Università
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Dipartimento
di Geoscienze

A continent entrapped inside a mineral

(nanogranitoid inclusions in metamorphic rocks)

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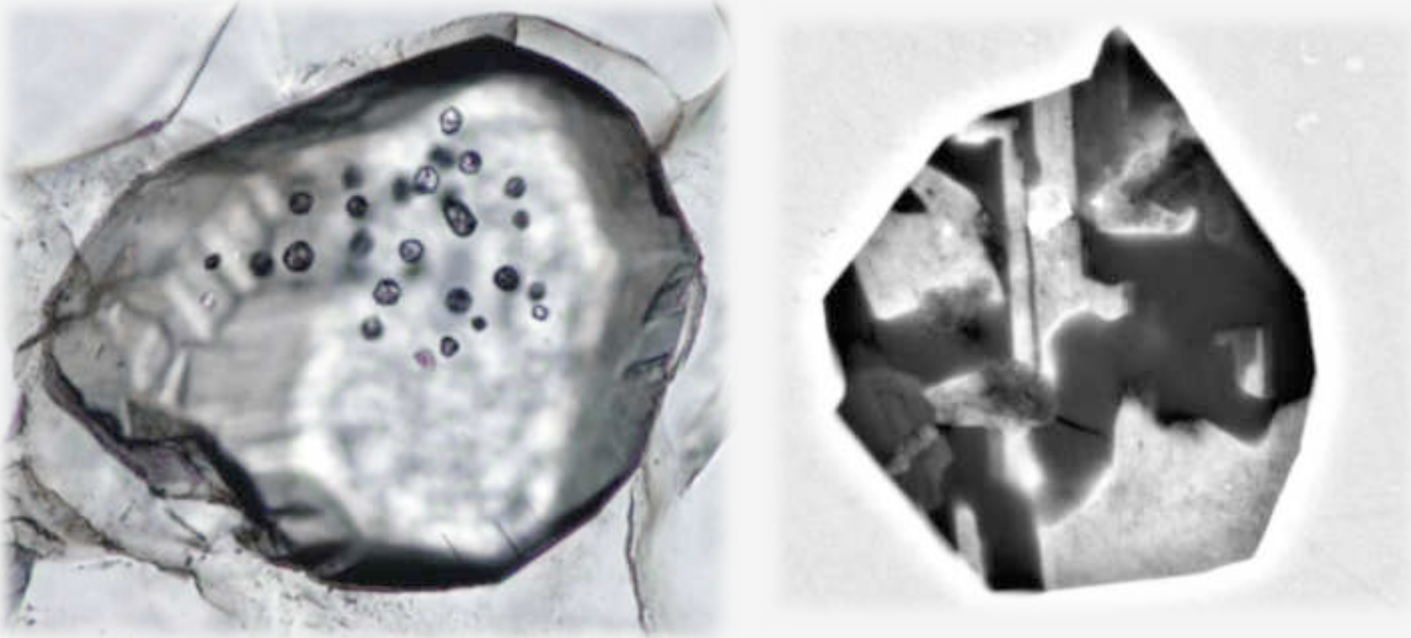


Seminar Outline

- How do melt inclusions form?
- Melt inclusions in igneous rocks
- High-temperature metamorphism
- Entrapment of melt inclusions during crustal anatexis
- How are melt inclusions identified ?
- How are melt inclusions microstructurally characterized ?
- How can melt inclusions be analyzed ?
- What can we learn from nanogranitoids inclusions ?
- Problems and pitfalls
- Concluding remarks

What are melt inclusions?

"Melt inclusions are small droplets of silicate melt that are trapped in minerals during their growth in a magma"

[Audétat & Lowenster, 2014]

Olivine (Mauna Loa volcano, Hawaii)

Small → difficult to recognize
Silicate* melt → containing >50% dissolved silicate
Minerals → the host
Growth in a magma → magmatic crystallization

* carbonatitic MI, sulfide MI

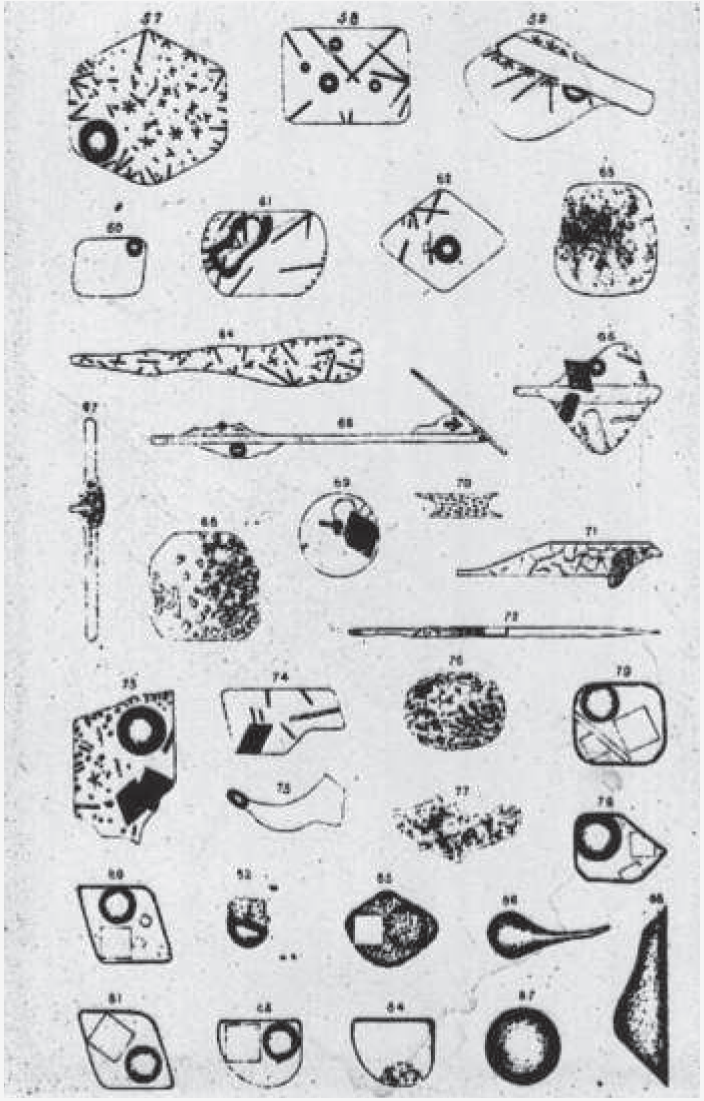
In the beginning …

The first detailed discussion of melt inclusions within a rigorous geological and petrological context was by

Henry Clifton Sorby
(1826-1908)

Development and application of microscopy to materials such as thin sections of rocks and metals, pioneering the field of microscopical petrography.

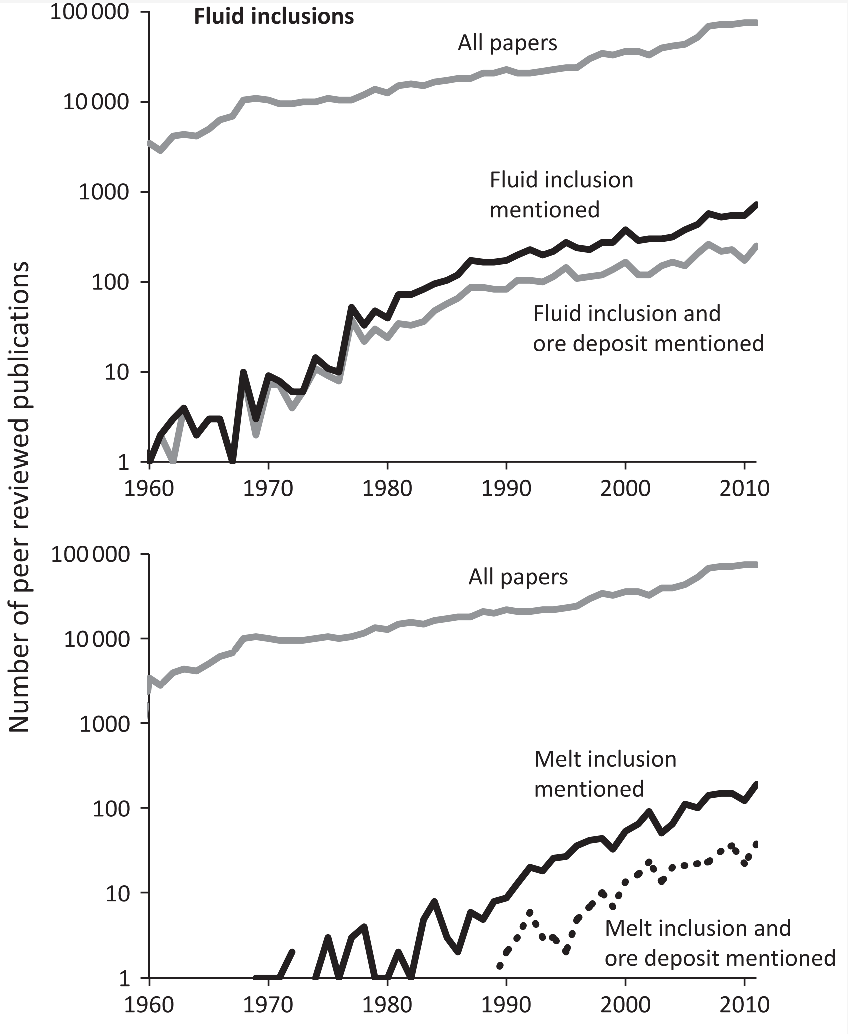
In the beginning …



*"The formation of crystals from a state of **igneous fusion** is in every respect analogous to what takes place when crystals are formed in water…There is thus a most perfect analogy between **glass- and stone-cavities** and fluid-cavities in every respect except the nature of the included substances"* (Sorby, 1858)

Little attention was given to melt inclusions during the next hundred years

Progress during the Last 50 Years



[Kesler et al., 2013]

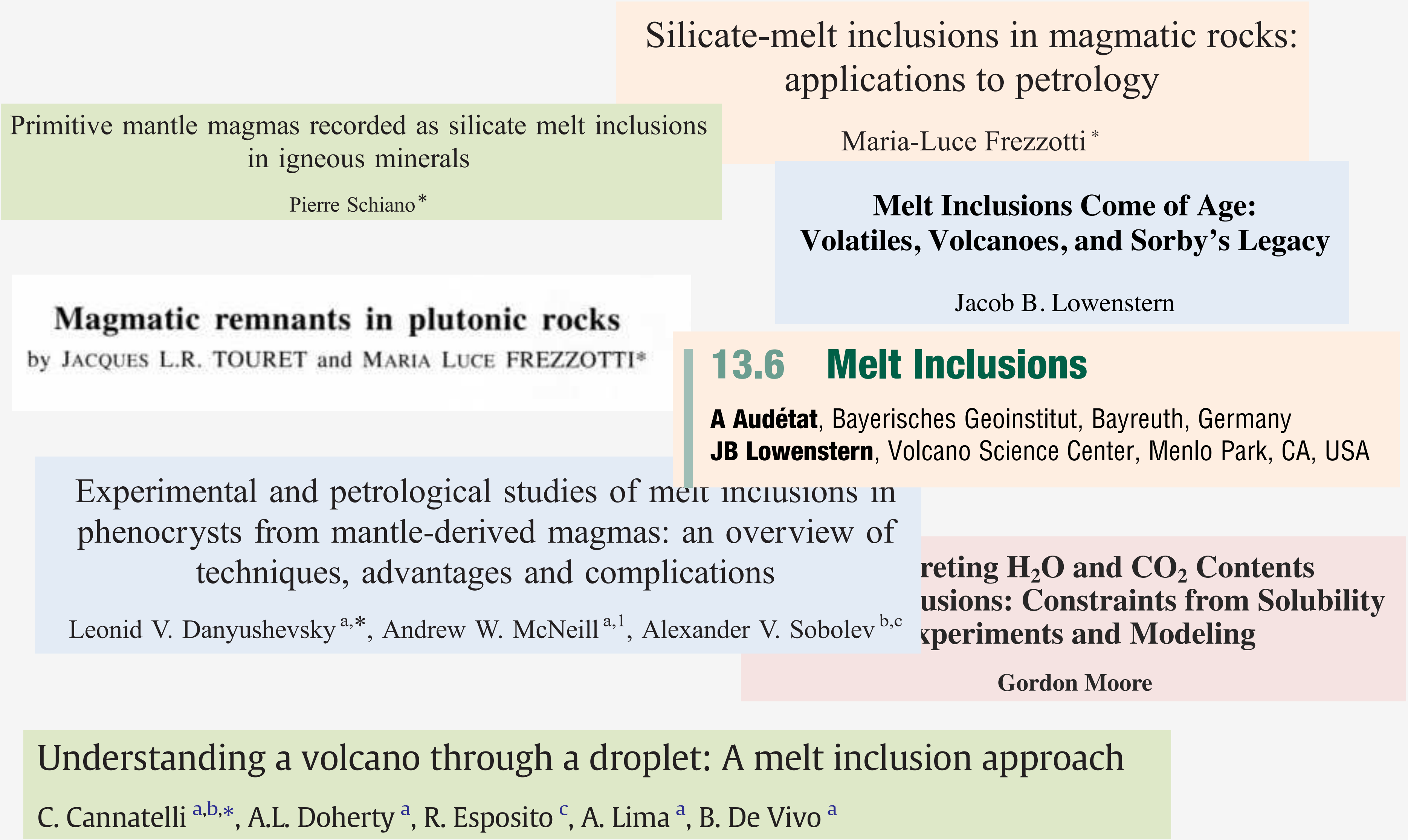
Their 20th century renaissance was slow. Whereas fluid inclusion studies began to grow in about 1960, the rise in melt inclusion studies did not begin until about 1980

Sobolev & Kostyuk, 1975 → application of MI to the study of volcanic rocks

Roedder & Weiblen, 1970 → application of MI to lunar samples

Clocchiatti, 1975; Roedder, 1979 → origin and methods to investigate MI

Progress during the Last 50 Years



Silicate-melt inclusions in magmatic rocks:
applications to petrology

Maria-Luce Frezzotti[*]

Primitive mantle magmas recorded as silicate melt inclusions
in igneous minerals

Pierre Schiano[*]

Melt Inclusions Come of Age:
Volatiles, Volcanoes, and Sorby's Legacy

Jacob B. Lowenstern

Magmatic remnants in plutonic rocks

by JACQUES L.R. TOURET and MARIA LUCE FREZZOTTI[*]

13.6 Melt Inclusions

A Audétat, Bayerisches Geoinstitut, Bayreuth, Germany
JB Lowenstern, Volcano Science Center, Menlo Park, CA, USA

Experimental and petrological studies of melt inclusions in
phenocrysts from mantle-derived magmas: an overview of
techniques, advantages and complications

Leonid V. Danyushevsky[a,*], Andrew W. McNeill[a,1], Alexander V. Sobolev[b,c]

reting H_2O and CO_2 Contents
usions: Constraints from Solubility
xperiments and Modeling

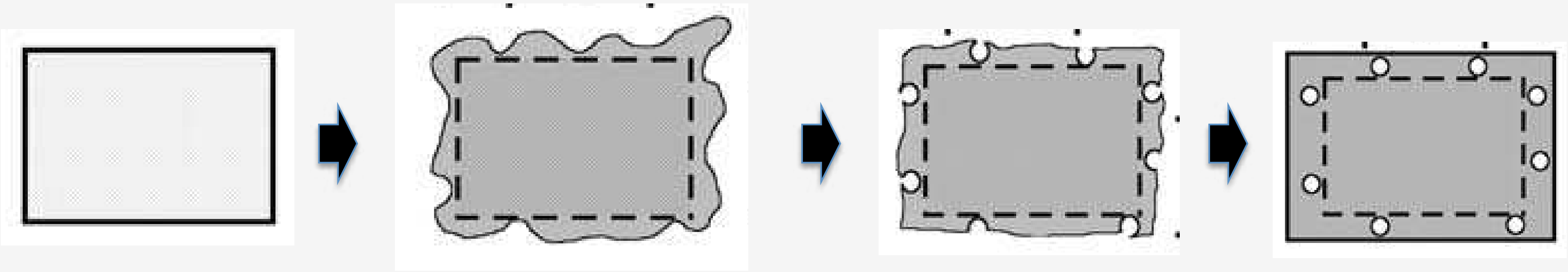
Gordon Moore

Understanding a volcano through a droplet: A melt inclusion approach

C. Cannatelli[a,b,*], A.L. Doherty[a], R. Esposito[c], A. Lima[a], B. De Vivo[a]

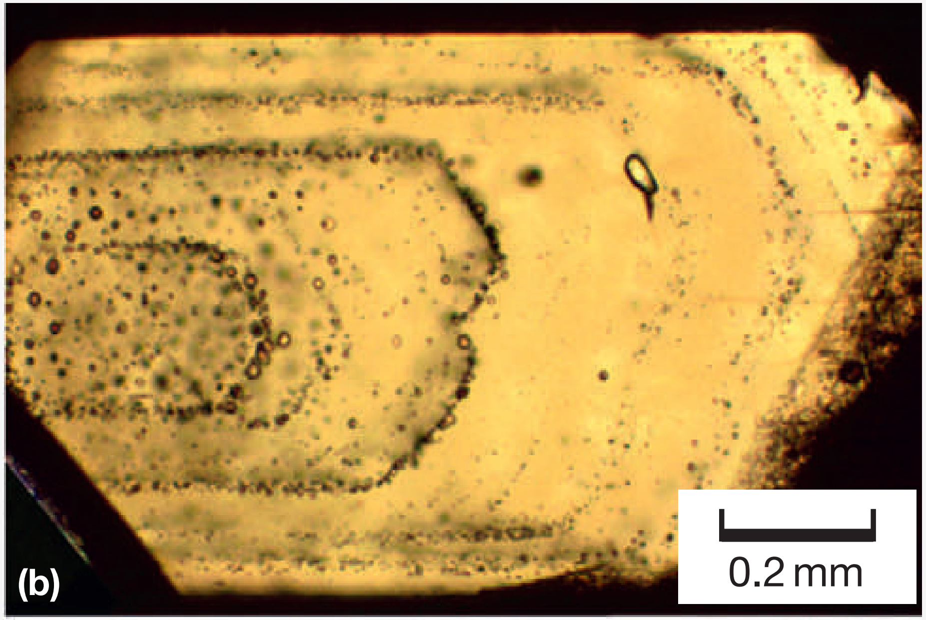
How do melt inclusions form?

1) Entrapment of a melt inclusion not only requires **rapid growth that destabilizes the planar crystal–melt interface and creates embayments** (regions of melt bounded on three sides by a crystal in planar view), but also a period of **slower growth that "seals" the mouth of the embayment** to create a melt inclusion



[Baker 2008]

How do melt inclusions form?



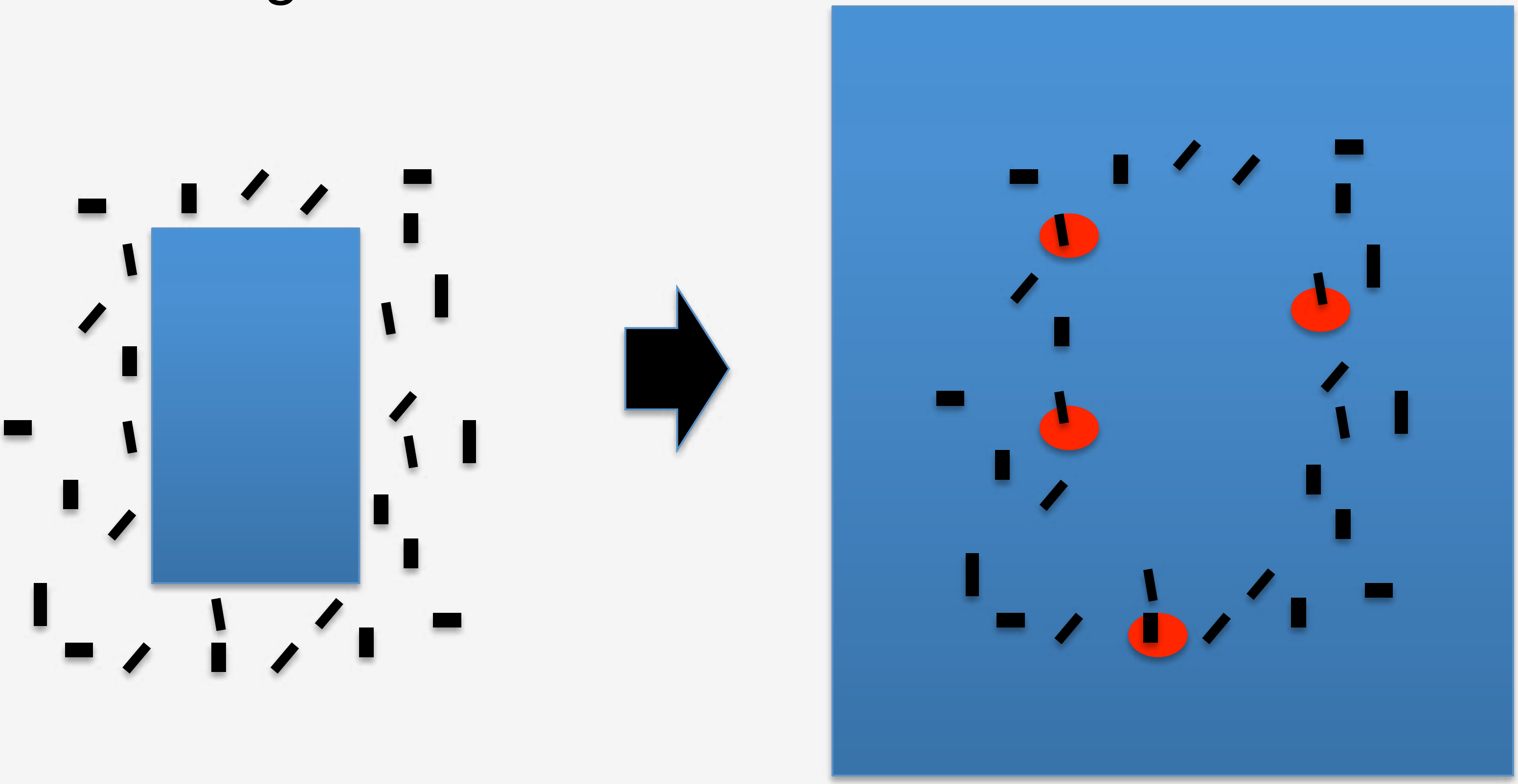
[Audétat & Lowenster, 2014]

[Cannatelli et al., 2016]

Melt inclusions concentrated along growth zones, produced as a result of short pulses of rapid crystal growth

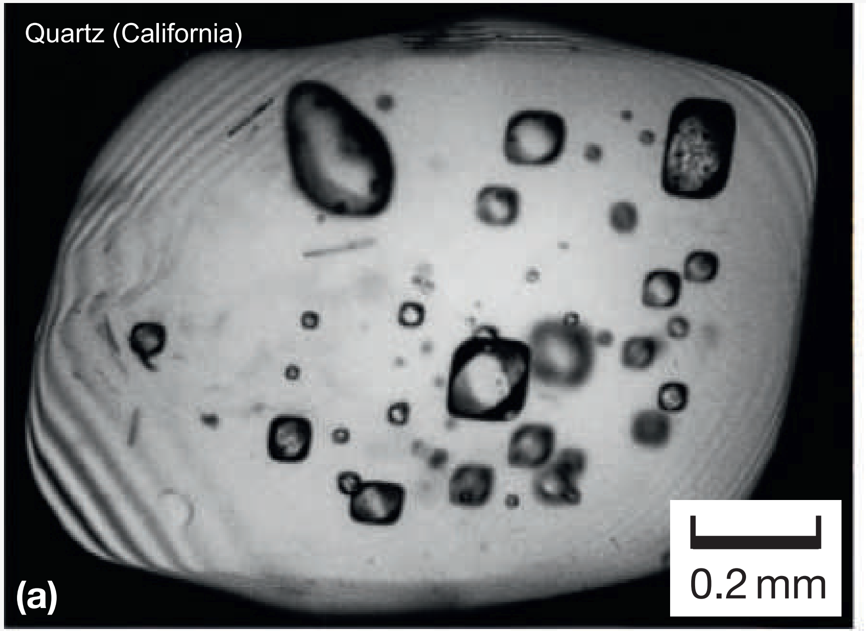
How do melt inclusions form?

2) Another common mechanism is **melt entrapment in response to the presence of surface irregularities** (i.e., adhering mineral grain, vapor bubble, impurities) which act as surfaces to which the melt could cling or adhere



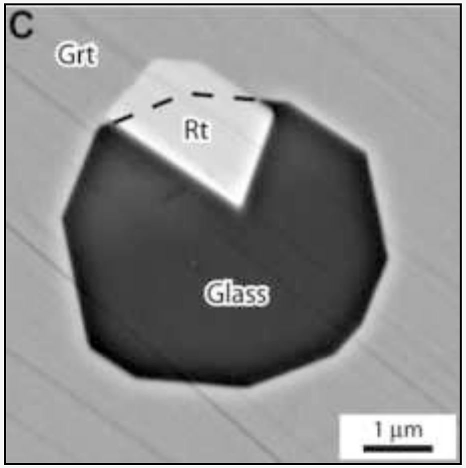
How do melt inclusions form?

Accidental minerals trapped with the melt commonly show a relative large size (compared with the size of MI) and the presence of indentations within the MI walls

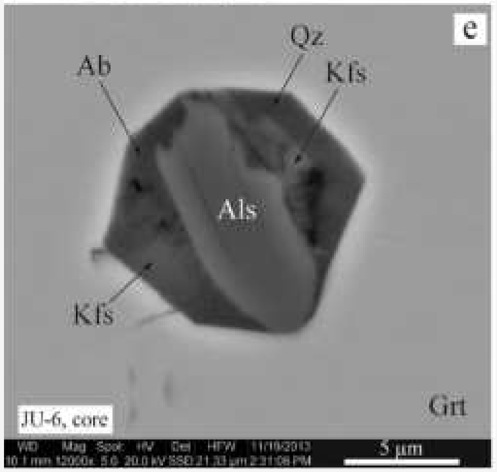


[Audétat & Lowenster, 2014]

This process generally creates large, randomly distributed melt inclusions



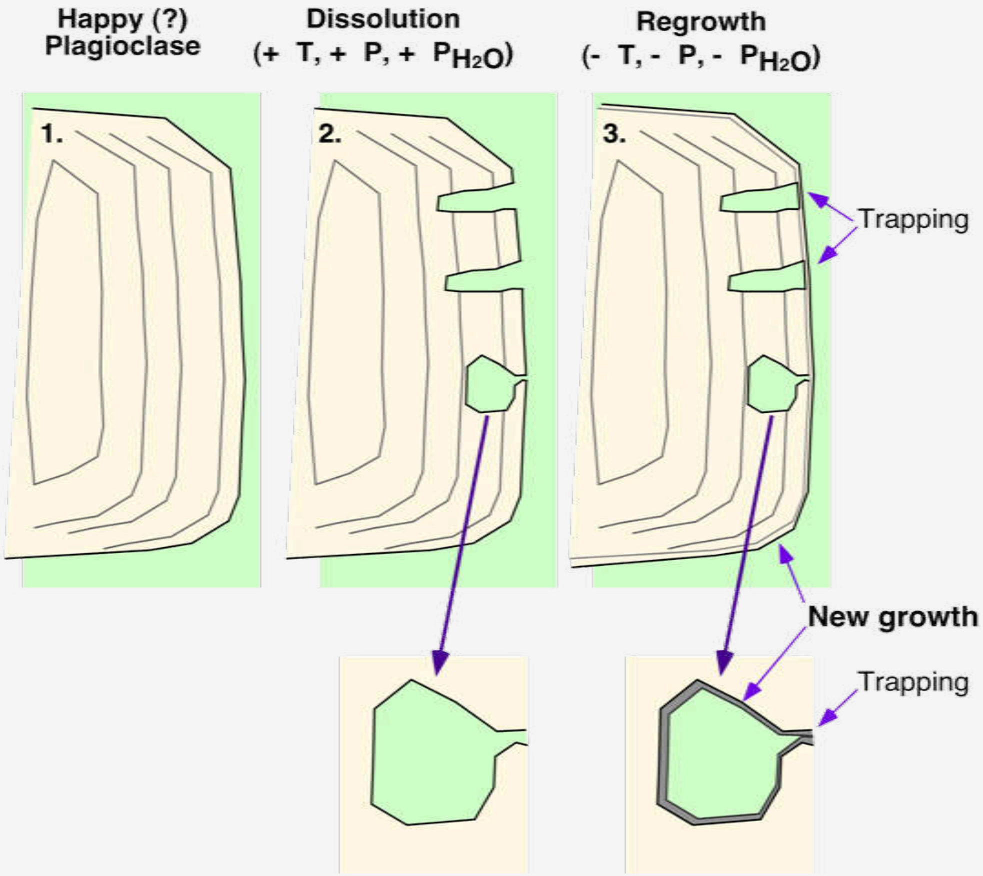
[Cesare et al. 2009]

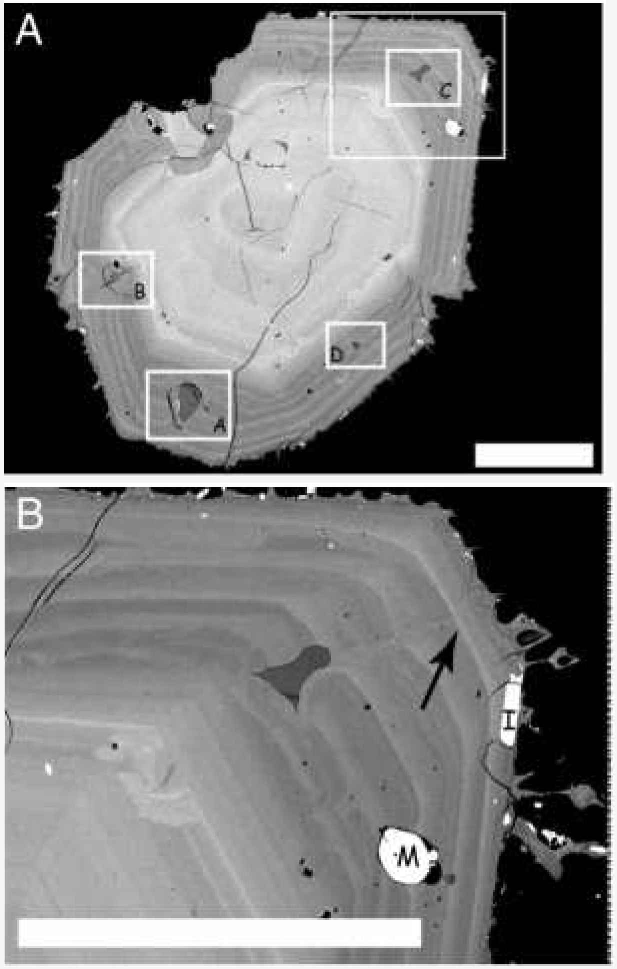


[Barich et al. 2014]

How do melt inclusions form?

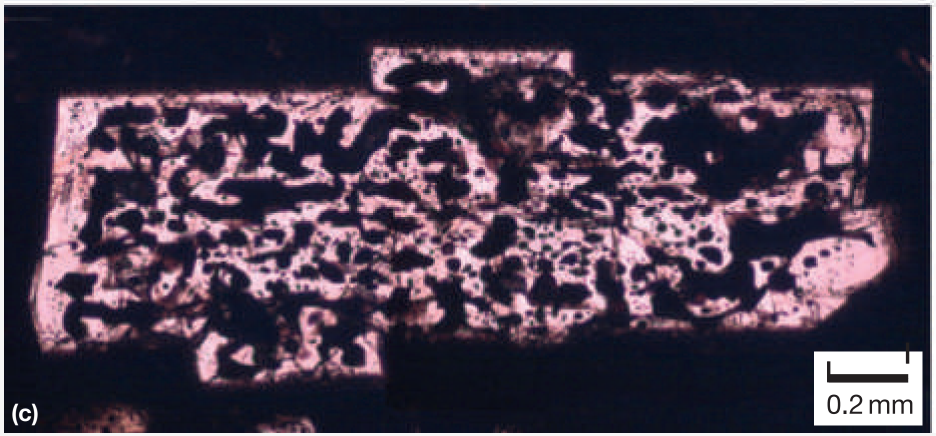
3) Another process is **melt entrapment in response to rapid dissolution followed by growth**





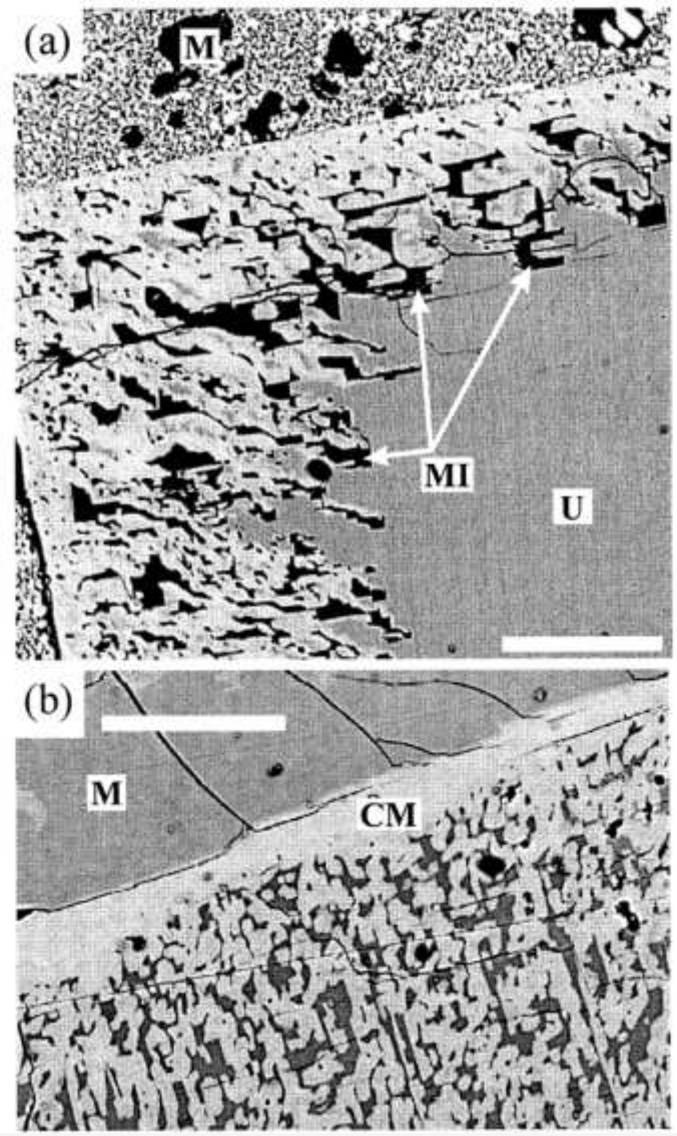
[Blundy & Cashman 2005]

How do melt inclusions form?



[Audétat & Lowenster, 2014]

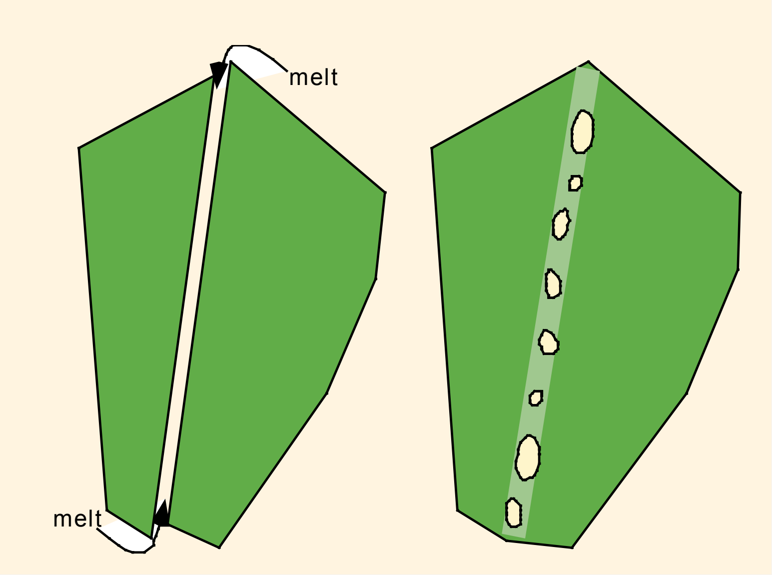
Melt inclusions formed in response to crystal dissolution may give rise to the sieve texture commonly observed in plagioclase phenocrysts



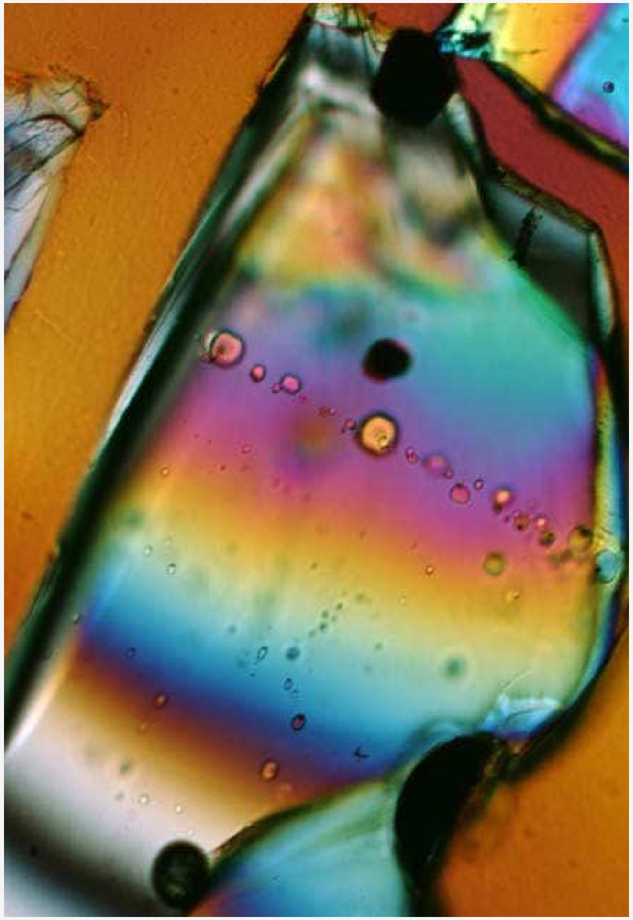
[Nakamura & Shimakita, 1998]

How do melt inclusions form?

4) Melts may be **trapped in cracks** developed after crystal growth

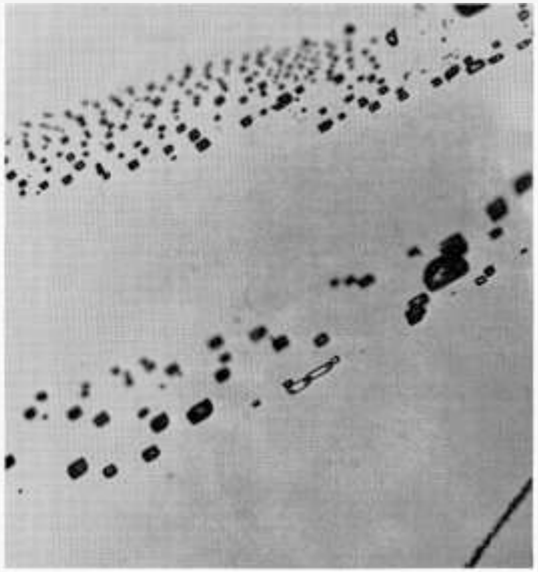


Typically small, define planar surface



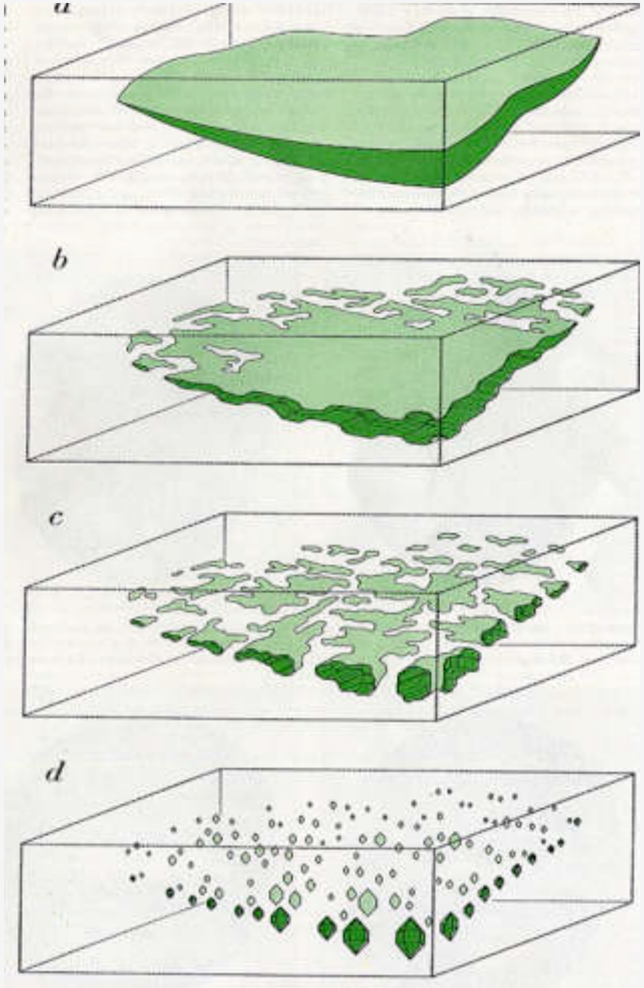
How do melt inclusions form?

4) Melts may be **trapped in cracks** developed after crystal growth



TWO HEALED FRACTURES in quartz (magnified 14.5 diameters) contain numerous secondary three-phase inclusions. Phases can be seen in the flattened pair of inclusions at center that resemble paper clips: liquid (*light oblong areas*) and gaseous carbon dioxide (*two adjacent light circular areas*), and saline water (*tiny light area at lower left*).

Typically small, define planar surface

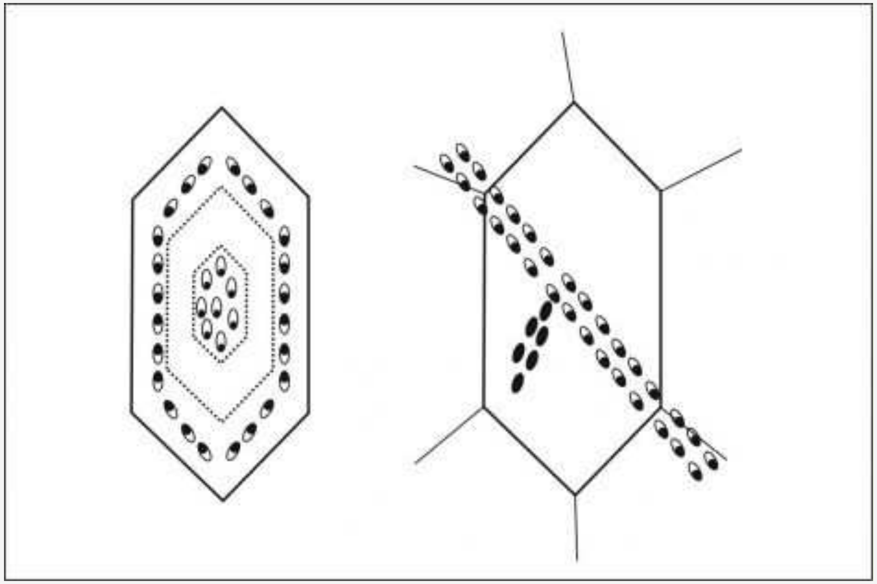


[Roedder, 1962]

Primary vs. secondary MI

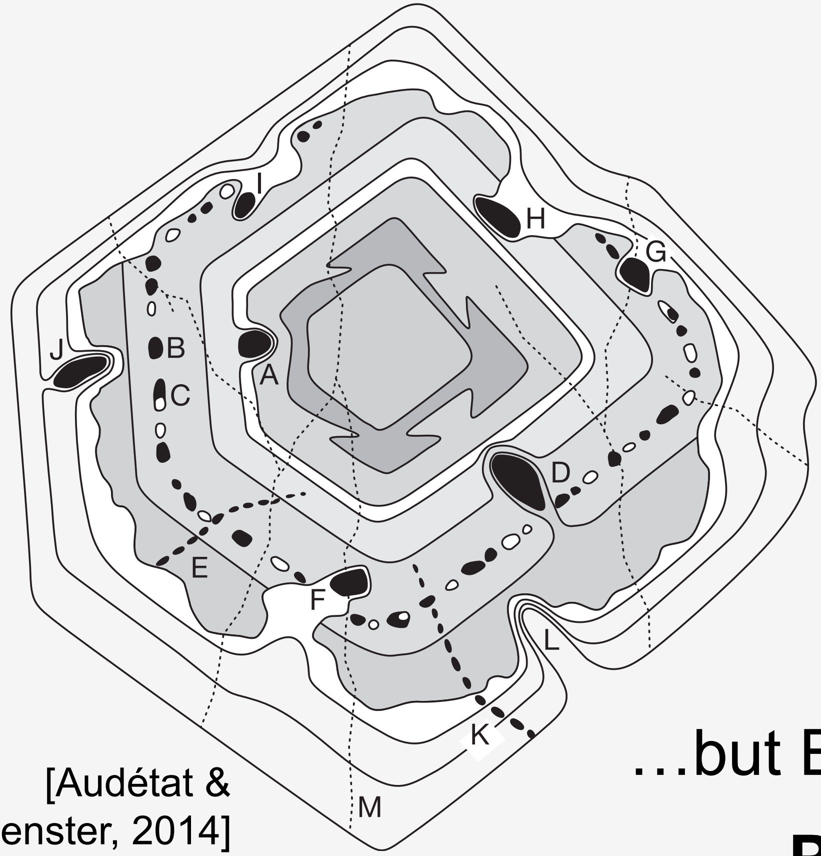
→ **DURING**, and as a direct result of, host growth (**PRIMARY**)

→ **AFTER** host growth is complete (**SECONDARY**)



Clearly, the different modes have **totally different implications**

Primary vs. secondary MI



[Audétat & Lowenster, 2014]

- **Primary** melt inclusions:

  A, B, C, D, F, G, H, I, J

  → formed by various entrapment mechanisms (along surface irregularities, along with an accidental trapped mineral, etc…)

- **Secondary** melt inclusions:

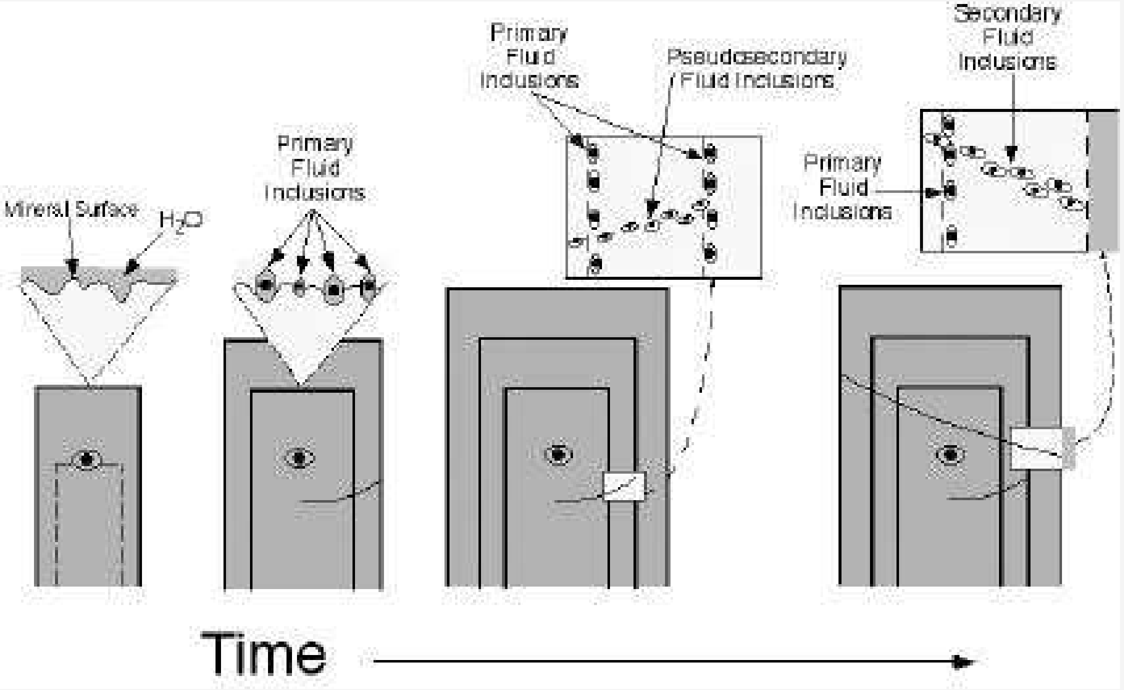
  K → formed by healing of fractures in the host

…but E ??

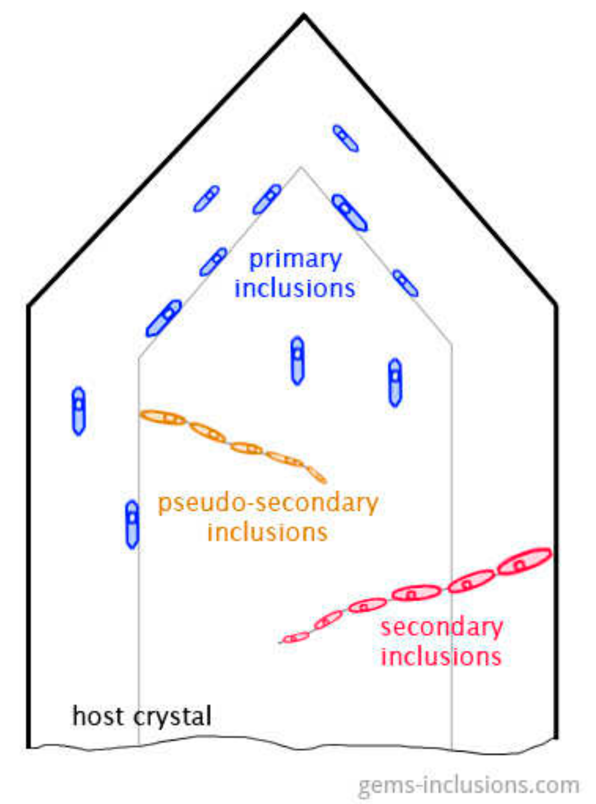
- **Pseudosecondary** melt inclusions:

  → formed when fracturing occurs during growth of the crystal. Their formation is followed by additional crystal growth

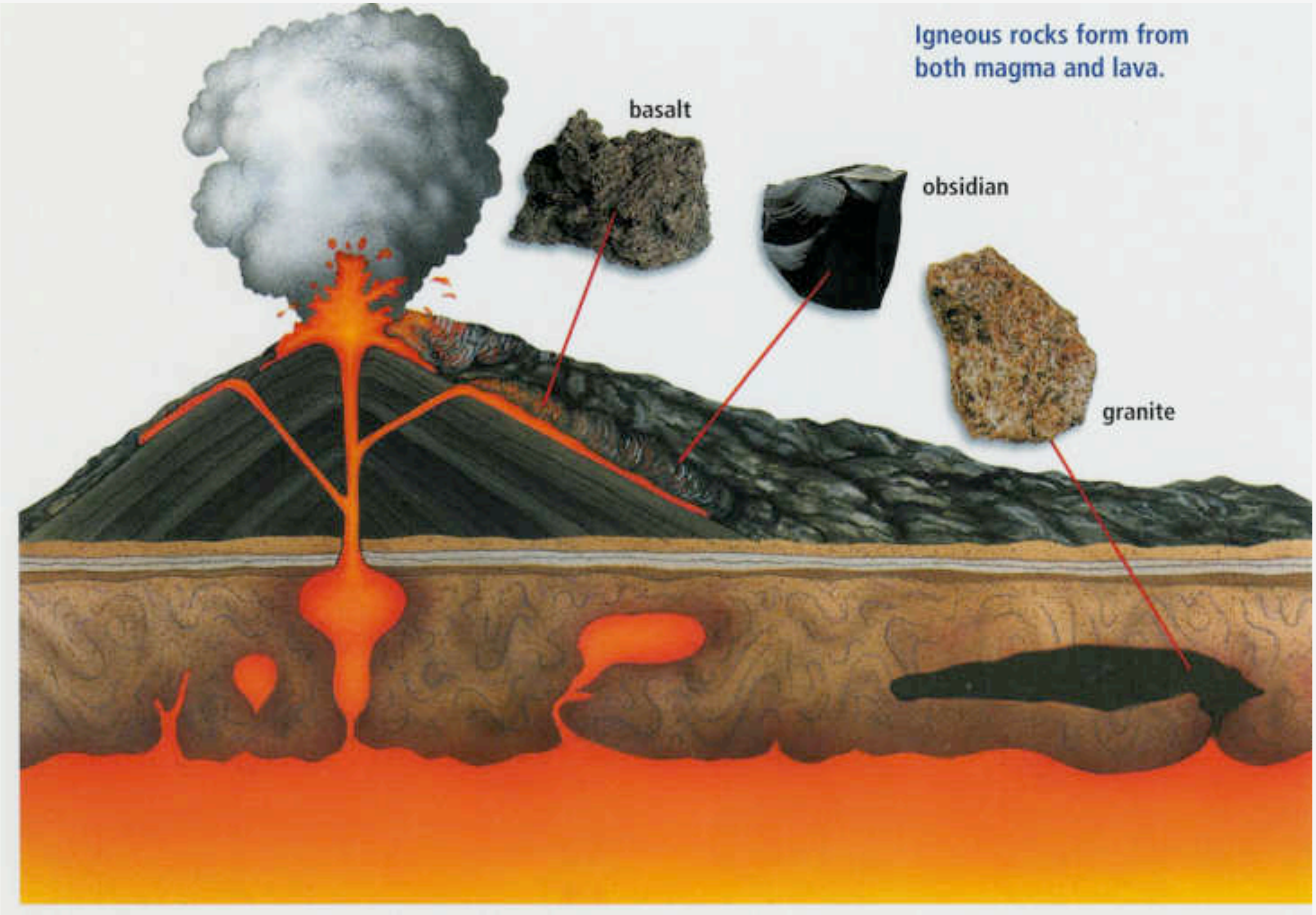
Primary vs. secondary MI



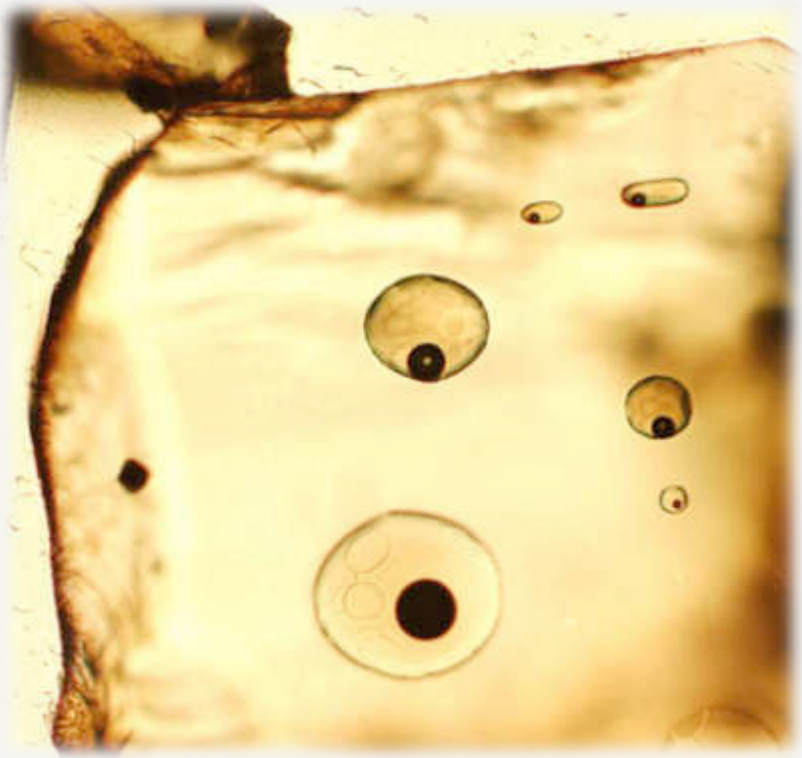
[Bodnar, 2003]



Melt inclusions in igneous rocks



Melt inclusions in igneous rocks

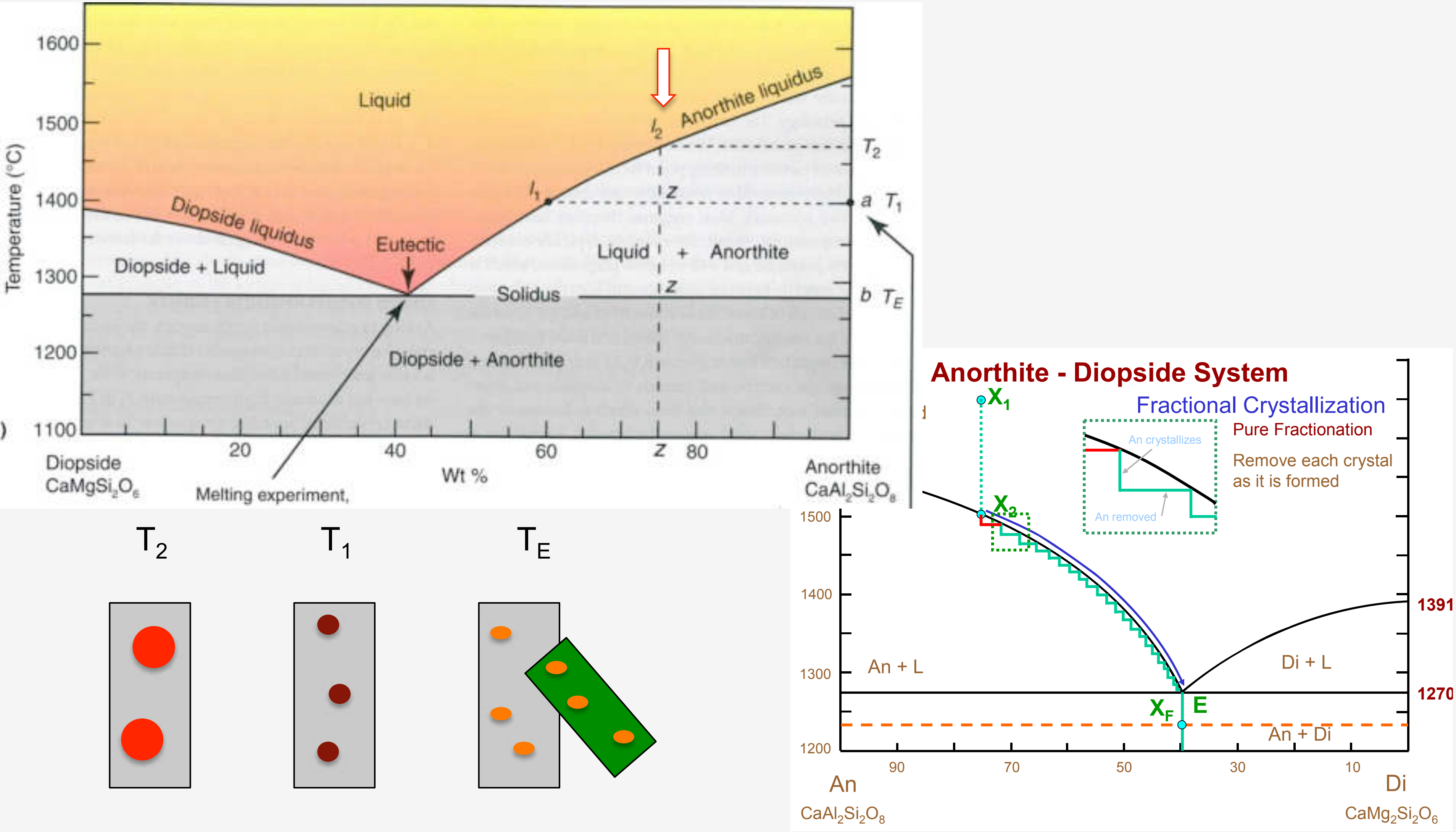


The widespread occurrence of melt inclusions in basaltic rocks shows that their formation is a normal part of the process of **crystallization in igneous rocks**

“(primary) *Melt inclusions are small droplets of silicate melt that are trapped in minerals* ***during their growth in a magma***”

Melt inclusions in igneous rocks

– BINARY EUTECTIC SYSTEM –

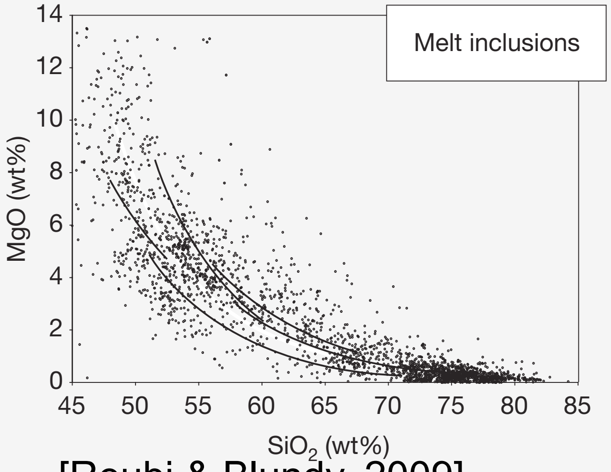


Melt inclusions in igneous rocks

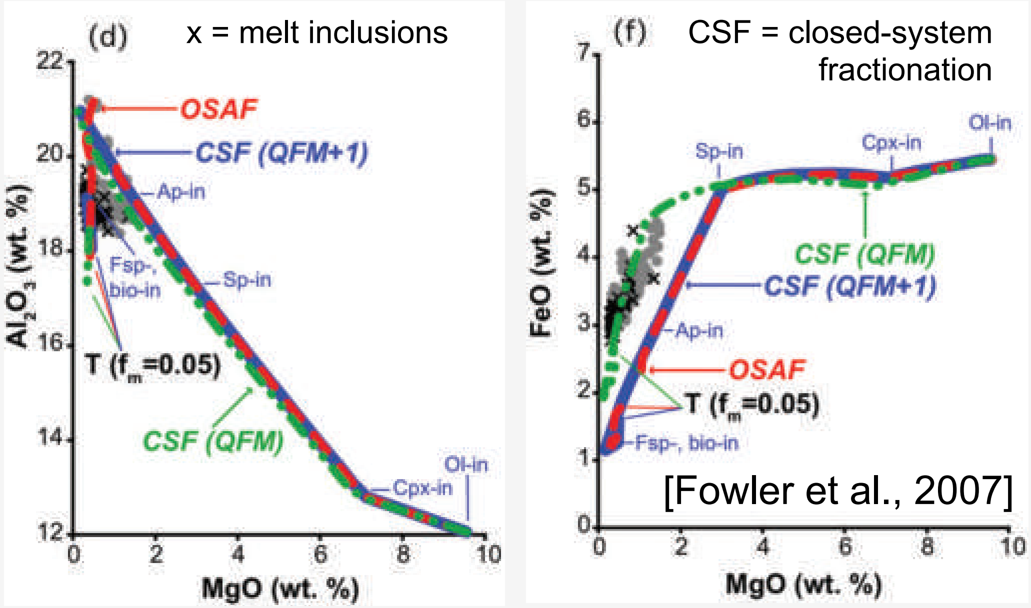
Because they contain liquids formed in thermodynamic equilibrium with their host minerals, **primary melt inclusions** produced at different stages of evolution of the melts will **record the <u>liquid line of descent</u>* of magmatic systems** → MI are like time capsules**

* series of liquids derived from single parent magma

** assuming they behave as closed systems (isolated from the surrounding environment) after their entrapment



[Reubi & Blundy, 2009]



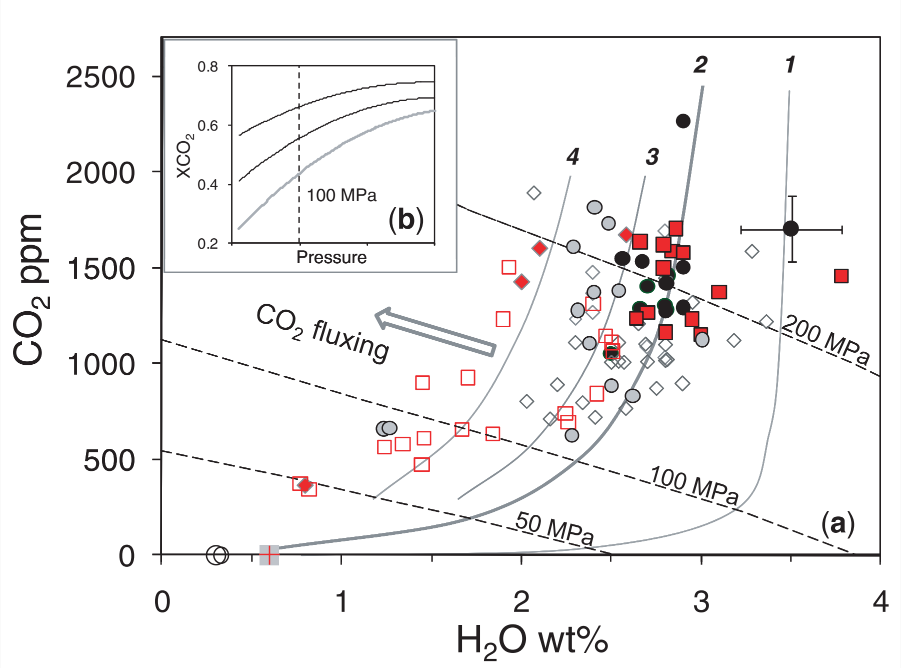
x = melt inclusions

CSF = closed-system fractionation

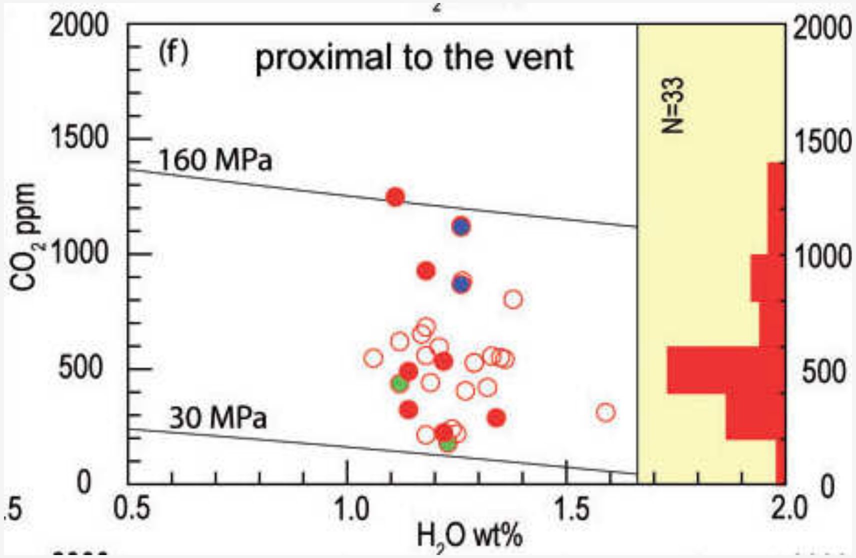
[Fowler et al., 2007]

Melt inclusions in igneous rocks

Melt inclusions in igneous rocks may record **the pre-eruptive volatile content** that usually is lost during degassing and differentiation of magmas



[Métrich et al., 2010]

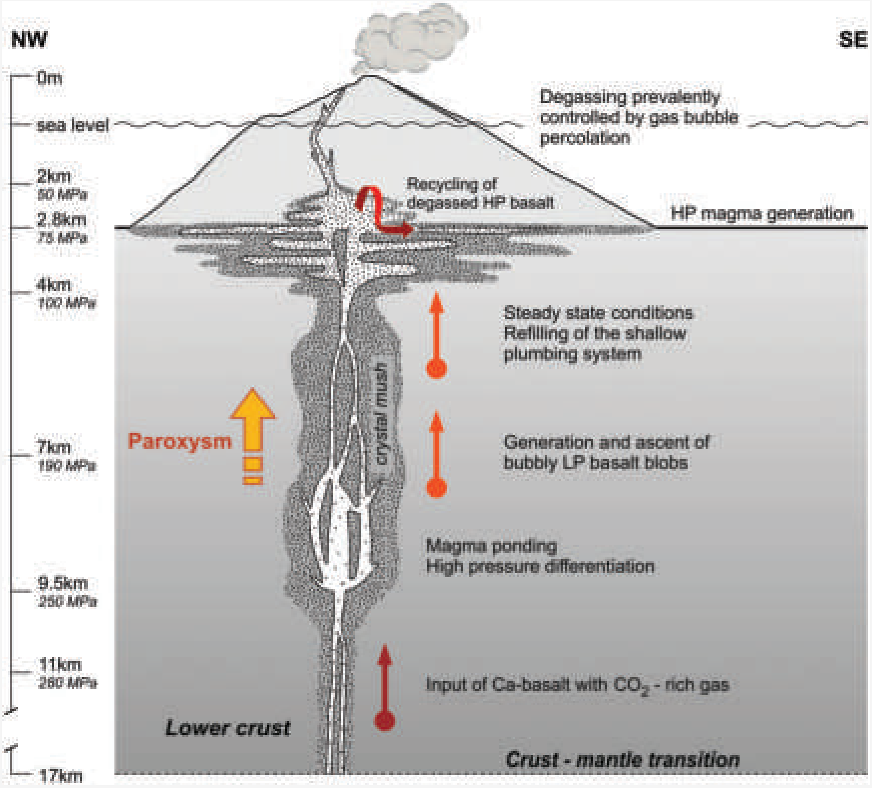


[Esposito et al., 2011]

Melt inclusions in igneous rocks

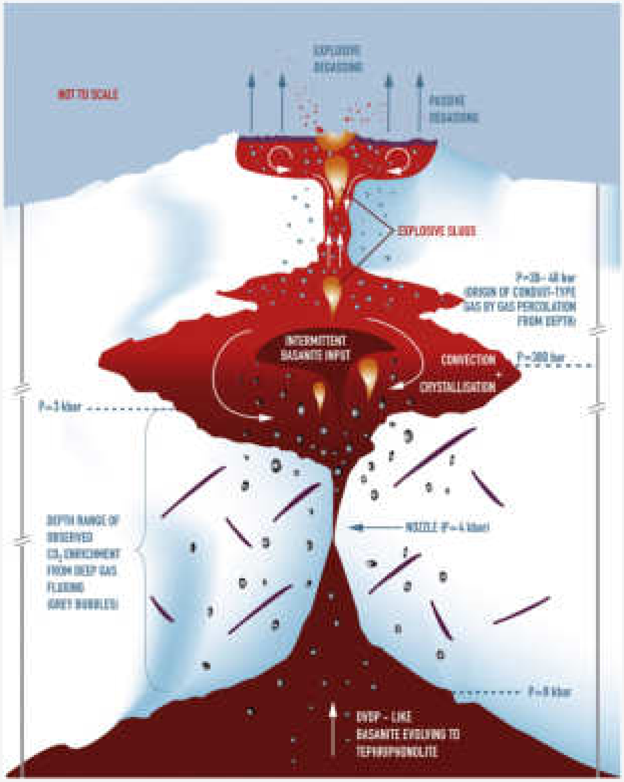
Combining the melt saturation pressures retrieved from the CO_2 and H_2O contents of melt inclusions is possible to build models of the magmatic plumbing system of volcanoes

Stromboli (Italy)



[Métrich et al., 2010]

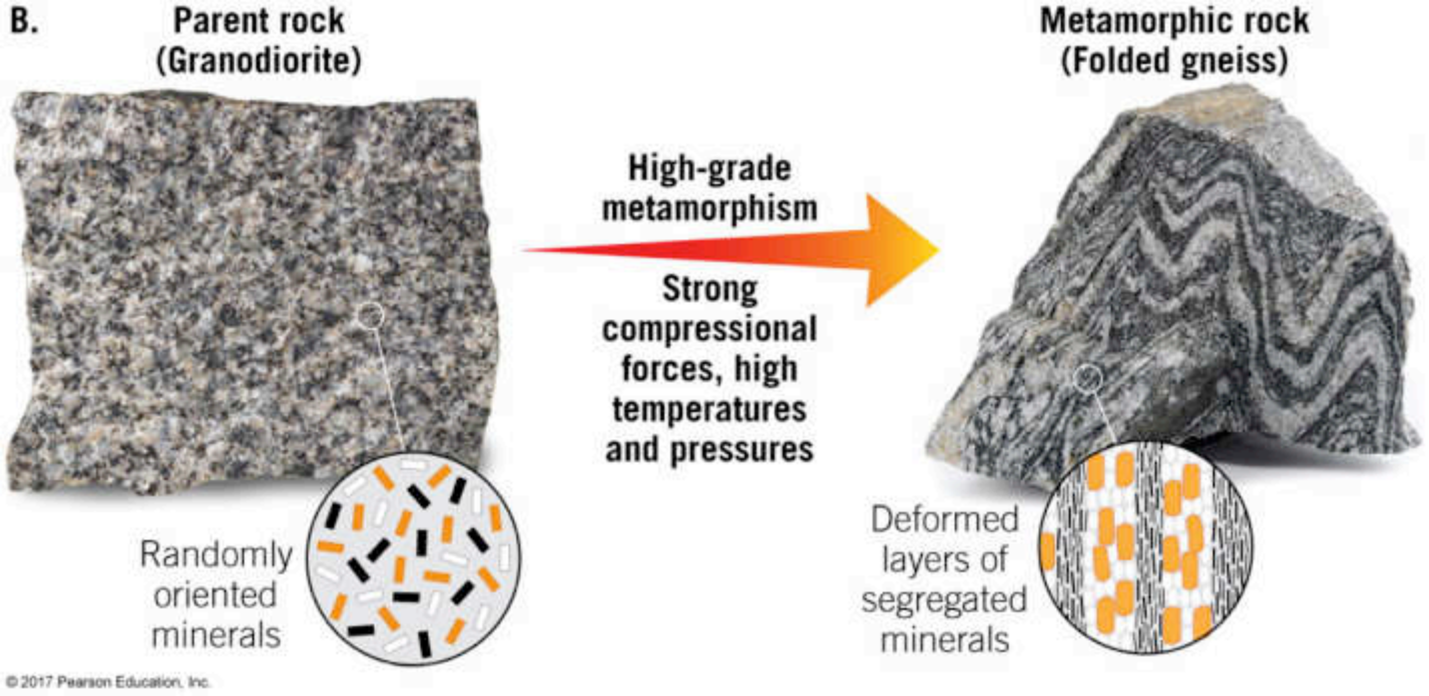
Erebus (Antarctica)



[Oppenheimer et al., 2011]

Metamorphism

Metamorphism means "to change form"



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Metamorphism includes all changes that affect rock's mineralogy and texture as a result of changes in pressure, temperature or composition of fluids in the environment

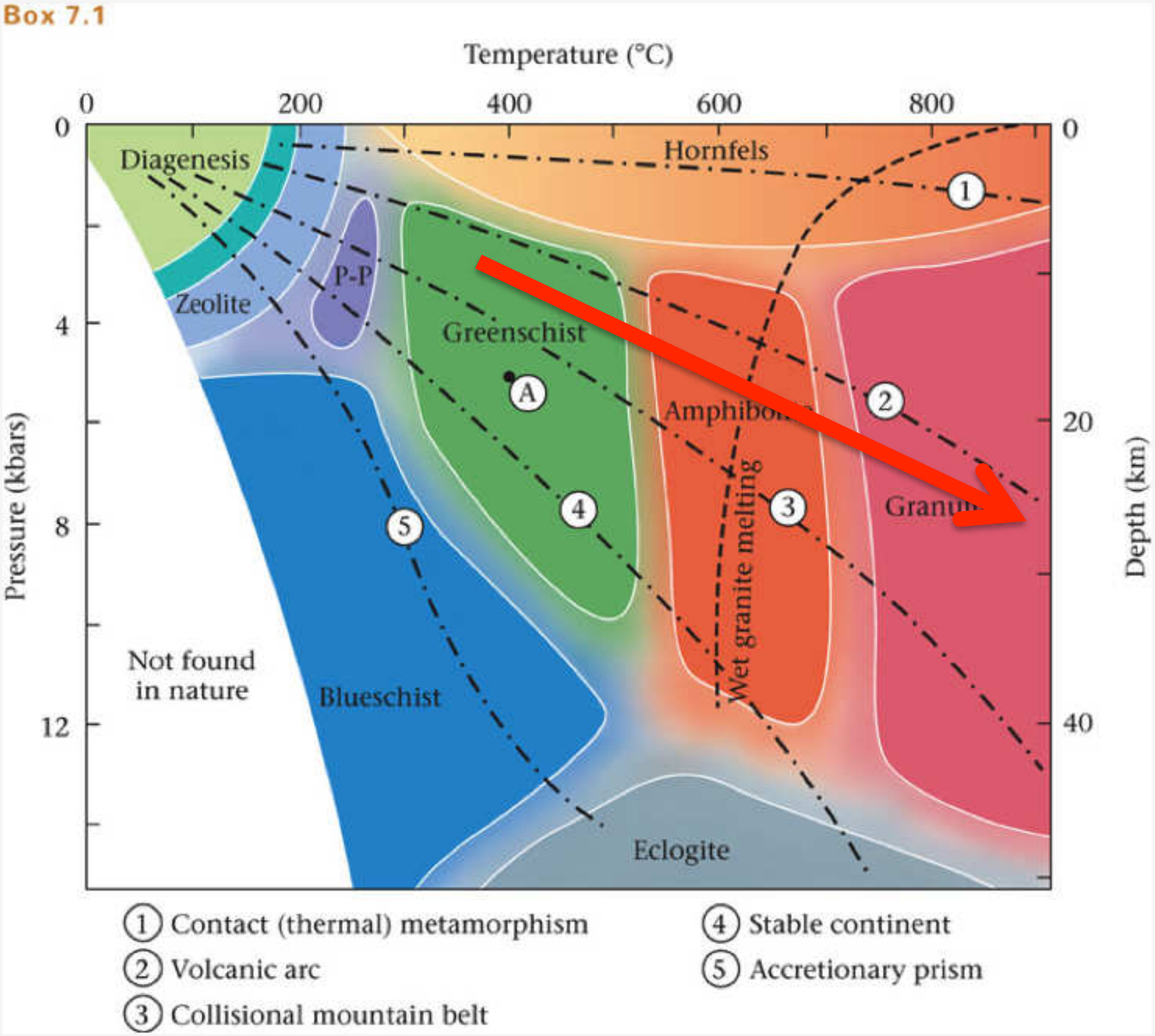
Agents of metamorphism

Heat

Pressure (stress)

Fluids

High-temperature metamorphism

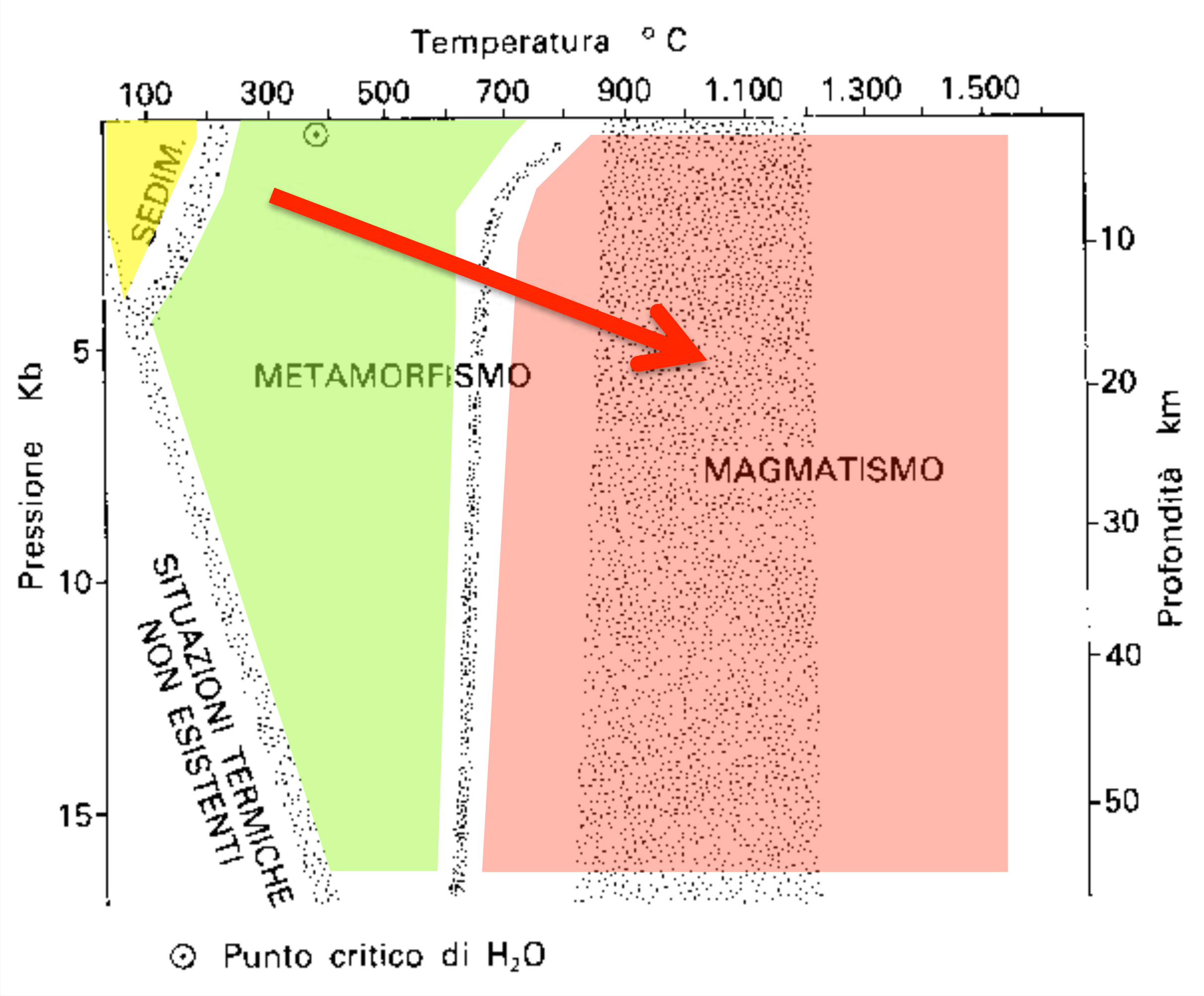


What can we expect when we heat the crust to vey high temperatures (700-1000 °C) ?

High-temperature metamorphism

This question bridges the gap between metamorphic and igneous processes

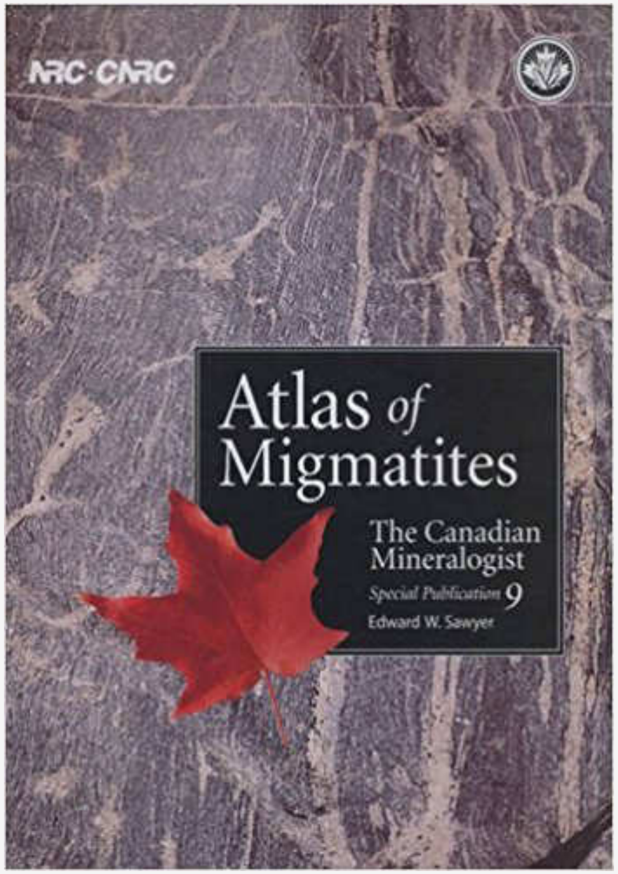
The temperature may rise enough to cause **partial melting**



Crustal anatexis

Rocks formed during crustal melting (anatexis) consist of a mixture of melt (silicate liquid) and metamorphic rock (the residue) and are known as **migmatites** (migma → mixture)

Crustal anatexis



NRC·CNRC

Atlas of Migmatites

The Canadian Mineralogist

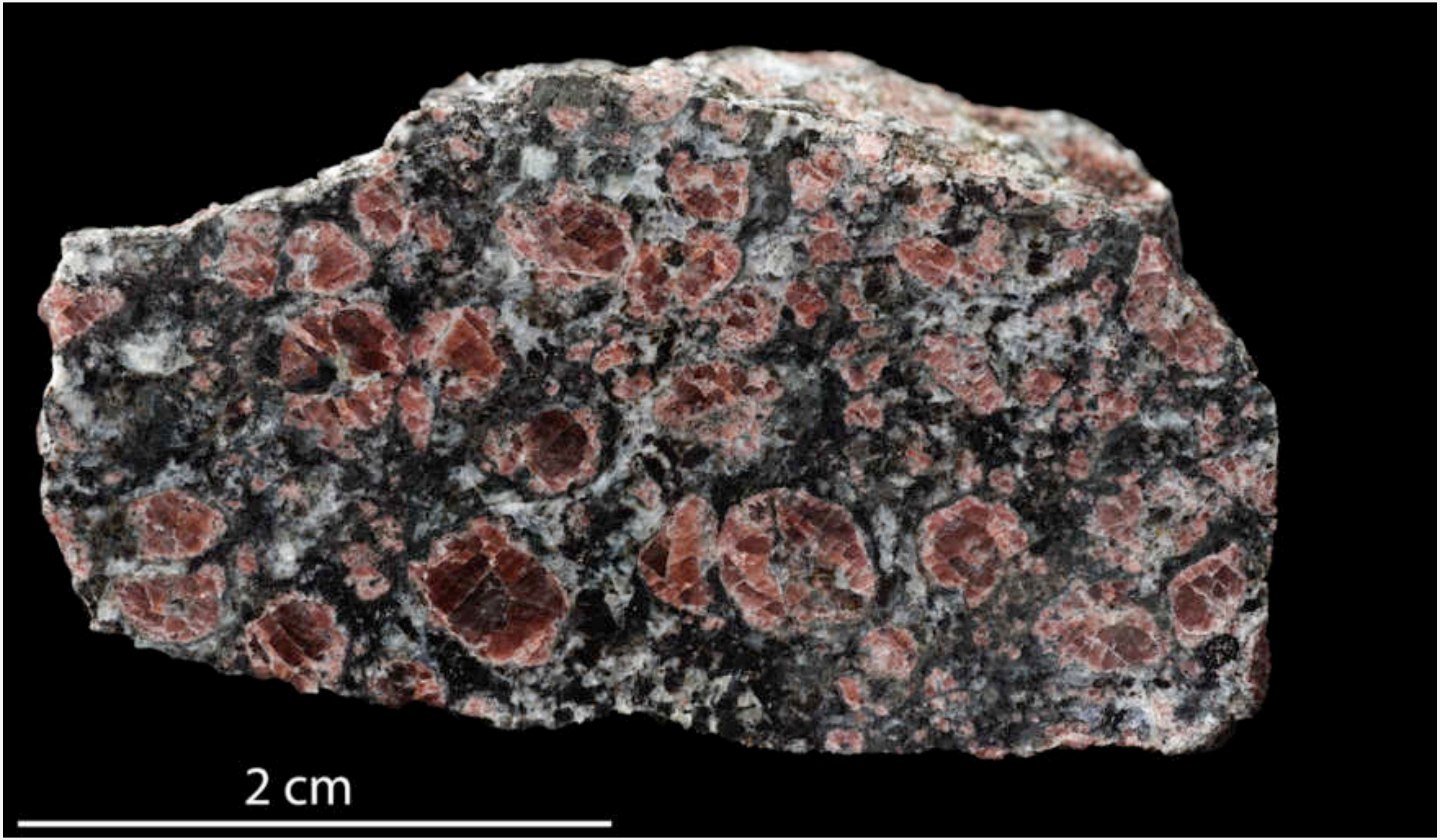
Special Publication 9

Edward W. Sawyer

“Migmatites are spectacular, complex-looking rocks that can inspire or confuse geologists”
(Edward W. Sawyer)

Crustal anatexis

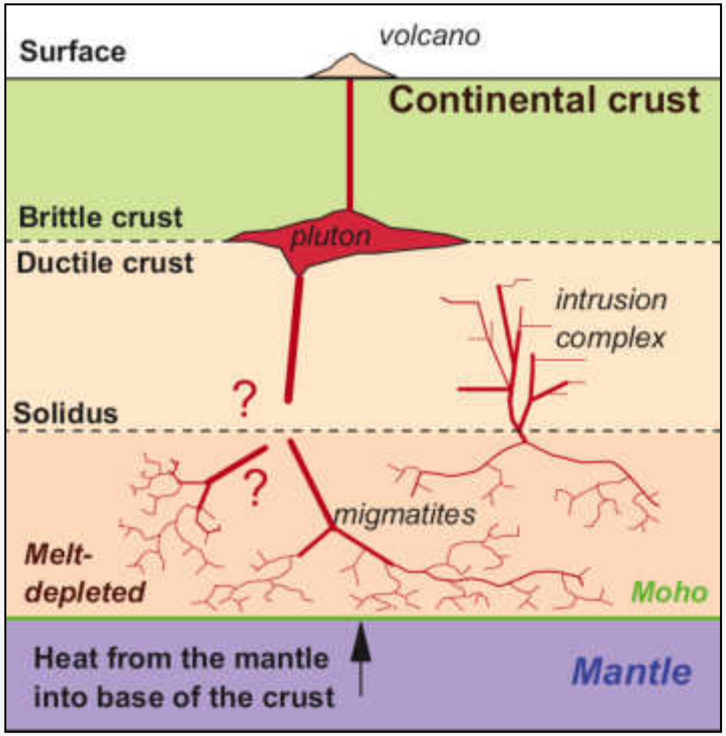
Residual granulites → melt-depleted, HT metamorphic rocks



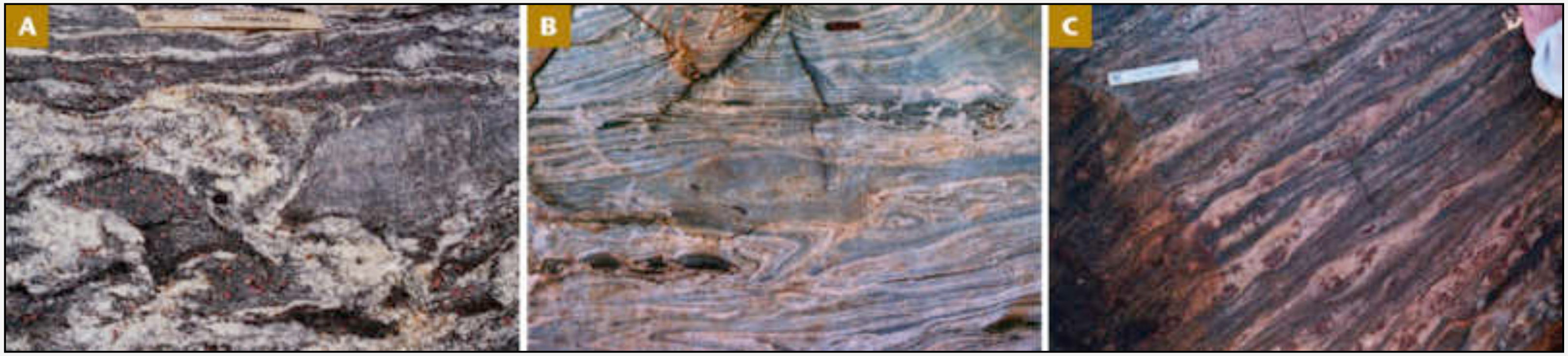
Crustal anatexis

Determines/affects:

- geochemical differentiation
- rheology of rocks
    - *mountain building processes*
    - *exhumation processes*
- igneous activity
    - *volcanism*
    - *plutonism*

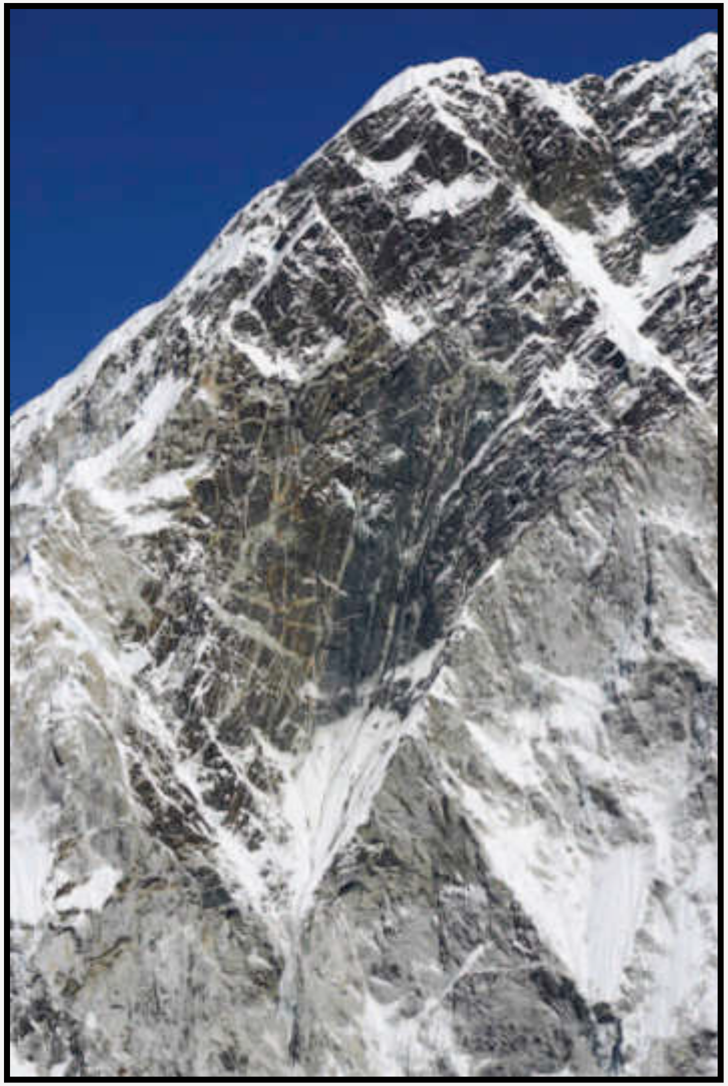


[Sawyer et al., 2011]

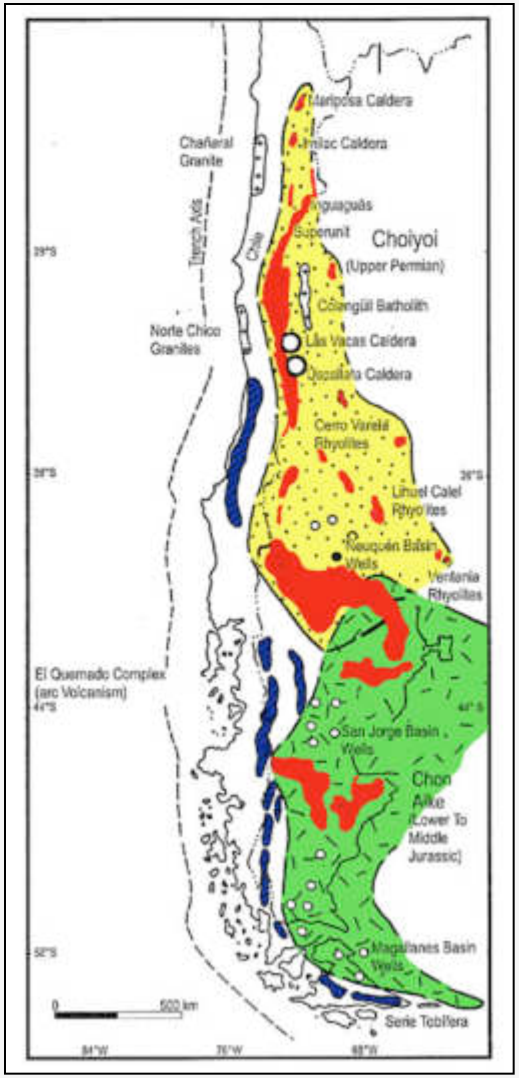


Crustal anatexis

Leucogranites on Spider Wall, Nuptse, Nepal



Rhyolitic provinces in South America



Melting reactions

CONGRUENT MELTING → solid and liquid have the same compositions

1) Qtz + Pl + Kfs + H_2O = liquid

3) Ms + Pl + Qtz + H_2O = liquid

4) Qtz + Bt + Sil + H_2O = liquid

INCONGRUENT MELTING → the composition of the liquid differs from that of the initial solid

2) Bt + Qtz + Pl + Als + H_2O = Grt + liquid

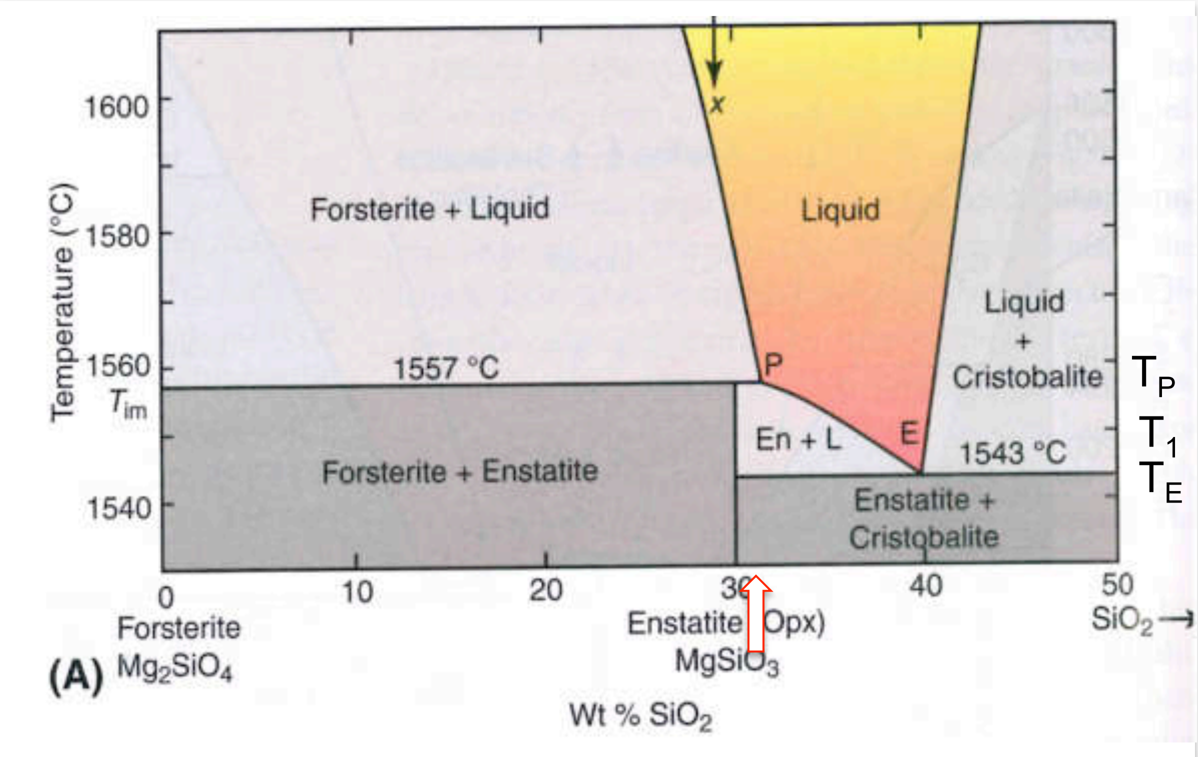
5) Bt + Pl + Qtz + H_2O = Grt + Crd + liquid

6) Bt + Pl + Qtz + Sil = Grt + Opx + liquid

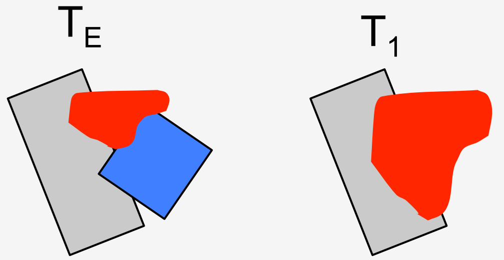
Peritectic mineral: the solid product of incongruent melting reactions

Incongruent melting

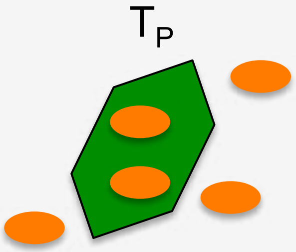
– BINARY PERITECTIC SYSTEM –



A rock composed of En + Qtz is heated



Solid phases are consumed → no way to trap melt inclusions



Enstatite melts incongruently to a liquid not of its own composition plus a new solid phase. **The growing forsterite may trap droplets of coexisting melt**

Incongruent melting

Mineral C is produced (grows) together with L (liquid), thereby creating the necessary conditions for primary entrapment of MI

$$A + B = C + L$$

Geological examples of incongruent melting range from the well-known, ideal reaction:

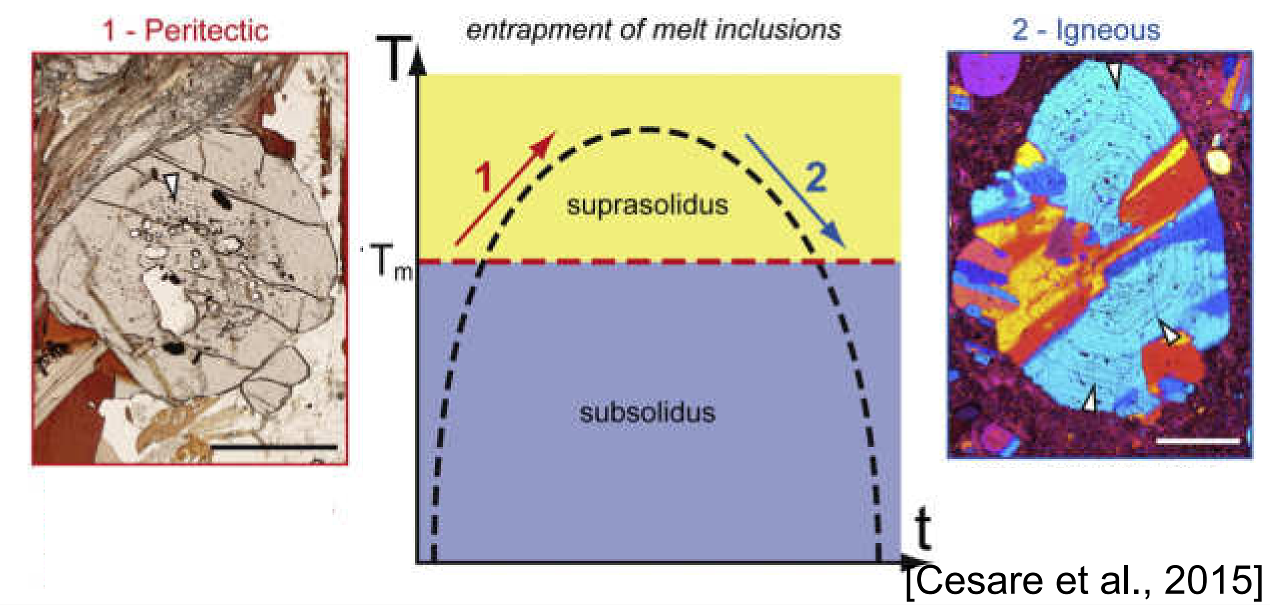
$$\mathrm{En} = \mathrm{Fo} + \text{liquid}$$

to the more complex, and of particular relevance to metapelites, reaction

$$\mathrm{Bt} + \mathrm{Pl} + \mathrm{Qtz} + \mathrm{Sil} = \mathrm{Grt} + \text{liquid}$$

Entrapment of MI, a twofold process

Requirement → growth of minerals in the presence of melt



[Cesare et al., 2015]

1- INCONGRUENT MELTING

- ✓ little consideration so far
- ✓ in migmatites and granulites
- ✓during HEATING

2- MAGMA CRYSTALLIZATION

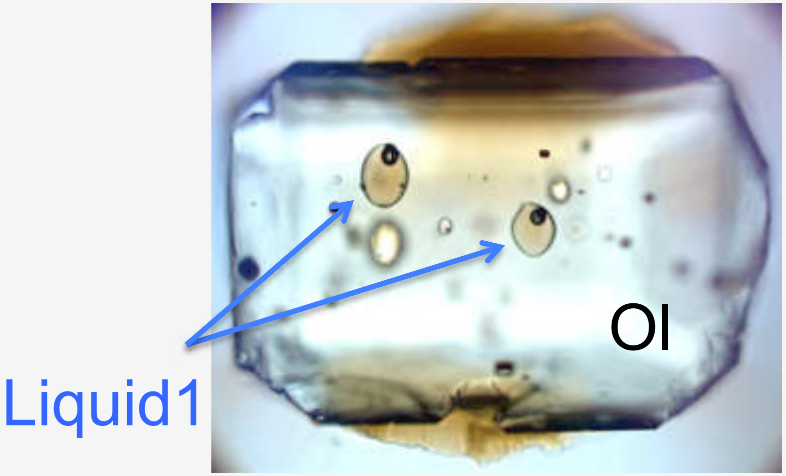
- ✓ the most common process
- ✓ observed in igneous rocks
- ✓during COOLING

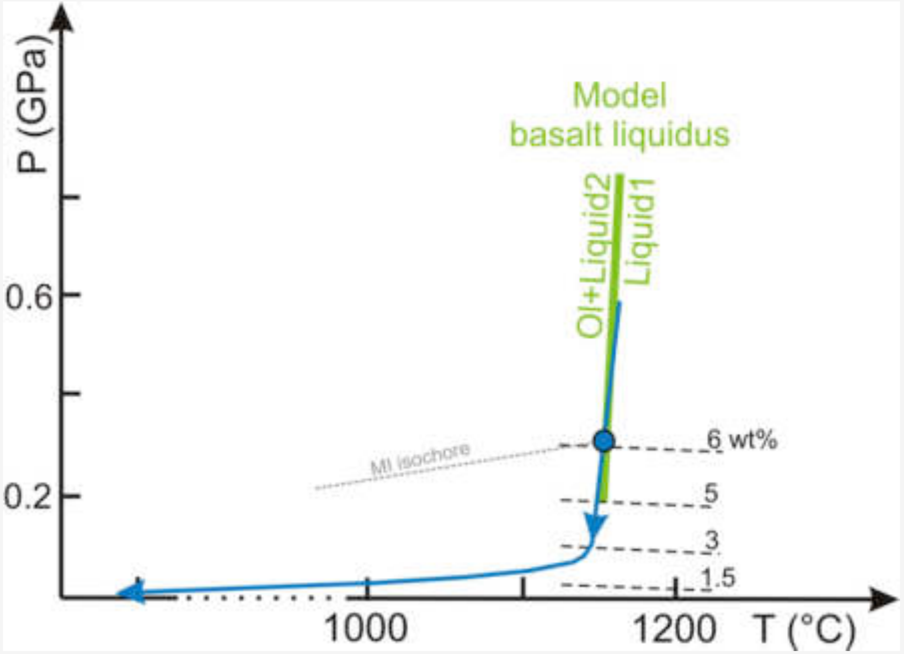
Entrapment of MI, a twofold process

Requirement → growth of minerals in the presence of melt

2- MAGMA CRYSTALLIZATION

$\text{Liquid}_1 = \text{Ol} + \text{Liquid}_2$





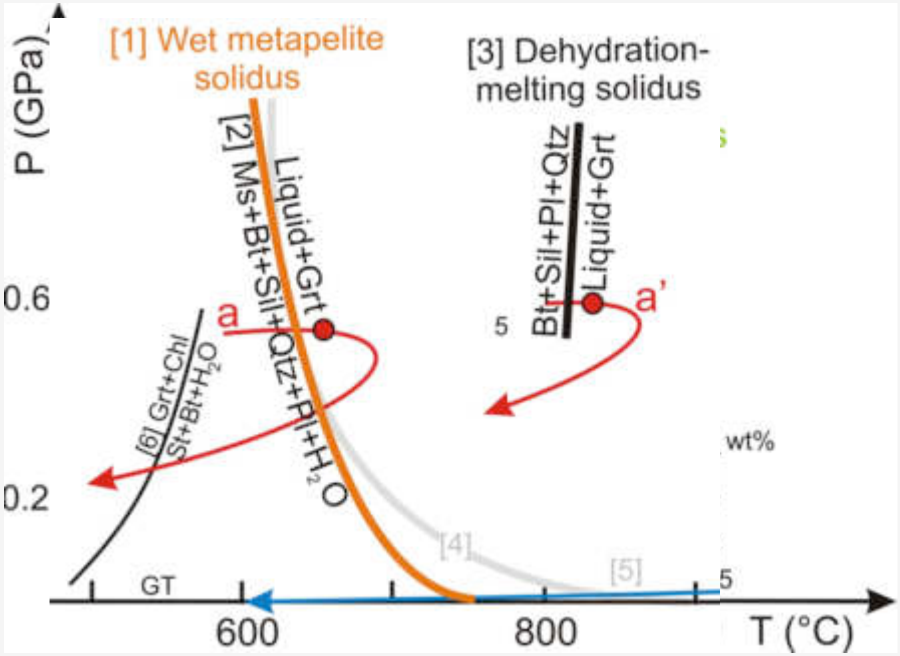
[Bartoli et al., 2014]

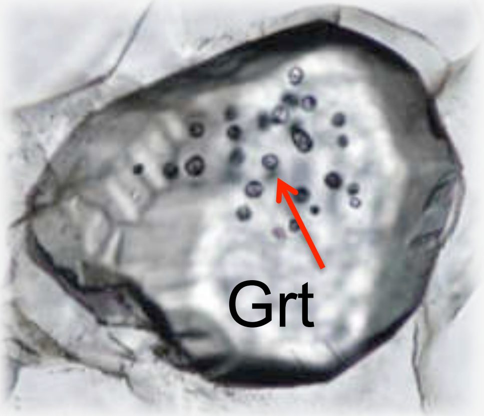
Entrapment of MI, a twofold process

Requirement → growth of minerals in the presence of melt

1- INCONGRUENT MELTING

Qtz + Pl + Bt + Sil = liquid + Grt



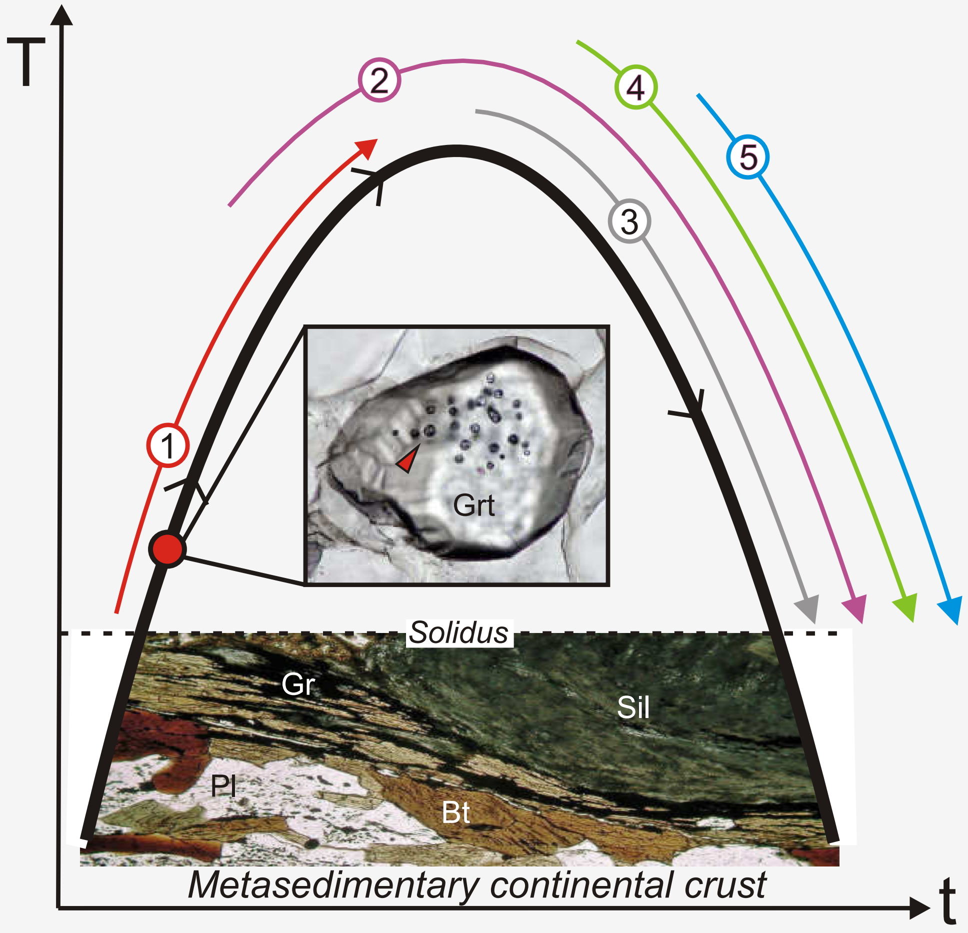


[Bartoli et al., 2014]

Changing the viewpoint

Entrapment **upon heating**
and not upon cooling

the melt being trapped
is a **pristine <u>primary</u>**
crustal melt



[Bartoli et al., 2016]

① Melt formation and MI entrapment
Bt + Sil + Pl + Qtz = Grt + melt (± Kfs)[1]

② Melt segregation

③ Magma crystallization and differentation

④ Volatile degassing

⑤ Entrapment of “classic” MI

What are melt inclusions?

"Melt inclusions are small droplets of silicate melt that are trapped in minerals during their growth in a magma"

[Audétat & Lowenster, 2014]

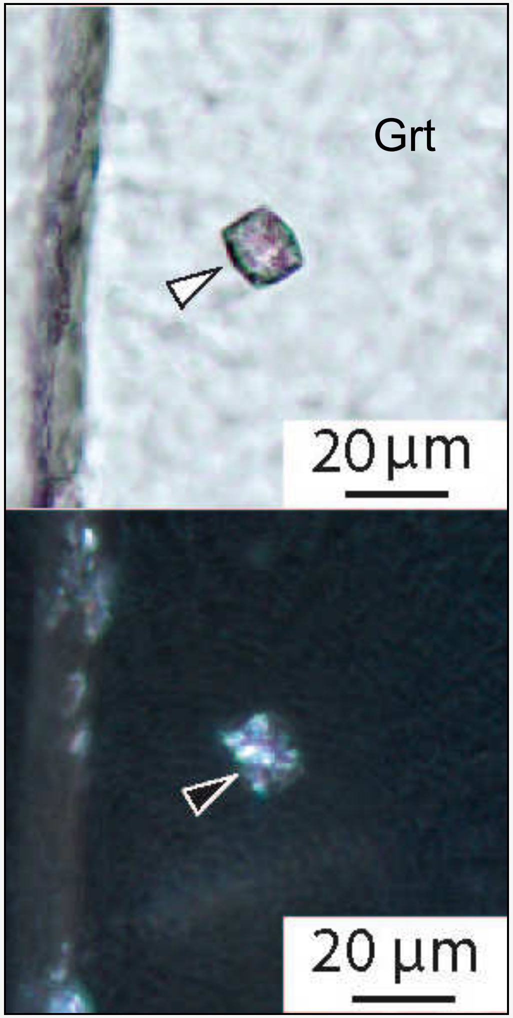
"Melt inclusions are small droplets of silicate melt that are trapped in minerals during their growth ~~in a magma~~ **in the presence of a melt phase**"

[Cesare et al., 2015]

How are melt inclusions identified?

Melt inclusions are very small (< 20 μm, often <10 μm)

They commonly are polycrystalline and birefringent

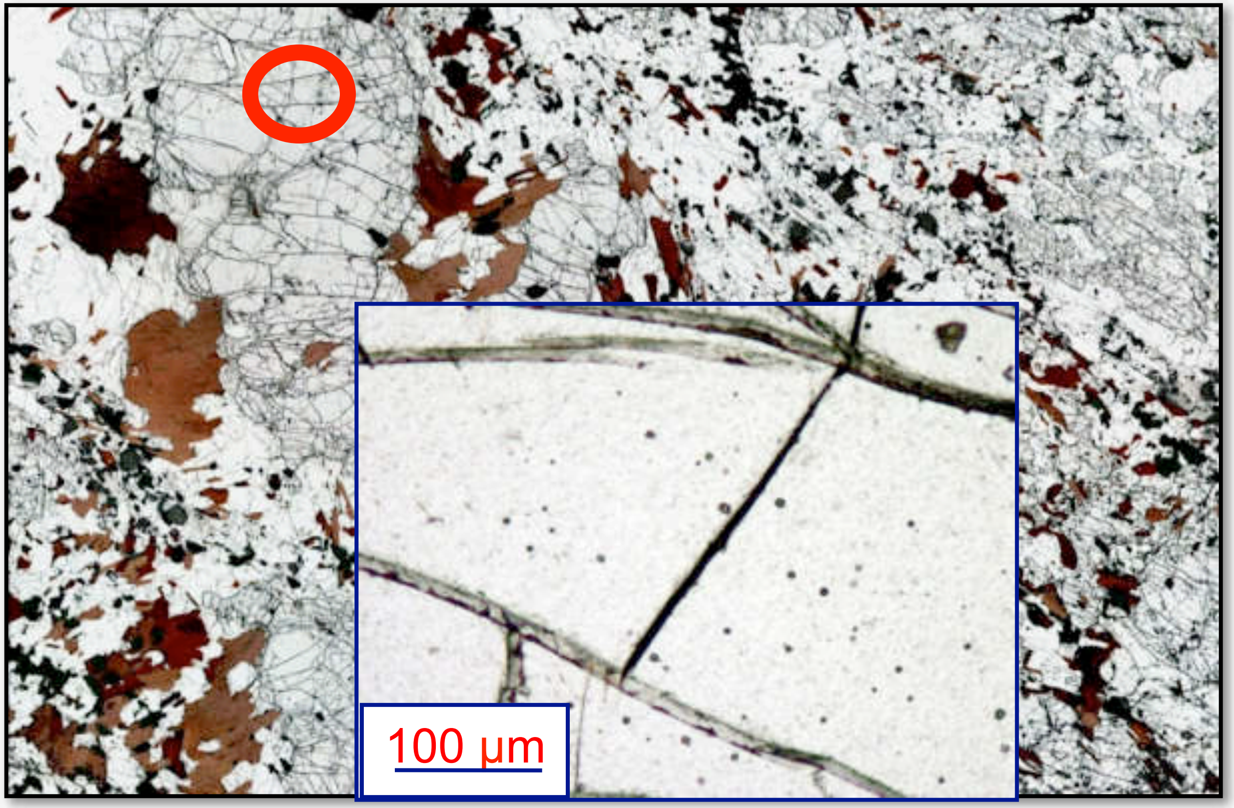


[Cesare et al., 2009]

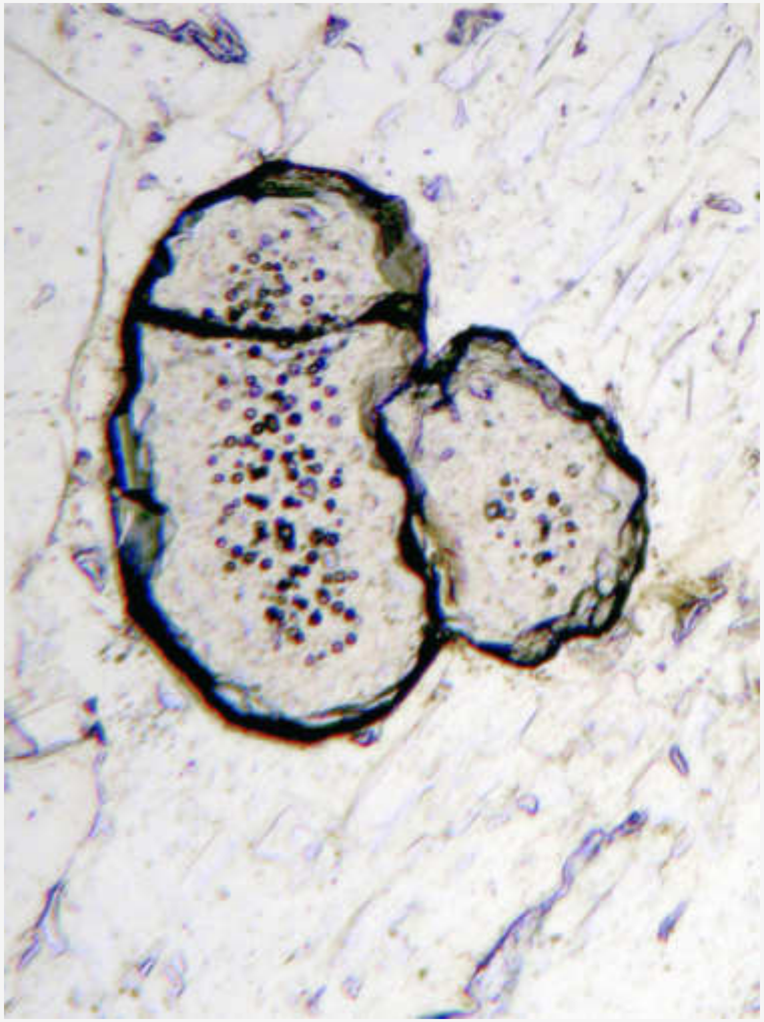
How are melt inclusions identified?

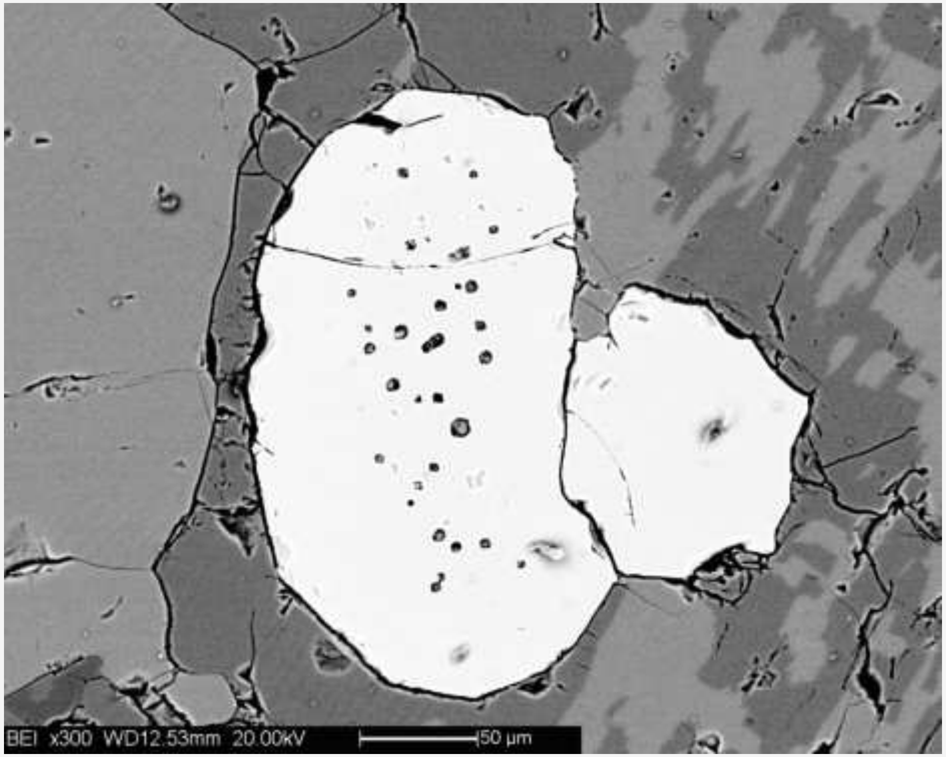
Melt inclusions can be easily overlooked or considered bad sample preparation or dust

A good optical microscope and well-prepared thin sections are all one needs to make the preliminary, essential observations



How are melt inclusions identified?





How are melt inclusions microstructurally characterized?

X-ray computed microtomography (X-µCT; both synchrotron radiation- and X-ray tube-based) can be applied to investigate in a non-invasive way the 3D spatial distribution of primary melt inclusions in garnet porphyroblasts

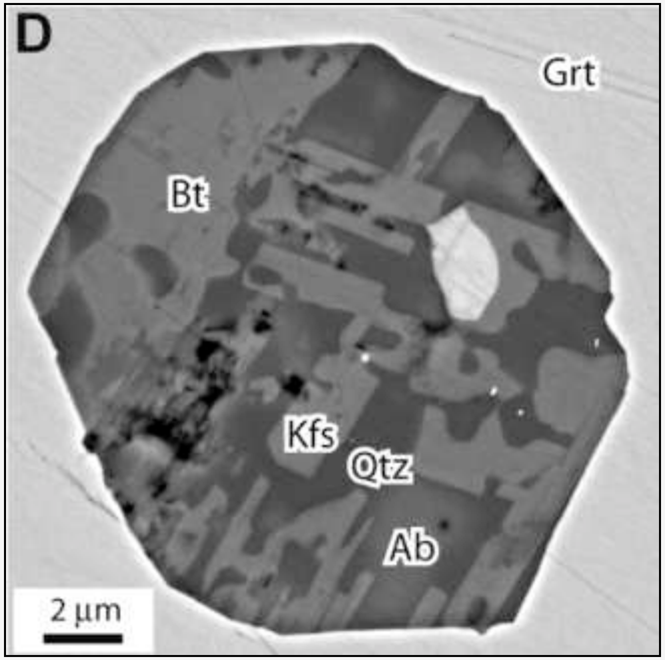
[Parisatto et al., 2018]

How are melt inclusions microstructurally characterized?

The microstructures of MI can be successfully characterized with back-scattered electron (BSE) imaging, using Field Emission Gun (FEG)-based electron microscopes

- Cryptocrystalline
- Negative crystal shape
- Micro- and nano-porosity

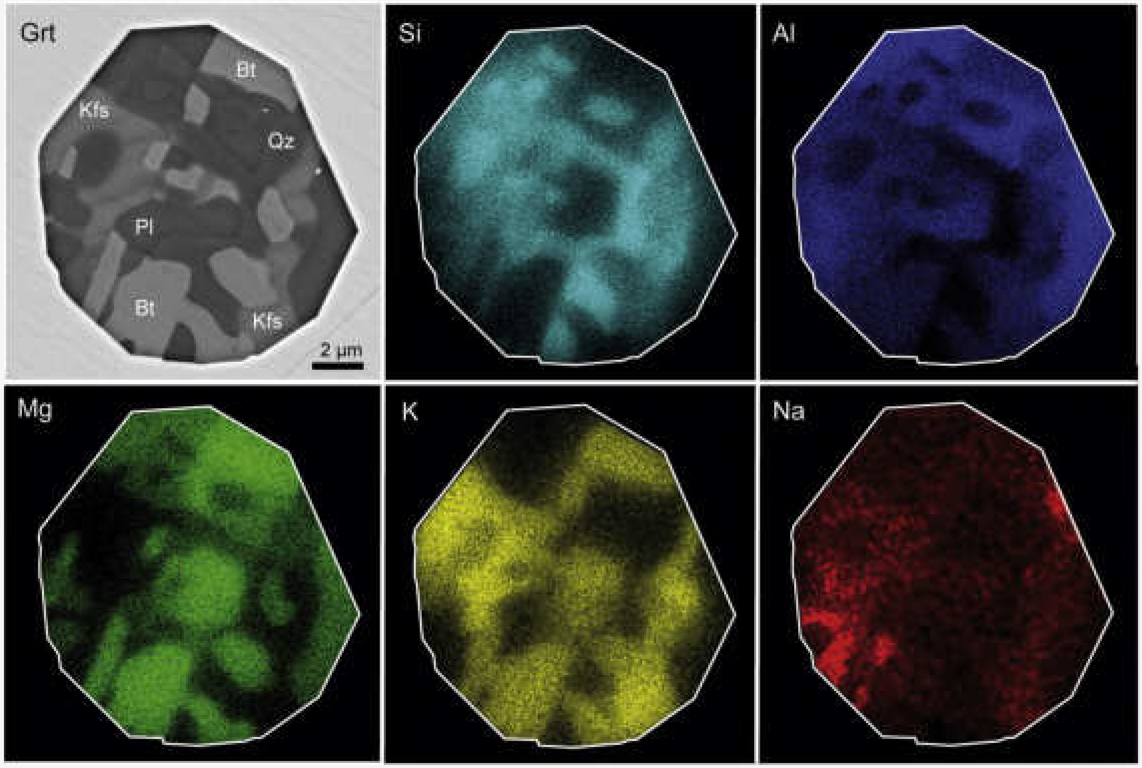
(volume contraction?)



[Cesare et al., 2009]

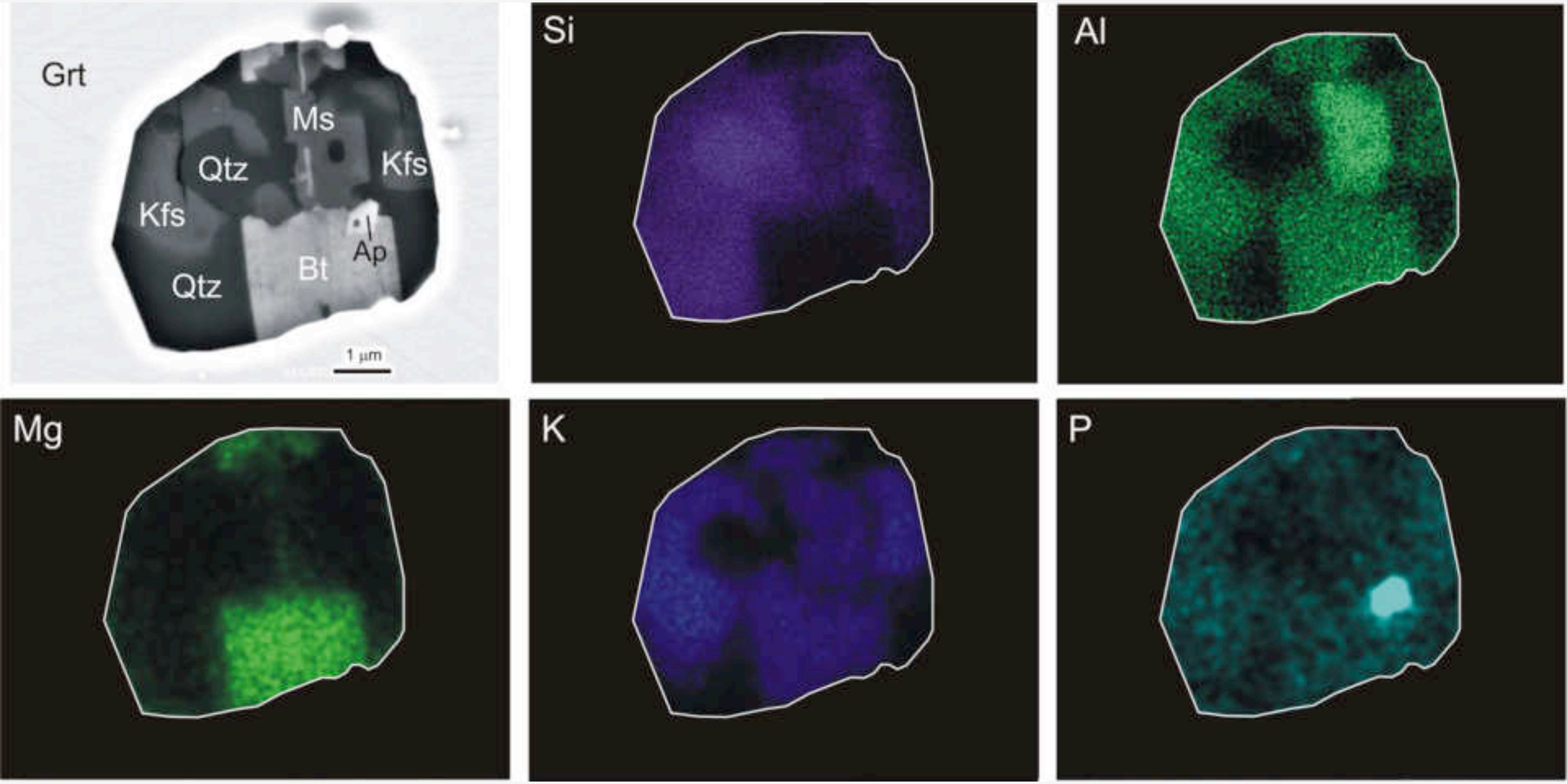
How are melt inclusions microstructurally characterized?

MI-forming crystals can be identified by acquiring EDS spectra and/or X-ray maps of the major elements



[Cesare et al., 2015]

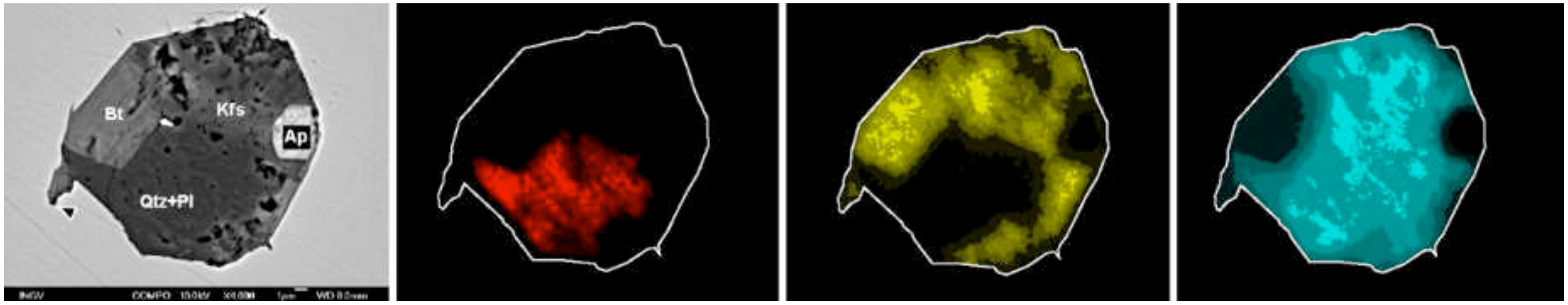
How are melt inclusions microstructurally characterized?



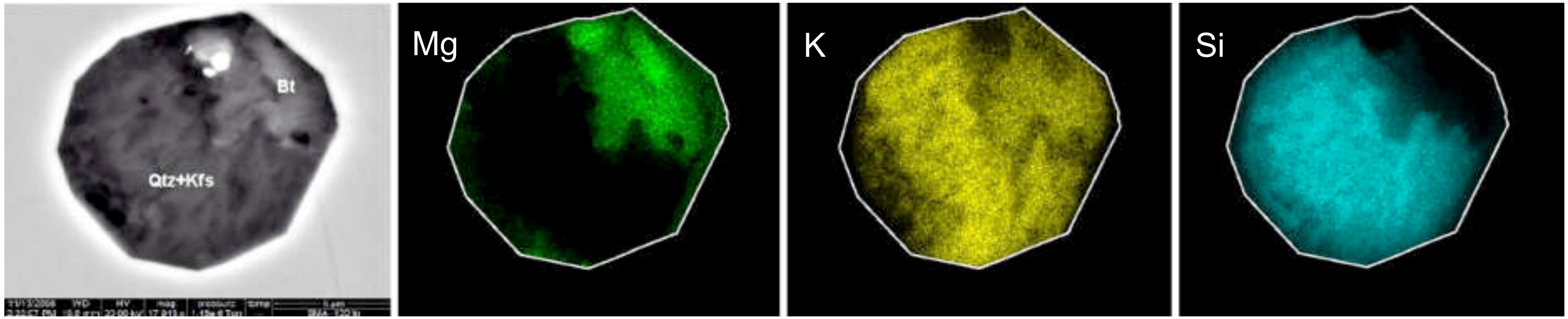
[Bartoli et al., 2016]

How are melt inclusions microstructurally characterized?

- Granophyric intergrowths: Plagioclase + Quartz



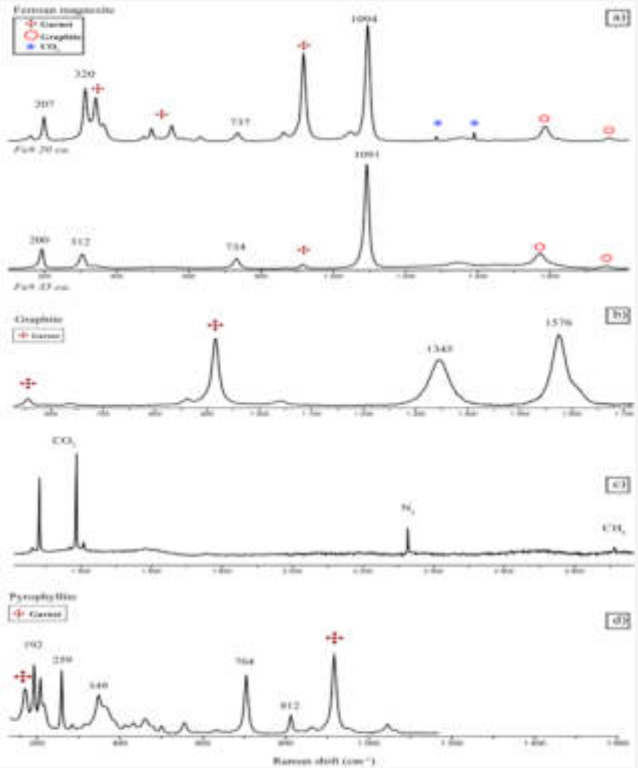
- Micrographic intergrowths: K-feldspar + Quartz

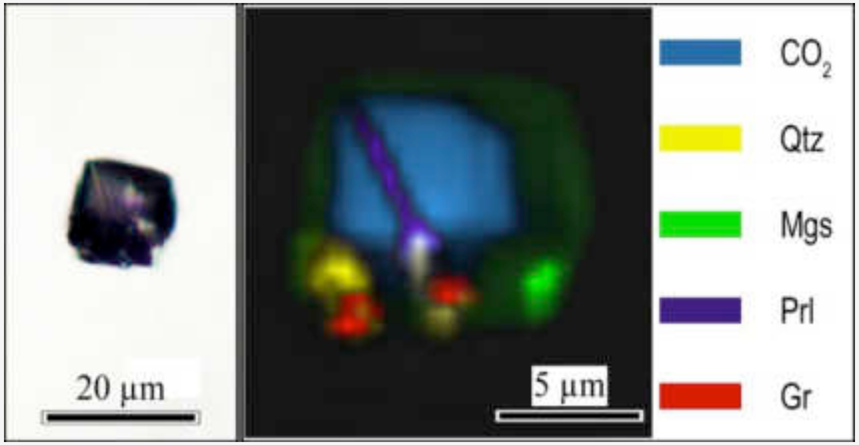


[Ferrero et al., 2012]

How are melt inclusions microstructurally characterized?

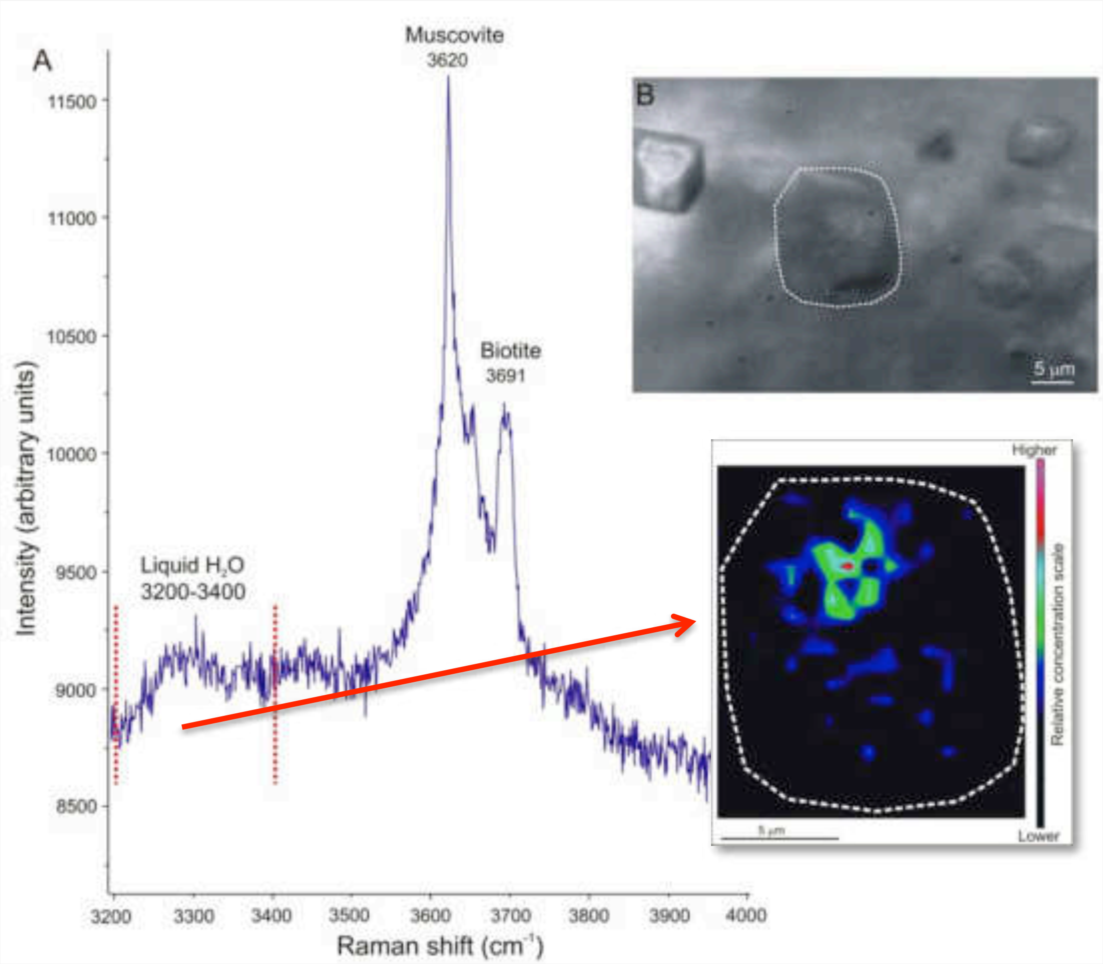
Given the small size of the crystals, Raman microspectroscopy represents a rapid way to identify the phases





[Tacchetto et al., submitted]

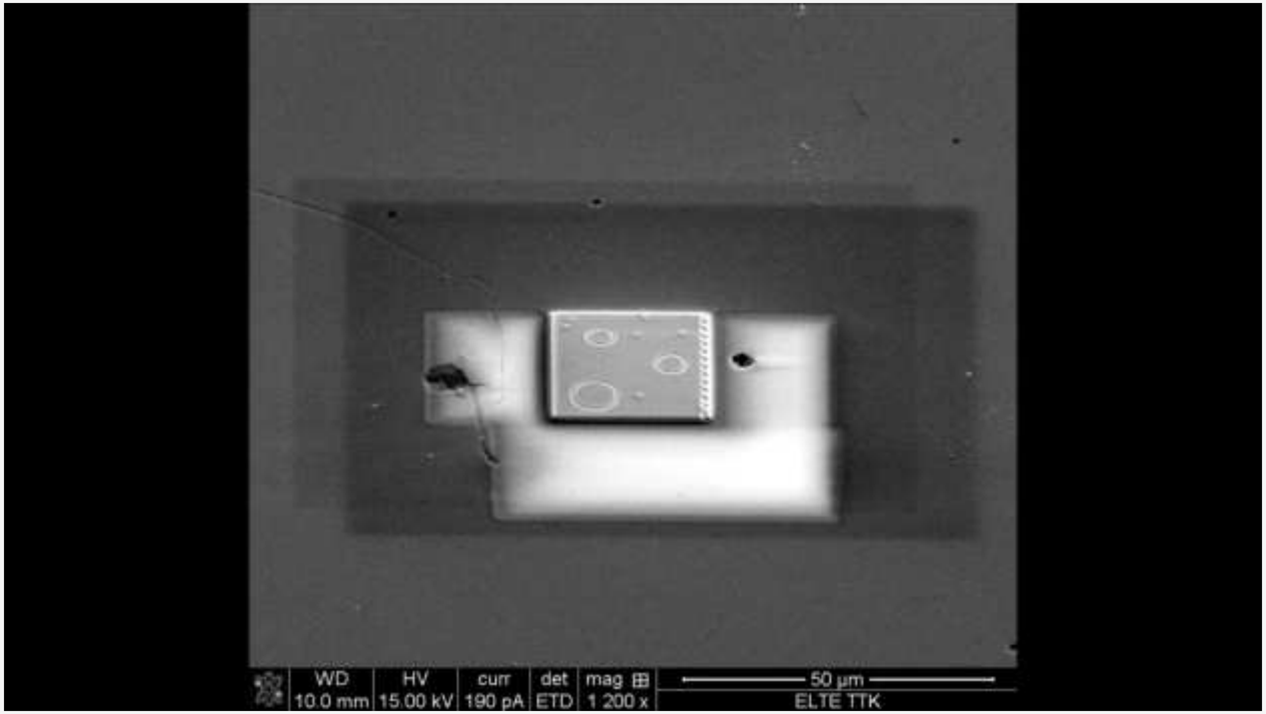
How are melt inclusions microstructurally characterized?



[Bartoli et al., 2013]

Micro Raman spectroscopy mapping has revealed the presence of **liquid H_2O in micro- and nanopores** of MI located below the surface of the studied thin section, i.e. entirely enclosed within the host

How are melt inclusions microstructurally characterized?

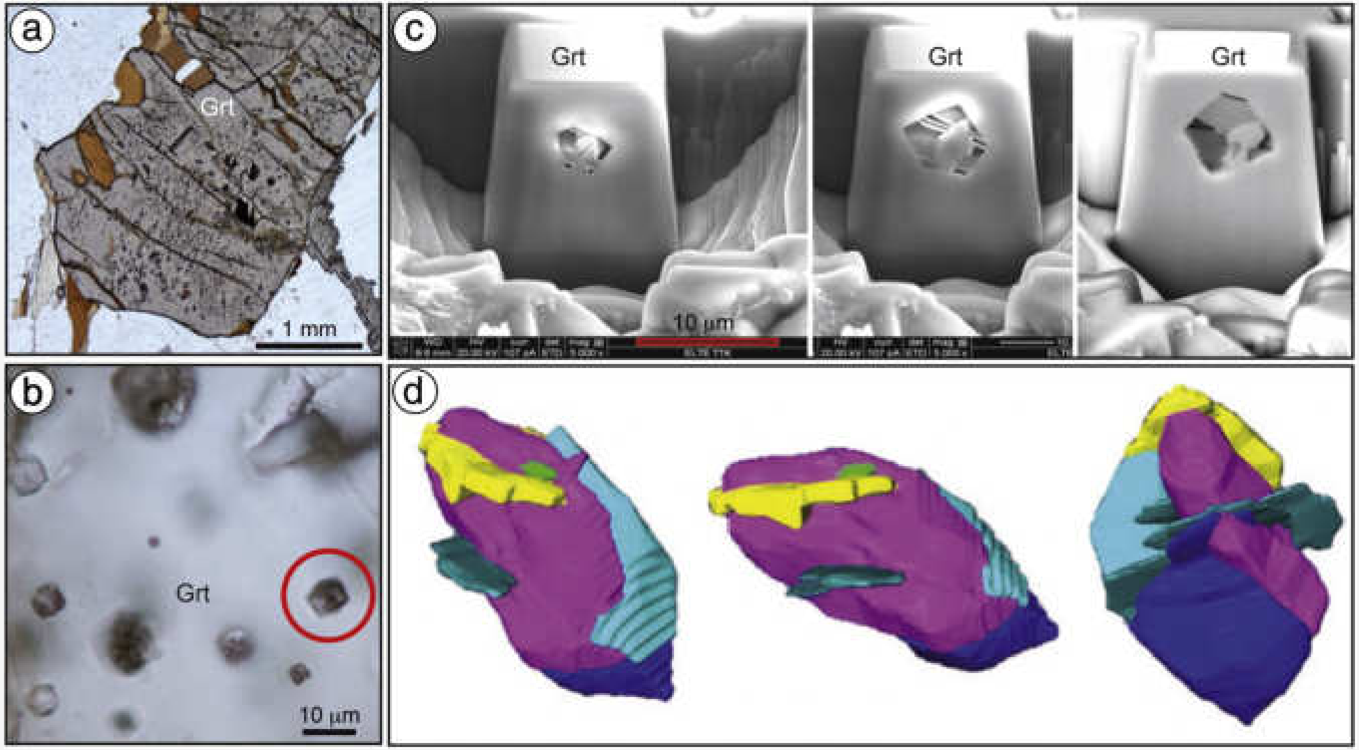


Dual-beam focused ion-beam-scanning electron microscope (FIB-SEM)

This technique permits to remove thin foils (250 nm)

How are melt inclusions microstructurally characterized?

3D reconstruction of unexposed inclusion



[Cesare et al., 2015]

Nanogranitoids inclusions

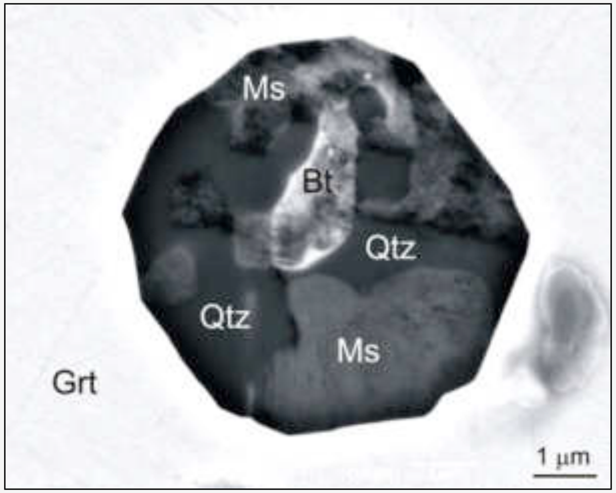
- Cryptocrystalline
- Granitoid phase assemblage (Qtz+Pl+Kfs+Bt+Ms)

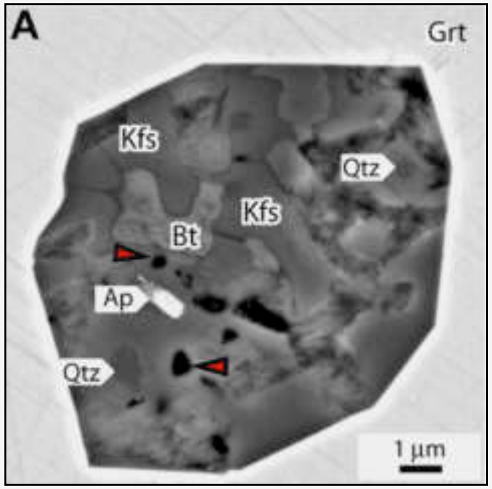
NANOGRANITES

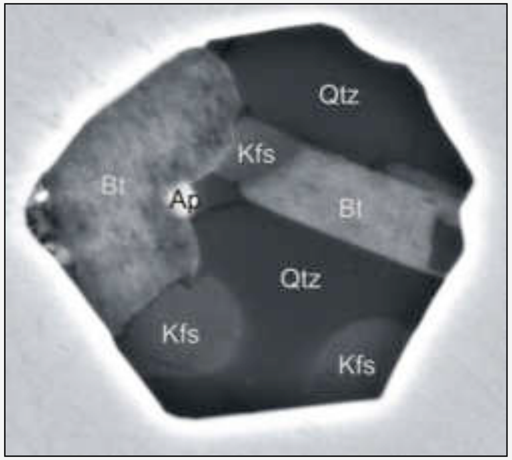
(Cesare et al. 2009)

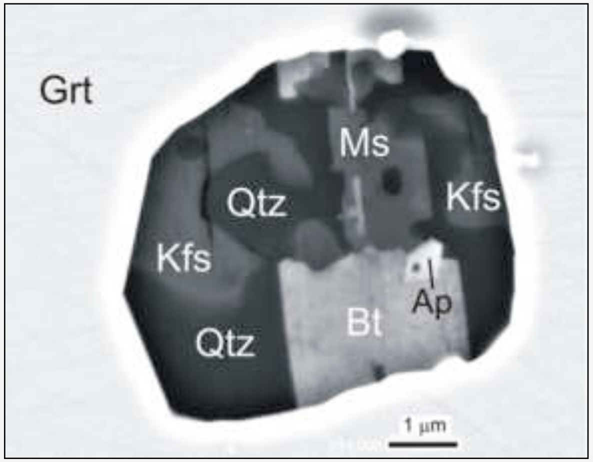
NANOGRANITOIDS

(Cesare et al. 2015; Bartoli et al., 2016)



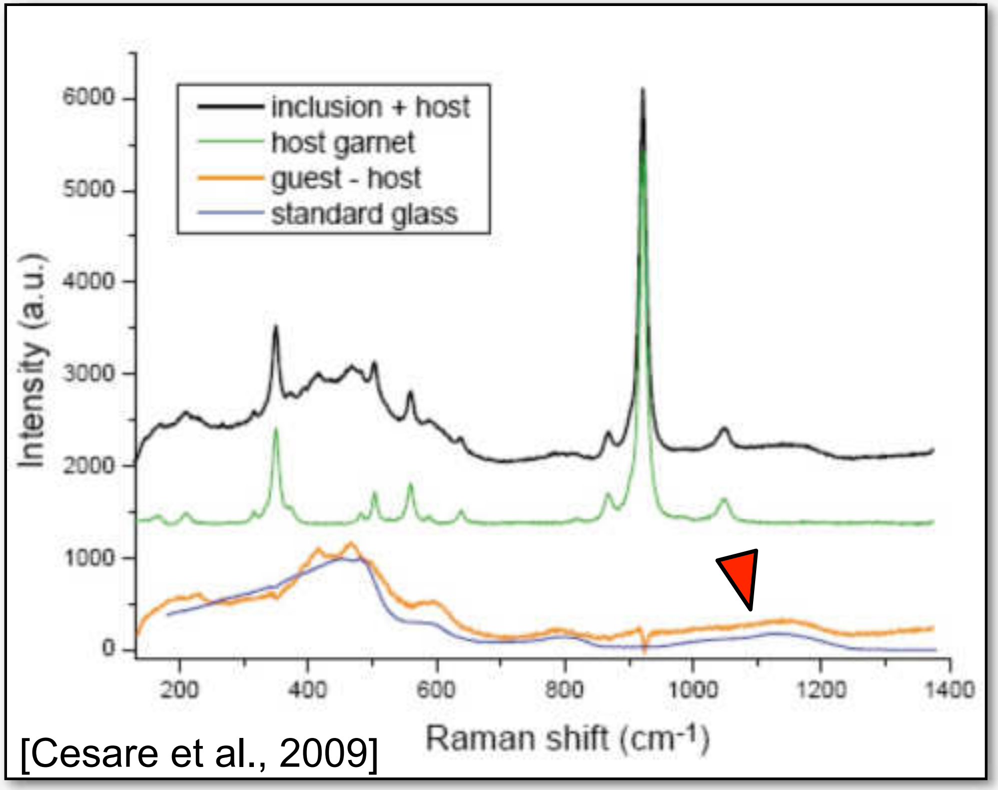




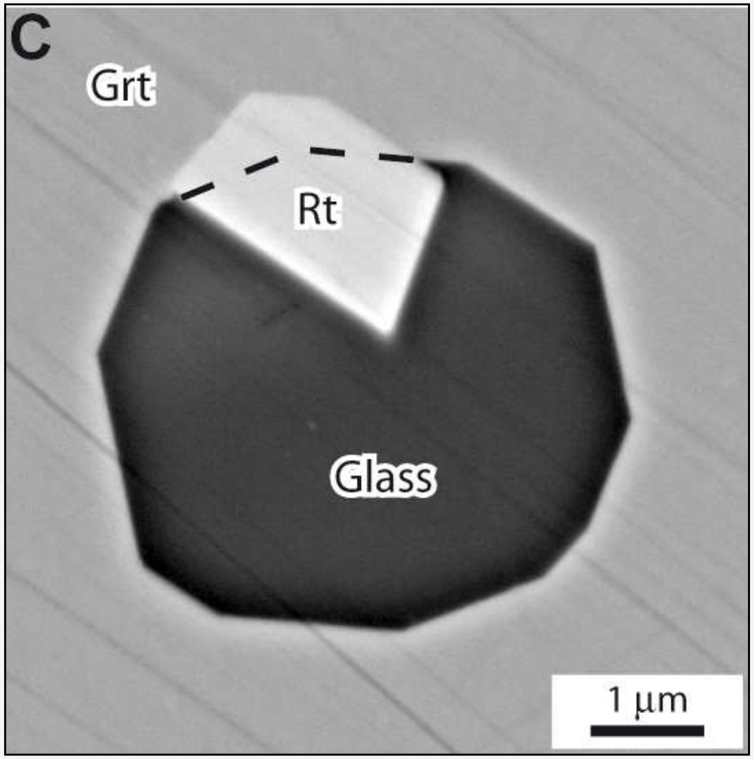


The surprise: *glassy* inclusions

Glass ± trapped phases



[Cesare et al., 2009]



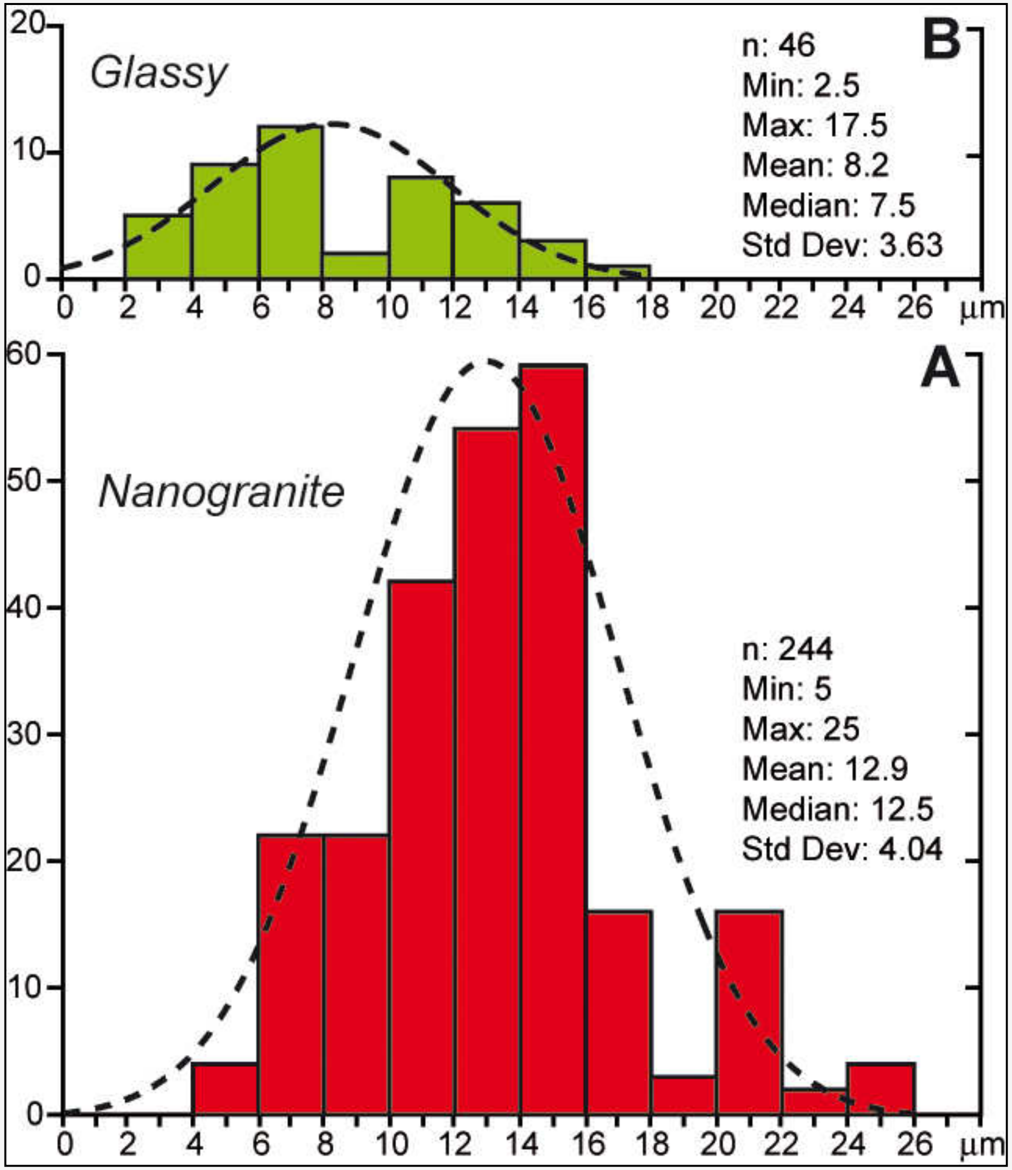
They coexist together in the same cluster

The surprise: *glassy* inclusions

Although there is a significant overlap, the two populations are statistically different,

→ **12.9 vs 8.2 µm**

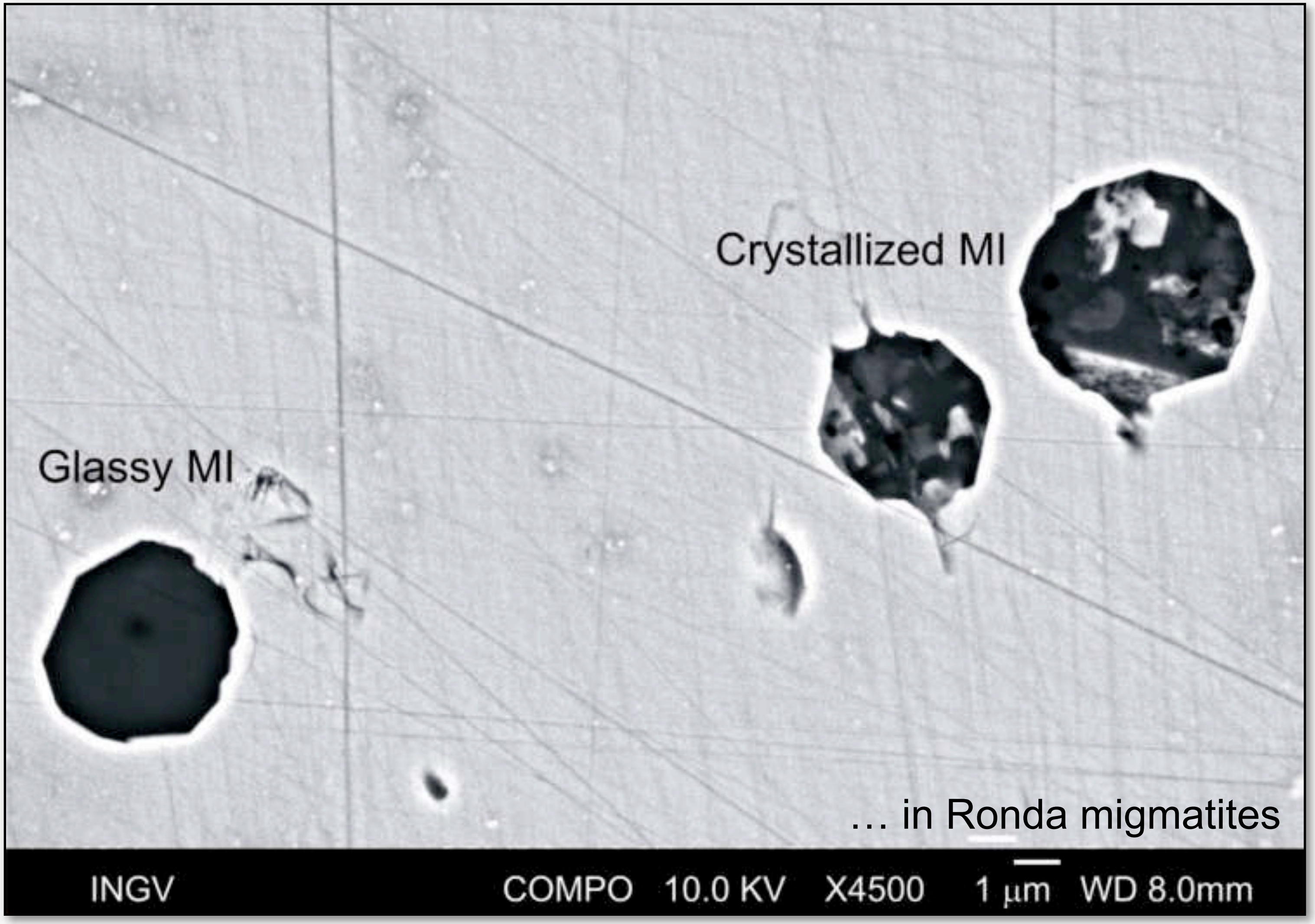
Most of the smaller inclusions remained amorphous (glassy) because of inhibited nucleation



[Cesare et al., 2009]

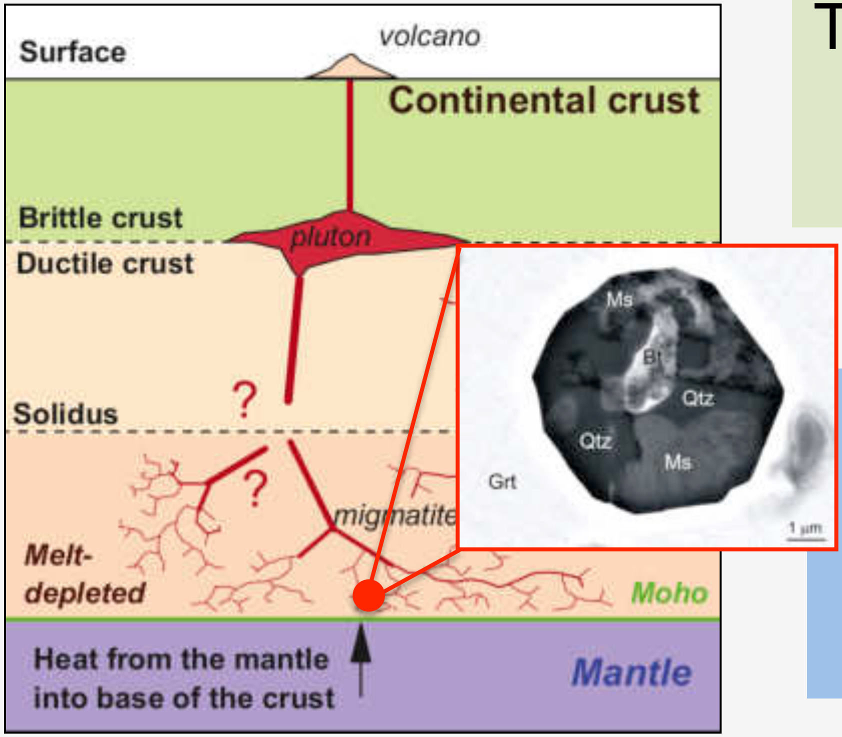
Does size really matter ?

We need more data…



… in Ronda migmatites

Nanogranitoid inclusions



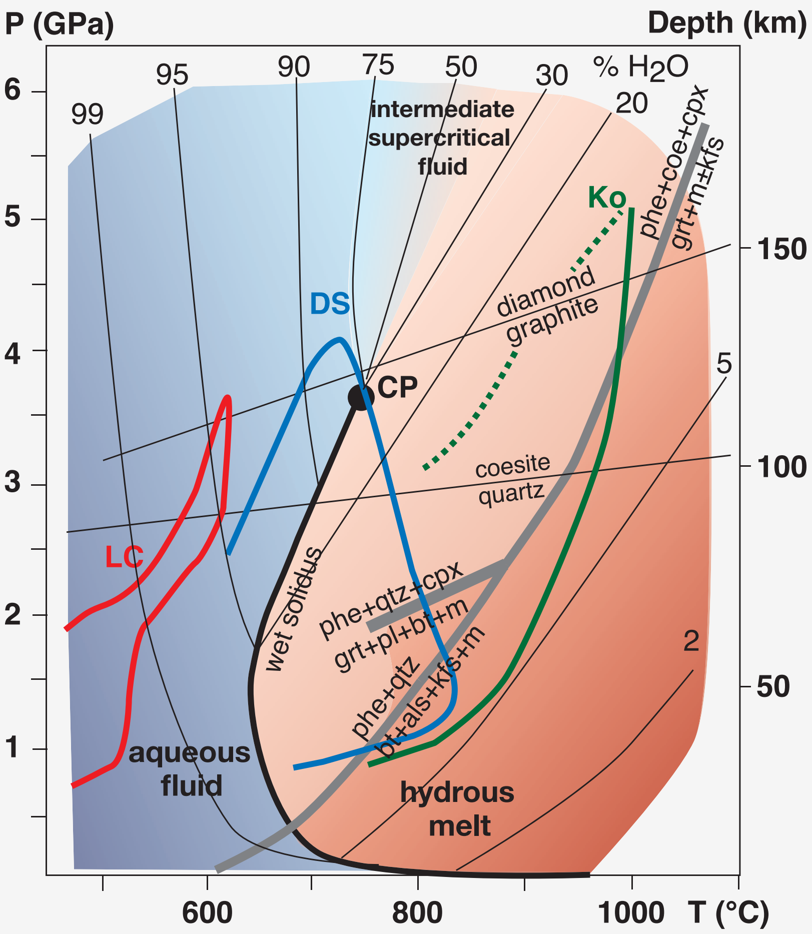
[Sawyer et al., 2011]

These small data repositories can provide the primary composition of crustal melts at the source

Nanogranitoids, which totally crystallized upon slow cooling, represent the embryos of the upper crustal granitoid magmas

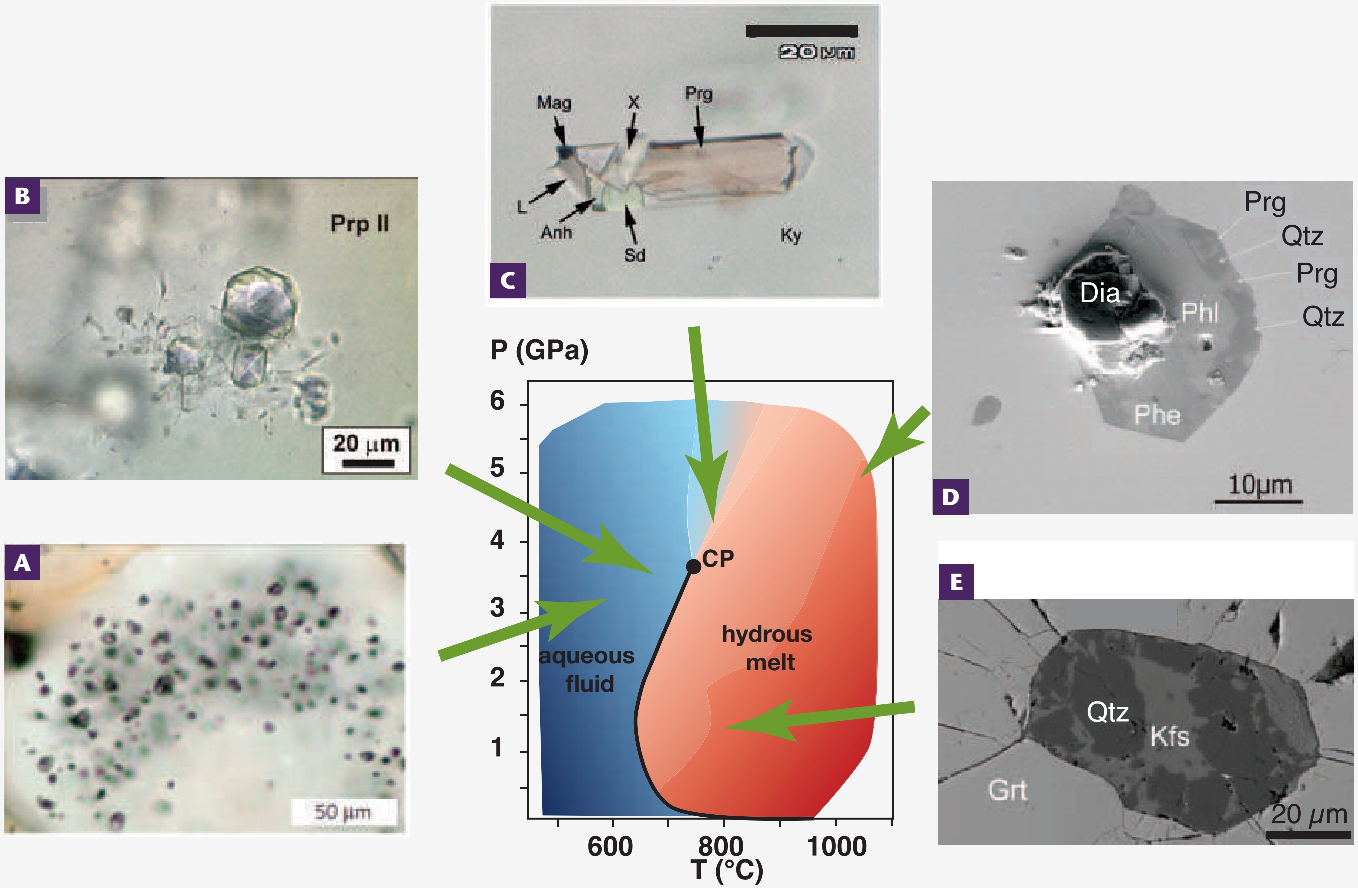
Fluids in the crust

The phase relations of rocks containing fluids at crustal pressures are well understood. For high water contents the fluid phase is called an “**aqueous fluid**”, whereas for low water and high solute contents, the fluid phase is a “**hydrous melt**”. **Supercritical fluids** are present above the CP; their water contents are transitional between those of aqueous fluid and hydrous melt



[Hermann et al., 2013]

Fluids in the crust



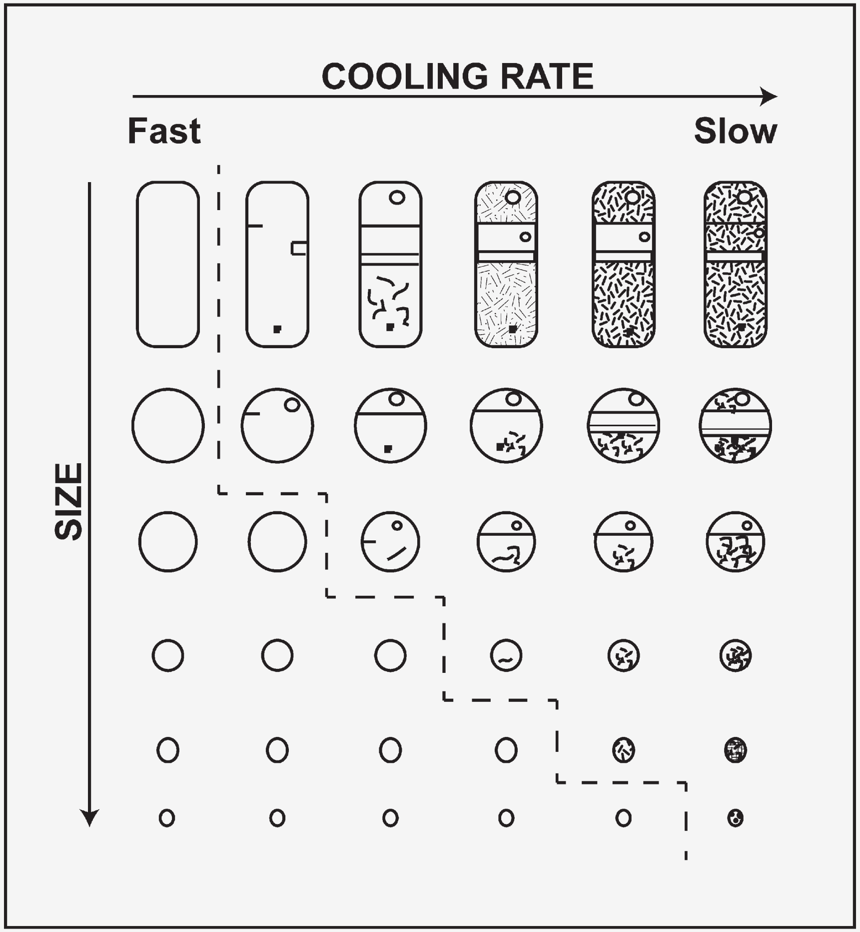
[Hermann et al., 2013]

In HP-UHP rocks, the term “multiphase solid inclusions” is often used (see Frezzotti & Ferrando, 2015)

How can nanogranitods be analyzed?

Recovering complete compositional data, including the volatile contents, requires the heating and remelting of the crystallized melt inclusions to a **homogeneous liquid**, reversing the phase change that occurred along cooling path after their entrapment (i.e. crystallization of daughter phases and fluid exsolution).

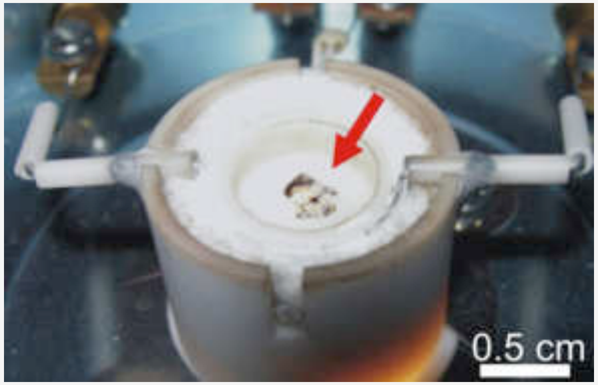
Experimental reheating



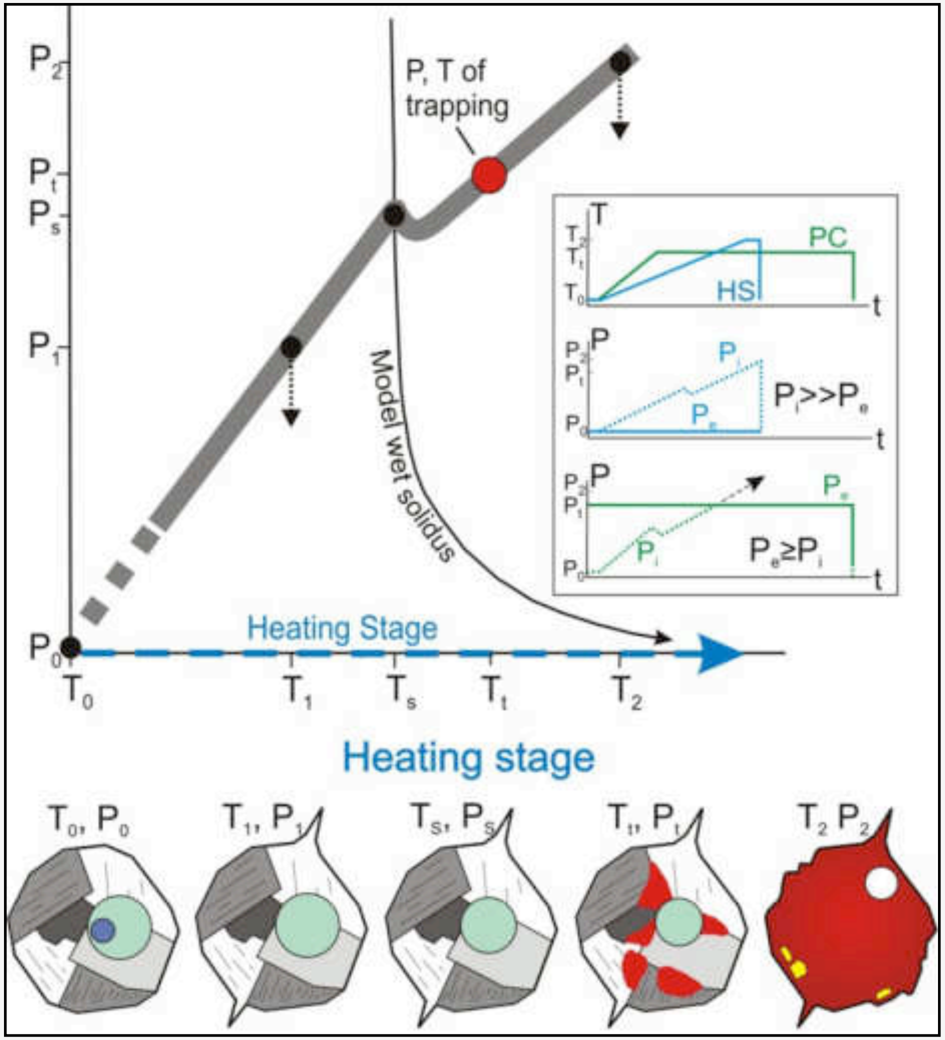
[Cannatelli et al., 2016]

How can nanogranitods be analyzed?

In the case of the microscope-mounted heating stage, the heating is usually conducted in an inert atmosphere of He to prevent sample oxidation.
Rock wafers containing MI-bearing minerals (e.g. garnet) are separated from double-polished thick (commonly 100–250 µm) sections.



How can nanogranitods be analyzed?



[Bartoli et al., 2013]

The obvious disadvantage of the remelting experiments at room pressure is the large overpressure generated in the MI $P_i >> P_e$

Nanogranitoids often decrepitate before remelting, with loss of volatiles (H_2O)

The rehomogenization occurs at temperature higher than the trapping conditions, favoring melt–host interaction and new minerals

How can nanogranitods be analyzed?

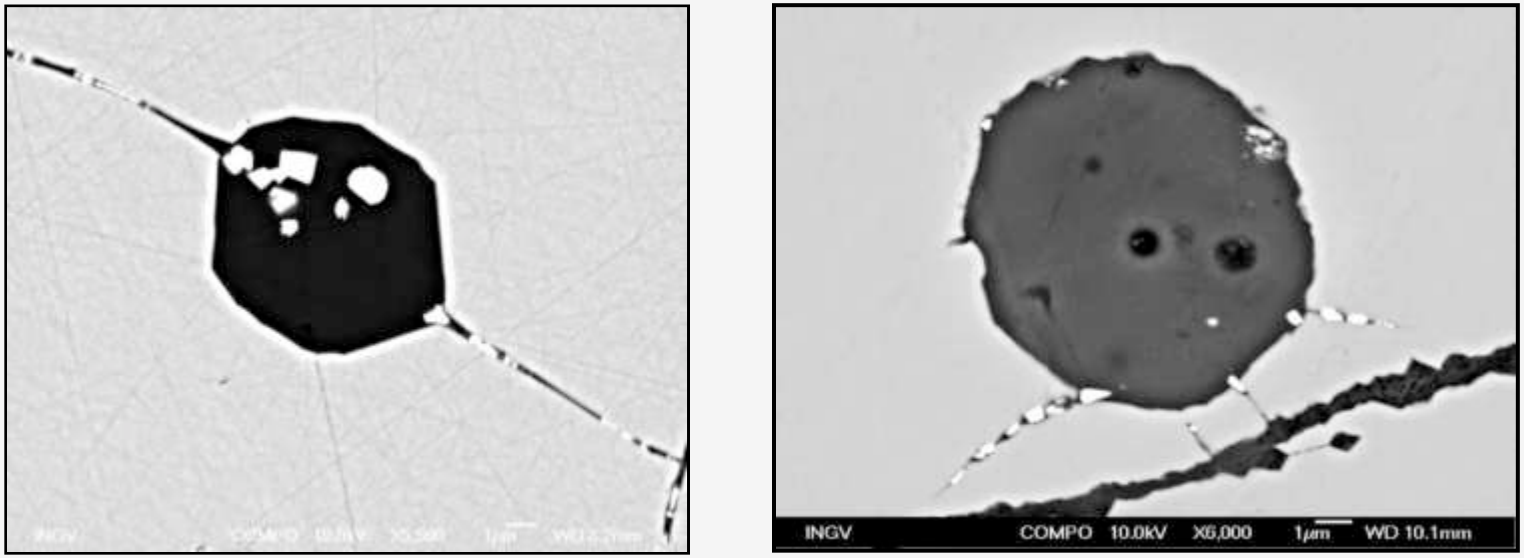
Nanogranitoids experimentally remelted by the heating stage are commonly characterized by

i) **irregular walls**

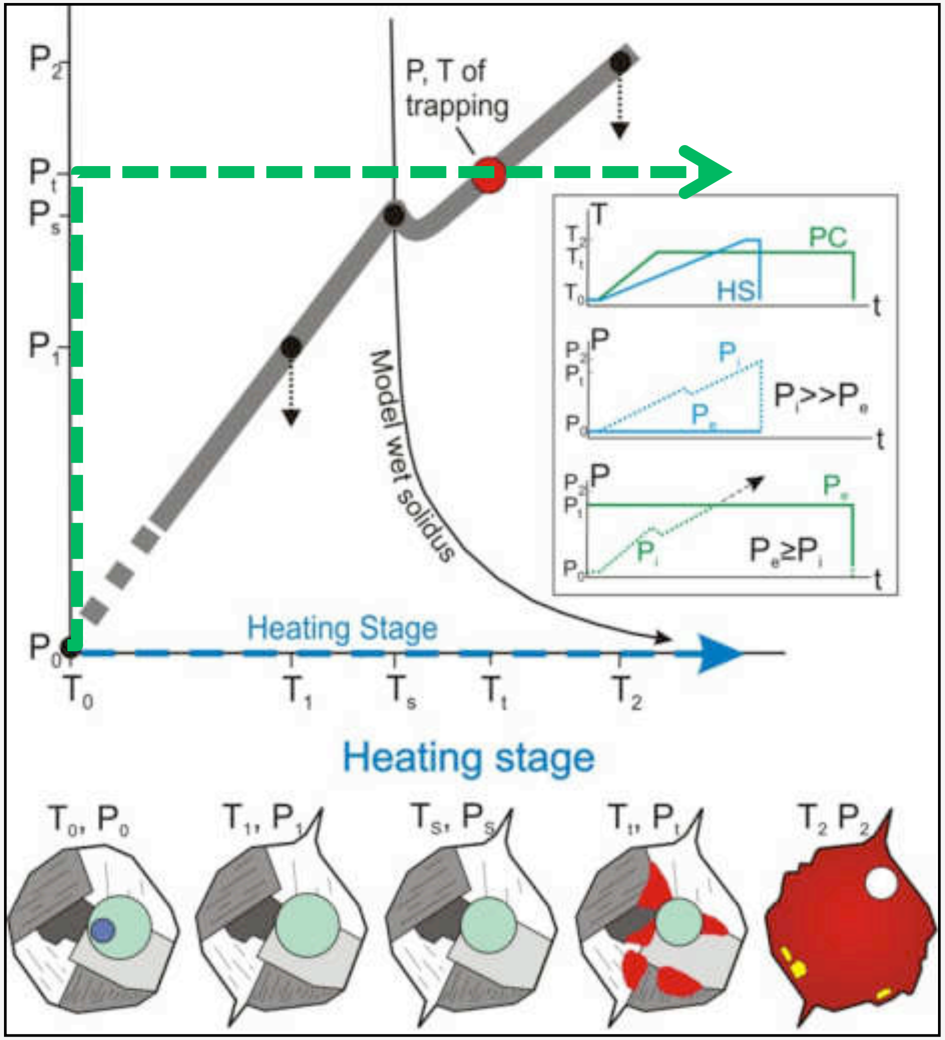
ii) decrepitation **cracks** filled with melt

iii) presence of **new crystals** (i.e., not observed in the starting material)

iv) the presence of **empty** (vacuum) **bubbles** formed to accommodate the volume lost by H_2O and melt leaving the inclusion



How can nanogranitods be analyzed?



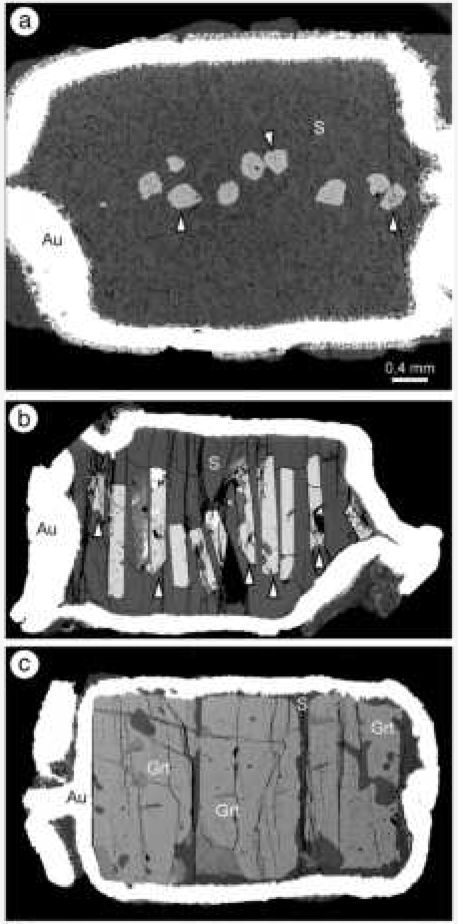
[Bartoli et al., 2013]

Homogenization under confining pressure using **a piston cylinder apparatus** may overcome the problems described above

How can nanogranitods be analyzed?

MI-bearing minerals are loaded into Au or Pt capsules (external diameter of 3 and 5 mm) together with powdered silica

Because the abundance and the microstructural distribution of nanogranitods vary from sample to sample, <u>different strategies can be adopted</u>

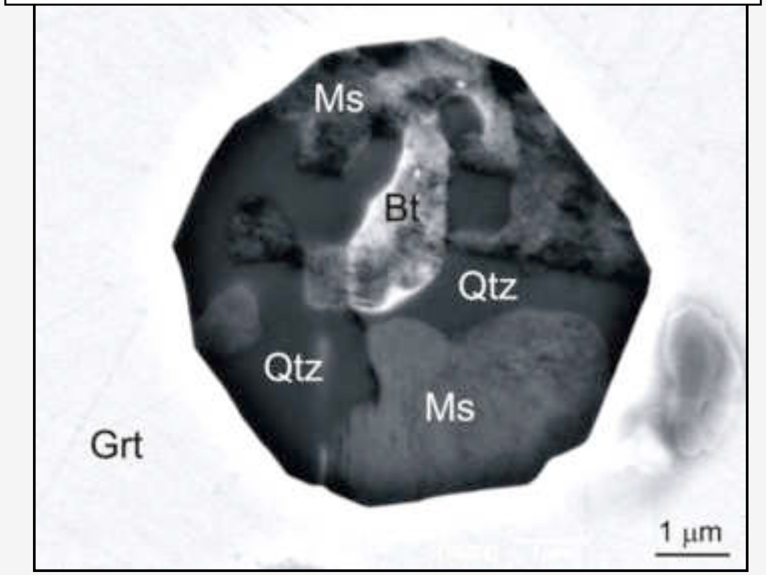


[Cesare et al., 2015]

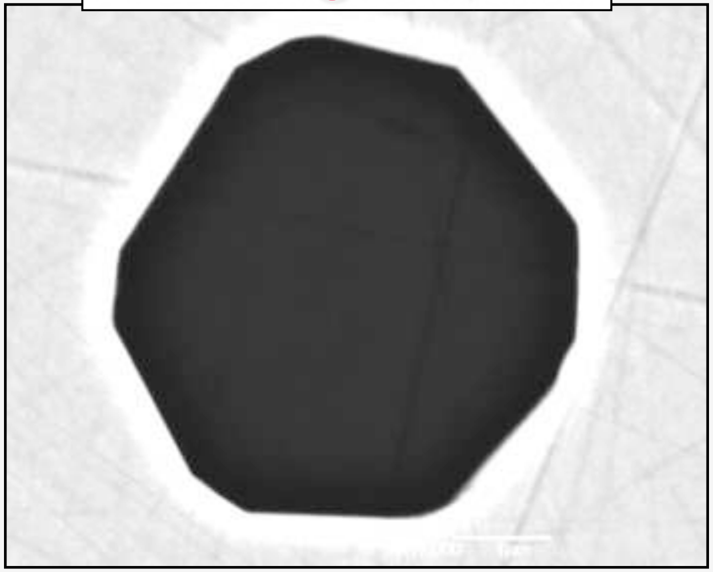
How can nanogranitods be analyzed?

Despite the <u>trial-and-error nature of this approach</u>, much better quality compositional data can be obtained using a piston-cylinder because several MI-bearing crystals, and in turn a large number of MI, can be rehomogenized simultaneously, once the trapping conditions are determined

Nanogranite inclusions at Ronda: BEFORE



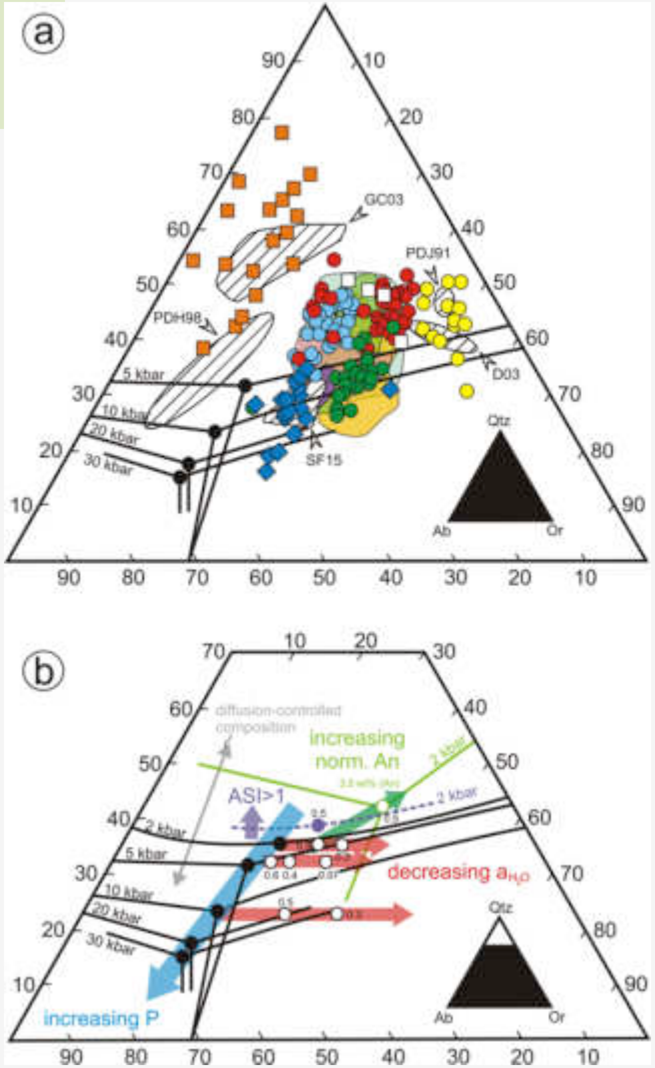
AFTER 24h @ 700°C, 5 kbar

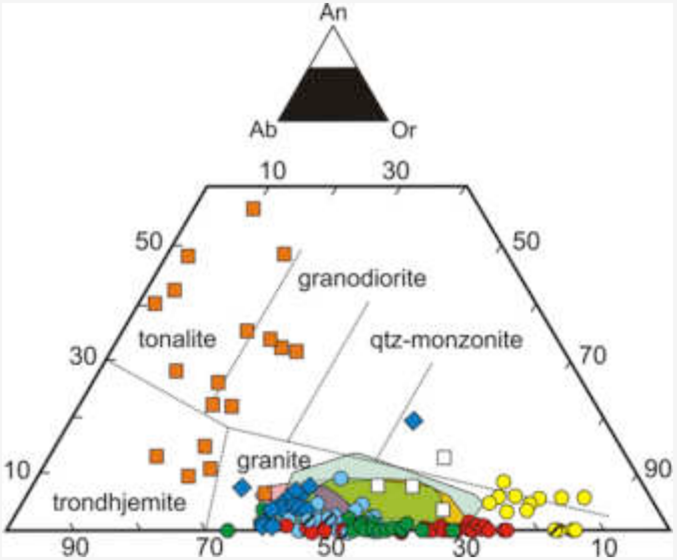


How can nanogranitods be analyzed?

Regarding the major elements, approximately 600 nanogranitoids in migmatites and granulites have been analyzed by EMP

Nanogranitoids from each locality show some spread and, at the same time, a distinctive composition with respect to each other

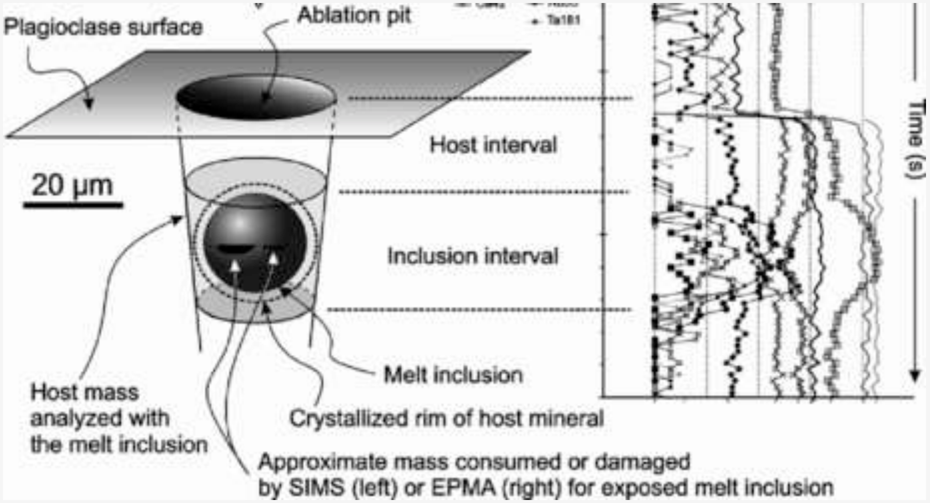




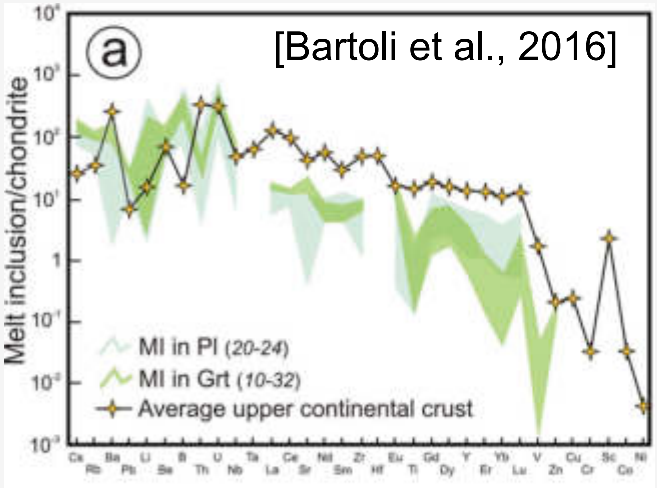
[Bartoli et al., 2016]

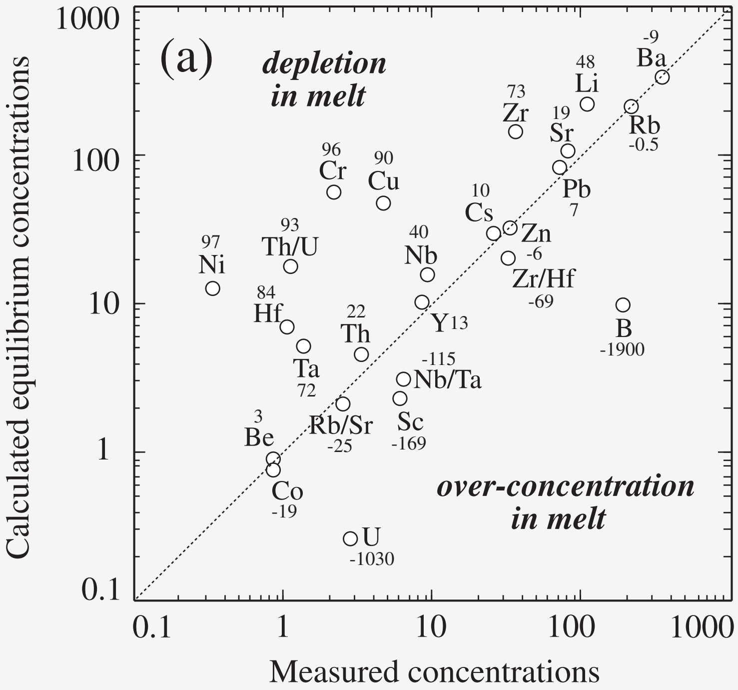
How can nanogranitods be analyzed?

LA-ICP-MS (trace elements)



[Petke et al., 2006]

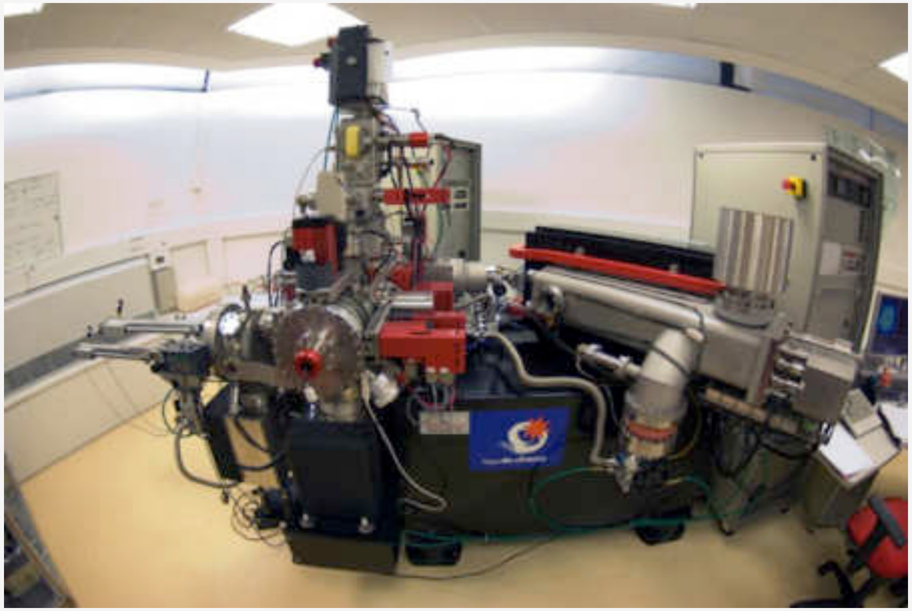

[Bartoli et al., 2016]

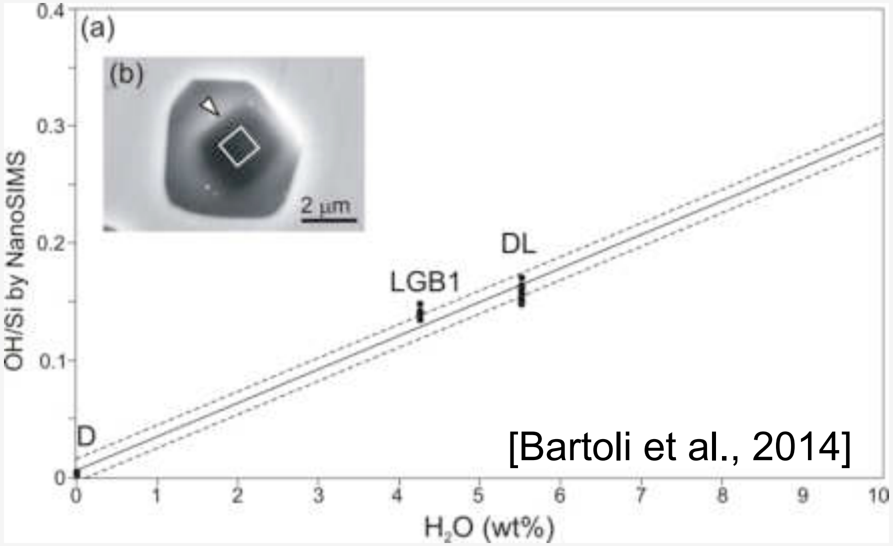


[Acosta-Vigil et al., 2012]

How can nanogranitods be analyzed?

NanoSIMS (H_2O and CO_2)





[Bartoli et al., 2014]

Pausa ???

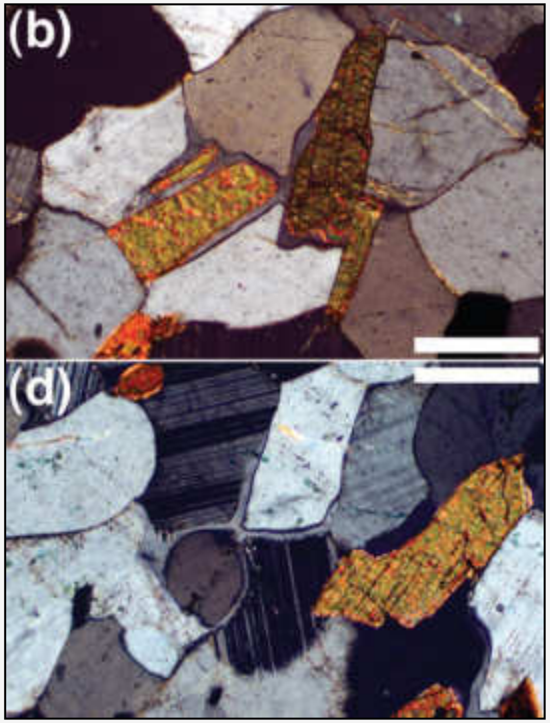
Seminar Outline

- How do melt inclusions form?
- Melt inclusions in igneous rocks
- High-temperature metamorphism
- Entrapment of melt inclusions during crustal anatexis
- How are melt inclusions identified ?
- How are melt inclusions microstructurally characterized ?
- How can melt inclusions be analyzed ?
- What can we learn from nanogranitoids inclusions ?
- Problems and pitfalls
- Concluding remarks

What can we learn from nanogranitoids?

1) That a rock has melted

There are many microstructural criteria for inferring the former presence of melt in regionally metamorphosed migmatite and granulite terrains which have undergone slow cooling over millions of years

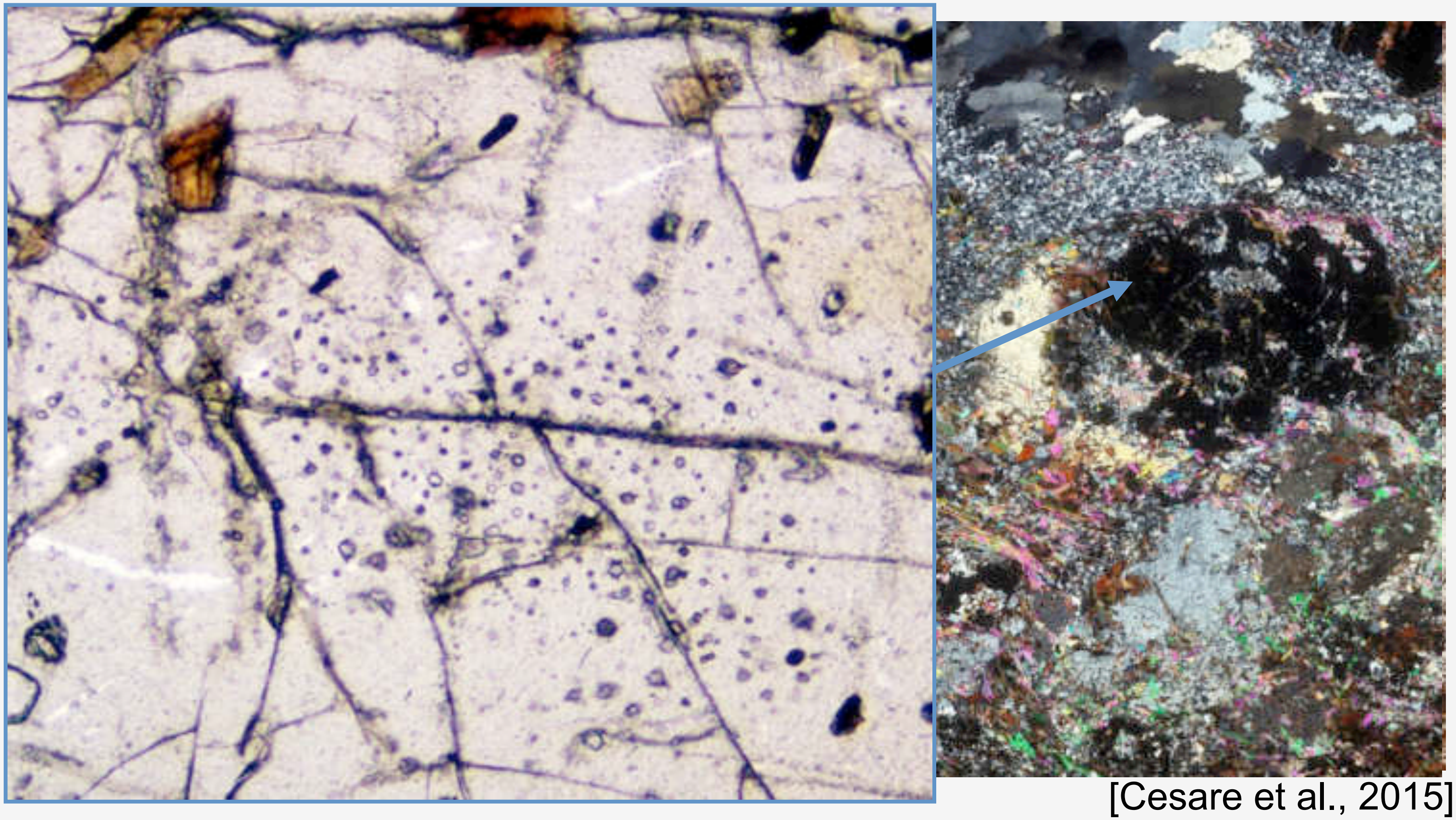

Mineral pseudomorphs after melt films and pools


Crystals with euhedral shapes

[Holness & Sawyer, 2008]

What can we learn from nanogranitoids?

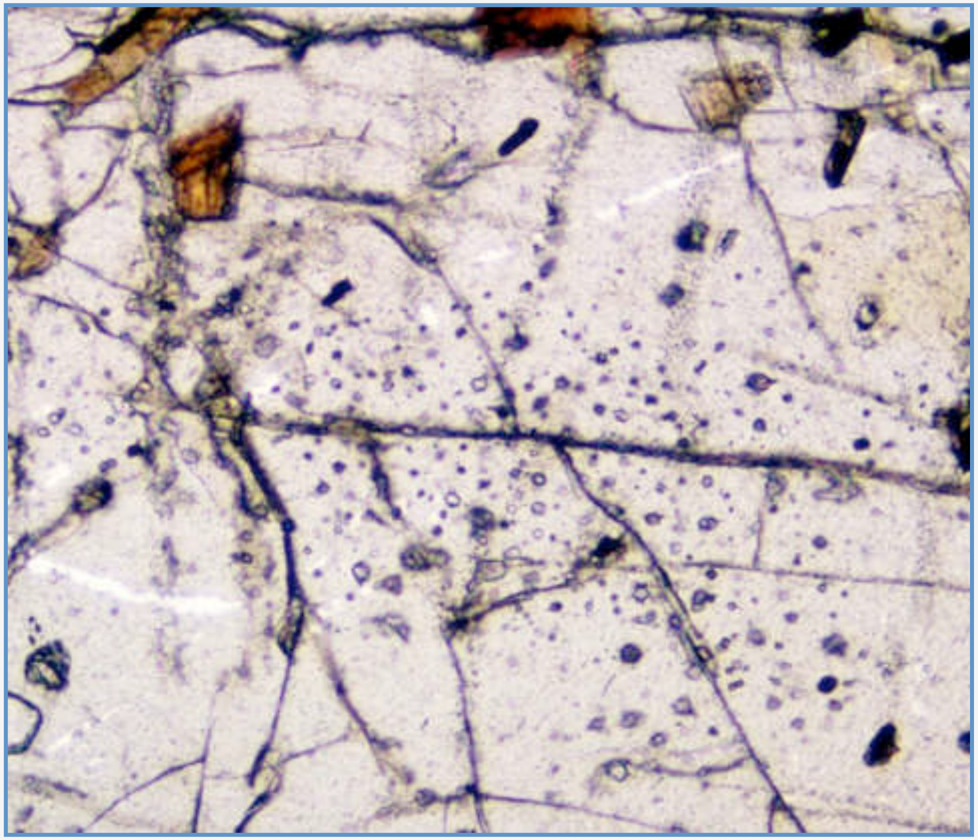
However, recrystallization and deformation in the subsolidus may completely erase most or all evidences of partial melting



[Cesare et al., 2015]

What can we learn from nanogranitoids?

1) That a rock has melted

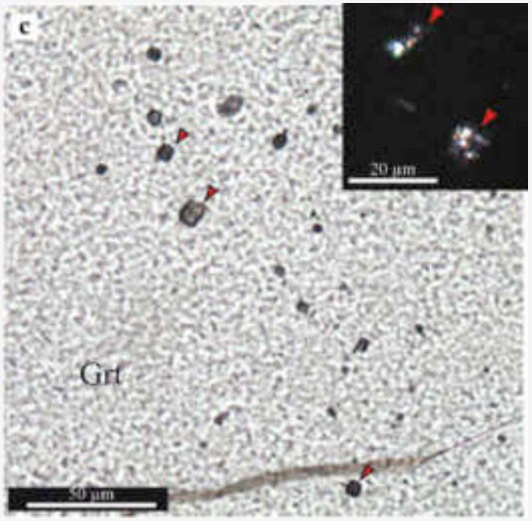


The only evidence that these rocks underwent anatexis at some time in their complex history is represented by the occurrence of nanogranitoid inclusions within relics of Variscan garnet

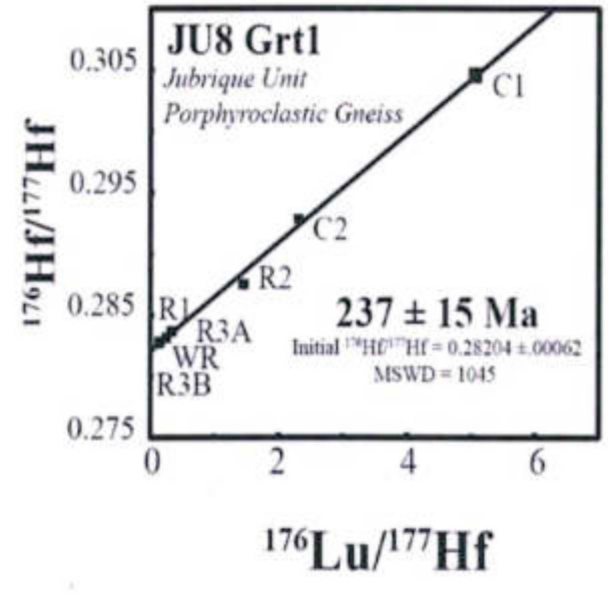
What can we learn from nanogranitoids?

2) When a rock has melted

Because nanogranitoids attest to the growth of a mineral during crustal melting, the geochronology applied on that host mineral allows anatectic events to be dated with unprecedented confidence



[Acosta-Vigil et al., 2016]

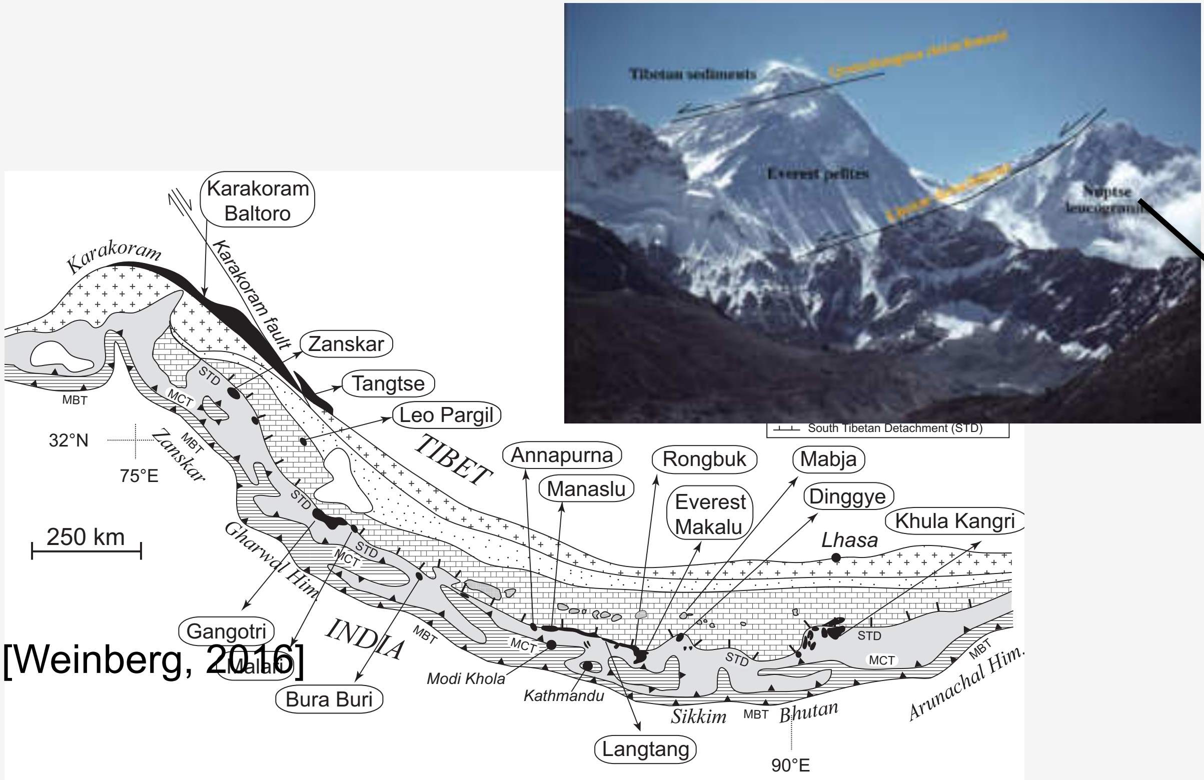


[Barich et al., in prep.]

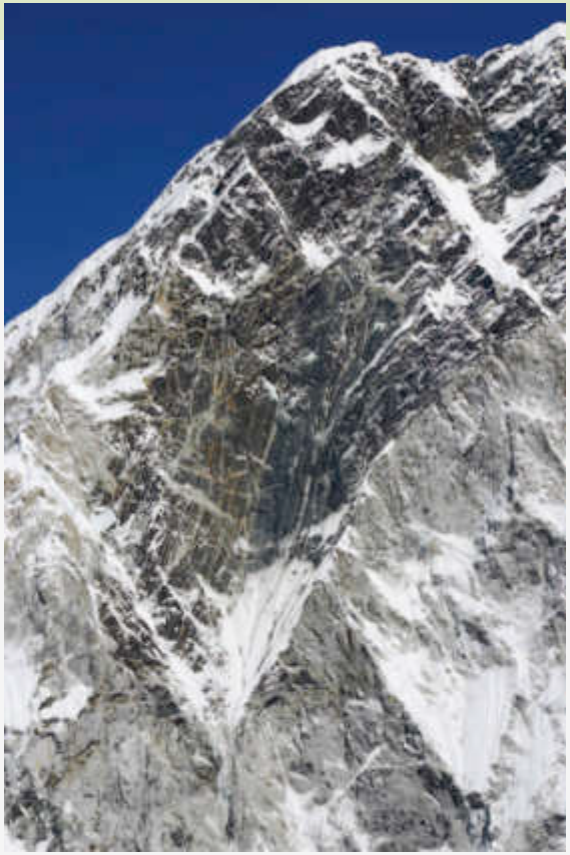
What can we learn from nanogranitoids?

2) When a rock has melted

Very little evidence of partial melting during prograde metamorphism has been reported until now (Himalayas)



[Weinberg, 2016]



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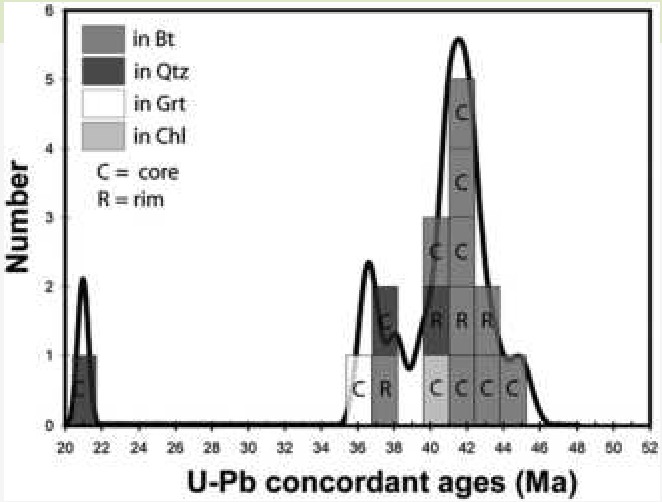
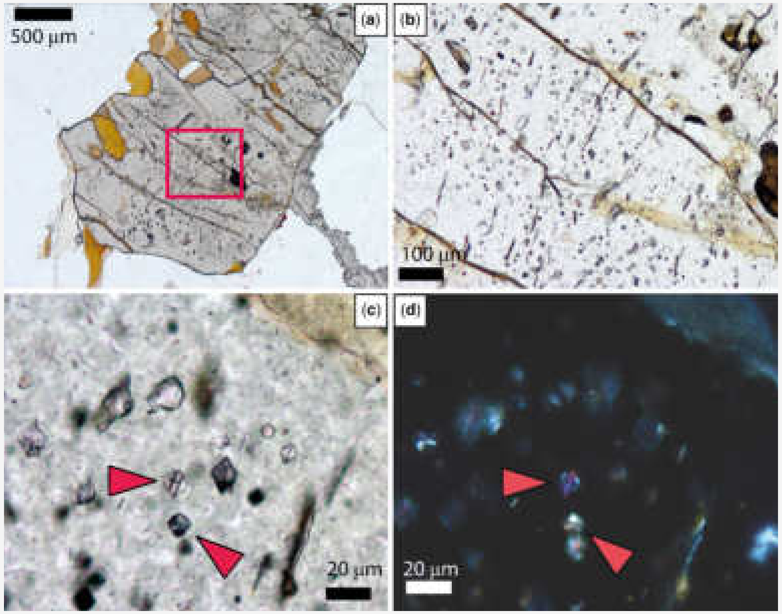




[Carosi et al., 2015]

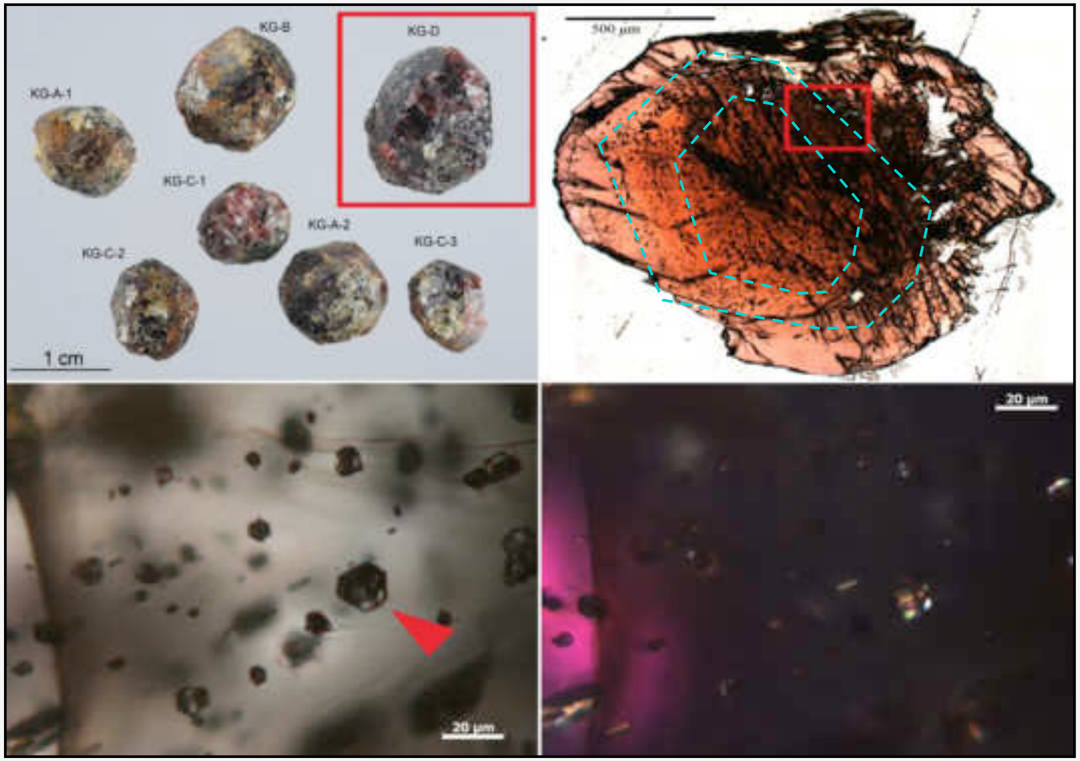
In situ U–Th–Pb dating of monazite included in garnets, in the same structural positions as MI, constrains the beginning of partial melting at 41–36 Ma

What can we learn from nanogranitoids?

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

MI show a systematic distribution in an annulus around garnet core. This distribution matches the concentric chemical zoning of the garnet

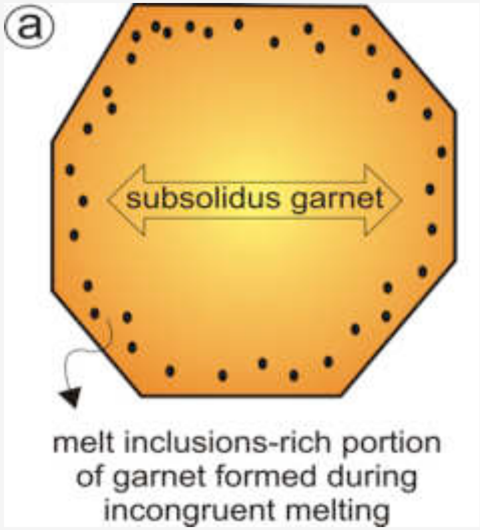
These microstructures demonstrate that the MI-rich annuli certainly formed during anatexis

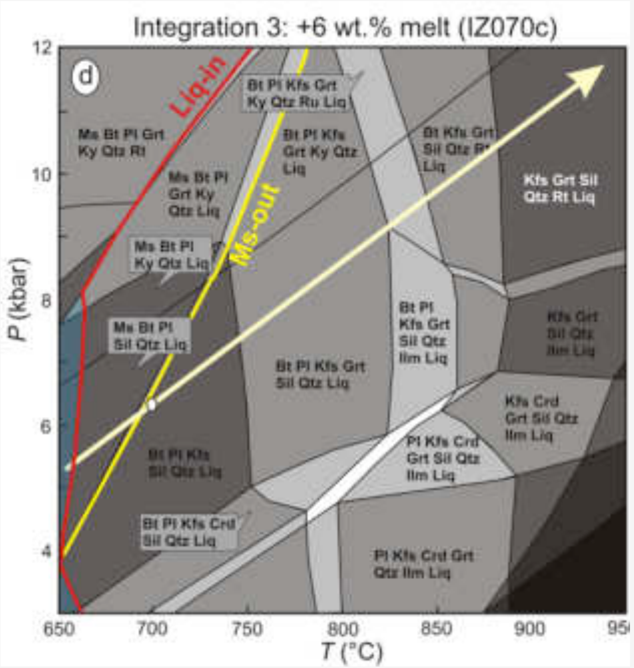


[Cesare et al., 2015]

What can we learn from nanogranitoids?

4) The construction of a plausible effective bulk composition for the melting event can take advantage of both i) **the reintegration of nanogranitoid composition** and ii) **the removal of elements fractionated in the subsolidus garnet core**

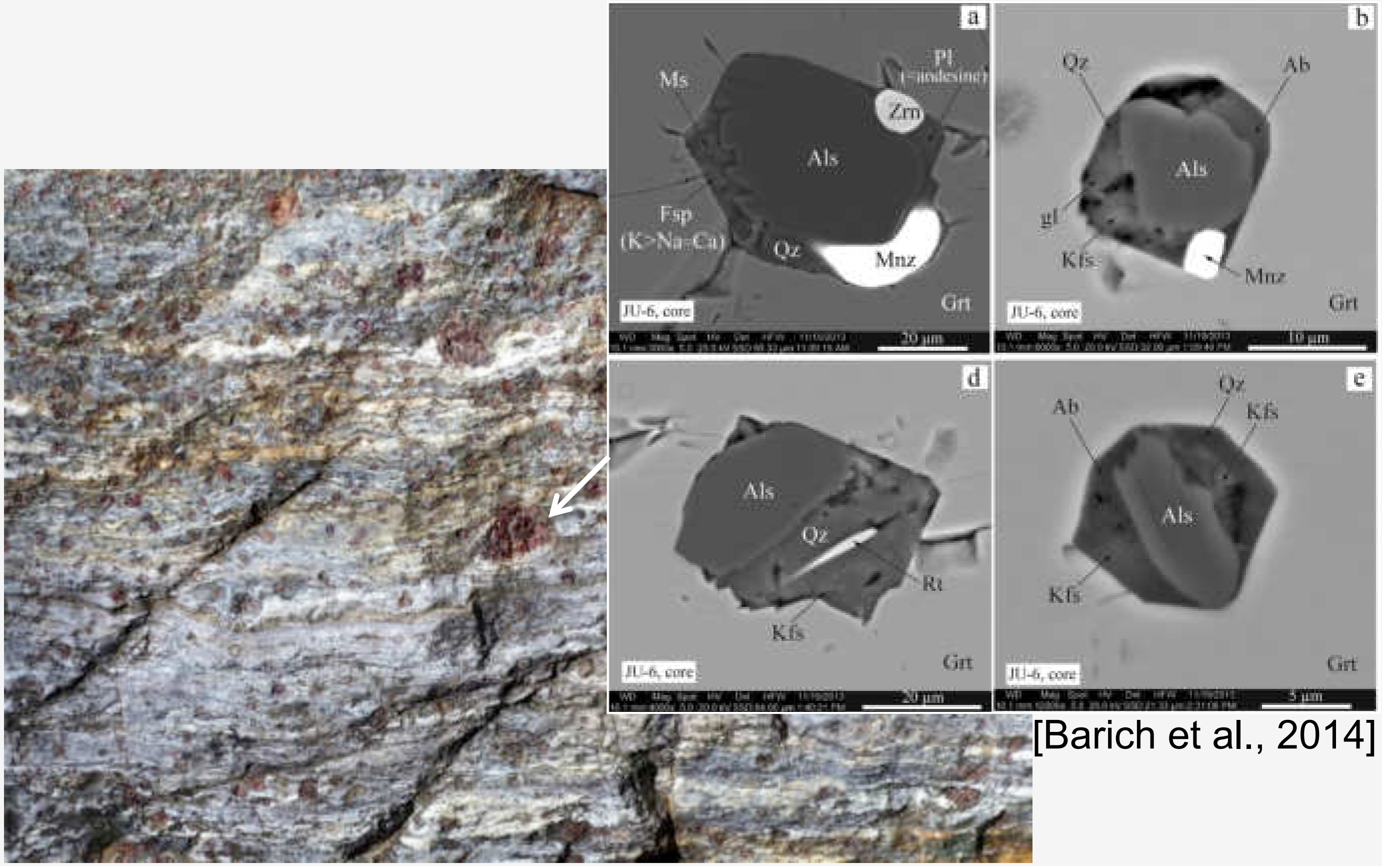




[Bartoli, 2018]

What can we learn from nanogranitoids?

5) Placing melt in the right phase assemblage



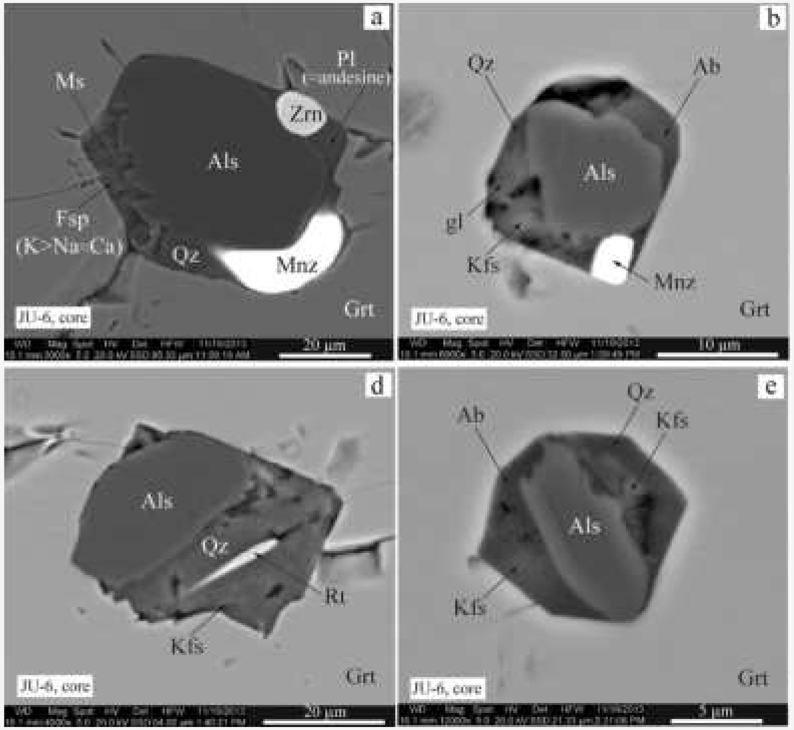
[Barich et al., 2014]

Crystals of kyanite represent the main solid inclusion that favored the entrapment of melt during Grt growth

What can we learn from nanogranitoids?

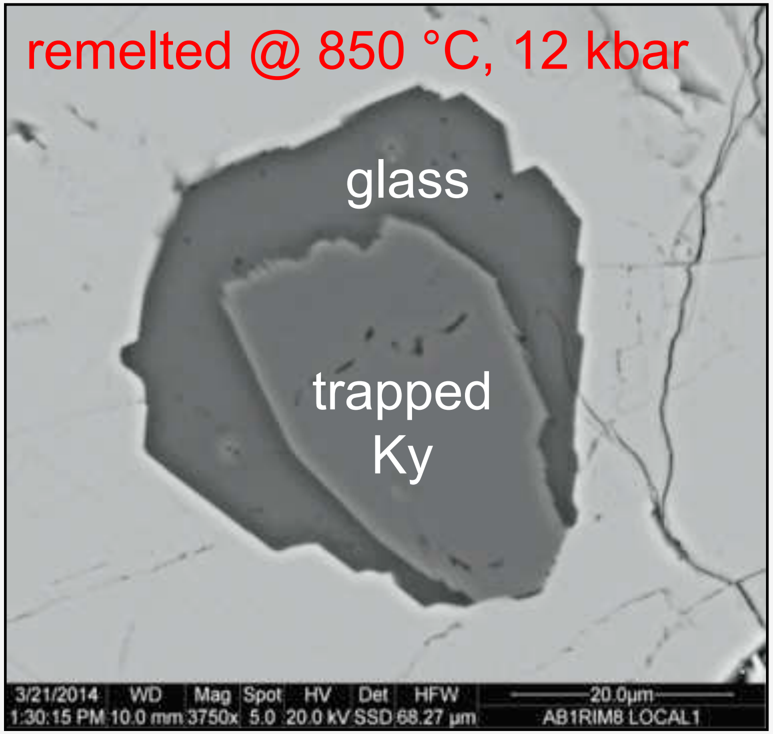
5) Placing melt in the right phase assemblage

Before



[Barich et al., 2014]

After



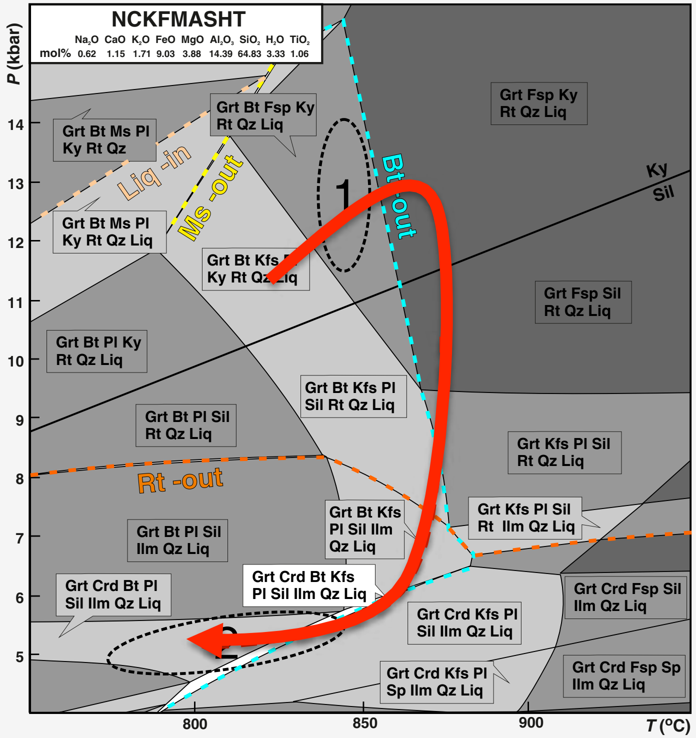
[Acosta-Vigil et al., 2016]

What can we learn from nanogranitoids?

5) Placing melt in the right phase assemblage

Earlier studies proposed that anatexis started in the field of sillimanite during decompression from peak pressures (Platt et al., 2003)

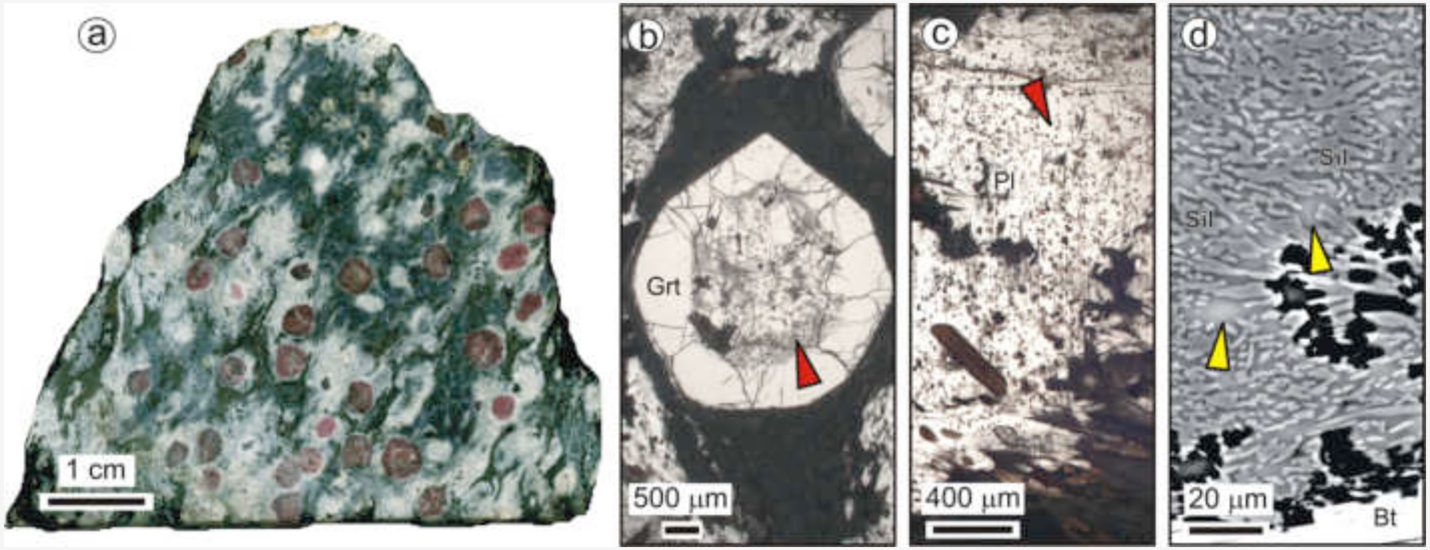
The study of nanogranitoids demonstrated that melt was already present in the system at peak conditions in the kyanite field (Barich et al., 2014)



[Barich et al., 2014]

What can we learn from nanogranitoids?

6) Mechanisms of crustal melting



[Bartoli, 2017]

These enclaves represent a snapshot of anatexis in the medium-to-lower crust, frozen due to the extrusion and rapid cooling of the host lava (frozen migmatites)

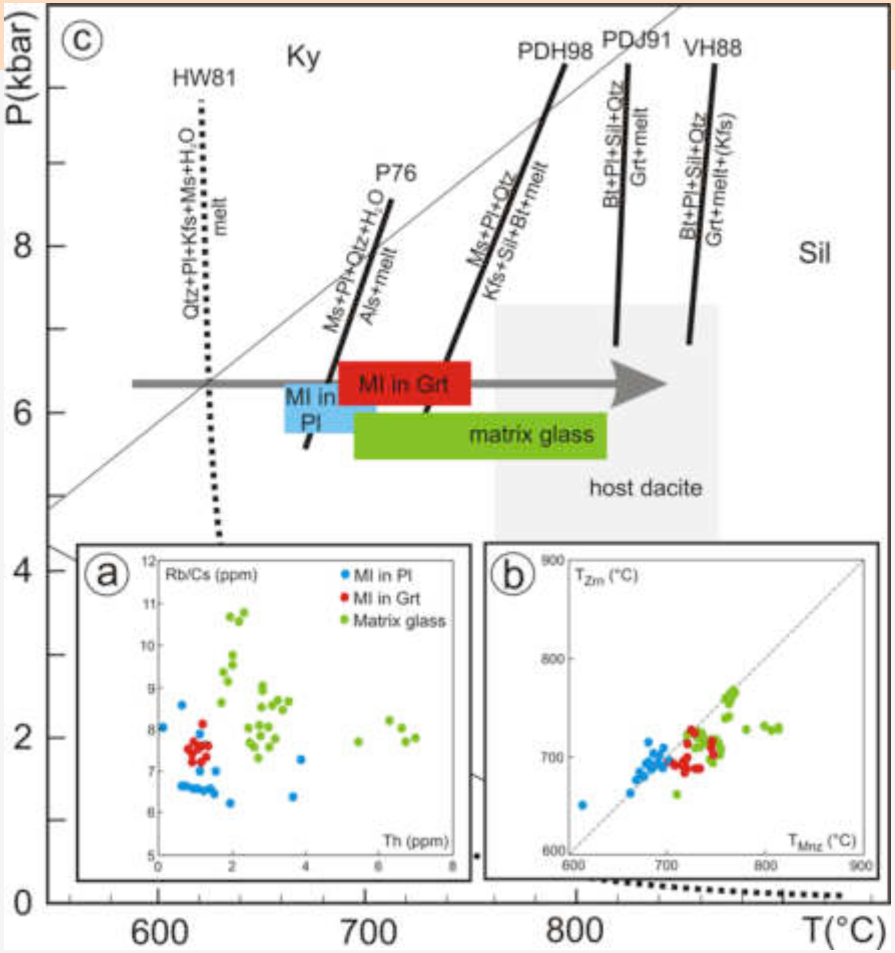
What can we learn from nanogranitoids?

6) Mechanisms of crustal melting

MI in plagioclase → earliest granitic melts produced by fluid-present to fluid-absent muscovite melting

MI in garnet → produced simultaneously to slightly later via fluid-absent melting of muscovite

Matrix melt → formed at higher temperatures by biotite dehydration-melting reactions

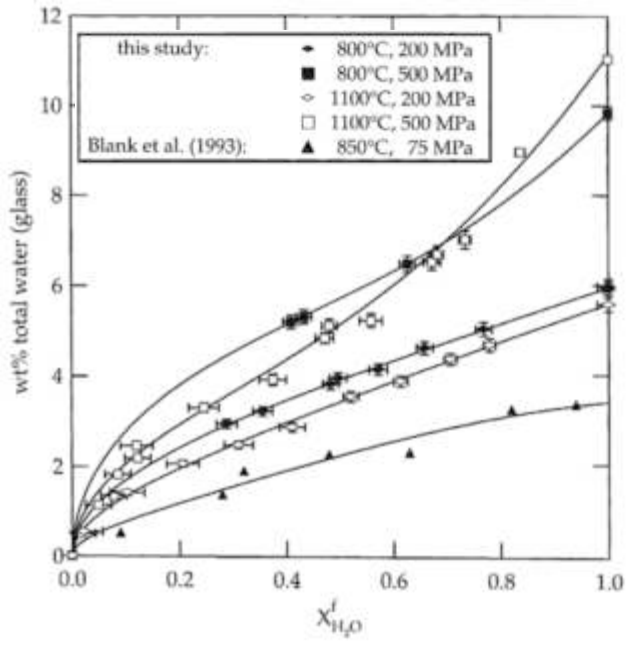


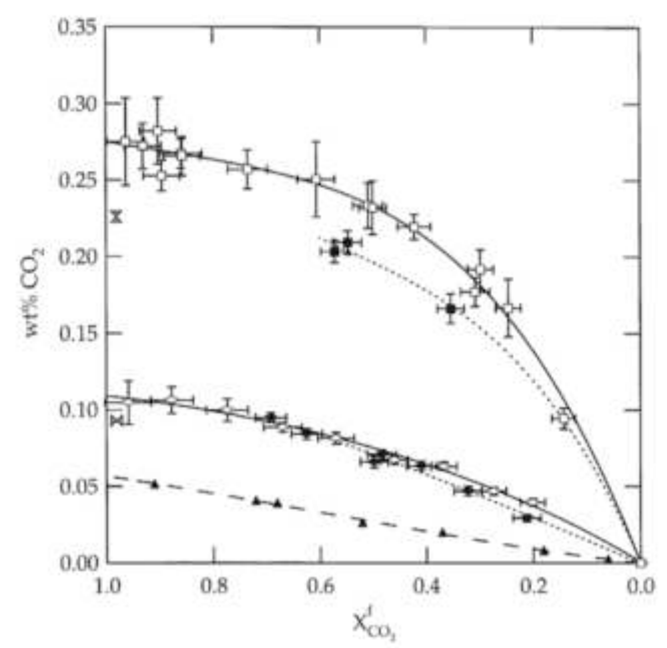
[Bartoli et al., 2016]

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility

Melt-fluid immiscibility in anatectic systems occurs when the quantity of fluid exceeds the amount that is soluble/miscible in the melt at the pressure and temperature of interest



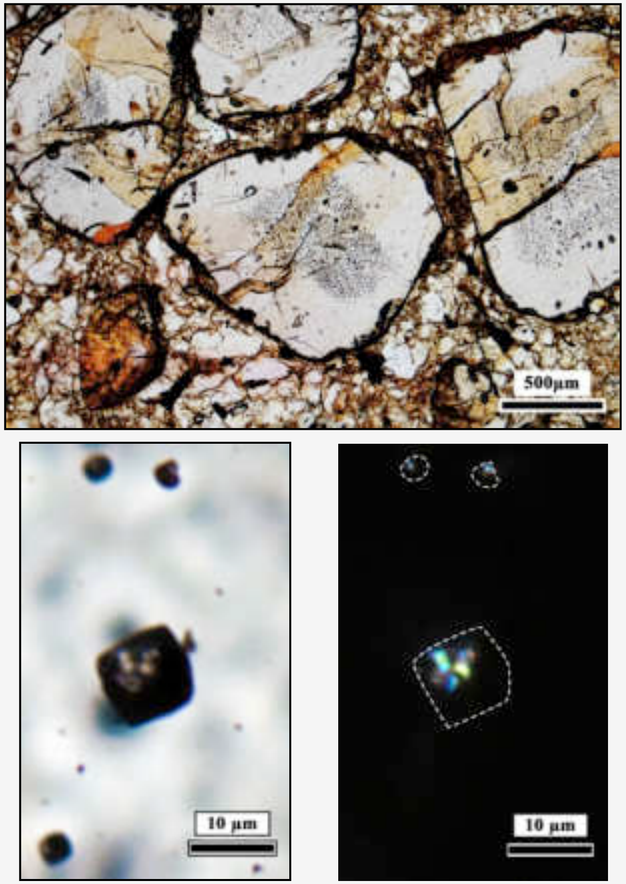


[Tamic et al., 2001]

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility

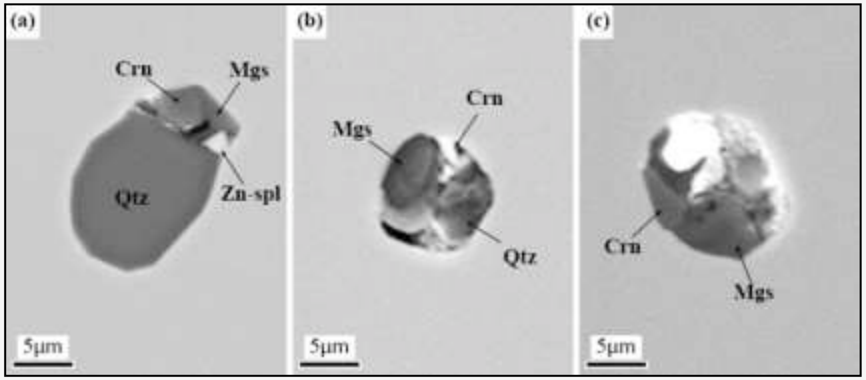
[Tacchetto et al., submitted]



The zonal distribution of inclusions supports their primary origin i.e., that they have been trapped during the garnet growth

What can we learn from nanogranitoids?

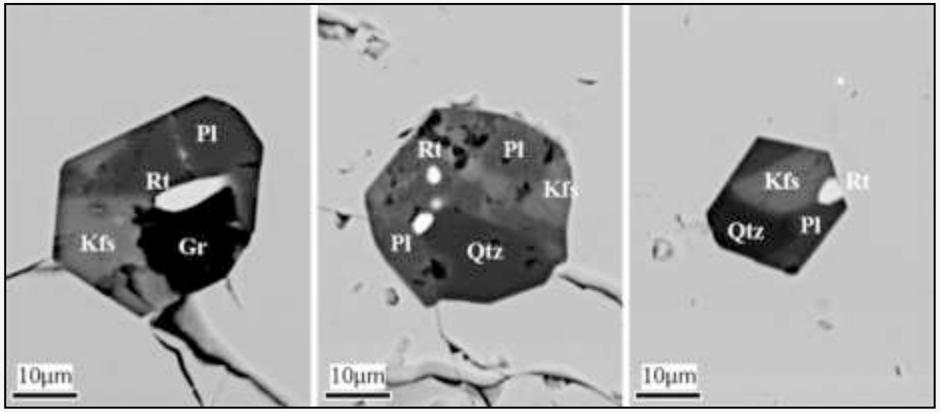
7) Melt-fluid immiscibility



TYPE I
5 < Ø < 10 μm
Quartz
Mg-Fe-Ca carbonates
Corundum
Gr ± Spl

SEM analysis

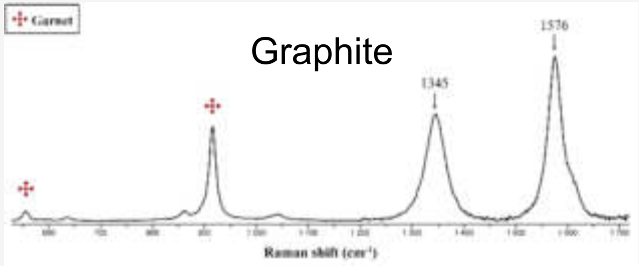
TYPE II (nanogranitoids)
10 < Ø < 20 μm
Quartz
K-feldspar
Plagioclase
Gr ± Rt ± Bt ± Al-Si

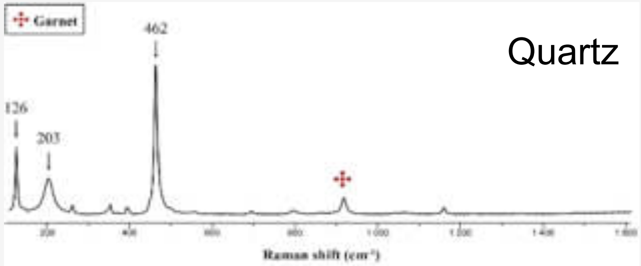


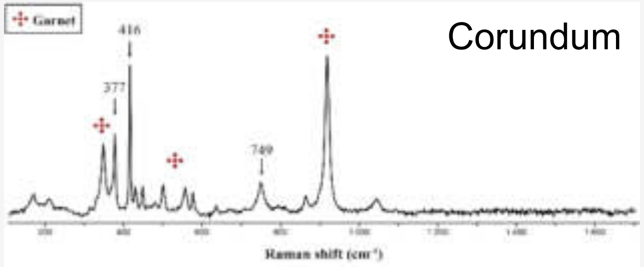
[Tacchetto et al., submitted]

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility

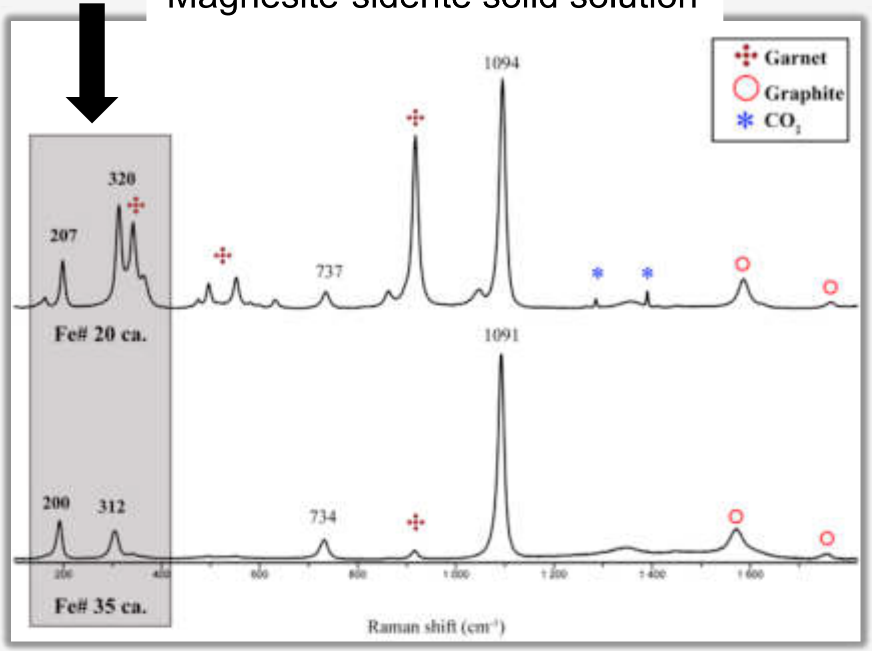

Graphite


Quartz


Corundum

Raman microspectroscopy (Tipe I)

Magnesite-siderite solid solution

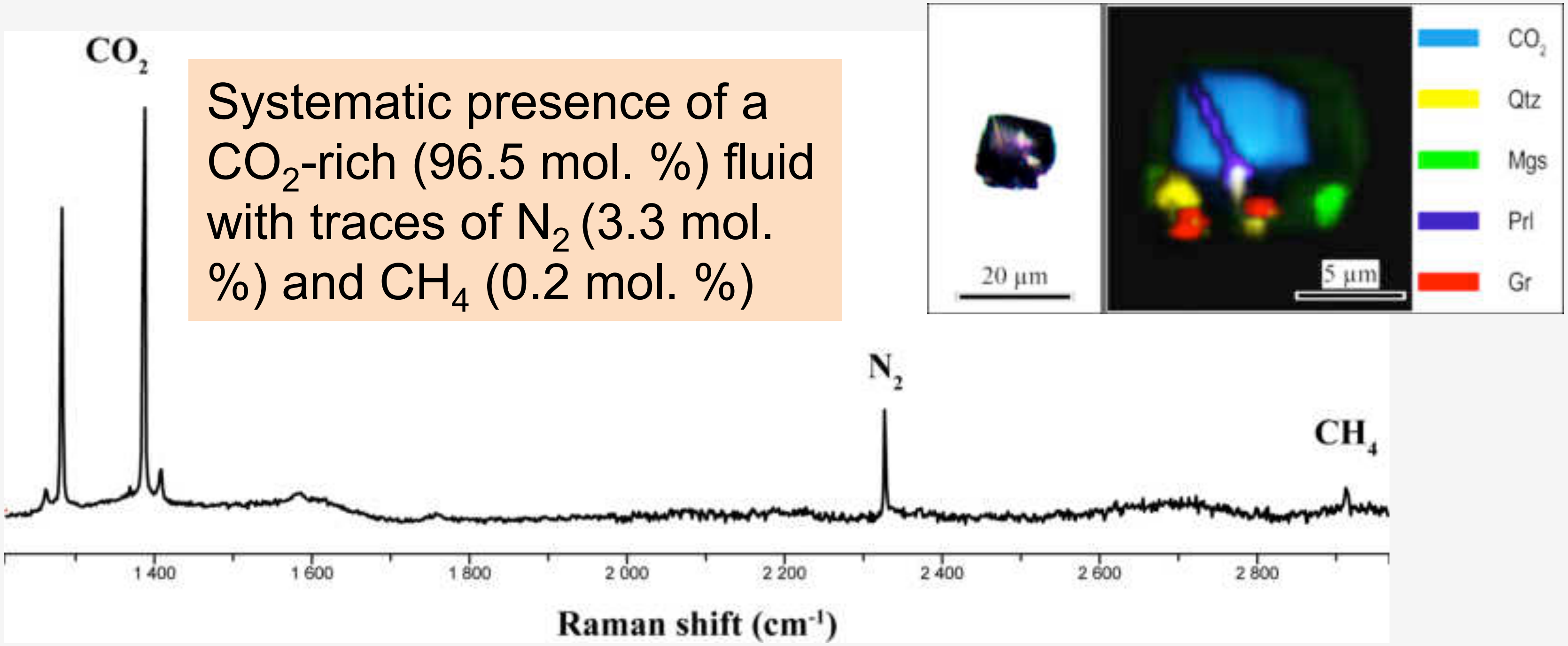


[Tacchetto et al., submitted]

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility

Raman microspectroscopy (Tipe I)



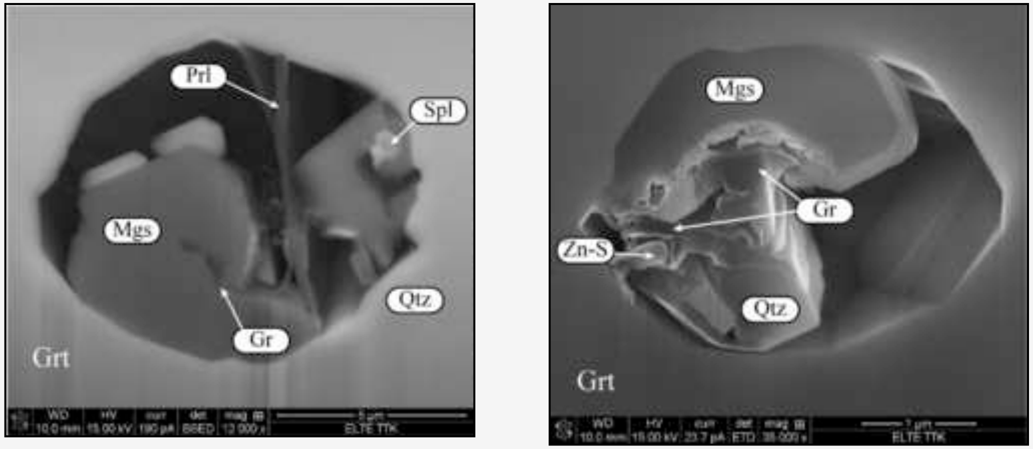
Systematic presence of a CO_2-rich (96.5 mol. %) fluid with traces of N_2 (3.3 mol. %) and CH_4 (0.2 mol. %)

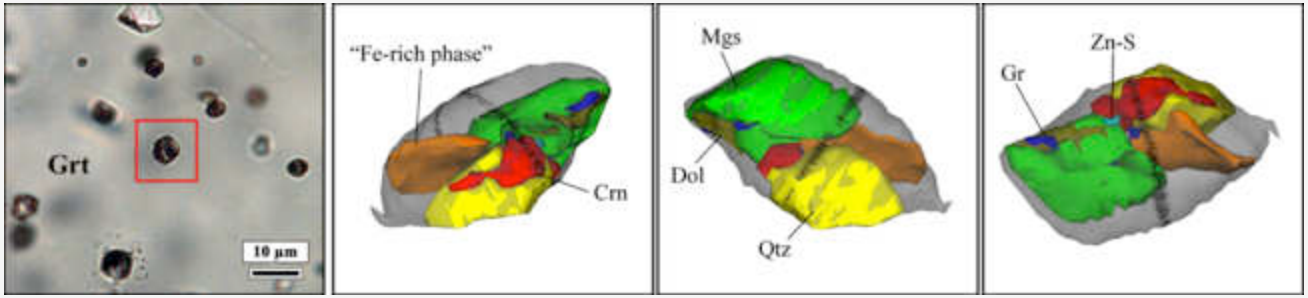
[Tacchetto et al., submitted]

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility

FIB-SEM analyis (Tipe I)



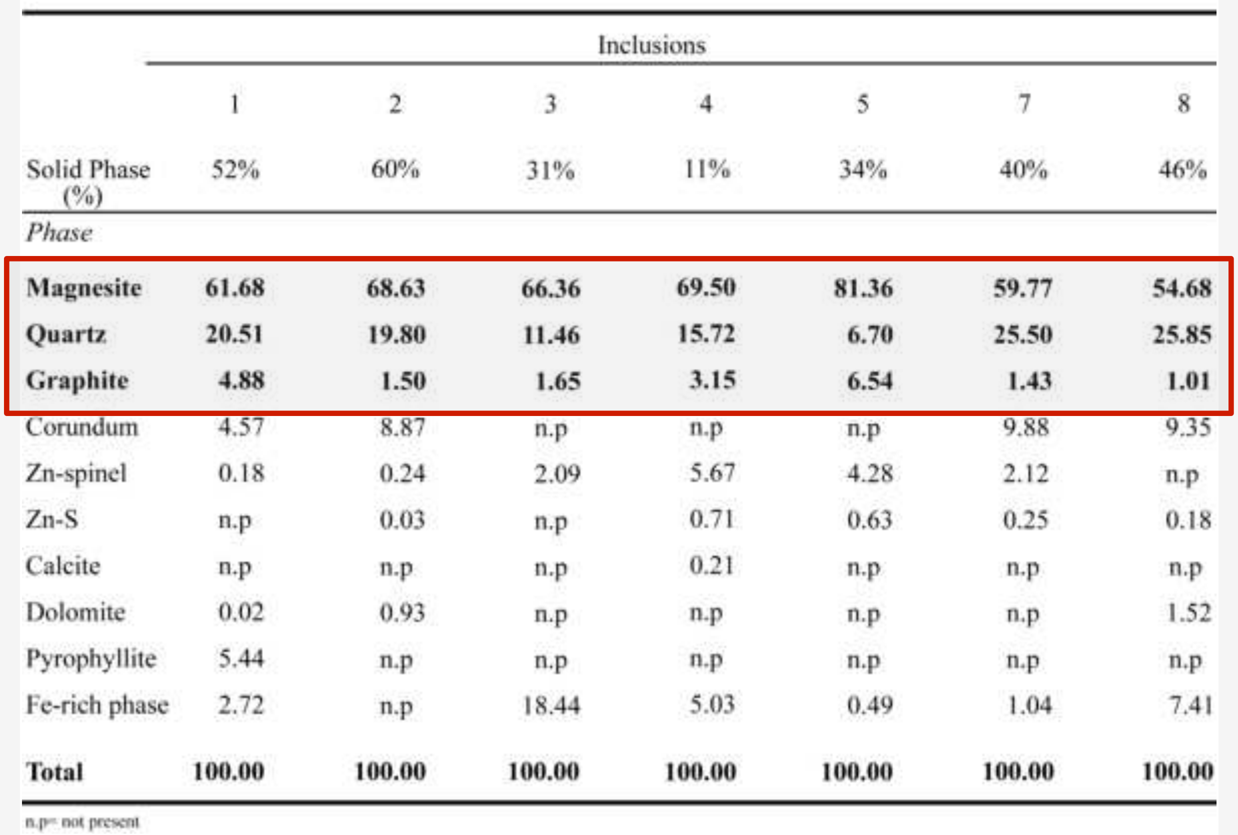


[Tacchetto et al., submitted]

The polycrystalline assemblage is always composed of ferroan magnesite, quartz and graphite. Corundum, Zn-spinel and a S-Zn bearing phase are also present

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility



	Inclusions						
	1	2	3	4	5	7	8
Solid Phase (%)	52%	60%	31%	11%	34%	40%	46%
Phase							
Magnesite	**61.68**	**68.63**	**66.36**	**69.50**	**81.36**	**59.77**	**54.68**
Quartz	**20.51**	**19.80**	**11.46**	**15.72**	**6.70**	**25.50**	**25.85**
Graphite	**4.88**	**1.50**	**1.65**	**3.15**	**6.54**	**1.43**	**1.01**
Corundum	4.57	8.87	n.p	n.p	n.p	9.88	9.35
Zn-spinel	0.18	0.24	2.09	5.67	4.28	2.12	n.p
Zn-S	n.p	0.03	n.p	0.71	0.63	0.25	0.18
Calcite	n.p	n.p	n.p	0.21	n.p	n.p	n.p
Dolomite	0.02	0.93	n.p	n.p	n.p	n.p	1.52
Pyrophyllite	5.44	n.p	n.p	n.p	n.p	n.p	n.p
Fe-rich phase	2.72	n.p	18.44	5.03	0.49	1.04	7.41
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

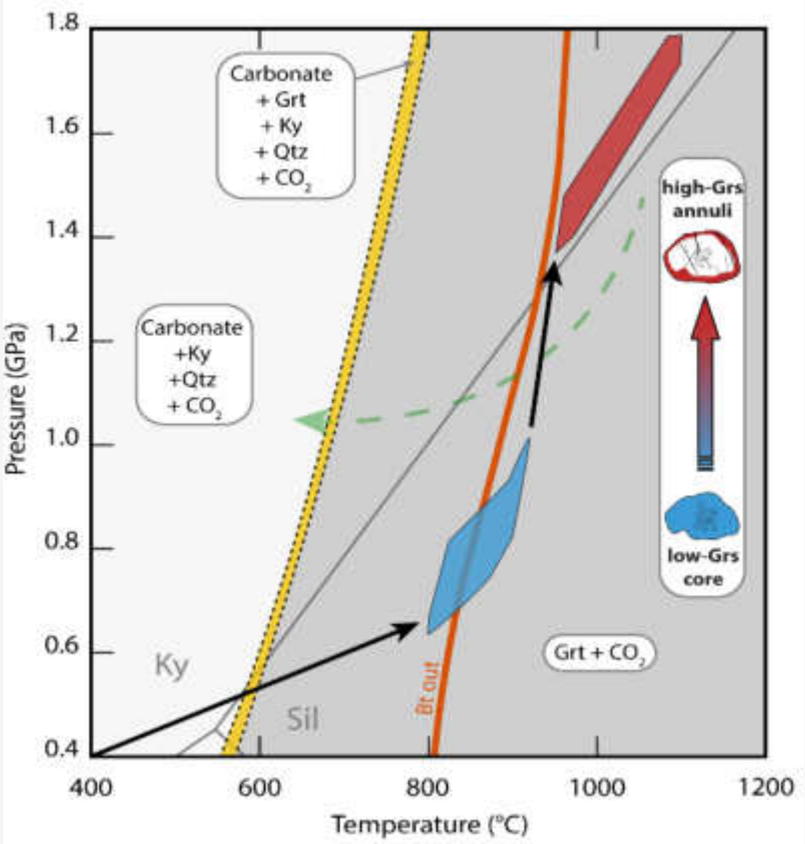
n.p= not present

FIB-SEM analyis

HOMOGENEOUS FLUID

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility



[Tacchetto et al., submitted]

Coexisting primary Type I and II inclusions → they are related to the same melting event (i.e., trapped at the same P-T conditions; 800-900 °C, 0.6-1.0 GPa)

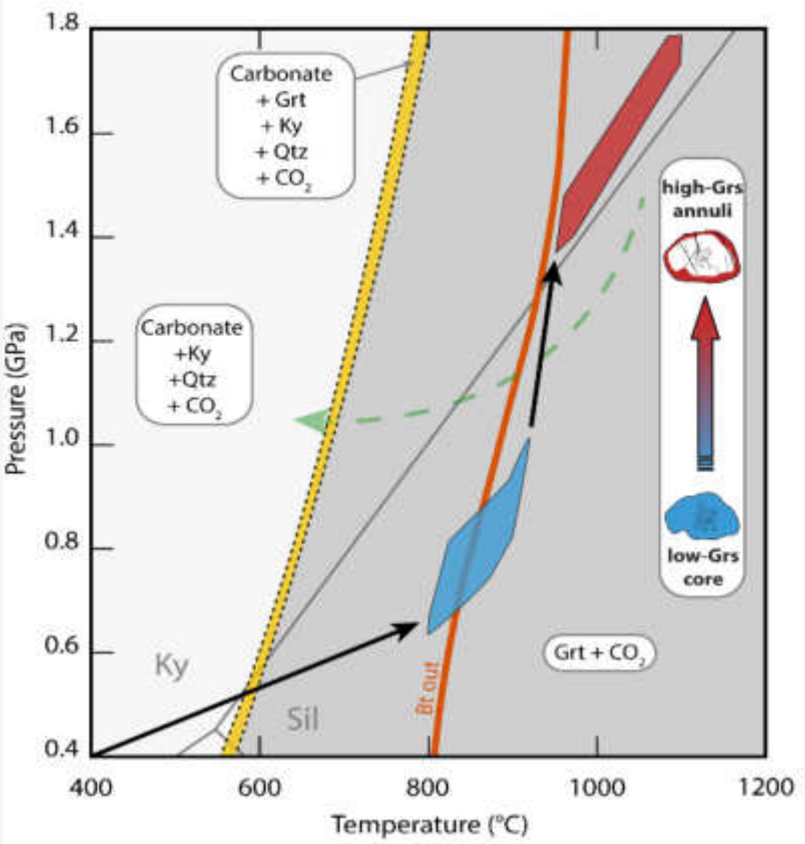
They represent **different fluids** present in the system during anatexis

Type II (nanogranitoids) → anatectic melt

Type I → ????

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility



[Tacchetto et al., submitted]

Carbonation reaction:

garnet + CO_2 = carbonate + kyanite

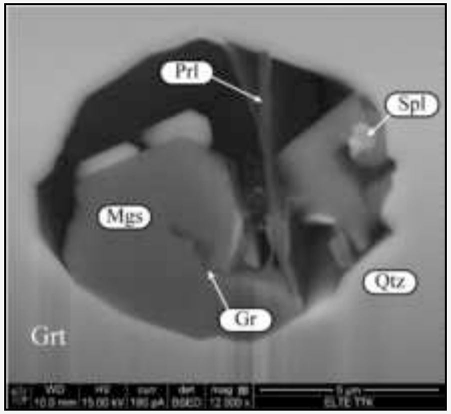
garnet + CO_2 = carbonate + corundum + quartz

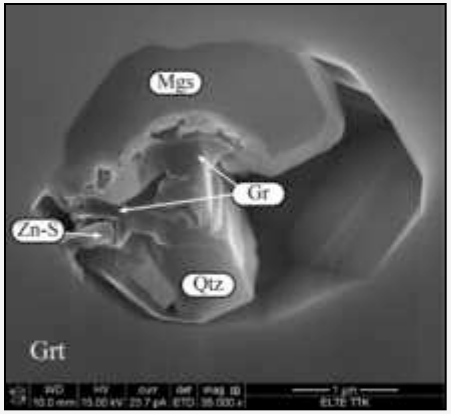
This reaction formed the solid assemblage observed in Type I inclusions (Crn + Qtz were able to grow metastably due to the very small size of Type I inclusions)

What can we learn from nanogranitoids?

7) Melt-fluid immiscibility

Type I and II inclusions indicate the **coexistence of a carbon-rich fluid and a silicate melt during anatexis**, in a situation of **melt-fluid immiscibility**





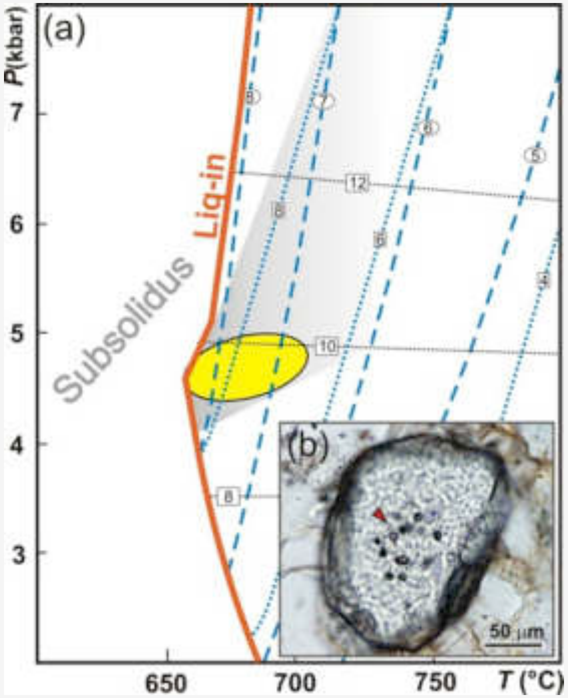
This finding clearly shows evidence of **carbon mobility during the Neoarchean** (2.5-2.6 Ga) anatexis in a back-arc setting

[Tacchetto et al., submitted]

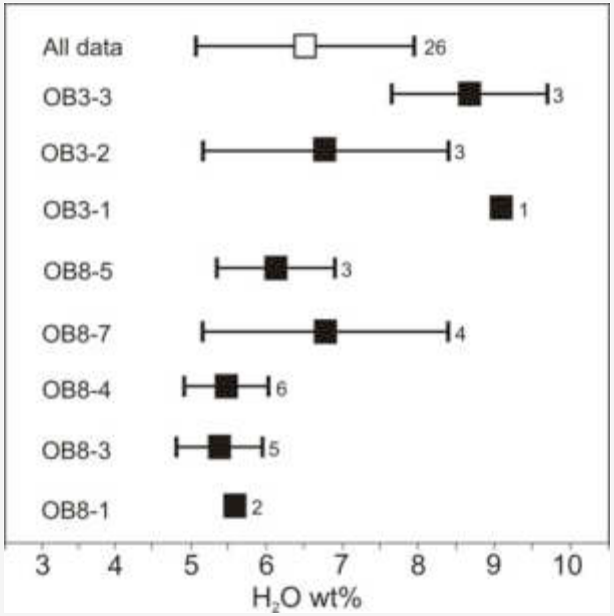
What can we learn from nanogranitoids?

8) H_2O contents and fluid regime during melting

Constraining the fluid regime during crustal melting is an issue that has received very recently renewed attention



[Bartoli et al., 2014]

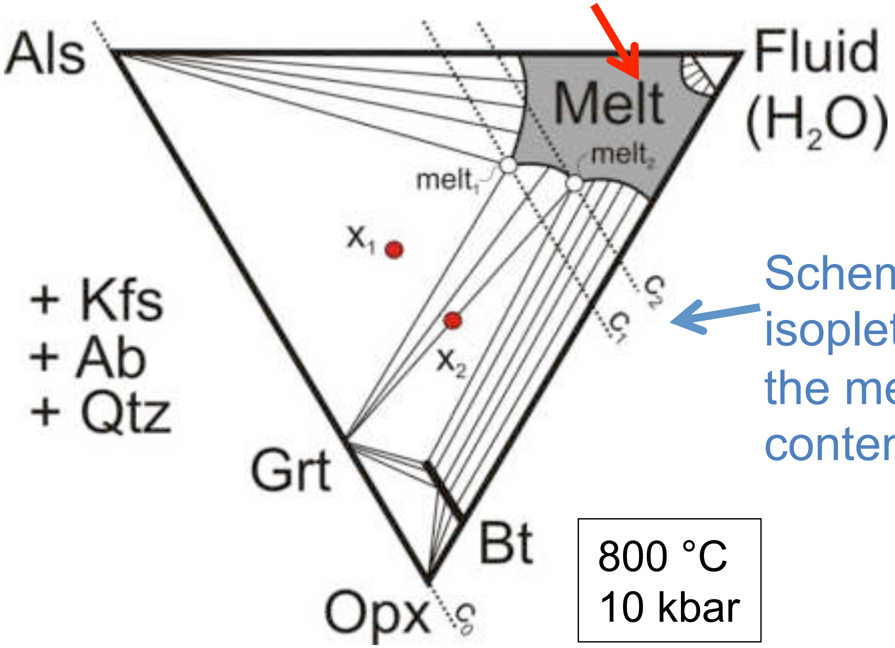


Variable H_2O contents, but relatively uniform values in nanogranitoids from the same host crystal

What can we learn from nanogranitoids?

8) H_2O contents and fluid regime during melting

All the possible melt compositions



Schematic isopleths of the melt water contents

[Bartoli et al., 2014]

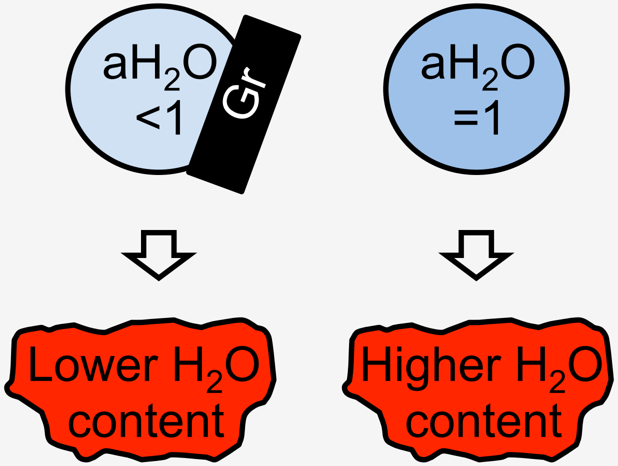
Metasedimentary rocks represent heterogeneous materials → granitic melts displaying different H_2O contents may form in the same rock under conditions of “mosaic equilibrium”

What can we learn from nanogranitoids?

8) H_2O contents and fluid regime during melting

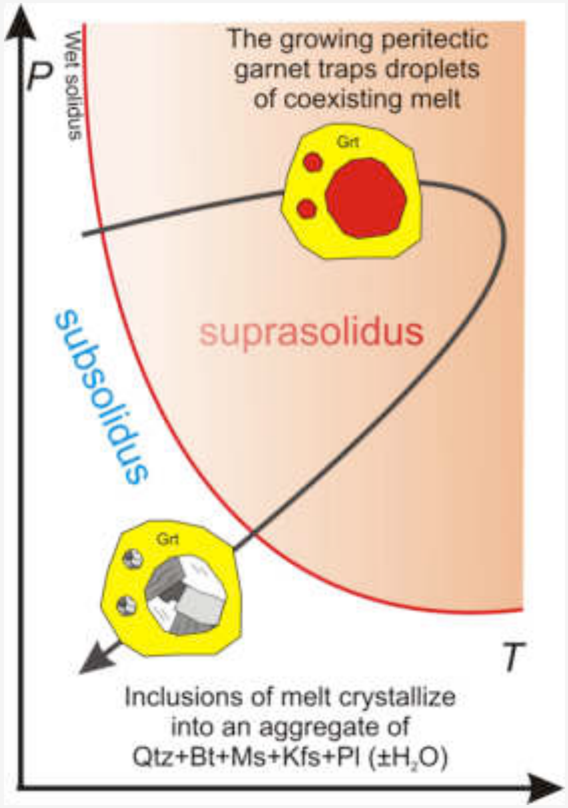
Conditions of “mosaic” equilibrium can also affect the aH_2O in the coexisting fluid phase

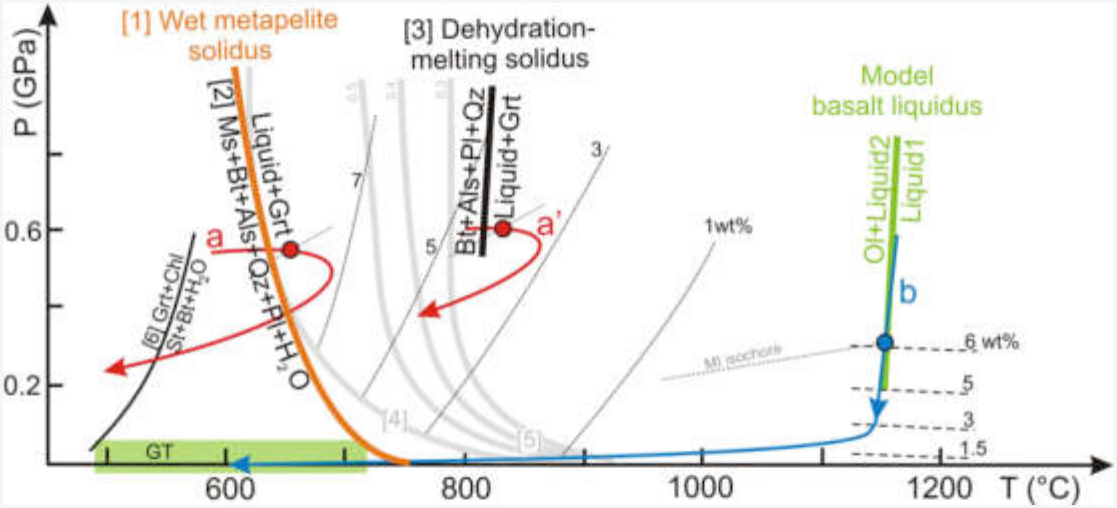
The first discrete fractions of melt produced in different rock microdomains (graphite-bearing vs. graphite-free) may contain different amounts of water



Problems and pitfalls

Nanogranitoid inclusions **are not a panacea**; their limitations and challenges must also be understood to fully harness their potential



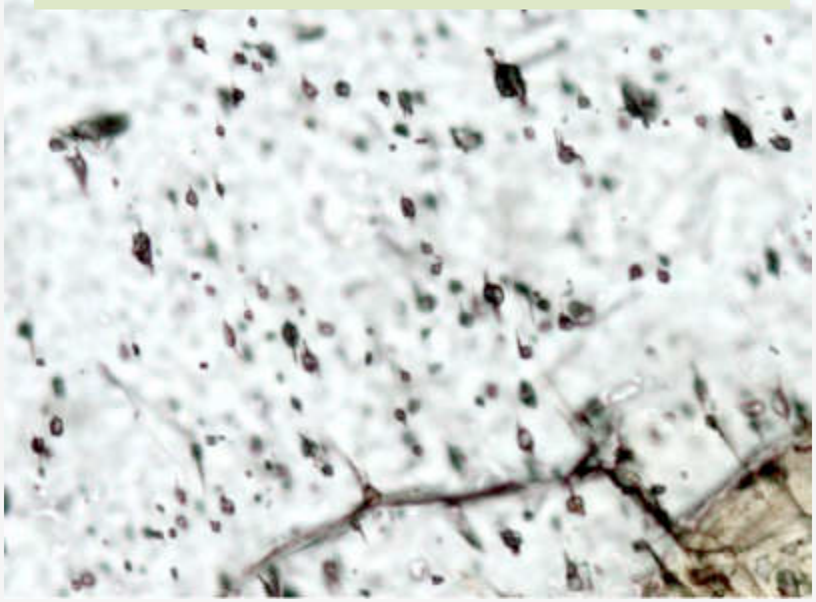


Problems and pitfalls

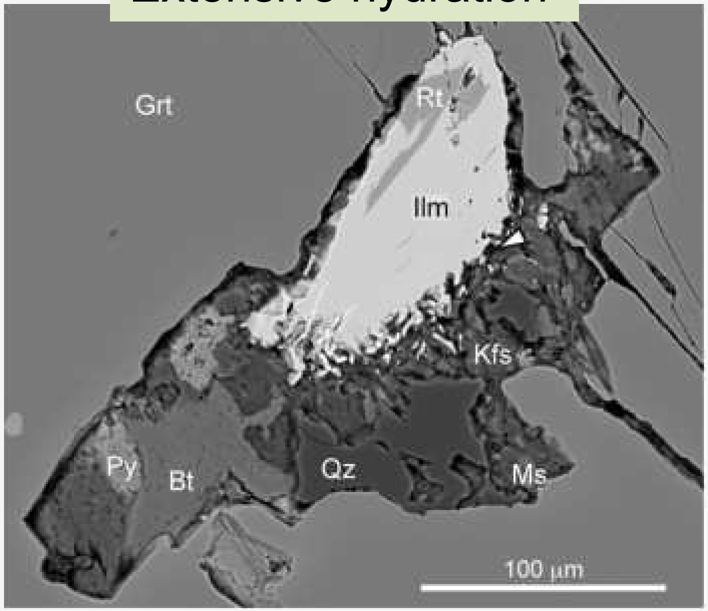
Nanogranitoid inclusions **are not a panacea**; their limitations and challenges must also be understood to fully harness their potential

Post-entrapment modifications

Decrepitation and microfracturing

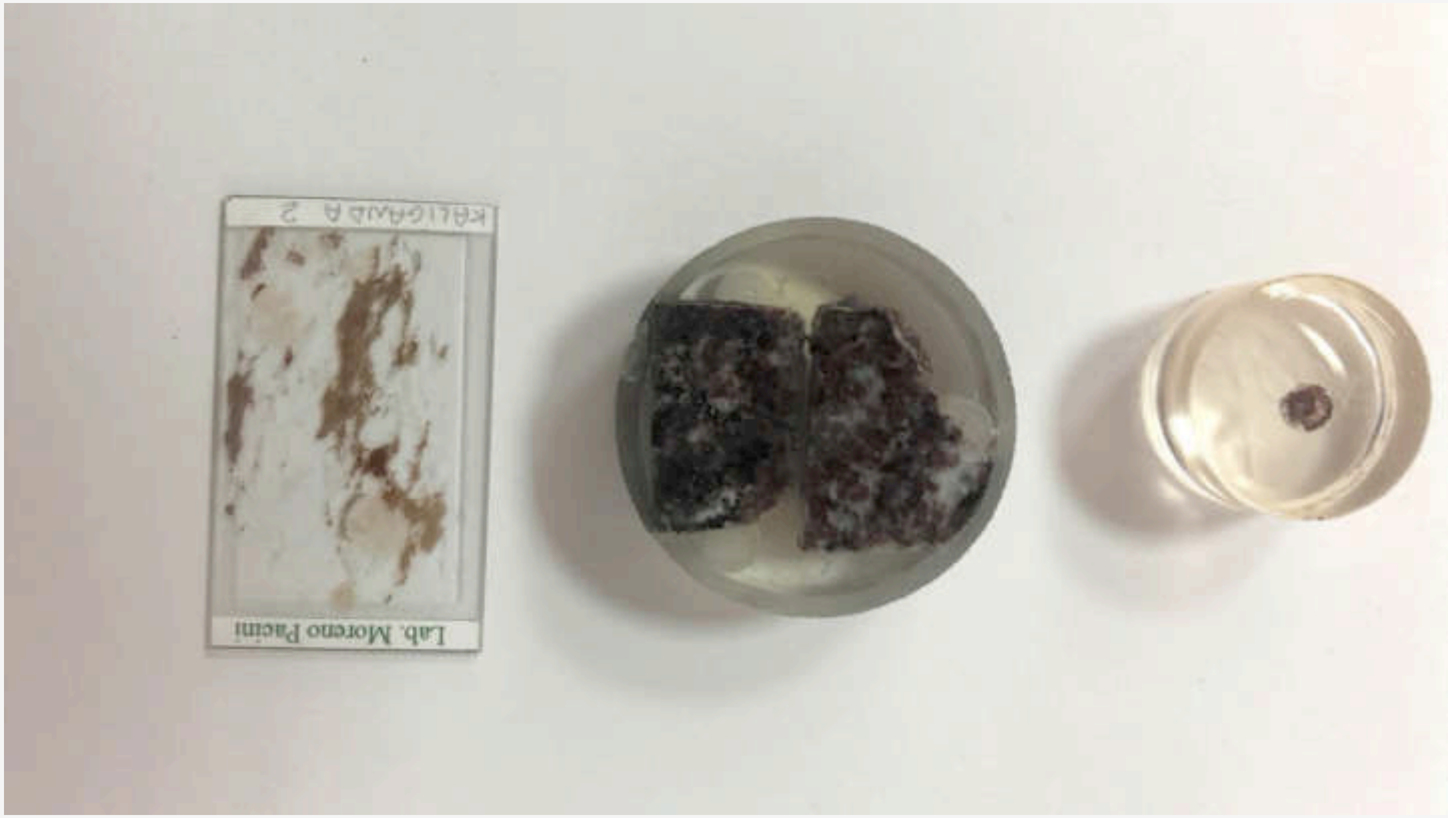


Extensive hydration



Problems and pitfalls

Uncovering and polishing the nanogranitoids is a **crucial problem**. The polishing of crystal-bearing MI often results in the complete or partial mechanical removal of the inclusion content



Concluding remarks

→ A good optical microscope and well-prepared thin sections are all one needs to make the preliminary, essential observations that allow to decide **if nanogranitoids are present and suitable for a subsequent, detailed study**

→ The characterization of nanogranitoids requires **a time-consuming preparation** and **use of cutting-edge techniques** in addition to more routine ones, but the results so obtained are very satisfactory

→ The small-size of nanogranitoids and of daughter minerals crystallized in them still poses some limitations to a full and fast chemical analysis of these objects. However, in a few years from now, **the rapid improvement of analytical techniques will have overcome these problems**