

The pegmatites and their economic potential

Master SMGE

2025-2026



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geo
Ressources



UNIVERSITÉ
DE LORRAINE

1. The economic potential of pegmatites

2. Pegmatite textures

3. Origin of pegmatites

4. The rare elements pegmatites

5. Examples in South Africa and the Variscan Belt

1. The economic potential of pegmatites

Pegmatites as source of rare elements (or rare metals)

Rare elements or metals = Li, Ta, Nb, Cs, Be, W, Sn, REE, ...

Main source of tantalum (Ta) and lithium (Li) in the world.

Li : battery, ceramic an electronic industries



Ta: electronic industry (capacitors)



But also significant source of caesium (Cs), rubidium (Rb), tin (Sn), tungsten (W), niobium (Nb), beryllium (Be), REE (Rare earth elements), uranium (U), ...



1. The economic potential of pegmatites

➤ Some examples of important pegmatite deposits

Greenbushes (Western Australia)

70.4 Mt (1.2 %) Li

4.7 Mt (0.06 %) Ta

28 Mt (0.114 %) Sn

Tanco (Manitoba, Canada)

22.3 Mt (0.64 %) Li

1.9 Mt (0.216 %) Ta₂O₅

0.3 Mt (23.3 %) Cs₂O

0.8 Mt (0.2 %) BeO

Manono – Kitolo (D. R. of Congo)

~ 35 Mt (0.6 %) Li

Zimbabwe

Kamativi: 100 Mt (0.28 %) Li and (0.11 %) Sn

Bikita: 10.8 Mt (3%) Li

Namibia

UIS belt: 87 Mt (0.13 %) Sn

Karibib: 1.1 Mt (1.4 %) Li

Mibra (Brazil)

20 Mt (0.5 %) Li, (0.03 %) Ta₂O₅
and (0.04 %) Sn

1. The economic potential of pegmatites

But pegmatites are not only a important source of rare metal.....

Granitic pegmatites are also a major source of industrial materials such as feldspar, quartz and micas!

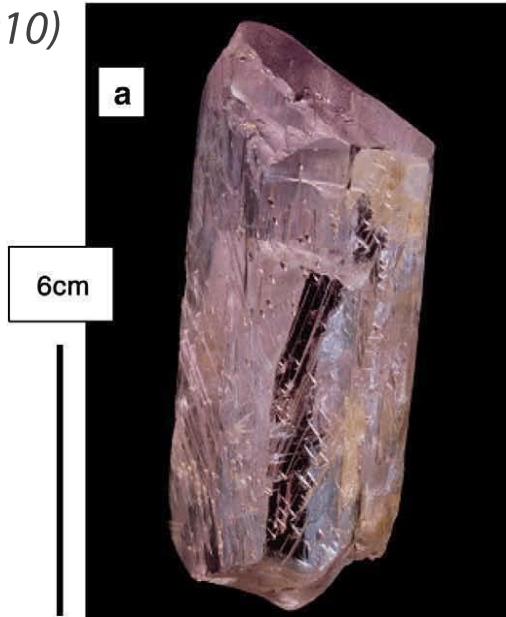
- ✓ Primary source of feldspar for the glass and ceramic industries due to their low Fe and Ca content
- ✓ Major source of quartz for the glass and electronic industries (ultrapure quartz)

Finally, large number of gemstones are mined from pegmatites

1. The economic potential of pegmatites

➤ Economically significant Li minerals found in pegmatites

(Dill, 2010)



Spodumene ($\text{LiAlSi}_2\text{O}_6$)



Amblygonite [$\text{LiAlPO}_4(\text{F,OH})$]



Petalite ($\text{LiAlSi}_2\text{O}_6$)



Lepidolite [$\text{K}(\text{Li,Al})_3(\text{Si,Al})_4\text{O}_{10}(\text{F,OH})_2$]

1. The economic potential of pegmatites

➤ Economically significant Ta minerals

Mostly columbite – tantalite (coltan) group minerals $[(\text{Fe}, \text{Mn})(\text{Nb}, \text{Ta})_2\text{O}_6]$ and less commonly wodginite $[\text{Mn}(\text{Sn}, \text{Ta})\text{Ta}_2\text{O}_8]$ and microlite $[(\text{Na}, \text{Ca})_2\text{Ta}_2\text{O}_6(\text{O}, \text{OH}, \text{F})]$



Mangano-tantalite,
Tanco pegmatite (Canada)
 MnTa_2O_6



Wodginite,
Tanco pegmatite (Canada)



Microlite, Alto Ligonha Pegmatite,
Province Zambezia (Mozambique)

1. The economic potential of pegmatites

- Example of others economically significant minerals in pegmatites



Pollucite from the Tanco pegmatite (Canada)
 $(\text{Cs}, \text{Na})_2\text{Al}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$



Beryl from the Alstead pegmatite district (USA)
 $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$

But also cassiterite (SnO_2), monazite ($\text{Ce}, \text{La}, \text{Nd}, \text{Th}$) PO_4 , uraninite (UO_2),
allanite ($\text{Ce}, \text{Ca}, \text{Y}$) $_2(\text{Al}, \text{Fe})_3(\text{SiO}_4)_3(\text{OH})$,

2. Pegmatite textures

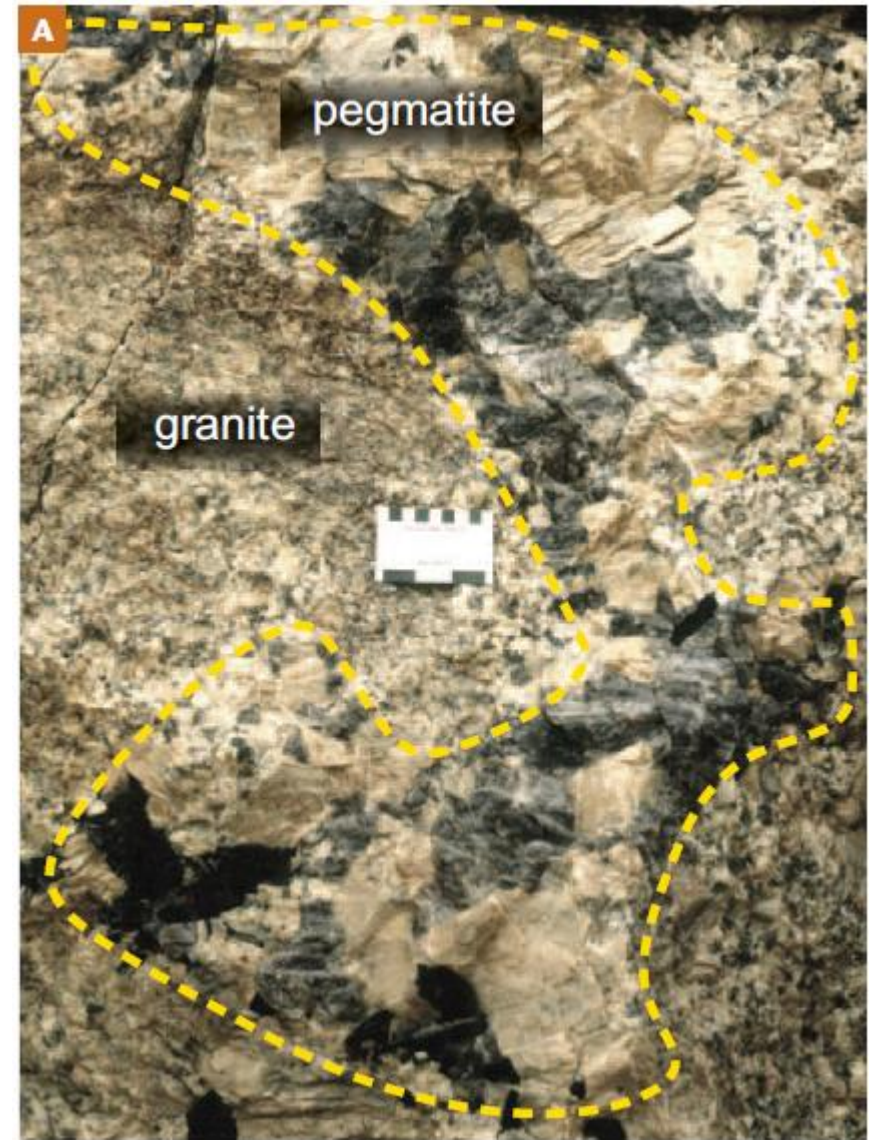
Pegmatite:

Coarse-grained (> 2 cm) magmatic rock of generally granitic composition bearing quartz-feldspar-micas. Pegmatites are commonly associated with aplites (fine-grained granite)

Can occur in association with mafic magmatism but rare (they are called pegmatoids)

Commonly contain tourmaline, garnet, apatite, Fe-Ti oxide minerals as accessory phases

Chemically complex pegmatites bearing Li, Ta, Be, Cs, REE (etc.) minerals are scarce (~ 1 % of pegmatites) and are called rare elements pegmatites



A pegmatitic segregation within granite, Middletown, Connecticut (USA).

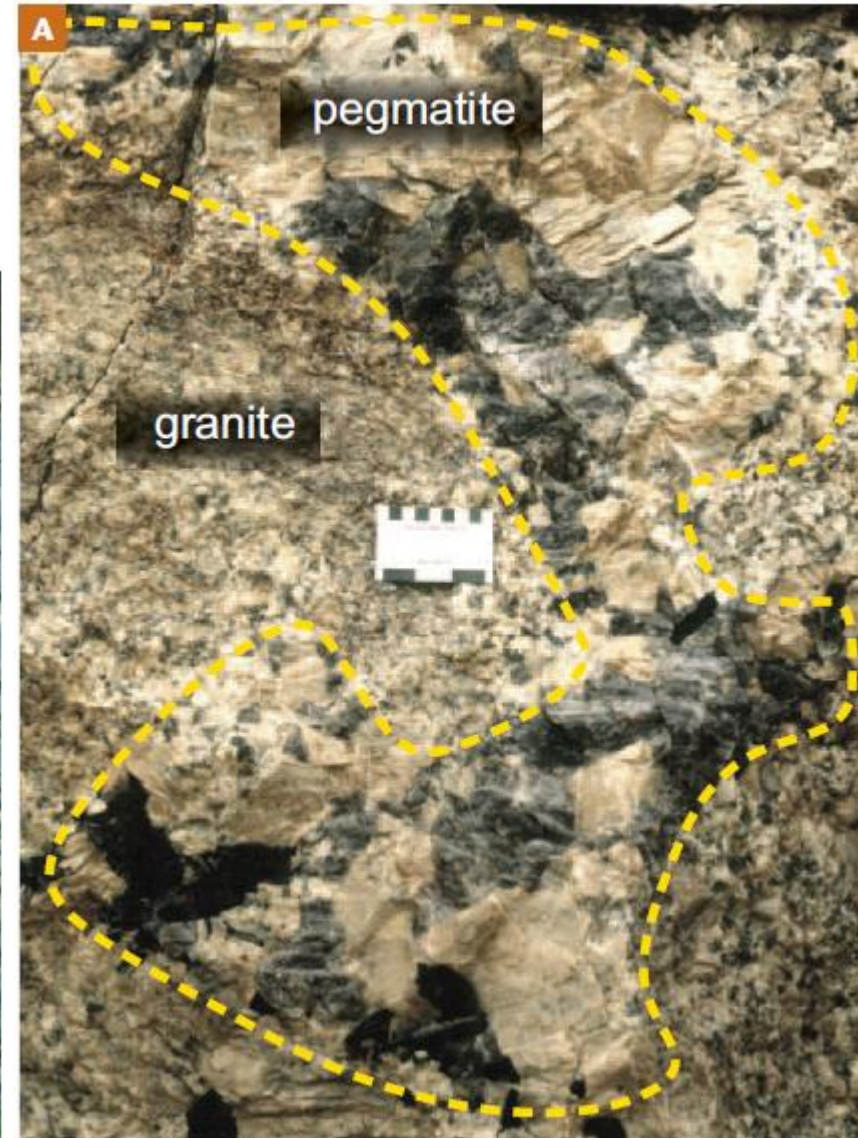
London and Morgan (2012)

2. Pegmatite textures

Generally occur as irregular dykes or lenses in granites and metamorphic rocks. Their width vary from few centimetres to ~50 m.

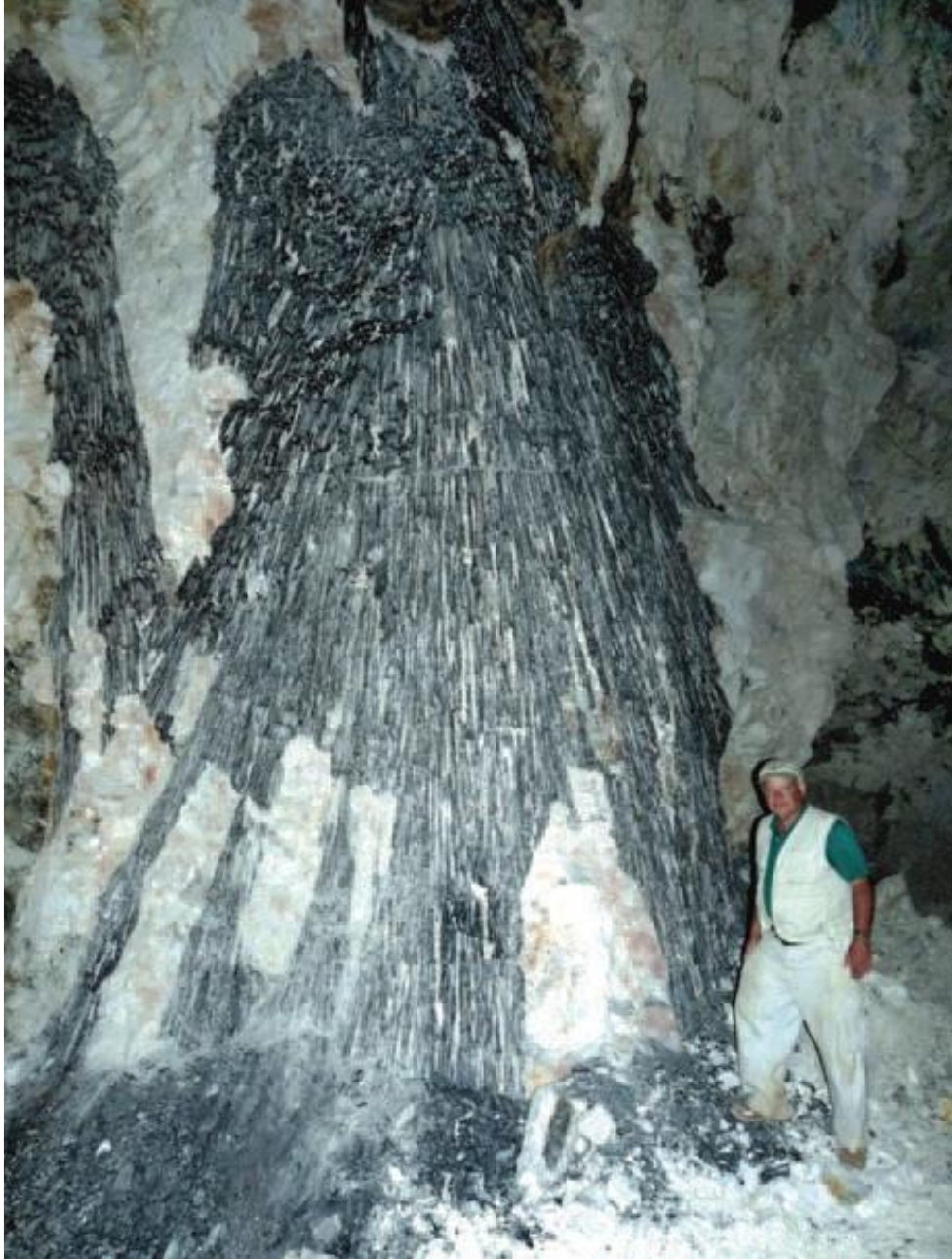


Parallel pegmatite dikes that cut amphibolite and gneiss, Haddam, Connecticut (USA).



A pegmatitic segregation within granite, Middletown, Connecticut (USA).

2. Pegmatite textures



The world biggest crystals formed in pegmatites

A gigantic skeletal crystal of tourmaline radiating into a pegmatite from the upper contact, from the Água Santa pegmatite, Coronel Murta, Jequitinhonha valley, MinasGerais, Brazil

(London and Morgan, 2012)

2. Pegmatite textures



London and Morgan (2012)

Graphic granite: intergrow of quartz (gray) and microcline (white), Colorado (USA). This texture is unique to pegmatites.

2. Pegmatite textures



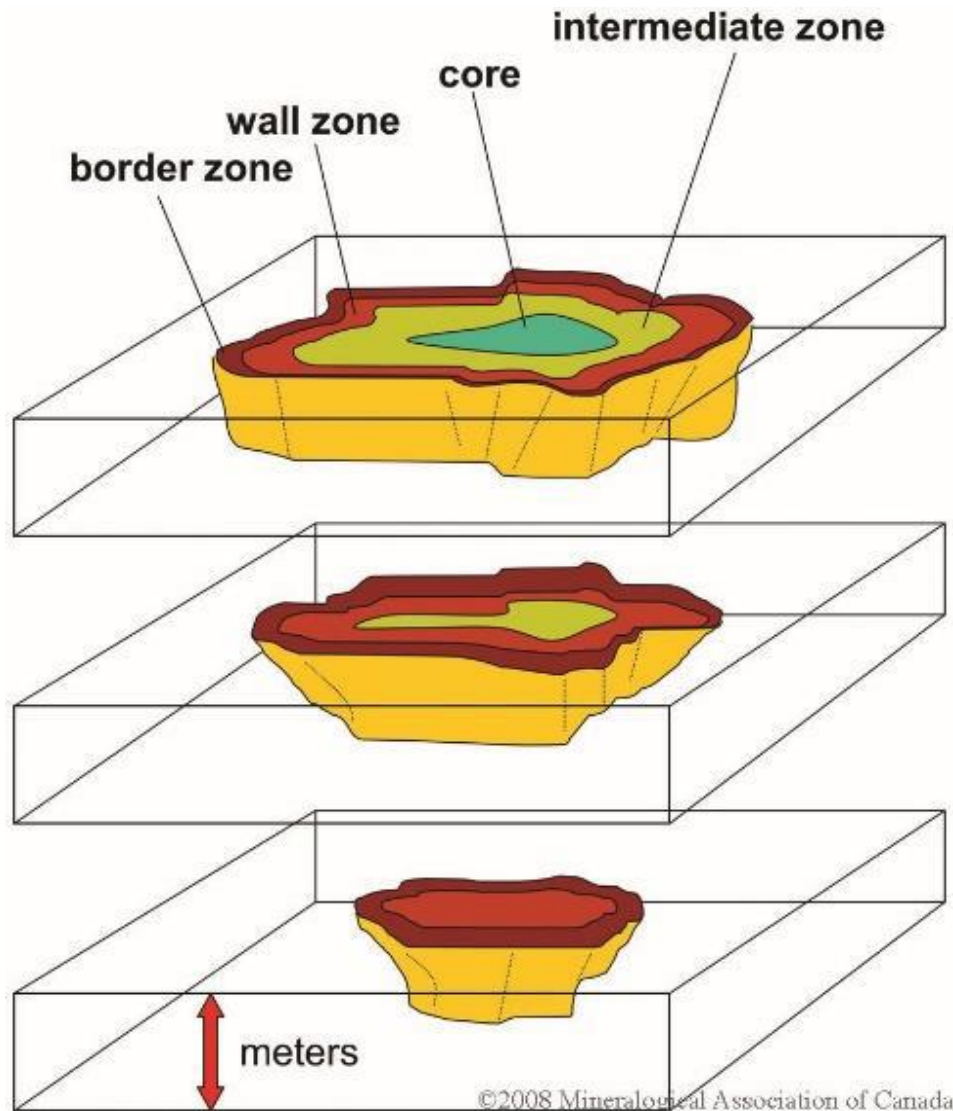
Skeletal biotite, Cap de Creus (Spain)

2. Pegmatite textures



Layered aplite, Chabanne, Limousin (France)

2. Pegmatite textures



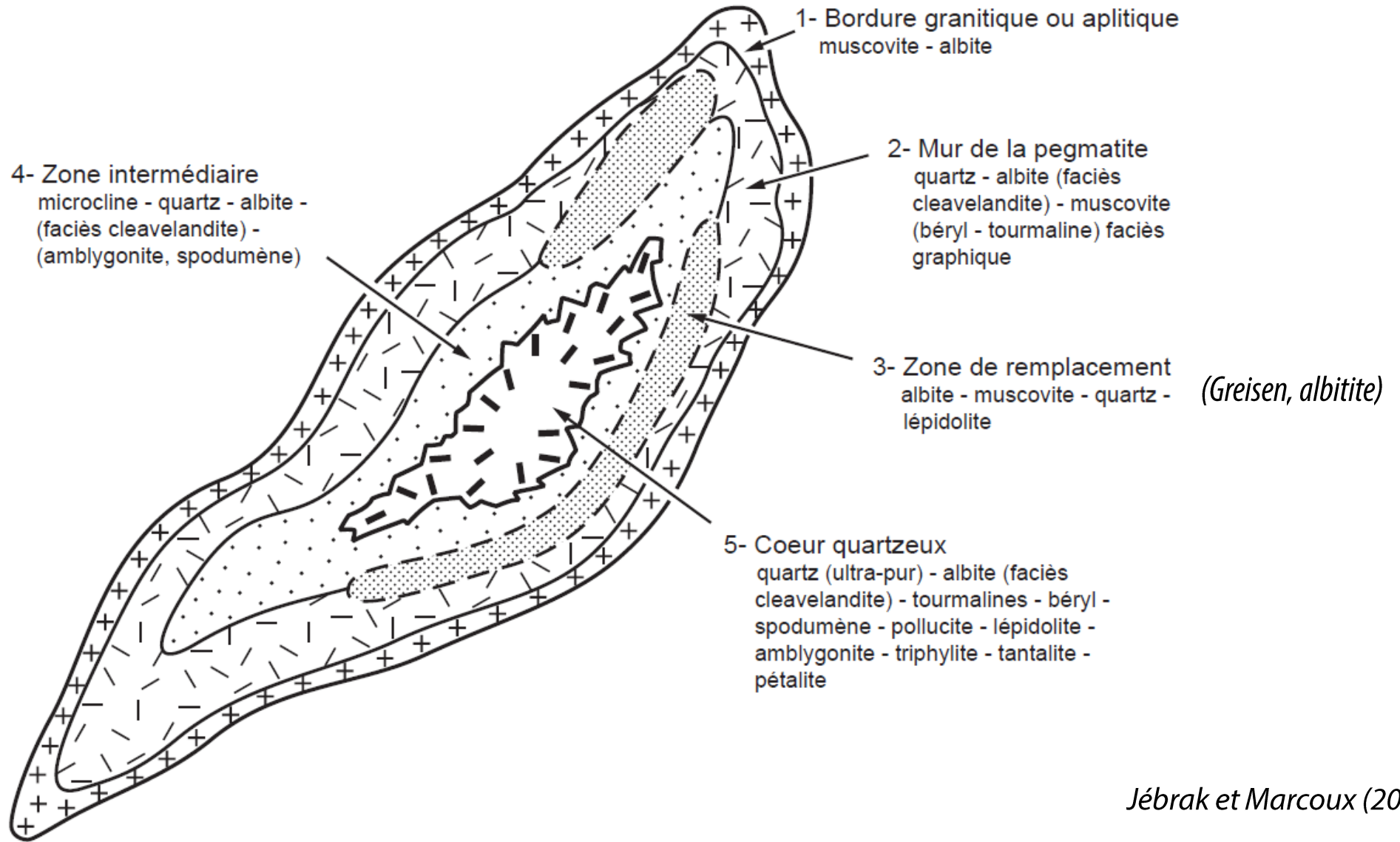
Variable internal textures from homogeneous to heterogeneous

- Border zone : granitic to aplitic
- Wall zone: pegmatitic, graphic, aplitic or skeletal textures
- Intermediate zone: blocky texture (rare element mineral-bearing)
- Core: quartz-(feldspar)

Typical internal zonation observed in granitic pegmatites

London (2008)

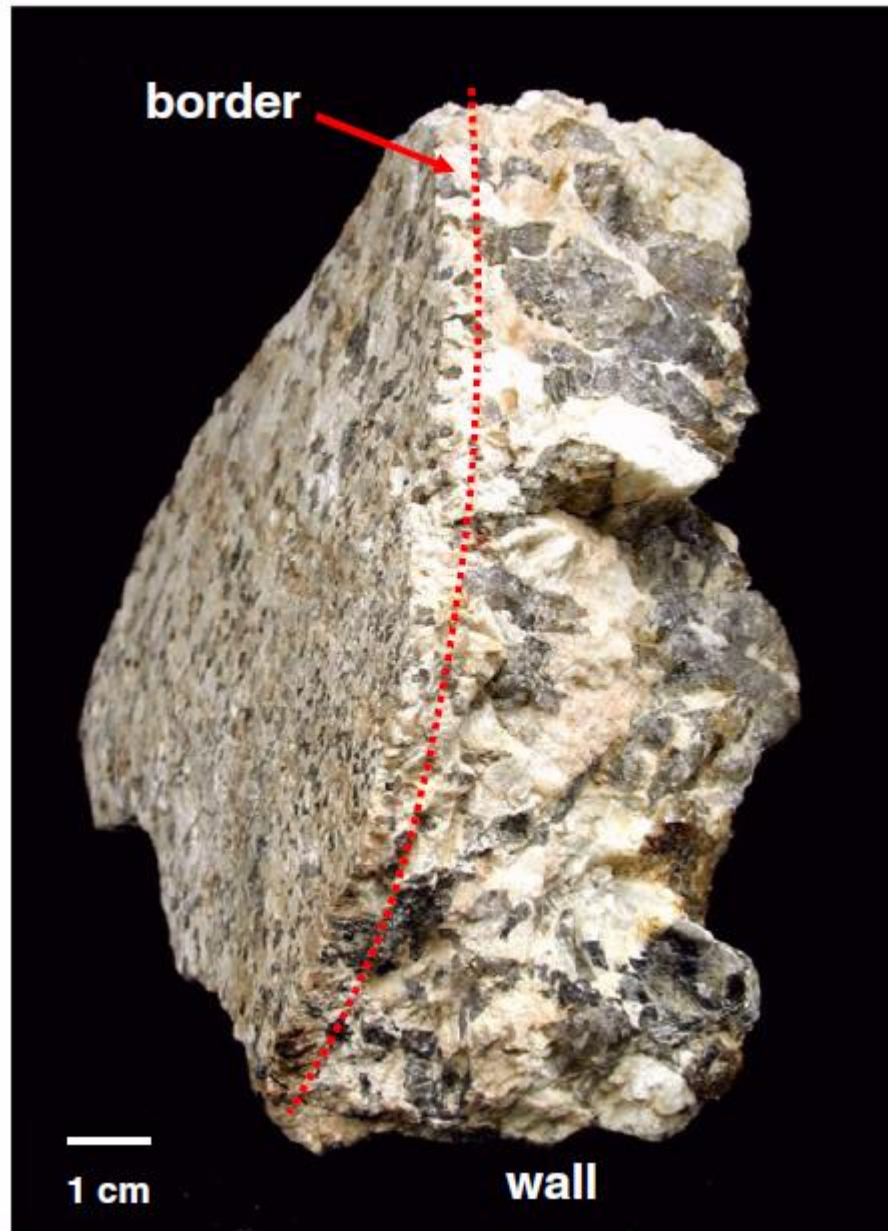
2. Pegmatite textures



Jébrak et Marcoux (2008)

Figure 5.24 - Zonalité idéalisée dans une pegmatite à quartz et éléments rares. Les minéraux rares ou peu abondants sont entre parenthèses.

2. Pegmatite textures

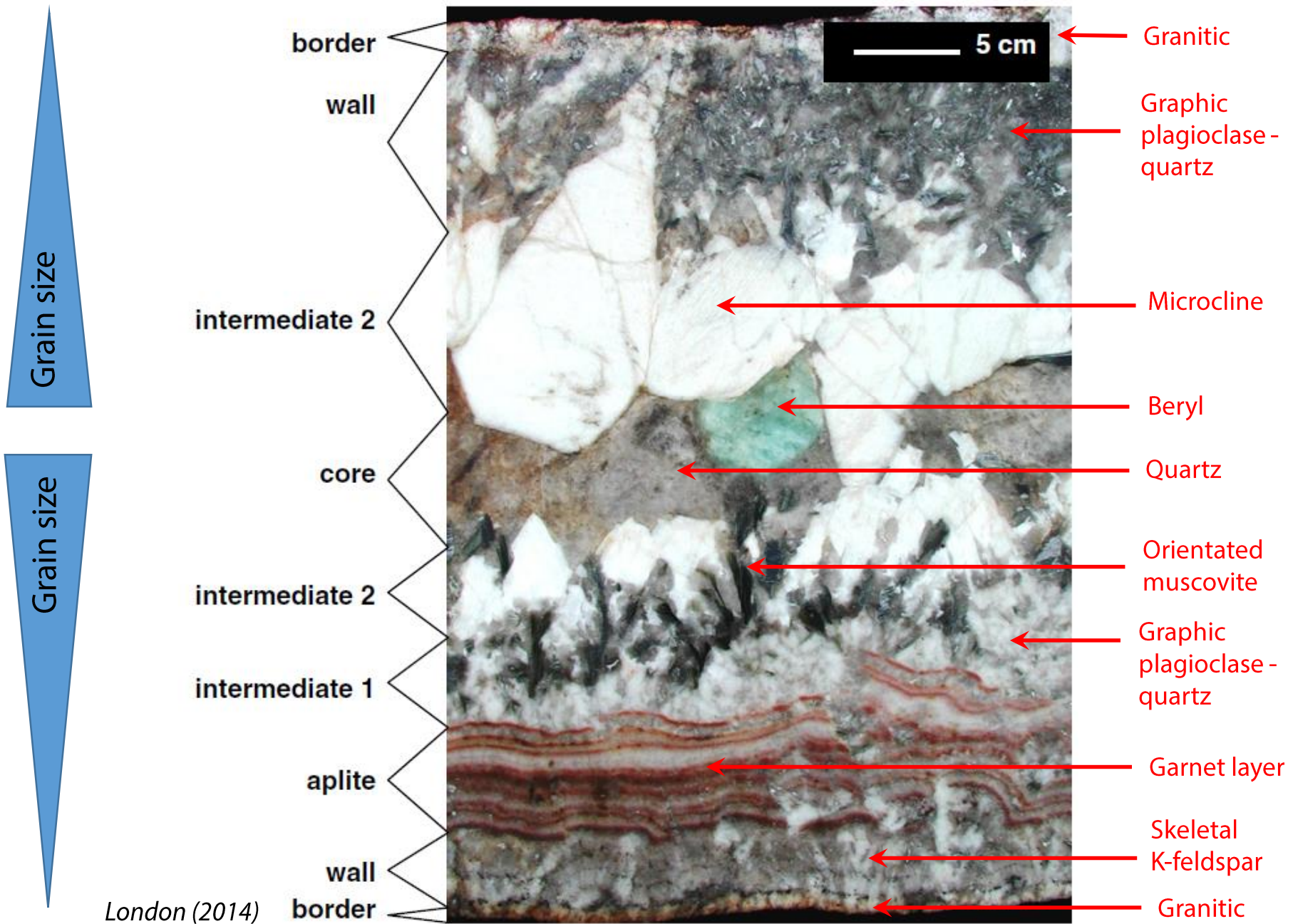


Border and wall zone

*Case #1 pegmatite, Portland,
Connecticut, USA*

London (2014)

2. Pegmatite textures



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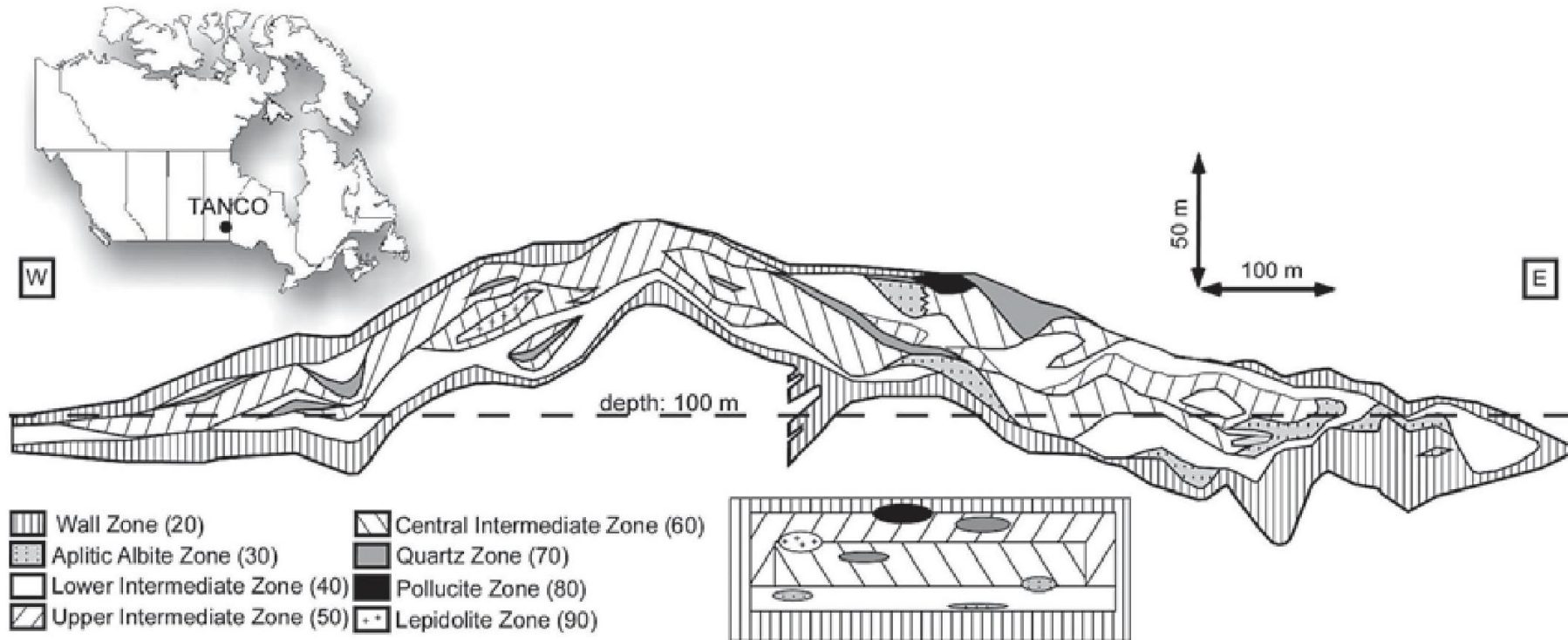
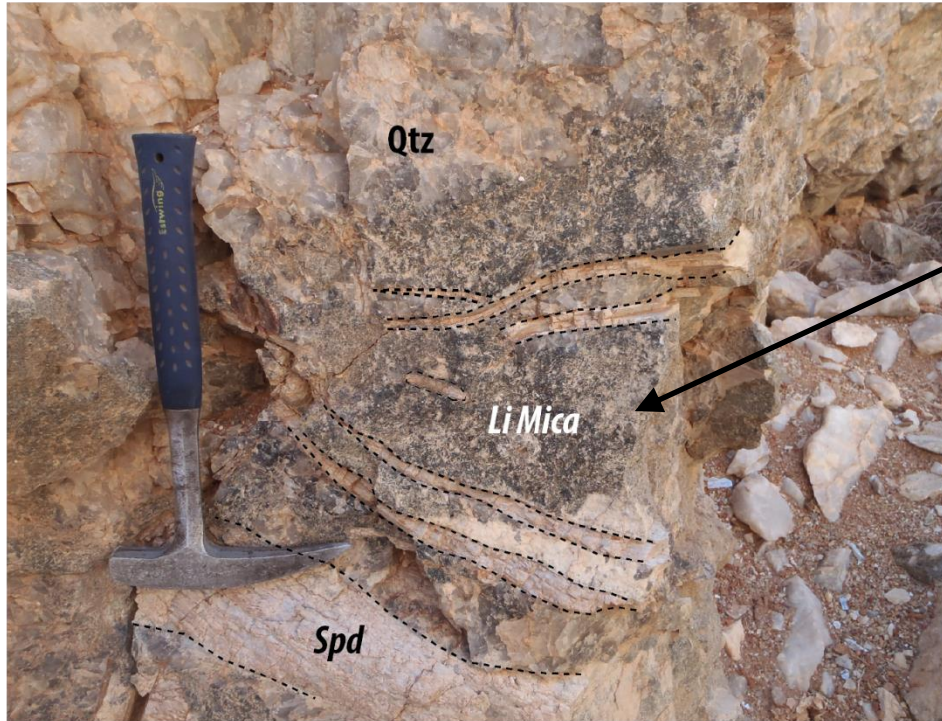


FIG. 1. East-west cross-section through the Tanco pegmatite (from Tanco geologists). A very schematic and simplified view of its zone distribution is shown beside the legend. Note that the vertical scale is doubled to allow a better view of the zoning.

2. Pegmatite textures

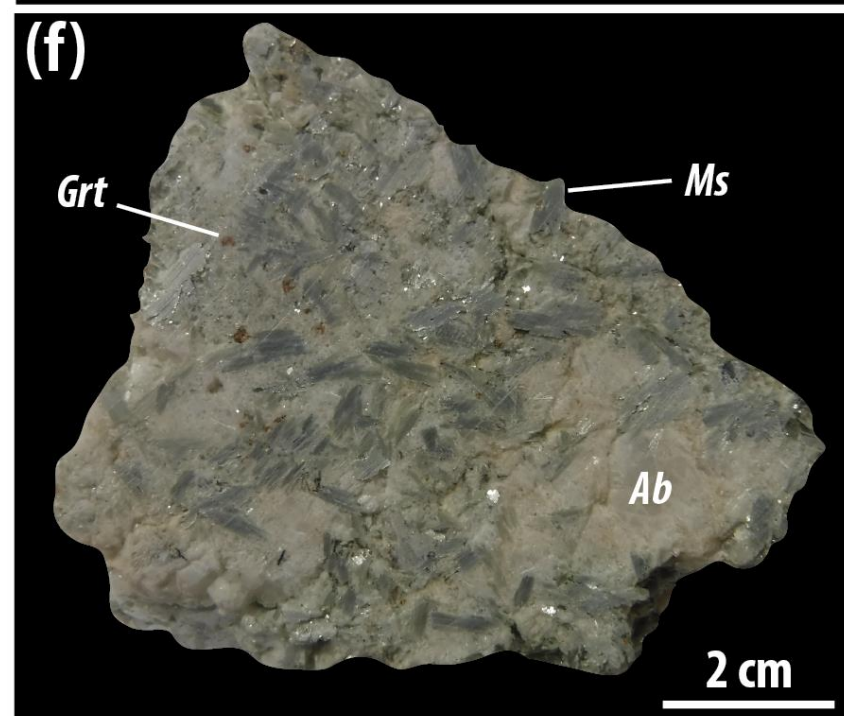
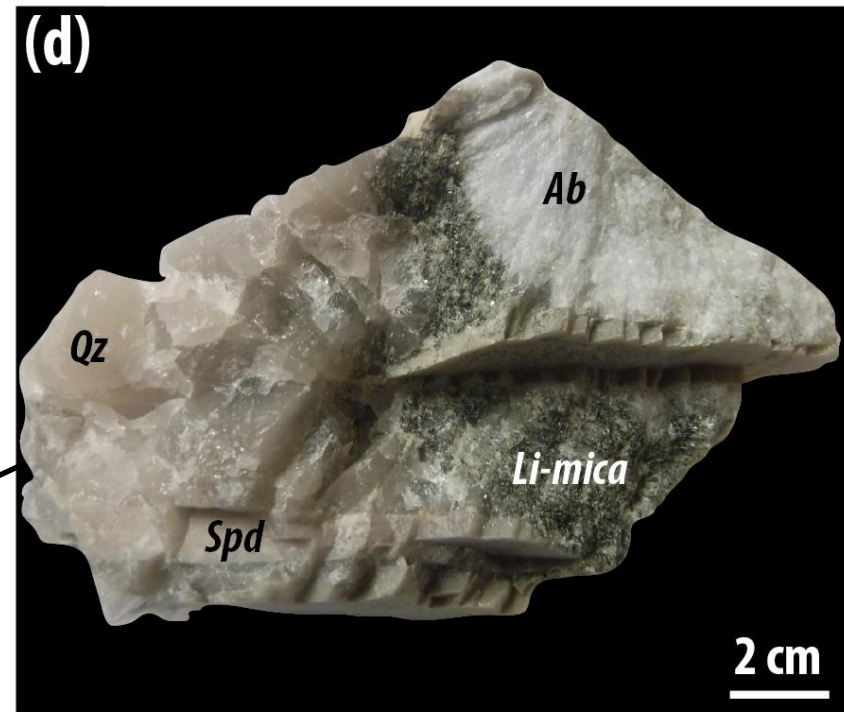
Metasomatic rocks (replacement zones):
Greisens and albitites



Orange River pegmatite belt, South Africa, Ballouard et al. 2020

Spd: spodumene, Qtz: quartz, Ab: albite; Grt: garnet

Albitites (albite) and greisens (muscovite + quartz) are secondary and form by the replacement of the primary mineral assemblage of the pegmatite



3. Origin of pegmatite textures

Still debated...

(Jahns and Burhman, 1989; London, 2005, 2014, Thomas et al., 2012)

***So no completely accepted general model...
but what we know is that pegmatite likely form by the***

**crystallization of an undercooled
flux- and water-rich or flux- and water-bearing granitic melt**

*Fluxing elements such as H_2O , F, B and P will increase
elemental diffusion, decrease crystal nucleation
and thus favor the crystallization of big crystals*

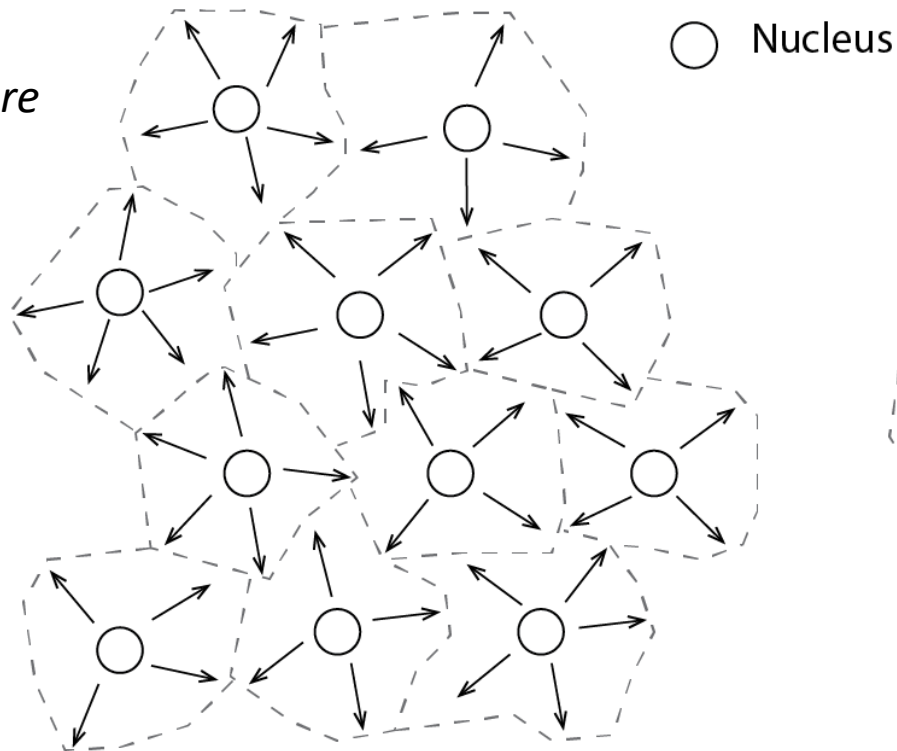
*Undercooling inhibits crystal nucleation, increase crystal growth rate. This
will also favor the formation of a boundary layer liquid-enriched in
fluxing elements at the crystallization front (constitutional zone refining)*

3. Origin of pegmatite textures

The role of water and other fluxing elements for crystal nucleation, elemental diffusion and crystal size

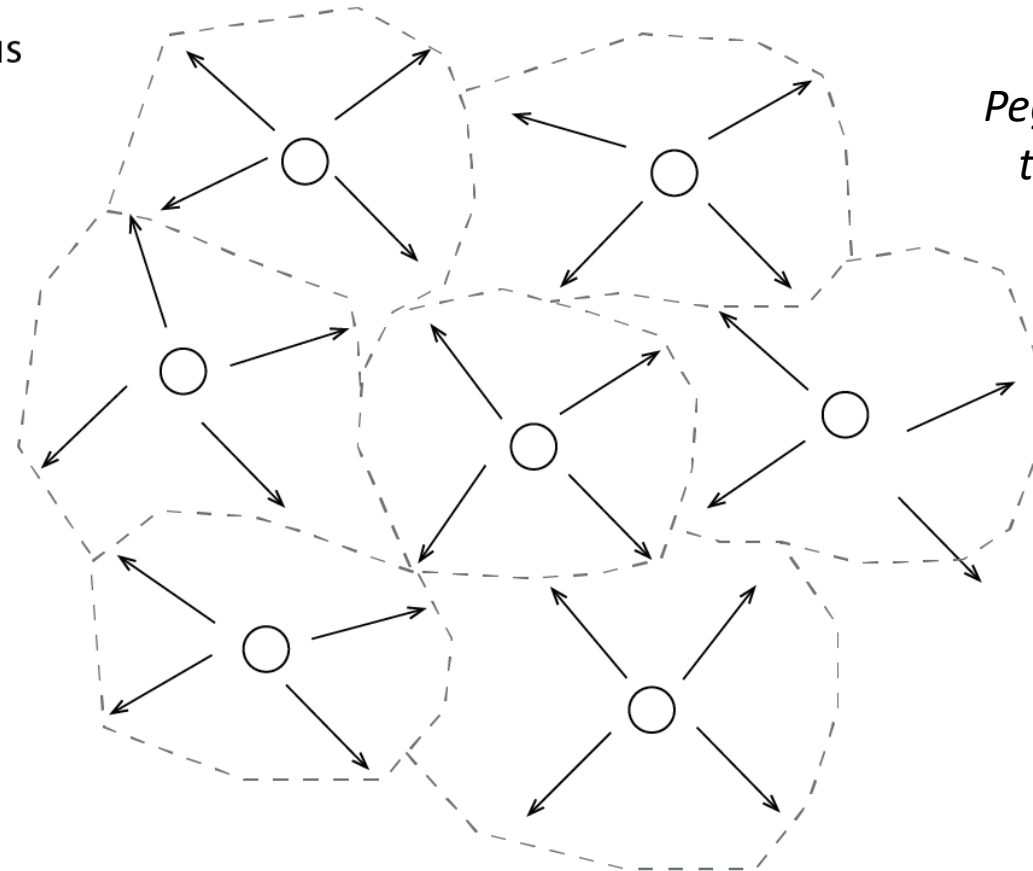
Water- and flux-poor granitic melt

Aplitic texture



Water- and flux-rich granitic melt (pegmatite)

Pegmatitic texture



3. Origin of pegmatite textures

Exercise (water and granites):

What is the water content of a regular granitic melt?

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Max 20 %

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Muscovite: $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH},\text{F})_2$

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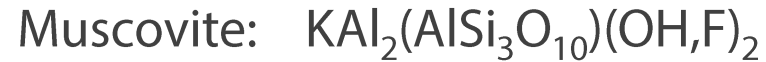
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3. Origin of pegmatite textures

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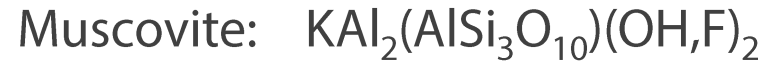
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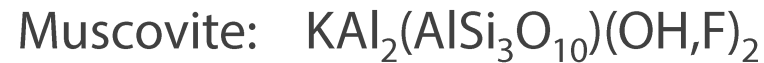
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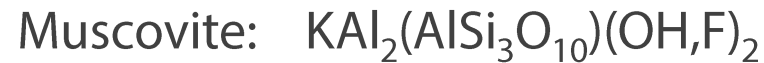
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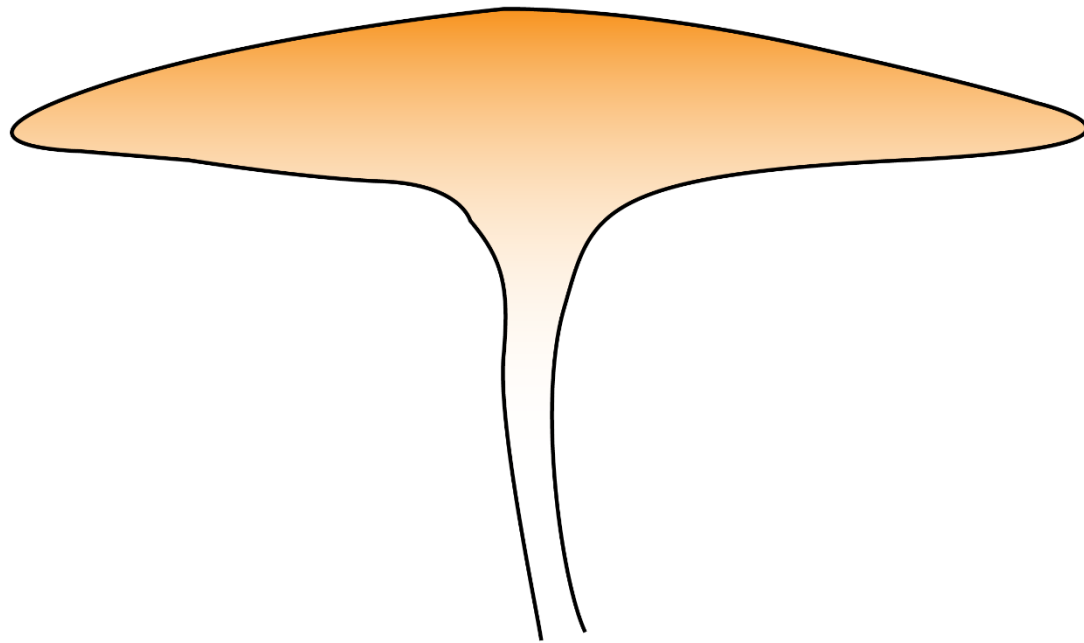
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$$[\text{H}_2\text{O}]_{\text{pegmatite melt}} \text{ can be up to } 30 \text{ wt.}\%$$

$$[\text{H}_2\text{O}]_{\text{quartz vein}} \sim 80-90 \text{ wt.}\%$$

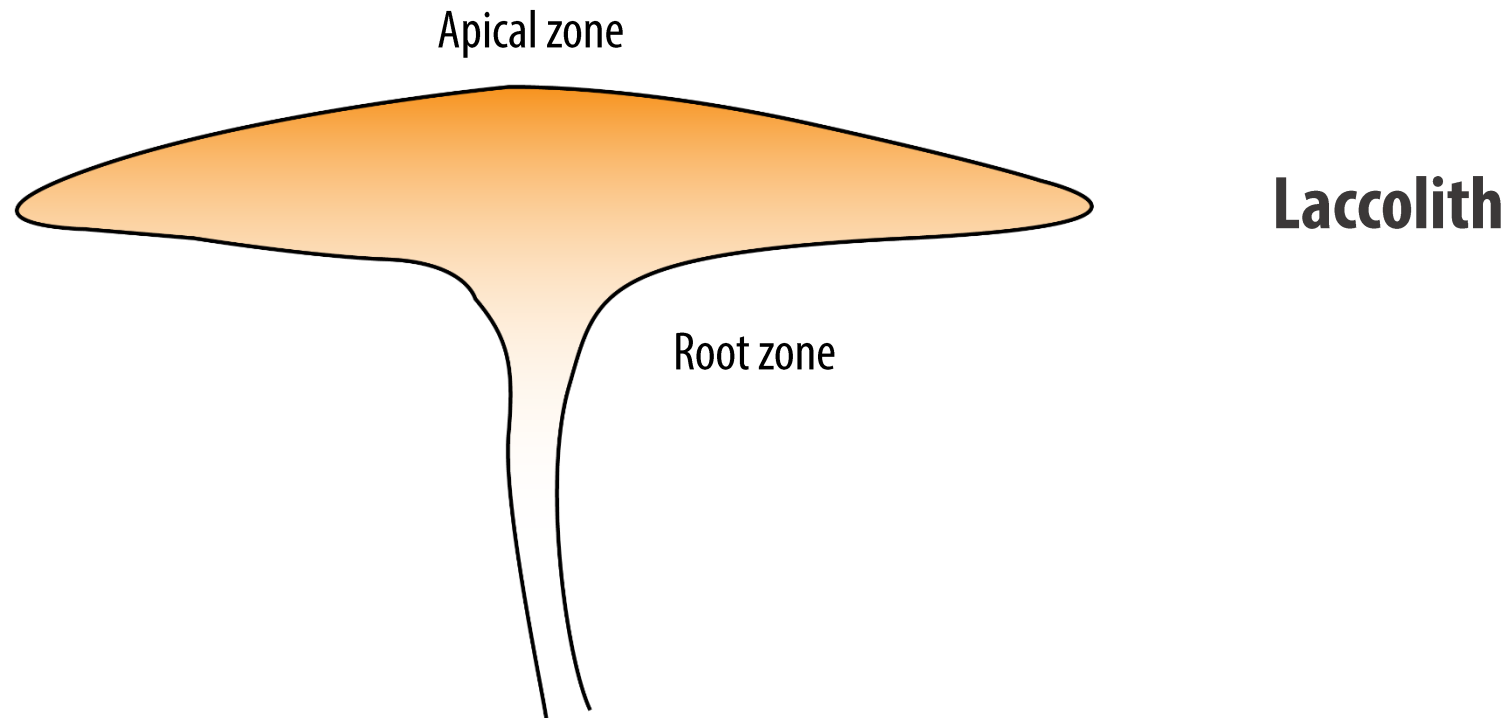
3. Origin of pegmatite textures

**The magmatic-hydrothermal
transition**

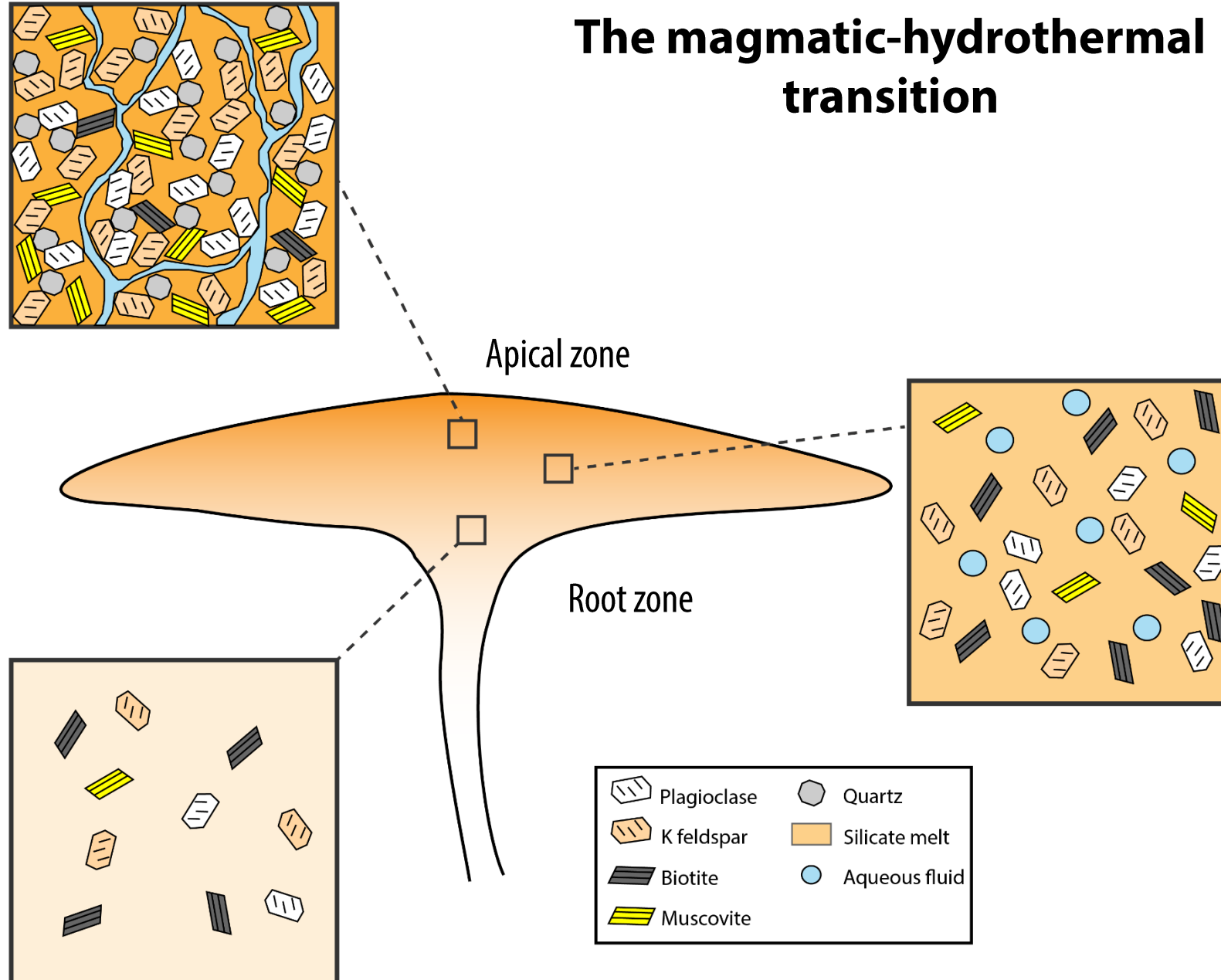


3. Origin of pegmatite textures

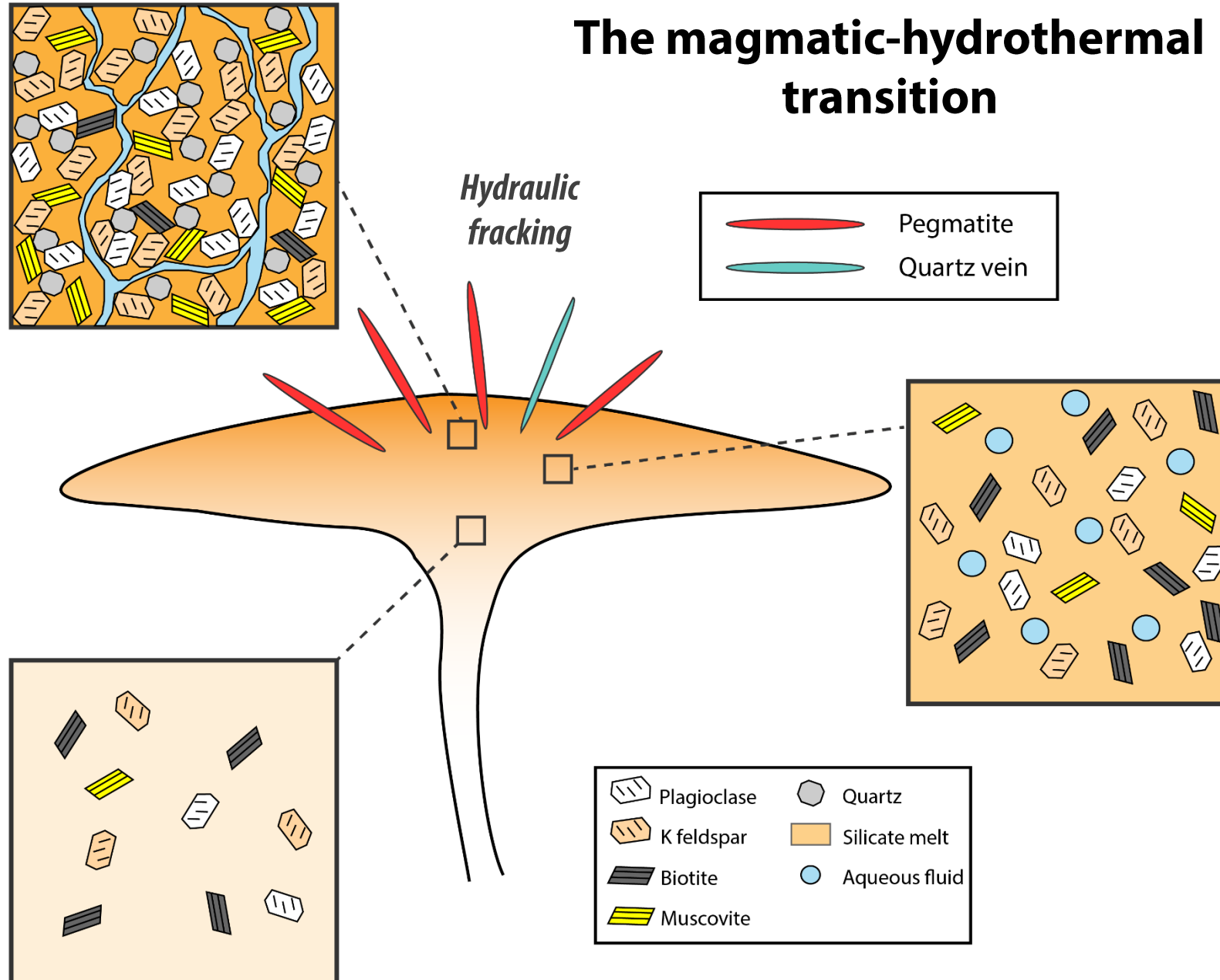
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3. Origin of pegmatite textures

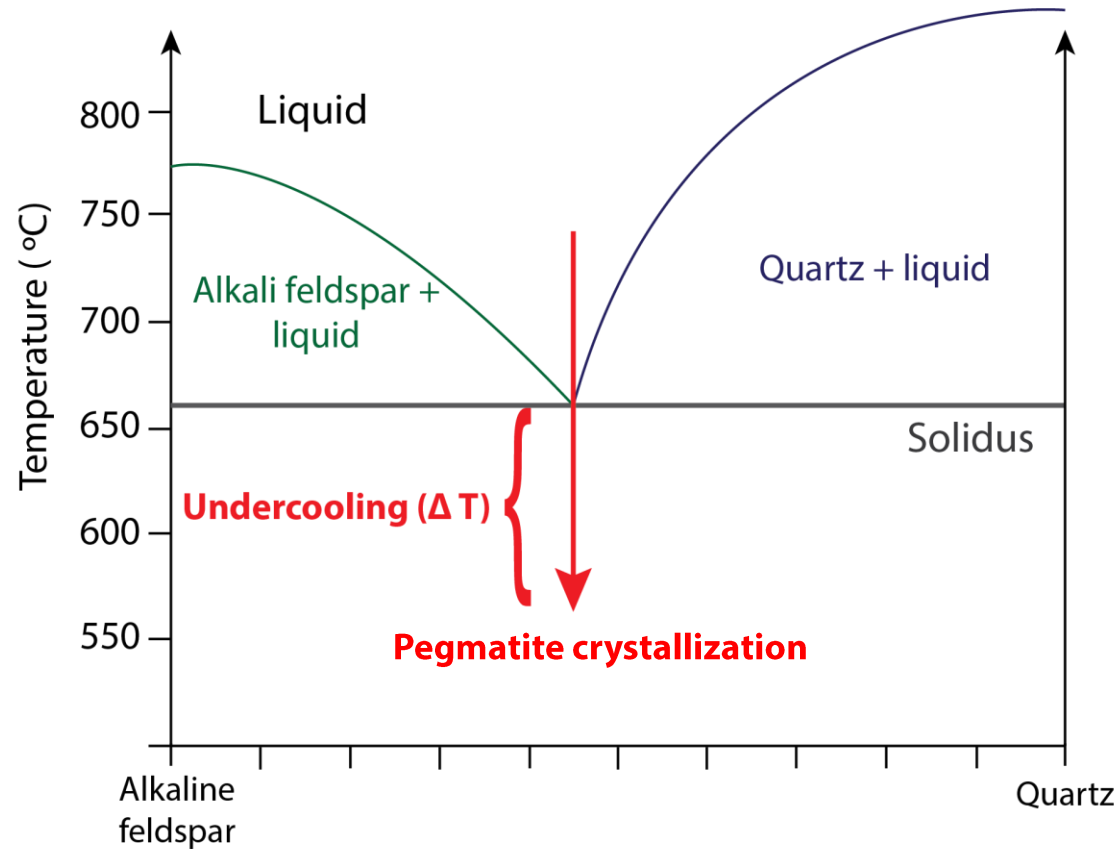


3. Origin of pegmatite textures



3. Origin of pegmatite textures

Undercooling (or supercooling) processes



Geochemical and experimental studies have shown that numerous pegmatites crystallized at 550 - 450 °C degrees, so 100 – 200 °C below the wet granite solidus (~650°C°).

This means that the pegmatite magma is metastable (undercooled) when it begins to crystallize.

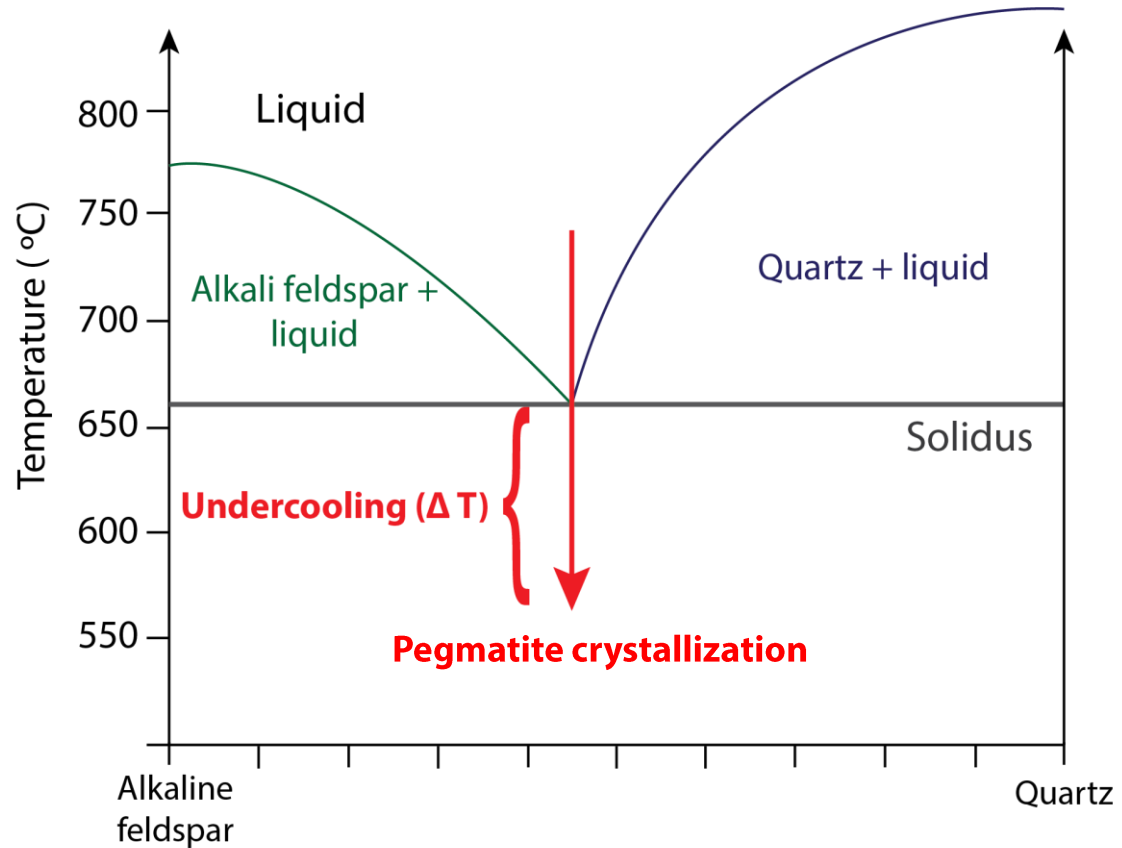
This can be due to the emplacement in cooler country-rocks or fluid exsolution

3. Origin of pegmatite textures

Undercooling (or supercooling) processes



Photo by S. Salvi (Cap de Creus, Spain)



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3. Origin of pegmatite textures

Undercooling (or supercooling) processes



<https://www.youtube.com/watch?v=laH8uq5oFD8>

When a phase is liquid at a temperature below its solidus temperature (~ 650 °C for a granitic magma and 0 °C for the water) we say that it is metastable (undercooled)

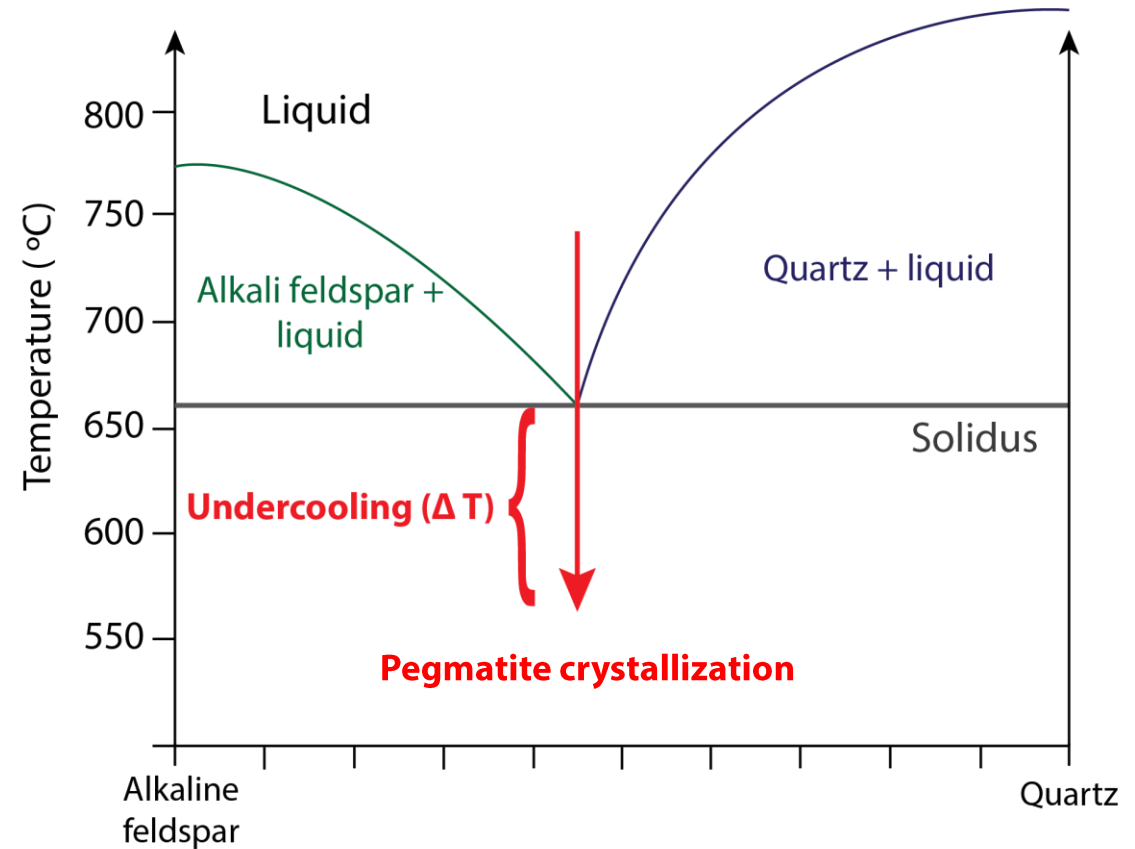
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Undercooling (or supercooling) processes

Graphic granite



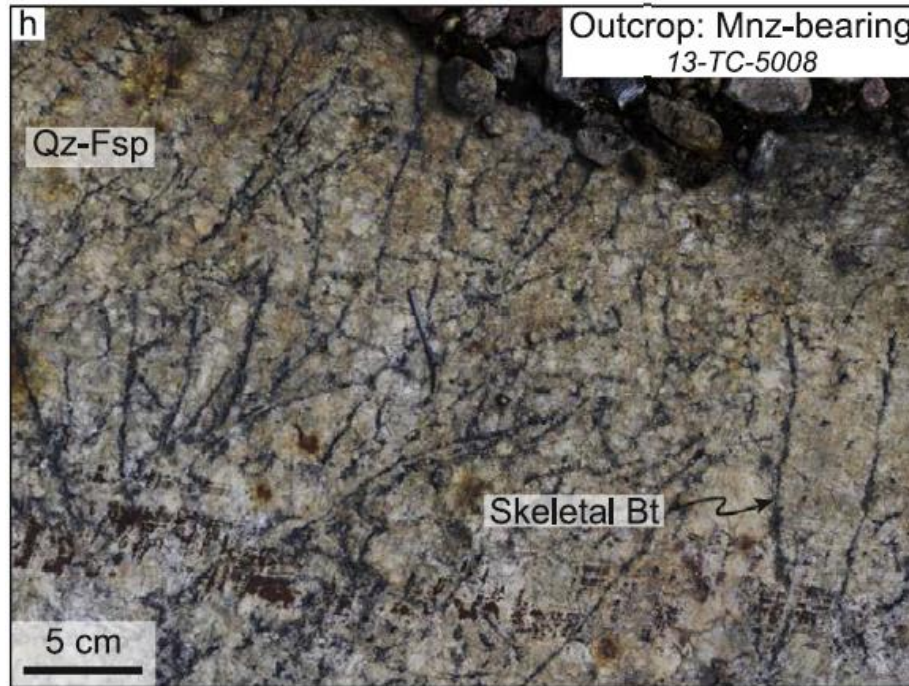
London and Morgan (2012)



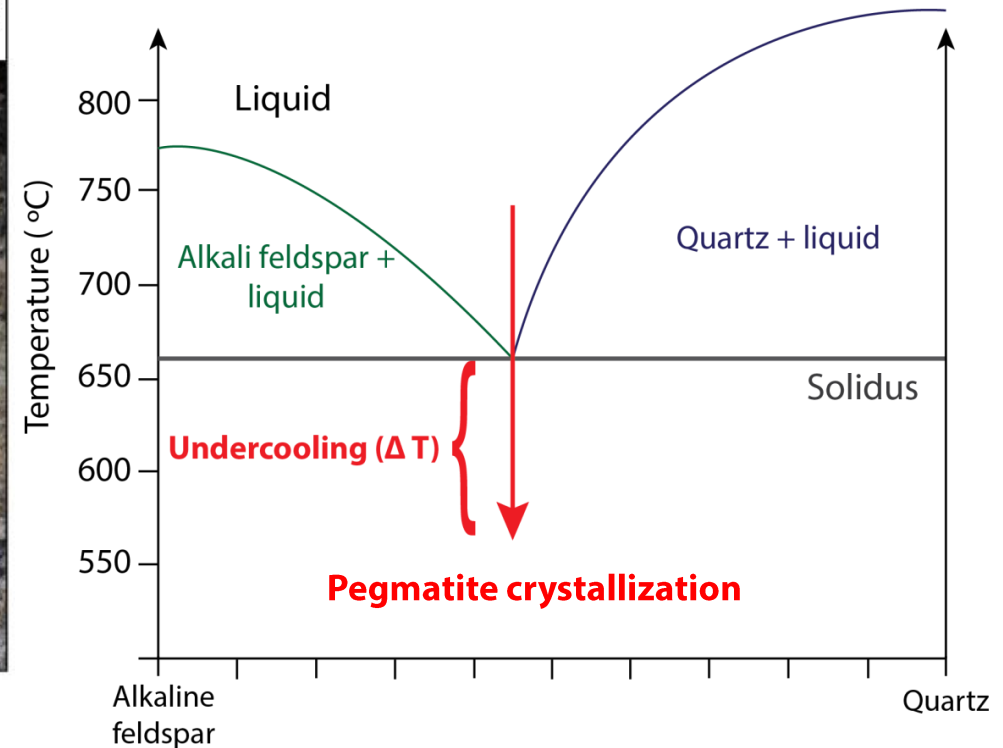
Graphic textures that are unique to pegmatites have been only reproduced experimentally by undercooling processes. They form along a rapidly advancing crystallization front.

3. Origin of pegmatite textures

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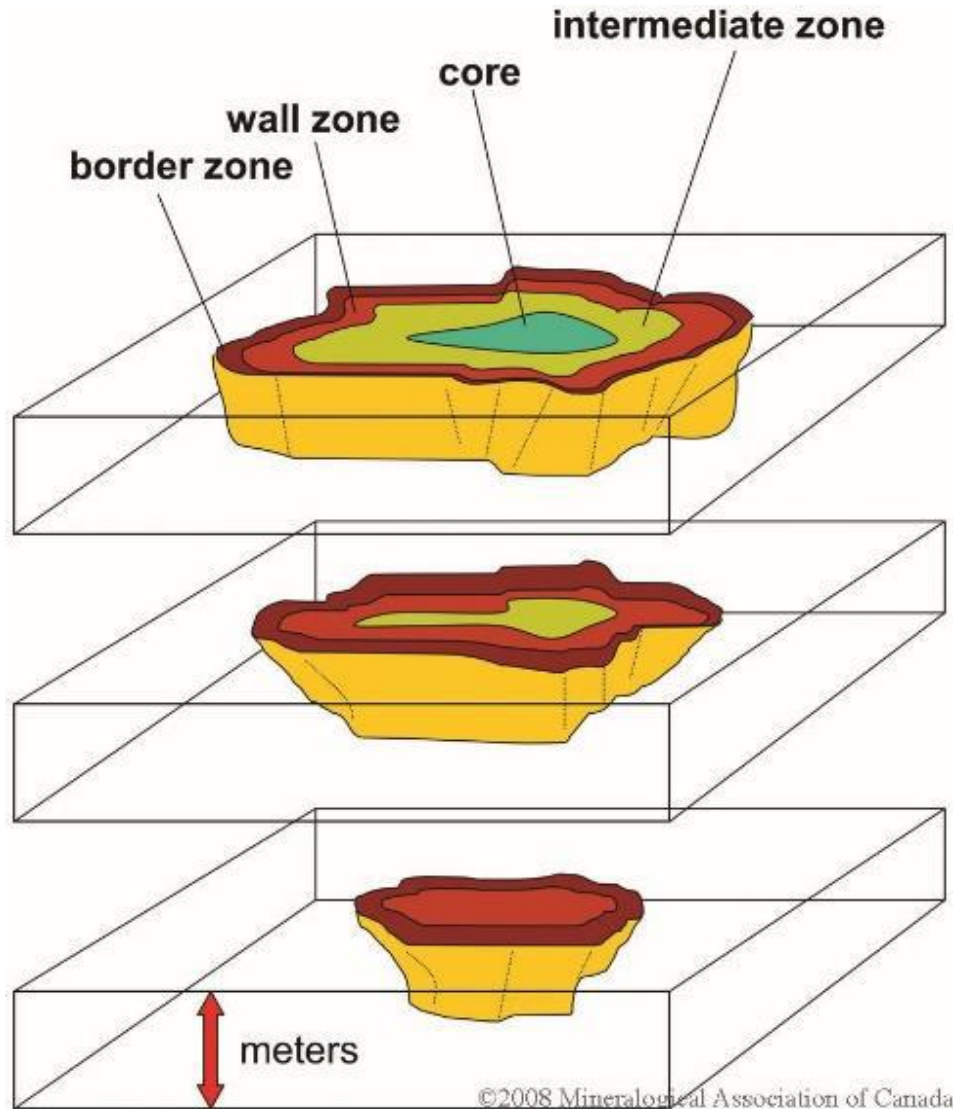


Skeletal biotite, Canada (Quebec), Turlin et al. (2017)



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Idem for skeletal textures

3. Origin of pegmatite textures



Variable internal textures from homogeneous to heterogeneous

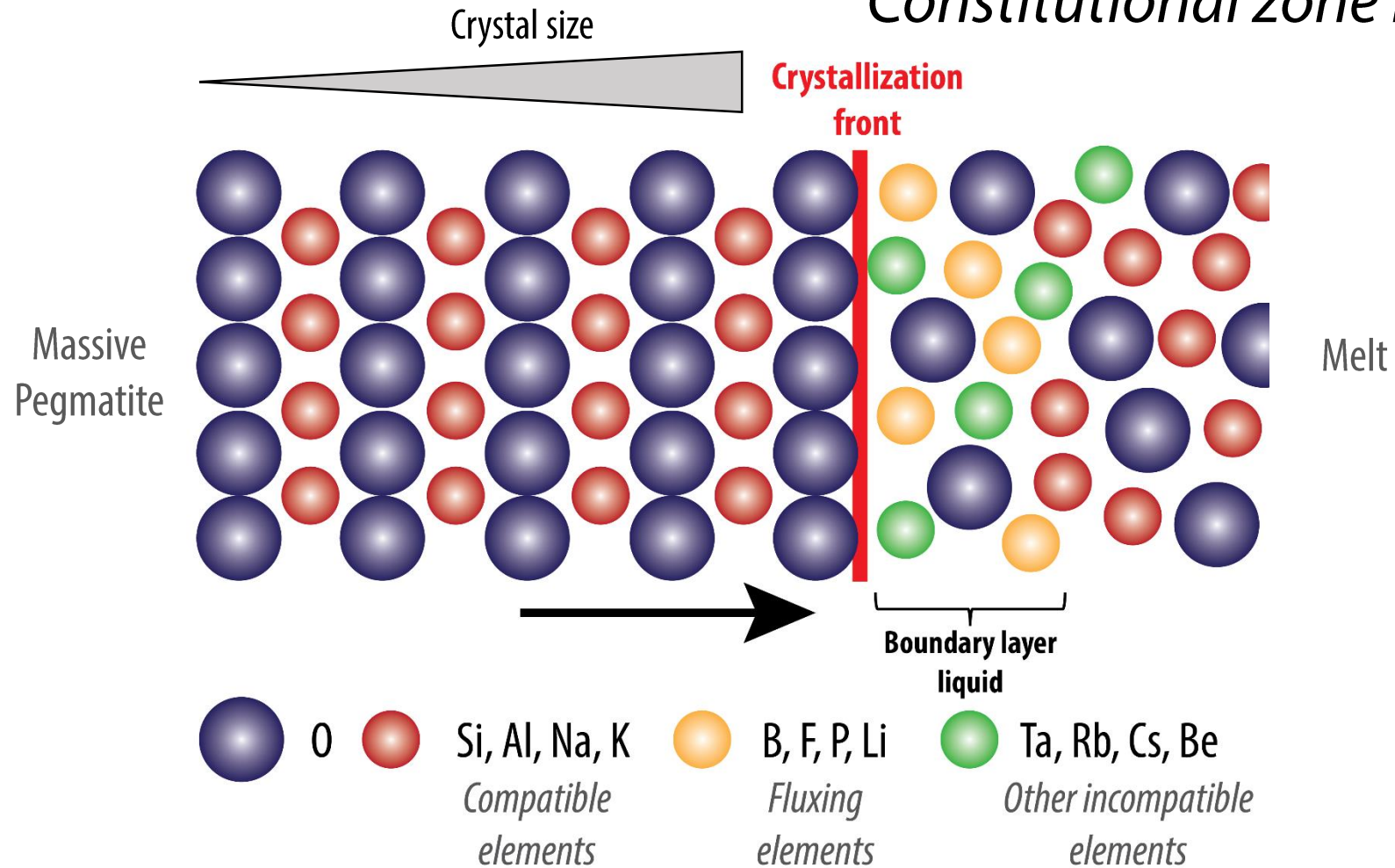
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- Intermediate zone: blocky texture (rare elements minerals bearing)
- Core: quartz-(feldspar)

Typical internal zonation observed in granitic pegmatites

London (2008)

3. Origin of pegmatite textures

Undercooling processes *Constitutional zone refining*

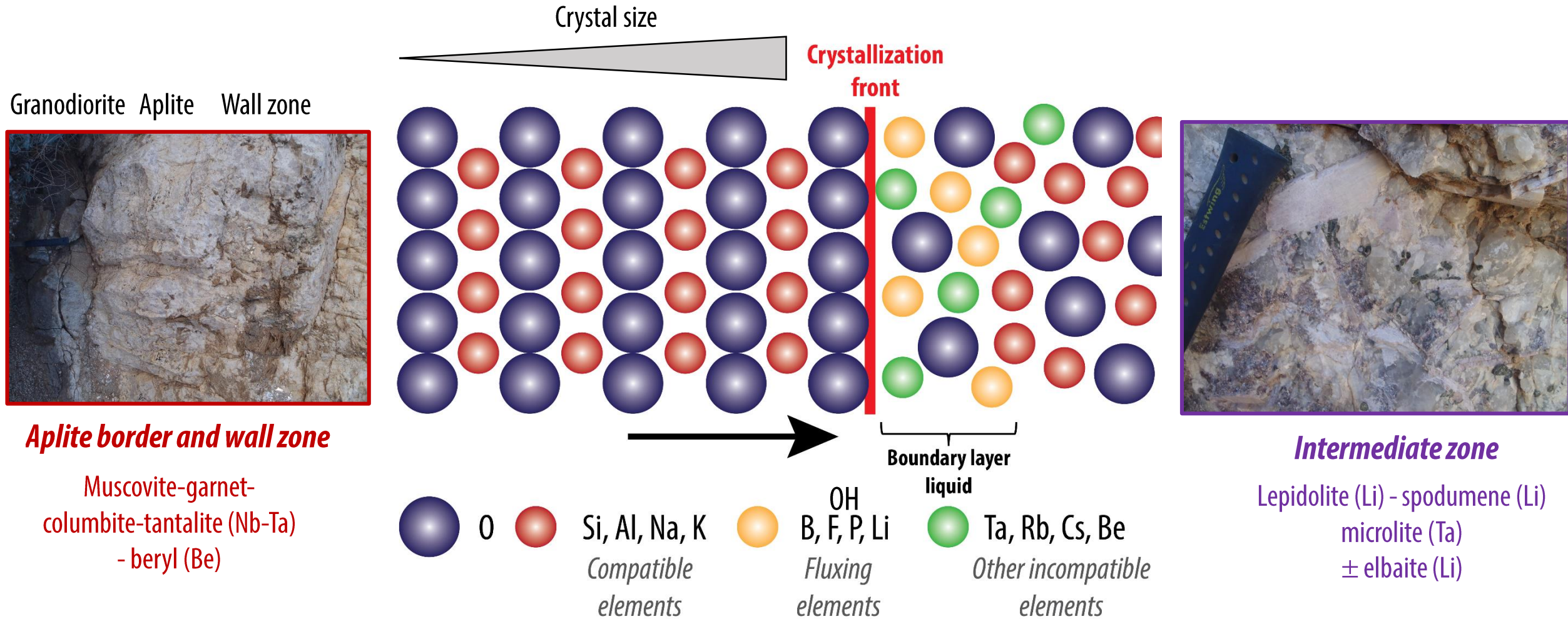


Undercooling of a fluxing element-rich melt will lead to high rate of crystallization and induce the formation of a boundary layer liquid enriched in fluxing element. The migration of this boundary layer from the border to the core of the pegmatite will induce an increase of the crystal size and an enrichment in incompatible element.

Schematic model representing the behavior of elements during constitutional zone refining (modified from London and Morgan 2012)

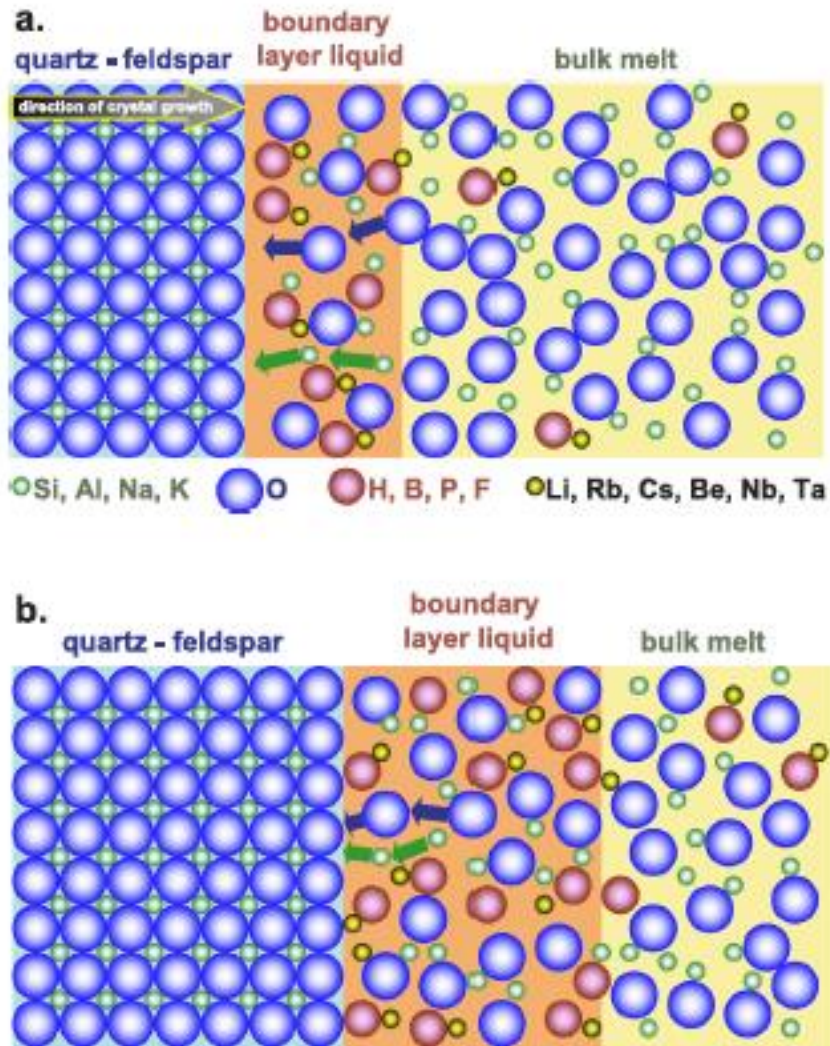
Evolution interne des pegmatites minéralisées

Constitutional zone refining / migration of a boundary layer liquid?



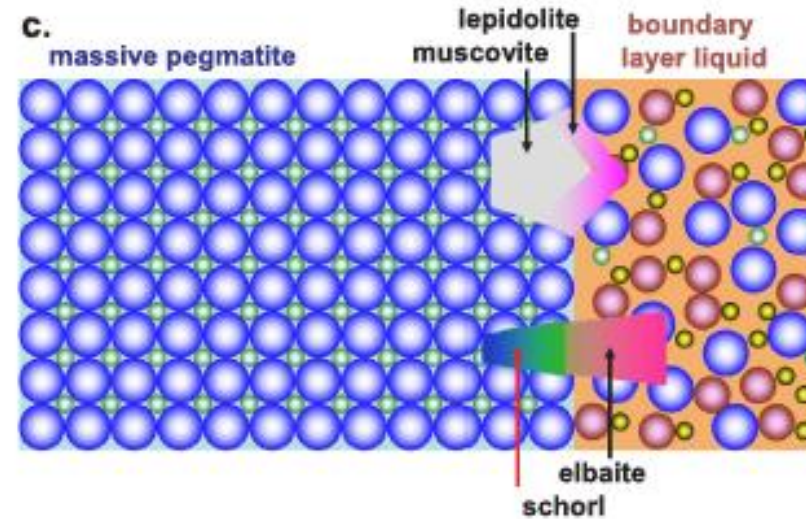
Modified from London 2014

3. Origin of pegmatite textures



Undercooling processes

Constitutional zone refining



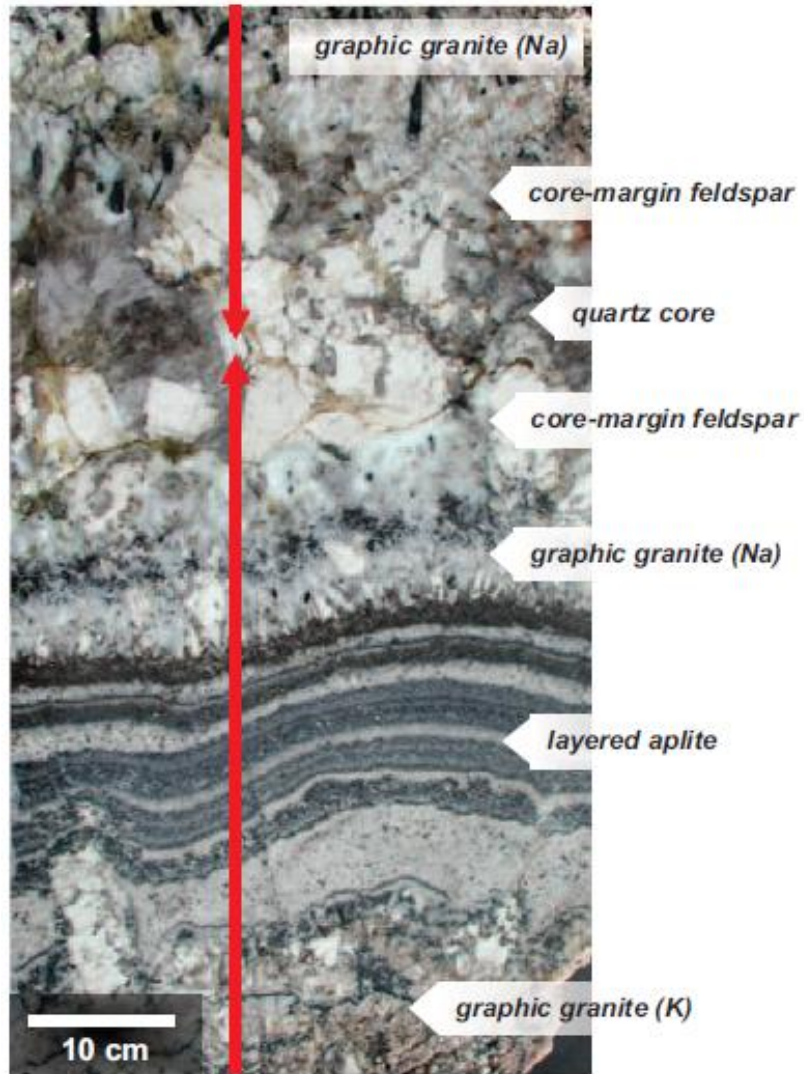
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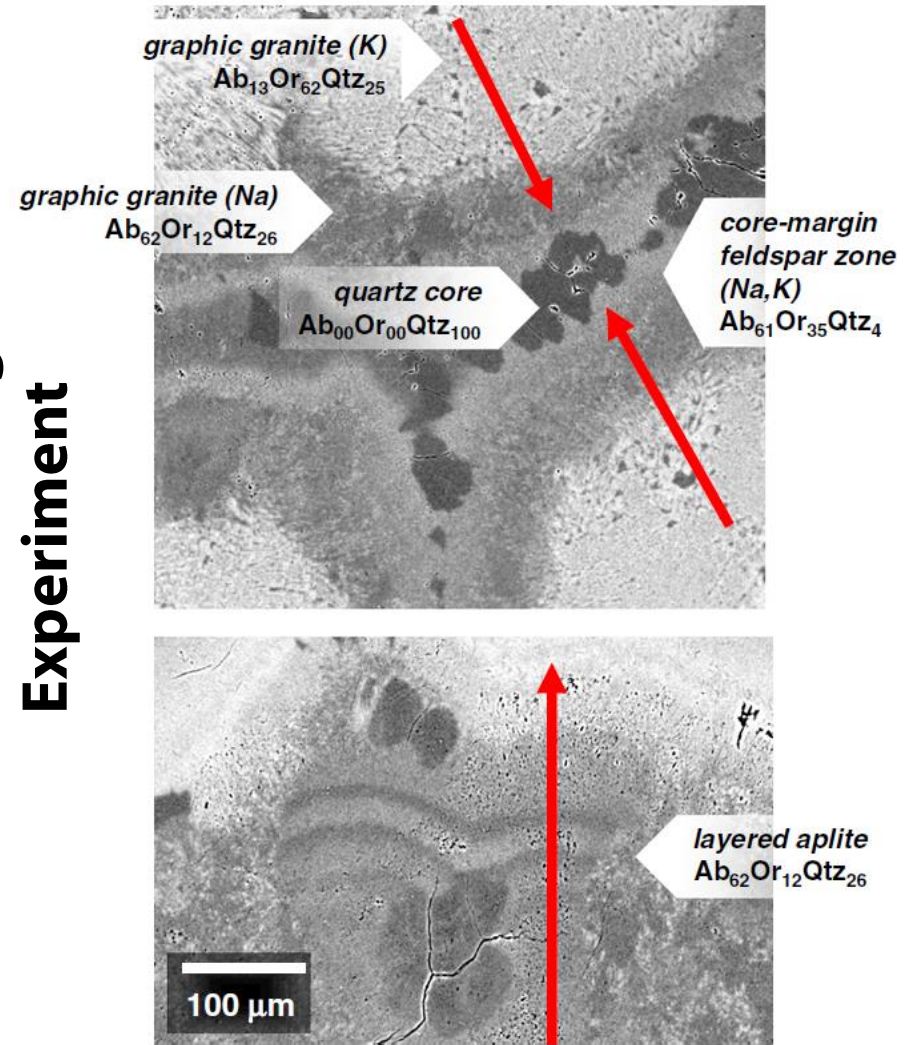
3. Origin of pegmatite textures

Undercooling (or supercooling) processes

Nature



Undercooling
Experiment

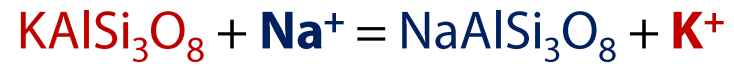


Undercooling experiment using a flux element-bearing haplogranitic glass can reproduce many pegmatite textures

London and Morgan (2012)

3. Pegmatite textures

Albitization:

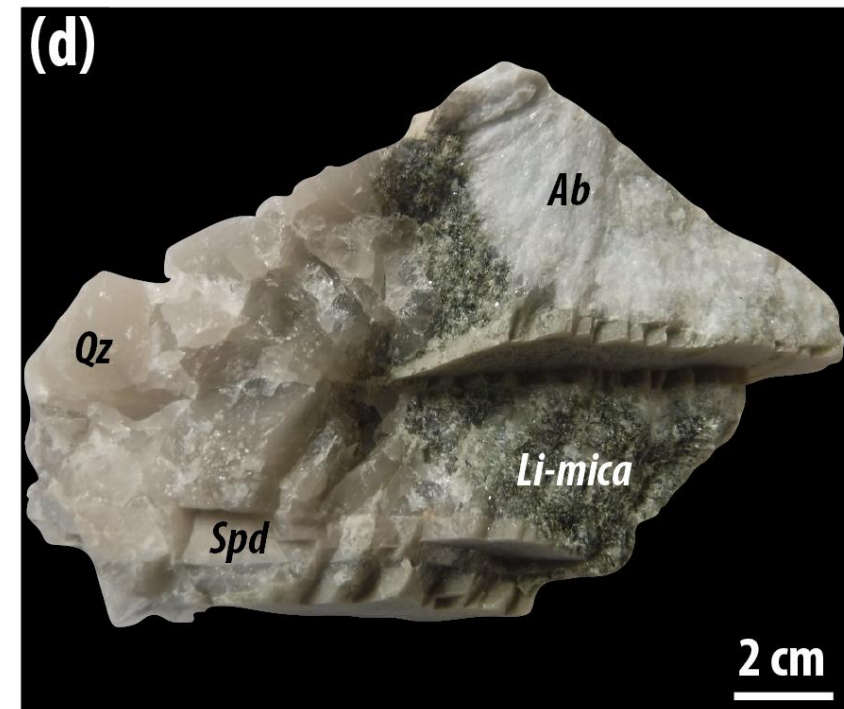
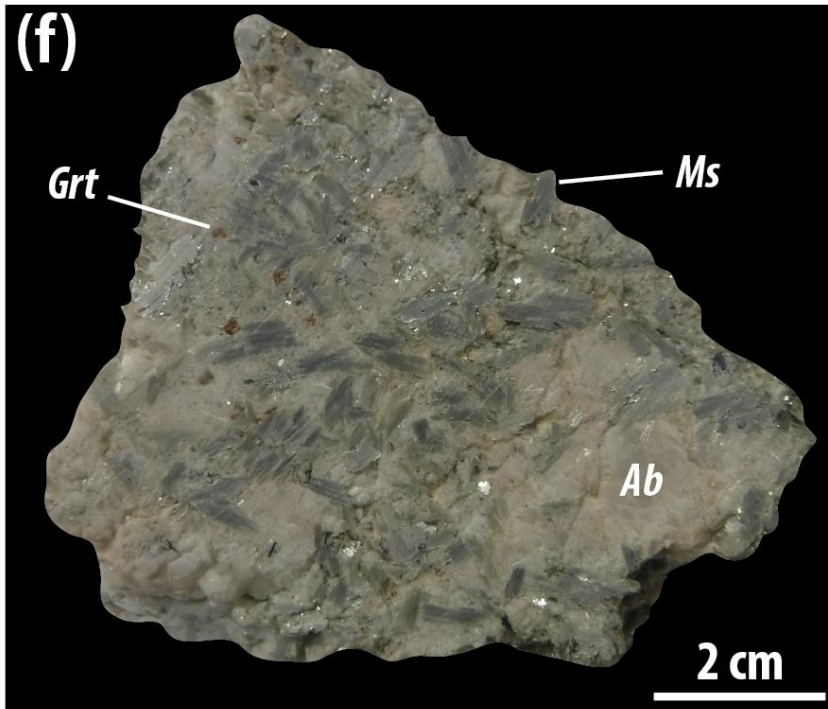


Greisenization:



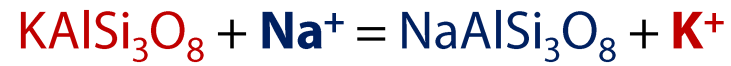
Metasomatism

(greisens and albitites)



3. Pegmatite textures

Albitization:



K-feldspar

Albite

Greisenization:



Albite

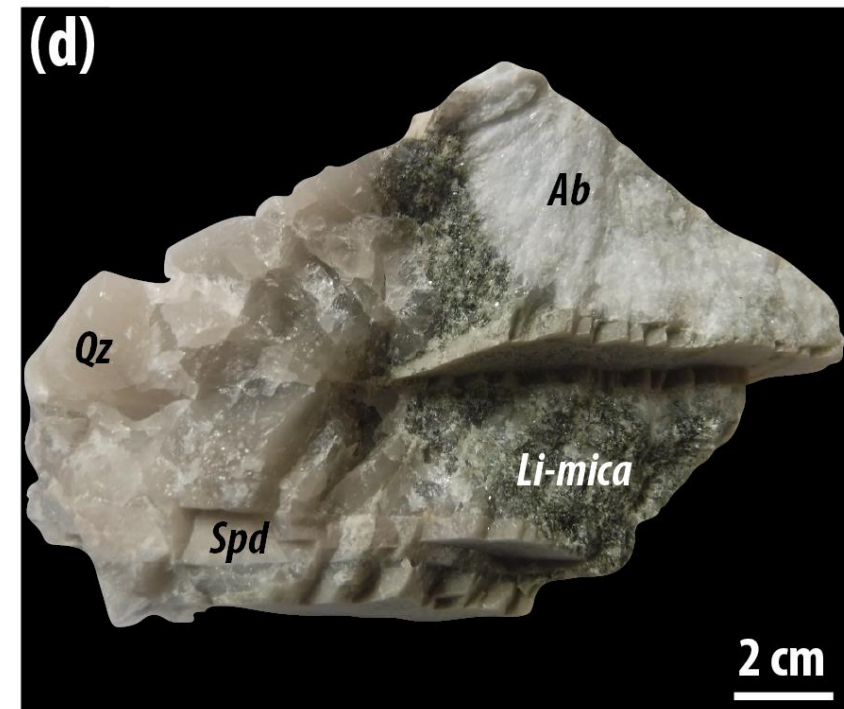
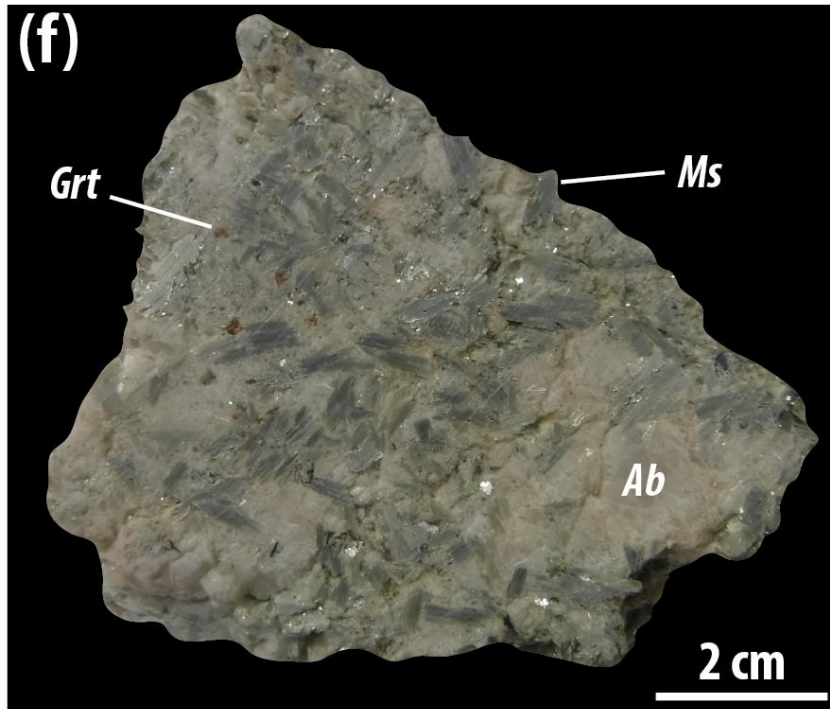
Acidic fluid

Muscovite

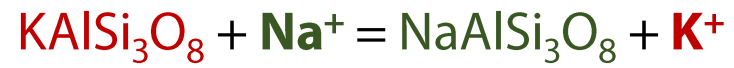
Quartz

Metasomatism

(greisens and albitites)



Albitization:



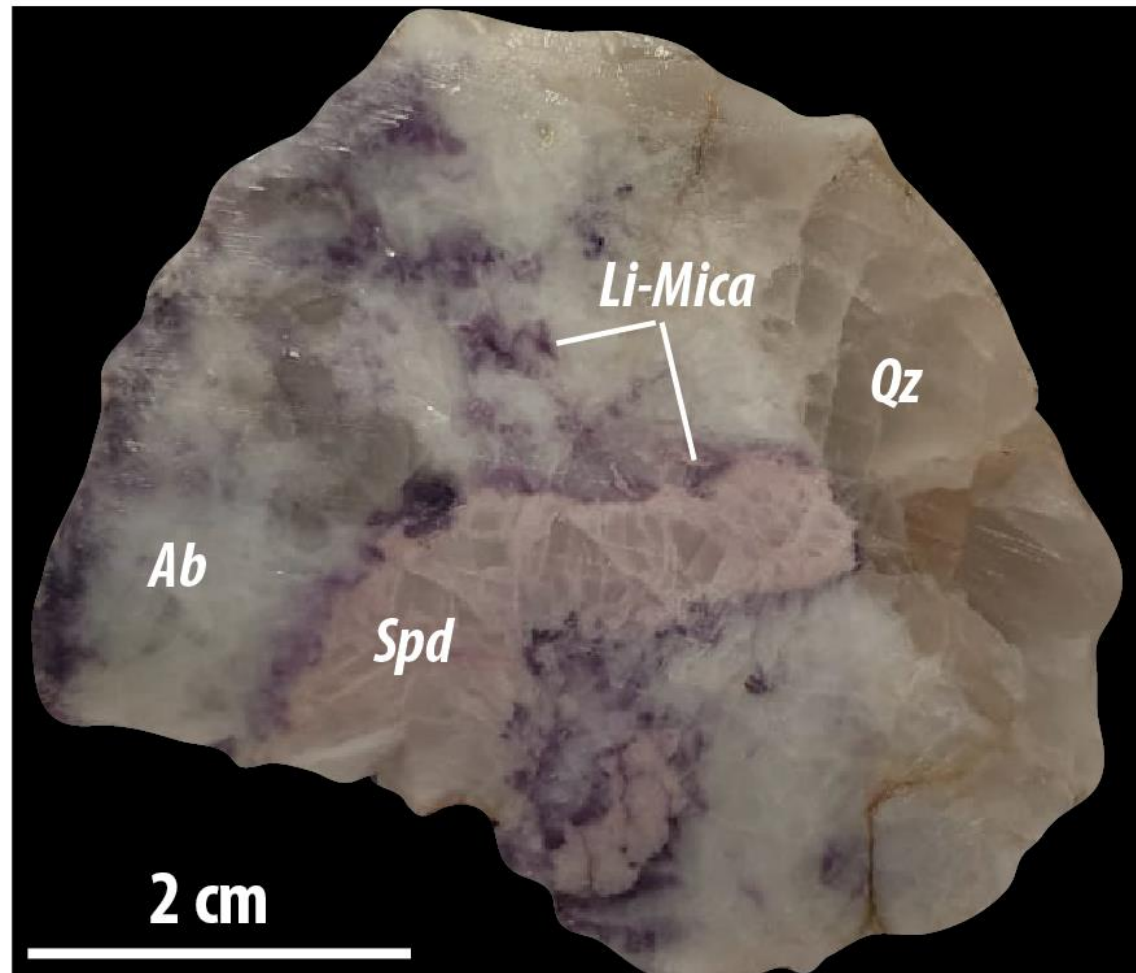
K-feldspar

Albite

3. Pegmatite textures

Metasomatism

(greisens and albitites)

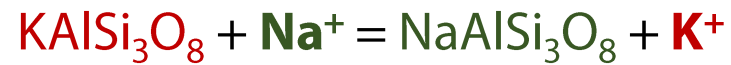


Ab: albite

Qz: quartz

Lpd: lépidolite

Albitization:



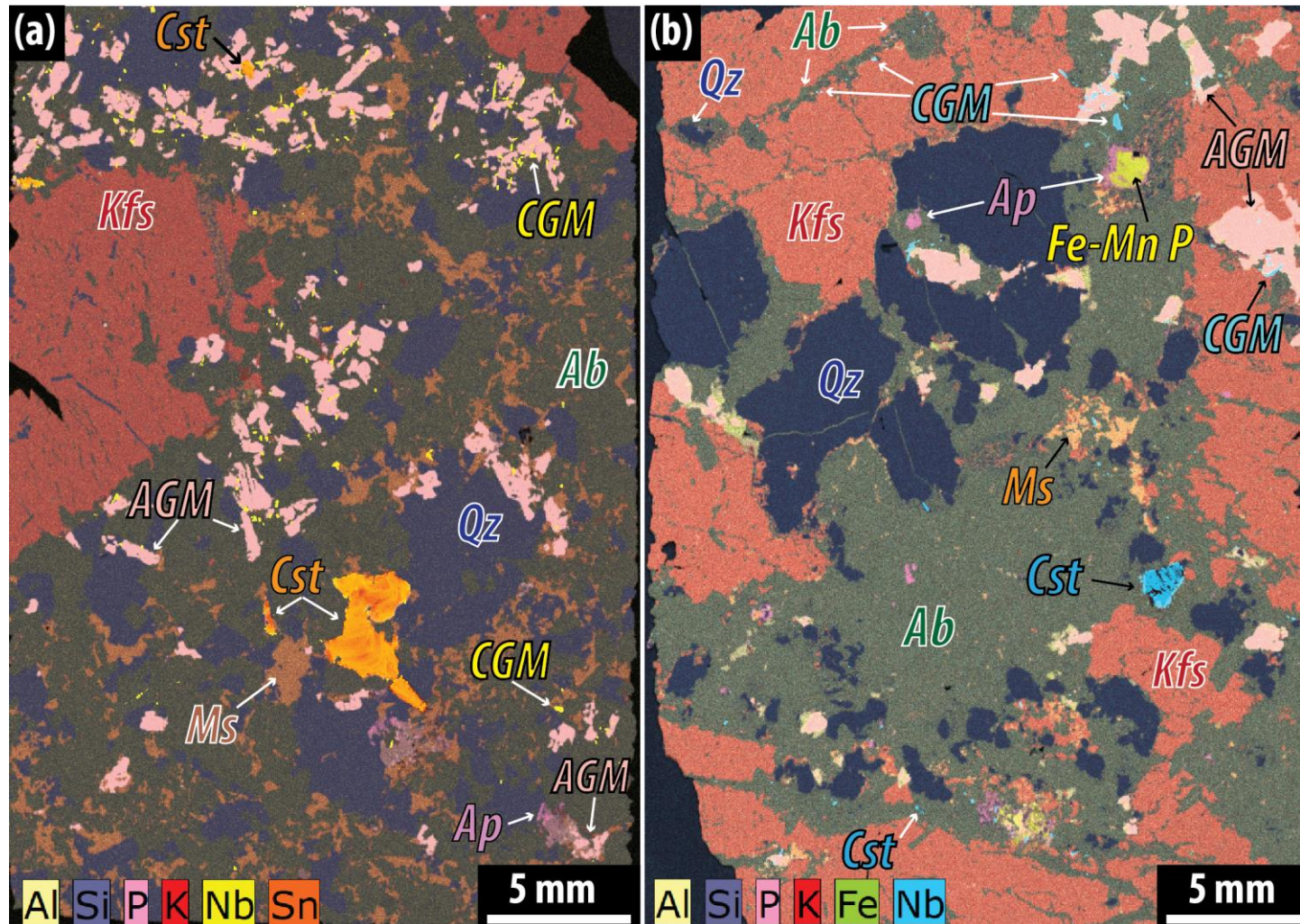
K-feldspar

Albite

3. Pegmatite textures

Metasomatism

(greisens and albitites)



CGM: columbite-group minerals

AGM: amblygonite-group minerals

Cst: cassiterite

Ab: albite

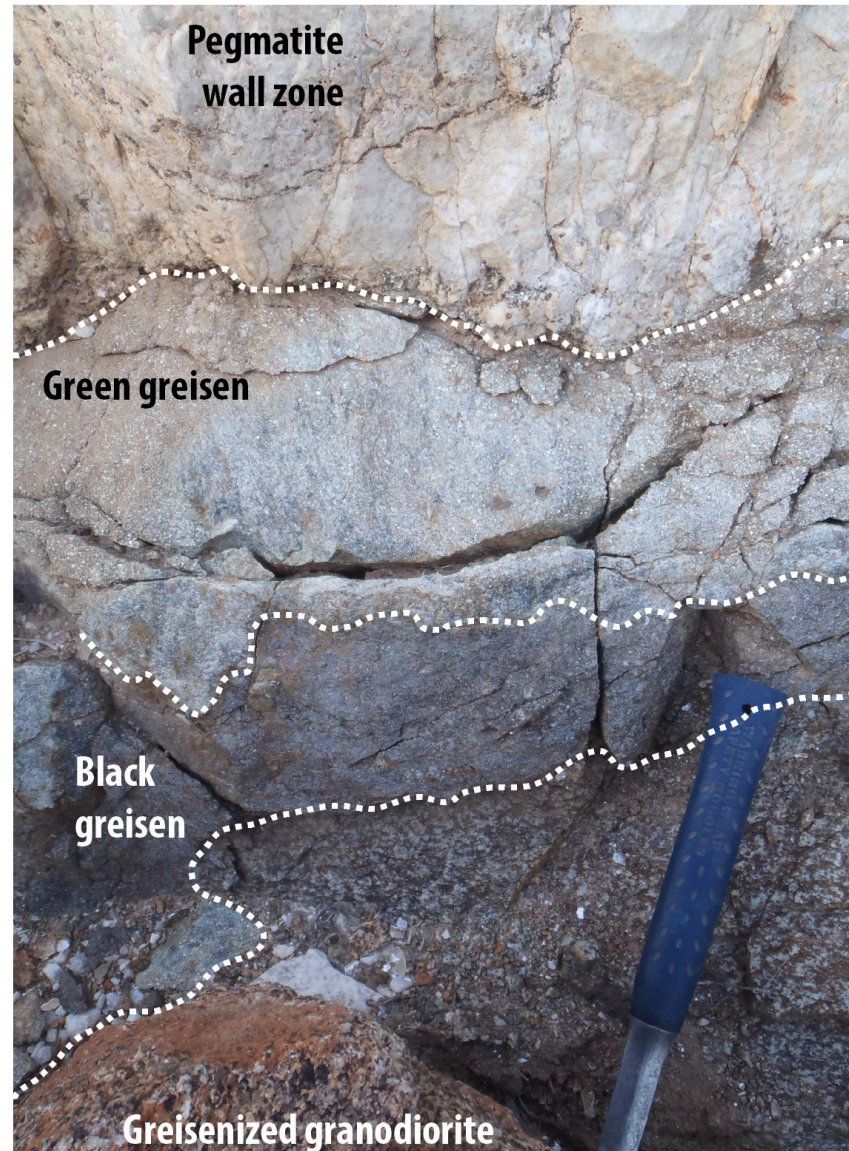
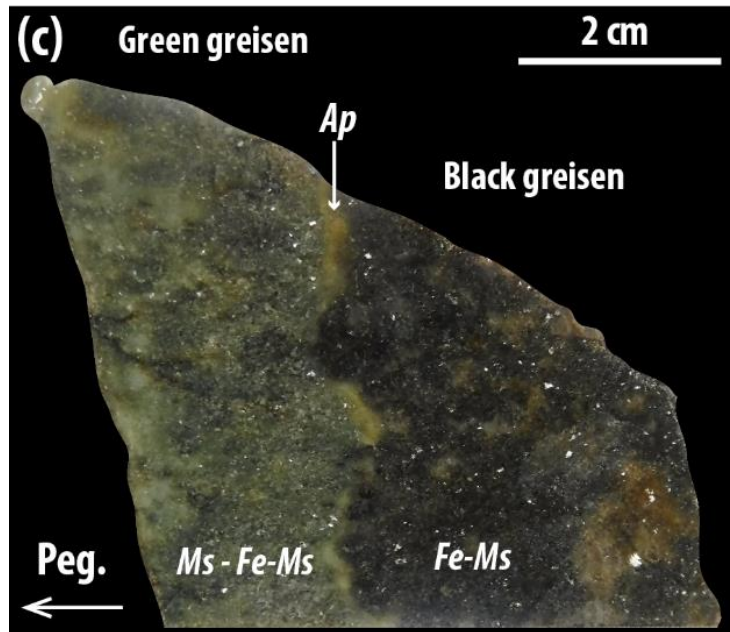
Kfs: K-feldspar

Fe-Mn P: Fe-Mn phosphate

Ms: muscovite

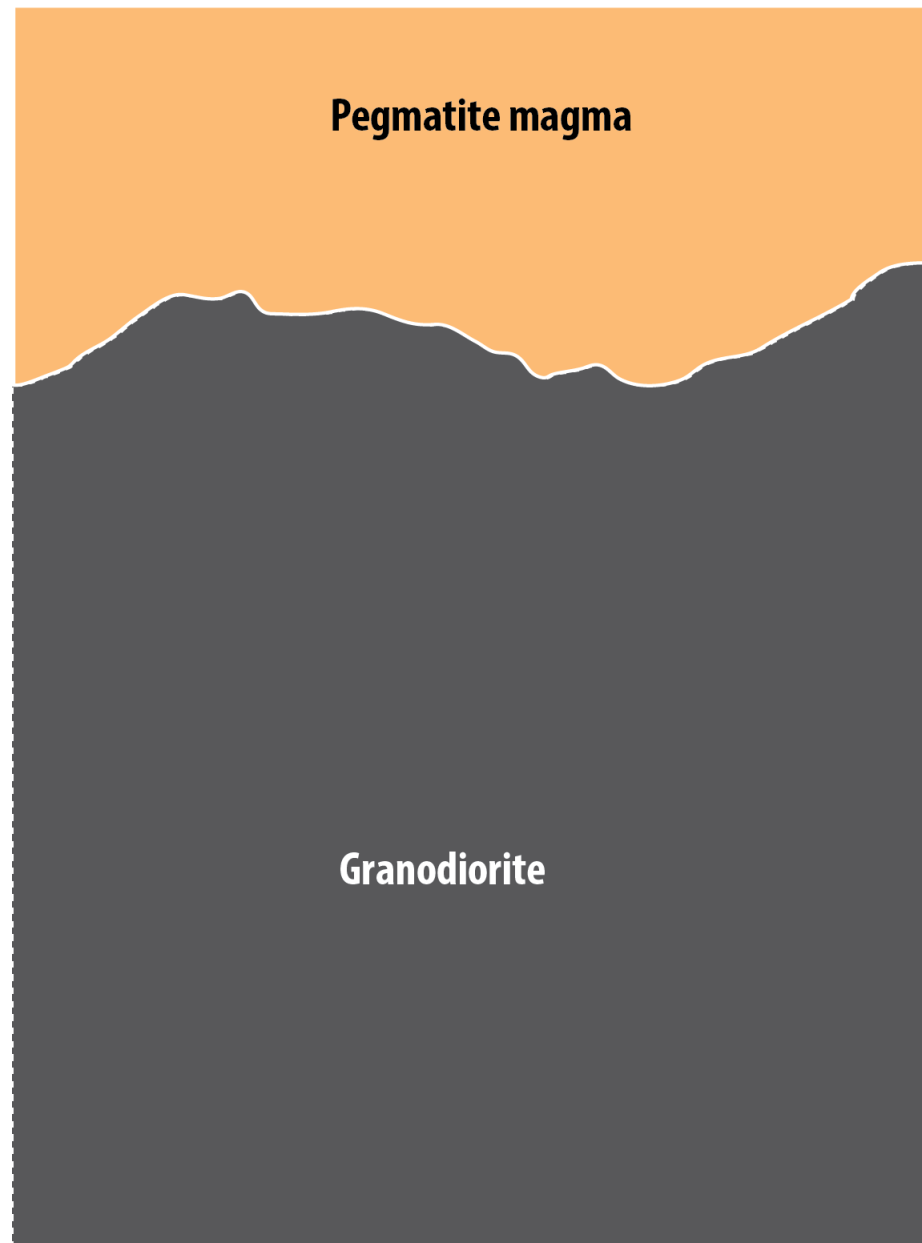
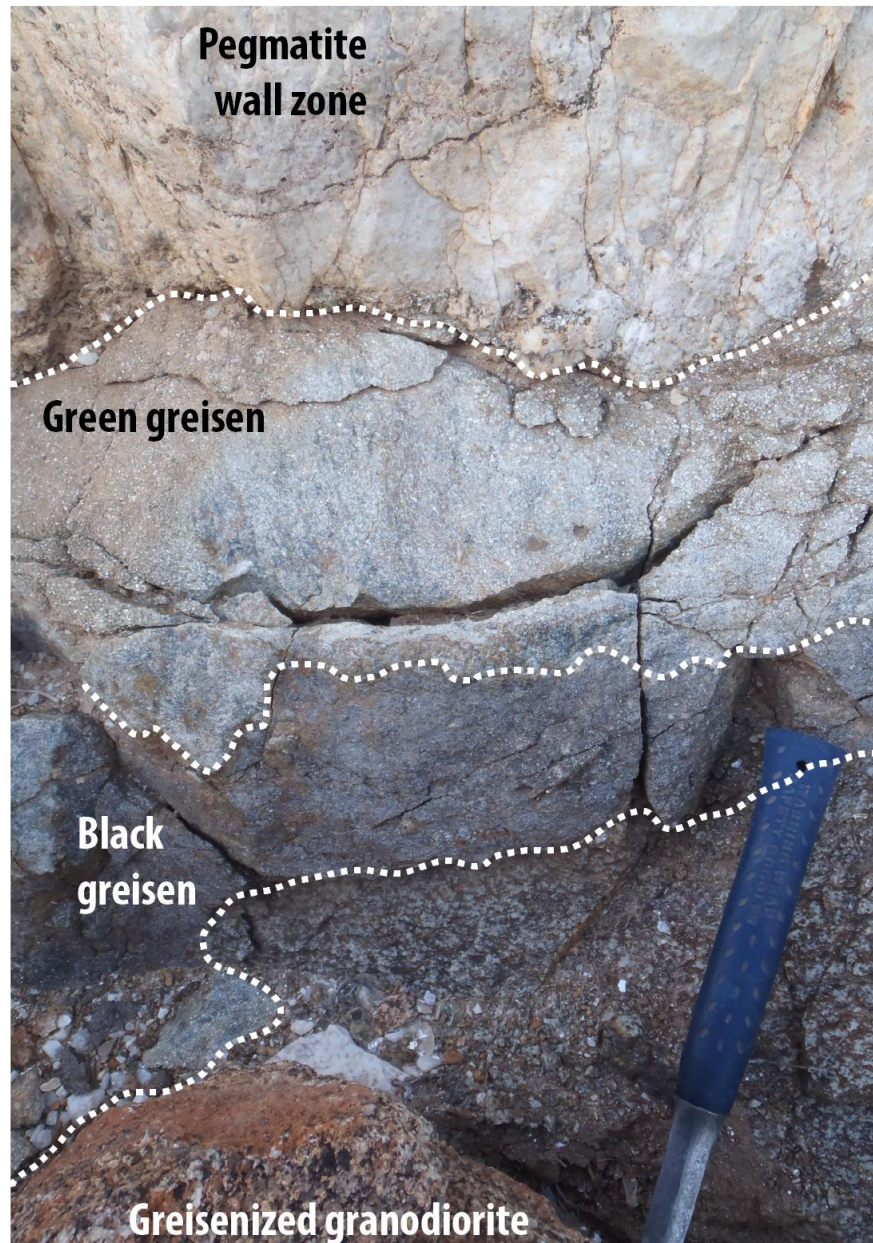
Qz: quartz

3. Origin of pegmatite textures

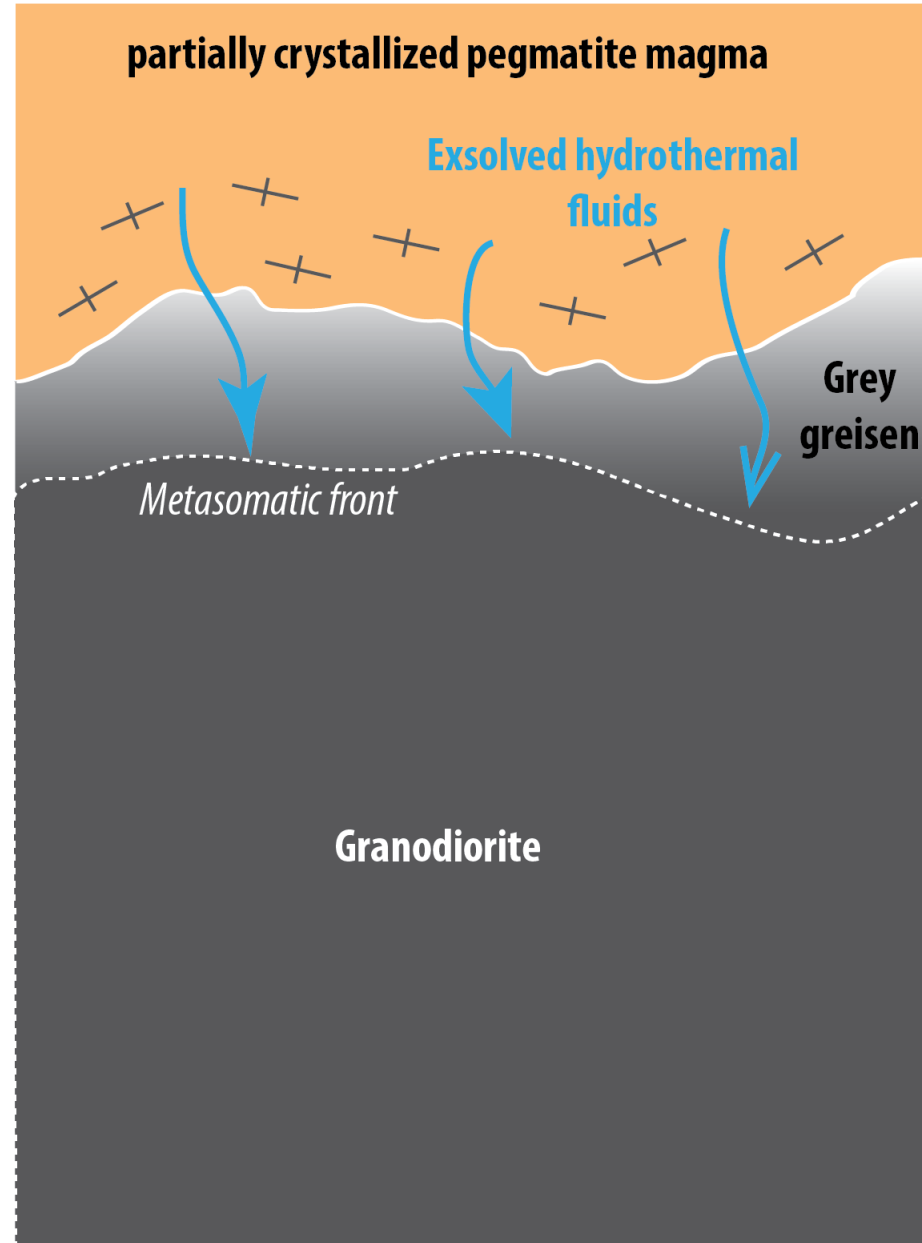
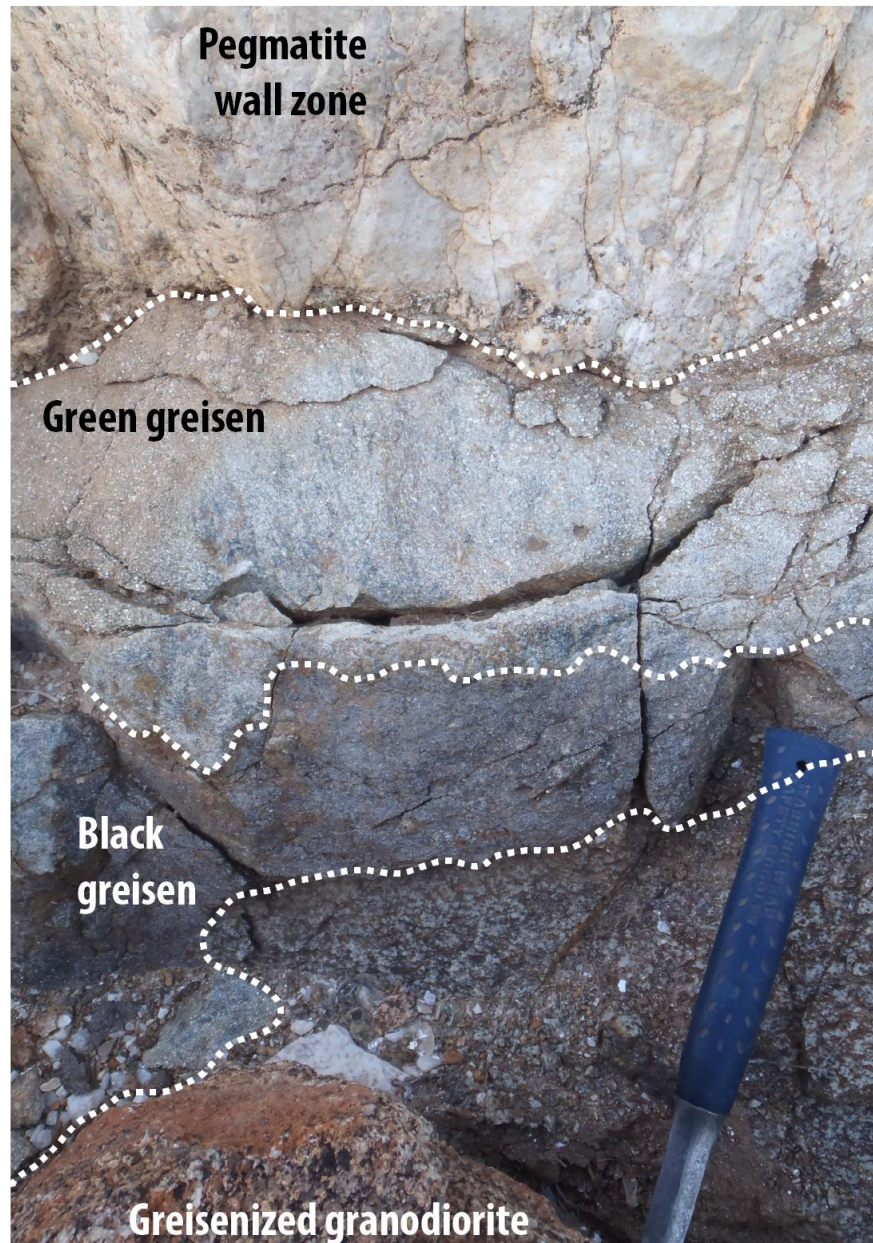


Greisenization

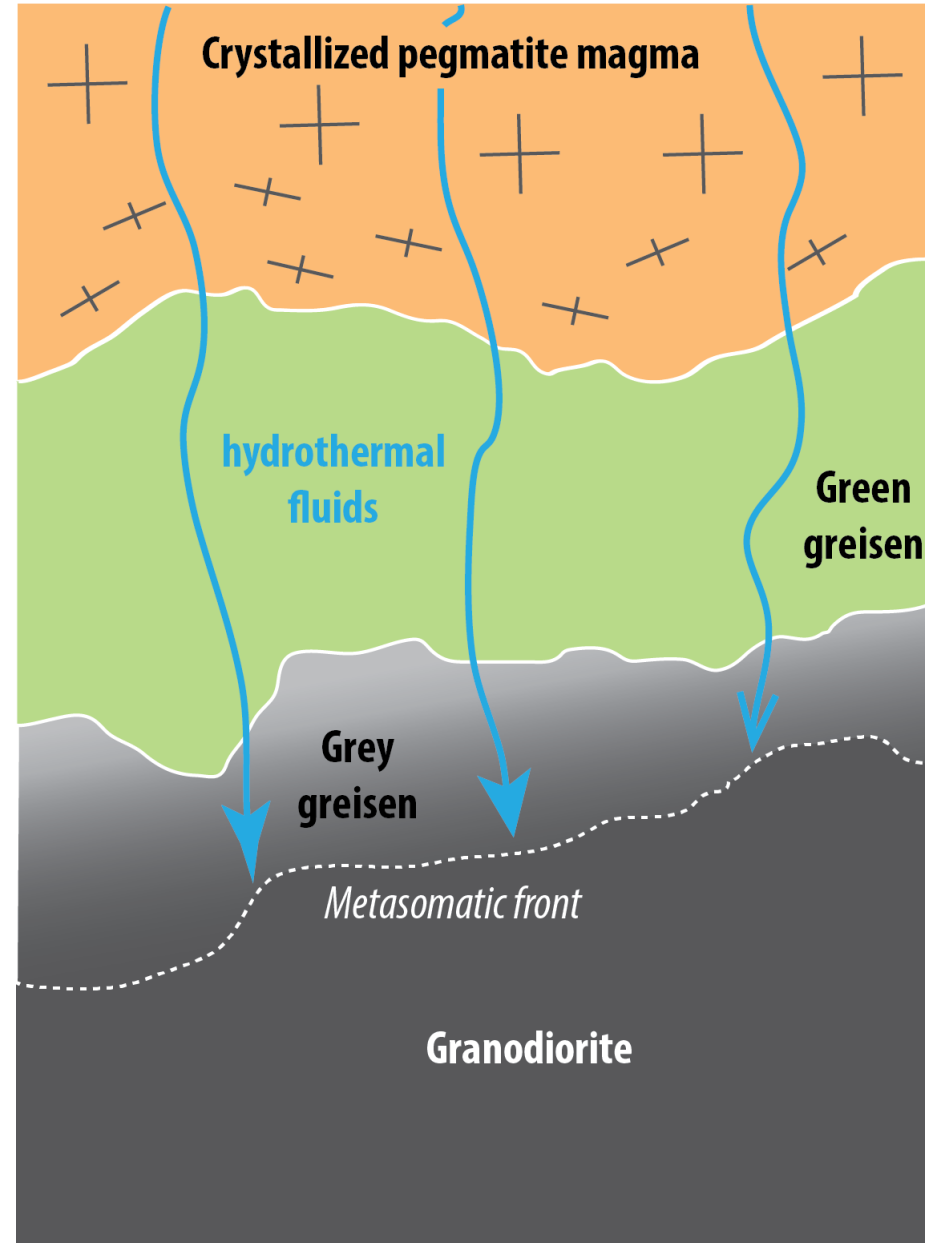
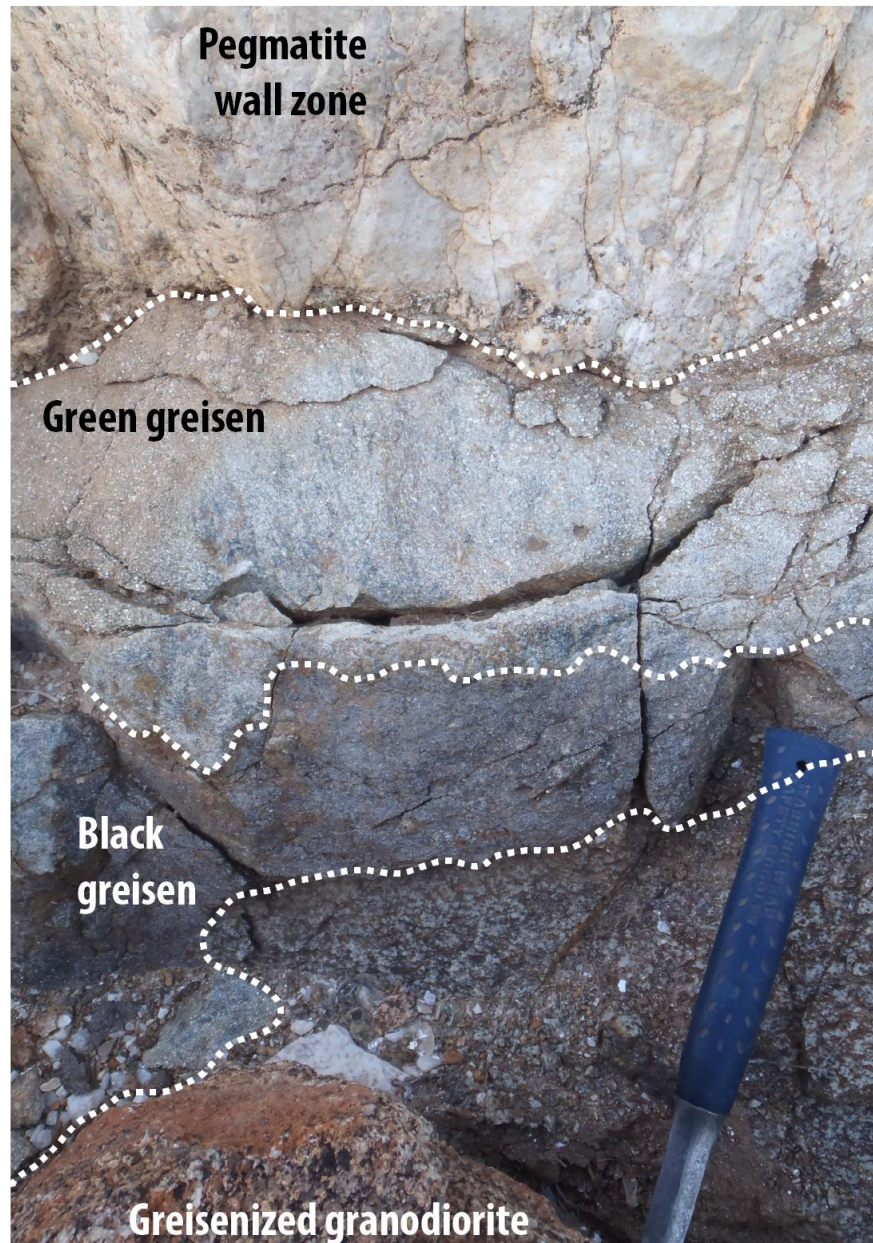
Greisenized country-rock, Orange River pegmatite belt, South Africa (Ballouard et al. 2020)



Greisenization

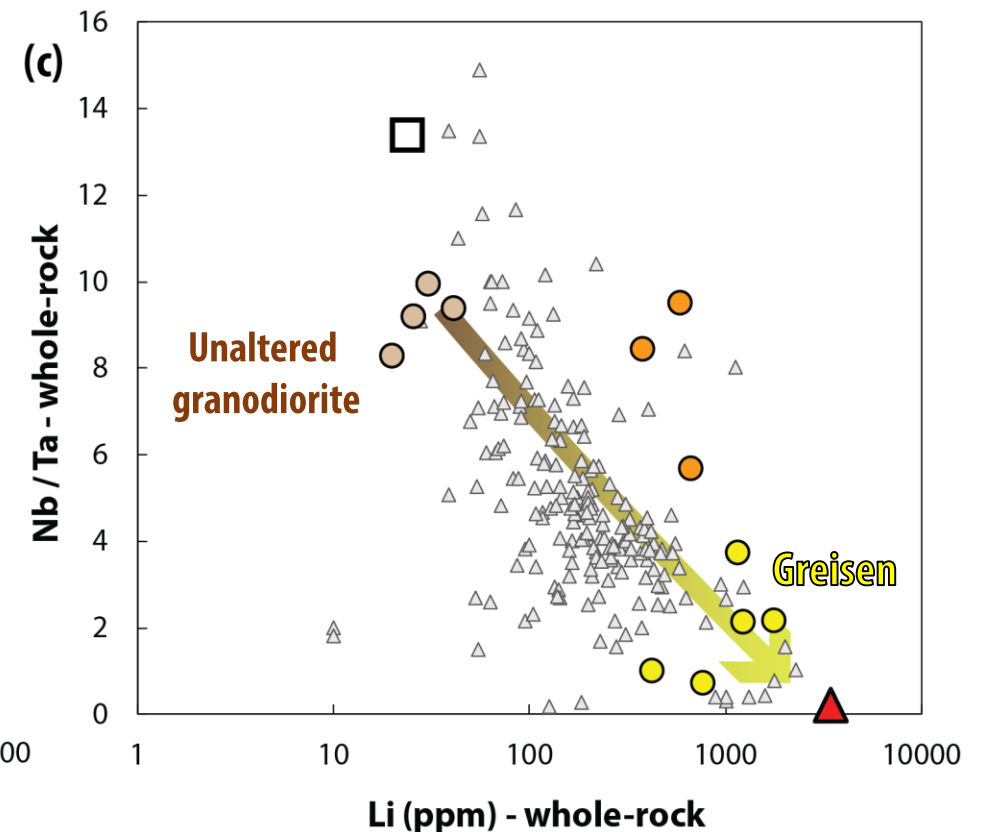
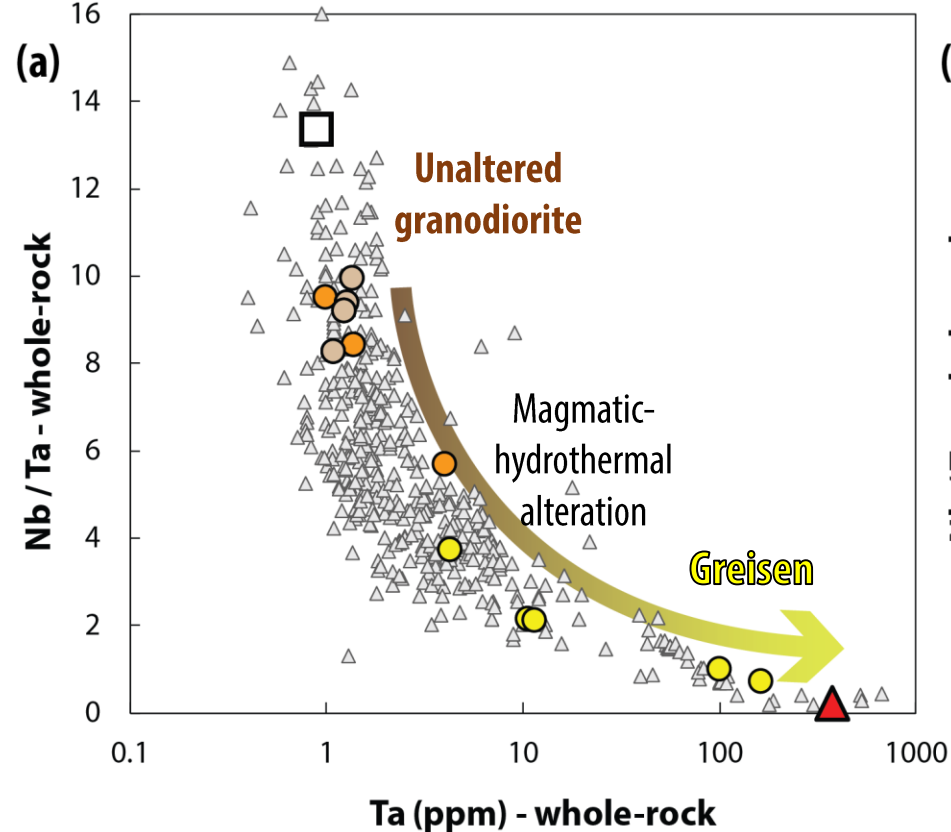
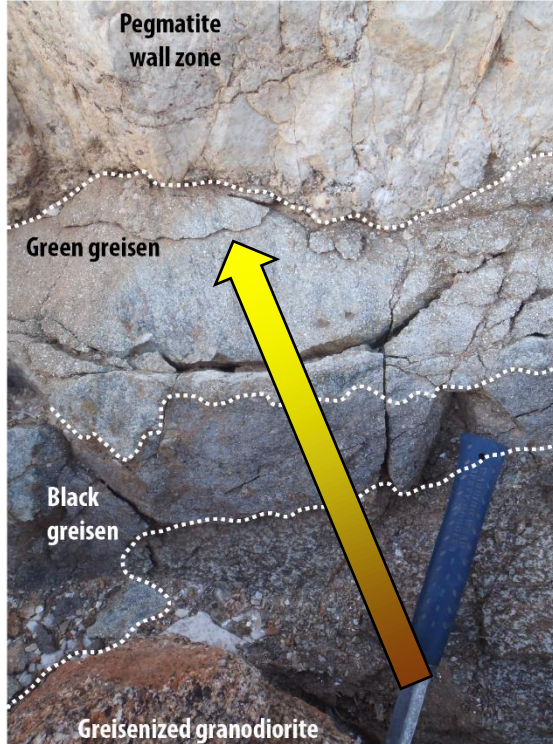


Greisenization



Greisenization

Whole-rock trace element analyses



- Unaltered Gaarseep granodiorite (*Macey et al. 2017*)
- Weakly and moderately metasomatized Gaarseep granodiorite (*this study*)
- Strongly metasomatized Gaarseep granodiorite (*this study*)

- △ Highly peraluminous granites (*Ballouard et al. 2016*)
- ▲ Tanco LCT pegmatite (*Stilling et al. 2006*)
- Upper continental crust (*Rudnick and Gao, 2004*)

Ballouard et al. 2020

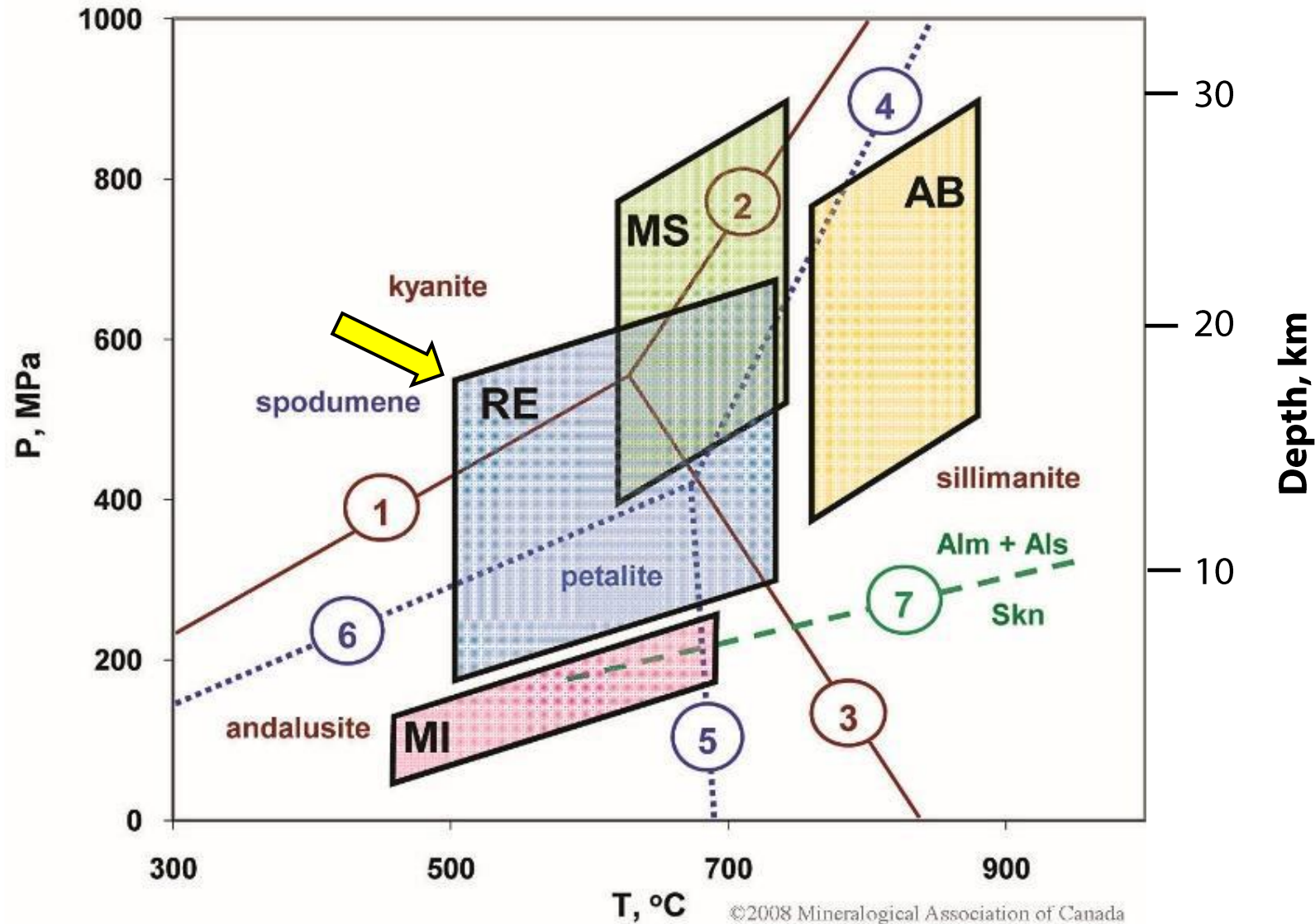
Evidence for strong hydrothermal mobility of metals during pegmatite magma crystallization

3. Origin of pegmatites

Take home messages

- Pegmatites are interpreted as water- and fluxing element-rich (or –bearing) granitic melts. They may represent the last liquids exsolved from a granitic body but are also common in migmatitic domes
- Fluxing elements (F, B, P and H₂O) decrease the nucleation and increase elemental diffusion in silicate melts and favor the crystallization of big crystals
- Undercooling processes, that increase crystal growth rate and inhibit crystal nucleation, play also a major role and can explain several pegmatite textures (graphic, skeletal, ...) as well as their internal zonation
- Greisens and albitites generally form at the end of the crystallization of pegmatites during the interaction with exsolved hydrothermal fluids. These fluids are able to mobilize a significant amount of rare-metals

4. The rare elements (RE) pegmatites



P-T diagram of pegmatite stability. **AB = Abyssal pegmatites, MS = Muscovite pegmatites, RE: Rare elements pegmatites, MI = Miarolitic pegmatites** (London, 2008).

4. The rare elements pegmatites

*Amphibolite –
granulite facies*

*Amphibolite
facies*

*Amphibolite –
upper greenschist
facies*

*Lower amphibolite
- greenschist
facies*

Class	Subclass	Type	Subtype	Family
Abyssal	HREE			NYF
	LREE			
	U			NYF
	BBe			LCT
Muscovite				
Muscovite– rare element	REE			NYF
	Li			LCT
Rare element	REE	allanite–monazite euxenite gadolinite		NYF
	Li	beryl	beryl–columbite beryl–columbite–phosphate	LCT
		complex	spodumene petalite lepidolite elbaite amblygonite	
		albite–spodumene albite		
Miarolitic	REE	topaz–beryl gadolinite–fergusonite		NYF
	Li	beryl–topaz spodumene petalite lepidolite		LCT

The classification of granitic pegmatites (Černý et al., 2012)

4. The rare elements pegmatites

The LCT and NYF pegmatite families

Class	Subclass	Type	Subtype	Family
Rare element	REE	allanite–monazite euxenite gadolinite		NYF
	Li	beryl complex albite–spodumene albite	beryl–columbite beryl–columbite–phosphate spodumene petalite lepidolite elbaite amblygonite	LCT

*Amphibolite –
upper greenschist
facies*

LCT for Li – Cs – Ta enrichment ➡ related to highly peraluminous “S-type” granites
=> muscovite-bearing peraluminous granites

NYF for Nb – Y – F enrichment ➡ related to peralkaline, metaluminous or slightly
peraluminous “A -type” granites

4. The rare elements pegmatites

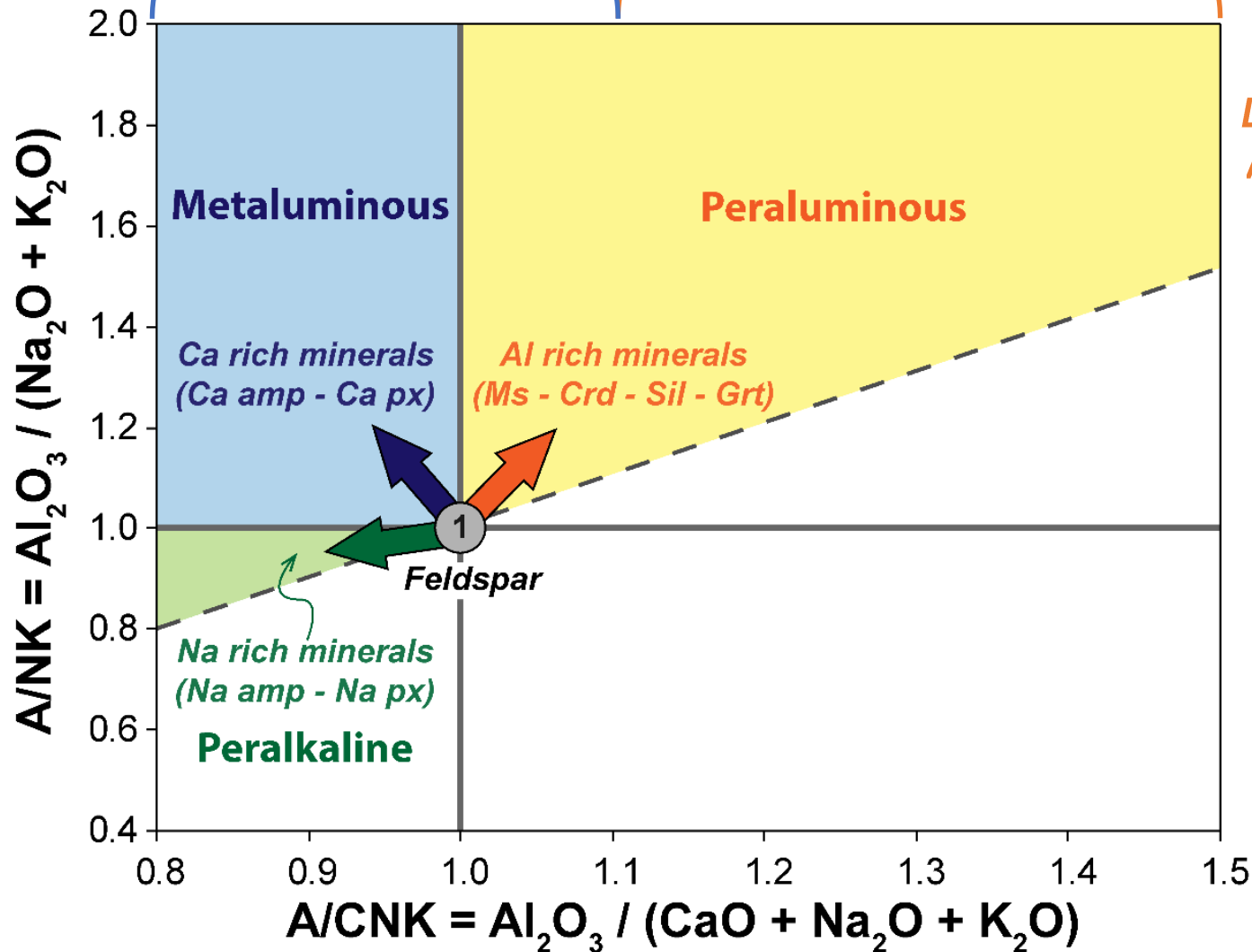
REE (Y) ± Nb ± F ± Ca -rich minerals

NYF pegmatites

LCT pegmatites

Li ± Ta ± Al-rich minerals

$$A/CNK = 1.1$$

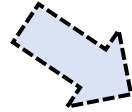
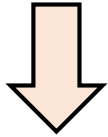


Titanite (Ca, Ti), magnetite, allanite (REE, Ca), monazite (REE, Th, P), fluorite (F, Ca), topaz (F), gadolinite (REE, F, Be), euxenite (REE, Nb, Ta, Ca), columbite (Nb), pyrochlore (Nb), cassiterite (Sn)

Lepidolite (Li, Al), spodumene (Li, Al), petalite (Li, Al), amblygonite (Li, P), Li-tourmaline (elbaite), columbite (Nb)-tantalite (Ta), microlite (Ta, U), wodginite (Ta, Sn), cassiterite (Sn), topaz (F, Al), beryl (Be, Al)

Les lignées/suites magmatiques felsiques à potentiel à métaux rares

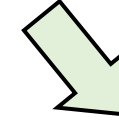
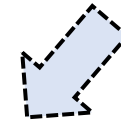
**Li-Cs-Ta-Sn
deposits**



Highly peraluminous leucogranites

*Metaluminous to slightly peraluminous
granites and syenites*

**Nb-REE-Zr-Y-Th
deposits**



**Peralkaline to metaluminous
granites and (feldspathoid) syenites**

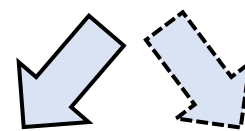
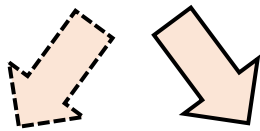
*Two-mica or muscovite-bearing peraluminous granites (MPG)
~S-type magmatism*

&

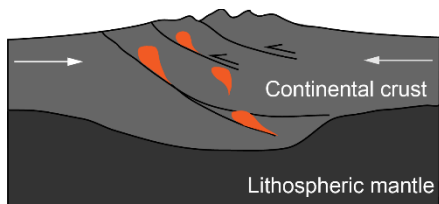
Li-Cs-Ta (LCT) pegmatites

*Nb-Y-F (NYF) pegmatites
= A2-type (KCG) magmatism*

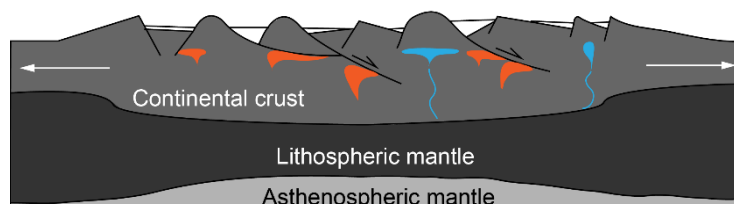
**Nb-Y-F (NYF) pegmatites
= A1-type (PAG) magmatism**



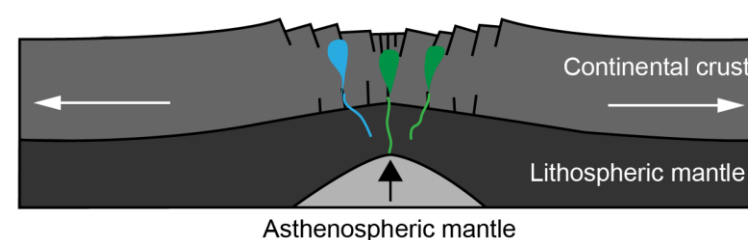
Continental collision



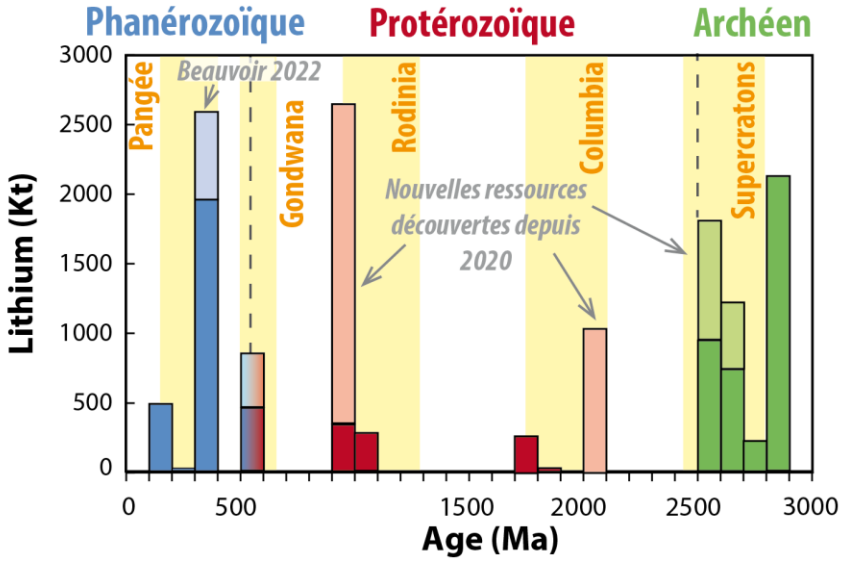
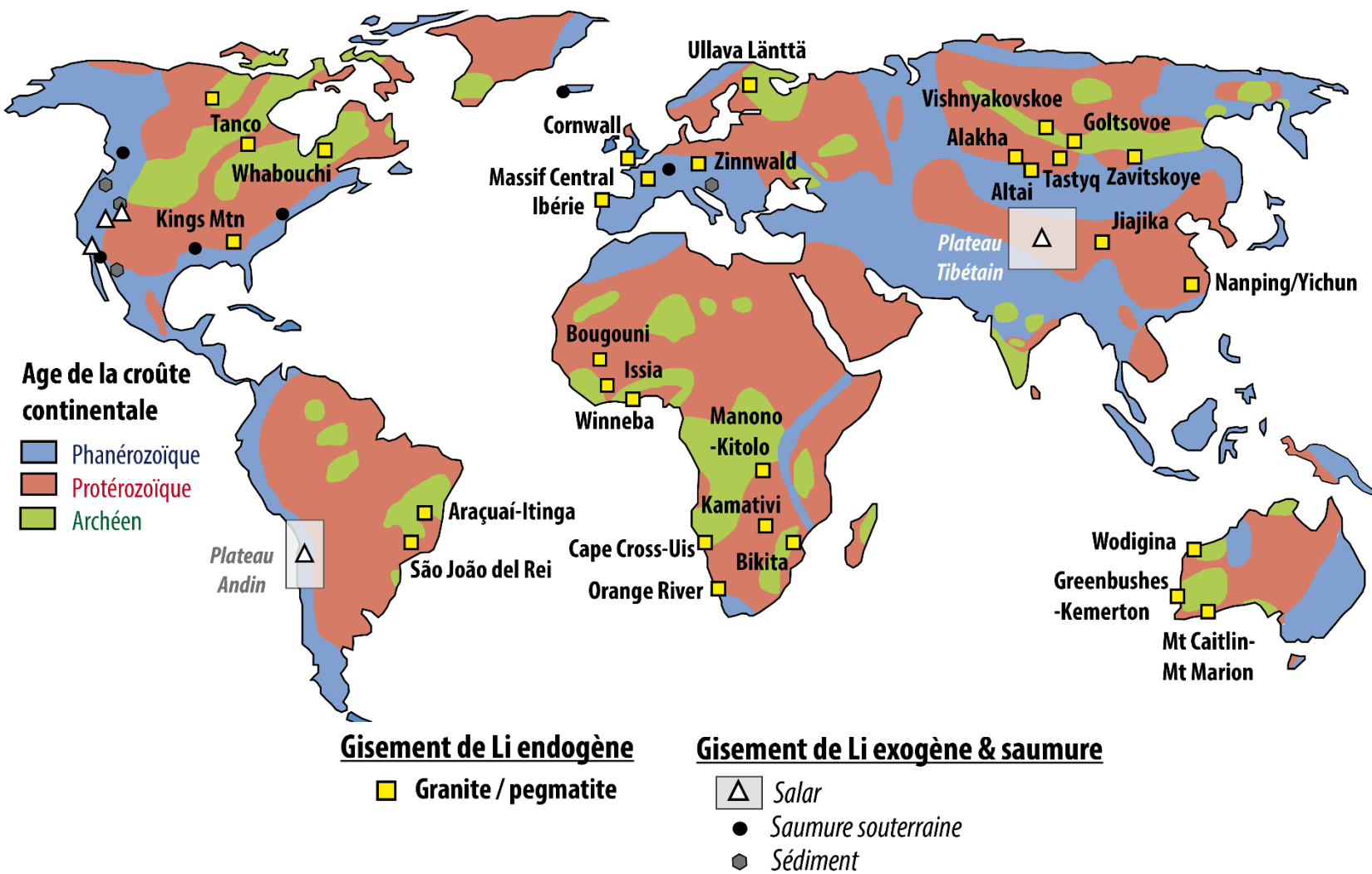
Late-orogenic extension



Continental rifting

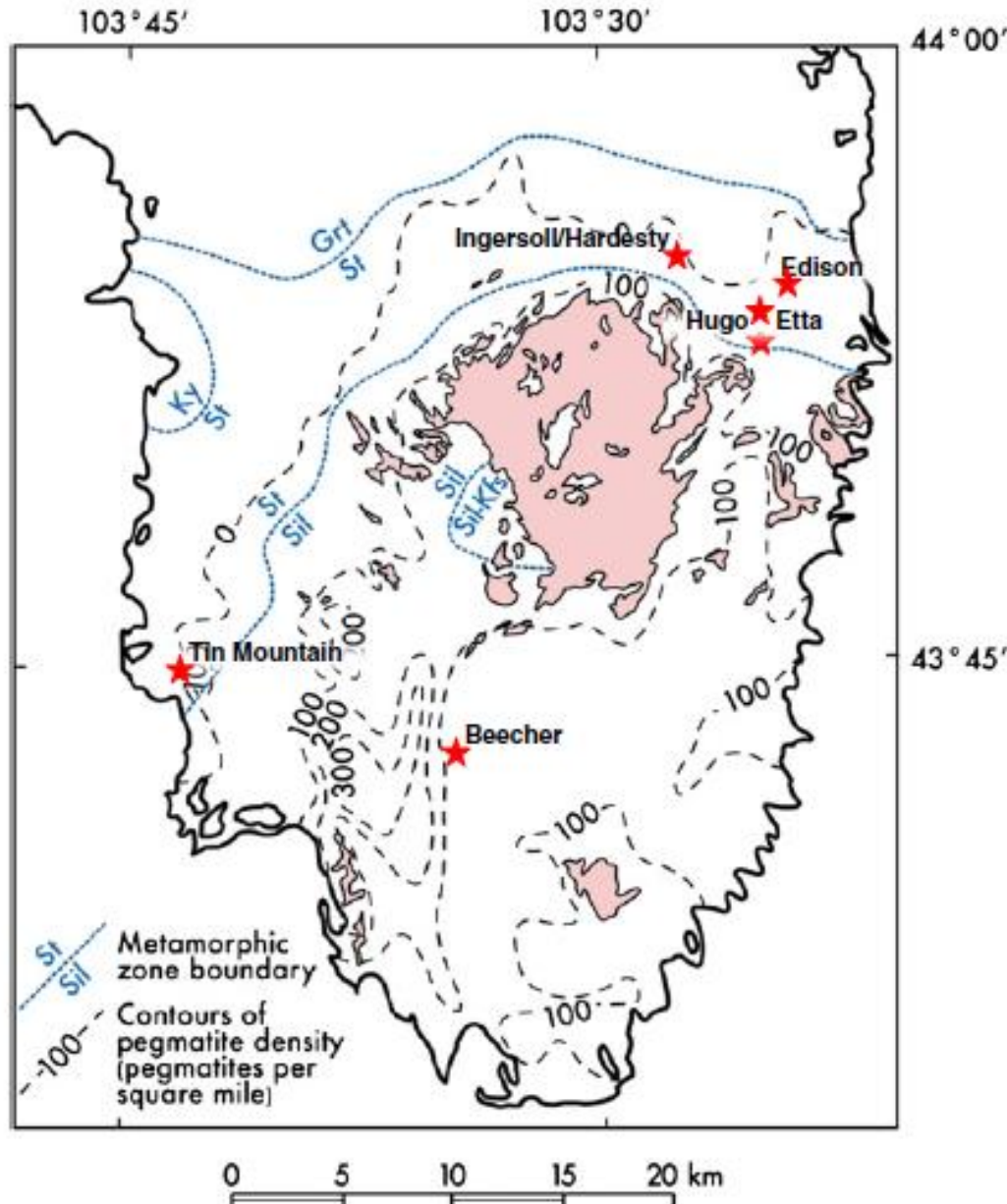


Répartition spatiale et temporelle des ressources en Li associées aux granites et pegmatites



Carte simplifiée de l'âge de la lithosphère continentale (après Saunders et al. 2018)

4. The rare elements pegmatites (LCT)

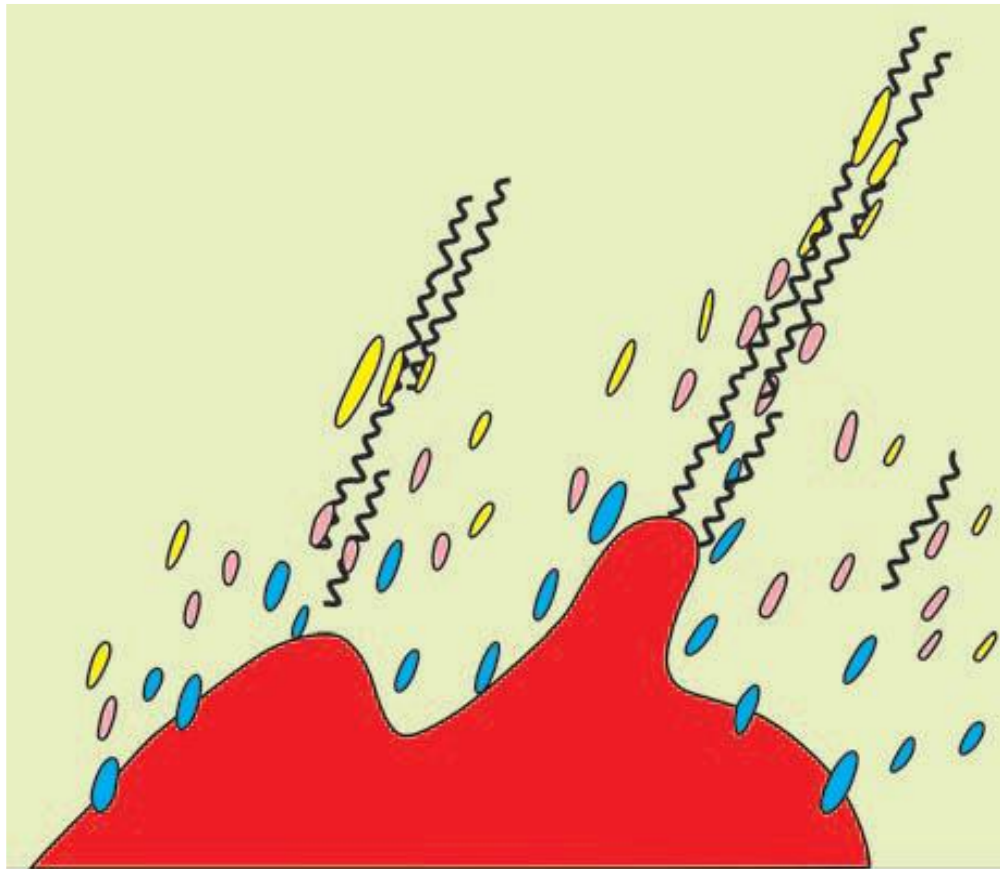


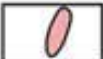
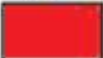
Regional zonation of rare elements pegmatites

Contour density of pegmatites per square mile in the Black Hill, South Dakota (USA). Outcrops of the Harney Peak and Calamity Peak granites are stippled. Of ~24,000 pegmatite bodies in the district, Page et al. (1953) identify only seven that are lithium-rich, and 32 that are beryl-rich. The rest are common pegmatites lacking any distinctive rare-element enrichment. The lithium-rich pegmatites, denoted by red stars, mostly lie at the distal margins of the district, or in the regions of lowest pegmatite density.

(London, 2014))

4. The rare elements pegmatites (LCT)



-  Complex Li-Cs-Ta-Sn rich
-  Be-Nb rich
-  Barren to Be rich
-  Source granite (or migmatites)
-  Regional fault

Idealized zoned pegmatite field around a source granite. The maximum distance of pegmatites from the source granite is on the order of kilometers or, at most, tens of kilometers.

The pegmatites with the more significant economic values will be found far away from the contact of the source granites (or migmatite domes), close to fault zones

(Linnen et al., 2012)

4. The rare elements pegmatites (LCT)

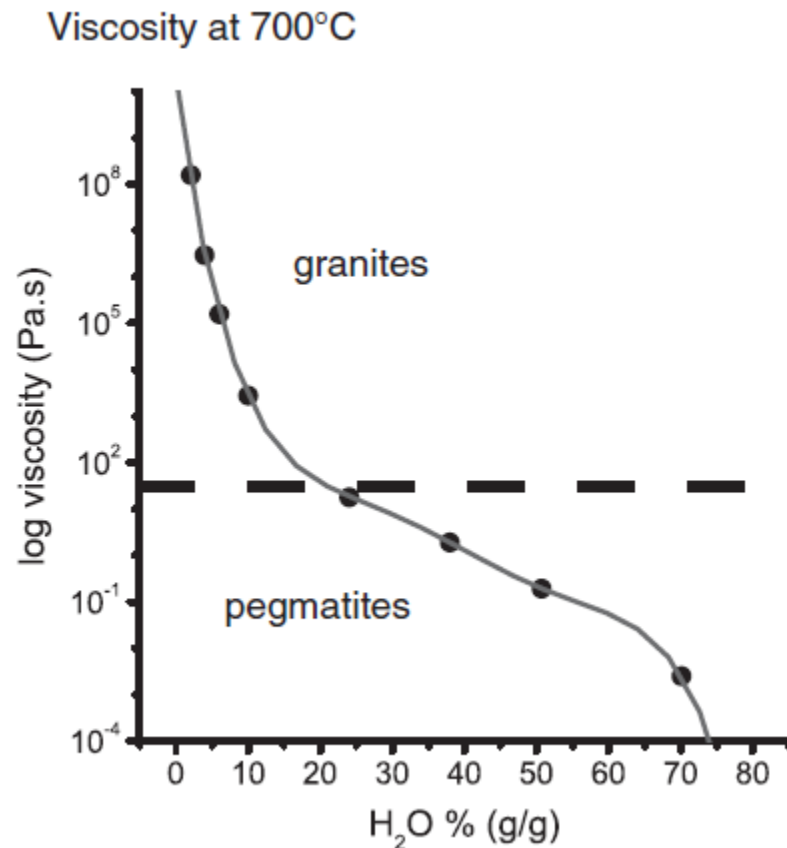
The role of fluxing elements :

The high content of fluxing elements (F, B, P, H₂O, Li) decrease the viscosity and lower the solidus of silicate melts.

Consequence:

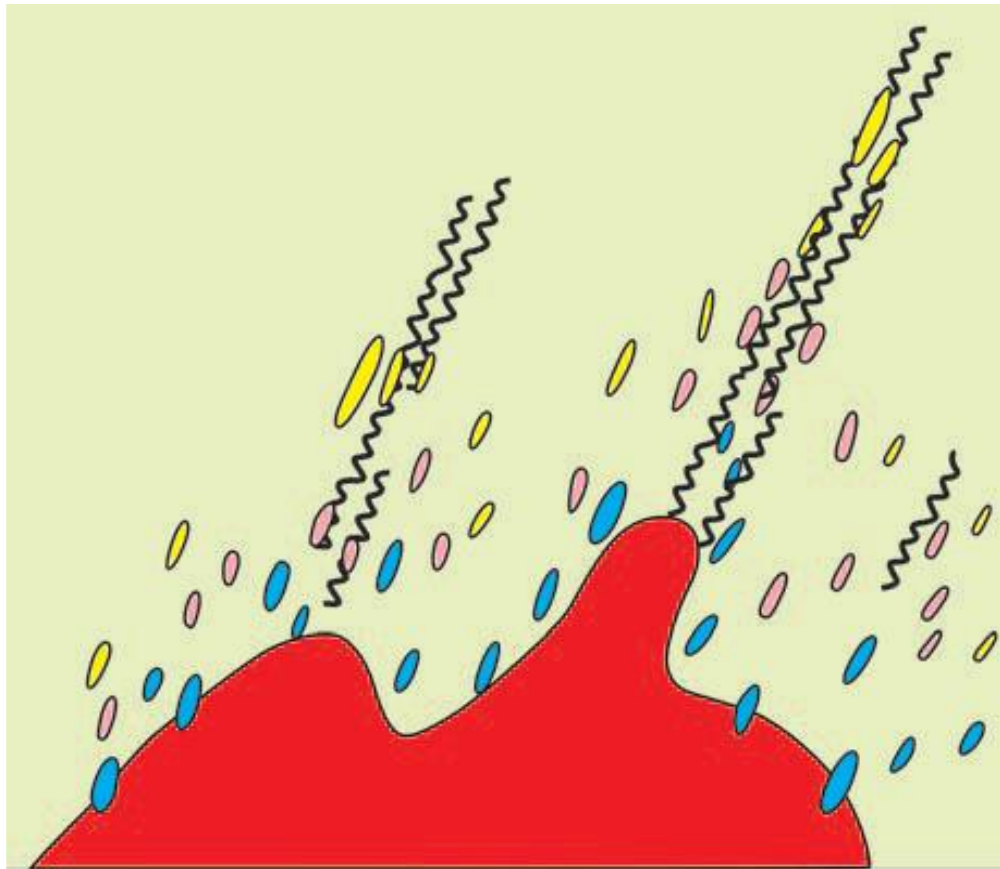
1/ pegmatite melts can travel a long way in the crust before complete crystallization

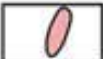
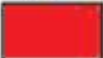
2/a low viscosity allows a high degree of mineral-melt segregation (fractional crystallization) that can lead to a high enrichment in incompatible elements (rare metals)



Viscosity of a peraluminous granite and pegmatite melt at 700 °C in relation to water content (Thomas and Davidson, 2012)

4. The rare elements pegmatites (LCT)



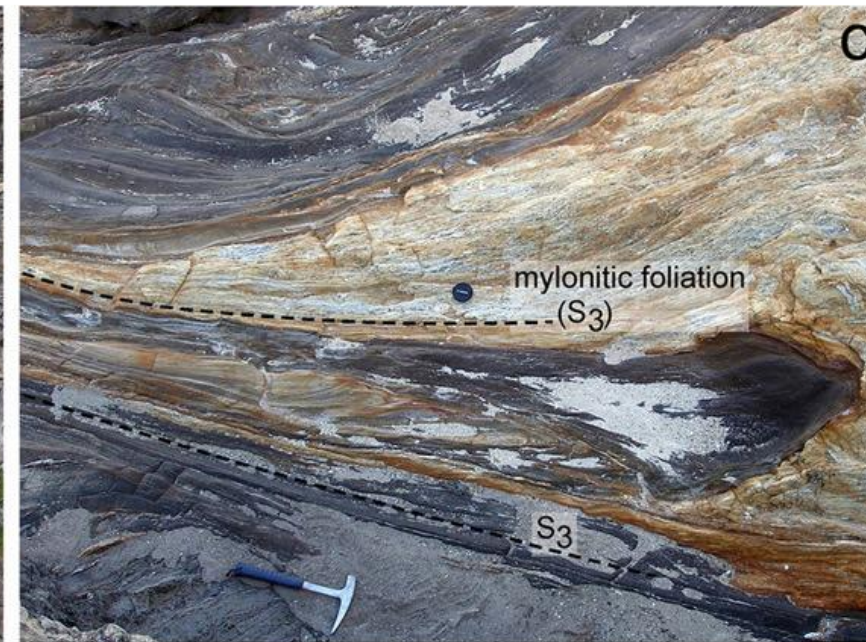
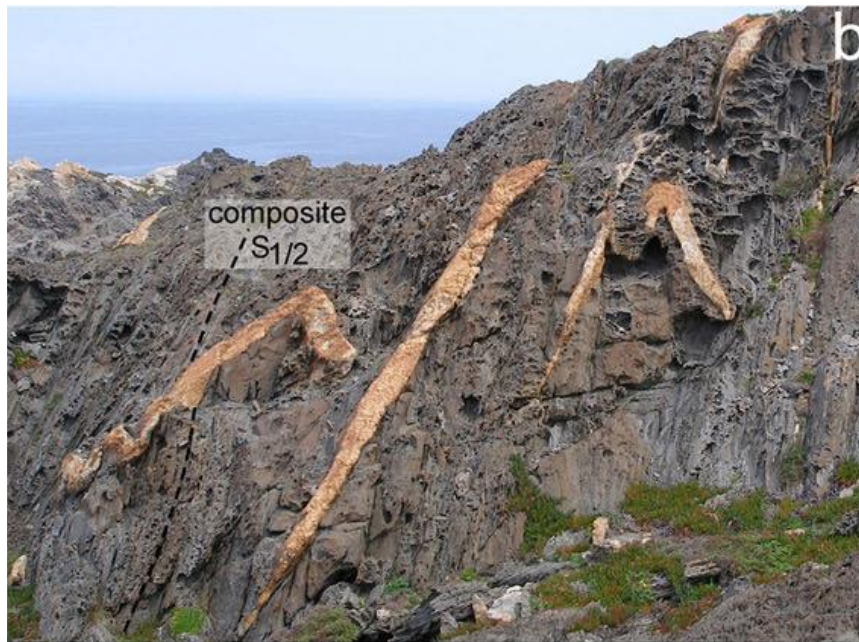
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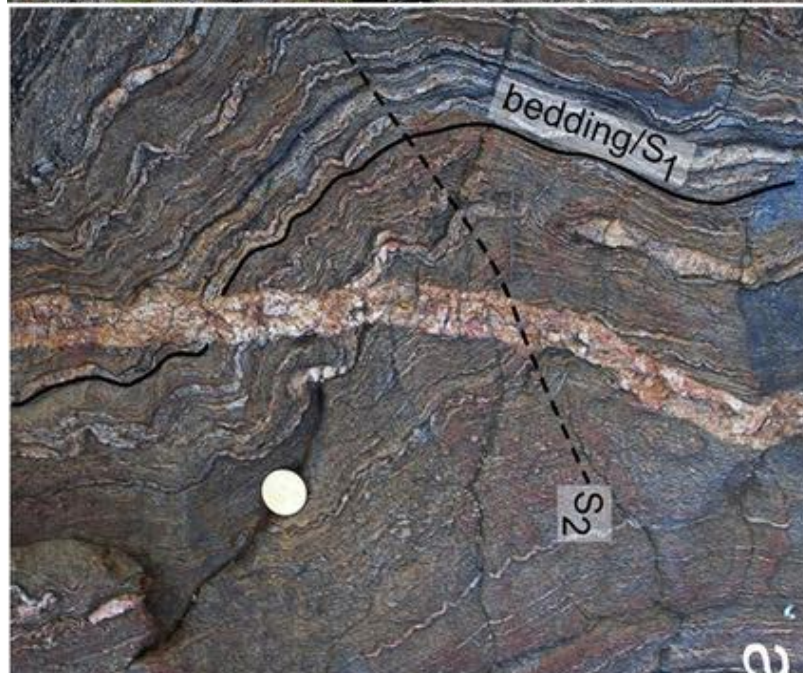
The pegmatites with the more significant economic values will be found far away from the contact of the source granites (or migmatite domes), close to fault zones

(Linnen et al., 2012)

4. The rare elements pegmatites (LCT)



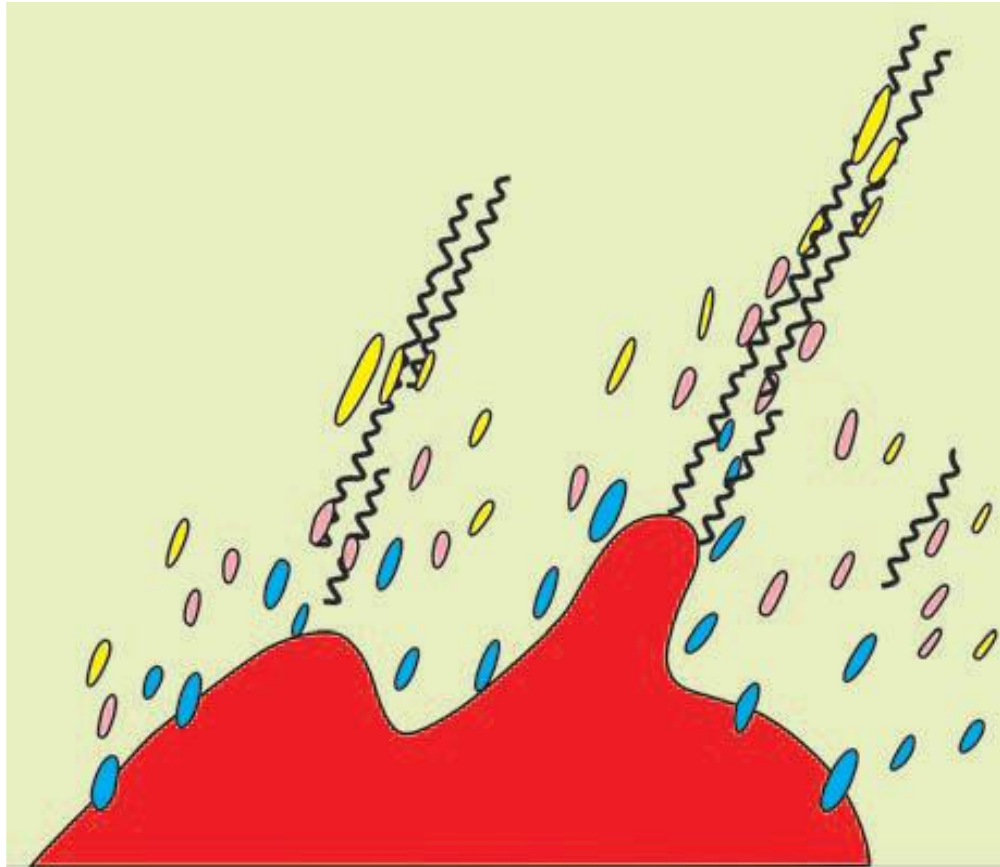
Cap de Creus pegmatites, NE Spain

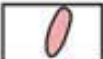
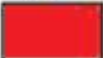


**Relationship between
deformation and rare element
pegmatites**

(Van Lichtenvelde et al., 2017)

4. The rare elements pegmatites (LCT)



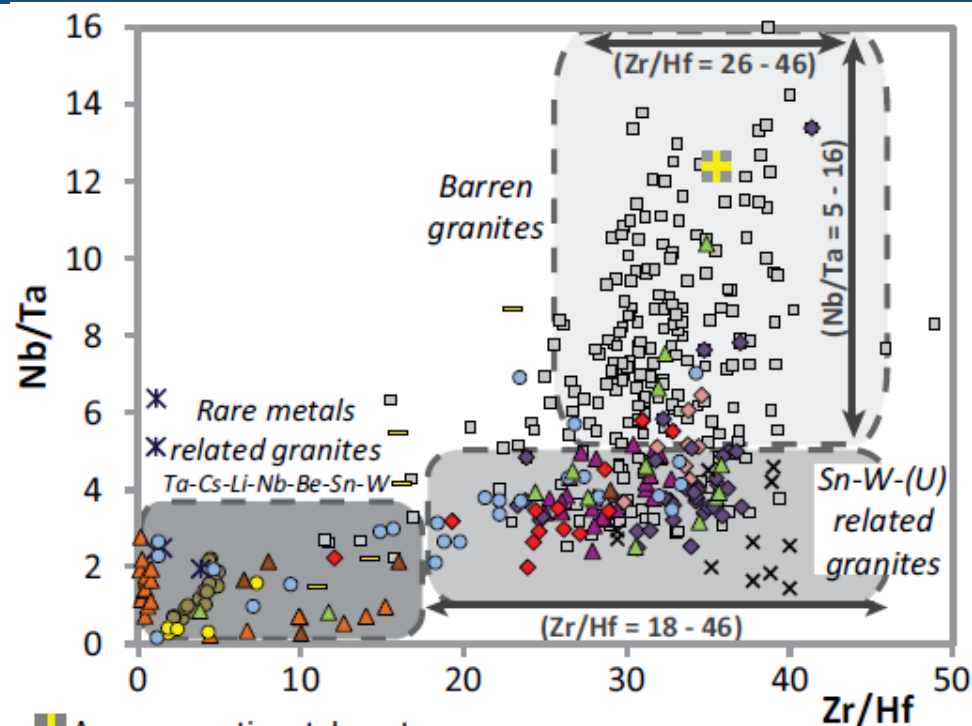
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(Linnen et al., 2012)

4. The rare elements pegmatites (LCT)



- ✚ Average continental crust
- Barren granites
- ◆ Lizio granite - Armorican Massif : Sn
- ◆ Questembert and Guérande granites - Armorican Massif : U - (Sn)
- ▲ Beariz, Jalama and Carbalinno granites - Iberian Massif : Sn - W - (Nb - Ta)
- ◆ Cornubian batholith : Sn - W - (Cu)
- Li - mica granites and greisens from the Erzgebirge : Sn - W
- × Leucogranites and greisens from the Davis Lake pluton - SMB : Sn
- ✚ Tanjungpandan pluton - Belitung - Indonesia : Sn-W
- Leucogranites from the Kukul'bei Complex - Transbaikalia : W - Sn
- ▲ Dulong granites - Yunnan Province - South China : Sn
- Ongonites from Ongon Kairkhan, Central Mongolia : W
- Li - F granites from the Kukul'bei Complex - Transbaikalia : Ta
- ▲ Beauvoir granite - Massif Central : Ta - Be - Sn - Li
- ▲ Ponte Segade granite - Iberian Massif : Sn - Ta - Nb - Li - Be - Cs

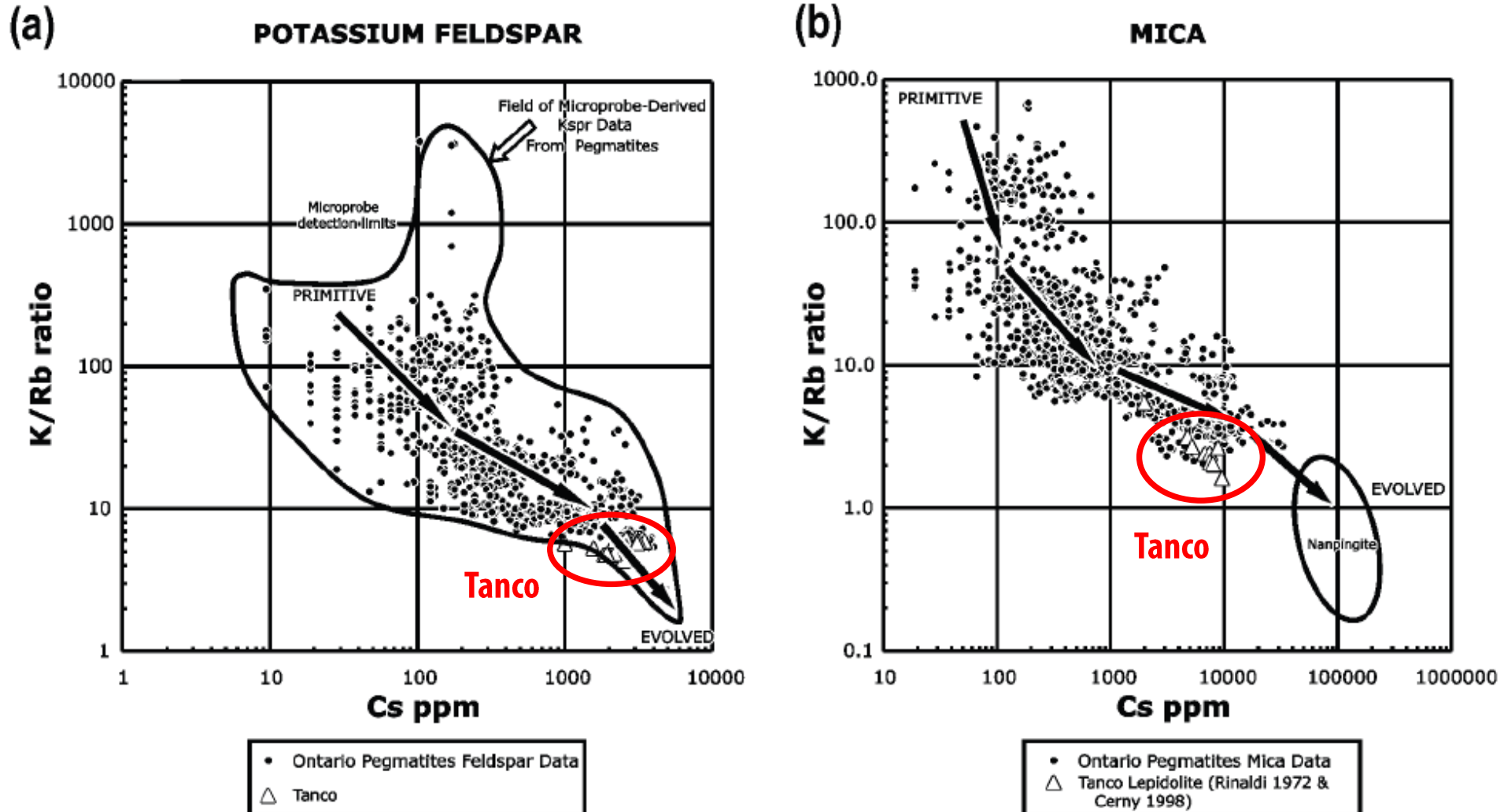
Peraluminous systems

Geochemical exploration (bulk rock)

The fractionation of geochemical twins
Zr-Hf & Nb-Ta

4. The rare elements pegmatites (LCT)

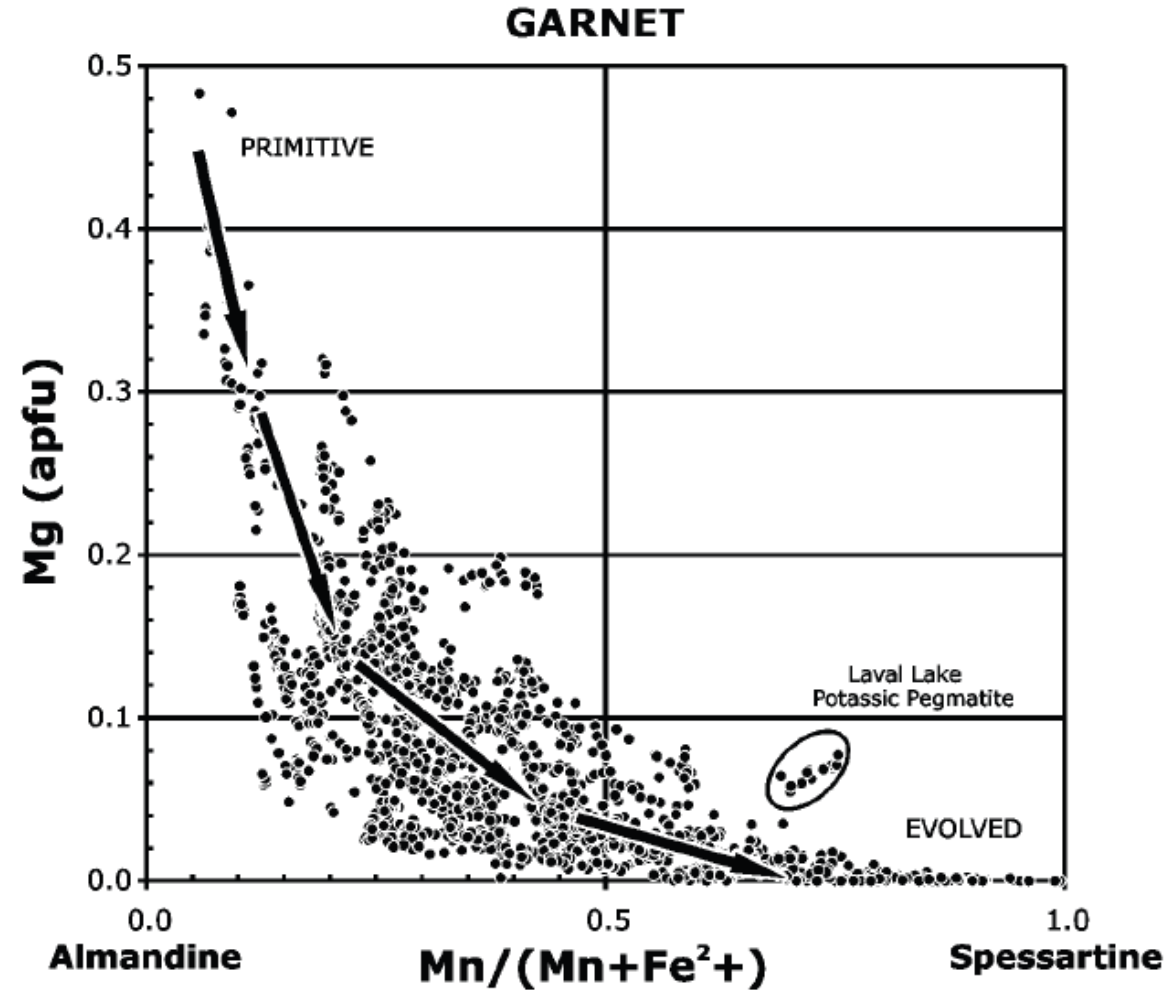
Geochemical exploration (minerals)



Evolution trends for K-feldspar and mica of pegmatites from Ontario, Canada (Selway et al. 2005)

4. The rare elements pegmatites (LCT)

Geochemical exploration (minerals)

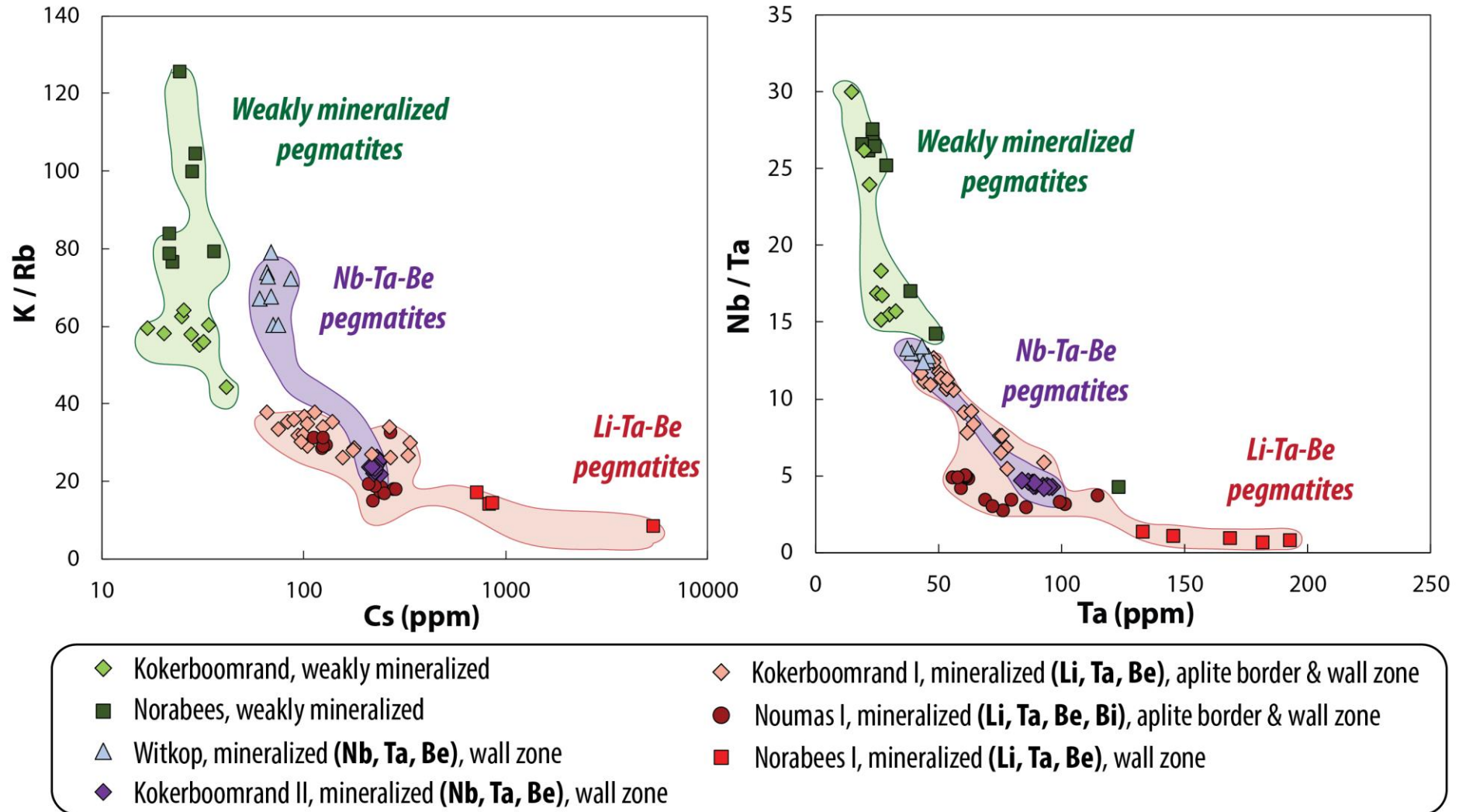


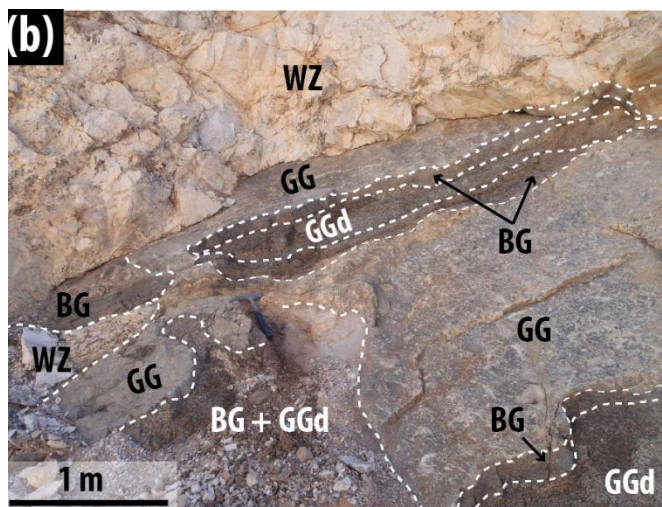
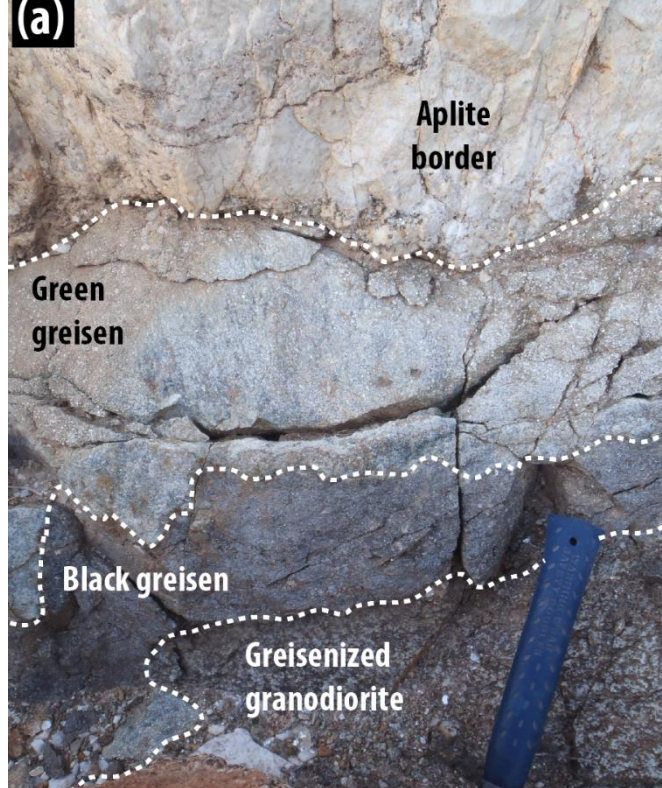
Evolution trends for garnet of pegmatites from Ontario, Canada (Selway et al. 2005)

The Orange River pegmatite belt

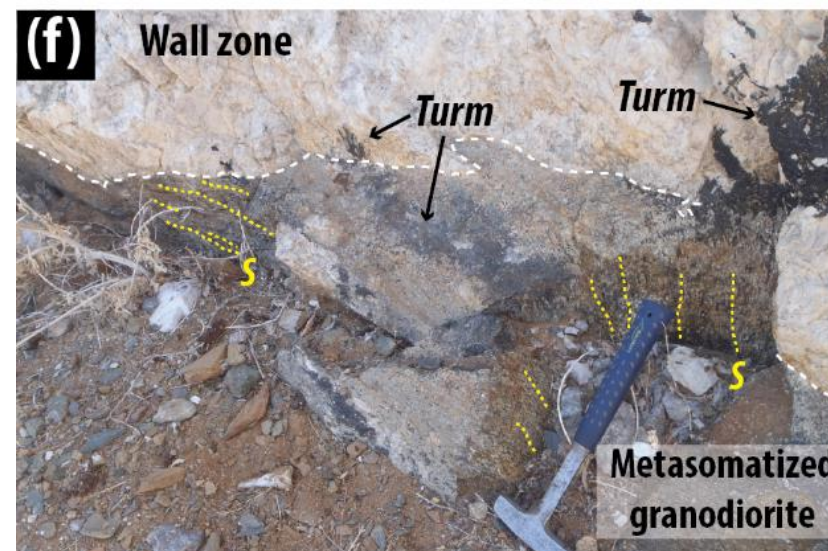
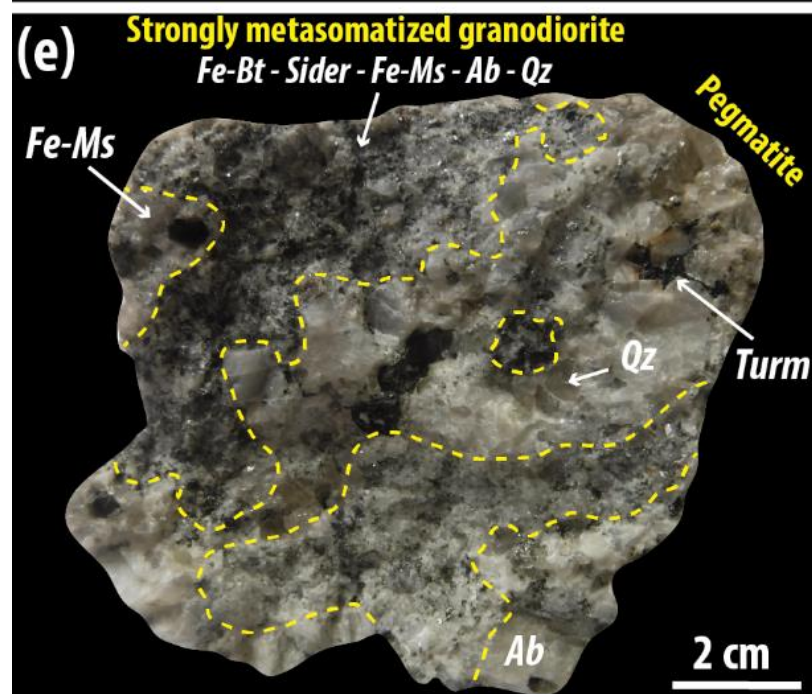
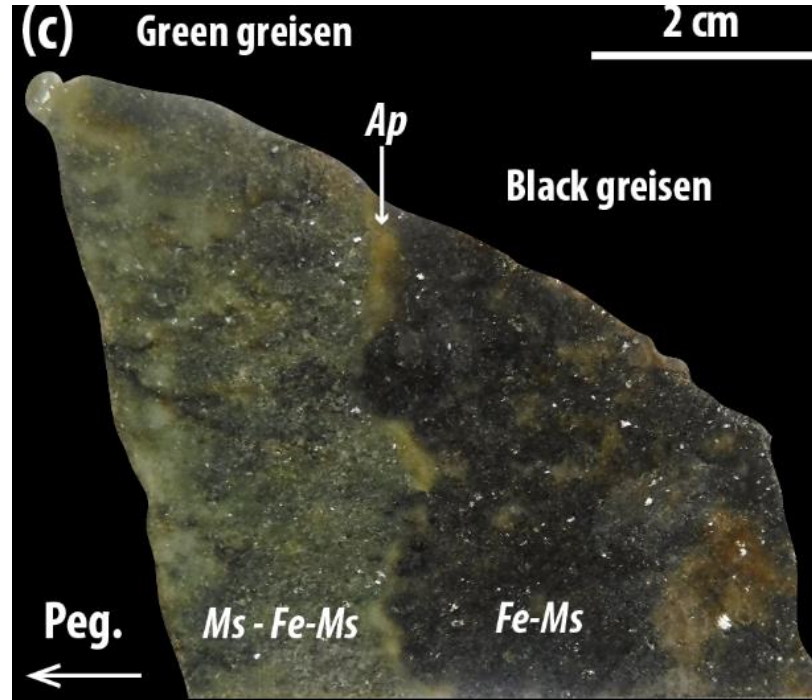
Chemical composition of muscovite

Ballouard et al. 2020





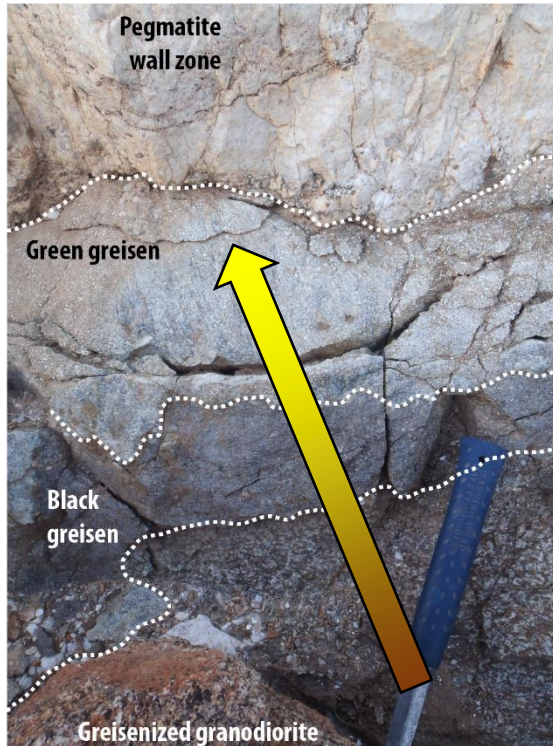
WZ: Wall zone; GG: Green greisen; BG: Black greisen;
GGd: greisenized granodiorite



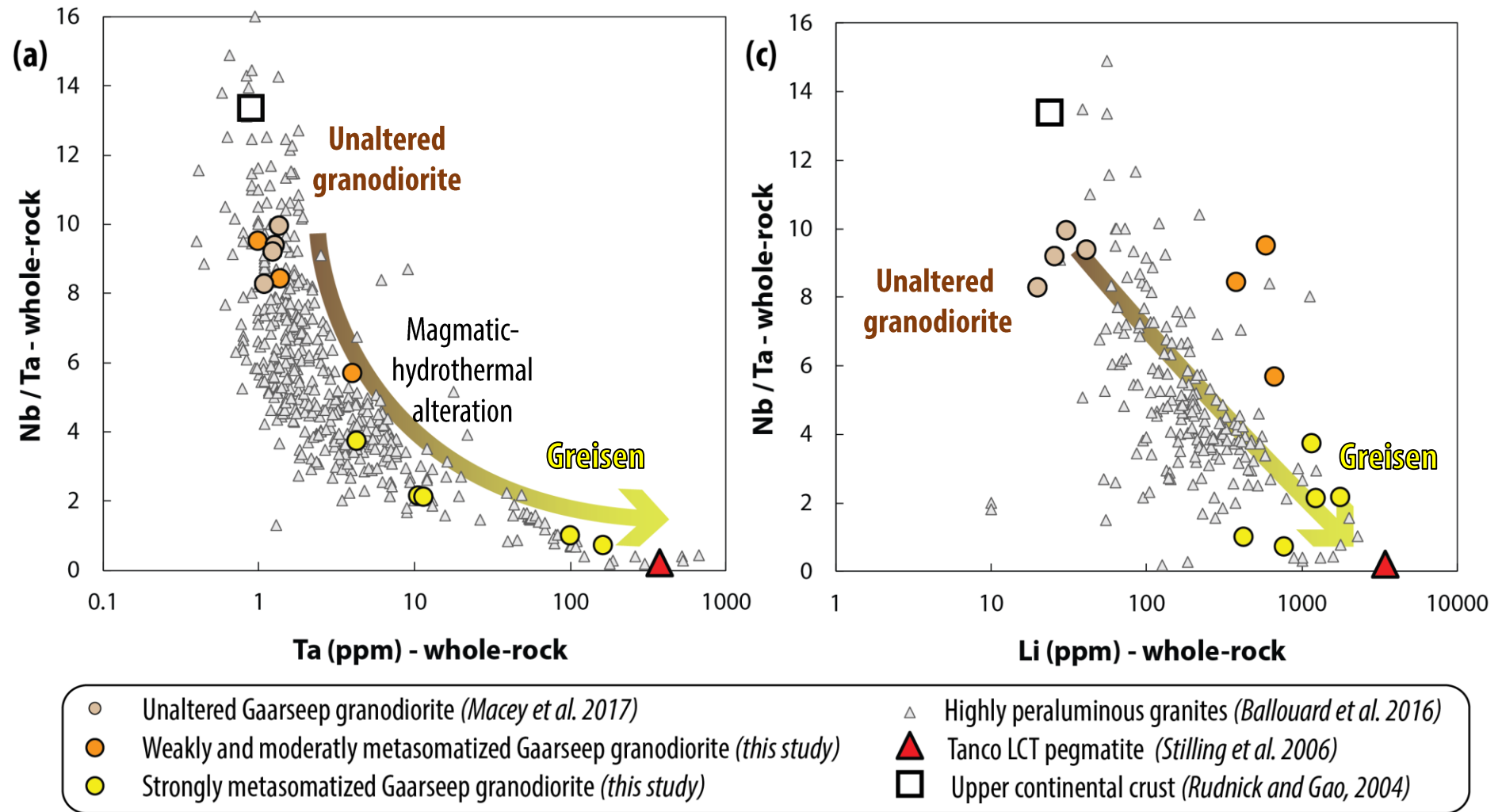
Geochemical exploration
(country-rock alteration haloes)
Namaqualand, South Africa, Ballouard et al. 2020

4. The rare elements pegmatites (LCT)

Geochemical exploration (country-rock alteration haloes)



Ballouard et al. 2020



Evidence for strong hydrothermal mobility of metals in country rocks during pegmatite magma crystallization

4. The rare elements pegmatites (LCT)

J. Errandonea-Martin et al.

Ore Geology Reviews 150 (2022) 105155

Geochemical exploration (country-rock alteration haloes)

Errandonea-Martin et al. 2022

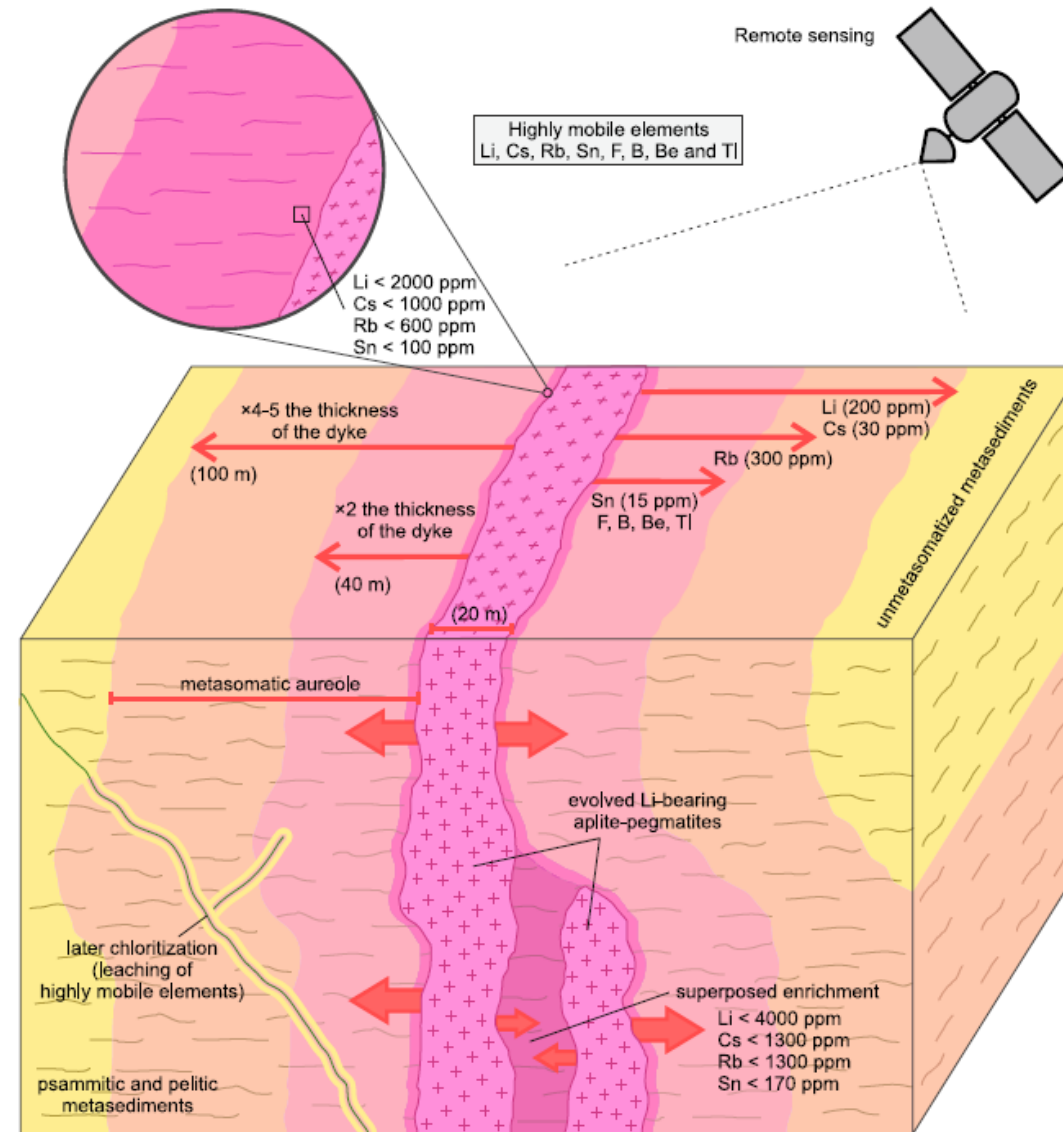


Fig. 14. Idealized schematic representation of a metasomatic aureole generated by the intrusion of an evolved aplite-pegmatite in the Fregeneda-Almendra Pegmatite Field.

4. The rare elements pegmatites (LCT)

Geochemical exploration (country-rock alteration haloes)

Sweetapple et al
2024

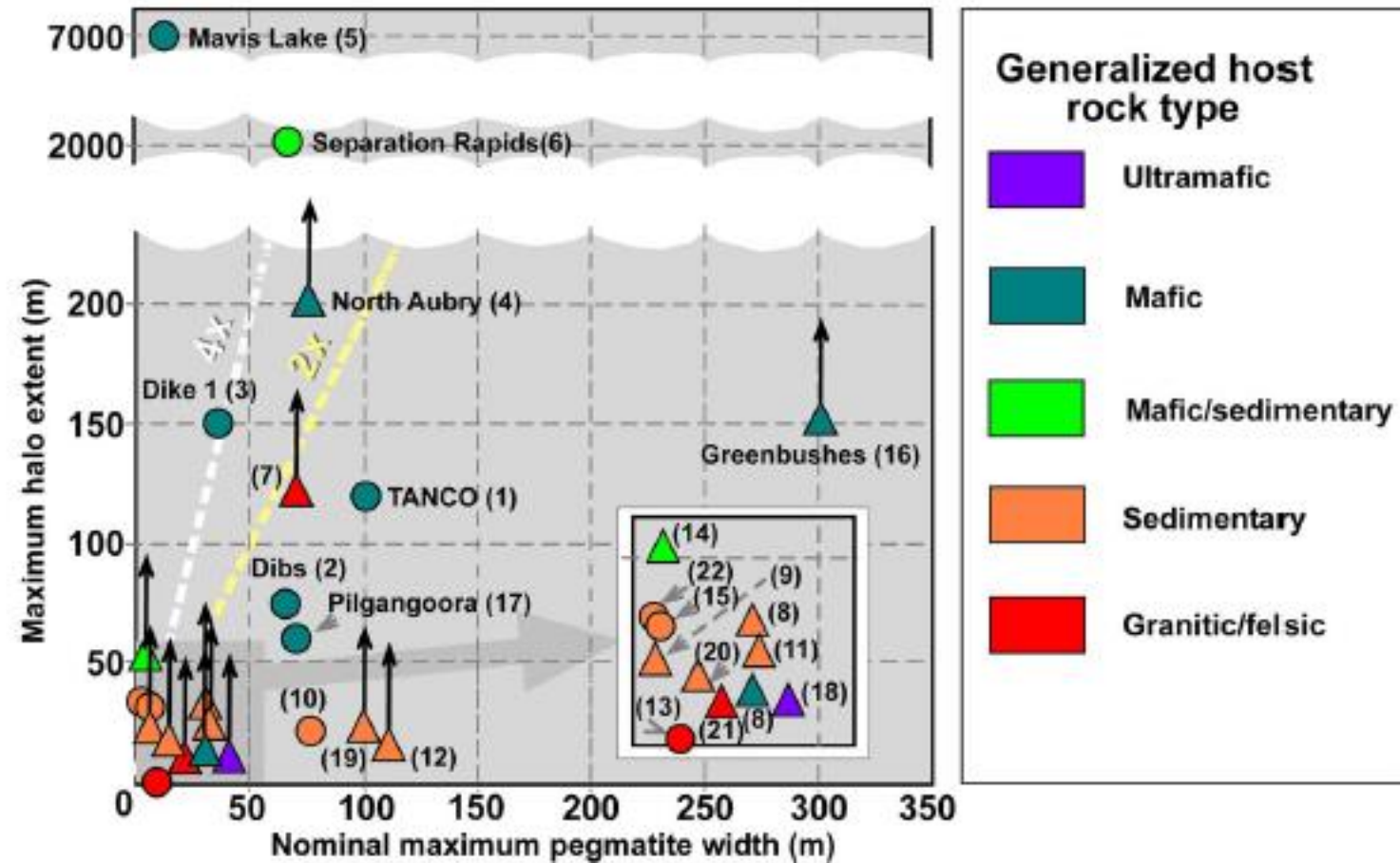


Figure 3. Plot of maximum extent of measured lithium dispersion halo against nominal maximum pegmatite width for pegmatite occurrences numbered as per Table 2, with data plotted by host-rock type. Host-rock type refers to protolith composition, without regard to metamorphic grade. Maximum pegmatite width is used as a proxy for volume of pegmatite, to permit comparison of different data sets. Circles indicate a known outer limit of the dispersion halo, whereas triangles show the maximum known extent, with arrows indicating a likely further dispersion. The dashed lines relate to ratios of halo extent to pegmatite width from Errandonea-Martin *et al.* (2022).

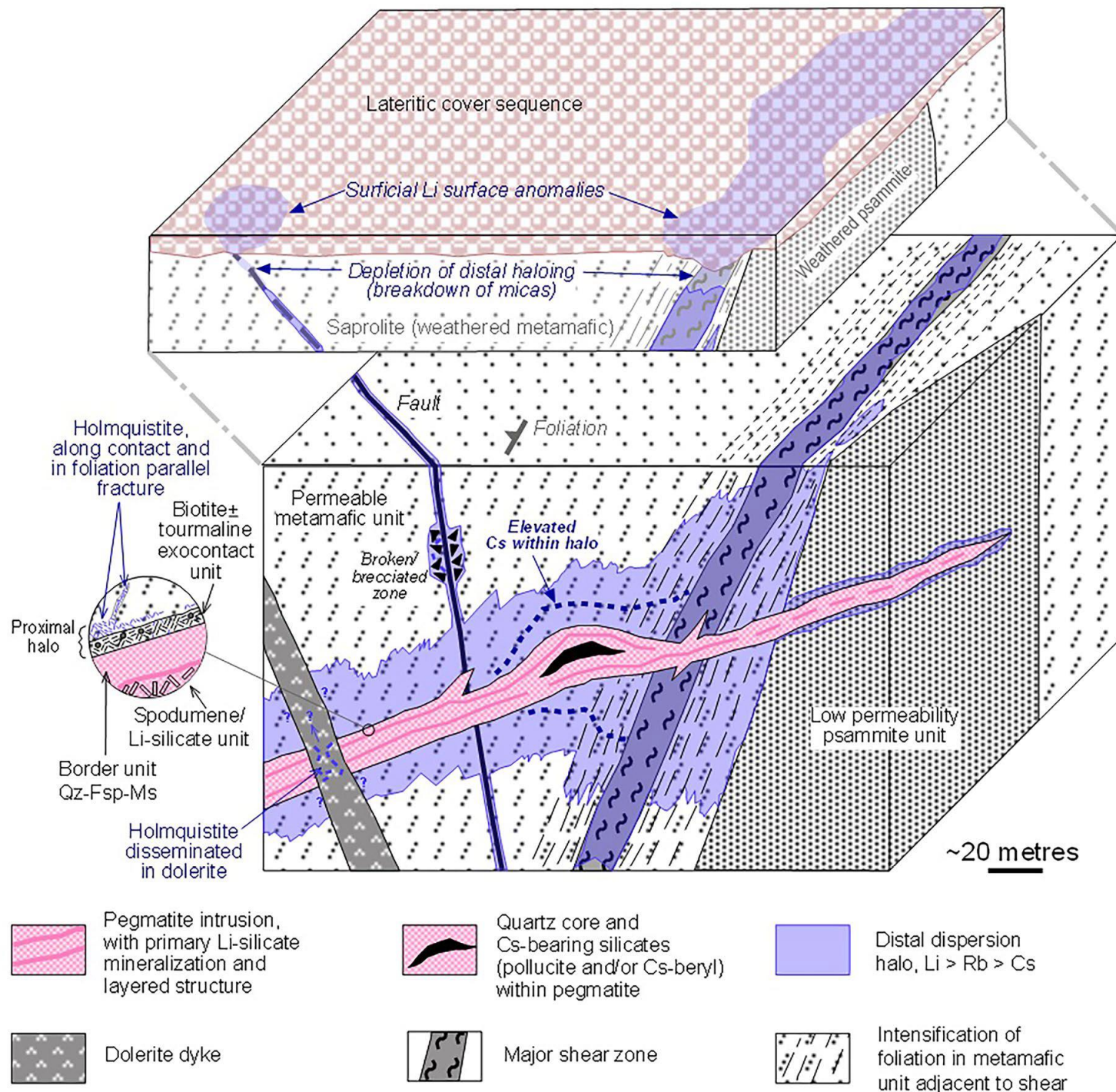
4. The rare elements pegmatites (LCT)

Geochemical exploration (country-rock alteration haloes)

Sweetapple et al.
2024



Holmquistite-bearing shear zone in
mafic igneous rock



4. The rare elements pegmatites (LCT)

Geochemical exploration (country-rock alteration haloes)

*Harlaux et al.
2025*

It works also for rare-
metal granites

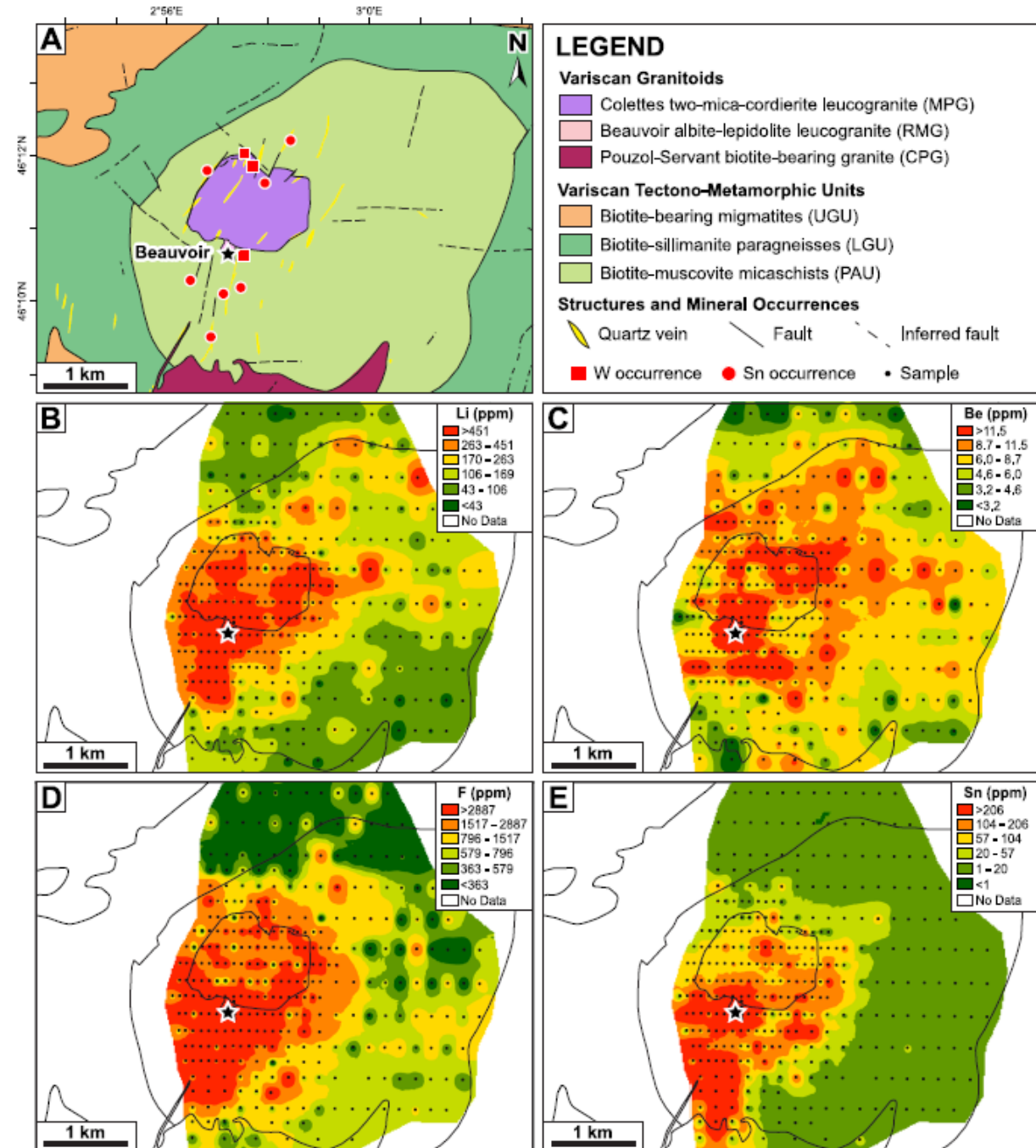
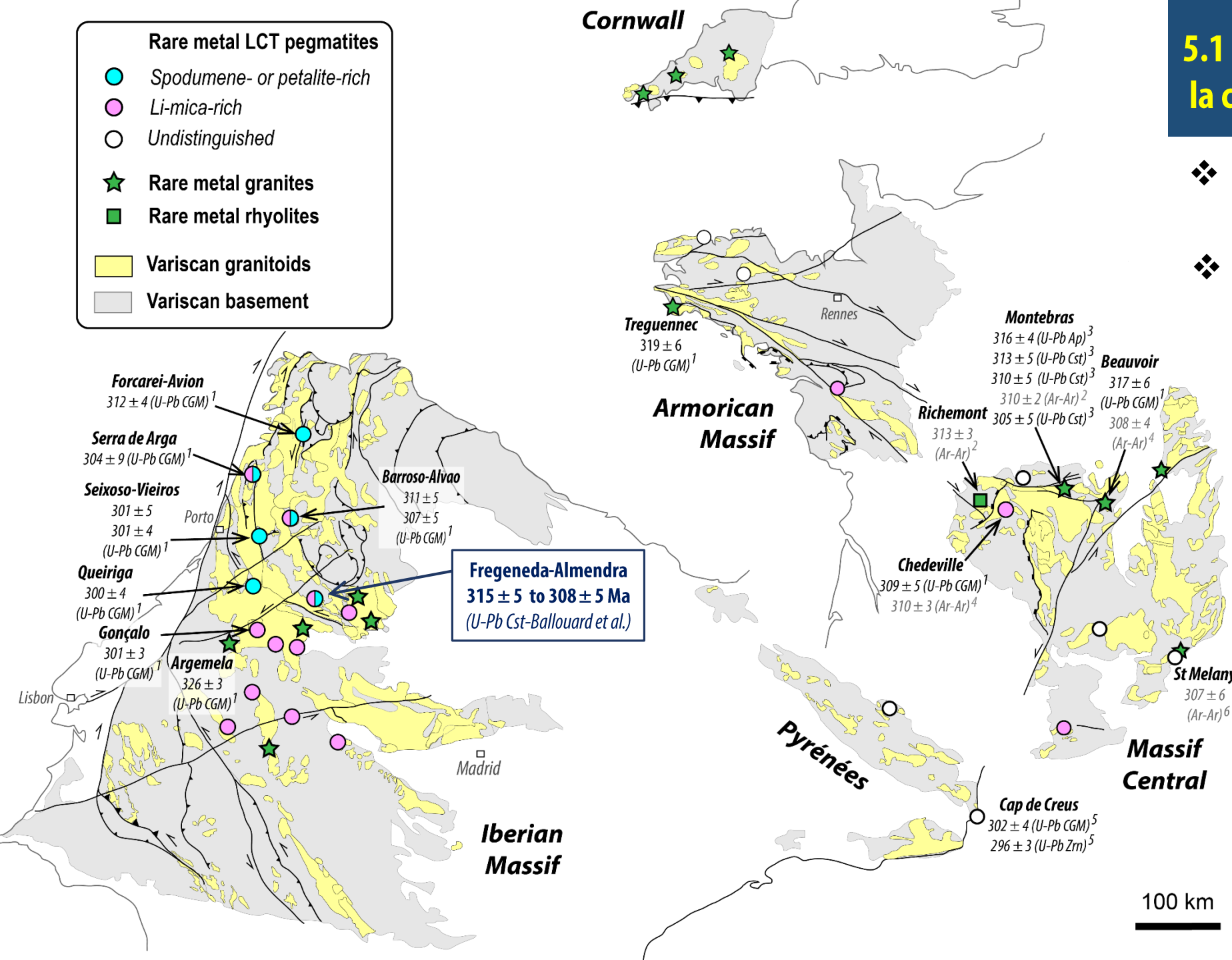


Fig. 8. Geological map and element distribution maps for Li, Be, F and Sn around the Beauvoir granite in the Echassières district. Inverse distance weighted (IDW) interpolation based on georeferenced lithogeochemical data from Aubert (1969) and Raimbault et al. (1995).

5.1 Le magmatisme à métaux rares de la chaîne varisque ouest-européenne

- ❖ Principalement tardi-carbonifère entre ca. 320 et 300 Ma
- ❖ Des granites à métaux rares et deux types principaux de pegmatites à Li (LCT)



1: Gourcerol et al. 2019; Melleton et al. (2022)

2: Cuney et al. 2002

3: Marcoux et al. (2021)

4: Cheilletz et al. (1992)

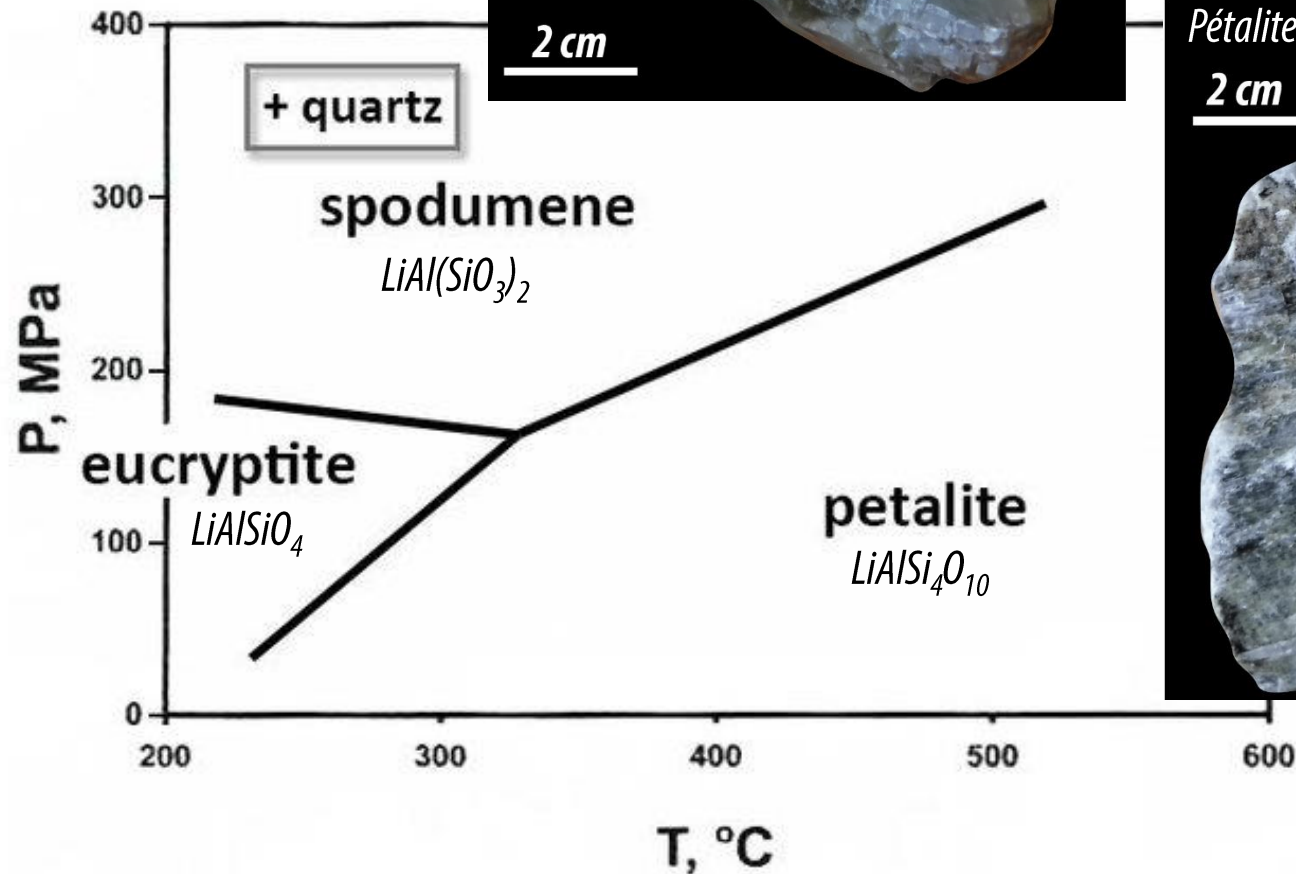
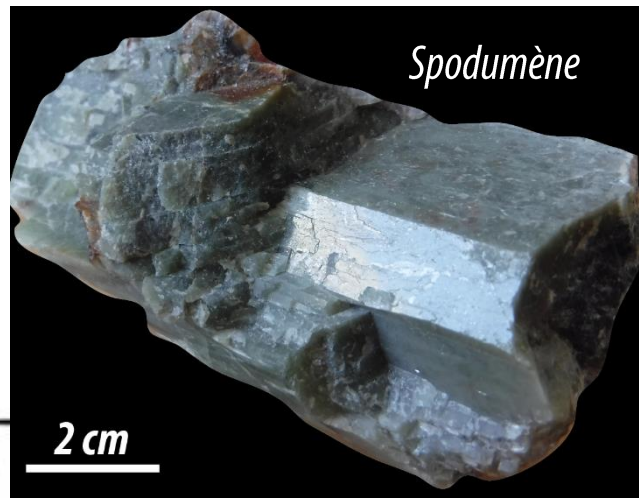
5: Van Lichtervelde et al. (2017)

6: Chauvet et al. 2012

Quels paramètres contrôlent la nature des silicates porteurs du Li dans les pegmatites?

Spodumène - $\text{LiAl}(\text{SiO}_3)_2$
vs **Péталite** - $\text{LiAlSi}_4\text{O}_{10}$

→ Dépendant des conditions
pression-température

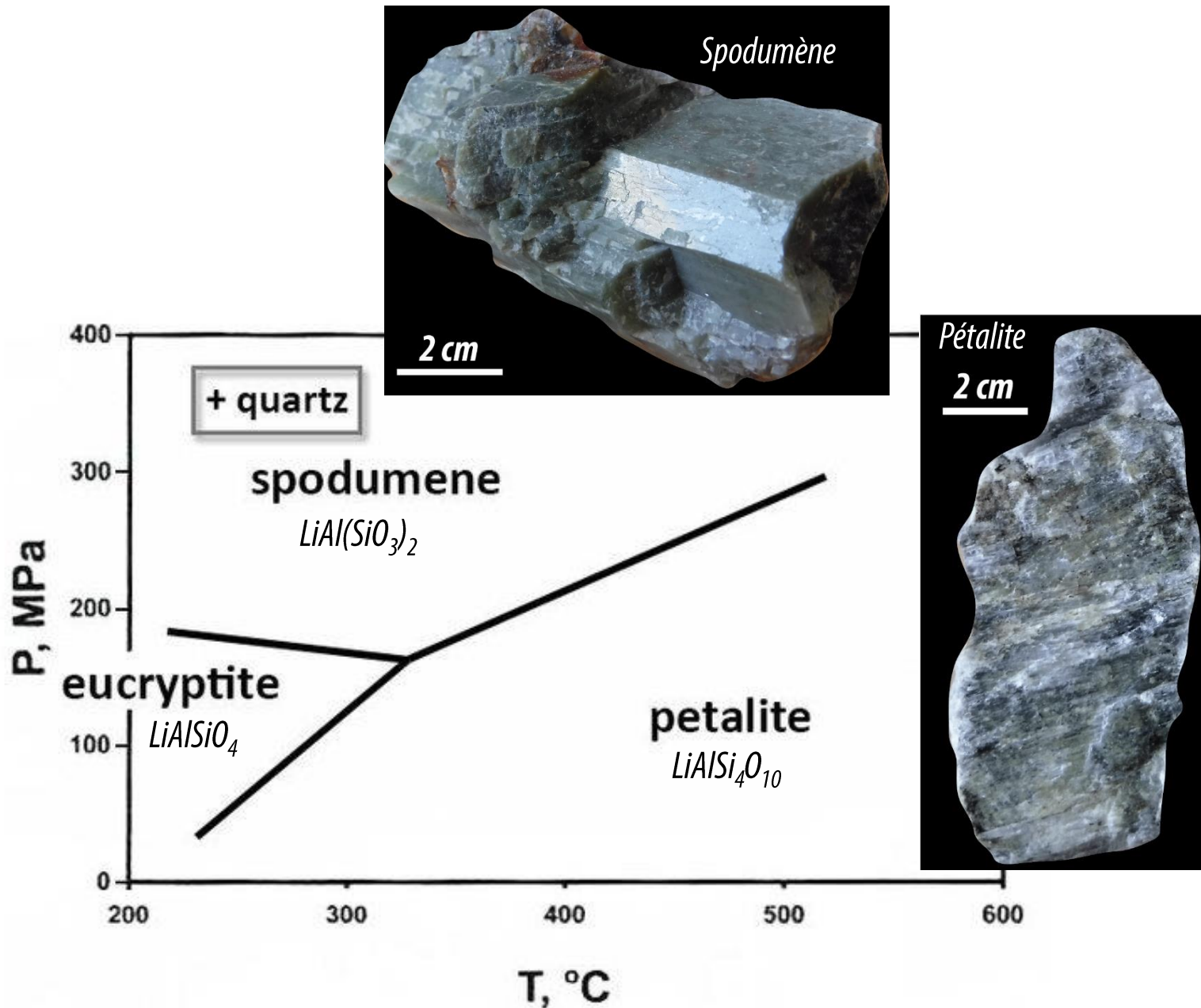


Champ de stabilité des aluminosilicates de Li (London 1984)

Quels paramètres contrôlent la nature des silicates porteurs du Li dans les pegmatites?

Spodumène - $\text{LiAl}(\text{SiO}_3)_2$
vs **Pétalite** - $\text{LiAlSi}_4\text{O}_{10}$

→ Dépendant des conditions
pression-température

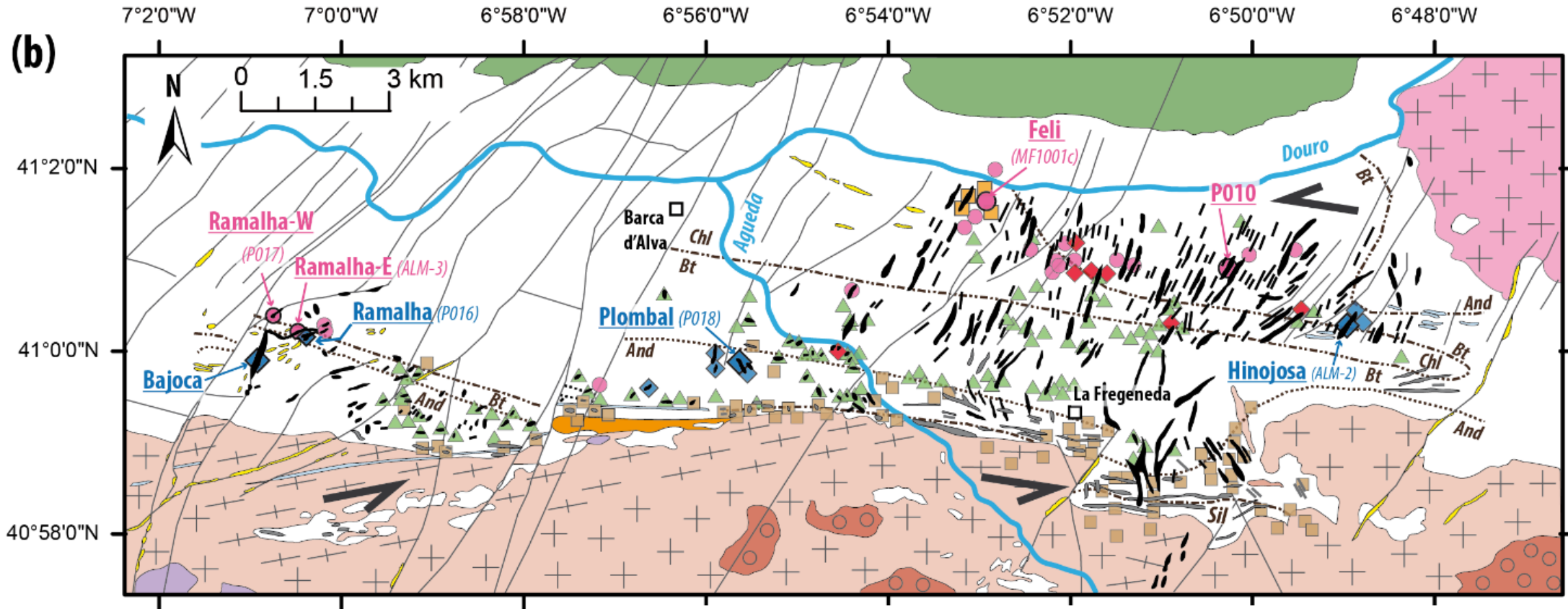


Champ de stabilité des aluminosilicates de Li (London 1984)



Lépidolite - $\text{K}(\text{Li},\text{Al})_3(\text{Si},\text{Al})_4\text{O}_{10}(\text{F},\text{OH})_2$

→ Dépendant de la composition du
liquide (activité en F)



Carte géologique du champ de pegmatite de Fregeneda-Almendra

Ballouard et al. 2024

*Adapted from Villar et al. 1990;
da Silva et al. 1991a, 1991b; Diez
Montes et al. 1991; Robles 1994;
Vieira et al. 2011*

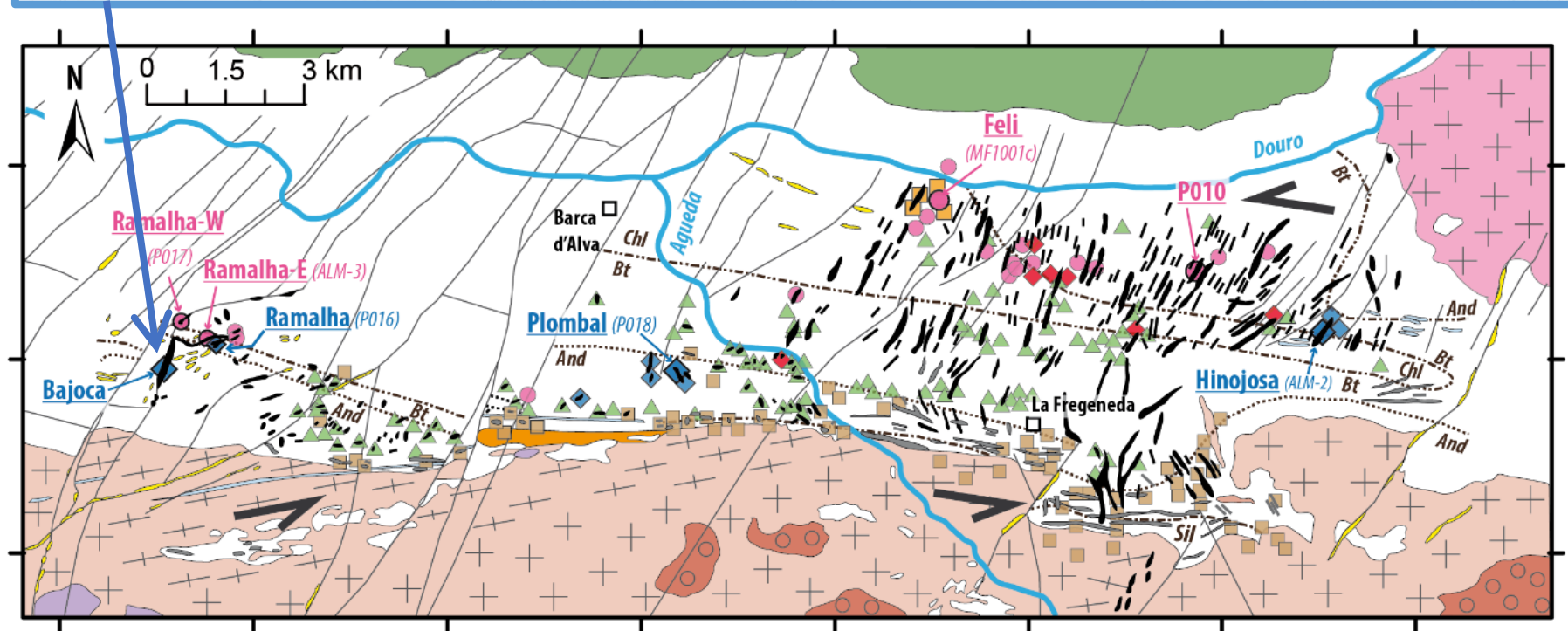
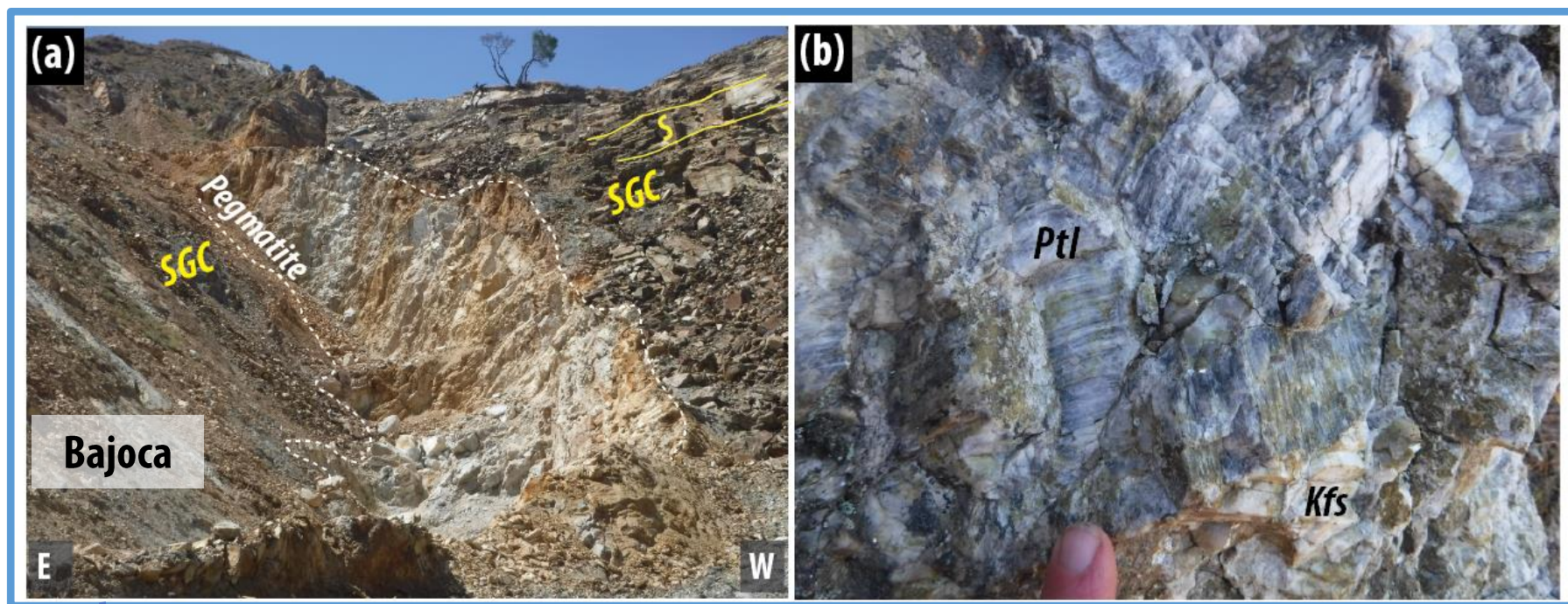
Detailed pegmatite typology

Group 3	Mineralized discordant pegmatites (Qz-Ab ± Kfs ± Ms -AGM-CGM-Cst)
	◆ Petalite-bearing ◆ Spodumene-bearing ● Li-mica ± spodumene-bearing ■ Quartz-cassiterite-rich
Group 2	Weakly mineralized discordant pegmatites (Qz-KFs-Ab-Ms-Fe-Mn phosphate ± Amb ± Turm ± CGM ± Cst ± Py)
Group 1	Barren concordant and/or variably deformed pegmatites (Qz-KFs-Ab-Ms-Turm ± Grt ± And)

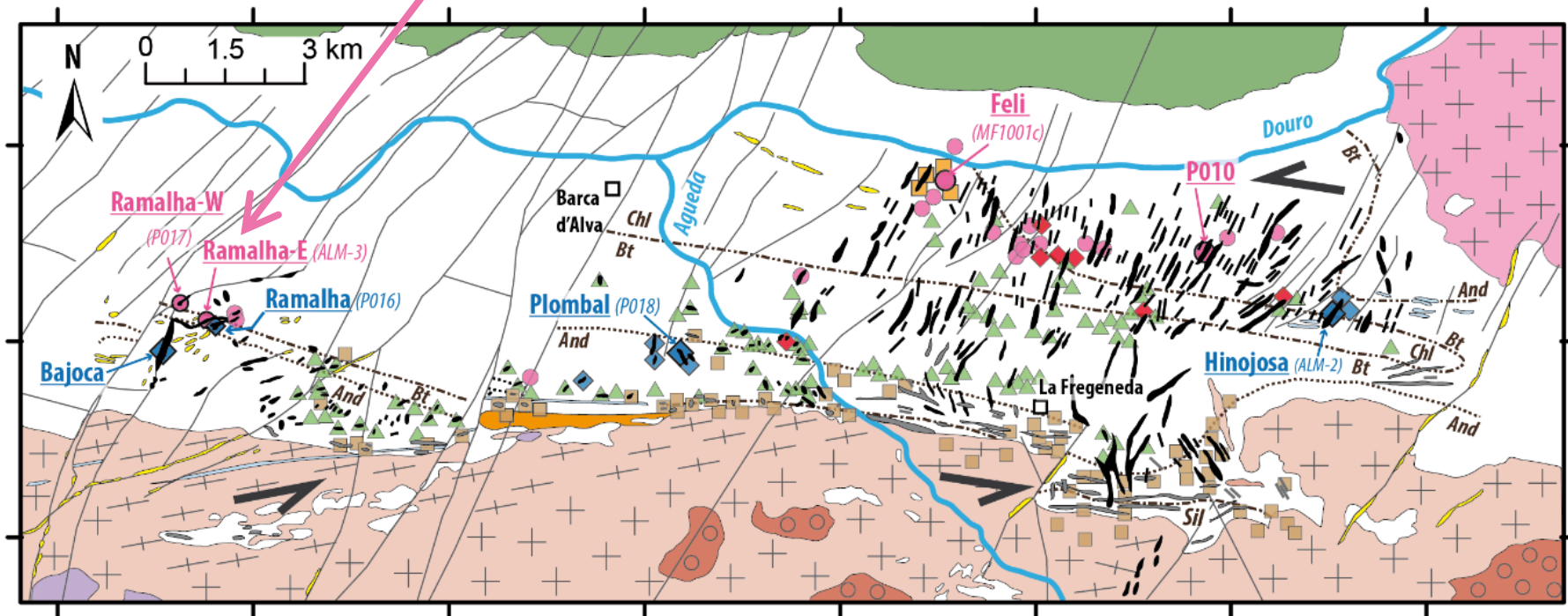
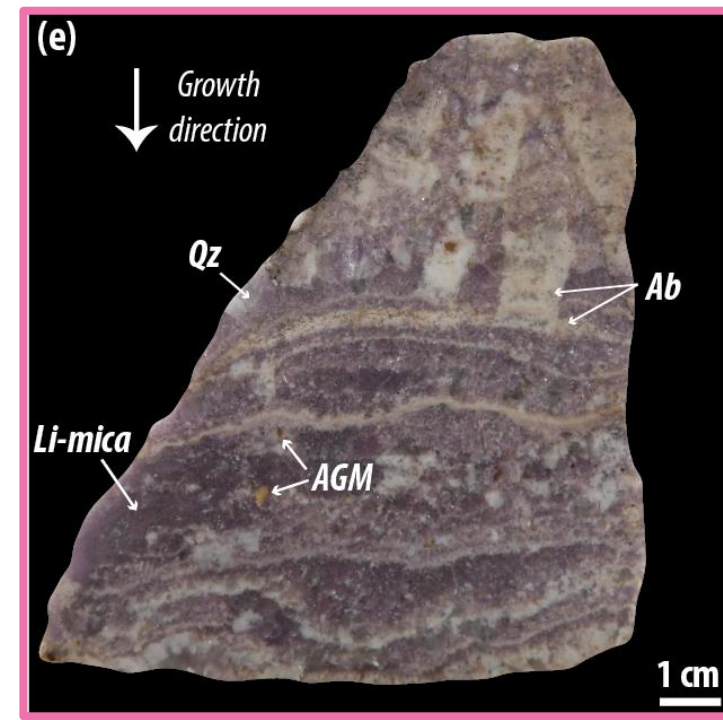
N

S

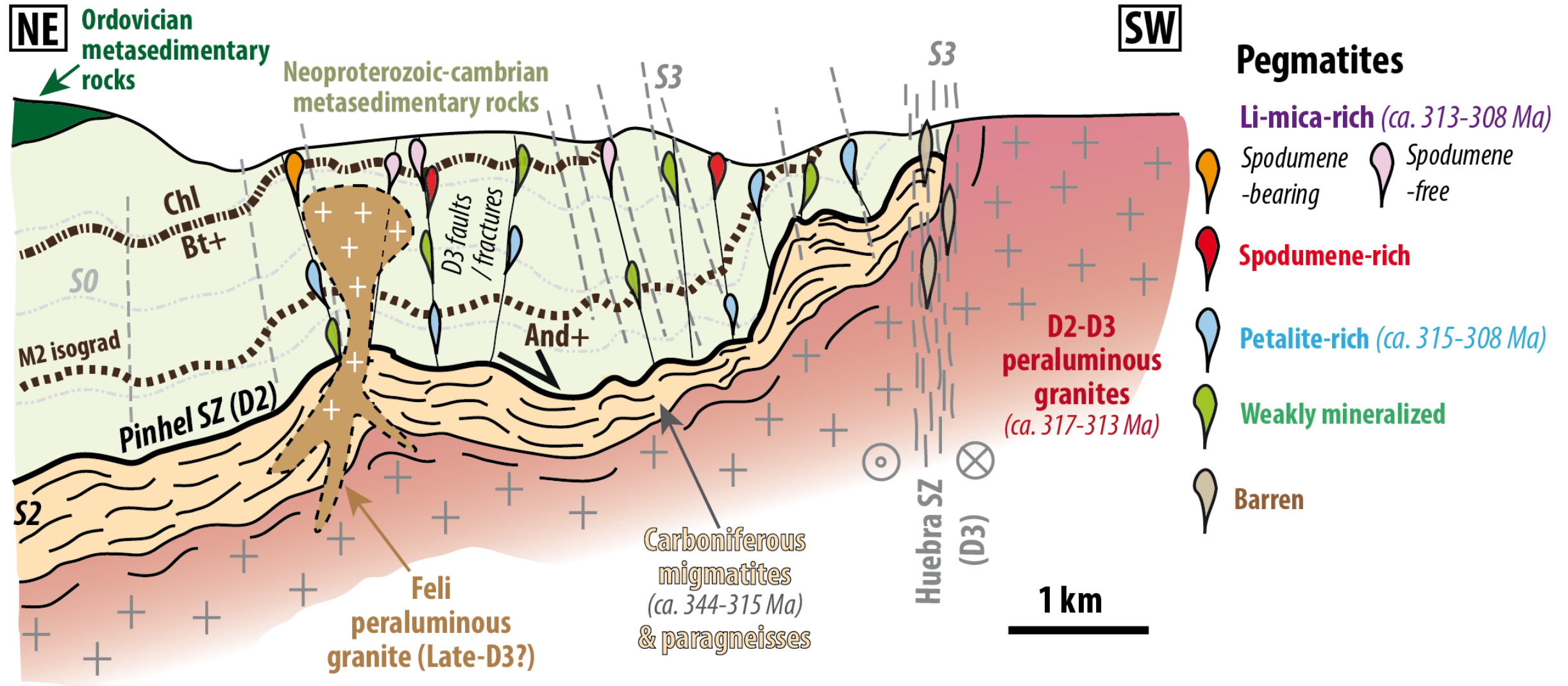
Pegmatites à pétalite (Ptl)



Pegmatites à lépidolite (Li-mica)

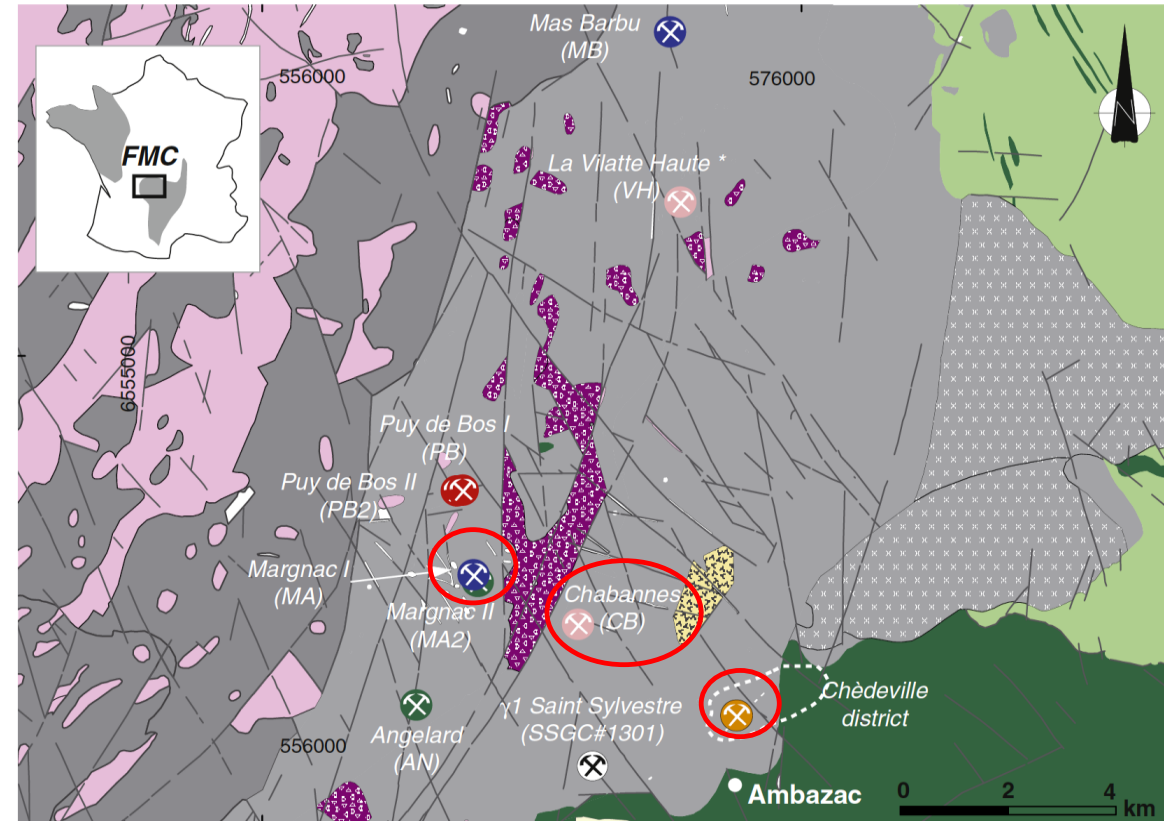
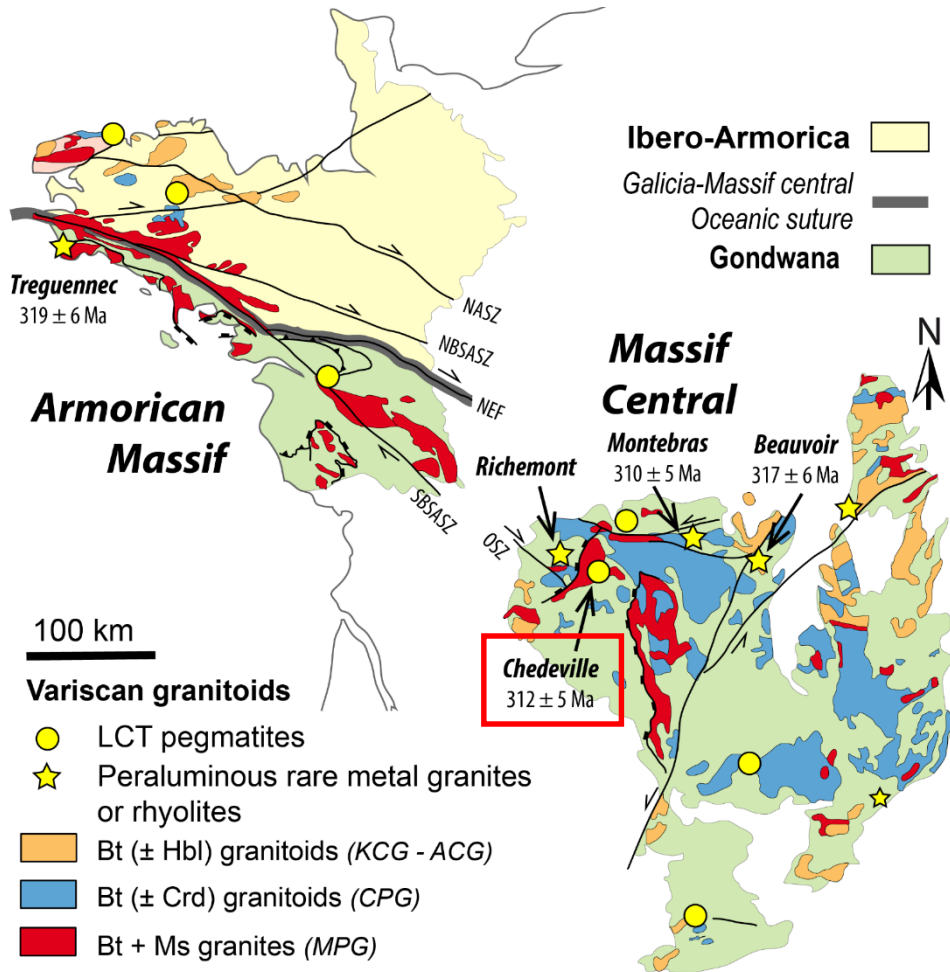


Coupe géologique du champ de pegmatite de Fregeneda-Almendra



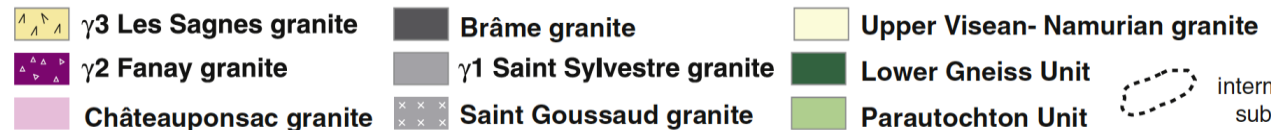
Variscan belt

Pegmatites des monts d'Ambazac



Geological map

* name of pegmatitic dike sampled

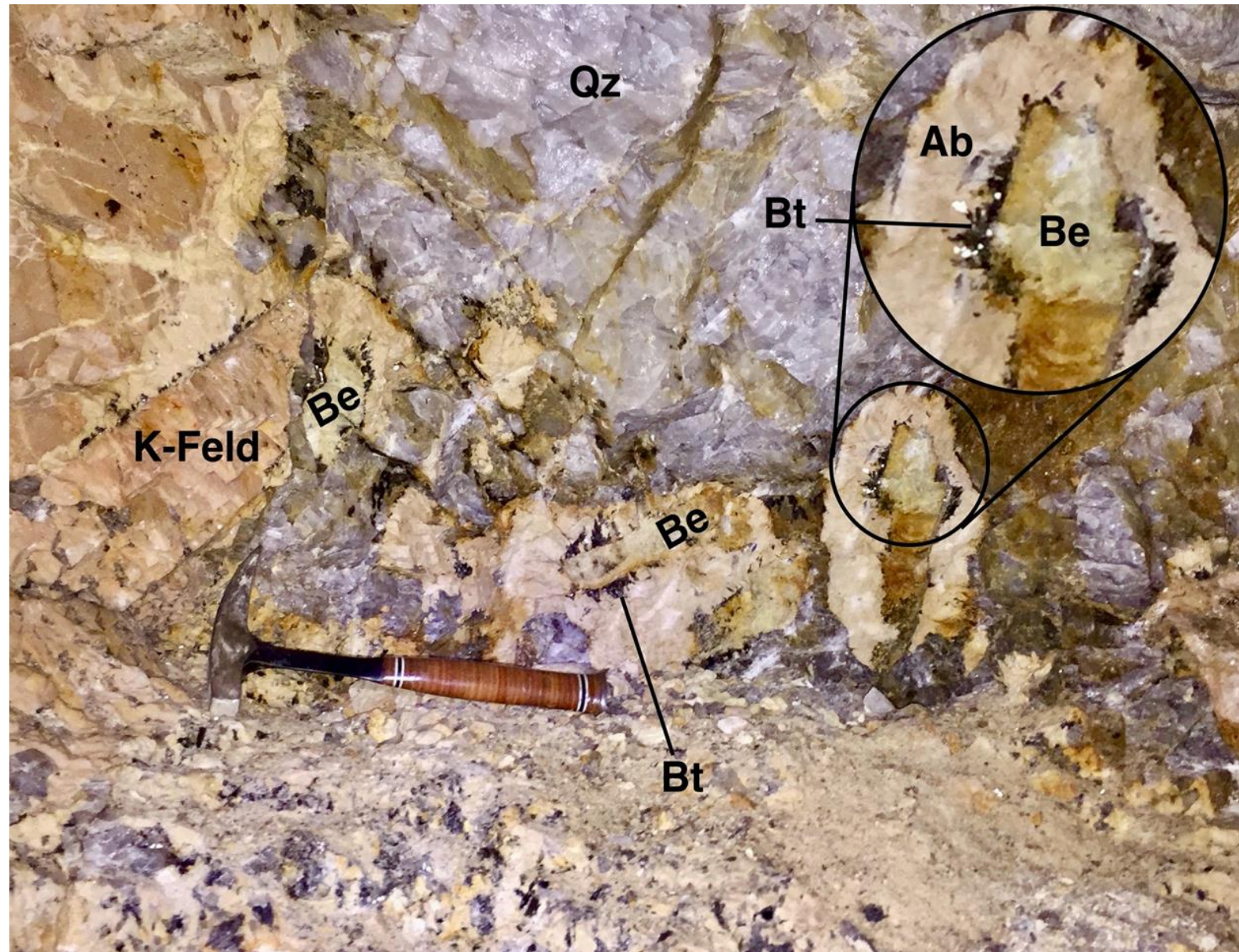


Chèdeville district
intermediate lepidolite- petalite
subtype (Černý and Ercit's
classification 2005)

Deveaud et al. 2015

■ Pegmatite de Margnac :

- *LCT, sous-type Béryl-Colombite (signature géochimique à Be, Nb >< Ta ($\pm$ Sn, B), type IV*
- *Puissance de l'ordre de 7 m*
- *Pegmatite zonée :*
 - Unité de quartz graphique
 - Unité intermédiaire
 - Unité à quartz squelettique et biotite
 - Unité en blocs
 - Cœur à quartz et muscovite
- *Dans la zone interne : hydroxyapatites zonées, colombo-tantalites, albite, quartz, biotite plaquée sur des bérils, orthose, muscovite*



Pegmatite de Margnac, à bérils centimétriques (Be), enveloppe albitisée (Ab), et de biotite (Bt) avec Orthose (K-Feld) et quartz (Qz)

Pegmatite de Margnac



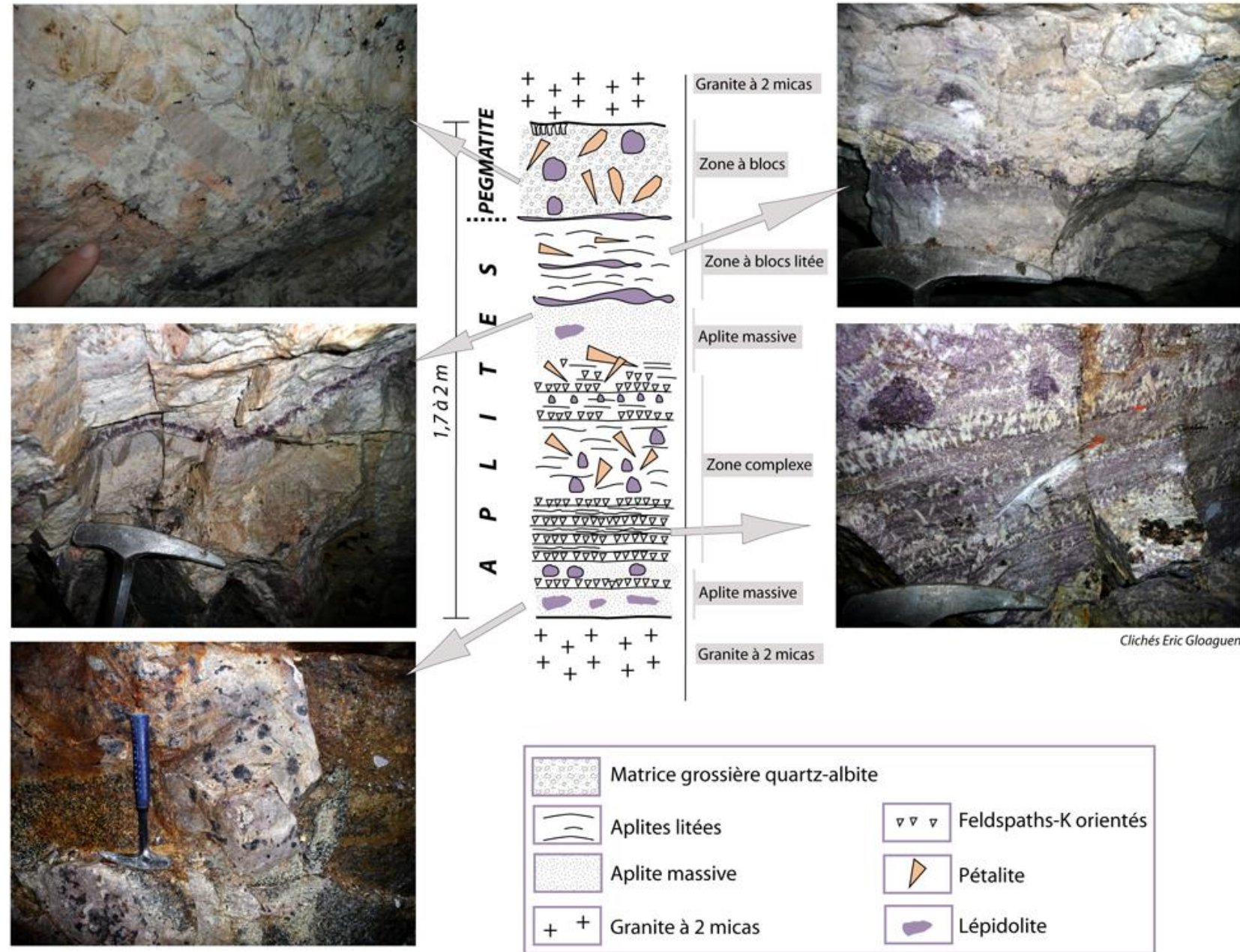
Pegmatite de Chabannes: aplite litée au contact avec le granite de St Sylvestre

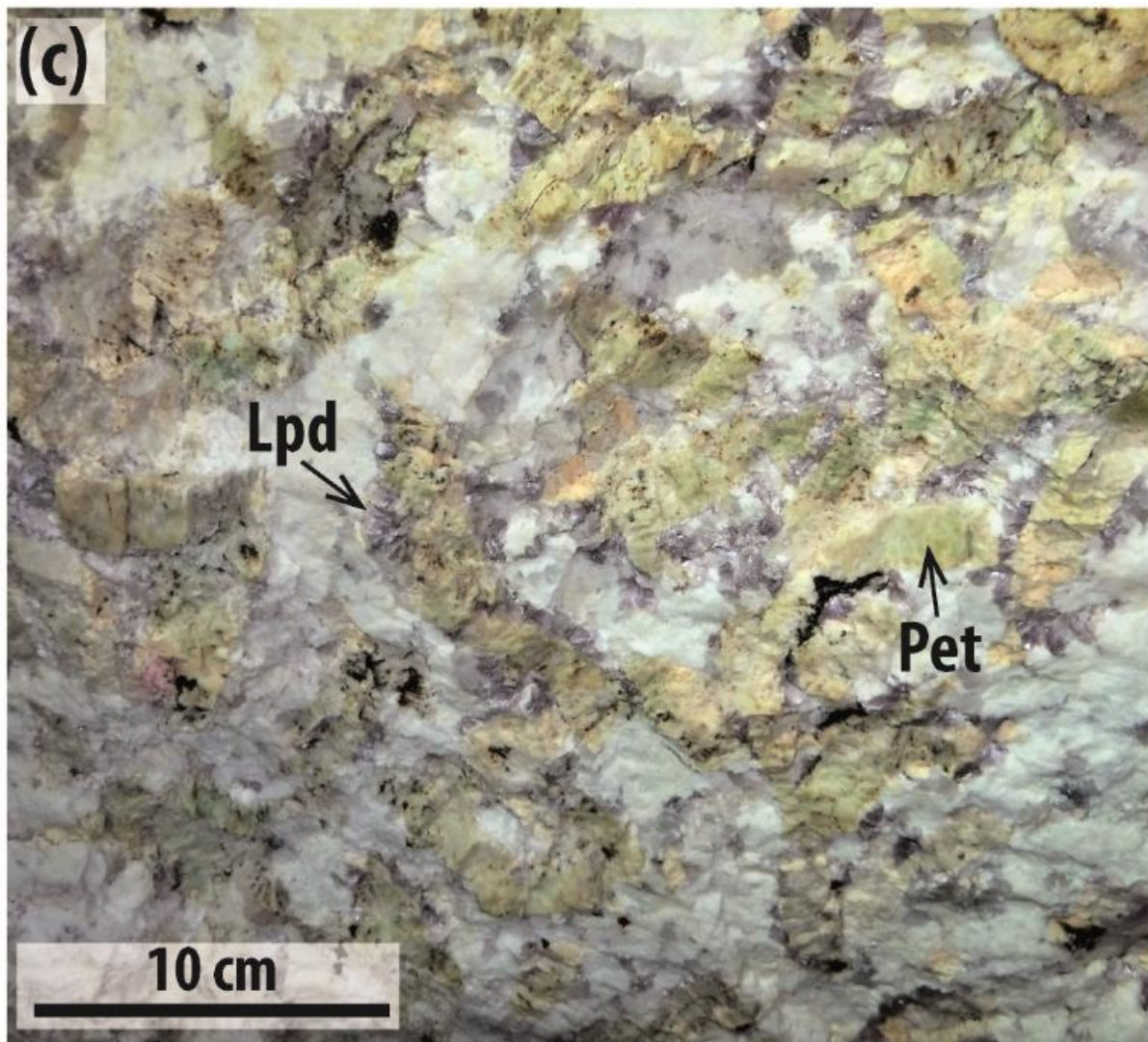


Chèdeville

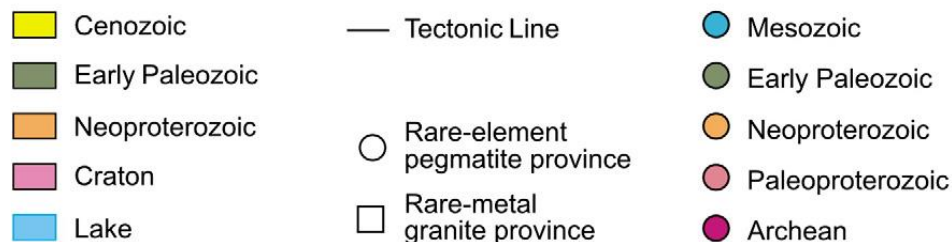
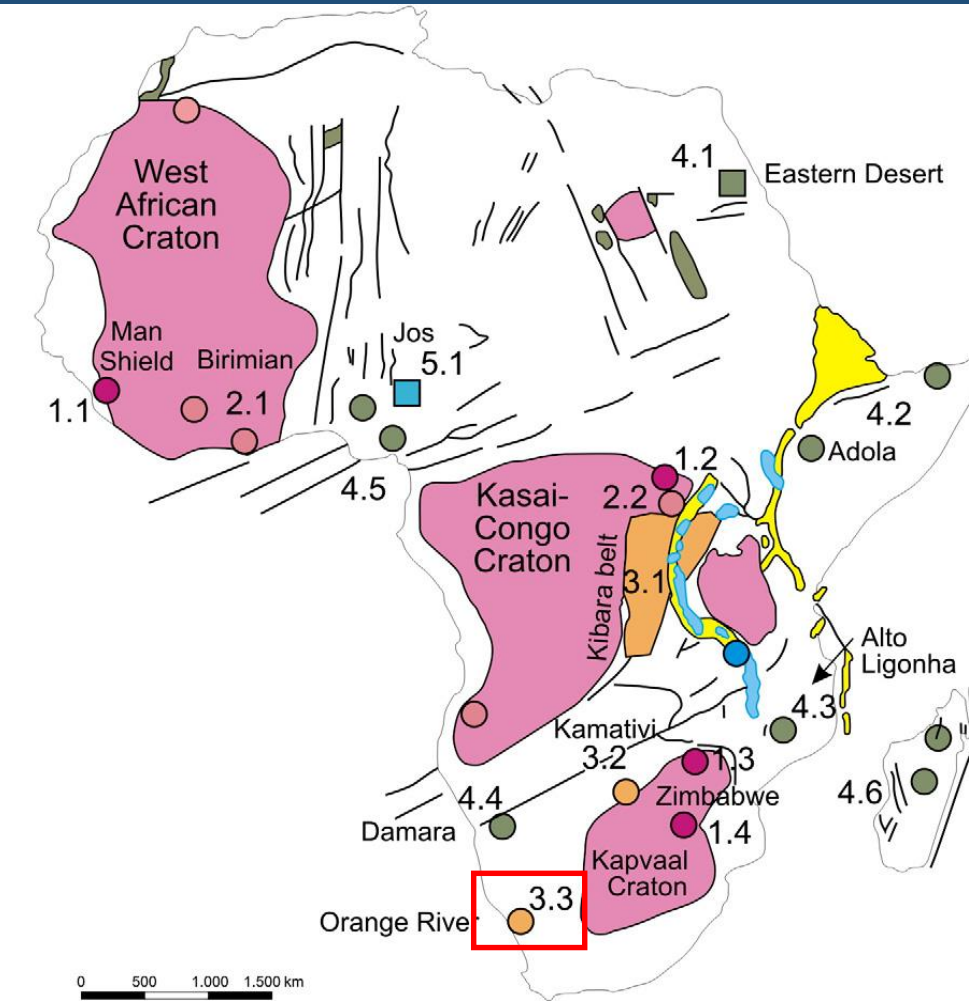
■ Pegmatite de Chèdeville :

- LCT, à lépidolite et pétalite (signature géochimique à $Li, Rb, Cs, Be, Ta > Nb$ ($Sn, Ga, P, F \pm B$))
- Pegmatites au sein de dykes
- Pegmatite zonée :
 - Zone à blocs
 - Zone en blocs stratifiés
 - Zone aplitique
 - Zone complexe
- Exploitée jusqu'en 1938 par Saint-Gobain : 7078 T de minerais de Li extraites





5. The Orange River pegmatite Belt

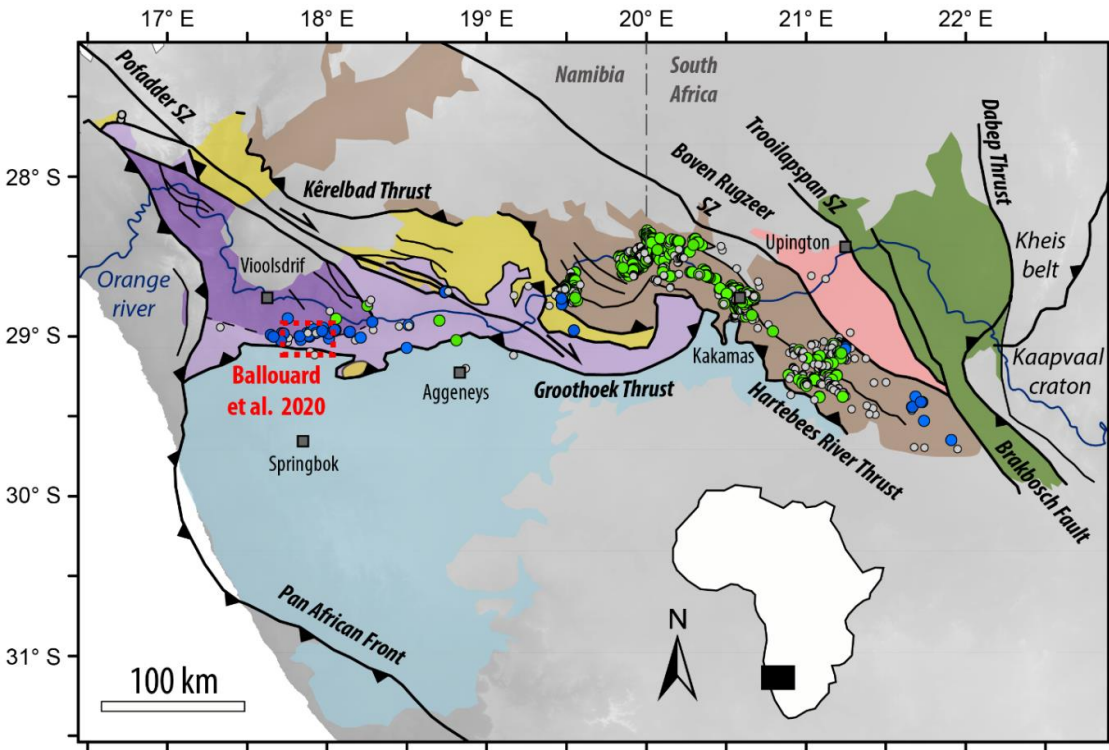


Map of African rare-element pegmatite and rare-metal granite provinces (different symbols). Colours indicate age provinces. The following numbered provinces are :

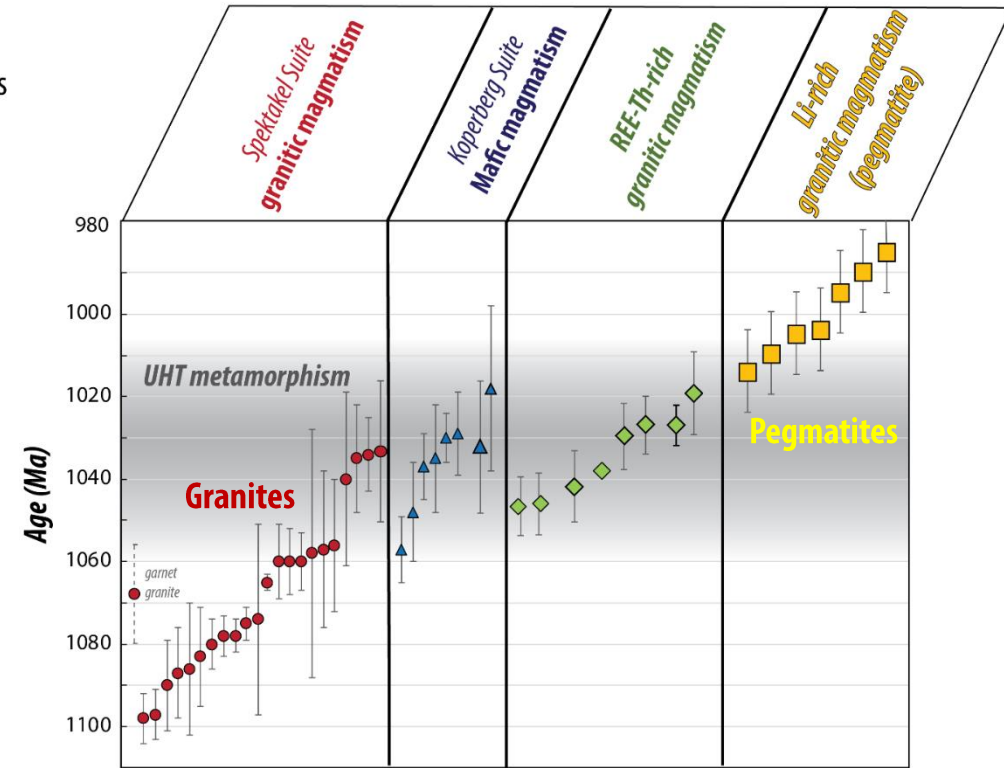
- 1.1 Man Shield,
- 1.2 Congo Craton
- 1.3 Zimbabwe Craton
- 1.4 Kaapvaal Craton
- 2.1 Birimian Province
- 2.2 Kibalian in north-eastern DRC
- 3.1 Kibara Belt
- 3.2 Kamativi Schist Belt
- 3.3 Orange River Belt
- 4.1 Eastern Desert,
- 4.2 Adola Belt,
- 4.3 Alto Ligonha Province
- 4.4 Damara Belt
- 4.5 Older Granites (Nigeria)
- 4.6 Madagascar
- 5.1 Younger Granites (Nigeria).

(Melcher et al., 2015)

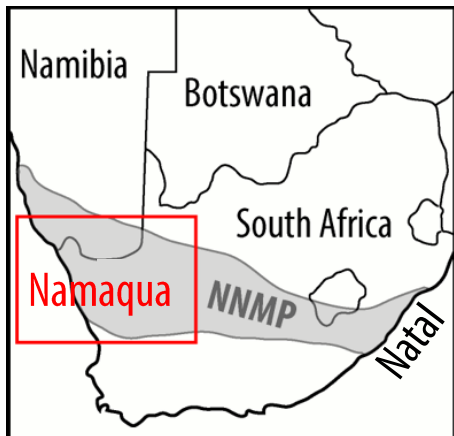
Magmatisme pegmatitique à métaux rares mésoprotérozoïque du Namaqualand (Afrique du Sud/Namibie)



- Lower Fish-River Onseepkans thrust Zone
- Kakamas Domain
- Areachap Domain
- Bushmanland Subprovince
- Richtersveld magmatic arc
- Violsdrif Domain
- Pella Domain
- Kaaiken Domain
- Orange River pegmatite belt
- Li-Ta pegmatite
- REE pegmatite
- Undifferentiated pegmatite
- Tectonic contact



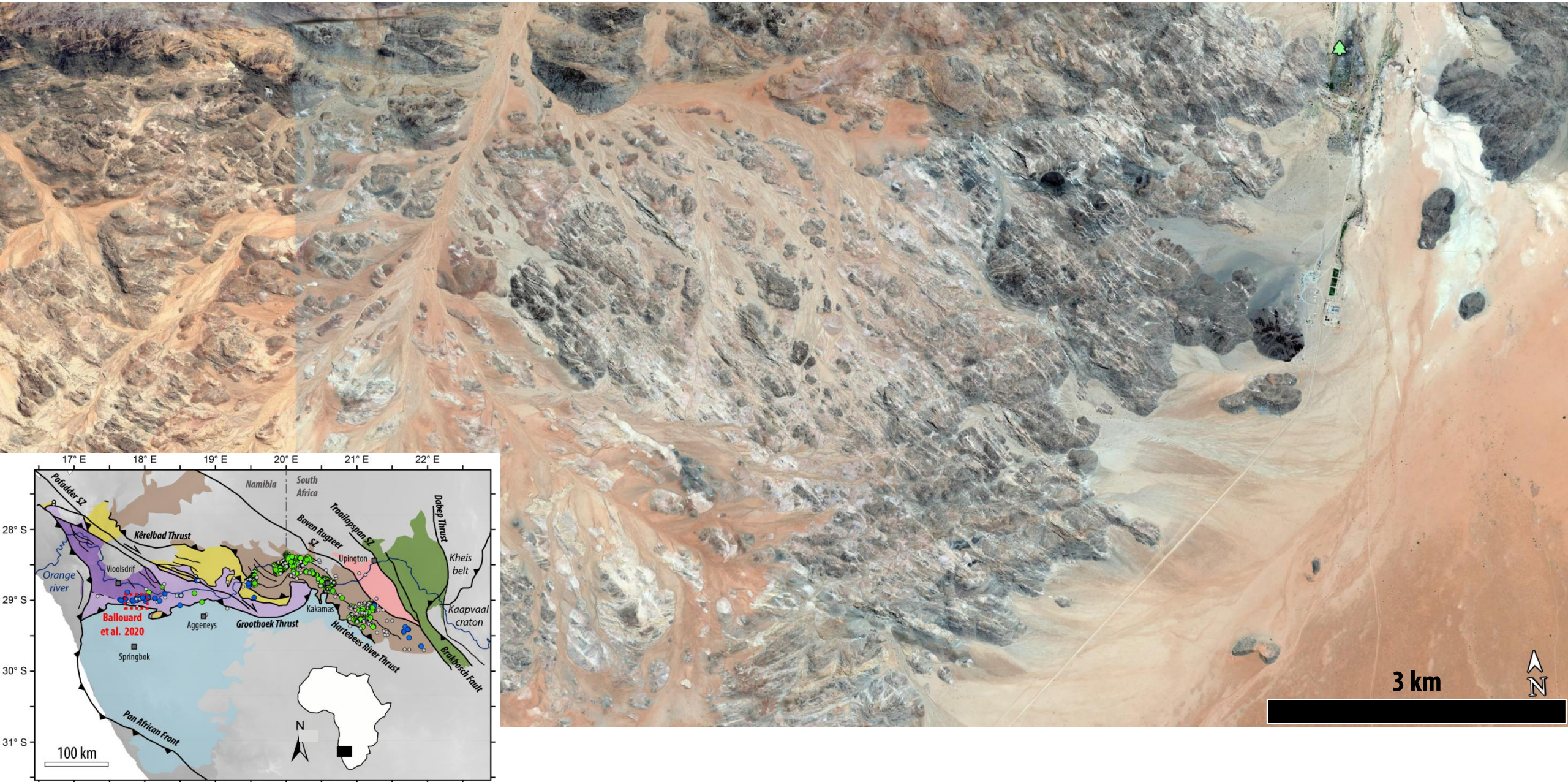
Lambert 2015; Macey et al. 2017; Daggart 2019; Ballouard et al. 2020, 2021



NNMP:
Namaqua-Natal
metamorphic province
(1.3-1.0 Ga)

- **Ceinture de pegmatite de la rivière Orange : > 10000 pegmatites (réparties sur 450 x 50 km)**
- **Zonation géochimique d'échelle régionale entre des pegmatites minéralisées en Li-Ta-Be (LCT) et REE (NYF)**
- **mises en place entre 1030 et 980 Ma: postdate le métamorphisme HT et magmatisme granitique régional**

Contrôle tectonique N0-SE (prépondérant sur l'ensemble de la ceinture)



The Pofadder shear zone

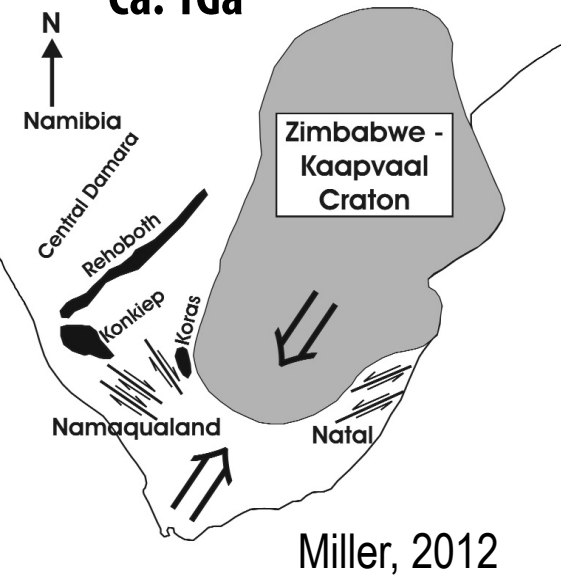
Rivière Orange

Namibie

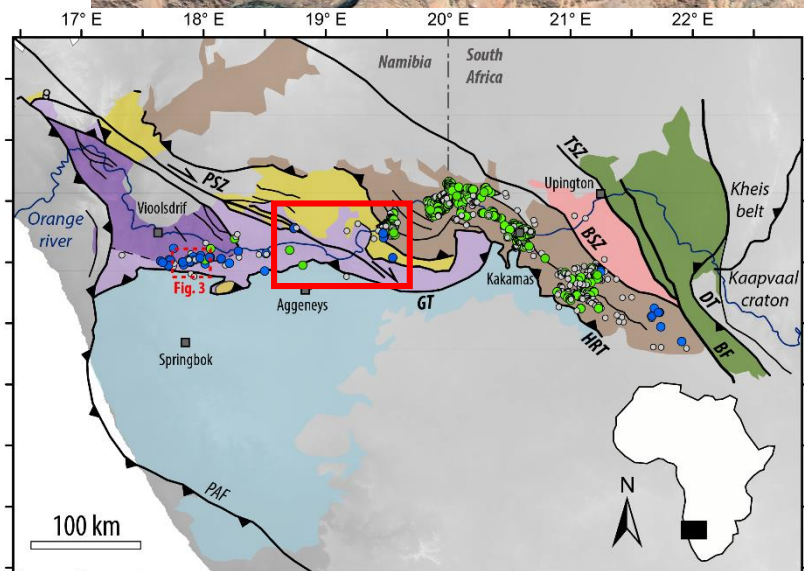
Afrique du Sud

Tantalite
valley

Ca. 1Ga

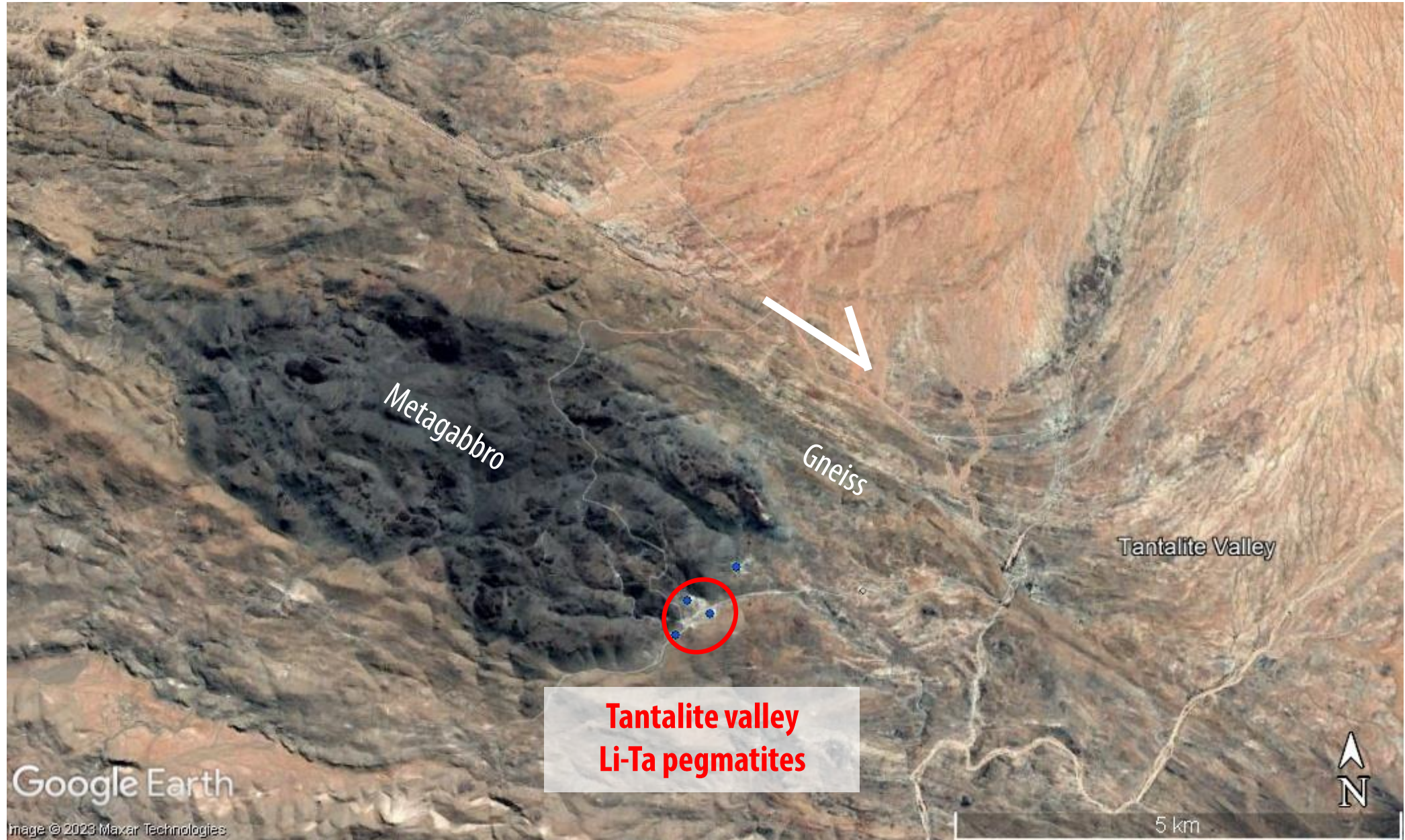


Miller, 2012

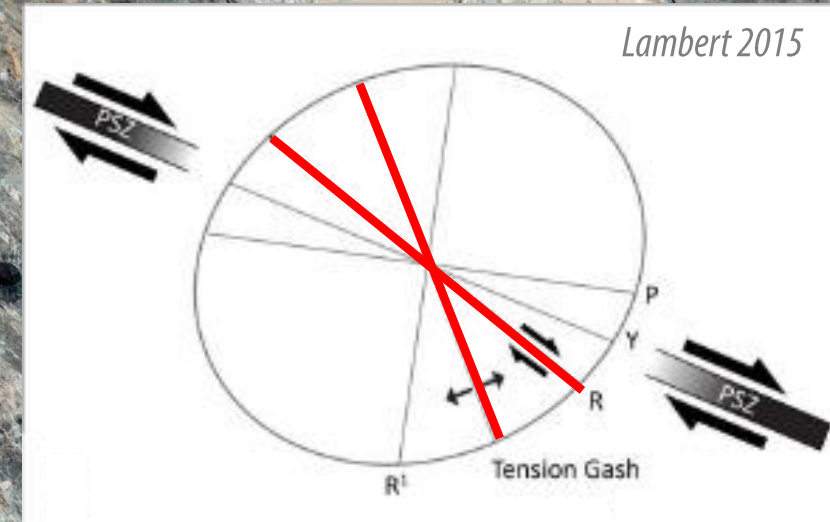
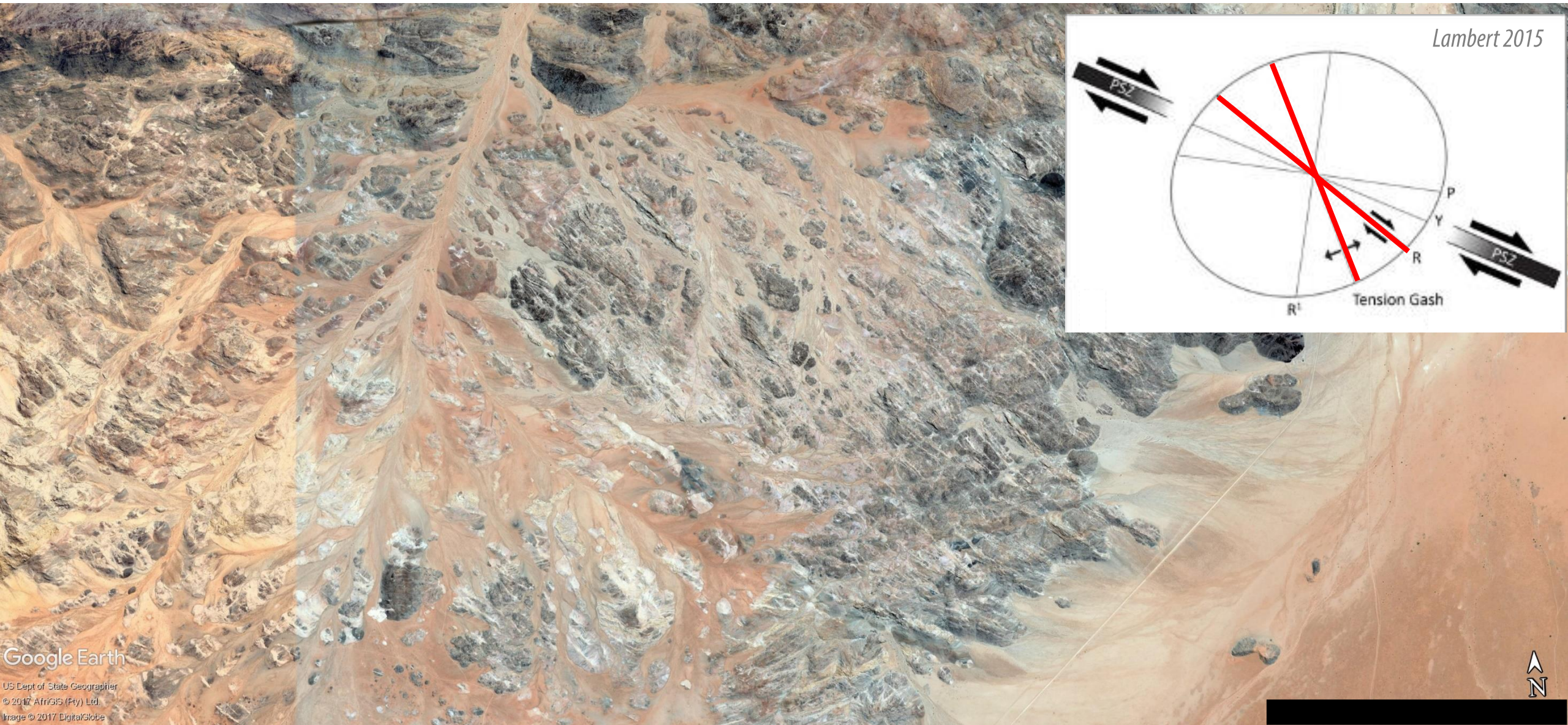


30 km

The Pofadder shear zone



Contrôle tectonique N0-SE (prépondérant sur l'ensemble de la ceinture)

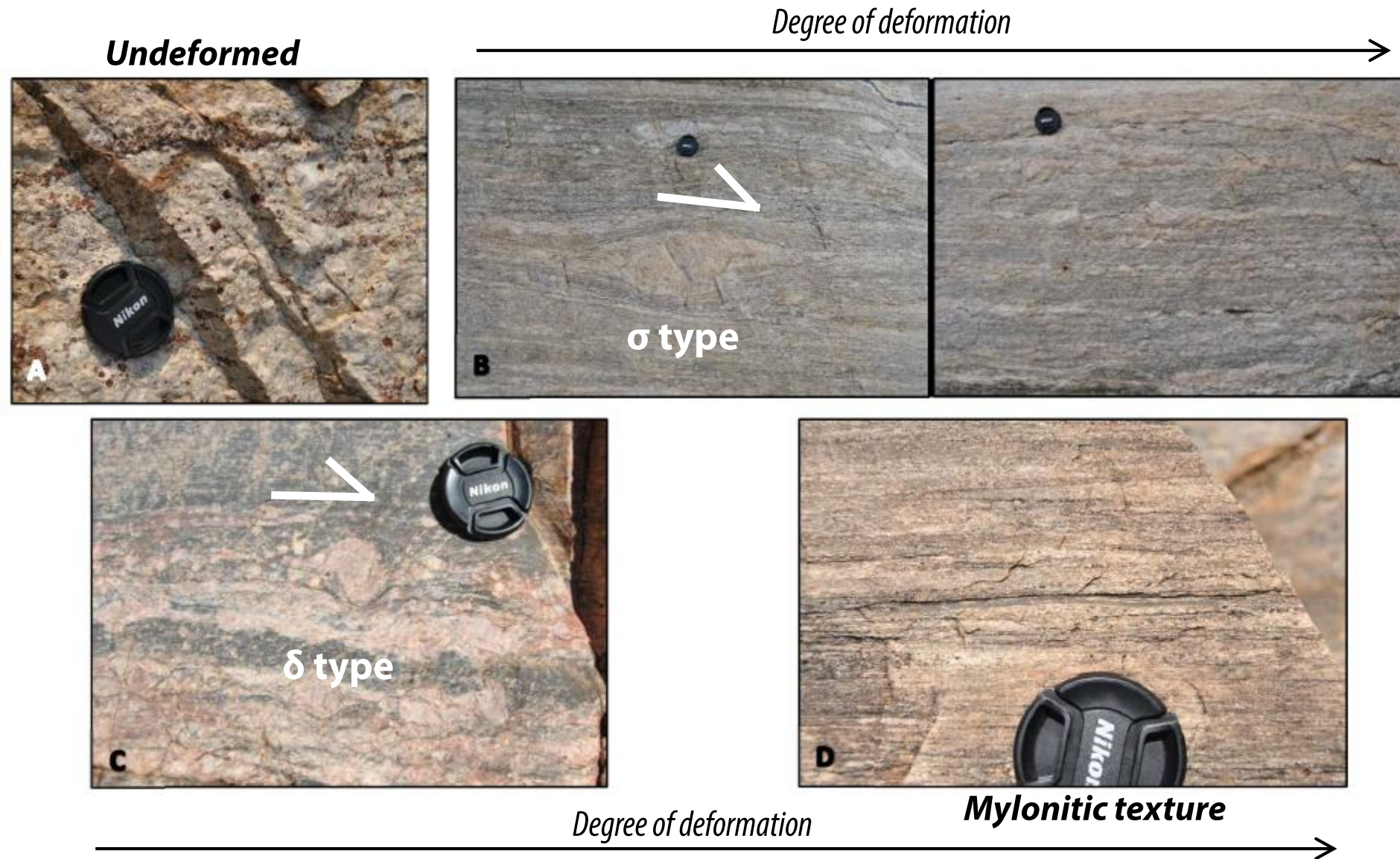


3 km

5.1. The Orange River pegmatite belt

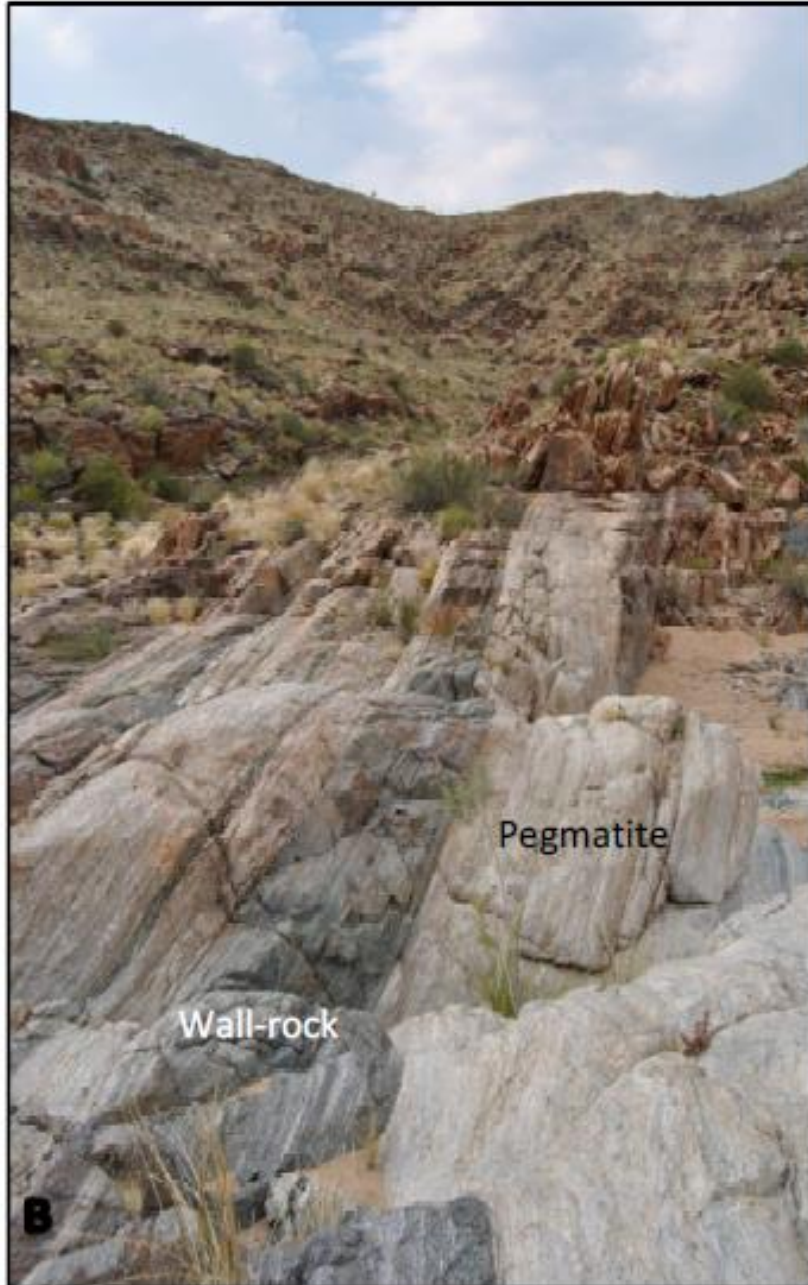


5.1. The Orange River pegmatite belt



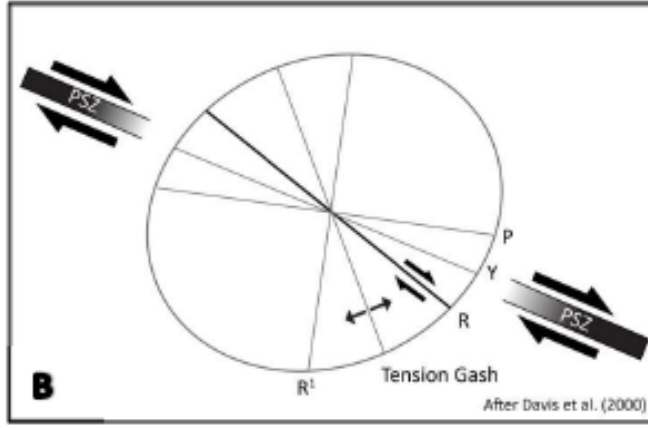
Variability of deformation degrees of pegmatites from the Pofadder shear zone area (Lambert, 2013)

5.1. The Orange River pegmatite belt



Pegmatites striking parallel the foliation in
the Pofadder shear zone area
(Lambert, 2013)

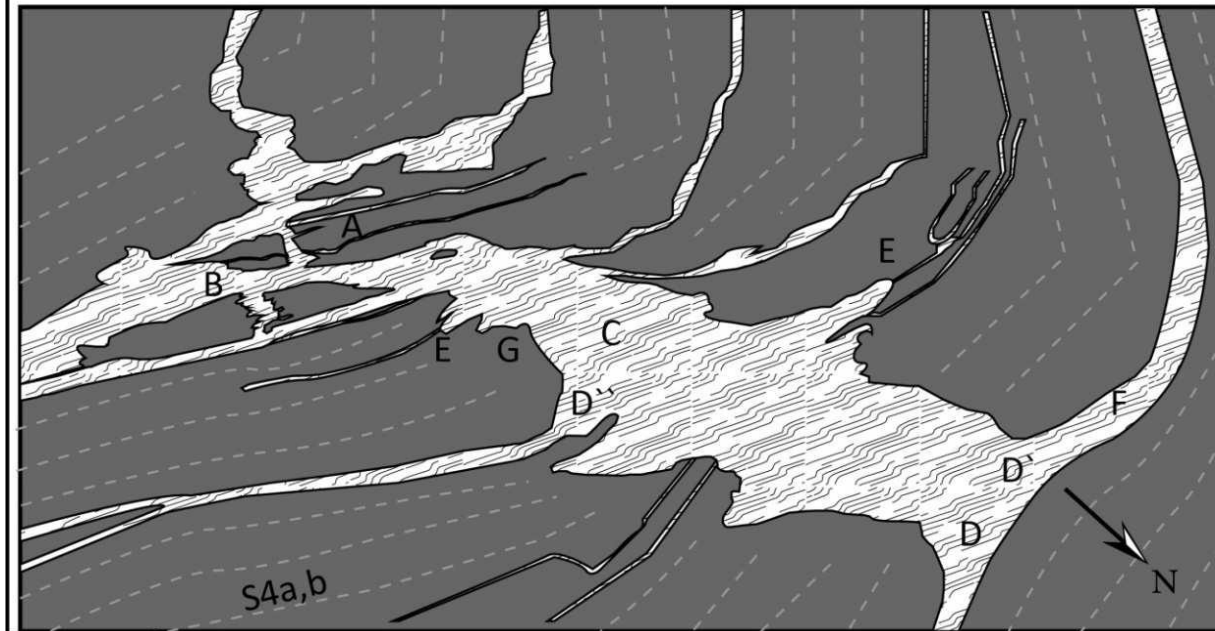
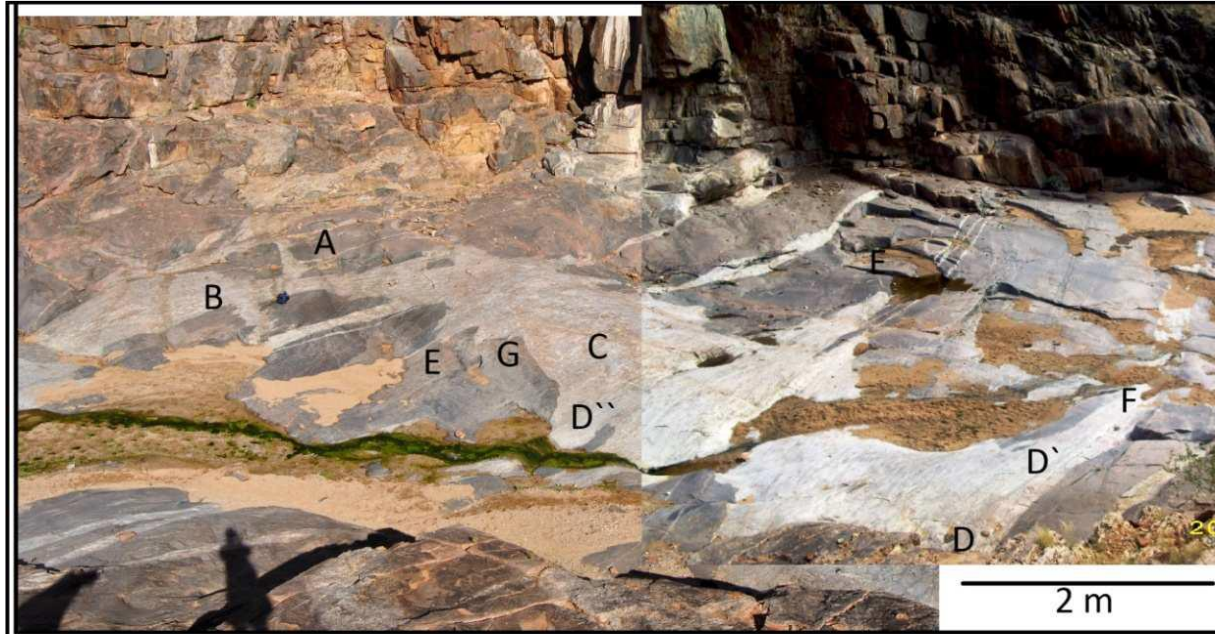
5.1. The Orange River pegmatite belt



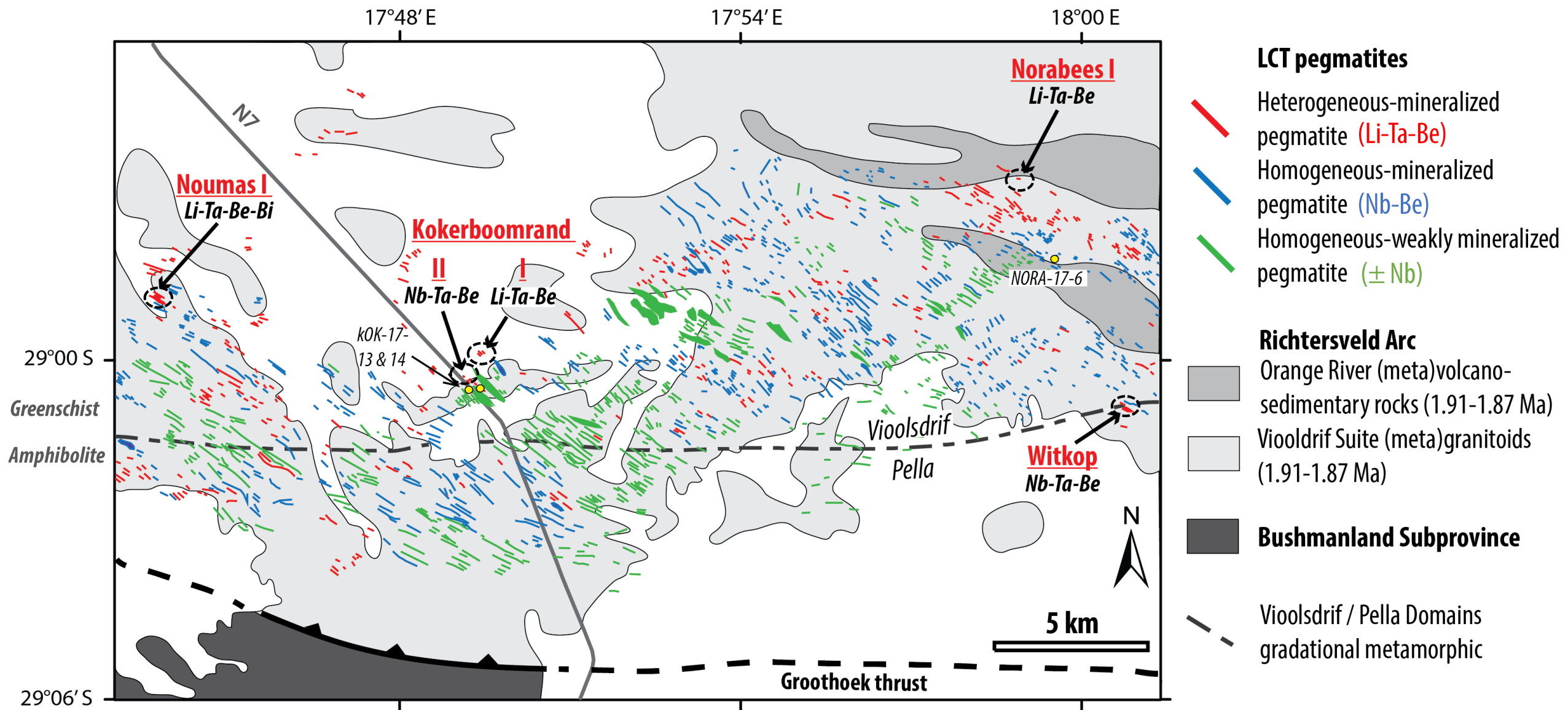
Pegmatites striking parallel and slightly oblique (R fractures) to the foliation in the Pofadder shear zone area (Lambert, 2013)



5.1. The Orange River pegmatite belt



Jog like pegmatite geometries along the Pofadder shear zone (Lambert, 2013)

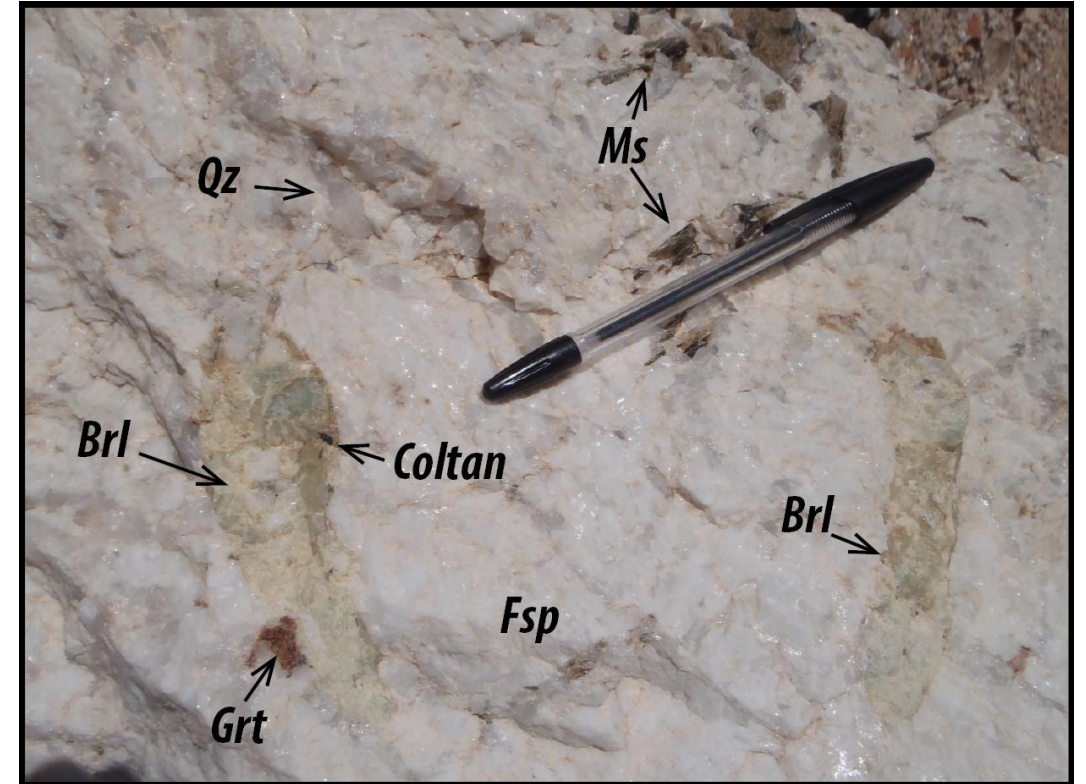


*Simplified geological map of the western part of the Orange River pegmatite belt (Macey et al. 2017).
Pegmatite typology after Schutte (1972).*

Trois types de pegmatite marqués par un degré variable de minéralisation



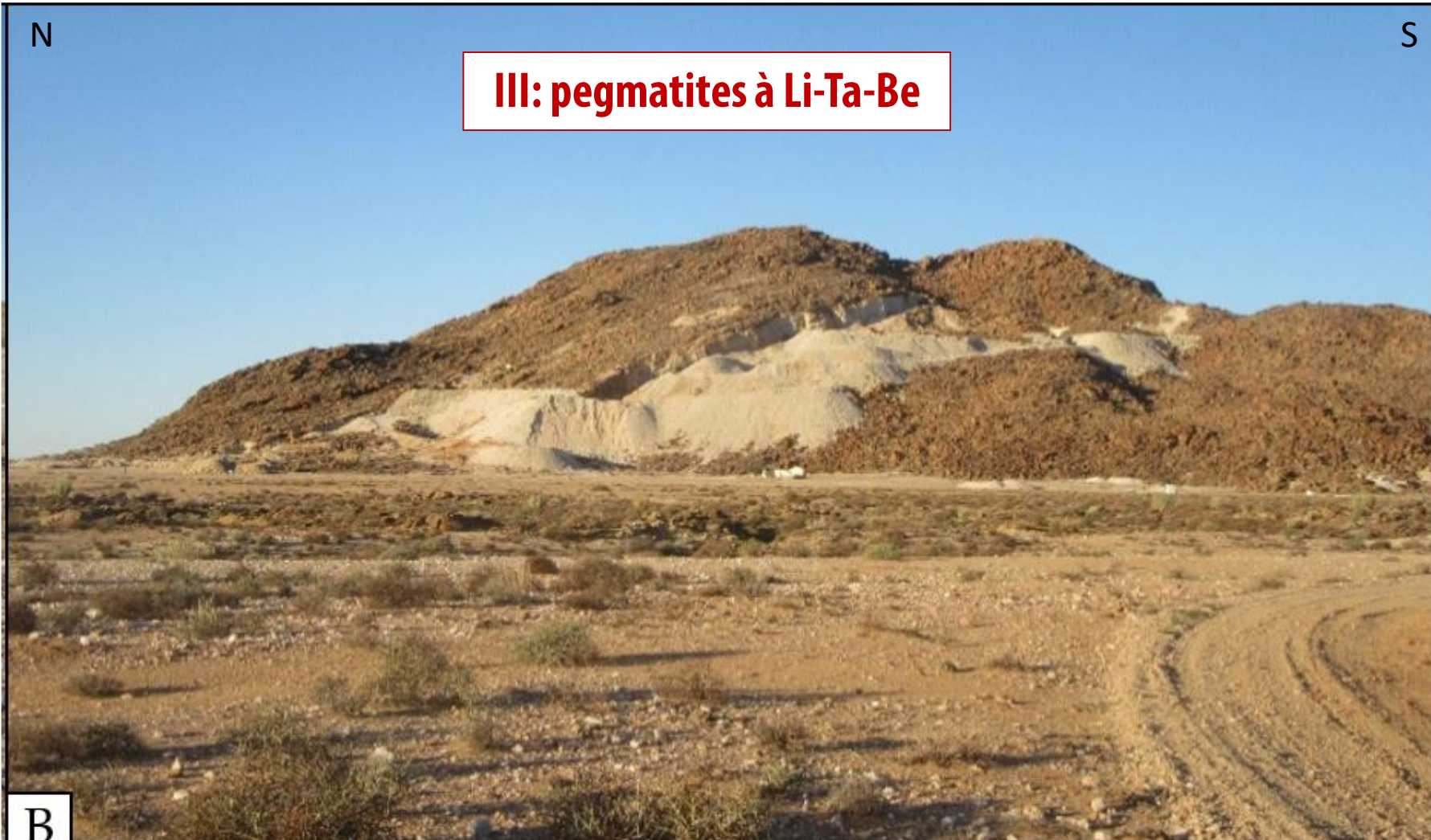
I: pegmatites graphiques faiblement minéralisées
Muscovite-grenat



II: pegmatites à Nb-Be
Muscovite-grenat-colombite (Nb)-béryl (Be)

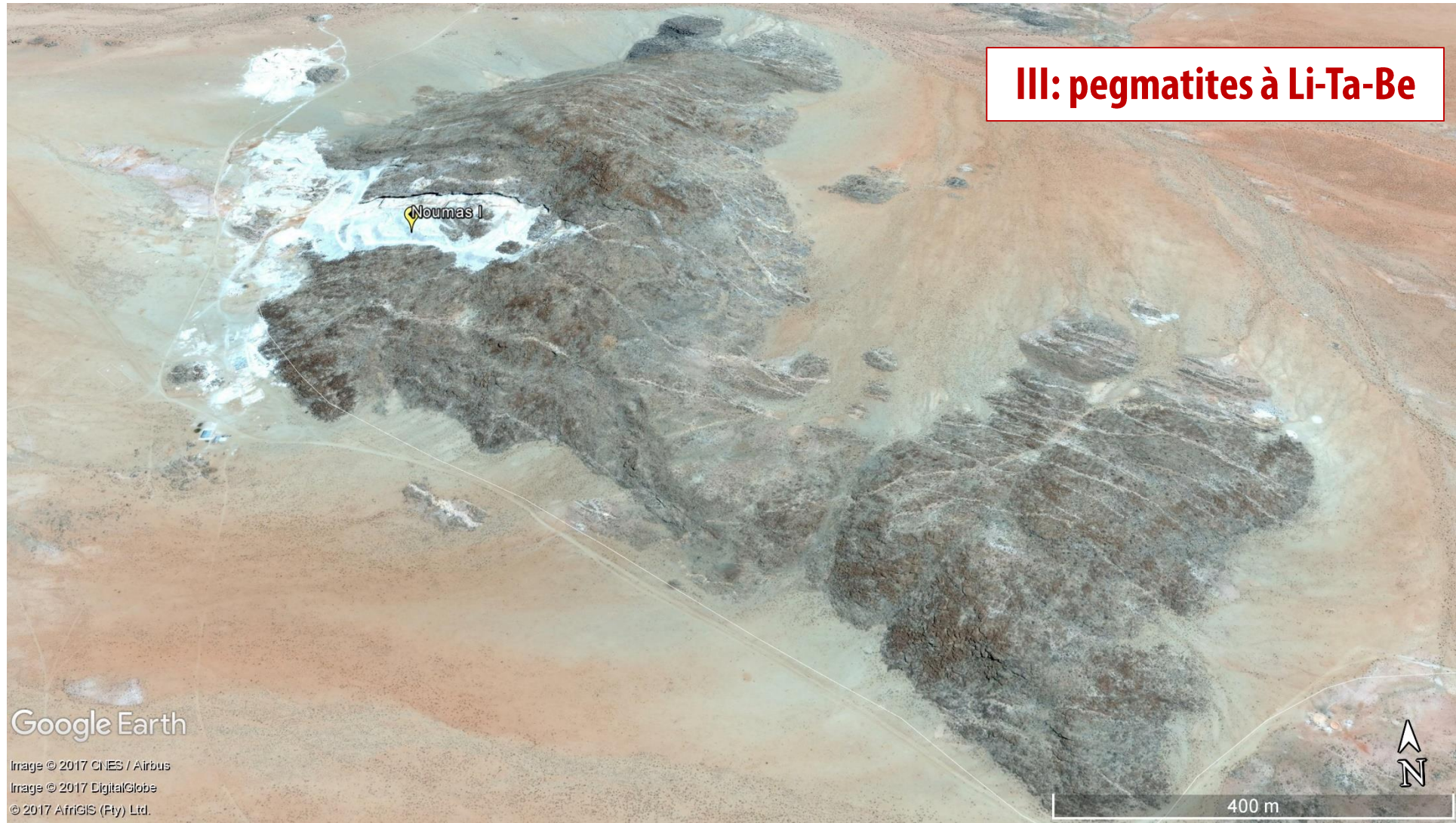
The Noumas 1 pegmatite (Blesberg mine)

Biggest pegmatite from the Namaqualand and first to be mined for bismuth (Bi) in 1925 but contains also spodumene (Li), lepidolite (Li), tantalite (Ta)-columbite (Nb) that were mined until the 1970s. It is currently subject to exploration.



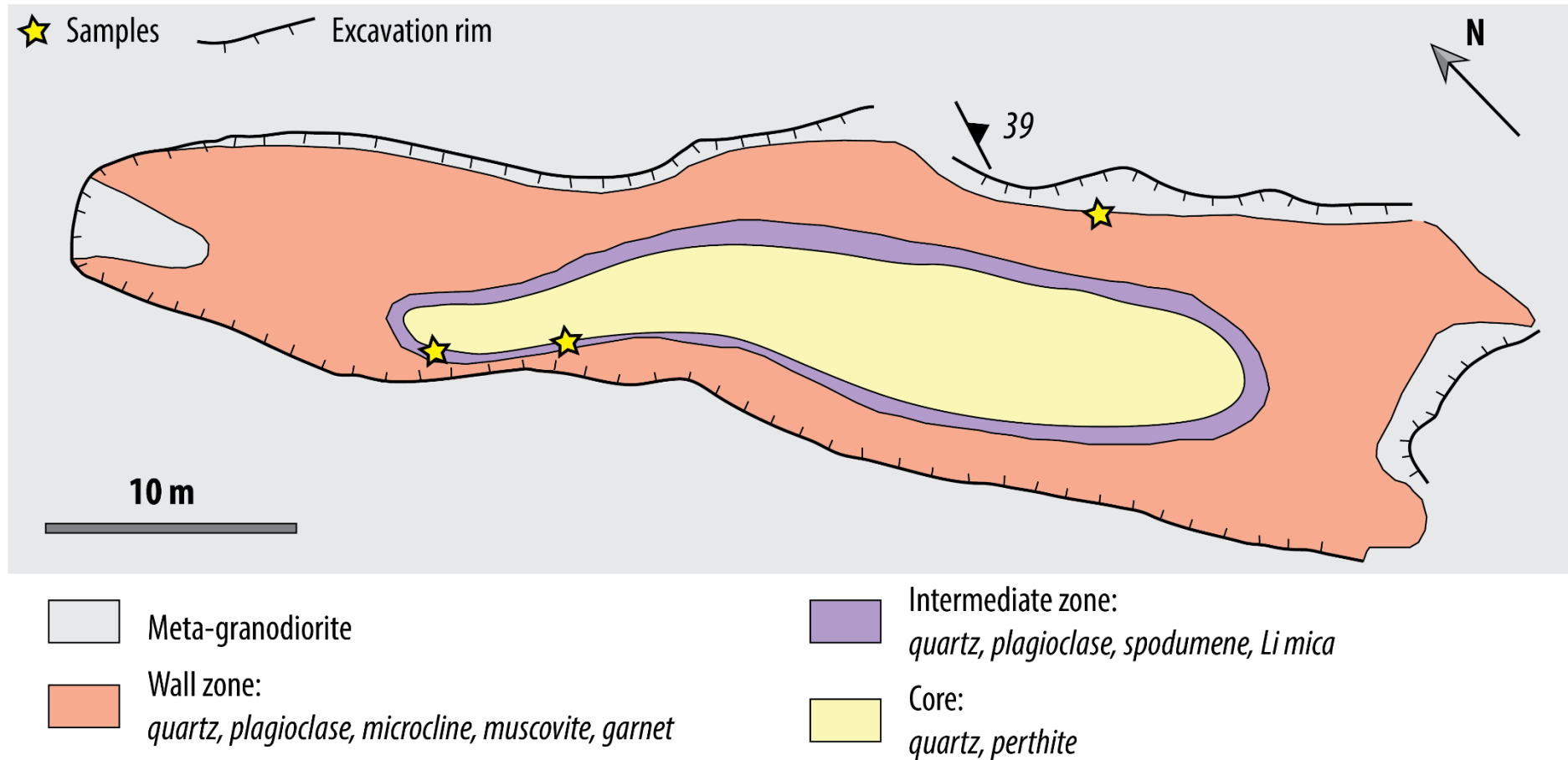
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5.1. The Orange River pegmatite belt

Ballouard et al. 2020

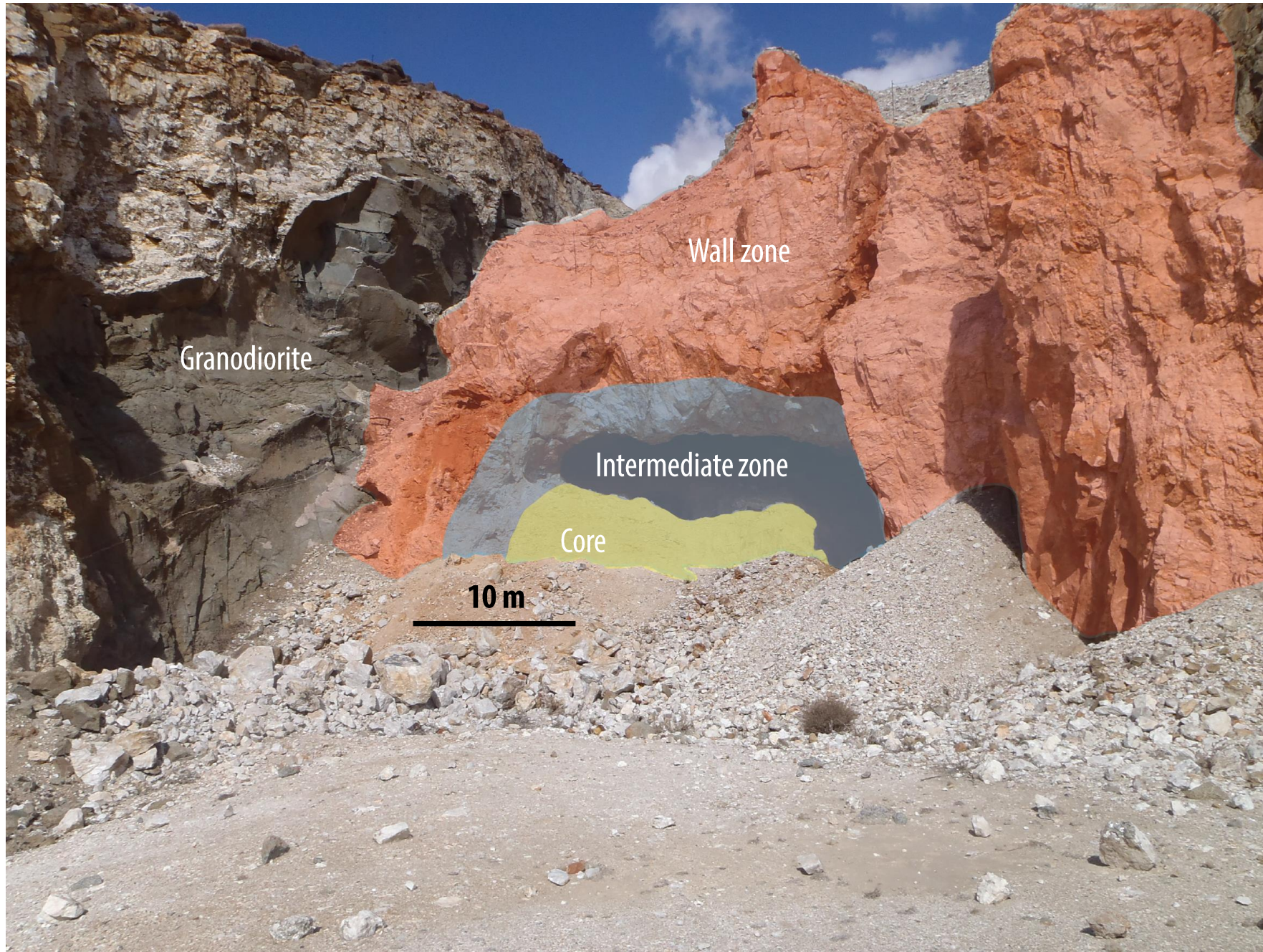


Simplified geological map of the Kokerboomrand I pegmatite after Schutte (1972).

The Noumas 1 (Blesberg mine) pegmatite



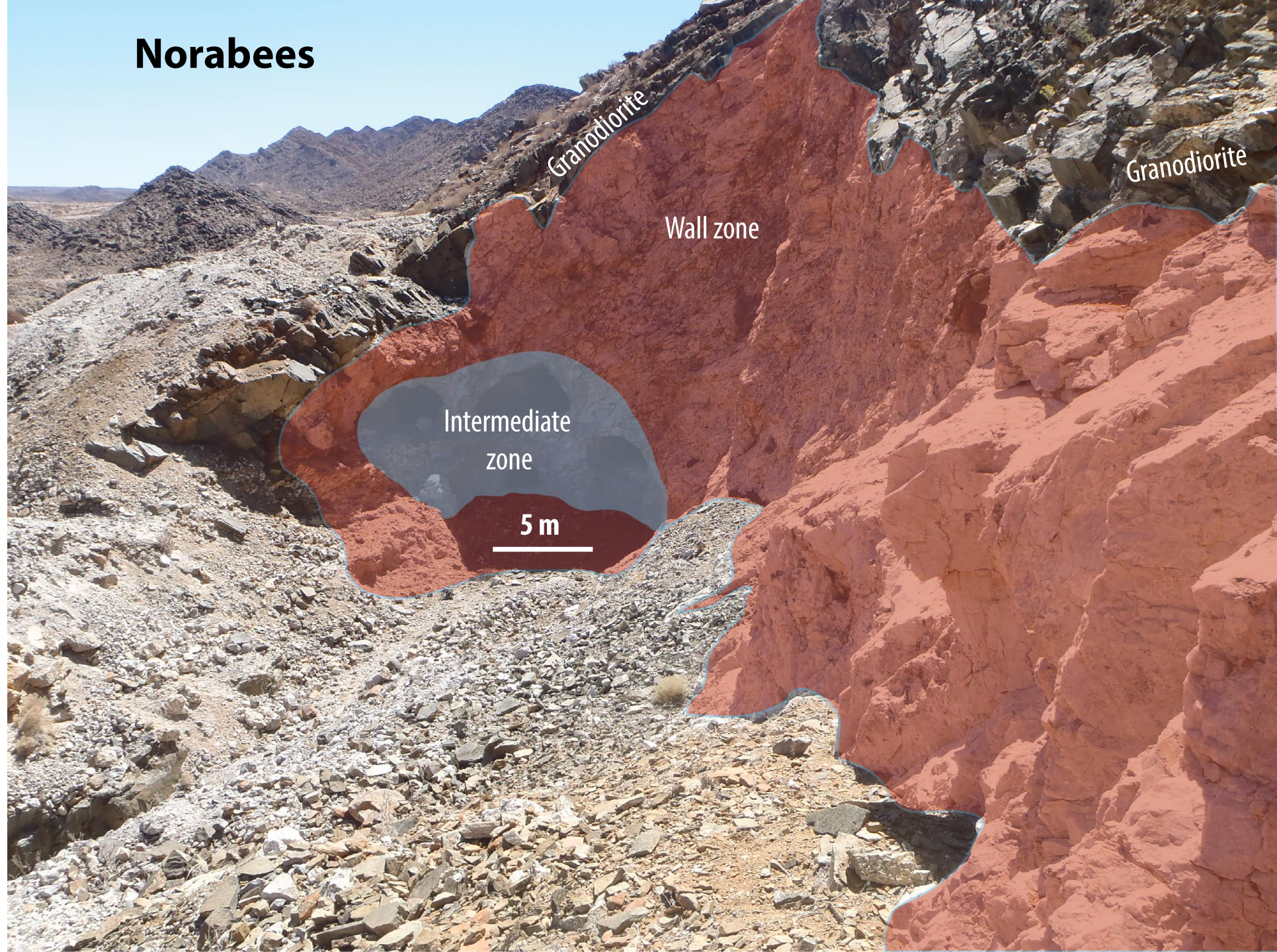
The Noumas 1 (Blesberg mine) pegmatite

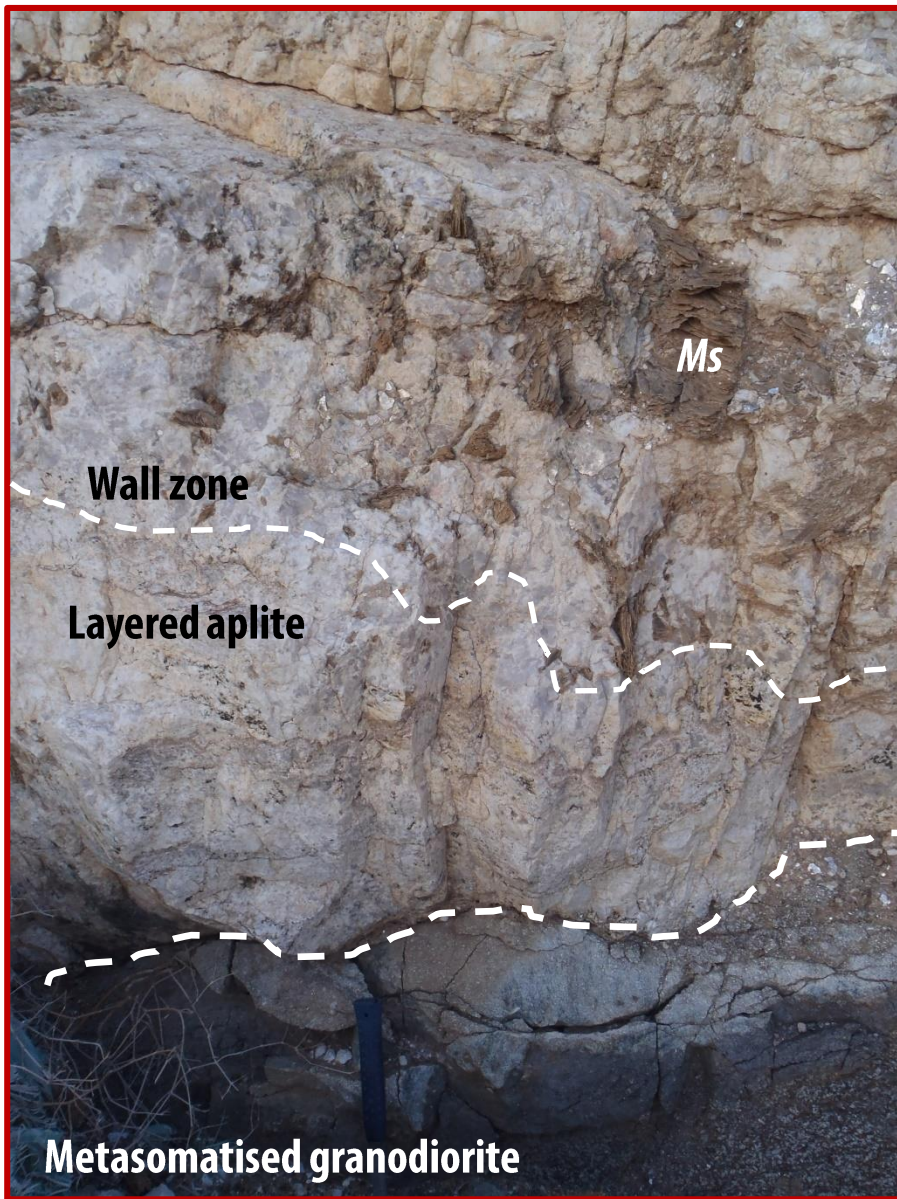


Norabees



Norabees





Contact zone, Noumas I

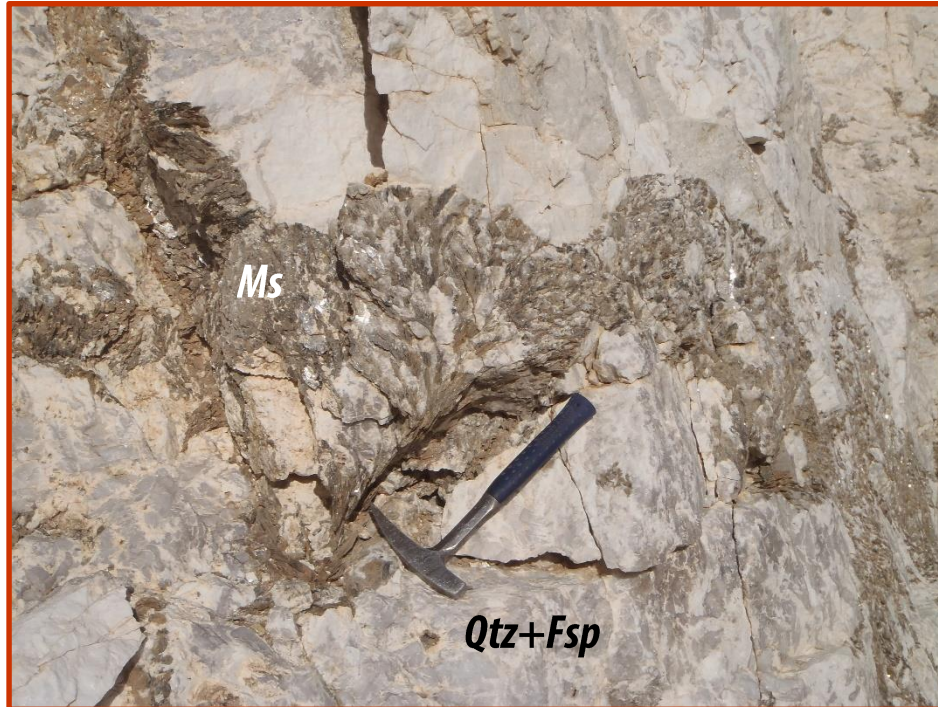


Layered aplite, Noumas I

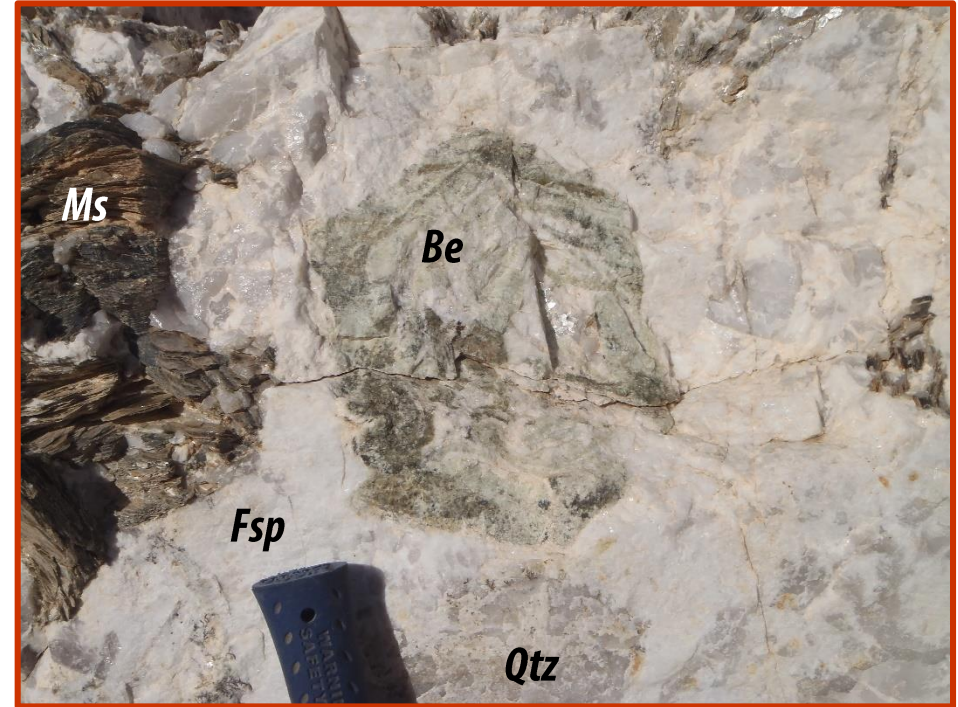
Ms: muscovite, Gt: garnet

Border zone

Wall zone

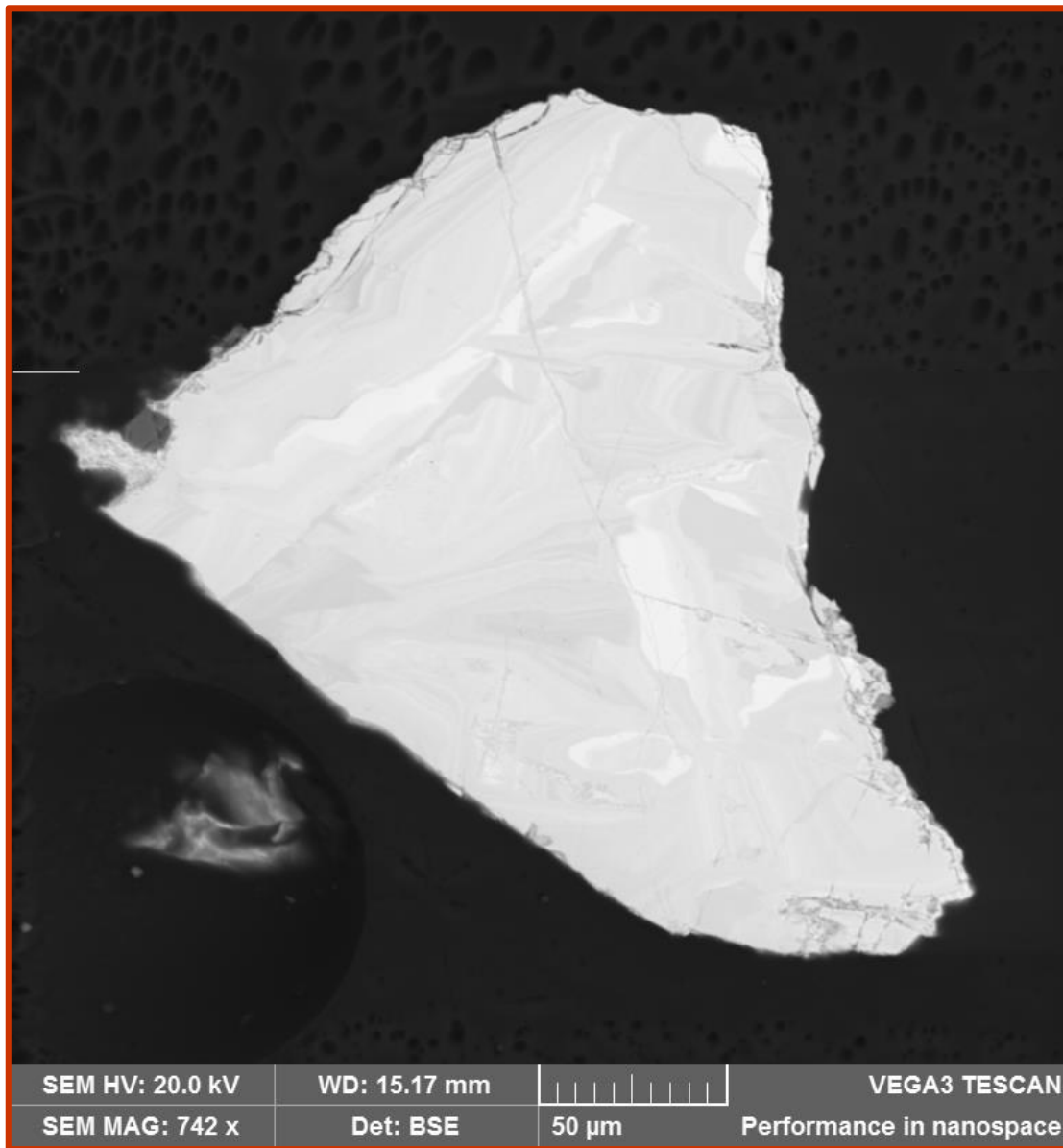


Skeletal muscovite, wall zone, Noumas I



Skeletal beryl, wall zone, Noumas I

Ms: muscovite, Be: beryl; Qtz: quartz, Fsp: feldspar

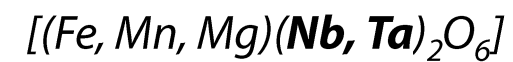


*Nb-Ta oxide (columbite-tantalite),
Noumas I*

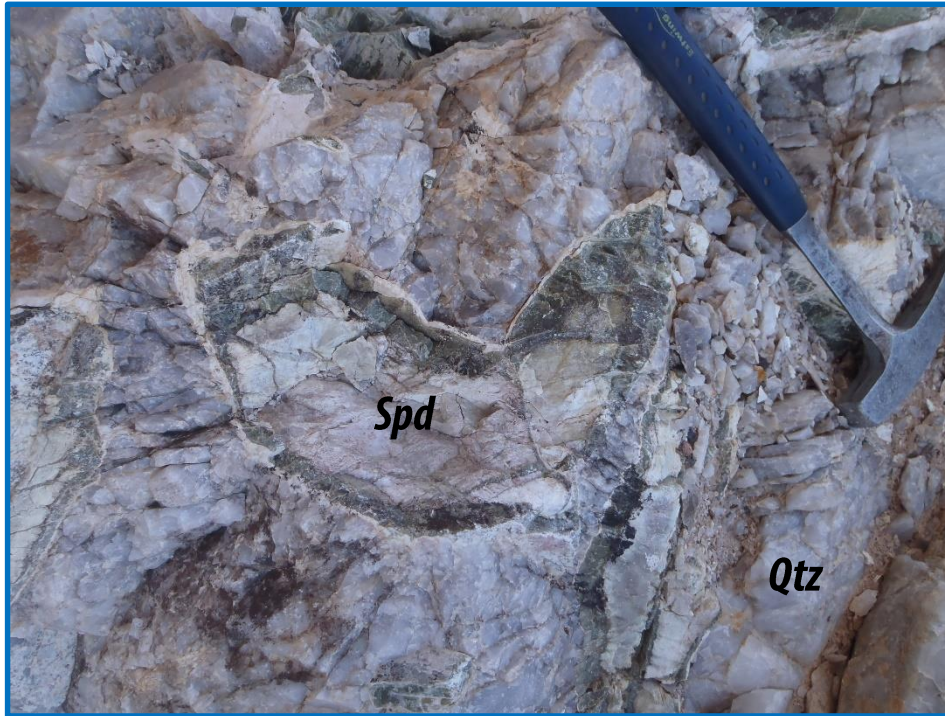
Wall zone



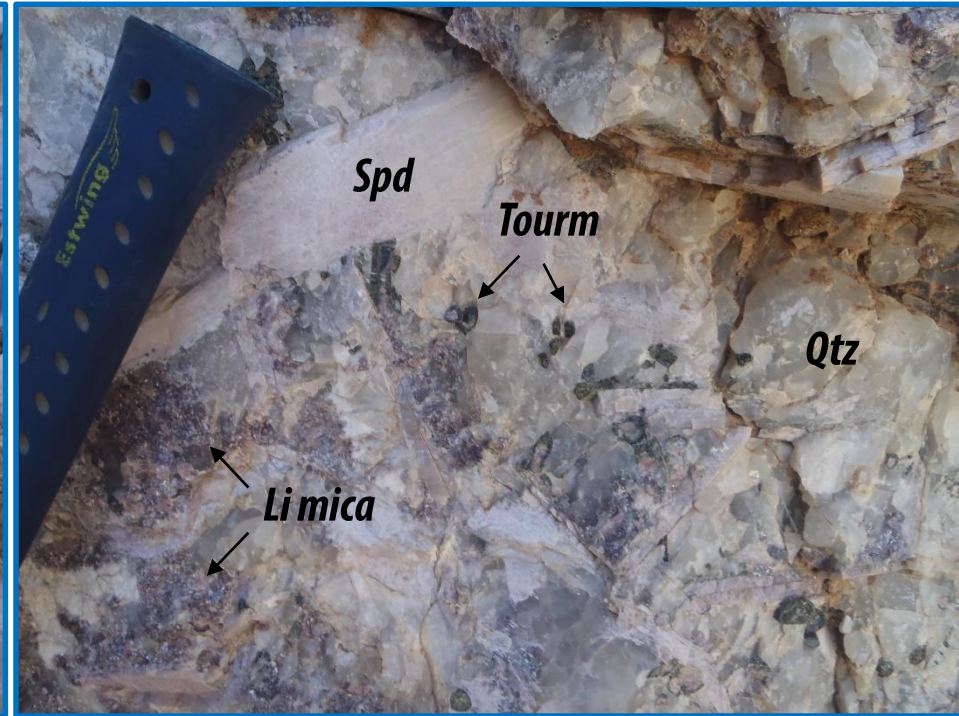
*Tantalite –columbite, Noumas I
pegmatite (www.mindat.org)*



Intermediate zone



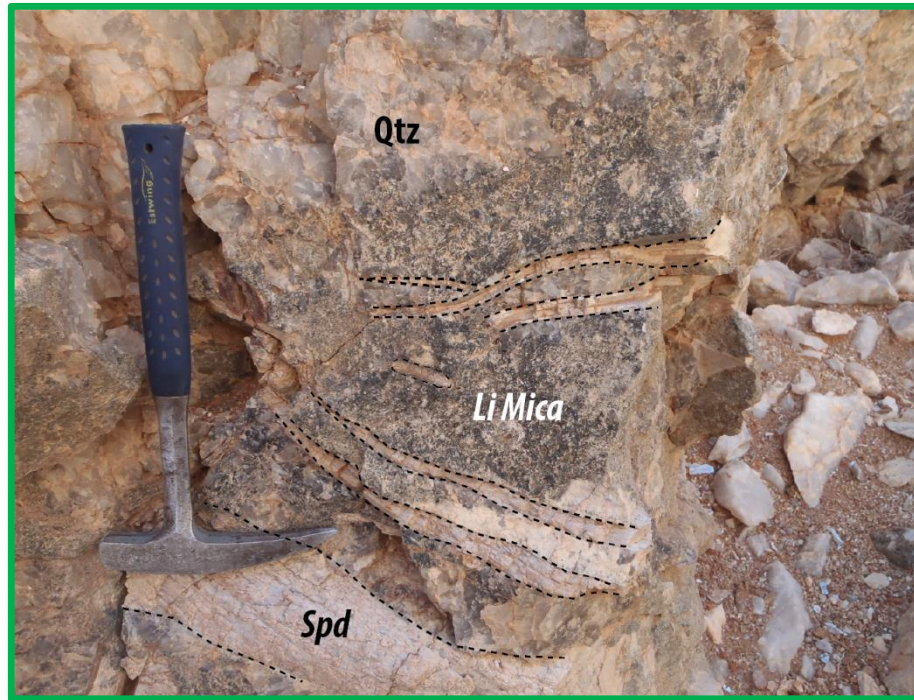
Intermediate zone, Noumas I



Intermediate zone, Norabees

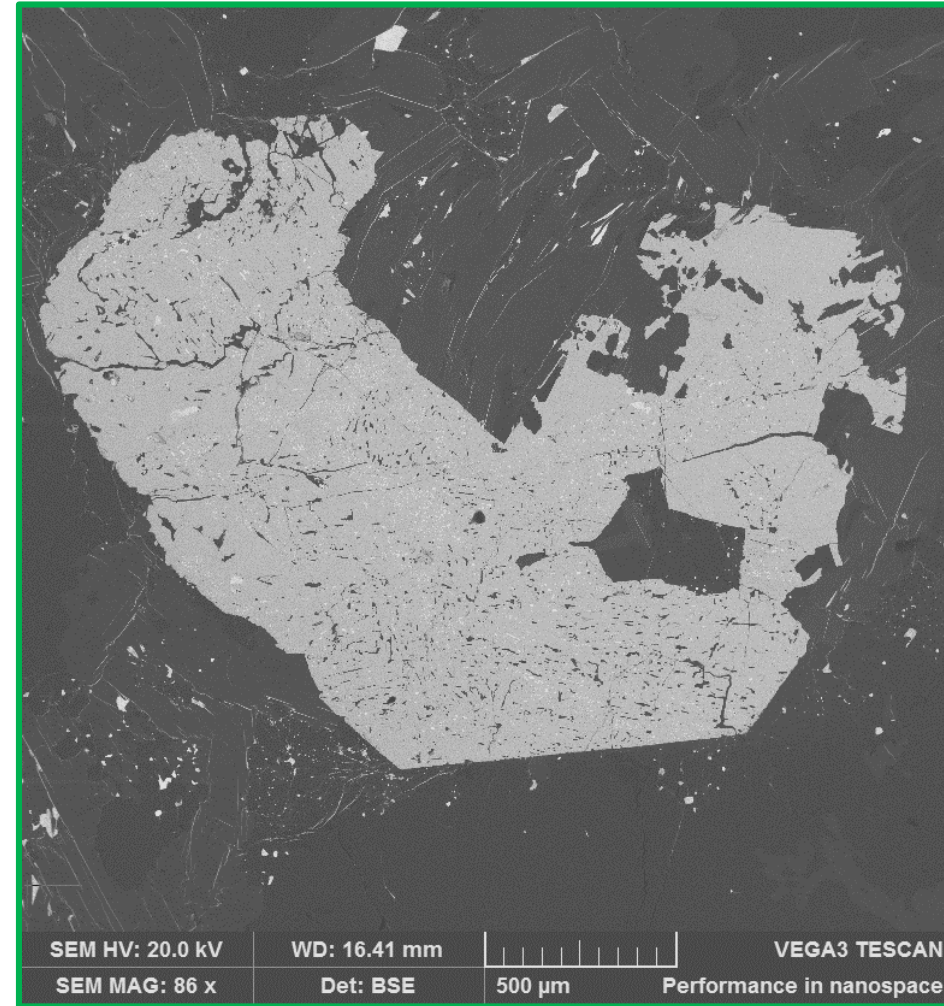
Spd: spodumene, Tourm: tourmaline, Qtz: quartz

Albitites and greisens



*Albitite an greisenized intermediate zone,
Kokerboomrand I*

Spd: spodumene, Qtz: quartz, Ab: albite; Grt: garnet



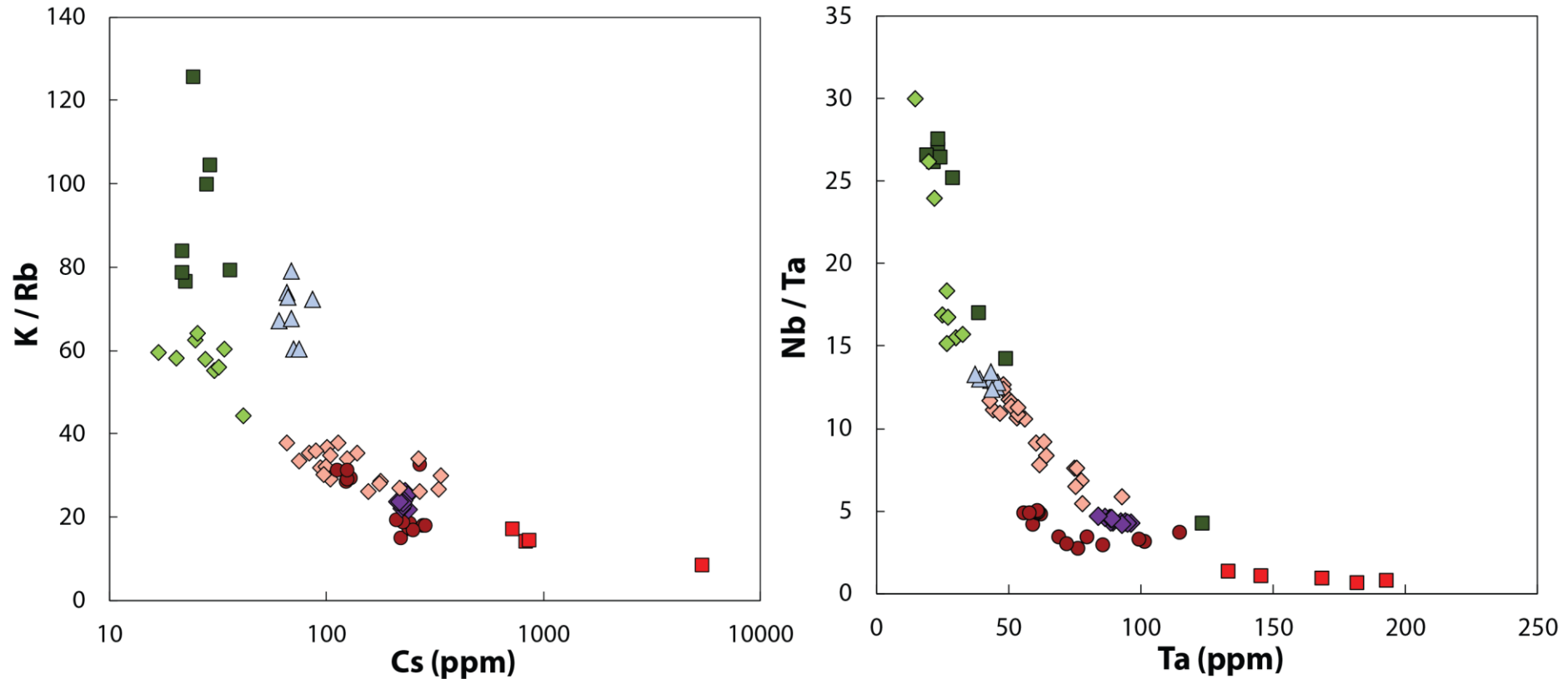
BSE image of microlite, Intermediate zone,
Kokerboomrand



The Orange River pegmatite belt

Chemical composition of muscovite

Ballouard et al. 2020



- ◆ Kokerboomrand, weakly mineralized
- Norabees, weakly mineralized
- ▲ Witkop, mineralized (**Nb, Ta, Be**), wall zone
- ◆ Kokerboomrand II, mineralized (**Nb, Ta, Be**), wall zone
- ◆ Kokerboomrand I, mineralized (**Li, Ta, Be**), aplite border & wall zone
- Noumas I, mineralized (**Li, Ta, Be, Bi**), aplite border & wall zone
- Norabees I, mineralized (**Li, Ta, Be**), wall zone

The Orange River pegmatite belt

Chemical composition of muscovite

Ballouard et al. 2020

