Pavia, October 10th 2019

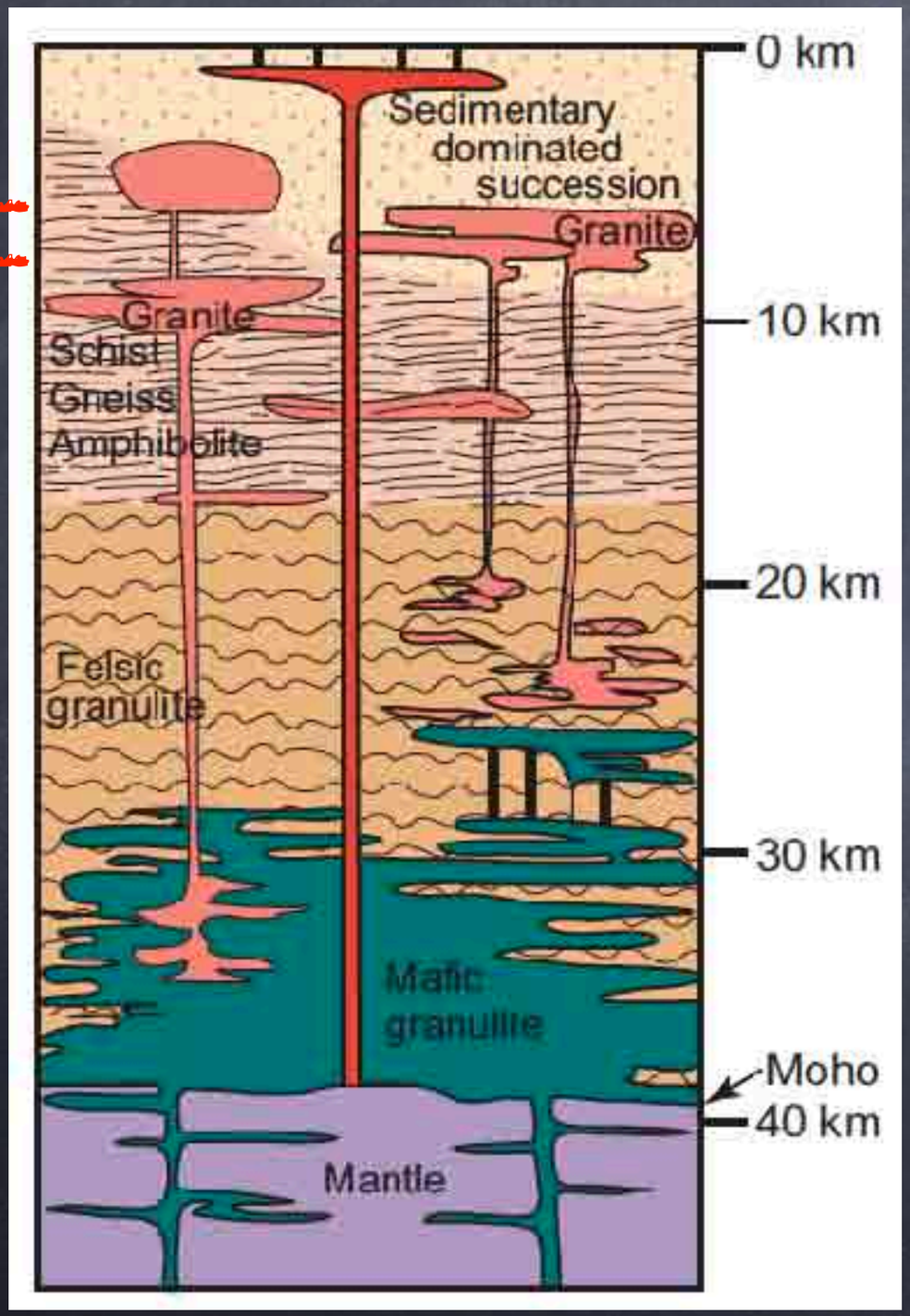
U-(Th)-Pb geochronology of zircon and monazite in the lower continental crust

Antonio Langone

Consiglio Nazionale delle Ricerche

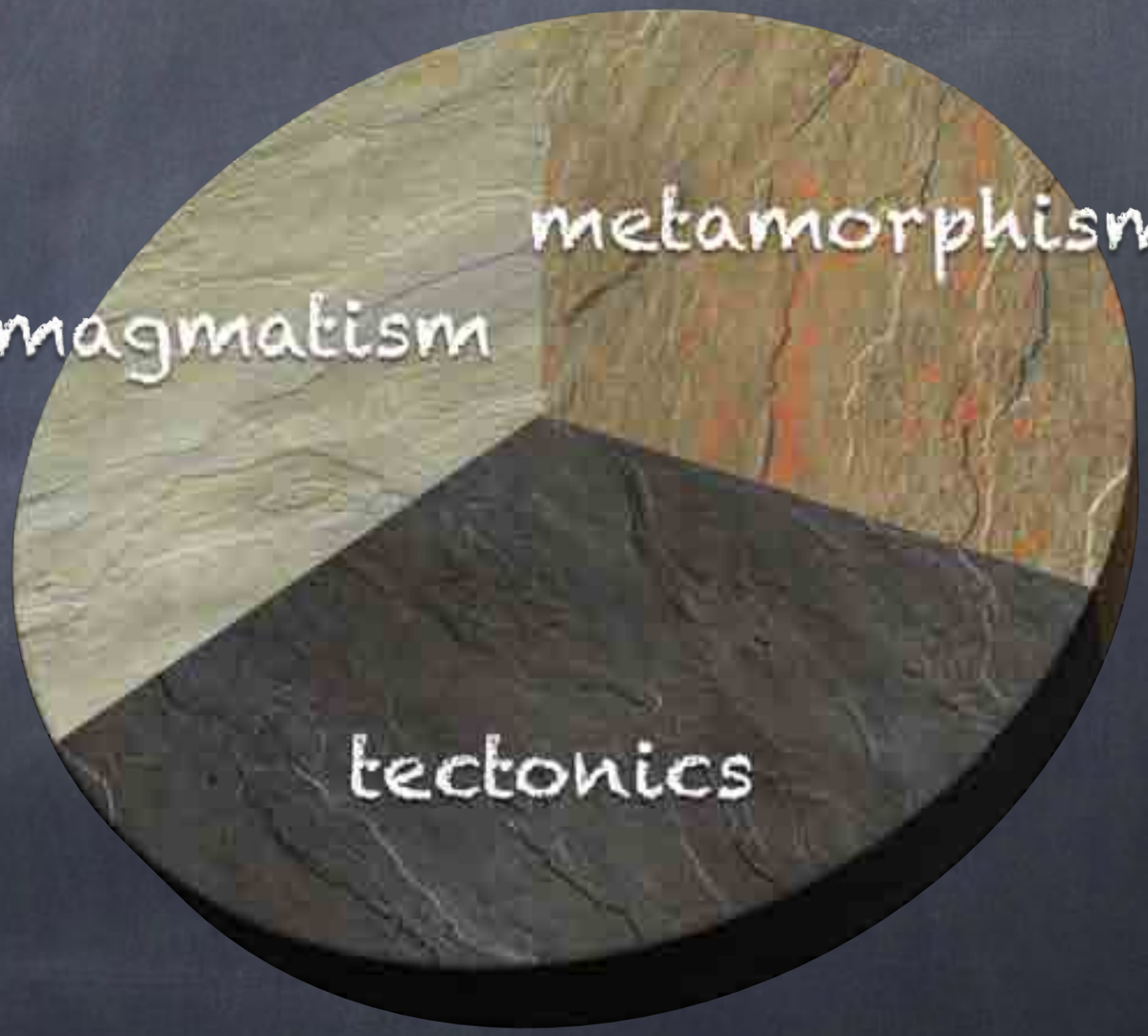
Istituto di Geoscienze e Georisorse – U.O.S. di Pavia

Making the continental crust.....



adapted after from Cawood et al. 2013 GSA Bulletin

main processes:



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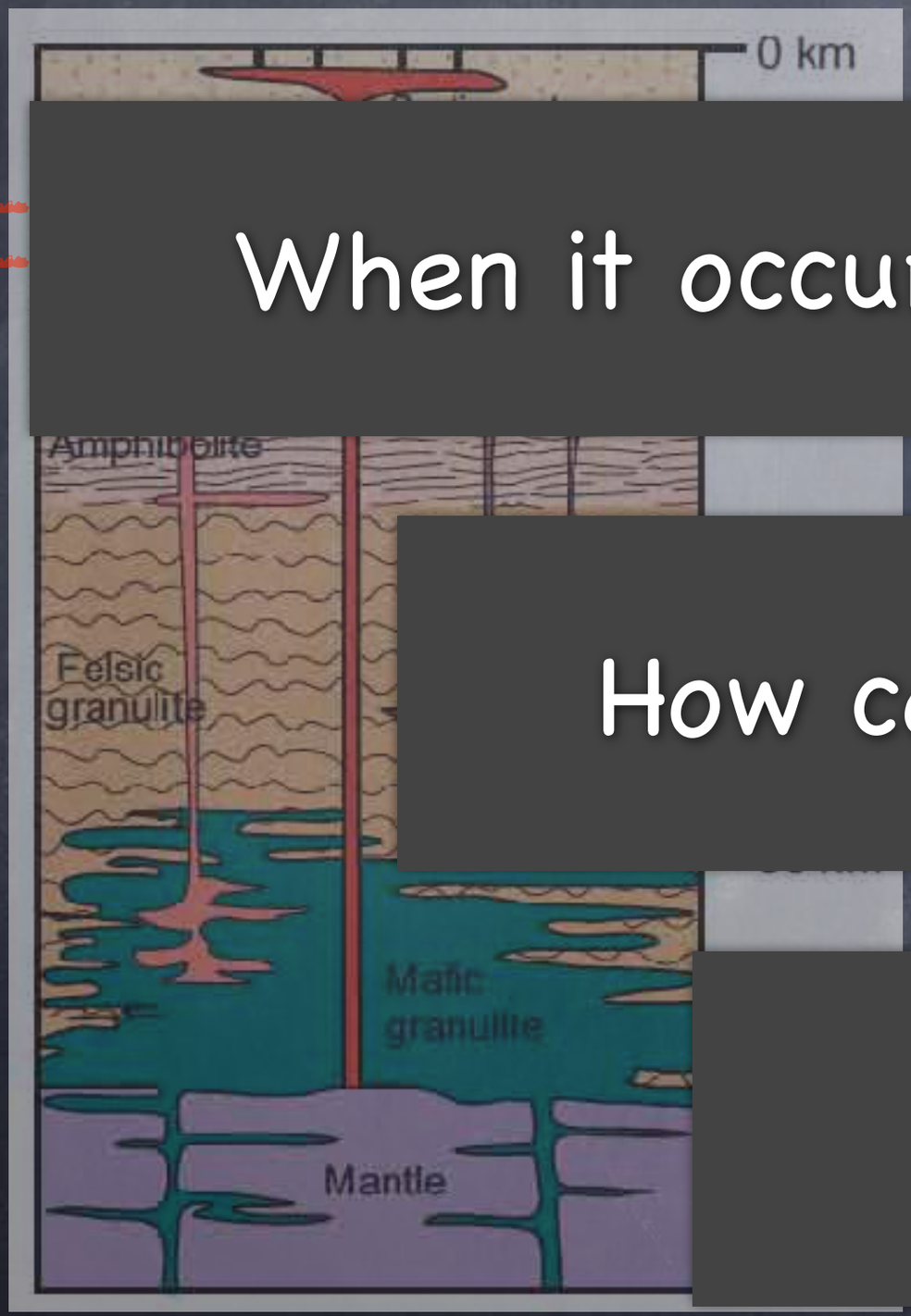
Making the continental crust.....



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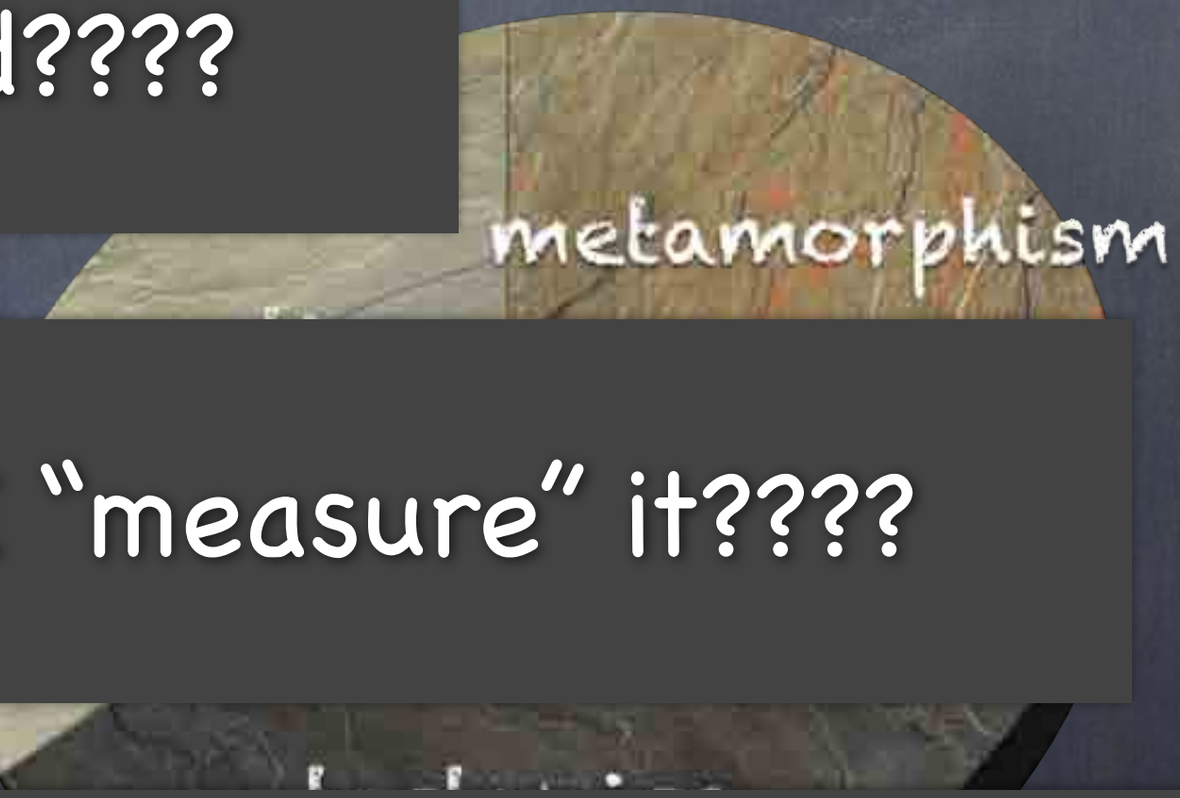

When it occurred????

How can I "measure" it????

How can I "discriminate" different processes????

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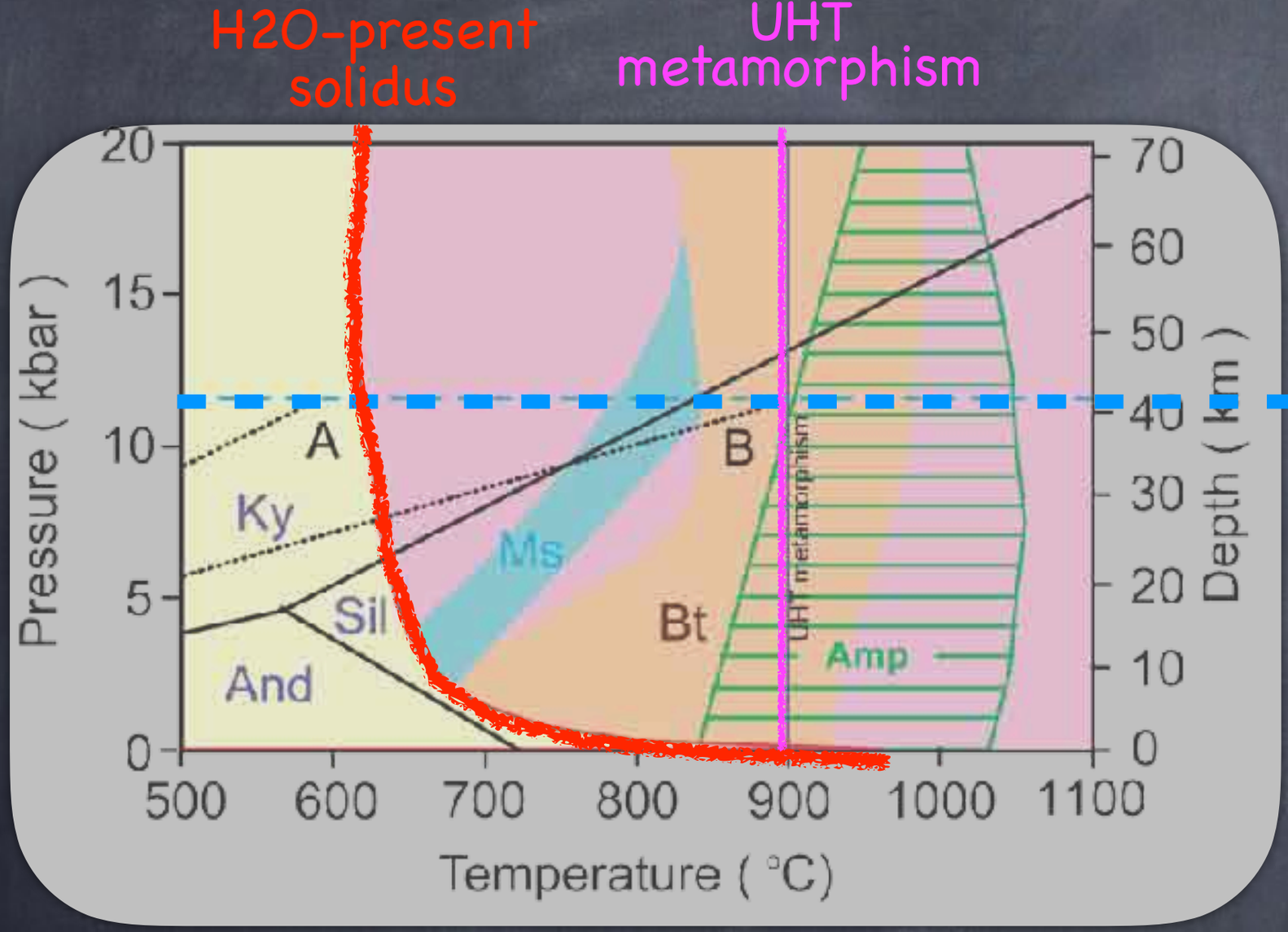
timing ⟷ P-T conditions



base of average crust

Sawyer et al., 2011

we need to find geochronometers able to record (and preserve) magmatic and HT metamorphic events...

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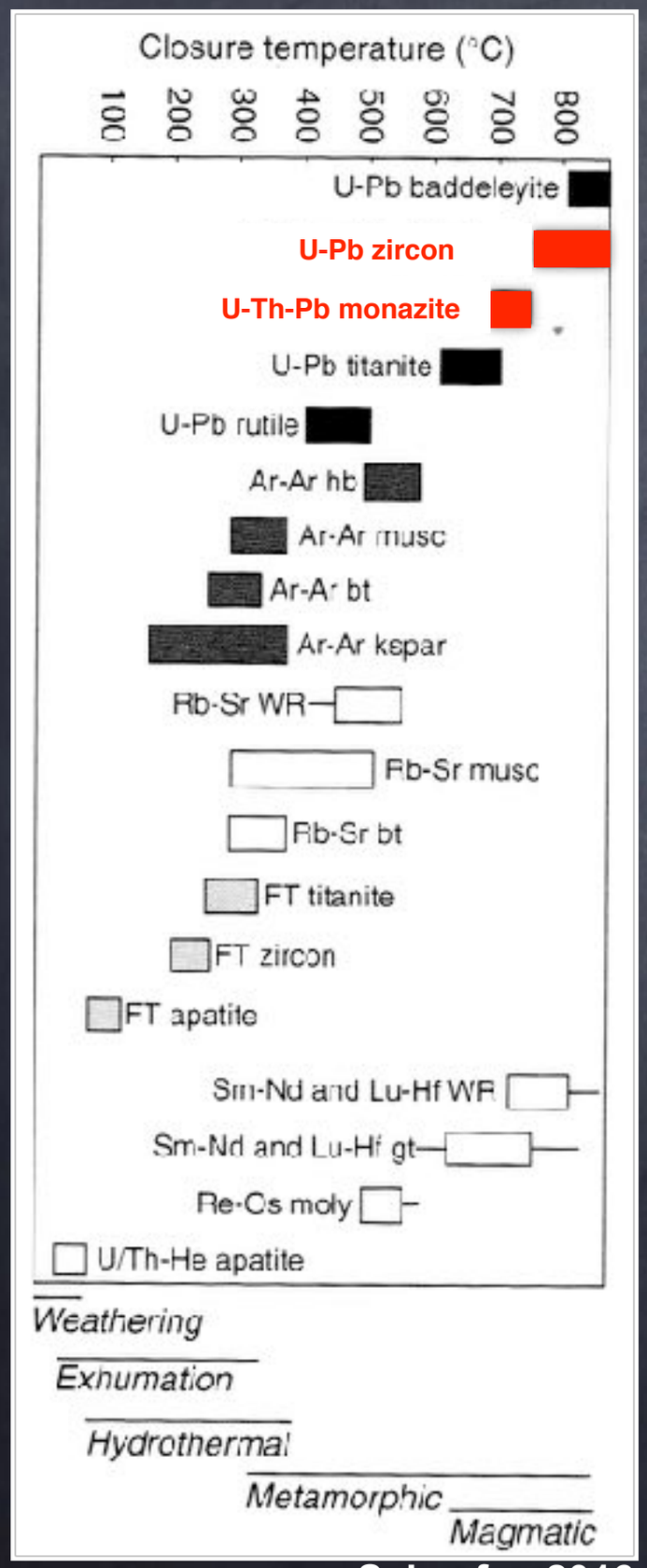
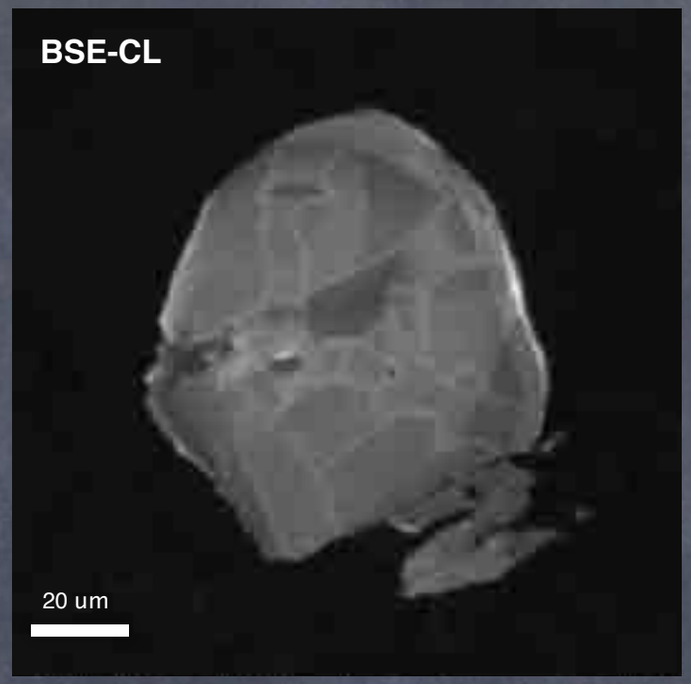
dating HT events: the best candidates

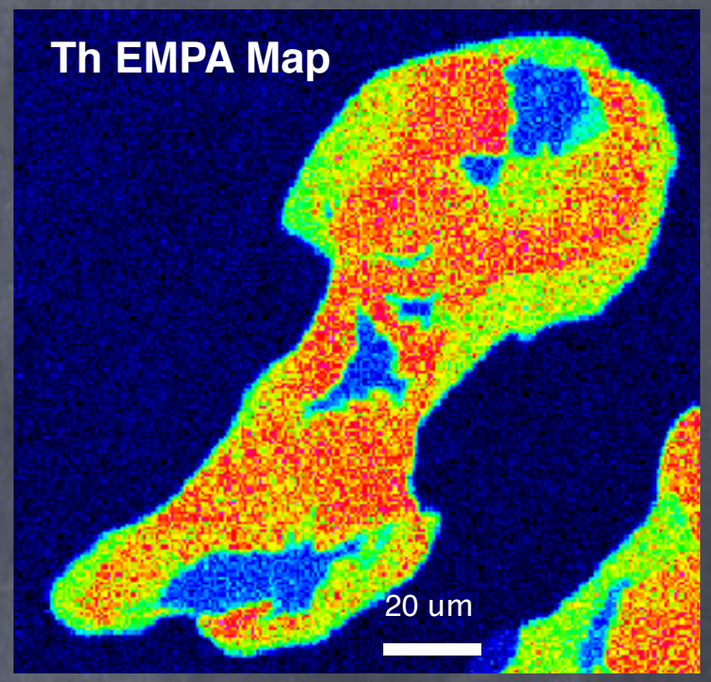


Schaefer, 2016

Zircon: $ZrSiO_4$



Monazite: $(REE)PO_4$



1) high closure temperature

2) widespread in magmatic and metamorphic rocks

3) chemically zoned: chemical domains reflect age domains

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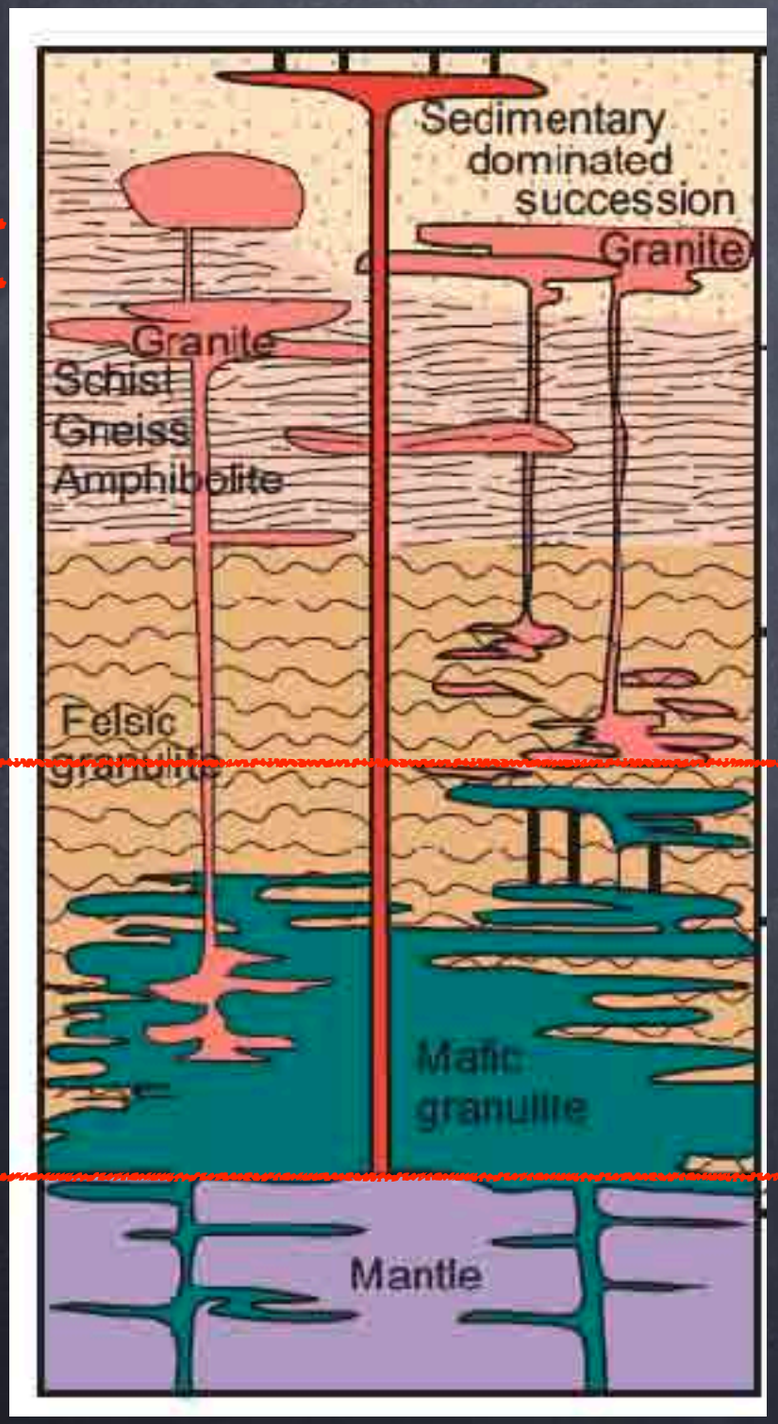
..occurrence of Zircon and Monazite



upper

Lower

adapted after from Cawood et al. 2013 GSA Bulletin

from Mantle
to sediments..

migmatites
granulites
mafic intrusives

from granulites to sediments..
rare/absent in (ultra)mafic rocks

migmatites
felsic granulites

metamorphic ages

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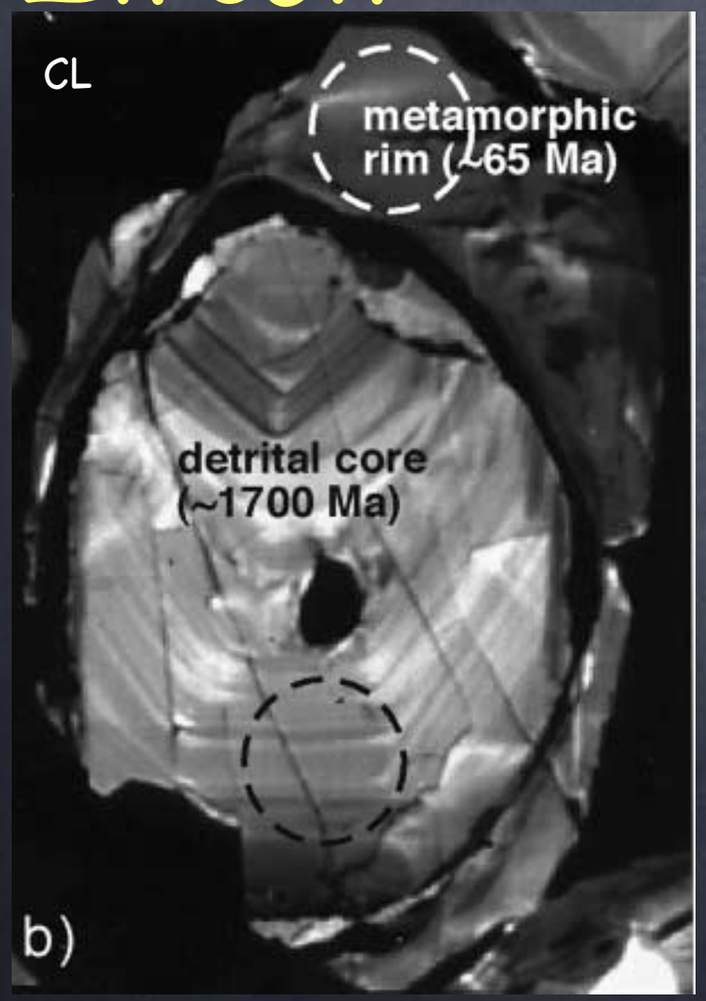
..chemically zoned

metamorphic reaction

"geological event"

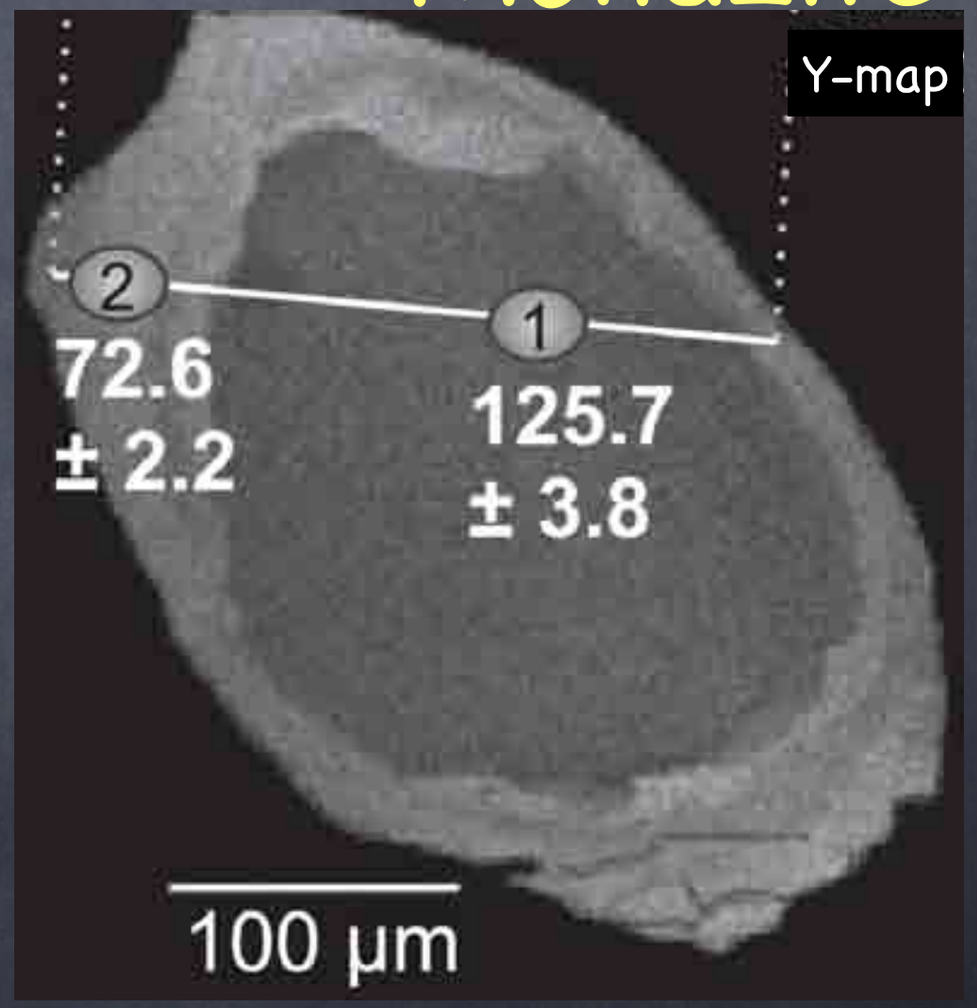
→ ZONING → different ages

Zircon



Zircon from eclogitic micaschist, Sesia-Lanzo Zone (Rubatto, 2002)

Monazite



Monazite from Grt+Ky micaschist, Canadian Cordillera (Gibson et al., 2004)

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Outlines of the seminar

- an overview of U-(Th)-Pb geochronology

- HT behaviour of zircon and monazite

- The IVREA-VERBANO ZONE case study

50%

50%

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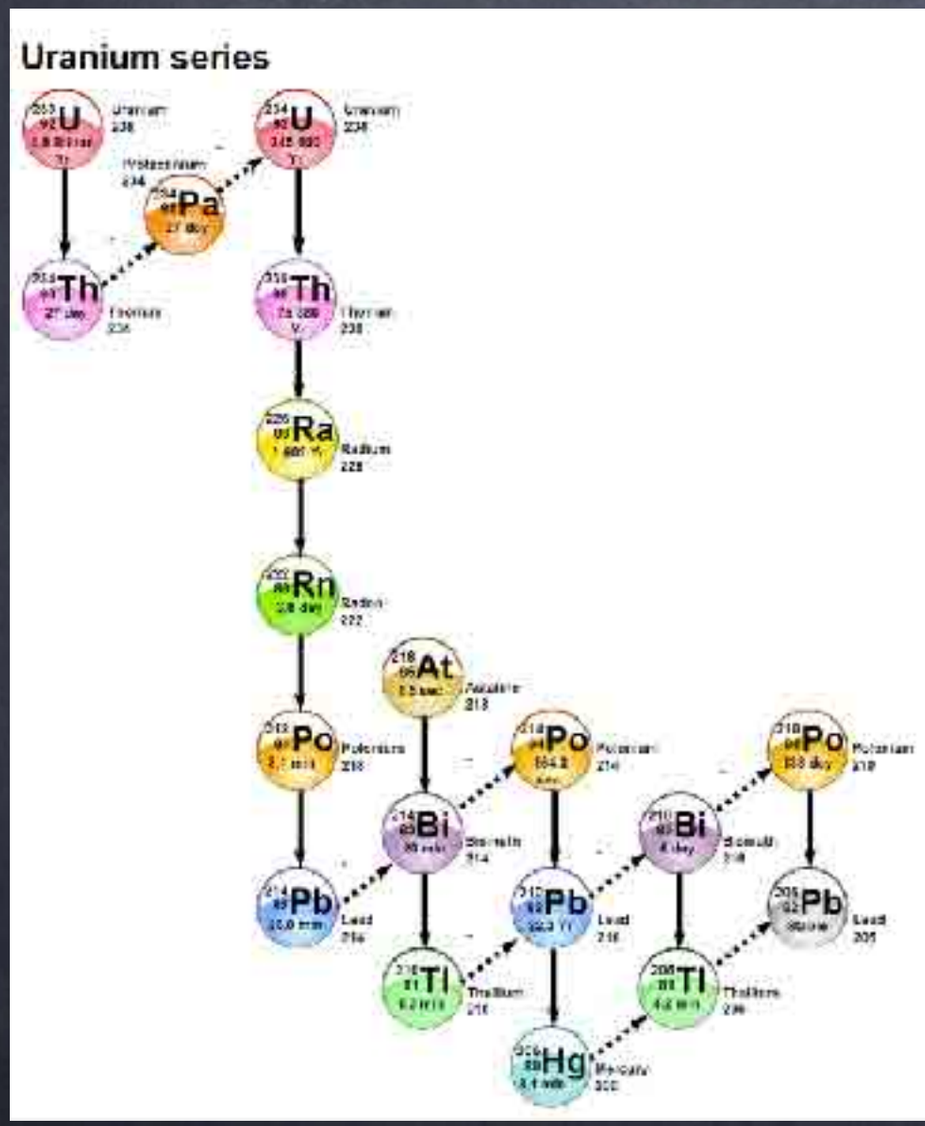
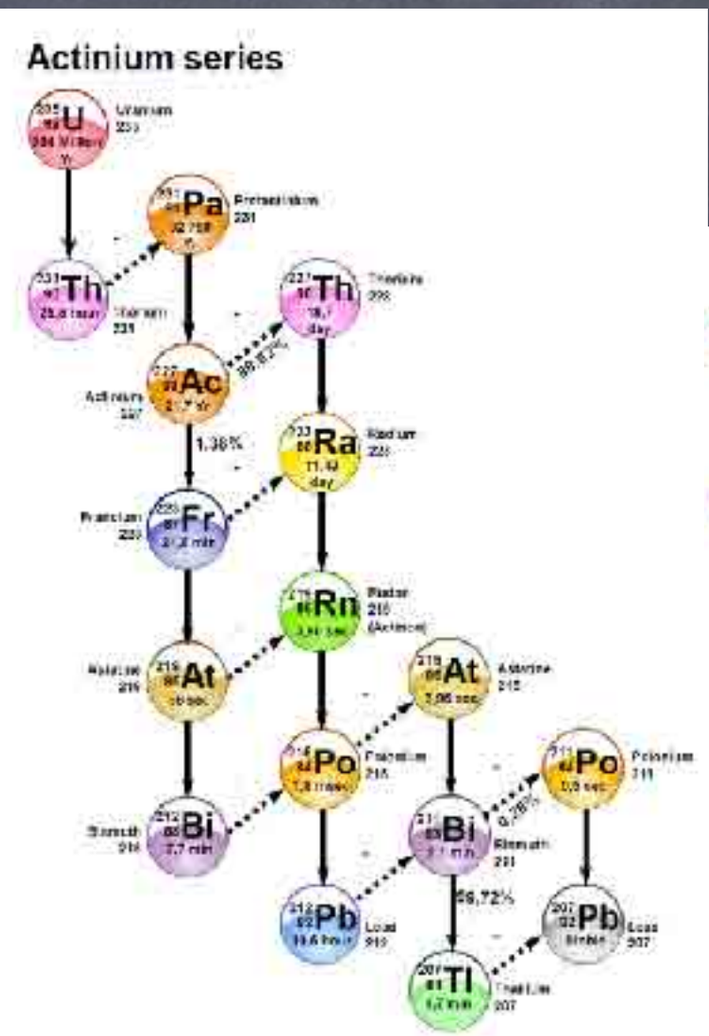
U-(Th)-Pb basics

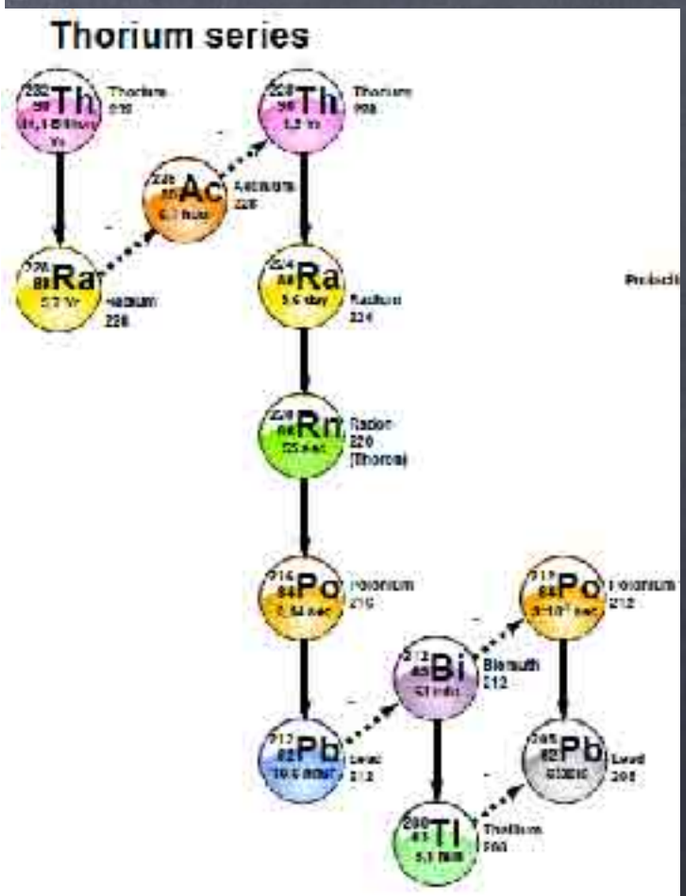
$^{238}U \rightarrow {}^{206}Pb$ $^{235}U \rightarrow {}^{207}Pb$ $^{232}Th \rightarrow {}^{208}Pb$



(half-life = 4470 m.y.)



(half-life = 700 m.y.)



(half-life = 14000 m.y.)

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U-(Th)-Pb geochronology: basics

- two isotopic U-Pb clocks with identical chemical characteristics but different rates of decay => robust check (concordance)

- the Th-Pb system is especially useful young monazite

- The U-Th-Pb system is especially useful for dating events with ages of 4500 to 5 m.y.

U-(Th)-Pb geochronology: basics

- why zircon and monazite are so reliable?

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U-(Th)-Pb geochronology: basics

- why zircon and monazite are so reliable?

Zrc, Mnz	high U content (up to 1000s ppm)
Mnz	high Th content (up to several wt%)
Zrc, Mnz	highly resistant

U-(Th)-Pb geochronology: basics

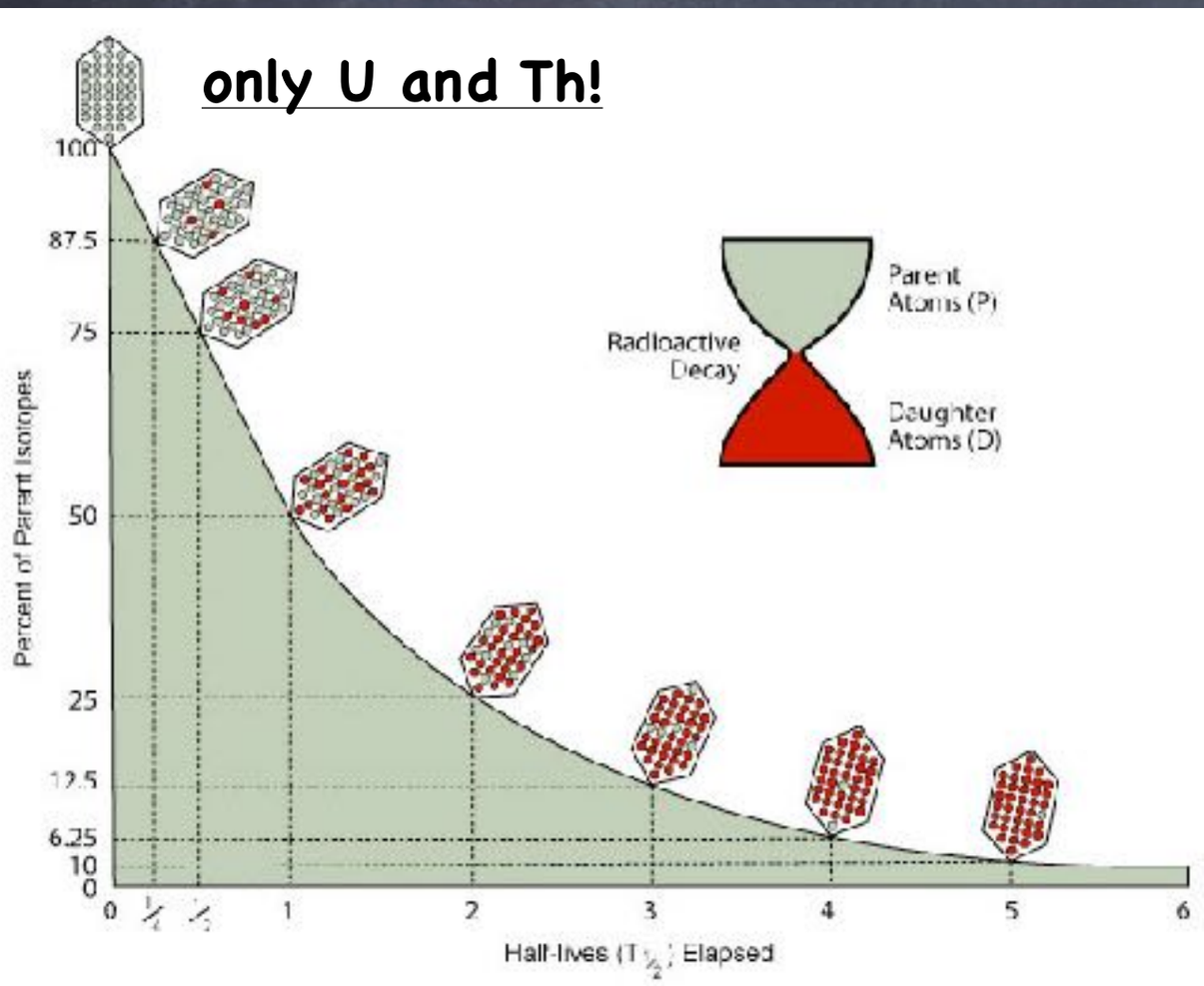
- (in theory) Zrc and Mnz do not incorporate Pb during crystallisation

measured Pb = radiogenic Pb + ~~common Pb~~

from U and Th decay

already present
when rock/mineral formed

only U and Th!



U-Th-Pb data representation

System	*Decay constant (Ma^{-1})*	*Solution*	
$^{238}U \rightarrow {}^{206}Pb$	1.55125×10^{-4}	$^{206}Pb = {}^{238}U \cdot \left(e^{\lambda_{238} t} - 1\right)$	▶ $^{206}Pb/^{238}U$
$^{235}U \rightarrow {}^{207}Pb$	9.8585×10^{-4}	$^{207}Pb = {}^{235}U \cdot \left(e^{\lambda_{235} t} - 1\right)$	▶ $^{207}Pb/^{235}U$
$(^{207}Pb/^{206}Pb)^*$		$\left(\frac{^{207}Pb}{^{206}Pb}\right)^* = \frac{1}{137.88}\left(\frac{e^{\lambda_{235} t} - 1}{e^{\lambda_{238} t} - 1}\right)$	▶ $^{206}Pb/^{207}Pb$
$^{232}Th \rightarrow {}^{208}Pb$	4.9475×10^{-5}	$^{208}Pb = {}^{232}Th \cdot \left(e^{\lambda_{232} t} - 1\right)$	▶ $^{208}Pb/^{232}U$

we can calculate four ages!

U-Th-Pb data representation

The Concordia (Wetherill) plot

$^{206}Pb/^{238}U$ age

=

$^{207}Pb/^{235}U$ age

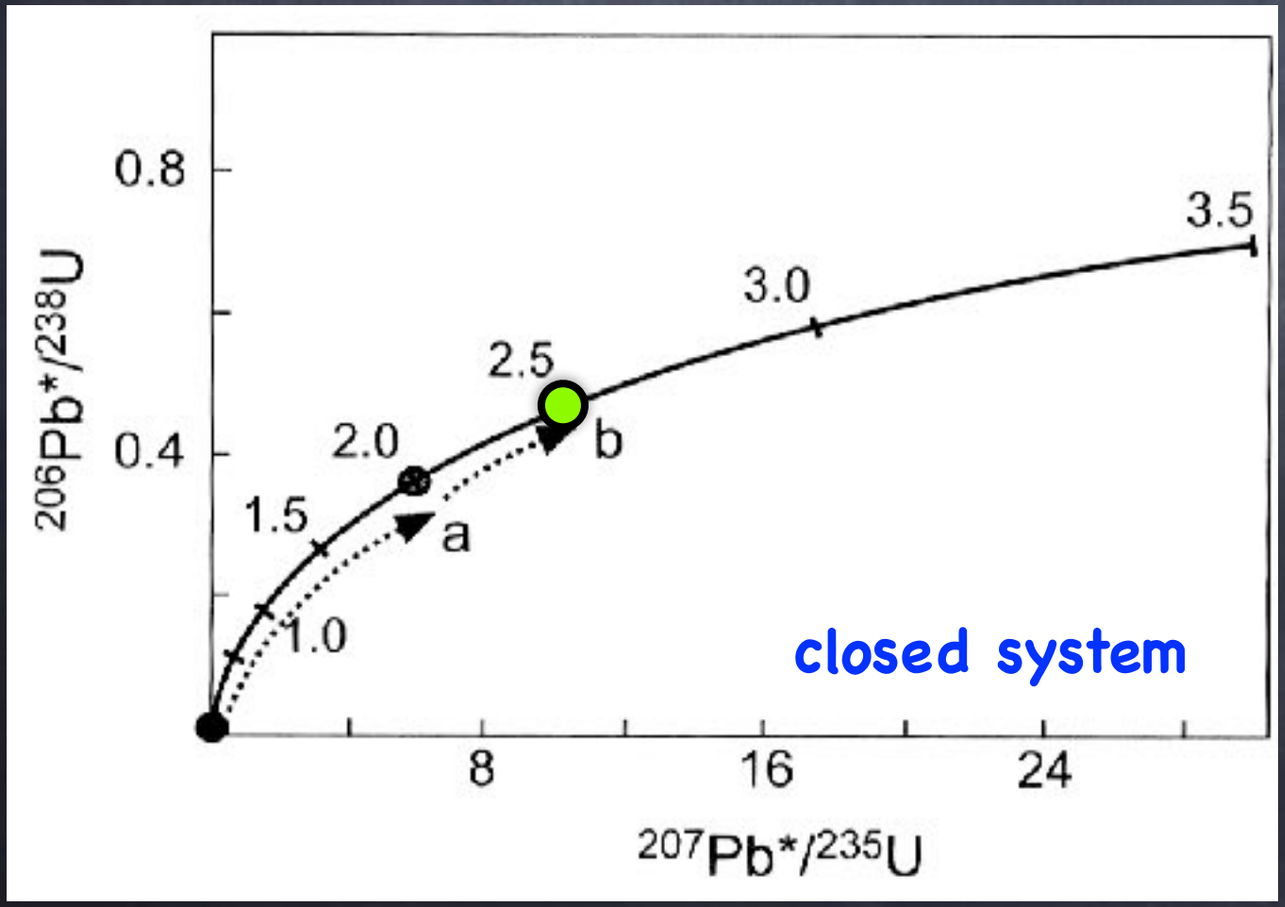
● concordant data

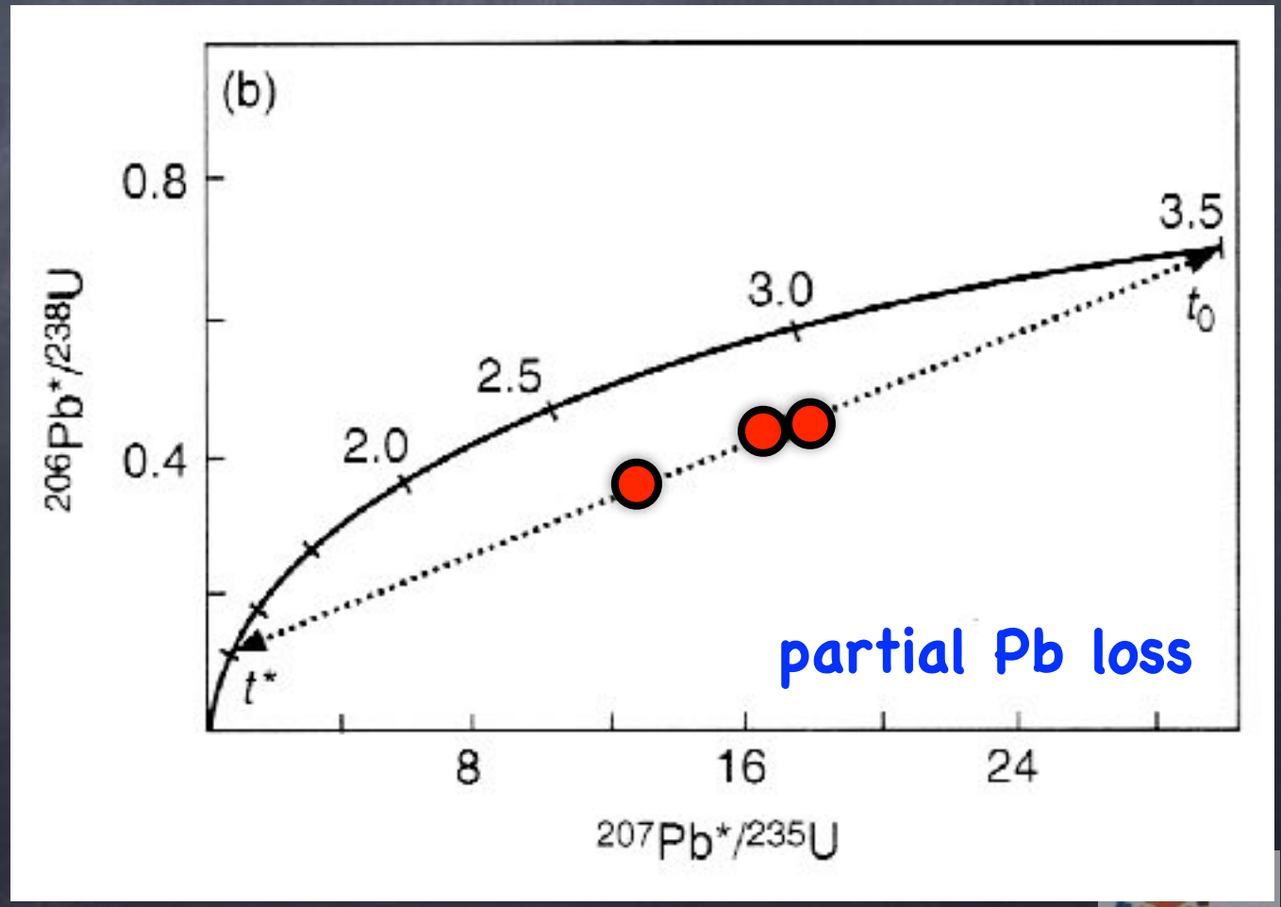
$^{206}Pb/^{238}U$ age

≠

$^{207}Pb/^{235}U$ age

● disconcordant data



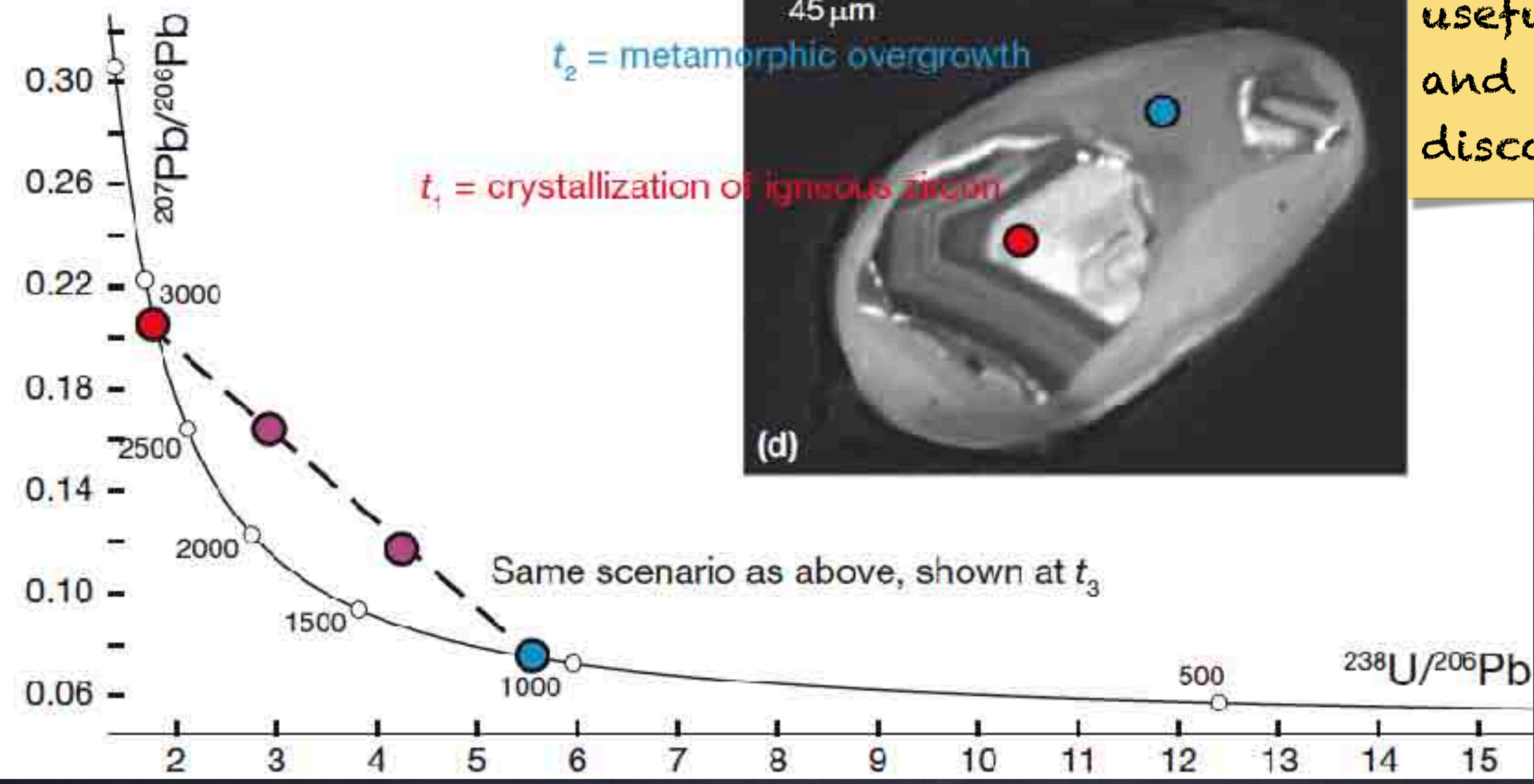


Schaefer, 2016

U-Th-Pb data representation

The Tera-Wasserburg plot { $^{238}U/^{206}Pb$, $^{207}Pb/^{206}Pb$

Schoene, 2015



useful to plot and interpret discordant data!

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How we can date zircon and monazite?

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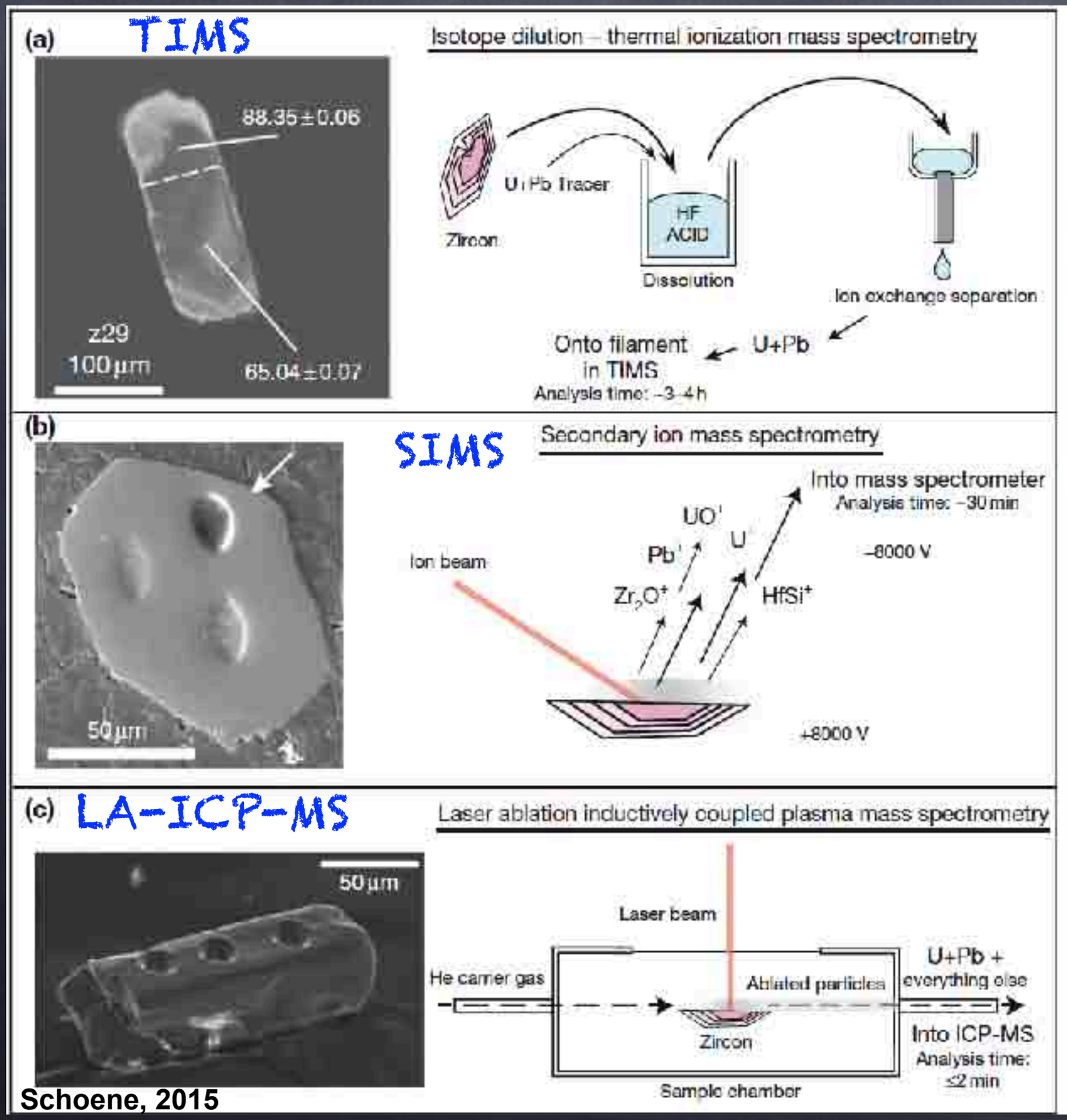
How we can date zircon and monazite?



Schoene, 2015

TIMS

- BULK technique
- high precise!
- magmatic Zrc/Mnz with simple T-t history

LA-ICP-MS and SIMS

- in situ technique
- magmatic and metamorphic Zrc/Mnz with complex T-t history

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Behaviour of zircon and monazite at HT conditions

the zircon and monazite reactivity

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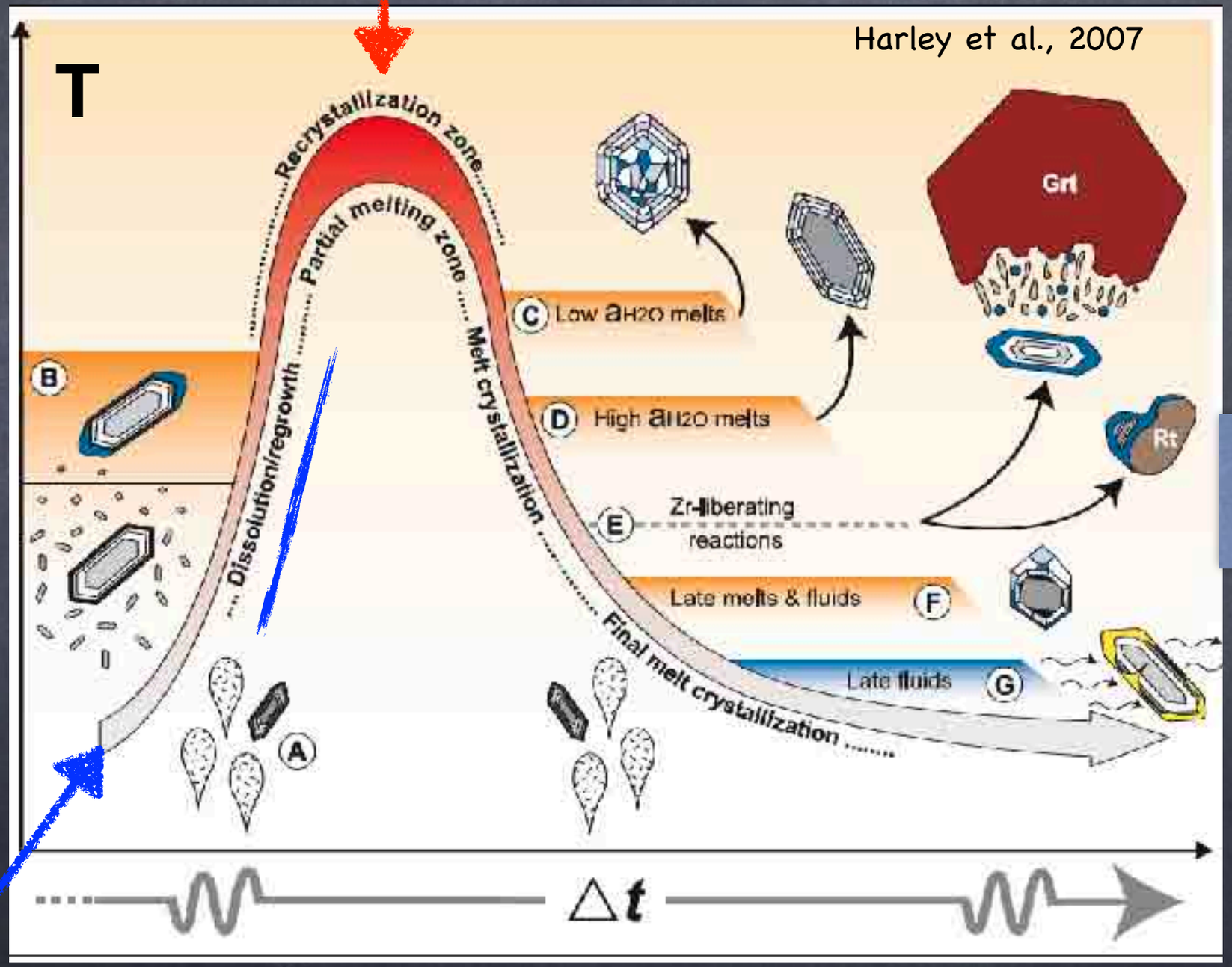
Zircon reactivity…

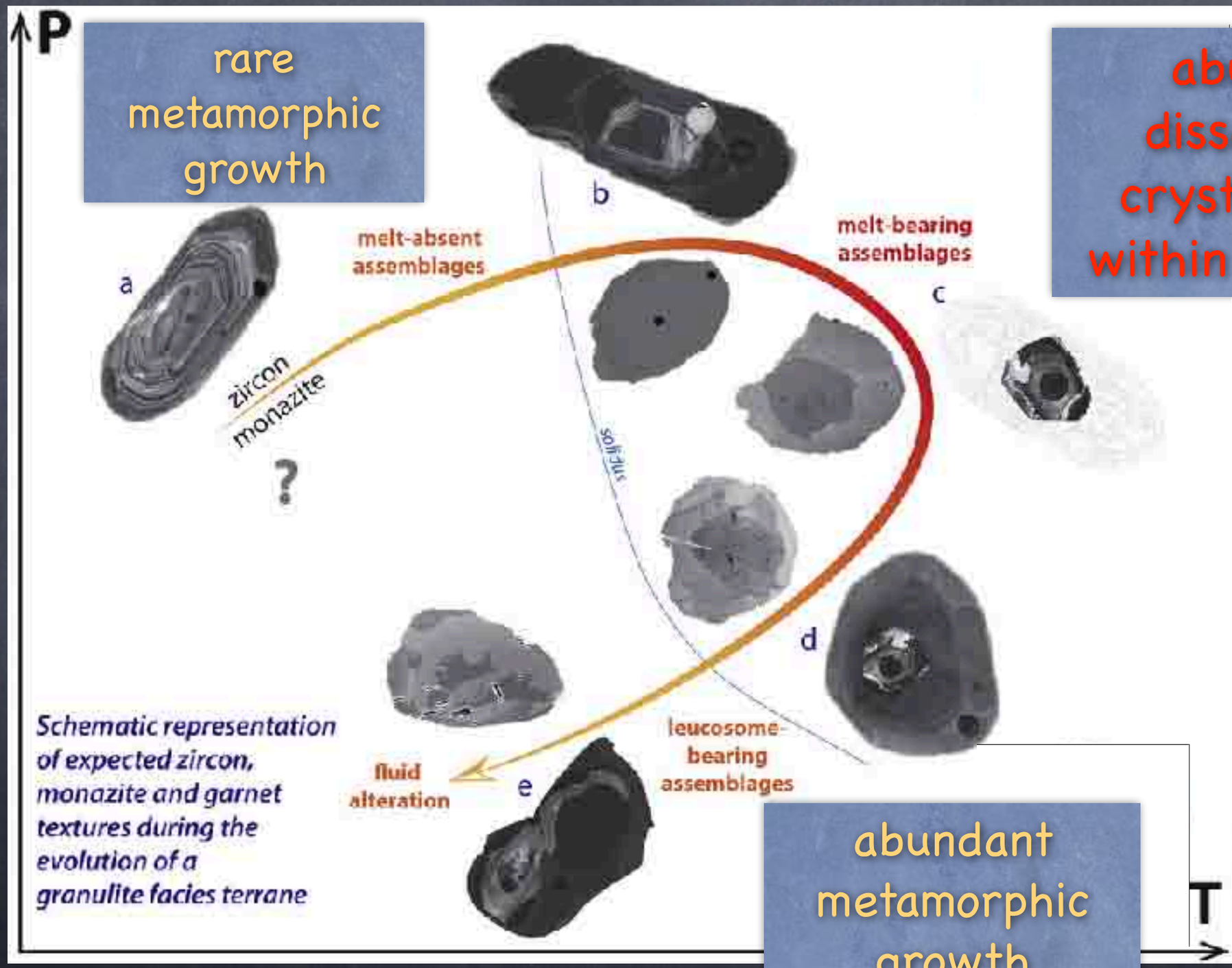
melt formation => abundant Zrc dissolution



Zrc-forming reaction

pre-existing & inherited zircon grains

Monazite reactivity…



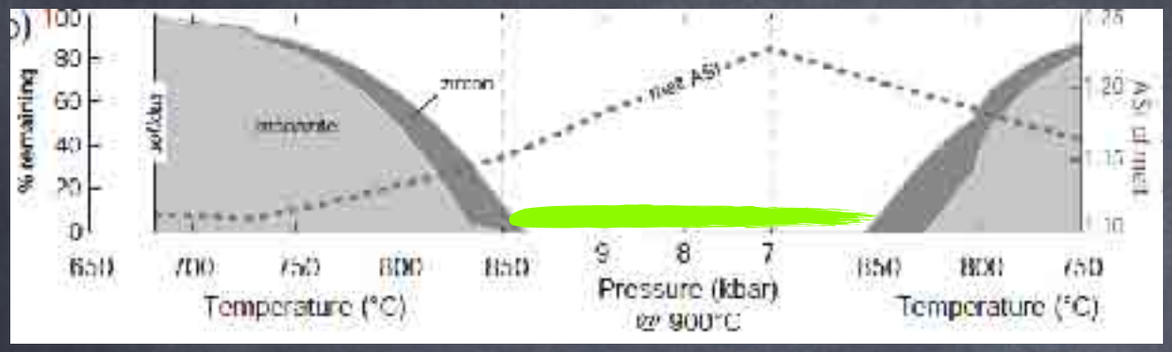
rare metamorphic growth

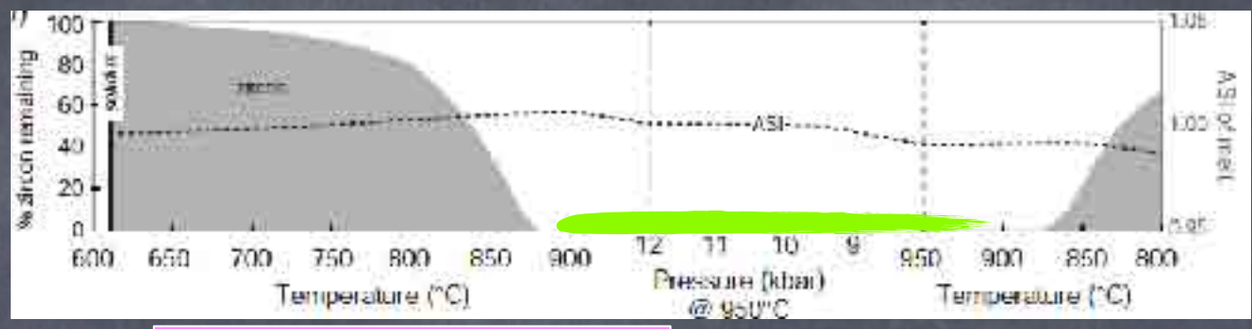
abundant dissolution+ crystallisation within the melts

abundant metamorphic growth

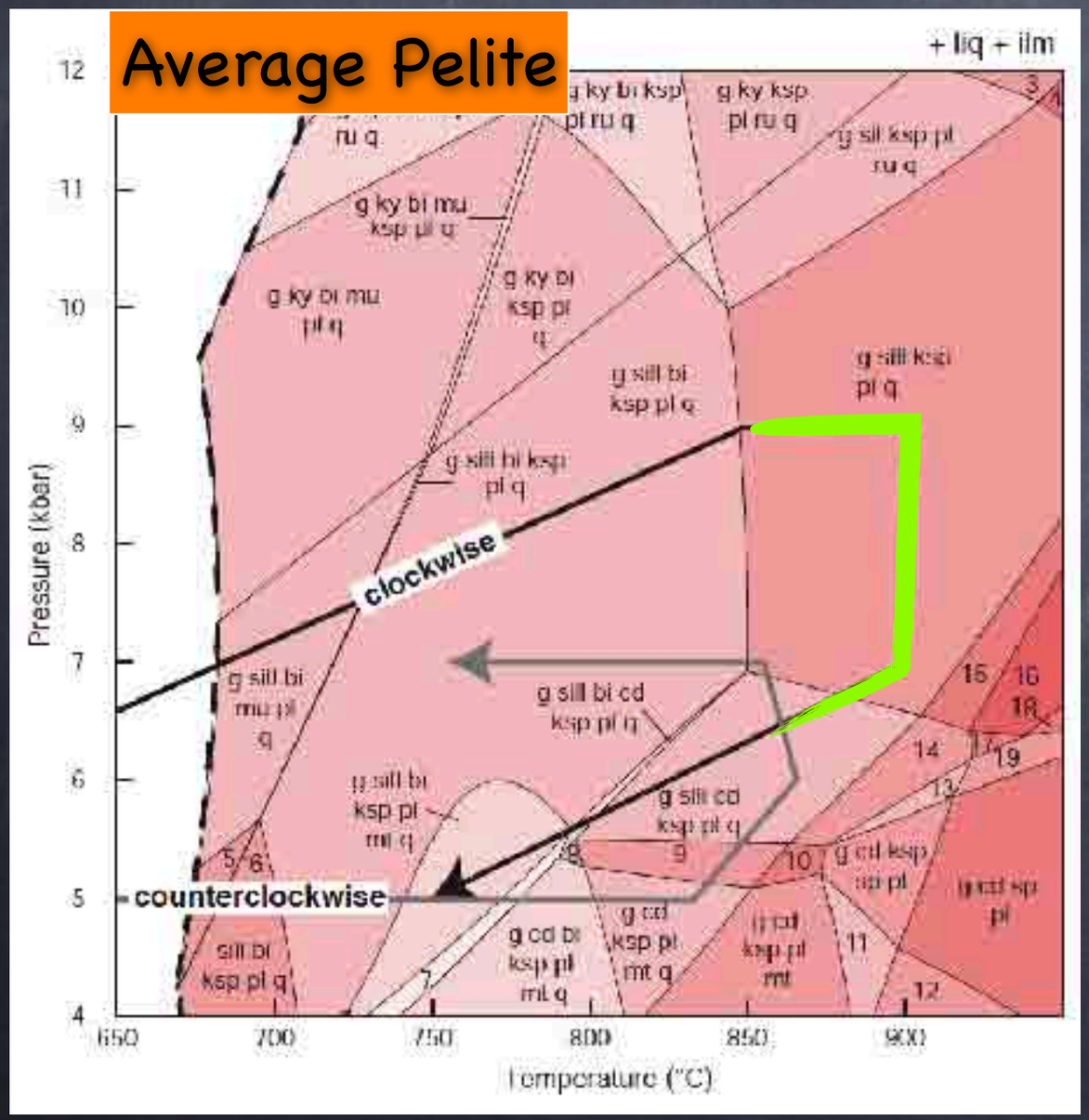
Taylor et al., 2016

zircon and monazite reactivity…

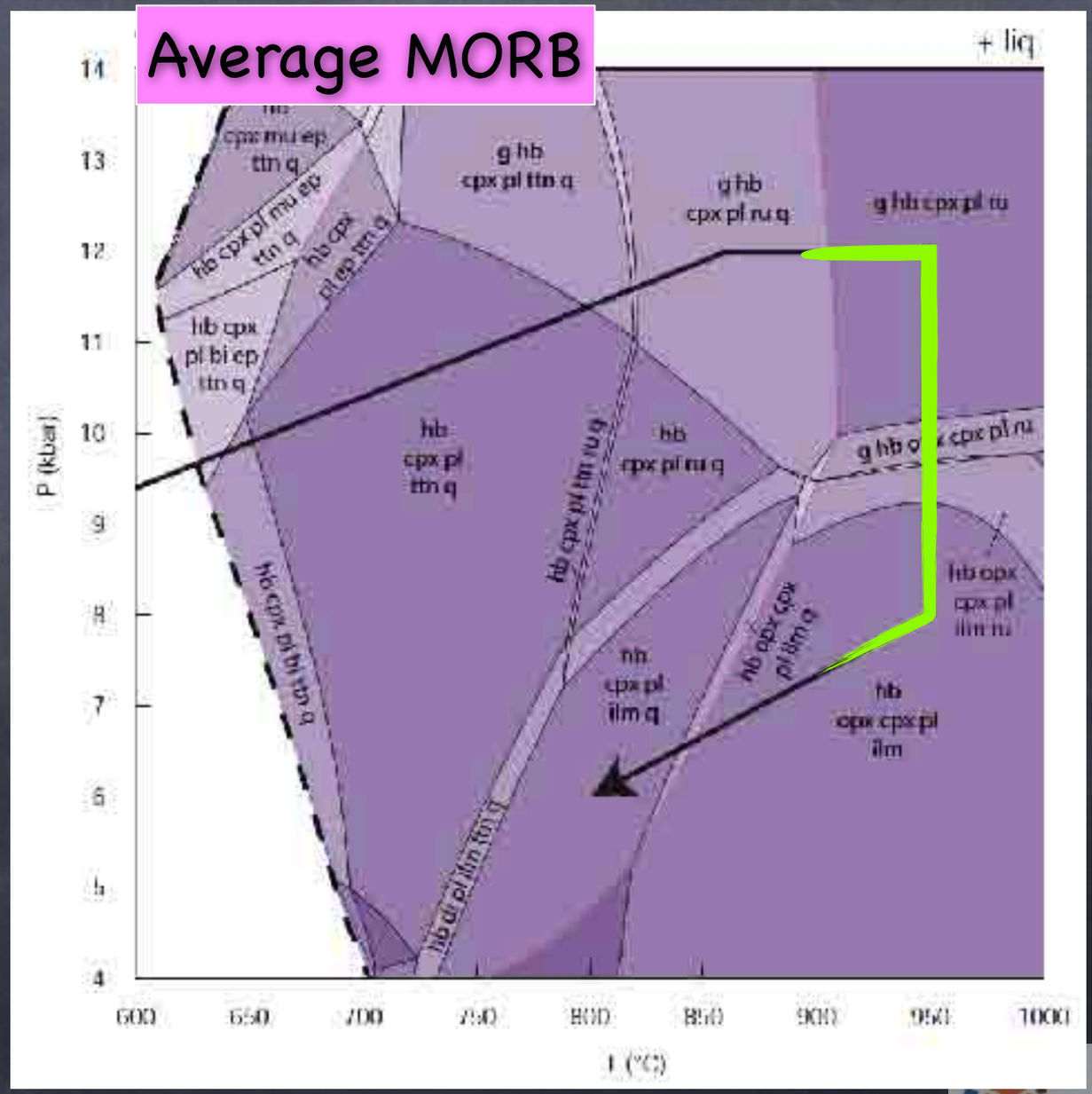




Average Pelite



Average MORB



(Yakymchuk et al., 2017)

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zircon and monazite reactivity

1 - abundant dissolution

@HT

2 - crystallisation within the melt

3- Zrc and Mnz-forming reaction during cooling

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zircon and monazite reactivity

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@HT

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3- Zrc and Mnz-forming reaction during cooling

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zircon and monazite reactivity:
the reaction mass balance

$$a + b = c + d$$

Si	Si	Si	Si
Al	...	Al	Fe
Mg		K	Mg...
Fe		...	
K			
...			

$$(a + b) - (c + d) = 0$$

what about minor and trace element?

Zr, P, REE, Y etc...????

zircon and monazite reactivity: the reaction mass balance

$$a + b = c + d$$

Si	Si	Si	Si
Al	...	Al	Fe
Mg		K	Mg...
Fe		...	
K			
...			

$$(a + b) - (c + d) \neq 0$$

"....reactants contain more Zr (Y, P, REE) than can be accommodated in the products => accessory minerals as mass balancing phases..."
(Bea et al., 2006)

Zircon-forming reaction...

@HT

- "old" Zrc => new Zrc (over)growth

  e.g., magmatic core => metamorphic rims

  older metamorphic core => younger metamorphic rim

  inherited core => magmatic/metamorphic rims

- Zr-bearing minerals => Zrc

(e.g. Yakymchuk et al., 2017 and references therein; Kohn et al., 2015)

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(e.g. Yakymchuk et al., 2017 and references therein; Kohn et al., 2015)

Zr content in minerals

Metapelites	Mafic granulites/ amphibolites	Zr (ppm)
Garnet	Garnet	10s
Clinopyroxene	Clinopyroxene	100s
	Amphibole	100s
	Epidote	10s
Ilmenite	Ilmenite	100s
	Titanite	100s
Rutile	Rutile	1000s

e.g., Fraser et al., 1997; Kohn et al., 2015; Bea et al., 2006; Rubatto, 2017

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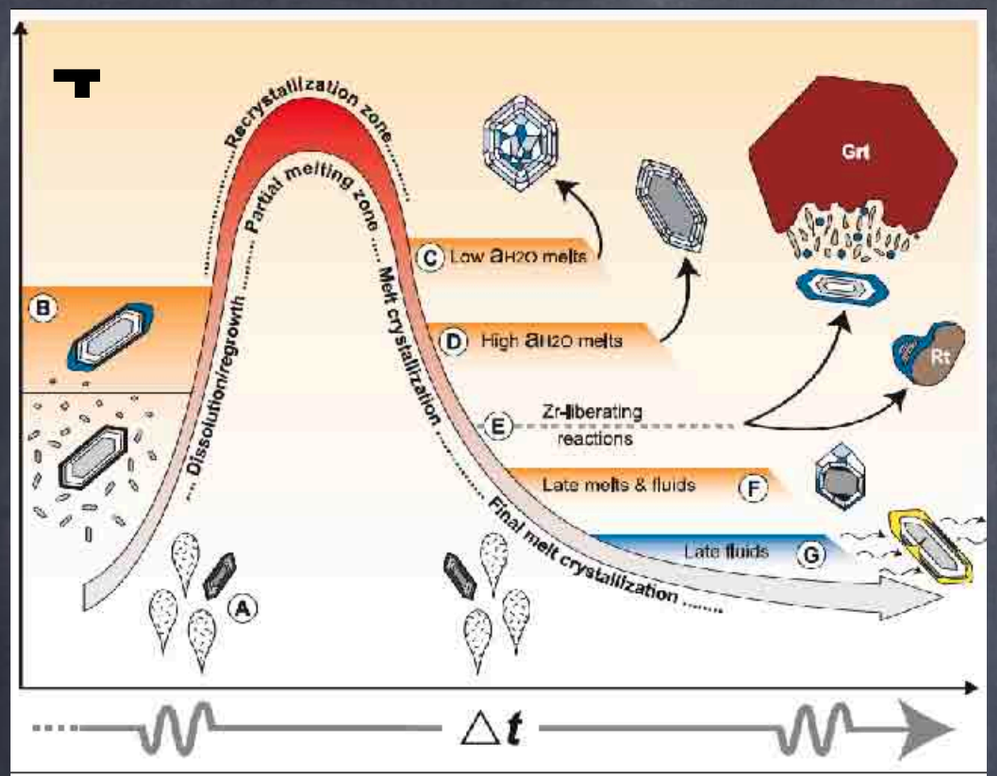
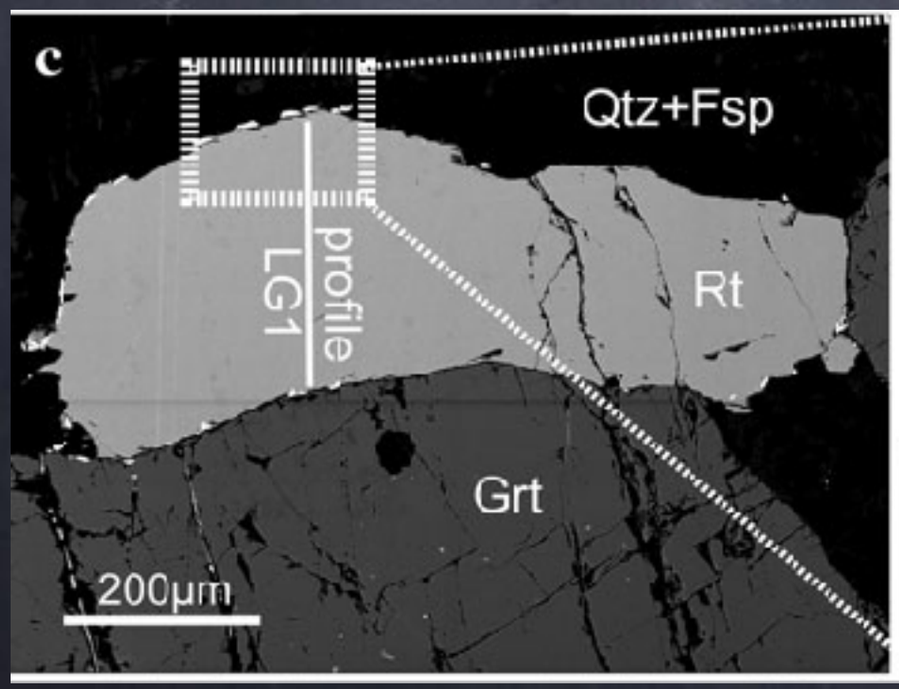
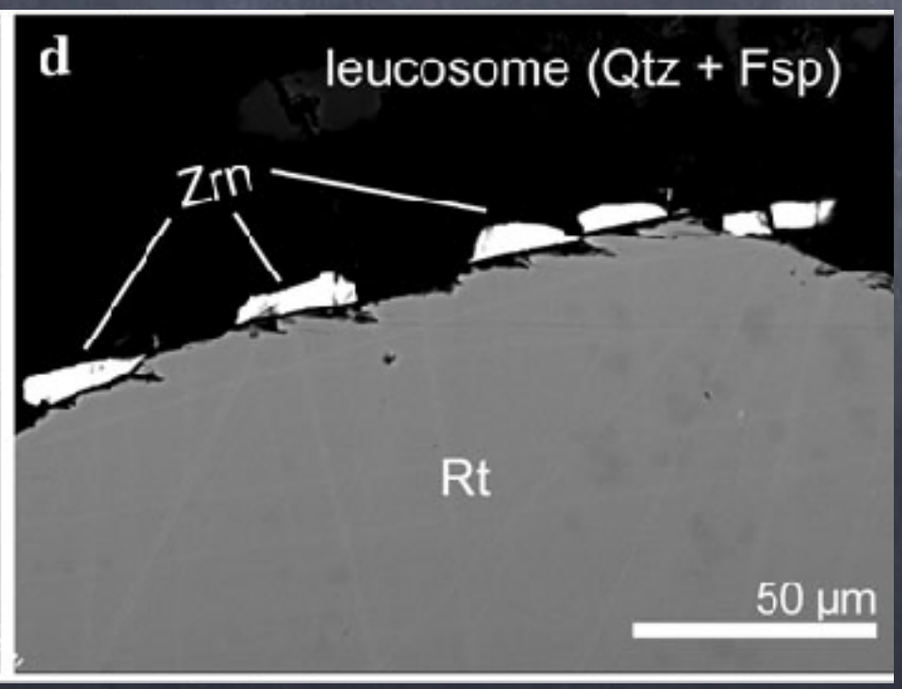
Zircon-forming reaction...



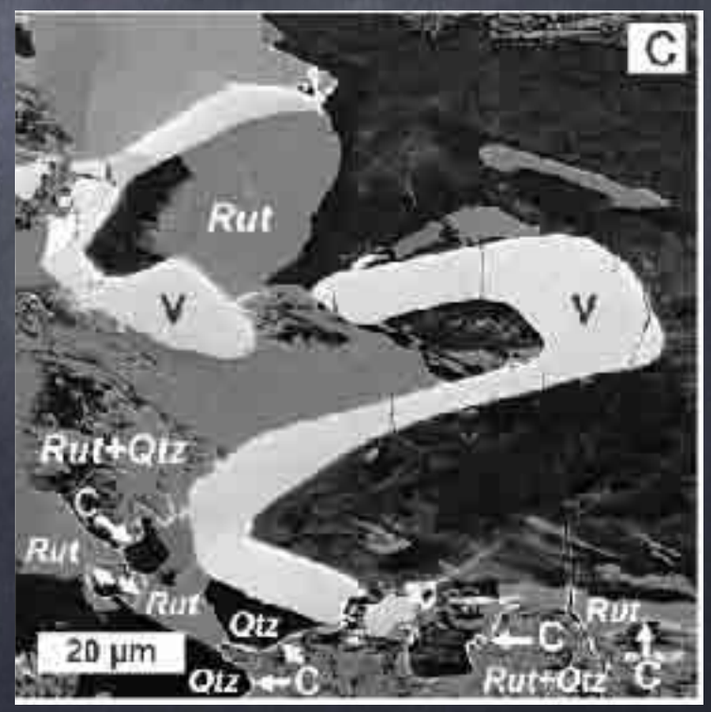
decreasing temperatures=>

decrease of Zr solubility in source minerals => precipitation of expelled Zr as metamorphic zircon grain/overgrowth (e.g. Rubatto, 2017)





(Ewing et al., 2013)



(Kovaleva et al., 2016)

See the poster of Heuser David!!

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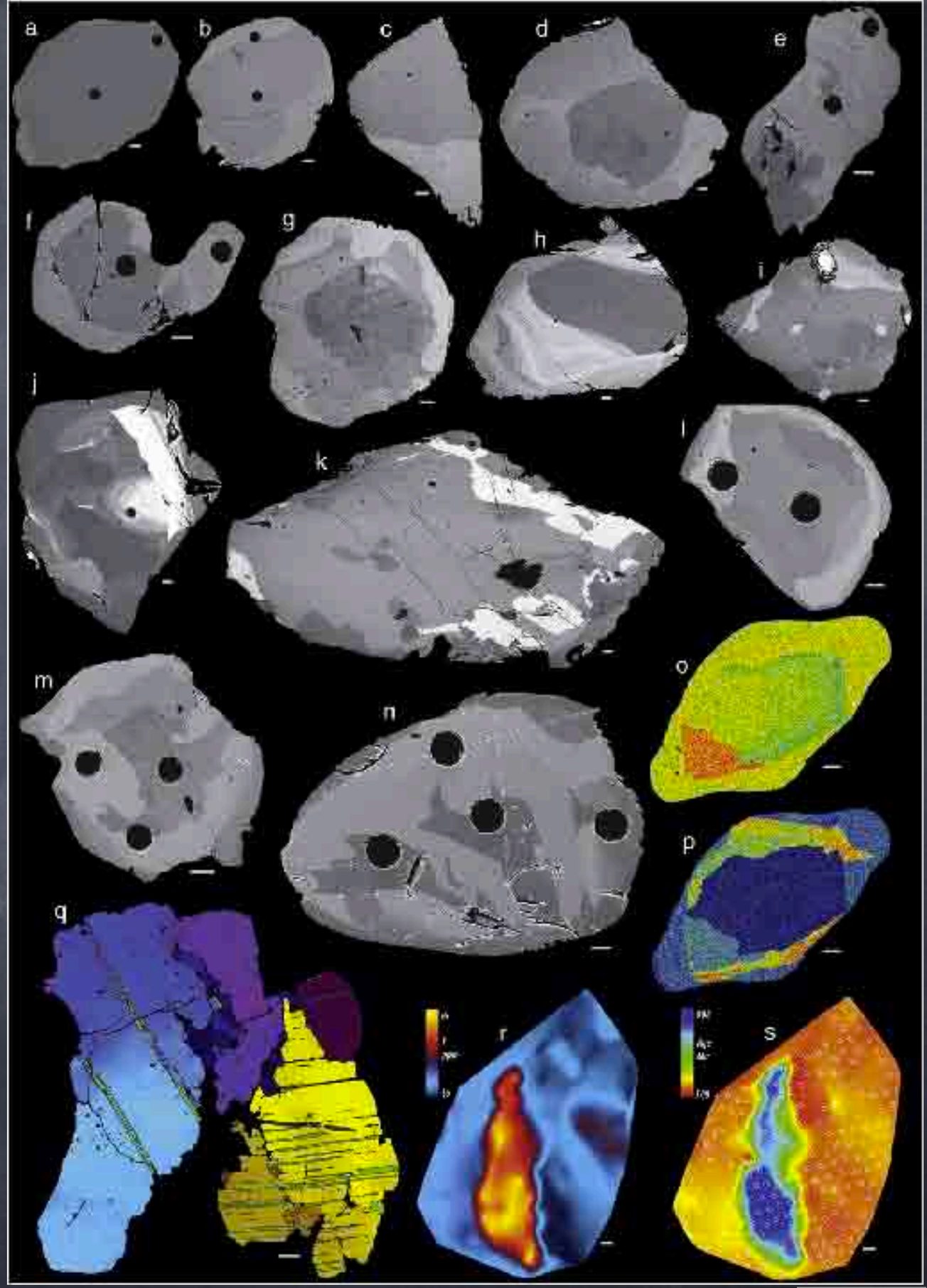
monazite reactivity...



Atlas of granulite-facies monazite (after Taylor et al., 2016)

Monazite-forming reaction...

@HT

- "old" Mnz => new Mnz (over)growth

  e.g., magmatic core => metamorphic rims

  older metamorphic core => younger metamorphic rim

  inherited core => magmatic/metamorphic rims

- other P- and REE-bearing minerals => Mnz

(e.g. Yakymchuk et al., 2017 and references therein)

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(e.g. Yakymchuk et al., 2017 and references therein)

monazite-forming reaction...

P- and REE content in minerals

Table 6. Typical modes and trace element concentrations of metamorphic materials.

Mineral	Mode (%)	P (ppm)	P (%)	LREEs (ppm)	LREEs (%)
Quartz	35	0	0	0	0
Garnet	5	200	1–2	<1	0
Plagioclase	20	300	8–15	25–50	5–50
Staurolite	0	~0	0	0?	0?
Biotite	10	~0	0	10–20	1–10
Kyanite	0	~0	0	0?	0?
Muscovite	20	~0	0	10–20	2–20
Chlorite	10	~0	0	10?	1–5?
Sum majors:	100	70	9–17	9–17	9–85
Apatite	0.2–0.4	185,000	83–91	500–2500	1–50
Sum majors and apatite:	100	400–800	100	10–27	10–100
Whole rock (measured)		400–800		20–100	

Kohn & Malloy, 2004

Monazite-forming reaction...

P- and REE content in minerals

Allanite (source of REE, Y, and Th+U)!
(REE-Th-epidote group minerals)

Apatite (source of P and REE)

other silicates (garnet, plagioclase, micas..)

e.g. Kohn & Malloy, 2004,
Bea et al., 2006

is it possible to link metamorphic reactions (P-T) with zircon and monazite growth (time)?

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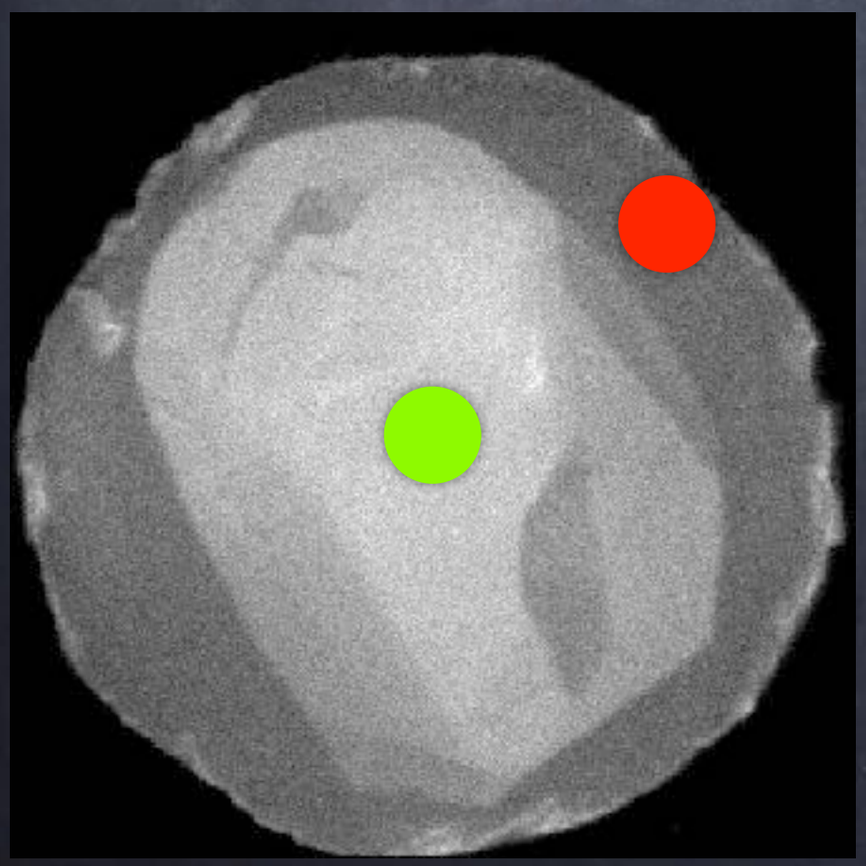
is it possible to link metamorphic reactions (P-T) with zircon and monazite growth (time)?

Zoning +



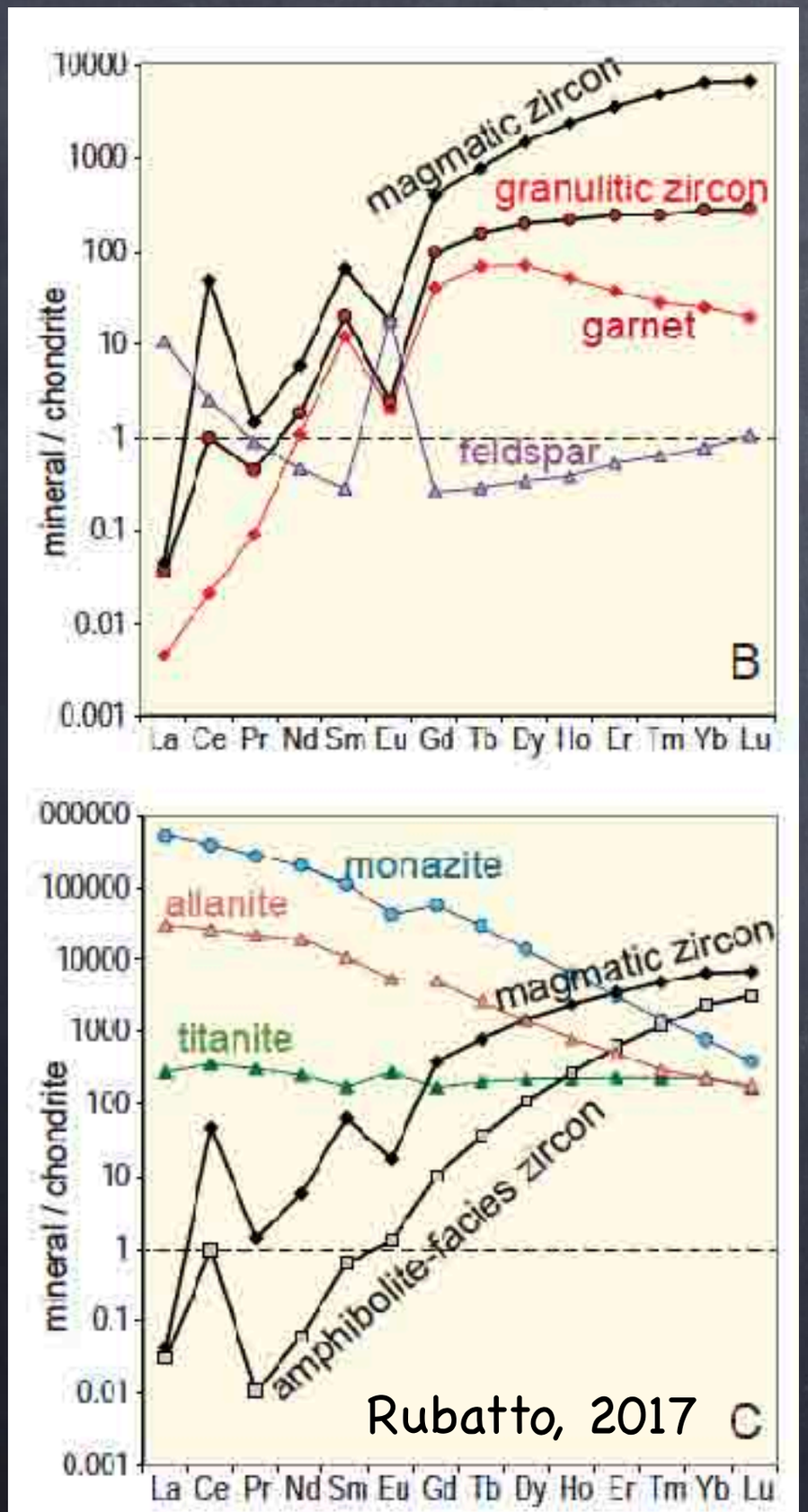
Age (isotopic ratio) +

trace elements

‼

INTERPRETATION!

mineral/zircon REE partitioning



Zircon REE patterns

⇓

coexistence of zircon with other minerals

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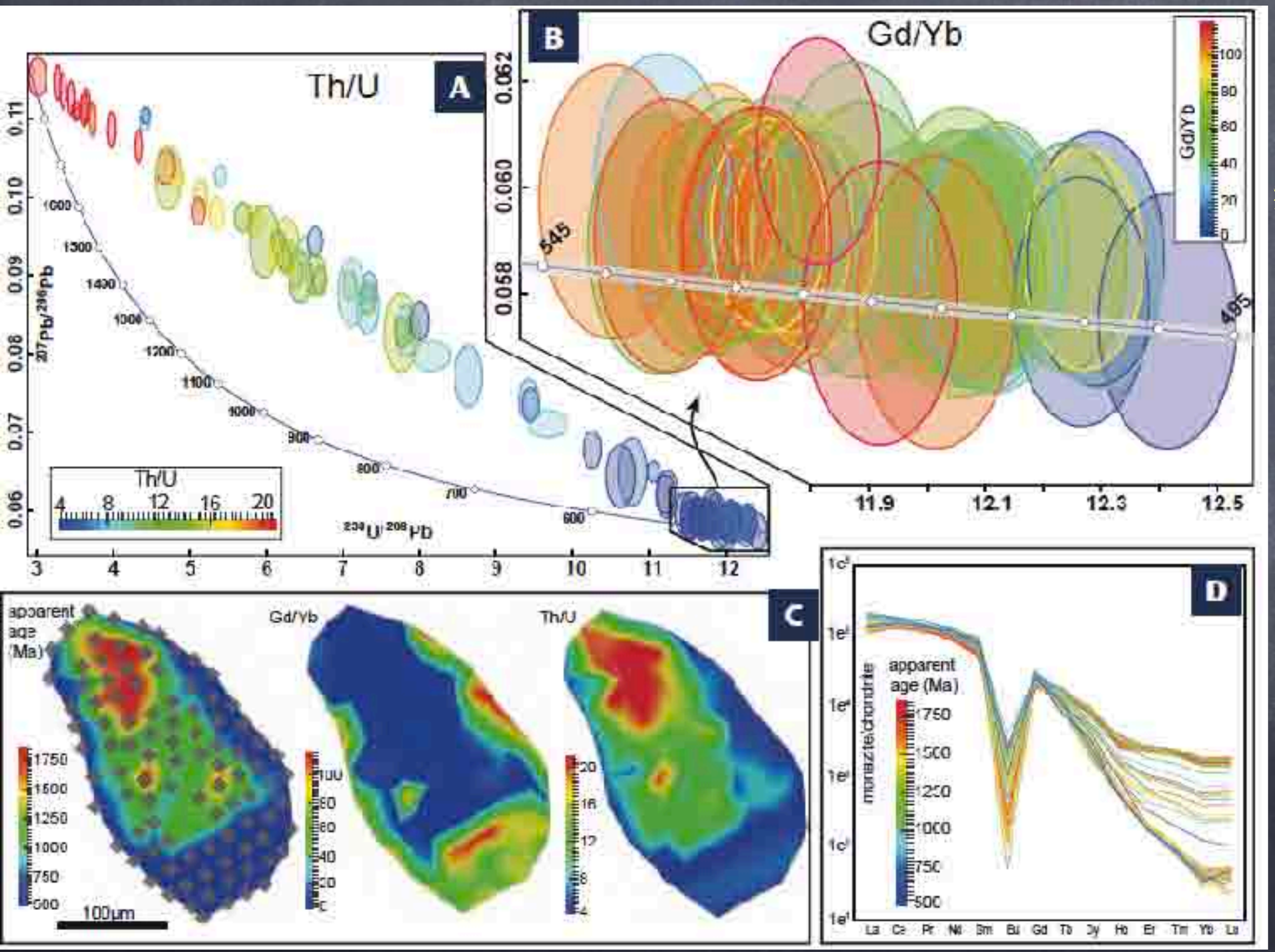
mineral/monazite element partitioning

LASS-ICM-MS:
simultaneous acquisition of U-Th-Pb isotopes and trace elements



low Yb content

⇓

recrystallisation of monazite in the stability field of garnet

in Woodhead et al., 2016; modified from Horton et al., 2016

zircon vs monazite reactivity:

ZrSiO4 (Ce,La,Nd,Th)PO4

P-T

Fluids

Bulk rock

Mineral assemblages

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Lower crustal magmatism

case study:

complexities from magmatic complexes...

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Lower crustal magmatism

case study:

complexities from magmatic complexes...

Why?
.. date the magmatic activity in the LC should be easier than the metamorphic events...

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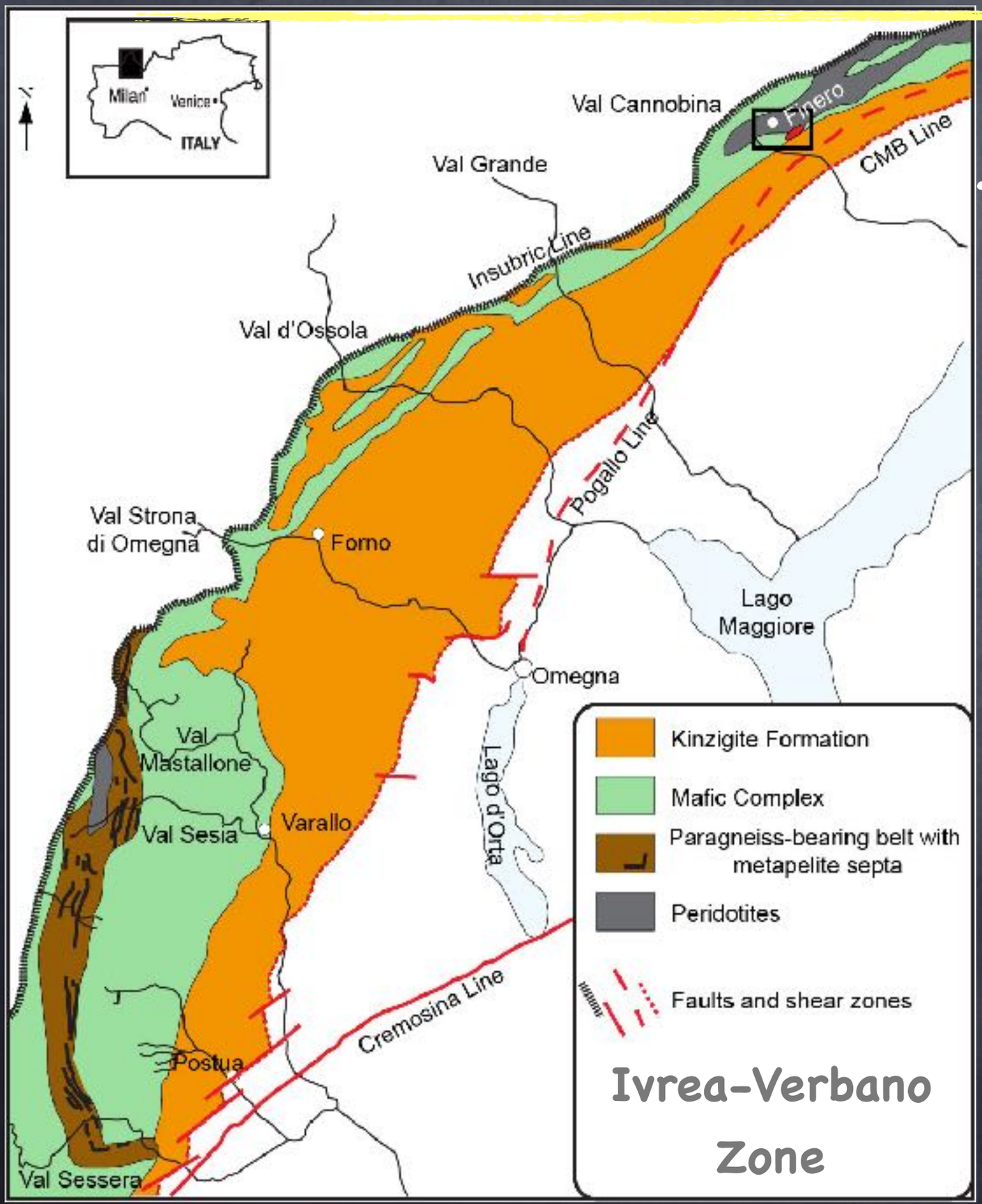
IVZ lower crustal magmatism



The mafic complex of the Ivrea-Verbano Zone

- one or multiple intrusions?
- Zircon crystallisation (magmatic) ages?
- deformation => zircon crystallisation

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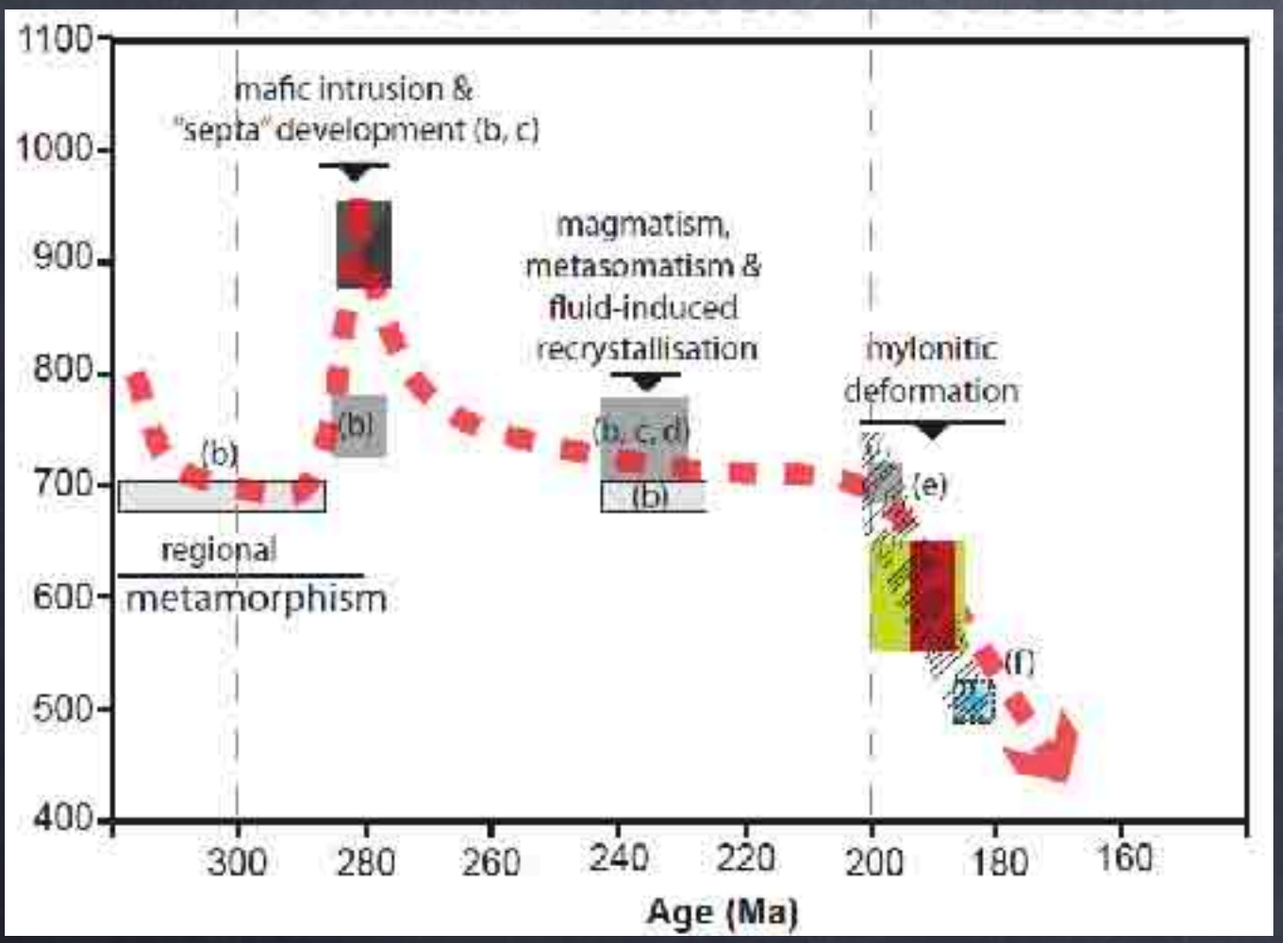
IVZ lower crustal magmatism

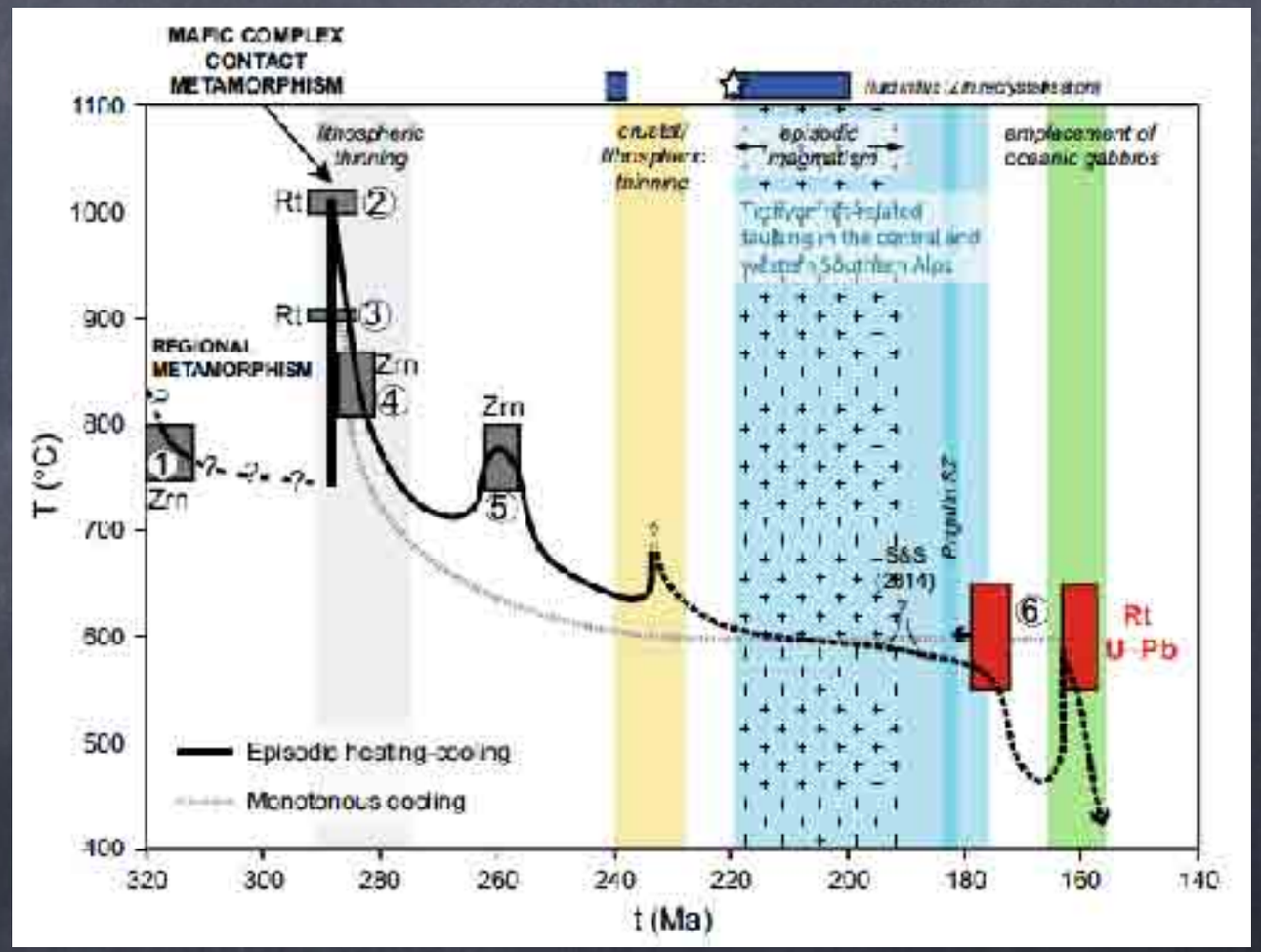
T-t evolution of lower crustal metamorphic rocks

Northern IVZ (Finero area)



Langone et al. in prep.
(Goldshmidt 2019)

Southern IVZ (Val Strona)



Ewing et al. 2015

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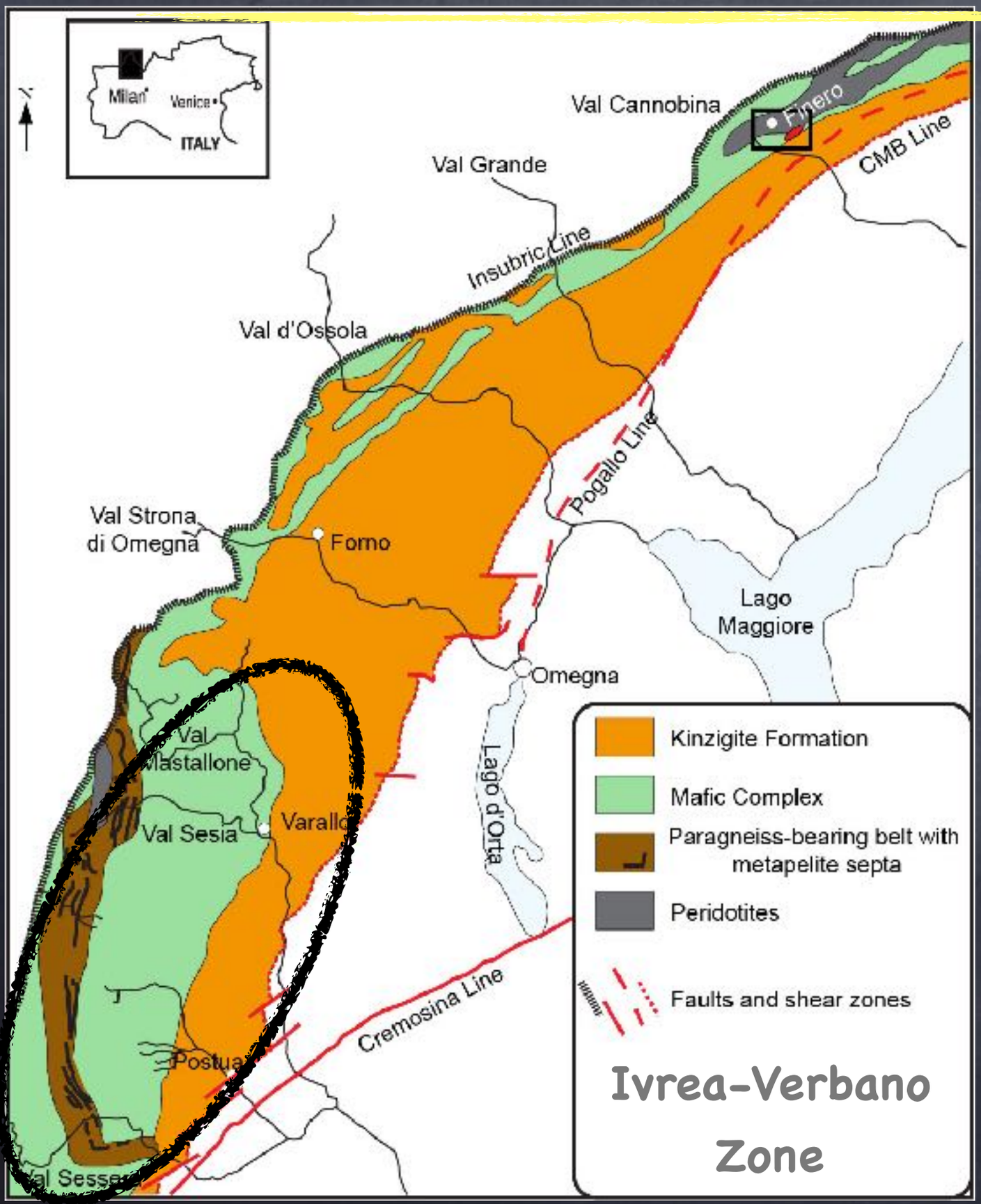
IVZ lower crustal magmatism



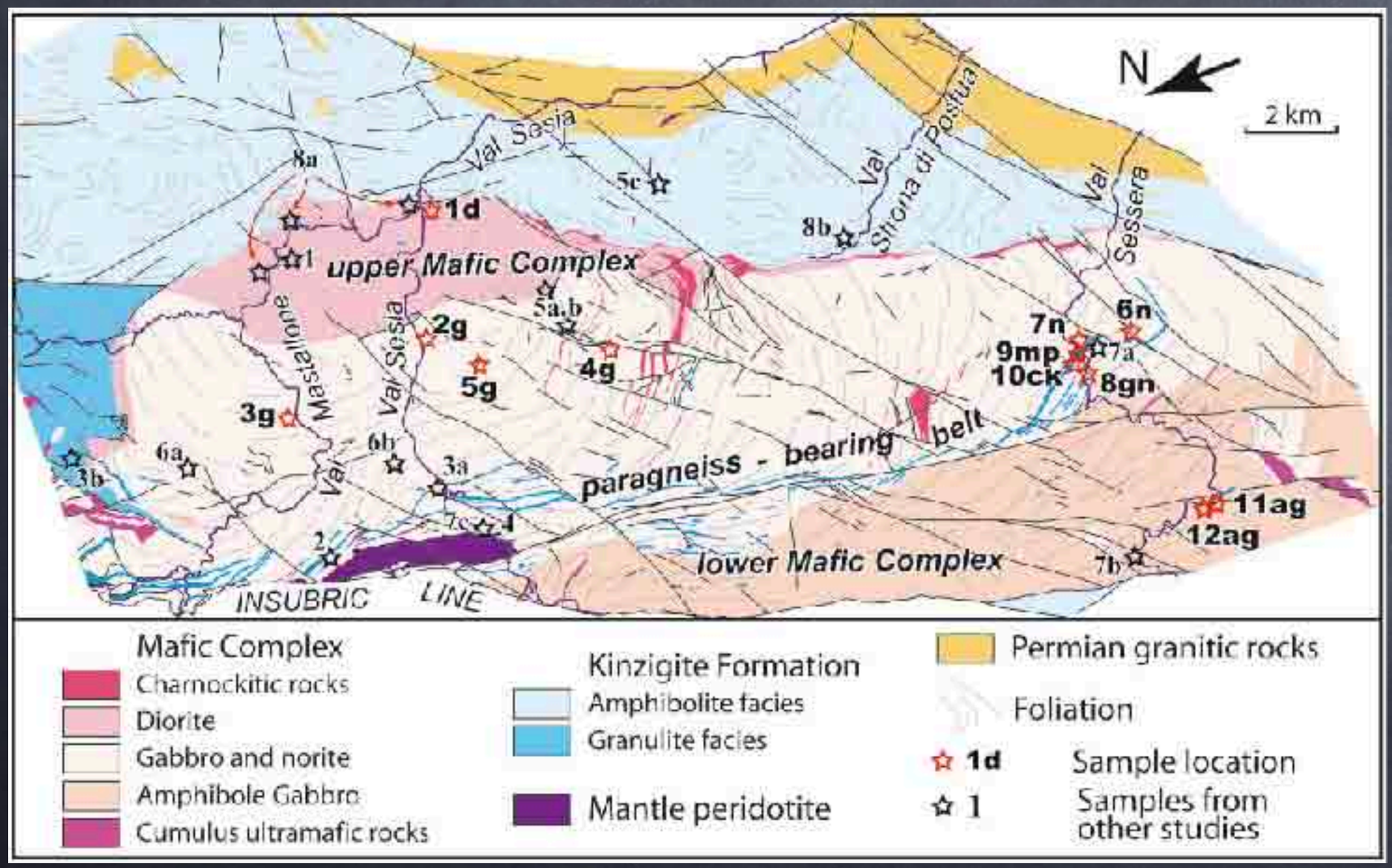
Duration of large mafic intrusion an heat transfer in the lower crust

Peressini et al. 2007

Langone Antonio

IVZ lower crustal magmatism

Mafic complex in Val Sesia



middle crust

lower crust

Peressini et al. 2007

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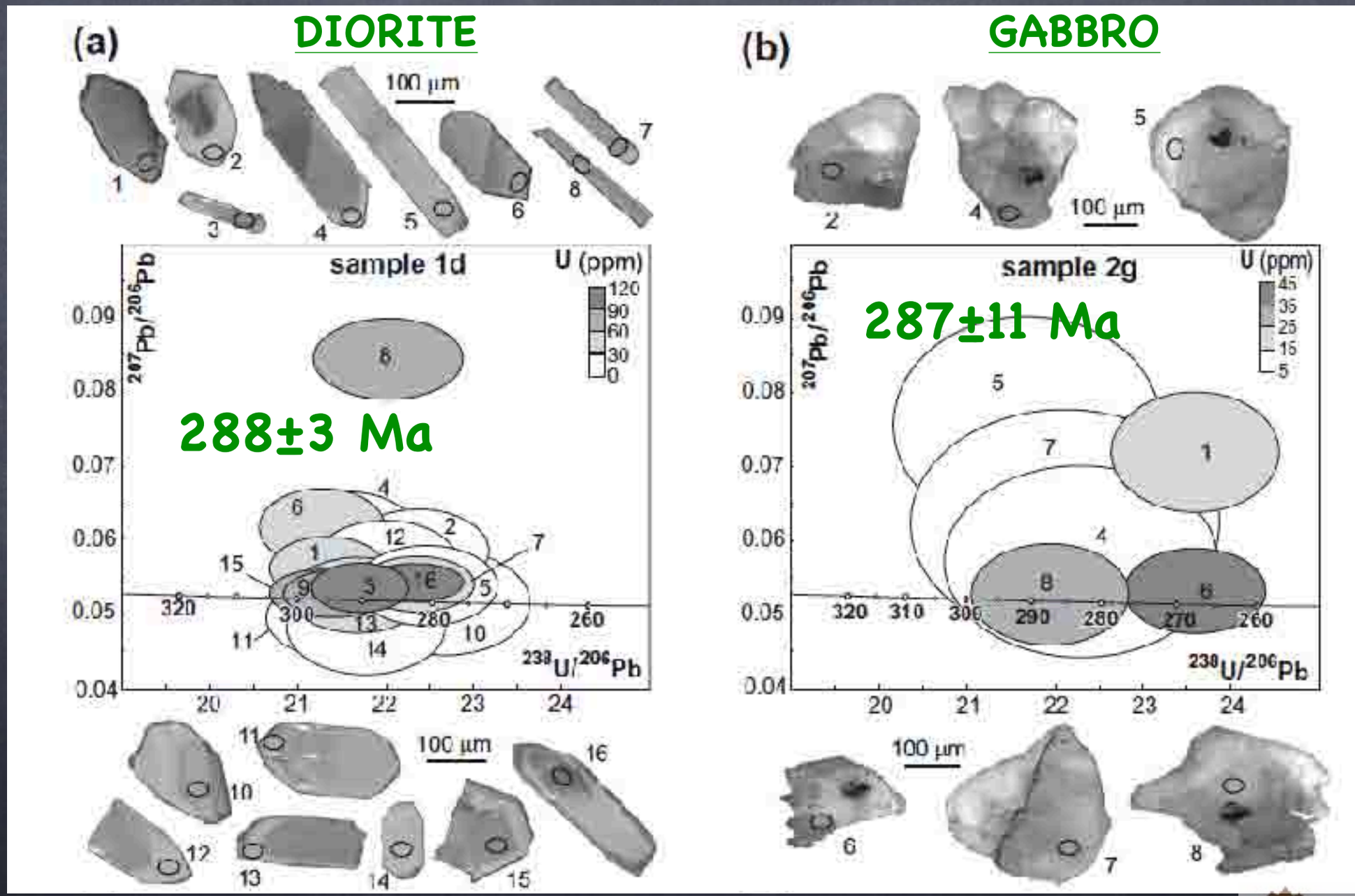
IVZ lower crustal magmatism

Zircon ages from the **Upper Mafic complex**

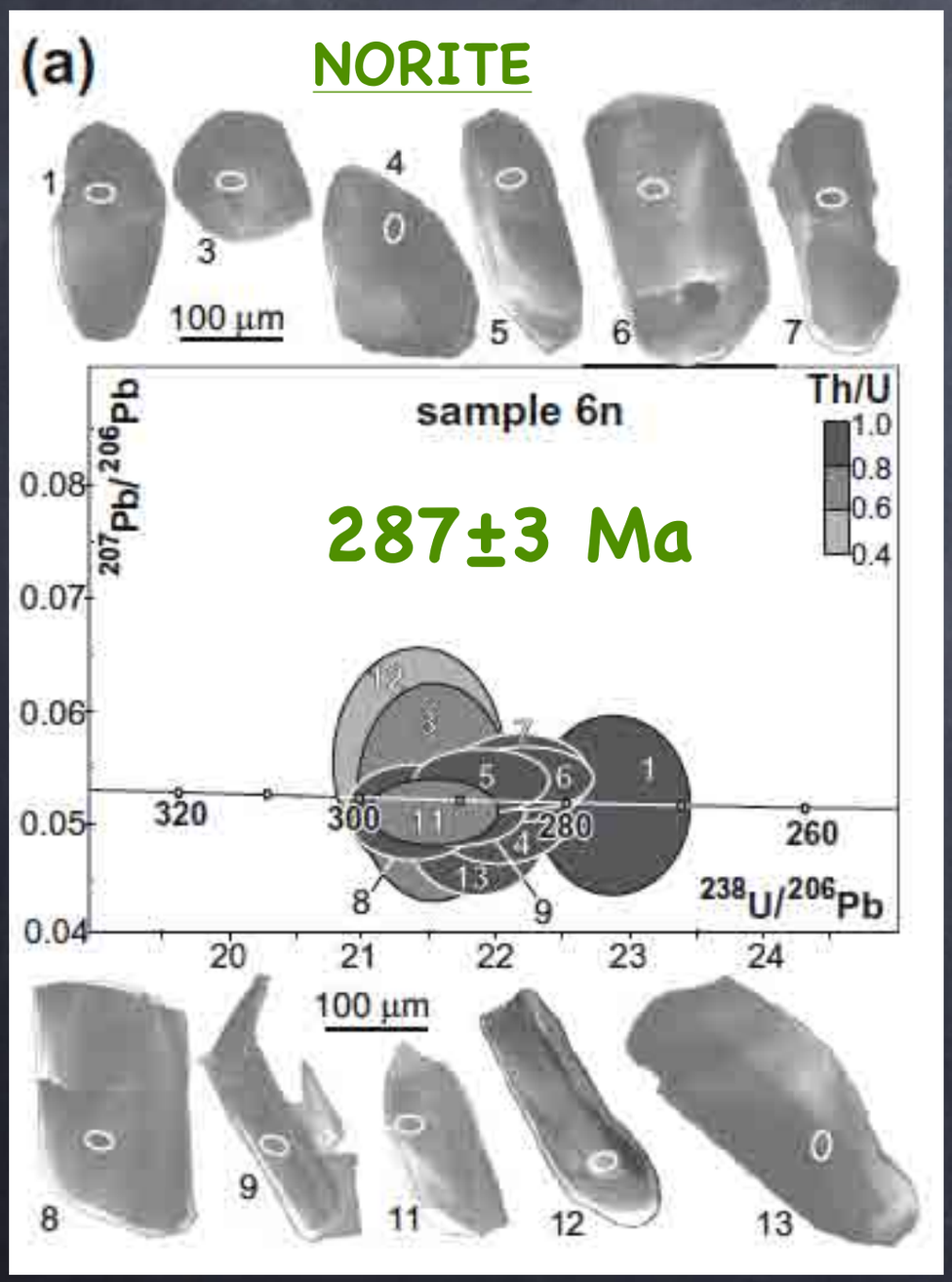


Peressini et al. 2007

IVZ lower crustal magmatism

Zircon ages from the Paragneiss-bearing belt

- Th/U typical of magmatic zircon
  - narrow age distribution



Peressini et al. 2007

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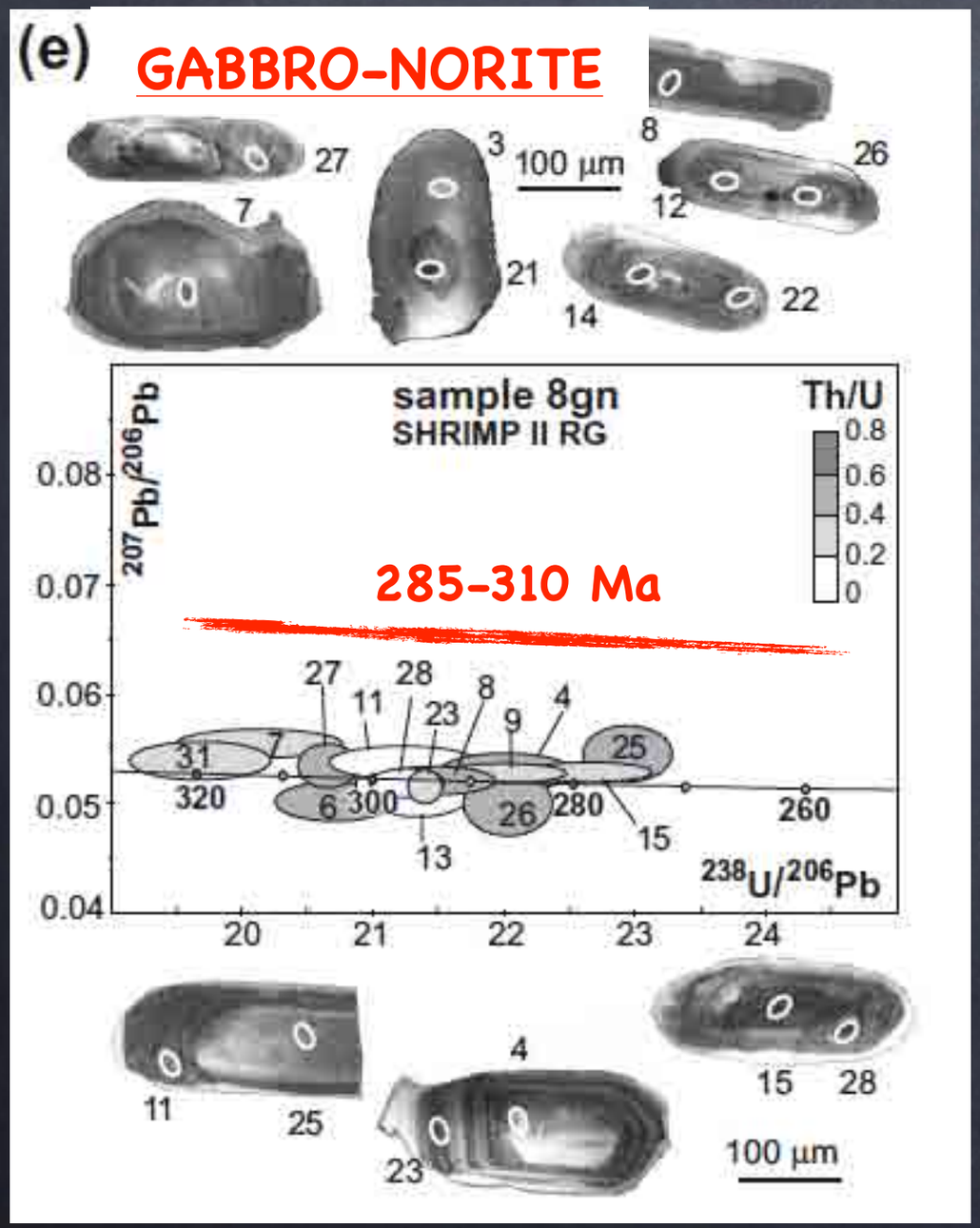
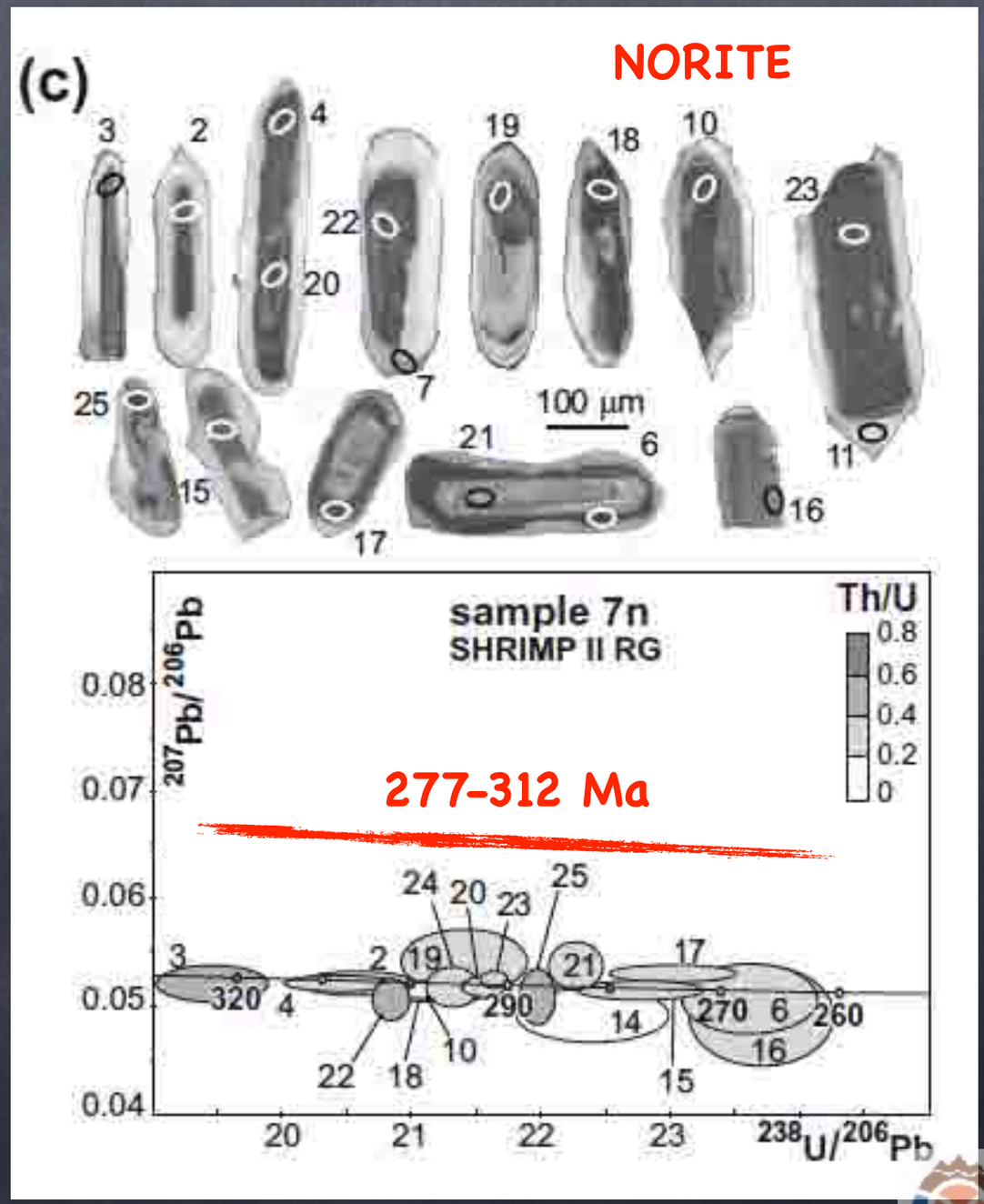
IVZ lower crustal magmatism

Zircon ages from the Lower Mafic complex

- lower Th/U ratios
- wide age distribution





Peressini et al. 2007

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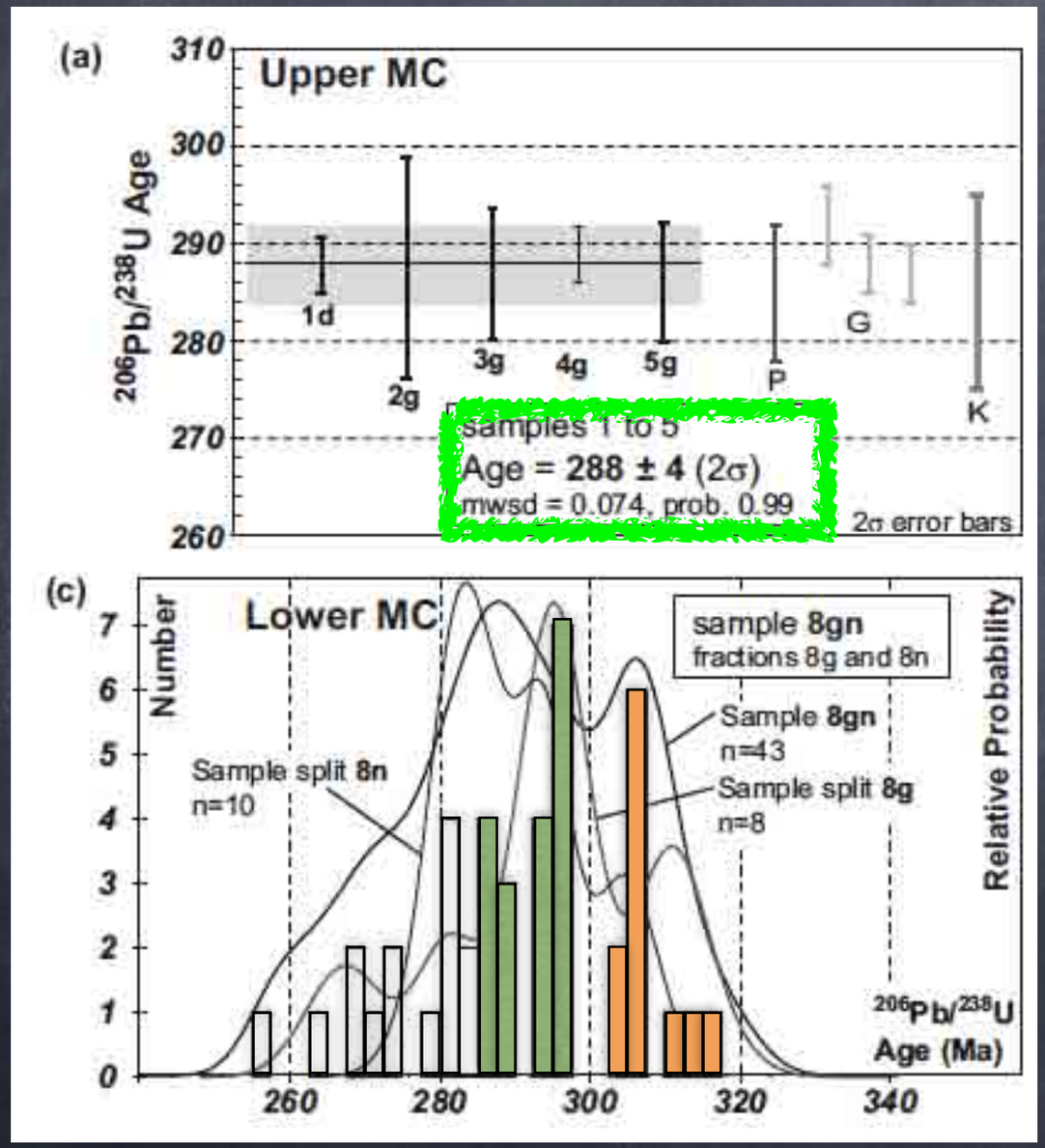
IVZ lower crustal magmatism

duration of lower crustal magmatism



UMC

LMC

PBB

intrusion of mantle-derived magma culminated by about 288 Ma

Peressini et al. 2007

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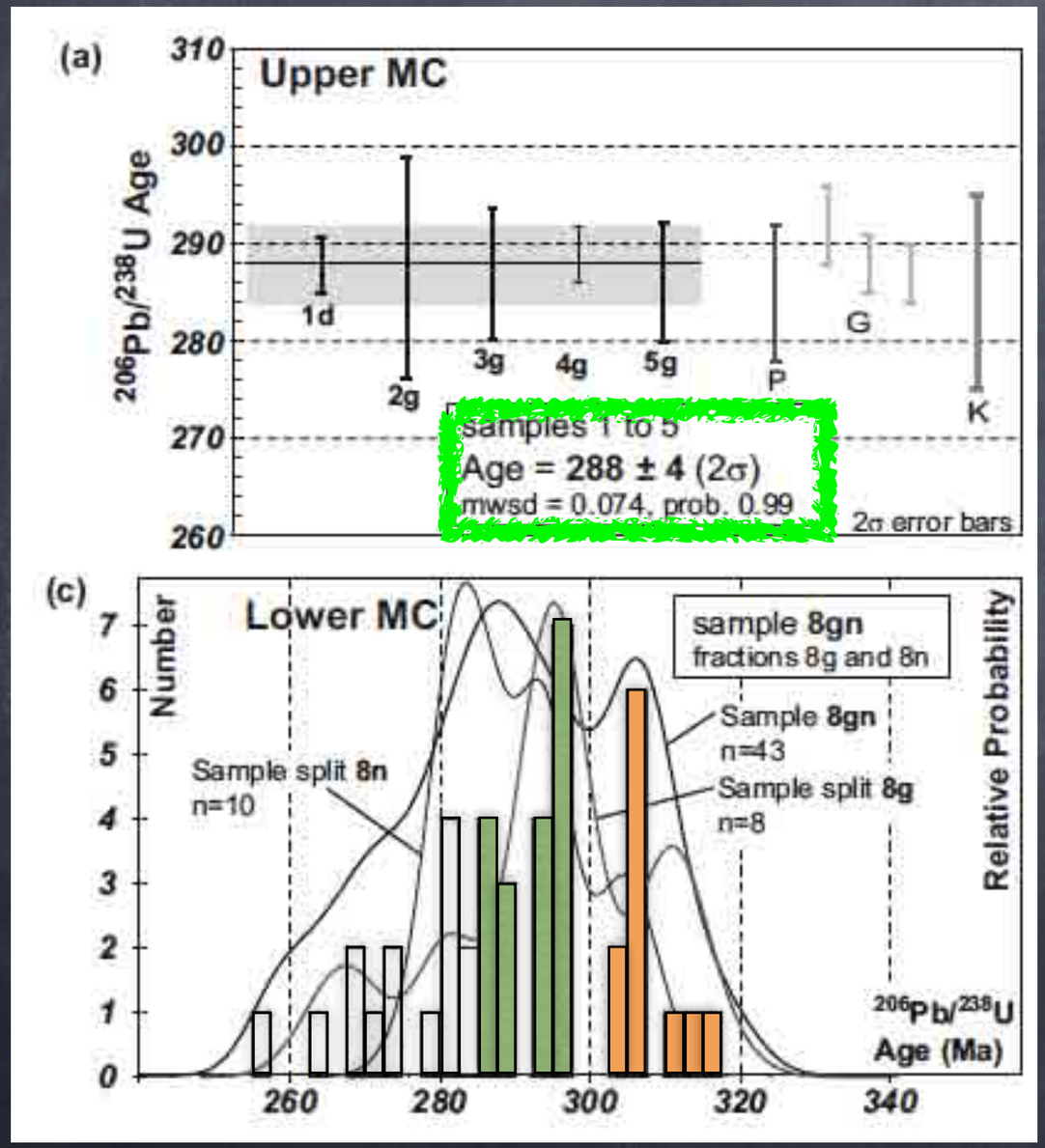
IVZ lower crustal magmatism

UMC

LMC

PBB

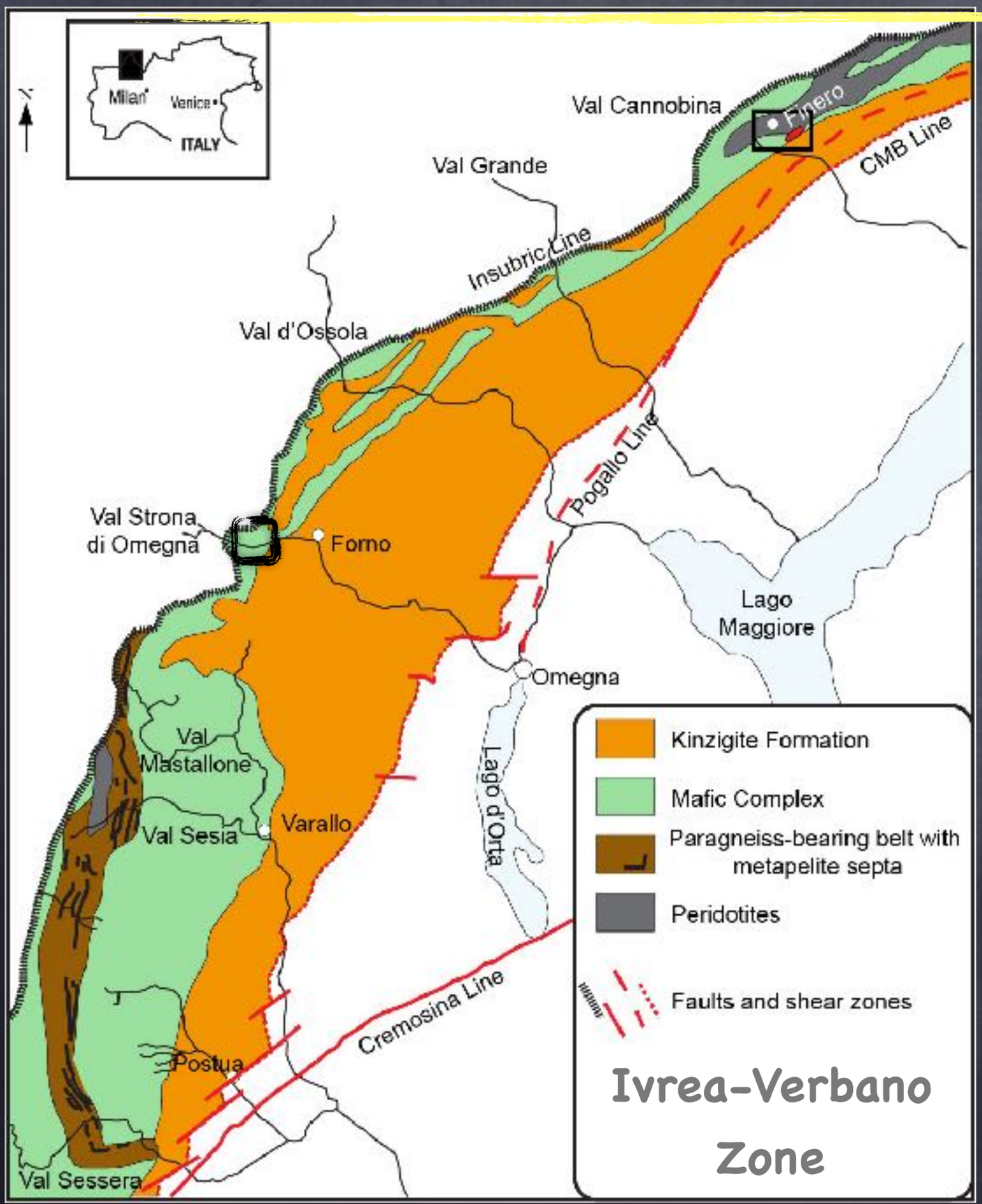


intrusion of mantle-derived magma culminated by about 288 Ma

about 310 Ma:
- inheritance from surrounding high-grade rocks and/or
- injections of dykes and sills during the onset of magmatism

Peressini et al. 2007

IVZ lower crustal magmatism



The La Balma - Monte Capio intrusion

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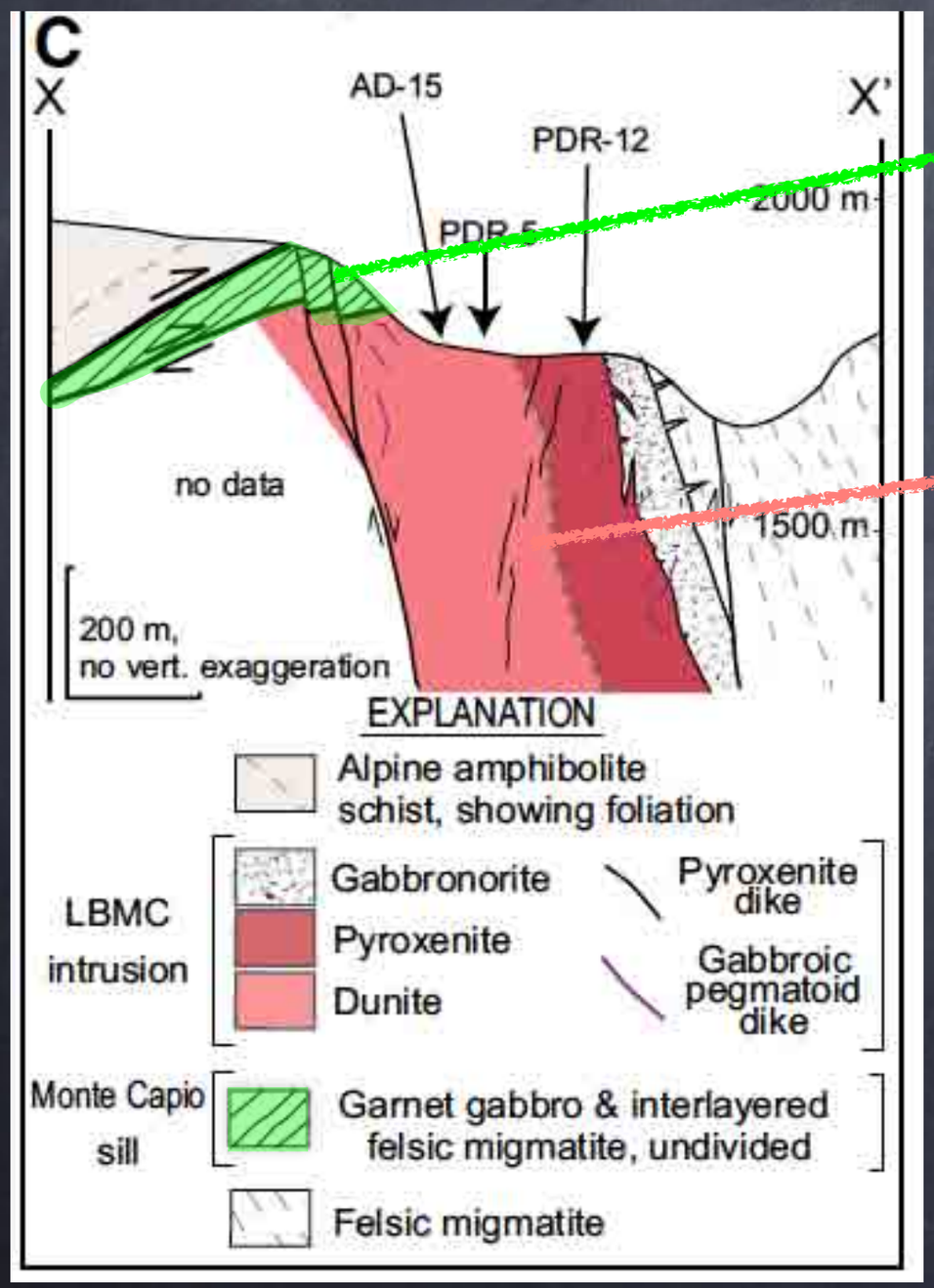
IVZ lower crustal magmatism

The La Balma - Monte Capio intrusion



(Denyszyn et al., 2018)

1) The Monte Capio Sill
(Klötzli et al., 2014)

2) La Balma intrusion
(Denyszyn et al., 2018)

IVZ lower crustal magmatism

Monte Capio sill: Amph-gabbro (±grt)

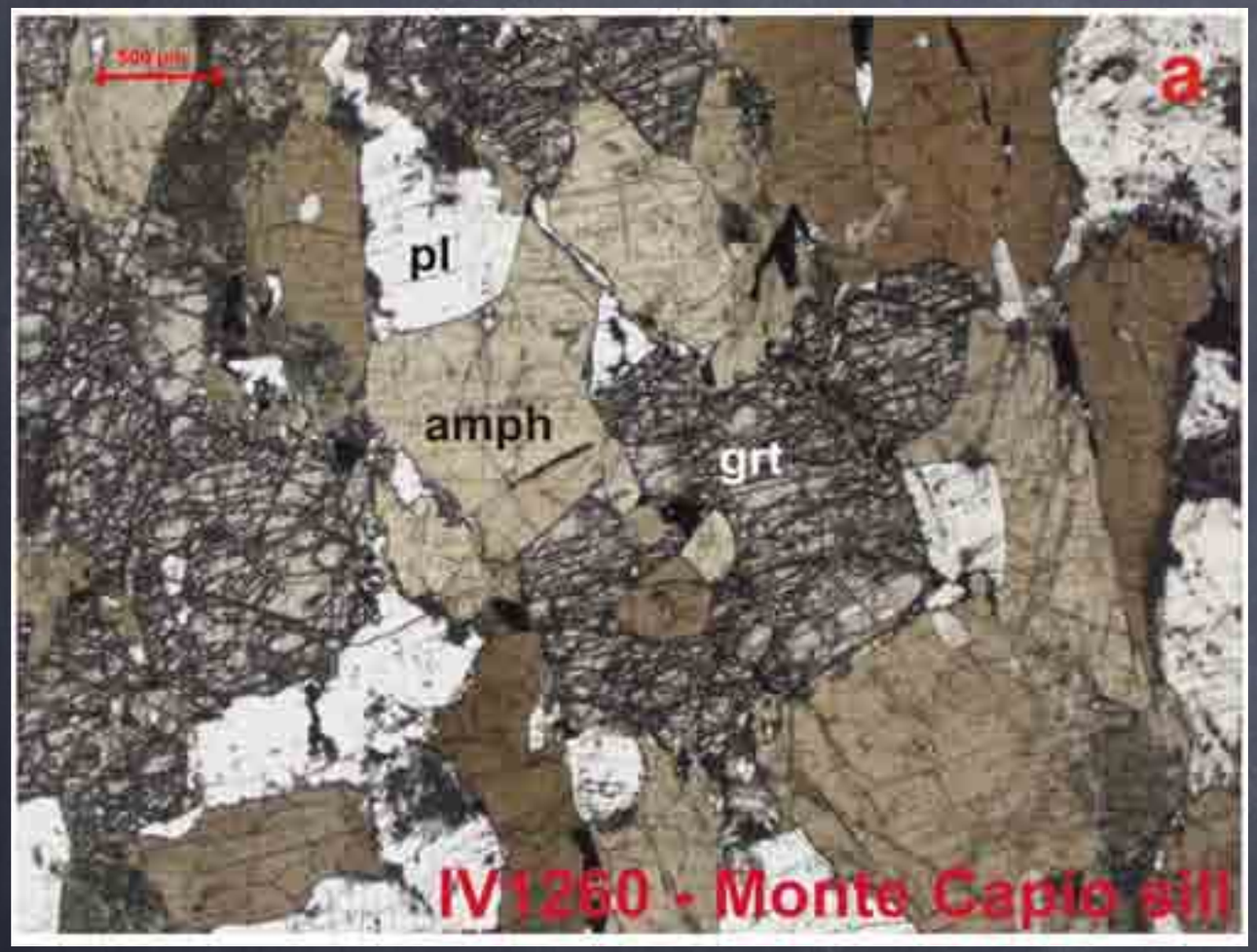


Fig. 3. CL images of zircon crystals from sample IV 1260 of the Monte Capio sill, reporting $^{206}Pb/^{238}U$ ages (±2 standard deviations). Color coding: blue: spots with Th/U < 0.12; green: spots with Th/U > 0.12; black: ages not used for mean age calculation because they are strongly discordant or interpreted as stemming from inheritance. Scale bars = 100 μm.

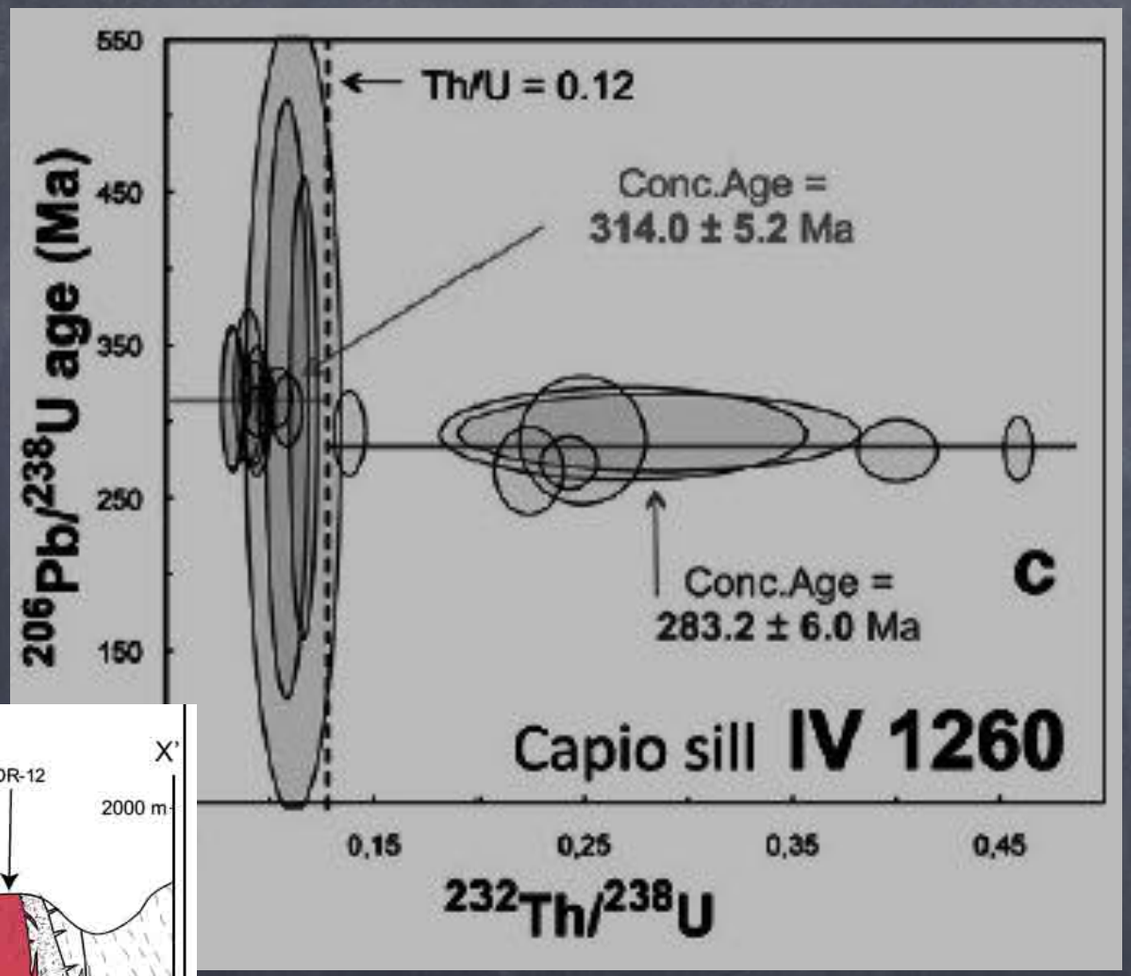
Th/U>0.12 younger

Th/U<0.12 Older

Klötzli et al., 2014

IVZ lower crustal magmatism

Monte Capio sill: Amph-gabbro (±grt)



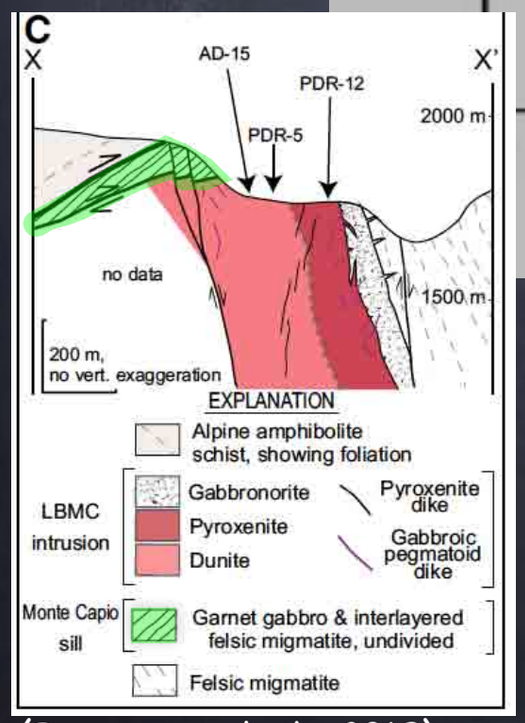
- Oscillatory zoning
- Th/U <0.12

314 Ma = Crystallization

283 Ma = artifact of recrystallization

- NO oscillatory zoning
- Th/U >>0.12

Klötzli et al., 2014



(Denyszyn et al., 2018)

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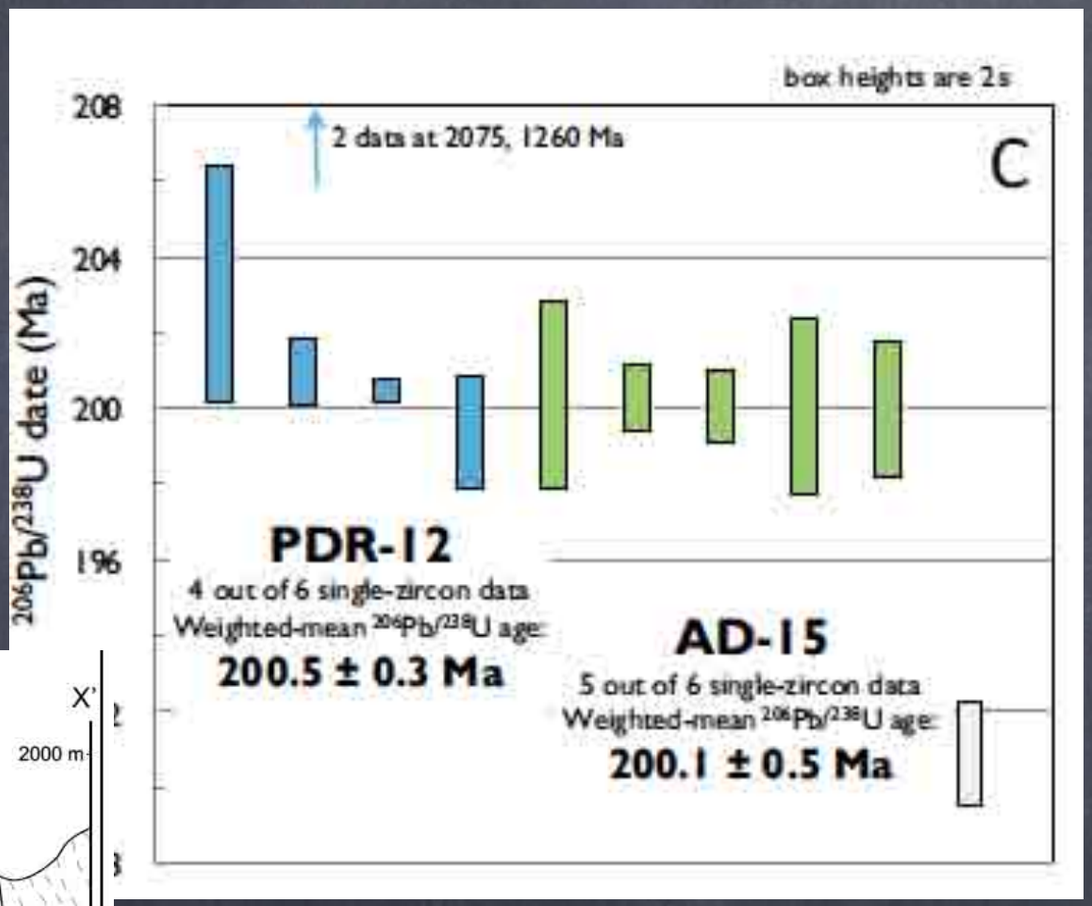
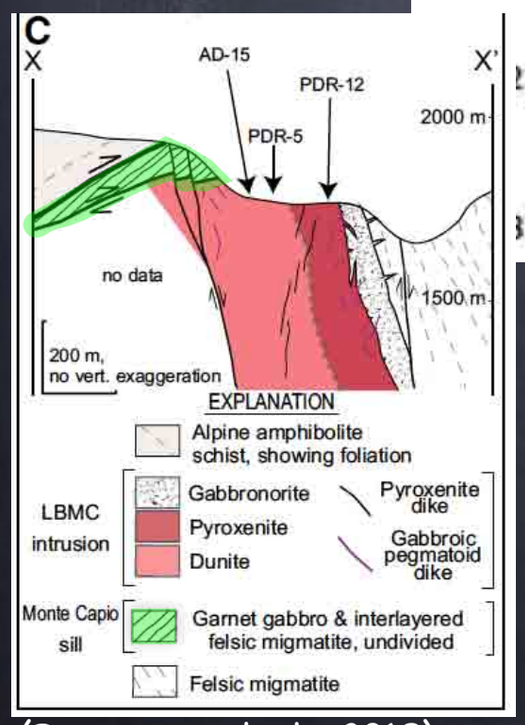
IVZ lower crustal magmatism

La Balma ultramafic rocks





(Denyszyn et al., 2018)

CA-ID-TIMS zircon ages of about 200 Ma

"short-lived mafic magmatism in the IVZ"

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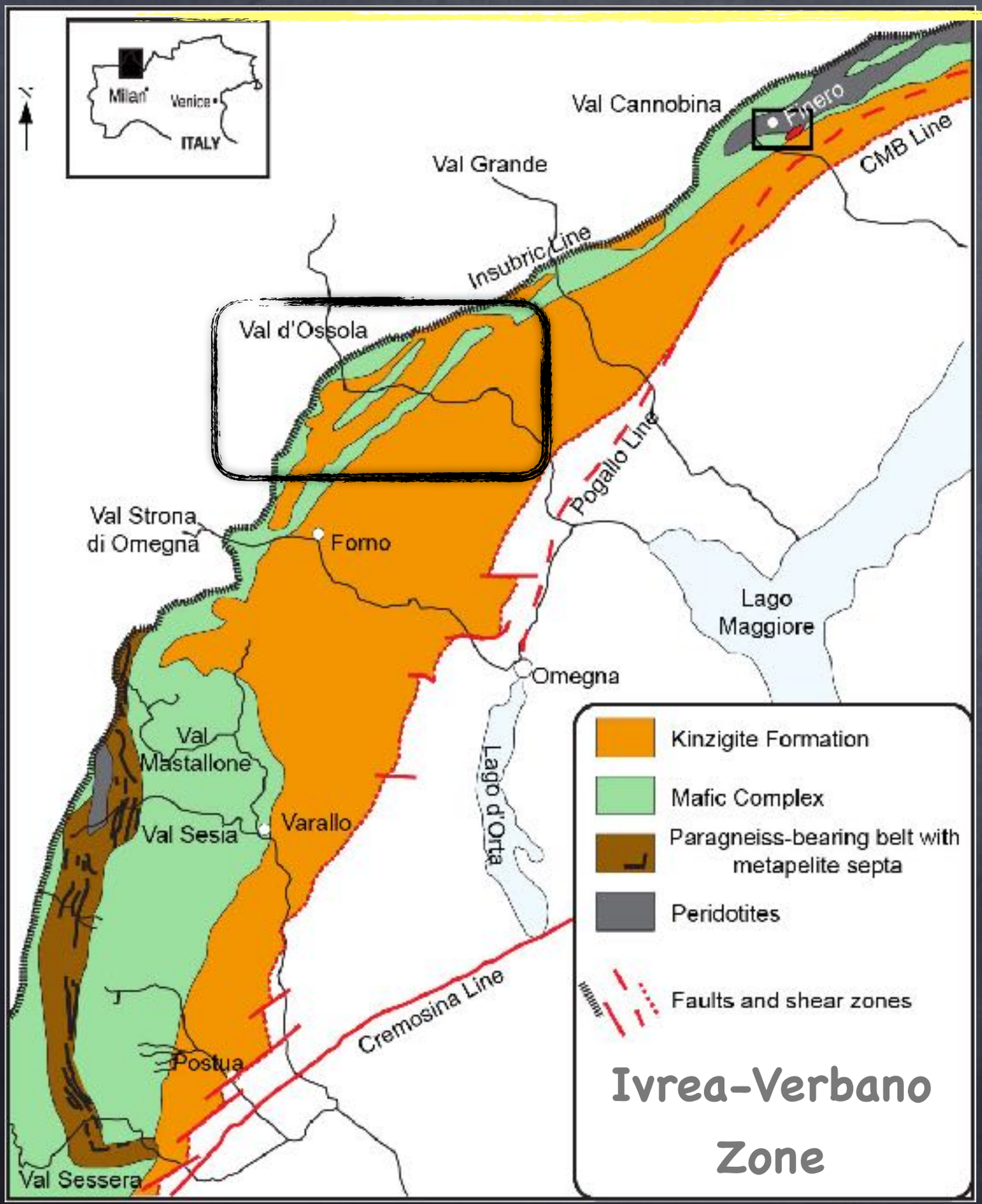
IVZ lower crustal magmatism



The "Loro mafic intrusion"

(Boriani 1966)

The "Anzola gabbro"

(Brodie et al., 1989)

No "robust" U-Pb data available from mafic intrusives!!

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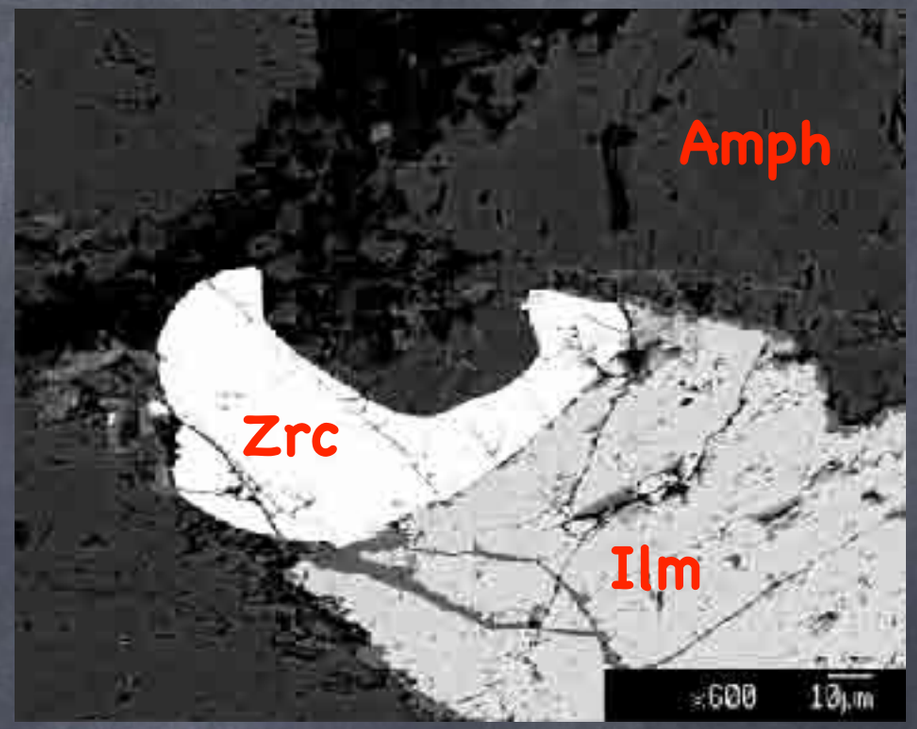
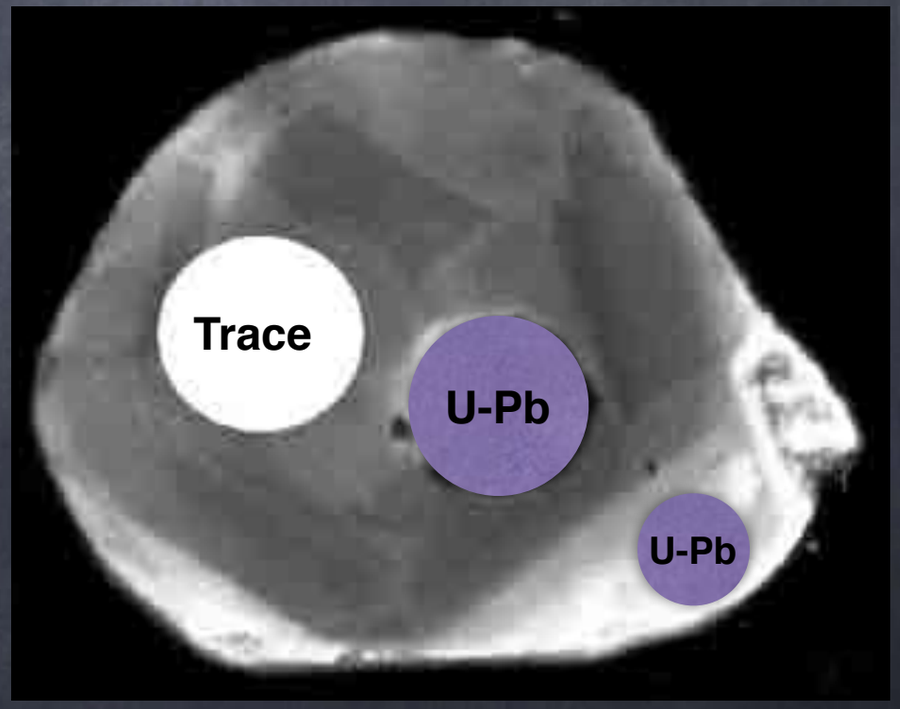
IVZ lower crustal magmatism

The "Loro mafic intrusion"





In collaboration with Tiepolo M. (University of Milan) and
J.L. Paquette (Laboratorie Magmas et Volcan of the University of Clermont-Ferrand)
Tesi Formoso F. (A.Y. 2016/2017)

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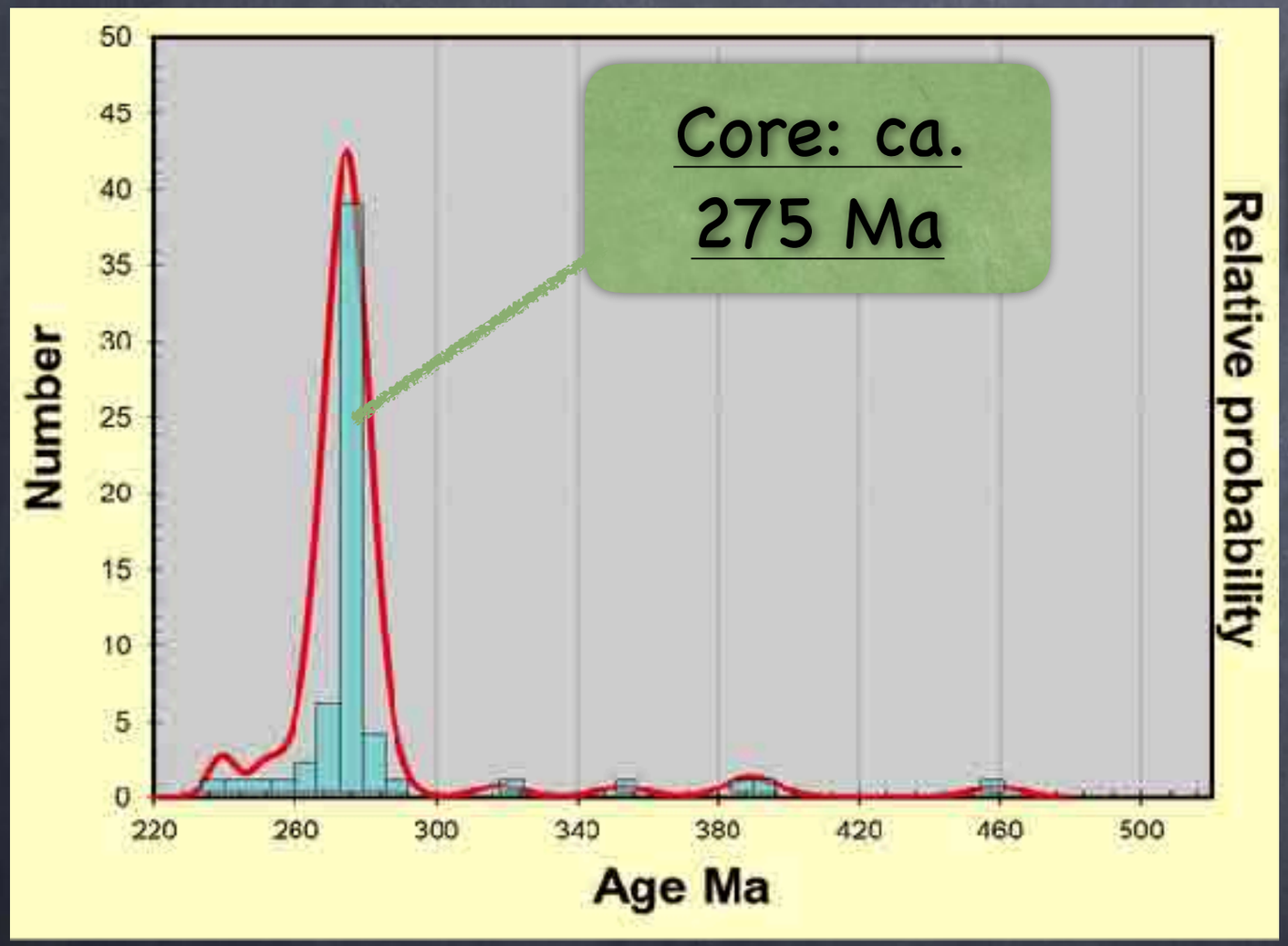
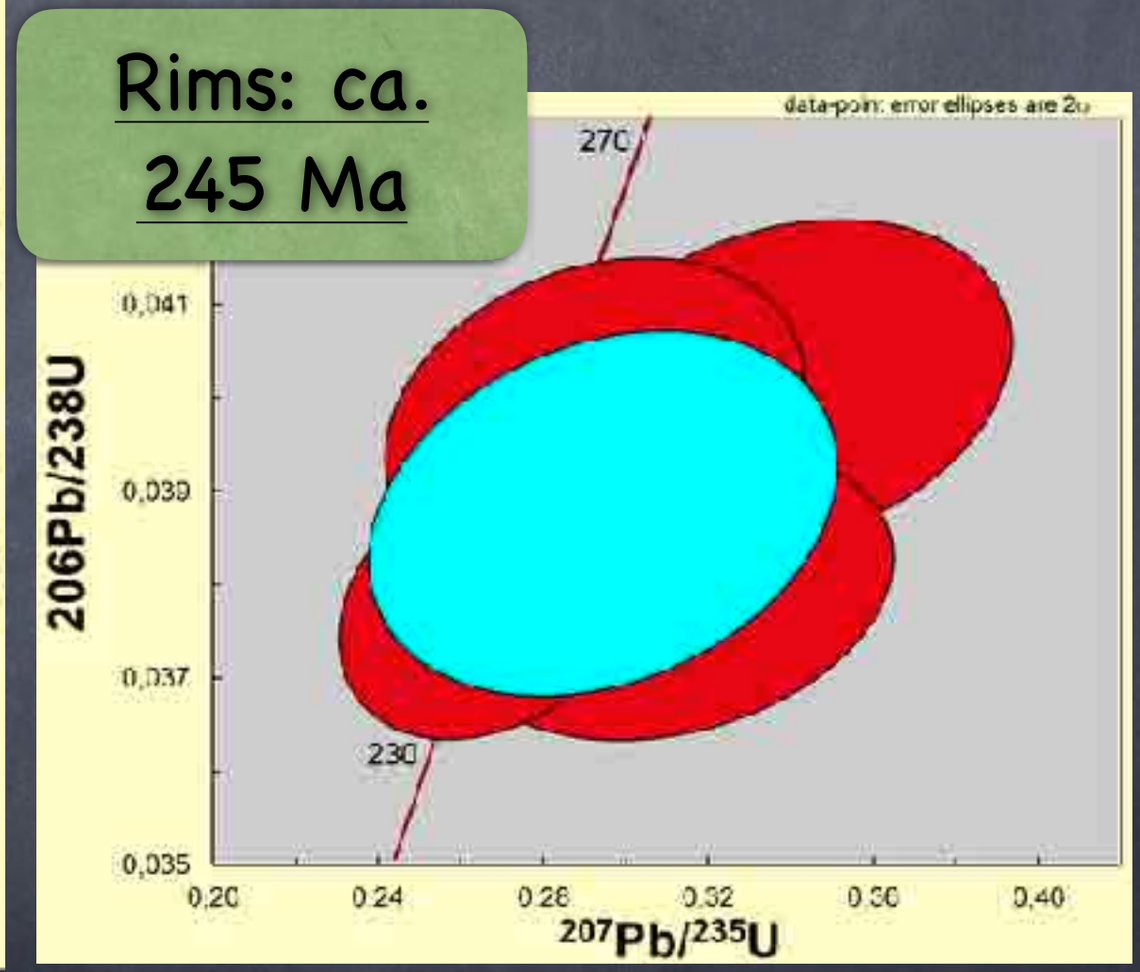
IVZ lower crustal magmatism





Crystallization age

HT metamorphism

In collaboration with Tiepolo M. (University of Milan) and
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Tesi Formoso F. (A.Y. 2016/2017)

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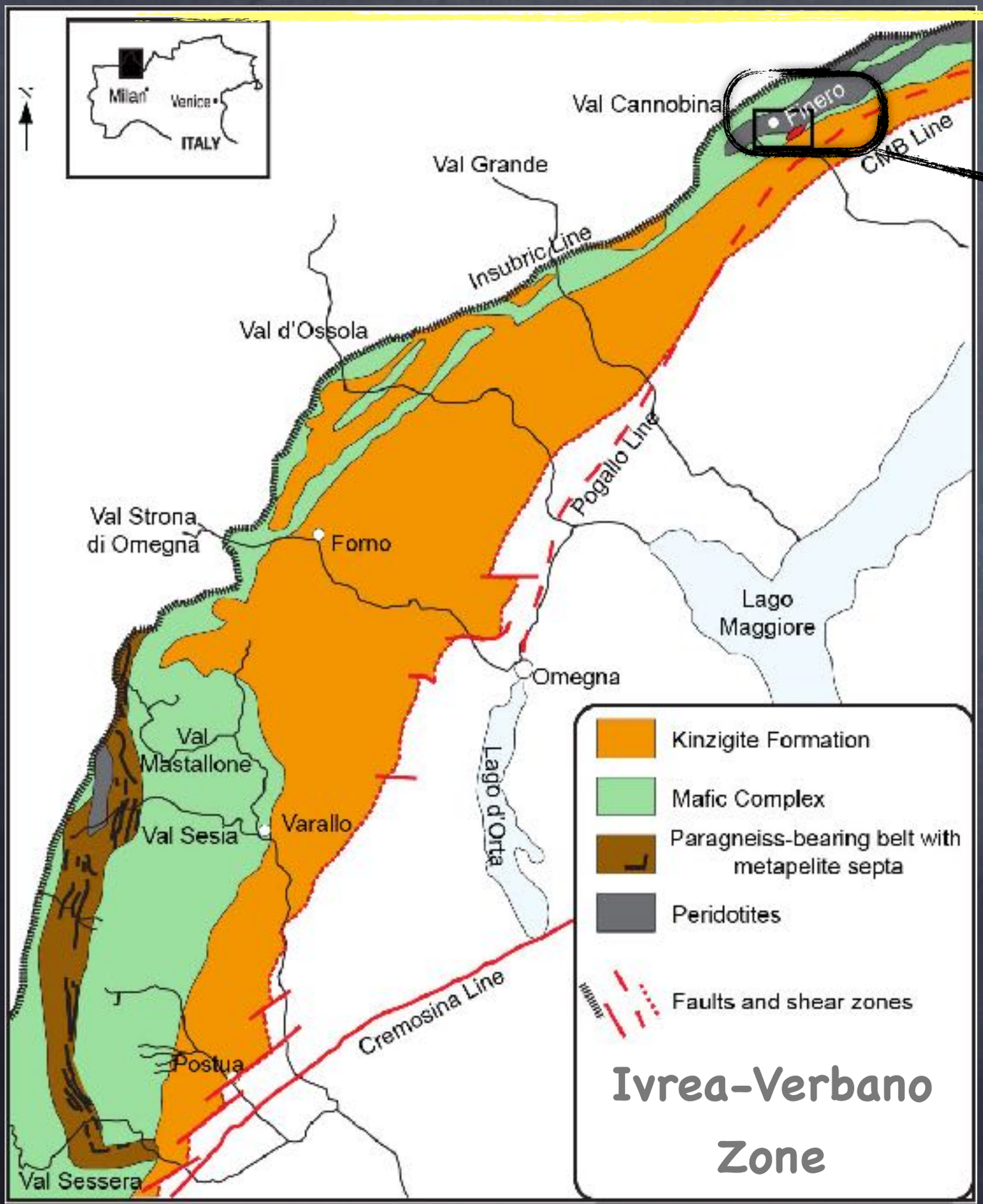
IVZ lower crustal magmatism



Finero area

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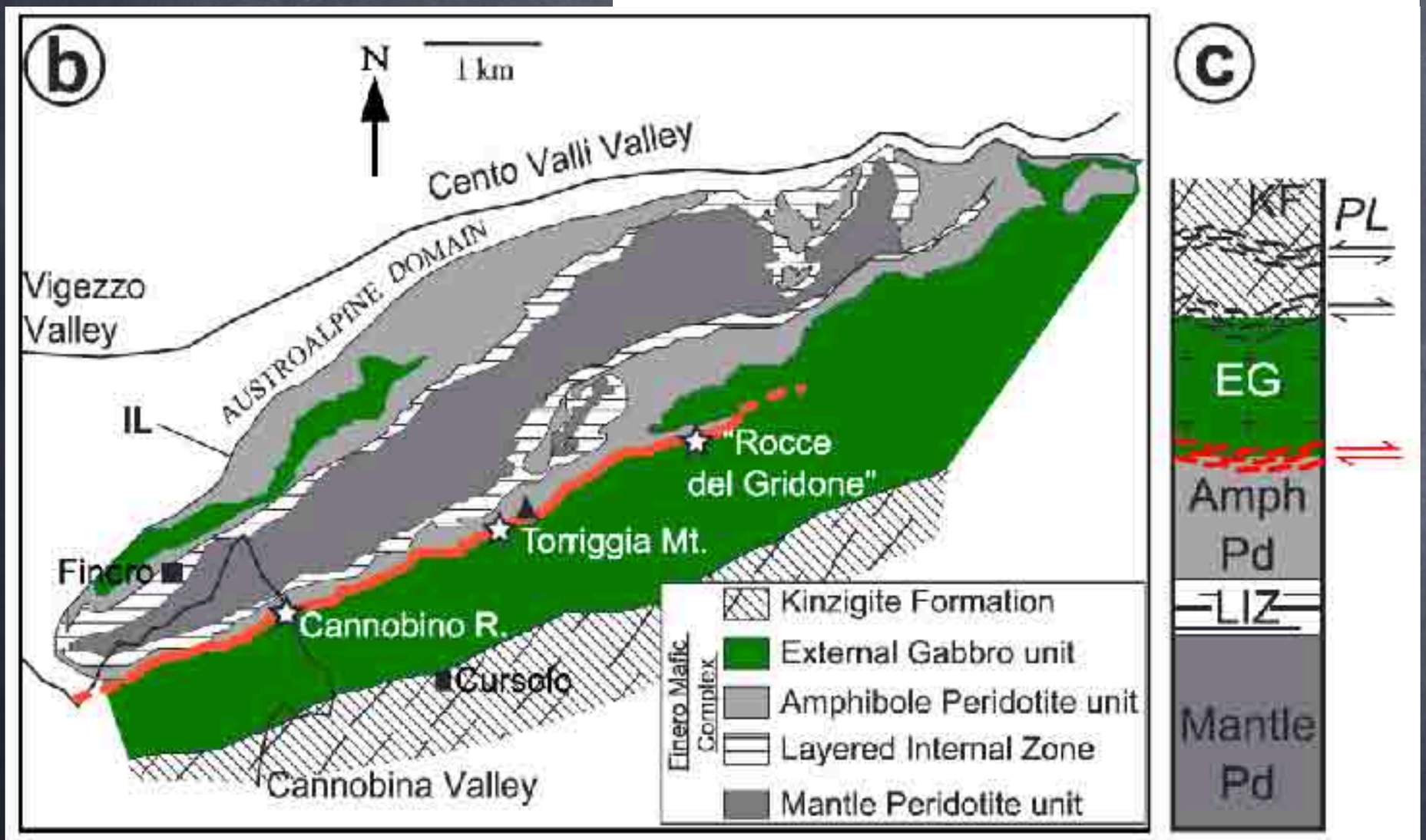
IVZ lower crustal magmatism

The External Gabbro (EG)

thickness ca. 500m



Amph-bearing gabbro and diorite (±grt)

Triassic and Permian intrusions

(Zanetti et al., 2013; Langone et al., 2017)

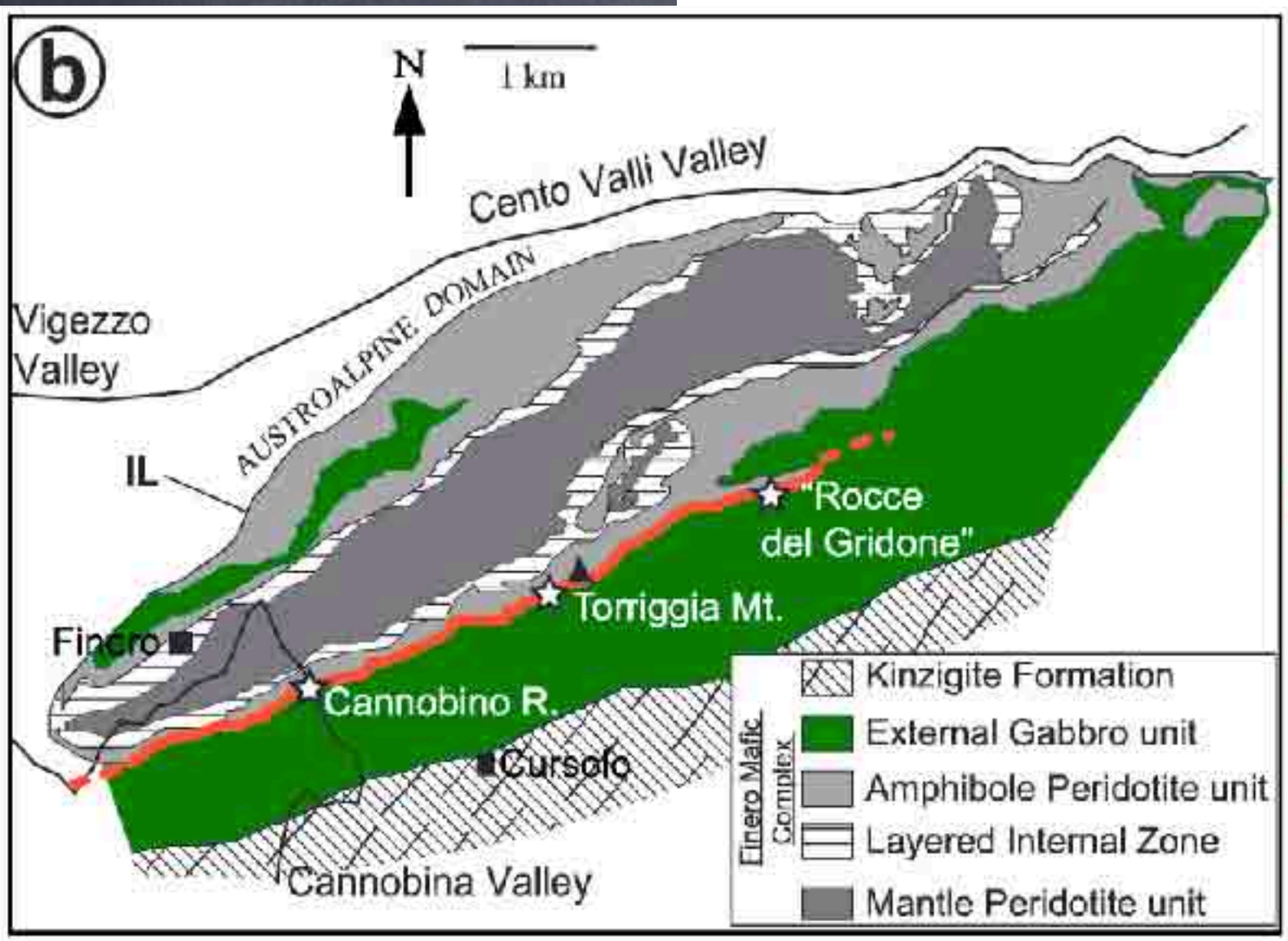
- metamorphic overprint
- ductile deformation

Langone et al., 2018

Langone Antonio

IVZ lower crustal magmatism

The External Gabbro (EG)

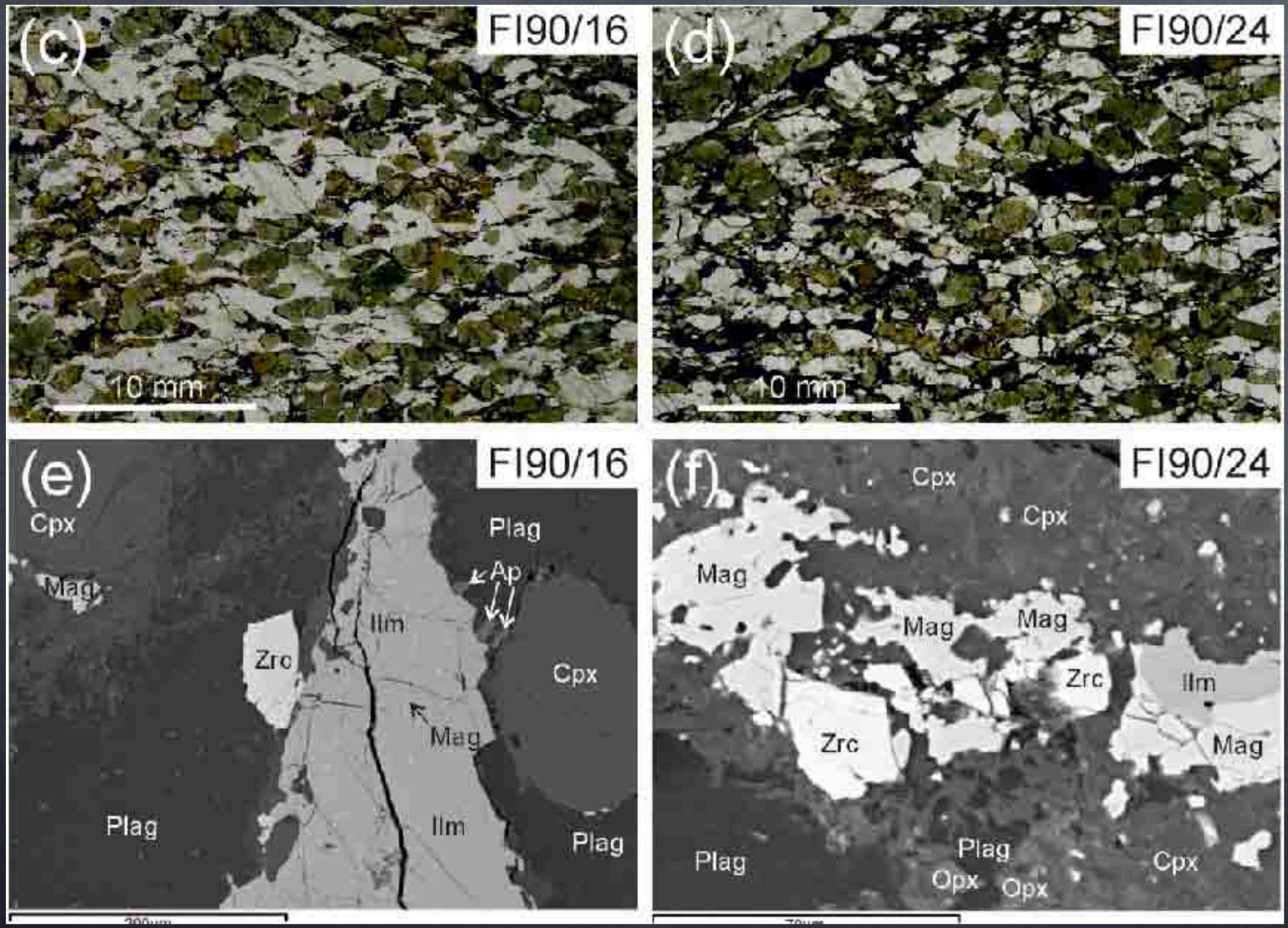


HT deformation

Langone et al., 2018

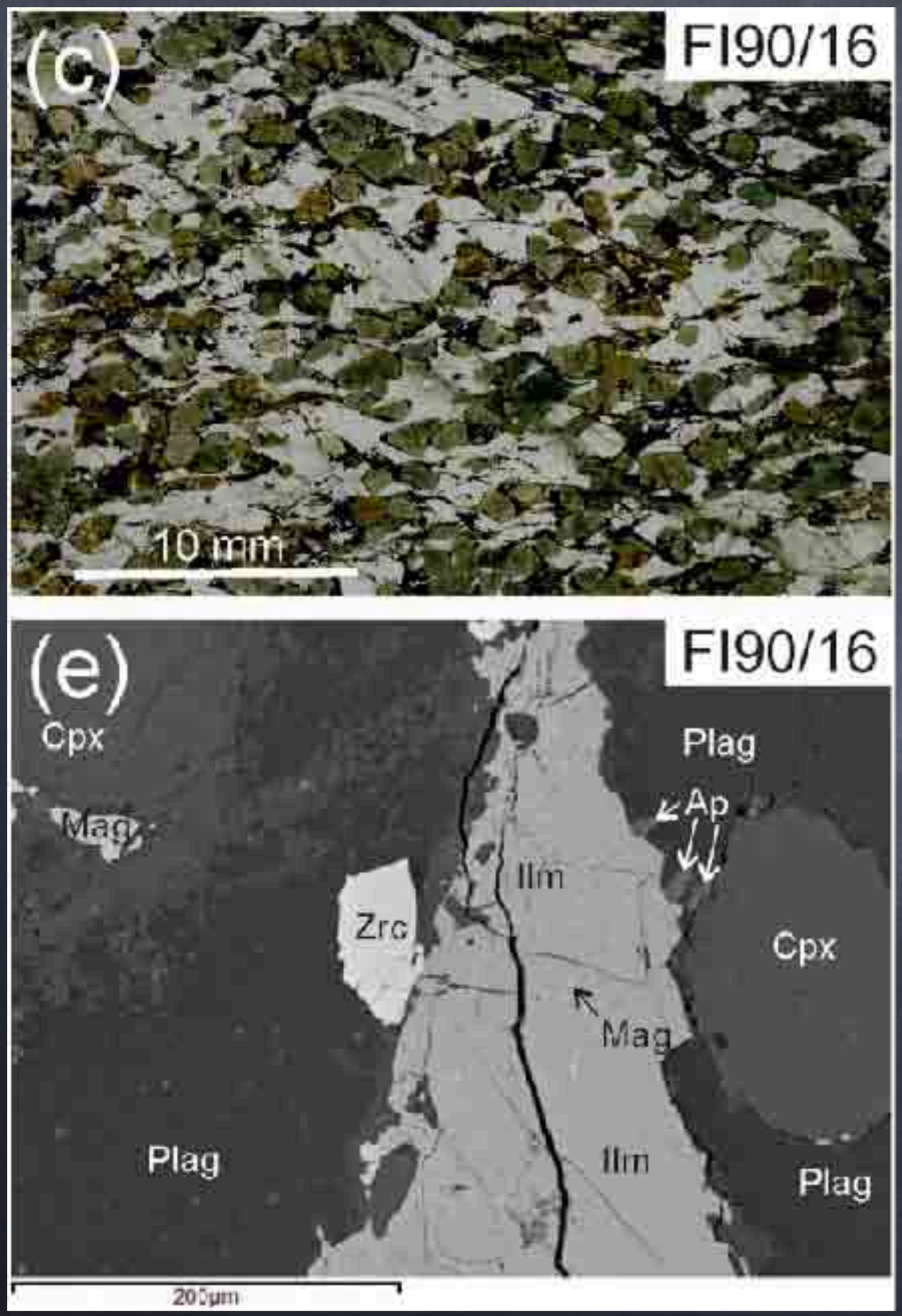
Langone Antonio

Lower crustal magmatism

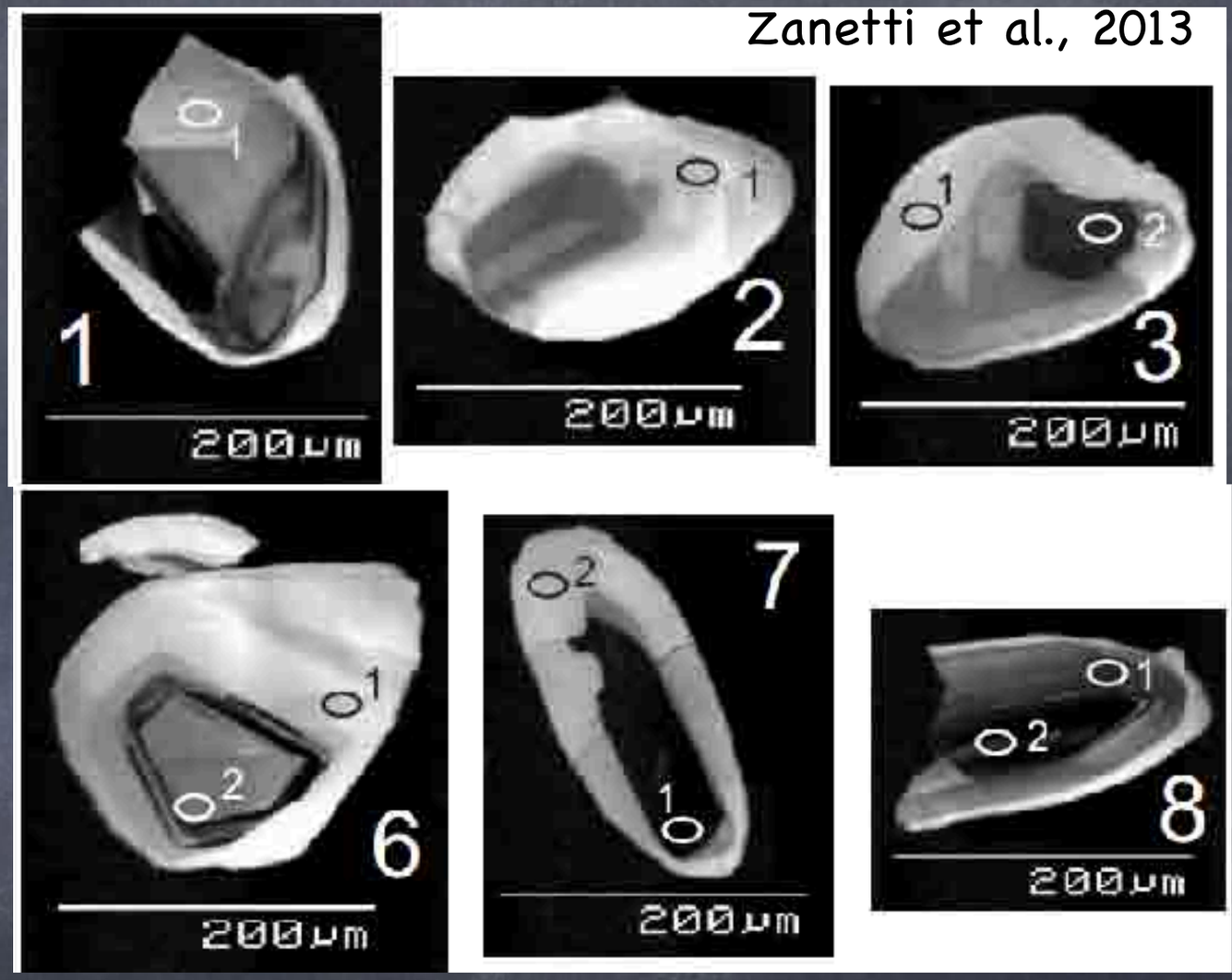


Zanetti et al., 2013

Lower crustal magmatism



Zanetti et al., 2013



- magmatic cores
- recrystallised rims

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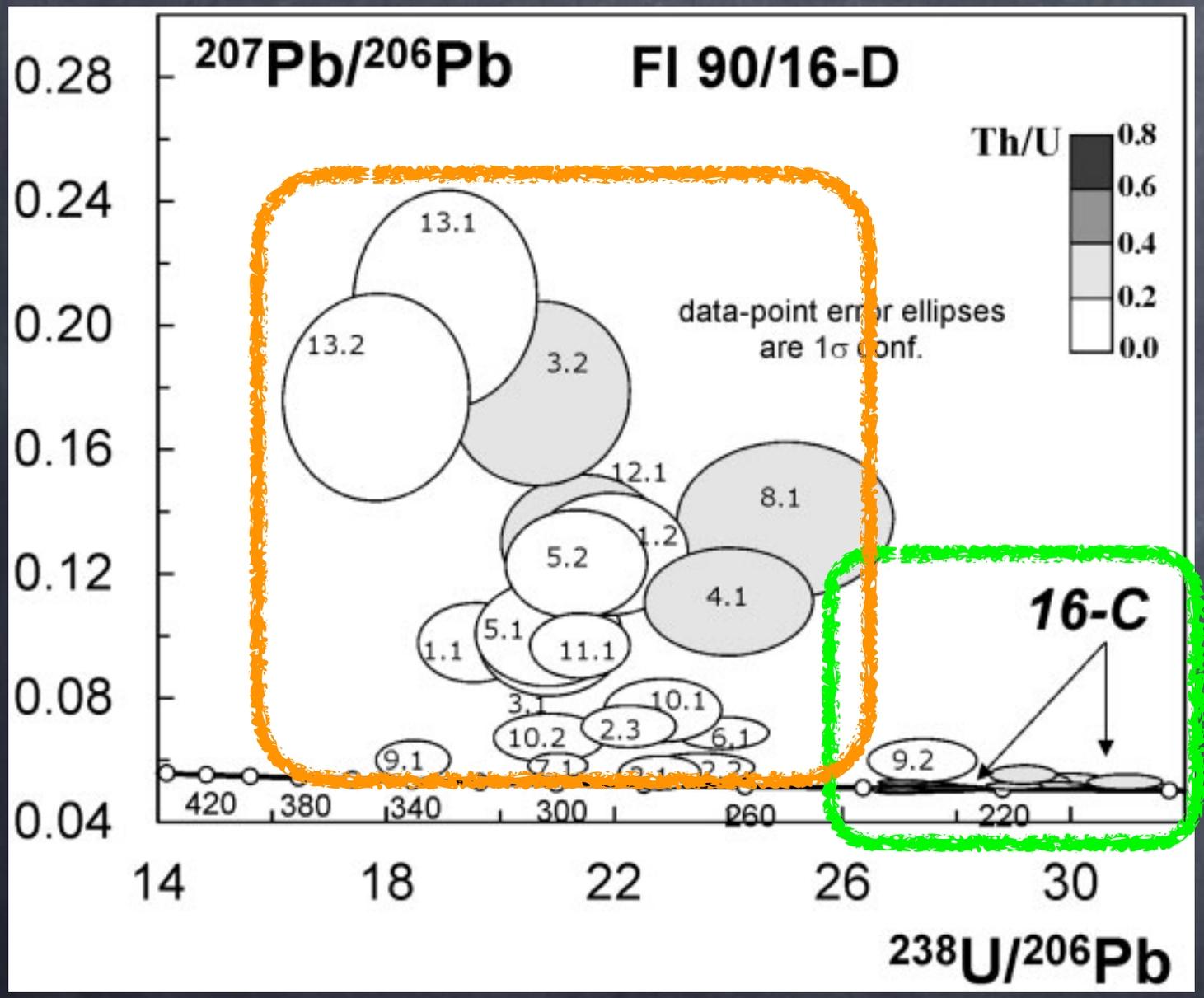
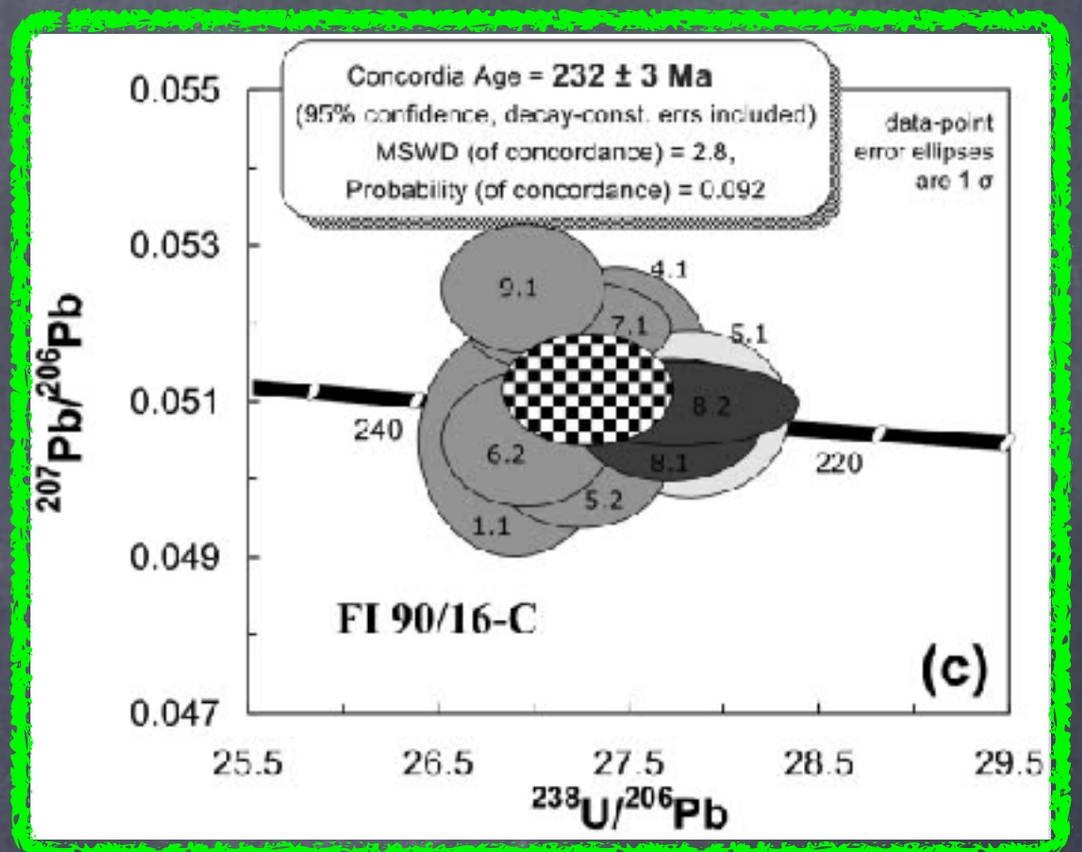
Lower crustal magmatism





Interpretation:

- Permian-Carboniferous inheritance
- Triassic crystallisation

Zanetti et al., 2013

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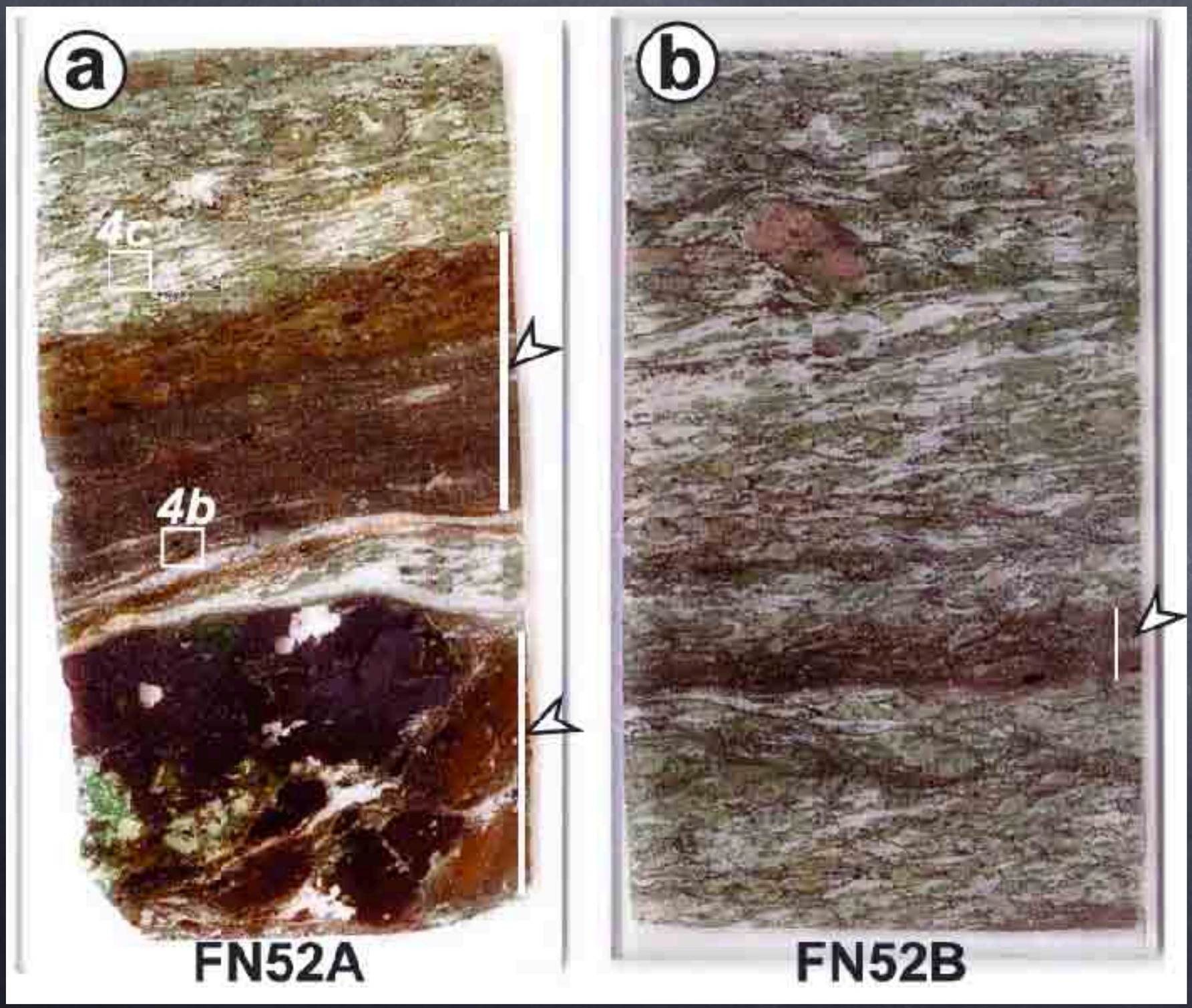
IVZ lower crustal magmatism



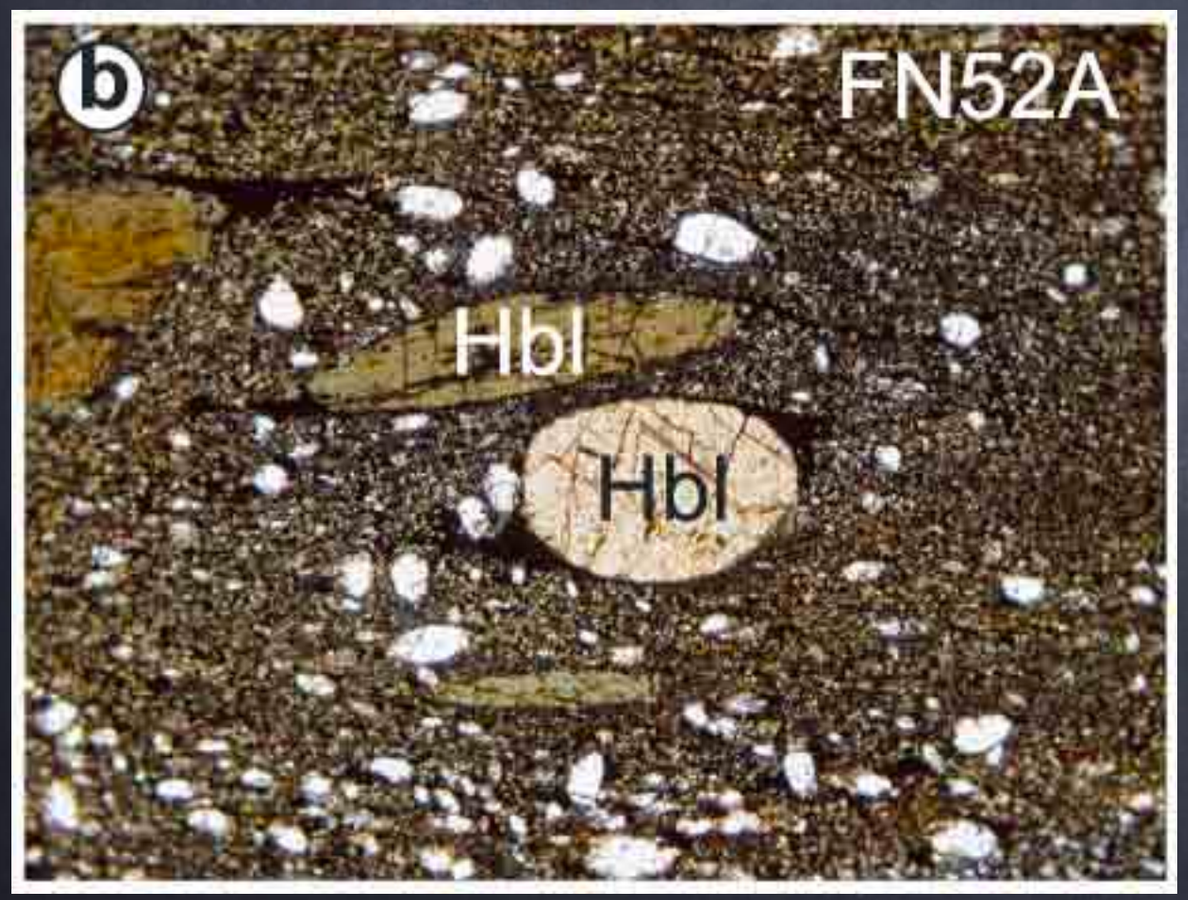
zircon dating of mylonites-ultramylonites

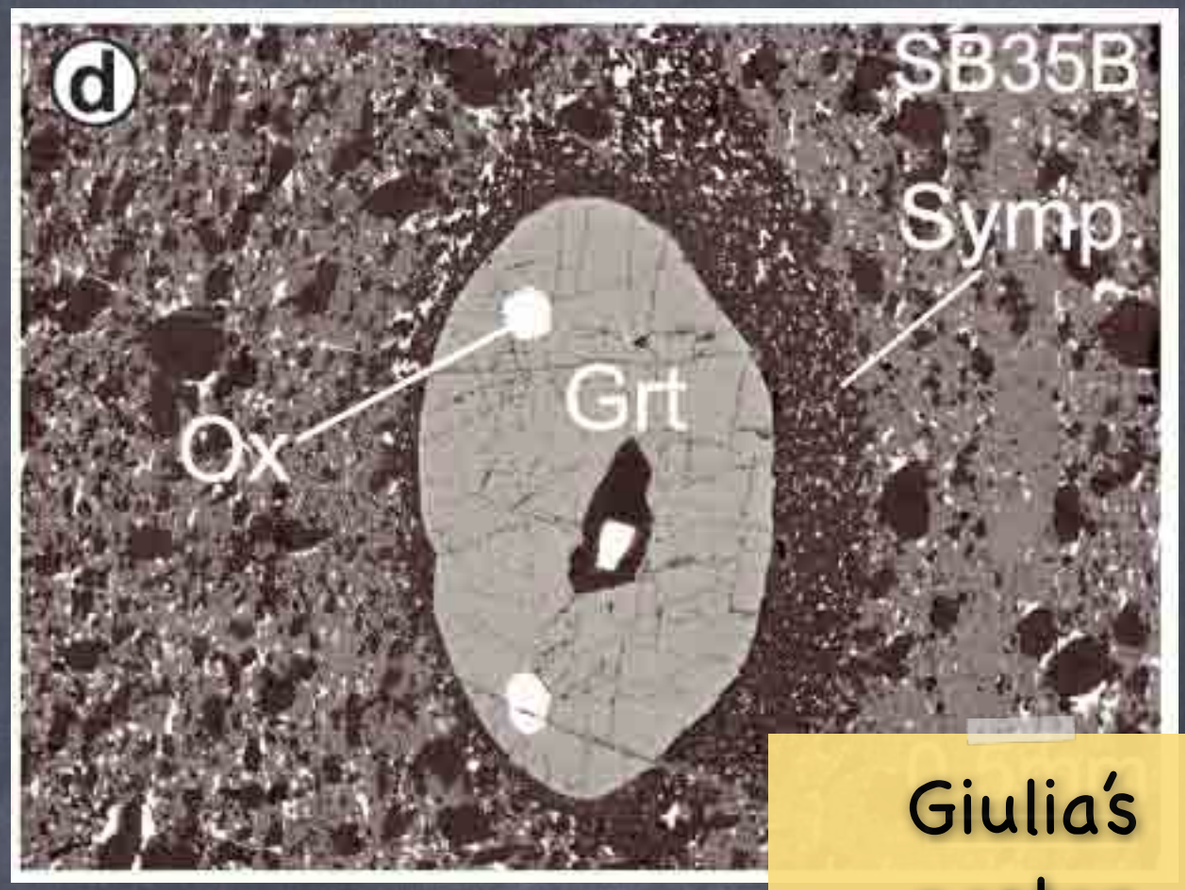
Langone et al., 2018

Langone Antonio

IVZ lower crustal magmatism

HT deformation features!





Giulia's poster

reactions involving: garnet, hornblende and ilmenite!

Langone et al., 2018 see also: Kenkmann and Dresen 2000; Degli Alessandrini et al., 2016; Degli alessandrini 2018.

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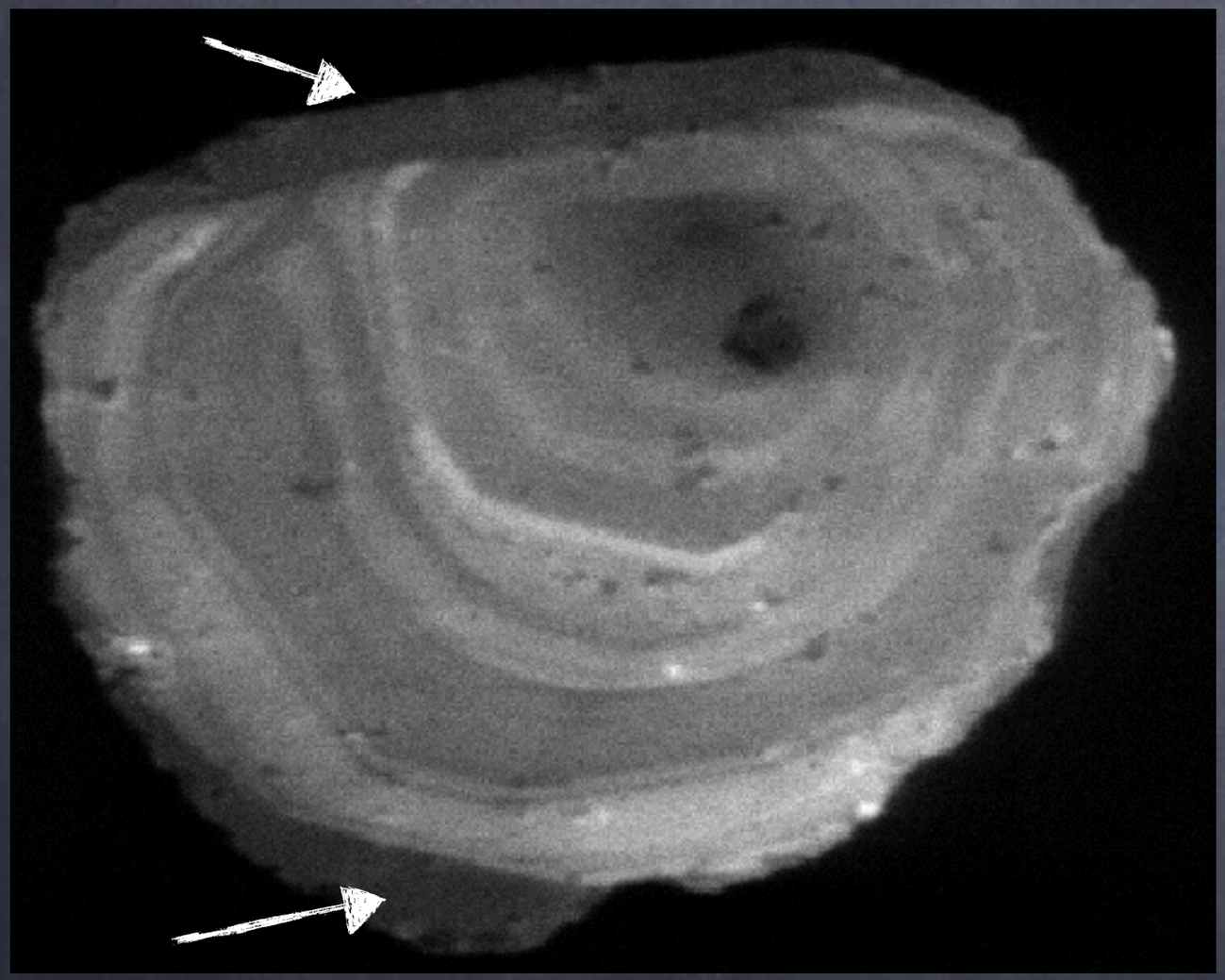
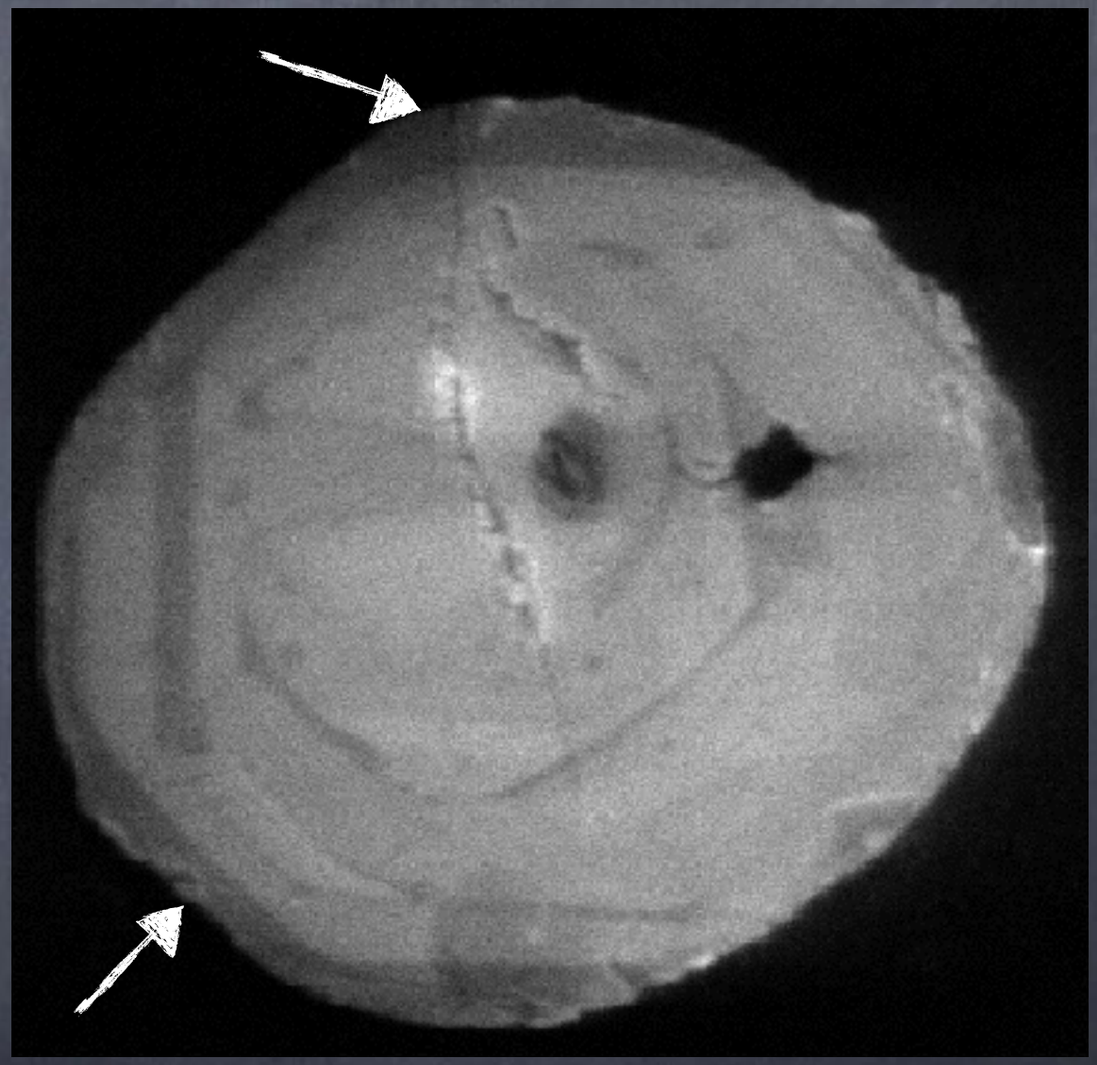
IVZ lower crustal magmatism



100um



50um

Langone et al., 2018

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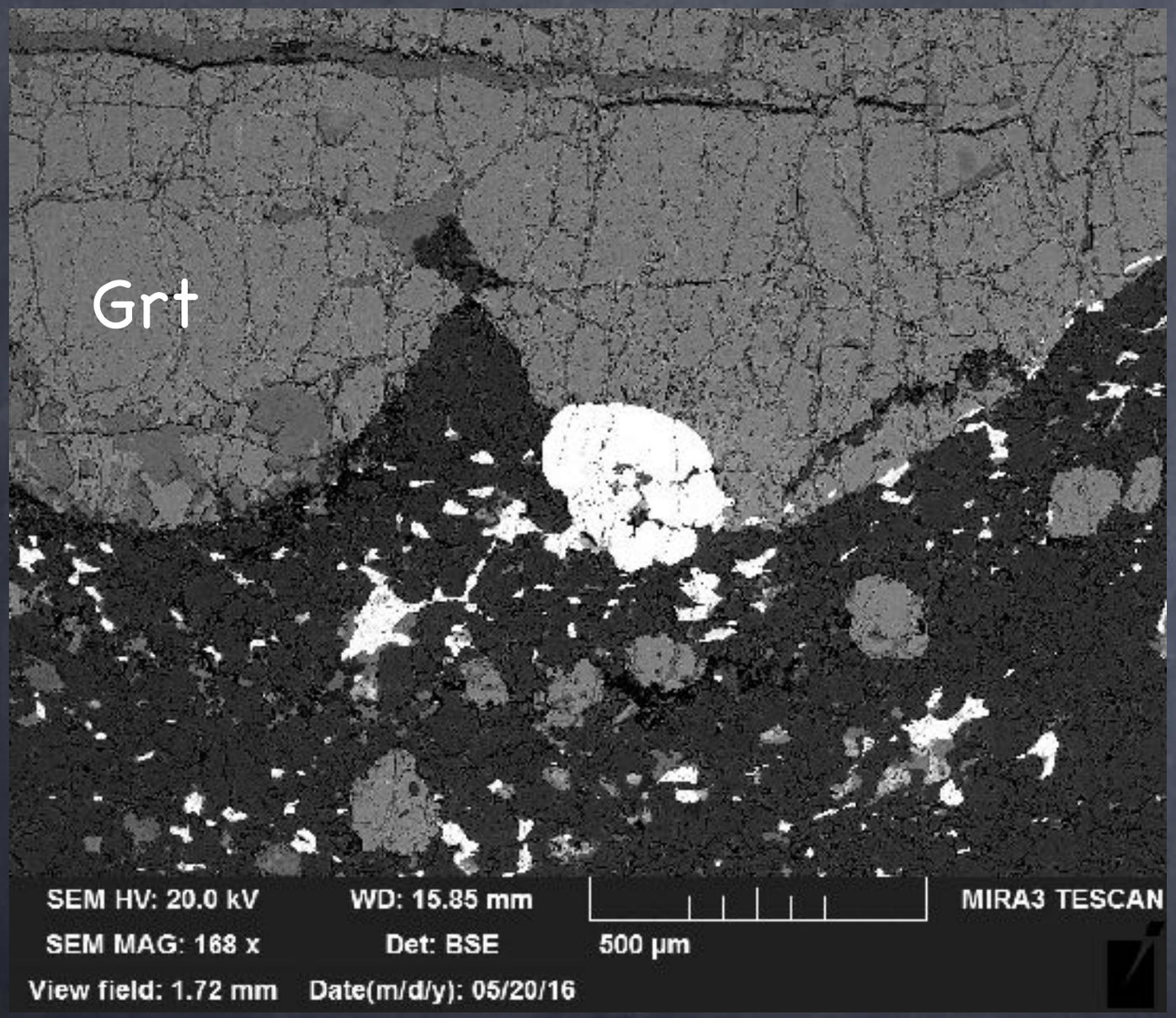
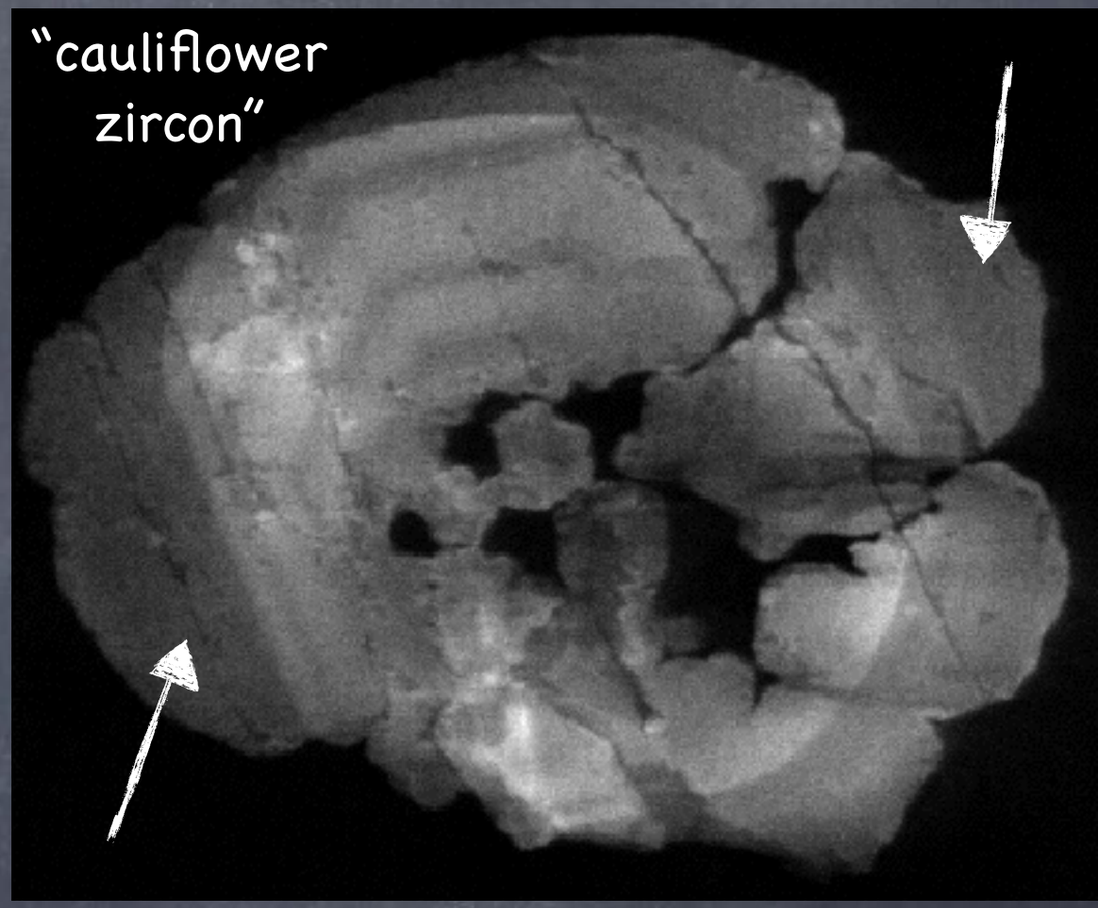
IVZ lower crustal magmatism

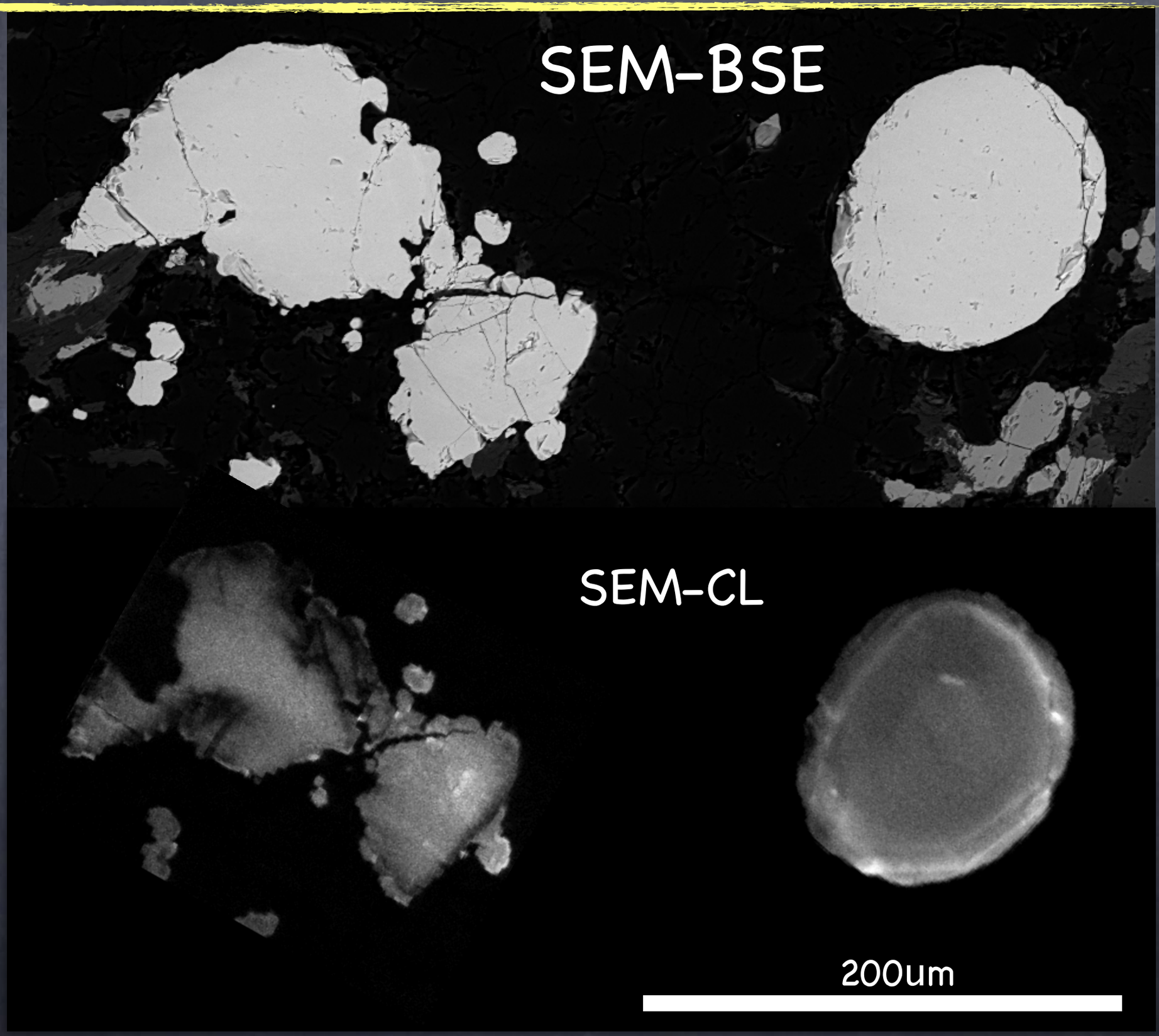




Langone et al., 2018

Langone Antonio

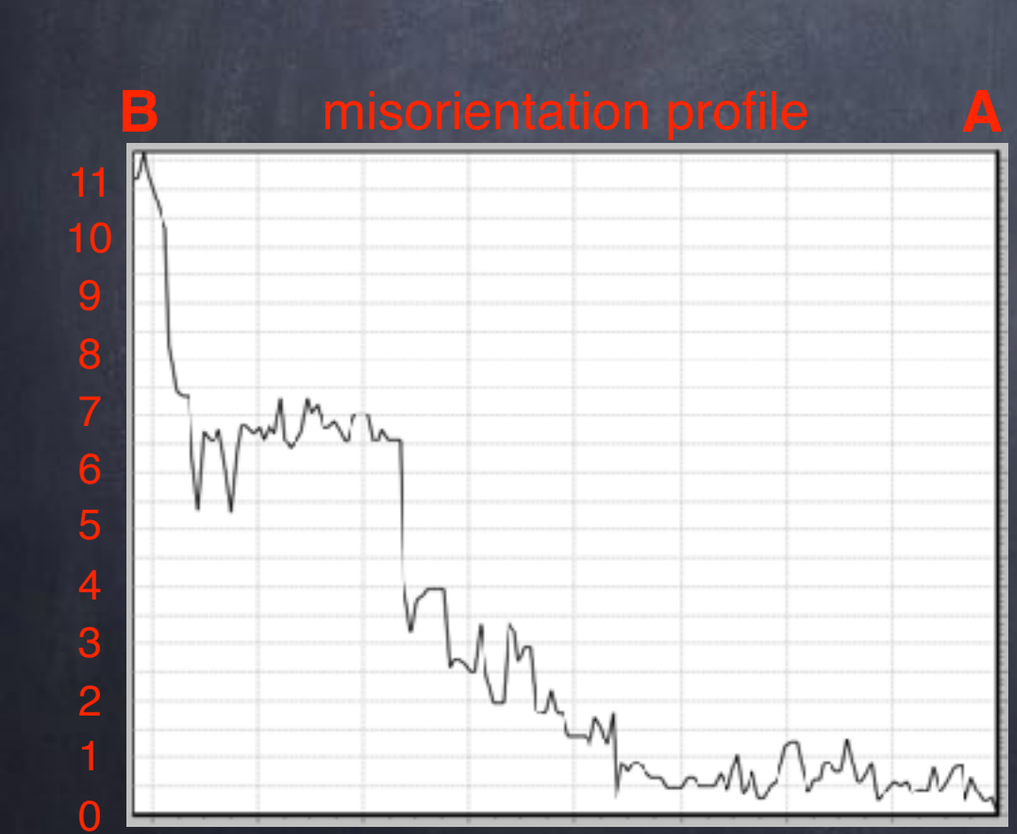
IVZ lower crustal magmatism

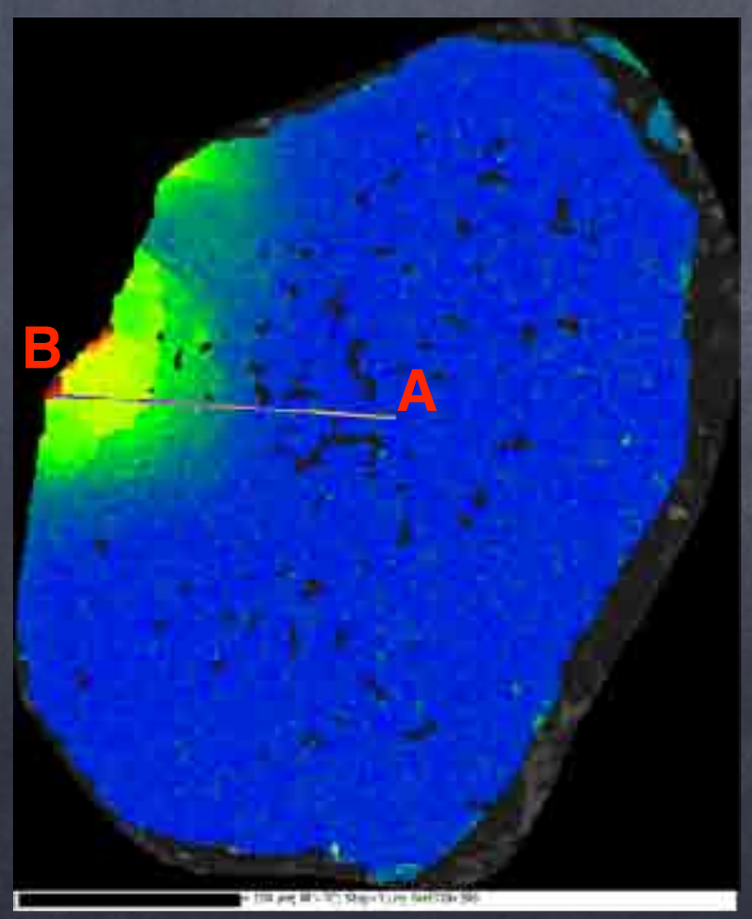


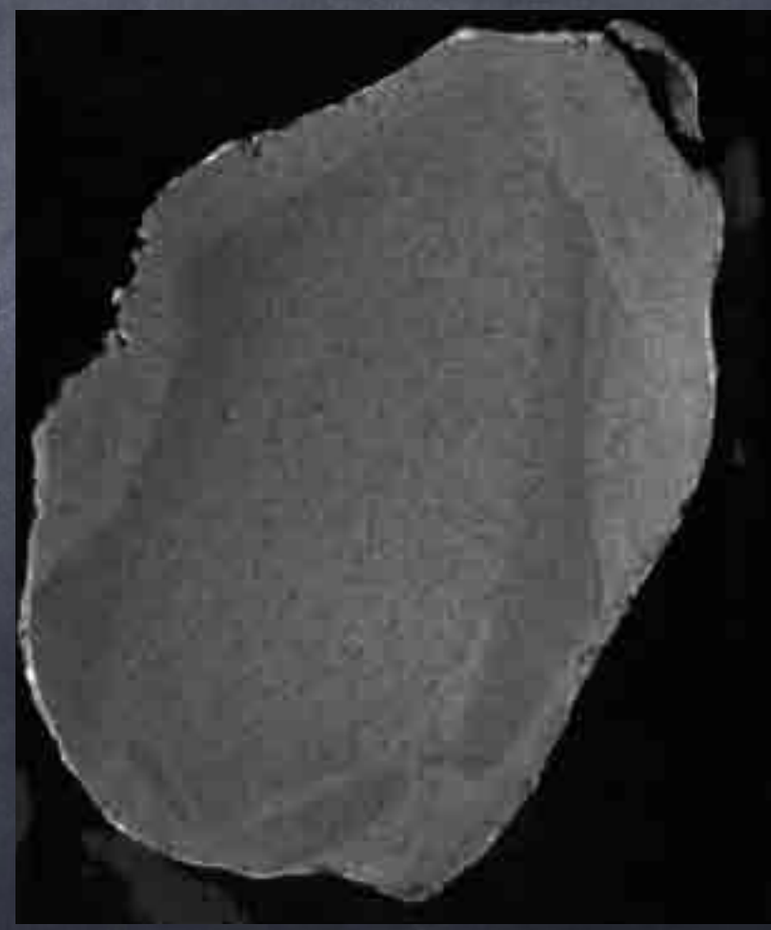
Langone et al., 2018

IVZ lower crustal magmatism

Zircon deformation features



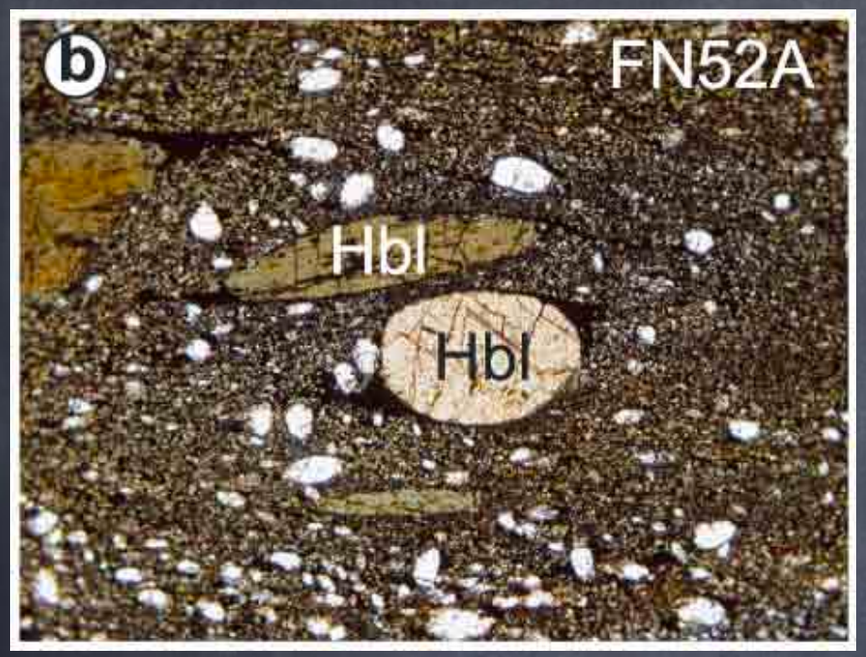




in collaboration with Piazolo S.

Langone Antonio

IVZ lower crustal magmatism



Deformation

⇓

Garnet and hornblende break-down

⇓

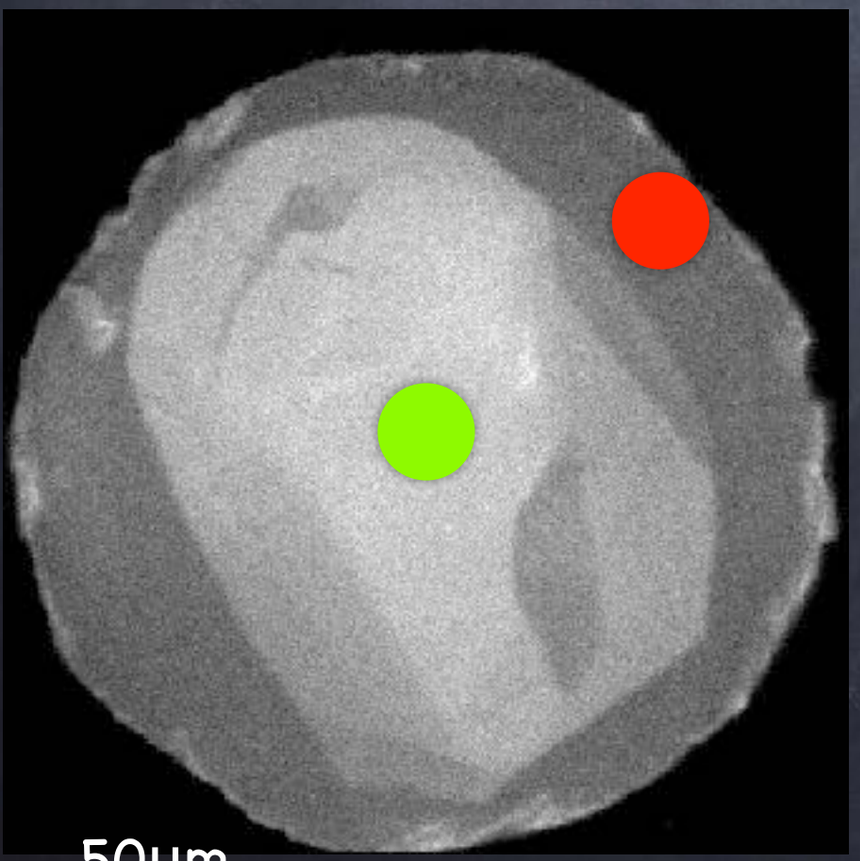
large amount of zirconium release

⇓

new zircon (anhedral and homogeneous CL)

+

zircon overgrowths (dark homogeneous rims)



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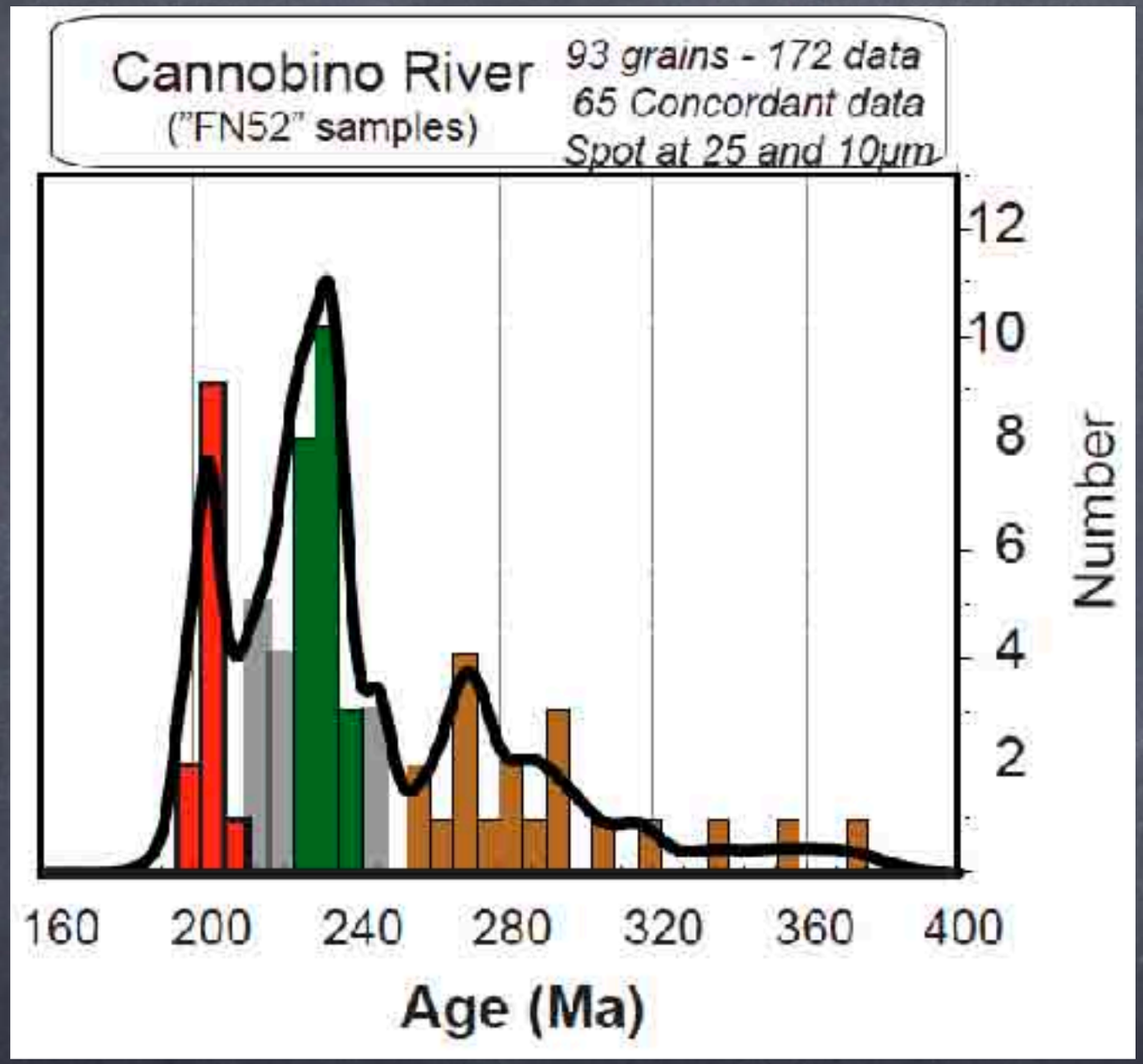
IVZ lower crustal magmatism



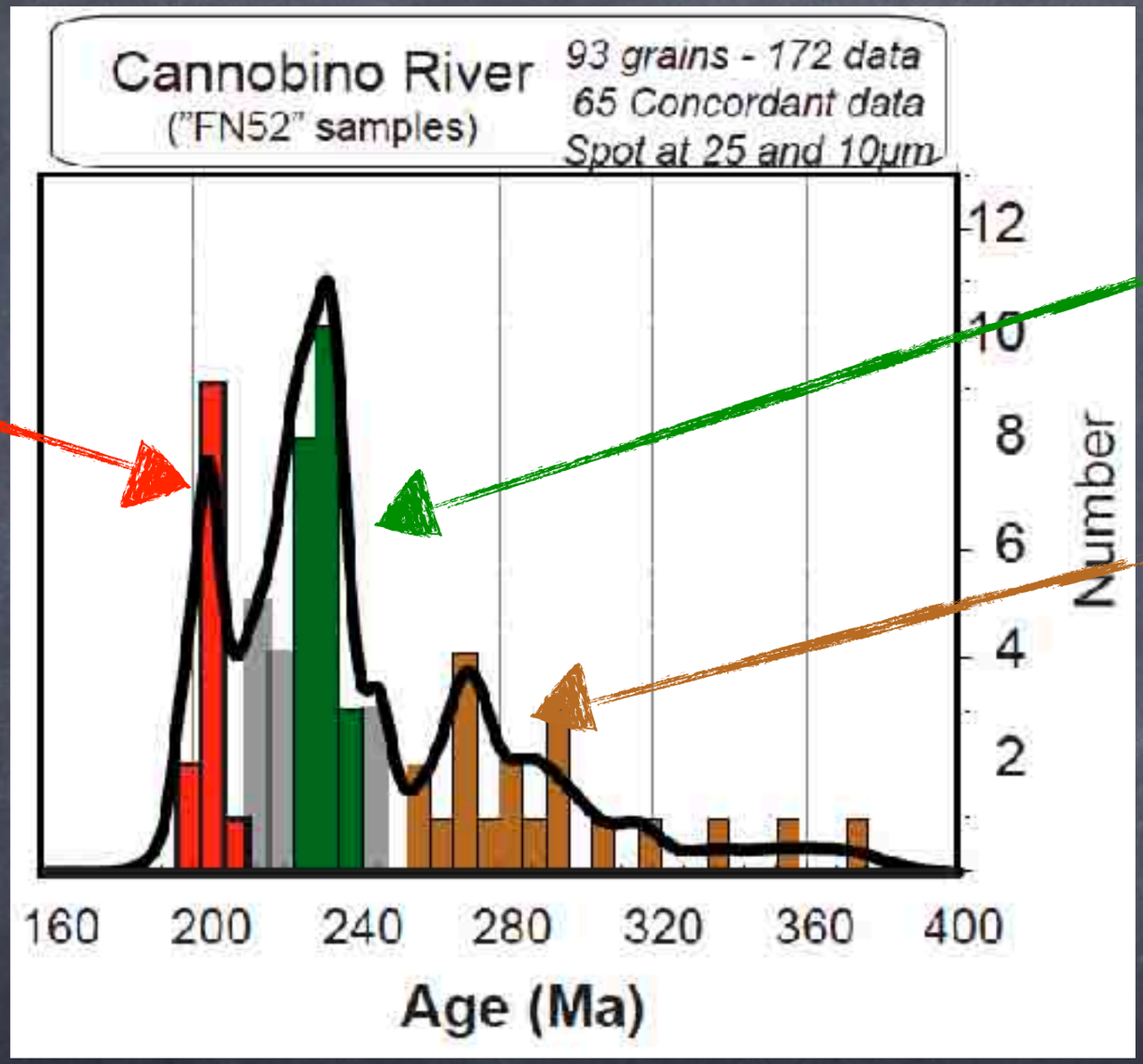
Langone et al., 2018

IVZ lower crustal magmatism

Deformation

Triassic intrusion

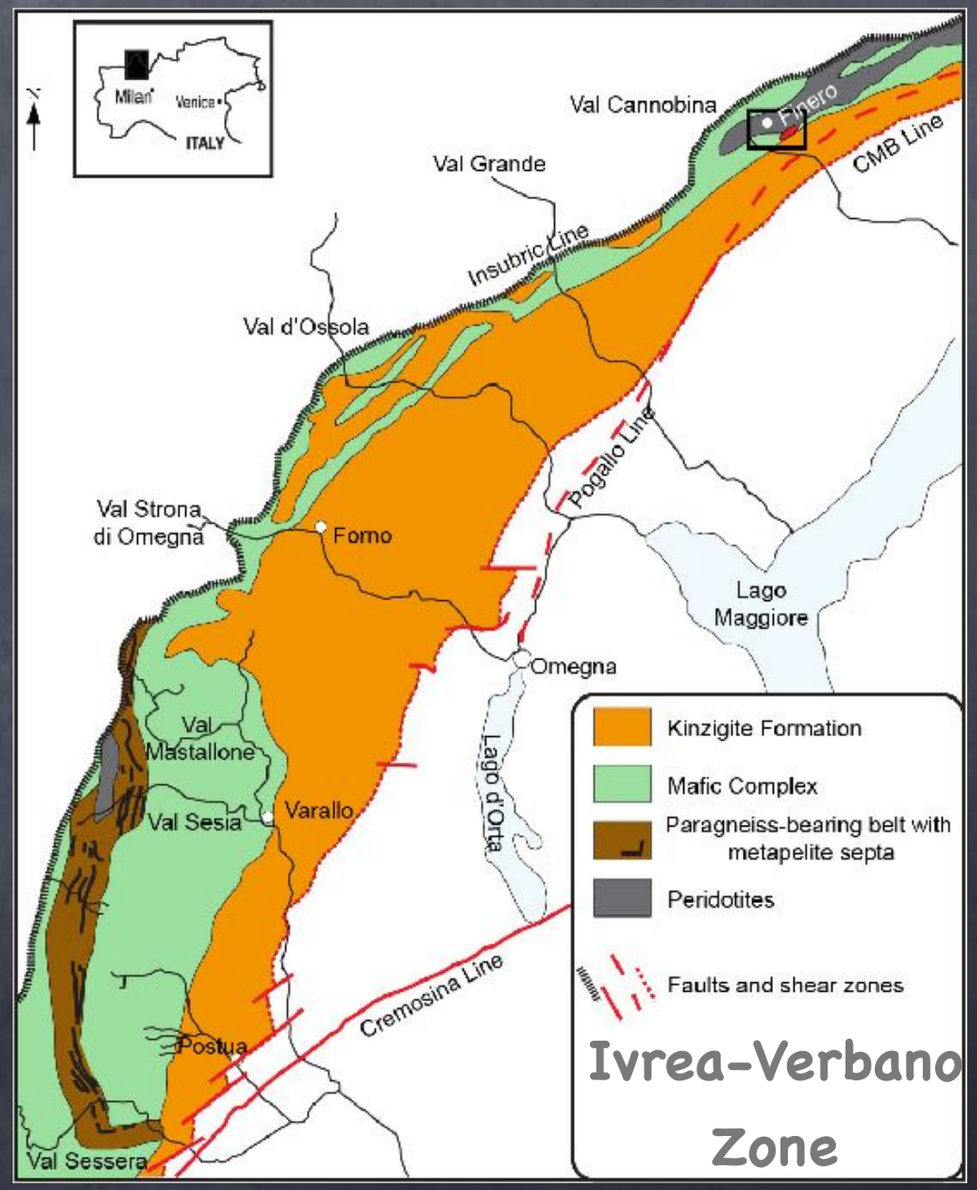
Inheritance



Langone et al., 2018

IVZ lower crustal magmatism

Summing up



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IVZ lower crustal magmatism

Summing up

crystallisation
HT deformation

~200 Ma

crystallisation
HT metamorphism

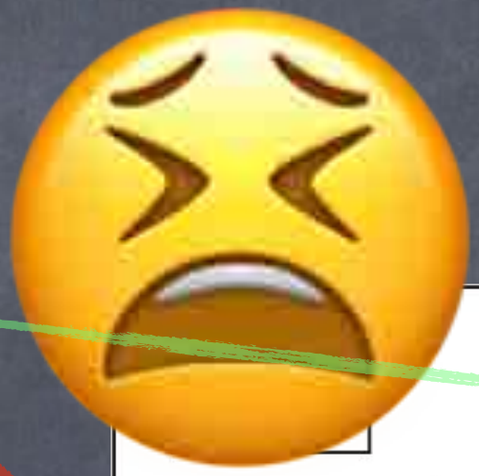
~ 245-230 Ma

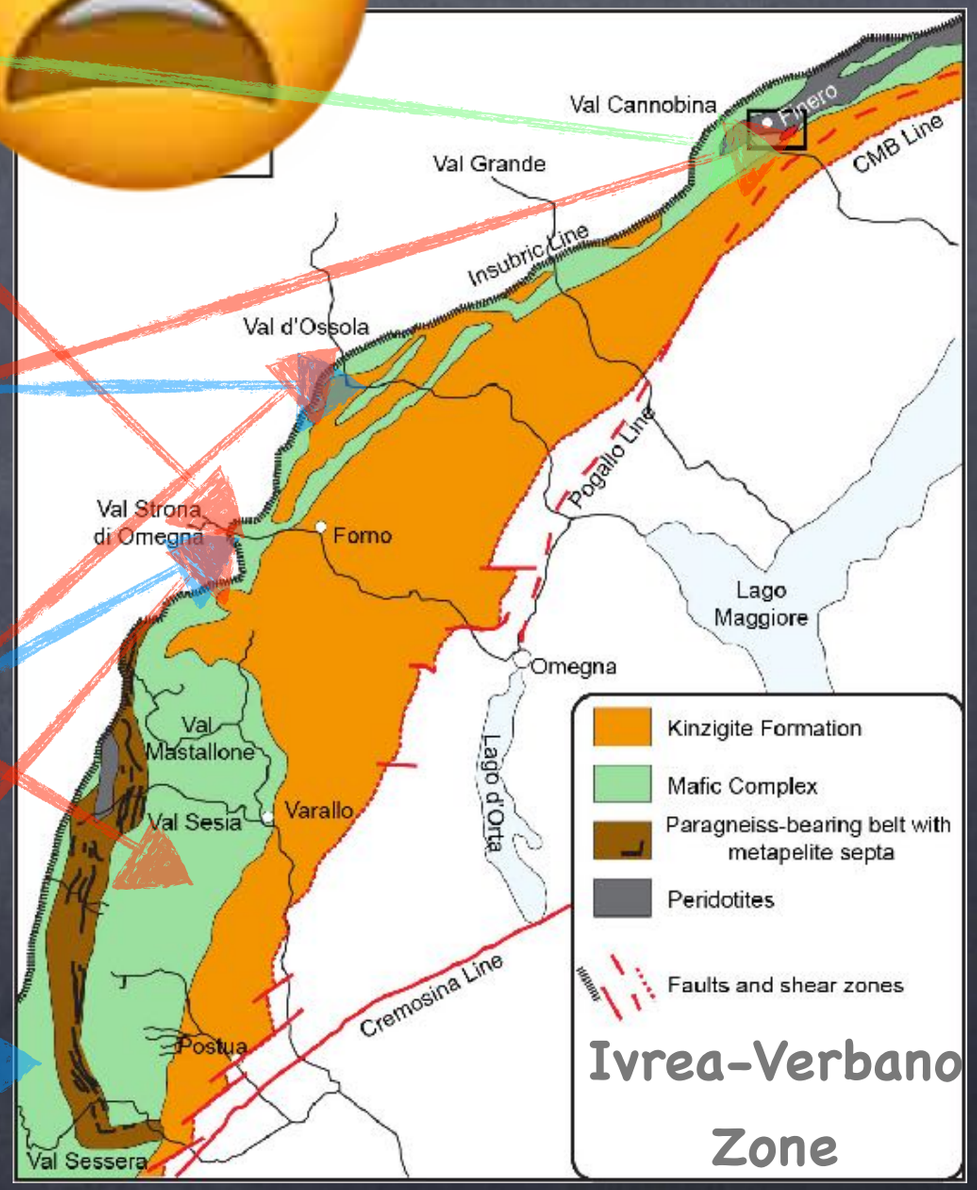
crystallisation
HT-metamorphism

~ 287-275 Ma

crystallisation
HT metamorphism

~ 310 Ma





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IVZ lower crustal magmatism

Summing up

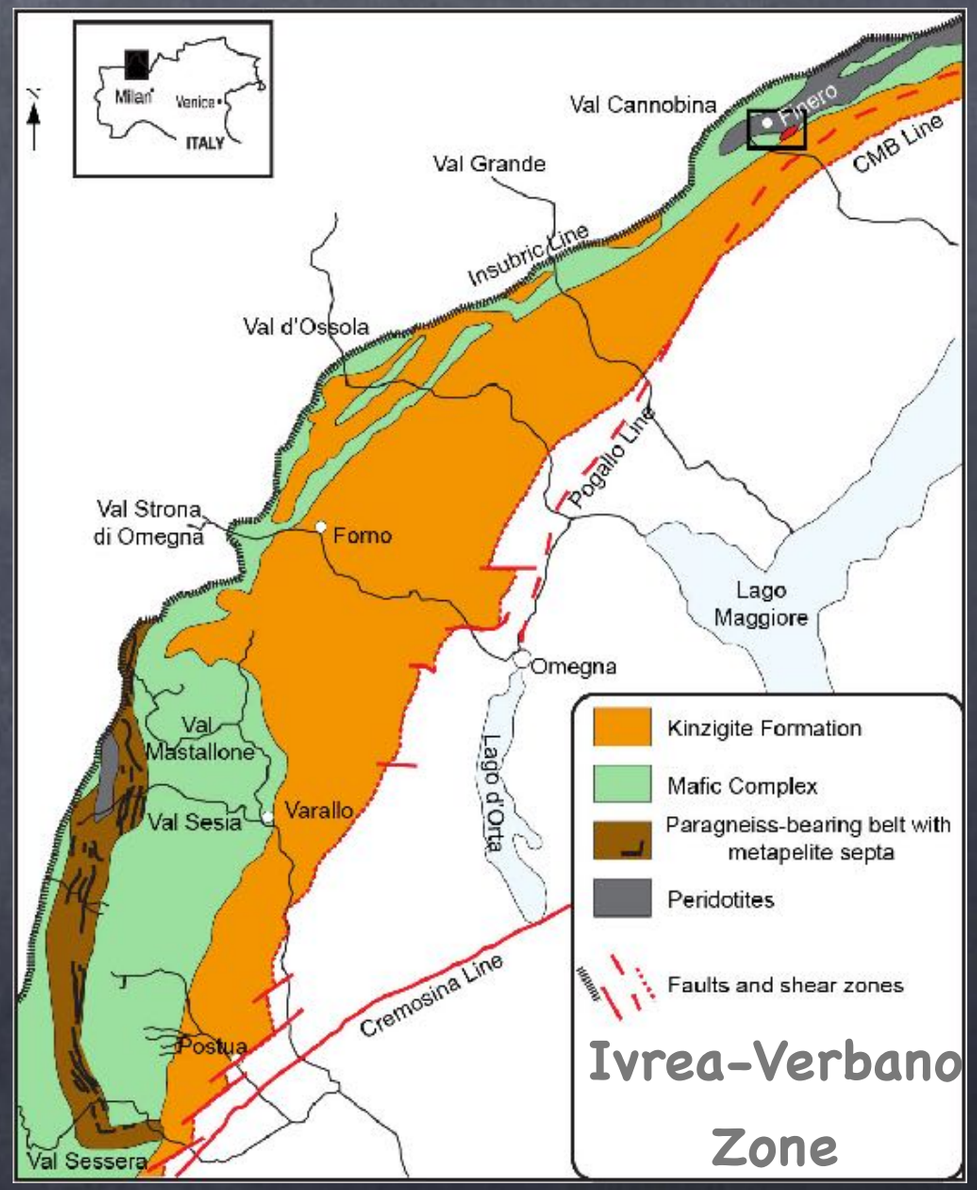
Conclusions:

1 - multiple intrusions (110Myr)???

2 - southern IVZ= mafic complex

3 - central and northern IVZ = discrete sill intrusions

4 - HT deformation of mafic rocks => abundant Zrc formation



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IVZ lower crustal magmatism

general take home messages:

- lower crustal mafic complexes should be approached as a "HT magmatic/metamorphic" complex

field

Silvano's teachings

microstructures

Sandra's teachings

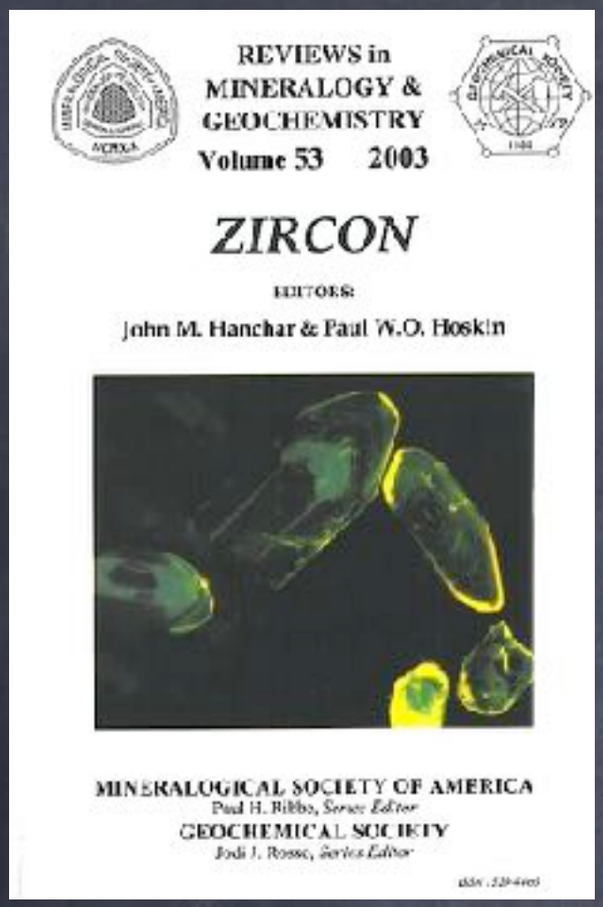
petrochrnology

Thoma's teachings

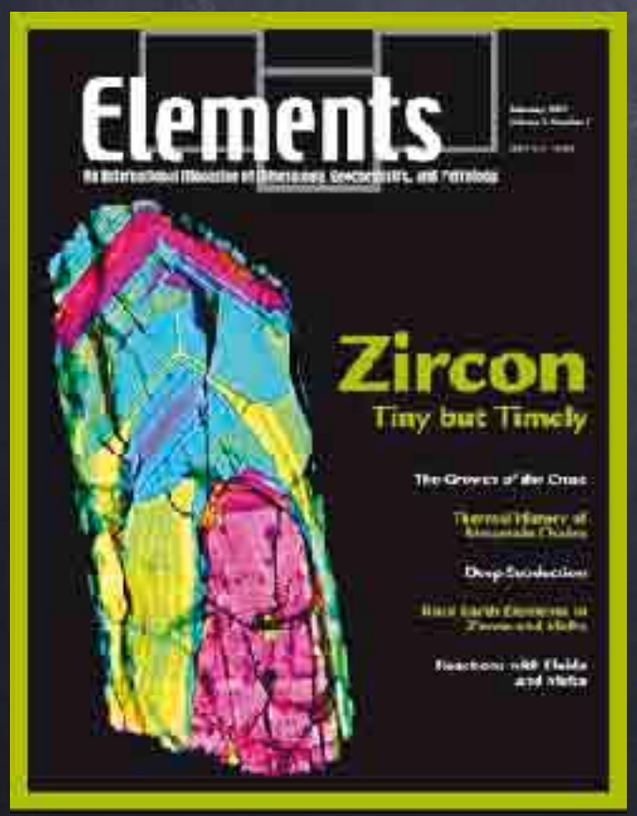
Langone Antonio

Fundamental books-volumes

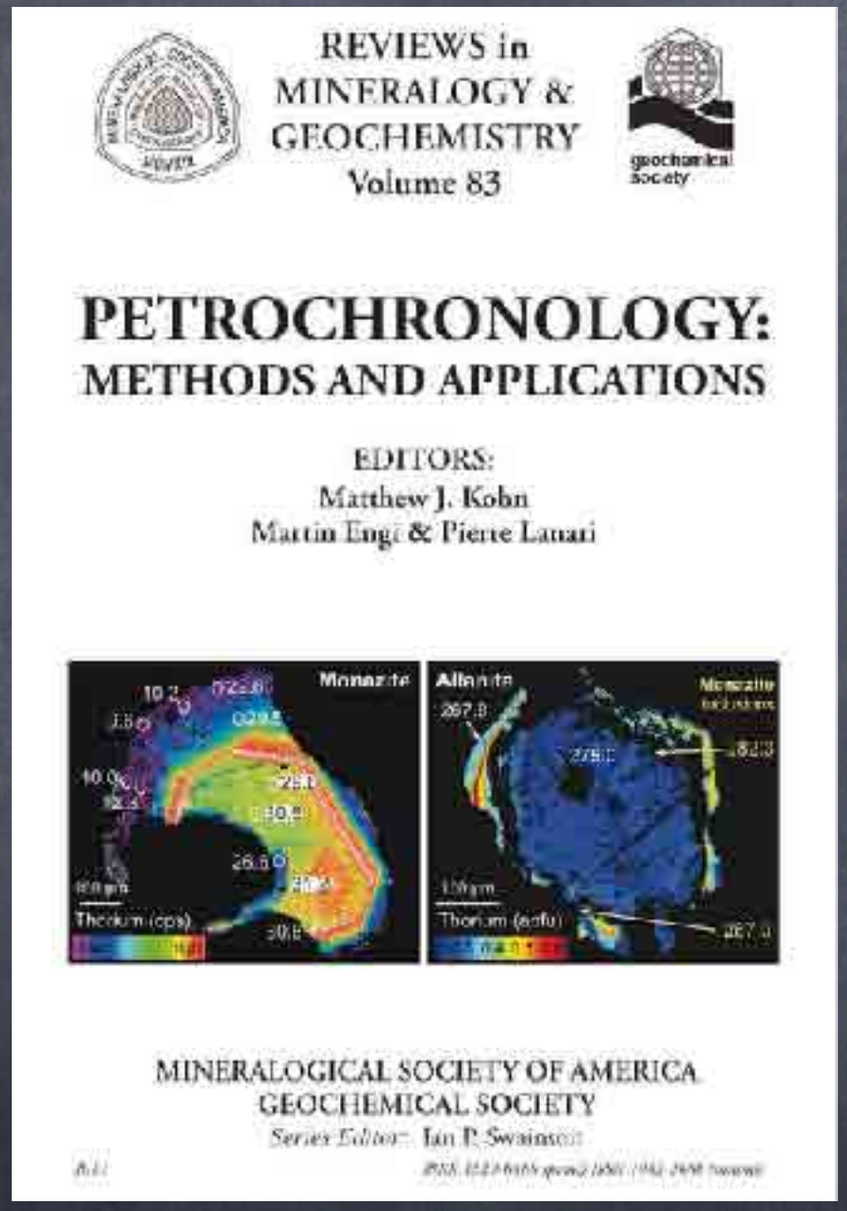
2003



2007



2017



2017