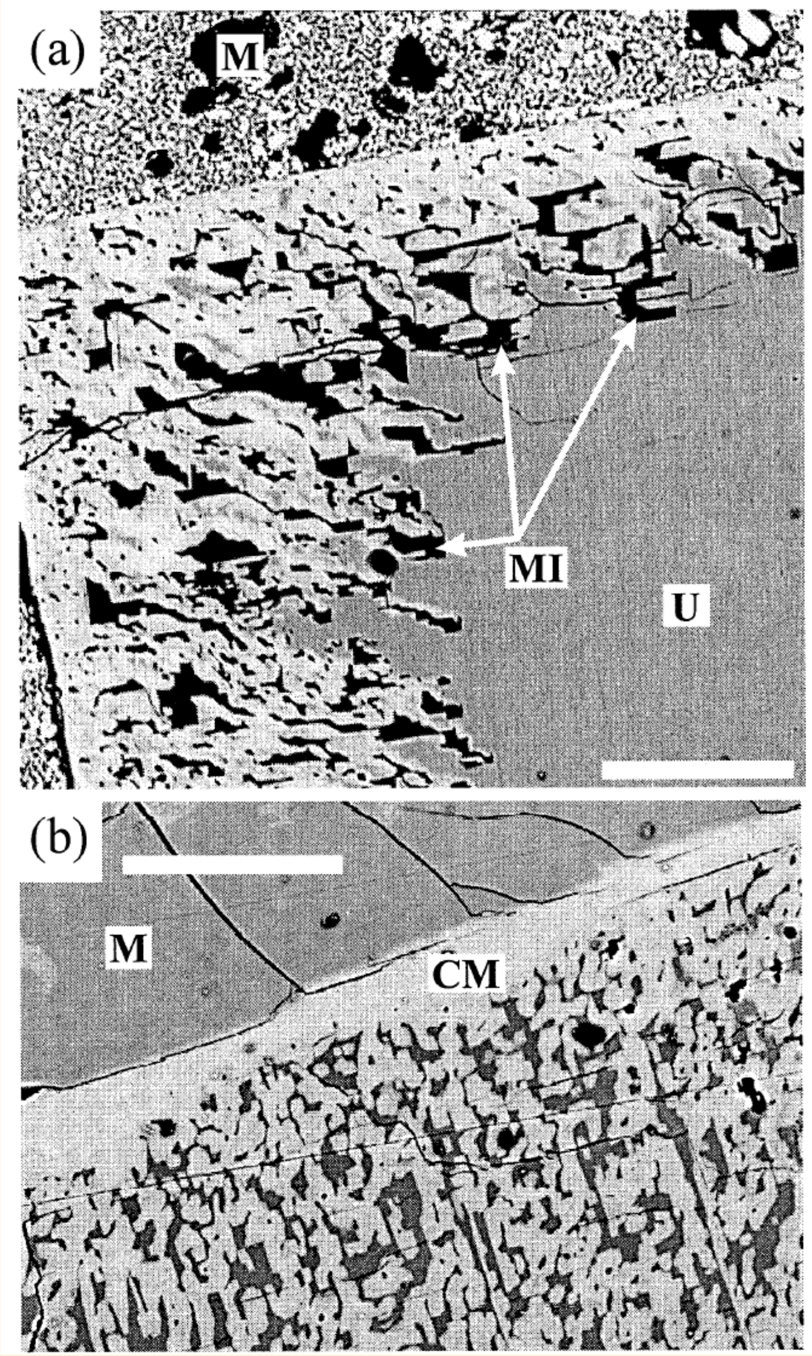
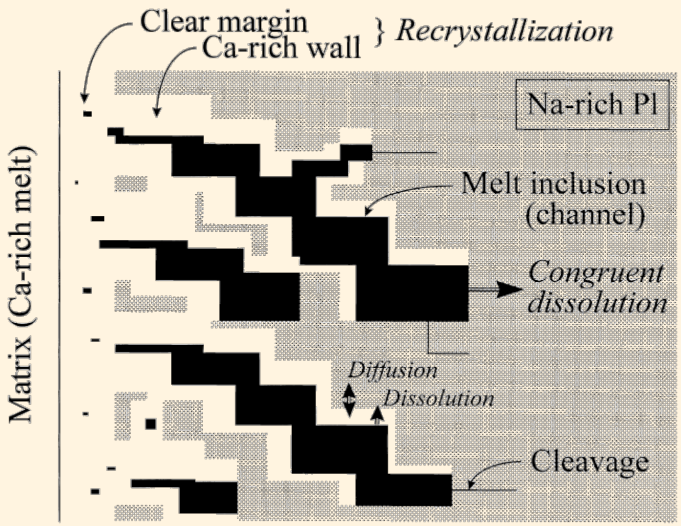


Fig. 5. A schematic illustration of cross-section cut by (100) showing that the dissolution proceeds through congruent dissolution and recrystallization process with subordinate diffusion in plagioclase.

Nakamura and Shimakita, 1998





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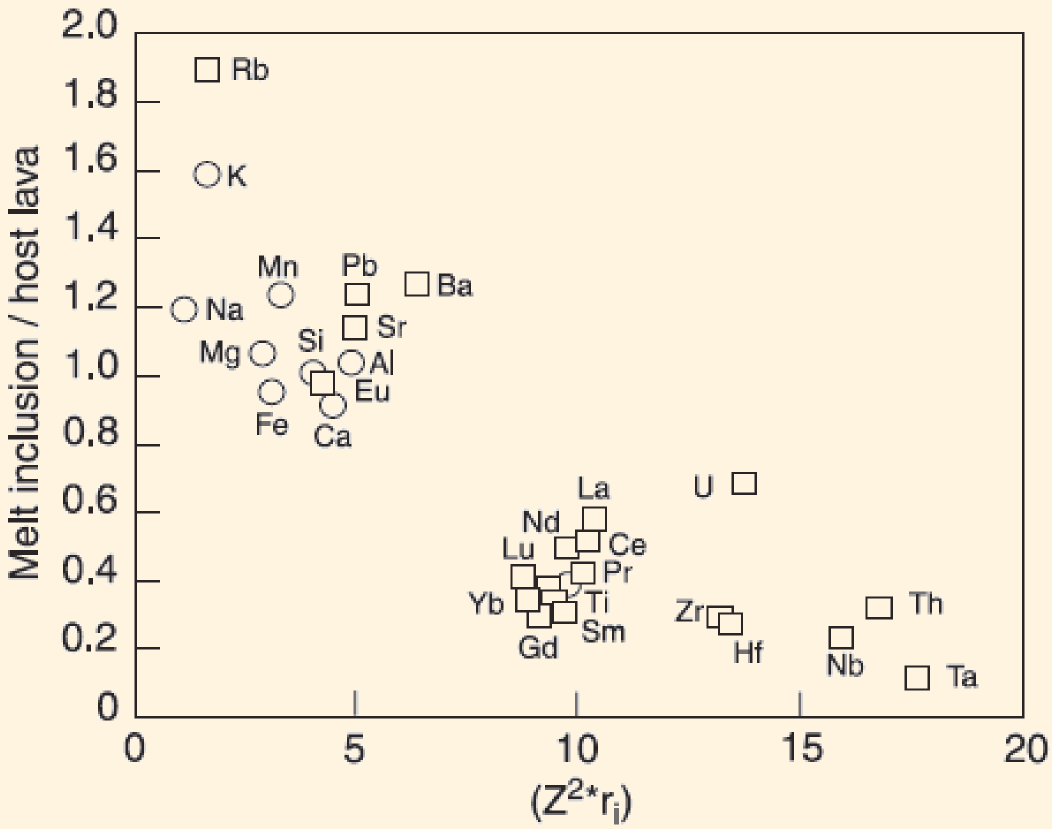
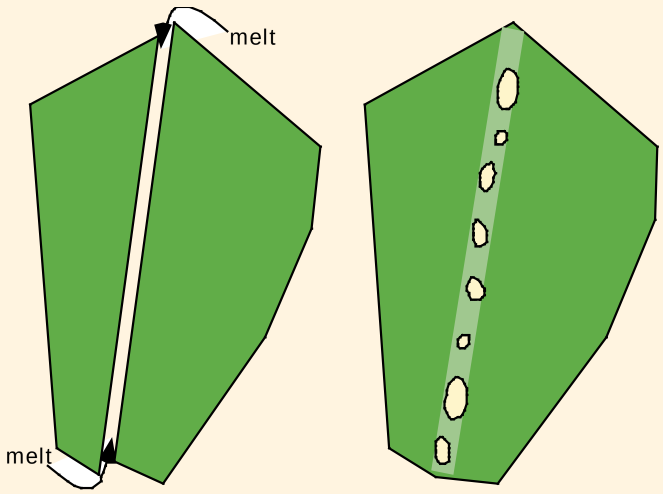
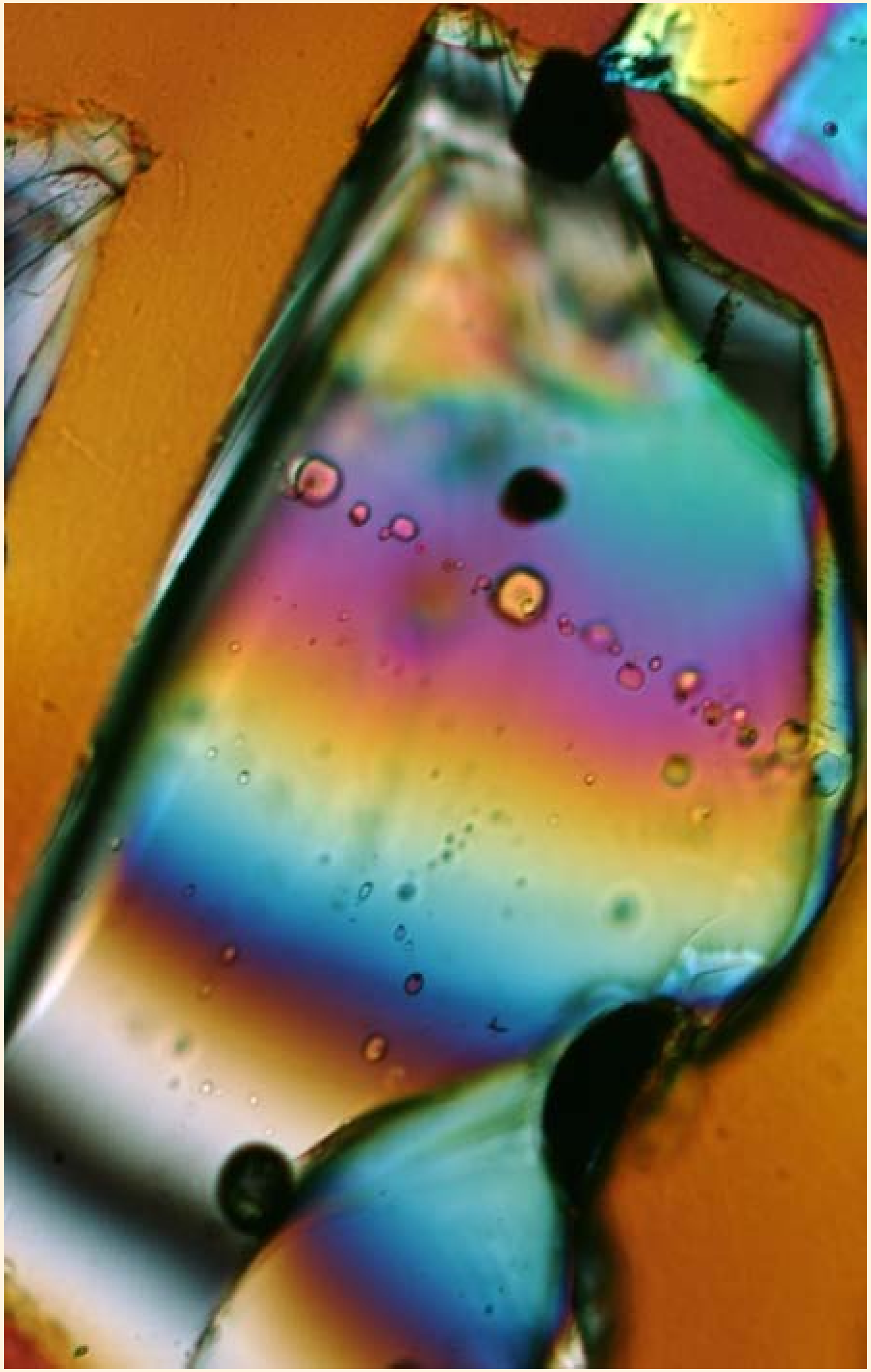


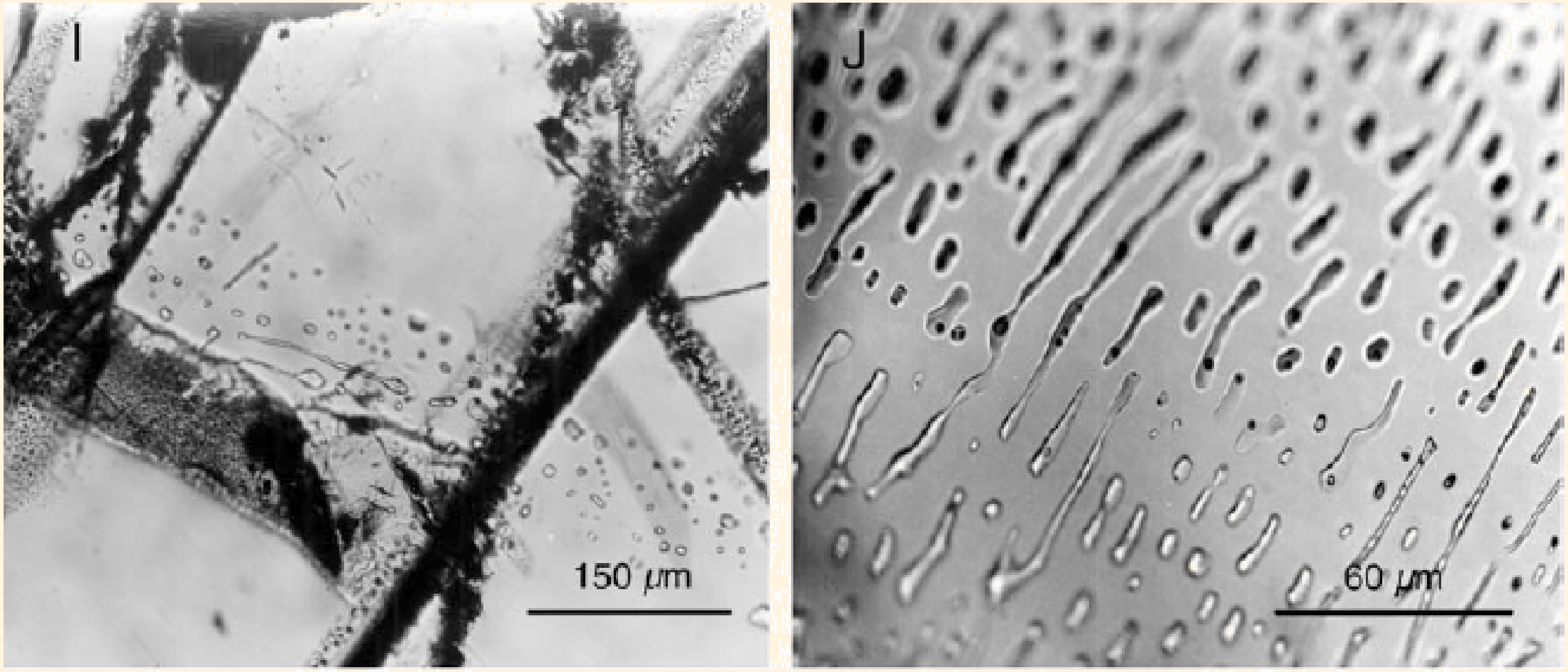
Michael et al. 2002

4. Melt filled fractures



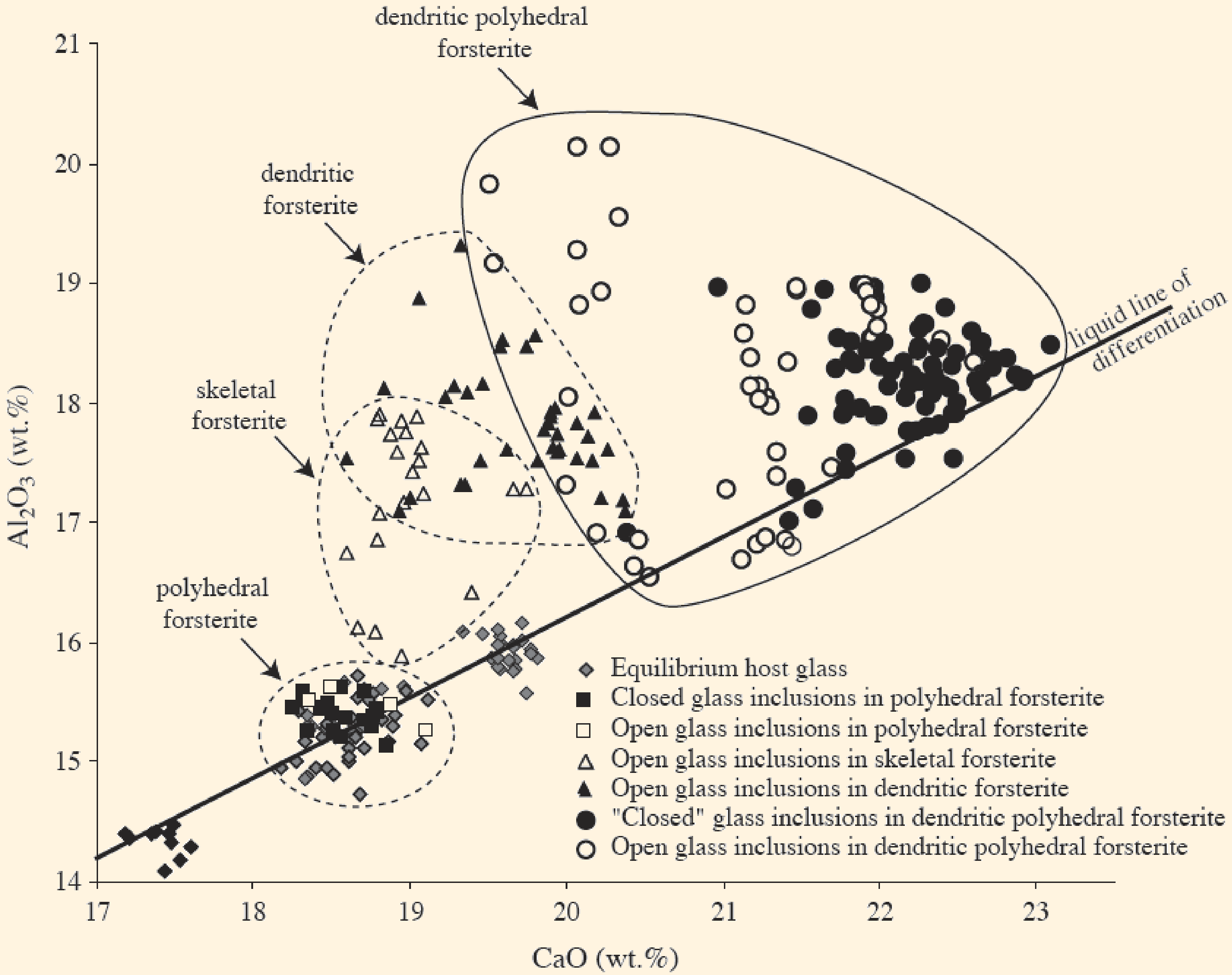
Typically small, hard to measure, define planar surface.

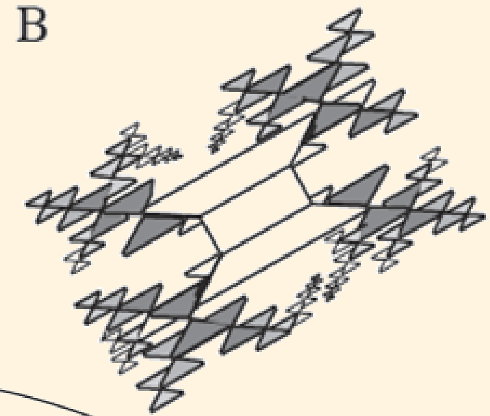


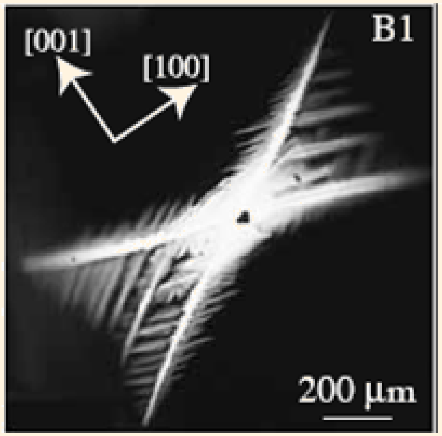


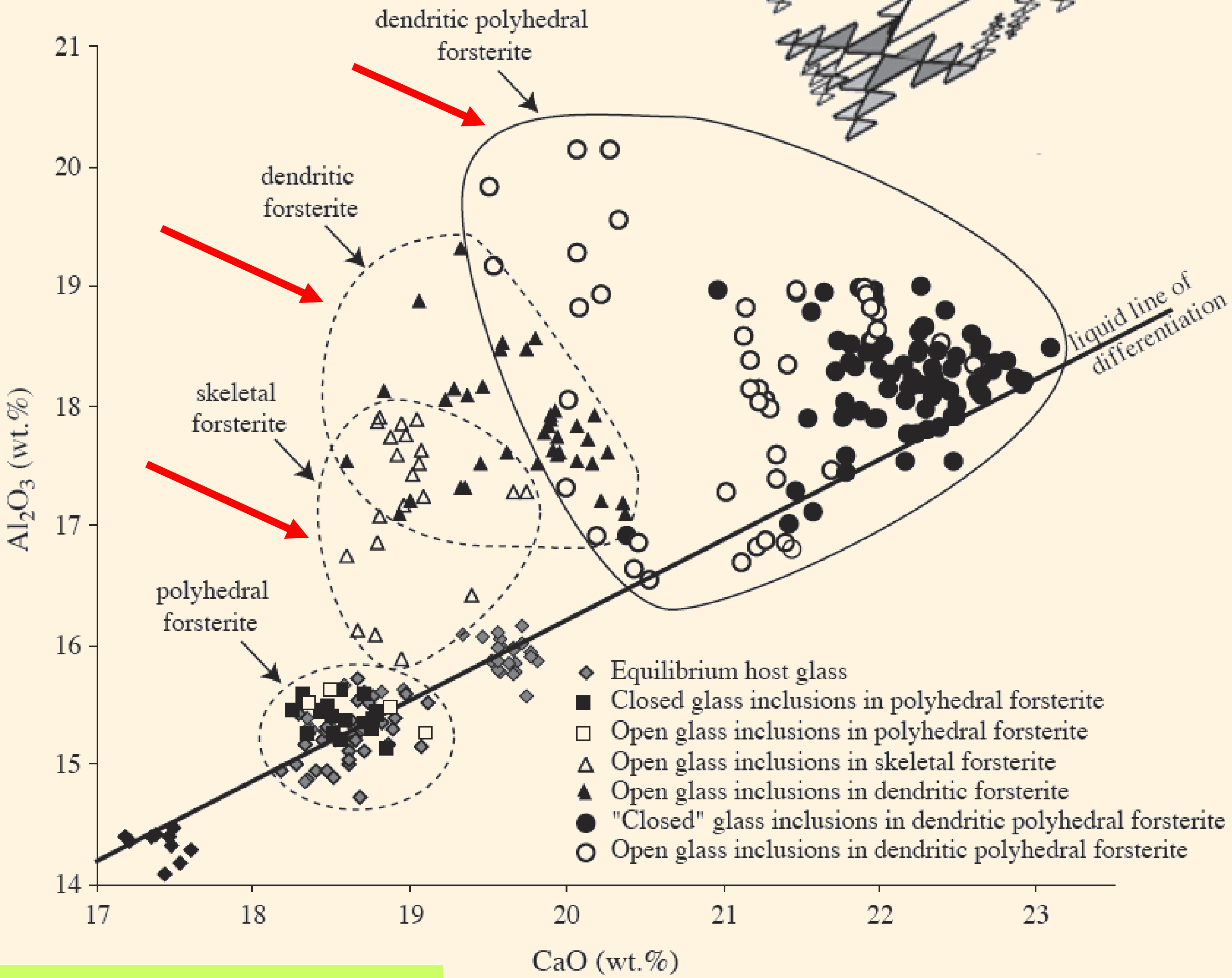
Schiano 2003

Faure and Schiano, 2005

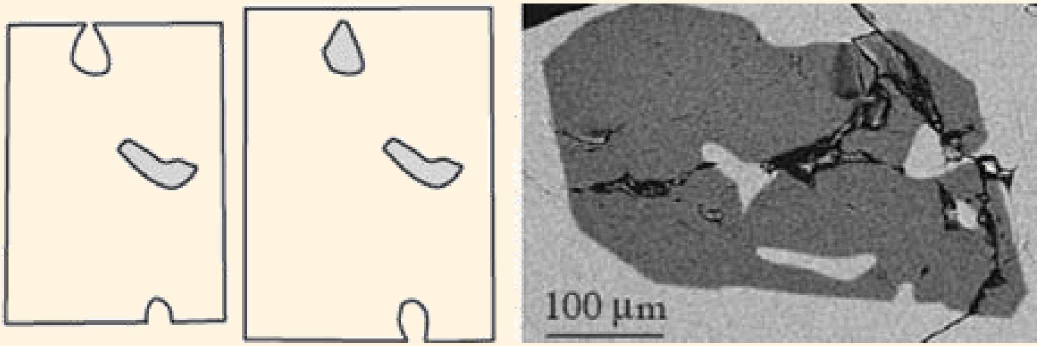


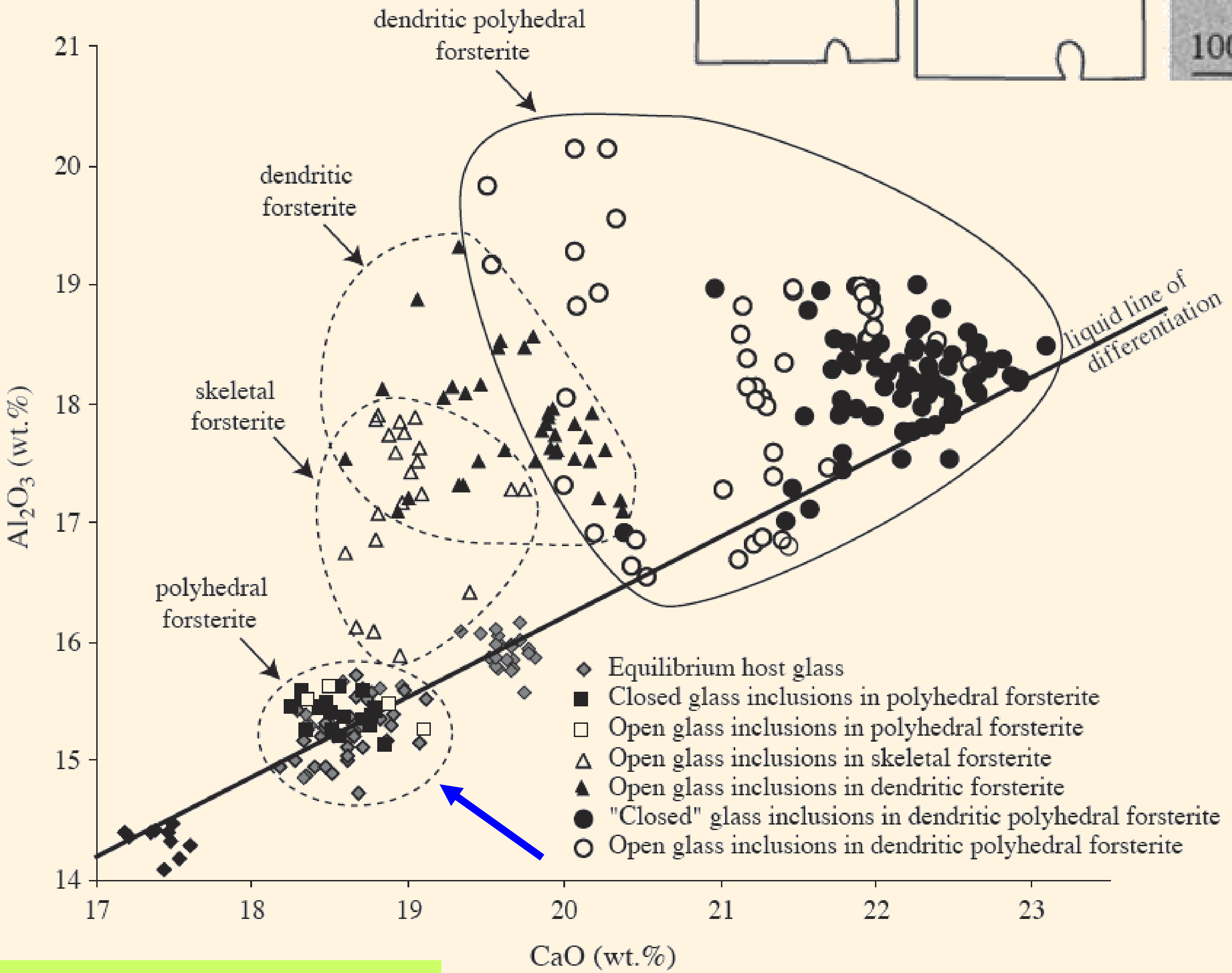




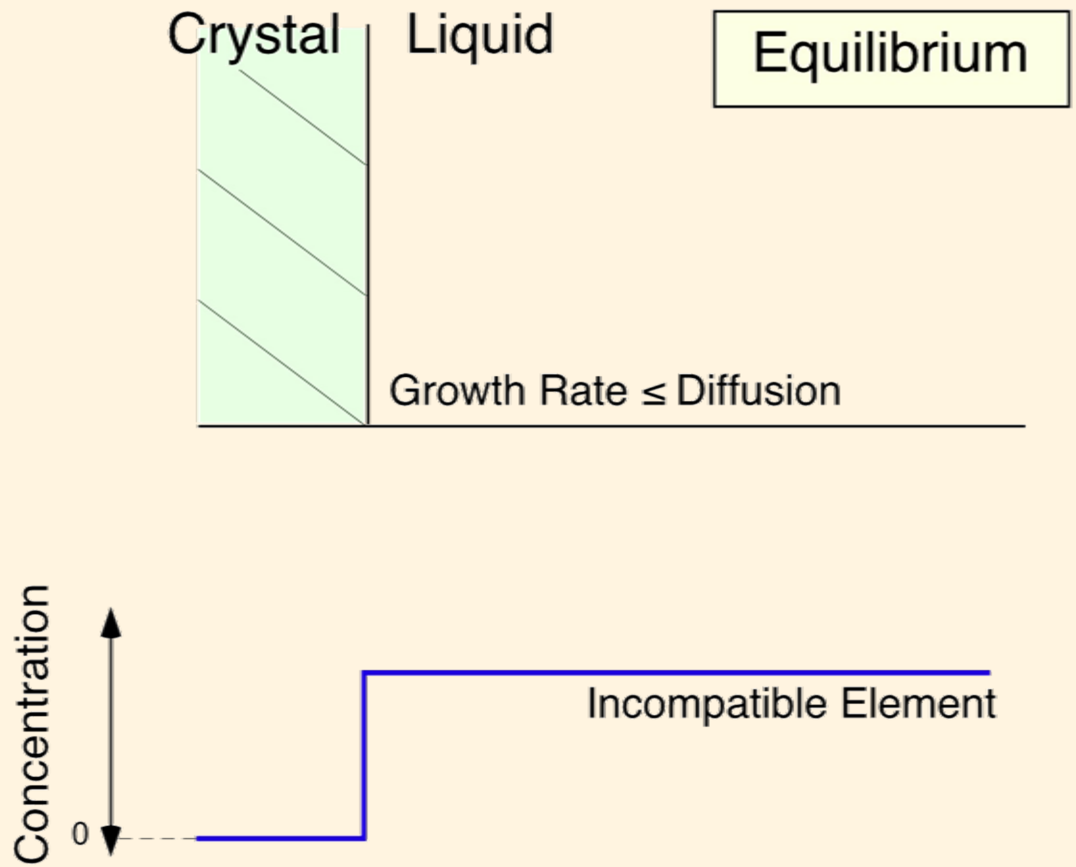


Faure and Schiano, 2005

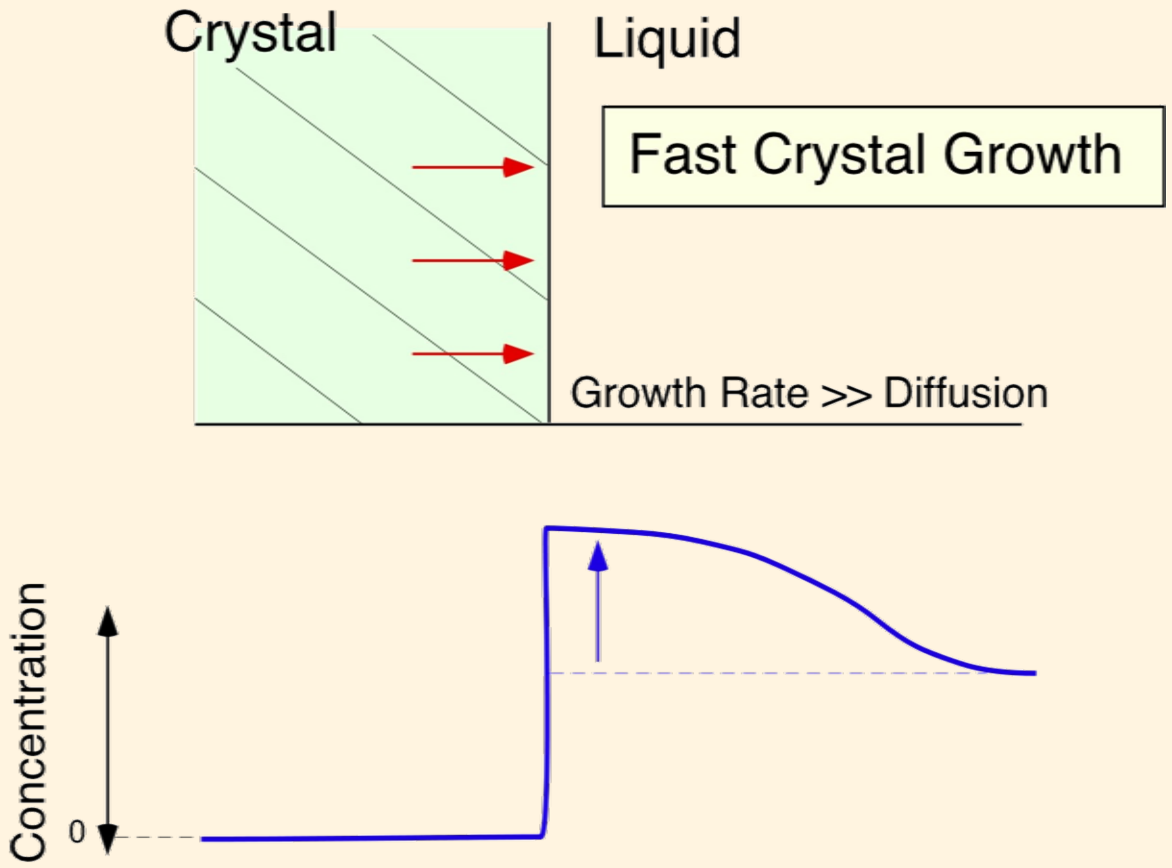


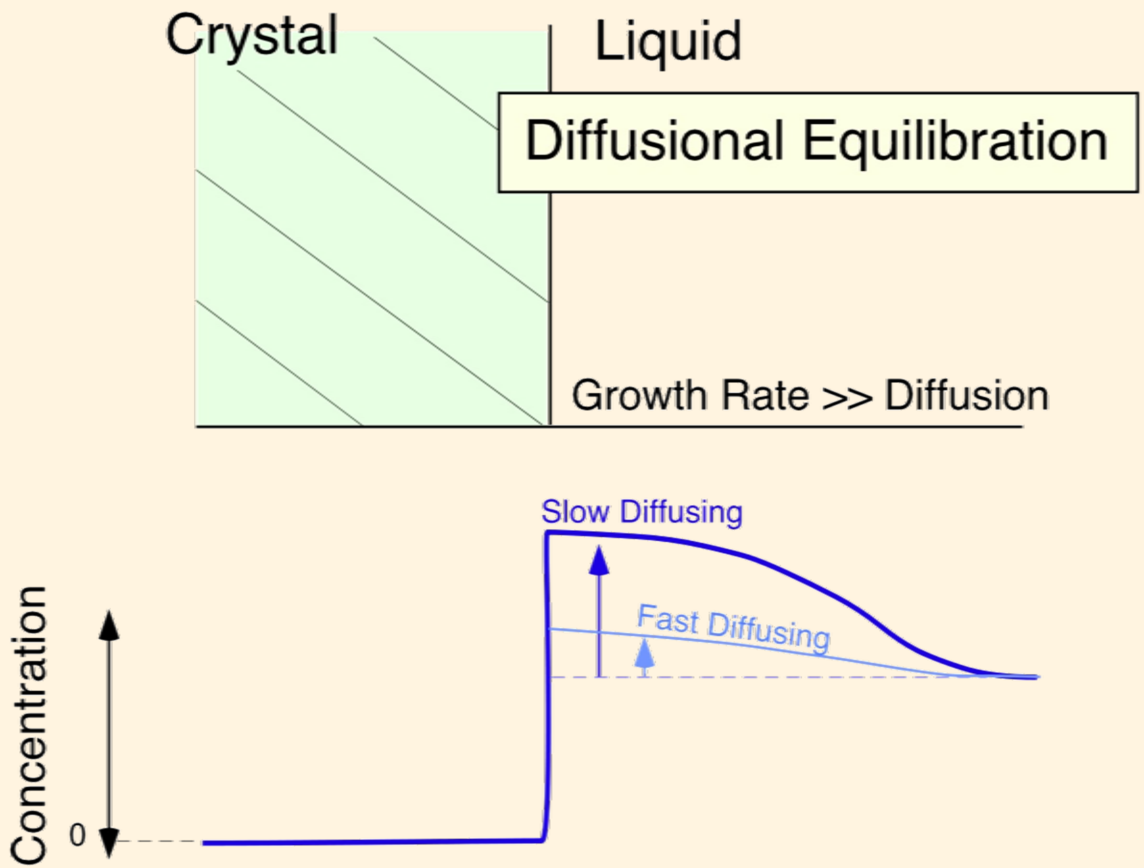


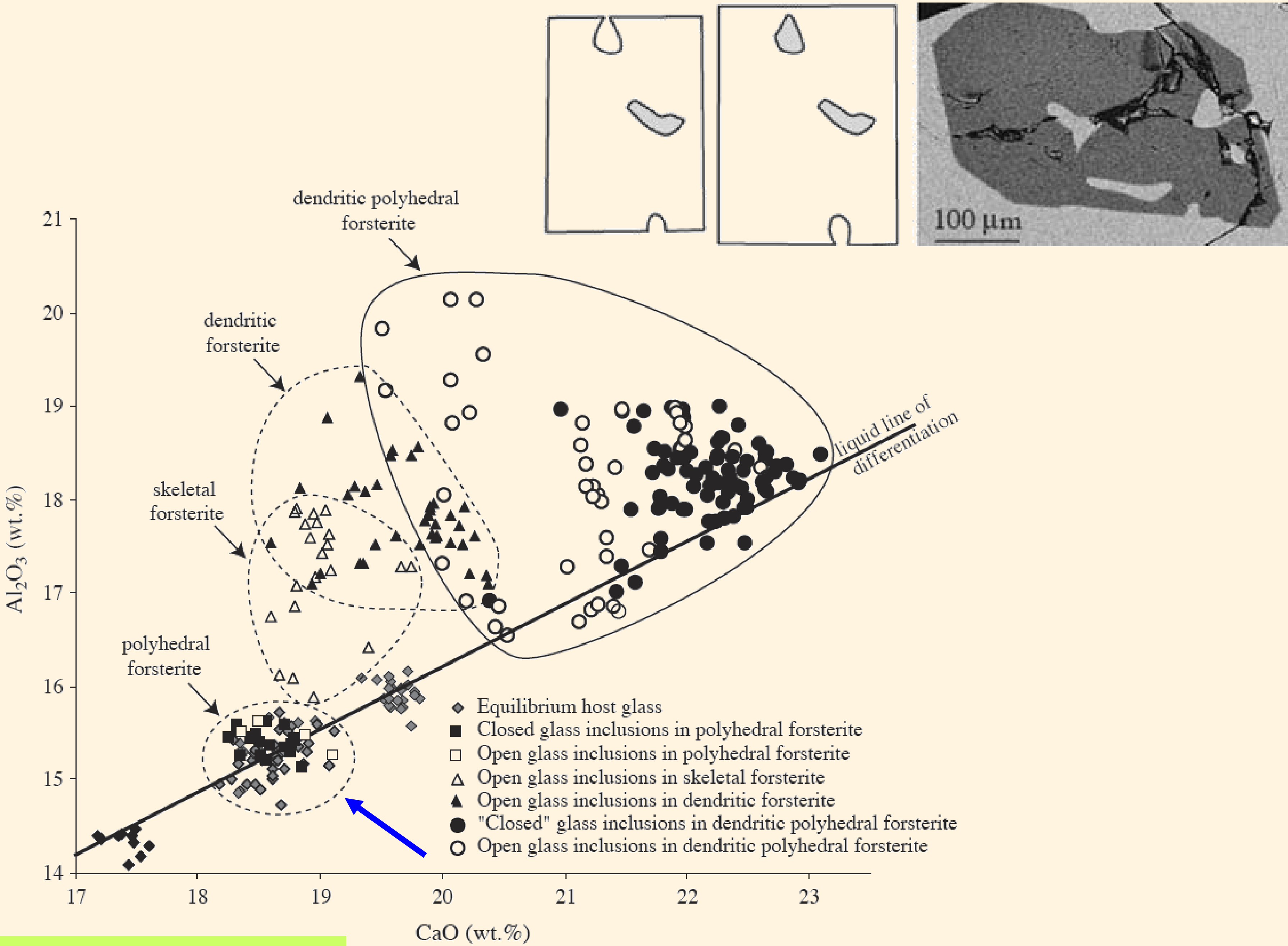
Faure and Schiano, 2005



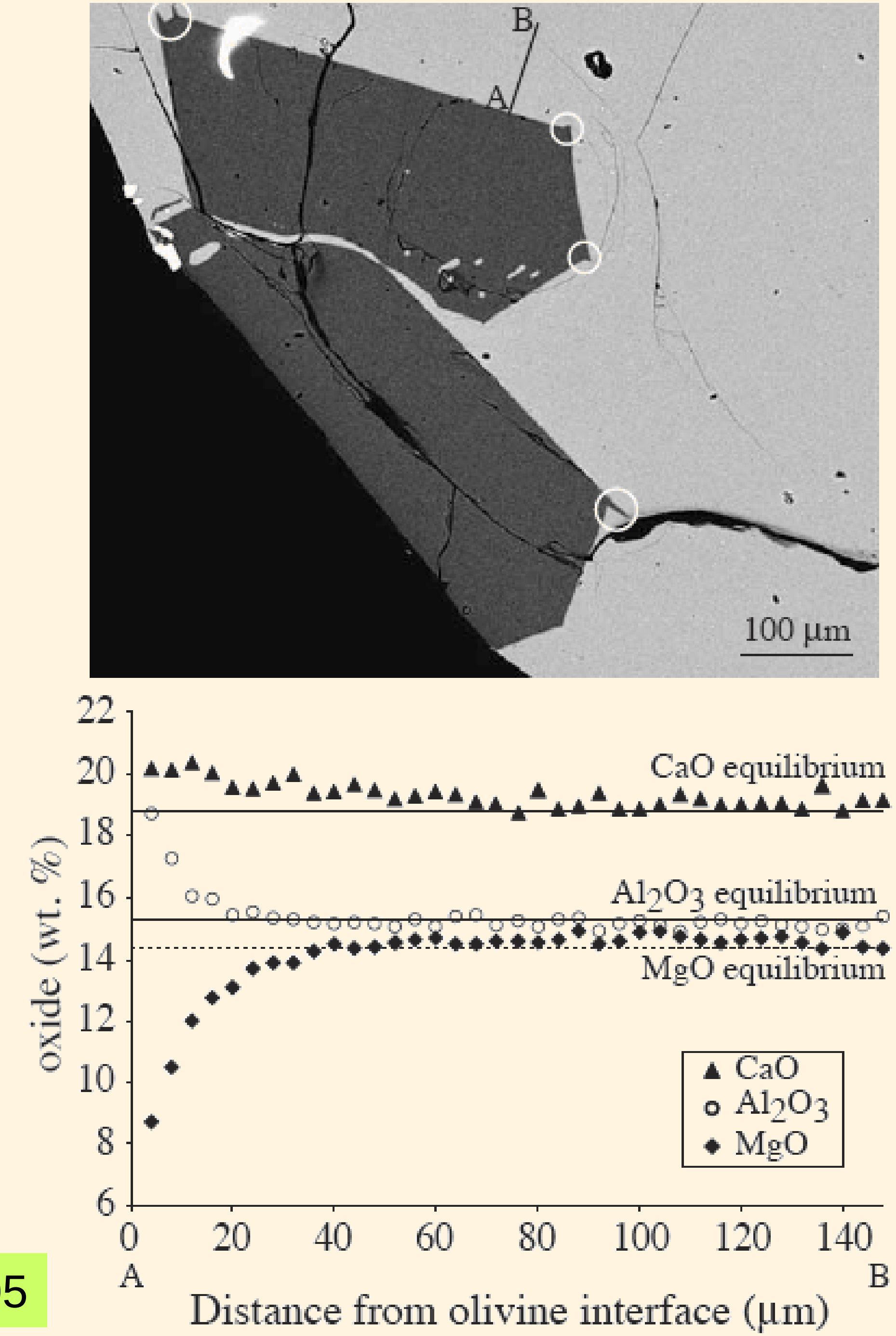
Crystal
Liquid
Equilibrium
Growth Rate ≤ Diffusion
Concentration
0
Incompatible Element


Crystal
Liquid
Fast Crystal Growth
Growth Rate >> Diffusion
Concentration
0


Crystal
Liquid
Diffusional Equilibration
Growth Rate >> Diffusion
Slow Diffusing
Fast Diffusing
Concentration
0



Faure and Schiano, 2005



Faure and Schiano, 2005

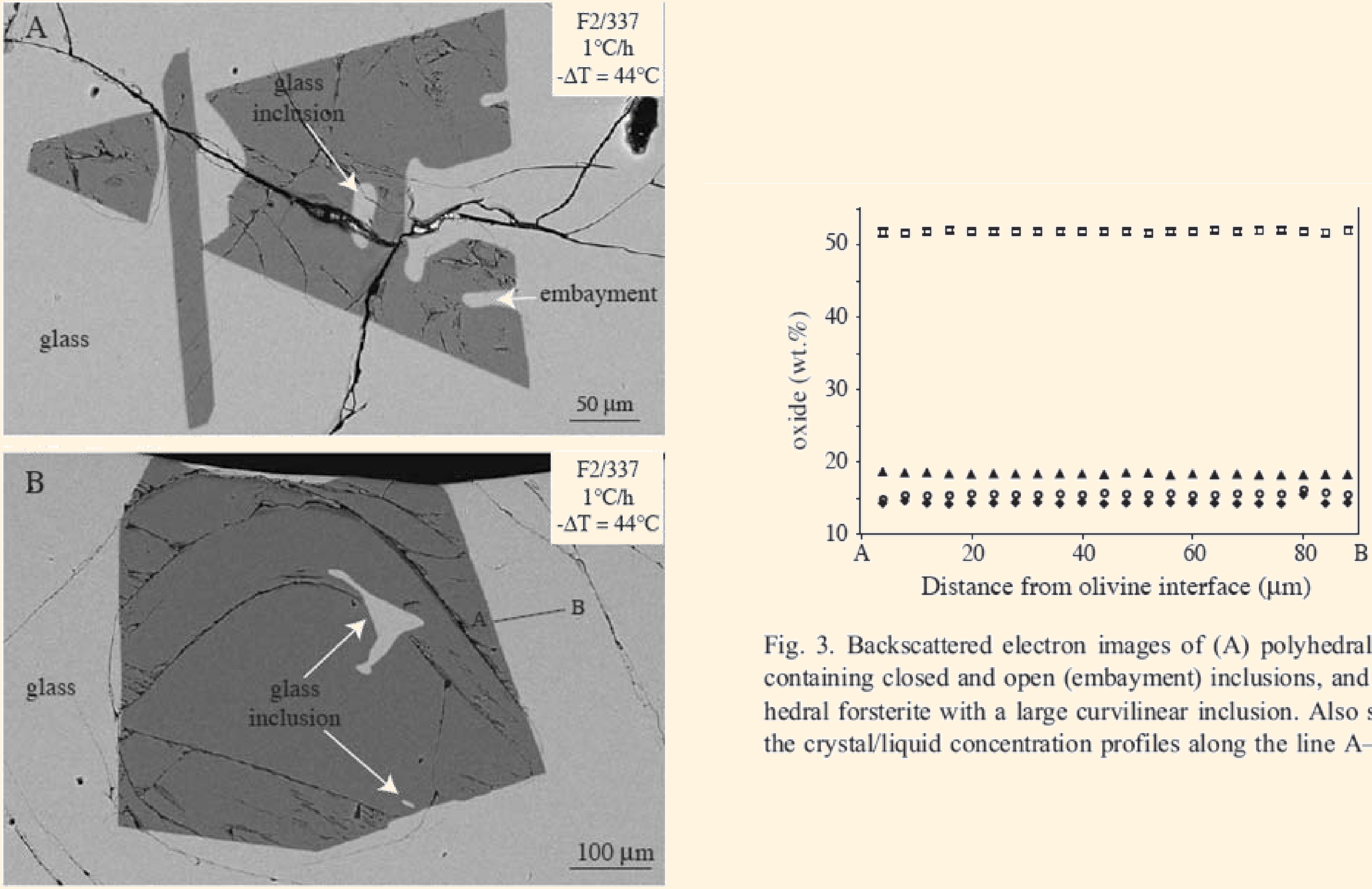
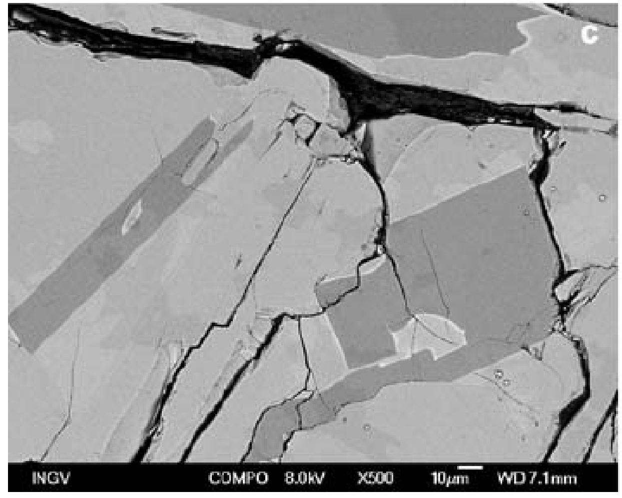
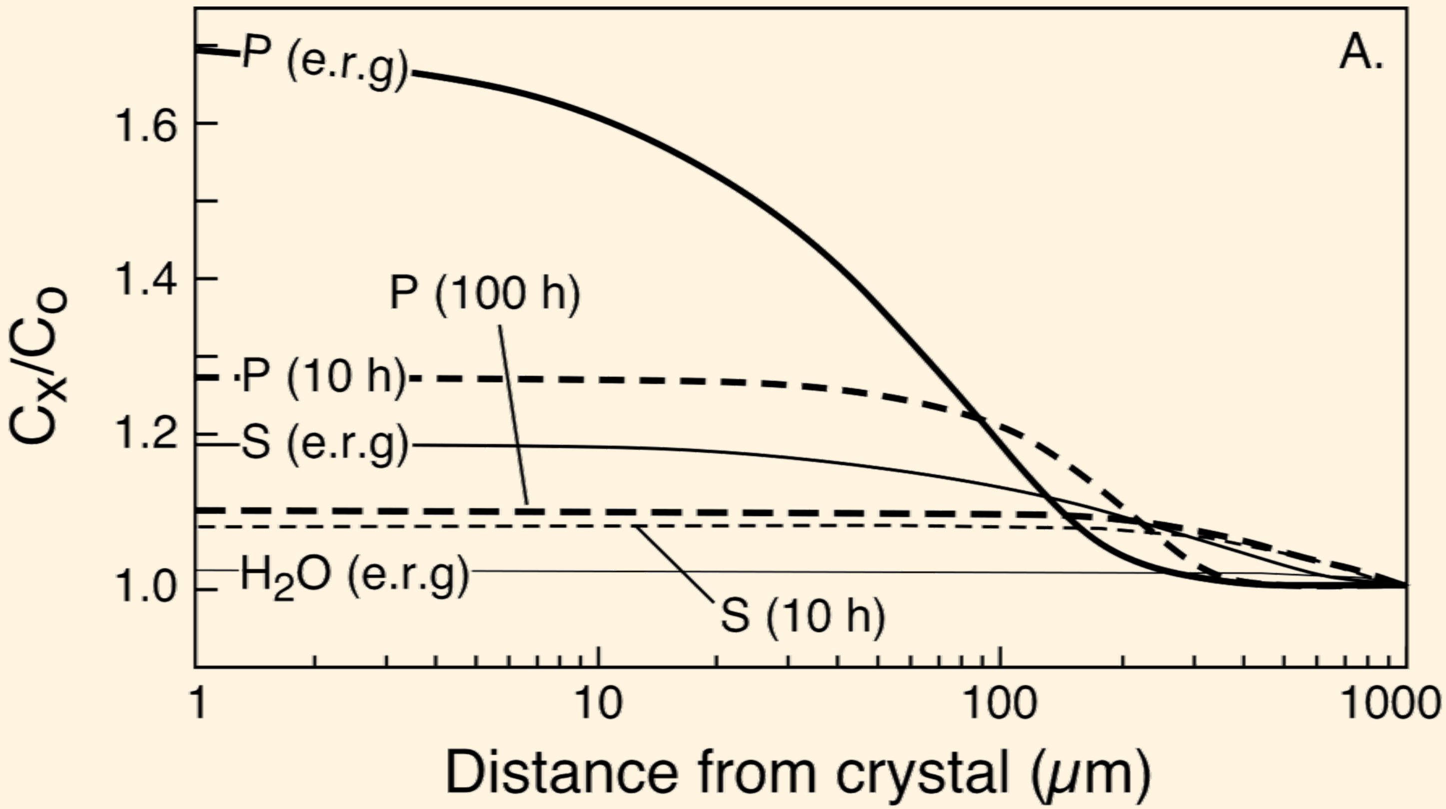


Fig. 3. Backscattered electron images of (A) polyhedral forsterite containing closed and open (embayment) inclusions, and (B) polyhedral forsterite with a large curvilinear inclusion. Also shown are the crystal/liquid concentration profiles along the line A–B.



Baker et al. 2008



Do natural melt inclusions trap boundary layers?

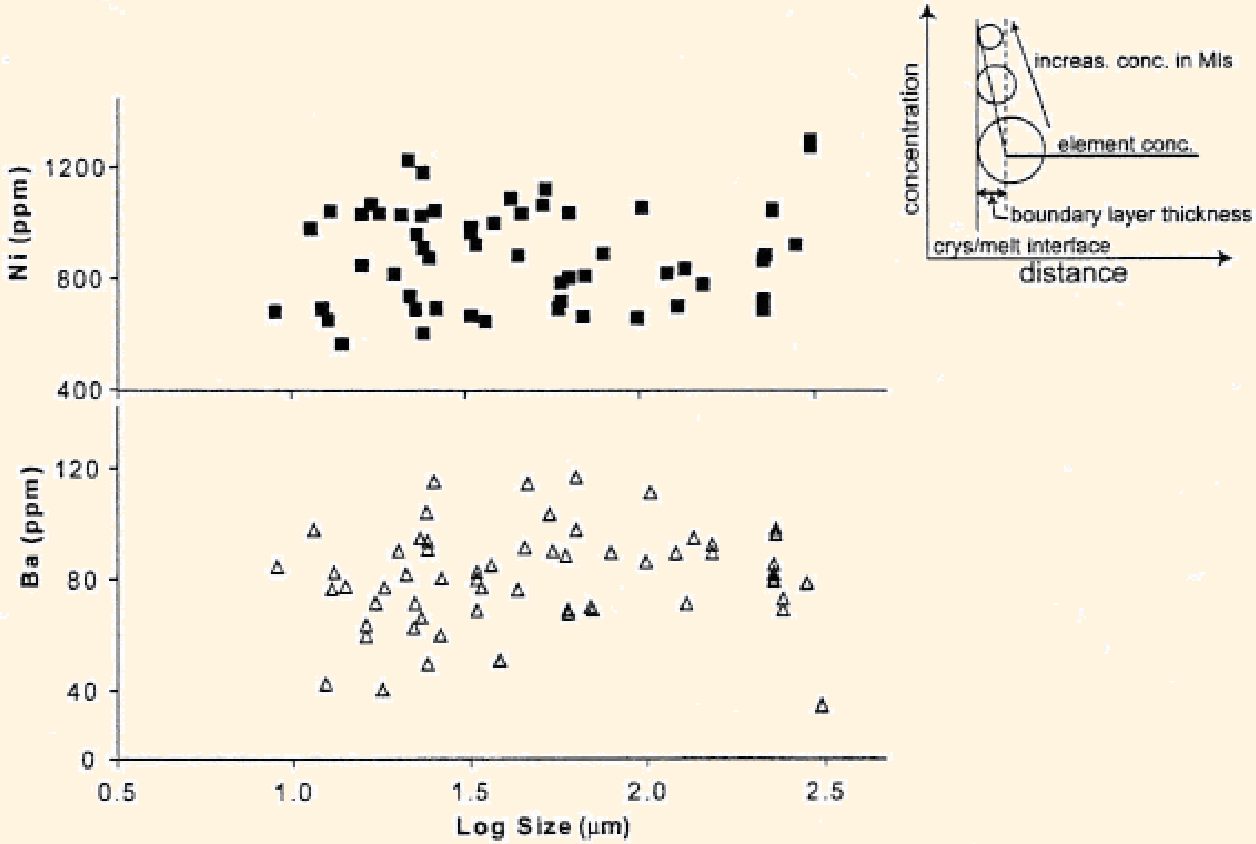


Fig. 1 - Concentration of Ni and Ba in MIs in olivine from Mauna Loa as function of MI size

Fedele et al. 2009

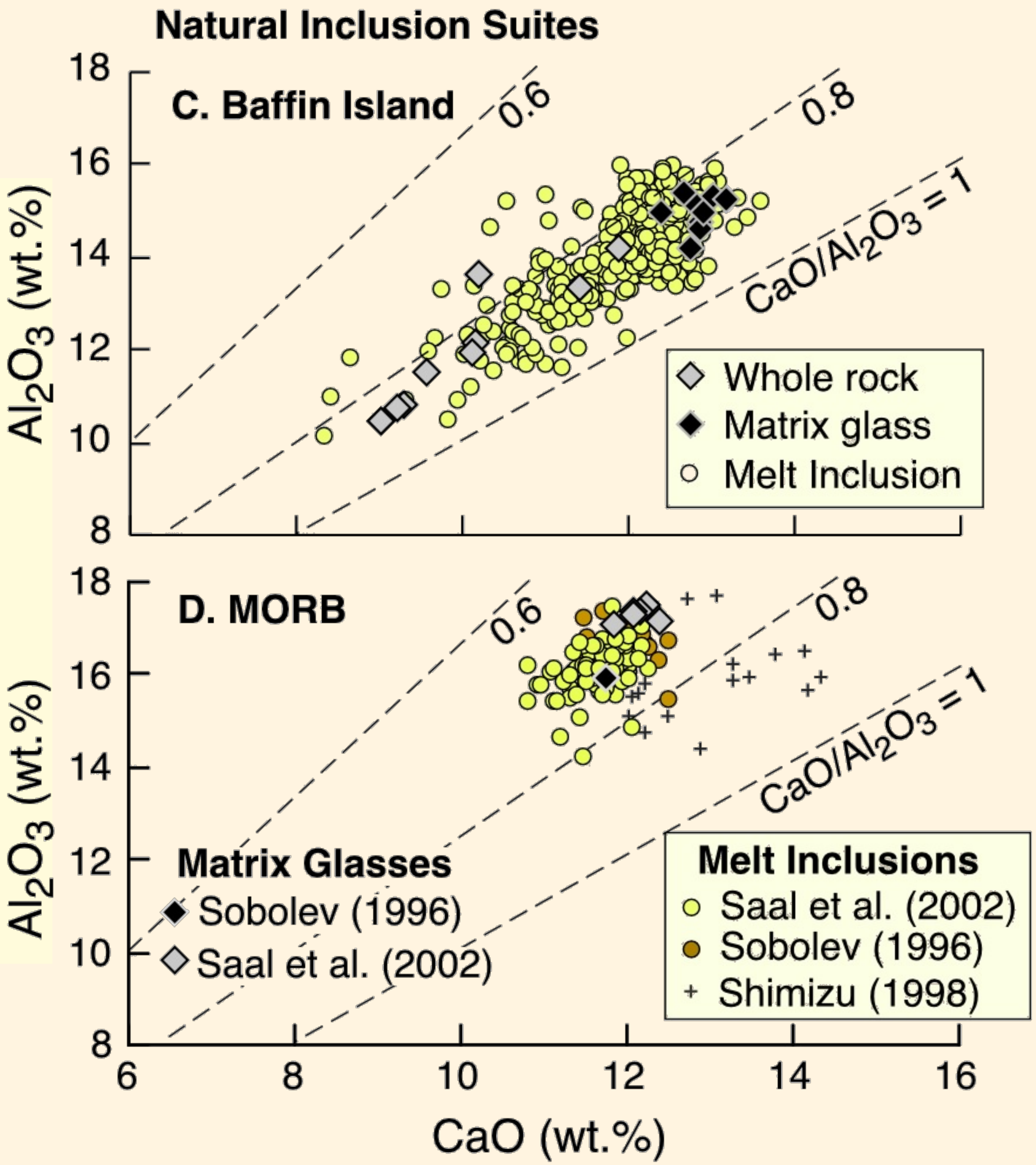
- Most natural suites do not show clear indications of boundary layer effects

- Perhaps we sample larger inclusions (only significant at < 30 μm)

- Longer isothermal times in natural samples

- Are boundary layers static?

- Kinetic experiments



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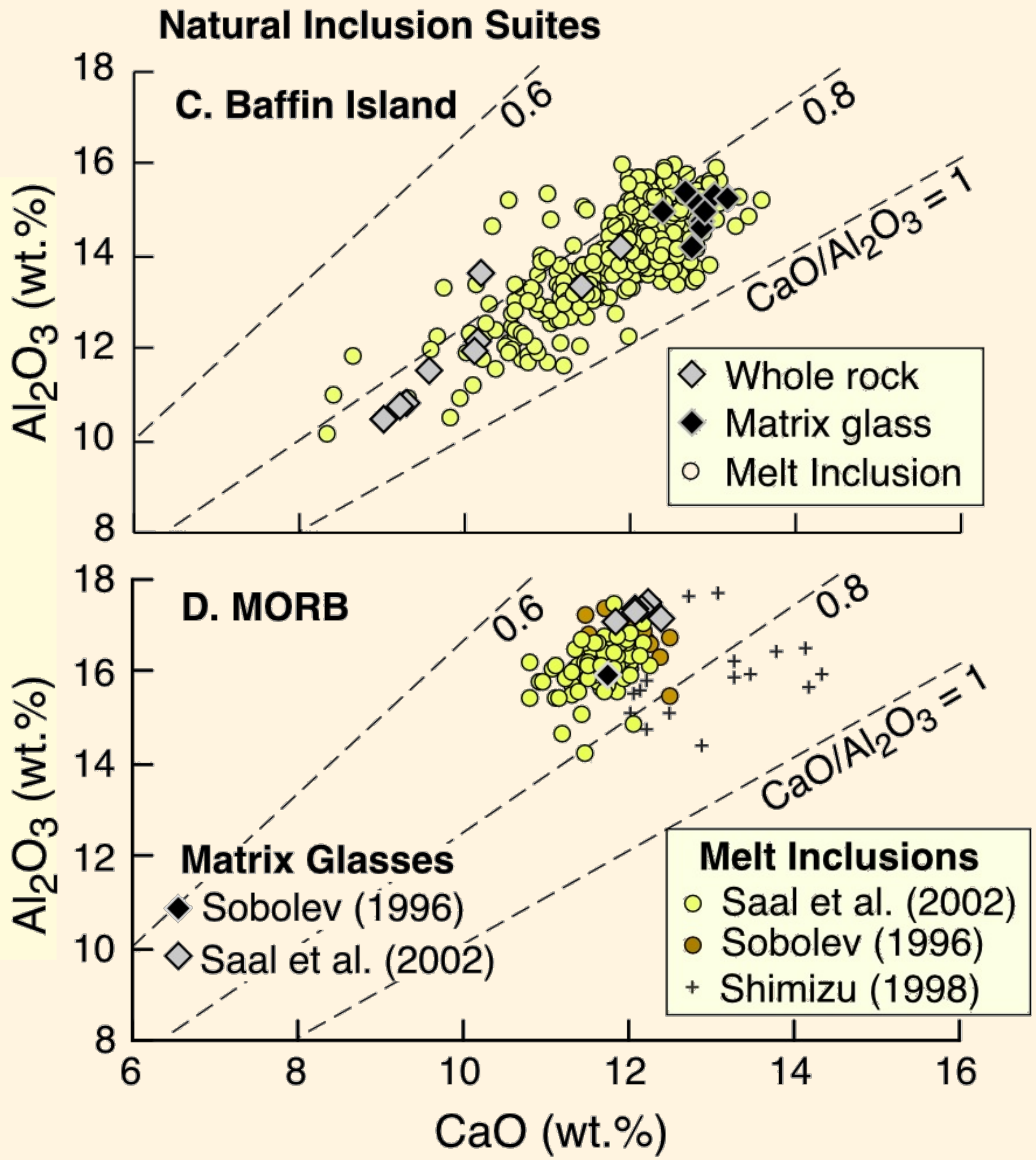
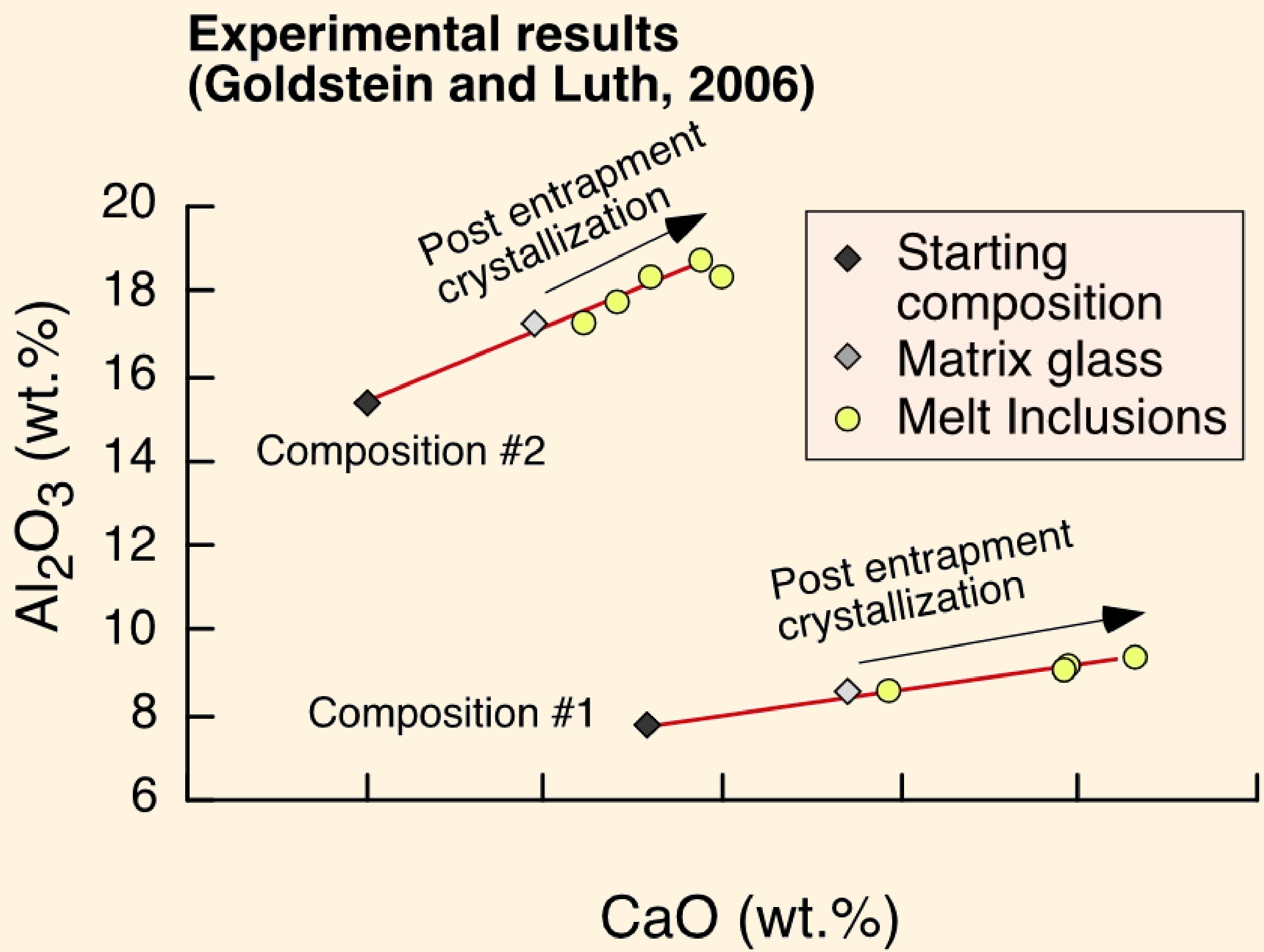
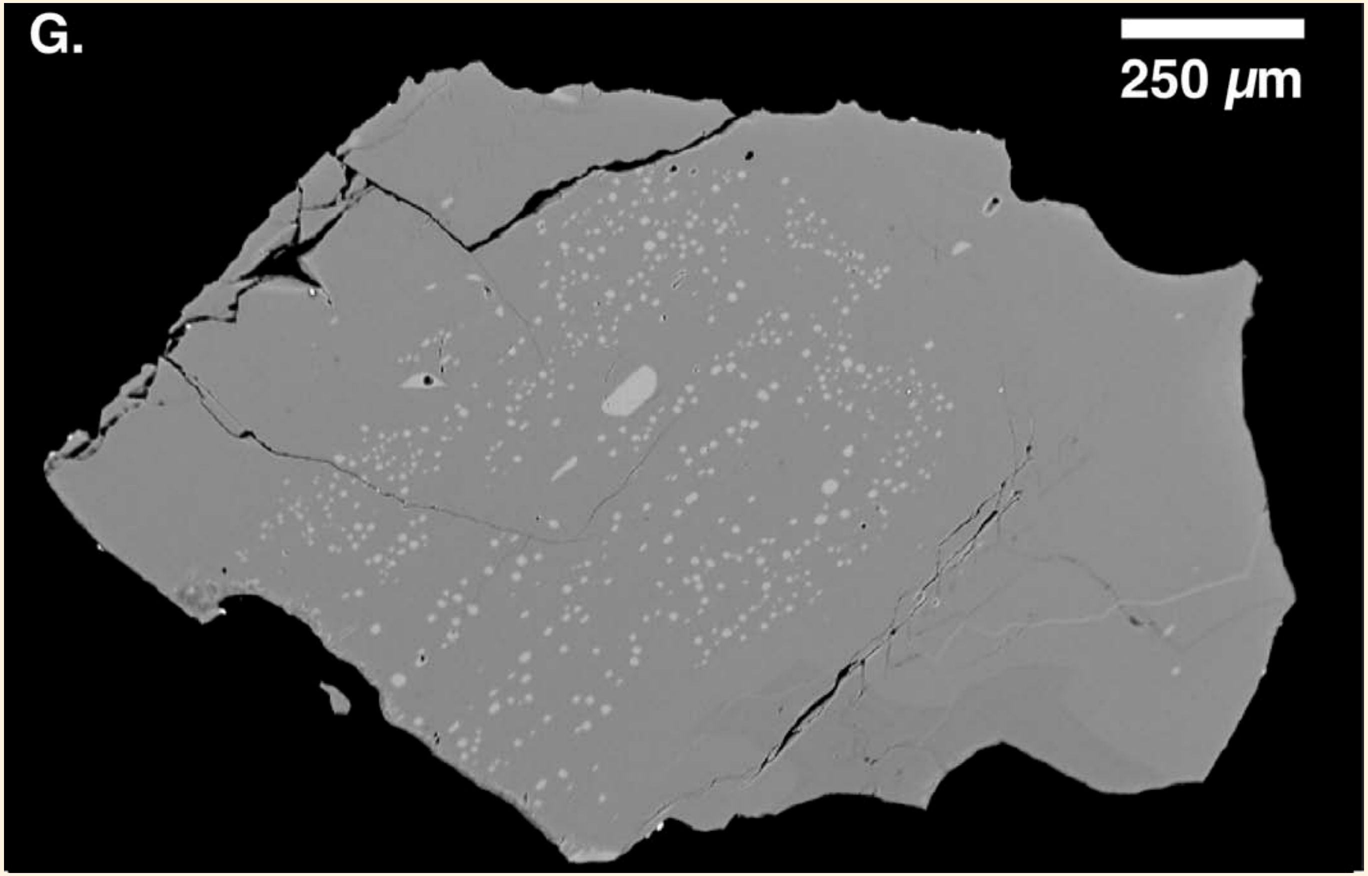
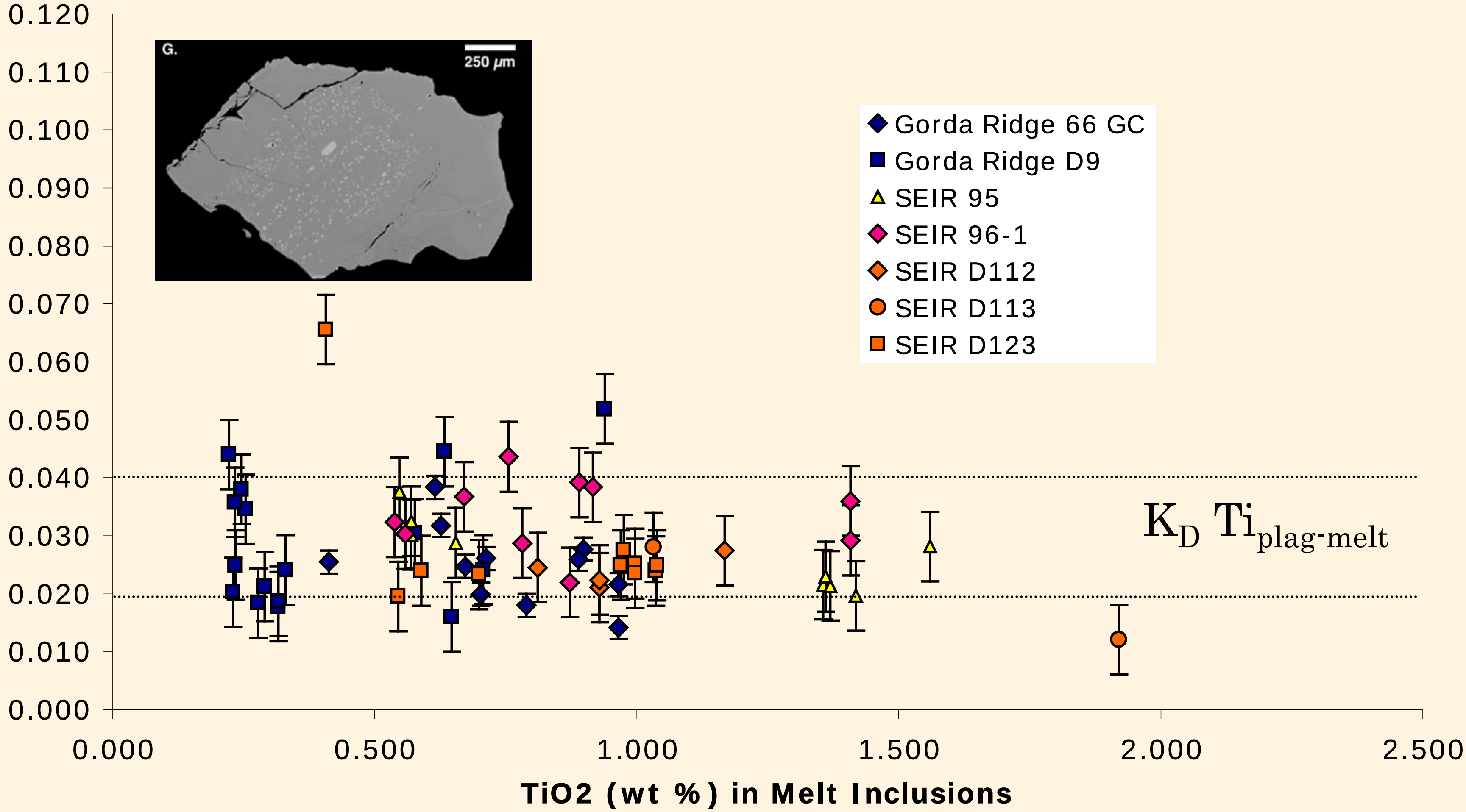


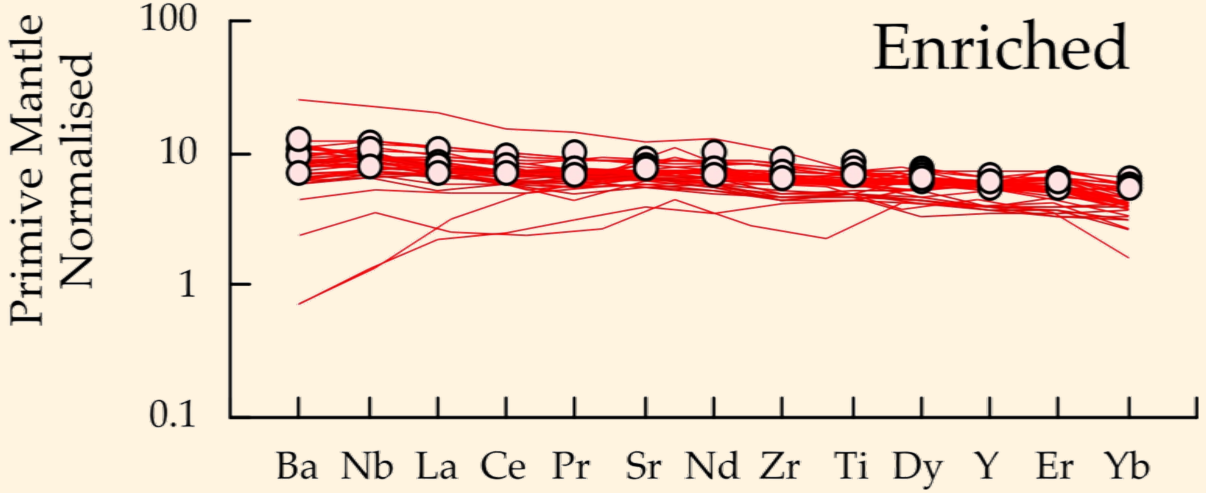


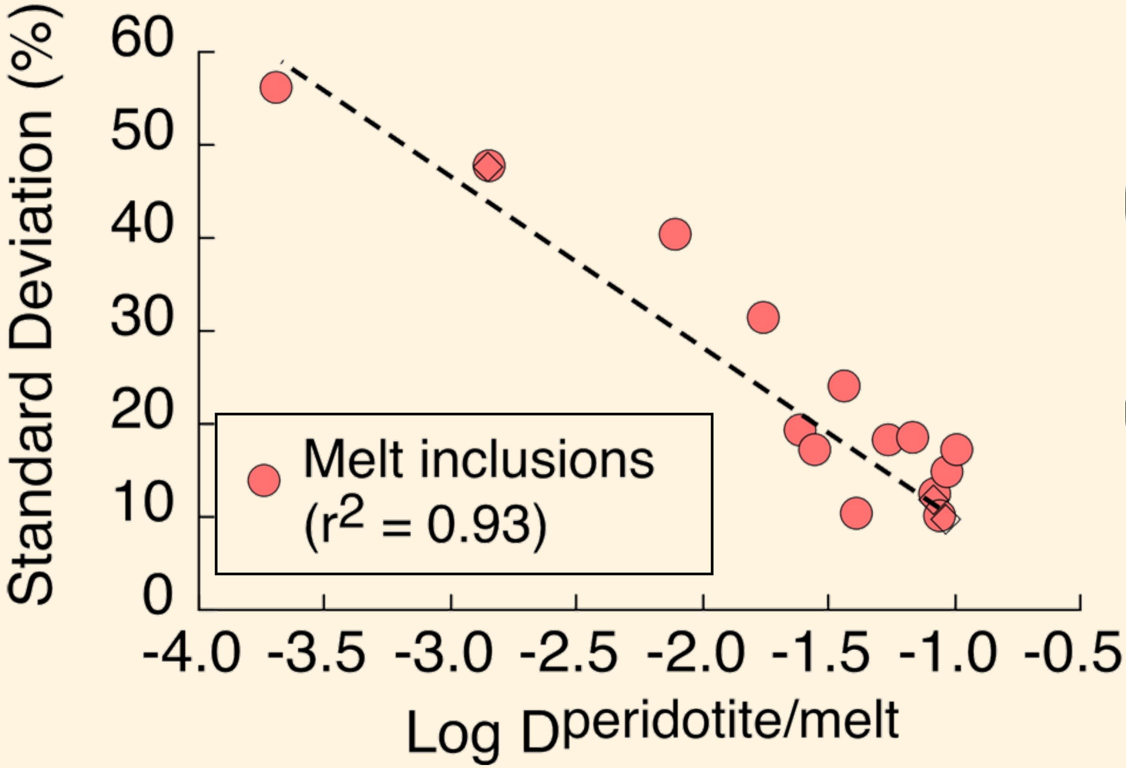
Not all experimental studies show boundary layer effects

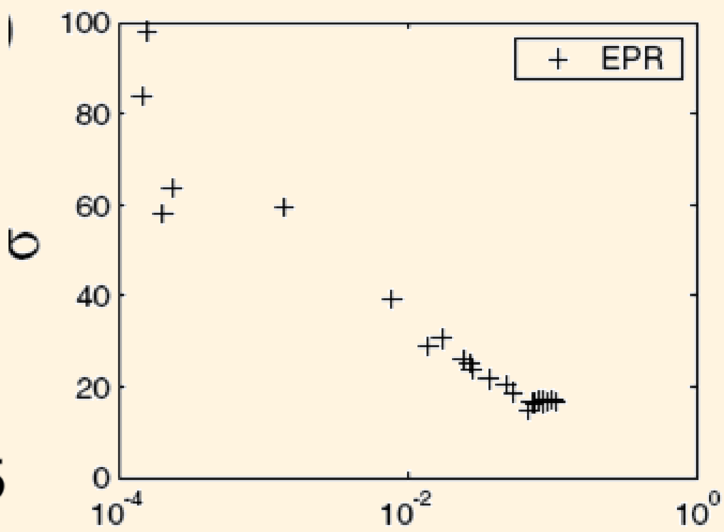

G.
250 μm

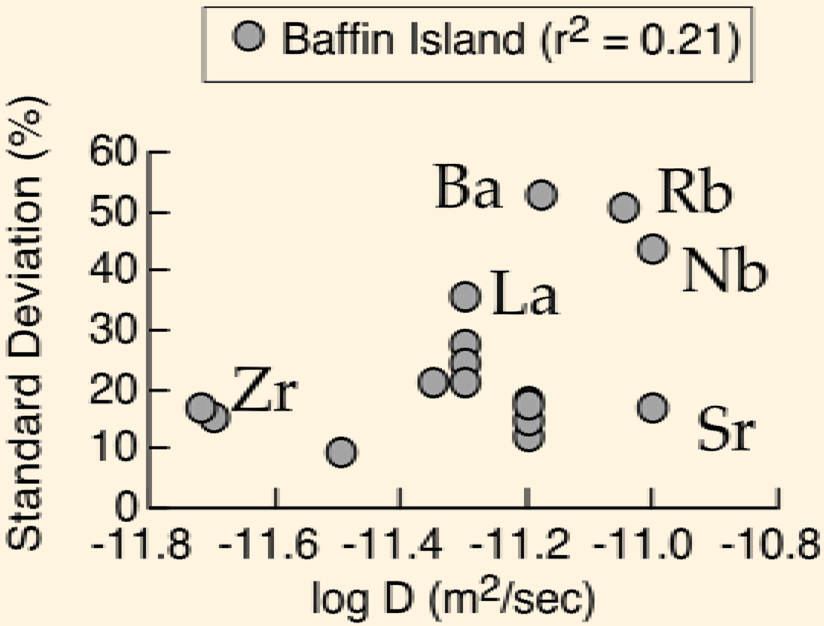


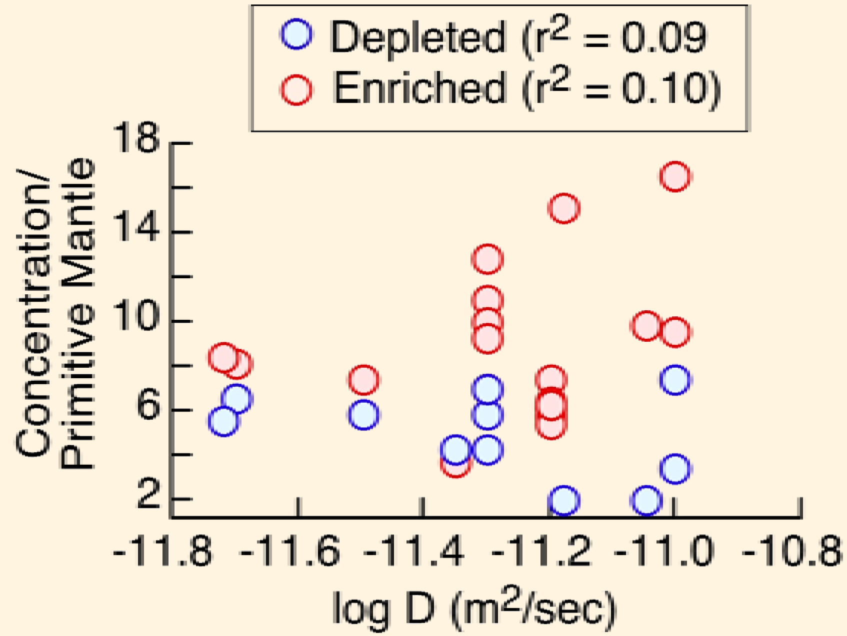
G.
250 μm
Gorda Ridge 66 GC
Gorda Ridge D9
SEIR 95
SEIR 96-1
SEIR D112
SEIR D113
SEIR D123
$K_D\ Ti_{plag\text{-}melt}$
0.120
0.110
0.100
0.090
0.080
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0.000
0.500
1.000
1.500
2.000
2.500
TiO2 (wt %) in Melt Inclusions


Enriched
Primitive Mantle Normalised
100
10
1
0.1
Ba Nb La Ce Pr Sr Nd Zr Ti Dy Y Er Yb


Standard Deviation (%)
60
50
40
30
20
10
0
Melt inclusions
(r^2 = 0.93)
-4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5
Log Dperidotite/melt


σ
100
80
60
40
20
0
EPR
10^{-4}
10^{-2}
10^{0}





No relation between diffusivity and variation or degree of enrichment/depletion

Points to remember

- Melt inclusion formation is a normal part of crystallization of many minerals
- Inclusion formation occurs in a few different ways but rapid growth followed by textural equilibration is probably most important
- The compositions of most melt inclusions do not appear to be effected by the trapping process