Evolution of Melt Inclusions

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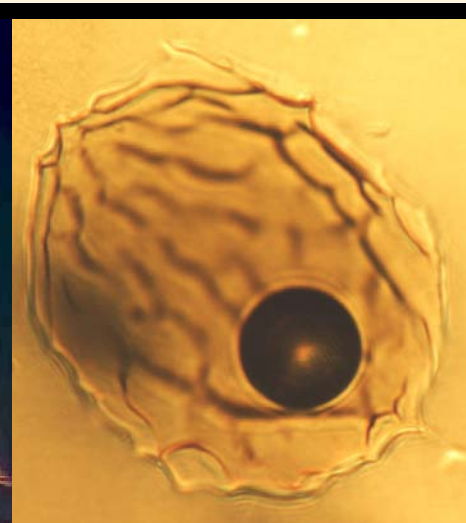
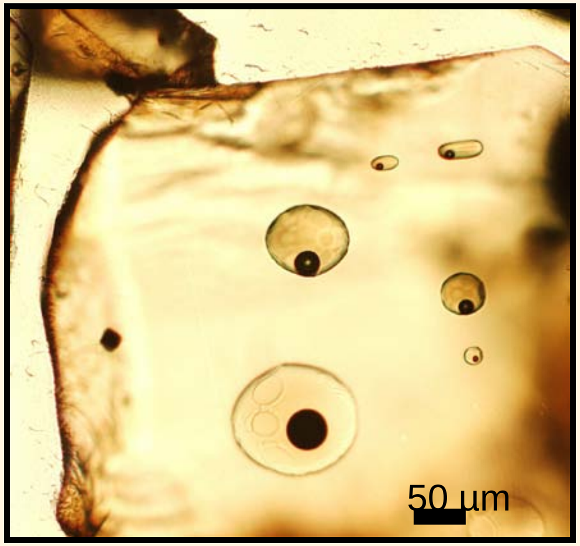


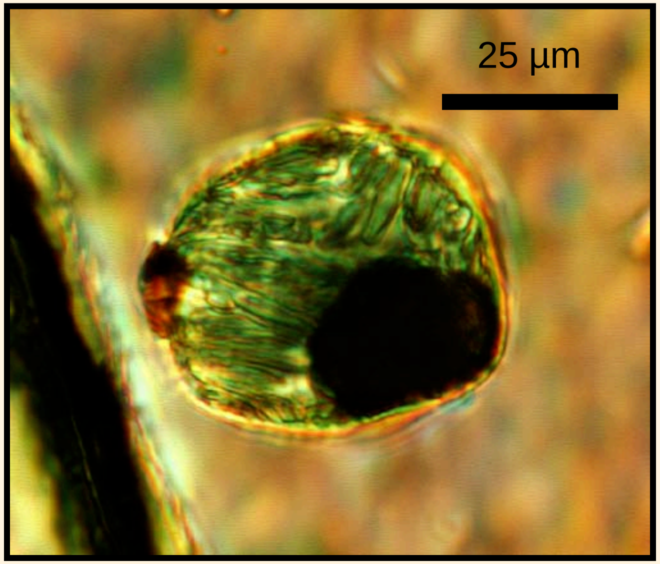
Key Questions

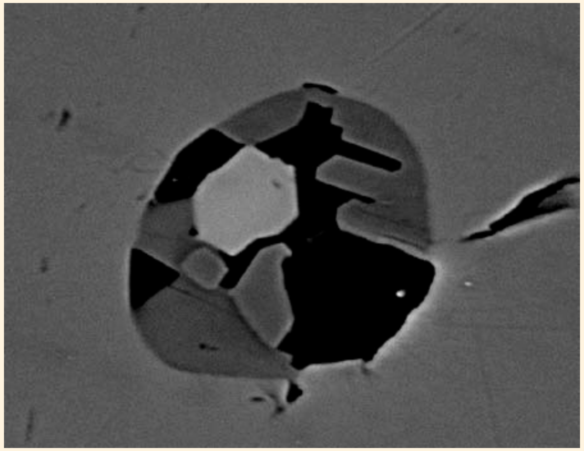
- What are the processes that control evolution of melt inclusions after trapping?
- Do these produce irreversible changes in composition?
- Can modification of melt inclusions during evolution be recognized and corrected?

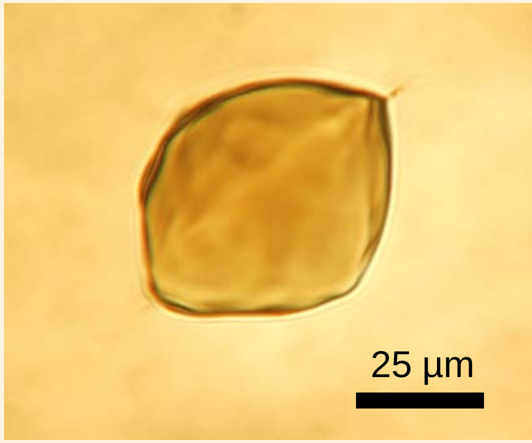
Evolution of melt inclusions after trapping

Important impact on physical appearance <u>and</u> chemical compositions









Melt Inclusion Variations

- Crystallization
- Assimilation
- Magma mixing
- Source heterogeneity
- Degassing*

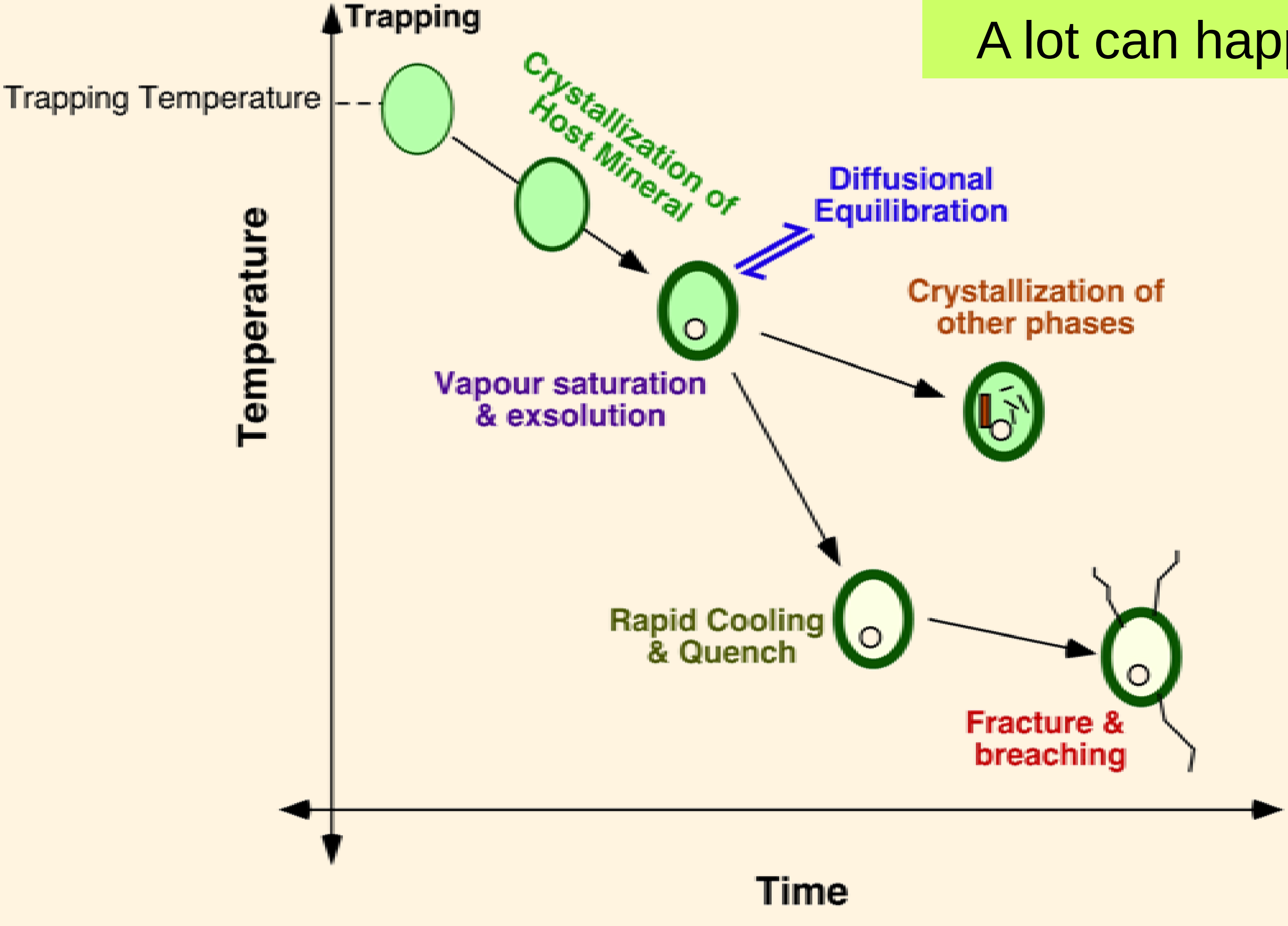
- Boundary layer Trapping
- Post-entrapment crystallization
- Re-equilibration with host or external melt†

*i.e. things that drive changes in magma compositions

† i.e. things that are unique to inclusions

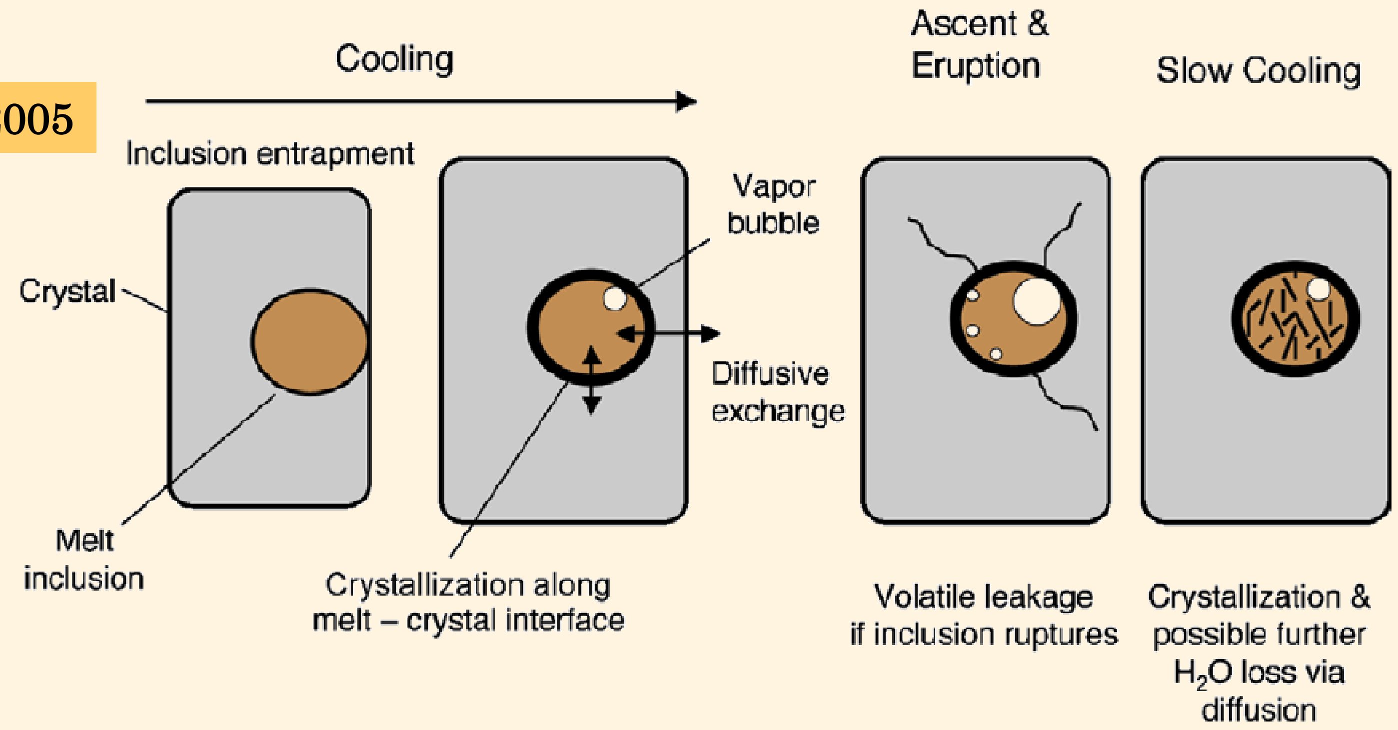
Evolution of melt inclusions after trapping

A lot can happen!



Evolution of melt inclusions after trapping

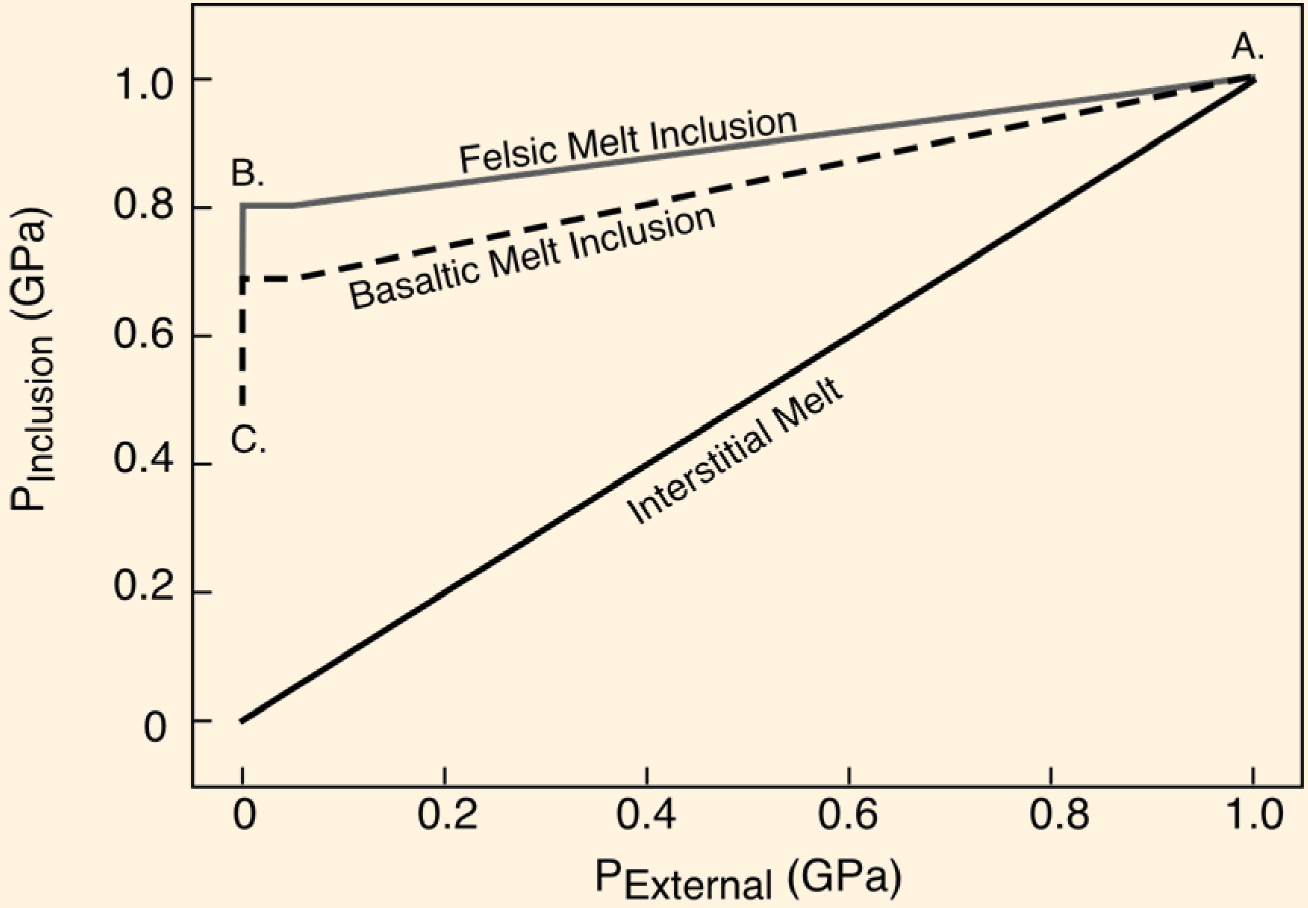
Wallace, 2005



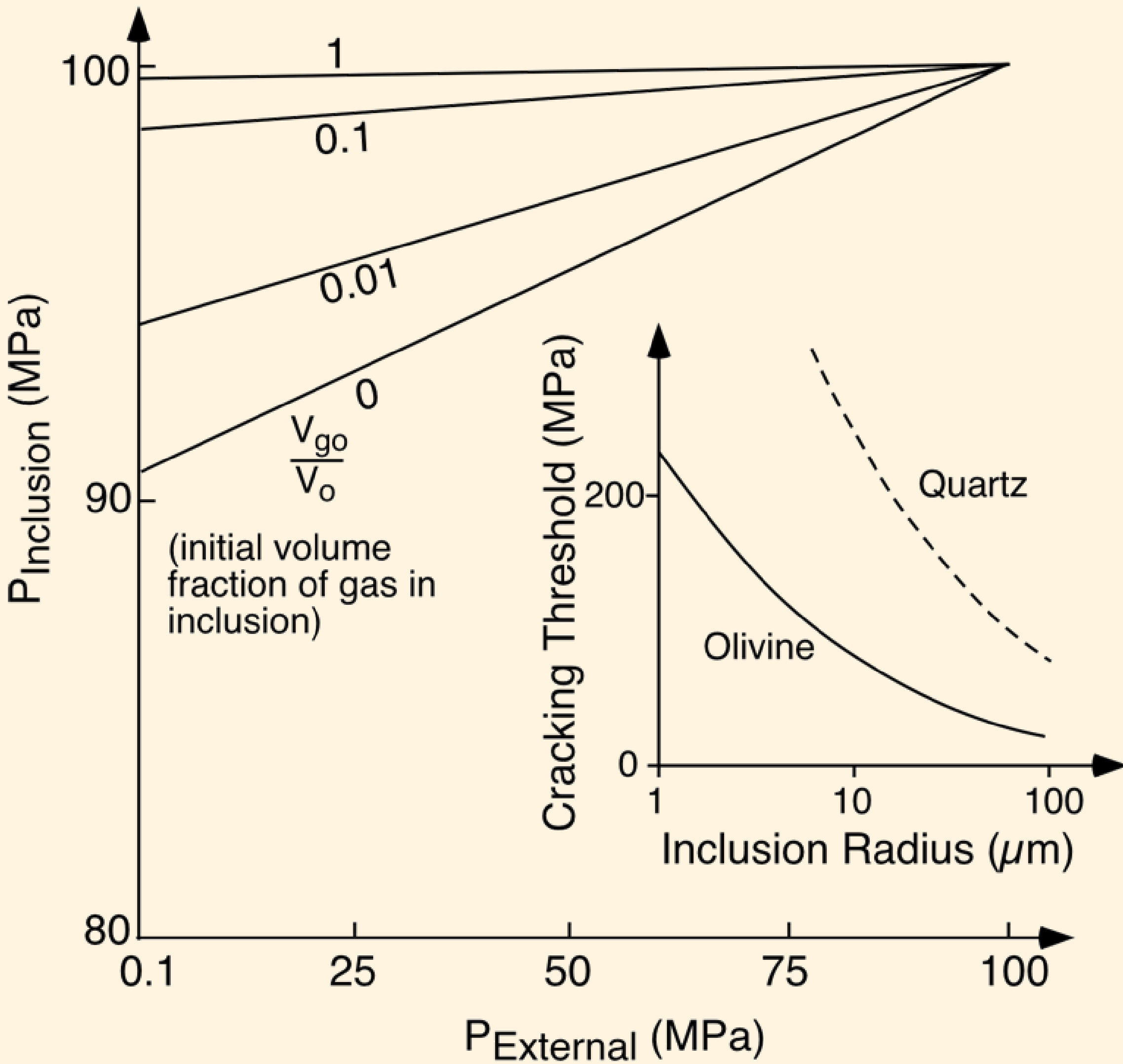
Inclusion evolution: Key Factors

Temperature	Diffusivity Vapour solubility
Cooling rate	Mineral growth rate Quench vs crystallization
Vapour content and composition	Vapour exsolution PT Diffusivity Internal pressure
Size/geometry	Breach probability Diffusional exchange
Host mineral	Bulk modulus, Diffusivity, Compatibility
Composition	Diffusivity, Vapour solubility, Phase equilibria

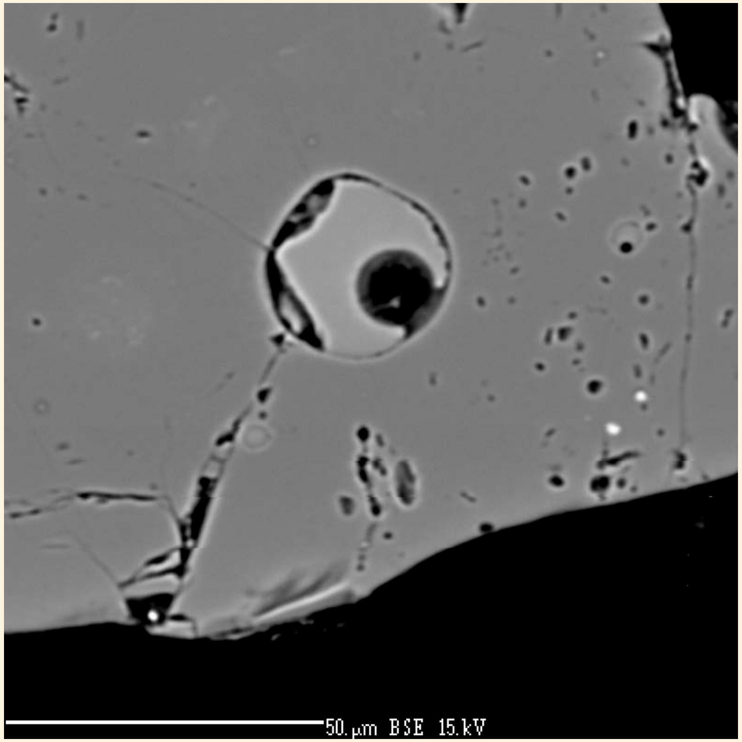
Changes in Pressure



Bulk moduli silicate liquids < elastic moduli silicate minerals



100
90
80
1
0.1
0.01
0
$\frac{V_{go}}{V_o}$
(initial volume fraction of gas in inclusion)
$P_{Inclusion}$ (MPa)
0.1
25
50
75
100
$P_{External}$ (MPa)
Cracking Threshold (MPa)
200
0
Quartz
Olivine
1
10
100
Inclusion Radius (μm)

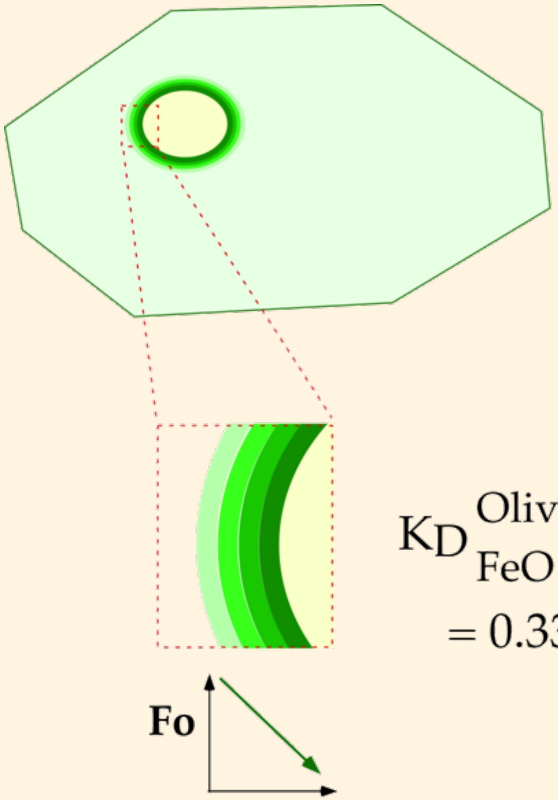


50 μm BSE 15.kV

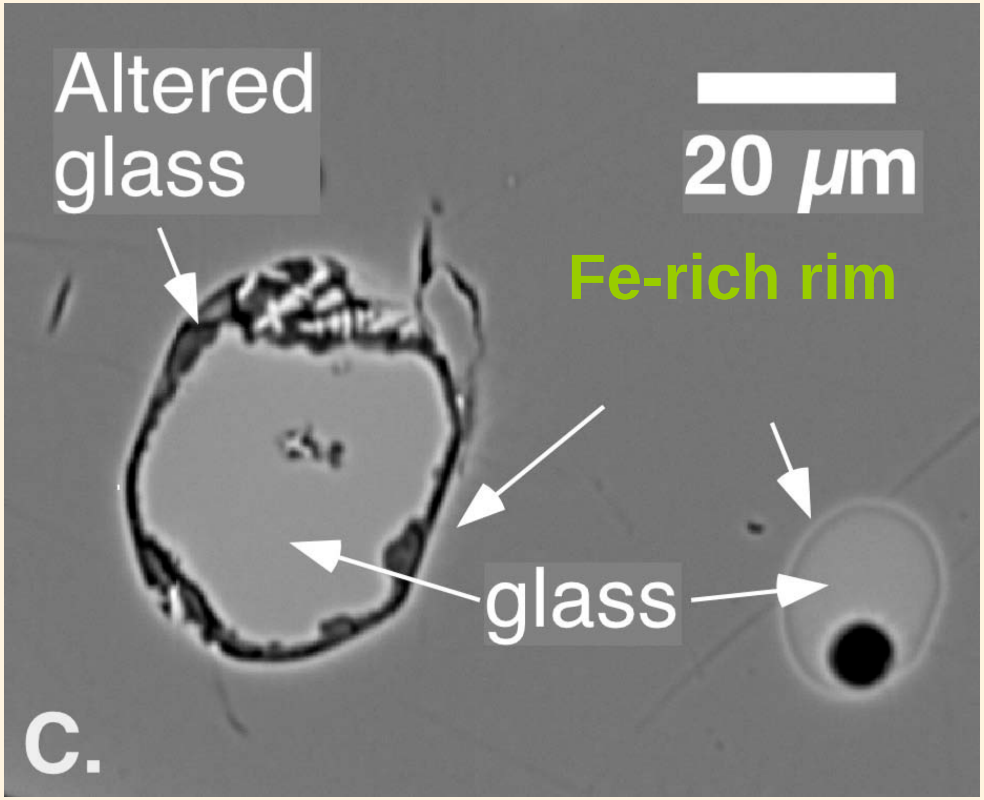
Melt Inclusion Evolution

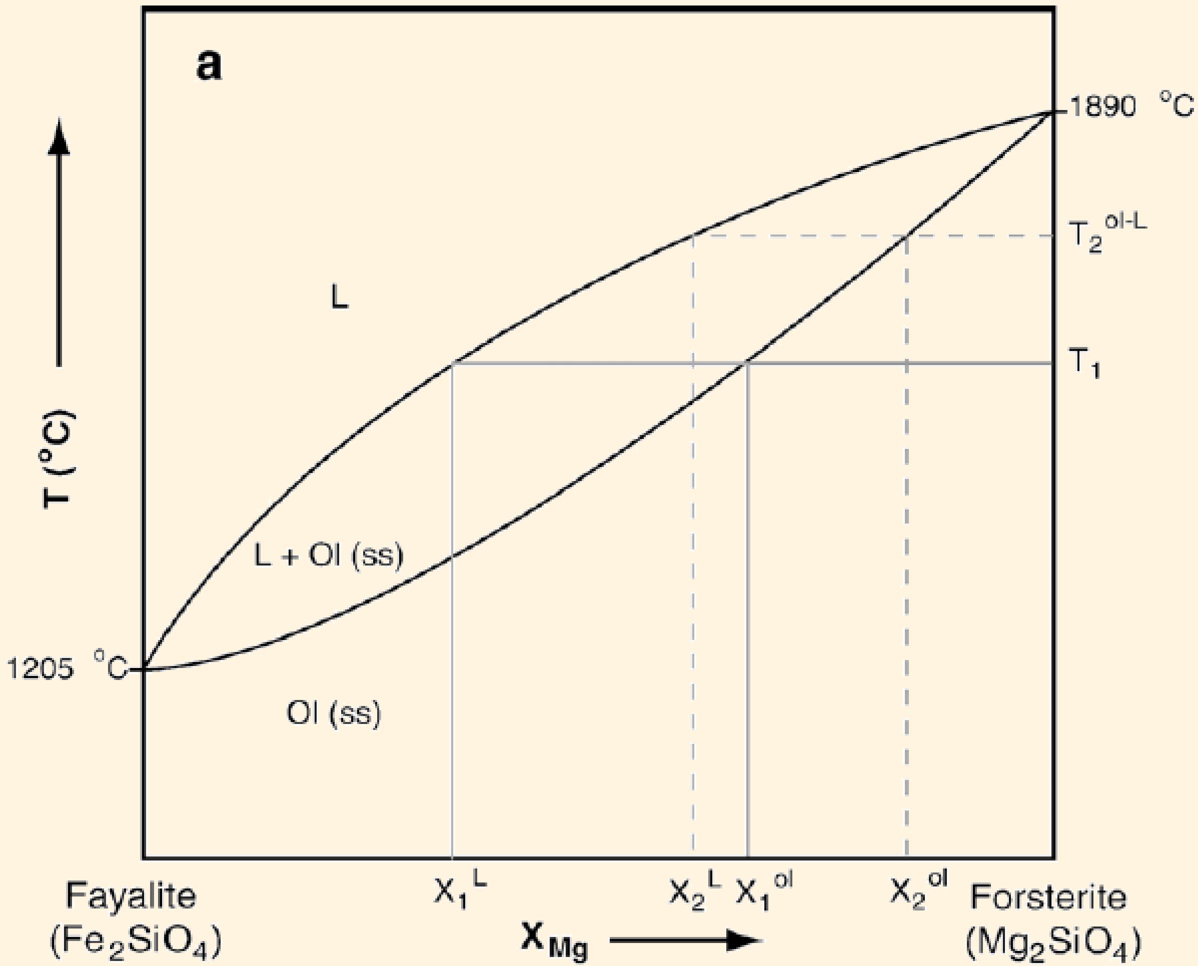
Post entrapment crystallization (PEC)
Diffusional Equilibration
Volatile Loss (Wallace)
Tests for Inclusion Fidelity

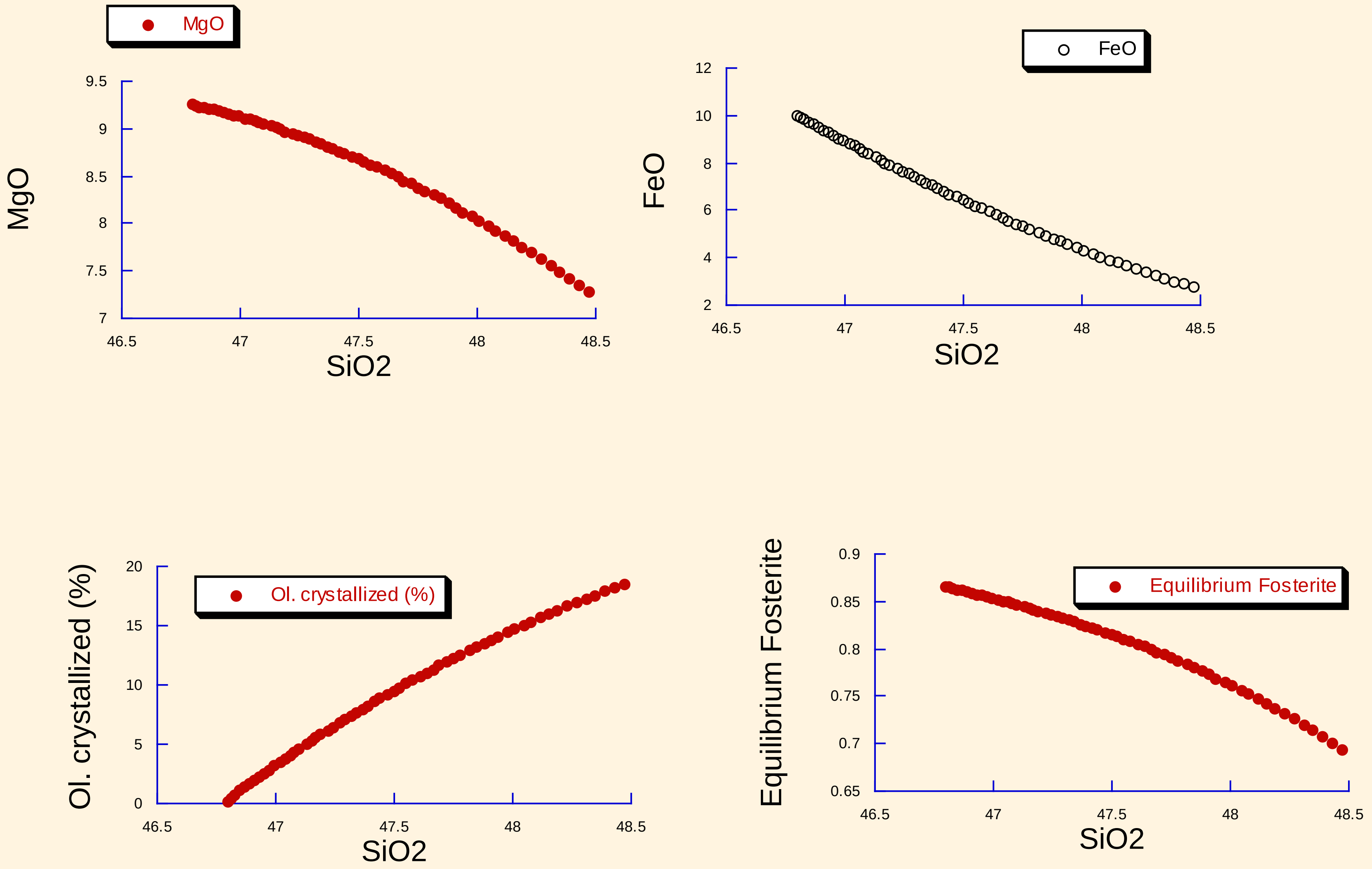
Postentrapment Crystallization



$$K_D{}^{\text{Olivine-Melt}}_{\text{FeO/MgO}} = 0.33 \pm 0.03$$




a
1890 °C
$T_2^{ol\text{-}L}$
L
T_1
T (°C)
L + Ol (ss)
1205 °C
Ol (ss)
X_1^L
X_2^L
X_1^{ol}
X_2^{ol}
Fayalite
(Fe_2SiO_4)
X_{Mg}
Forsterite
(Mg_2SiO_4)


MgO
MgO
SiO2
9.5
9
8.5
8
7.5
7
46.5
47
47.5
48
48.5
FeO
FeO
SiO2
12
10
8
6
4
2
Ol. crystallized (%)
Ol. crystallized (%)
20
15
10
5
0
Equilibrium Fosterite
Equilibrium Fosterite
0.9
0.85
0.8
0.75
0.7
0.65

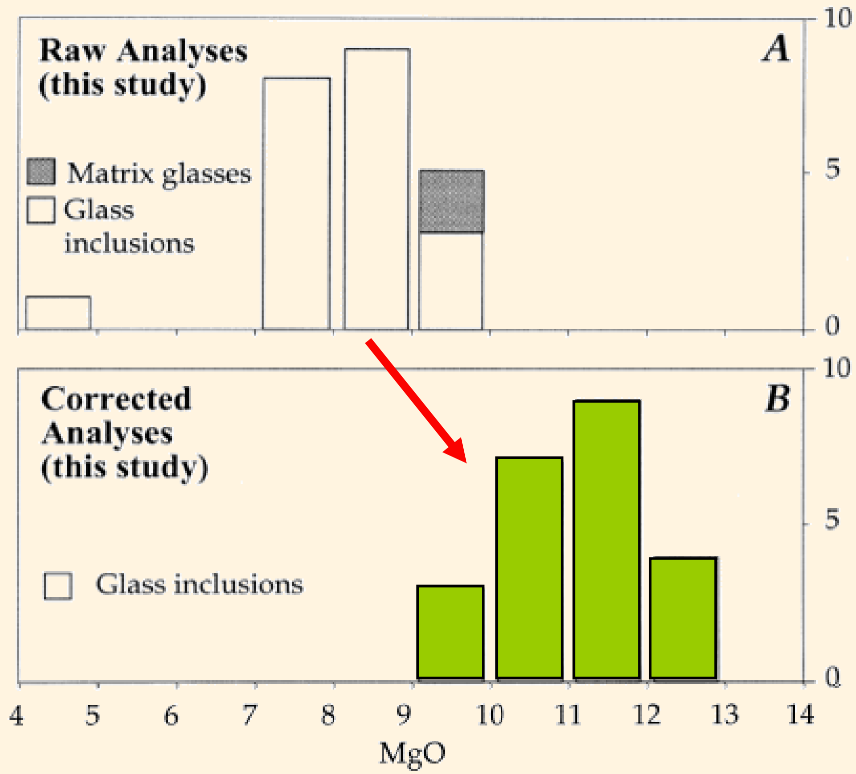
Correction for postentrapment crystallization

<u>Experimental</u>

- Reheat to (estimated) trapping temperature

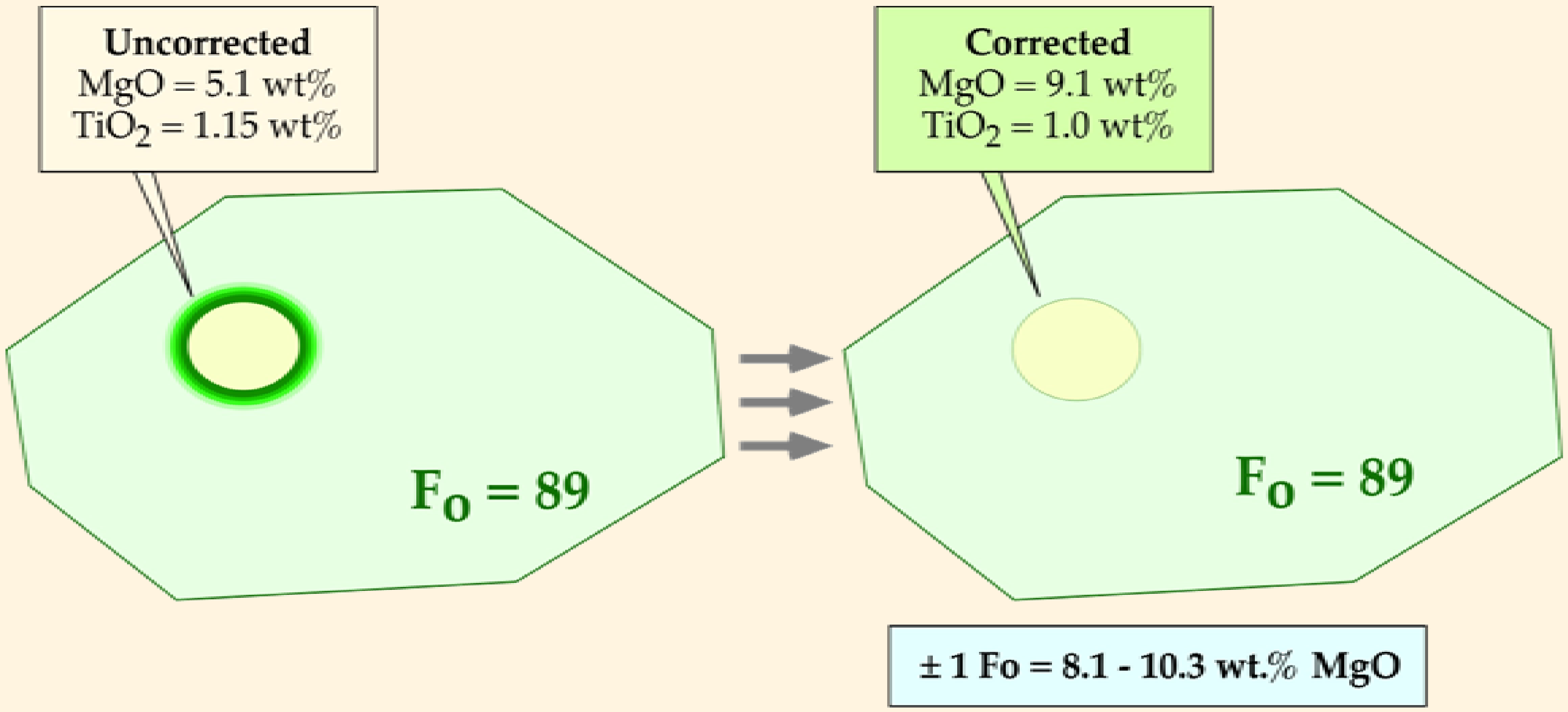
<u>Numerical</u>

- Based on chemical equilibrium
  - –Olivine: $K_D^{FeO^*/MgO} = 0.33 \pm 0.03$



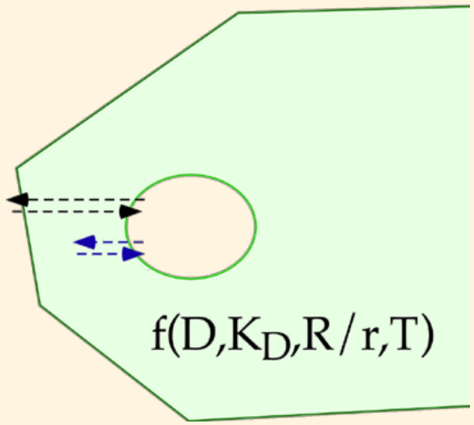
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

Loihi Seamount (Kent et al., 1999)



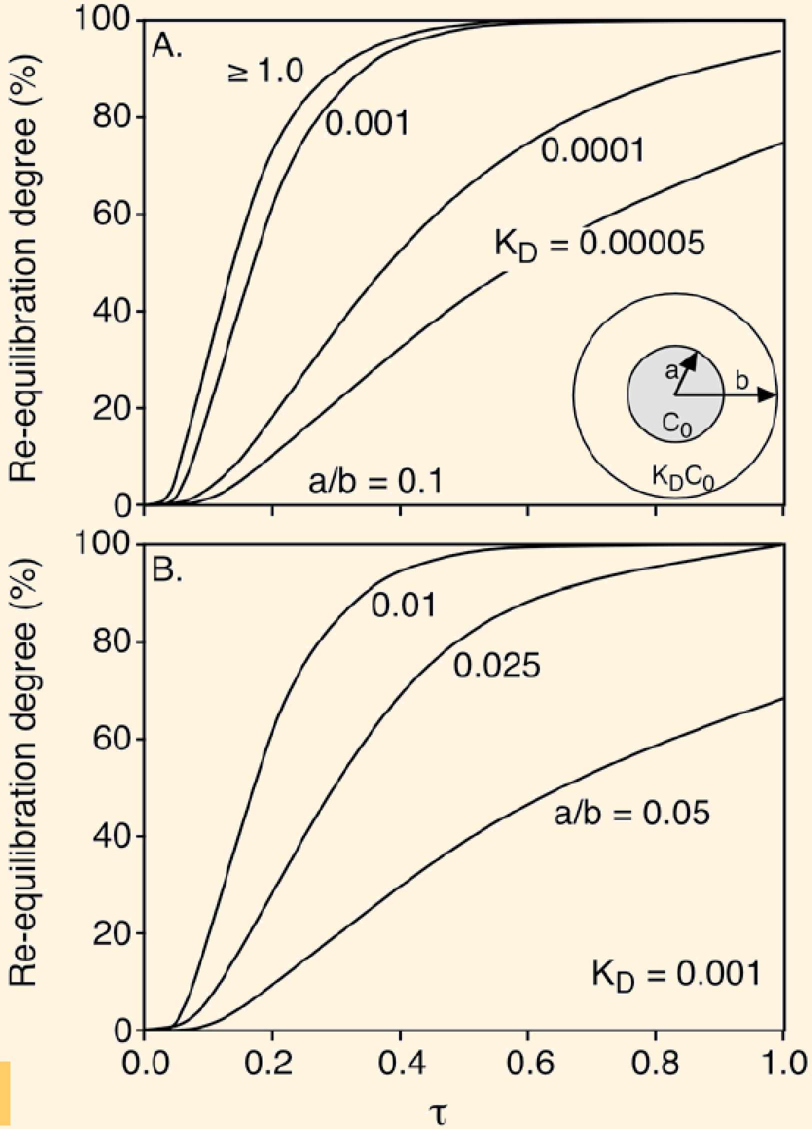
Compatible elements are the <u>least robust</u> after correction for post-entrapment crystallization

Equilibration between Host and Inclusion



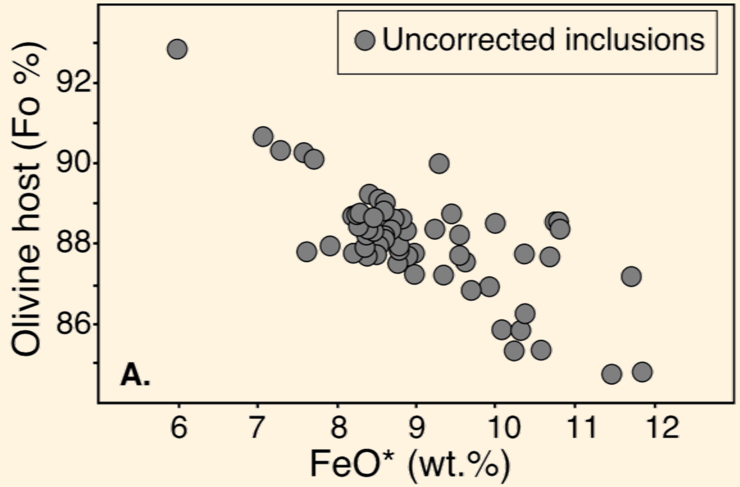
Equilibration more rapid at

- Higher Diffusivity
- Higher Temperatures
- More compatible
- Larger inclusion
- Smaller host



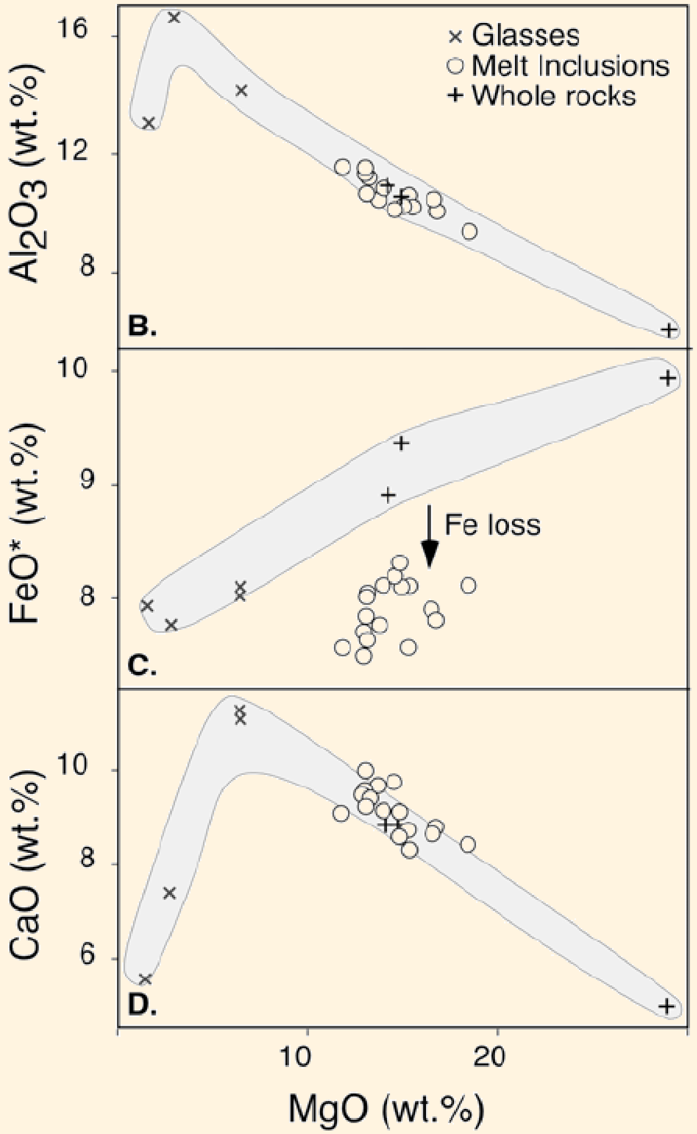
Qin et al. (1992)

Fe Loss

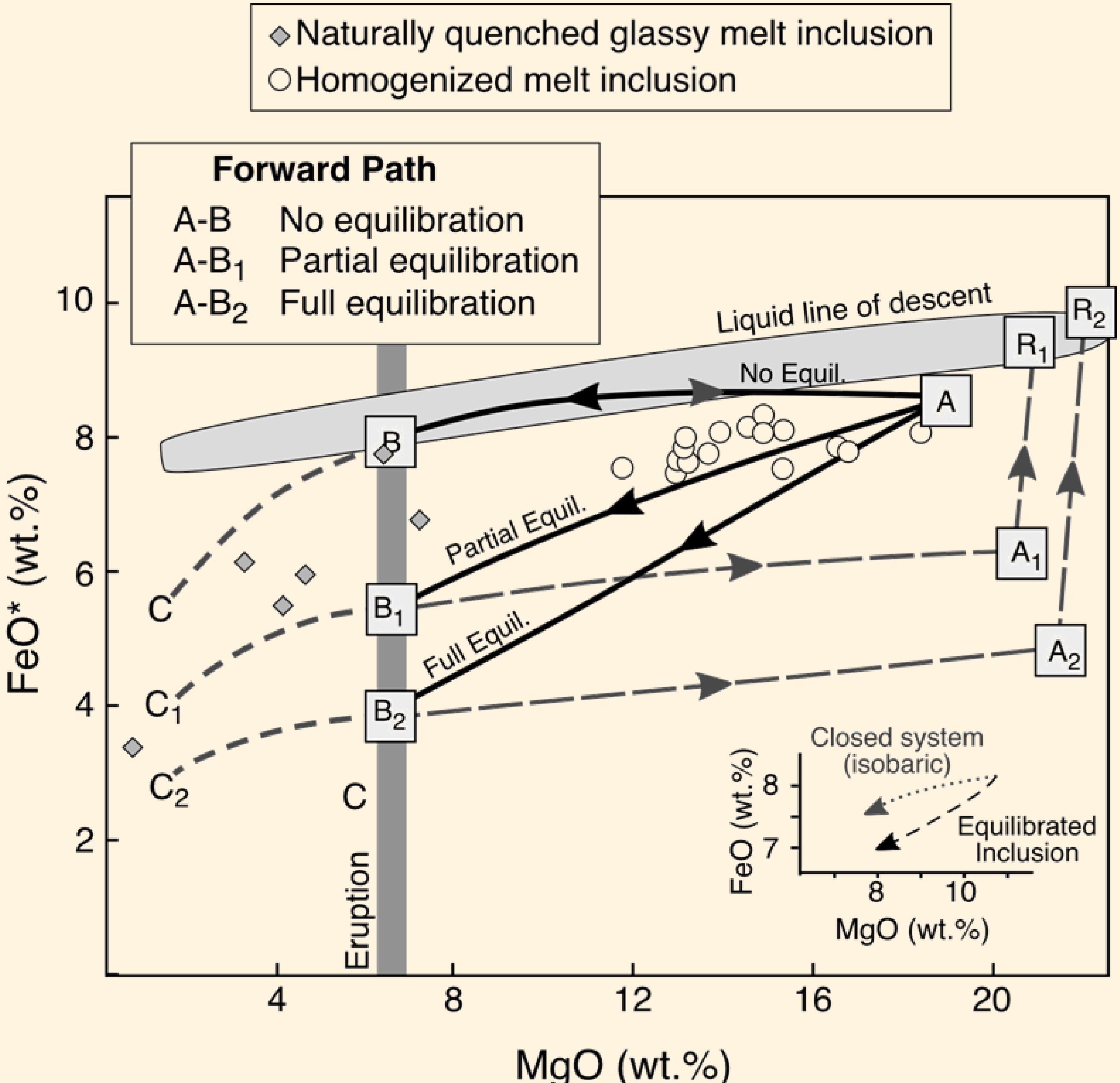


Yaxley et al. 2005

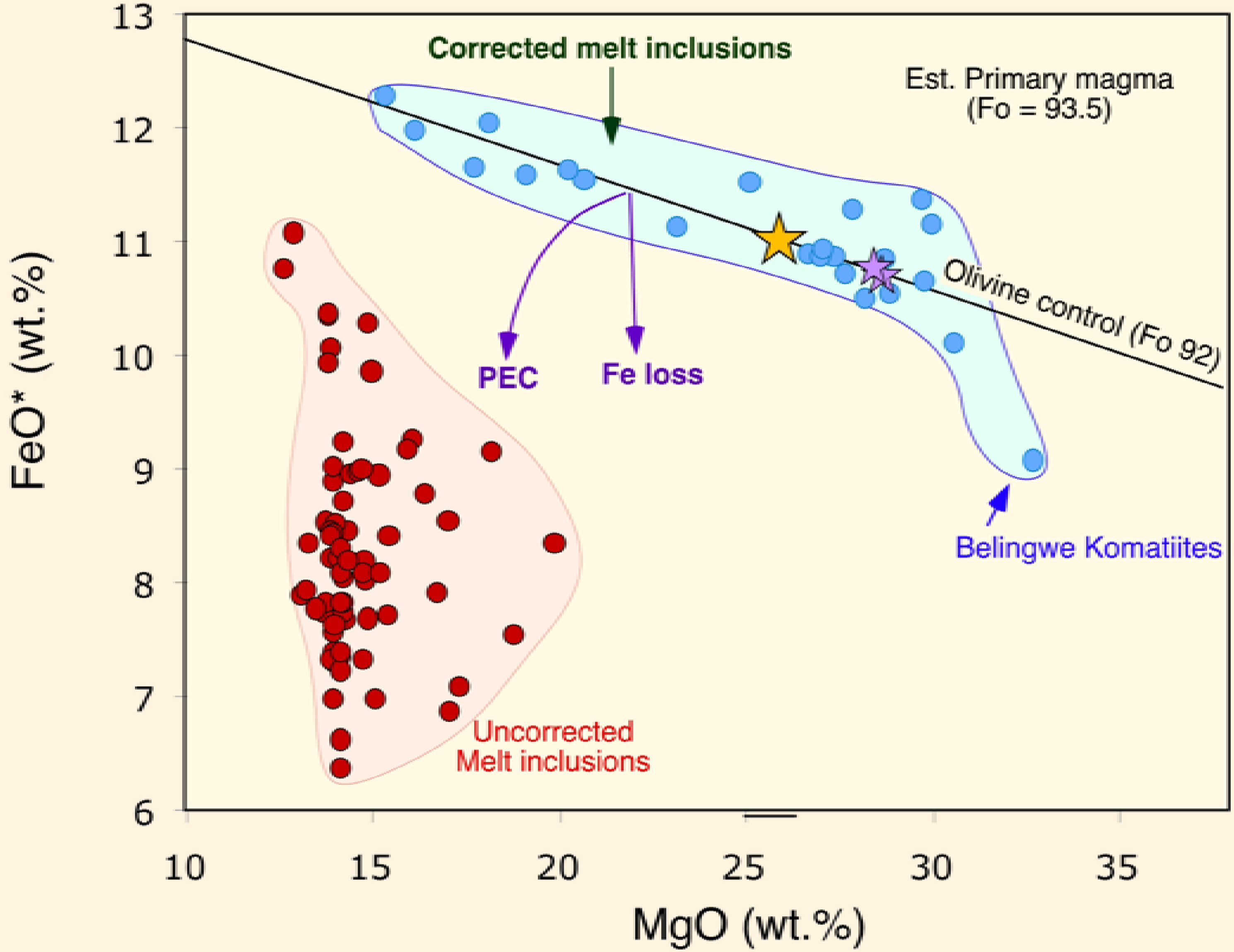
Danyushevsky et al. 2000



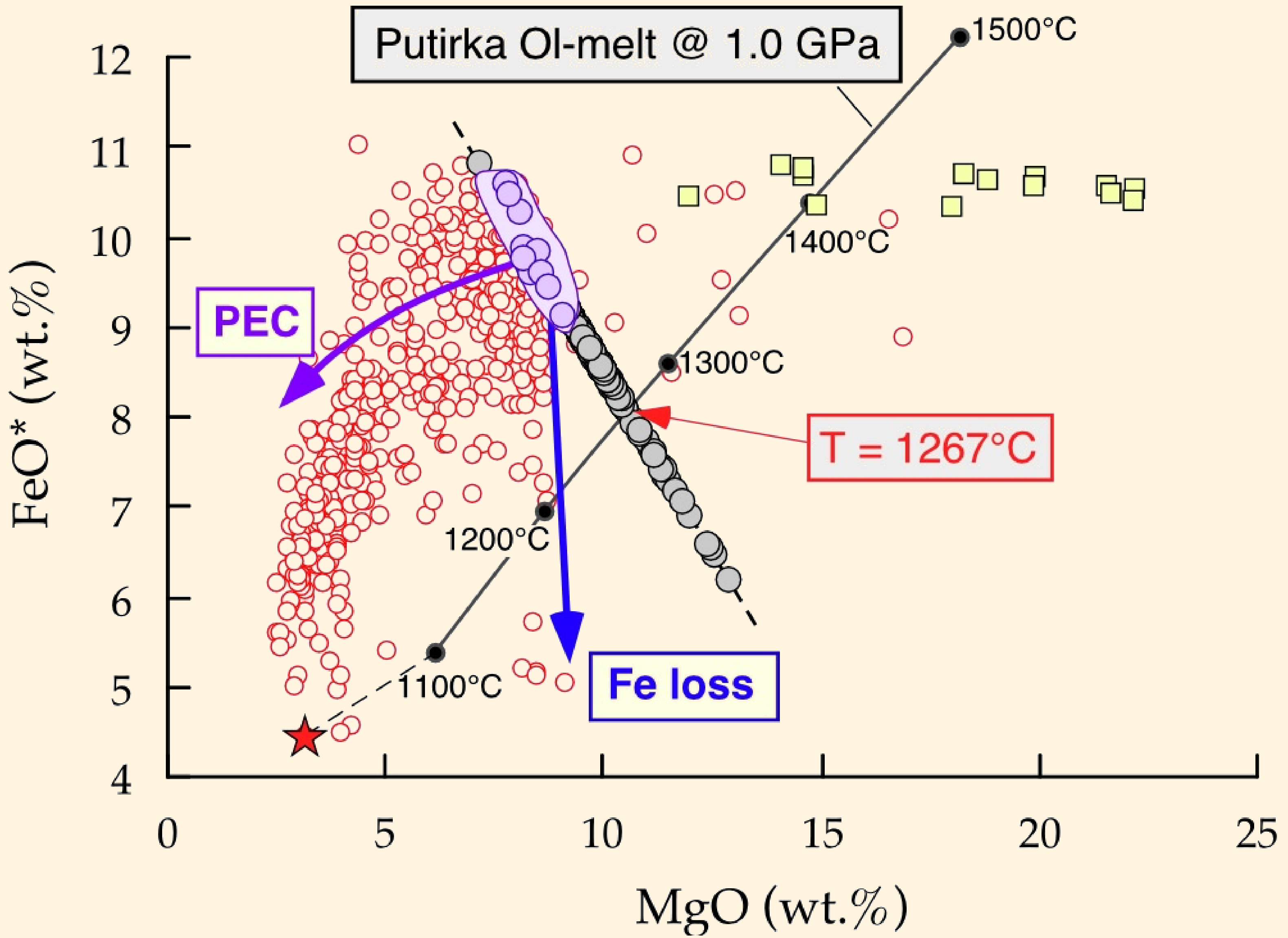
- Negative correlation between measured FeO* and Fo_{host}
- Anomalously low FeO* wrt liquid line of descent



Naturally quenched glassy melt inclusion
Homogenized melt inclusion
Forward Path
A-B No equilibration
A-B1 Partial equilibration
A-B2 Full equilibration
Liquid line of descent
No Equil.
Partial Equil.
Full Equil.
A
A1
A2
B
B1
B2
R1
R2
C
C1
C2
C
Eruption
Closed system
(isobaric)
Equilibrated
Inclusion
FeO (wt.%)
MgO (wt.%)
FeO* (wt.%)
MgO (wt.%)

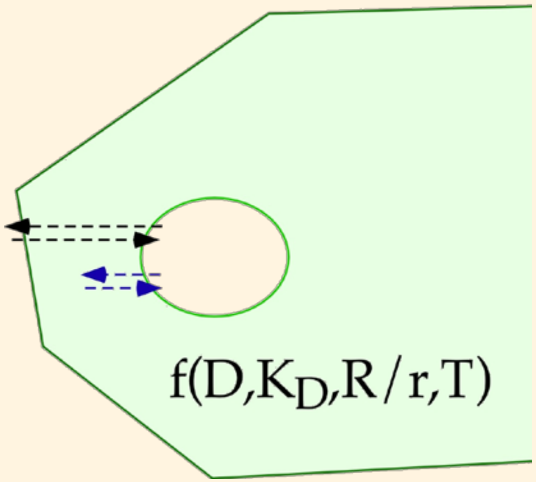


Corrected melt inclusions
Est. Primary magma
(Fo = 93.5)
Olivine control (Fo 92)
PEC
Fe loss
Belingwe Komatiites
Uncorrected
Melt inclusions
FeO* (wt.%)
MgO (wt.%)
13
12
11
10
9
8
7
6
10
15
20
25
30
35



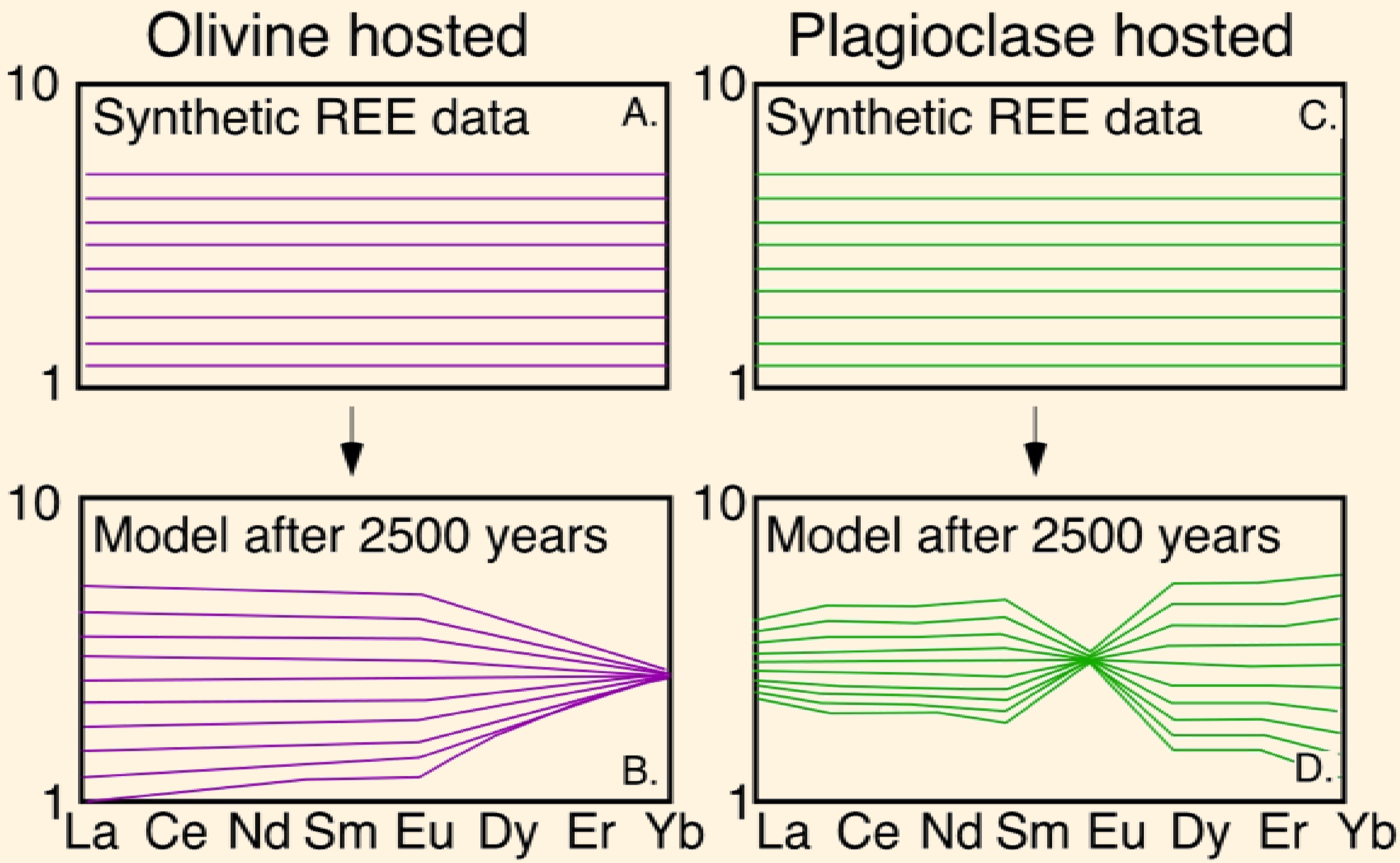
Putirka Ol-melt @ 1.0 GPa
1500°C
1400°C
1300°C
1200°C
1100°C
PEC
T = 1267°C
Fe loss
12
11
10
9
8
7
6
5
4
FeO* (wt.%)
0
5
10
15
20
25
MgO (wt.%)

Trace element re-equilibration



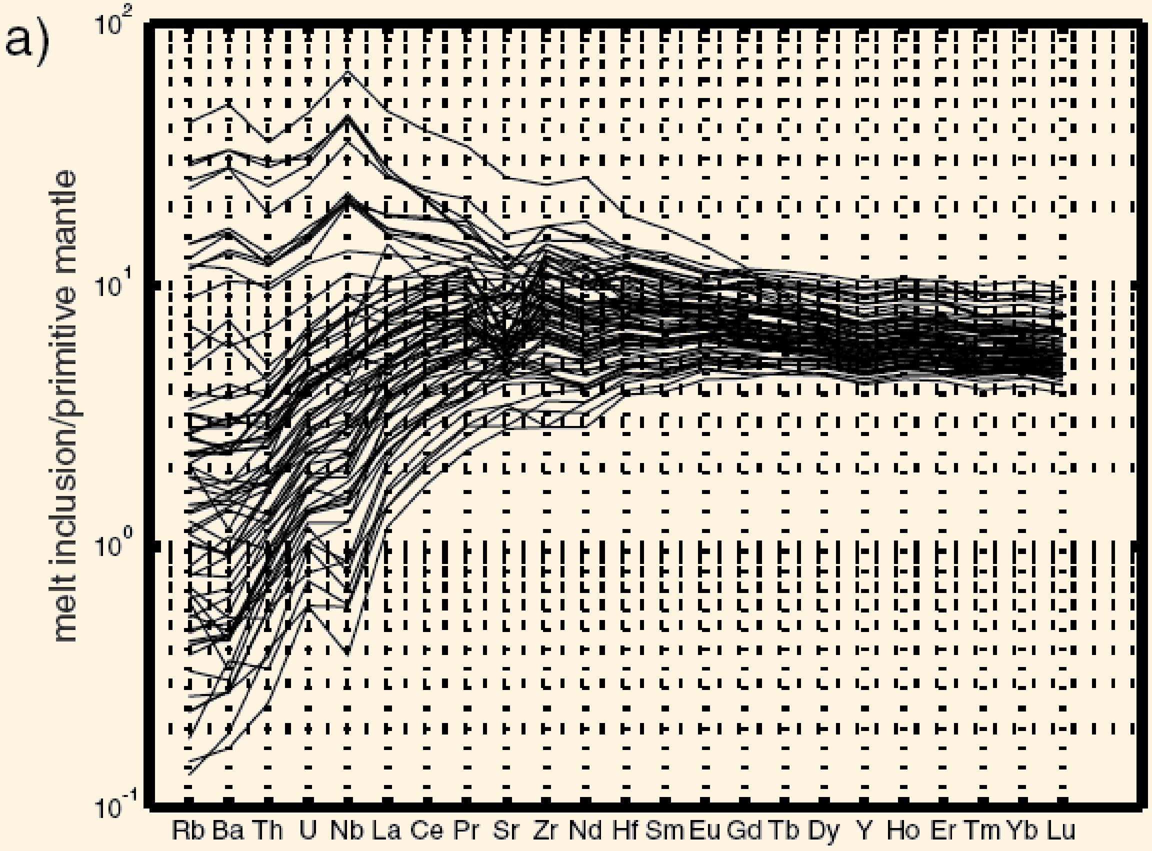
- The most robust data sources in melt inclusions are slow diffusing and incompatible elements
  - Altered only by dilution/concentration
  - Ratios unchanged

Are incompatible trace elements affected by diffusional re-equilibration?



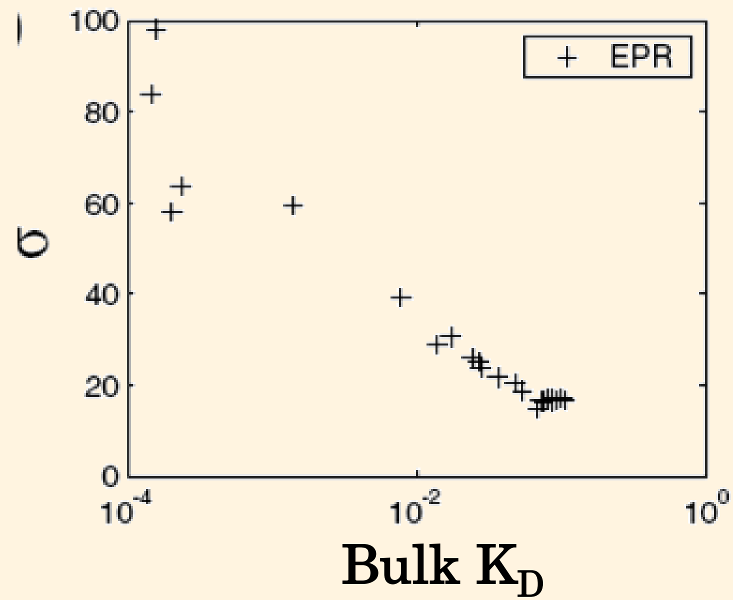
Cottrell et al. 2002

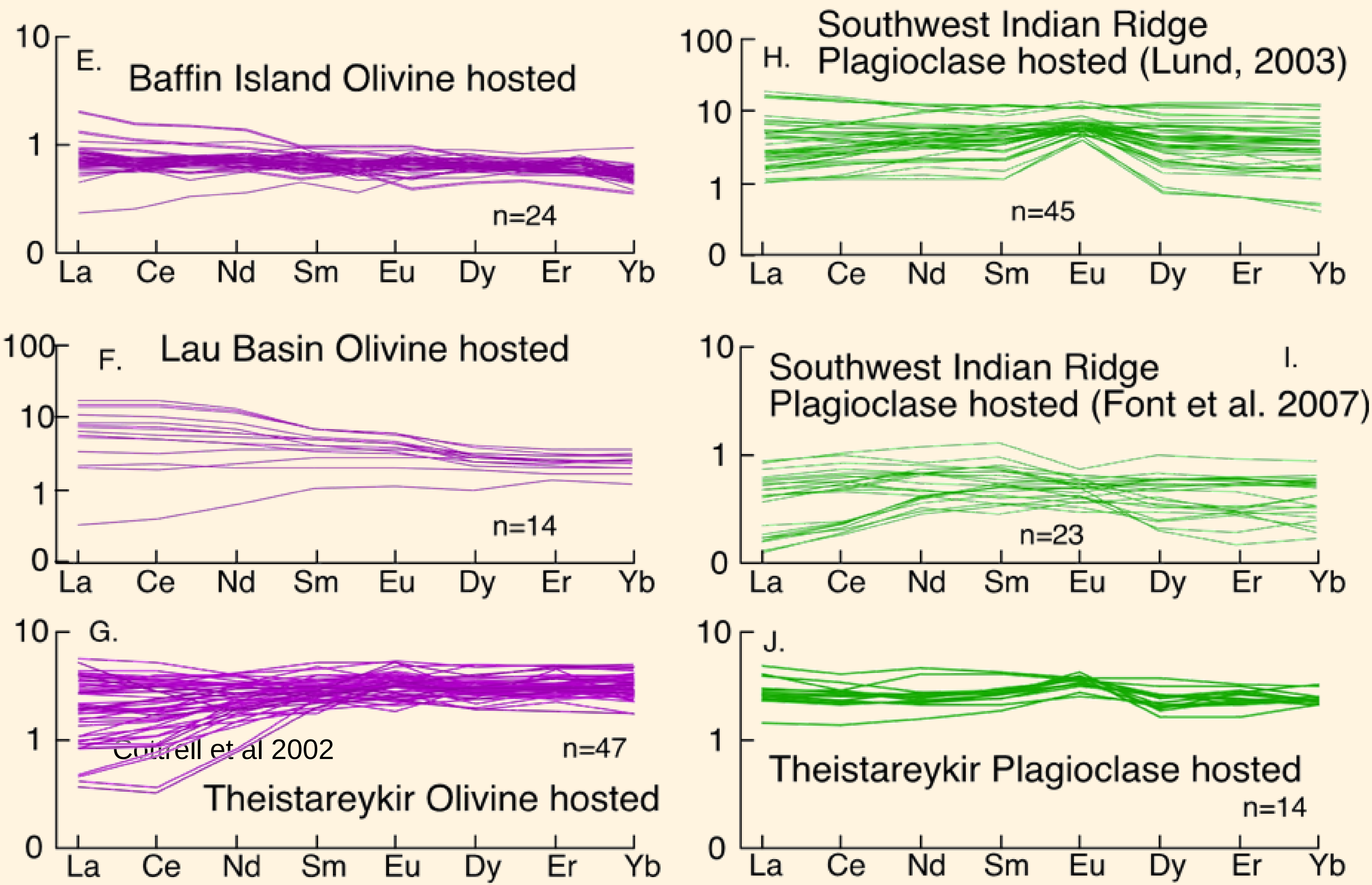
REE equilibration with host after 2500 years

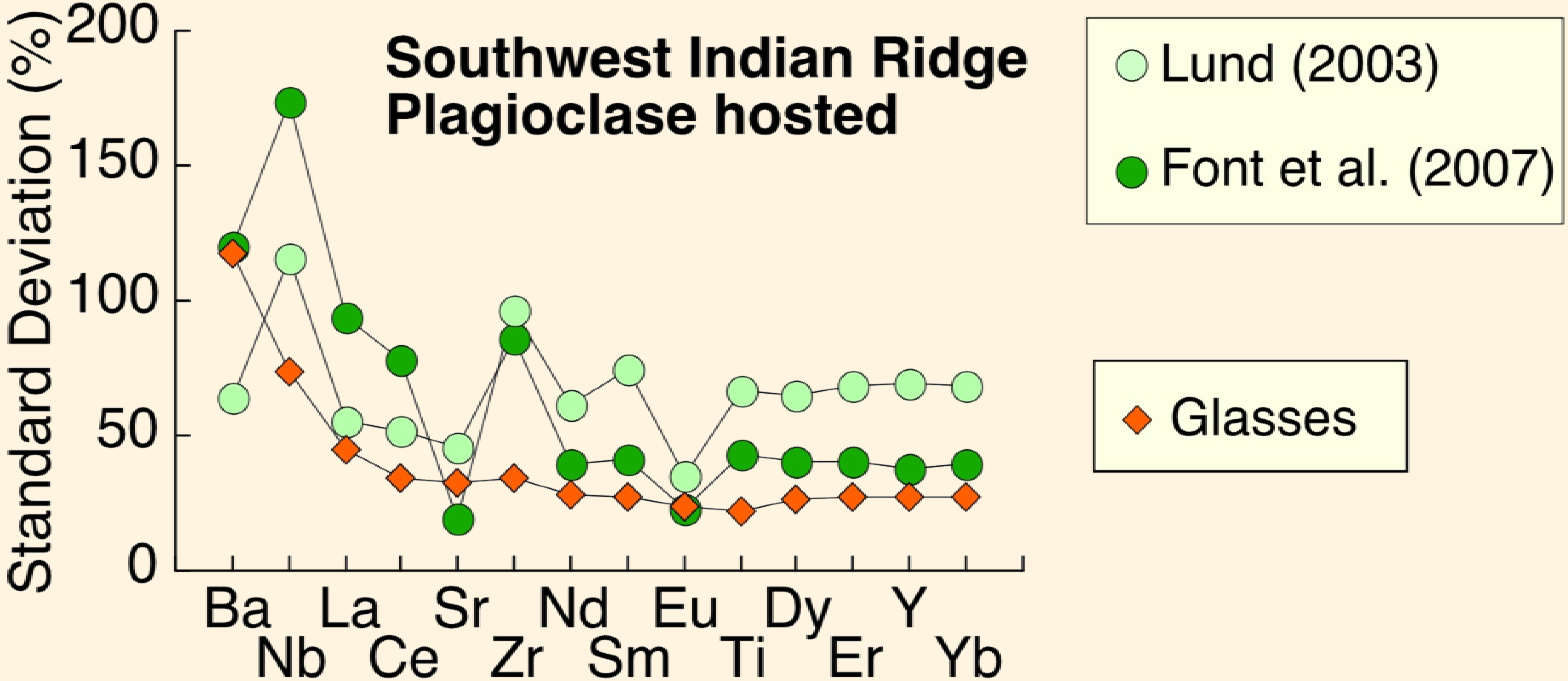


Mid Ocean Ridge basalt glasses

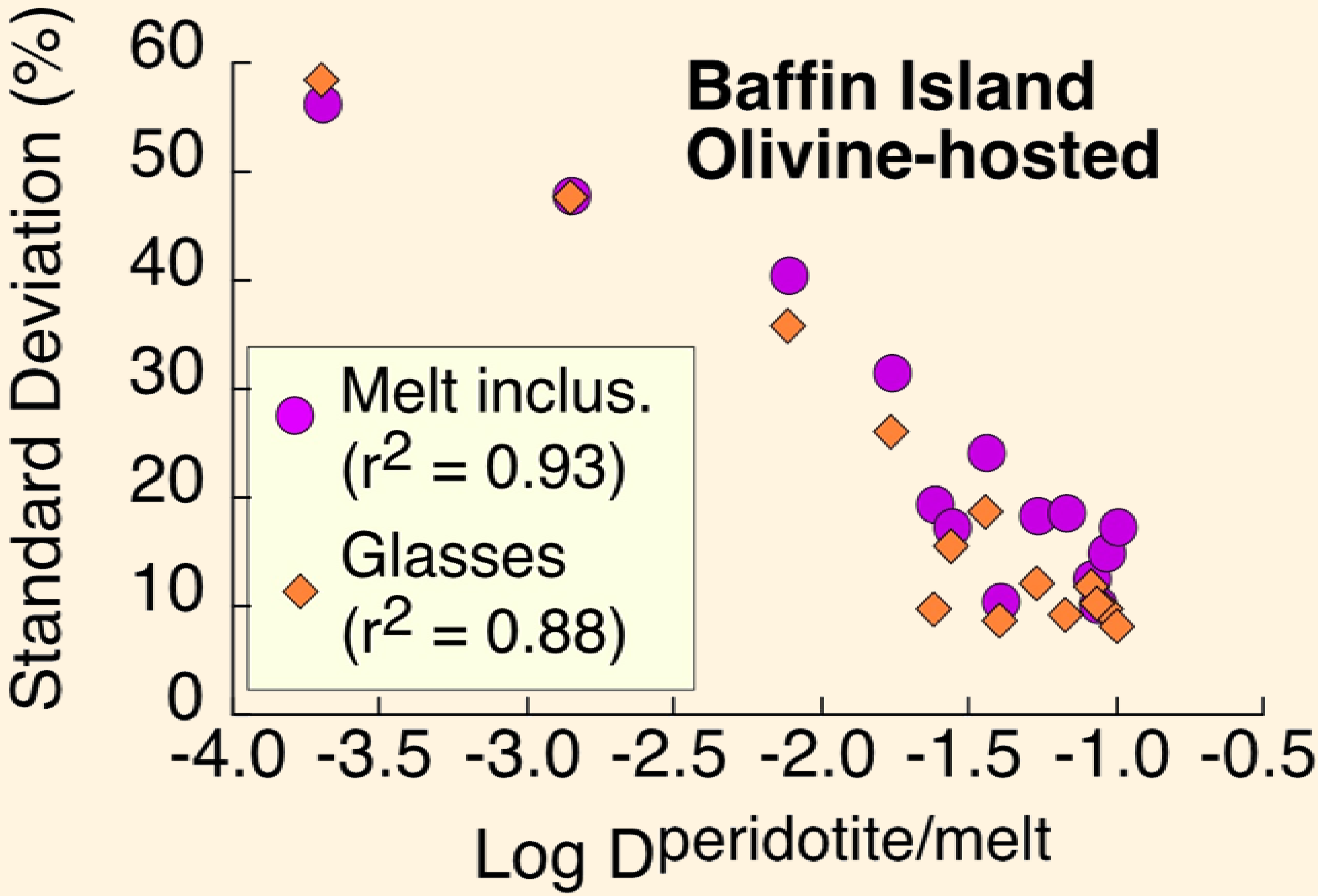
(Cottrell et al. 2002)



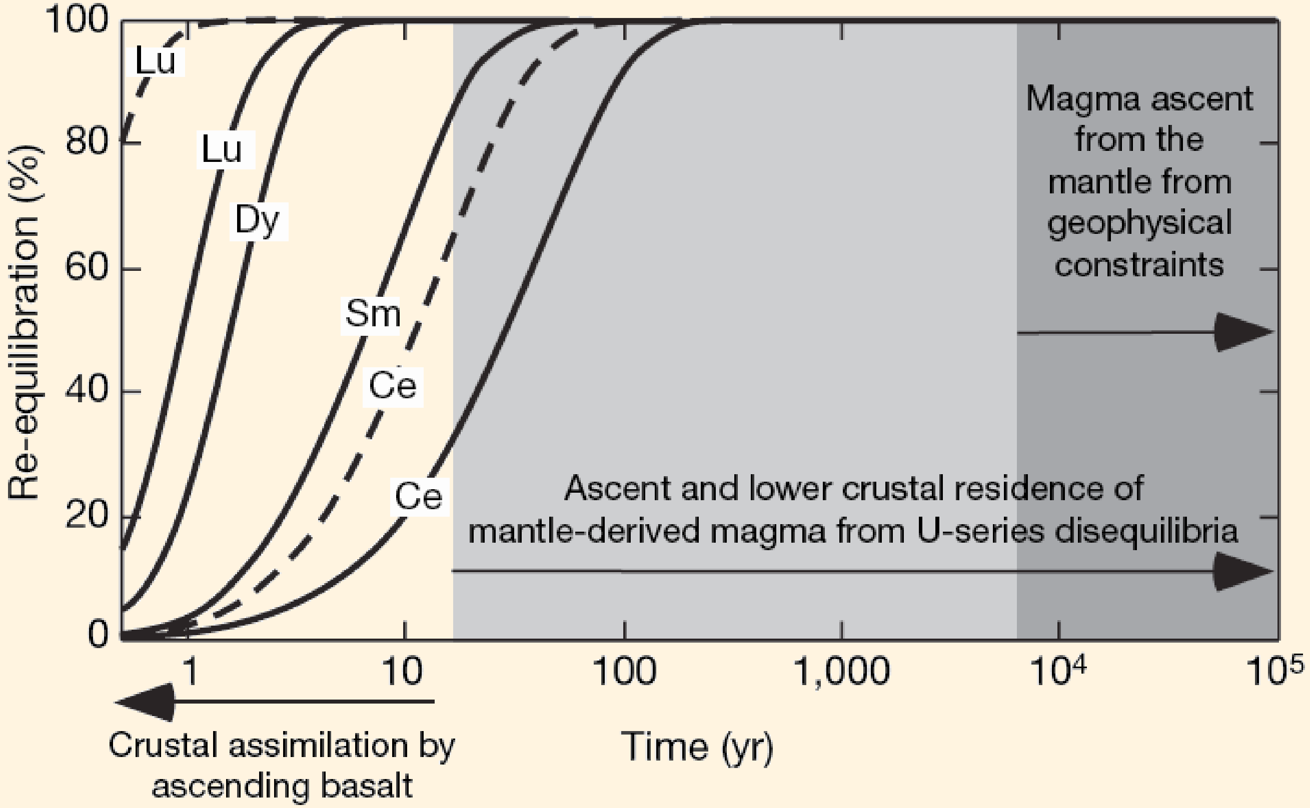

E.
Baffin Island Olivine hosted
n=24
H.
Southwest Indian Ridge
Plagioclase hosted (Lund, 2003)
n=45
F.
Lau Basin Olivine hosted
n=14
I.
Southwest Indian Ridge
Plagioclase hosted (Font et al. 2007)
n=23
G.
Cottrell et al 2002
n=47
Theistareykir Olivine hosted
J.
Theistareykir Plagioclase hosted
n=14
100
10
1
0
La Ce Nd Sm Eu Dy Er Yb



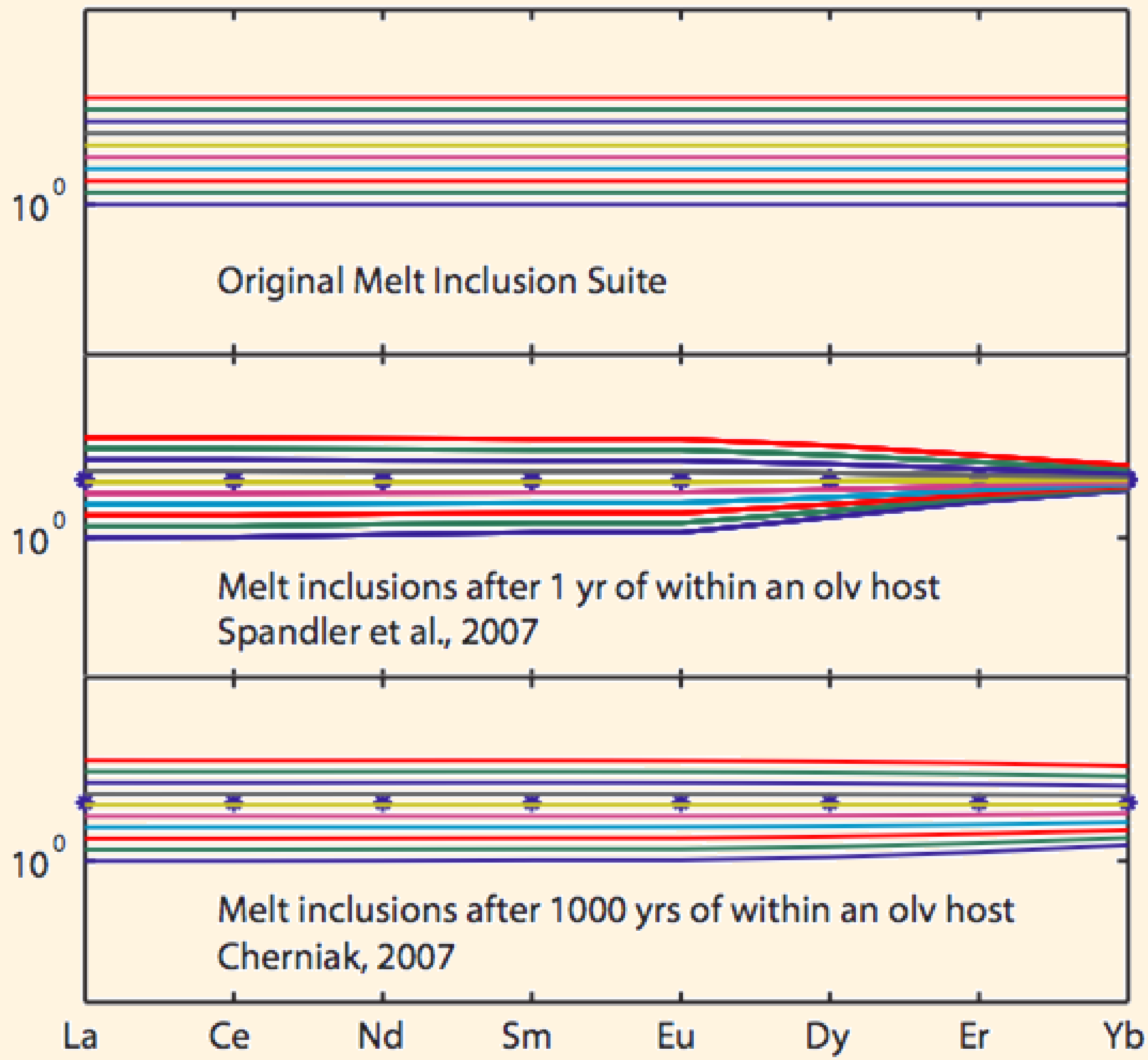
Southwest Indian Ridge
Plagioclase hosted
Standard Deviation (%)
200
150
100
50
0
Ba
Nb
La
Ce
Sr
Zr
Nd
Sm
Eu
Ti
Dy
Er
Y
Yb
Lund (2003)
Font et al. (2007)
Glasses


Baffin Island
Olivine-hosted
Standard Deviation (%)
60
50
40
30
20
10
0
Melt inclus.
(r2 = 0.93)
Glasses
(r2 = 0.88)
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
Log Dperidotite/melt

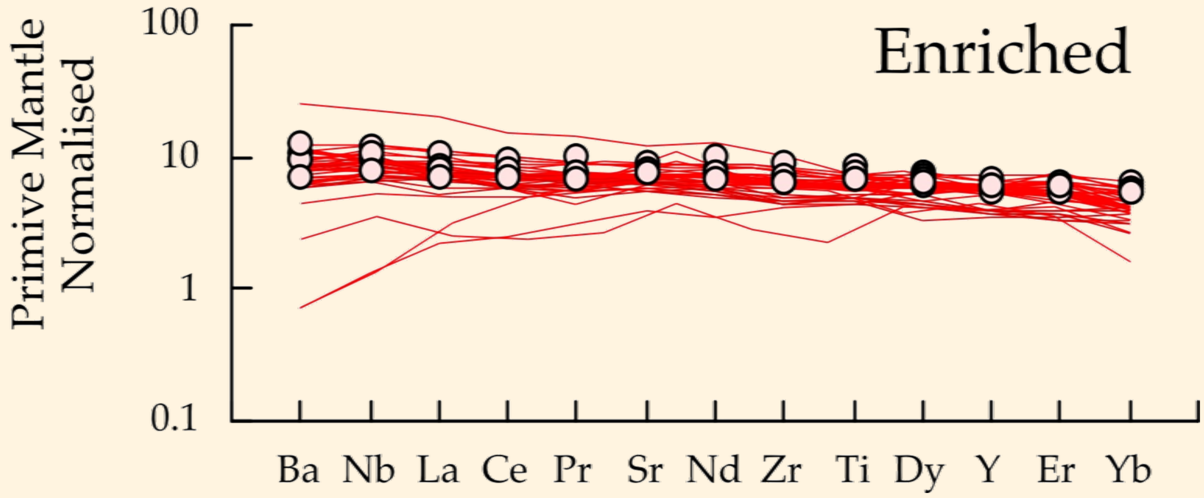
Trace element re-equilibration

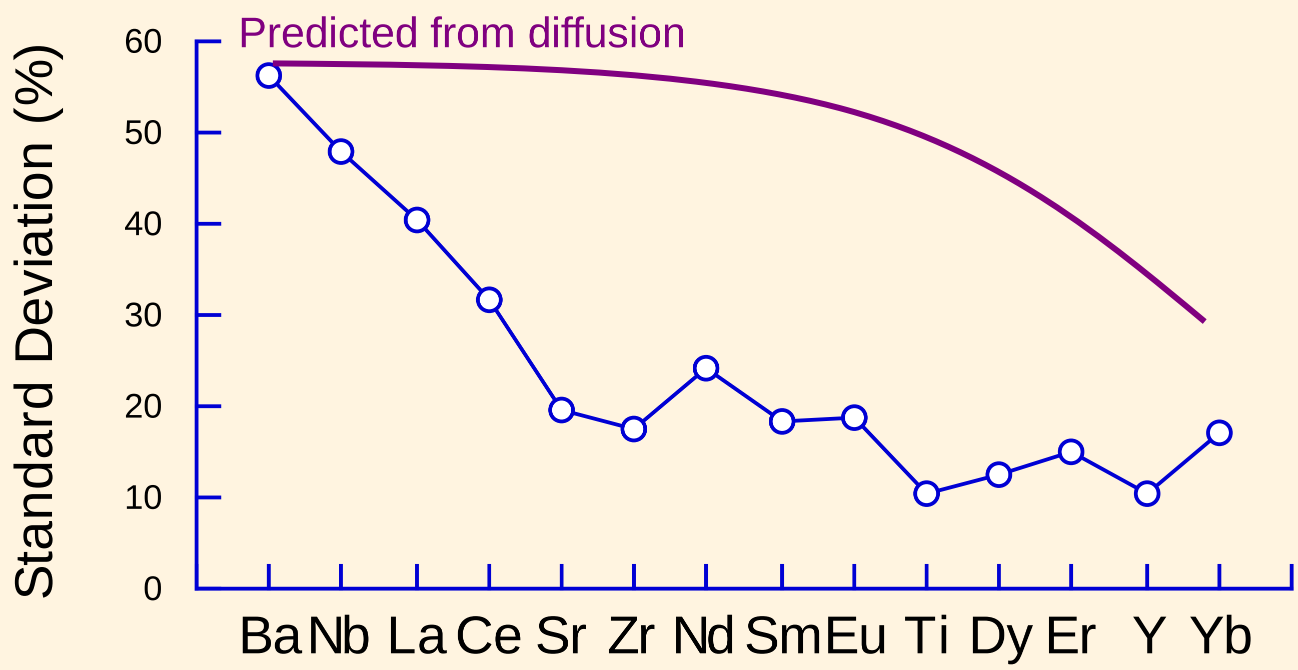


Spandler et al. 2007

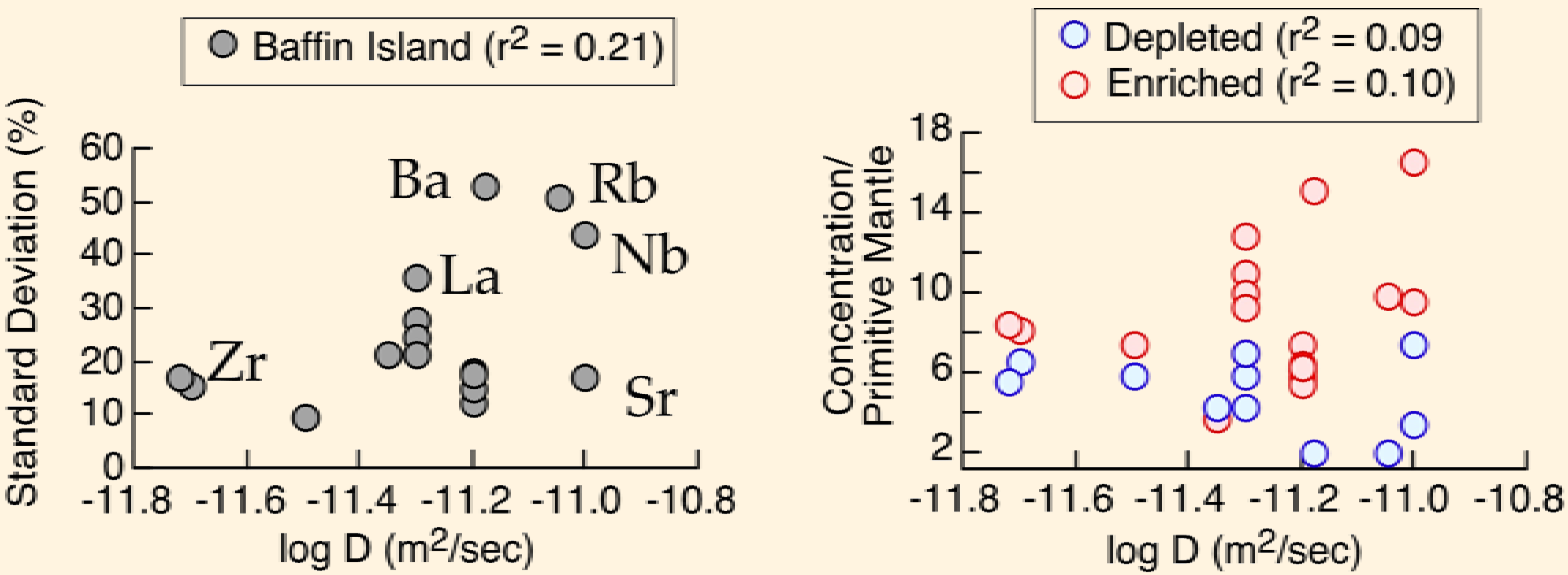


10^0
Original Melt Inclusion Suite
10^0
Melt inclusions after 1 yr of within an olv host
Spandler et al., 2007
10^0
Melt inclusions after 1000 yrs of within an olv host
Cherniak, 2007
La
Ce
Nd
Sm
Eu
Dy
Er
Yb


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

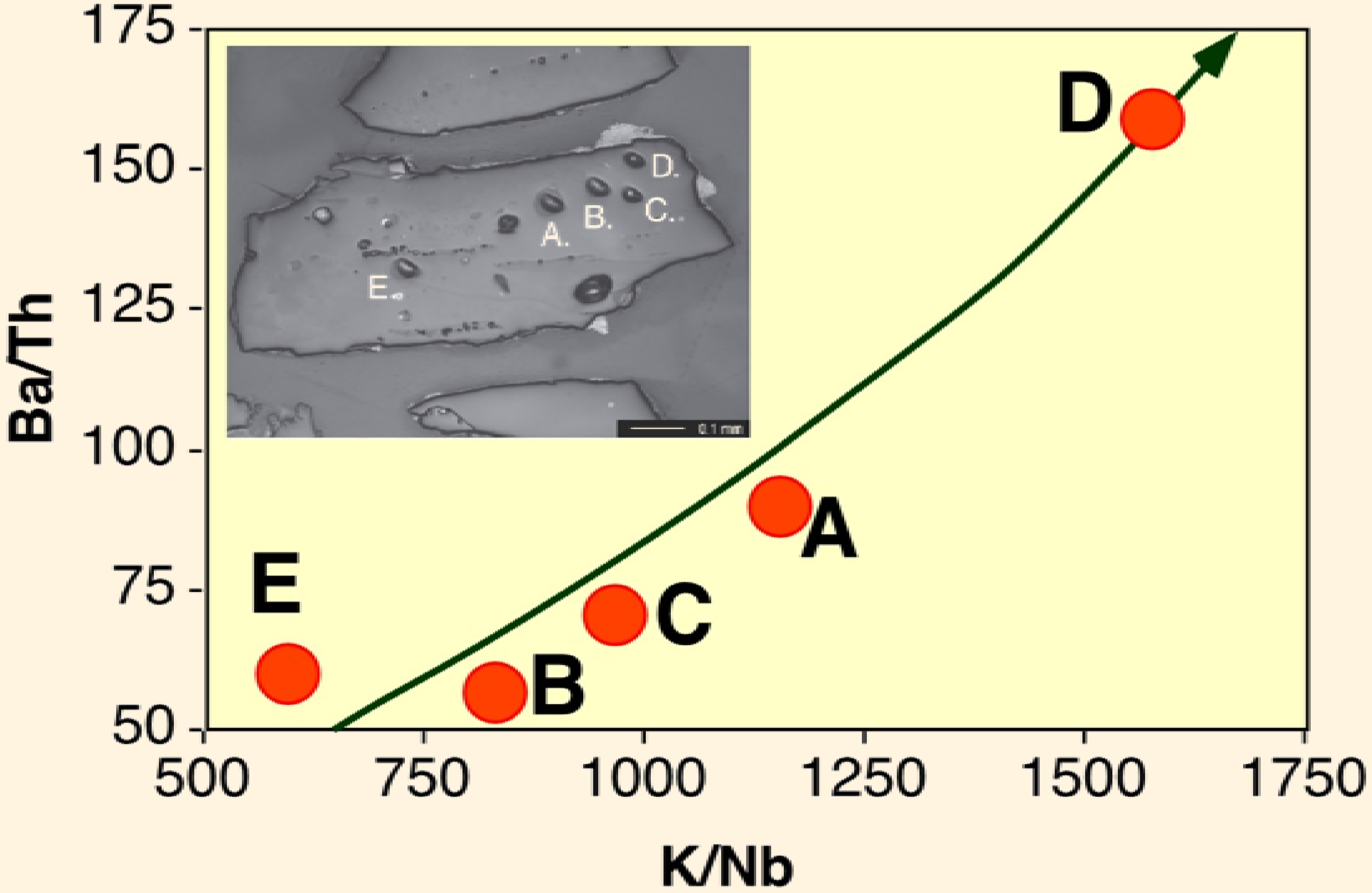

Predicted from diffusion
Standard Deviation (%)
60
50
40
30
20
10
0
Ba Nb La Ce Sr Zr Nd Sm Eu Ti Dy Er Y Yb

Baffin Island olivine-hosted n = 103



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

Preserve inter-crystal variations

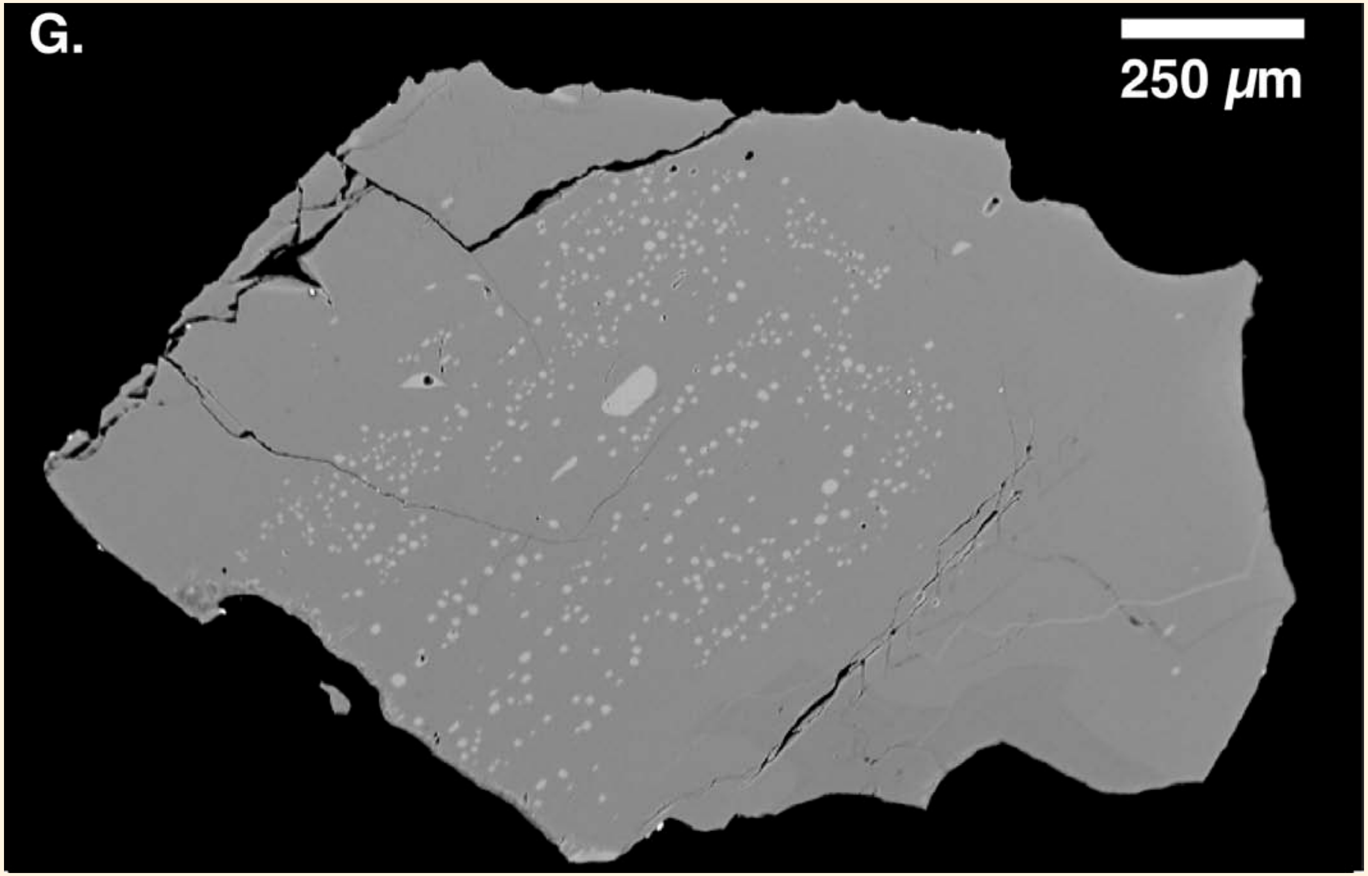


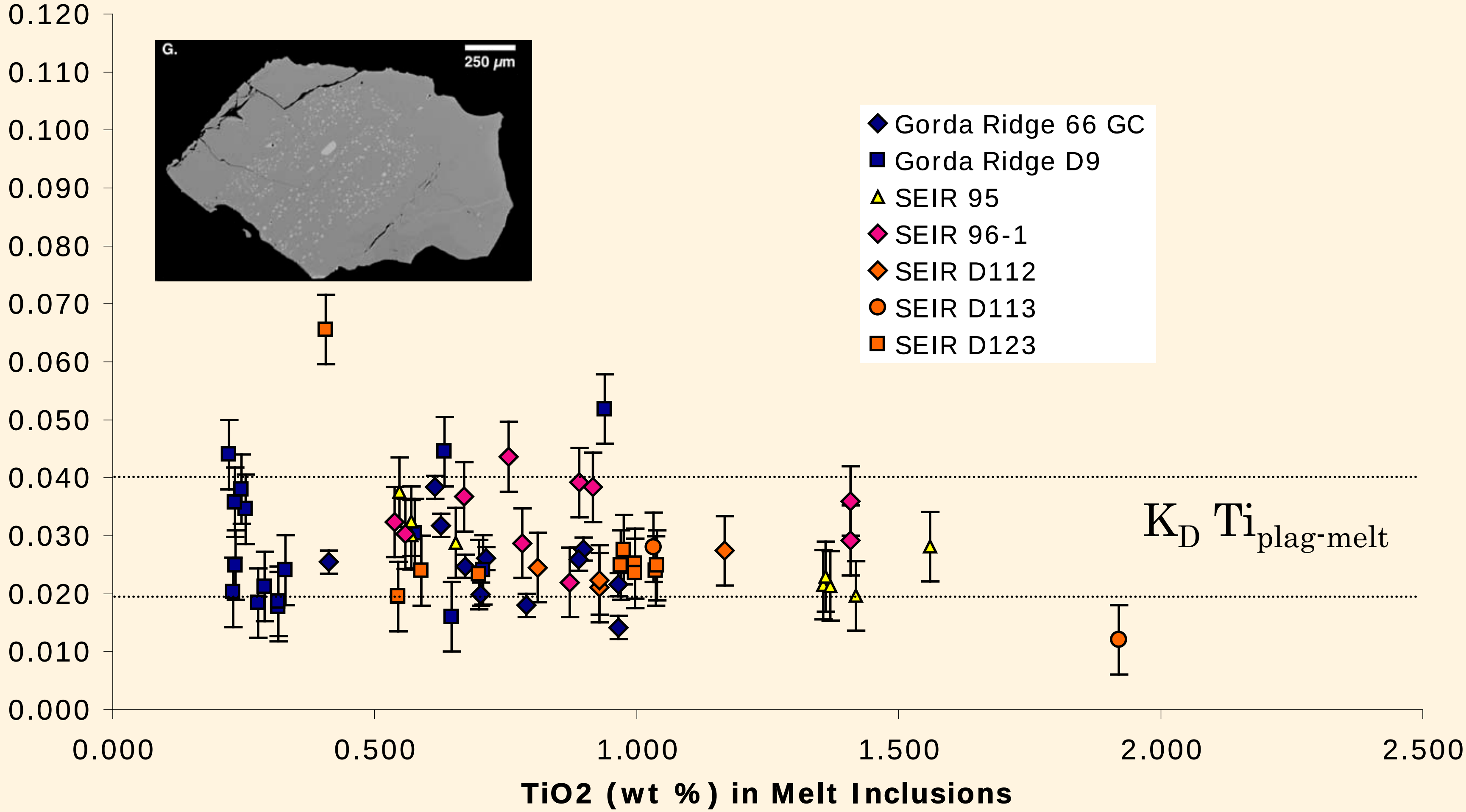
Driving Force?

Investigating the Fidelity of Melt Inclusions

Investigate:

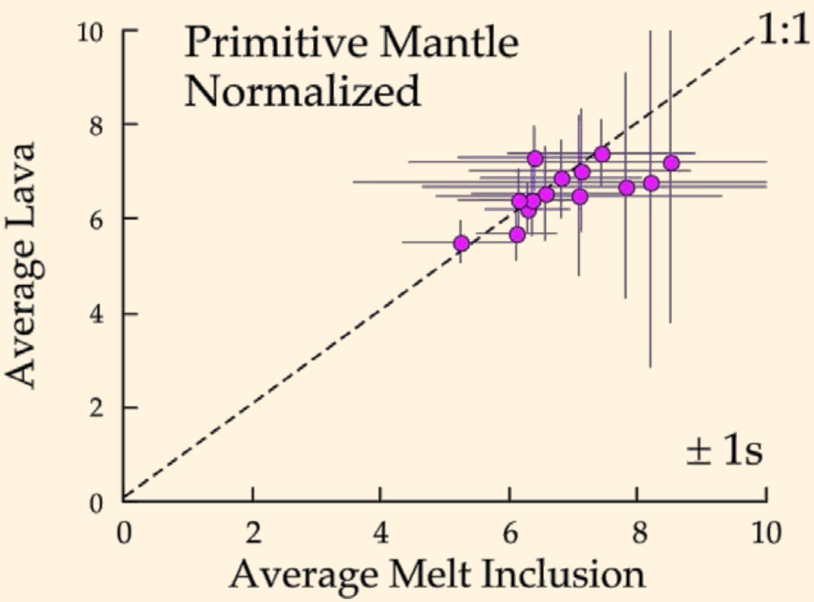
1. The relationship between inclusions and host minerals
2. Relationship between host crystals and host melt
3. Relationship between trapped melt compositions and host
4. Relationships amongst inclusions
5. Test specific hypotheses - diffusion, boundary layer trapping etc.

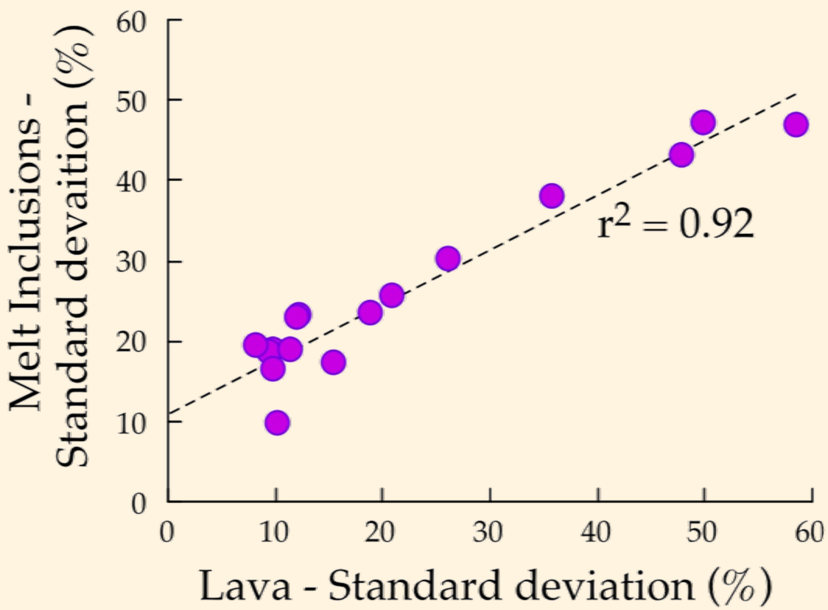

G.
250 μm



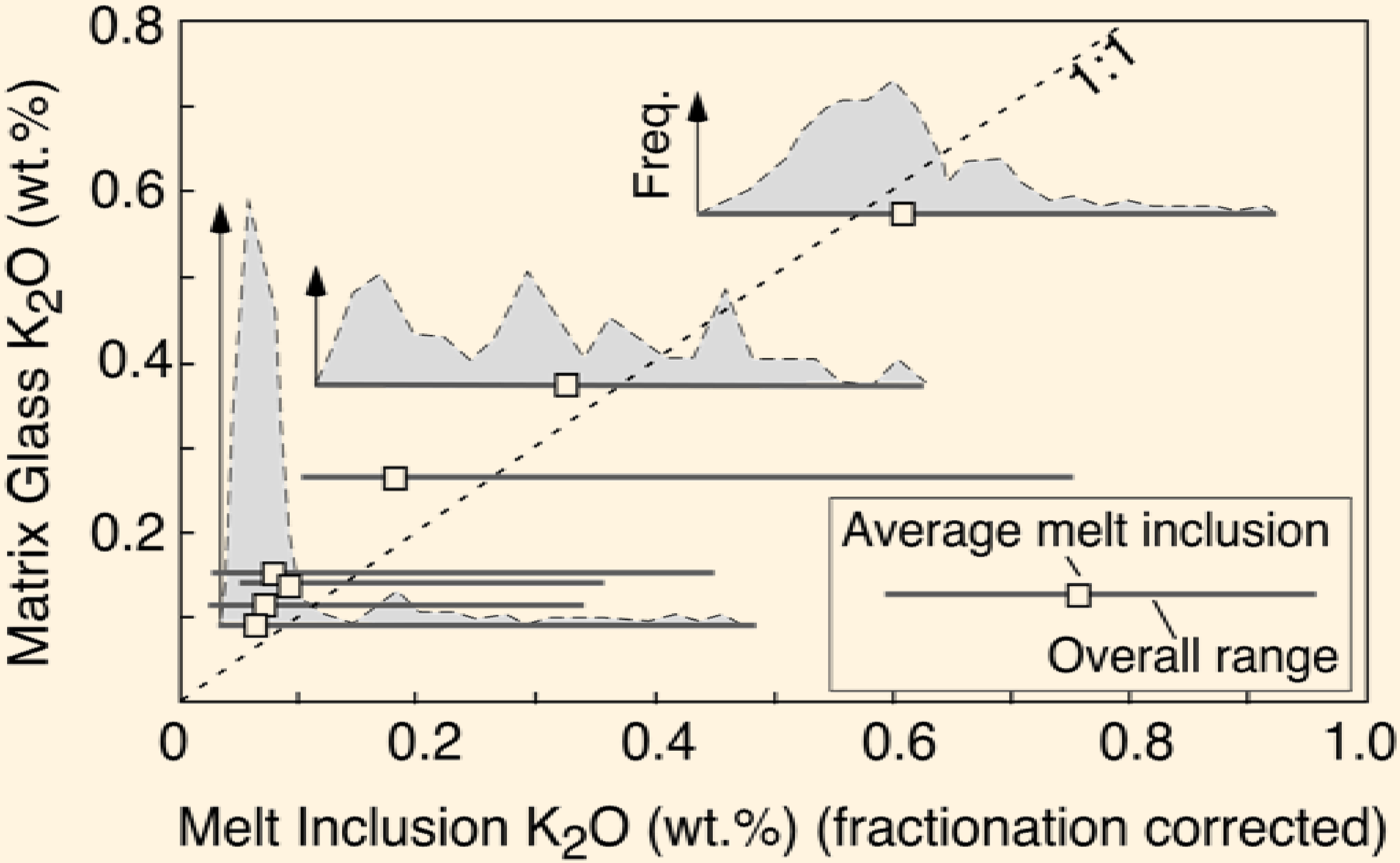
G.
250 μm
0.120
0.110
0.100
0.090
0.080
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0.000
0.500
1.000
1.500
2.000
2.500
TiO2 (wt %) in Melt Inclusions
Gorda Ridge 66 GC
Gorda Ridge D9
SEIR 95
SEIR 96-1
SEIR D112
SEIR D113
SEIR D123
K_D $Ti_{plag-melt}$

Inclusions vs. Host





Sours-Page et al. 1998



Key Points

- After trapping melt inclusions may undergo significant changes - primarily related to crystallization of the host mineral
- Other potential phenomenon include diffusional equlibration, vapour exsolution, crystallization and venting
- Careful examination of data can generally let you decide if inclusion compositions are reliable