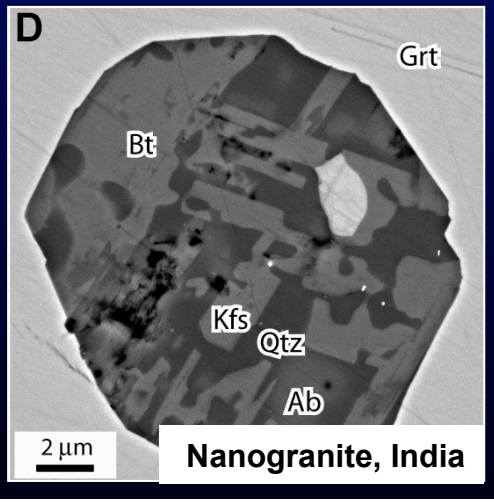
Melt inclusions in migmatites

Antonio Acosta-Vigil – IACT, CSIC-Univ. Granada

IACT
INSTITUTO ANDALUZ DE CIENCIAS DE LA TIERRA

CSIC

UNIVERSIDAD DE GRANADA

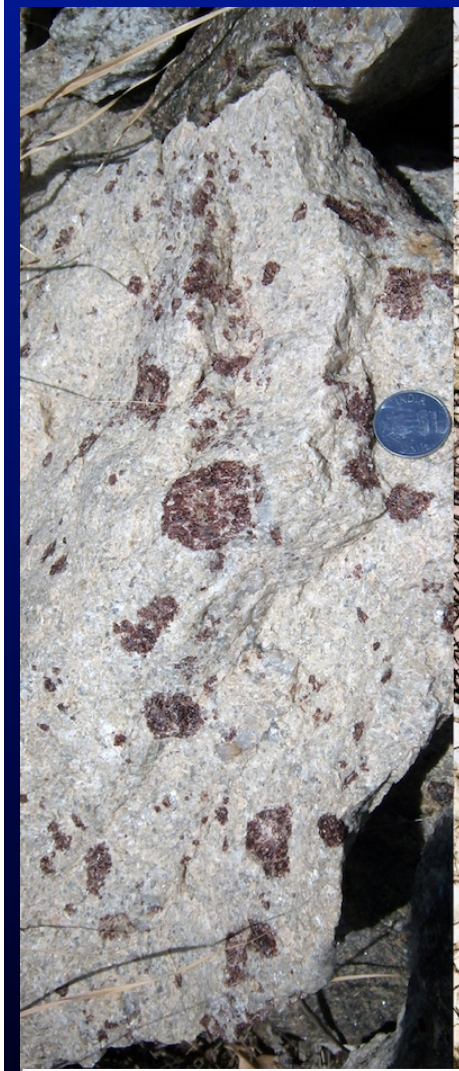


Nanogranite, India

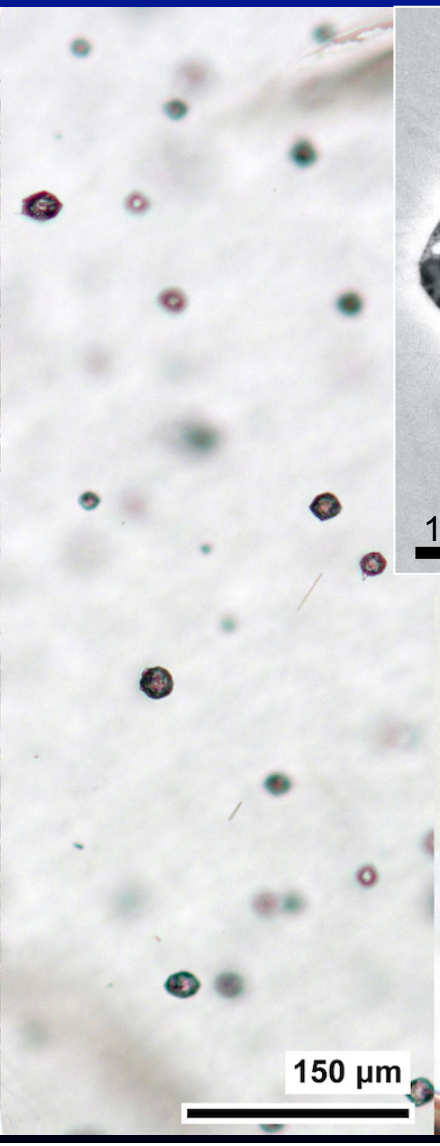
Migmatites-granulites, S Spain

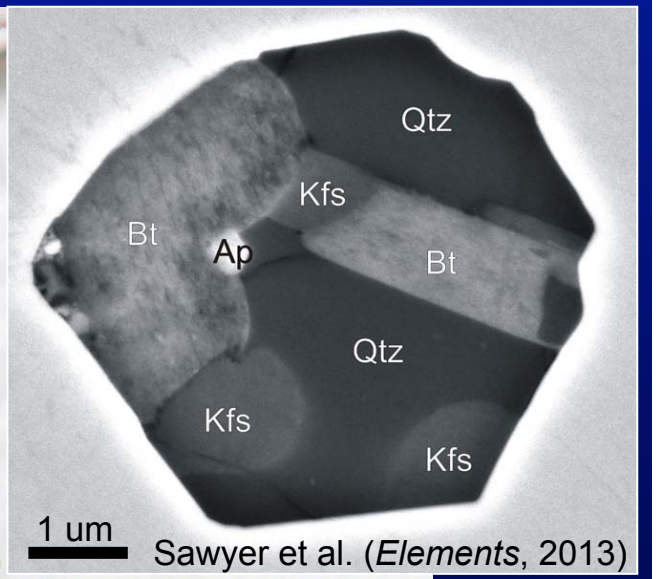
Melt inclusions in migmatites

Cesare et al. (2009) have described MI in a regional anatectic terrane. Appear in many anatectic terranes. Very small, crystallized, “nanogranites”.

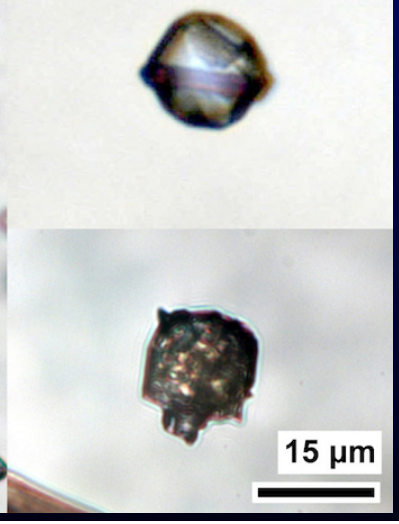


Cesare et al. (Geology, 2009)

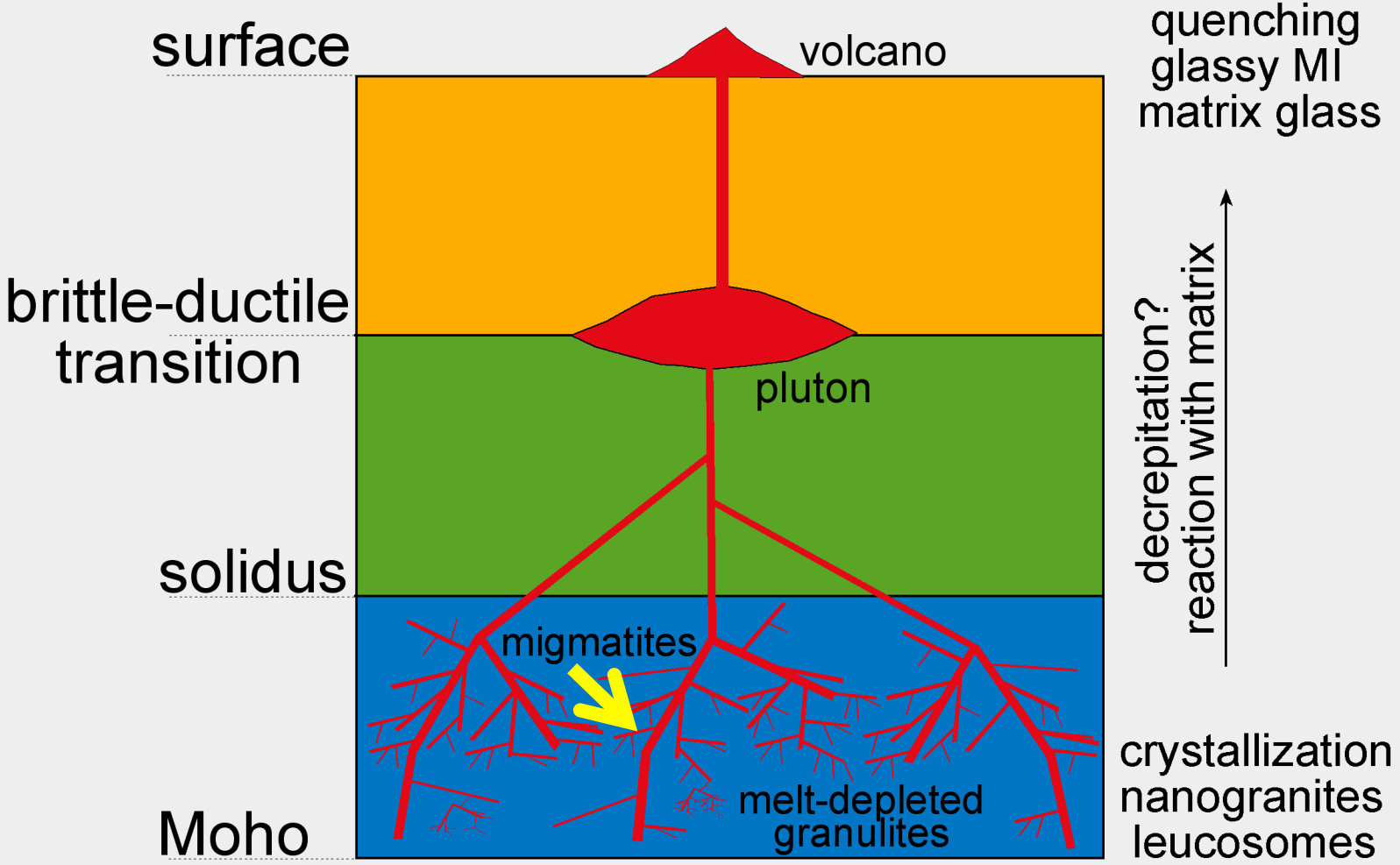




Sawyer et al. (*Elements*, 2013)



Melt inclusions in migmatites

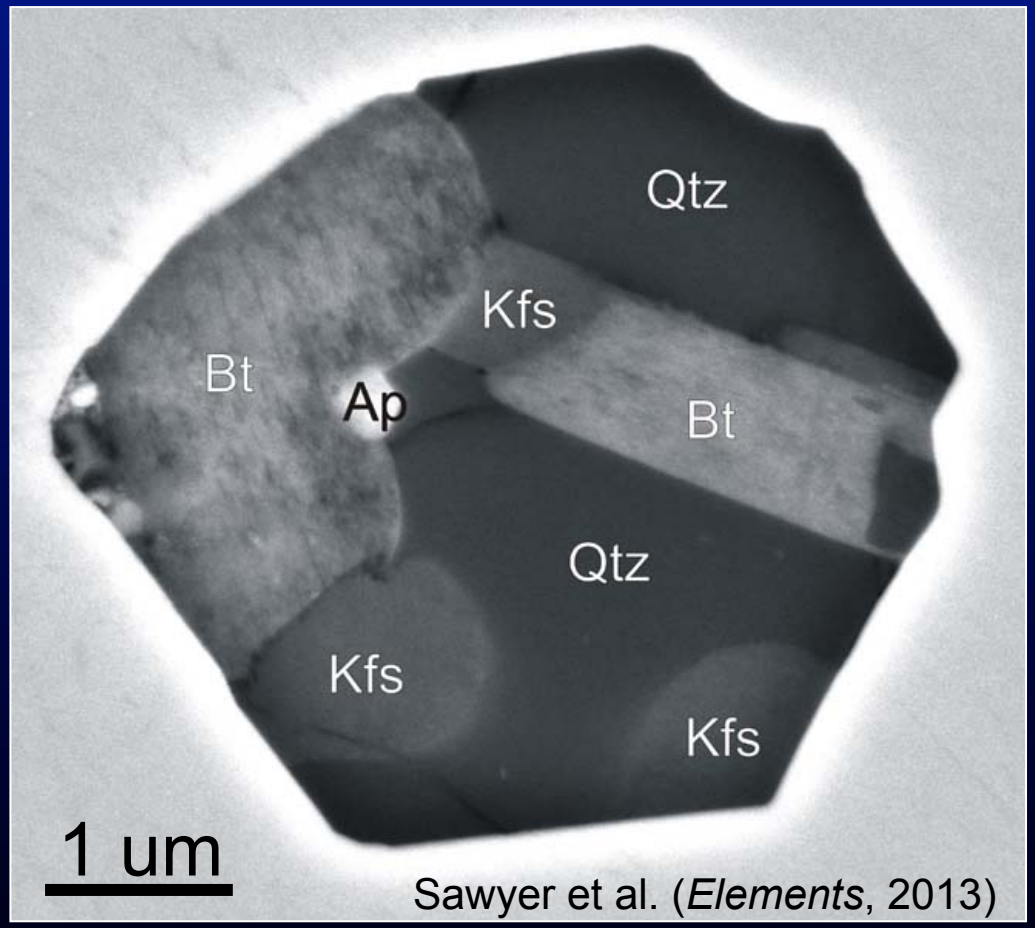


Modified after Sawyer et al. Elements (2011)

Melt inclusions in migmatites

Melt inclusions, definition modified by Cesare et al. (2015), to include those present in regional migmatites:

Small droplets of melt that are trapped in minerals during their growth in the presence of a melt phase (Cesare et al. 2009, 2015). NANOGRANITOIDS



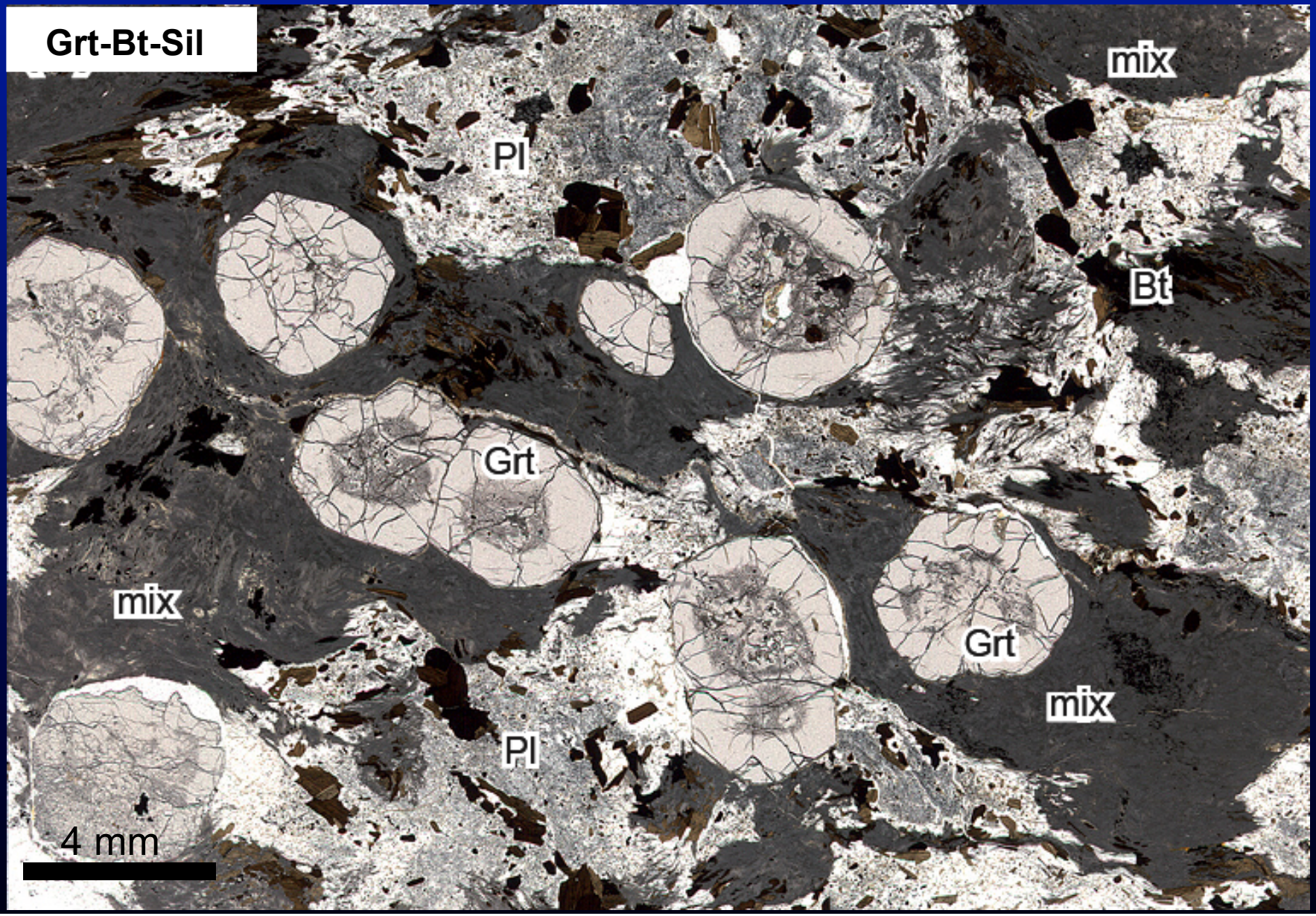
Sawyer et al. (*Elements*, 2013)

For reviews on melt inclusions of volcanic rocks (CLASSIC melt inclusios):

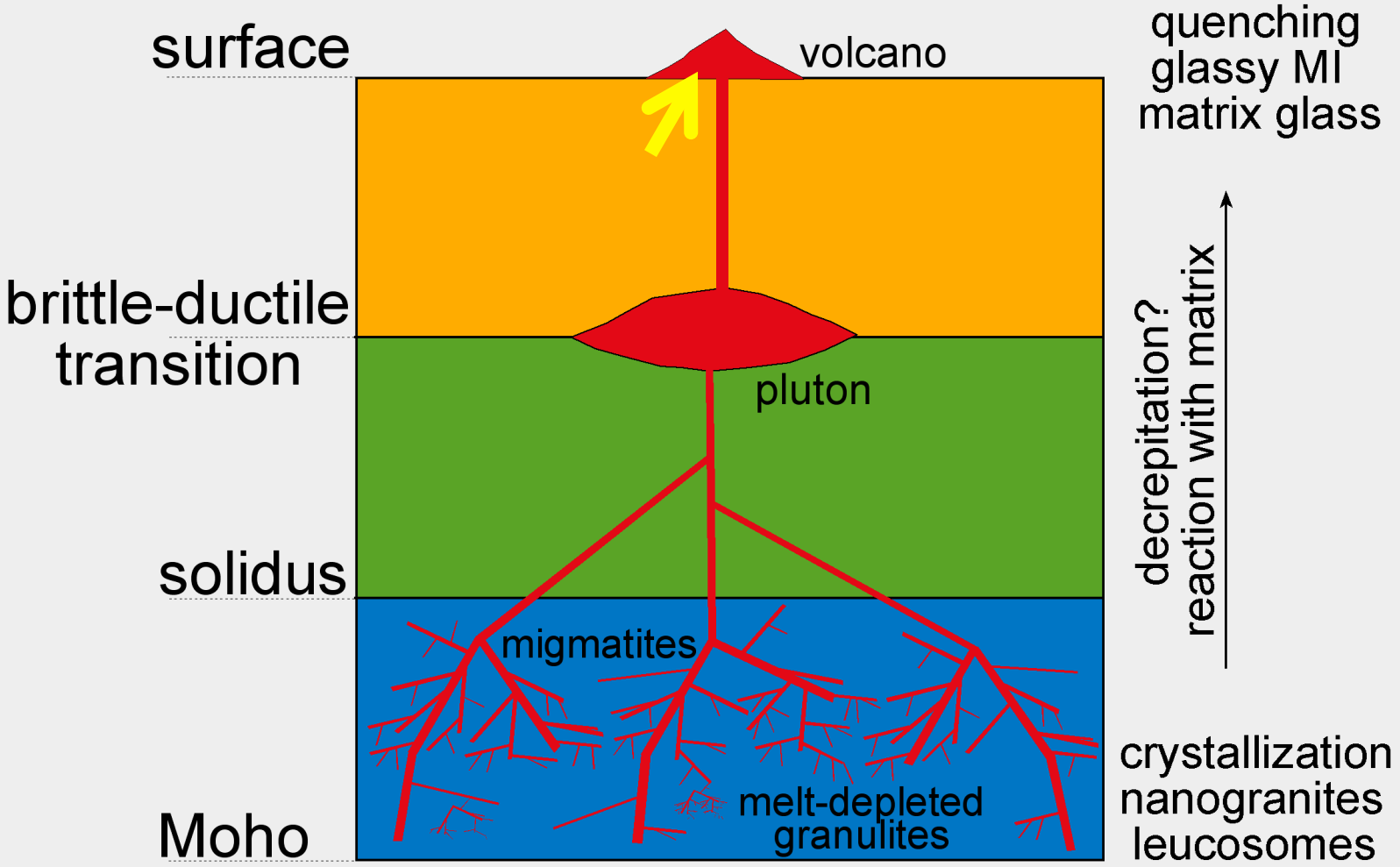
Roedder (1979)
Schiano (2003)
Audétat & Lowerstern (2014)
Frezzotti & Ferrando (2015)

Melt inclusions in anatectic enclaves

Cesare et al. (1997), Cesare (2008)

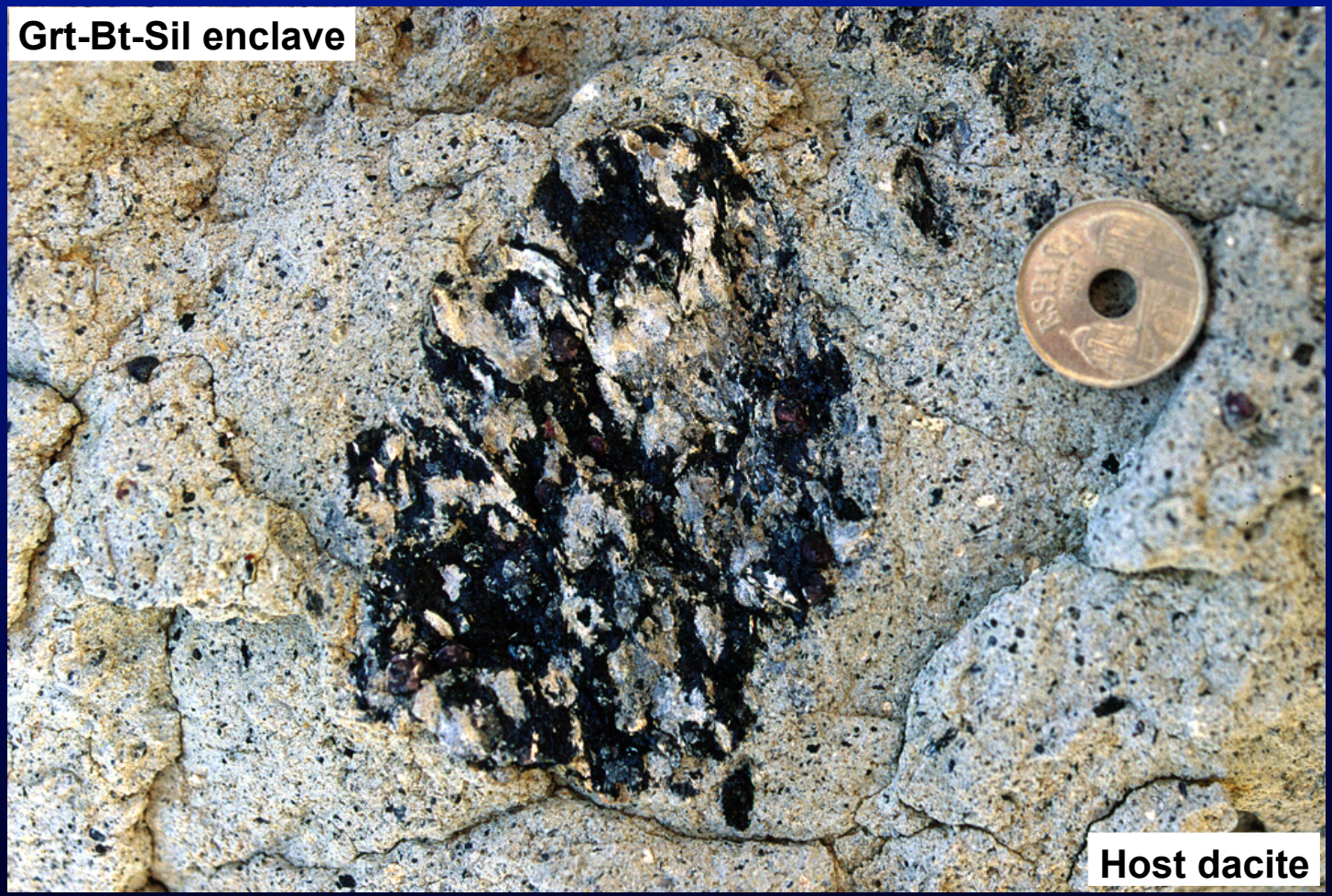


Melt inclusions in anatectic enclaves



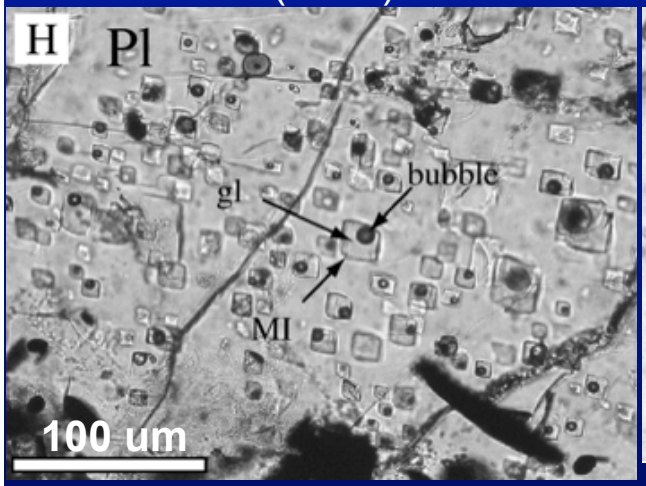
Modified after Sawyer et al. Elements (2011)

Melt inclusions in anatectic enclaves

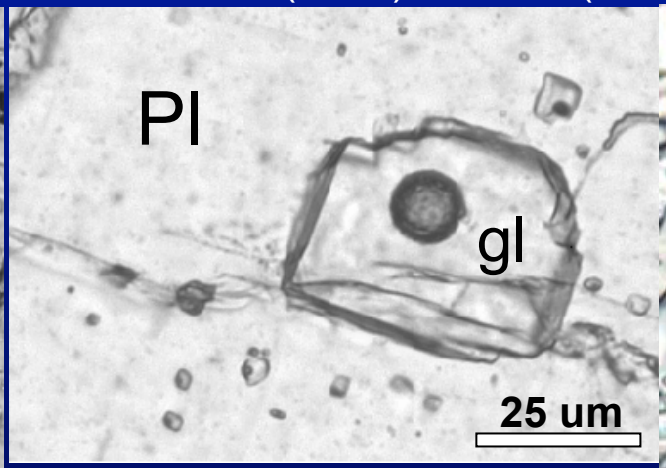


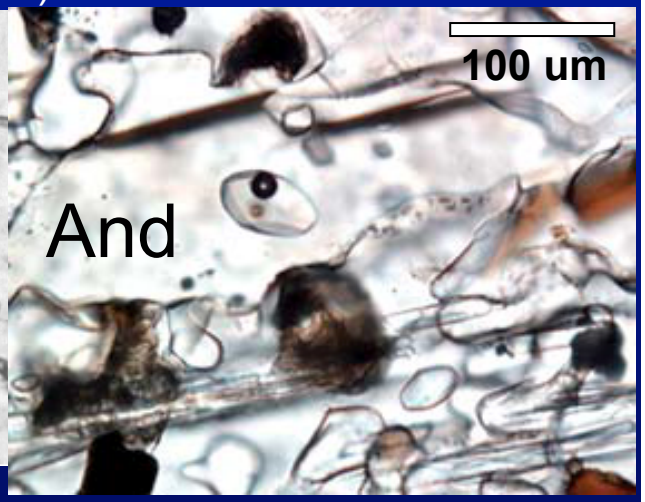
Melt inclusions in anatectic enclaves

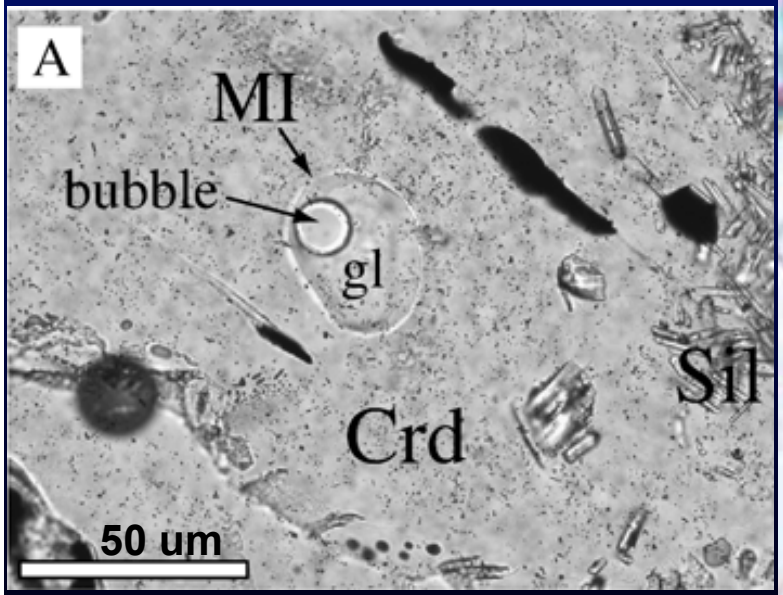
Acosta et al. (2007)

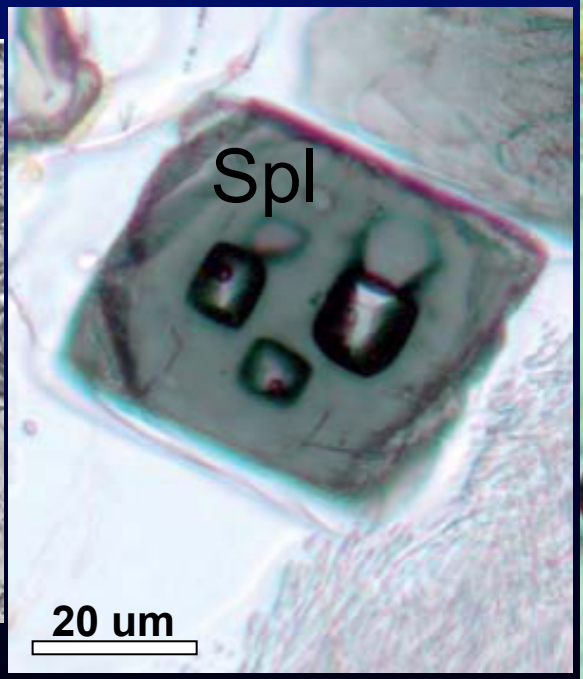


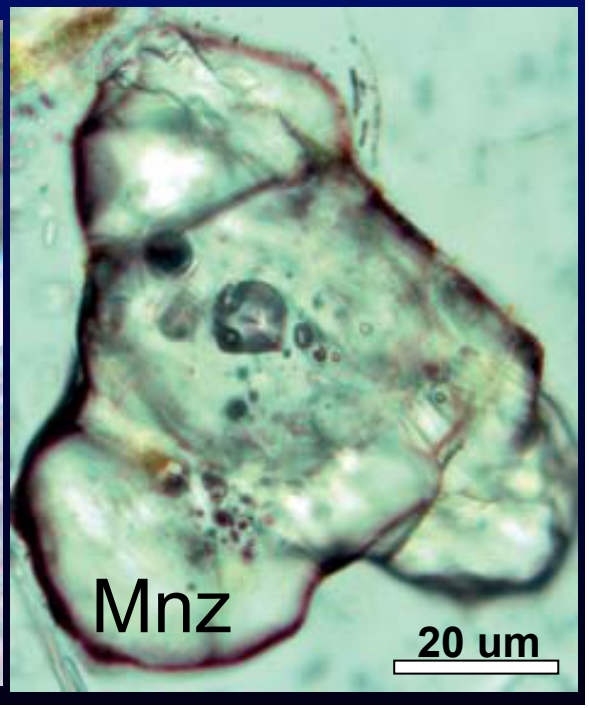
Cesare et al. (1997), Cesare (2008)



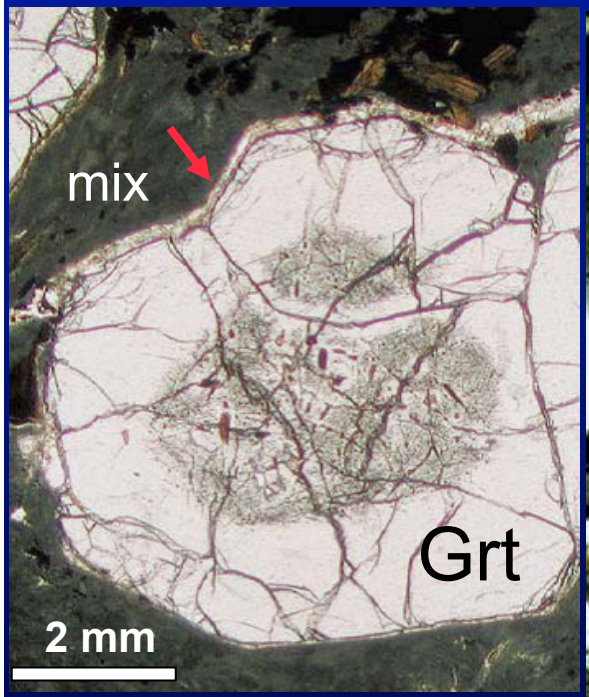




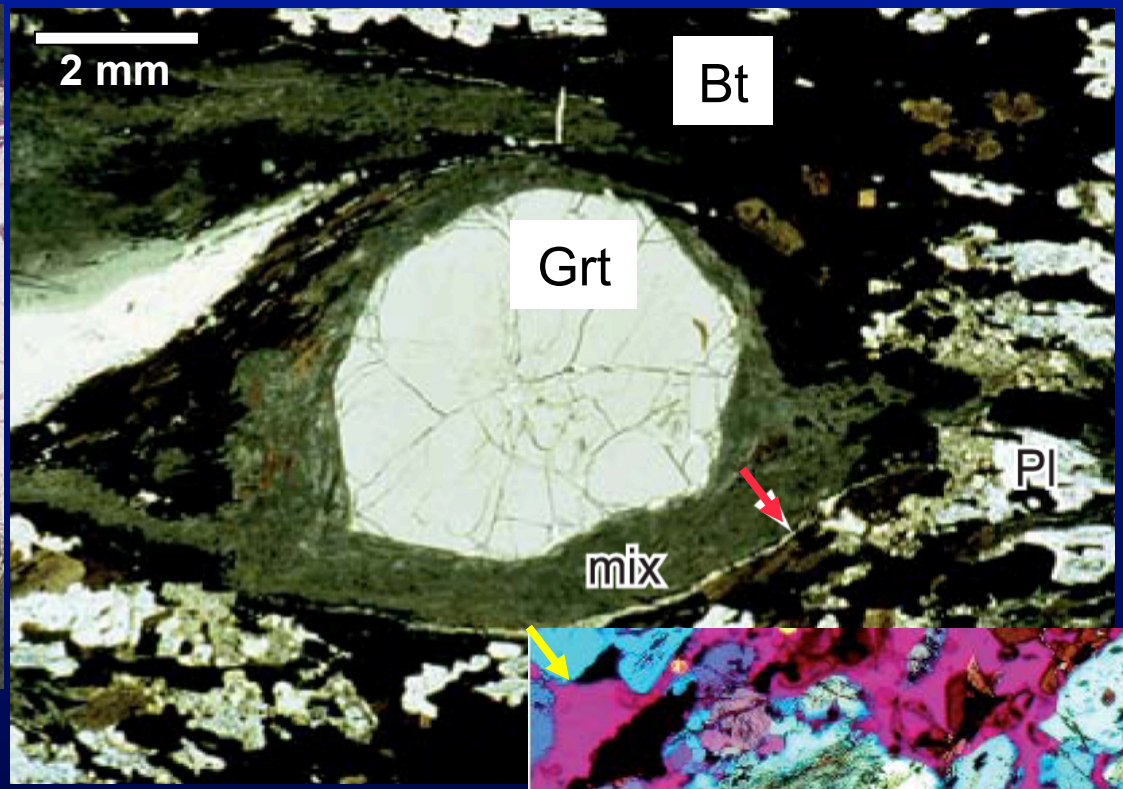


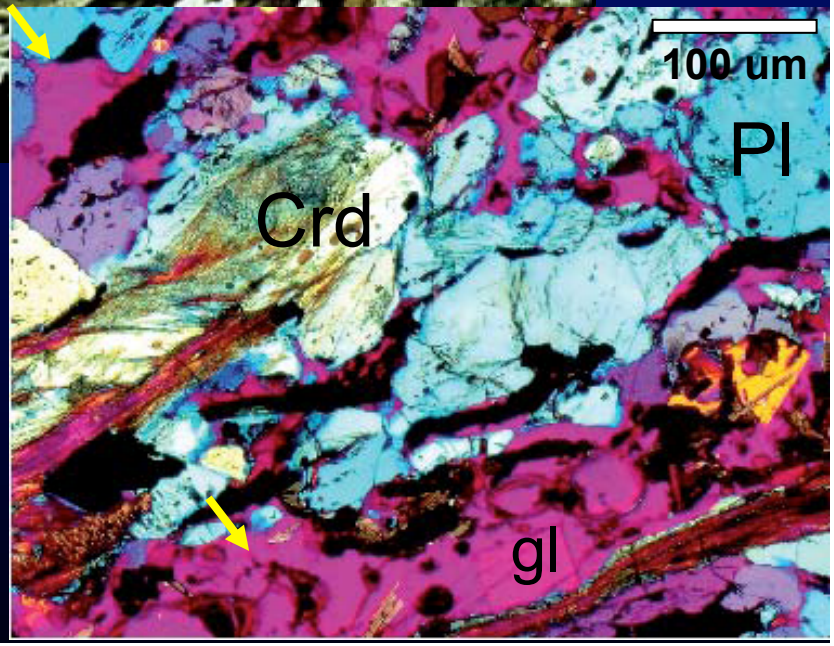


Melt inclusions in anatectic enclaves



Cesare (2008)

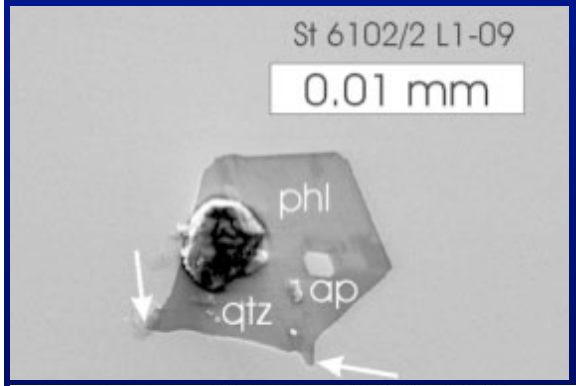


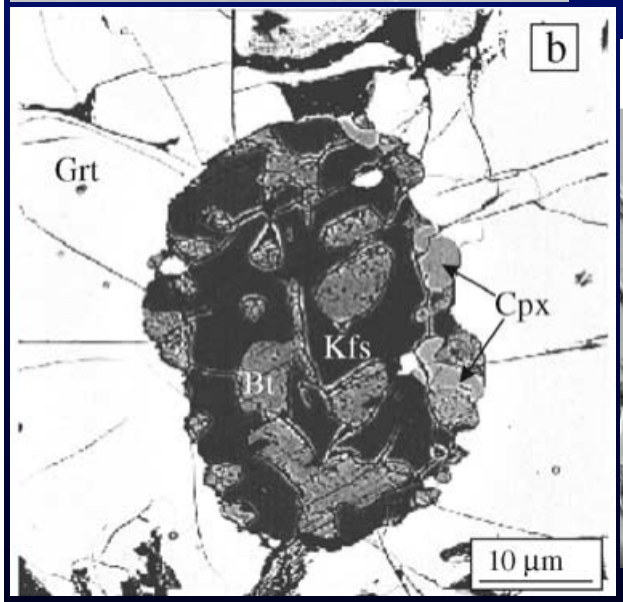


Inclusions in UHP crustal rocks

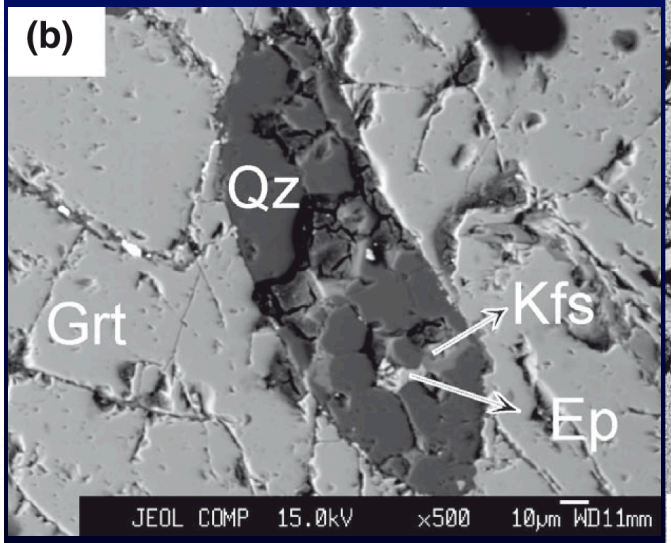
Inclusions, reported by 2001 in high-grade crustal rocks, taken to mantle depths, i.e. UHP crustal rocks: Melt, polyphase or multiphase inclusions

Stöckhert et al. (2001), Erzgebirge, Germany

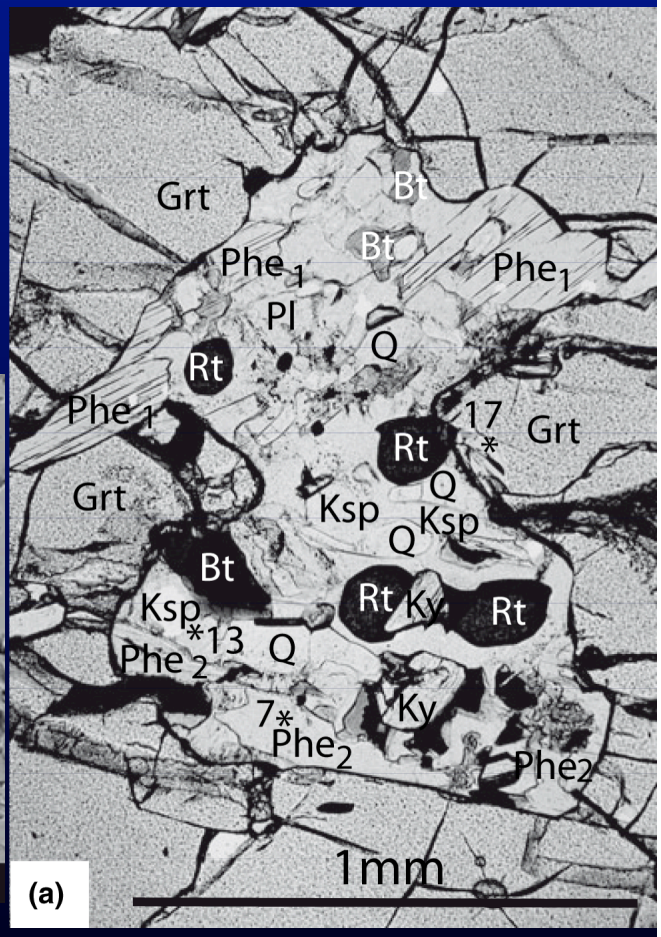




Korsakov & Hermann (2006)
Kokchetav, Kazakhstan



Gao et al. (2001)
Dabie-Sulu, China

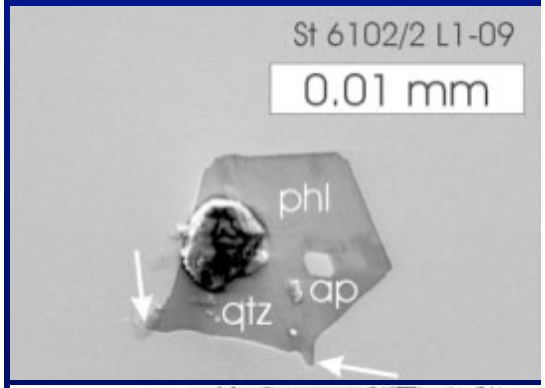


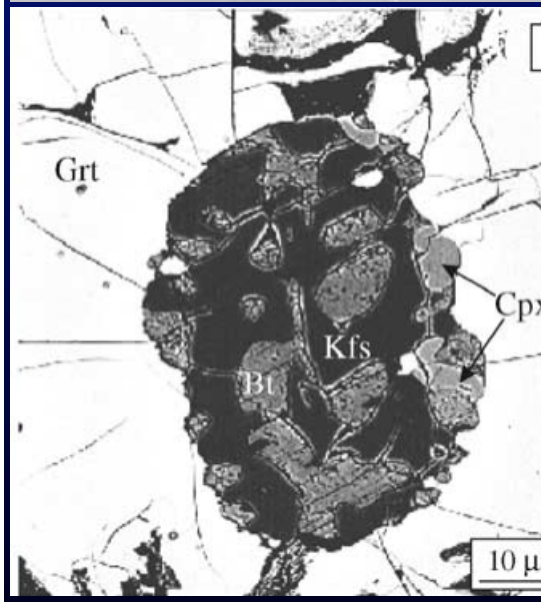
Lang & Gilotti (2007)
Caledonian, Greenland

Inclusions in UHP crustal rocks

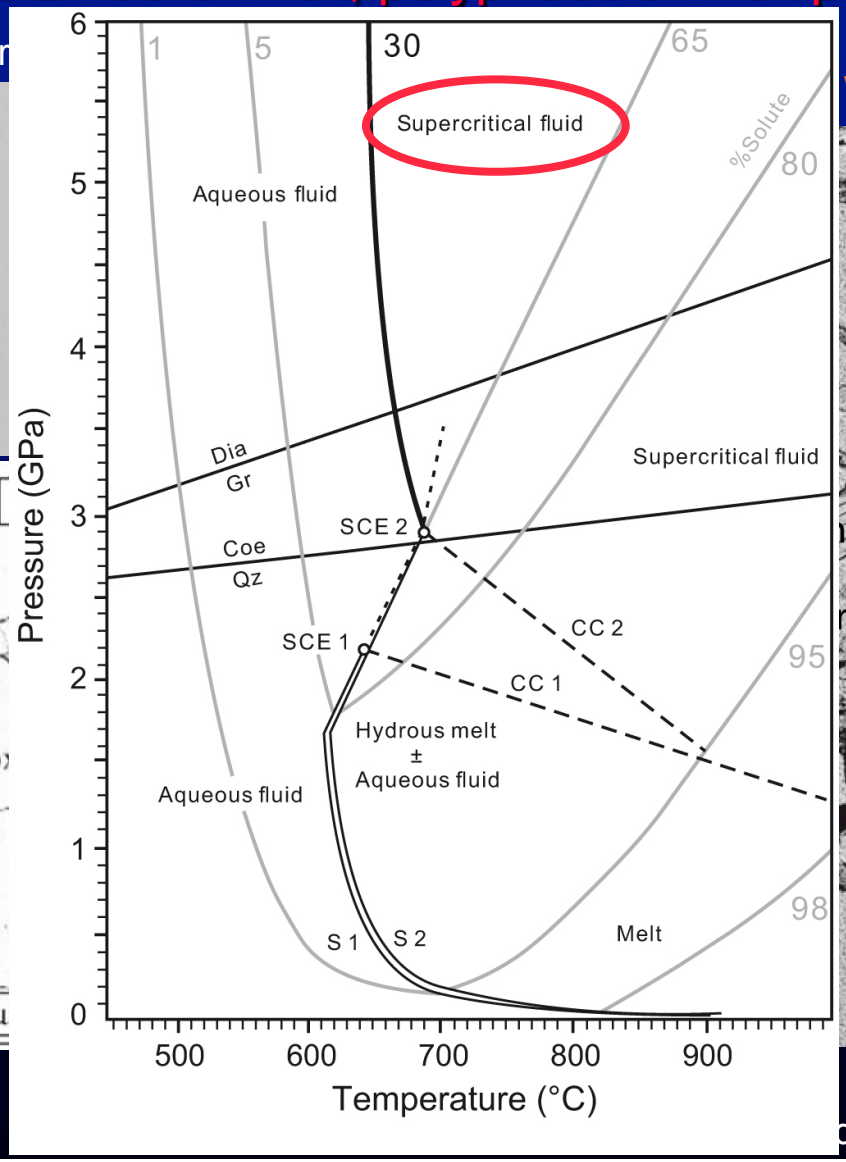
Inclusions, reported by 2001 in high-grade crustal rocks, taken to mantle depths, i.e. UHP crustal rocks: Melt, polyphase or multiphase inclusions

Stöckhert et al. (2001), Erzgebir

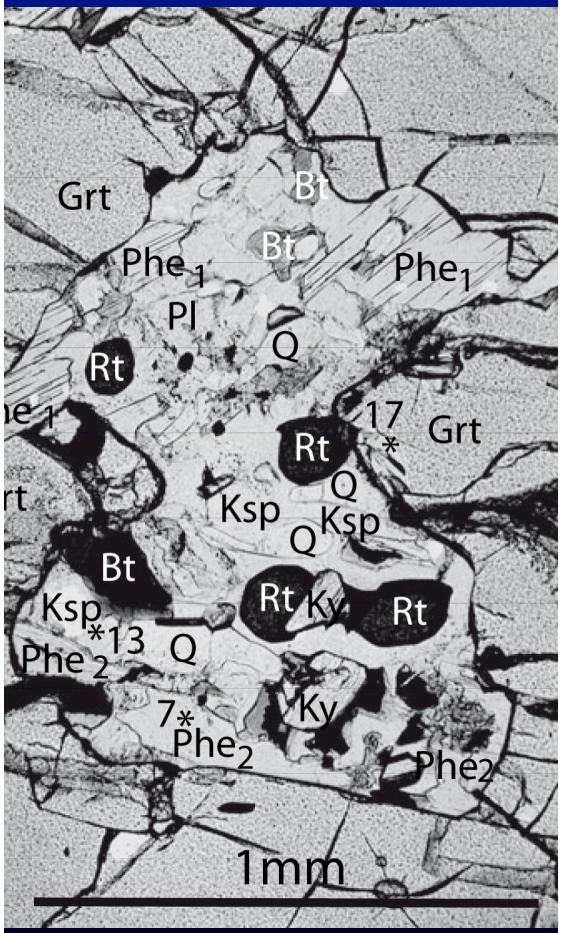




Korsakov & Hermann (2006)
Kokchetav, Kazakhstan



Wang et al. (2017)

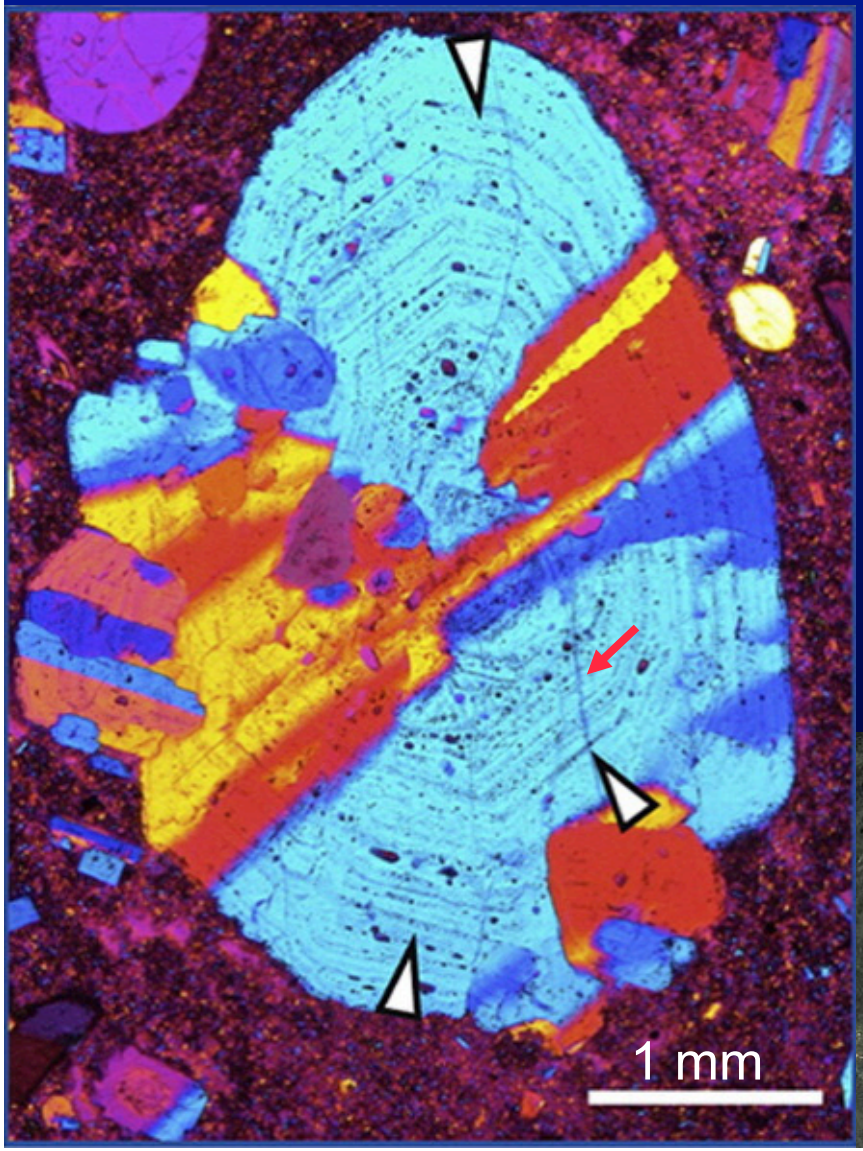


& Gilotti (2007)
donian, Greenland

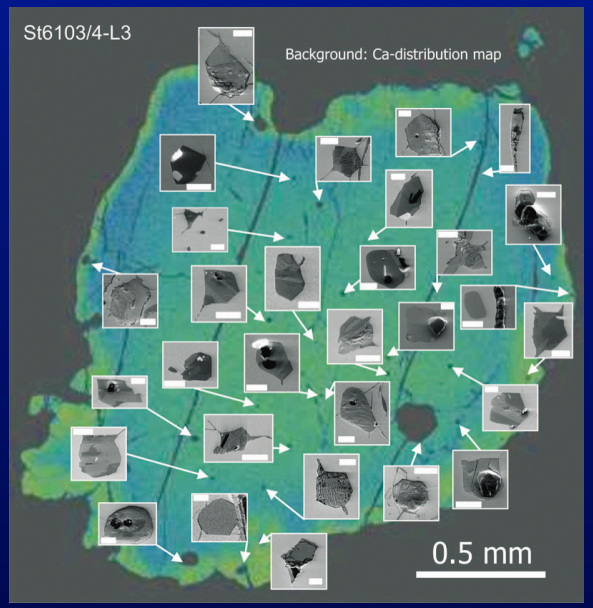
Primary vs secondary melt inclusions

See Roedder (1979)

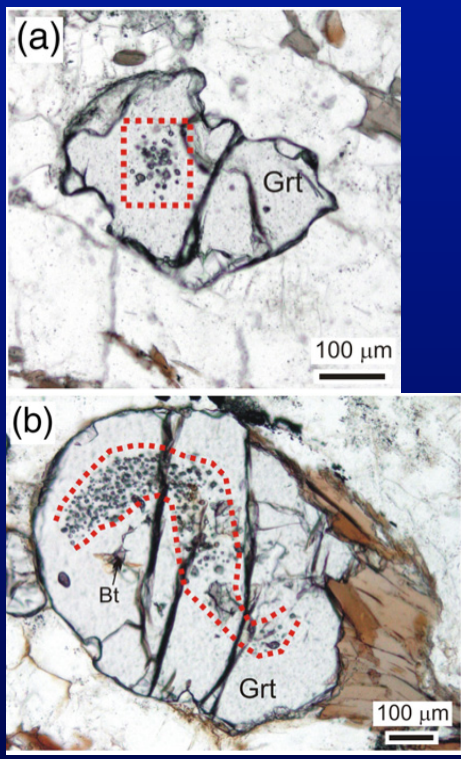
Cesare et al. (2015)



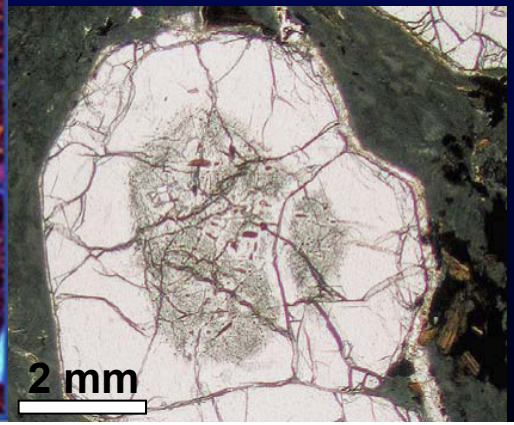
Stöckhertl et al. (2009)



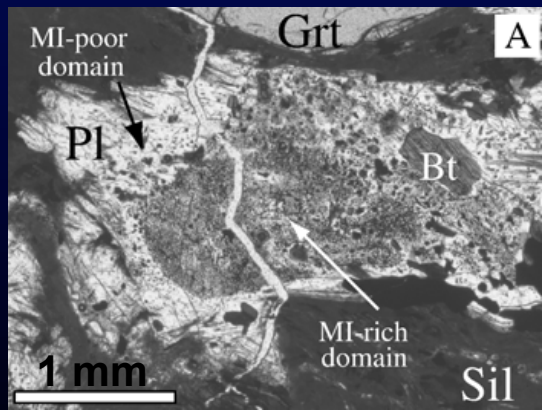
Bartoli et al. (2016)



Cesare (2008)

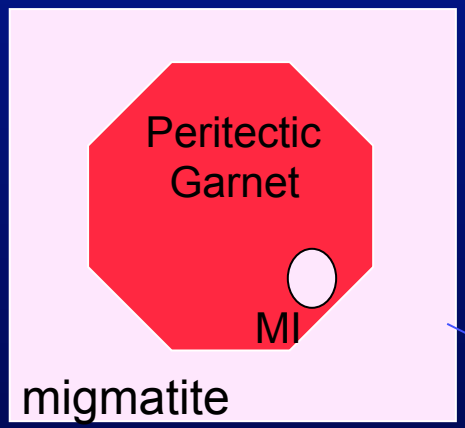


Acosta-Vigil et al. (2007)



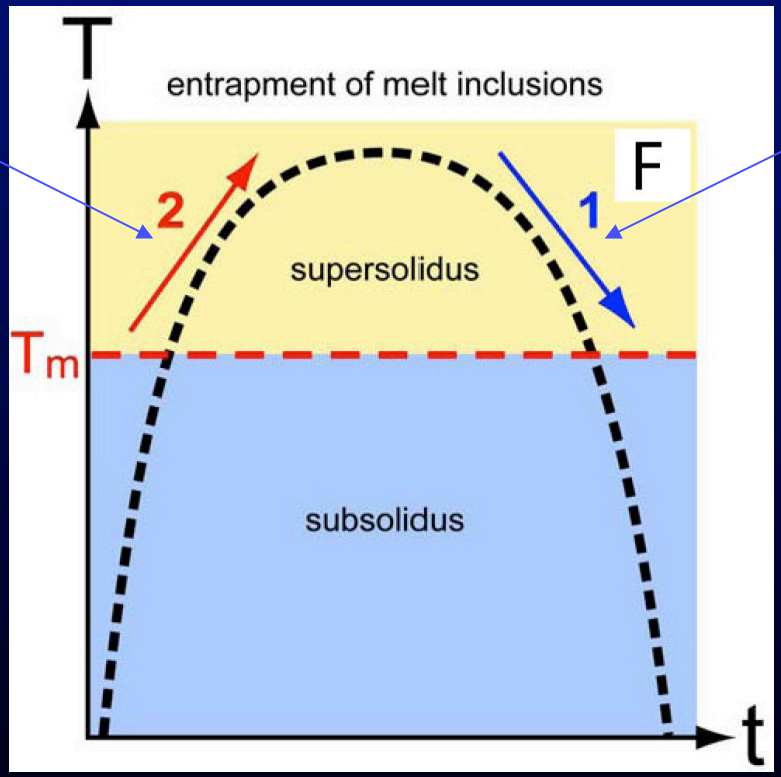
Melt inclusions in anatectic rocks versus volcanic rocks

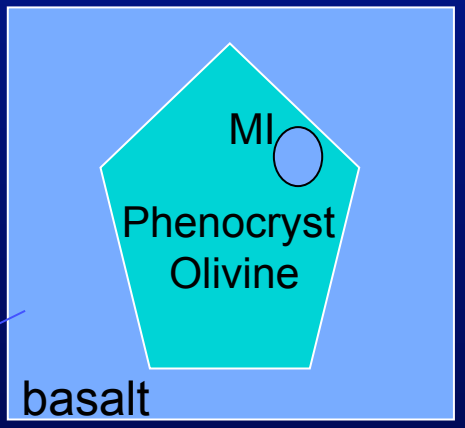
Melt inclusions in anatectic rocks represent primary melts produced at the source rocks of crustal granites upon melting



PRIMARY MELTS

Bt+Sil+Qtz+Pl= melt+Grt





EVOLVED MELTS

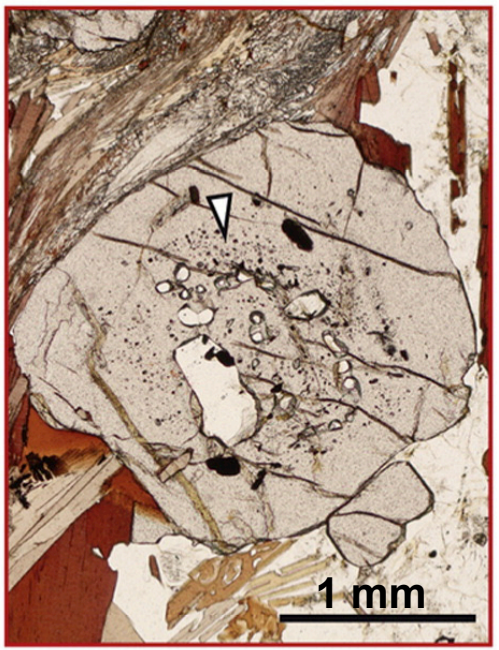
melt 1= Ol + melt 2

Cesare et al. J Virt Expl (2011)
& Bartoli et al. EPSL (2014)

Melt inclusions in anatectic rocks versus volcanic rocks

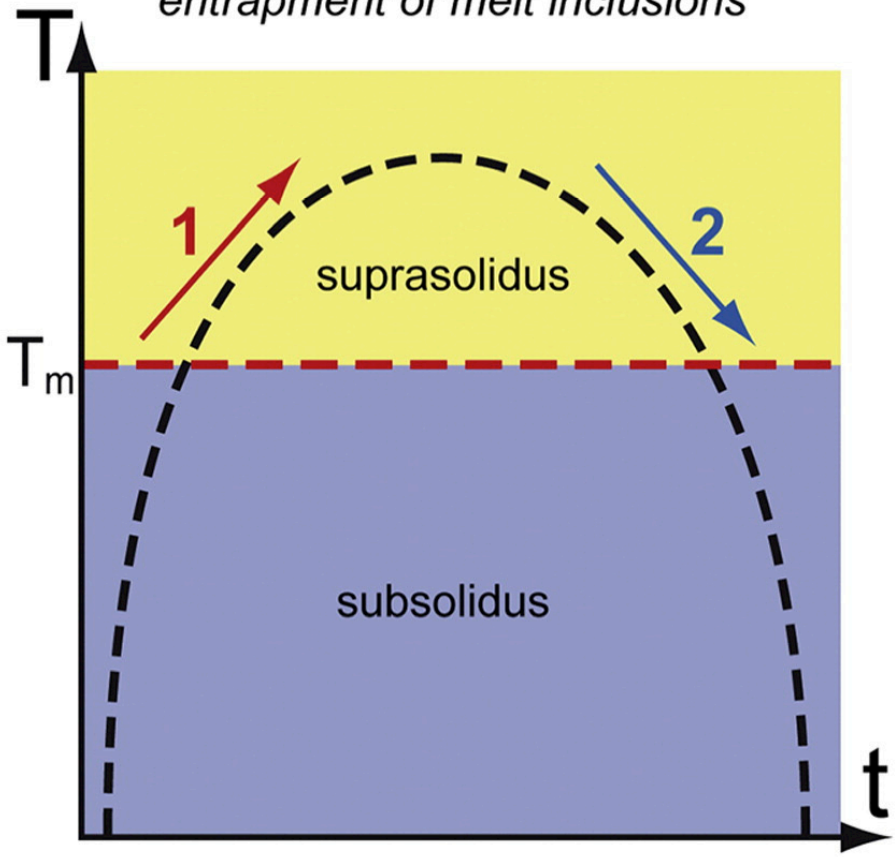
Melt inclusions in anatectic rocks represent primary melts produced at the source rocks of crustal granites upon melting

1 - Peritectic

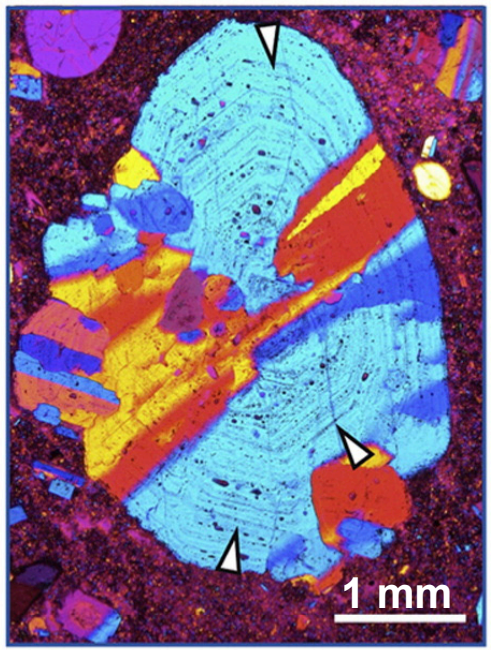


-Migmatites, granulites
-Enclaves and xenoliths in lavas
-Host growth in solid framework
-Entrapment during heating
-Primary melt composition

entrapment of melt inclusions



2 - Igneous

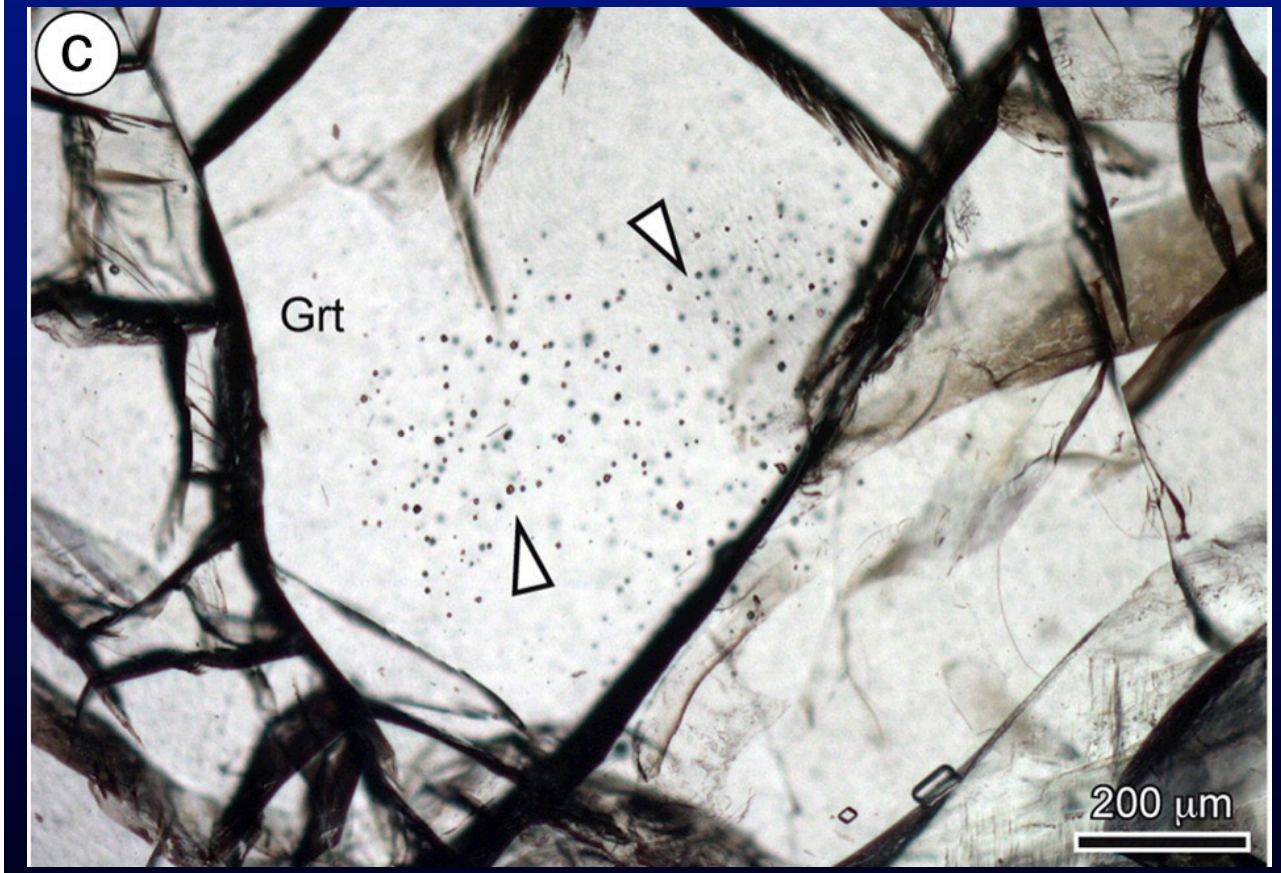


-Intrusive and extrusive rocks
-Leucosomes in migmatites
-Host growth in magma
-Entrapment during cooling
-Evolved melt composition

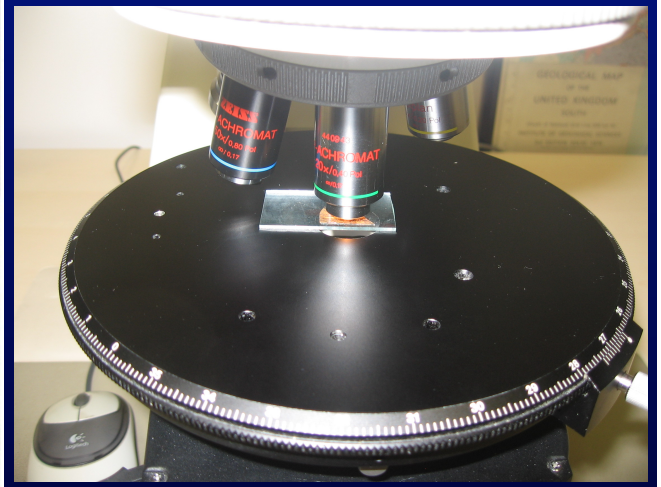
Cesare et al. (2015)

Identifying melt inclusions in migmatites

1. Optical microscope on regular, but well-polished, thin sections
- Regular, crystal-negative shape, brownish color (at least 20x)
- Polycristalline and/or glassy nature, multiple birefringent phases and/or isotropic



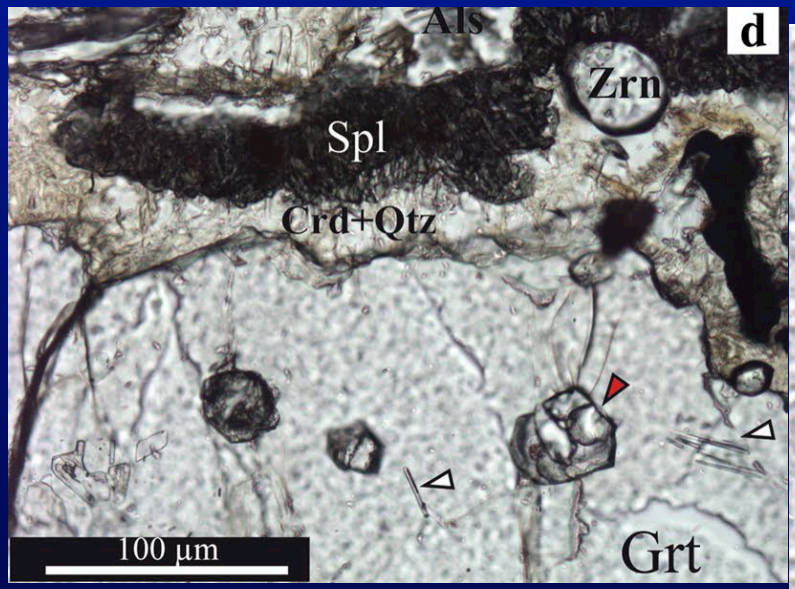
Cesare et al. (2015)

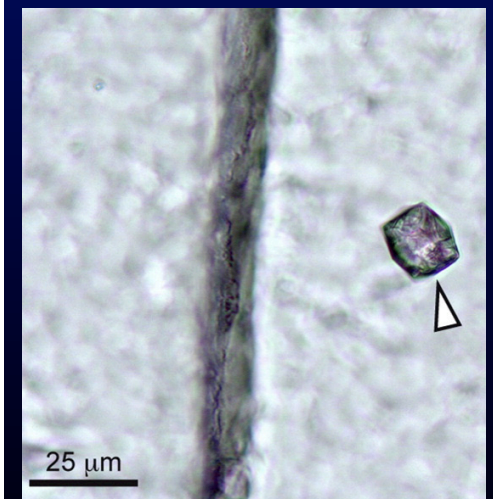


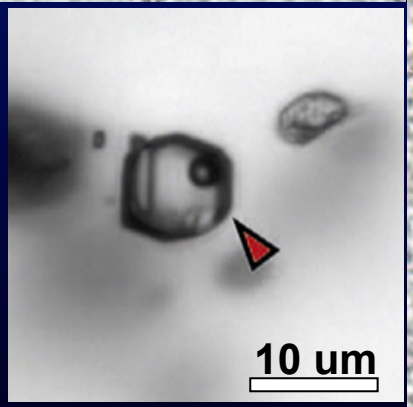
Identifying melt inclusions in migmatites

1. Optical microscope on regular, but well-polished, thin sections

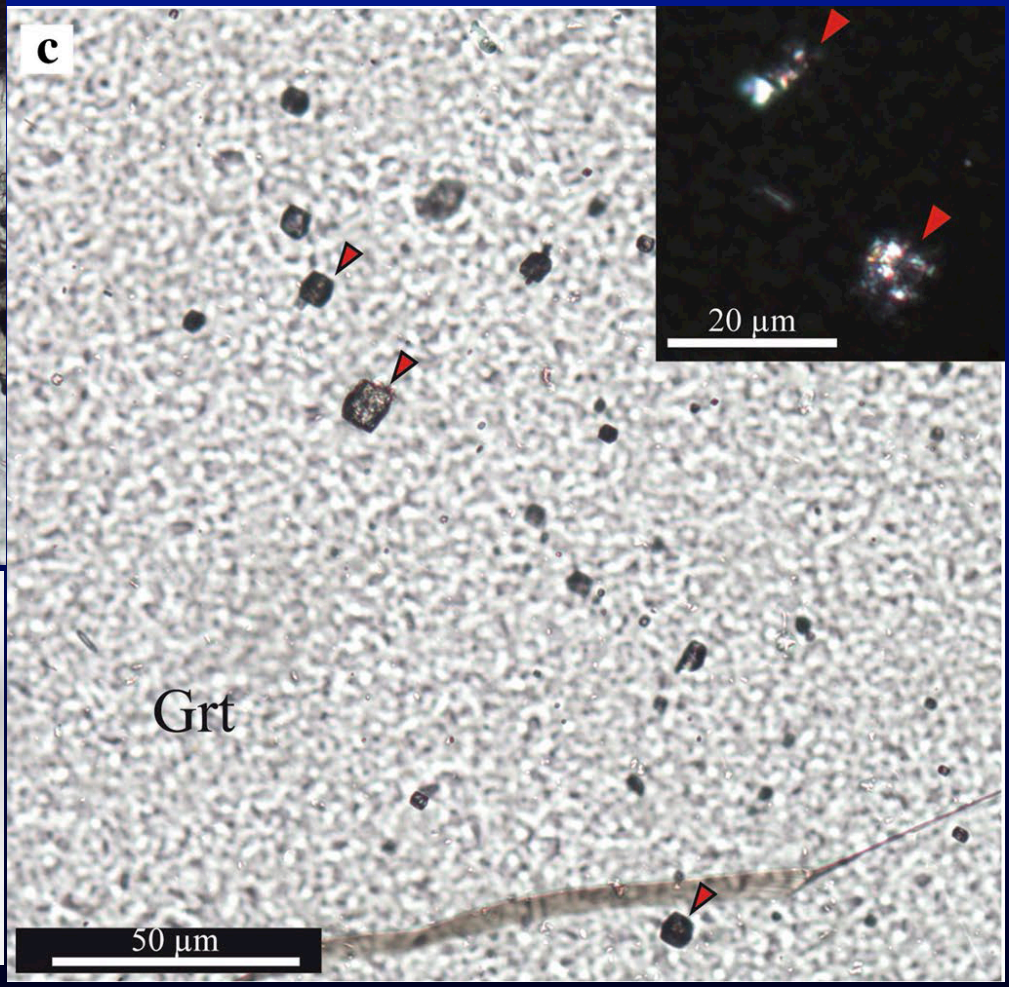
- Regular, crystal-negative shape, brownish color (at least 20x)
- Polycristalline and/or glassy nature, multiple birefringent phases and/or isotropic







Cesare et al. (2015)

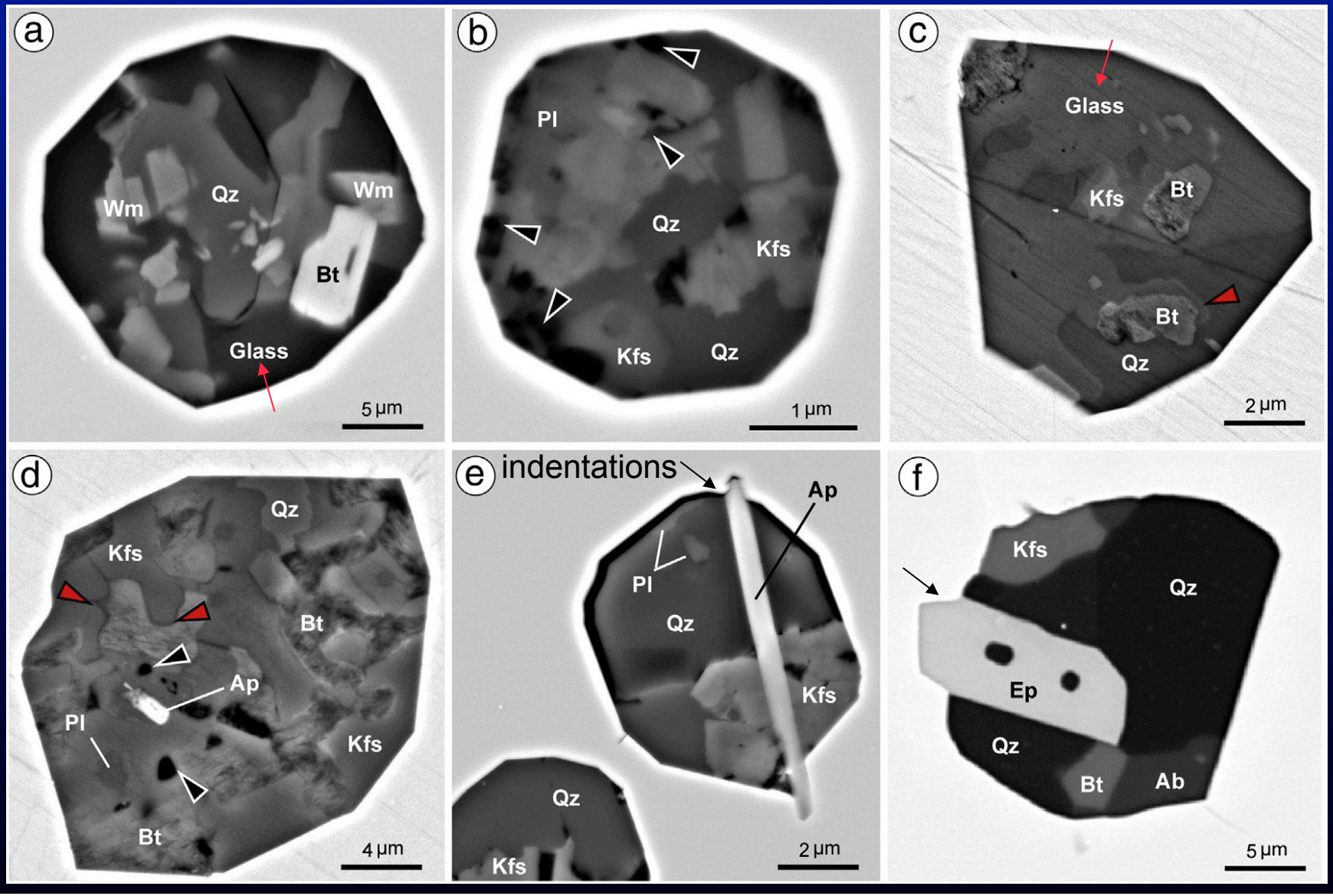


Barich et al. (2014), Acosta-Vigil et al. (2016)

Characterization of melt inclusions

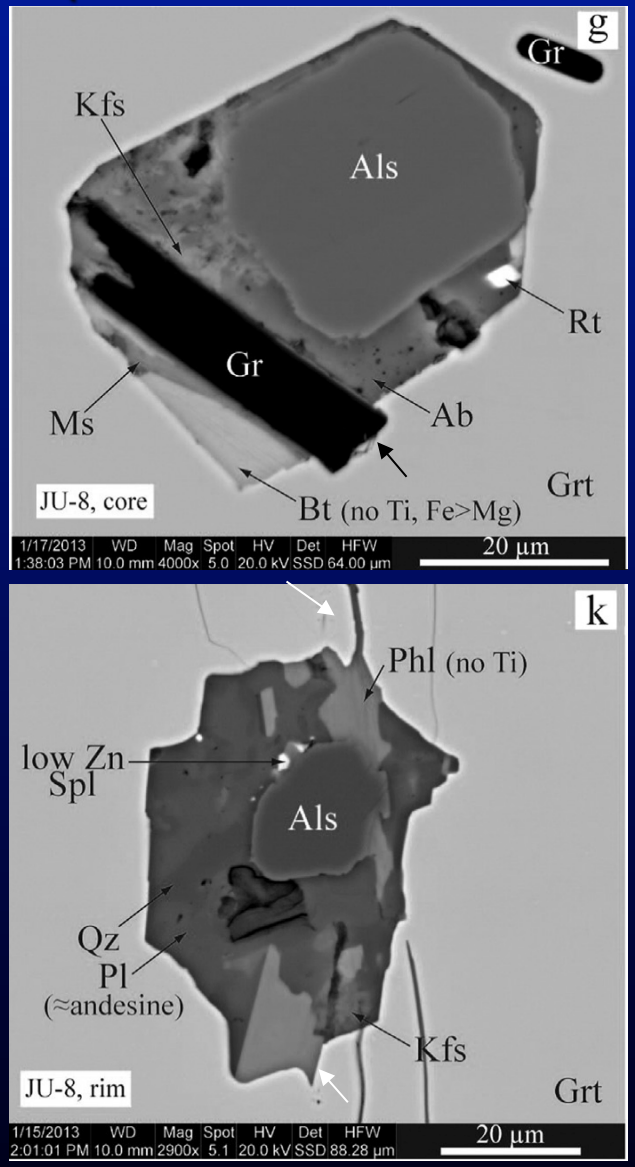
2. SEM (Field Emission, 5-10 microns MI)

Cesare et al. (2015)

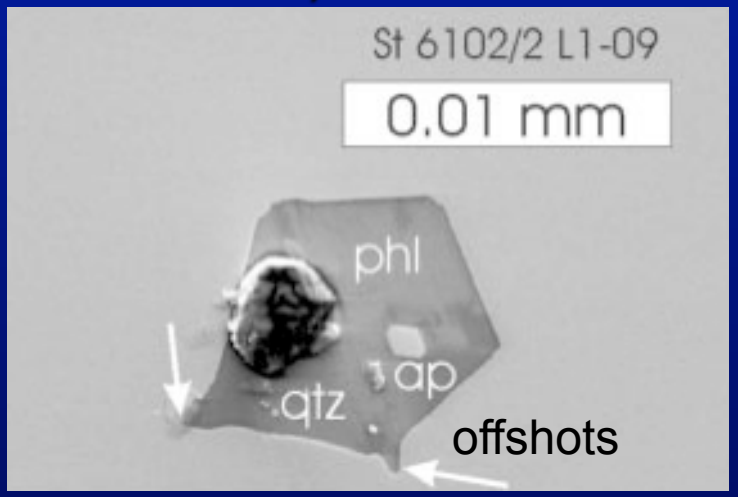


Characterization of melt inclusions

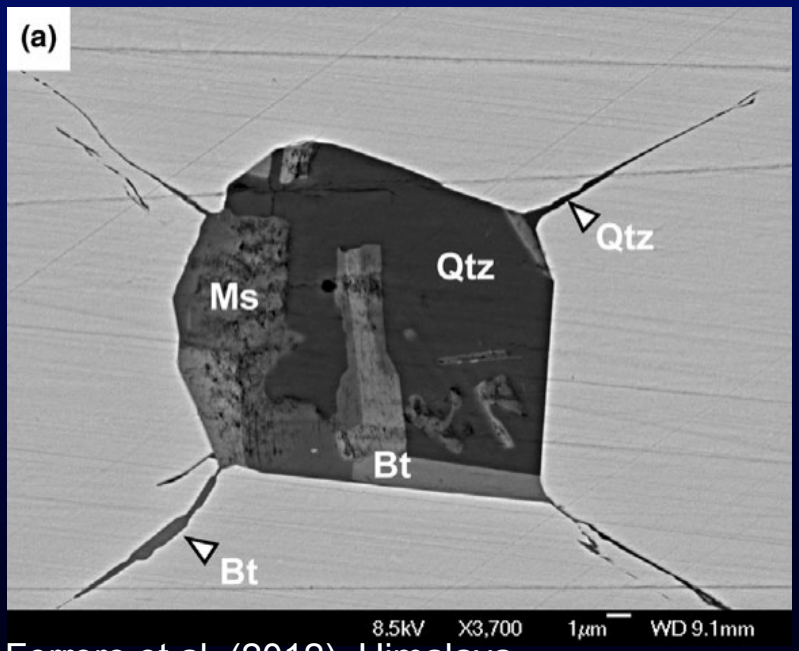
2. SEM (Field Emission, 5-10 microns MI)



Barich et al. (2014), Ronda



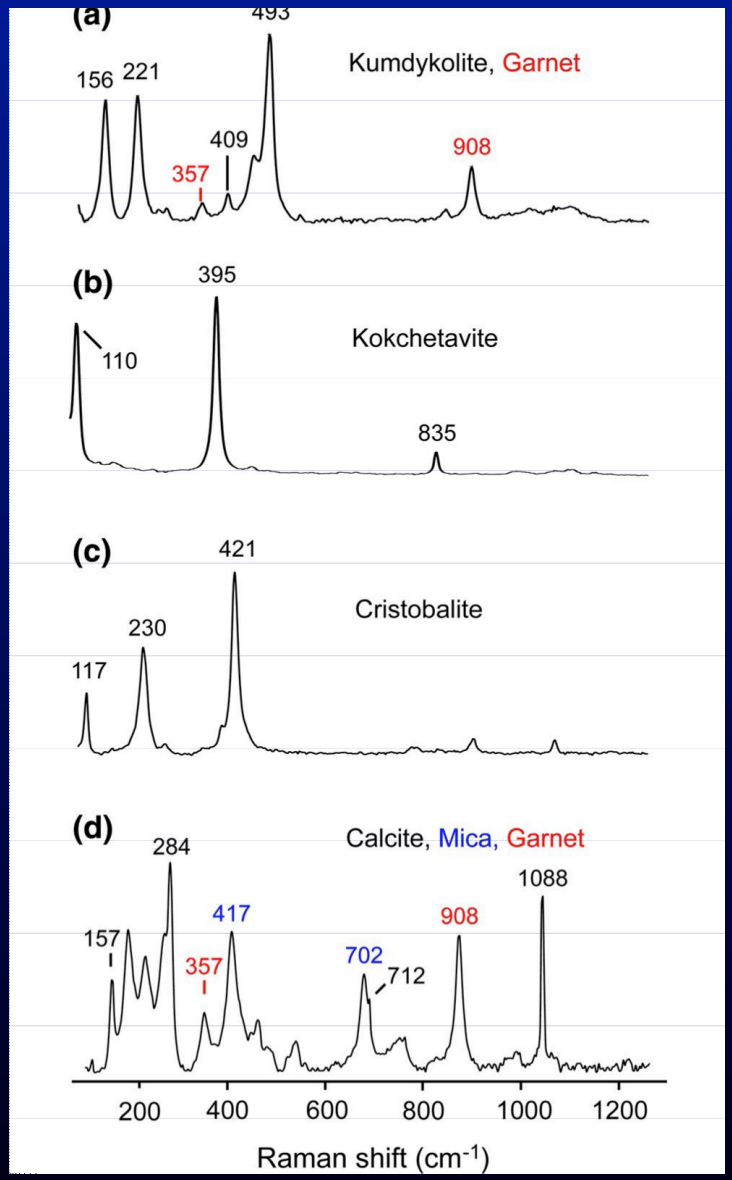
Stöckhert et al. (2001), Erzgebirge



Ferrero et al. (2012), Himalaya

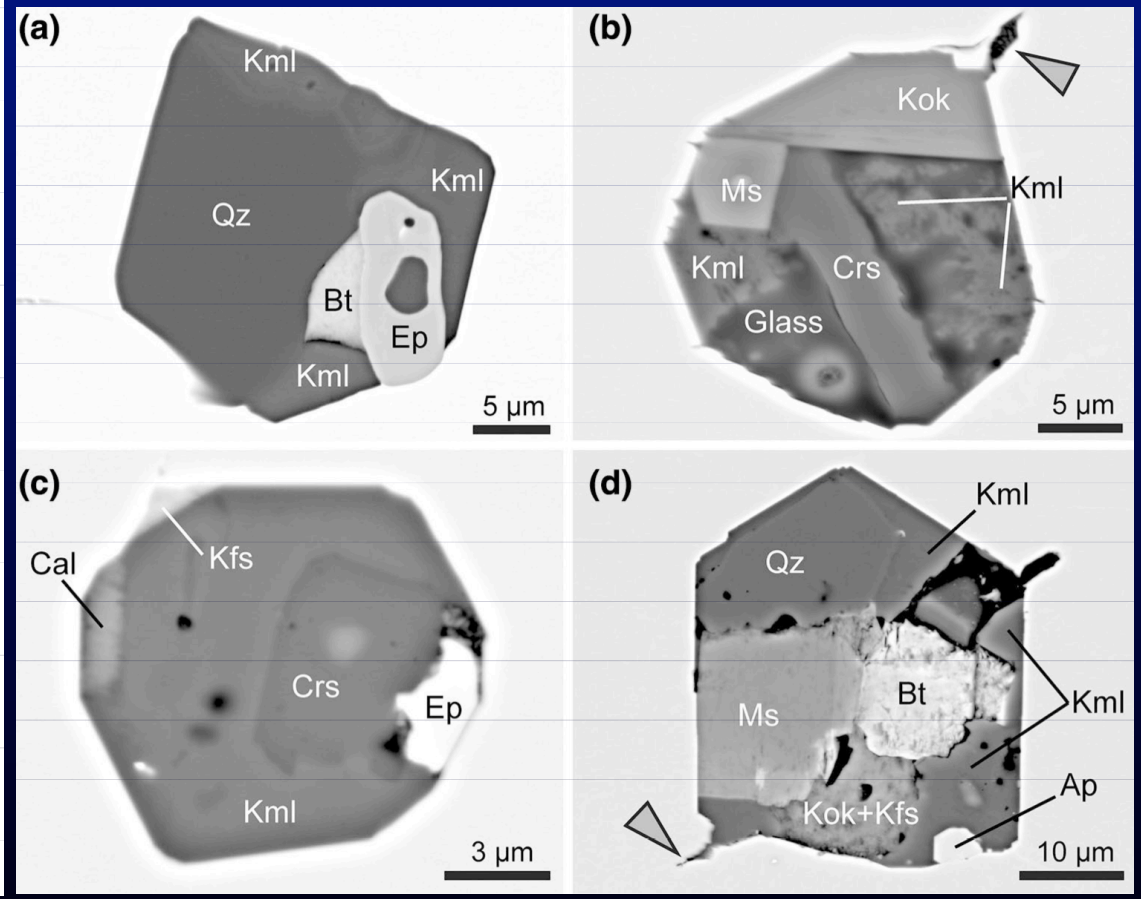
Characterization of melt inclusions

3. Micro Raman Spectroscopy



Kumdykolite, polymorph of albite
Kokchetavite, polymorph of alkali feldspar
Cristobilite, polymorph of quartz

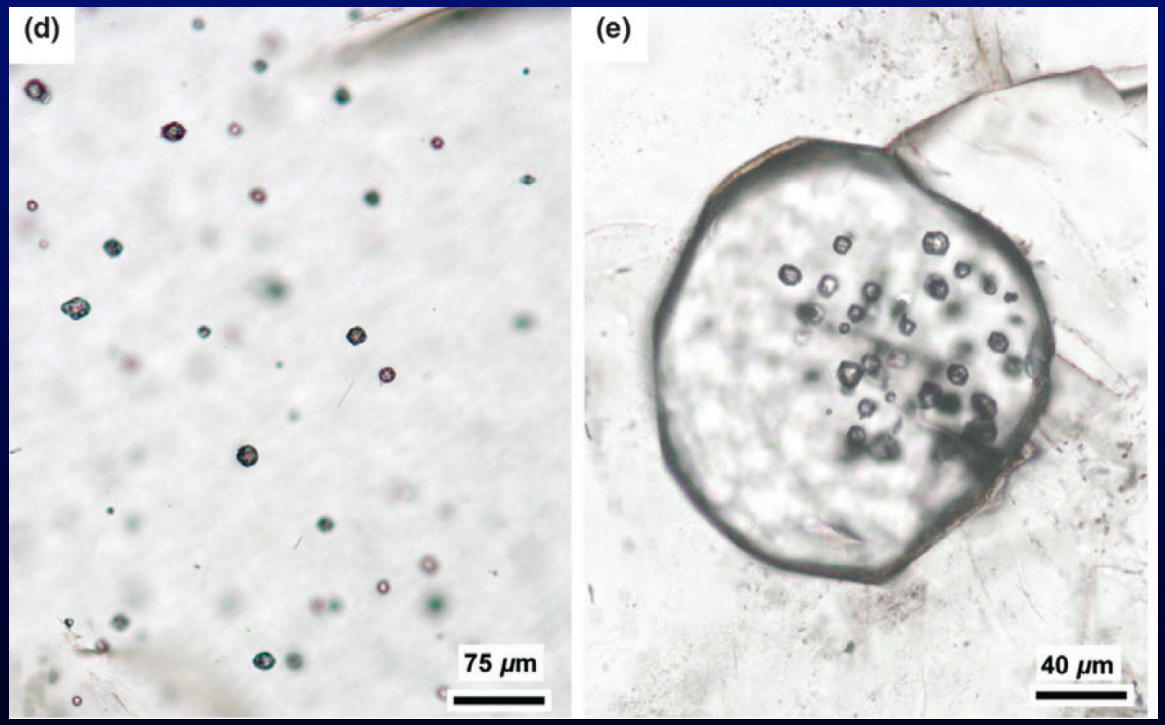
Ferrero et al. (2016)



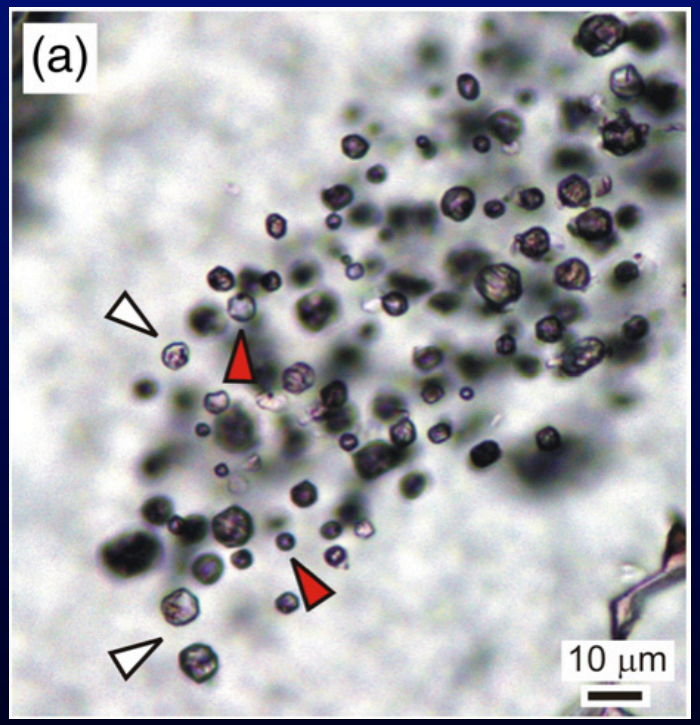
Analysis of melt inclusions

4. Re-homogenization experiments: piston cylinder (pressure)

- Prepare several thin sections from the rock under study (focus on Grt)
- Identify the thin section with the most abundant and best preserved MI (no offshots!)
- Prepare double polished, >200 micron thick, sections
- Select areas under the microscope rich in MI, individualize MI-rich areas.



Ferrero et al. (2012)

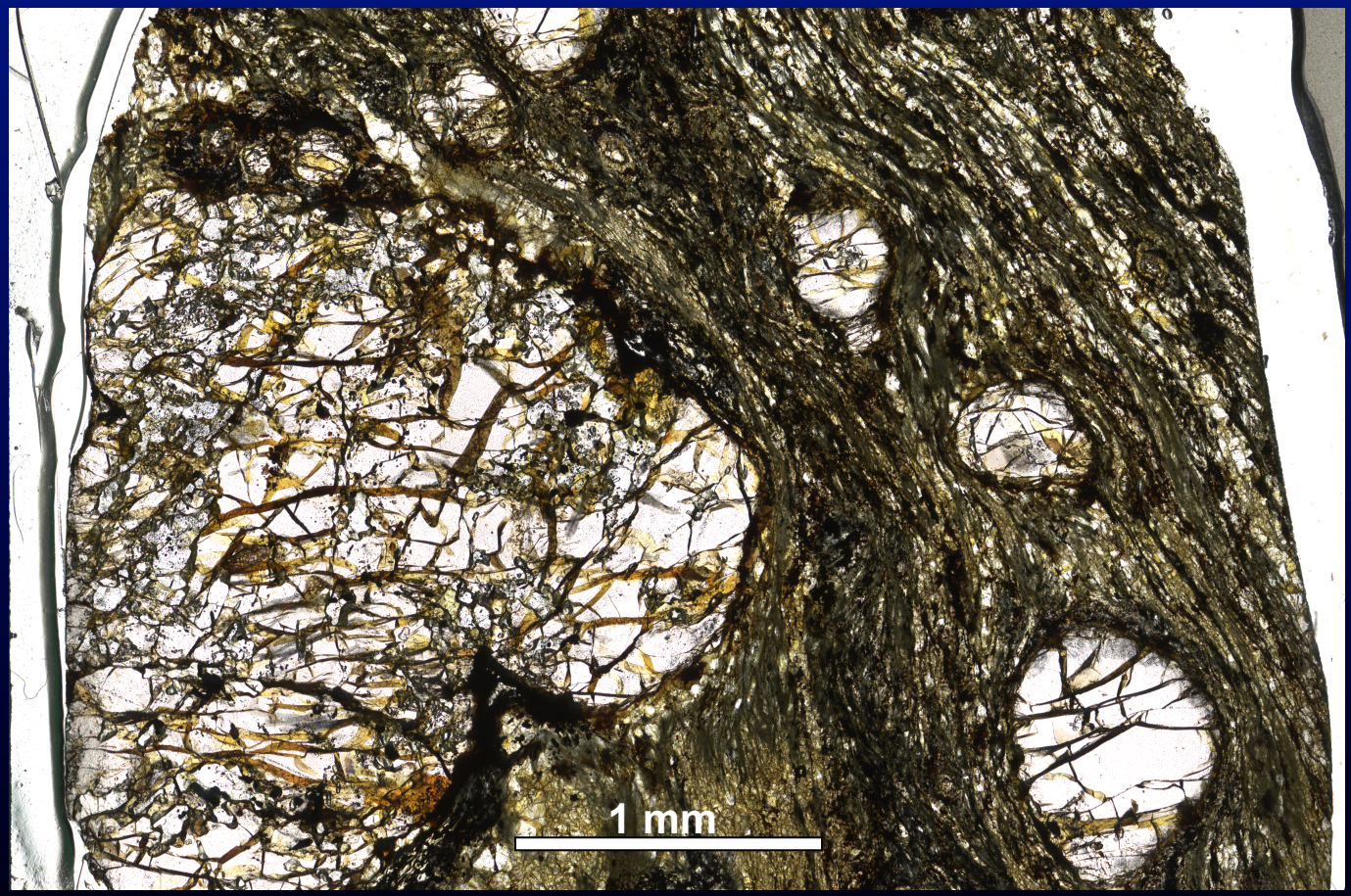


Bartoli et al. (2016)

Analysis of melt inclusions

4. Re-homogenization experiments: piston cylinder (pressure)

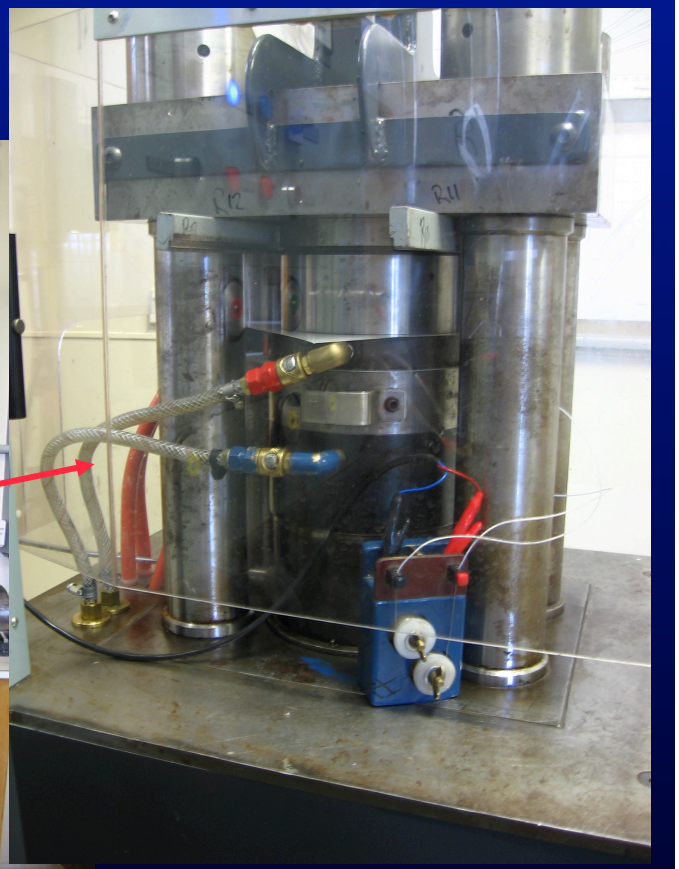
- Prepare several thin sections from the rock under study (focus on Grt)
- Identify the thin section with the most abundant and best preserved MI (no offshots!)
- Prepare double polished, >200 micron thick, sections
- Select areas under the microscope rich in MI, individualize MI-rich areas.



Analysis of melt inclusions

4. Re-homogenization experiments: piston cylinder (P)

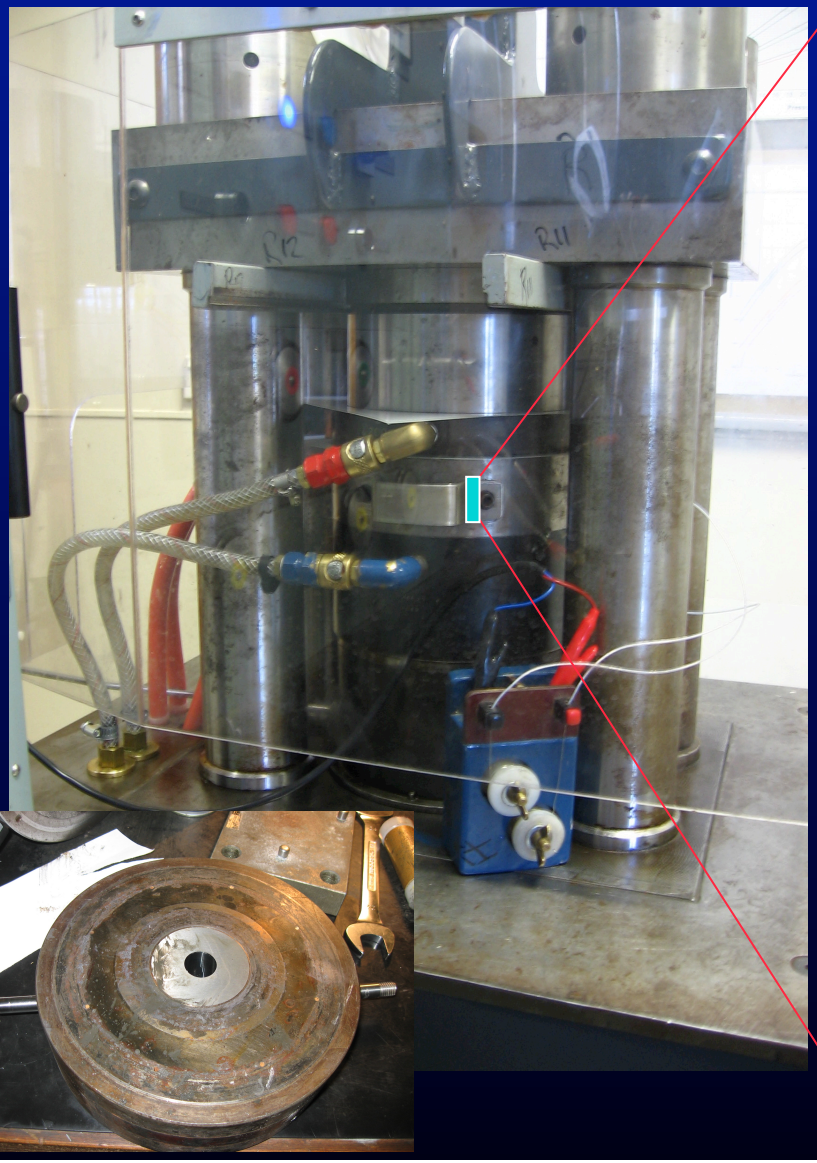
Australian National University, Canberra

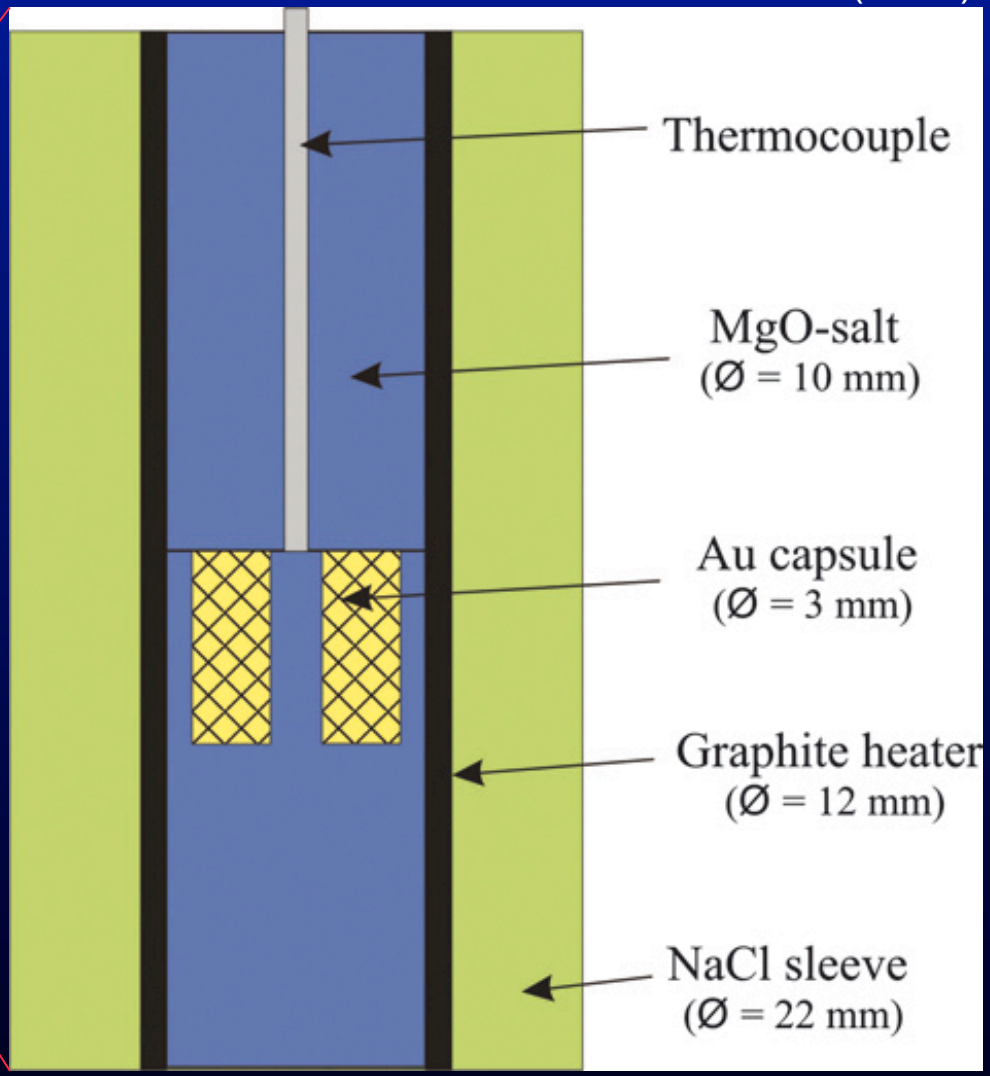


Analysis of melt inclusions

4. Re-homogenization experiments: piston cylinder (P)

Bartoli et al. (2013)





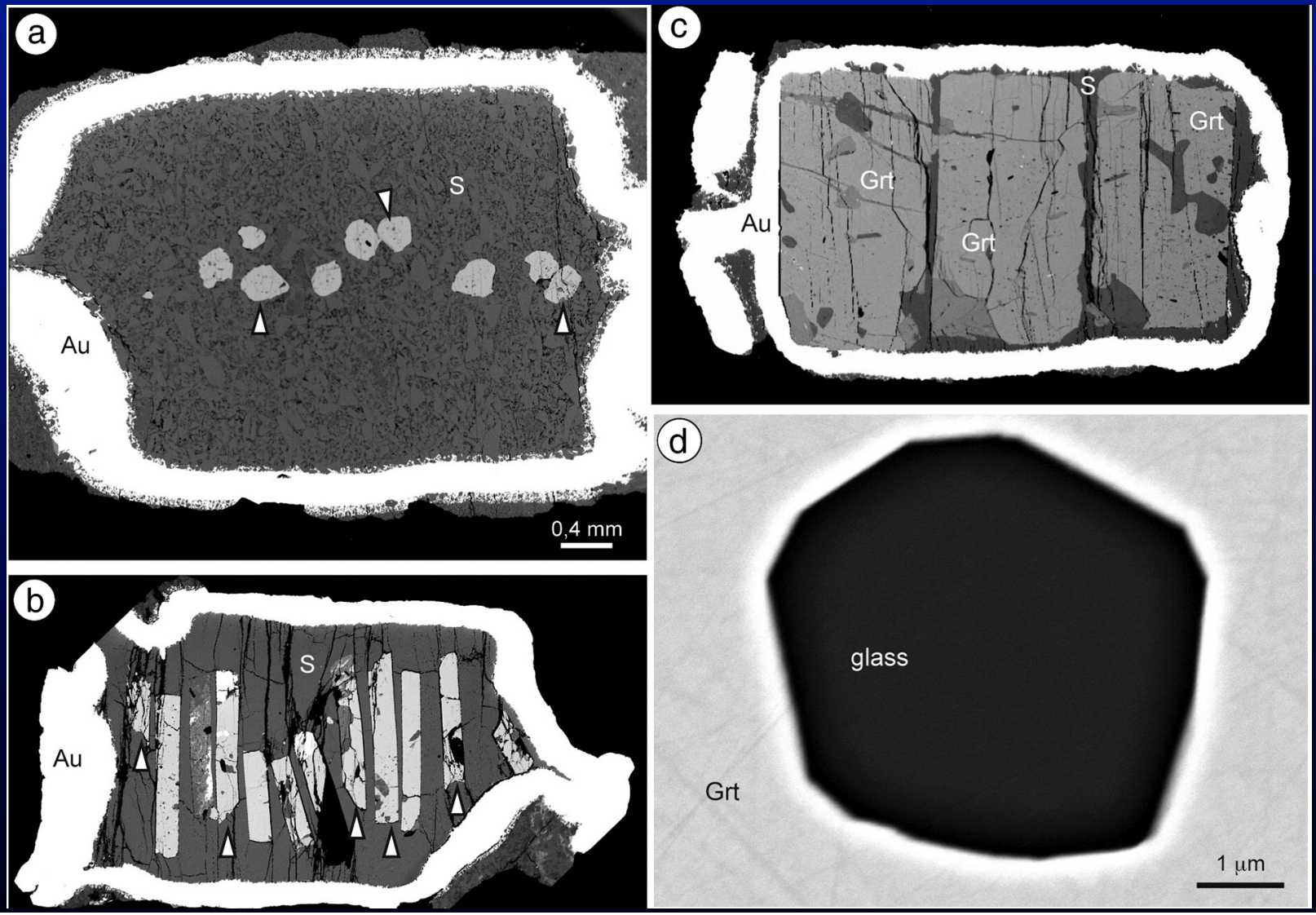
Analysis of melt inclusions

4. Re-homogenization experiments: piston cylinder (P)

Analysis of melt inclusions

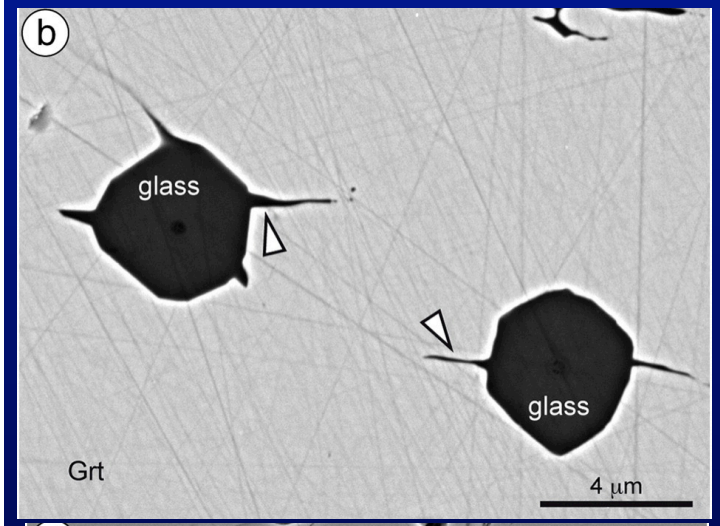
4. Re-homogenization experiments: piston cylinder (P)

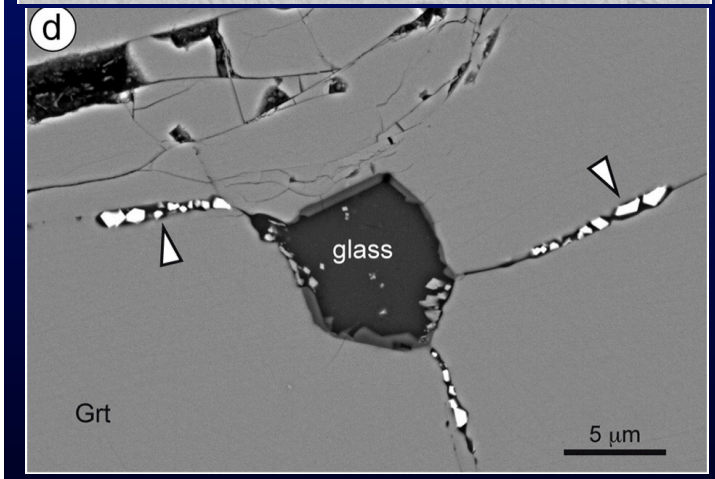
Cesare et al. (2016)



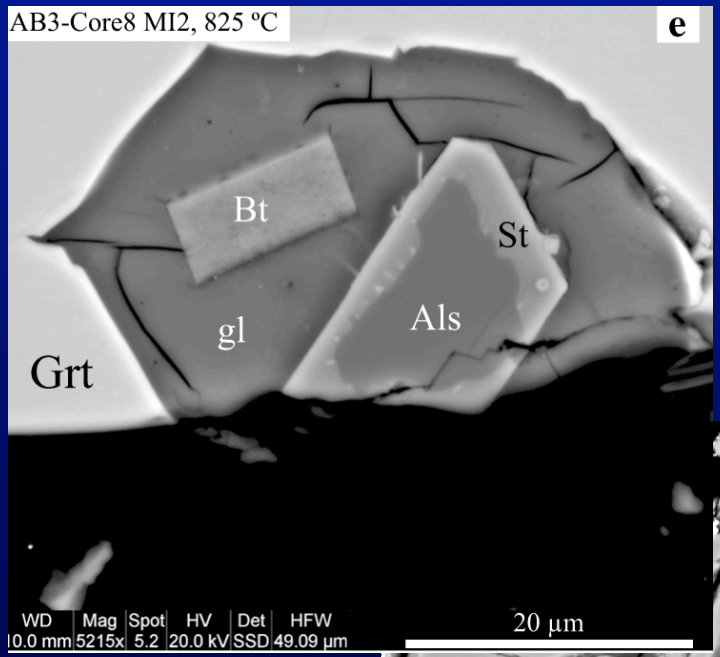
Analysis of melt inclusions

4. Re-homogenization experiments: piston cylinder (P)

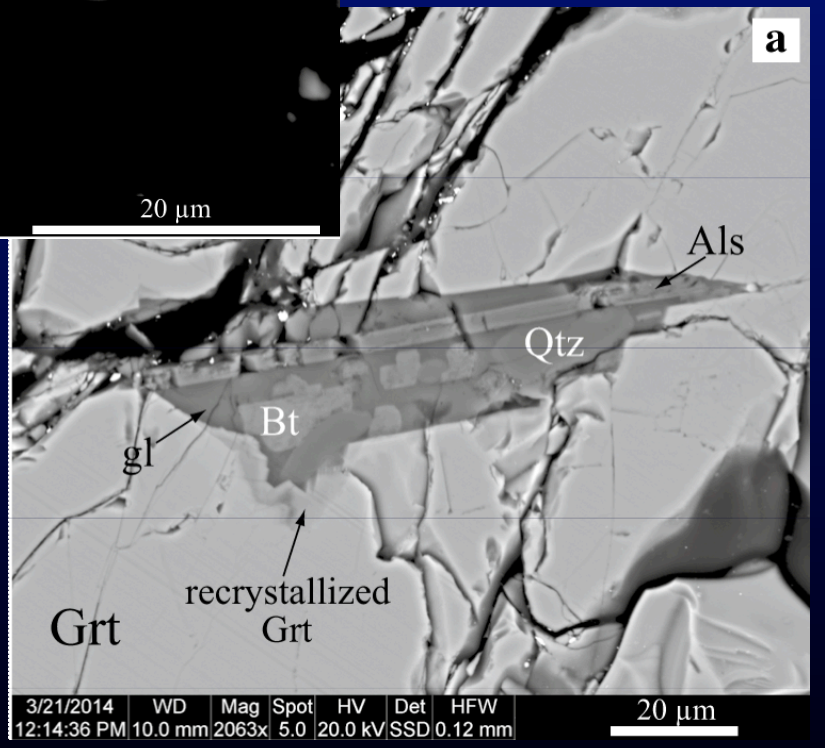




Bartoli et al. (2013)
Cesare et al. (2015)



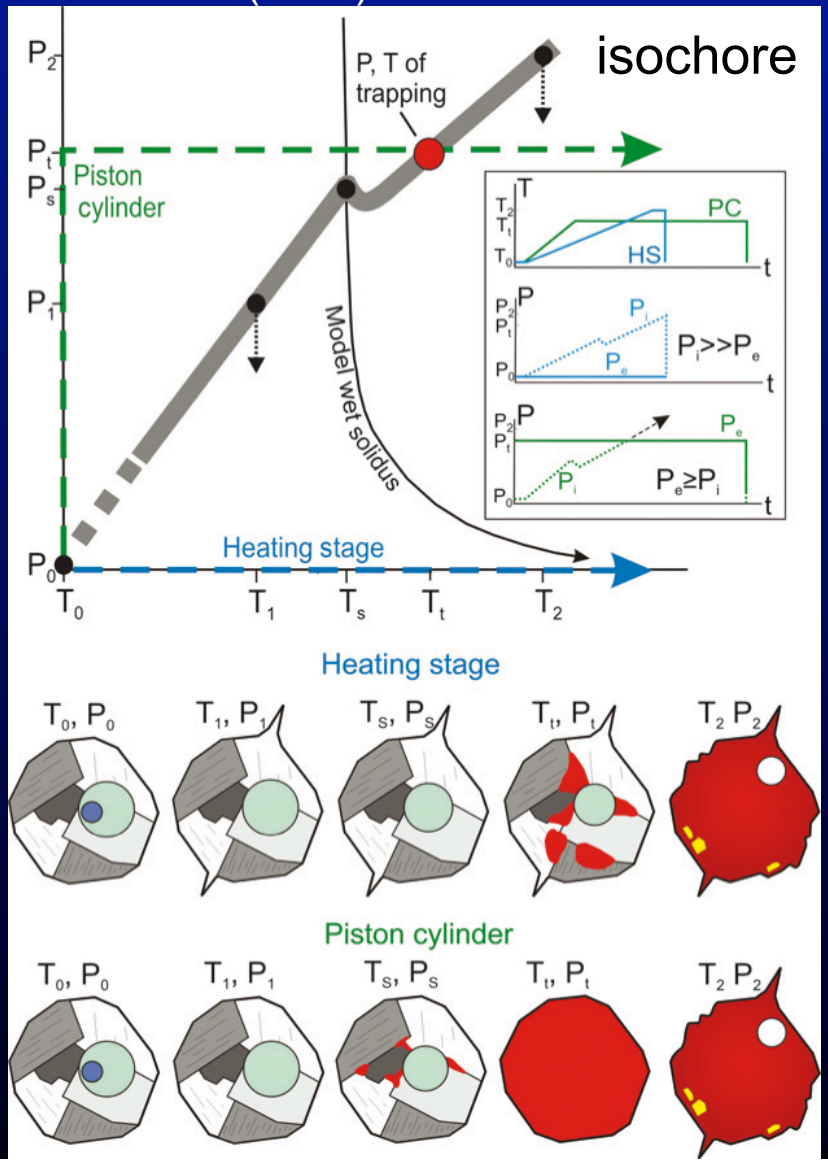
Acosta-Vigil et al. (2016)



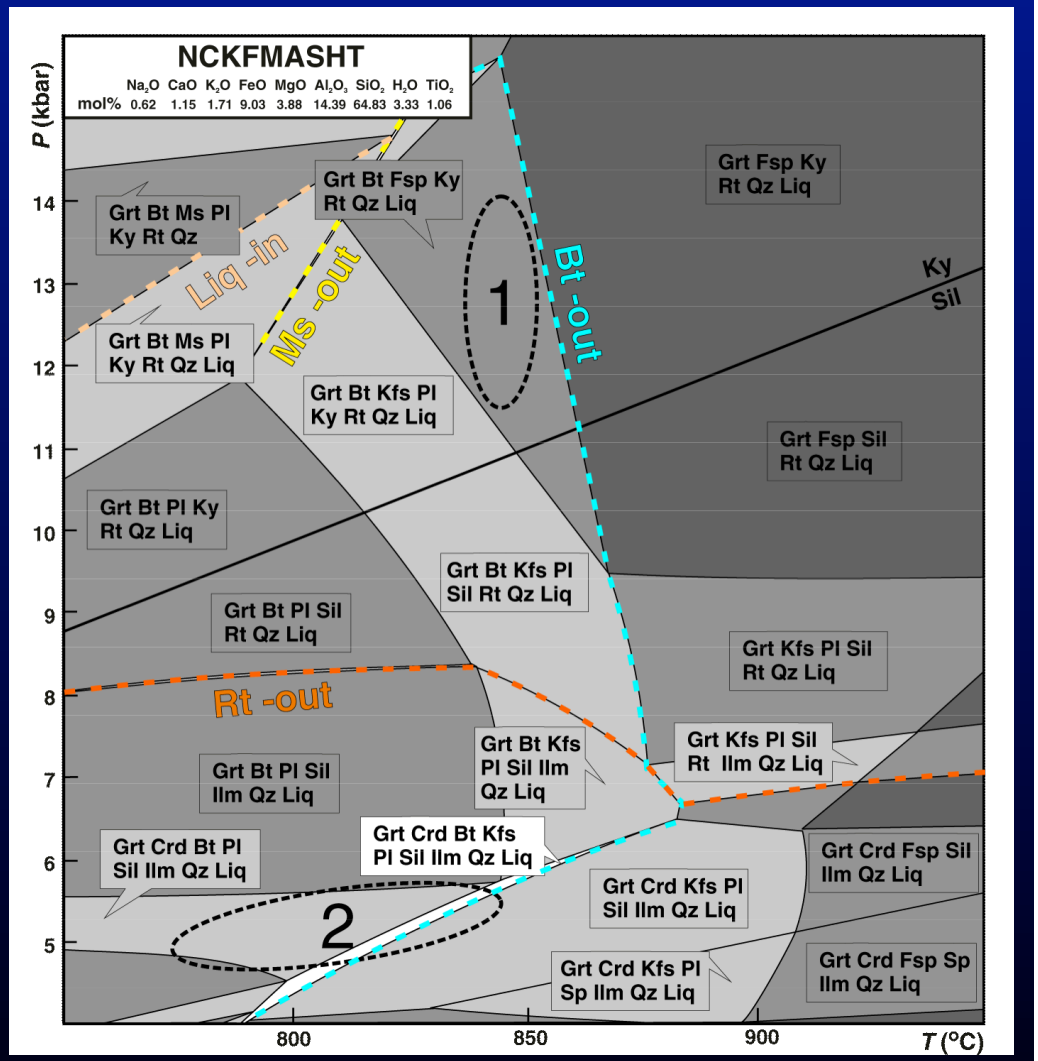
Analysis of melt inclusions

4. Re-homogenization experiments: piston cylinder (P)

Bartoli et al. (2013)

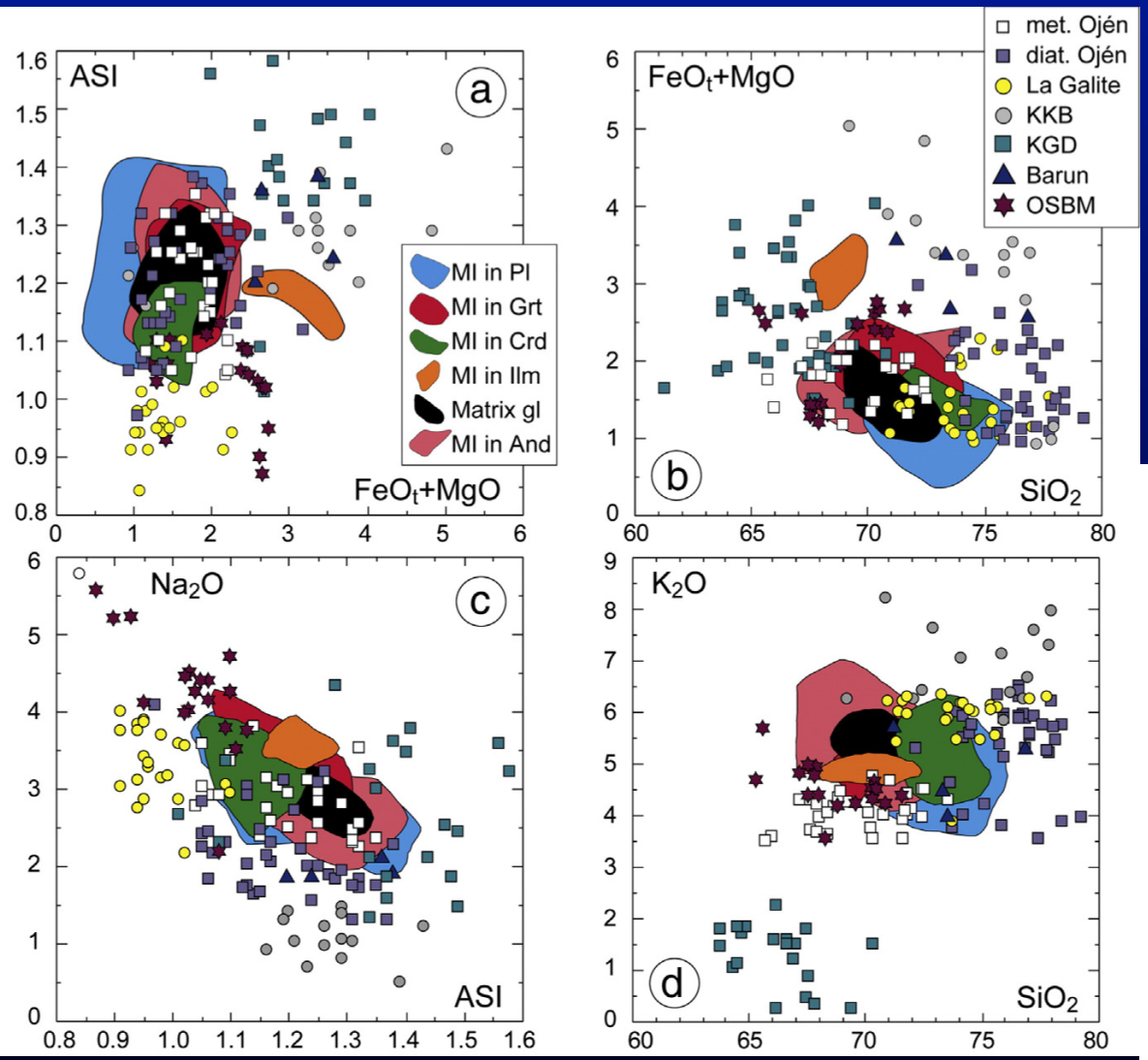


Barich et al. (2014)

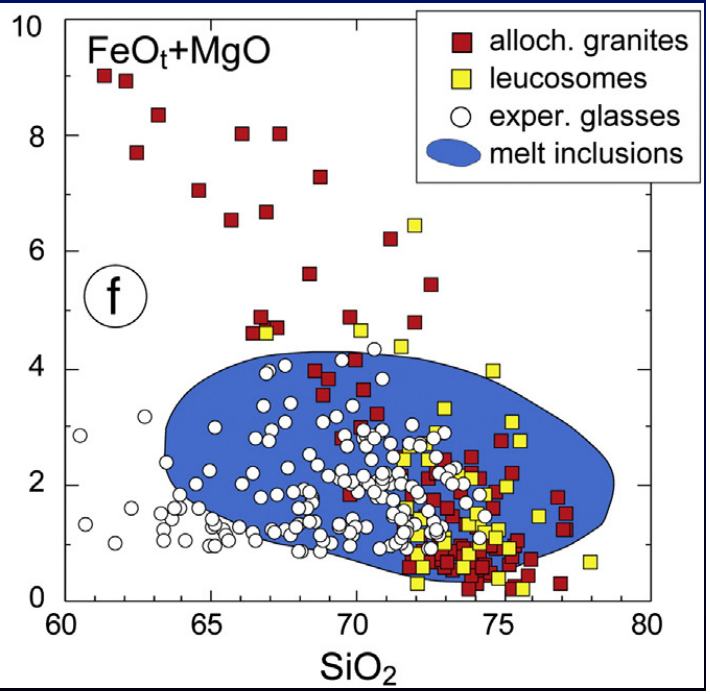


Analysis of melt inclusions

5. Electron microprobe analyses (major elements)



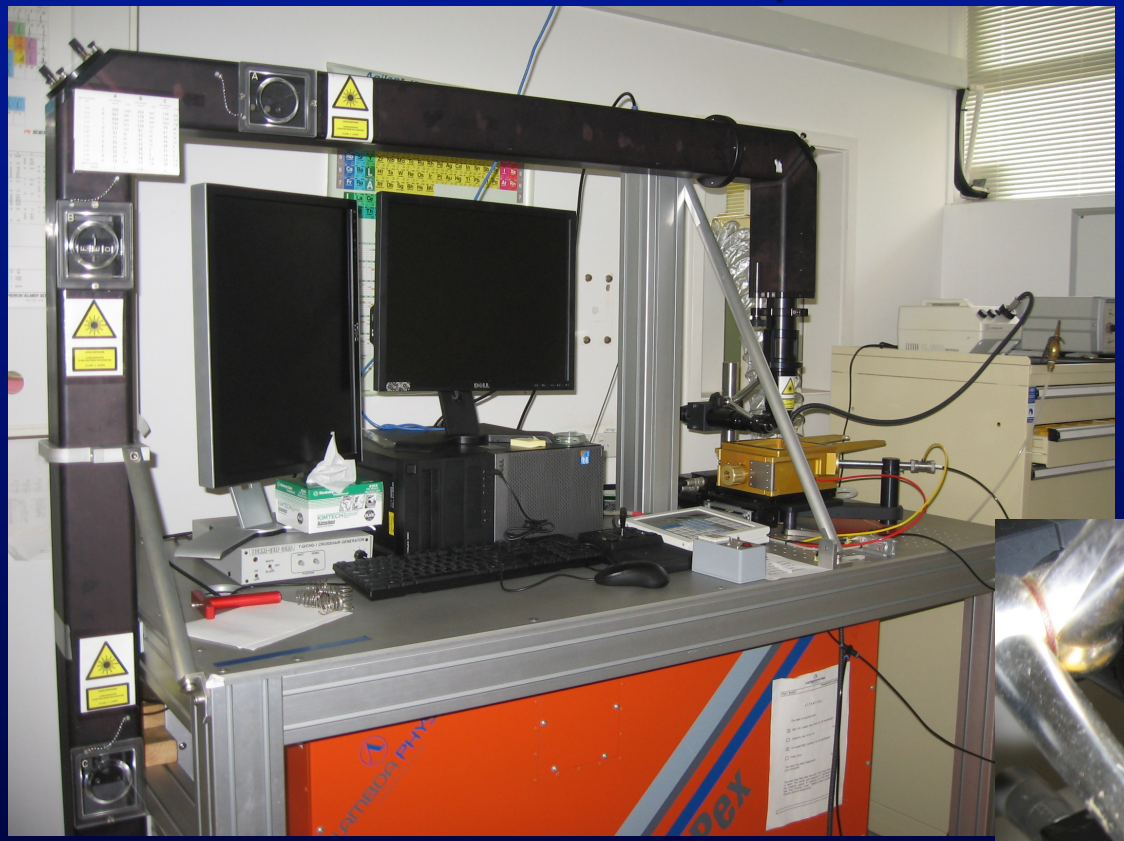
Comparison of melt inclusions with leucosomes in migmatites and granites intruded in the upper continental crust

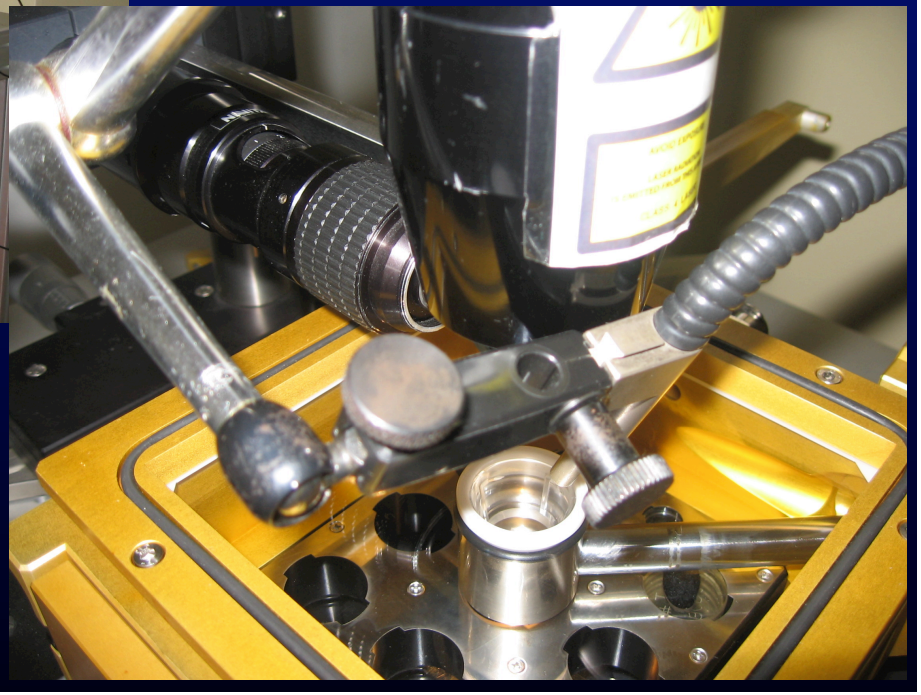


Cesare et al. (2015)

Analysis of melt inclusions

6. Laser ablation ICP-MS (trace elements)

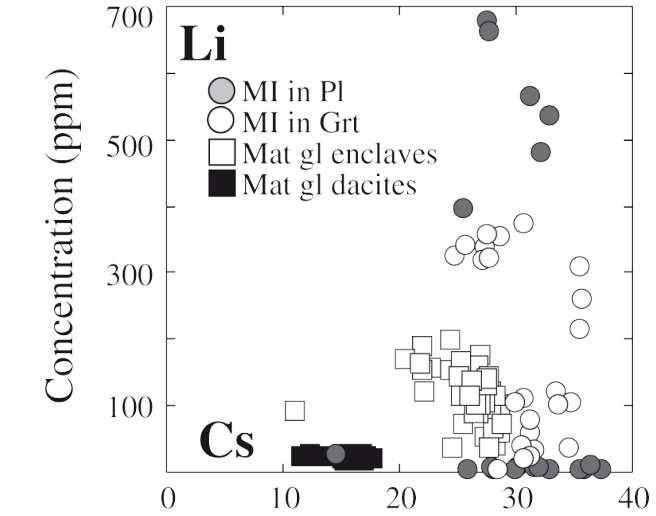


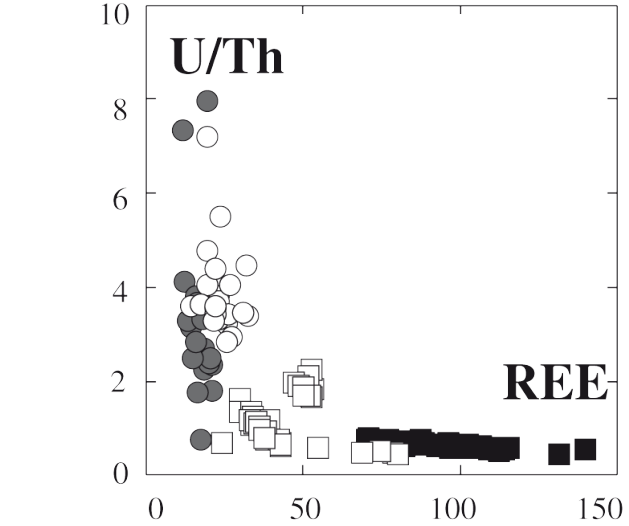


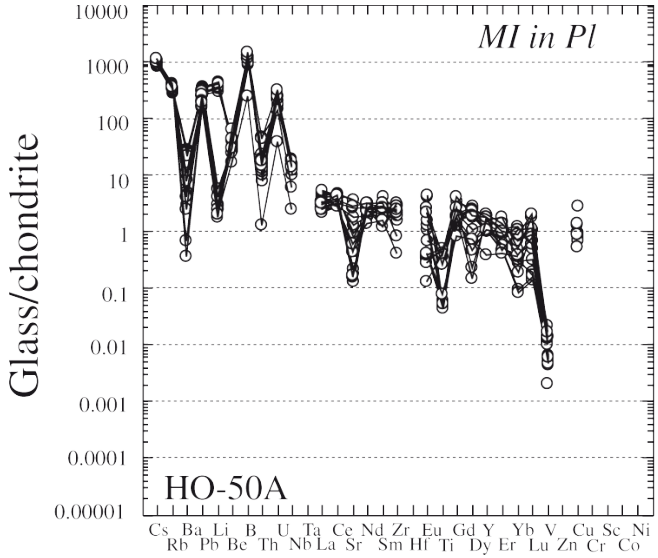
Australian National University, Canberra
smaller beam diameter was 19 microns

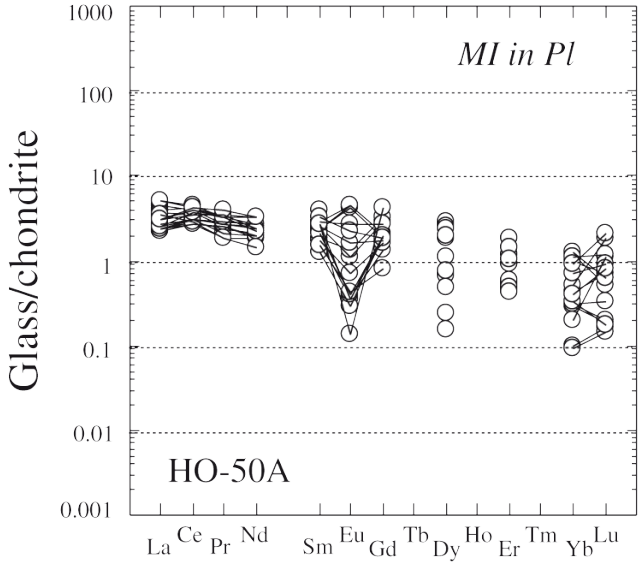
Analysis of melt inclusions

6. Laser ablation ICP-MS (trace elements)





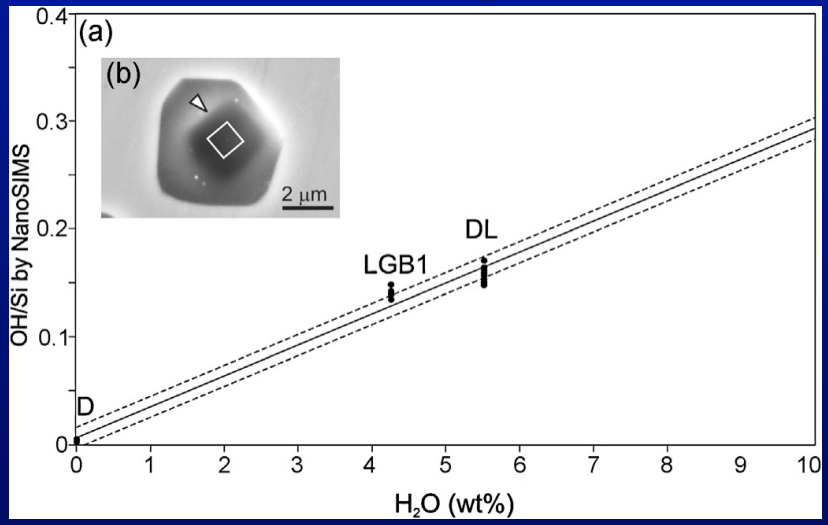


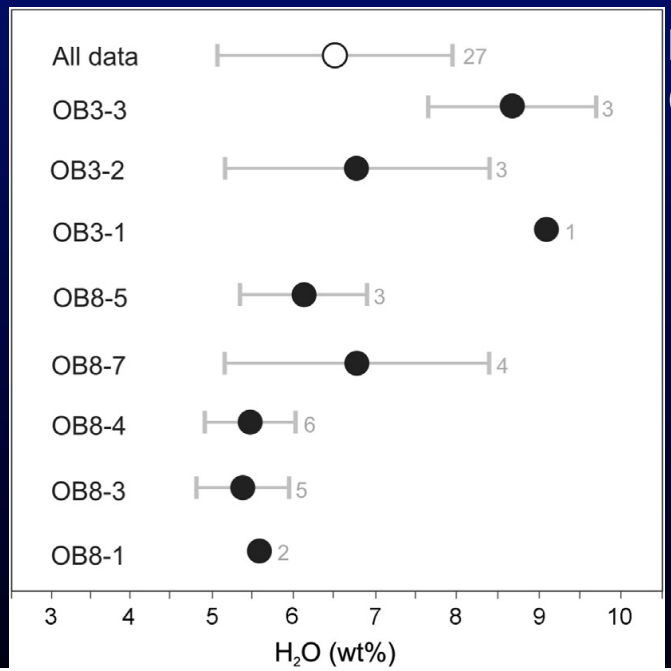


Acosta-Vigil et al. (2010)

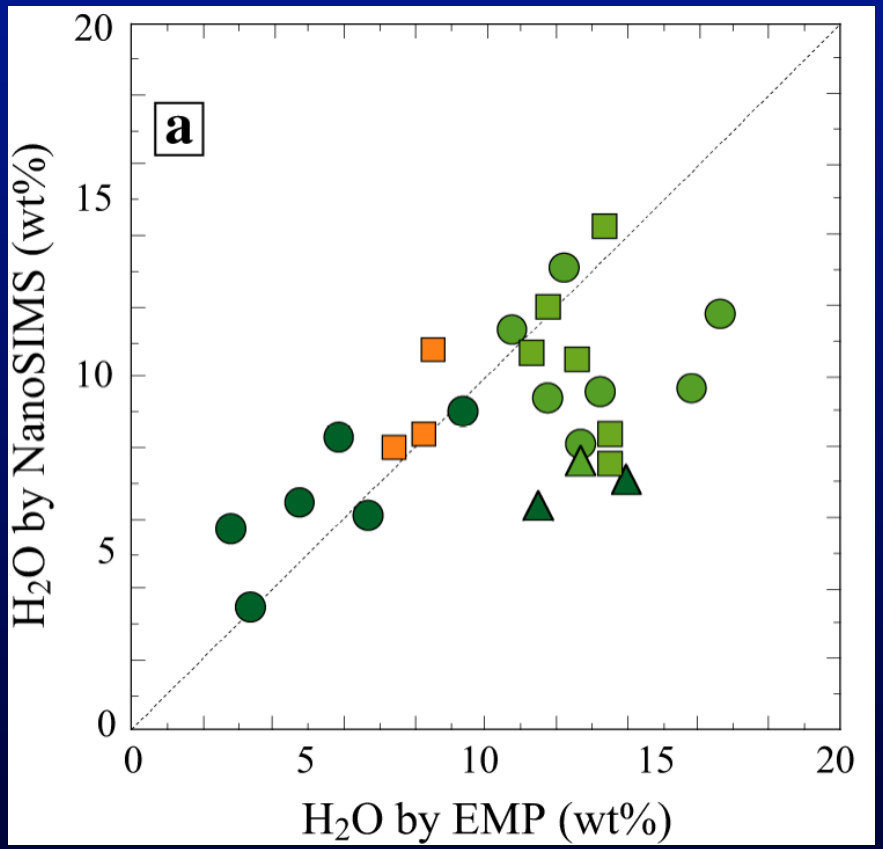
Analysis of melt inclusions

7. NanoSIMS (H_2O)





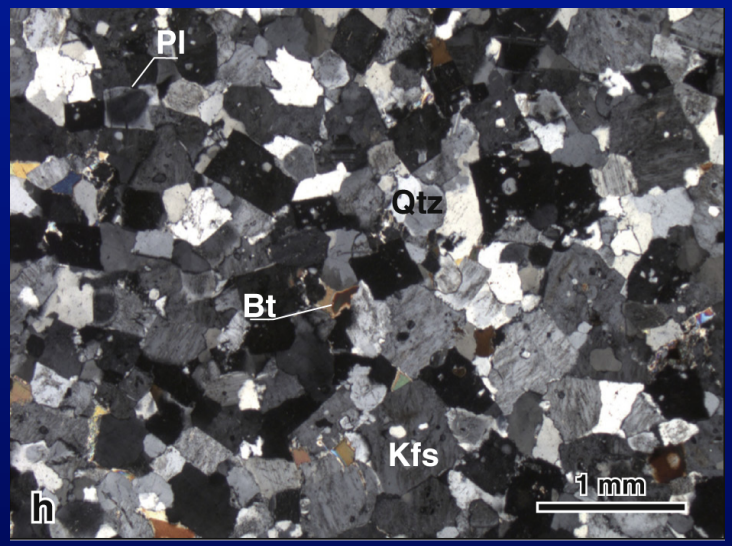
Bartoli et al. (2016)



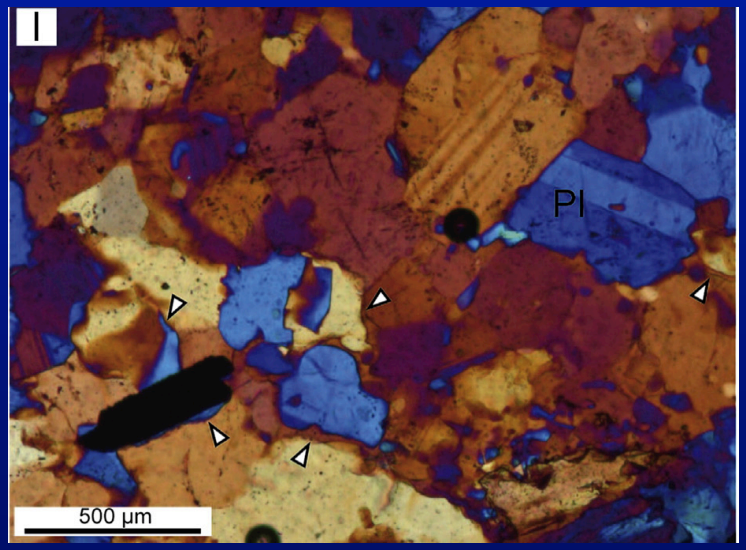
Acosta-Vigil et al. (2016)

Information from study of melt inclusions

1. That a rock has melted



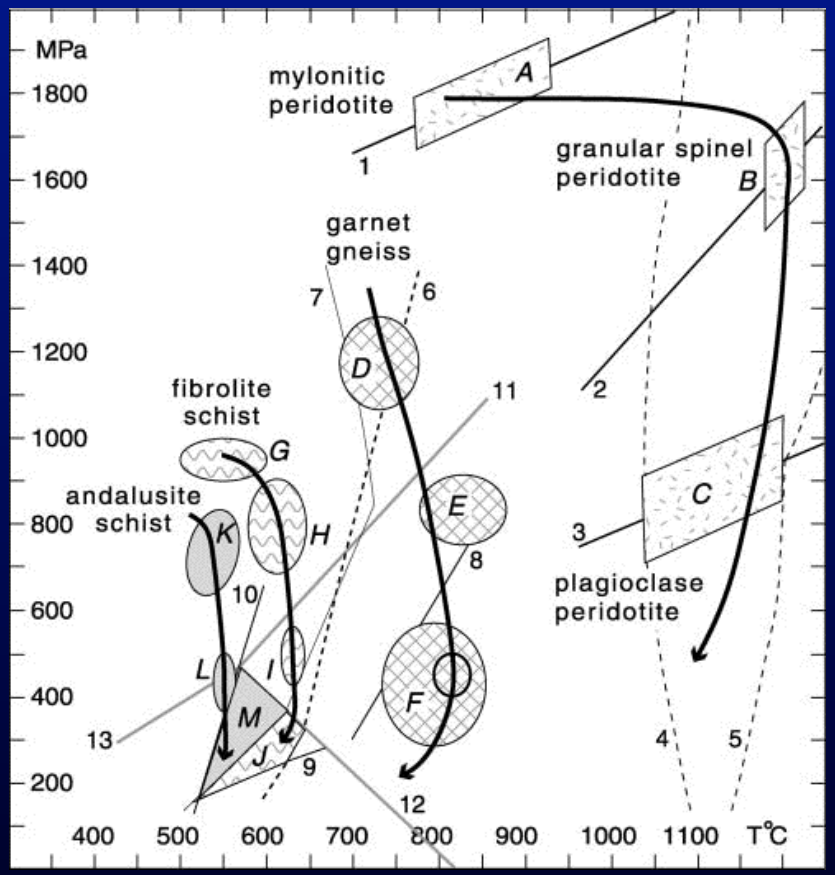
Acosta et al. (2014)



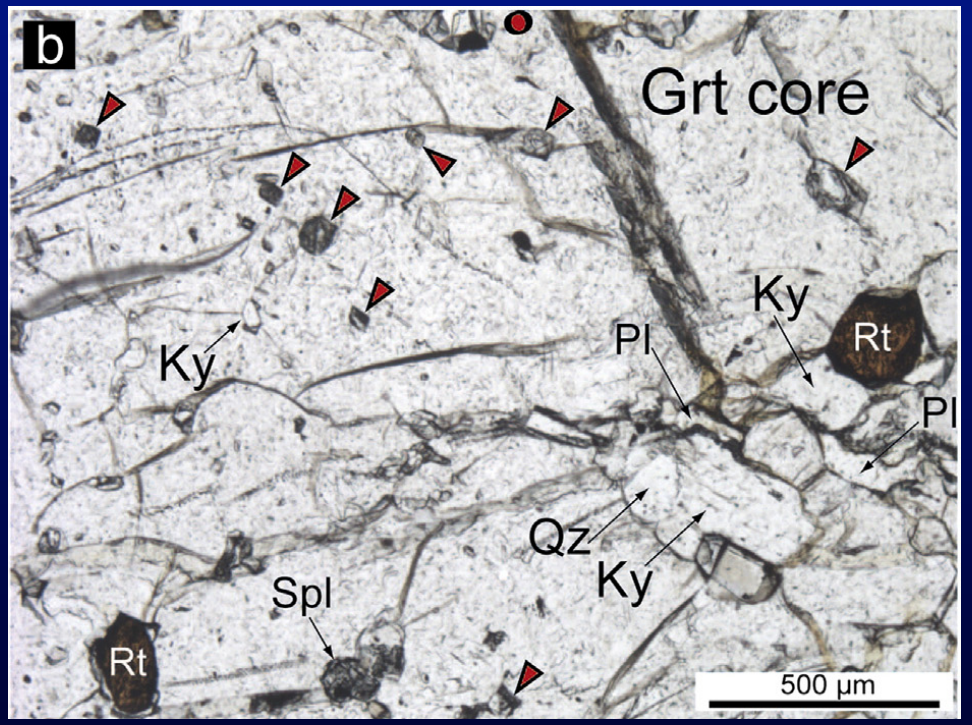
Barich et al. (2014)

Information from study of melt inclusions

2. That (part of) a mineral grew in the presence of melt



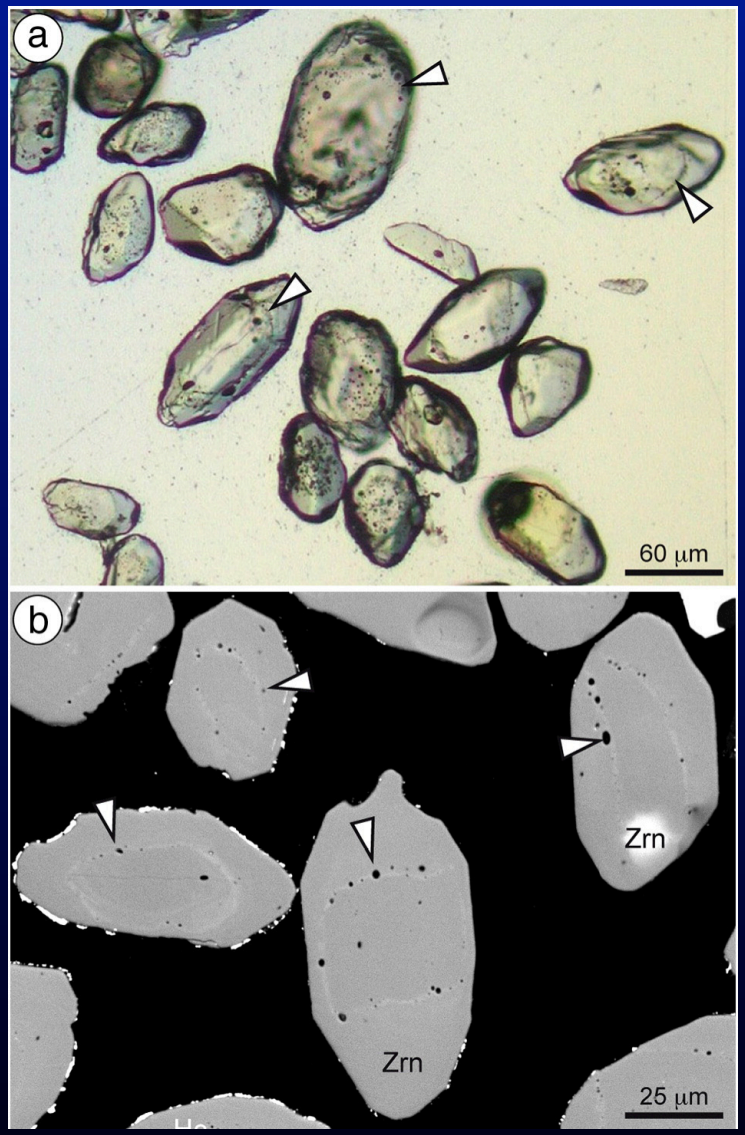
Platt et al. (2003)

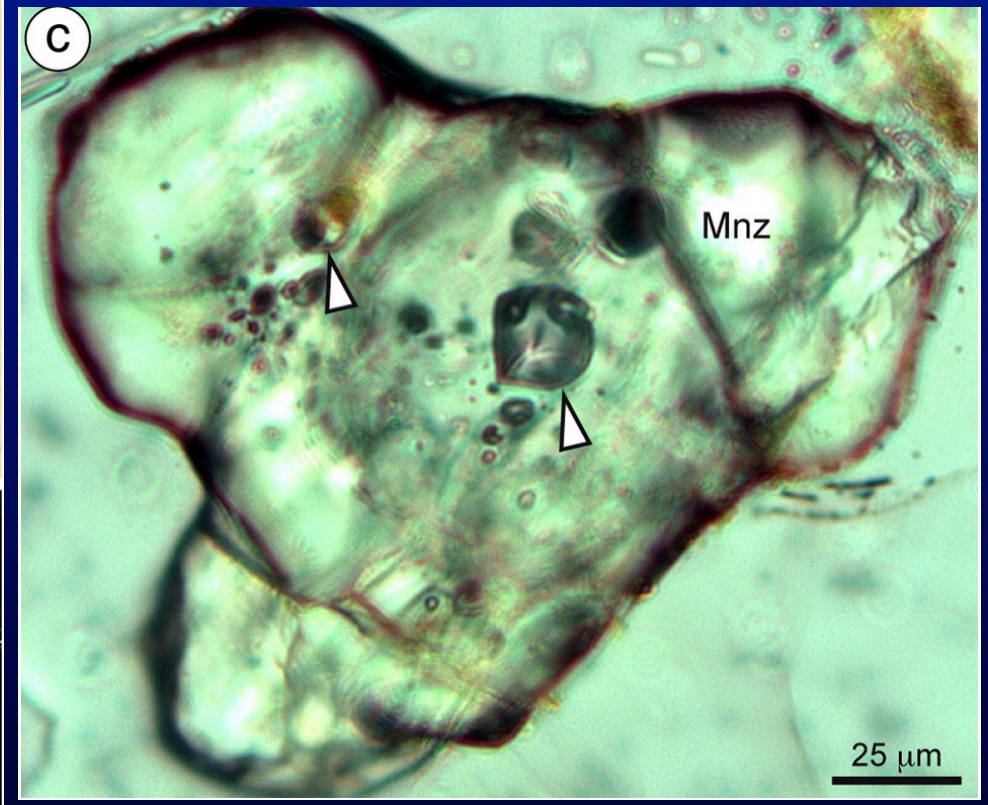


Barich et al. (2014)

Information from study of melt inclusions

3. When a rock has melted, and timeframes of melt extraction



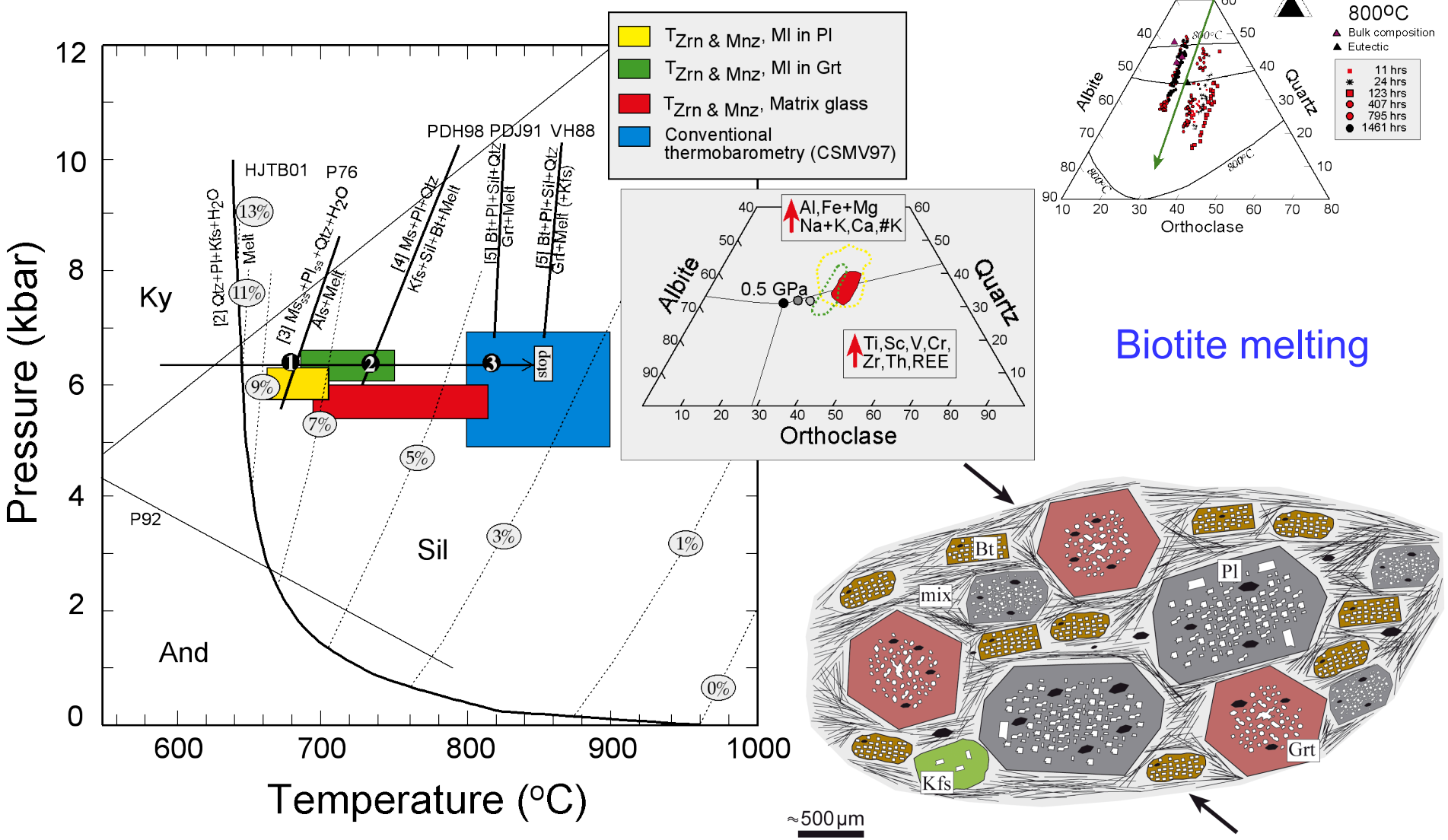


Cesare et al. (2015)

Information from study of melt inclusions

4. Primary melt compositions: mechanisms/nature of anatexis

Acosta-Vigil et al. CMP (2006), J Petrol (2010), and in preparation



Problems and pitfalls

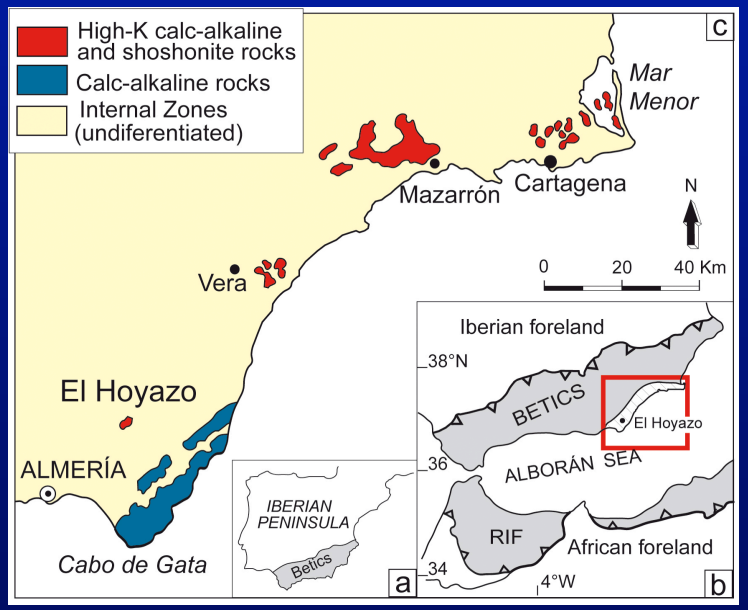
From the current available data, it is clear that nanogranitoids represent former melt, but:

a) How representative is the melt composition of the bulk melt in the system at the time of entrapment?
b) How much has the original composition been modified during/after the entrapment process? That is, how representative is the currently measured composition of the original melt at the surface of the growing mineral?

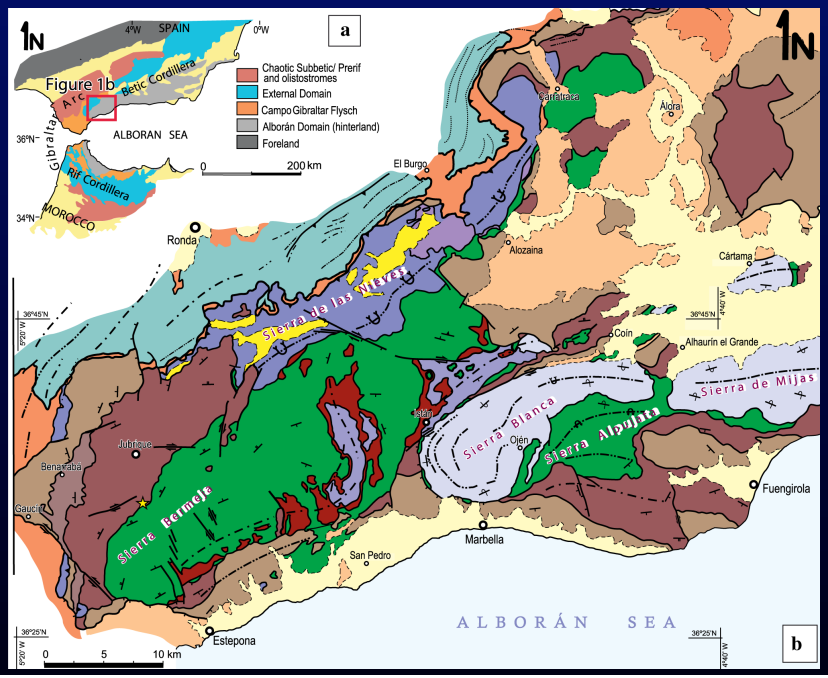
Through investigation and analysis of melt inclusions in many case studies

Case studies

Melt inclusions in anatectic enclaves of SE Spain, El Hoyazo

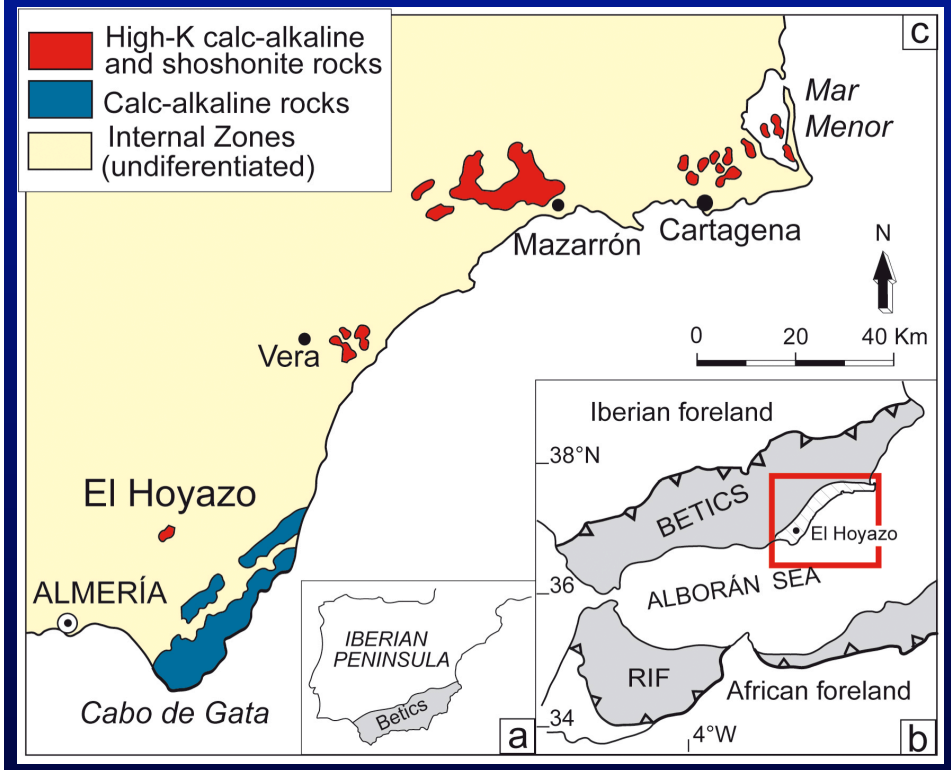


Melt inclusions in granulites of S Spain, Ronda area

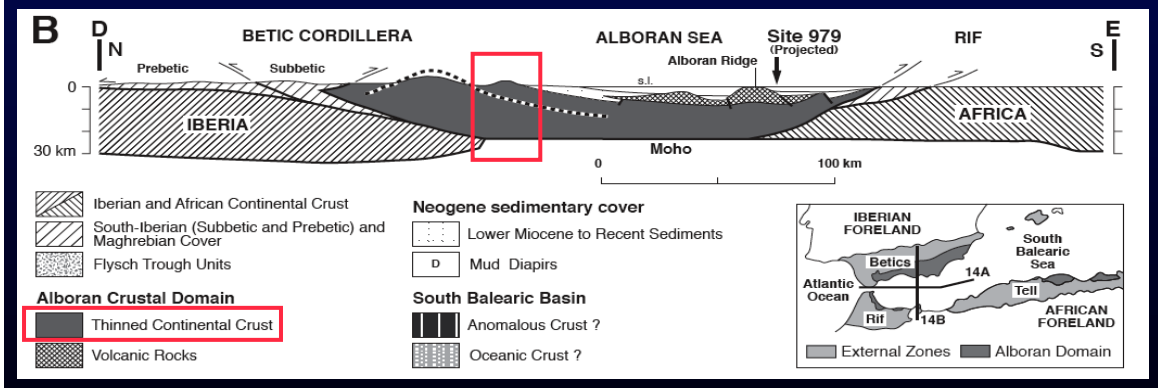


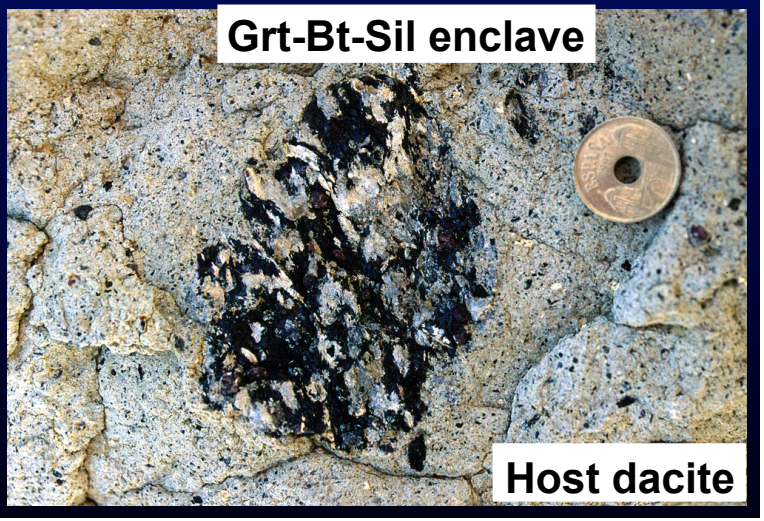
Time-consuming!

Melt inclusions in anatectic metapelitic enclaves from El Hoyazo, S Spain



López-Ruiz & Rodríguez-Badiola (1980) , Zeck (1992)



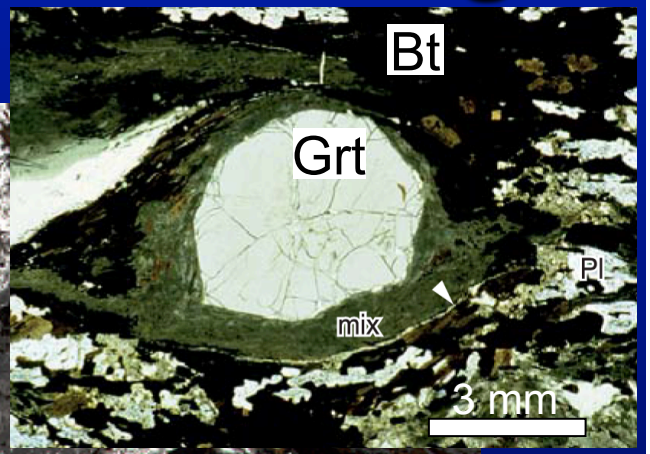


Petrography, P-T conditions of melting

Grt-Bt-Sil

37% Pl
20% Bt
13% Sil
12% Grt
11% glass
3% Kfs

Cesare (2008)

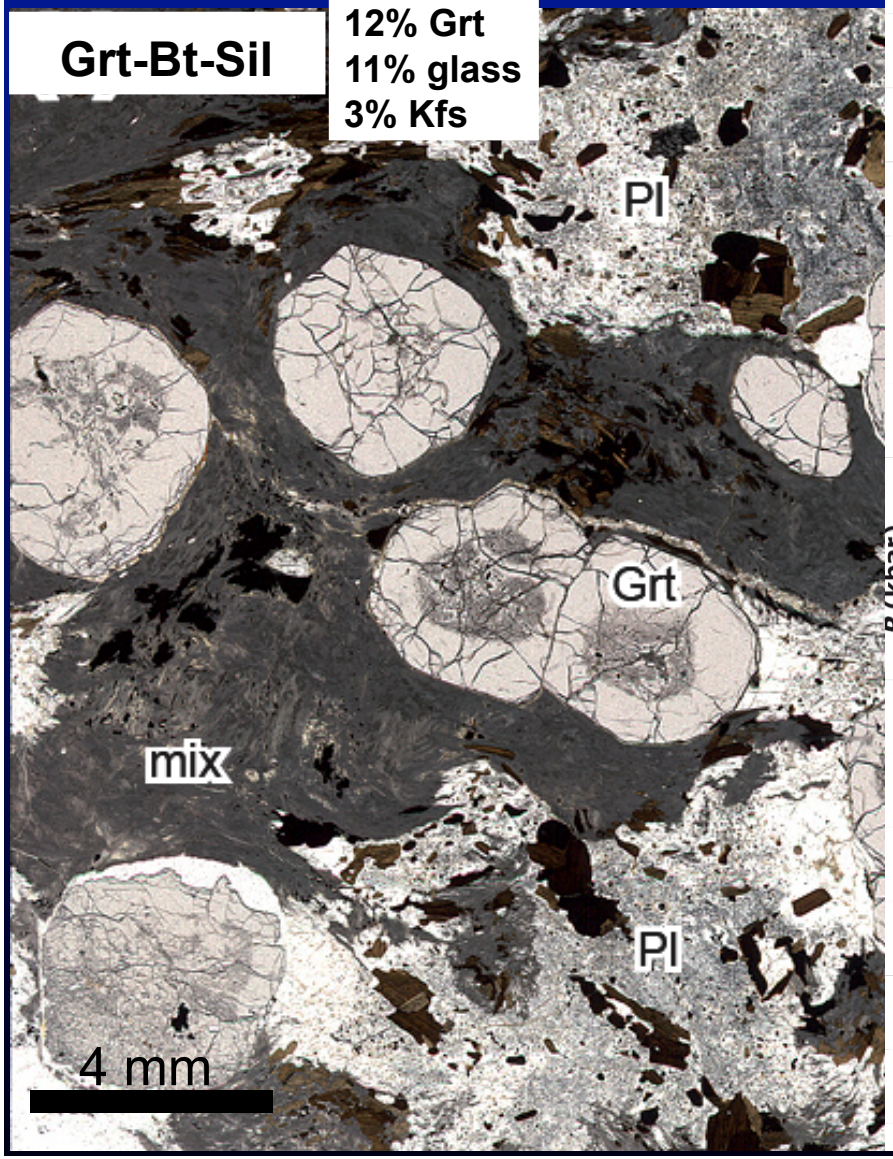


Pl
Bt
Grt
mix
Grt
mix
Pl
4 mm

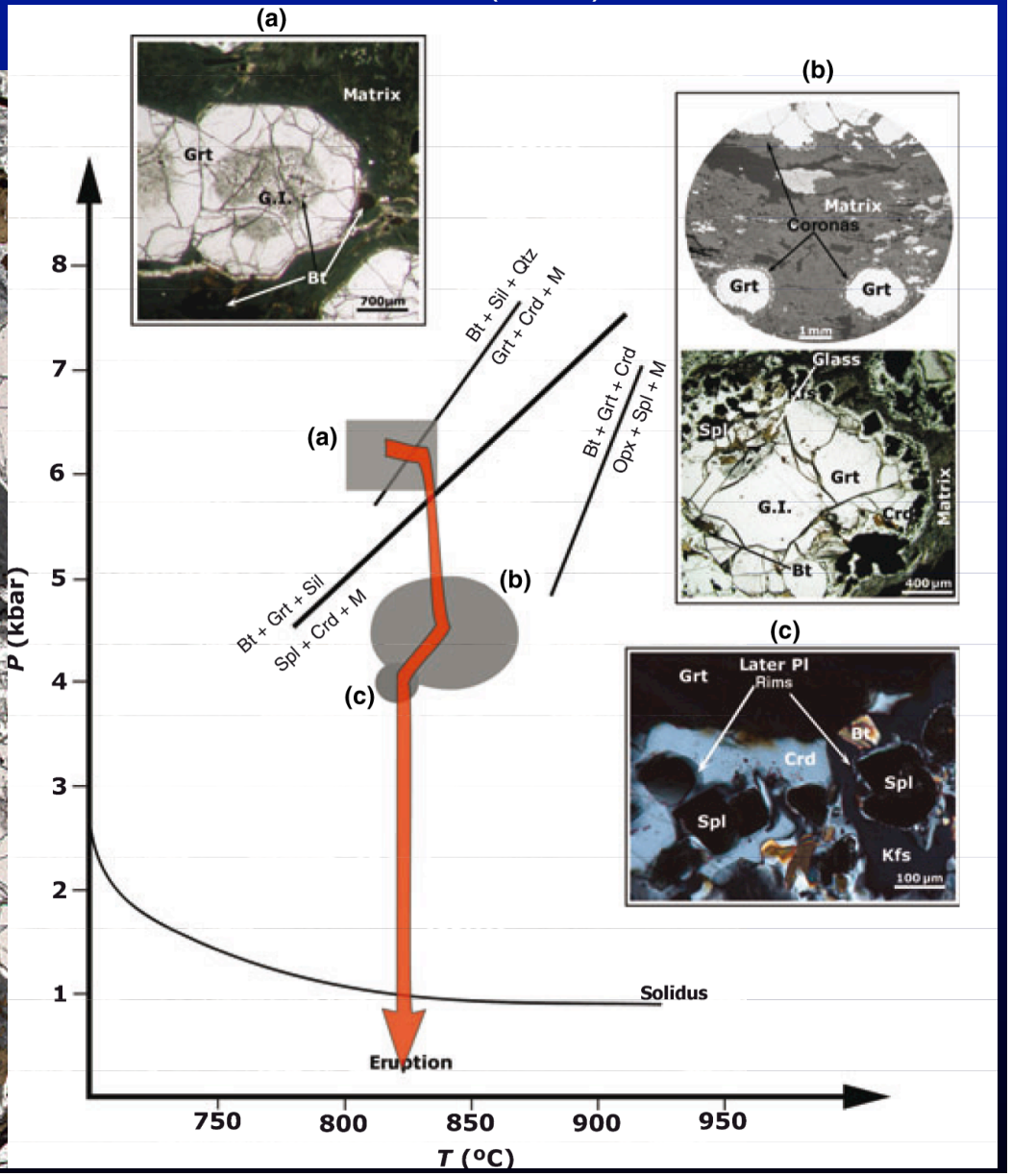
Petrography, P-T conditions of melting

Grt-Bt-Sil

37% Pl
20% Bt
13% Sil
12% Grt
11% glass
3% Kfs

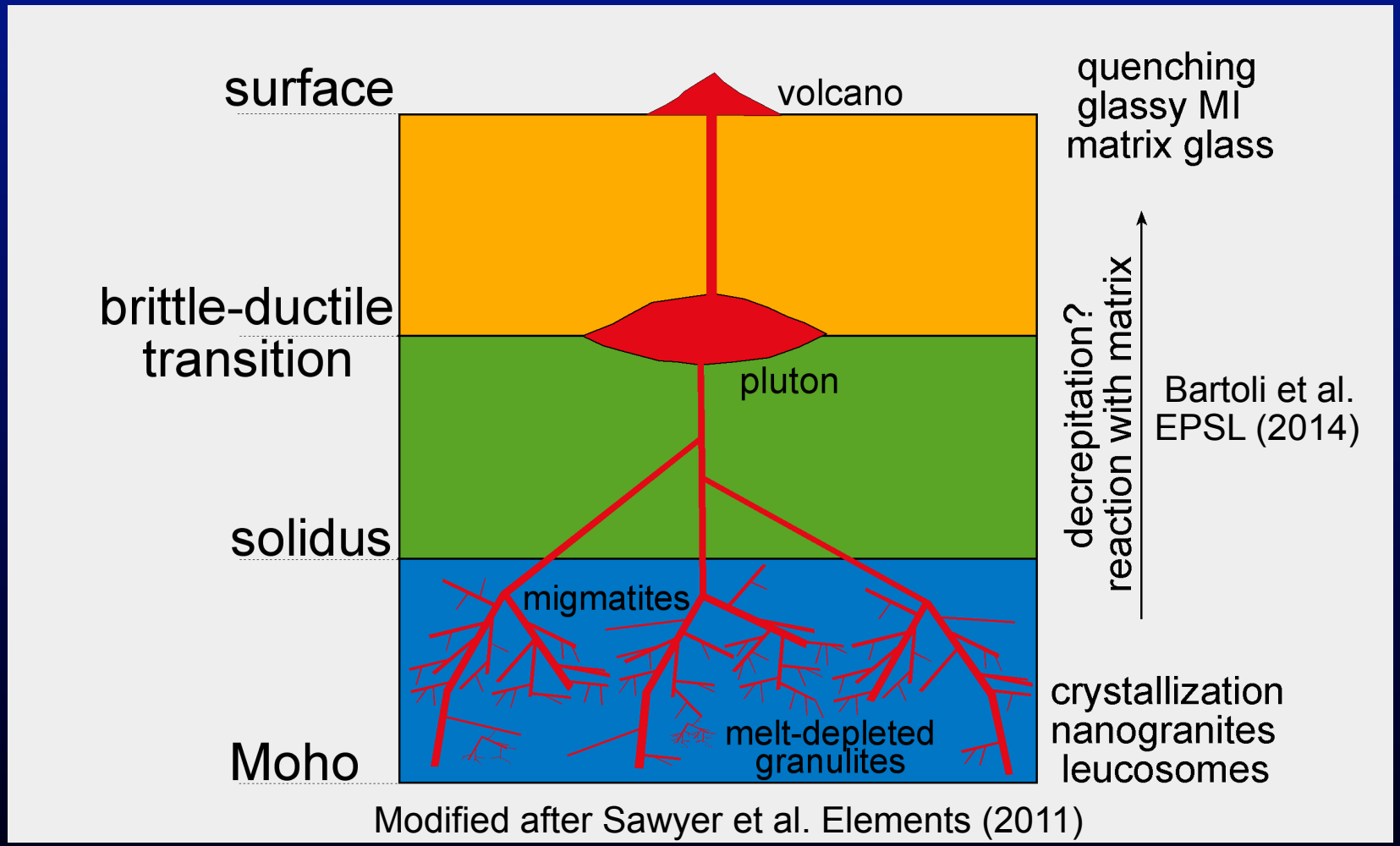


Álvarez-Valero et al. JMG (2007)



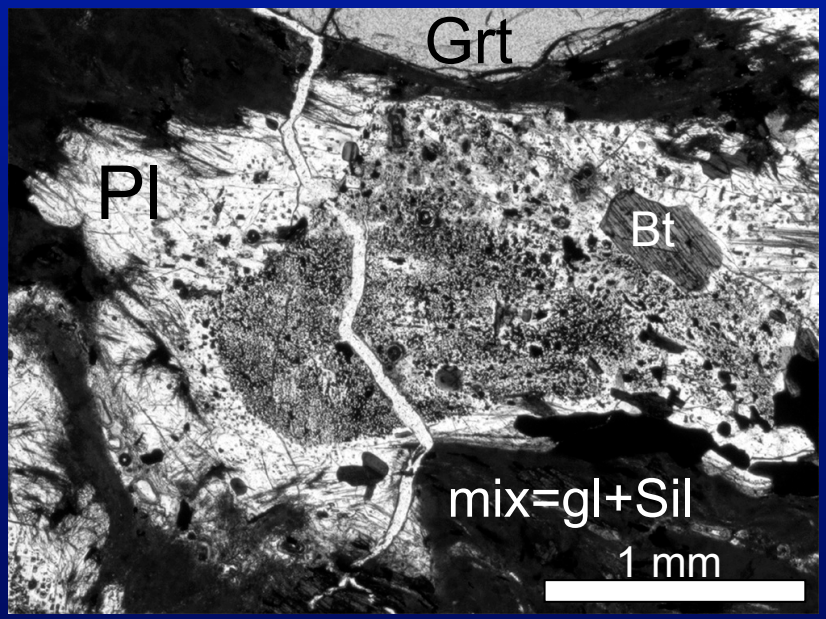
Melt inclusions in anatectic enclaves versus anatectic terranes

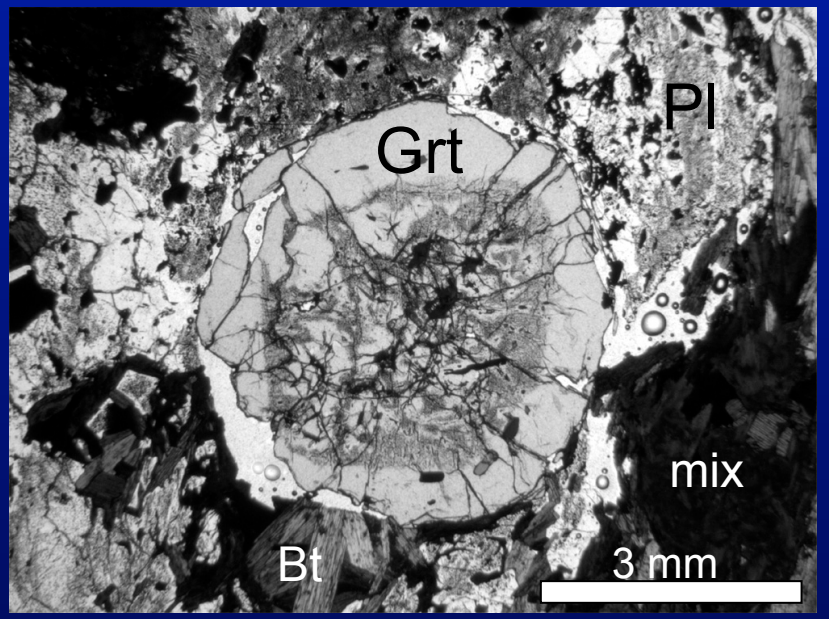
Pros-cons: quenching, matrix glass vs. decrepitation, abundance

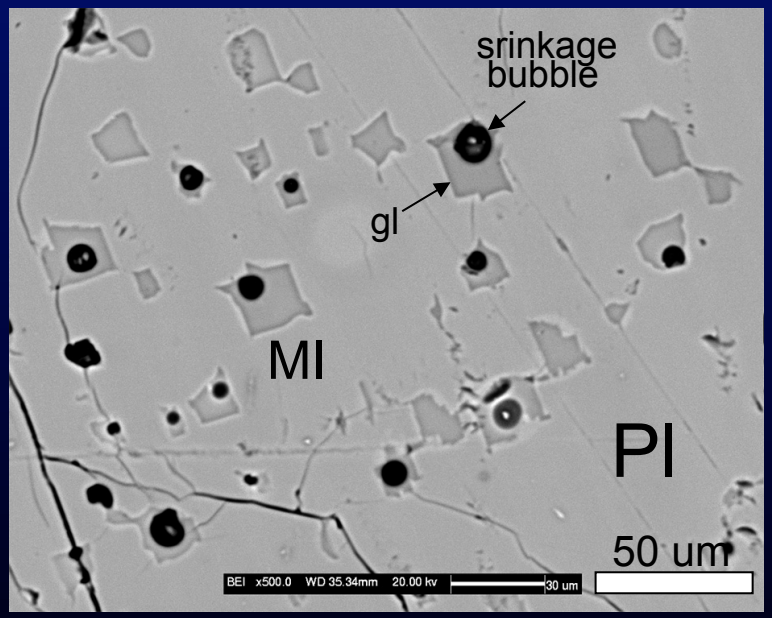


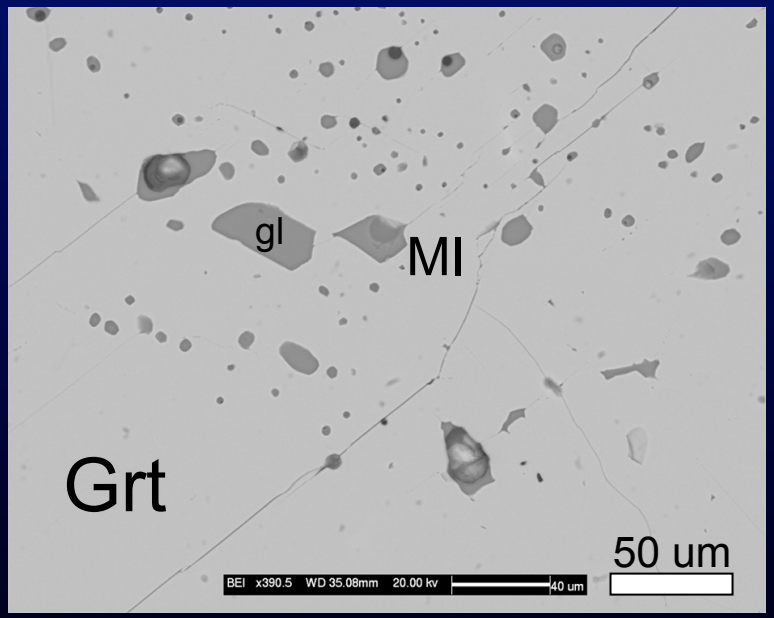
Modified after Sawyer et al. Elements (2011)

Melt inclusions under microscope/SEM



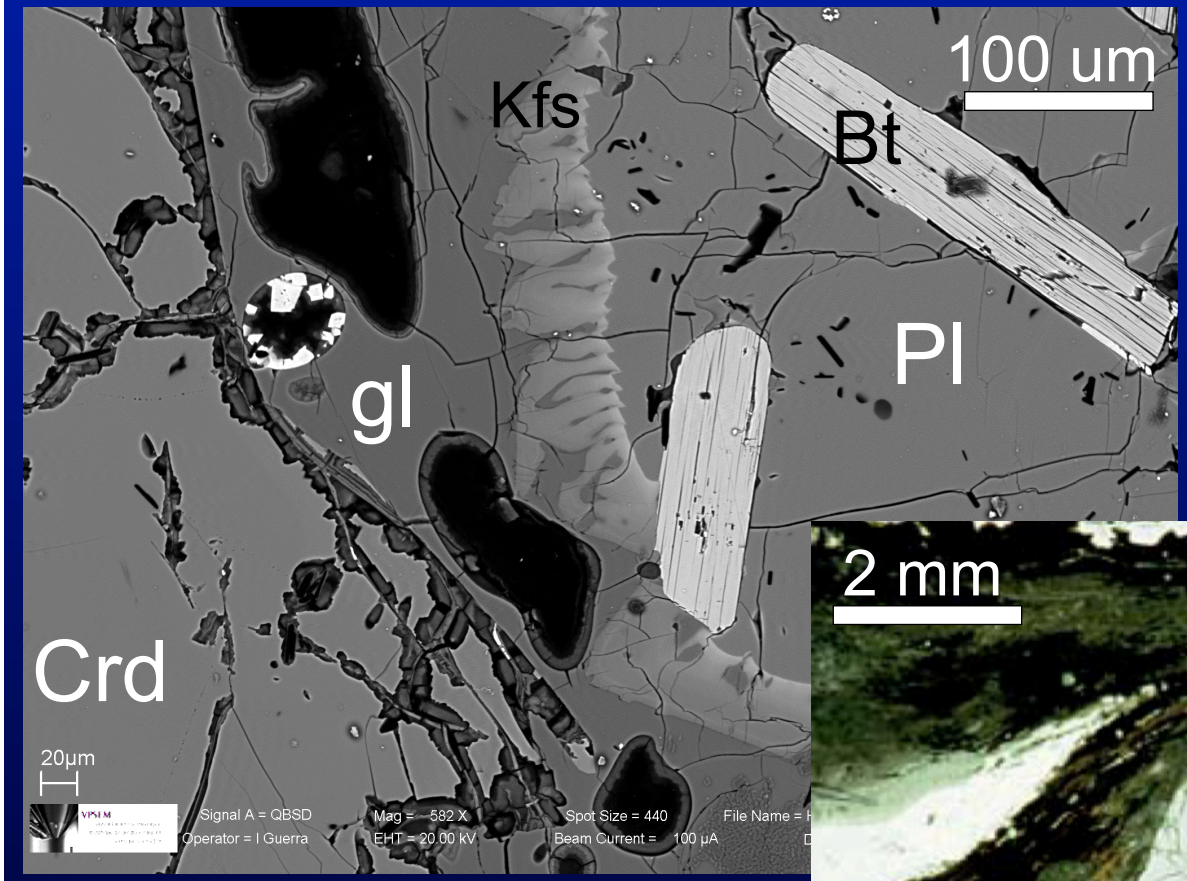






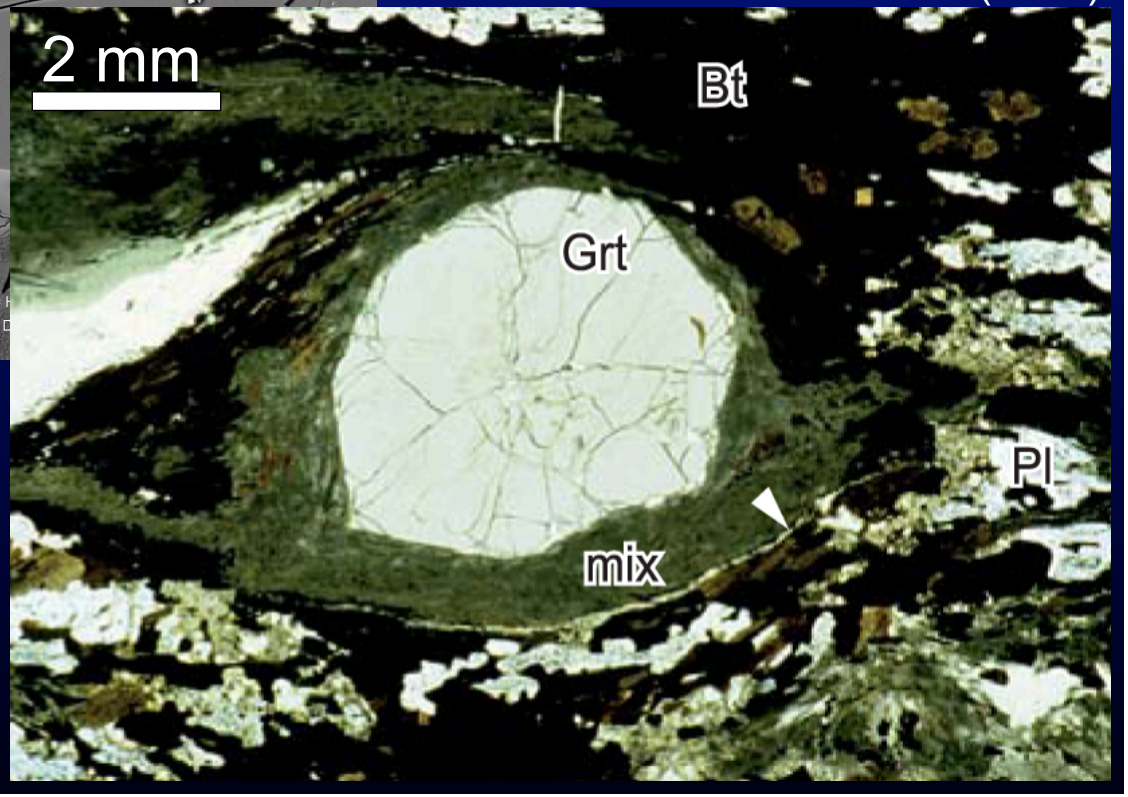
Acosta-Vigil et al. Chem Geol (2007)

Matrix glass under microscope/SEM

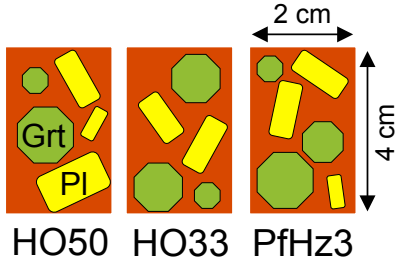


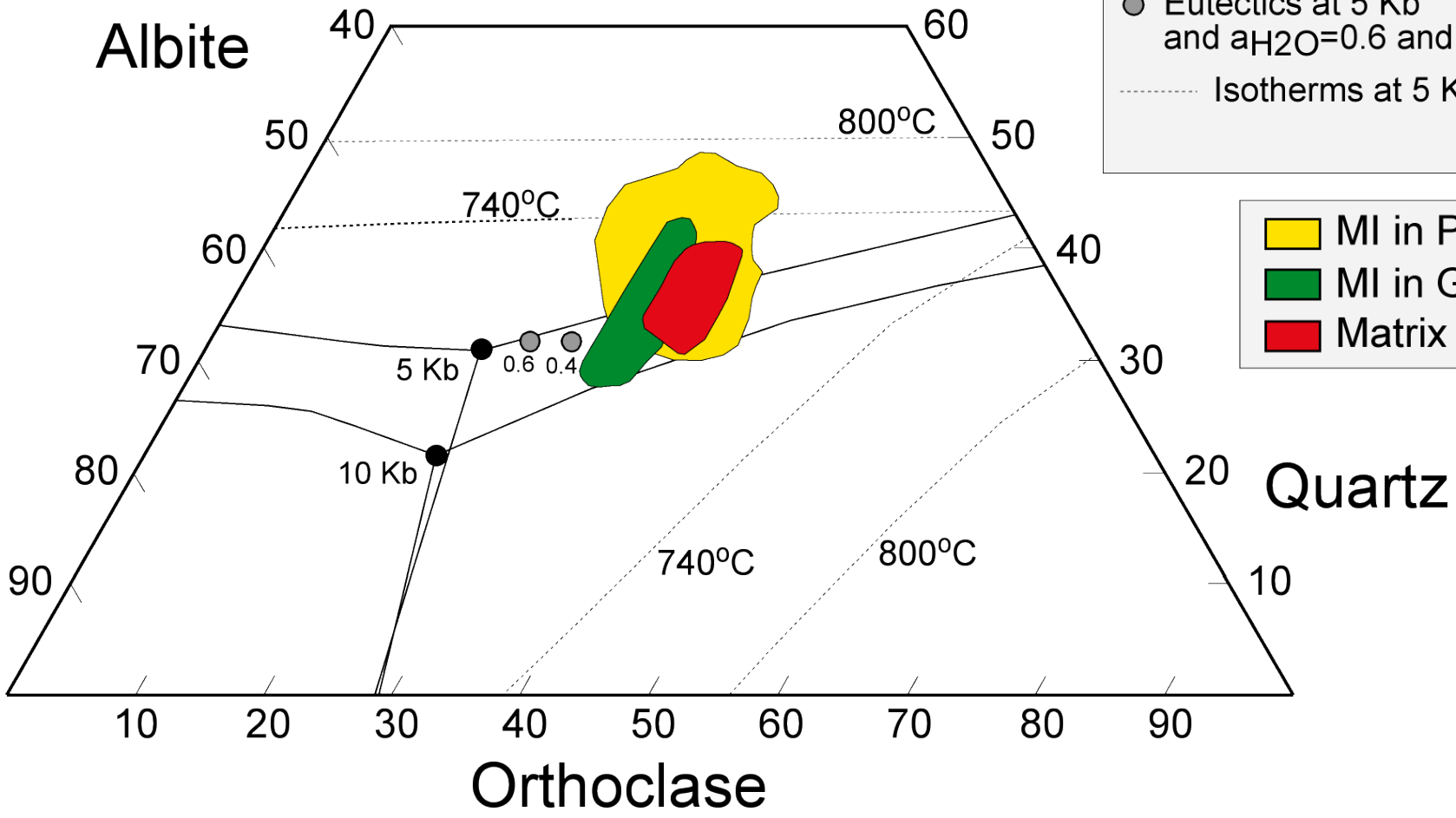
Acosta-Vigil et al. J Petrol (2010)

Cesare MAC Short Course (2008)



Normative composition of glasses



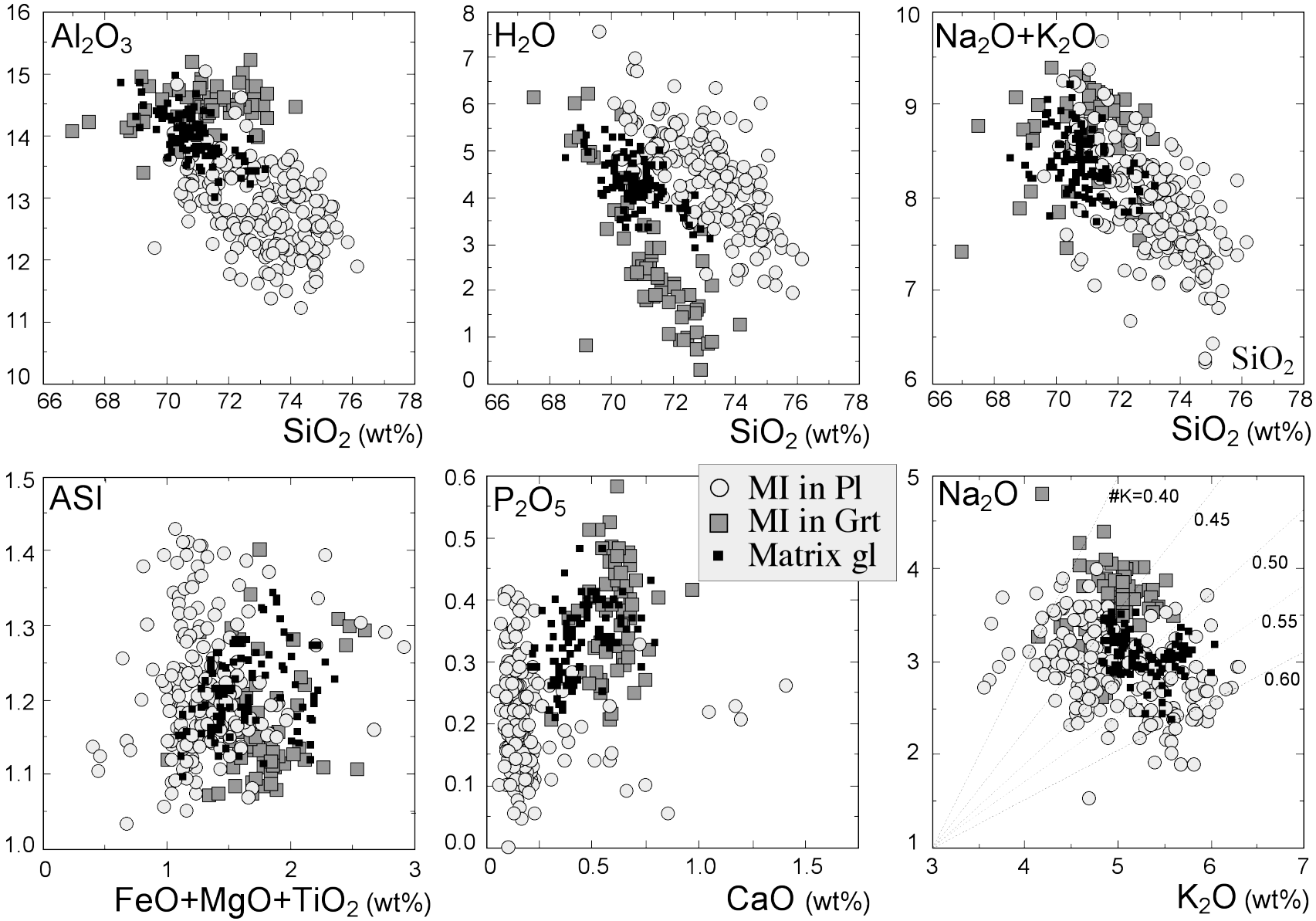


- Eutectics at 5 and 10 Kb H_2O
- Eutectics at 5 Kb and a_{H_2O}=0.6 and 0.4
- Isotherms at 5 Kb

- MI in Pl
- MI in Grt
- Matrix gl

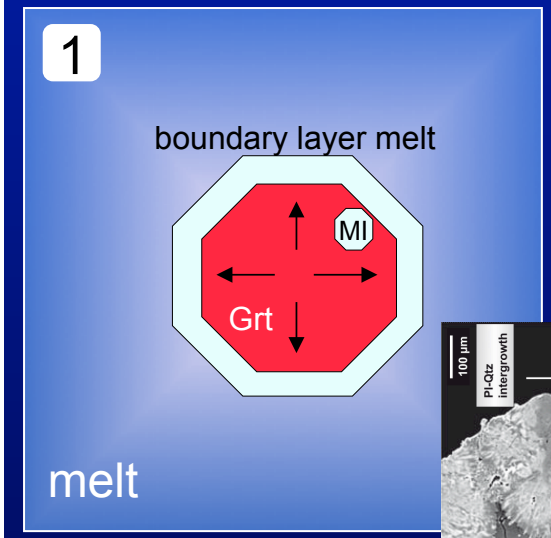
Acosta-Vigil et al. in preparation

Major element composition of glasses



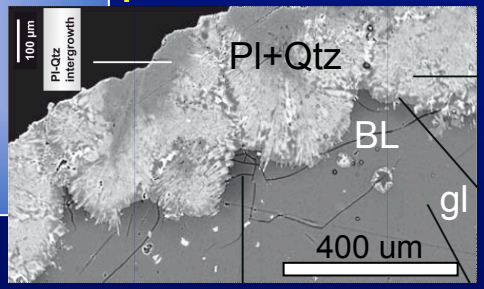
Acosta-Vigil et al. in preparation

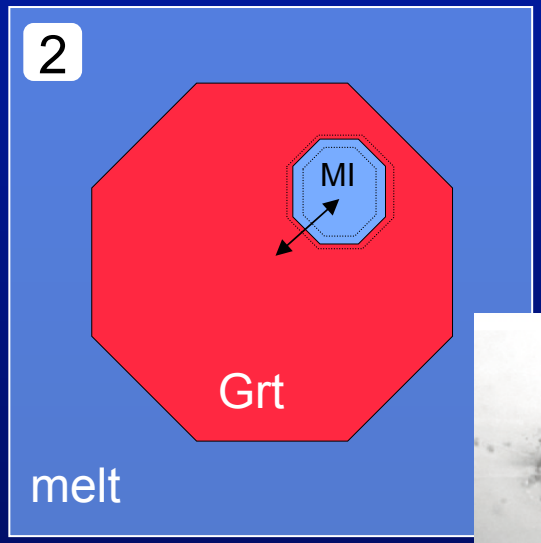
Processes changing composition of MI



London & Morgan (2012)

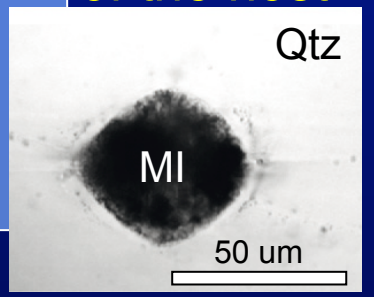
boundary layer phenomena

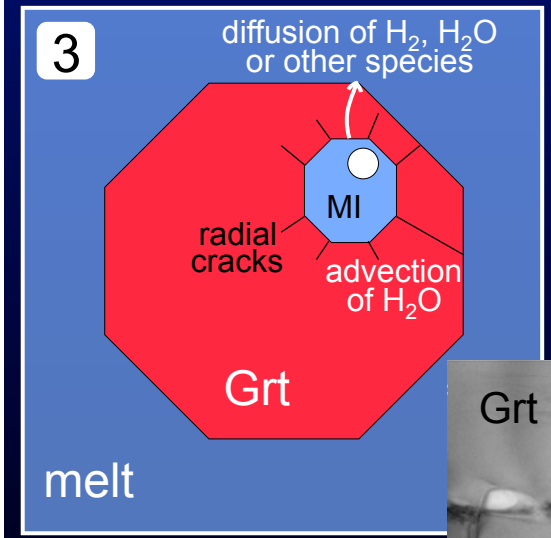




Audétat & Lowenstern (2014)

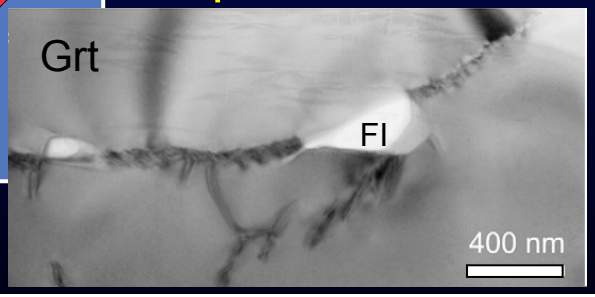
dissolution/ crystallization of the host

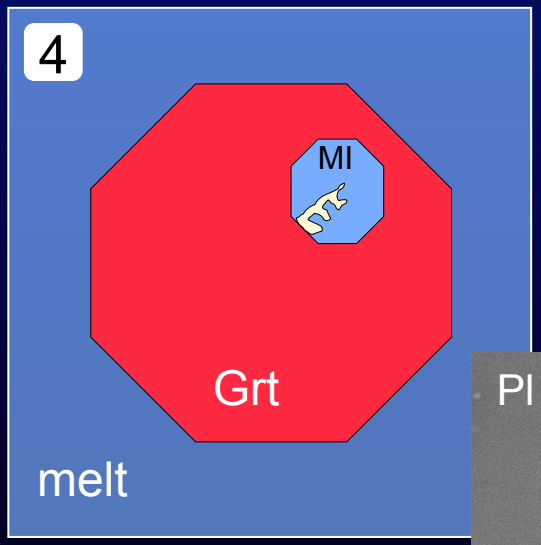




Ferrero et al. (2011)

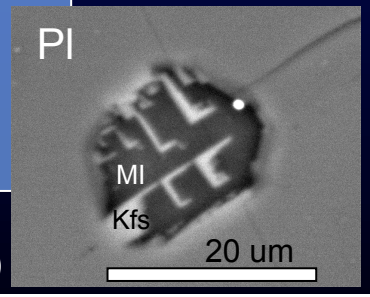
diffusive loss/ reequilibration



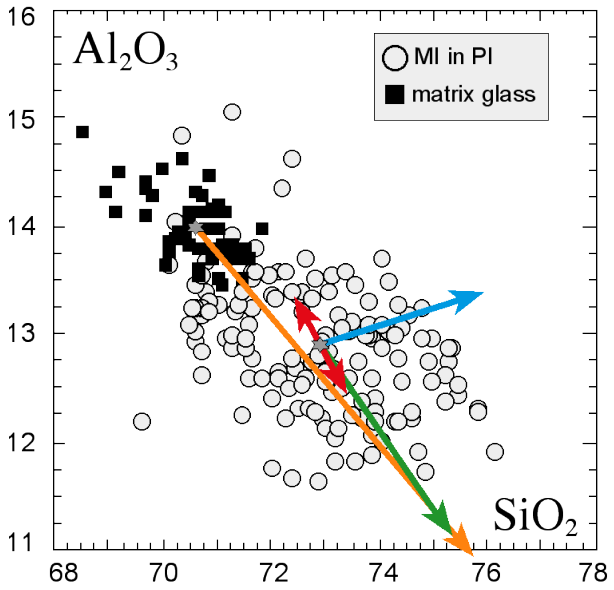


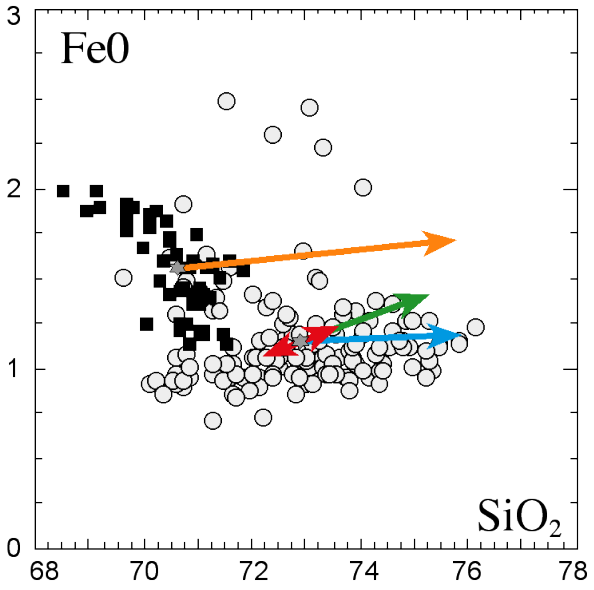
Acosta-Vigil et al. (2010)

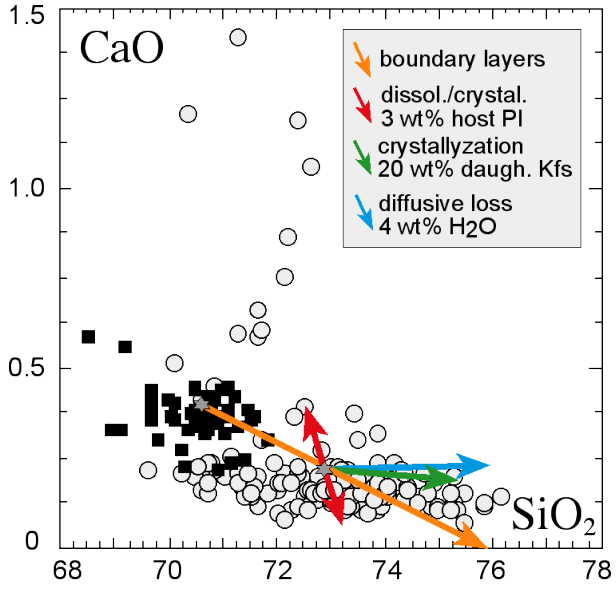
crystallization daughter minerals

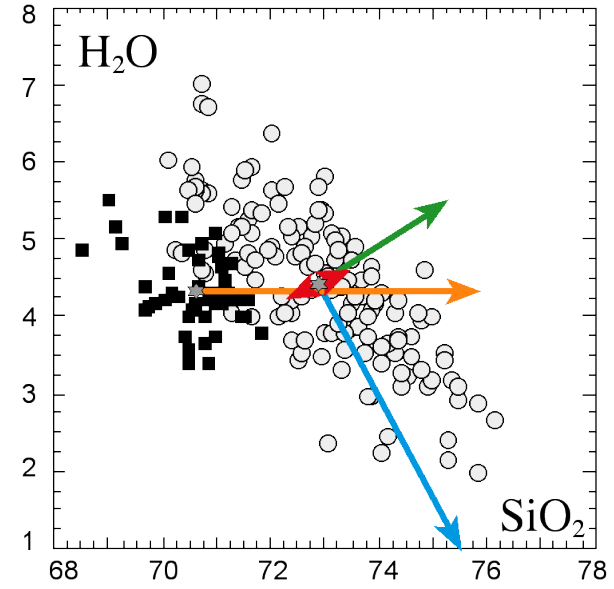


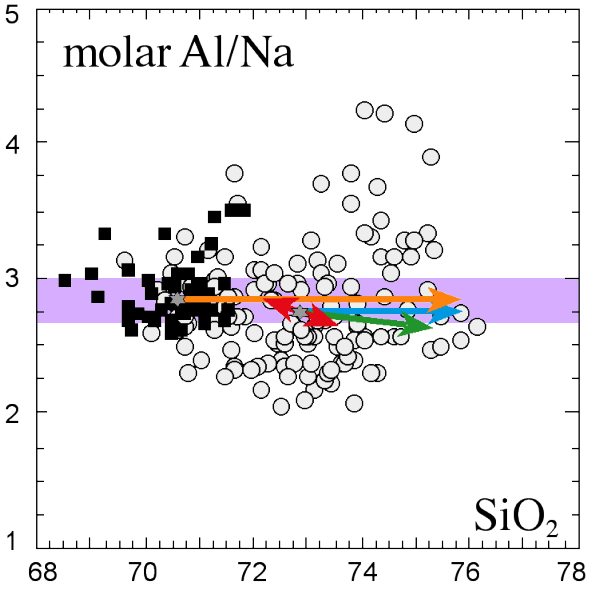
Mass balance modeling MI in Pl-matrix gl

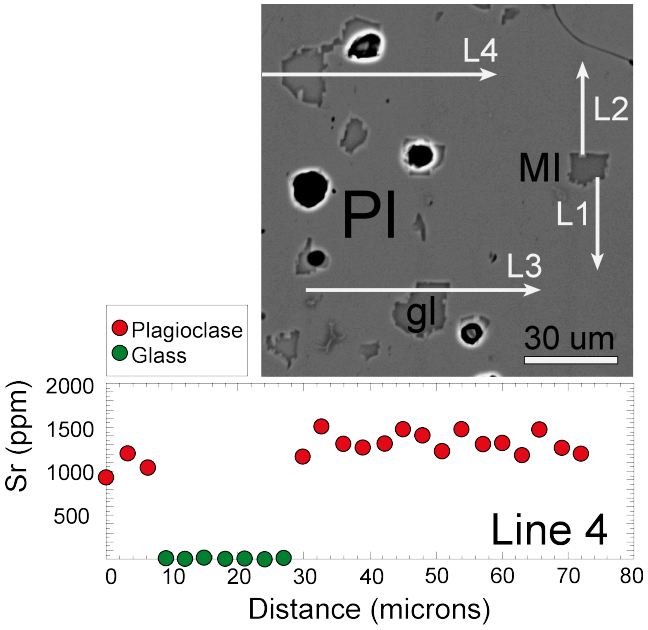




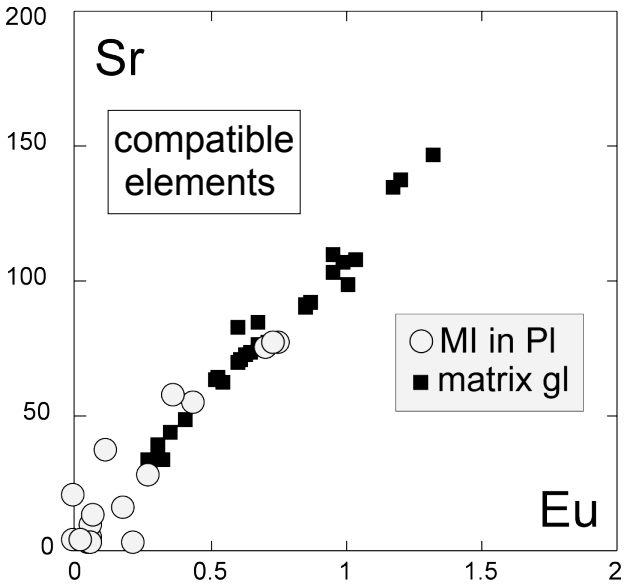


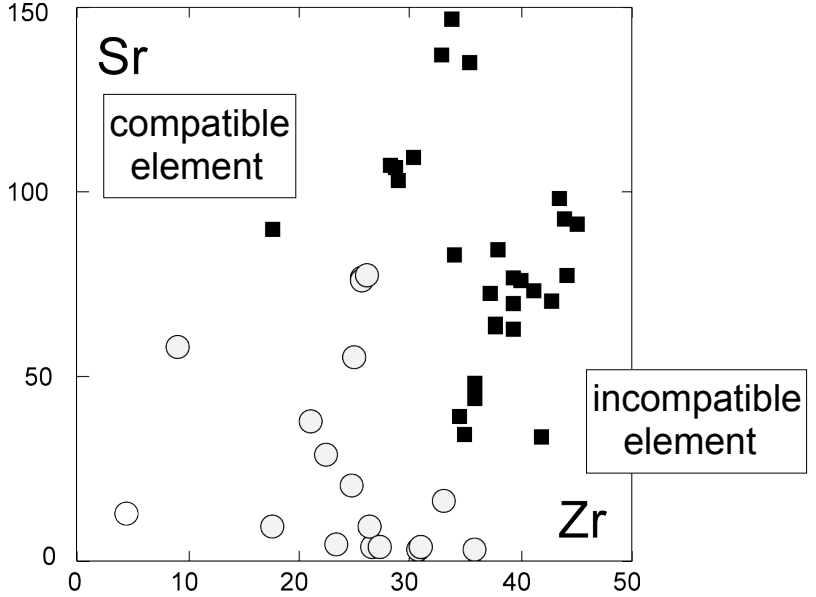


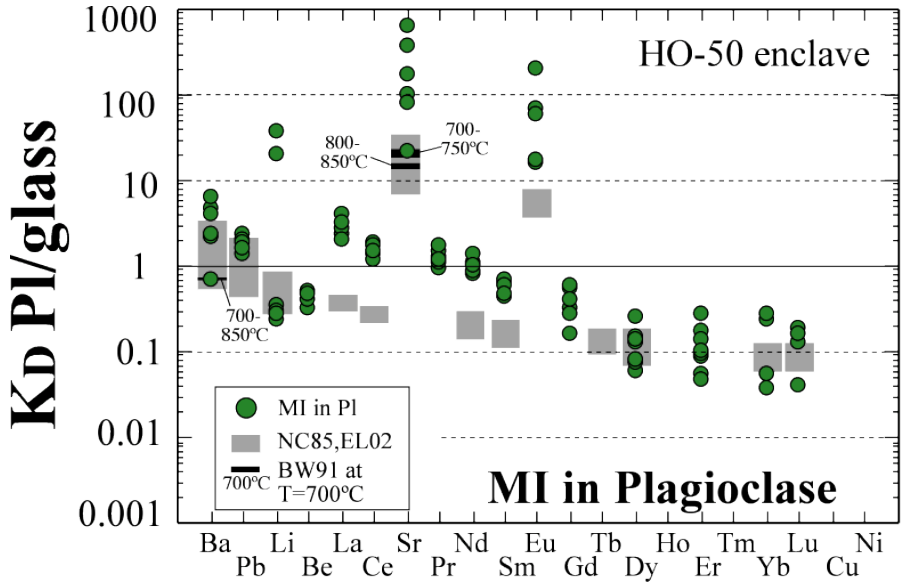




Mass balance modeling MI in Pl-matrix gl



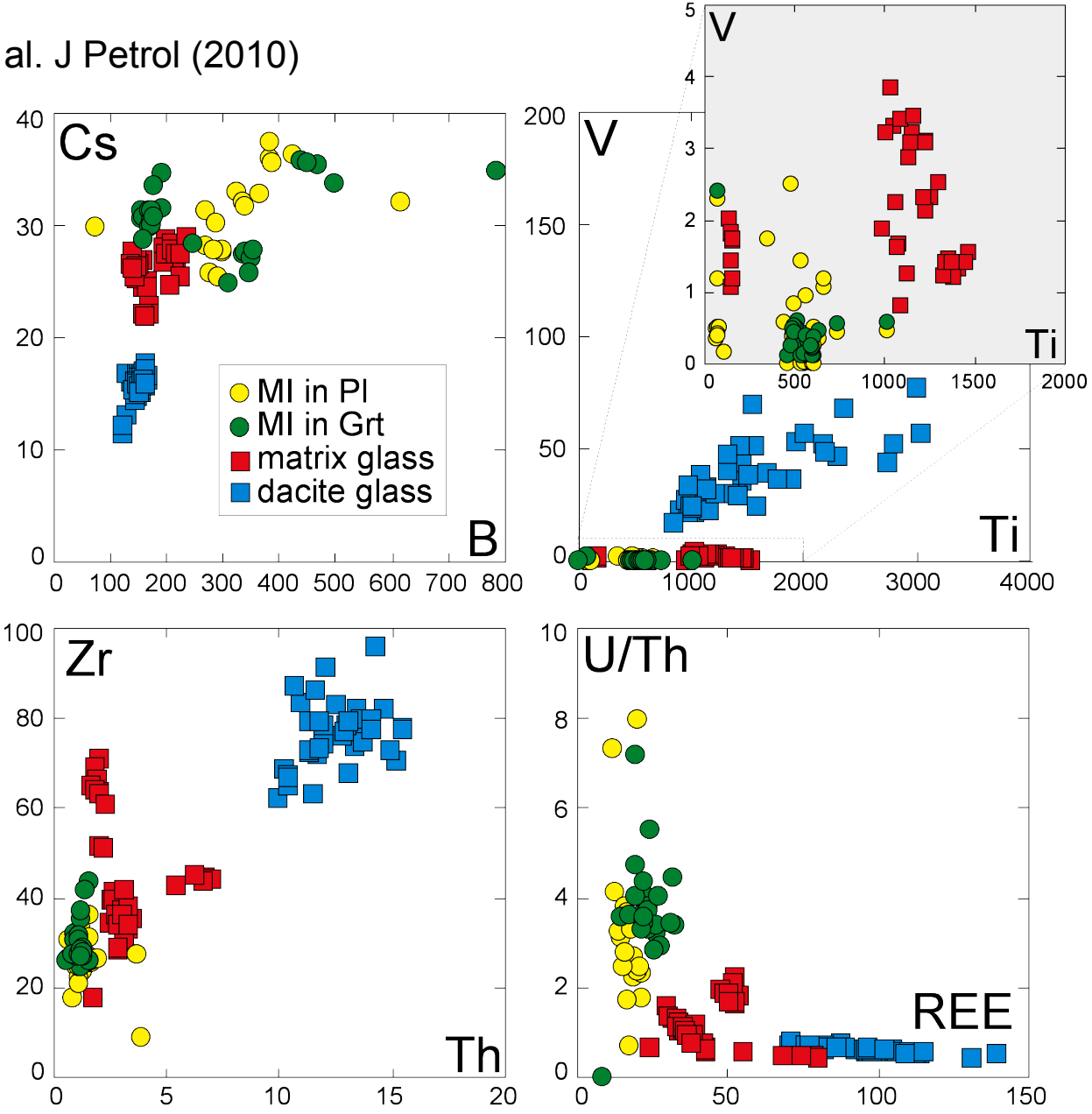




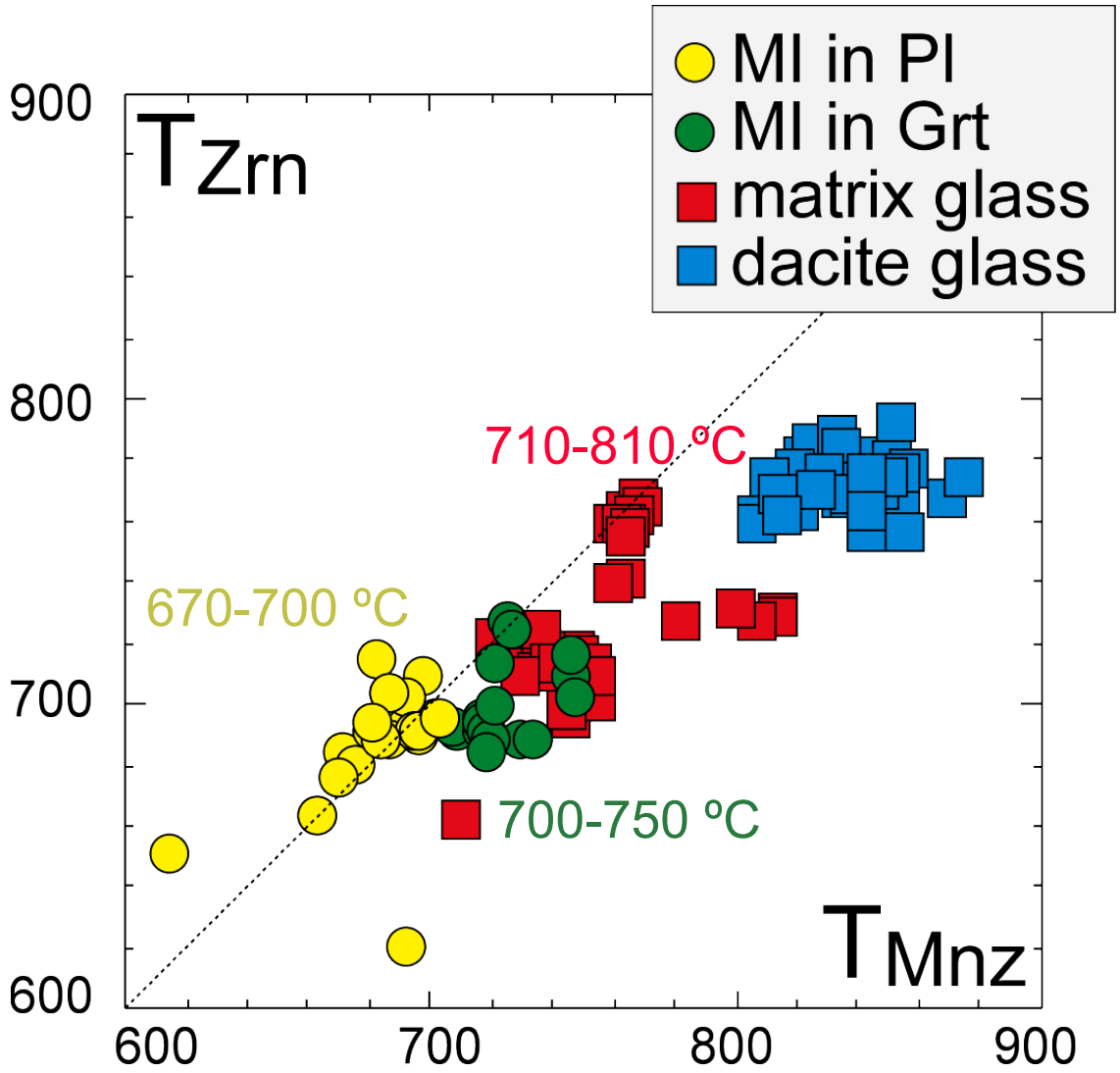
Acosta-Vigil et al. J Petrol (2012)

Trace element composition of glasses

Acosta-Vigil et al. J Petrol (2010)

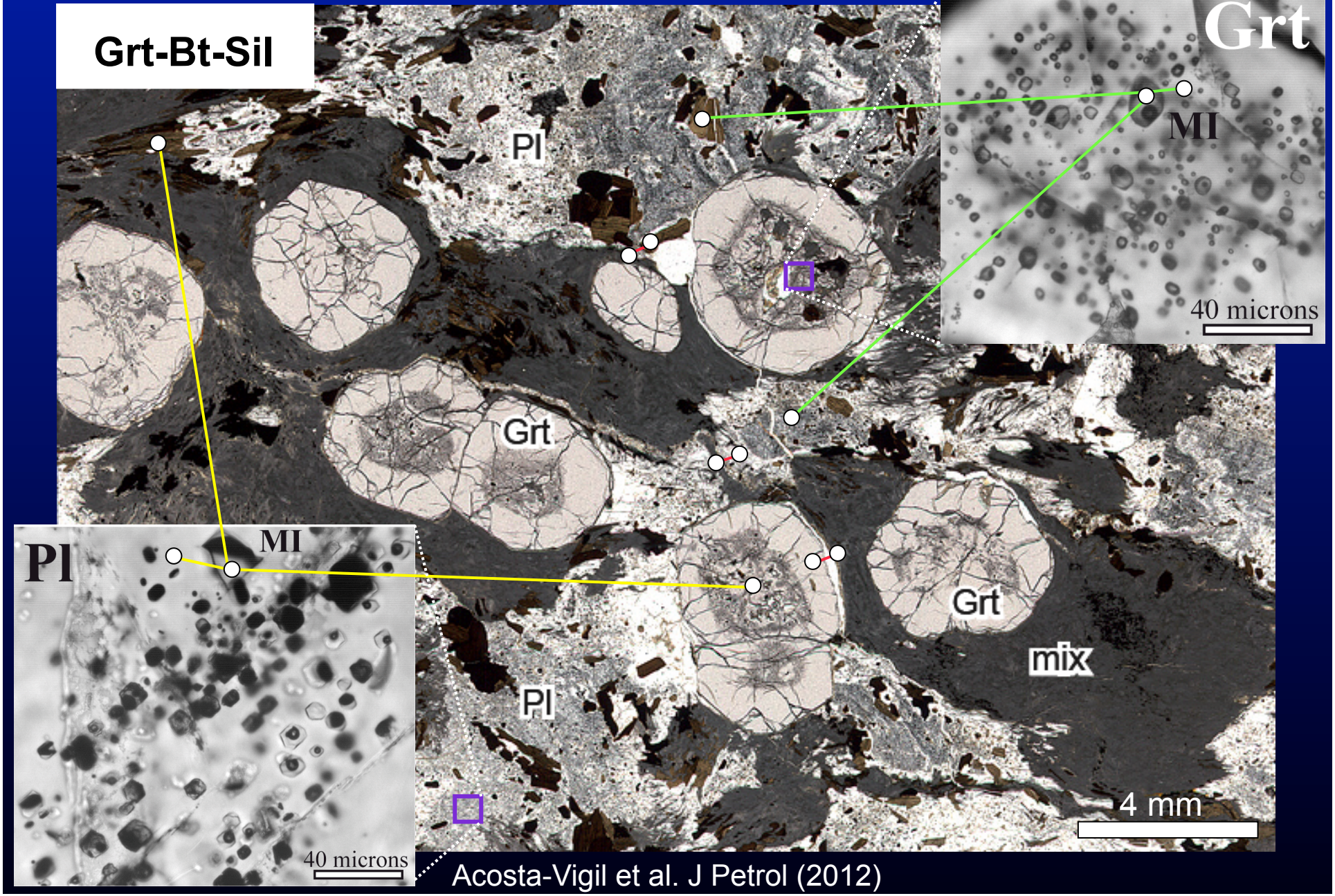


Zrn and Mnz saturation Temperatures



Acosta-Vigil et al. J Petrol (2010)

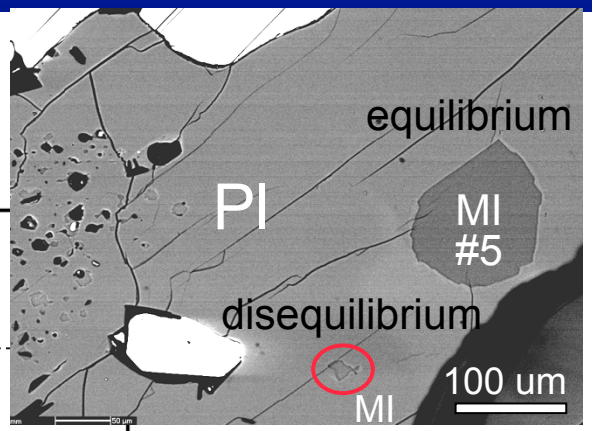
Extent of mineral-melt equilibrium (TE)

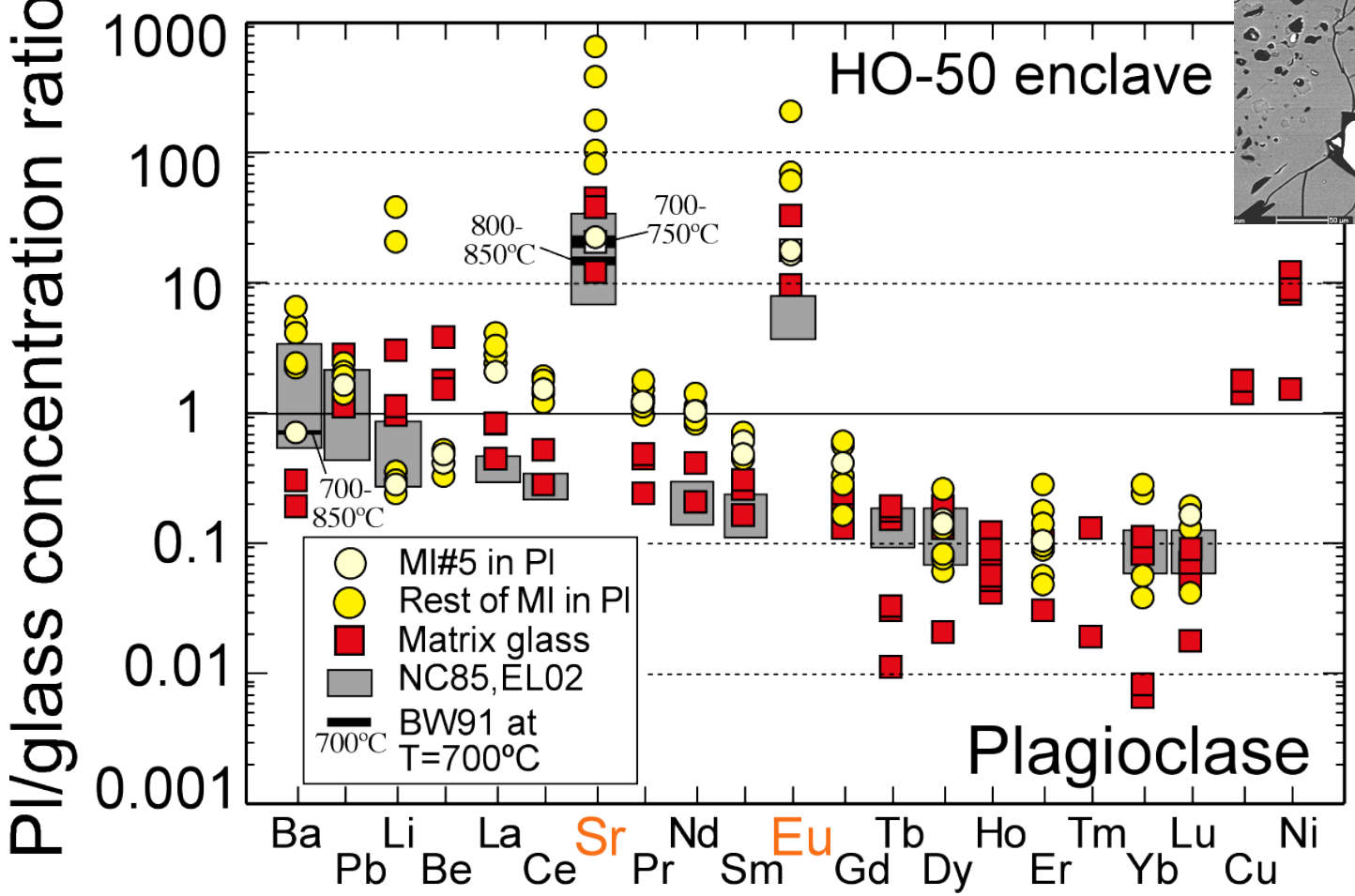


Acosta-Vigil et al. J Petrol (2012)

Extent of host Pl-MI and Pl-matrix melt equilibrium based on trace elements

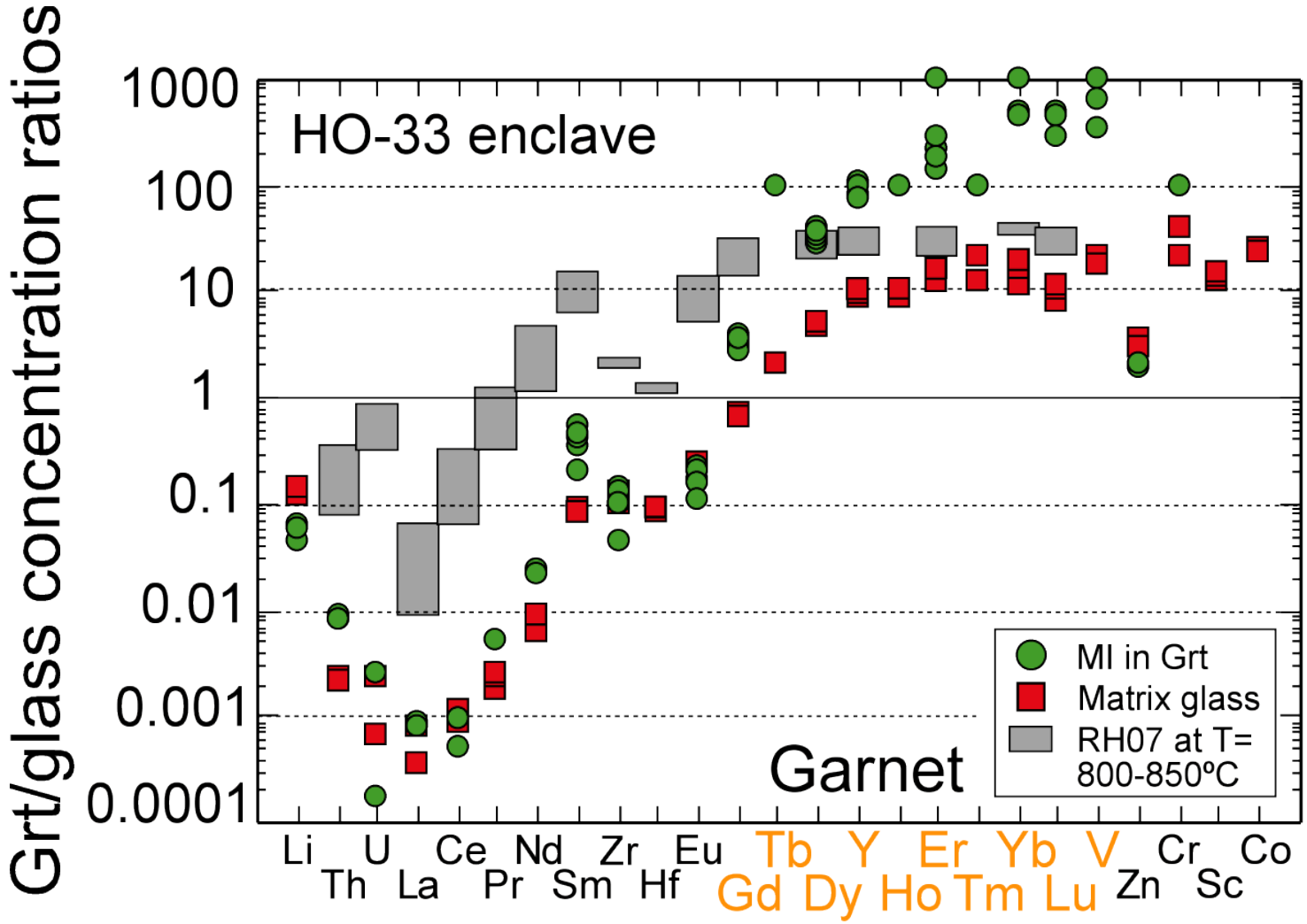
Acosta-Vigil et al. J Petrol (2012)





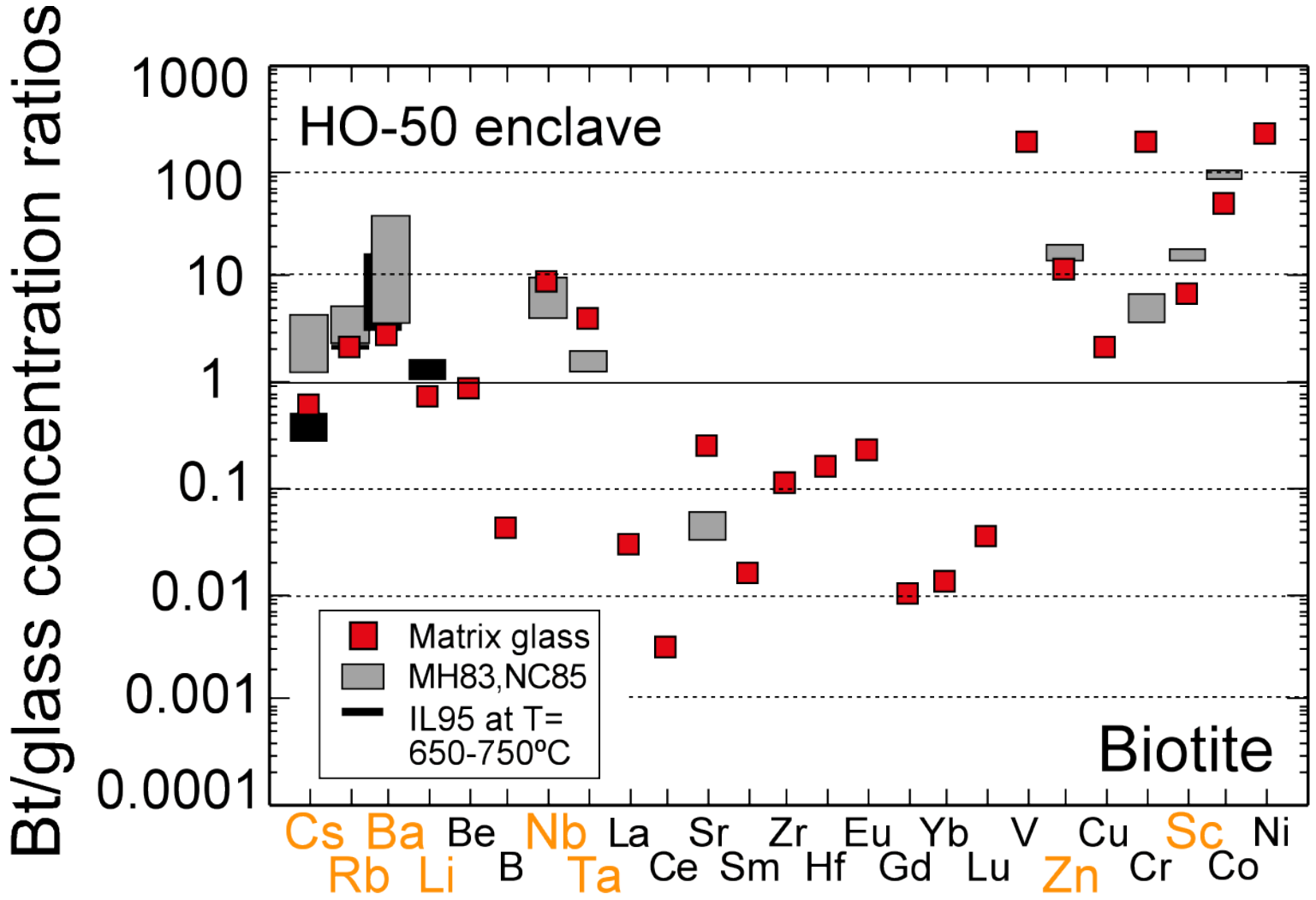
Extent of host Grt-MI and Grt-matrix melt equilibrium based on trace elements

Acosta-Vigil et al. J Petrol (2012)



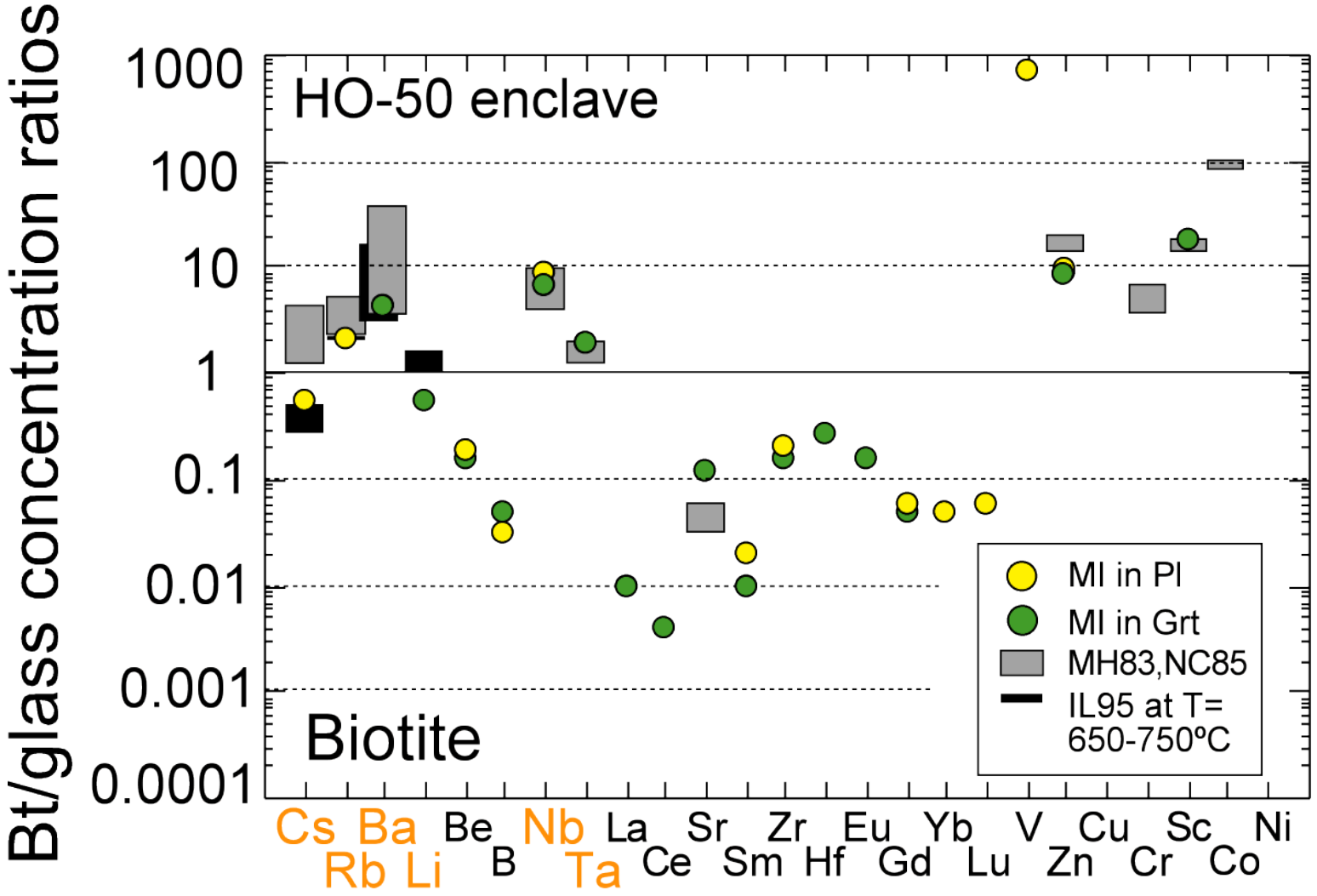
Extent of Bt-matrix melt equilibrium based on trace elements

Acosta-Vigil et al. J Petrol (2012)



Extent of equilibrium MI-matrix minerals, e.g. Bt, based on trace elements

Acosta-Vigil et al. J Petrol (2012)

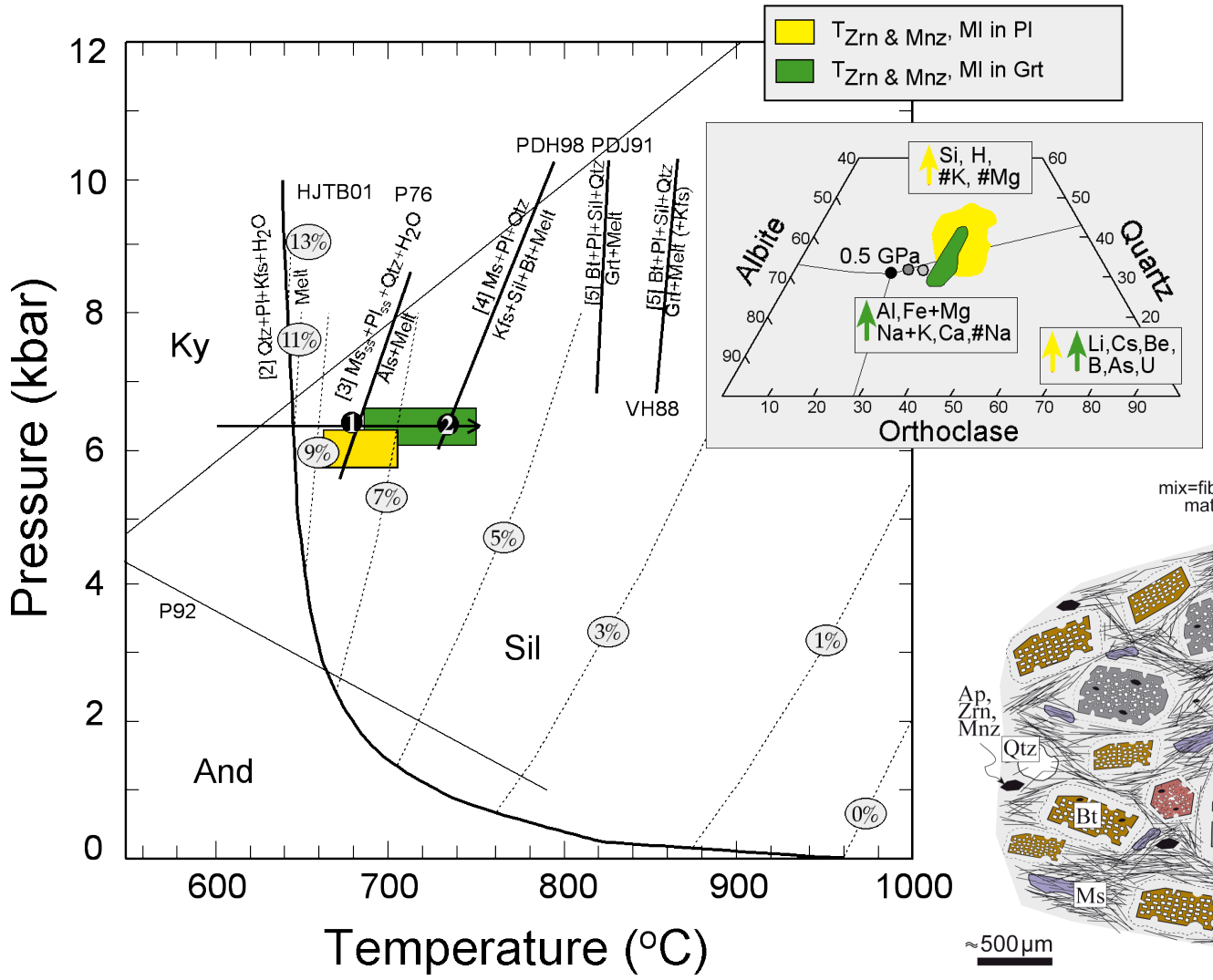


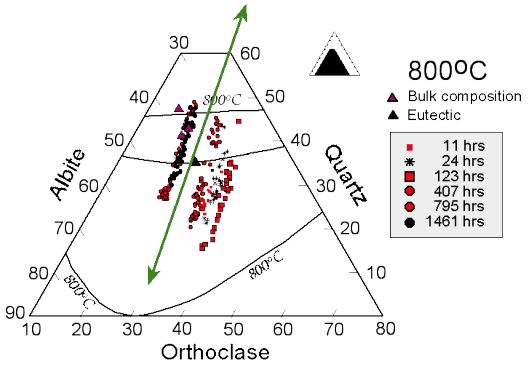
Origin of MI and matrix glass compositions?

- Primary MI, glassy, leucogranitic, peraluminous, similar to gl in experiments.
- GI of each microstructural location: variable, distinctive, non eutectic.
- H_2O concentrations indicate H_2O-undersaturated anatexis.
- Melt inclusions in Pl and Grt represent former melt films in contact with crystals, remains of first anatectic melts we have access to for study.
- MI in Pl, most heterogeneous and evolved compositions, lowest Zrn-Mnz saturation T. Matrix melt, more homogeneous and less compositionally evolved, highest Zrn-Mnz saturation T. MI in Grt, in between both.
- Differences among gl in several locations: not related to syn-, post-entrapment processes, likely reflecting matrix melt compositions at different T.
- Melt inclusions analyzed in several crystals/enclaves: matrix melt with well defined LILE-rich, HFSE- and REE-poor geochemical character. Matrix melt likely at or close to equilibrium with the residue (except Grt).
- Matrix glass: melts produced after MI, mostly at or close to equilibrium with rims of most minerals (except Grt).

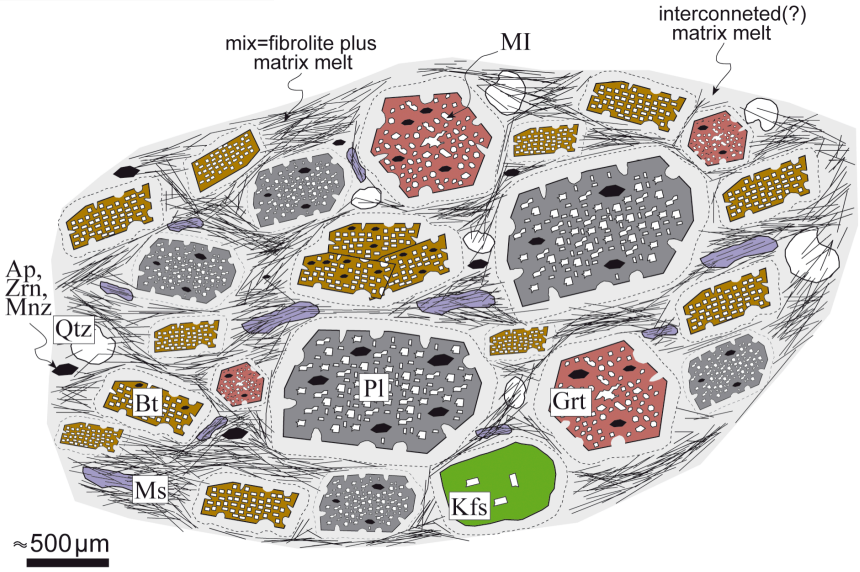
Petrogenesis of crustal anatectic systems from the study of melt inclusions

Acosta-Vigil et al. CMP (2006), J Petrol (2010), and in preparation



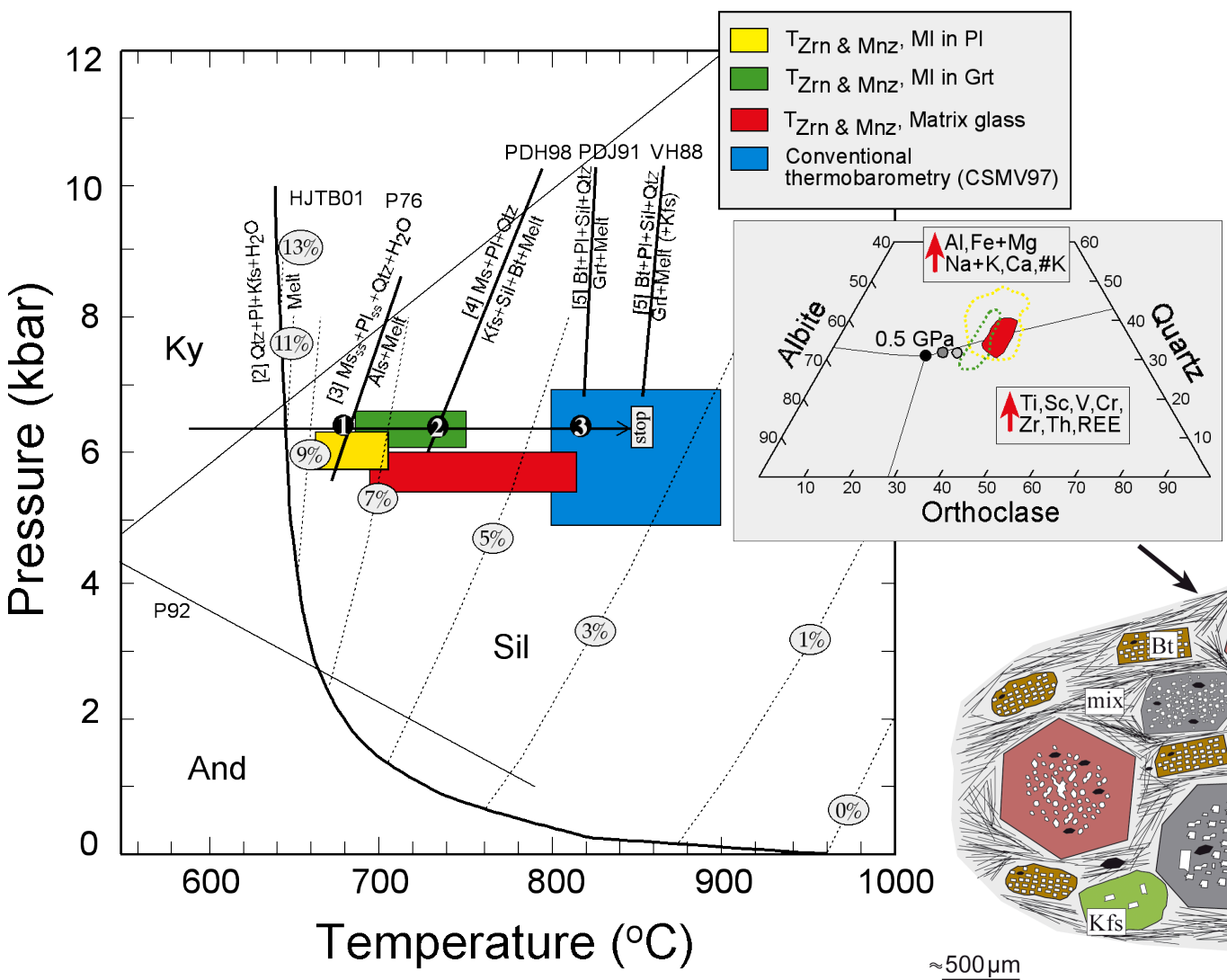


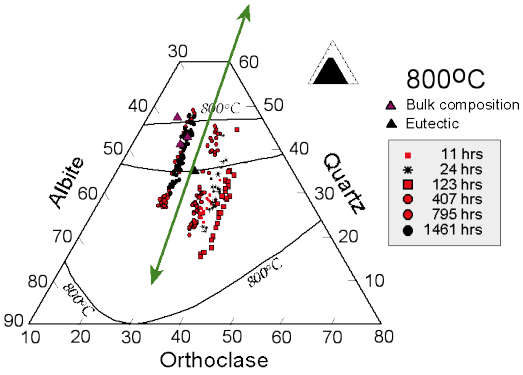
Muscovite melting



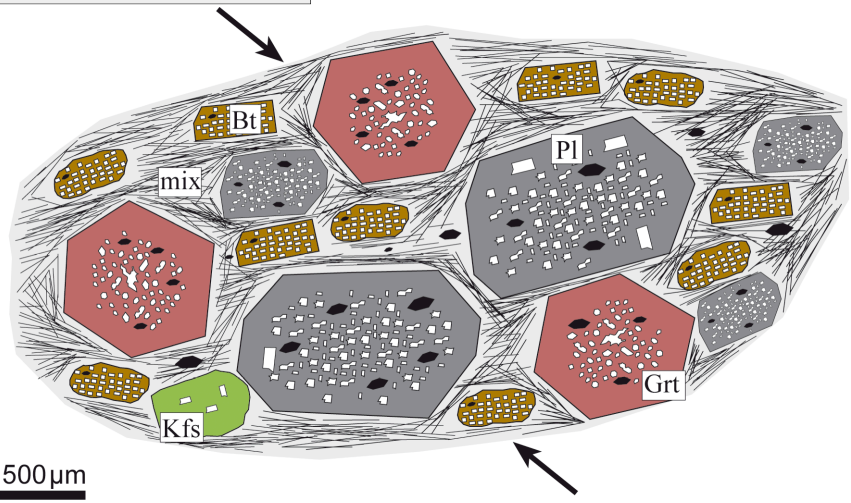
Petrogenesis of crustal anatectic systems from the study of melt inclusions

Acosta-Vigil et al. CMP (2006), J Petrol (2010), and in preparation

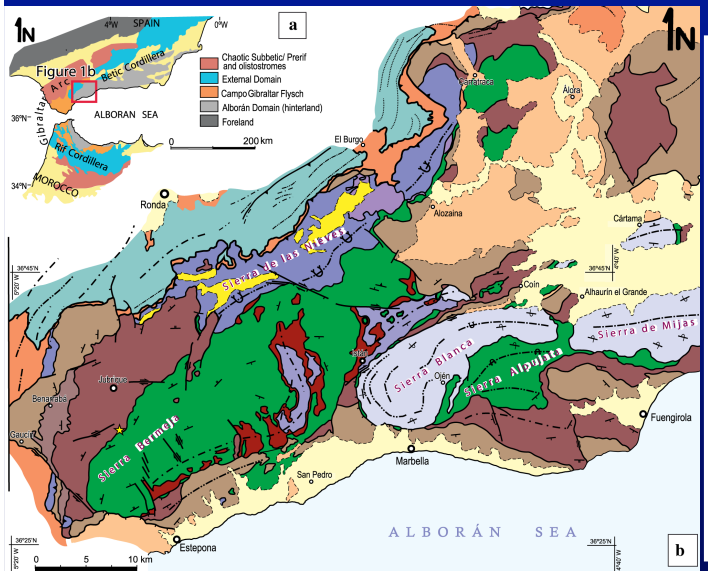


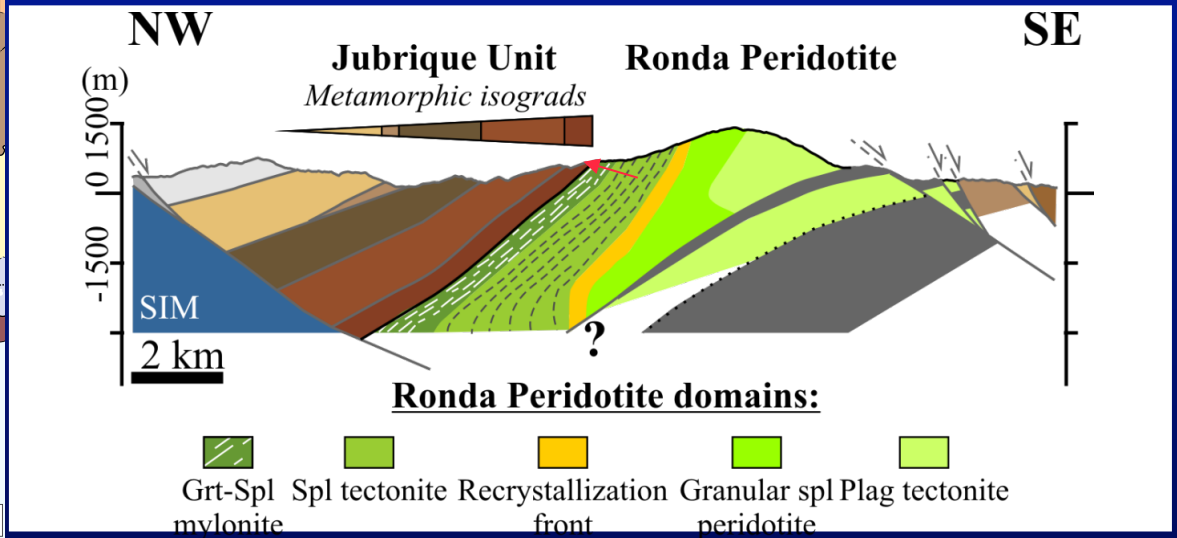


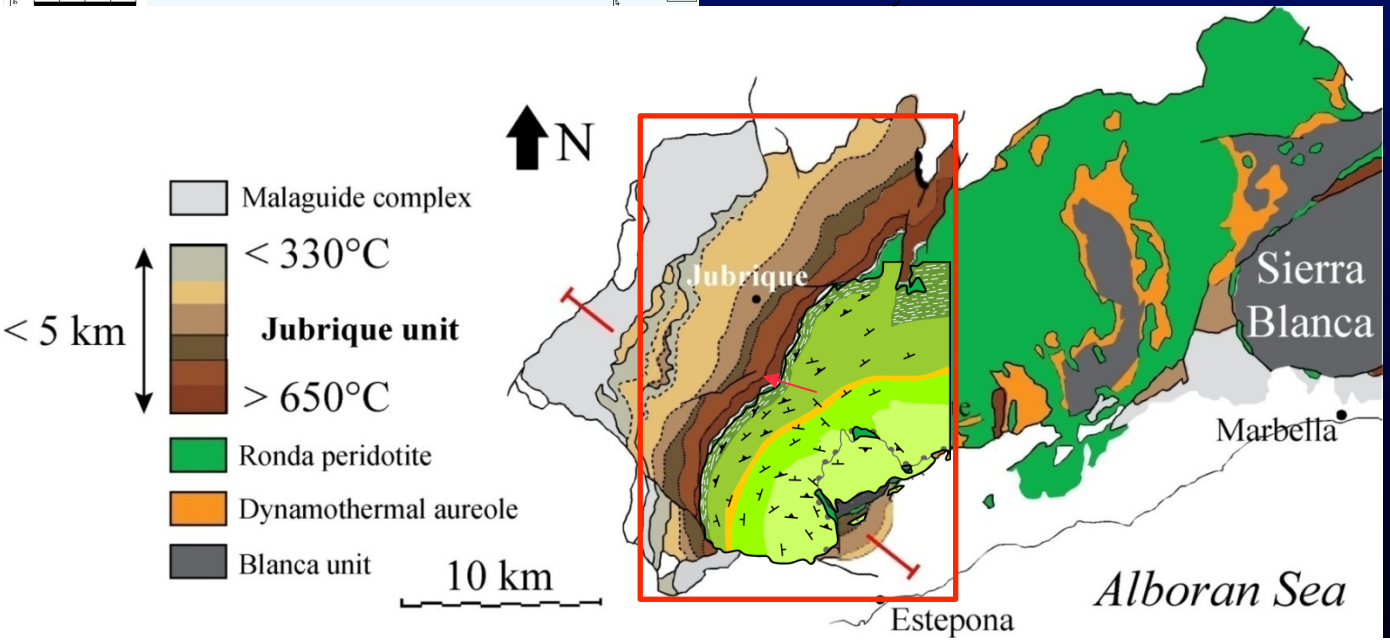
Biotite melting



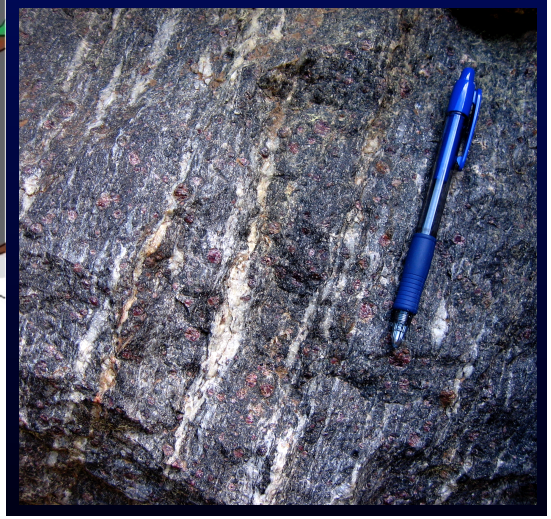
Melt inclusions in granulites from the Betic Cordillera, Ronda area, S Spain



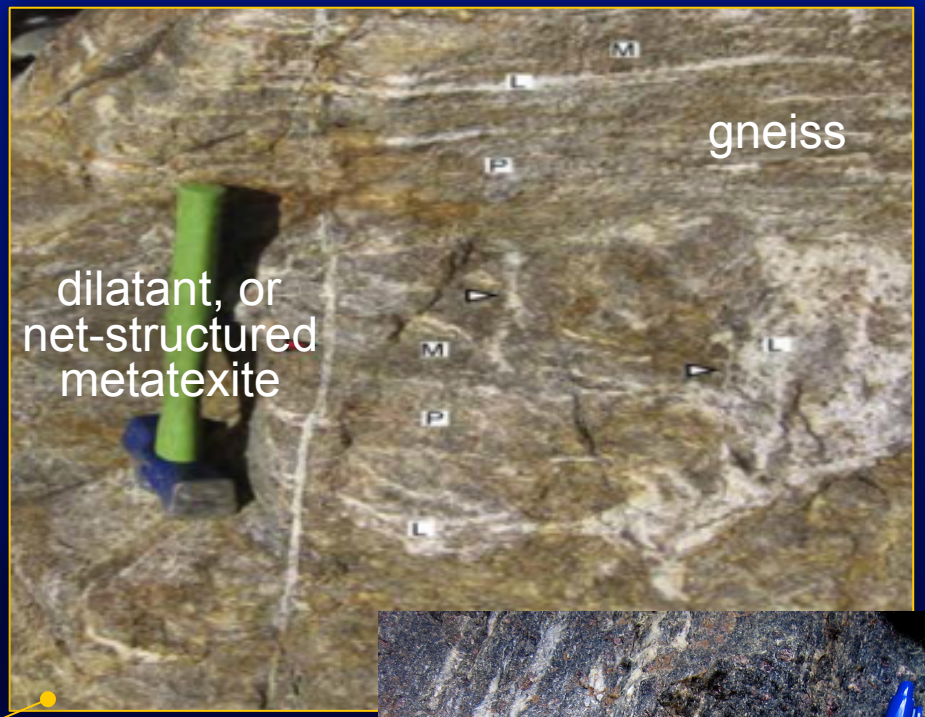




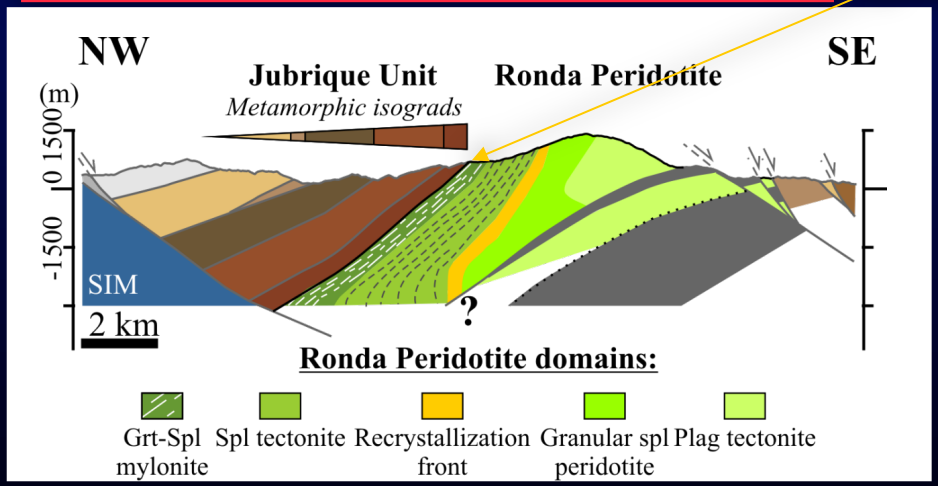
Barich et al. (2014), Barich PhD (2015)



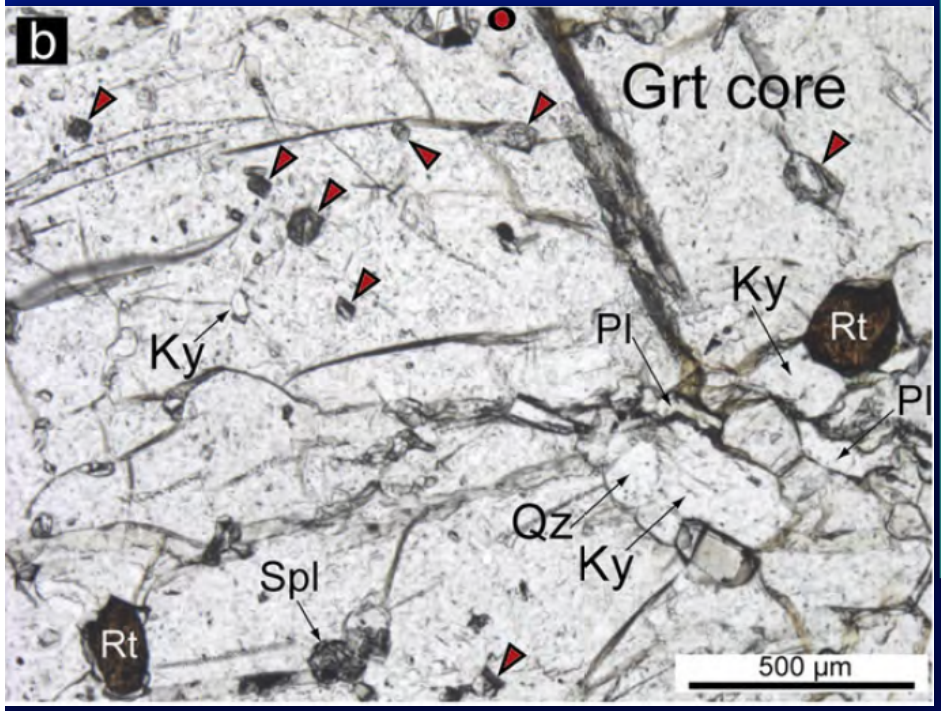
Field geology



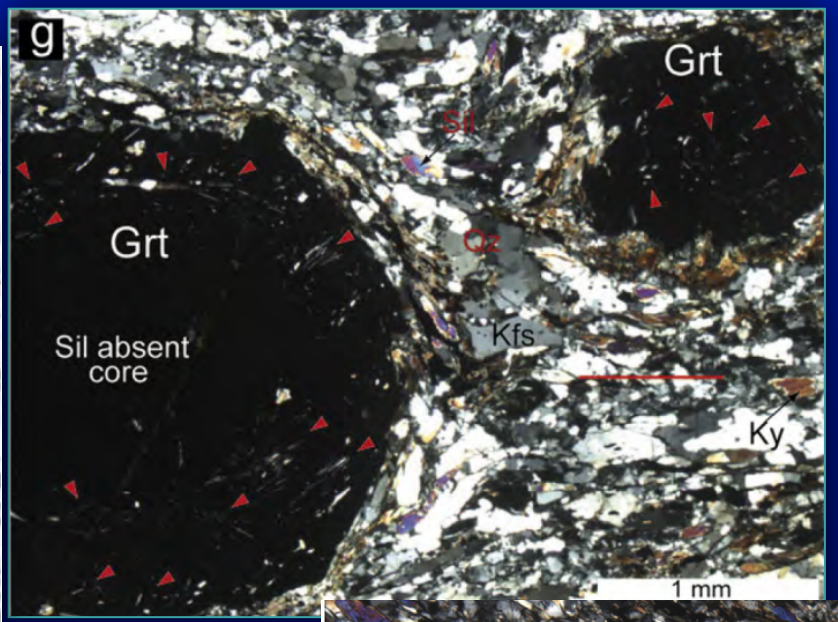
Mylonitic Gneisses
Massive Rocks, Grt-rich, Leucocratic Bands

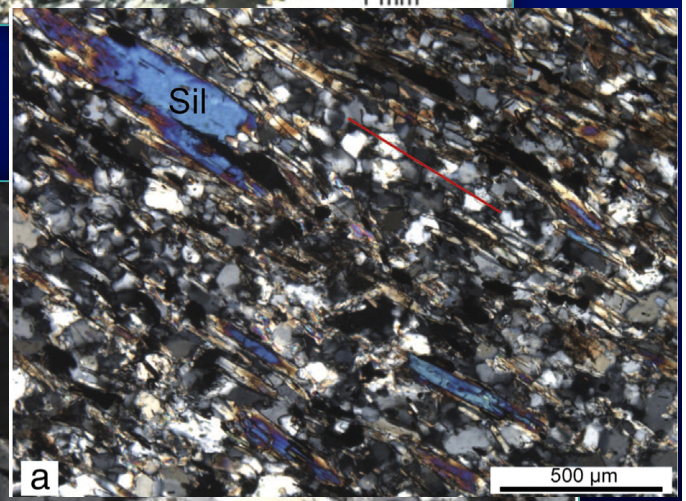


Petrography



Barich et al. (2014)





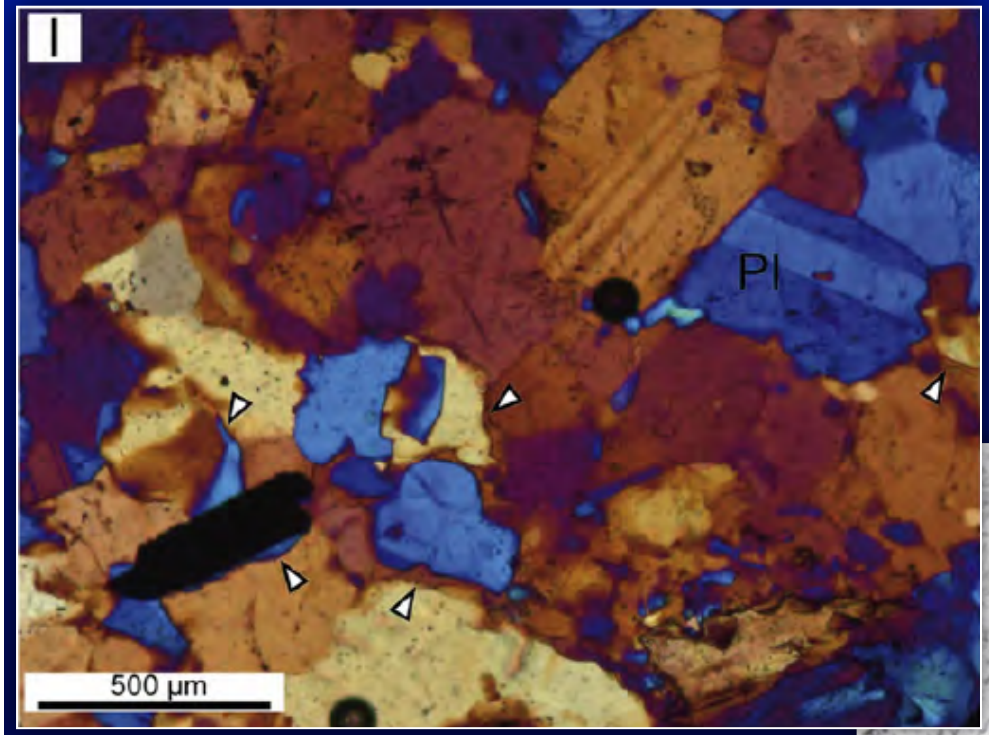
Grt-Ky-Sil-Qz-Pl-Kfs-Crd-Bt-Spl

Pre-Sp: Grt core+Ky+Rt+Fds+Qz+Bt

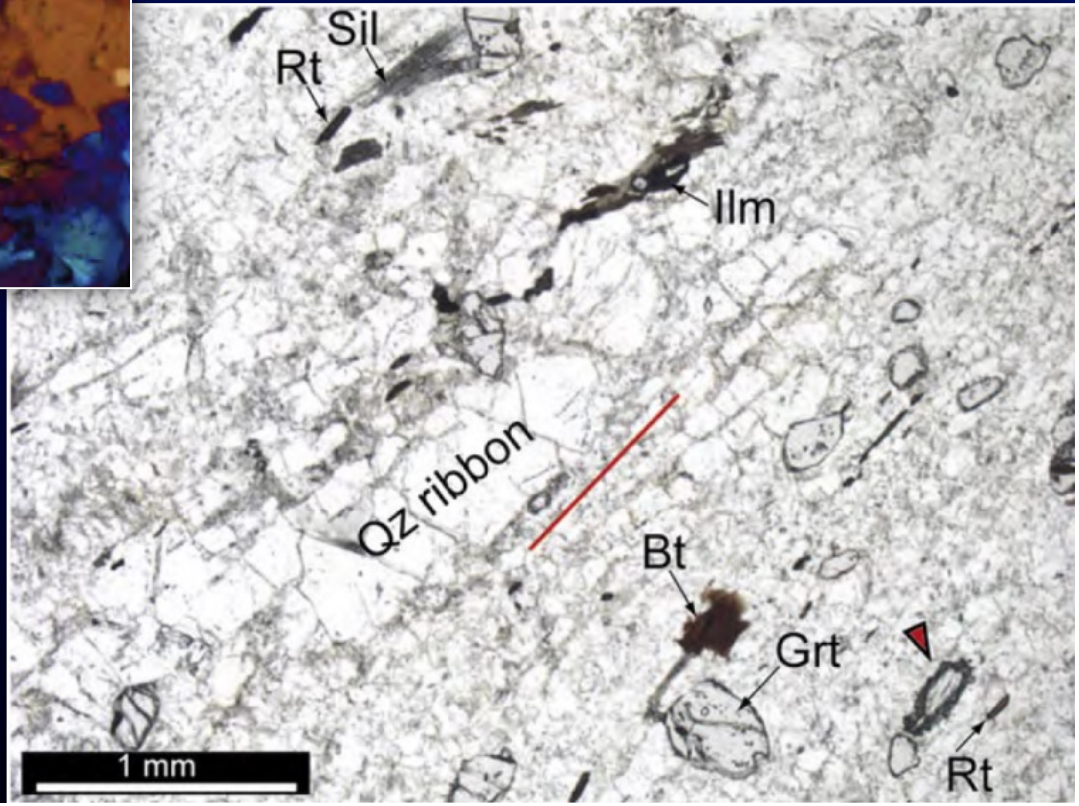
Syn-Sp: Grt rim+Sil+Qz+Fds+Ilm

Post-Sp: Crd+Qz+Bt+Spl+Pl+Kfs+Sil

Petrography

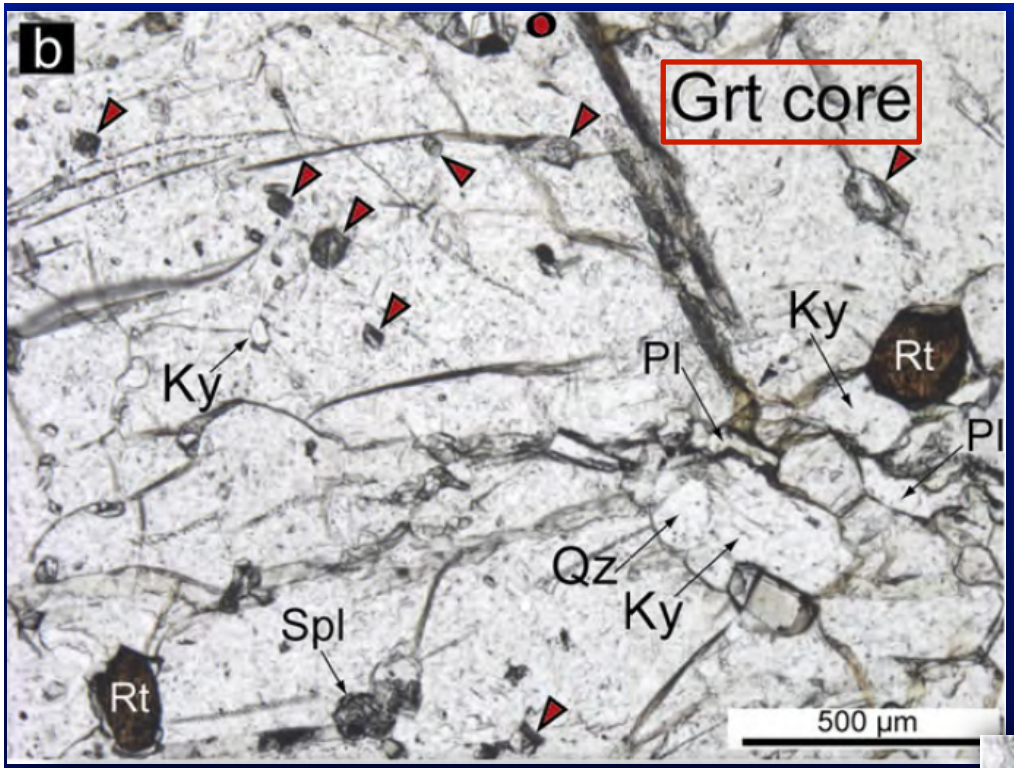


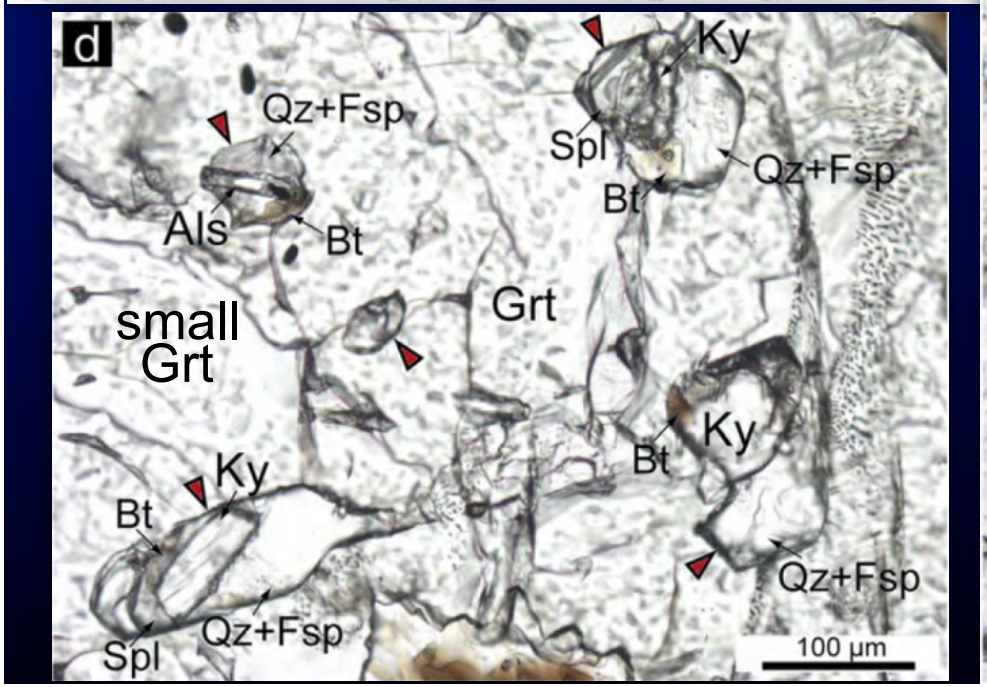
Barich et al. (2014)

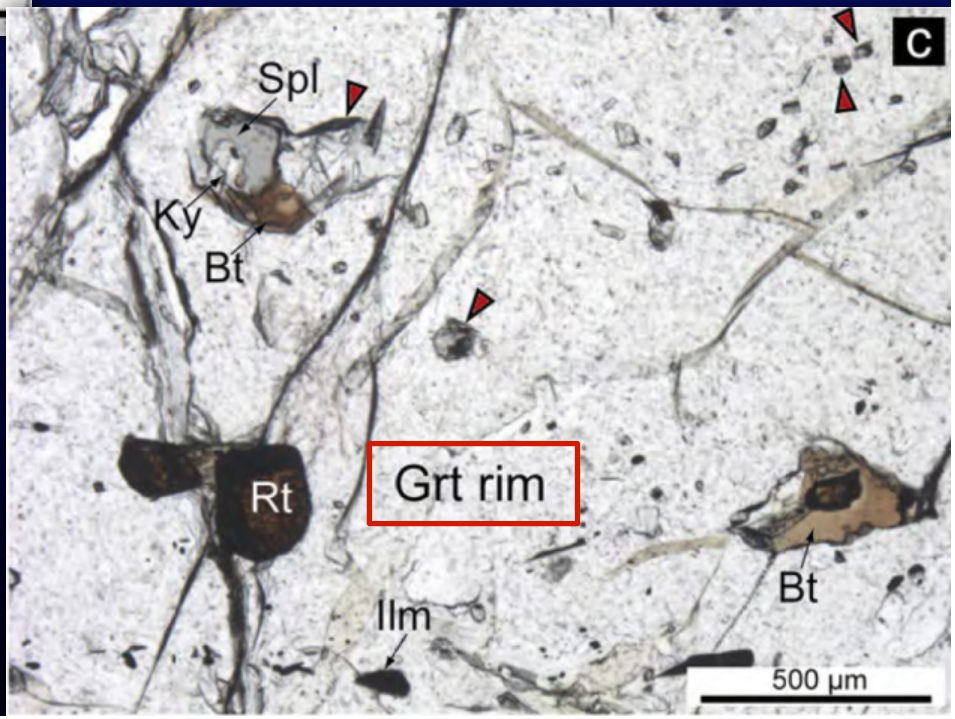


Petrography of the melt inclusions

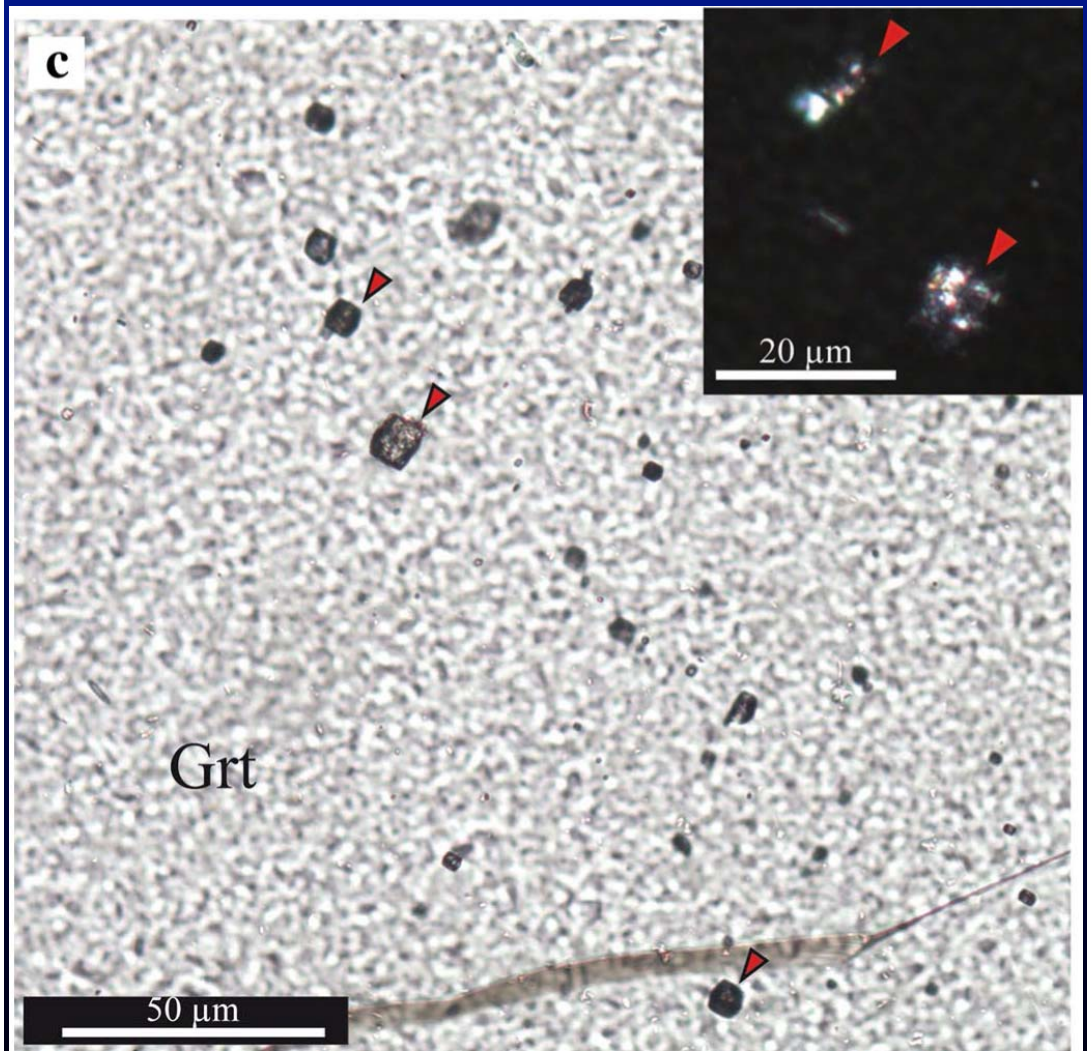
Barich et al. (2014)

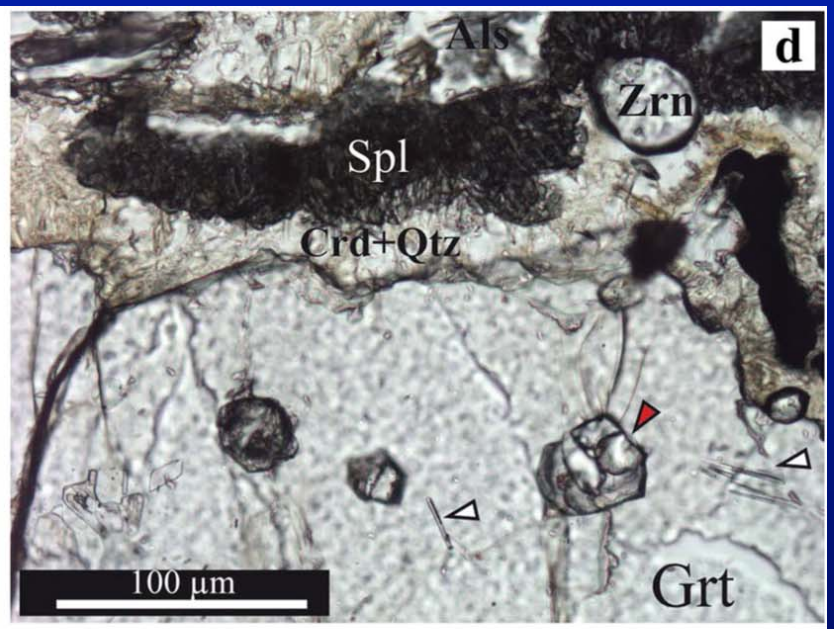


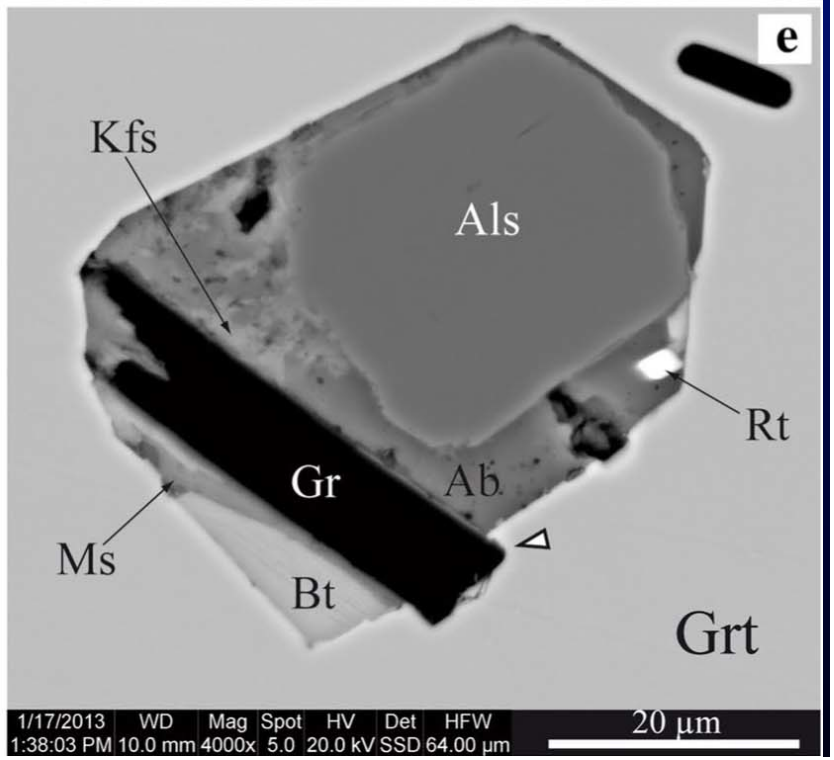




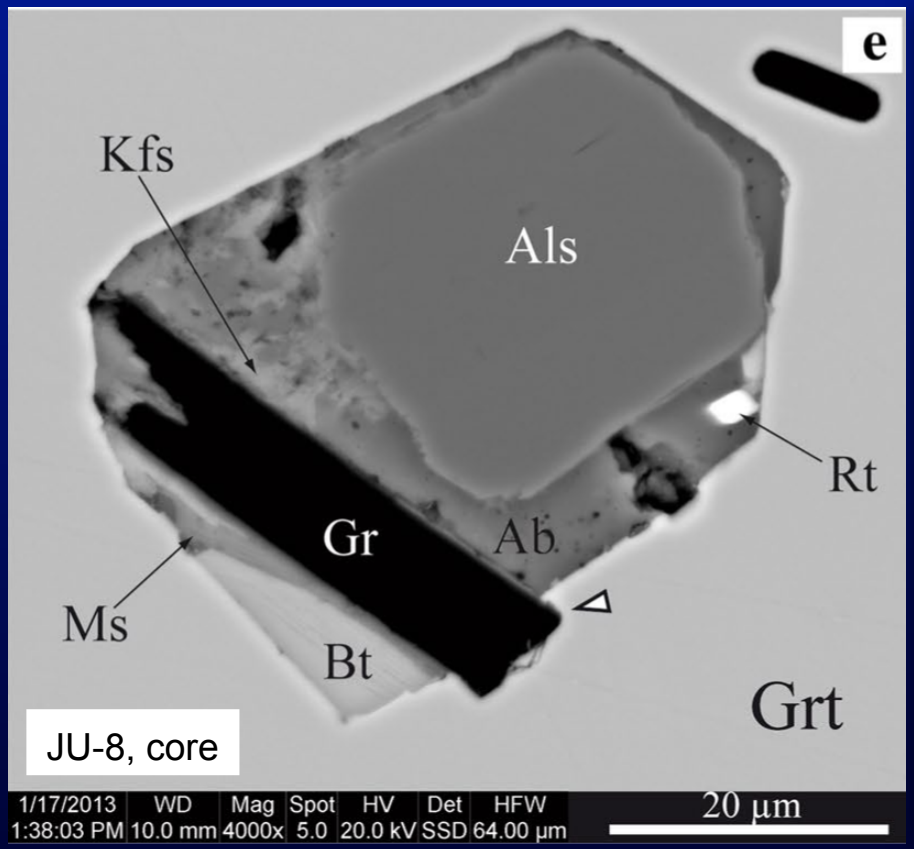
Petrography & SEM of the melt inclusions

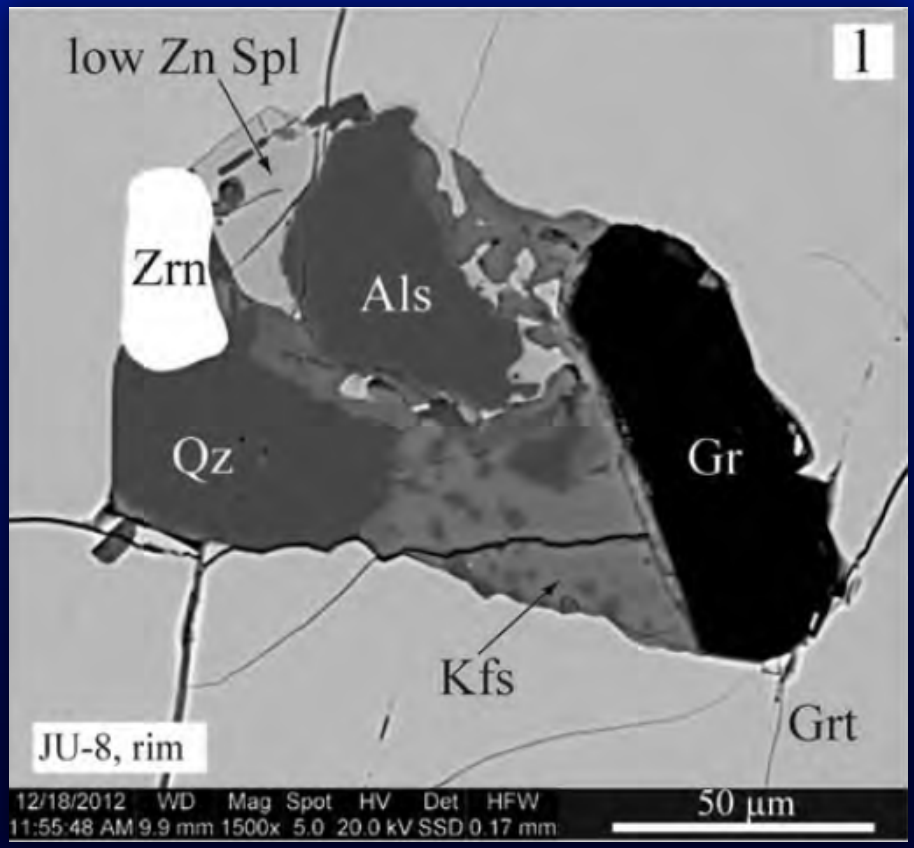






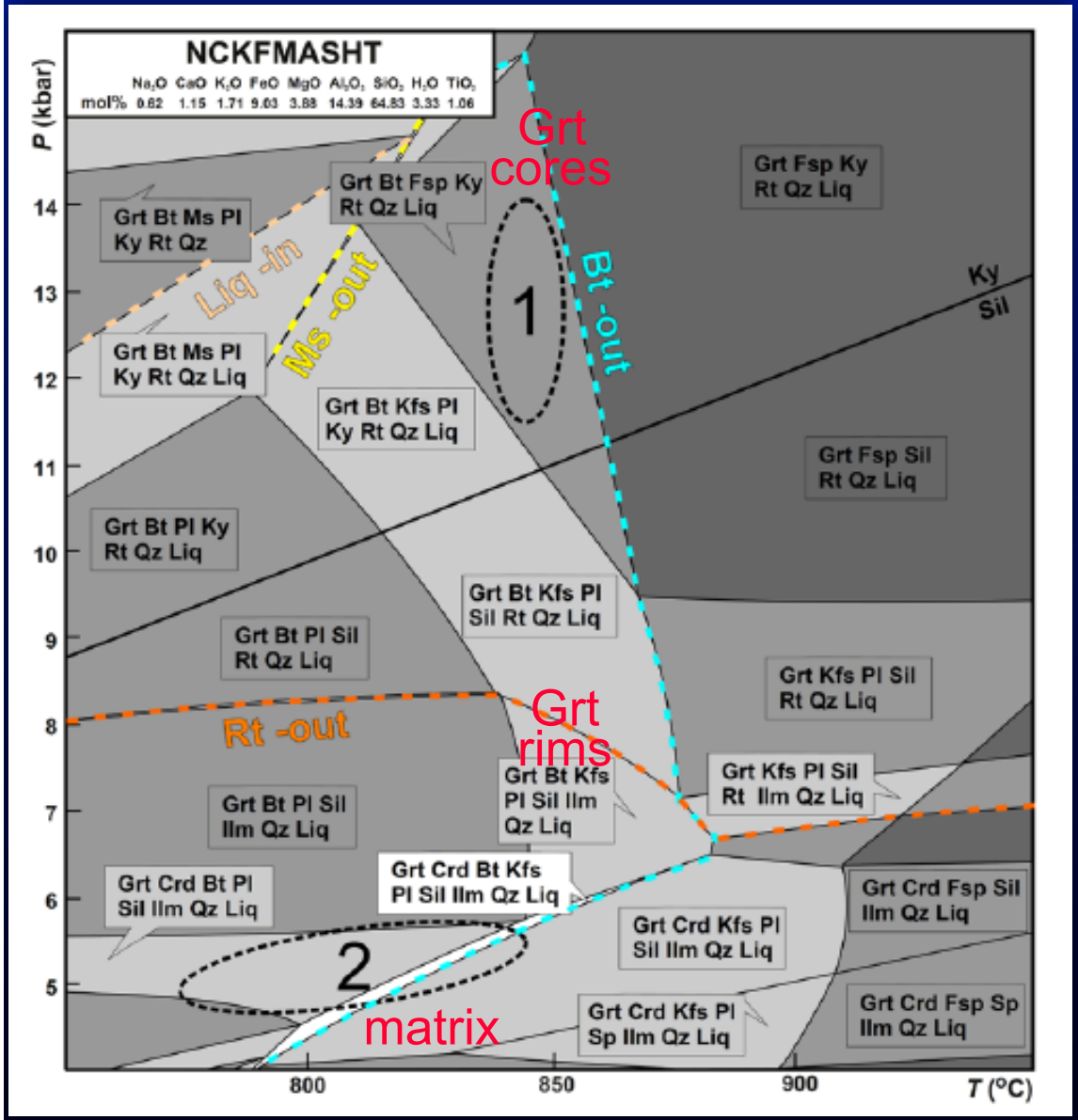
SEM of the melt inclusions



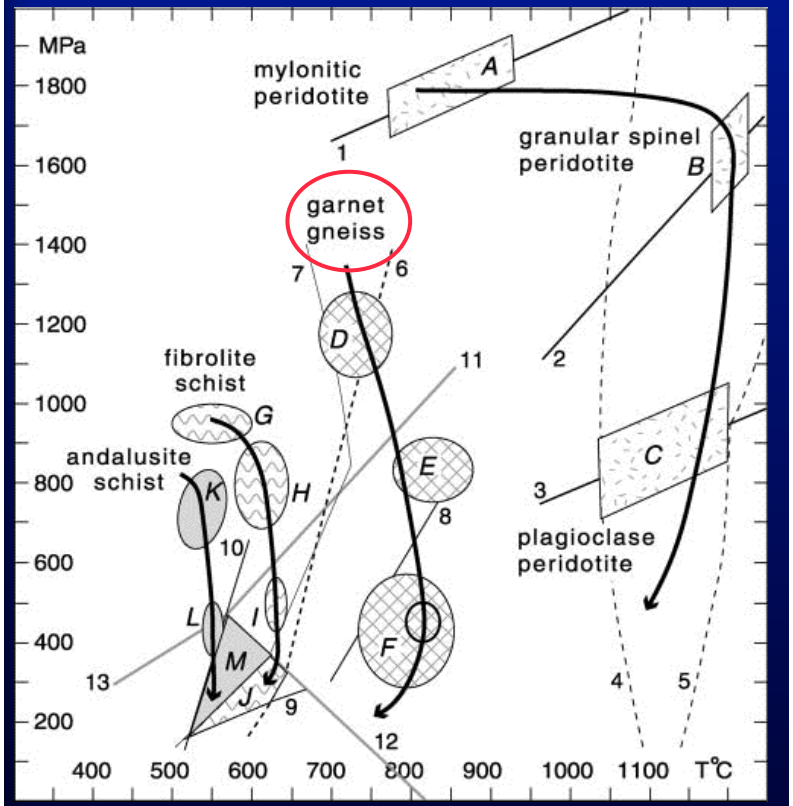


Barich et al. (2014)

P-T of host rocks



Barich et al. (2014)



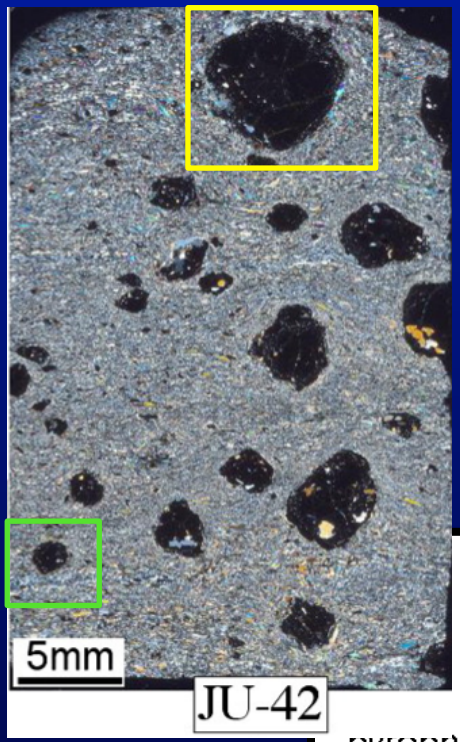
Platt et al. (2003)

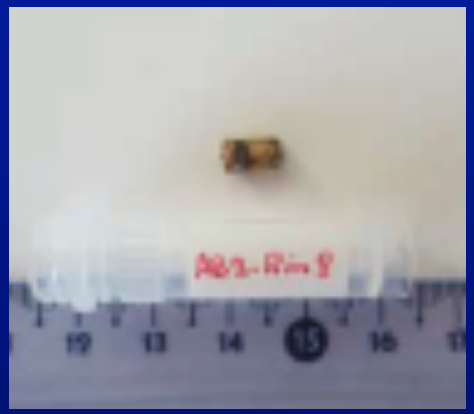
Melt inclusions in granulites from the Betic Cordillera, Ronda area, S Spain Field geology, petrography, SEM

- Melt inclusions are primary based on their distribution in the host garnet. Mostly crystallized.
- They appear from core to rim of large garnets and hence most garnets grew in the presence of melt.
- Melt inclusions were trapped both at peak conditions (12-14 kbar, 800-850°C; Grt cores) and post-peak conditions (5-6 kbar, 750-800°C; Grt rims+Matrix).
- They appear to have granitic mineral compositions (daughter minerals are Qz, Fds, micas).

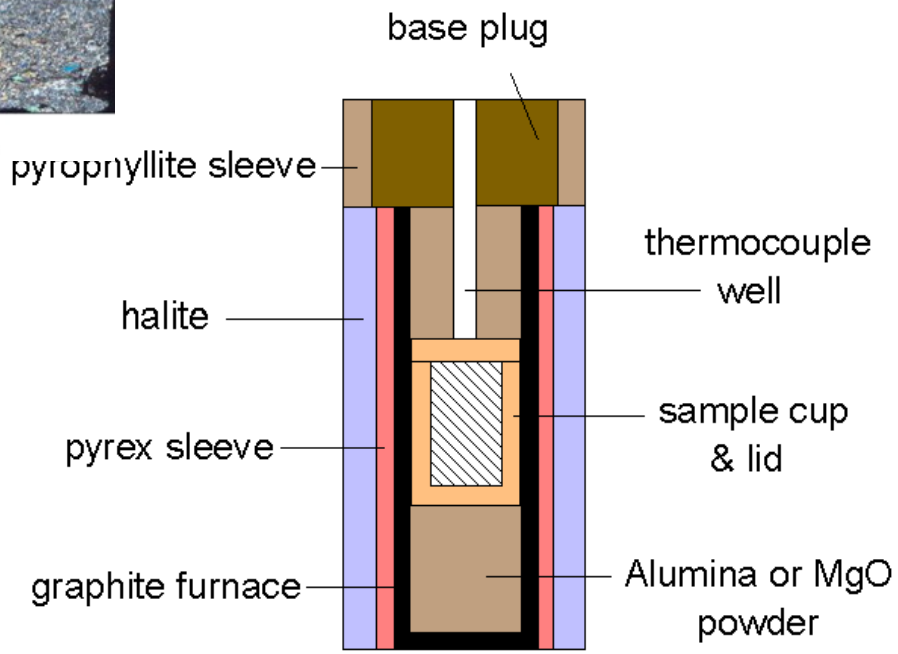
Experimental remelting: rehomogenizion

Piston Cylinder Apparatus (Univ. Of Milano)





Barich PhD (2014)



Experimental remelting: rehomogenizion

4 Experiments

15 Kbar
Dry (no added H_2O)
24h

850 ºC

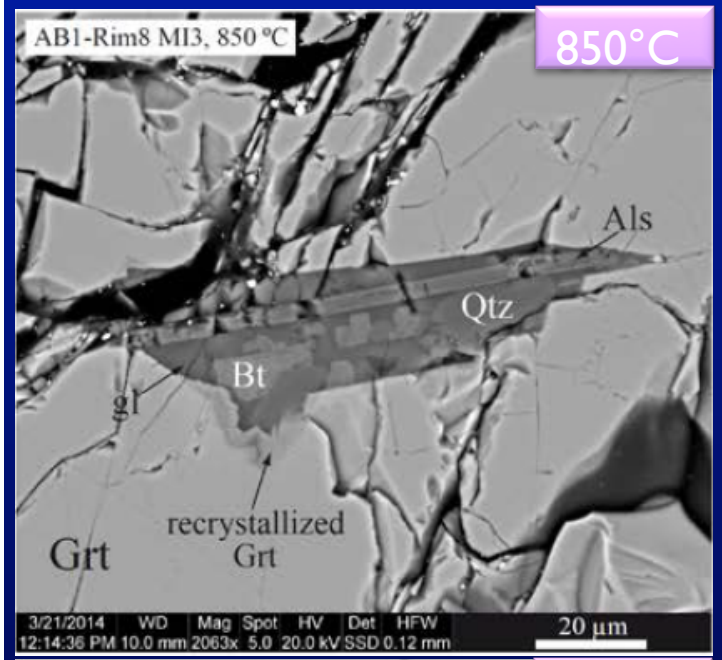
825 ºC

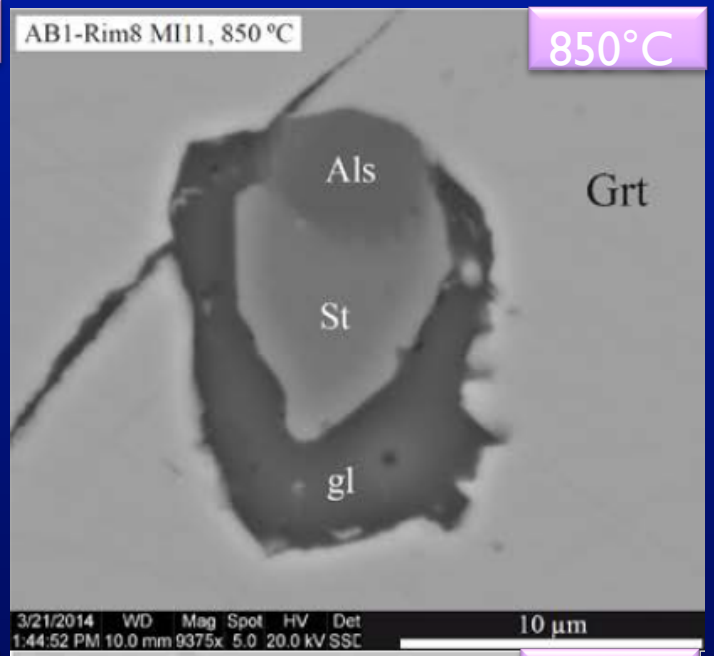
825 ºC

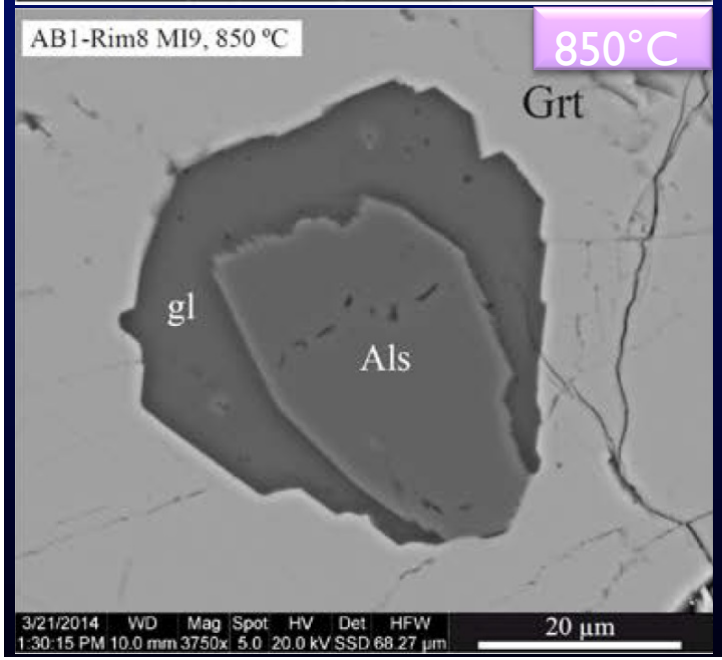
800 ºC

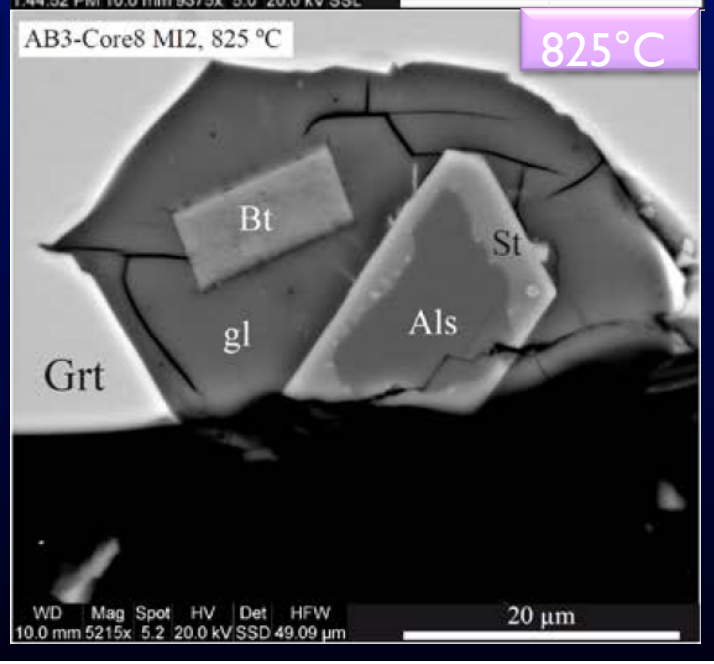
Barich PhD (2014)

Experimental remelting: SEM study





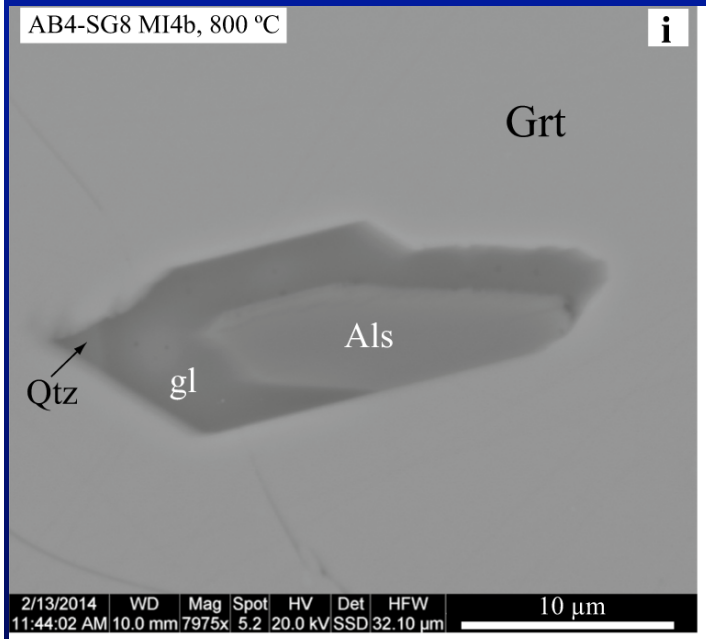


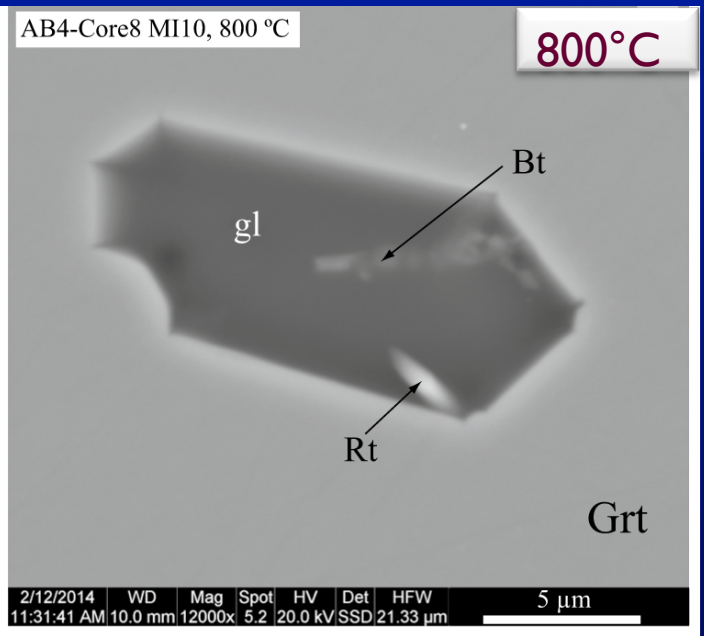


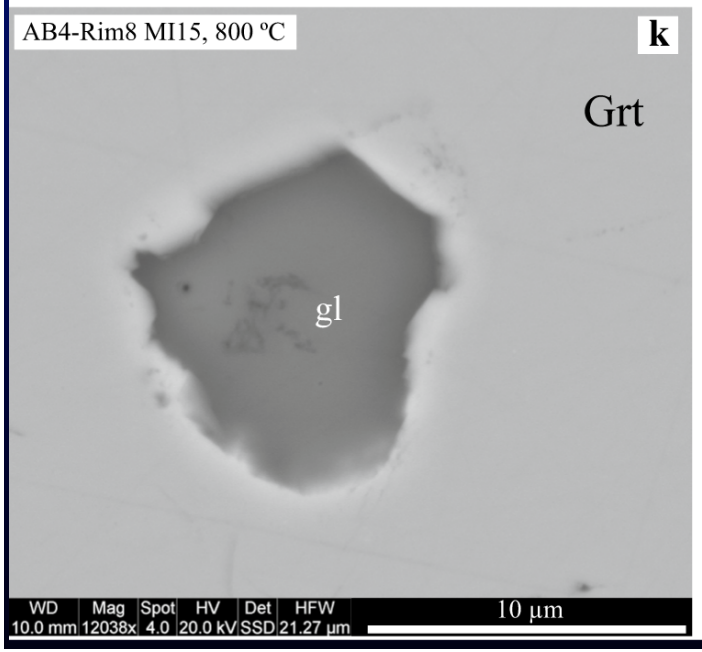
Remelted melt inclusions: having glass, but also
- Irregular walls,
- Daughter minerals,
- Offshots,
- Host recrystallization,
- Reactions between melt-accidental minerals.

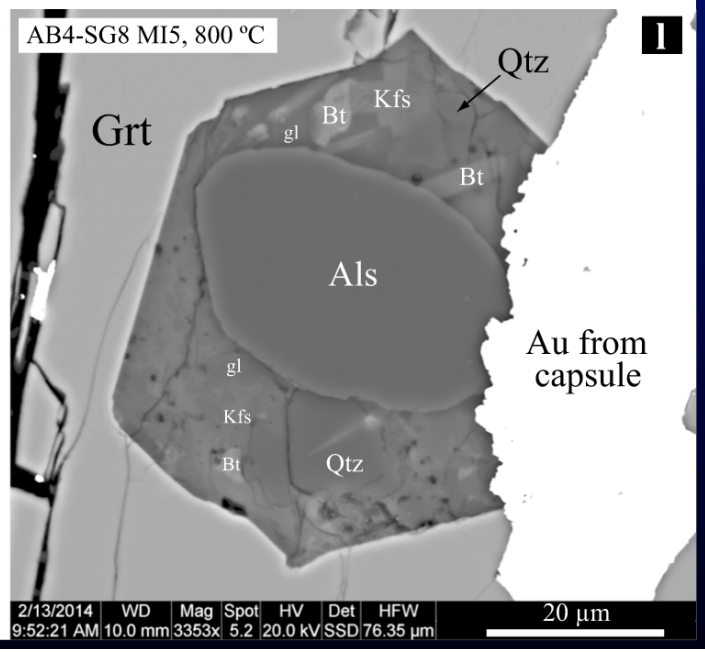
Acosta-Vigil et al. (2016)

Experimental remelting: SEM study





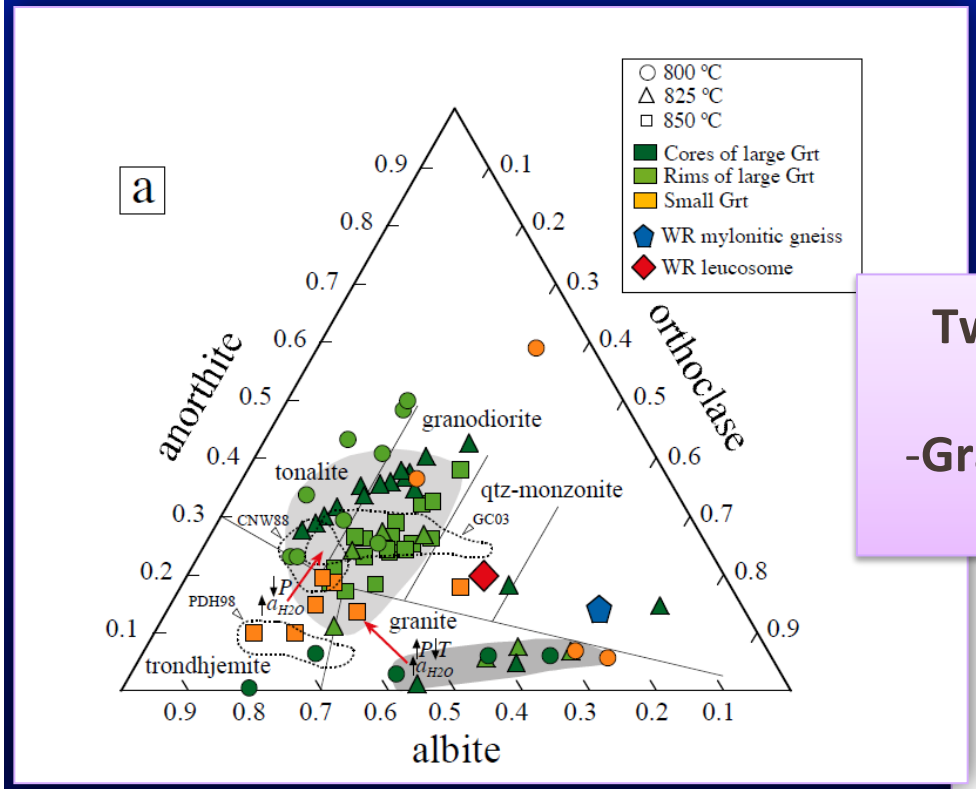




Rehomogenized melt inclusions:
having glass, and also
- Rregular walls,
- No daughter minerals,
- No offshots,
- No host recrystallization,
- No reactions between melt-accidental minerals.

Acosta-Vigil et al. (2016)

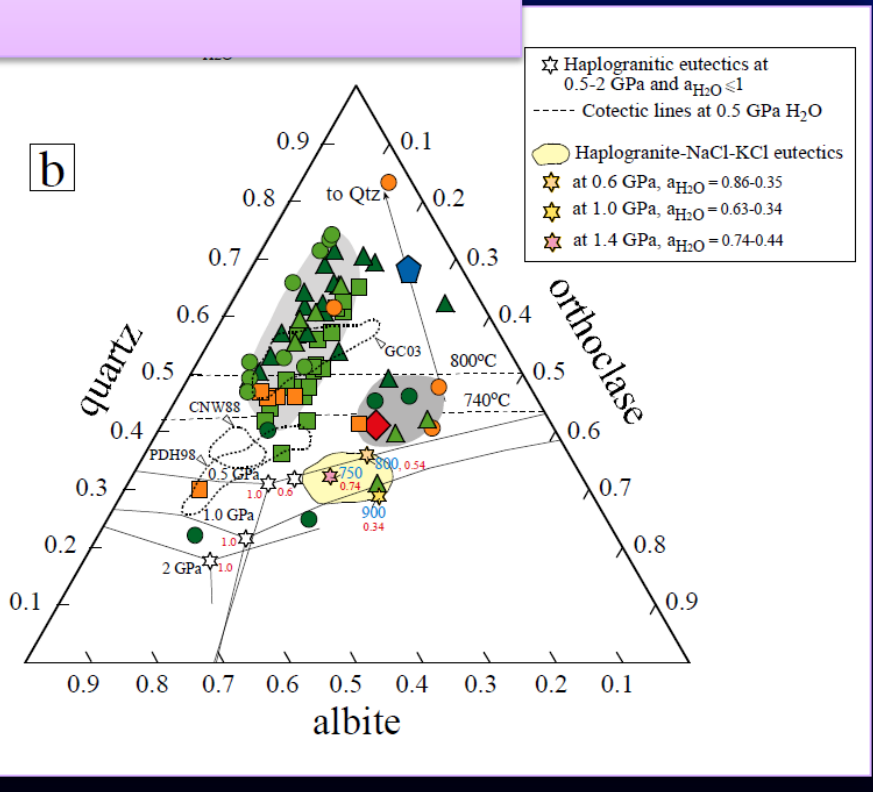
Experimental remelting: EMPA study



≈70 EMP analyses

Two main compositions:
-Leucogranites
-Granodiorites to Tonalites

Acosta-Vigil et al. (2016)



- Leucogranitic: plot close to water undersaturated haplogranitic eutectics
- Granodioritic to Tonalitic: plot close to Qz-Ab joint

Experimental remelting: EMPA study

Peraluminous

High SiO_2

Low $FeO+MgO+TiO_2$

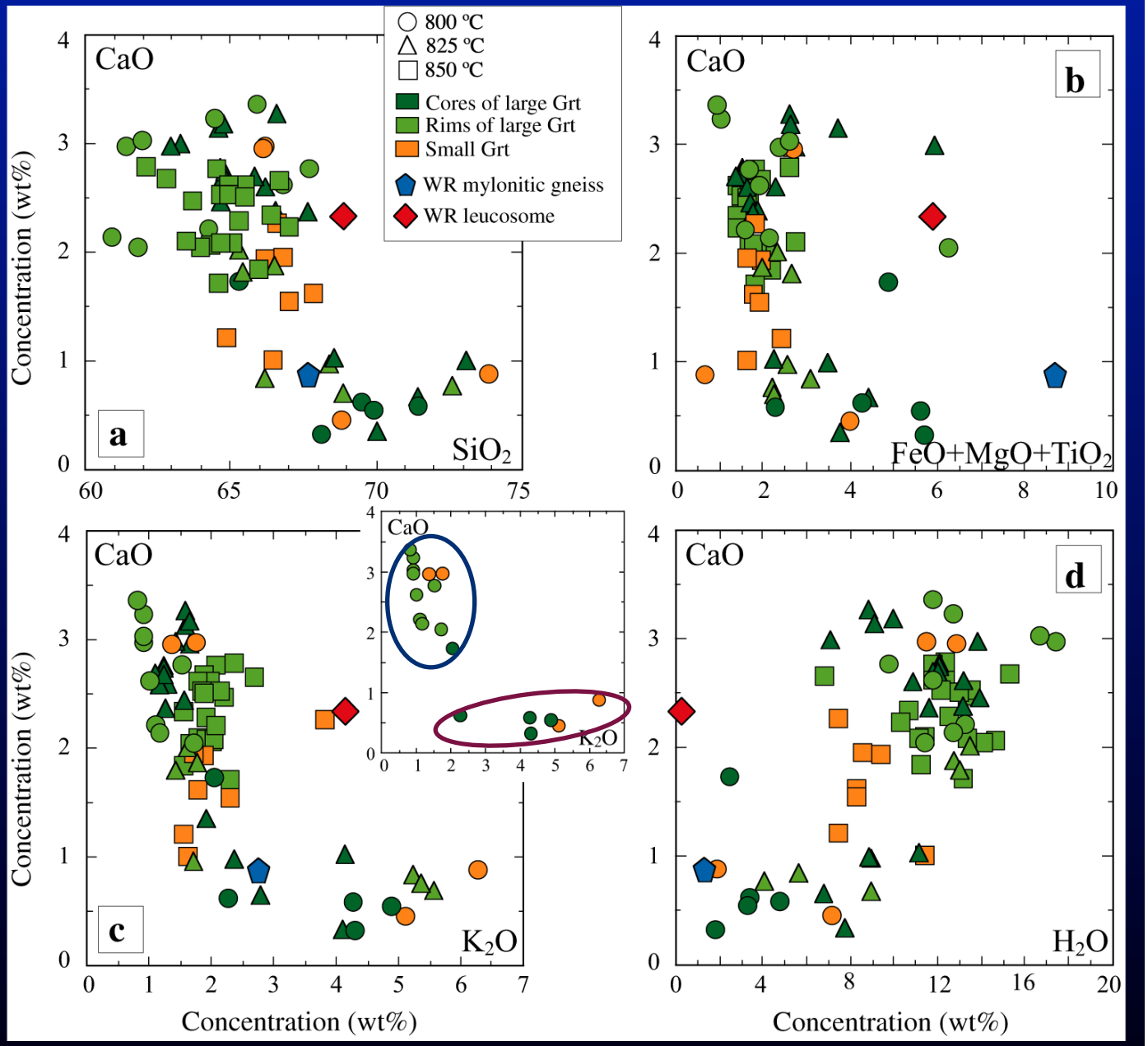
Variable CaO, alkalis and H_2O

Leucogranitic: Low Ca, H_2O; high K

Large Grt Cores

Granodioritic to Tonalitic: high Ca, H_2O; low K

Large Grt Rims



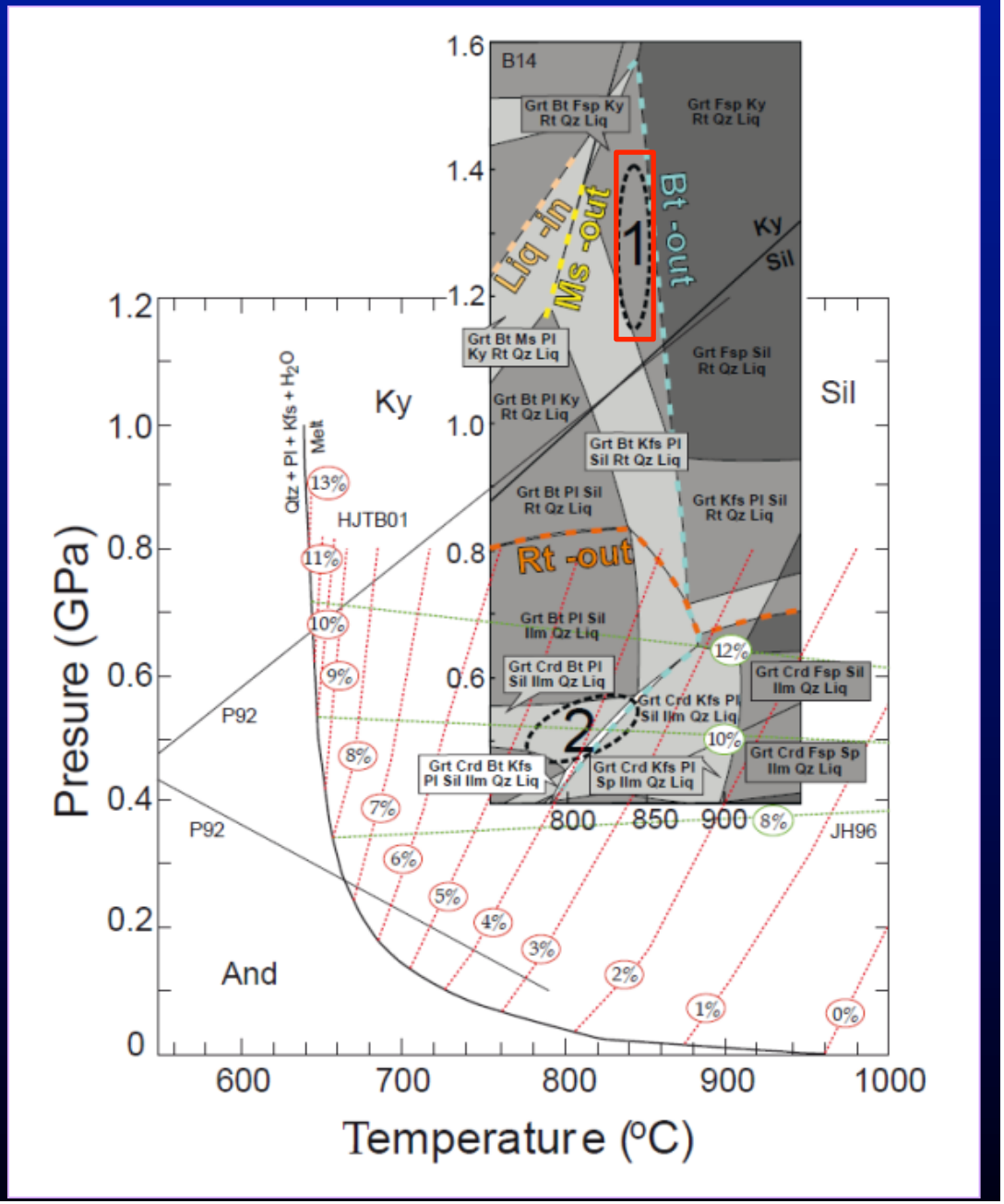
Jubrique granulites: Petrogenesis

Evidence for fluid-absent, Bt-breakdown melting

Type I MI / Grt Cores:

- Leucogranitic compositions, low H_2O (mean of 5 wt%)
- Composition and H_2O content similar to melt in fluid-absent Bt-melting experiments of metapelites
- No F and Cl, hence no brines involved

Acosta-Vigil et al. (2016)



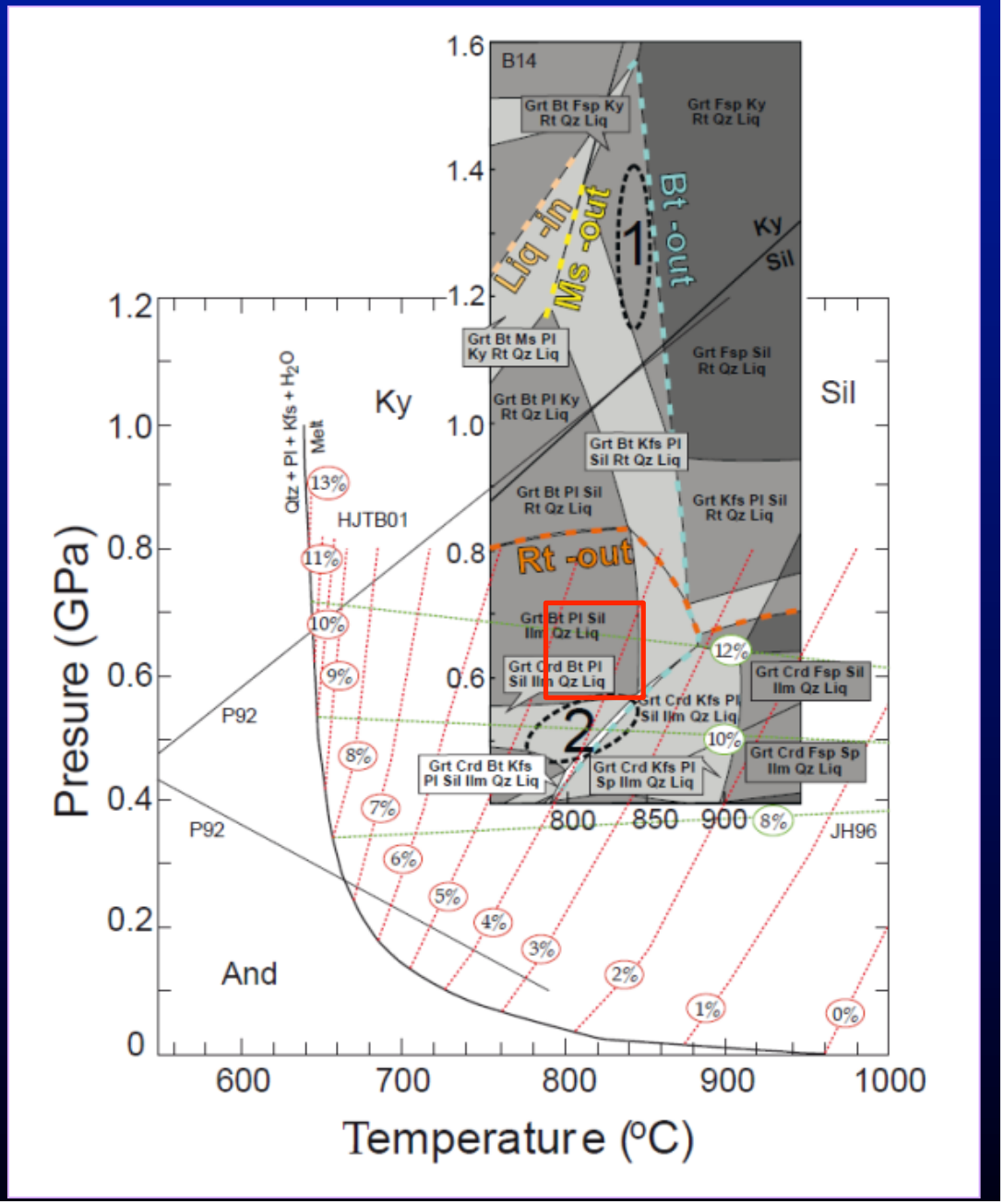
Jubrique granulites: Petrogenesis

Evidence for H_2O-saturated Melting

Type II MI / Grt Rims:

- Trapped in Grt rims P-T
- Granodioritic-tonalitic compositions, high H_2O (mean of 10-12 wt%)
- Composition and H_2O content similar to melt in H_2O-present experimental melting of metapelites
- Low F and Cl, hence no brines involved

Acosta-Vigil et al. (2016)

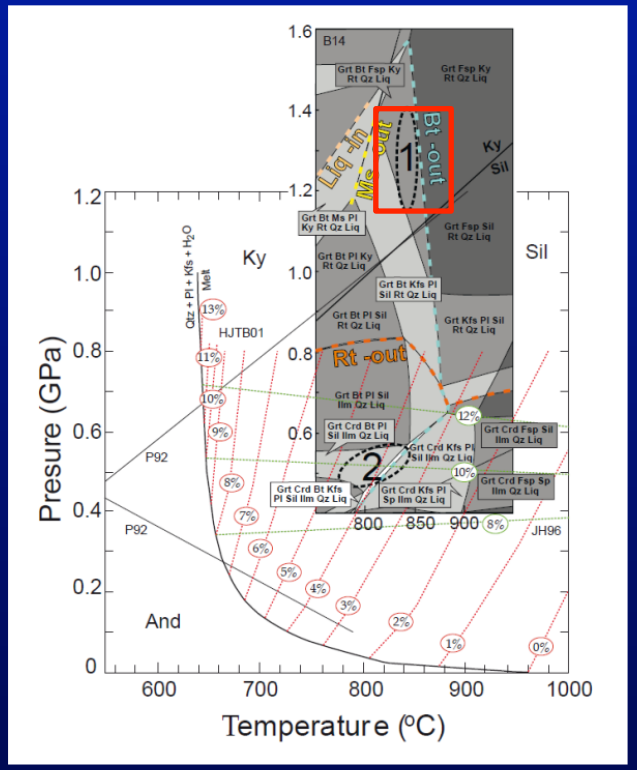


Jubrique granulites: Conclusions

Type I: Leucogranitic MI

P-T Conditions of Anatexis

Type I melt inclusions are trapped at the cores of large garnets, formed at <850 ºC (800 °C) and 12-14 kbar.



Significance of Glass Composition in the Remelted MI

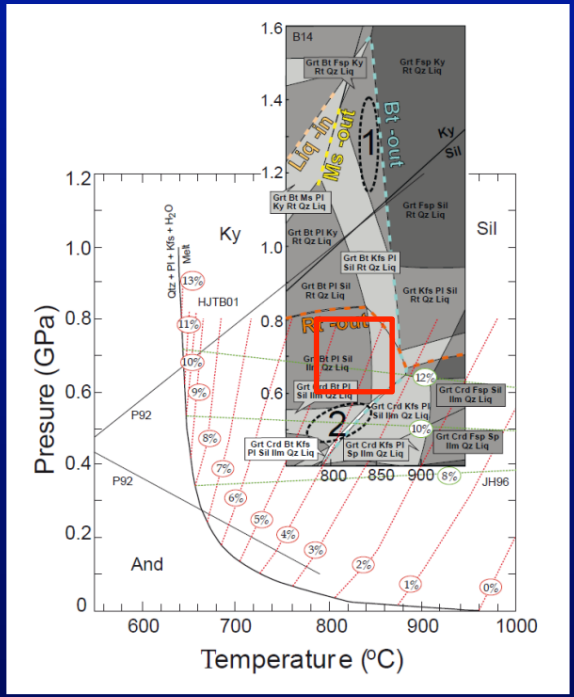
Leucogranitic melts in garnet cores were produced by anatexis at low activity of H2O. Likely due to fluid absent melting of hydrous minerals (e.g. biotite).

Geodynamic Setting

Closed-system anatexis at the bottom of a thickened continental crust in a context of a continental collision.

Jubrique granulites: Conclusions

Type II: Granodioritic-to-Tonalitic MI



P-T Conditions of Anatexis

Type II granodioritic-to-tonalitic MI are trapped at the rims of large garnets formed at ≈800 ºC and 6-8 kbar.

Significance of Glass Composition in the Remelted MI

Granodioritic-to-tonalitic melts were produced by H_2O-fluxed (saturated or nearly saturated) melting, likely the entrance of H_2O-rich fluids into the system.

Geodynamic Setting

Open-system anatexis at the bottom of a continental crust of regular thickness in a context of a continental extension.

Migmatites of Jubrique underwent two melting events under contrasting fluid regimes

Thank you