DIPARTIMENTO
DI GEOSCIENZE

Fluid regime during anatexis of the deep crust: clues from melt and fluid inclusions

Bruna B. Carvalho
bruna.borgescarvalho@unipd.it

Advances in Crustal MElting
http://www.eurispet.eu/ACME/Home.html

7th October 2019

UNIPV
PhD Program in Earth
and Environmental Sciences

Structure and Composition of the Lower Continental Crust – October 7-10

Outline

- Introduction
    - Anatexis and the debate on the fluid regime of the deep crust
    - A brief on melt inclusions

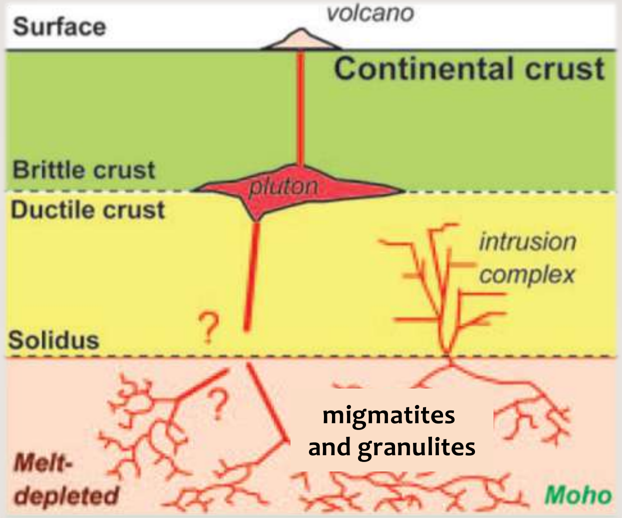
- General aspects of the Kinzigite Formation, Ivrea Zone

- Fluid regime of the deep crust : Case study of the metapelitic migmatites from the Kinzigite Formatiton
    - Nanogranitoid inclusions (former melt inclusions)
    - Fluid inclusions

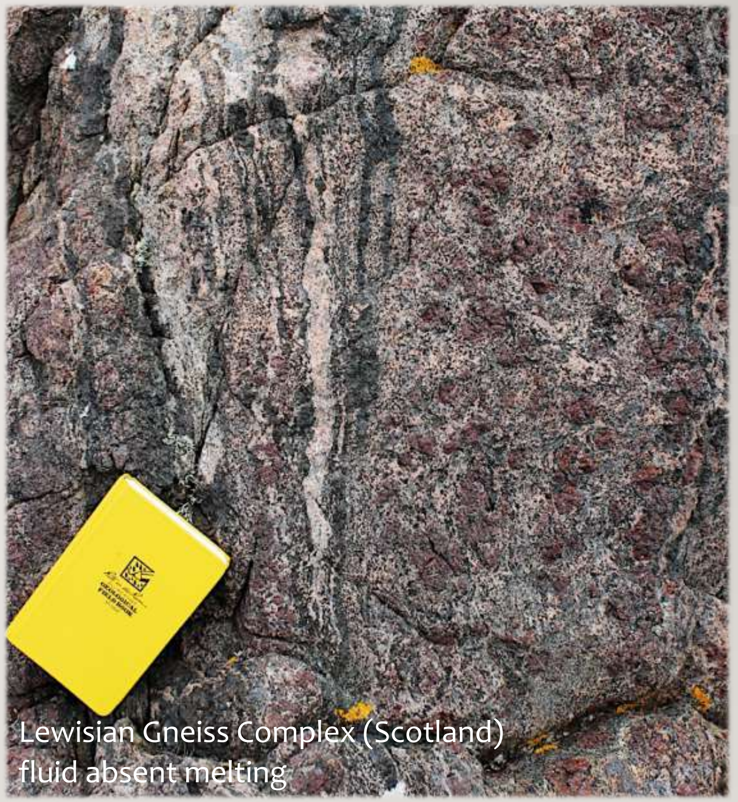
Introduction |anatexis and the debate on fluid regime|

Kinawa migmatite (Brazil)
water-fluxed melting

Low T anatexis



|Sawyer et al. 2011 – Elements|



Lewisian Gneiss Complex (Scotland)
fluid absent melting

High T anatexis

Melting conditions and dynamics in the crust are deeply affected by the fluid regime

Introduction |anatexis and the debate on fluid regime|

The role of fluids in **high-temperature metamorphism and anatexis** remains a largely **debated** topic

- **Dry lower crust and fluid-absent anatexis**

very low permeability of the crust and the prevalent H_2O-undersaturated character of crustal melts

|Thompson 1983 – JGSL| |Stevens & Clemens 1993 – CG|
|Yardley & Valley – JGR| |Clemens et al. 2016 – Prec Res|

- **Fluids (carbonic/aqueous/brines) as essential agents**

present along the heating path or at metamorphic peak conditions

|Newton et al. 1980 – Nature| |Touret 1985|
|Harlov et al 2005 – J.Pet| |Weinberg & Hasalova 2015 – Lithos|

Introduction |a brief on melt inclusions|

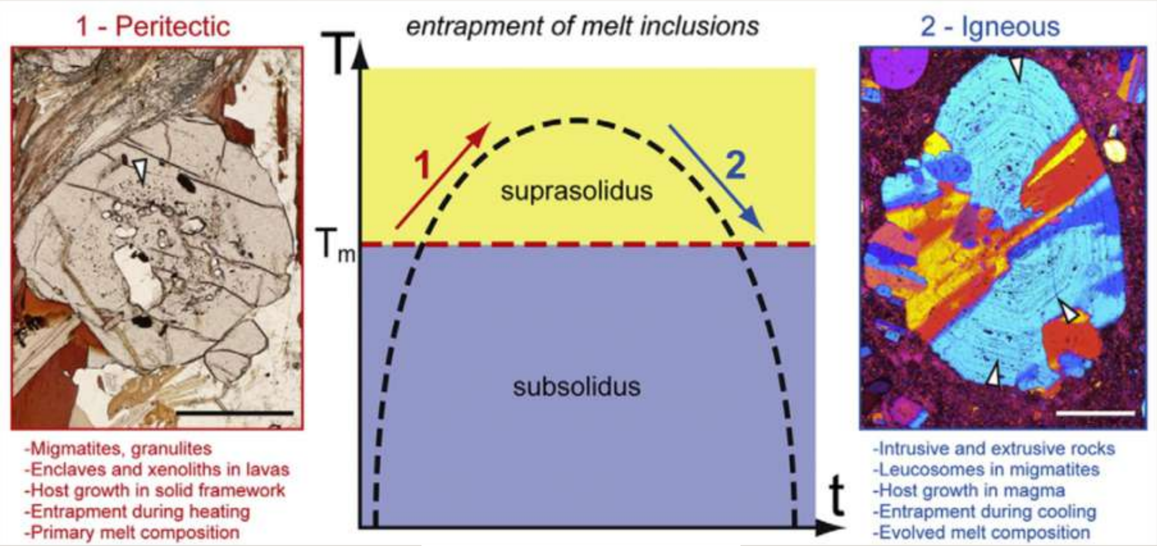
Melt inclusions

« Small droplets of melt that are trapped in minerals during their growth in the presence of a melt phase »

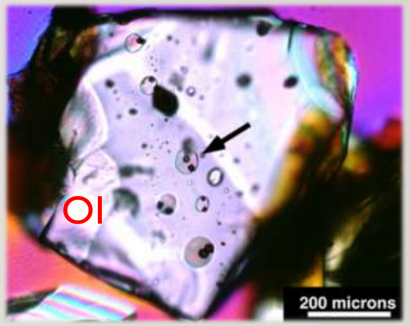
|Cesare et al 2011 – JVE|

Melting

Crystallization



|Cesare et al 2015 – L|



Metamorphic rocks

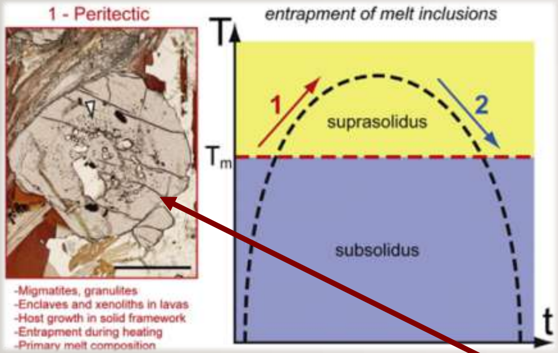
○ Primary

Igneous rocks

○ Evolved

Introduction |a brief on melt inclusions|

Melting



Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Invited review article

What can we learn from melt inclusions in migmatites and granulites?

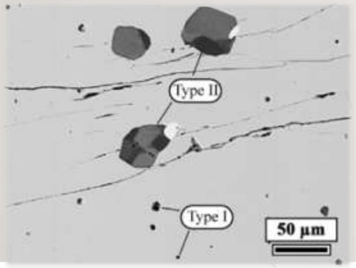
B. Cesare[a], A. Acosta-Vigil[a], O. Bartoli[a], S. Ferrero[b,c]

Melt

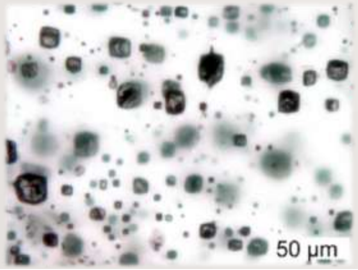
&

Fluid

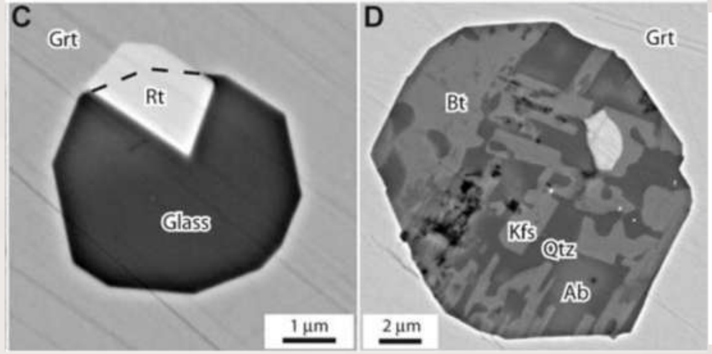
(if present)



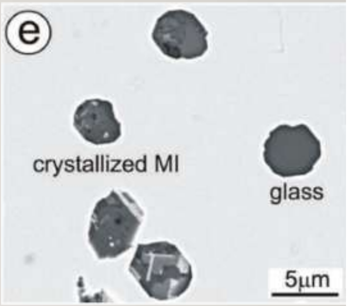
|Tacchetto et al 2018 – CG|



|Ferrero et al 2014 – JMG|



|Cesare et al 2009 – G|



|Bartoli et al 2016 – AM|

Glassy **Nanogranitoid**

Abundant in : enclaves migmatites/granulites

Bt + Sil + Pl + Qz = **Grt** + melt (± Kfs)

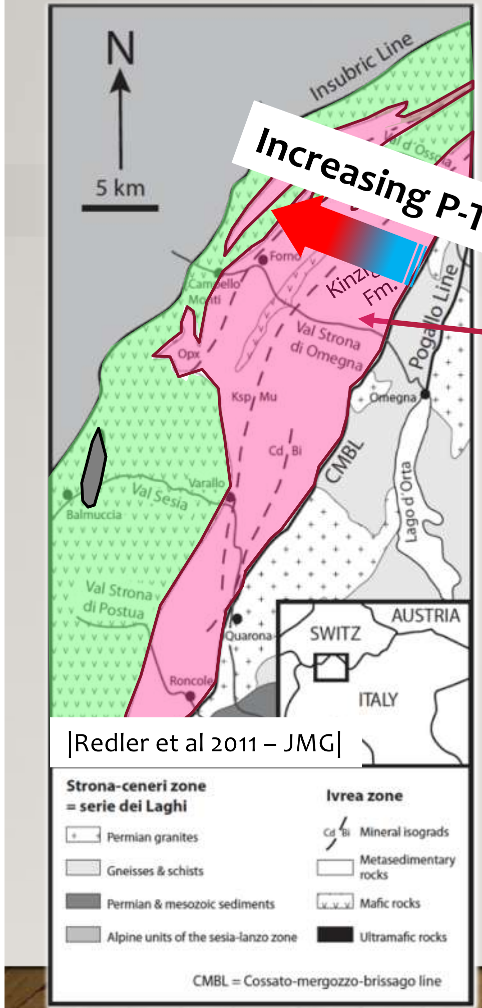
Investigate the primary composition of anatectic melts and fluid regime during crustal melting

More about…

« Melt Inclusions in Migmatites and Granulites »
by ***Bernardo Cesare*** (University of Padova)
Thursday 10th October 2019

General aspects of the Kinzigite Formation (Ivrea Zone)

General aspects of the Kinzigite Formation (Ivrea Zone – NW Italy)



|Redler et al 2011 – JMG|

- The Ivrea Zone (NW Italy) represents a cross section through the lower crust of the southern Alpine basement
  - i) Ultramafic rocks
  - ii) Mafic rocks of the Mafic Complex
  - iii) Supracrustal rocks of the **Kinzigite Formation**

Interlayered metapelites, metapsammites / metagreywackes, metabasic rocks with subordinate calc-silicates and marbles

- Dating (U-Pb zircon geochronology)

Regional metamorphism

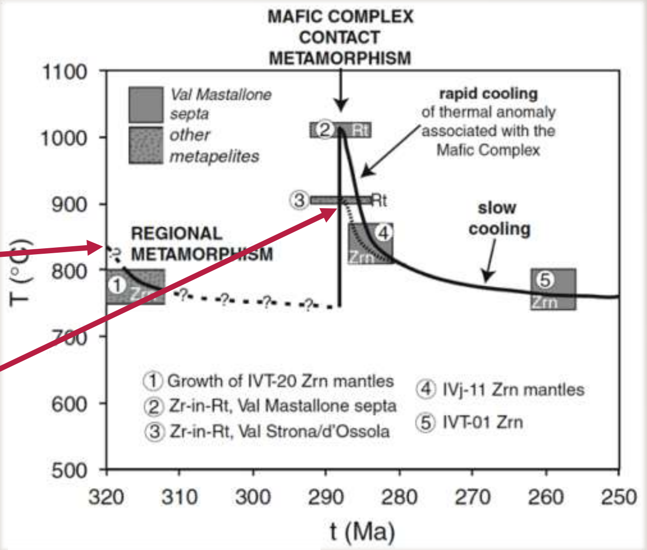
316 ± 3 Ma

Resetting 2-3 Km around the Mafic complex

284 ± 3 Ma

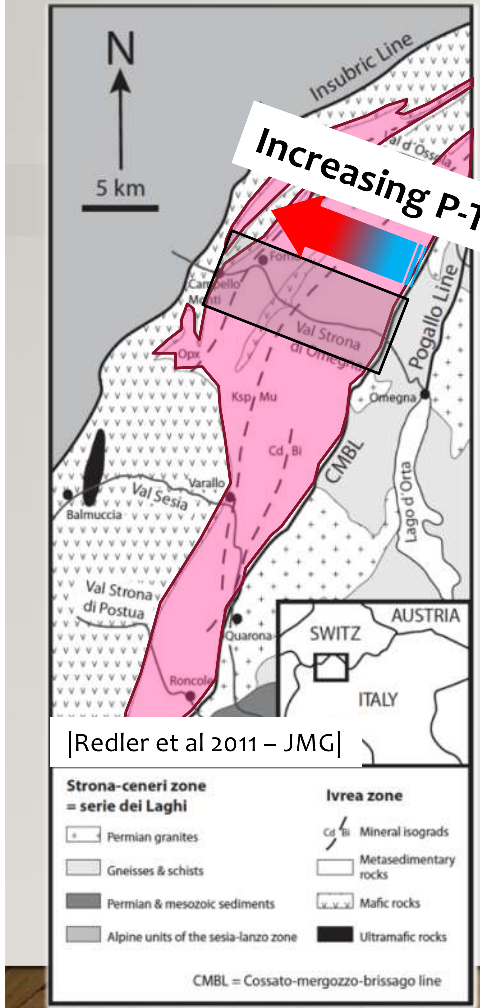
(close to the main event of intrusion **288 ± 4 Ma**)

|Peressini et al 2007 – JPet|



|Ewing et al 2013 – CMP|

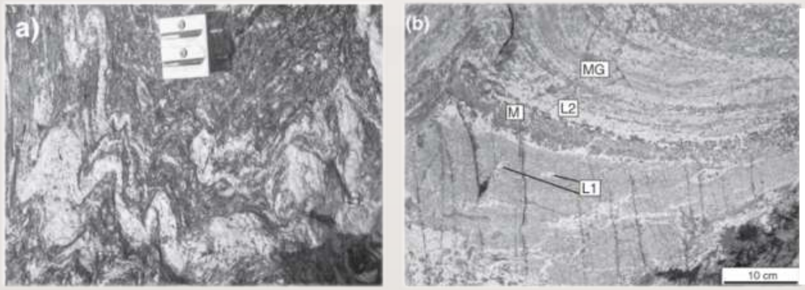
General aspects of the Kinzigite Formation (Ivrea Zone – NW Italy)



|Redler et al 2011 – JMG|

- Preserved metamorphic field gradient from amphibolite facies to granulite facies (increasing SE to NW)

Metapelites

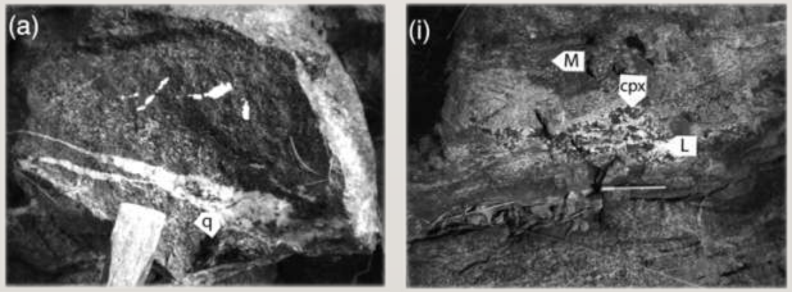


Schist

Metatexites to diatexites

|Redler et al 2013 – L|

Metamafic rocks

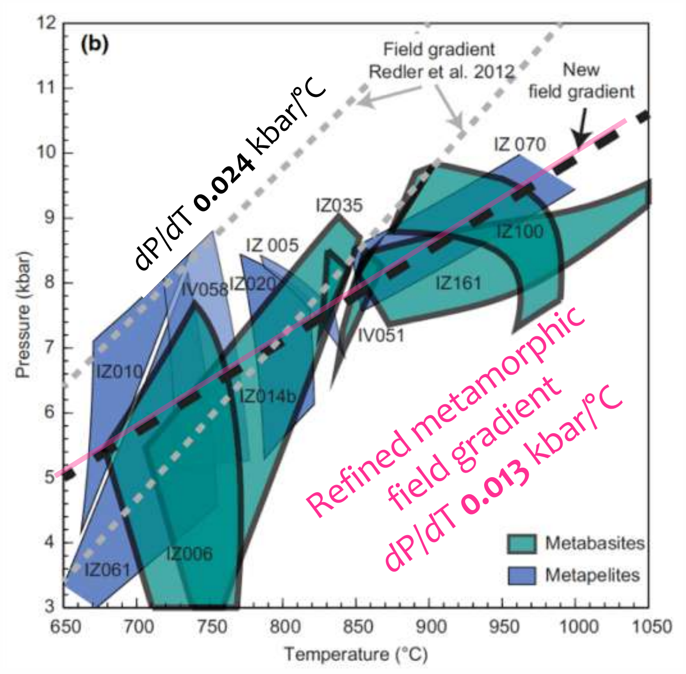


Fine-grained amphibolite

Patch to stromatic migmatite

|Kunz et al 2014 – L|

Combining metapelitic and metabasic information: more precisely constrained metamorphic field gradient (lower dP/dT)



|Kunz & White 2019 – JMG|

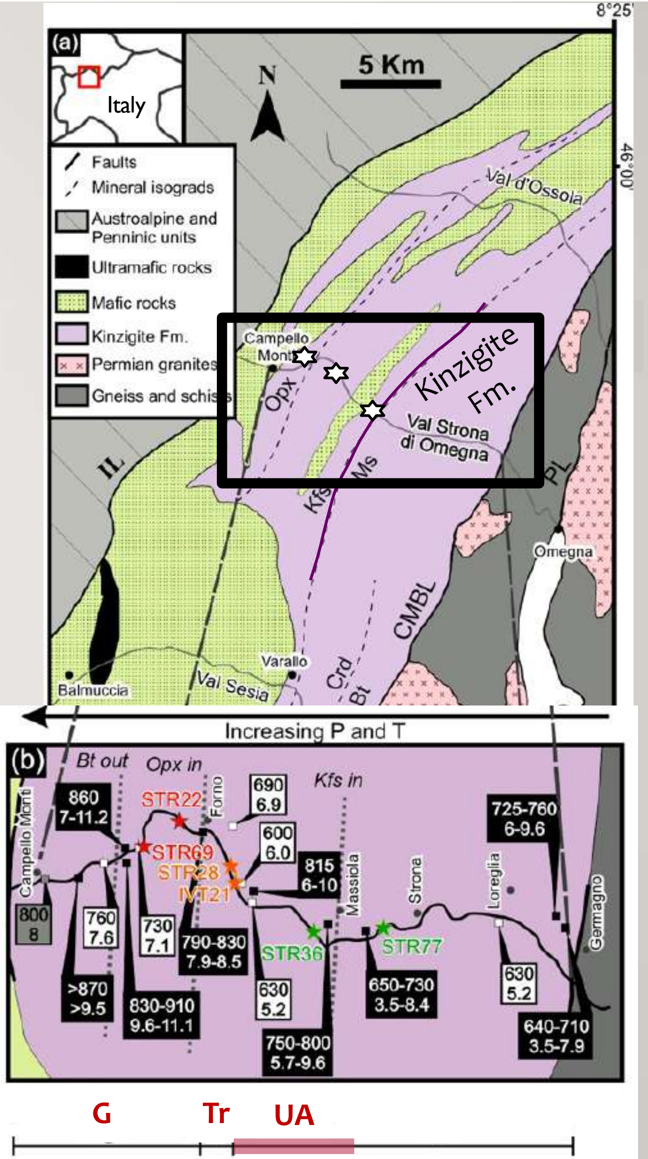
Fluid regime of the deep crust : Case study of the metapelitic migmatites from the Kinzigite Formatiton

Case study

Studied metapelitic migmatites were collected in the three main zones

- Upper Amphibolite (UA)
- Transition zone (Tr)
- Granulite (G)

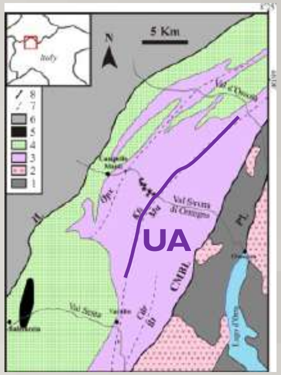
Main goals: *obtain the composition of the melts and fluid regime with increasing T*



|Carvalho et al 2019 – JMG|

Studied samples

◆ **Upper Amphibolite Facies**

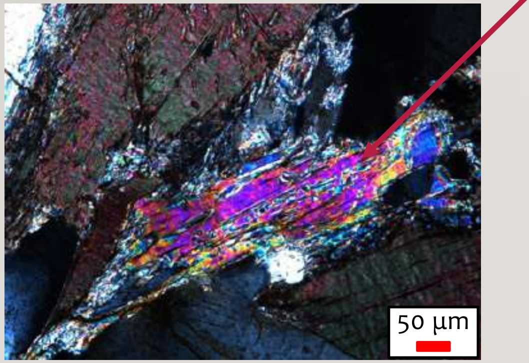


✓ Metatexite with narrow leucosomes

Bt ± relict Ms + Fibrolite (Sil) + Pl + Qz + Kfs + Gr + <u>Grt</u>
+ other accessory (Ap, Zir, Mnz)

Ms + Pl + Qz = melt + Sil + Kfs

Bt + Sil + Pl + Qz = <u>Grt</u> + melt (± Kfs)

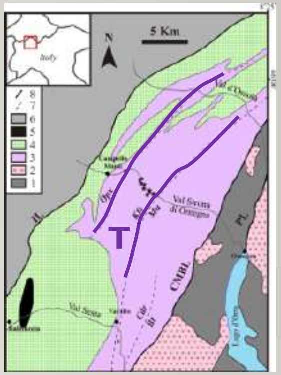


Small grains of garnet rich in inclusions

Studied samples

- **Transition Zone**

✓ **Stromatic metatexite**



Bt + (Fibrolitic to prismatic) Sil + Grt + Kfs + Pl + Qz + Gr
+ other accessory (Ap, Zir, Mnz, Ru)

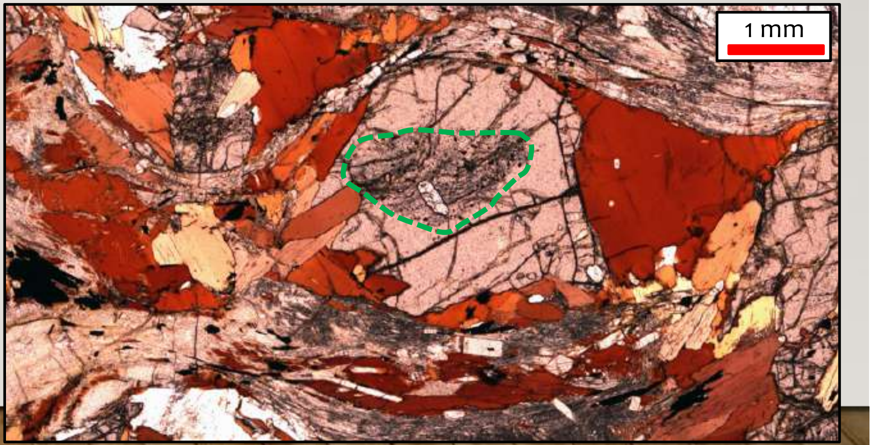
Kinzigite

used for rocks in which biotite is more abundant than garnet |Schmid 1968 – SMPM|

used for rocks preserving amphibolite facies assemblages |Schnetger, 1994 – CG|

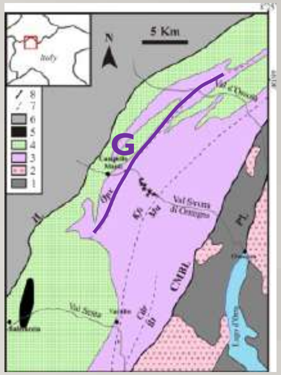
Bt + Sil + Pl + Qz = Grt + melt (± Kfs)

Large grains of garnet rich in inclusions



Studied samples

- **Granulite Facies**



✓ Residual diatexite

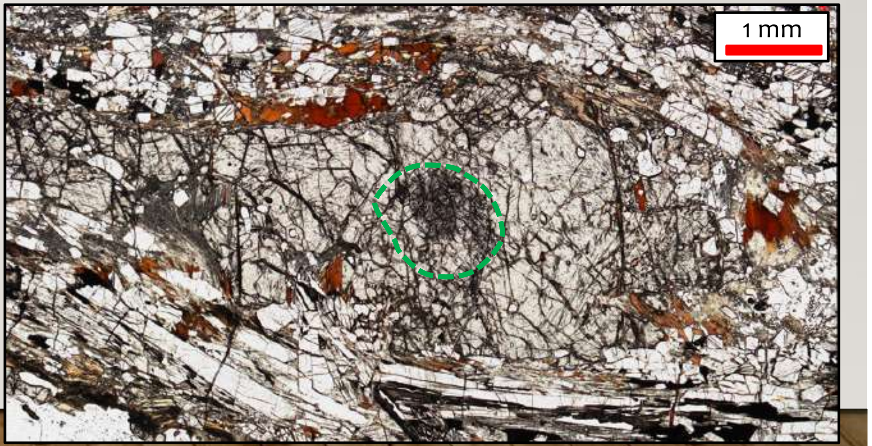
(*Prismatic*) Sil + Grt + Kfs + Pl + Qz ± Bt + Gr
+ other accessory (Ap, Zir, Mnz, Ru)

Stronalite

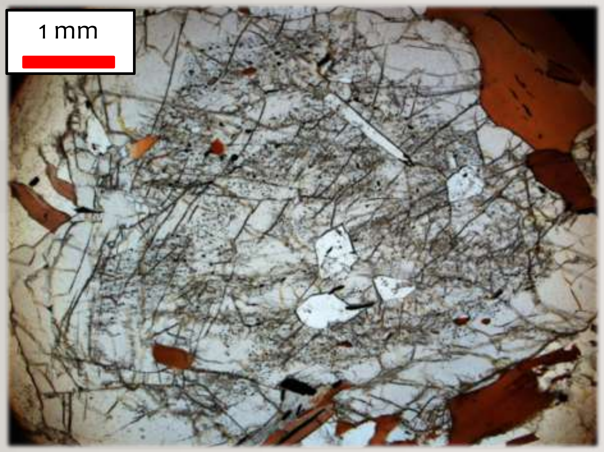
used for rocks in which garnet is more abundant than biotite |Schmid 1968 – SMPM|

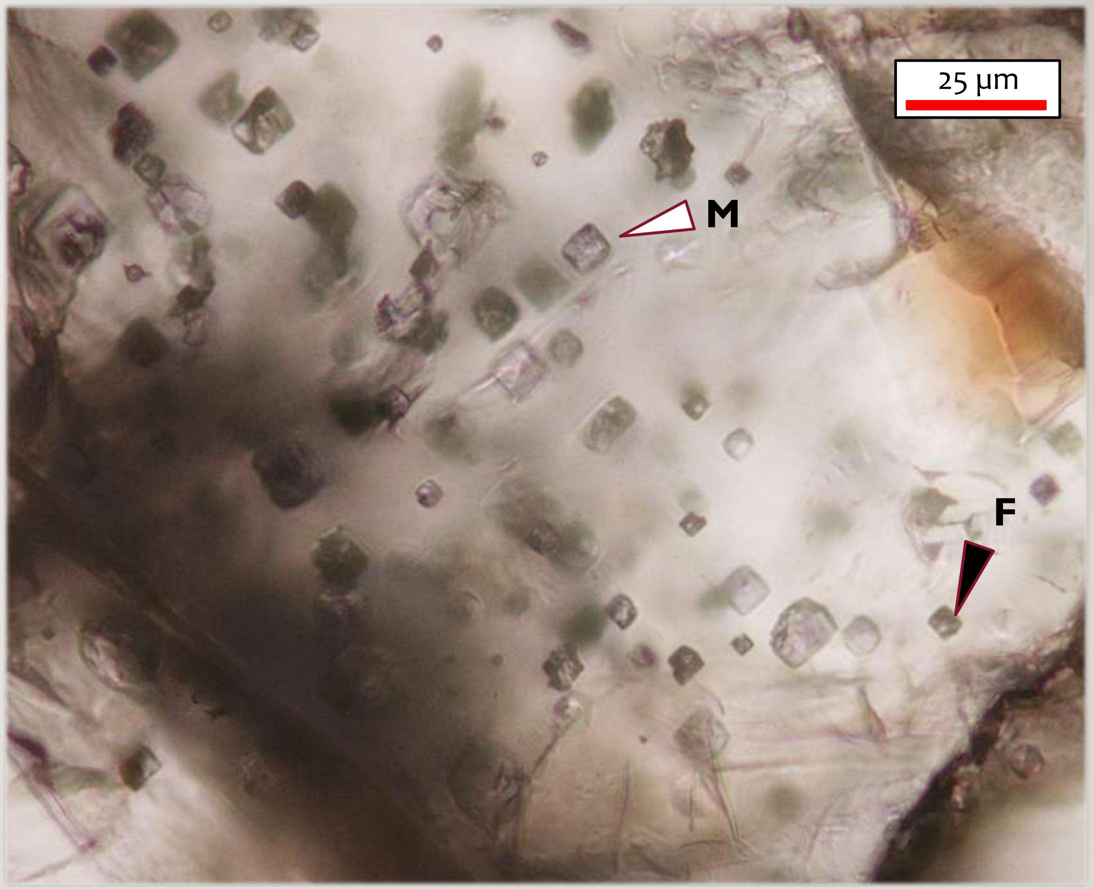
used for rocks preserving granulite facies assemblages |Schnetger, 1994 – CG|

Large grains of garnet rich in inclusions

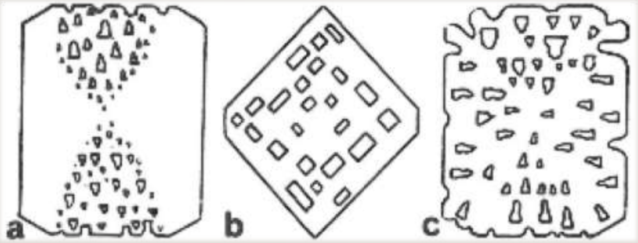


Melt and fluid inclusions





Primary inclusions



|Roedder 1984|

Melt and fluid inclusions were trapped in the same anatectic event

Fluid regime of the deep crust : Case study of the metapelitic migmatites from the Kinzigite Formatiton

Nanogranitoid inclusions

(former melt inclusions)

Journal of
METAMORPHIC GEOLOGY

ORIGINAL ARTICLE | Full Access

Anatexis and fluid regime of the deep continental crust: New clues from melt and fluid inclusions in metapelitic migmatites from Ivrea Zone (NW Italy)

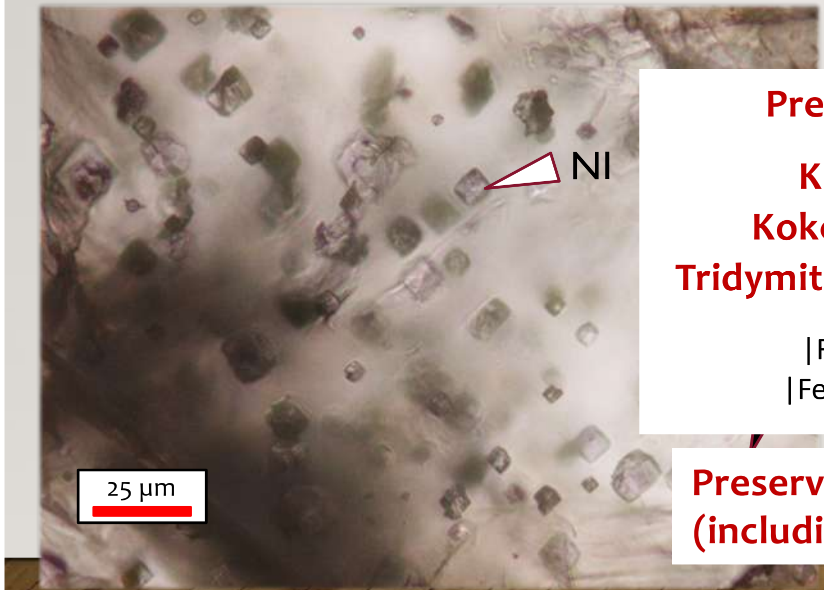
Bruna B. Carvalho, Omar Bartoli, Fabio Ferri, Bernardo Cesare, Silvio Ferrero, Laurent Remusat, Luca S. Capizzi, Stefano Poli

Nanogranitoid inclusions

- ✓ Absence of glassy inclusion
- ✓ Nanogranitoids (former melt inclusions now crystallized)

Qz + Kfs + Pl + Bt + Ms ± Chl

± Gr ± Sil ± Ap ± Mnz ± Ru ± Zir (trapped phases)

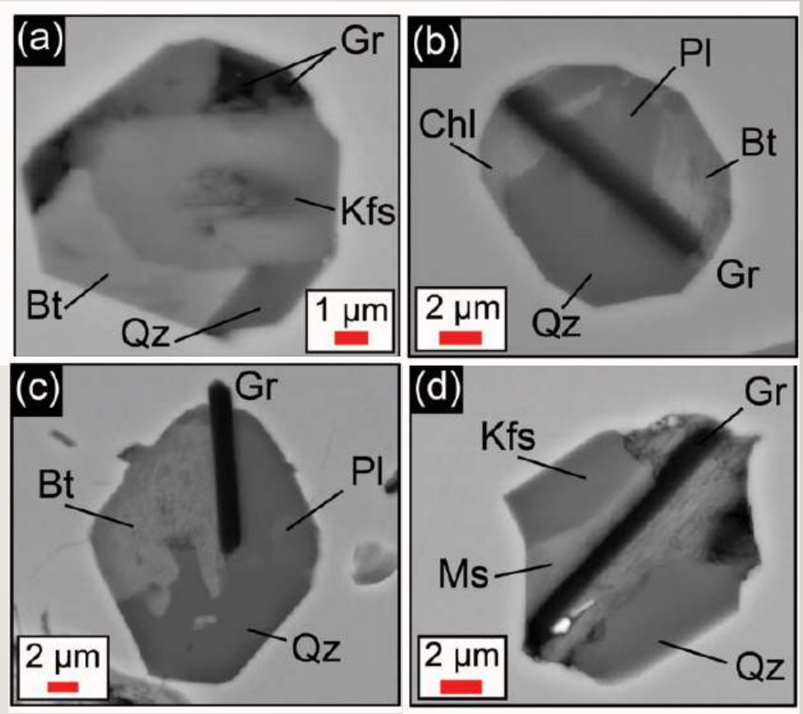


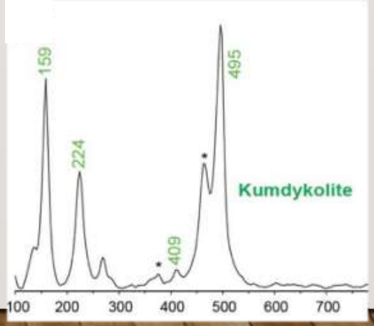
Presence of polymorphs

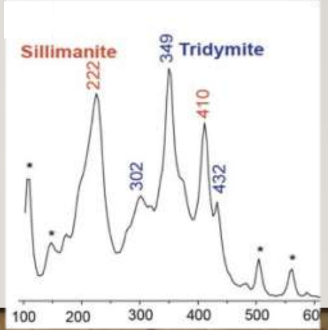
Kumdykolite (albite)
Kokchetavite (orthoclase)
Tridymite and Cristobalite (quartz)

|Ferrero et al (2016) – CMP|
|Ferrero & Angel (2018) – JPet|

Preserved original compositions (including volatiles H_2O and CO_2)







Re-melting experiments

- ✓ Experiments using a single-stage, Johannes-type piston cylinder


GEOFLUIDS

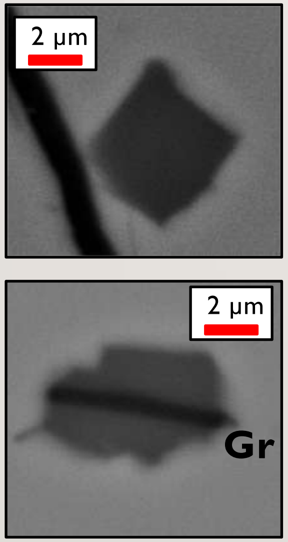
Geofluids (2013) 13, 405–420 doi: 10.1111/gfl.12038

Nanogranite inclusions in migmatitic garnet: behavior during piston-cylinder remelting experiments

O. BARTOLI, B. CESARE, S. POLI, A. ACOSTA-VIGIL, R. ESPOSITO, A. TURINA, R. J. BODNAR, R. J. ANGEL AND J. HUNTER

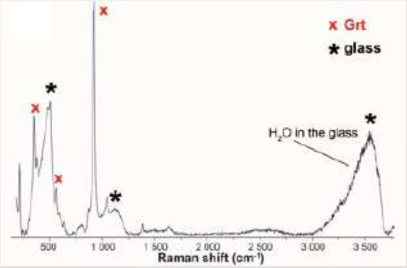
Upper Amphibolite

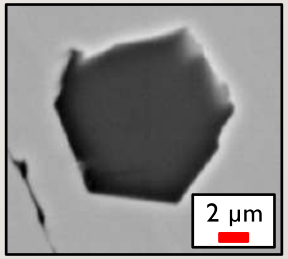
820°C – 1 GPa
20hs

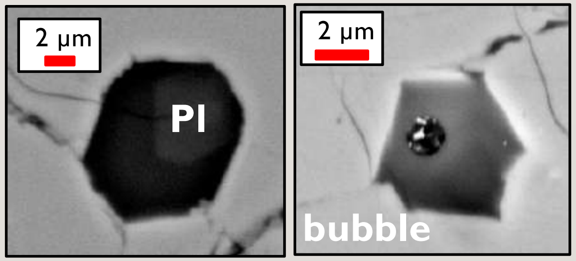


Transition zone

850°C – 1 GPa
20 hs

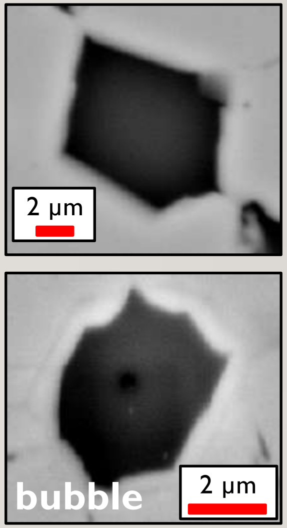






Granulite

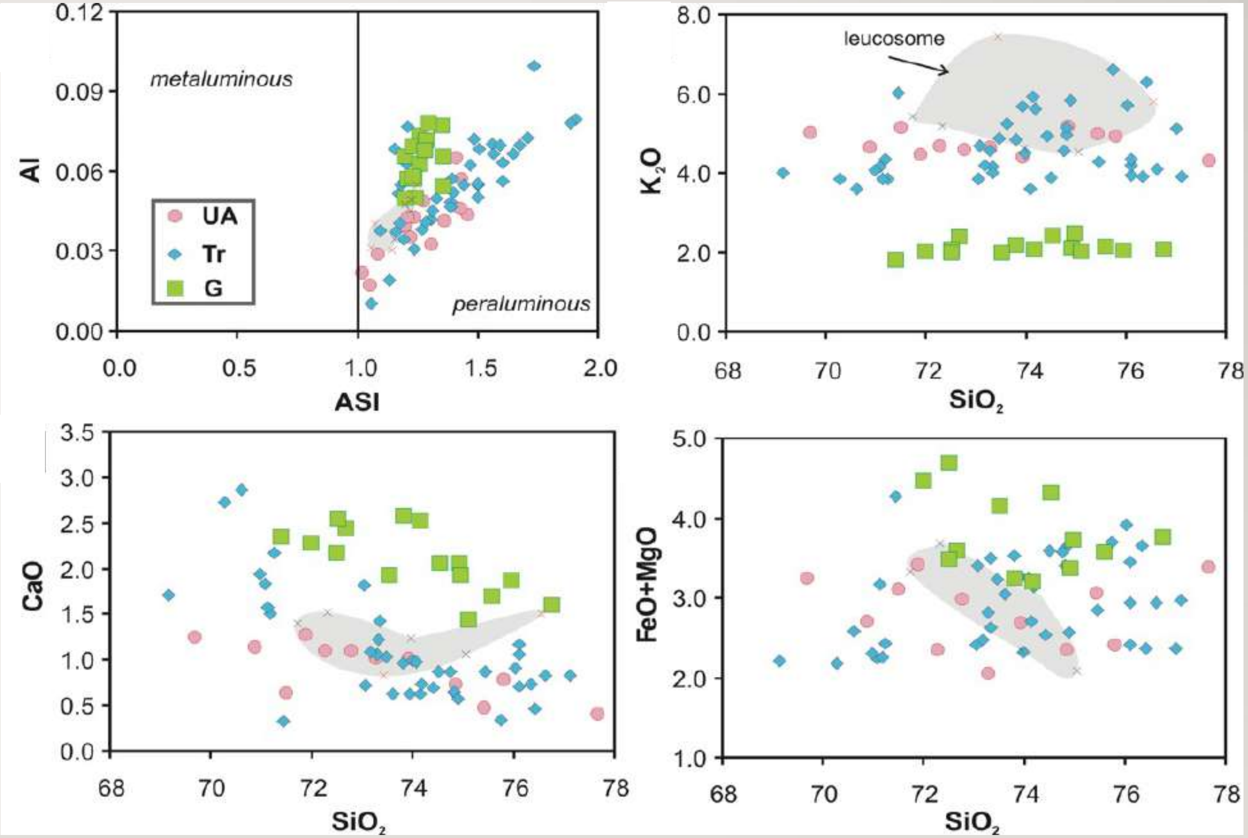
900°C – 1.2 GPa
5 hs



Homogeneous glass, glass + bubbles, glass + trapped phases

Major element composition of the melts

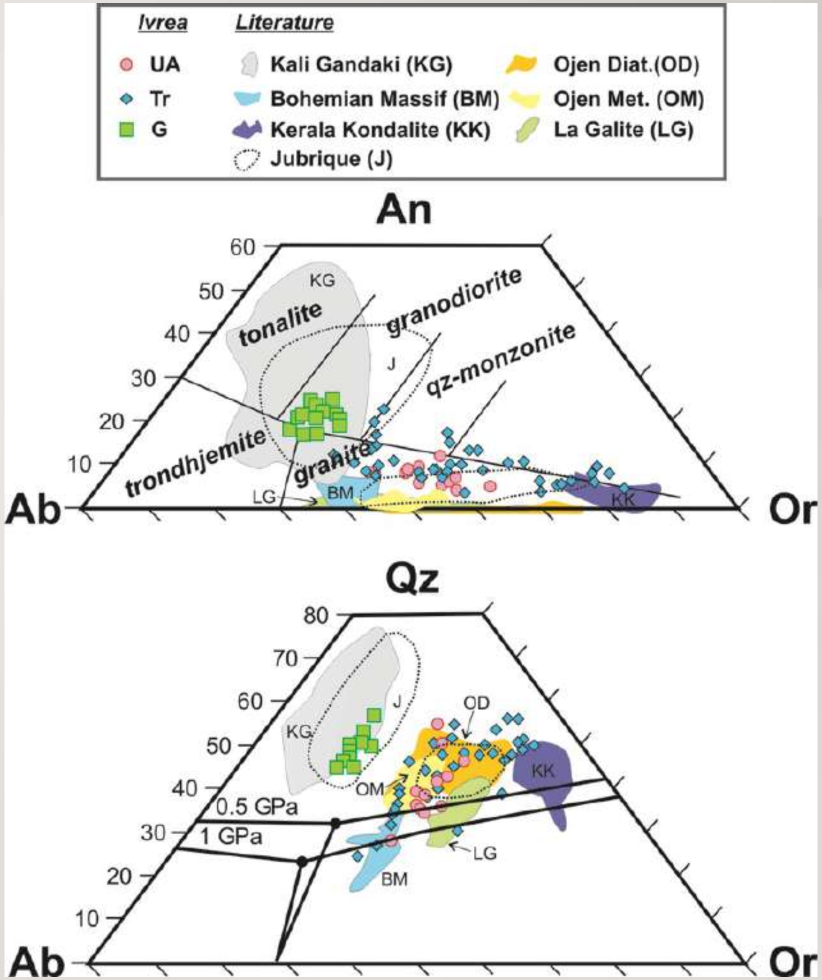
- ✓ All melts from the three zones are granitic (*s.l.*), peraluminous and have similar ranges of SiO_2 (70-78 wt.%)
- ✓ UA and Tr (similar) : higher K_2O, lower CaO and lowest FeO+MgO
- ✓ G : higher CaO and reach higher FeO+MgO



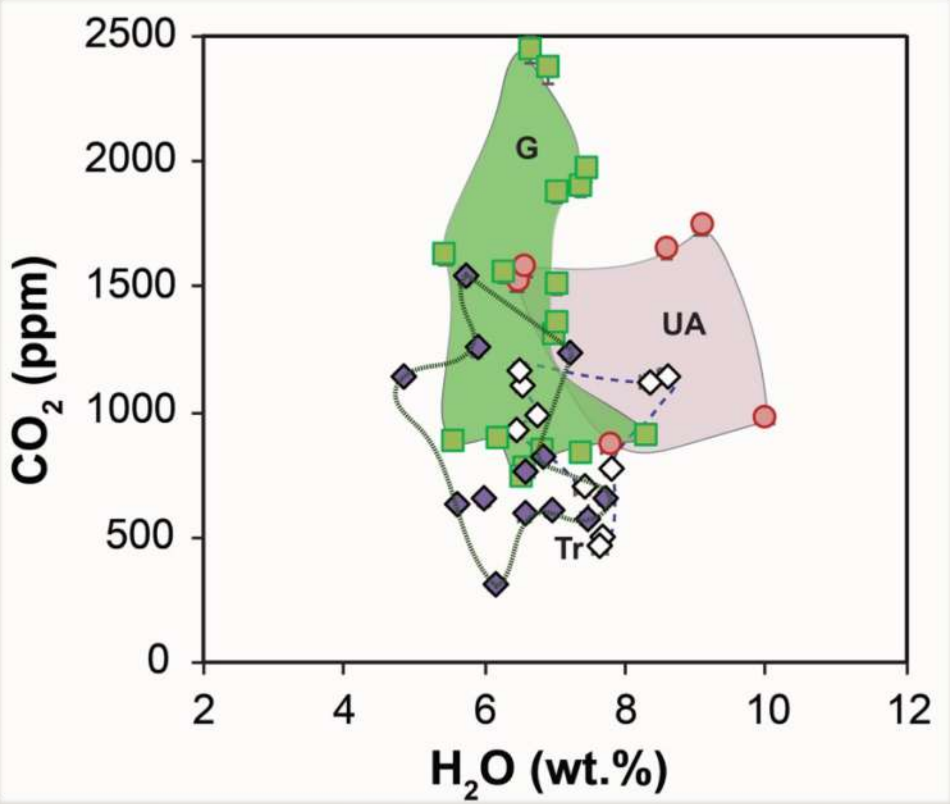
CIPW normative diagrams

- ✓ Melts have higher An than MI from the literature
- ✓ Two groups (UA + Tr) & G
- ✓ UA and Tr (similar) : granite with variable Or/Ab ratios
- ✓ G: granodiorite, higher An

- ✓ UA + Tr: similar to MI from the literature (variable Or/Ab ratios)
- ✓ G: much lower Or contents



CO_2 and H_2O of the melts



Circle = UA; diamond = Tr; square = G

- ✓ **CO_2** contents are **highest at granulite facies**, lowest in the transition zone

UA : 861 to 1738 ppm
T : 495 to 1534 ppm
G : 739 to 2444 ppm

- ✓ **Average H_2O** contents are progressively **lower with increasing T**

UA : 6.5 to 10 wt.%
T : 4.8 to 8.5 wt.%
G : 5.4 to 8.2 wt. %

Implications

✓ **Anatexis**

Microstructural evidence suggests primary coeval entrapment of NI and FI during the growth of peritectic garnet :

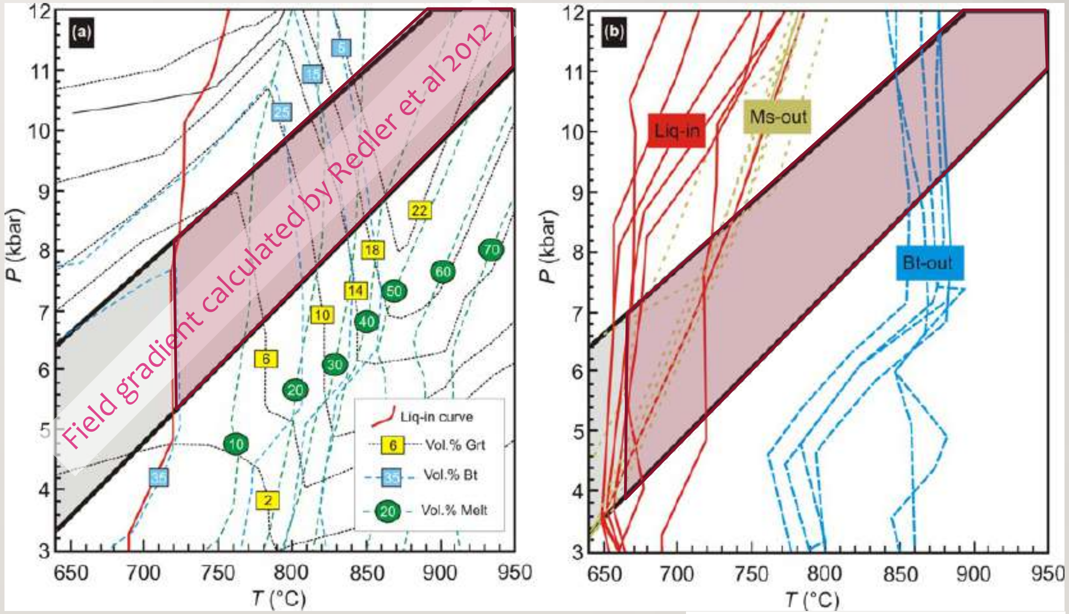
|Cesare et al 2015 – L; Roedder 1979|

- inclusions are related to the same anatectic event
- Following the field gradient garnet is able to trap melt + fluid at >730°C and > 5.2 kbar

Experiments with granulite facies sample : garnet has trapped melt at 900°C showing that rocks have approached UHT conditions (in agreement with other works)

|Luvizotto & Zack 2009 – CMP; Redler et al 2012 – JMG ; Ewing et al., 2013 – CMP|

Perple_X 6.8.6 software | Connolly, 2009 – G^3 |
Thermodynamic database | Holland and Powell, 2011 – JMG |
Equation of State for the fluid | Holland and Powell, 1998 – JMG |

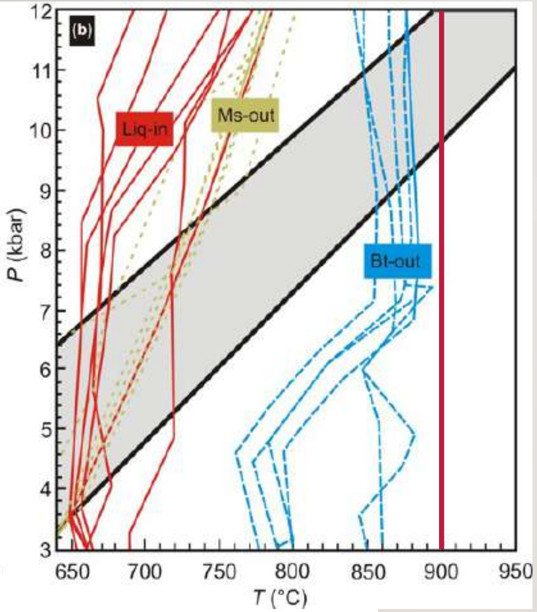


Field gradient calculated by Redler et al 2012

|Carvalho et al 2019 – JMG|

Implications

✓ **Anatexis**



|*Carvalho et al 2019 – JMG*|

Melt compositions are consistent with melting reactions consuming mica

Very contrasting compositions of anatectic melts at UA and T versus G :

<u>Melting</u>

- ○ Higher T : controls FeO + MgO and CaO of melts

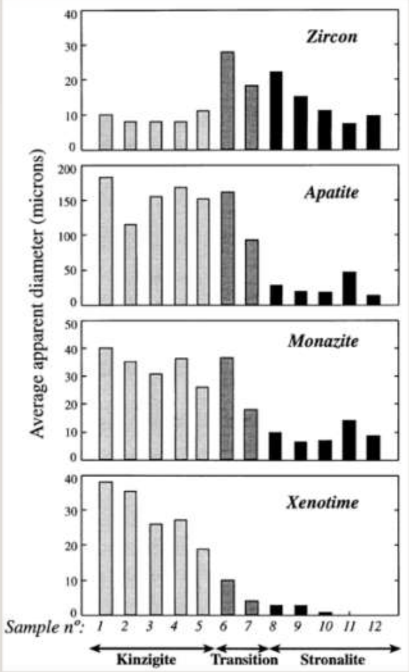
|Gao et al 2016 – L; Johannes & Holtz 1996 ; Montel & Vielzeuf 1997 – L|

- ○ Decrease in K_2O (biotite-out)

- ○ Possible (minor) role of apatite in the Ca budget

  elevated solubility of apatite in peraluminous melts

|Bea & Montero 1990 – GCA|



Increasing T

Implications

✓ Fluid regime

Anatexis of the metapelites in the Ivrea Zone has been regarded as fluid-absent

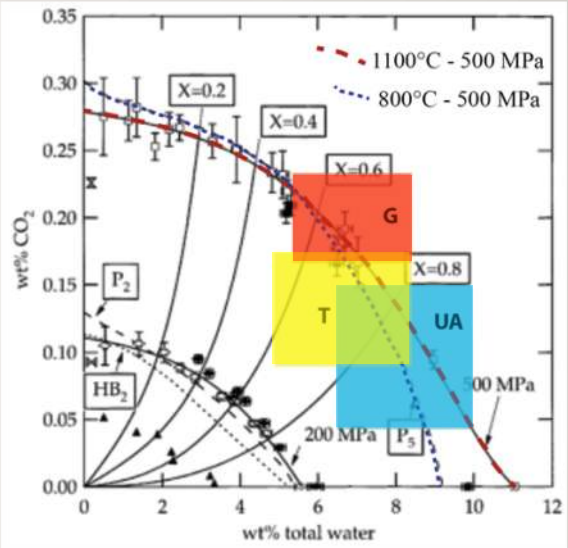
|Schnetger 1994 – CG; Sinigoi et al 1974 – CMP; Redler et al 2011 – L and references therein |

However

- coexistence of primary MI and C-bearing FI in in garnet and the measured CO_2 in the melts **imply the presence of a COH fluid during anatexis**

CO_2 contents in the melts are highest at granulite facies, and in agreement with expected values (rhyolite + COH fluid)

At granulite facies (850-900°C), the melts have higher H_2O contents than usually assumed



Modified after |Tamic et al 2001 – CG|

Fluid regime of the deep crust : Case study of the metapelitic migmatites from the Kinzigite Formatiton

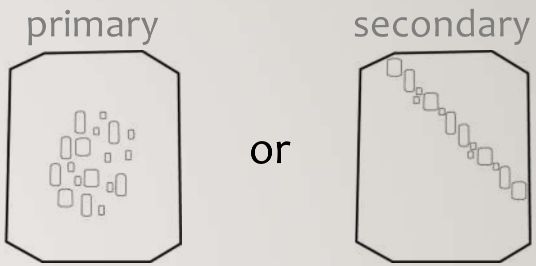
Fluid inclusions

|Carvalho et al submitted|

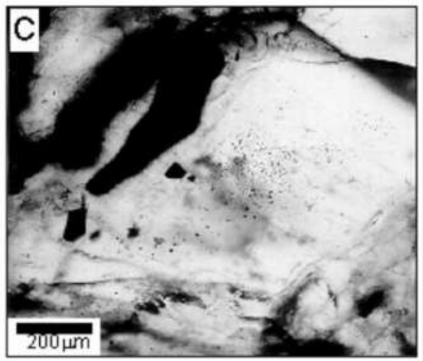
Introduction | importance of Fluid inclusions |

Fluid inclusions (FI) are small droplets of a fluid phase encapsulated into rock-forming minerals

|e.g. Roedder 1979|



Quartz



|Sakar et al 2003 – G|

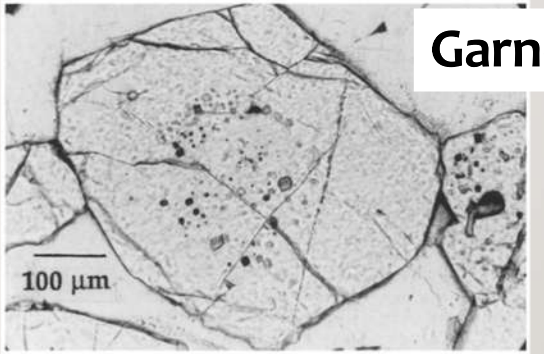
- host does not vith the fluid
- ubiquitous pl tamorphic rocks

- may be in ny stage of re-crystallization
- composi ed by deformation and gr n

most reliable witnesses of fluids operating during **deep crustal metamorphism**

primary FI in **peritectic minerals**

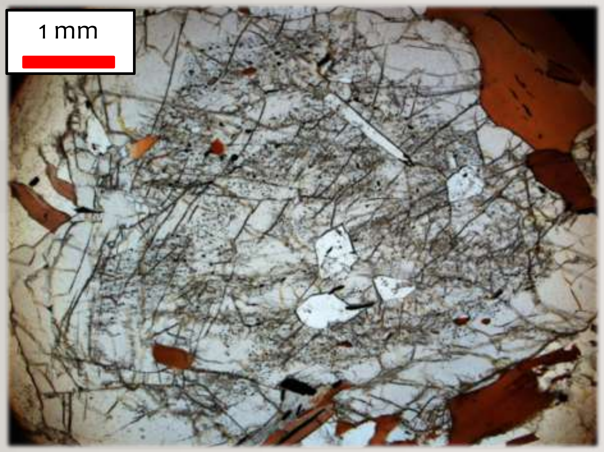
Garnet

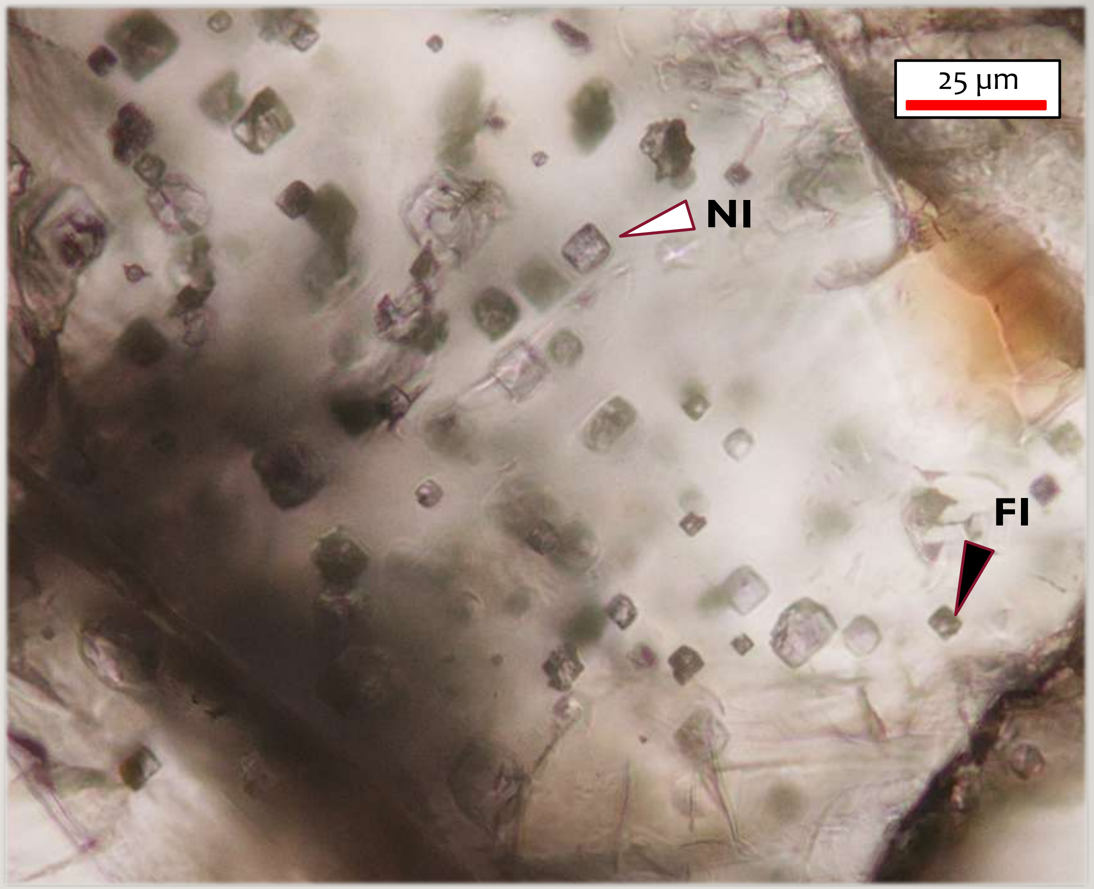


|Vry & Brown 1991 – CMP|

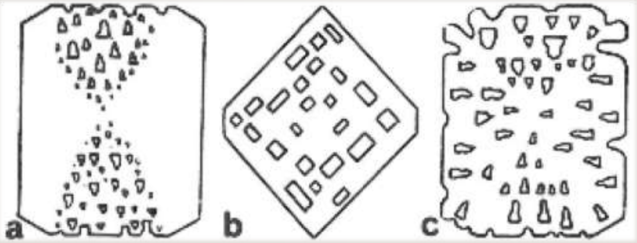
Carvalho et al. 2019 - Fate of primary COH fluid inclusions in garnet from high-grade rocks

Melt and fluid inclusions





Primary inclusions

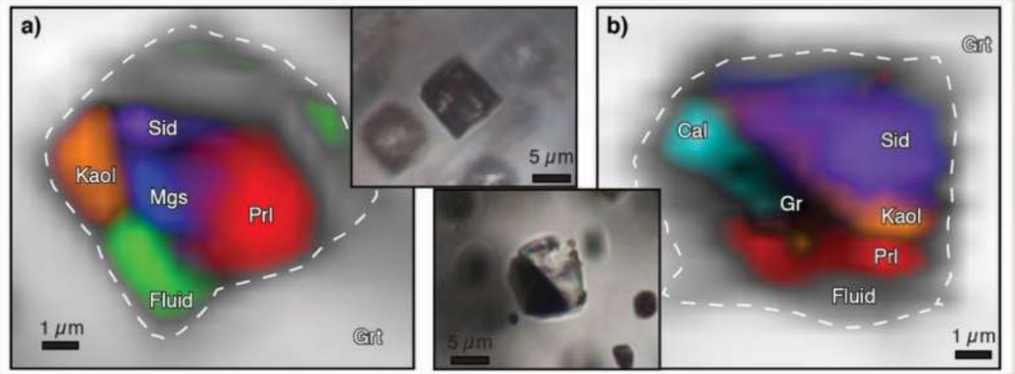


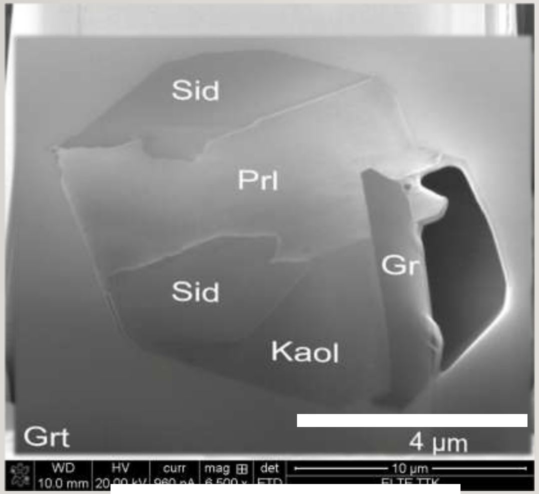
|Roedder 1984|

Melt and fluid inclusions were trapped
in the <u>same</u> anatectic event

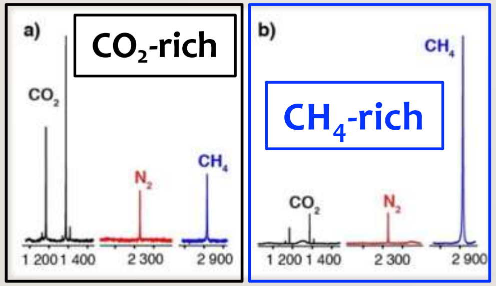
Fluid inclusions are multiphase!

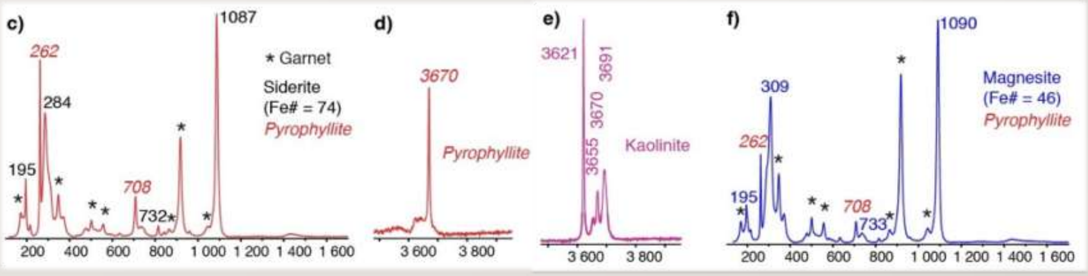
- ✓ Variable compositions and densities:
  - ○ CO_2-rich or CH_4-rich (traces of N_2)
  - ○ CO_2 densities : 0.1 - 0.6 g/cm³





Focused ion beam serial sectioning





Inclusions are not completely filled up with crystals :

33 to 48% porosity

(10-52 %) Sid (Fe# 69-74) + (3-48 %) Prl + (27-73 %) Kaol
± (<1.7 %) Gr ± (<2.7 %) Mgn (Fe# 26-46) ± (<2 %) Cal
± (<10 %) Qtz ± Cor

Discussion

The multiphase fluid inclusions are composed of
solids + fluid phase

Solid phases may be interpreted as :

- ⚠ Trapped minerals
- ⚠ Daughter (precipitated directly from the entrapped fluid)
- 👍 Step-daughter phases (interaction of the fluid with the host)

$Mg_3Al_2Si_3O_{12}$ $Ca_3Al_2Si_3O_{12}$
$Fe_3Al_2Si_3O_{12}$ $Mn_3Al_2Si_3O_{12}$

original fluid composition must have changed
density decreased by the reaction with the host

|e.g. Kleinefeld & Bakker 2000 – JMG ; Frezzotti & Ferrando 2007 – JMPS ; Berkesi et al 2012 – EPSL |

Discussion |Post-entrapment changes|

✓ Interaction host–fluid (phase equilibria modelling)

Perple_X 6.8.6 software | Connolly, 2009 – G^3 |
Thermodynamic database | Holland and Powell, 2011 – JMG |
Equation of State for the fluid | Holland and Powell, 1998 – JMG |

Two systems involving a finite amount of fluid and garnet in excess

- ○ Garnet (X_{Mg}=0.2) + pure CO_2 fluid
- ○ Garnet (X_{Mg}=0.2) + binary CO_2–H_2O fluid (XCO_2 = 0.7)

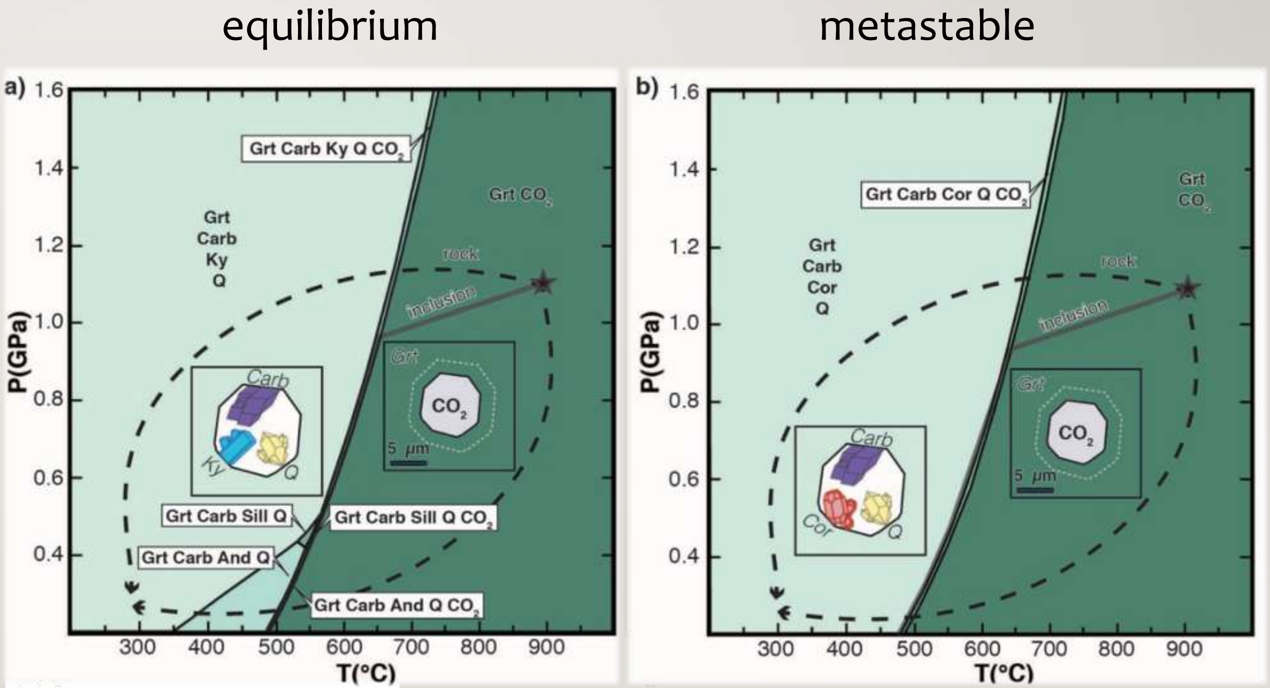
Based on the 3D reconstruction of Multiphase fluid inclusions

Discussion |Post-entrapment changes|

✓ Interaction host–fluid (phase equilibria modelling)

- Garnet (X_{Mg}=0.2) + pure CO_2 fluid

- independently of the retrograde path garnet and fluid will react in order to form multiphase fluid inclusions (residual fluid + solids)



Ca-free FMAS-CO_2 system

|Carvalho et al submitted|

Discussion |Post-entrapment changes|

✓ Interaction host–fluid (phase equilibria modelling)

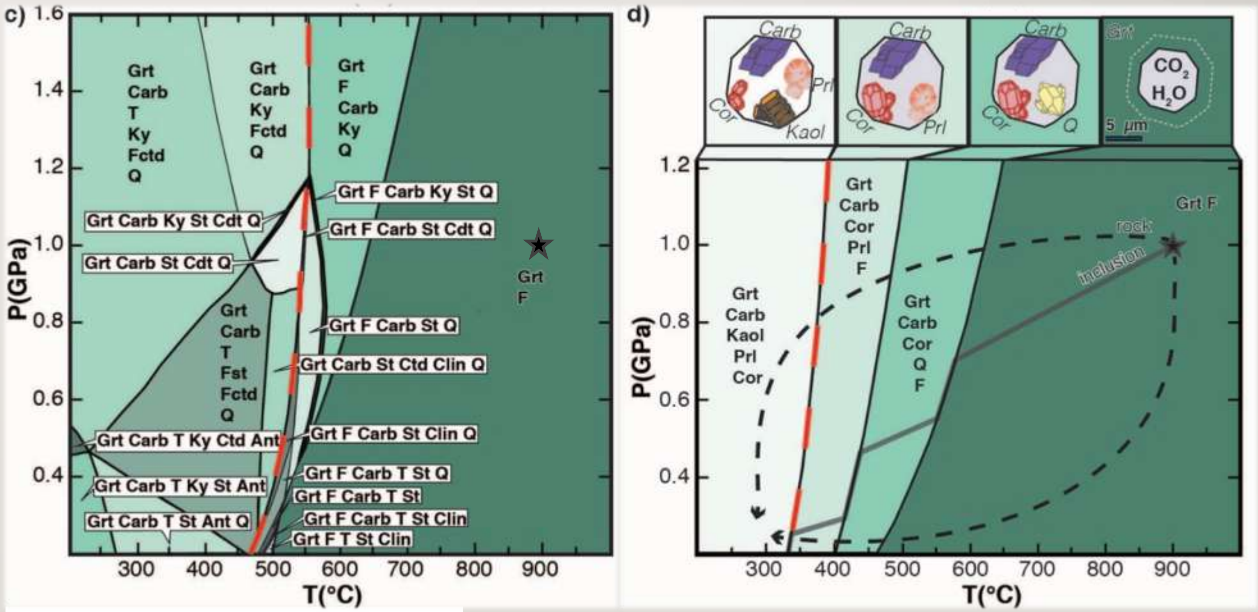
- Garnet (X_{Mg}=0.2) + binary CO_2–H_2O fluid (XCO_2 = 0.7)

- independently of the retrograde path garnet and fluid will react in order to form multiphase fluid inclusions (residual fluid + solids)

- CO_2 is the first fluid component to react with the host and form carbonates

- the solid assemblage is metastable

- starting H_2O of the fluid controls the preservation of Ky or Cor + Qtz


equilibrium

metastable

Ca-free FMAS-CO_2-H_2O system

|Carvalho et al submitted|

Discussion |What was the original composition of the fluid?|

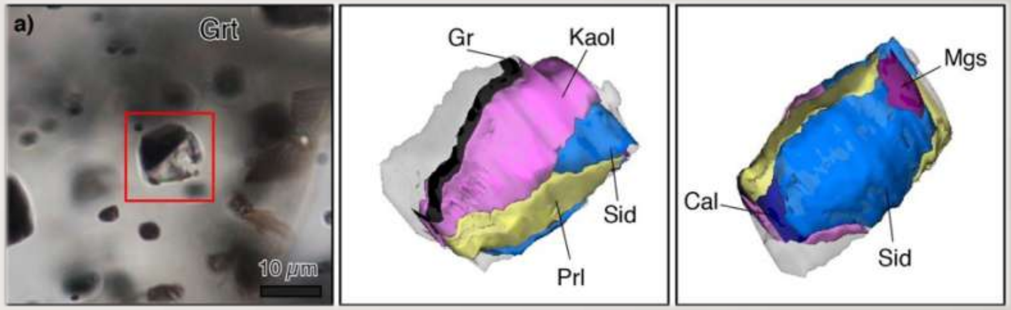
Quantitative estimate on the composition of the fluid *bounded in the step-daughter phases within the inclusions* was made by a mass-balance approach using:

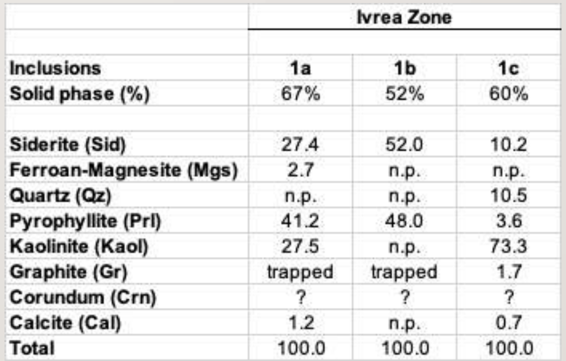
- volume estimates obtained by FIB-SEM serial sectioning.
- molar volume from the literature

- number of moles of carbonates and OH-bearing minerals

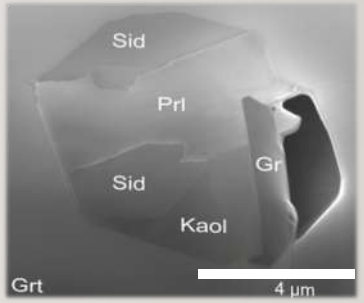
Composition of the fluid in a binary CO_2–H_2O system

X_{CO_2} (CO_2/CO_2+H_2O) **0.55 - 0.7**





	Ivrea Zone		
Inclusions	**1a**	**1b**	**1c**
Solid phase (%)	67%	52%	60%
Siderite (Sid)	27.4	52.0	10.2
Ferroan-Magnesite (Mgs)	2.7	n.p.	n.p.
Quartz (Qz)	n.p.	n.p.	10.5
Pyrophyllite (Prl)	41.2	48.0	3.6
Kaolinite (Kaol)	27.5	n.p.	73.3
Graphite (Gr)	trapped	trapped	1.7
Corundum (Crn)	?	?	?
Calcite (Cal)	1.2	n.p.	0.7
Total	100.0	100.0	100.0



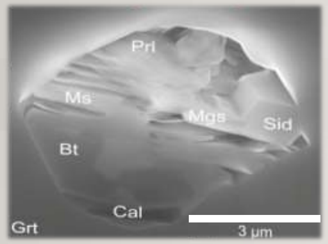
COH fluid

$CO_2 + H_2O + CH_4 + N_2$

Considerable proportions of **H_2O!!**

Discussion |How relevant is this?|

- ○ **Gruf Complex (Central Europe)**



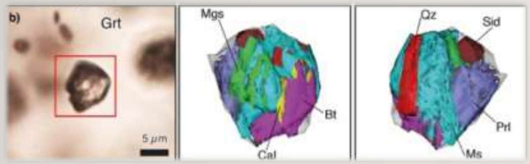
COH fluid

+

silicate melt

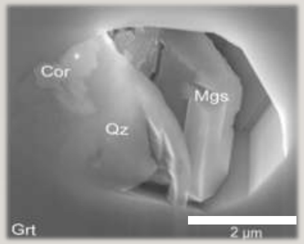
(mixed inclusion)

CO_2 + H_2O



Examples of occurrences reporting (n>22) **multiphase fluid inclusions** in high-grade rocks

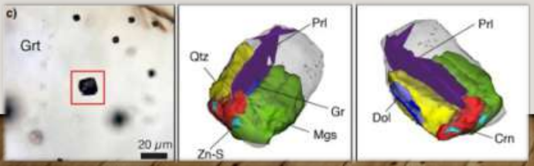
- ○ **Athabasca granulite (Canada)**

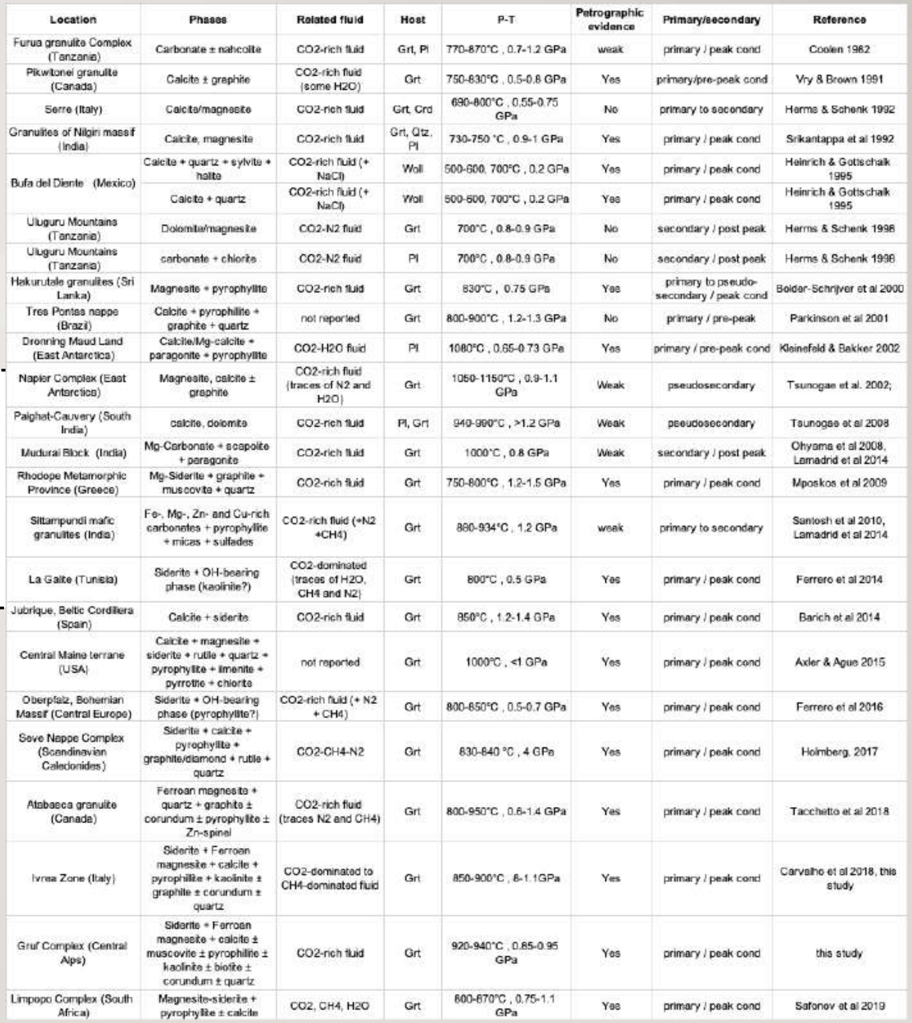


COH fluid

CO_2 ± H_2O

+ traces of CH_4 and N_2





Location	Phases	Related fluid	Host	P-T	Petrographic evidence	Primary/secondary	Reference
Furua granulite Complex (Tanzania)	Carbonate ± nahcolite	CO2-rich fluid	Grt, Pl	770-870°C , 0.7-1.2 GPa	weak	primary / peak cond	Coolen 1982
Pikwitonei granulite (Canada)	Calcite ± graphite	CO2-rich fluid (some H2O)	Grt	750-830°C , 0.5-0.8 GPa	Yes	primary/pre-peak cond	Vry & Brown 1991
Serre (Italy)	Calcite/magnesite	CO2-rich fluid	Grt, Crd	690-800°C , 0.55-0.75 GPa	No	primary to secondary	Herms & Schenk 1992
Granulites of Nilgiri massif (India)	Calcite, magnesite	CO2-rich fluid	Grt, Qtz, Pl	730-750 °C , 0.9-1 GPa	Yes	primary / peak cond	Srikantappa et al 1992
Bufa del Diente (Mexico)	Calcite + quartz + sylvite + halite	CO2-rich fluid (+ NaCl)	Woll	500-600, 700°C , 0.2 GPa	Yes	primary / peak cond	Heinrich & Gottschalk 1995
	Calcite + quartz	CO2-rich fluid (+ NaCl)	Woll	500-600, 700°C , 0.2 GPa	Yes	primary / peak cond	Heinrich & Gottschalk 1995
Uluguru Mountains (Tanzania)	Dolomite/magnesite	CO2-N2 fluid	Grt	700°C , 0.8-0.9 GPa	No	secondary / post peak	Herms & Schenk 1998
Uluguru Mountains (Tanzania)	carbonate + chlorite	CO2-N2 fluid	Pl	700°C , 0.8-0.9 GPa	No	secondary / post peak	Herms & Schenk 1998
Hakurutale granulites (Sri Lanka)	Magnesite + pyrophyllite	CO2-rich fluid	Grt	830°C , 0.75 GPa	Yes	primary to pseudo-secondary / peak cond	Bolder-Schrijver et al 2000
Tres Pontas nappe (Brazil)	Calcite + pyrophillite + graphite + quartz	not reported	Grt	800-900°C , 1.2-1.3 GPa	No	primary / pre-peak	Parkinson et al 2001
Dronning Maud Land (East Antarctica)	Calcite/Mg-calcite + paragonite + pyrophyllite	CO2-H2O fluid	Pl	1080°C , 0.65-0.73 GPa	Yes	primary / pre-peak cond	Kleinefeld & Bakker 2002
Napier Complex (East Antarctica)	Magnesite, calcite ± graphite	CO2-rich fluid (traces of N2 and H2O)	Grt	1050-1150°C , 0.9-1.1 GPa	Weak	pseudosecondary	Tsunogae et al. 2002;
Palghat-Cauvery (South India)	calcite, dolomite	CO2-rich fluid	Pl, Grt	940-990°C , >1.2 GPa	Weak	pseudosecondary	Tsunogae et al 2008
Mudurai Block (India)	Mg-Carbonate + scapolite + paragonite	CO2-rich fluid	Grt	1000°C , 0.8 GPa	Weak	secondary / post peak	Ohyama et al 2008, Lamadrid et al 2014
Rhodope Metamorphic Province (Greece)	Mg-Siderite + graphite + muscovite + quartz	CO2-rich fluid	Grt	750-800°C , 1.2-1.5 GPa	Yes	primary / peak cond	Mposkos et al 2009
Sittampundi mafic granulites (India)	Fe-, Mg-, Zn- and Cu-rich carbonates + pyrophyllite + micas + sulfades	CO2-rich fluid (+N2 +CH4)	Grt	880-934°C , 1.2 GPa	weak	primary to secondary	Santosh et al 2010, Lamadrid et al 2014
La Galite (Tunisia)	Siderite + OH-bearing phase (kaolinite?)	CO2-dominated (traces of H2O, CH4 and N2)	Grt	800°C , 0.5 GPa	Yes	primary / peak cond	Ferrero et al 2014
Jubrique, Beltic Cordillera (Spain)	Calcite + siderite	CO2-rich fluid	Grt	850°C , 1.2-1.4 GPa	Yes	primary / peak cond	Barich et al 2014
Central Maine terrane (USA)	Calcite + magnesite + siderite + rutile + quartz + pyrophyllite + ilmenite + pyrrotite + chlorite	not reported	Grt	1000°C , <1 GPa	Yes	primary / peak cond	Axler & Ague 2015
Oberpfalz, Bohemian Massif (Central Europe)	Siderite + OH-bearing phase (pyrophyllite?)	CO2-rich fluid (+ N2 + CH4)	Grt	800-850°C , 0.5-0.7 GPa	Yes	primary / peak cond	Ferrero et al 2016
Seve Nappe Complex (Scandinavian Caledonides)	Siderite + calcite + pyrophyllite + graphite/diamond + rutile + quartz	CO2-CH4-N2	Grt	830-840 °C , 4 GPa	Yes	primary / peak cond	Holmberg, 2017
Atabasca granulite (Canada)	Ferroan magnesite + quartz + graphite ± corundum ± pyrophyllite ± Zn-spinel	CO2-rich fluid (traces N2 and CH4)	Grt	800-950°C , 0.6-1.4 GPa	Yes	primary / peak cond	Tacchetto et al 2018
Ivrea Zone (Italy)	Siderite + Ferroan magnesite + calcite + pyrophillite + kaolinite ± graphite ± corundum ± quartz	CO2-dominated to CH4-dominated fluid	Grt	850-900°C , .8-1.1GPa	Yes	primary / peak cond	Carvalho et al 2018, this study
Gruf Complex (Central Alps)	Siderite + Ferroan magnesite + calcite ± muscovite ± pyrophillite ± kaolinite ± biotite ± corundum ± quartz	CO2-rich fluid	Grt	920-940°C , 0.85-0.95 GPa	Yes	primary / peak cond	this study
Limpopo Complex (South Africa)	Magnesite-siderite + pyrophyllite ± calcite	CO2, CH4, H2O	Grt	800-870°C , 0.75-1.1 GPa	Yes	primary / peak cond	Safonov et al 2019

Implications

- ✓ In the three case studies the petrological evidence and phase equilibria modeling suggest that these multiphase fluid inclusions are result of interaction of the fluid with the host during cooling (retrograde path – clockwise or anti-clockwise), and that that the assemblages within the inclusions are metastable (easier nucleation)

- ✓ **Our results suggest that primary CO_2-rich and COH FI entrapped in peritectic garnet are prone to change their nature to a carbonate ± hydrous silicate-bearing assemblage as a natural consequence of cooling**

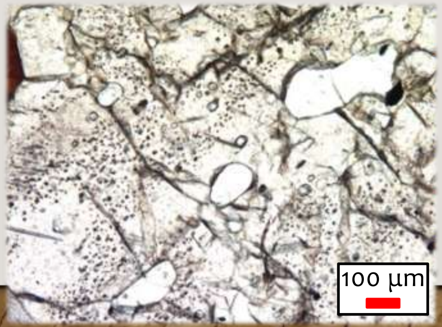
Supposed primary unmodified **monophase CO_2 FI in garnet** previously reported in the literature are, in most cases, **secondary**, **retrograde** features.

Take home message | fluid inclusions |

Our results undermine the **main pillar of the theory of carbonic fluid-assisted metamorphism**, casting doubts on the effective primary nature of many high-density carbonic FI in garnet from granulites.

BUT… we offer a novel and ground-breaking perspective to identify such a process:

only **multiphase FI in peritectic minerals** are true evidence of primary fluids operating at high grade conditions



and these occurrences are far from being uncommon…

Look for them at your thin sections too!!

Take home message | nanogranitoid inclusions |

Because the IZ records high-grade metamorphism and extraction of large volumes of crustal melt: it is considered an **ideal natural laboratory** to study melting processes that led to crustal differentiation and formation of S-type granites

Chemical Geology, 22 (1978) 157—176
© Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

CHEMICAL EVOLUTION OF HIGH-GRADE METAMORPHIC ROCKS ANATEXIS AND REMOTION OF MATERIAL FROM GRANULITE TERRAINS

G. PAOLO SIGHINOLFI* and CARLO GORGONI

Chemical Geology, 113 (1994) 71–101
Elsevier Science B.V., Amsterdam

Partial melting during the evolution of the amphibolite- granulite-facies gneisses of the Ivrea Zone, northern Ita

B. Schnetger^α

Journal of
METAMORPHIC GEOLOGY

J. metamorphic Geol., 2011 doi:10.1111/j.1525-1314.2011.00965.x

Phase equilibrium constraints on a deep crustal metamorphic field gradient: metapelitic rocks from the Ivrea Zone (NW Italy)

C. REDLER, T. E. JOHNSON, R. W. WHITE AND B. E. KUNZ

Contrib Mineral Petrol (2011) 162:691–707
DOI 10.1007/s00410-011-0619-2

ORIGINAL PAPER

The role of crustal fertility in the generation of large silicic magmatic systems triggered by intrusion of mantle magma in the deep crust

S. Sinigoi · J. E. Quick · G. Demarchi · U. Klötzli

Pergamon

Geochimica et Cosmochimica Acta

Behavior of accessory phases and redistribution of Zr, REE, Y, Th, and U during metamorphism and partial melting of metapelites in the lower crust: An example from the Kinzigite Formation of Ivrea-Verbano, NW Italy

Fernando Bea*,1 and Pilar Montero2

Just to quote a few examples….

Contrib Mineral Petrol (2013) 165:757–779
DOI 10.1007/s00410-012-0834-5

ORIGINAL PAPER

The robustness of the Zr-in-rutile and Ti-in-zircon thermometers during high-temperature metamorphism (Ivrea-Verbano Zone, northern Italy)

Tanya A. Ewing · Jörg Hermann · Daniela Rubatto

ORIGINAL ARTICLE

WILEY

Divergent behaviour of Th and U during anatexis: Implications for the thermal evolution of orogenic crust

Chris Yakymchuk[1] | Michael Brown[2]

Contents lists available at SciVerse ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

ELSEVIER

Migmatites in the Ivrea Zone (NW Italy): Constraints on partial melting and melt loss in metasedimentary rocks from Val Strona di Omegna

Charlotte Redler[1], Richard W. White*, Tim E. Johnson

THE GEOLOGICAL SOCIETY OF AMERICA®

Conservation of deep crustal heat production

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

ELSEVIER

Episodic heating of continental lower crust during extension: A thermal modeling investigation of the Ivrea-Verbano Zone

Andrew J. Smye[a,*], Luc L. Lavier[b,c], Thomas Zack[d,e], Daniel F. Stockli[c]

Carbonic fluid-present melting of the deep continental crust (together with breakdown melting reactions) may also represent an **important key process** in the origin of crustal anatectic granitoids

Grazie!

Obrigada!

Thank you!

Any questions?

🤔

bruna.borgescarvalho@unipd.it