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Melt Inclusions in Migmatites and Granulites







Geosciences Padova
ACME Group

Advances in Crustal MElting

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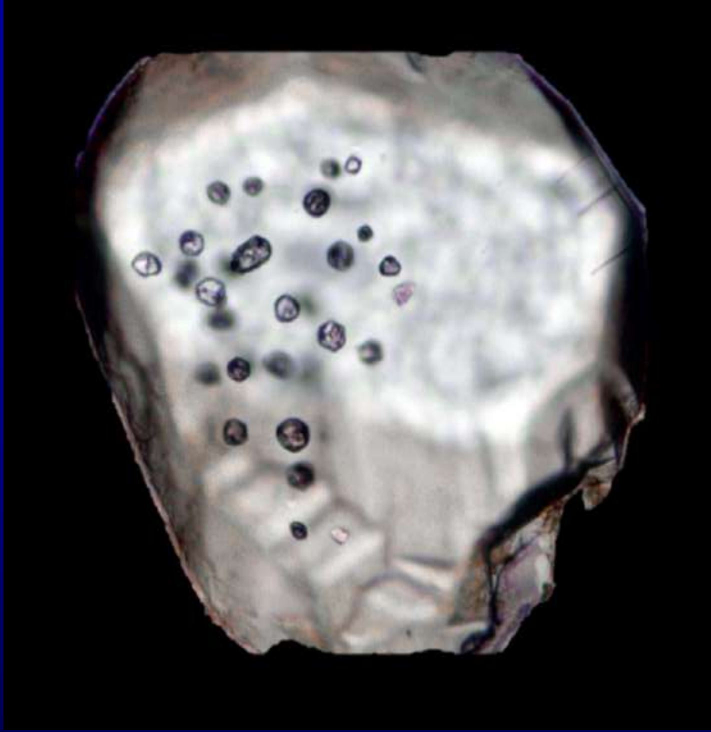
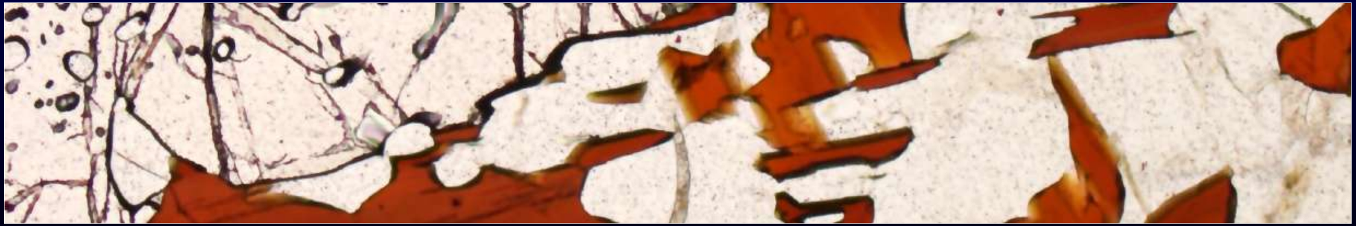
Structure and composition of the lower continental crust – Pavia, 9 October 2019

Outline of presentation

- Introduction
- NG: what, where, how, why?
- What can we learn from NG and MI?
- Recent outcomes
- New directions



assuming you are somehow familiar with fluid inclusions



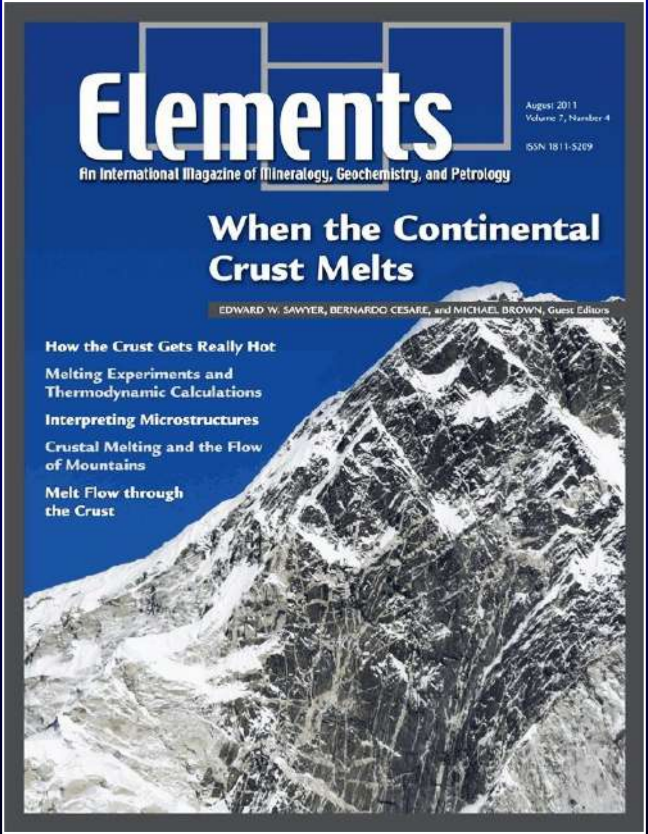
Introduction: *some questions in* ***anatexis***

Microstructures: are there new criteria to infer the former presence of melt in a migmatite?

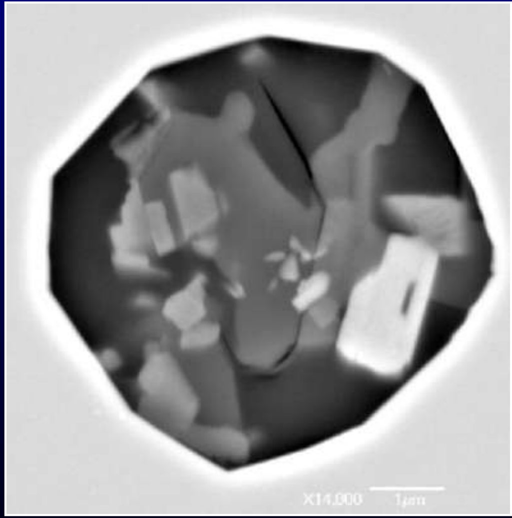
Migmatites and Granulites: how can we be sure that the melt is *in situ*, and not from another protolith?

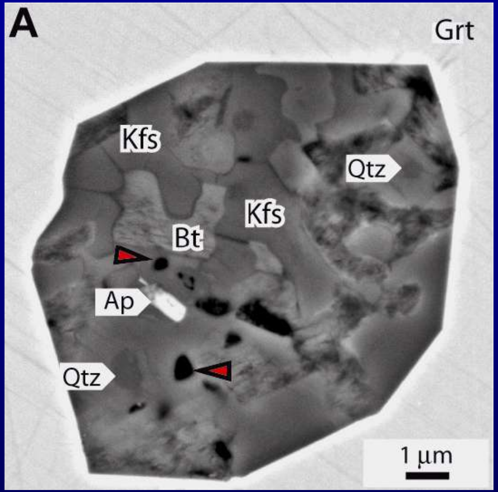
Rheology: what is the viscosity (*i.e.*, the H_2O content) of natural melts?

Geochemistry: what is the composition of natural crustal melts?



Nanogranitoids as answers?





A different perspective

Let us assume that *anatectic melt = Milk*

temporary storage

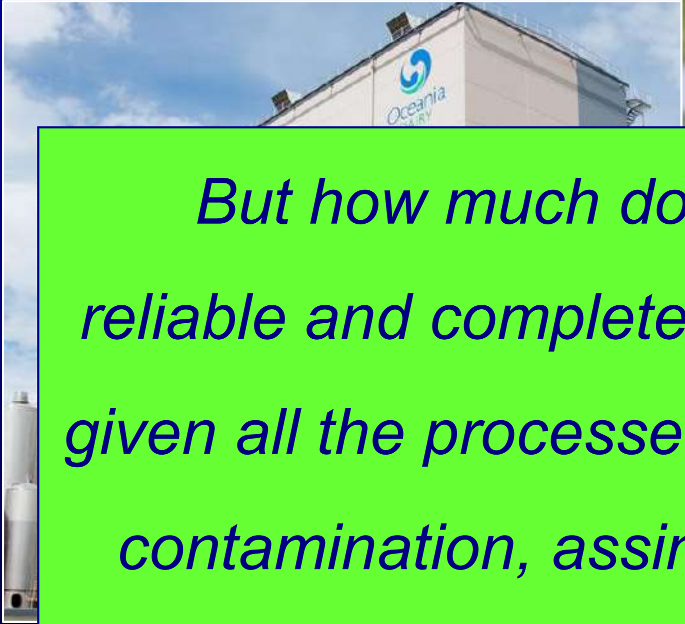
production and segregation

transport

Melt = Milk

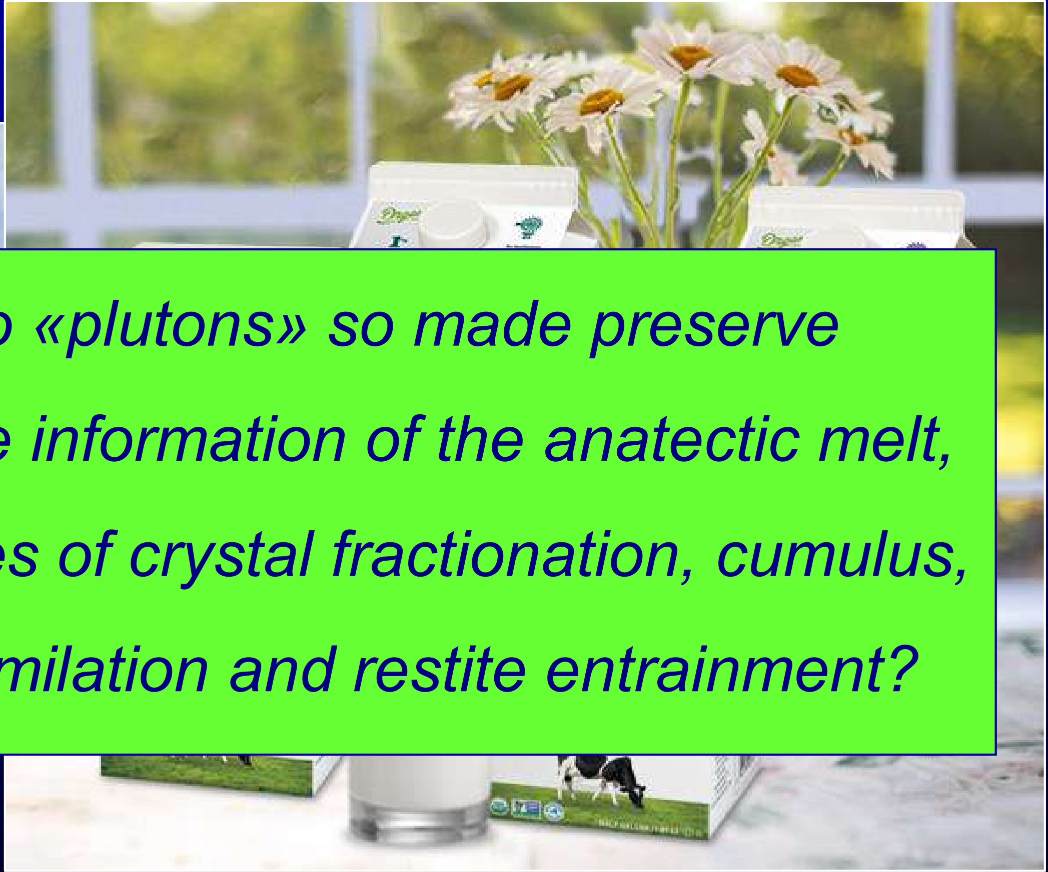
there are various modes, distances and speeds of transport

Melt = Milk



But how much do «plutons» so made preserve reliable and complete information of the anatectic melt, given all the processes of crystal fractionation, cumulus, contamination, assimilation and restite entrainment?

final storage



Plutons, at last!

Where to study primary melts…

In order to study primary anatectic melts one has to go to the source region…

Let us go to Migmatites!

This is the nanogranitoid approach!

Where to study primary melts…

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Let us go to Migmatites!

This is the nanogranitoid approach!

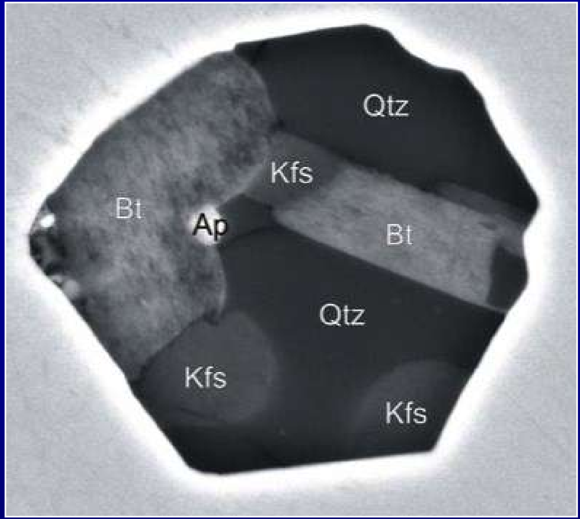
WHAT are nanogranitoids?

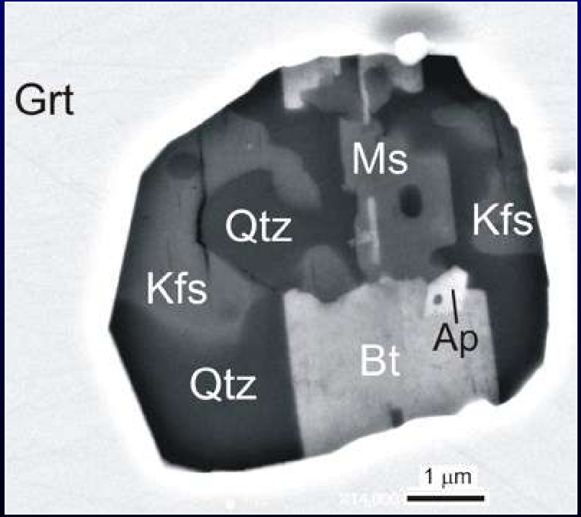
Nanogranitoids are small, polycrystalline inclusions in hosts of various nature, primarily garnet, found in high grade rocks.

They are the result of the crystallization of former melt inclusions (MI).

Discovered in 2009 and defined as *Nanogranites*, we have changed their name to *Nanogranitoids* in 2015 because of the wider compositional spectrum they exhibit.

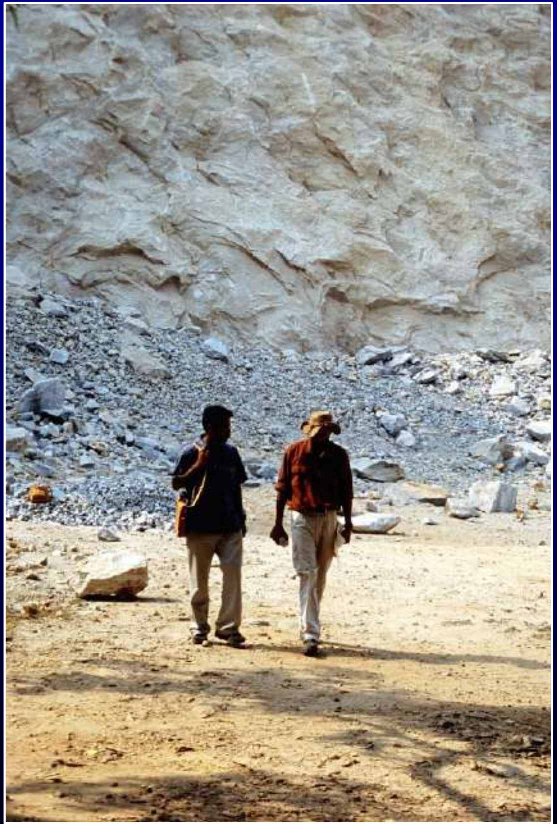
(Cesare et al. 2009, 2015; Bartoli et al. 2016)





The discovery...

Targeting Bt melting (widespread and fertile) we started to look for MI in garnets from several areas, until the first occurrence was found in the *khondalites* of the KKB (India)



The discovery...

Targeting Bt melting (widespread and fertile) we started to look for MI in garnets from several areas, until the first occurrence was found in the *khondalites* of the KKB (India)

Grt-Sil-Crd-Bt-Spl-Gr

P = 6-8 kbar

T > 900° C

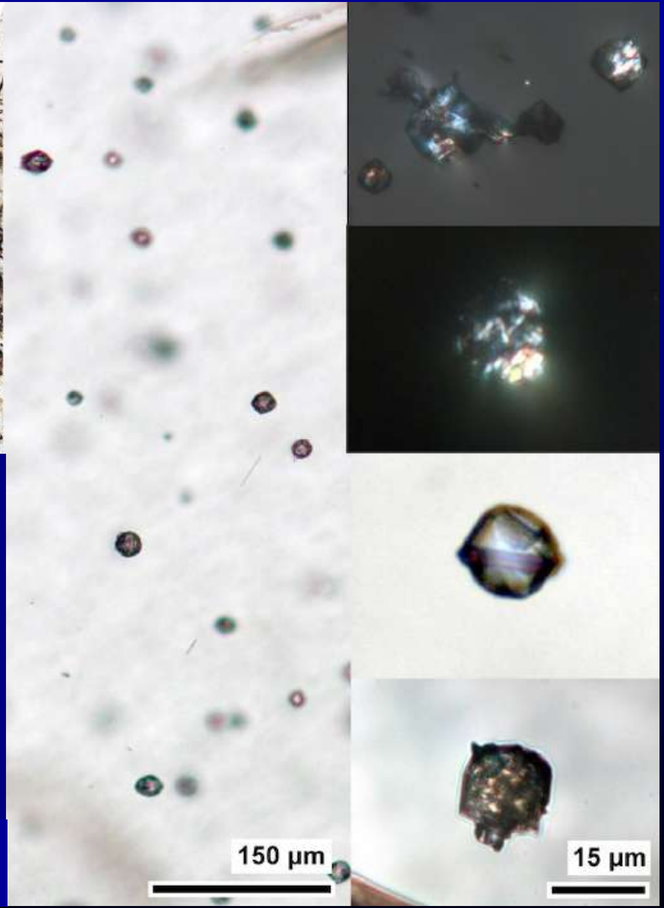
Age: 590-540 Ma

Slow cooling

Melt Inclusions are small!

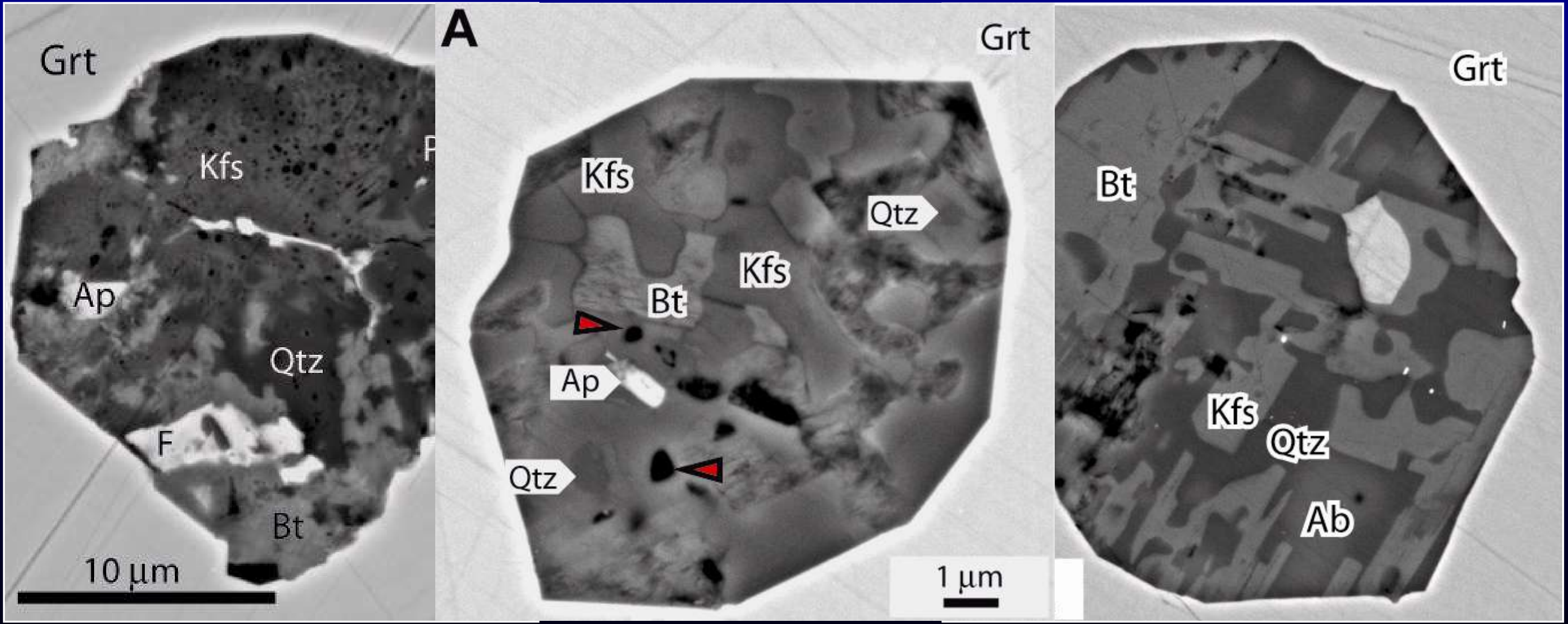
- <25 μm (often <10 μm), can be easily overlooked or considered bad sample preparation or dust
- Polycrystalline, birefringent

Details in Cesare et al., (2009, 2011); Ferrero et al., (2012)

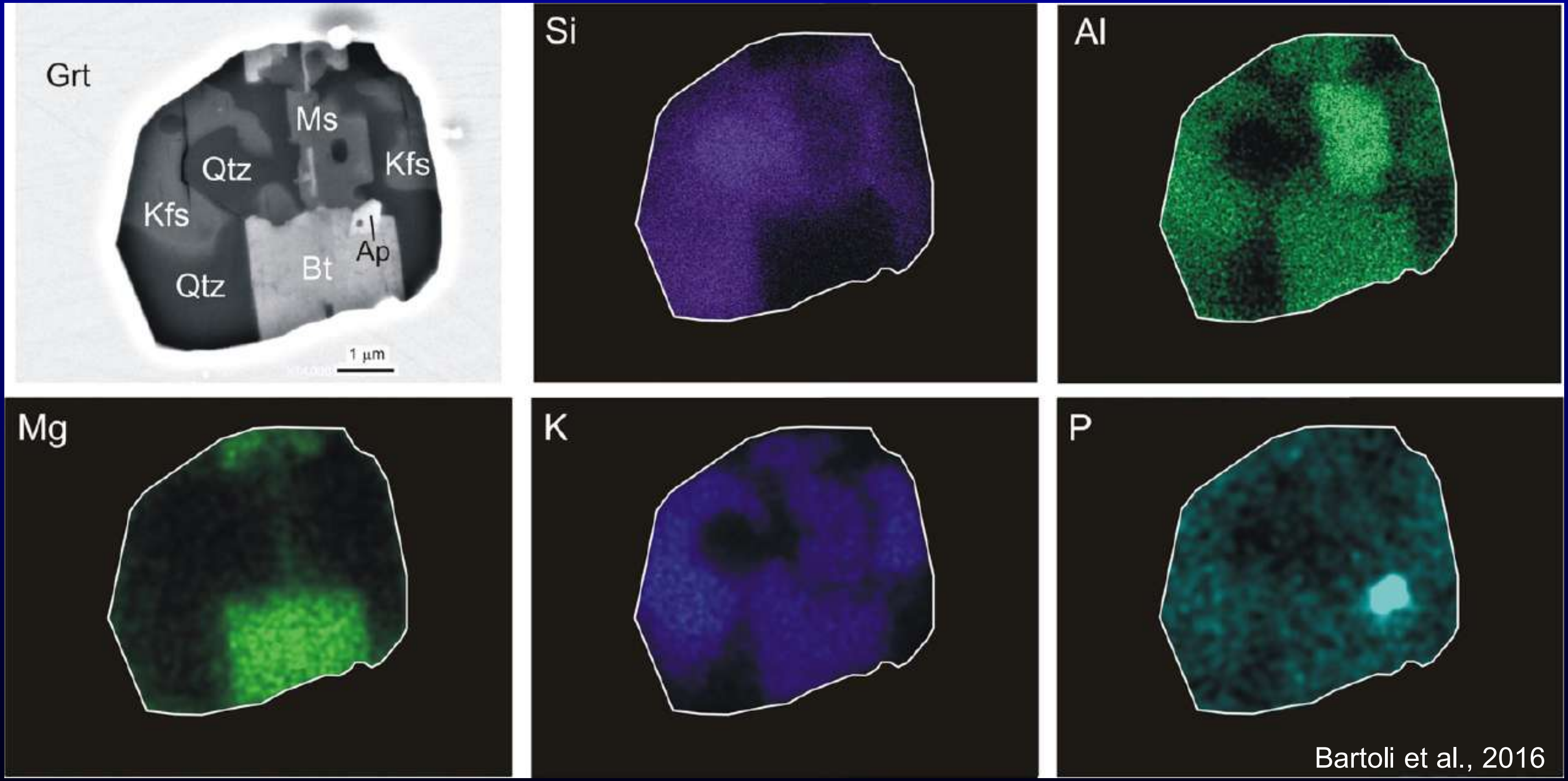


Textural features: *nanogranitoid*

- Cryptocrystalline
- "Granitoid" composition
- Negative crystal shape
- Porosity (volume contraction?)

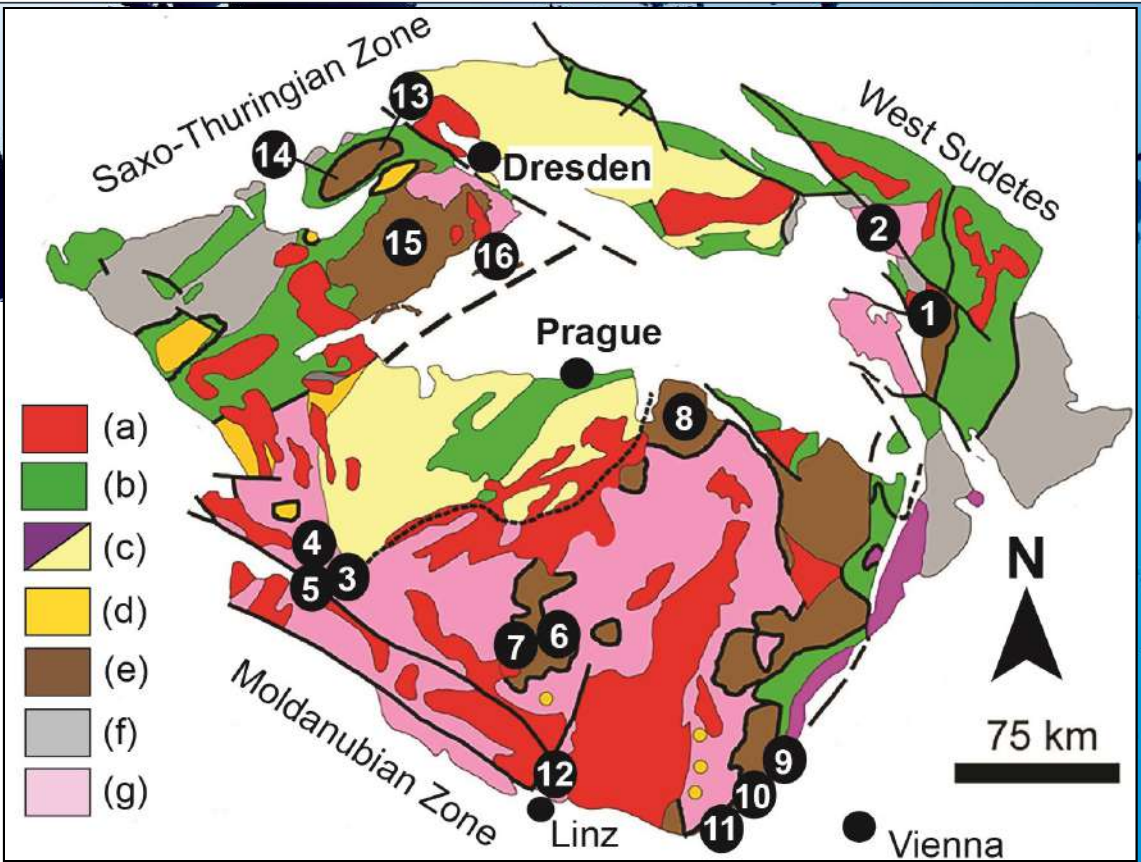


Microstructural-chemical characterization



since then…

KKB, India
Athabasca, Canada
Ronda, Spain
Central MS, USA
Gruf Complex, CH
Ivrea Zone, Italy
Ulten Zone, Italy
Barun, Nepal
Kaligandaki, Nepal
La Galite, Tunisia
DML, Antarctica
Lanterman, Antarctica
Bohemian Massif
Limpopo Belt
Barberton Belt
…and many more

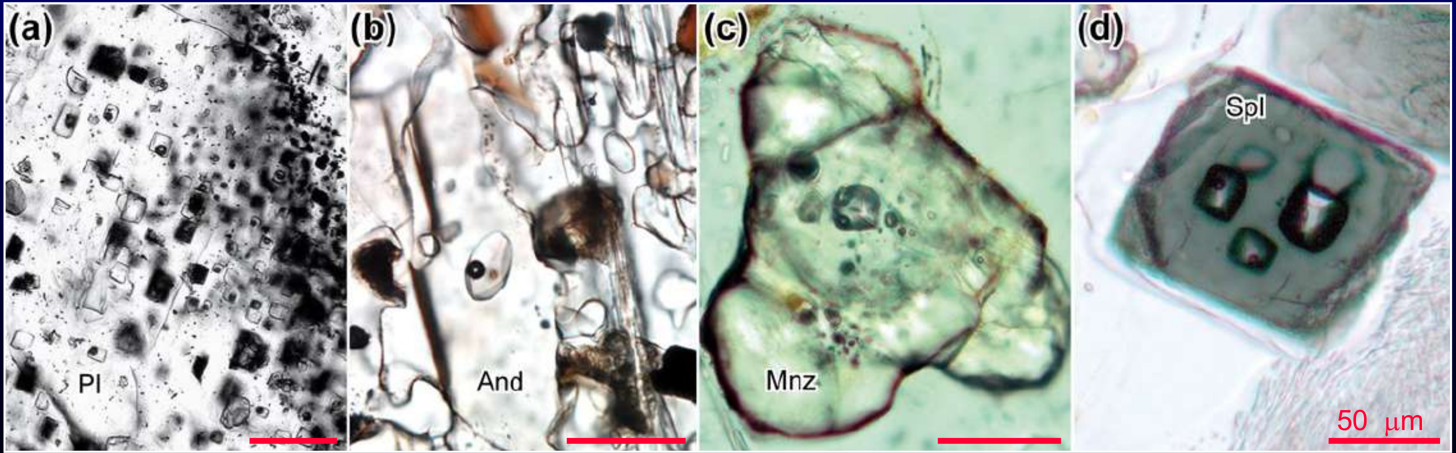


Rocks bearing nanogranitoids in the Bohemian Massif (Ferrero's group, Potsdam)

WHERE do NG occur?

Host Mineral
is generally Grt but also Zrn, Spl, Mnz, Ilm, Pl, And, Spr…

Host Rocks
are migmatites and granulites, mostly metasedimentary and felsic but also mafic and ultramafic, from LP to UHP settings.

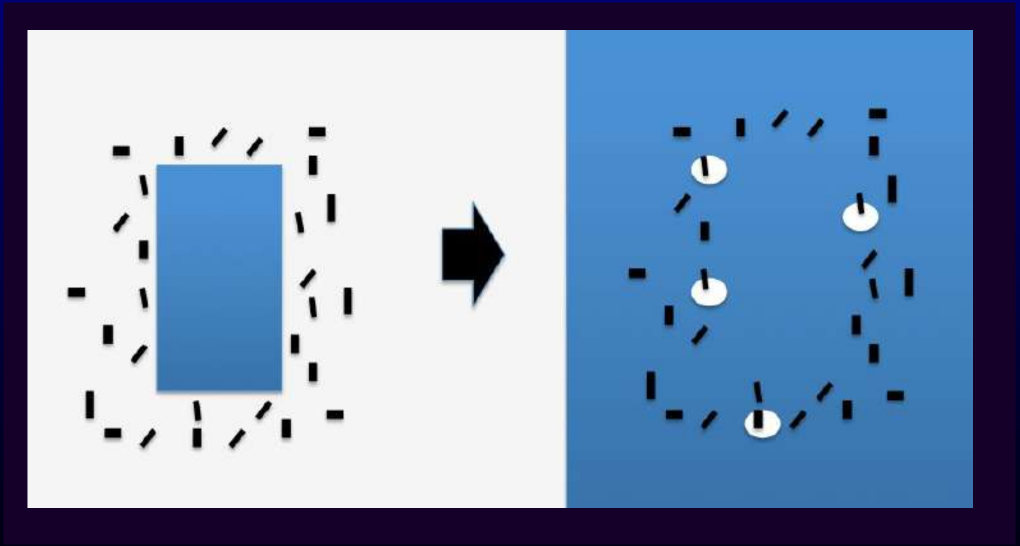


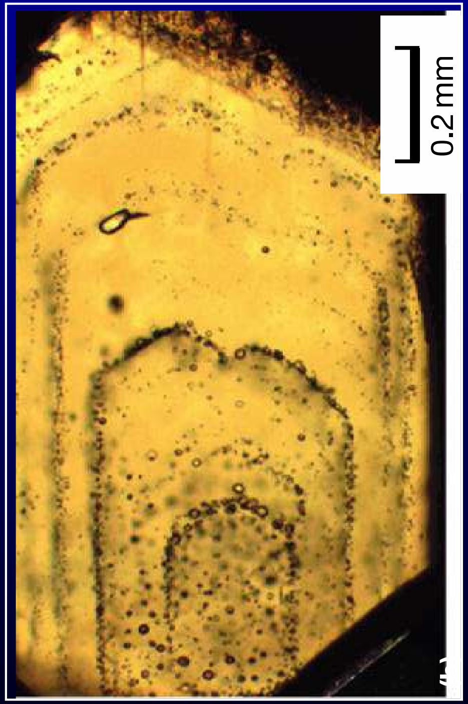
Ferrero et al., (2018)

HOW do NG form?

Like primary melt/fluid inclusions
nanogranitoids form during growth of the host, that includes (*traps*) small droplets of melt.

Fine-grained impurities (Ilm, Gr, Zrn, Rt) in the matrix around the growing host greatly help entrapment.



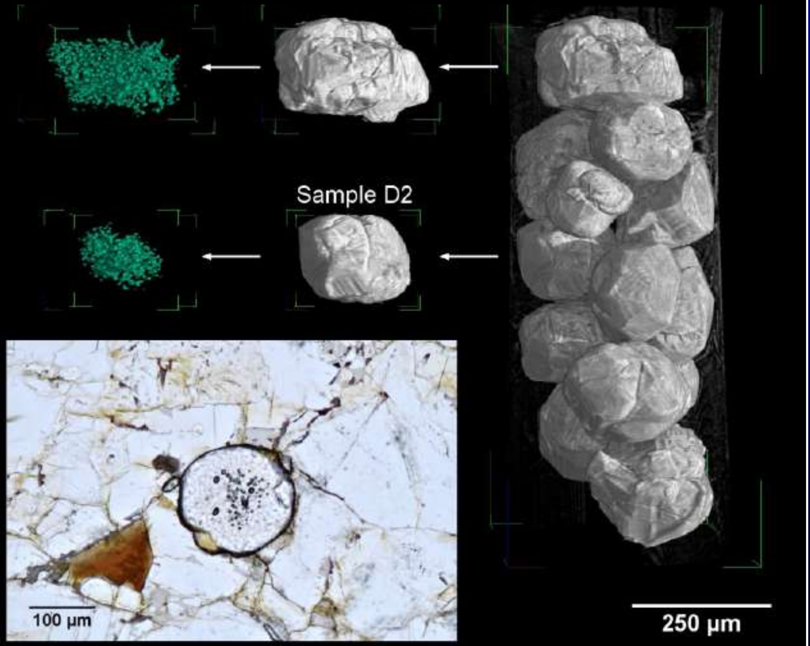


Audétat & Lowenstern, 2014

HOW do NG form?

The resulting microstructure is called "*zonal arrangement*" and demonstrates a primary origin.

NG in garnets from Sierra Alpujata, Ronda (Parisatto et al. 2018)



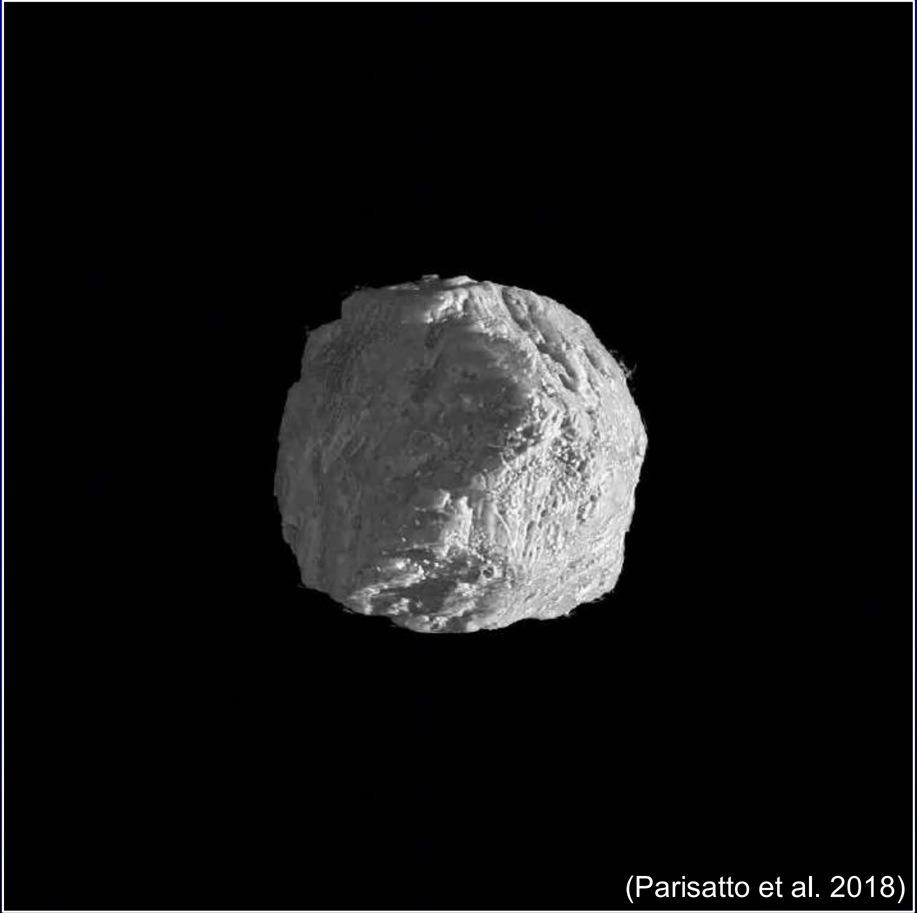
Garnets with melt inclusions (Acosta Vigil et al., 2007)

HOW do NG form?

- Synchrotron-based X-μCT study conducted at *SYRMEP* (Elettra, I)

- green: light i. (MI, FI, Pl, Sil)
  - well resolved polyhedral distribution of FI-MI
  - acicular Sil located at rim

- yellow: heavy i. (Ilm, Zrn, Mnz)
  - Heavy inclusions located mainly in the exterior of Grt.
  - Consistent with onset of Bt melting



(Parisatto et al. 2018)

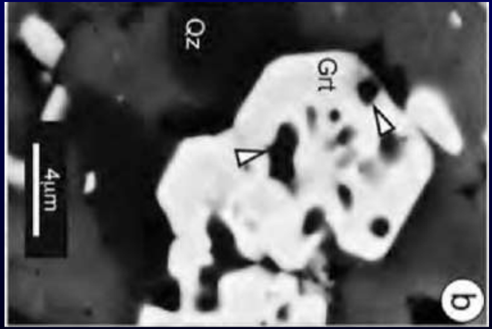
WHY do NG form?

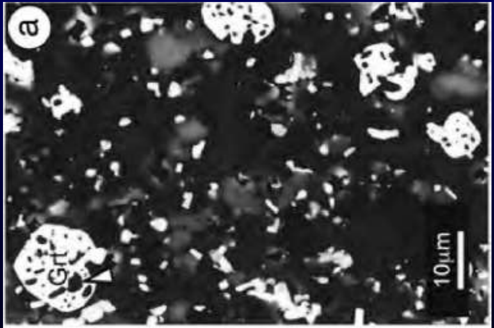
Since primary melt inclusions (i.e., NG) indicate **growth of the host in the presence of melt** their most obvious origin is related to CRYSTALLISATION.

However, in migmatites and granulites NG (and MI) can form by INCONGRUENT MELTING

A + B = melt + C

e.g., *Bt +Pl +Qz + Sil (± fluid) =* ***Grt + melt*** *(± Kfs)*





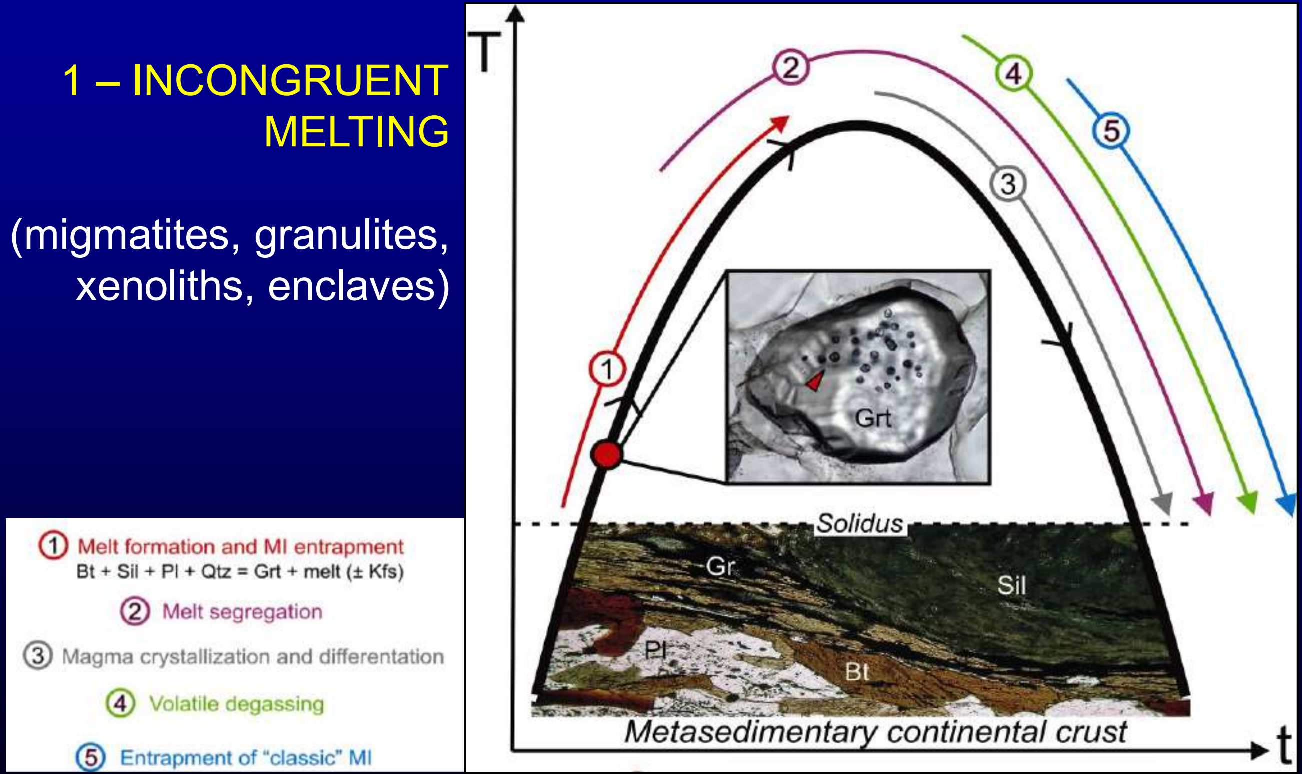
courtesy V. Gardien

NG in garnet from Athabasca (Tacchetto et al. 2018)

Entrapment of MI, a twofold process

1 – INCONGRUENT MELTING

(migmatites, granulites, xenoliths, enclaves)



Bartoli et al. (2016)

5 – MAGMA CRYSTALLISATION

(intrusive and extrusive rocks, leucosomes)

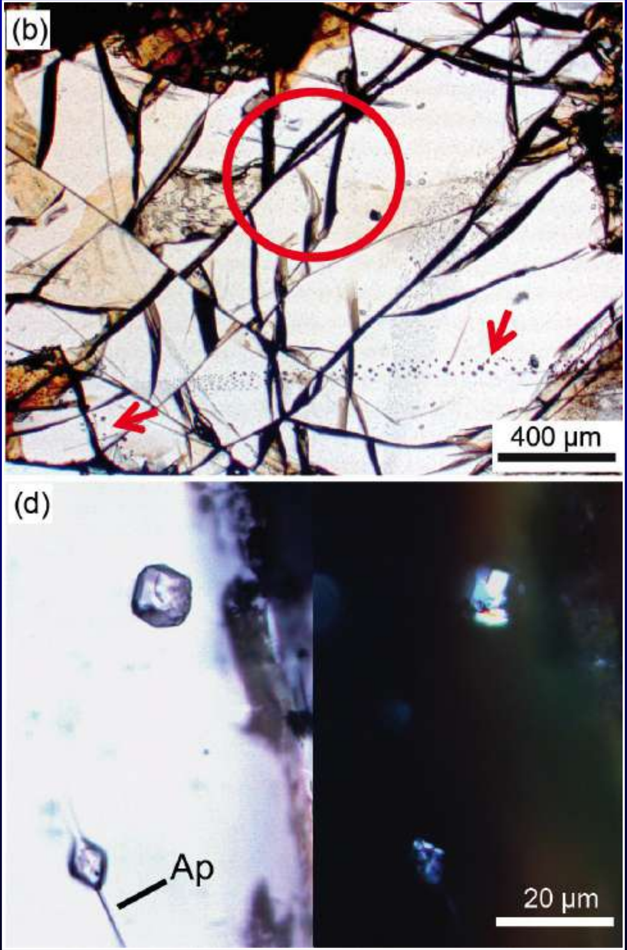
To sum up…

Nanogranitoids - and more in general MI - are former droplets of anatectic melt trapped by the growing host during (crustal) melting.

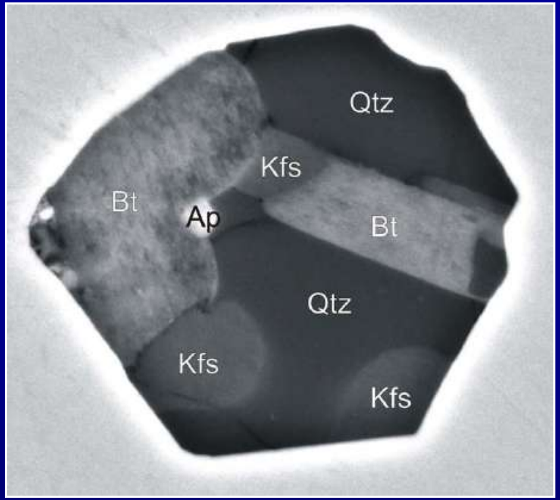
Host forms **WITH** melt, not FROM it.

NG contain **primary**, near solidus melt compositions.

With cooling, the melt crystallizes, even though some glass may remain.



Ferrero et al., (2018)



What can we learn from NG?

What can we learn from NG?

CHEMICALLY

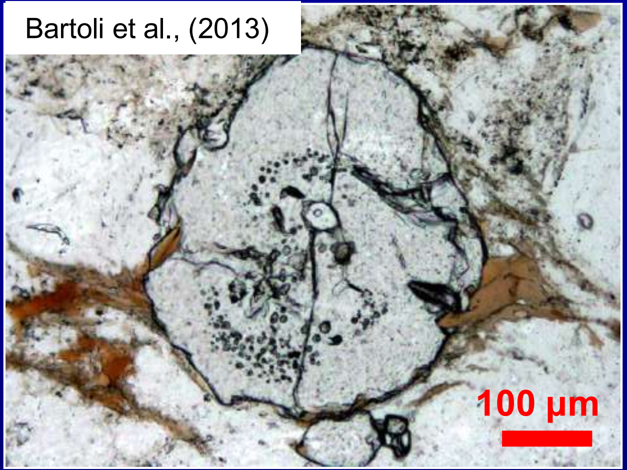
Since unequivocal microstructures indicate a primary origin for melt inclusions and nanogranitoids,

NG contain the anatectic melt present during the peritectic growth of their hosts.

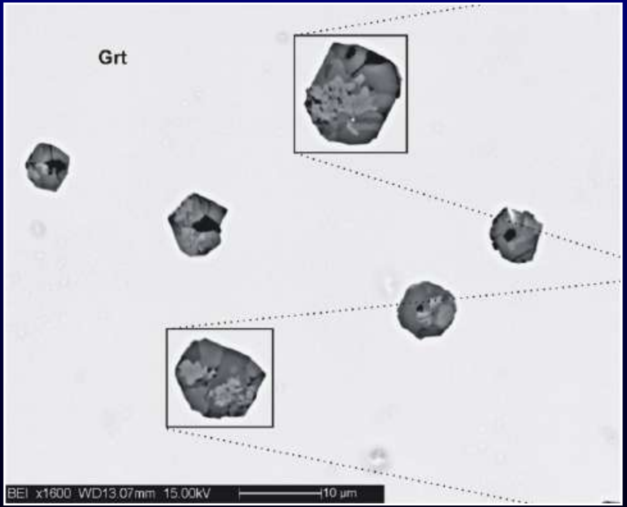
NG offer an unique possibility of analysing *in situ* the composition of natural, unmodified* crustal anatectic melts,

…BUT…

*) *not always…*



Bartoli et al., (2013)



Requires experimental remelting

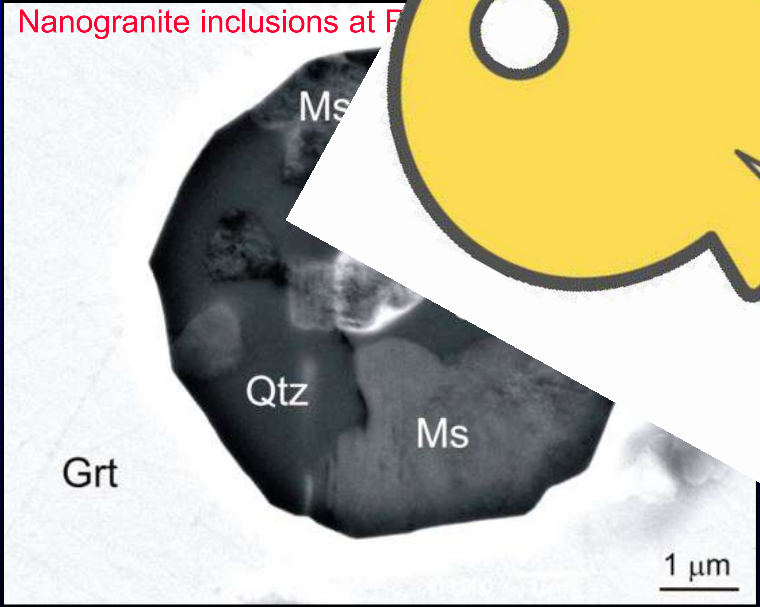
For crystallized MI, remelting to a homogeous glass is obtained by heating in a piston cylinder

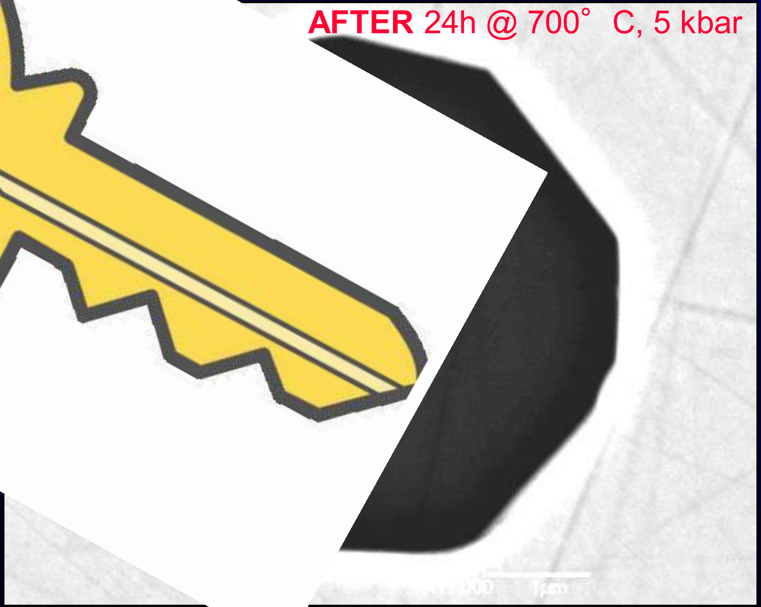
(more in Bartoli et al., *Geofluids*, 2013; *Geology*, 2013)

Requires experimental remelting

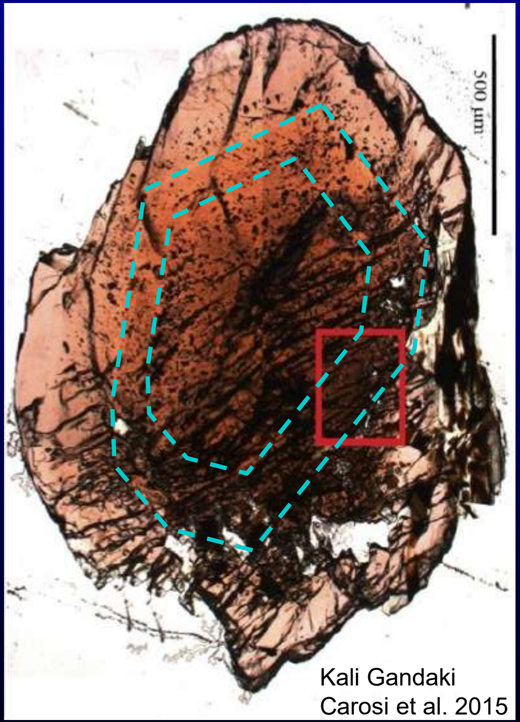
For crystallized MI, remelti[...] homogeous glass is obtained by heating in a piston cylind[...]

The glass can then be[...] ICP-MS, SIMS





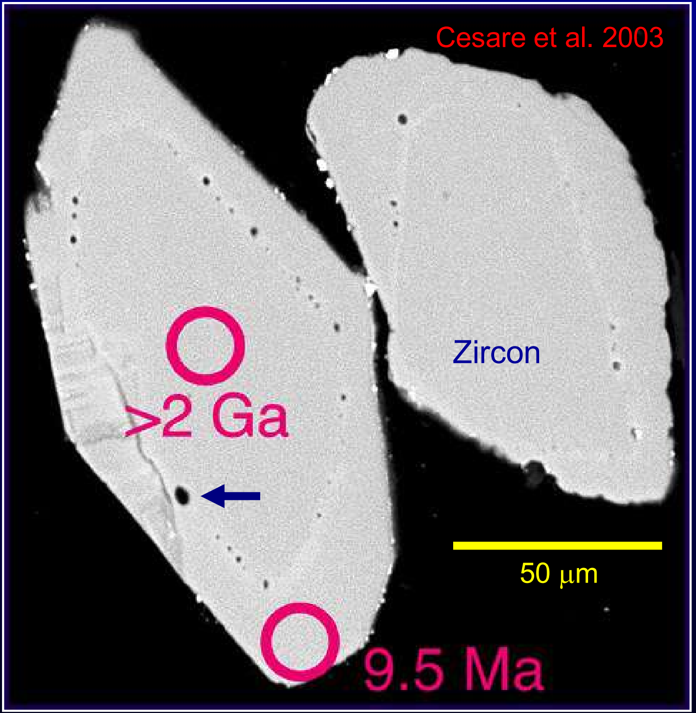
What can we learn from NG?



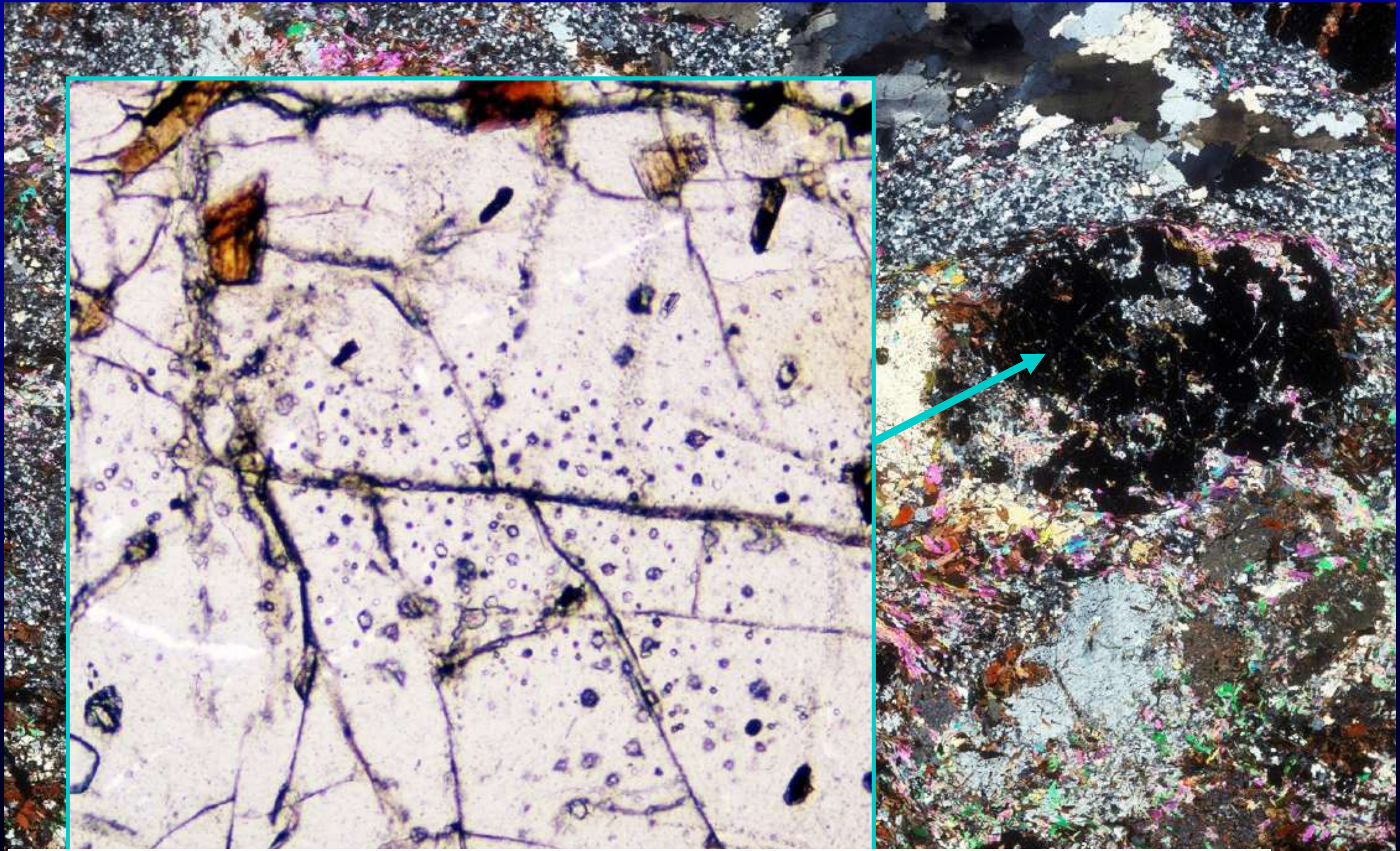
MICROSTRUCTURALLY

Primary NG attest for the growth of a host in the presence of melt, and tell:

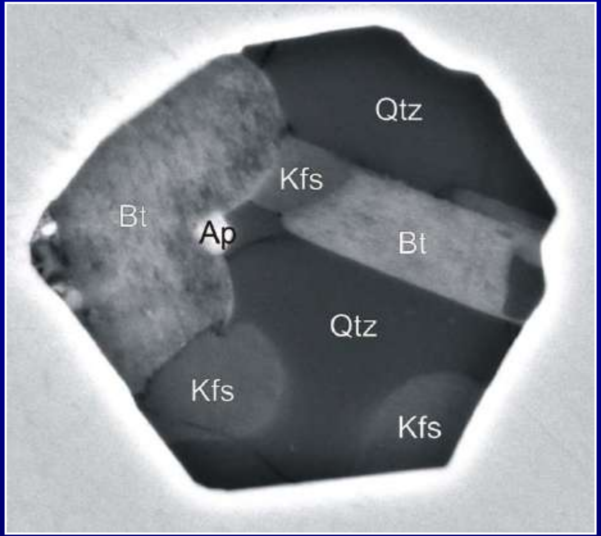
- That a rock has melted
- Which part of a host mineral is syn-anatectic
- When a rock has melted



That a rock has melted



Contact metamorphosed paragneiss from the southern aureole of Rieserferner, Eastern Alps. wv: 5



Some recent outcomes







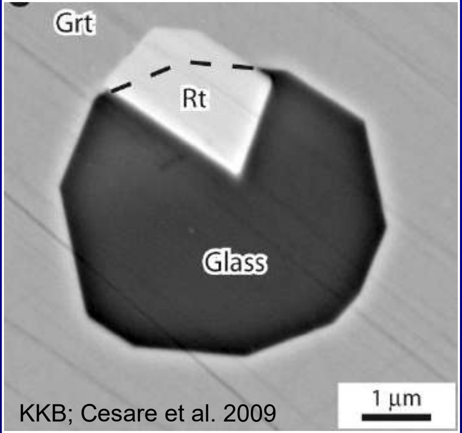
Metastability: glass and polymorphs

Glass is common (KKB, IVZ, Ronda, BM, Antarctica) even in rocks which cooled very slowly

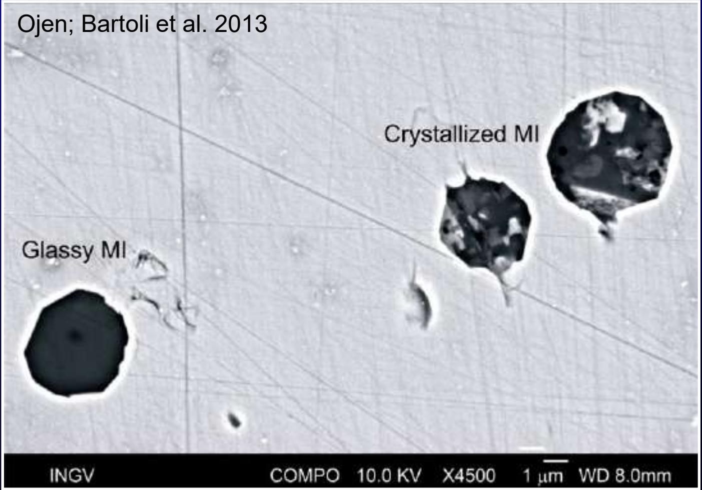
Probably related to nucleation inhibition in smallest inclusions

Demonstrates the nature of NG as former melt inclusions

Allows comparison with remelted NG in the same sample



KKB; Cesare et al. 2009



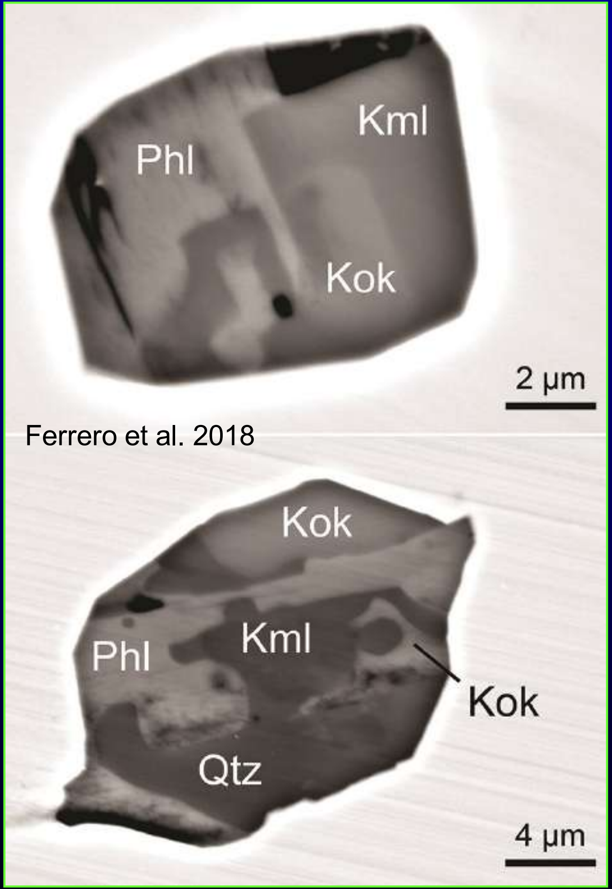
Ojen; Bartoli et al. 2013

Metastability: glass and polymorphs

NG show also other examples of metastable occurrences, such as kumdy-kolite $NaAlSi_3O_8$ kokchetavite $KAlSi_3O_8$, as well as cristobalite and trydimite

Their origin is under study, but probably related (as well as Crn+Qz) to the small size of cavity

They indicate that NG were preserved from decrepitation and post-crystallization modifications (Ferrero & Angel, J Petrol. 2018)



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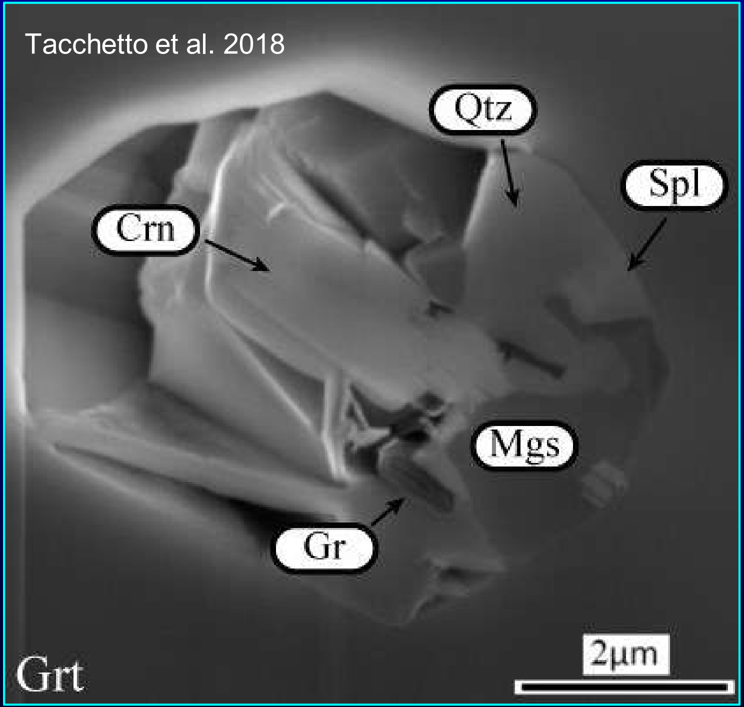

Composition of anatectic melts

	Ronda metatexites		Barun	KKB Khondalites	
	Hom.	Glassy	**Hom.**	**Hom.**	Glassy
SiO_2	68,78	69,69	74,51	73,96	77,72
TiO_2	0,08	0,08	0,09	0,11	0,04
Al_2O_3	11,42	11,78	12,90	12,95	11,90
FeO	1,59	1,2	2,51	3,03	1,01
MnO	0,14	0,09	0,25	0,04	0,04
MgO	0,12	0,07	0,53	0,65	0,01
CaO	0,44	0,39	0,85	0,53	0,03
Na_2O	2,74	3,09	1,90	1,10	0,97
K_2O	4,00	4,19	4,86	6,72	7,60
P_2O_5	0,35	0,18	0,02	0,03	0,15
Cl	n.a	n.a	n.a	0,25	n.a
Total	89,66	90,76	98,43	99,37	99,47
H_2O*	10,34	9,24	1,57	0,63	0,53
ASI	1,18	1,14	1,30	1,29	1,21

*by difference

CIPW normative composition

Cor	3	2	3	3	2
Qz	42	39	44	41	43
Ab	27	30	17	10	8
Or	28	28	31	43	46
An	1	1	4	3	0

Average EMP analyses from three occurrences of NG showing granitic composition

They display systematic differences and trends (e.g., alkalis, Ca, totals)

Composition of anatectic melts

	Ronda metatexites		Barun	KKB Khondalites		Kaligandaki
	Hom.	Glassy	Hom.	Hom.	Glassy	Hom.
SiO_2	68,78	69,69	74,51	73,96	77,72	65,78
TiO_2	0,08	0,08	0,09	0,11	0,04	0,14
Al_2O_3	11,42	11,78	12,90	12,95	11,90	14,26
FeO	1,59	1,21	2,51	3,03	1,01	2,58
MnO	0,14	0,09	0,25	0,04	0,04	0,11
MgO	0,12	0,07	0,53	0,65	0,01	0,45
CaO	0,44	0,39	0,85	0,53	0,03	**2,22**
Na_2O	2,74	3,09	1,90	1,10	0,97	2,72
K_2O	4,00	4,19	4,86	6,72	7,60	1,58
P_2O_5	0,35	0,18	0,02	0,03	0,15	0,34
Cl	n.a	n.a	n.a	0,25	n.a	n.a
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ASI	1,18	1,14	1,30	1,29	1,21	1,40

*by difference

CIPW normative composition

	Ronda Hom.	Ronda Glassy	Barun Hom.	KKB Hom.	KKB Glassy
Cor	3	2	3	3	2
Qz	42	39	44	41	43
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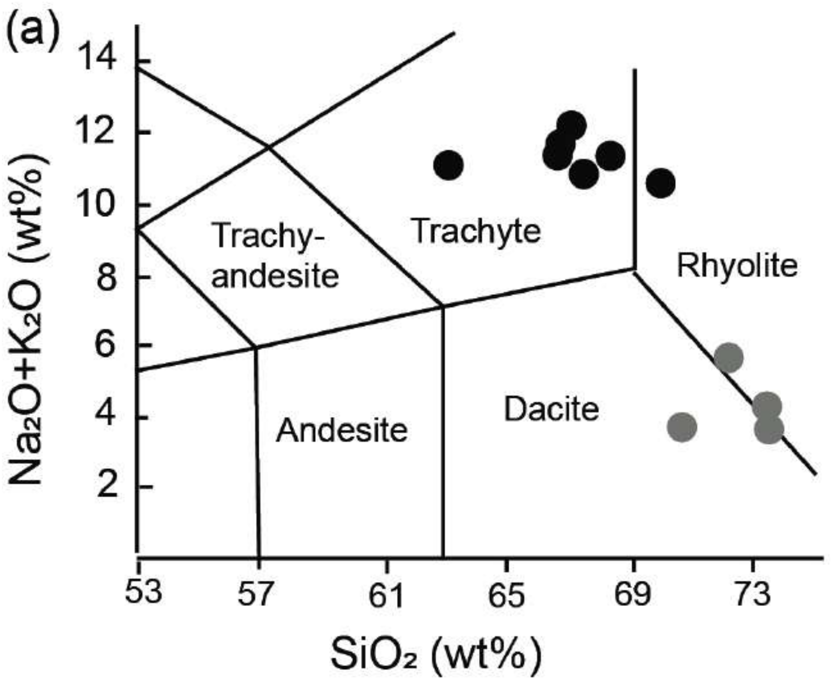
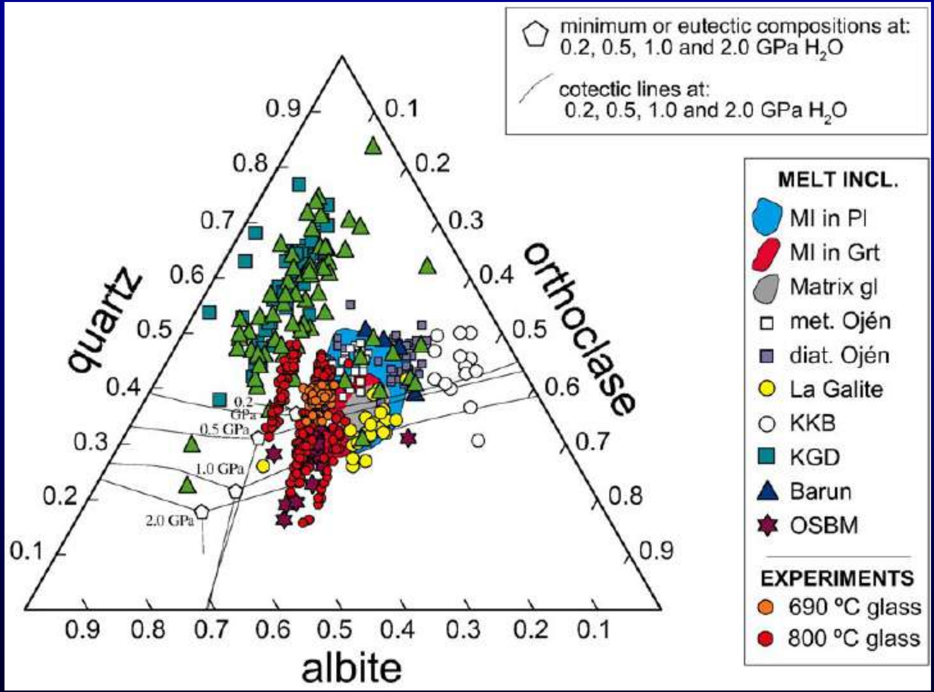
also *nanotonalites*

(Carosi *et al.* Geol Soc London, spec. pub., *2015*)

Composition of anatectic melts



Ferrero et al. 2018



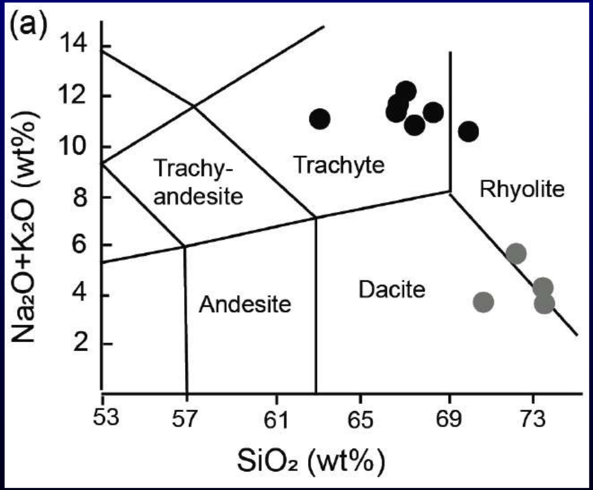
Acosta-Vigil et al. 2017

Compilation of major elements from several studied occurrences of NG in the haplogranite system

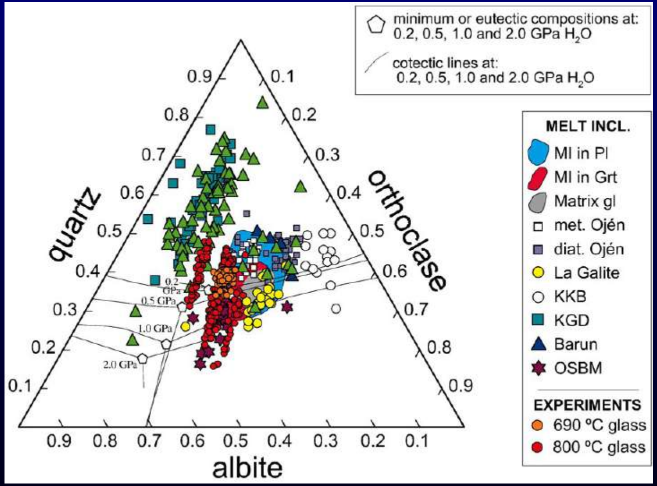
Most peraluminous rhyolite, but also dacite and trachyte

Clearly different melts from different protolith and/or P-T

Not really "*minimum melts*"!

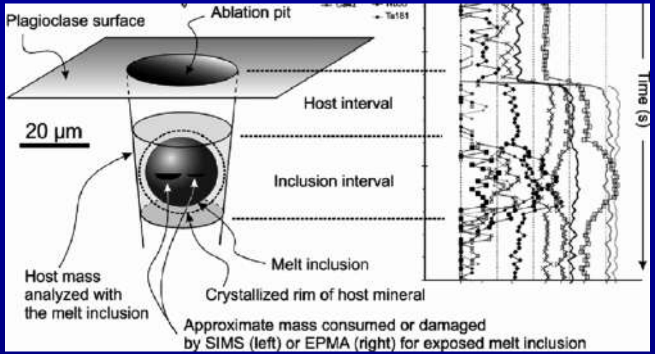


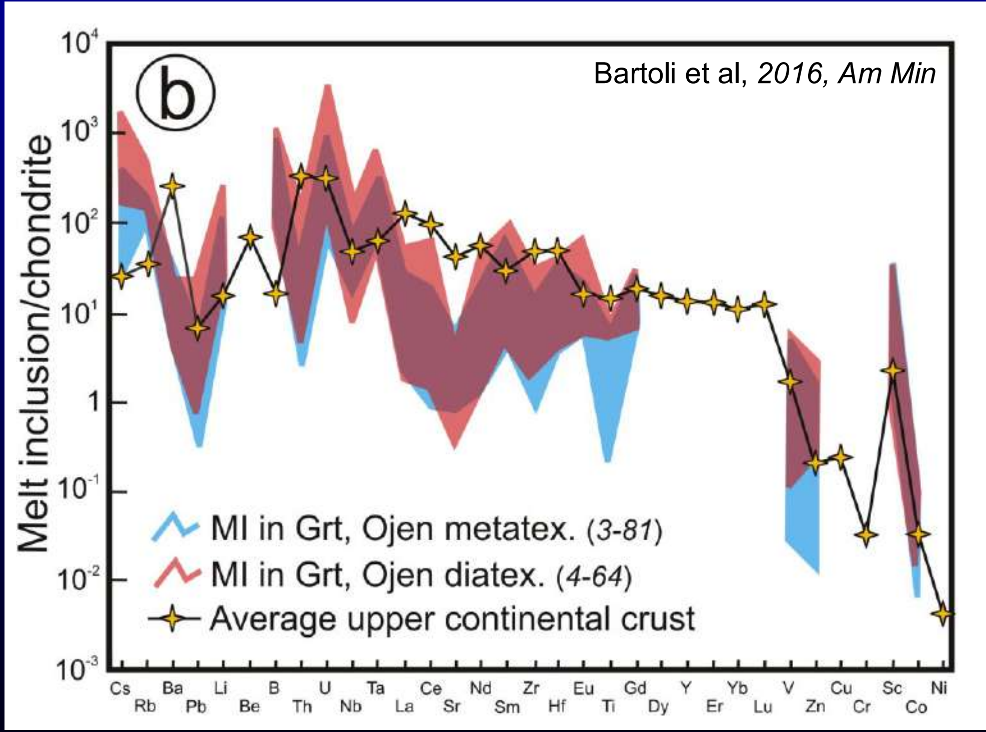
Ferrero et al. 2018

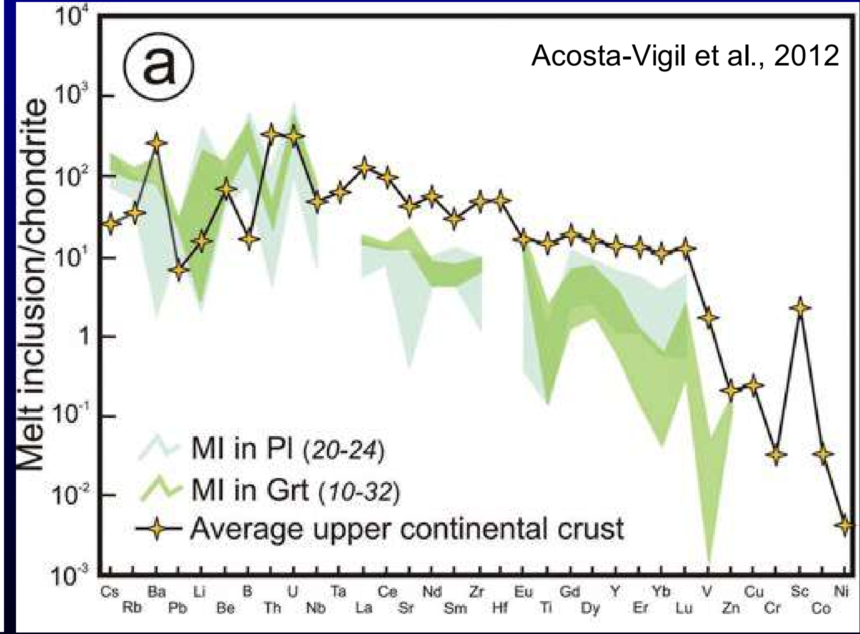


Acosta-Vigil et al. 2017

Also trace elements







H_2O and CO_2 contents

Map in the stretching region of liquid H_2O

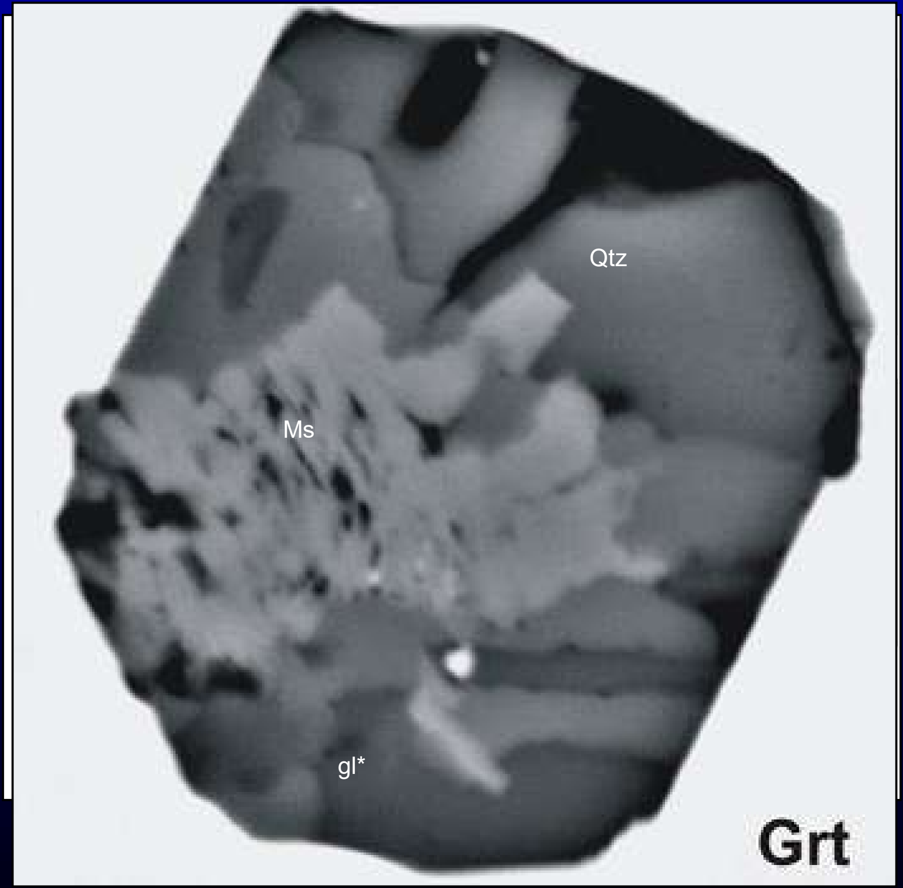
Micro- and nano-pores filled with liquid H_2O

H_2O exsolution in micro- and nano-bubbles

plus

H_2O consumption by mica crystallisation

crystallisation of hydrous melts to nanogranites!

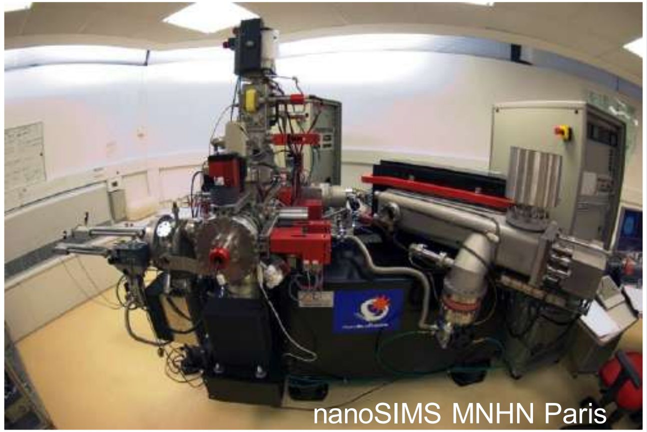


H_2O and CO_2 contents

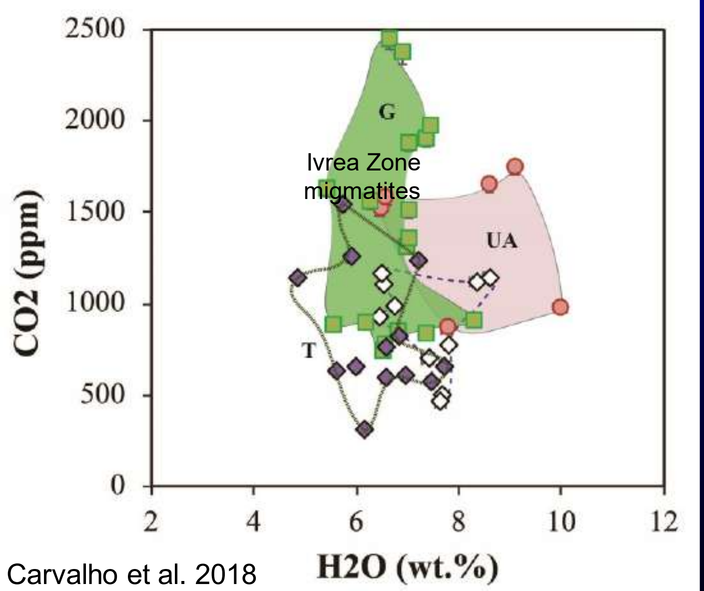
H_2O and CO_2 are quantified by nanoSIMS *Assumption: C = CO_2*

Results help understand the volatile budget during crustal melting, and can be used to constrain the fluid-absent vs. fluid-fluxed character of a melting episode

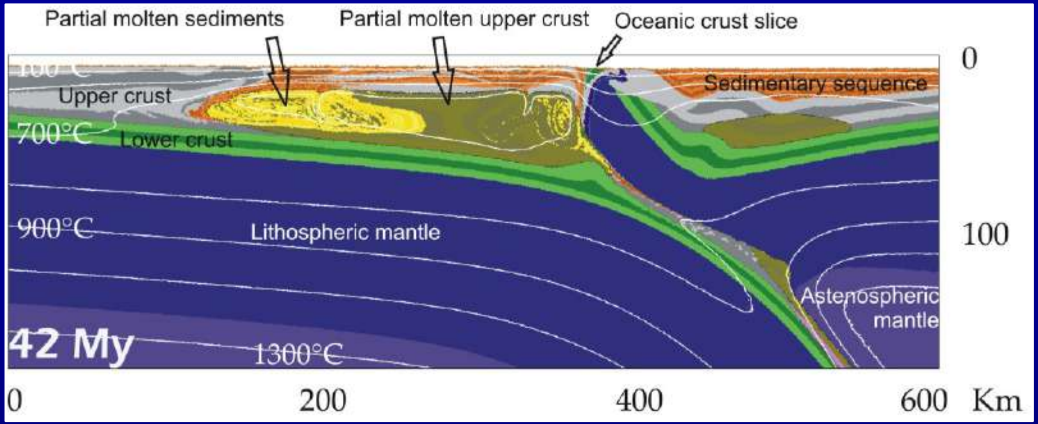
Needs extension to other volatiles

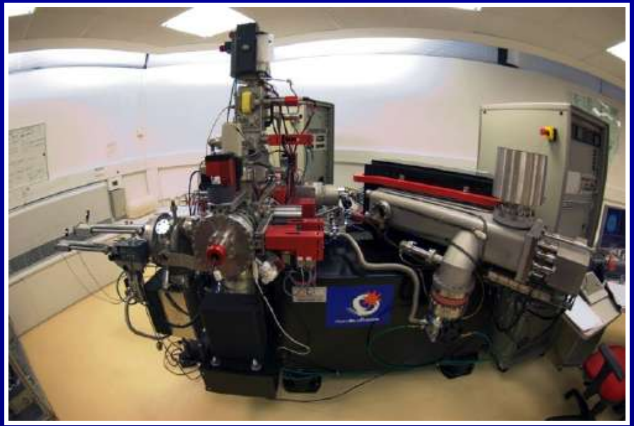


nanoSIMS MNHN Paris

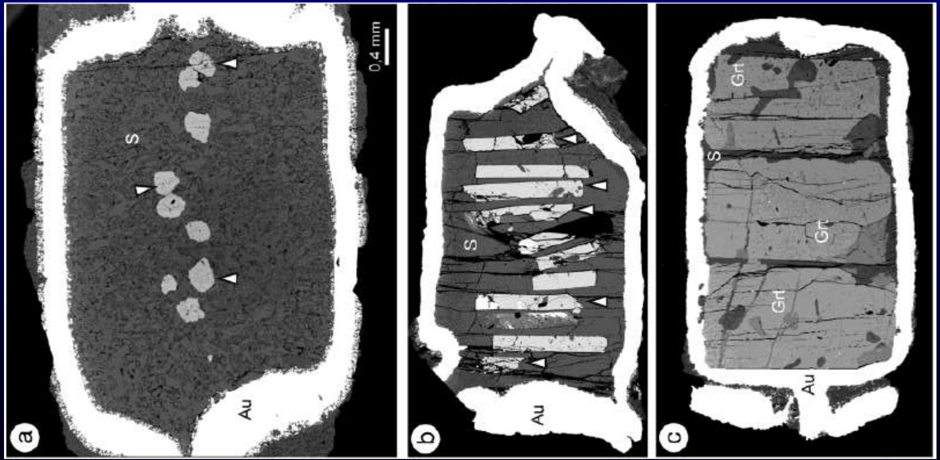


Carvalho et al. 2018





New Directions

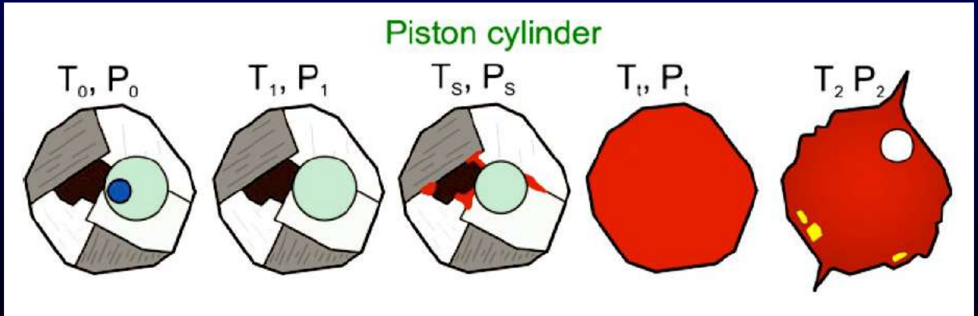


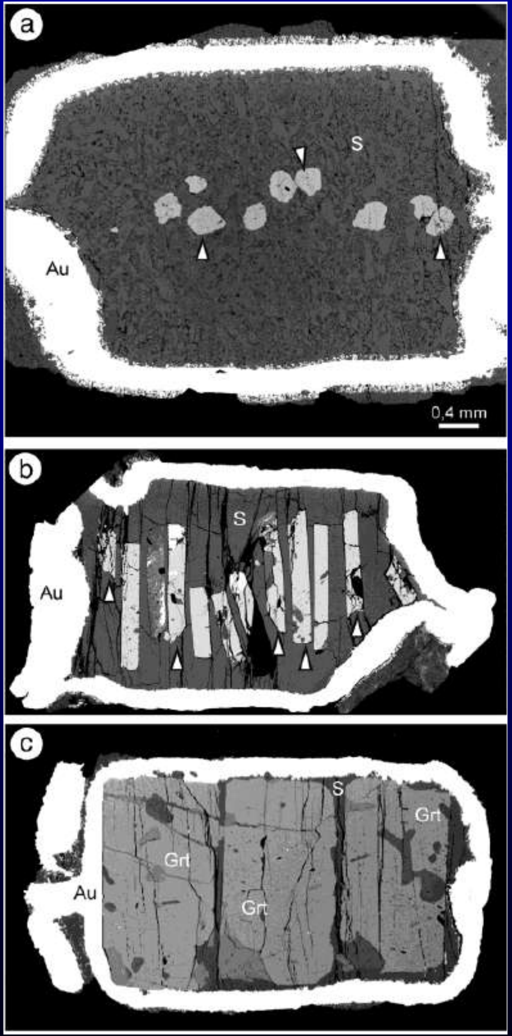
Remelting strategies

Remelting of NG is a time-consuming process based on a trial and error method

Each sample requires a different strategy

Need for an experimental technique that allows faster, successful remelting and subsequent analysis of the greatest # of remelted NG. *Diamond anvil cell?*

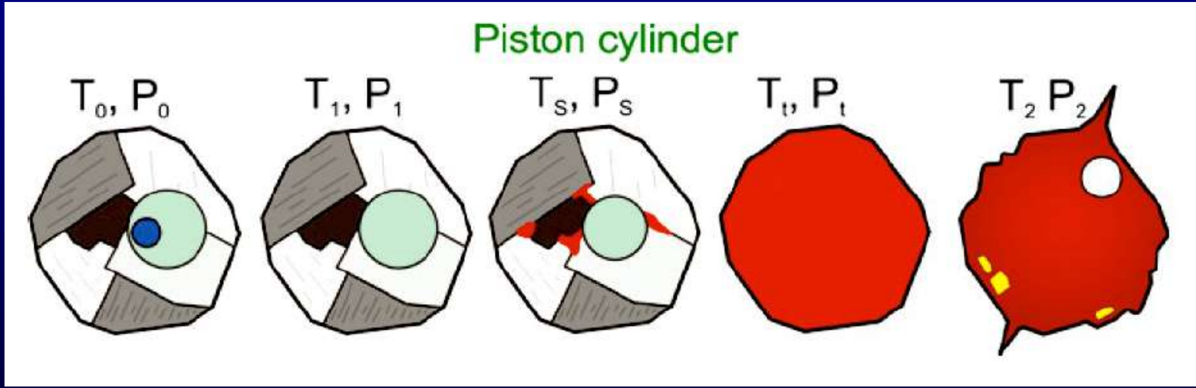




Time-resolved experiments

Does heating during remelting experiments alter the primary composition of NG by interaction with host?

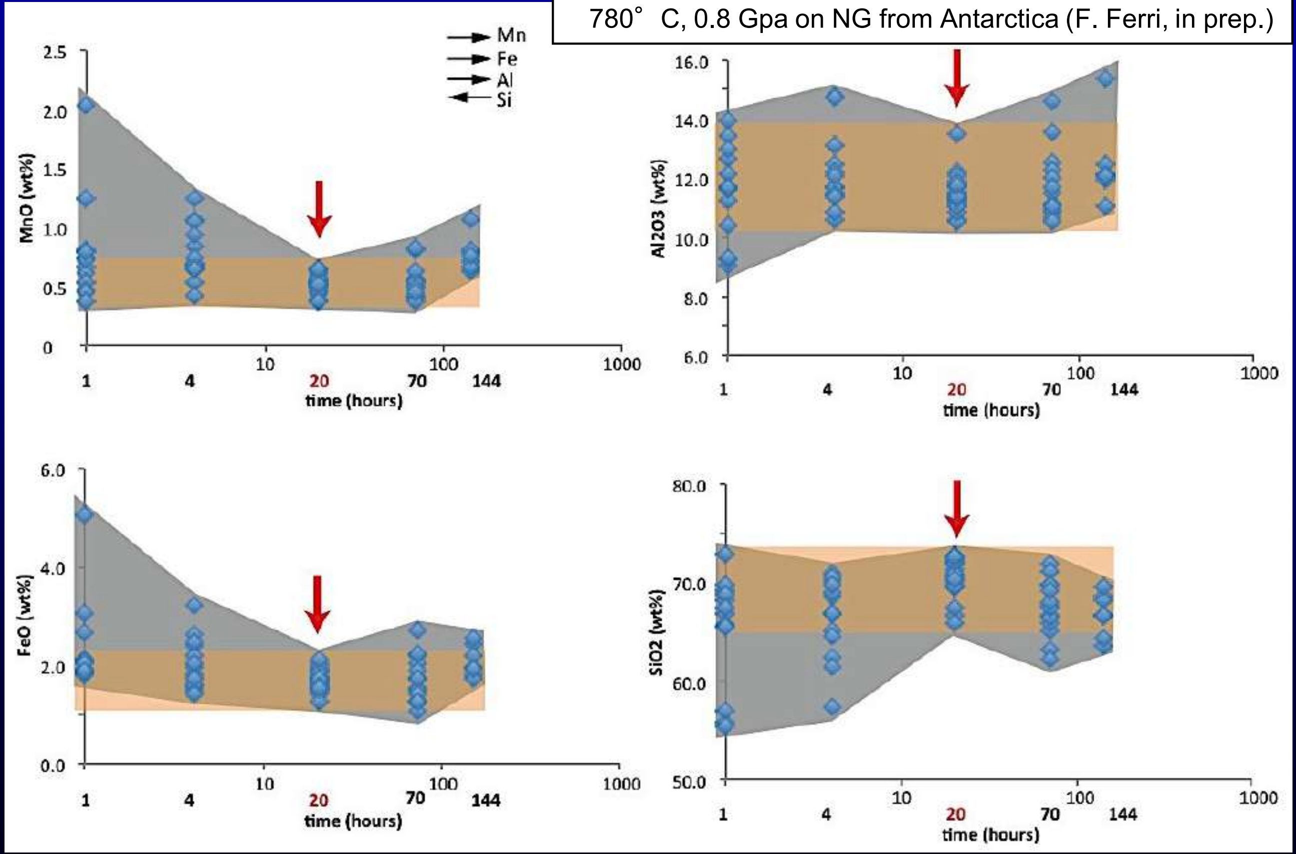
Comparison with glassy inclusions, where present, helps answer, BUT…



Once the correct melting T is found, time-resolved experiments are needed to evaluate changes of melt composition as a function of duration of experiment

Time-resolved experiments

780° C, 0.8 Gpa on NG from Antarctica (F. Ferri, in prep.)



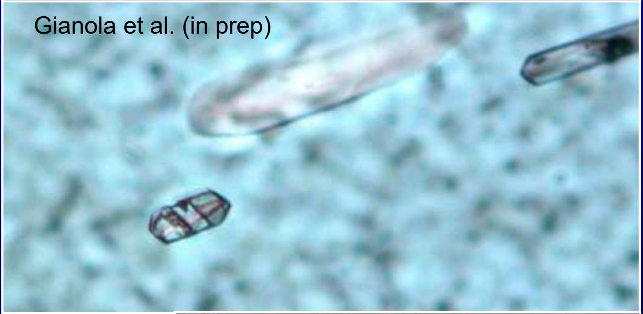
Ultra-high melting

The interest for UH- conditions prompts further studies of NG, in order to determine *in situ* the composition of melts at these P/T.

Plenty of room for UHP, already pioneered by Ferrero's group

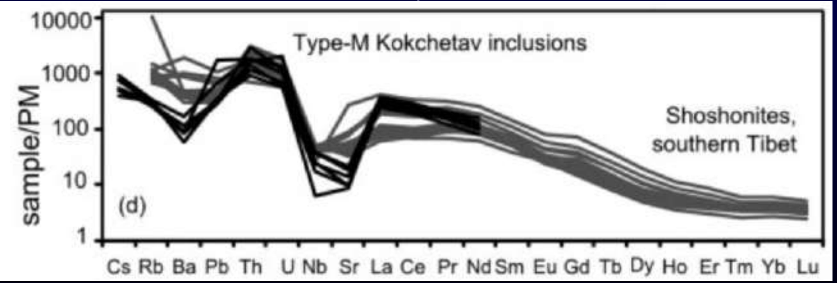
UHT just begun in the Spr-bearing granulites of Gruf (Antarctica soon)

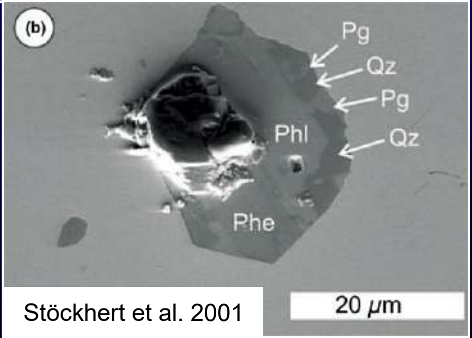
Ultra-old interesting, too…



Gianola et al. (in prep)

Kotchetav UHP massif, Stepanov et a. 2016



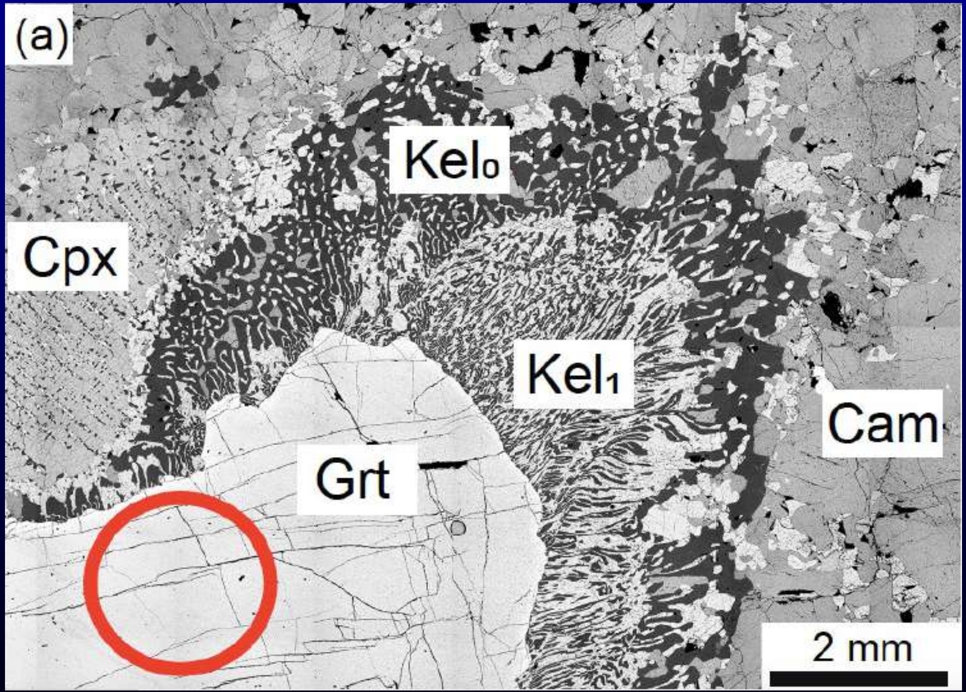


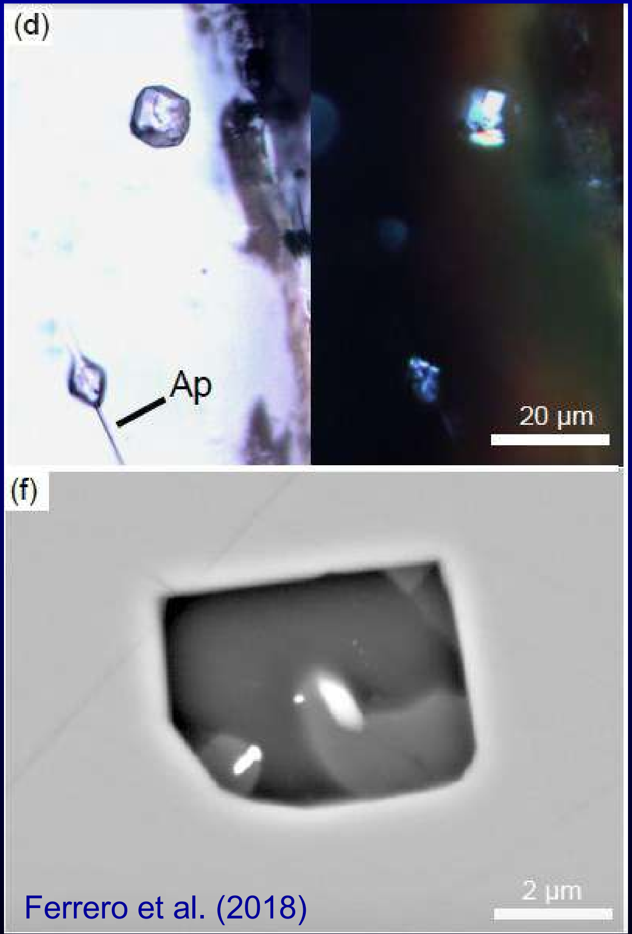
Stöckhert et al. 2001

Extending the approach

First report of NG in garnet from ultramafic rocks

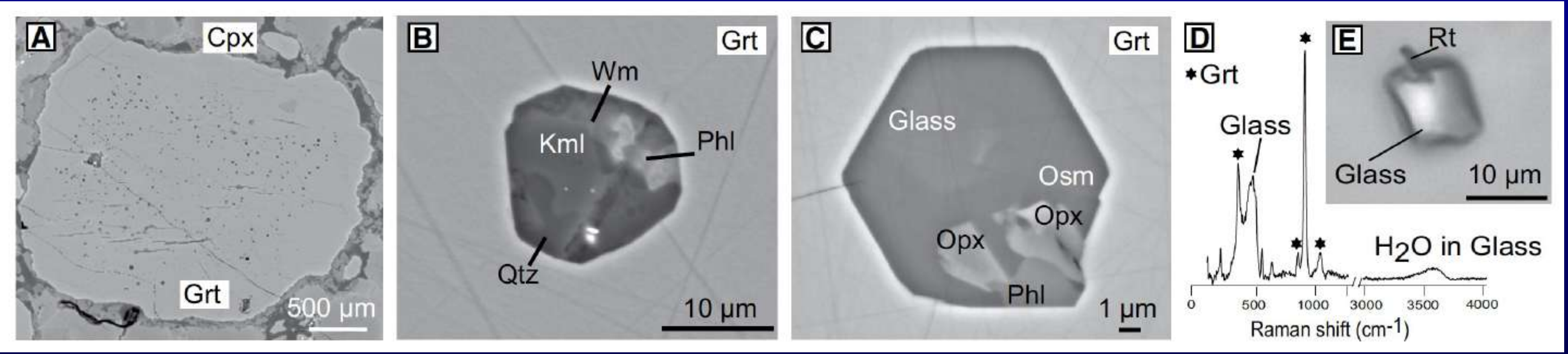
Dronning Maud Land (Antarctica)





Ultra-mafic melting

Second report of NG in garnet from ultramafic rocks (in the Bohemian Massif)



Granitoid melt inclusions in orogenic peridotite and the origin of garnet clinopyroxenite

Alessia Borghini[1], Silvio Ferrero[1,2], Bernd Wunder[3], Oscar Laurent[4], Patrick J. O'Brien[1], and Martin A. Ziemann[1]

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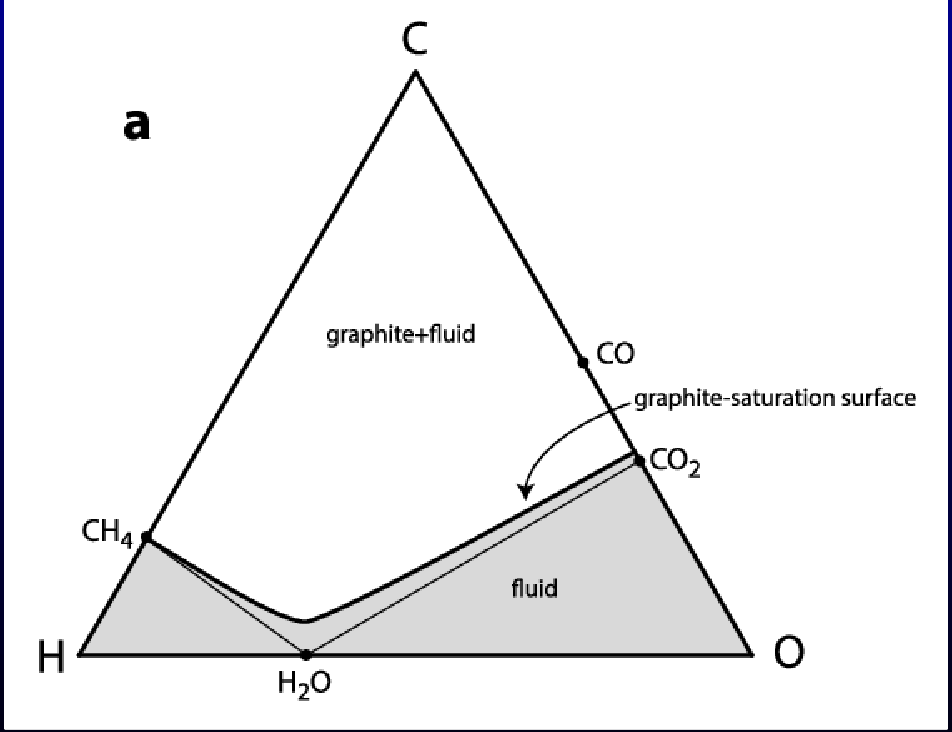
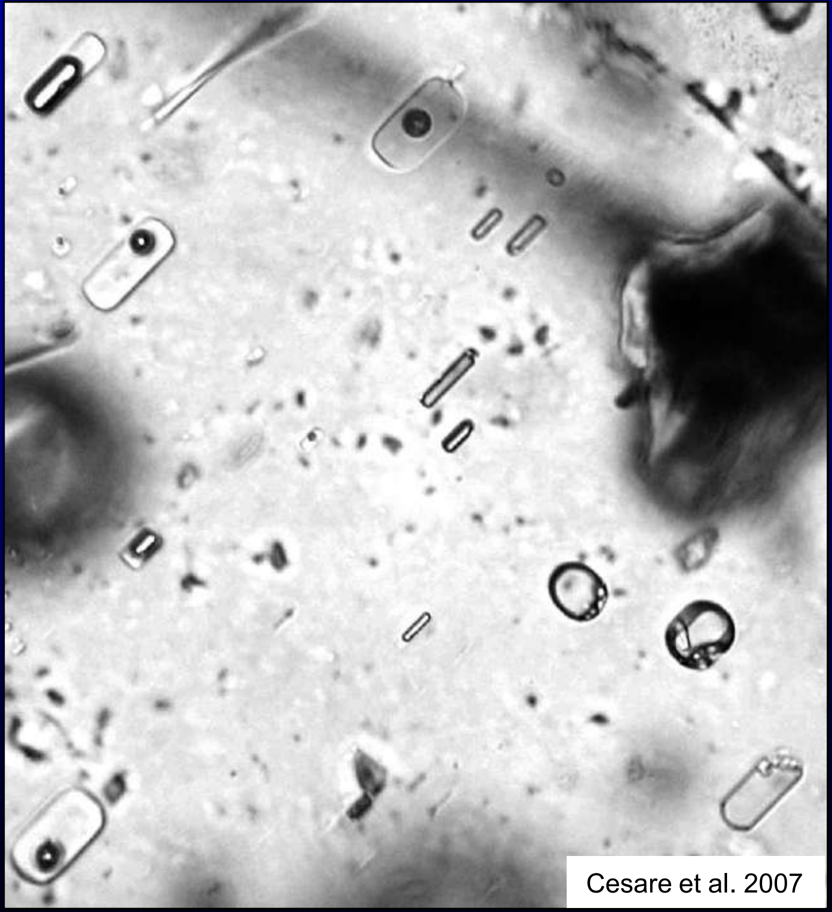
Carbonic Fluid - Melt immiscibility

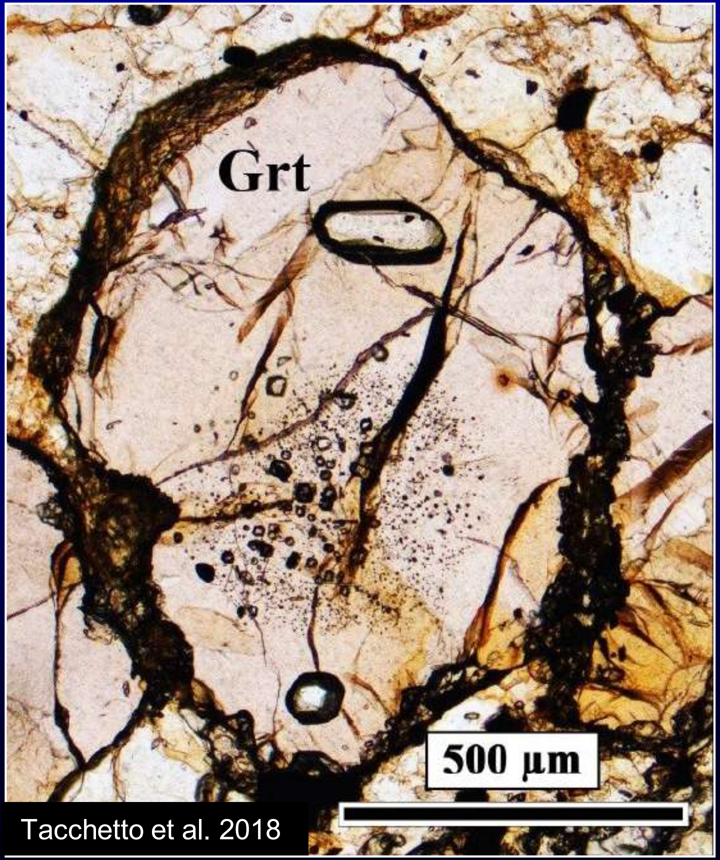
Silicate Liquid – Carbonic fluid immiscibility





Cesare et al. 2007

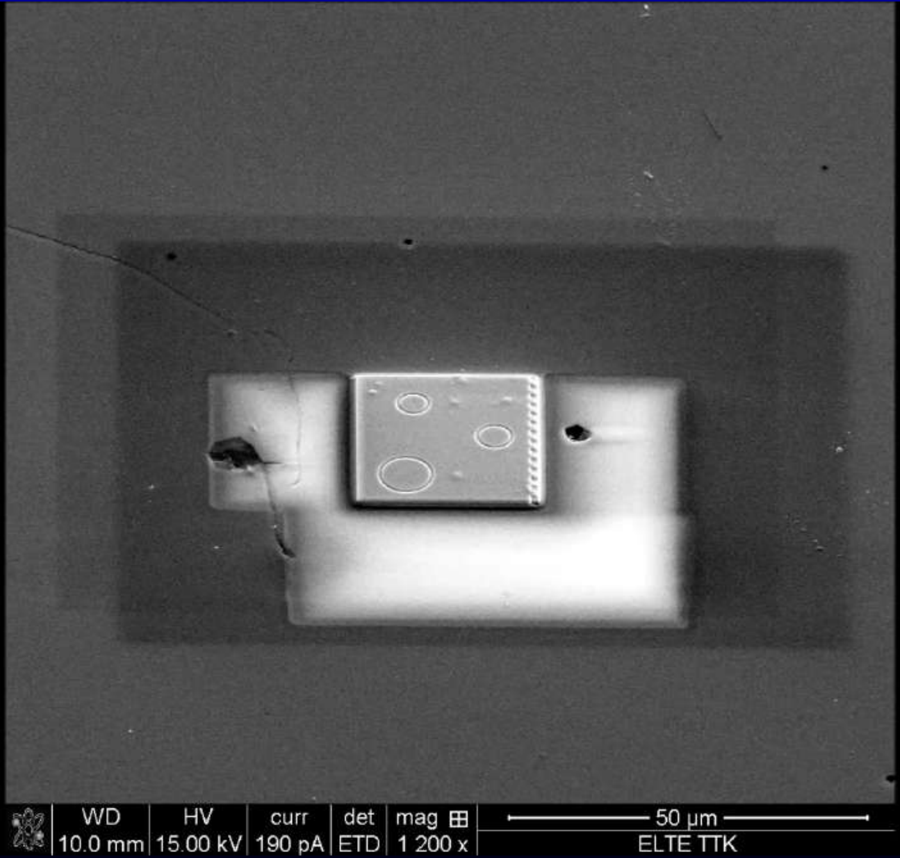
Carbonic Fluid - Melt immiscibility



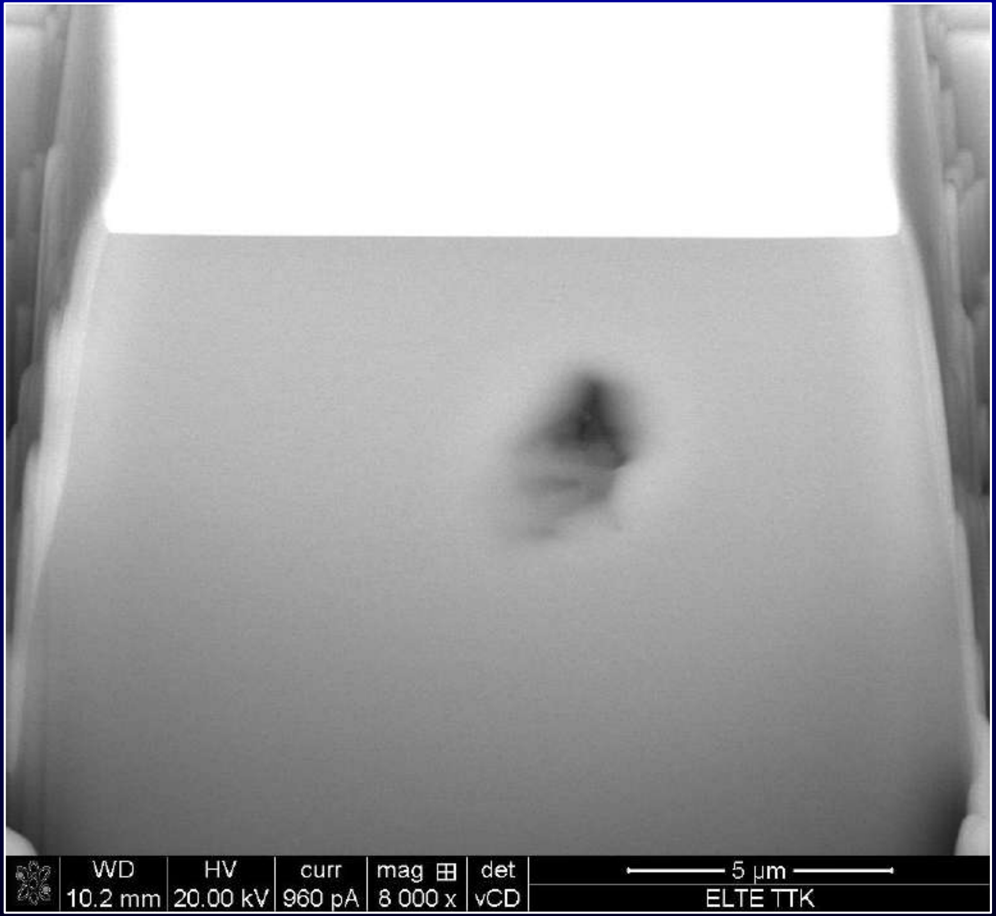
UHT felsic granulites from the Athabasca terrain, Canada

Multiphase inclusions coexisting with NG

Carbonic Fluid - Melt immiscibility



Tacchetto et al. 2018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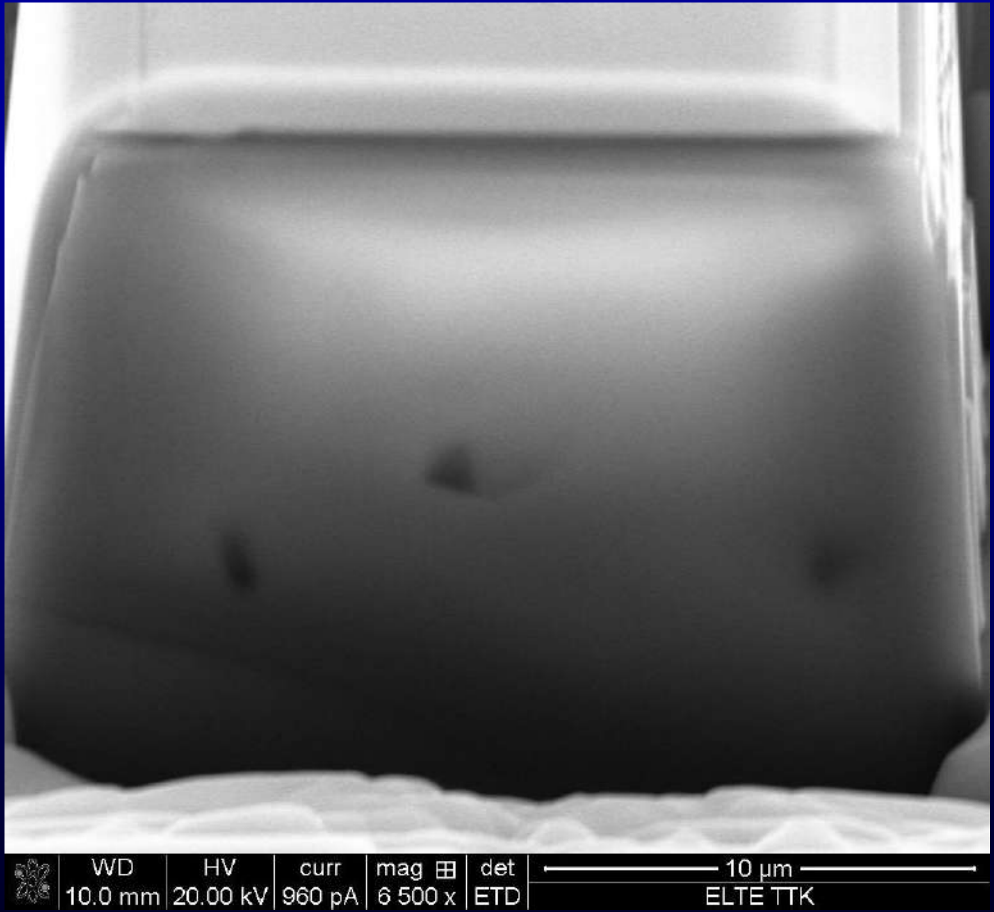
WD
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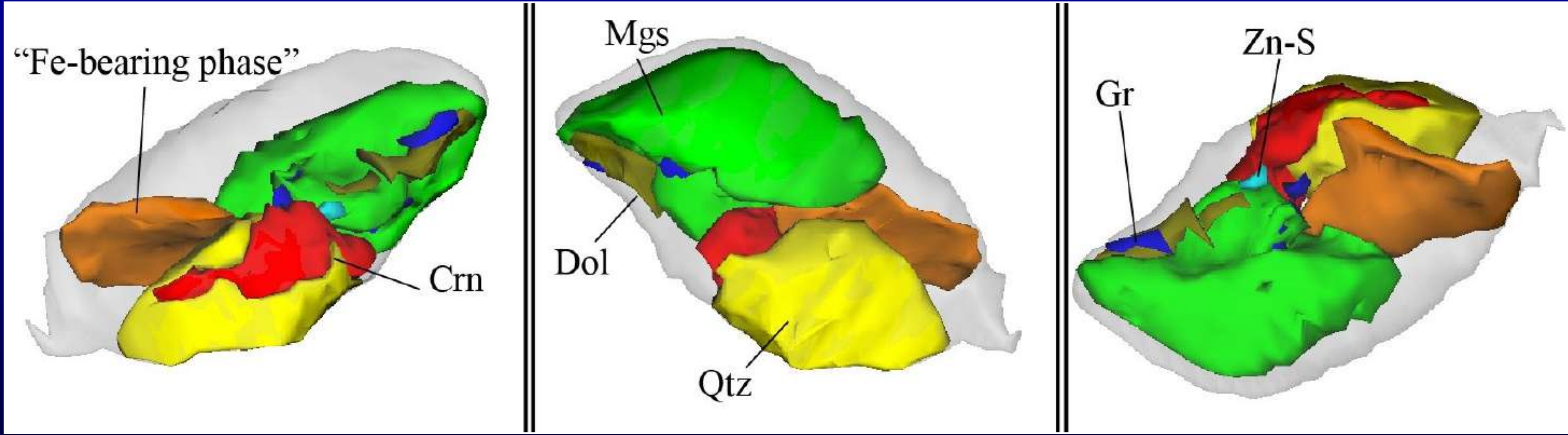
ELTE TTK

Carbonic Fluid - Melt immiscibility



Tacchetto et al. 2018

Carbonic Fluid - Melt immiscibility

As predictable, graphitic rocks (Athabasca, Ivrea Zone, Gruf, Antarctica) display evidence of fluid-melt immiscibility, with coexistence of NG and CO_2-bearing polycrystalline inclusions in the same cluster

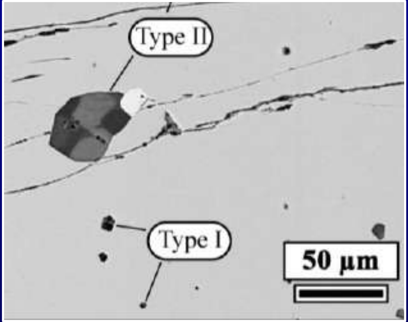
The latter comprise systematically a **CO_2-dominated** fluid (>40% vol.) and **Mg-Fe carbonate**, plus **Crn+Qz** or variable amounts of **Prl, Kao, Gr**.

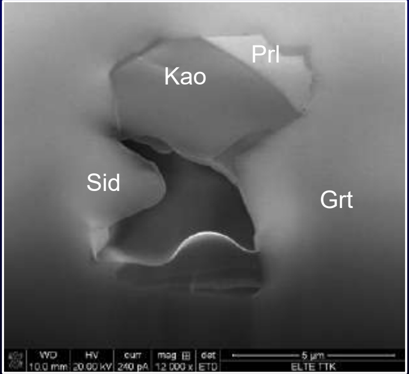
We interpret these inclusions as the result of interaction between garnet and **primary carbonic fluid inclusions,** through reactions such as:

$$Grt + CO_2 = Carb + Crn + Qz$$

$$Grt + CO_2 + H_2O + CH_4 = Carb + Prl + Kao \pm Gr$$

Implies a re-evaluation of the "superdense" CO_2 inclusions generally associated with granulites



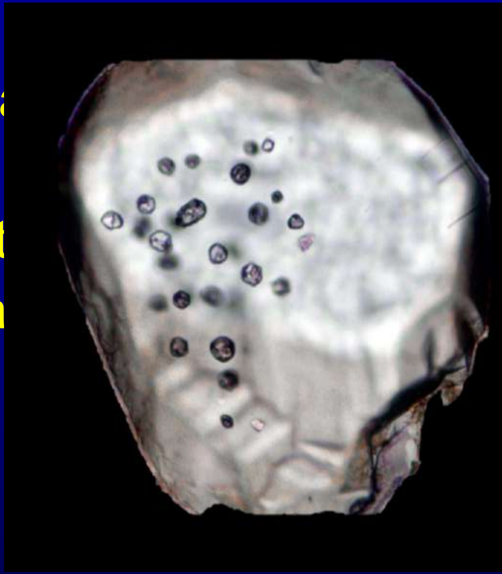


Conclusions - 1

- Our studies indicate that peritectic minerals, growing during incongruent melting reactions, act as hosts for inclusions of anatectic melt, and that in the general case of slow cooling of the crust these inclusions will have crystallized into *nanogranitoids*

- Melt inclusions should be targeted in strong and chemically “inert” minerals (also Rut, Ap, Zrn, Mnz) from the least deformed rock domains

Conclusions - 2

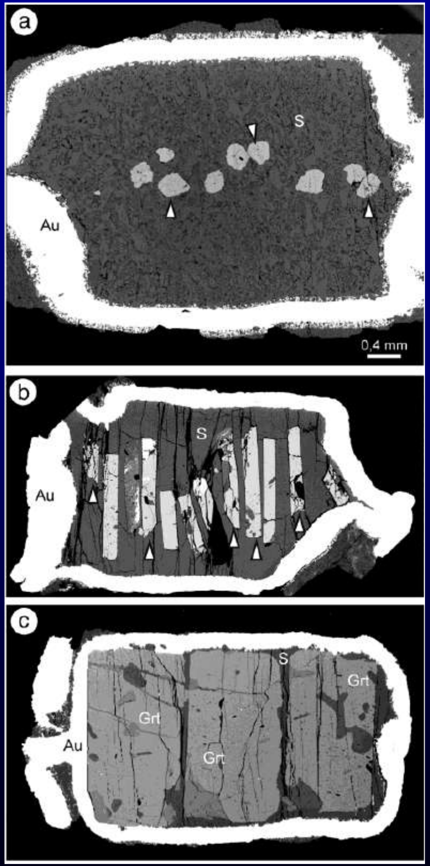


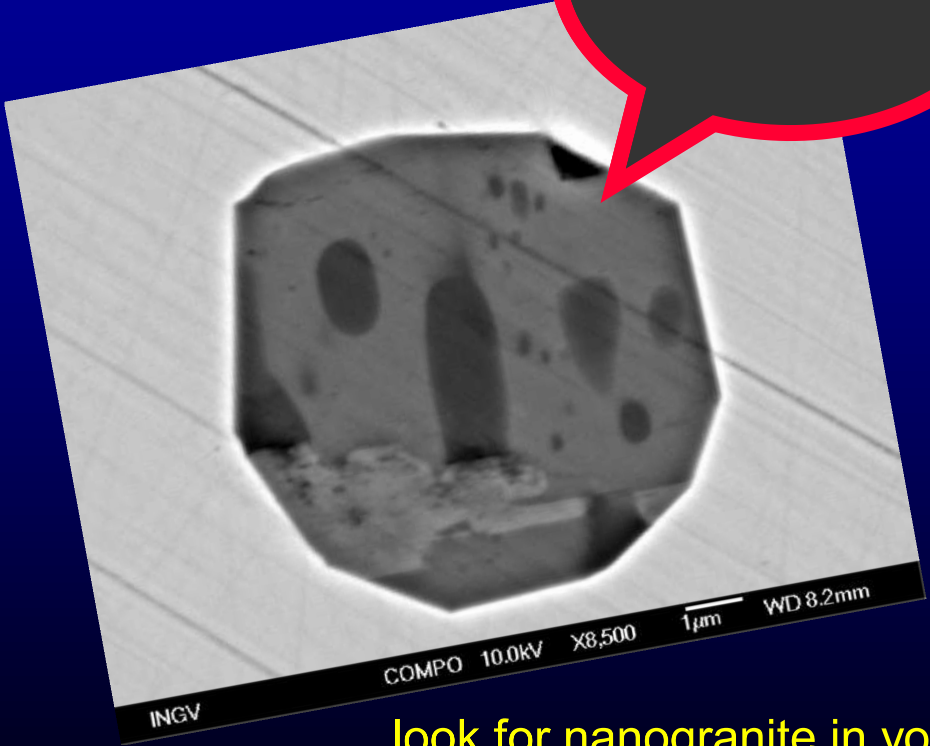
- From a microstructural point of view, MI (in particula *nanogranites*) are a proof that a rock was partially melted at some time in its history. Thus, nanogranit are among the most reliable microstructural criteria for the former presence of felsic melt in regional migmatites

- From a geochemical point of view, our results extend the frontiers of research in crustal melting, as the composition of anatectic melts can be directly analyzed rather than assumed.

Conclusions - 3

- A good optical microscope and well-prepared thin sections are all one needs to make the key observations and decide if NG are present and suitable for a study
- The chemical analysis of NG 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 NG still poses some limitations to a full and fast characterization of these objects. However, in a few years from now, the rapid improvement of analytical techniques will have overcome these problems





Thank You

…look for nanogranite in your samples…