Les granites

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Granit(e), c’est quoi donc ?

Granite

Ne doit pas être confondu avec granit.

Le **granite** est une roche plutonique magmatique à texture grenue, riche en quartz, qui comporte plus de feldspath alcalin que de plagioclase. Il est caractérisé par sa constitution en minéraux : quartz, feldspaths potassiques (orthoses) et plagioclases, micas (biotite ou muscovite). Le granite et ses roches associées forment l'essentiel de la croûte continentale de la planète[1]. C'est un matériau résistant très utilisé en construction, dallage, décoration, sculpture, sous l'appellation granit.

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Granite

Au menu aujourd'hui…
(et demain)

- Granite et granites
- L'origine des magmas granitiques:
  - Par fusion de la croûte – exemple du Massif Central
  - Par différentiation de magmas d'arc – exemple du Kohistan
- De la source au pluton
- Granites et cycle orogénique

Les granites

1. Granite et granite

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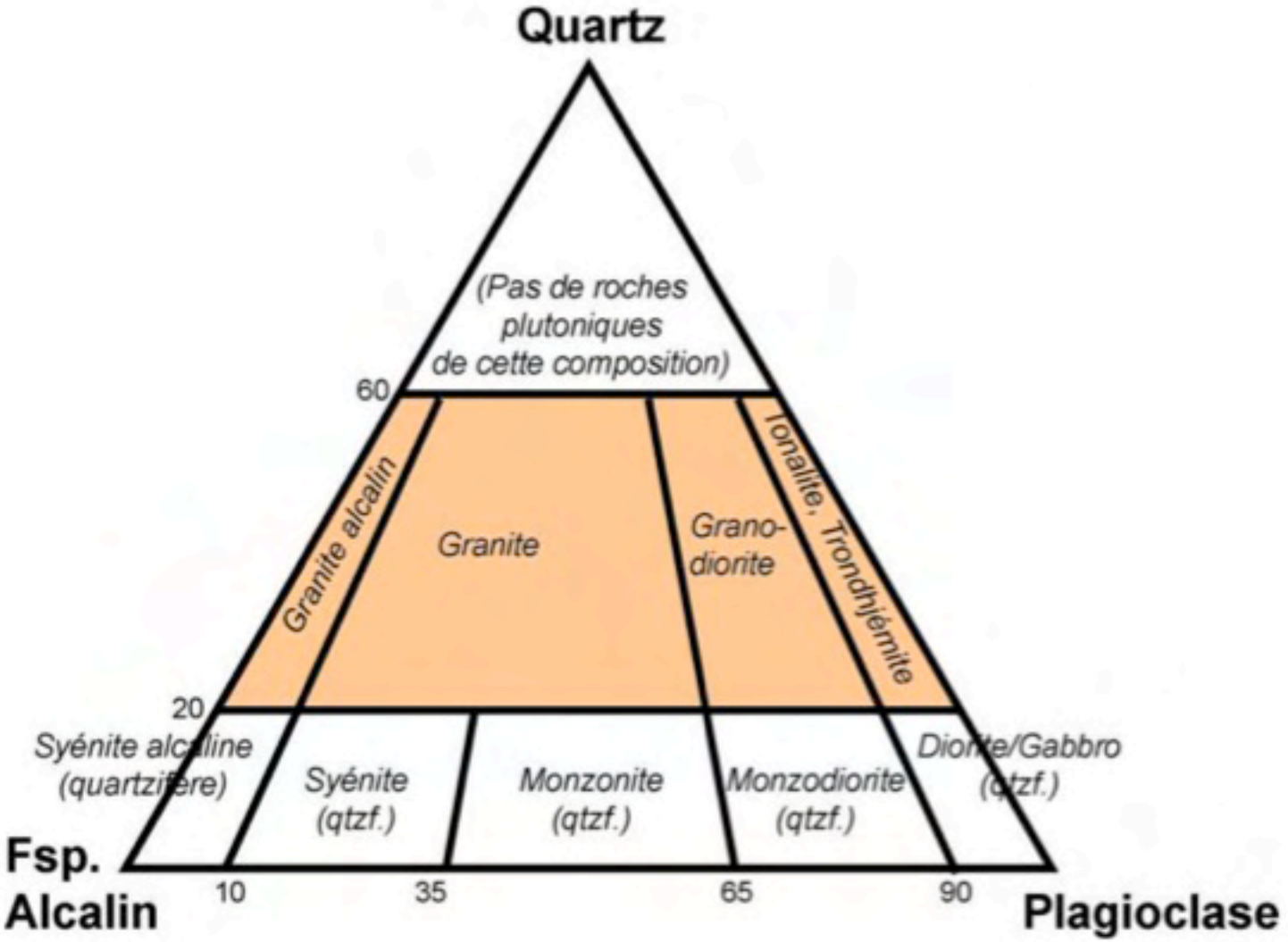
Herbert Harold Read *(1889-1970)*

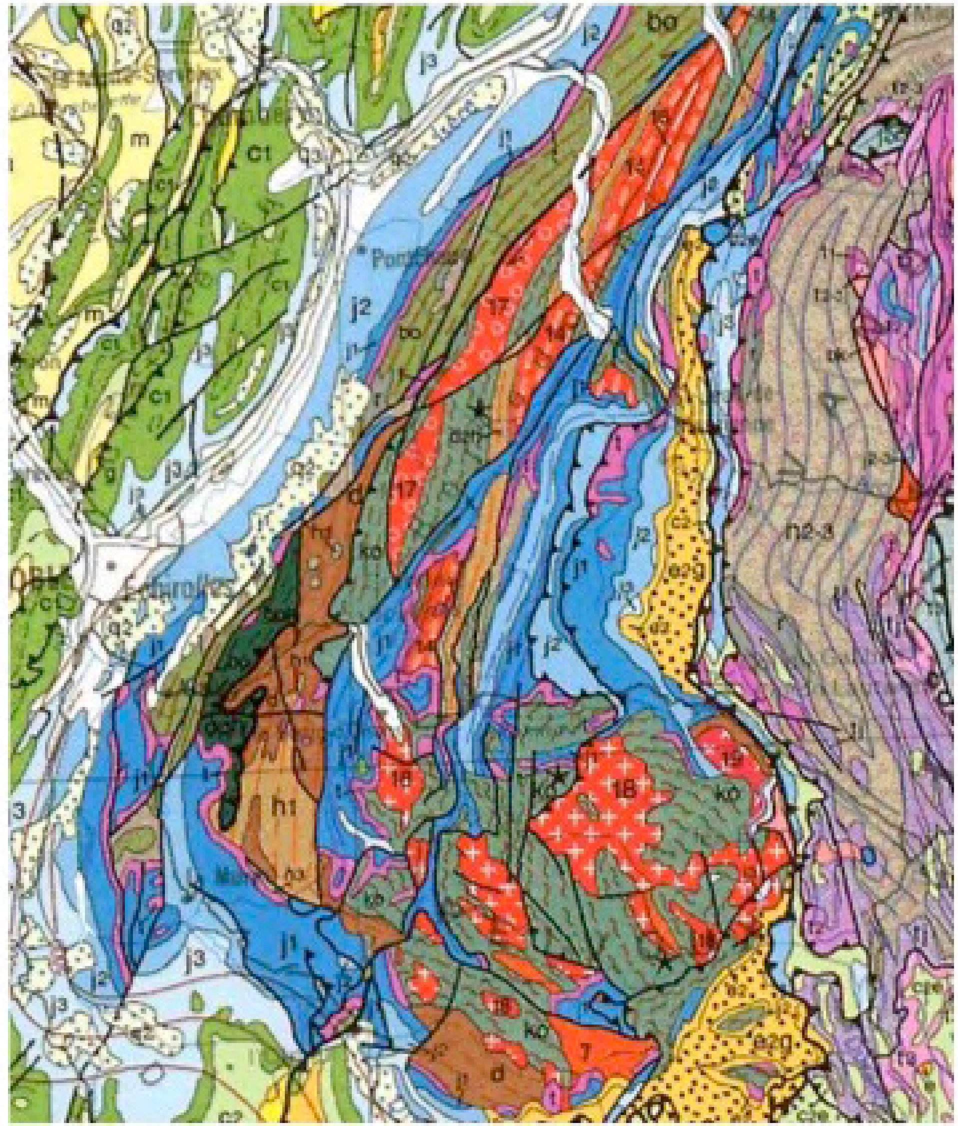
The Granite controversy

"There are granites and granites."

Classification des roches plutoniques

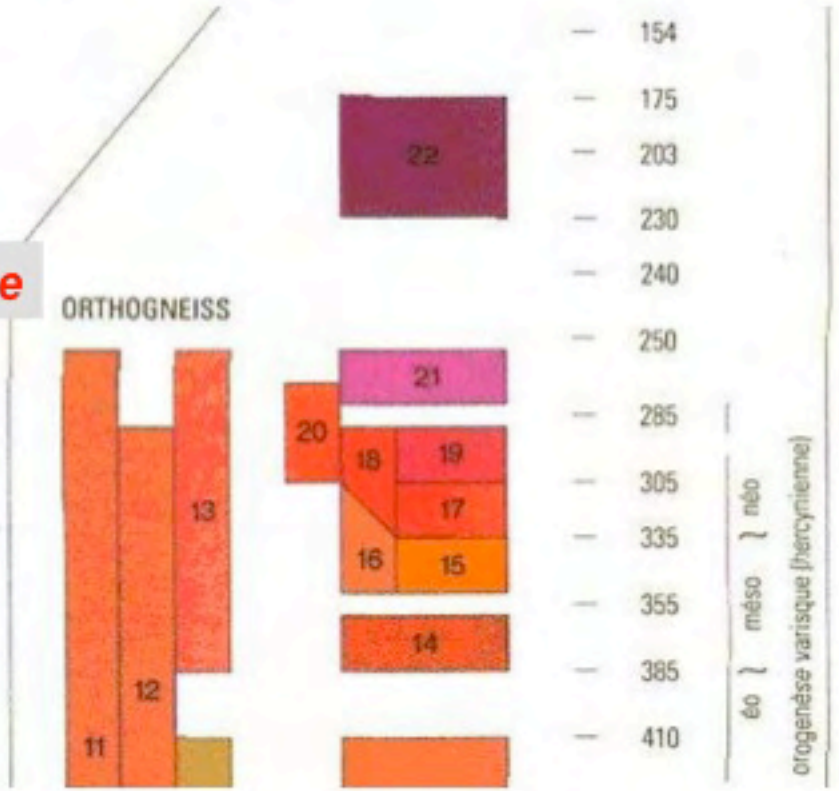


Les granites de Belledonne - Pelvoux

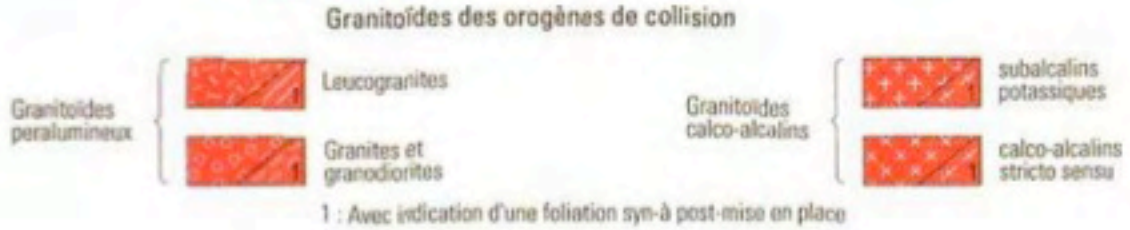


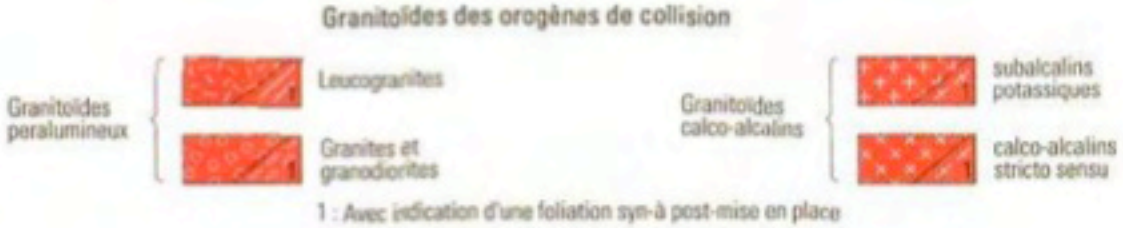
Sur la légende…

Age



Nature

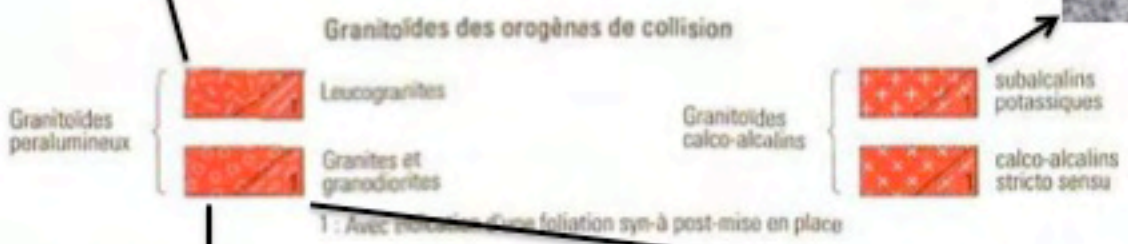




Qz, Fsp alcalin, plagioclase
(sinon c'est pas un granite !)

Gr. de Chambles
Bt+Ms

Gr. de Borne
Parfois amphibole, abondantes enclaves basiques



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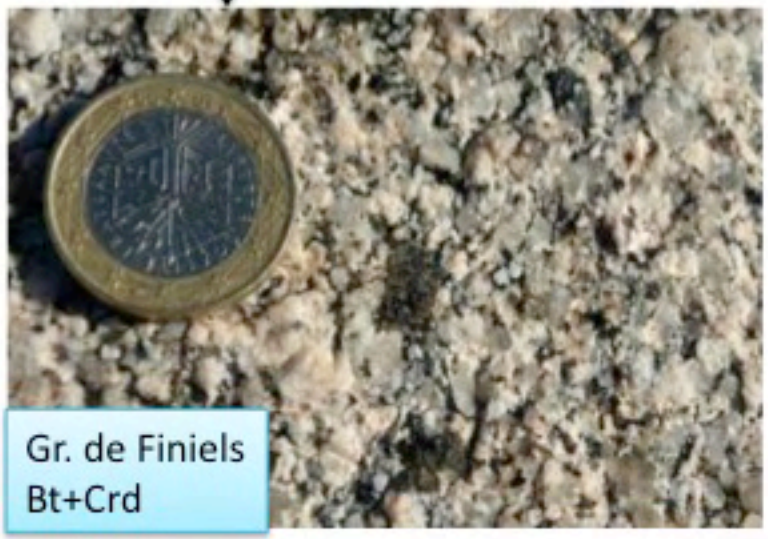
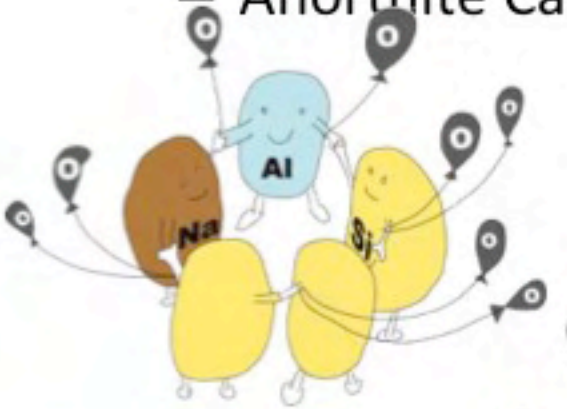


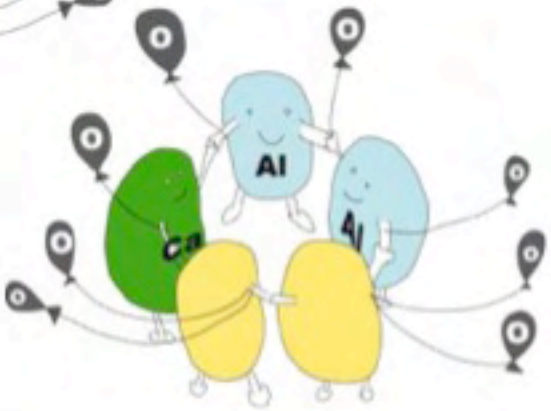
Gr. de Finiels
Bt+Crd

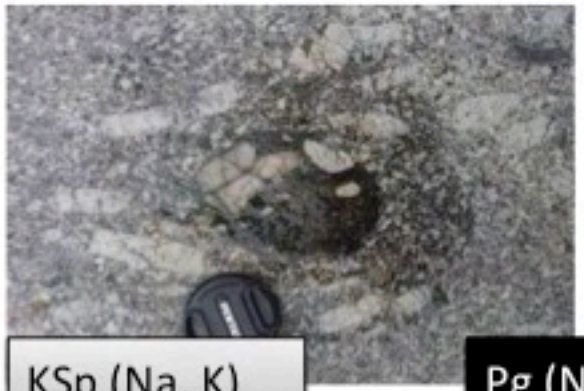
Gr. de Tournon
Bt seule

Les acteurs principaux…

- Des éléments (en fait des oxydes)
  - SiO_2
  - Al_2O_3
  - Na_2O (ou K)
  - CaO
- Des minéraux (surtout les feldspaths)
  - Albite $NaAlSi_3O_8$
  - Anorthite $CaAl_2Si_2O_8$



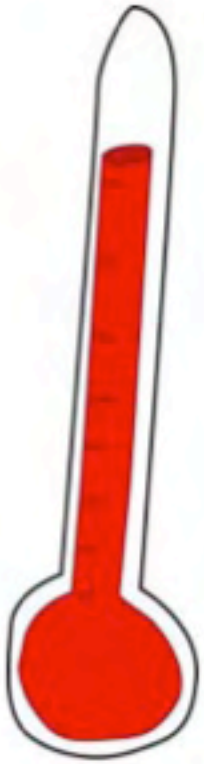


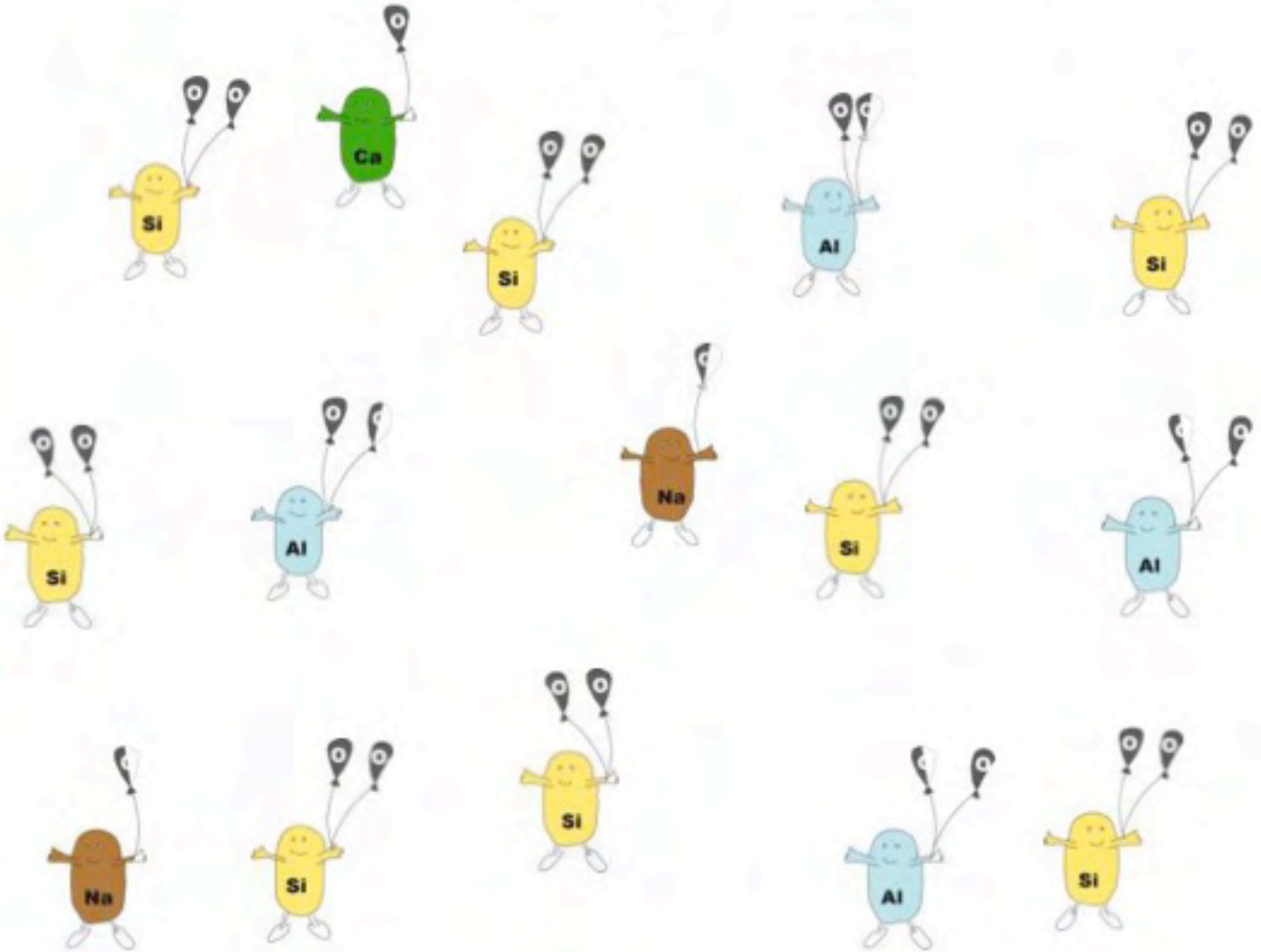


KSp (Na, K)

Pg (Na, Ca)

Du liquide au granite…





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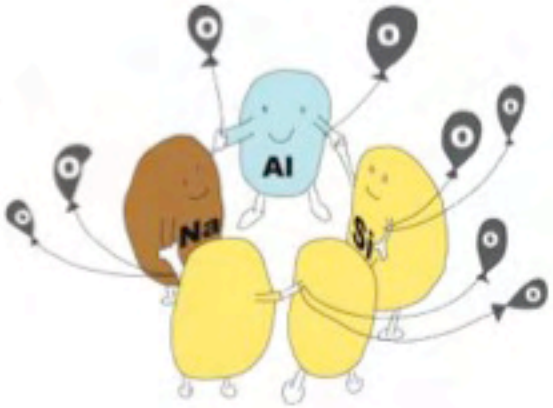
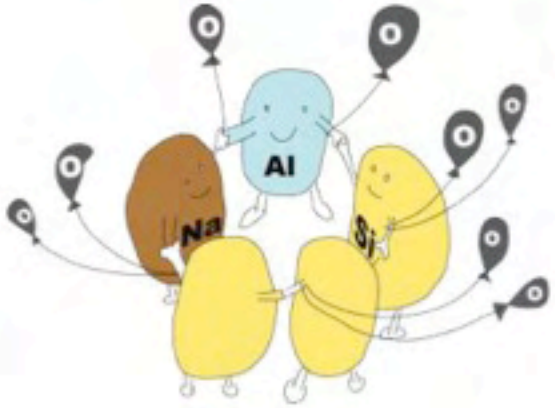
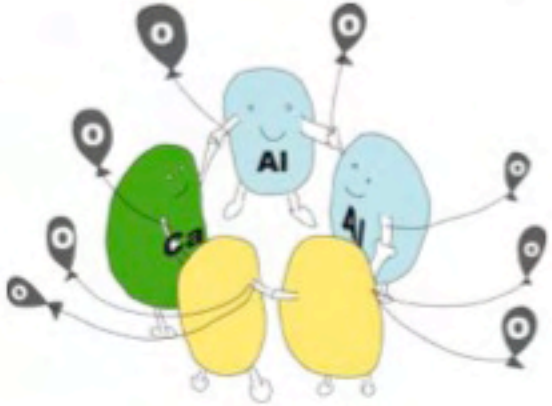
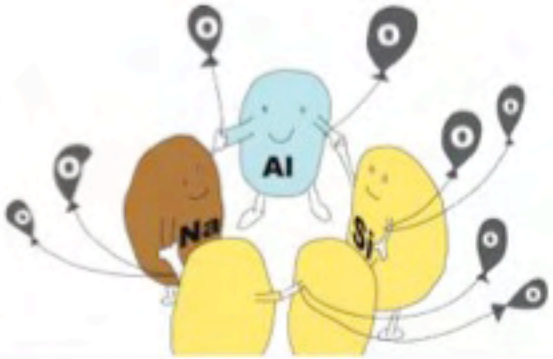
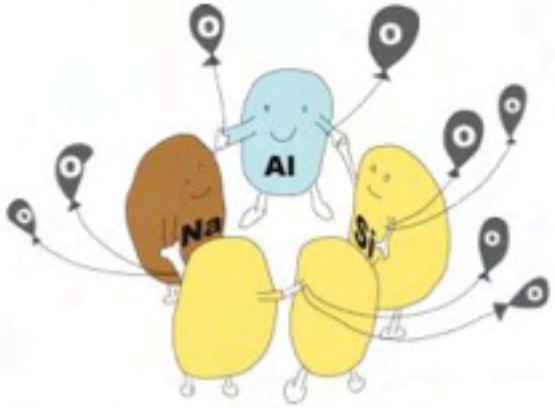




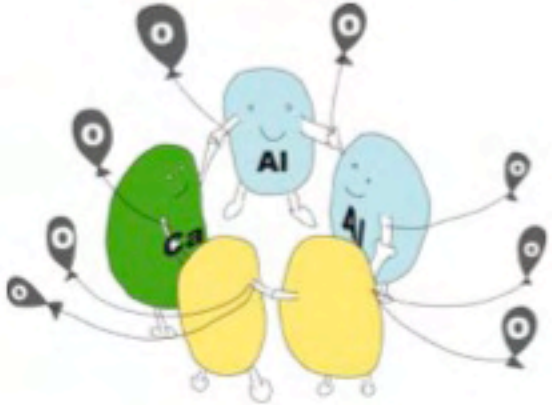


Du liquide au granite…

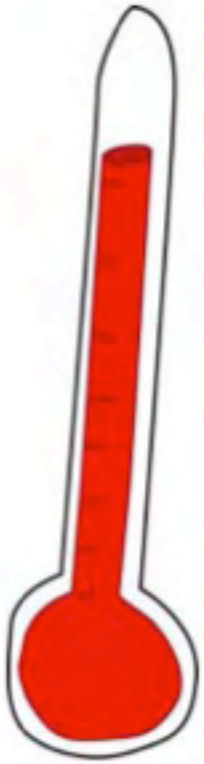


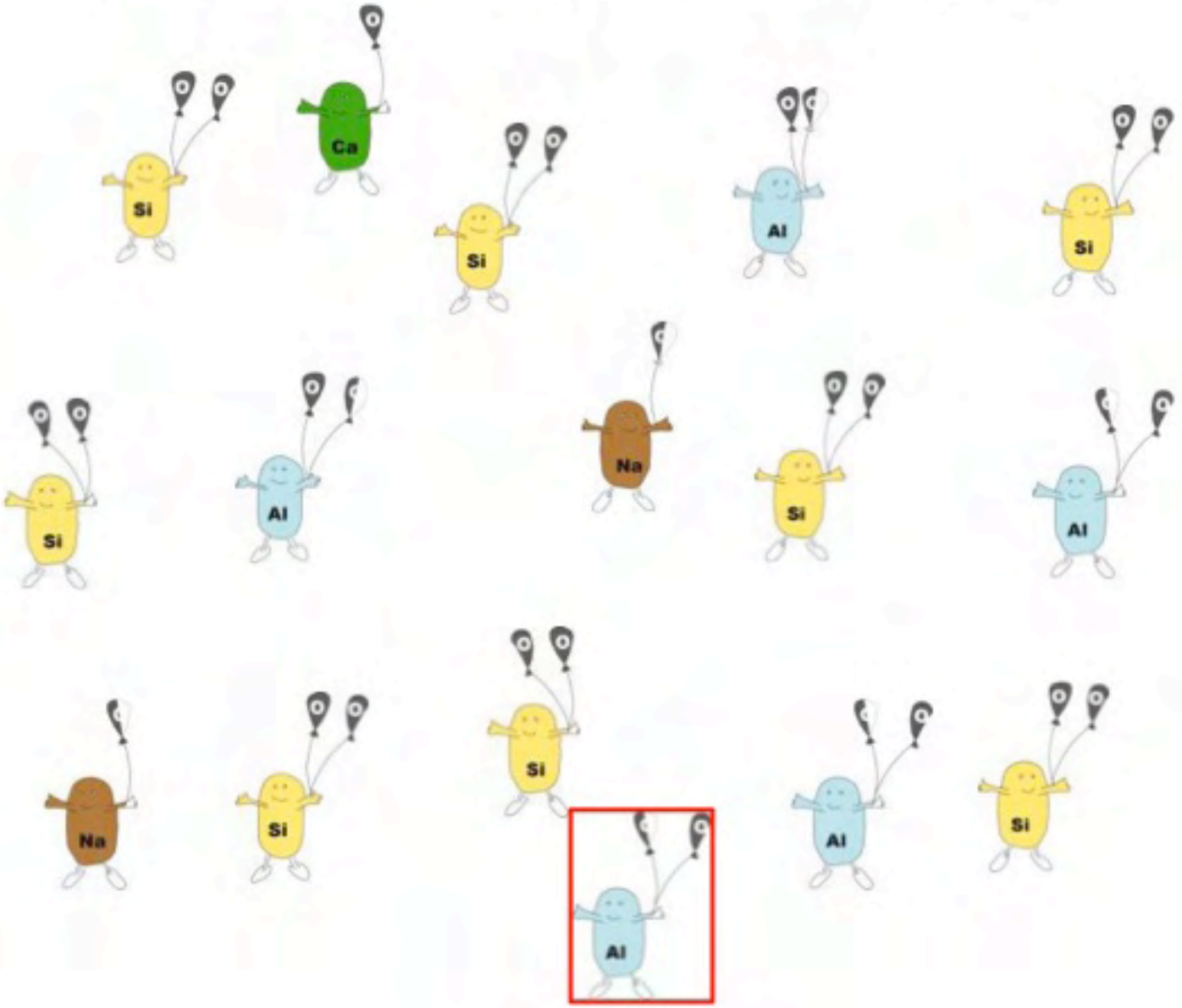


Magma avec les proportions exactes de Al, Na, Ca

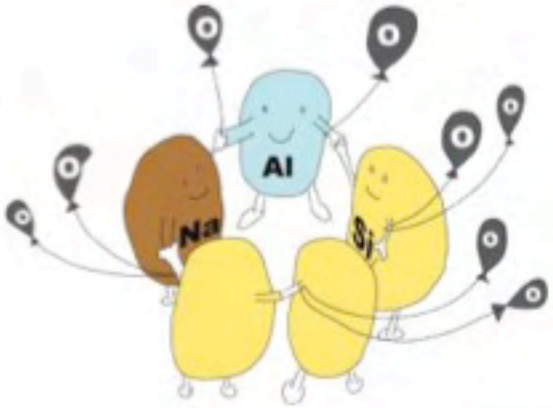


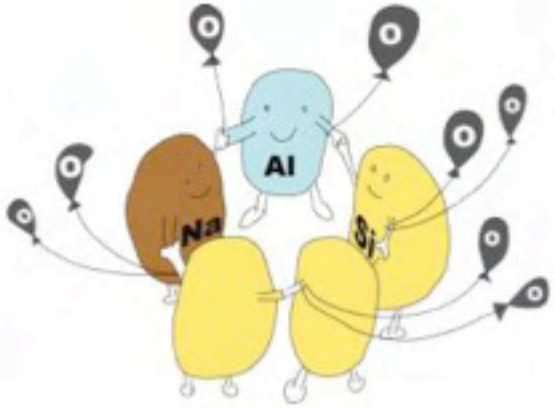
Du liquide au granite (2)…



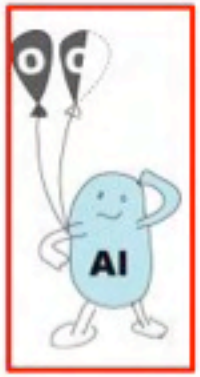


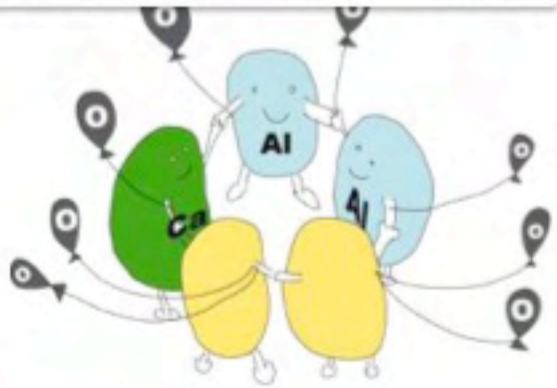
Du liquide au granite (2)…



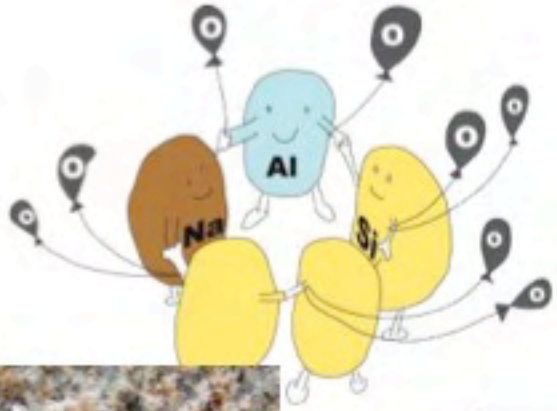


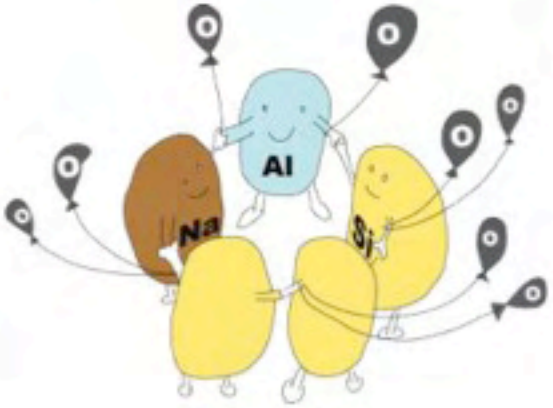
Magma « sursaturé » en Al





Du liquide au granite (2)…





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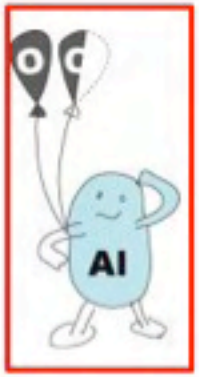
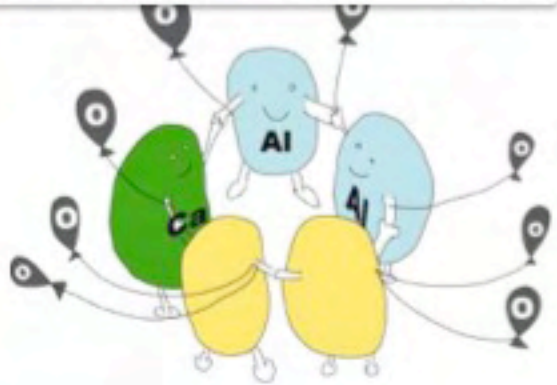
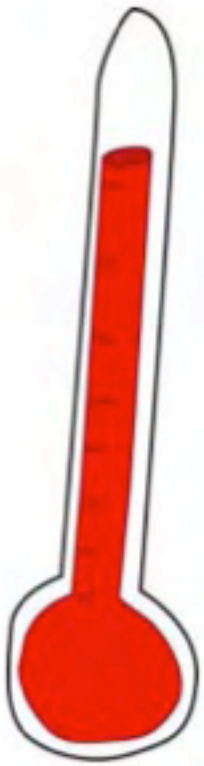
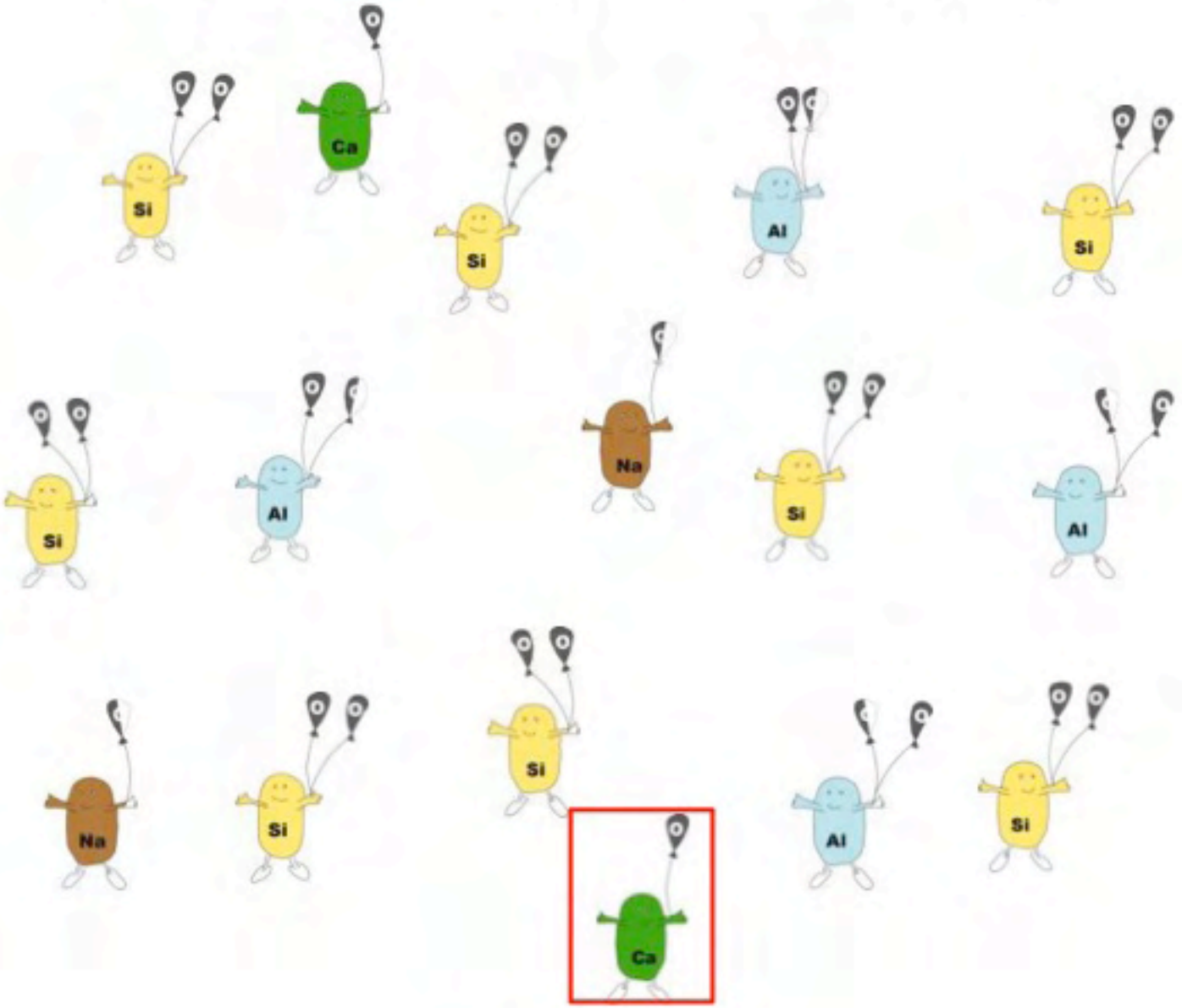




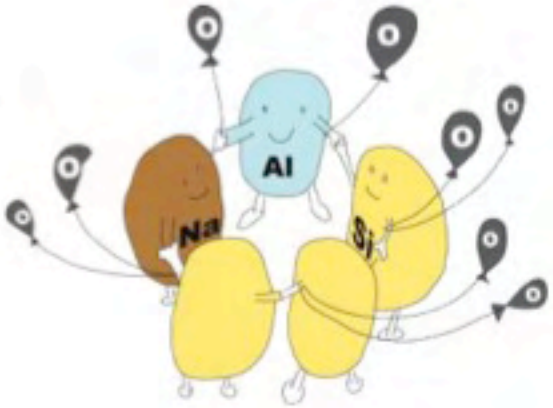
Minéraux alumineux (Ms, Crd…)

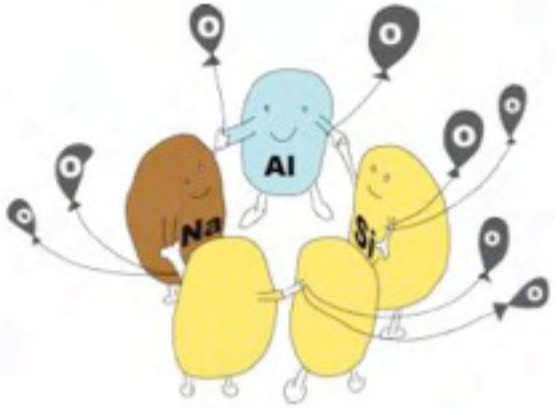
Du liquide au granite (3)…

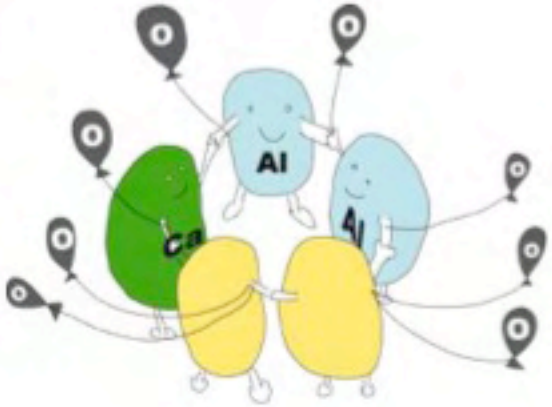




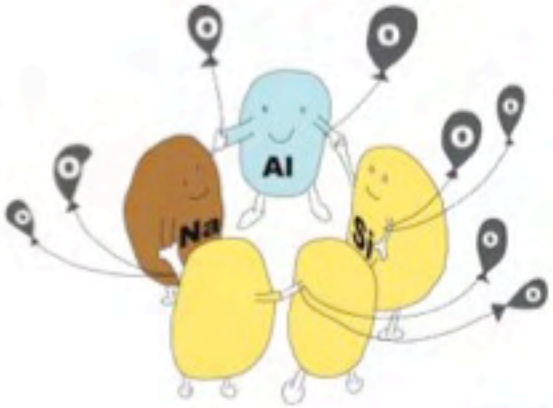
Du liquide au granite (3)…

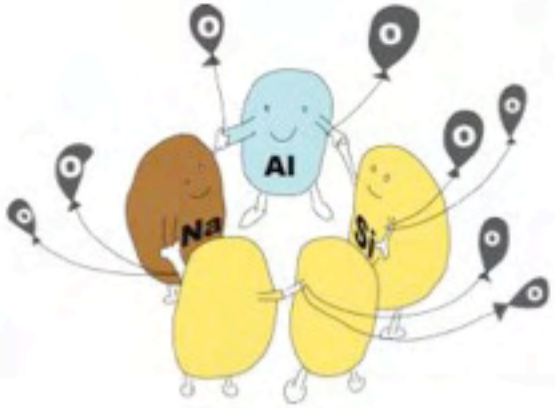




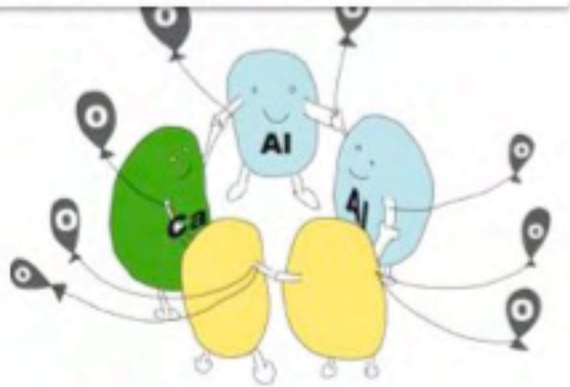


Du liquide au granite (3)…

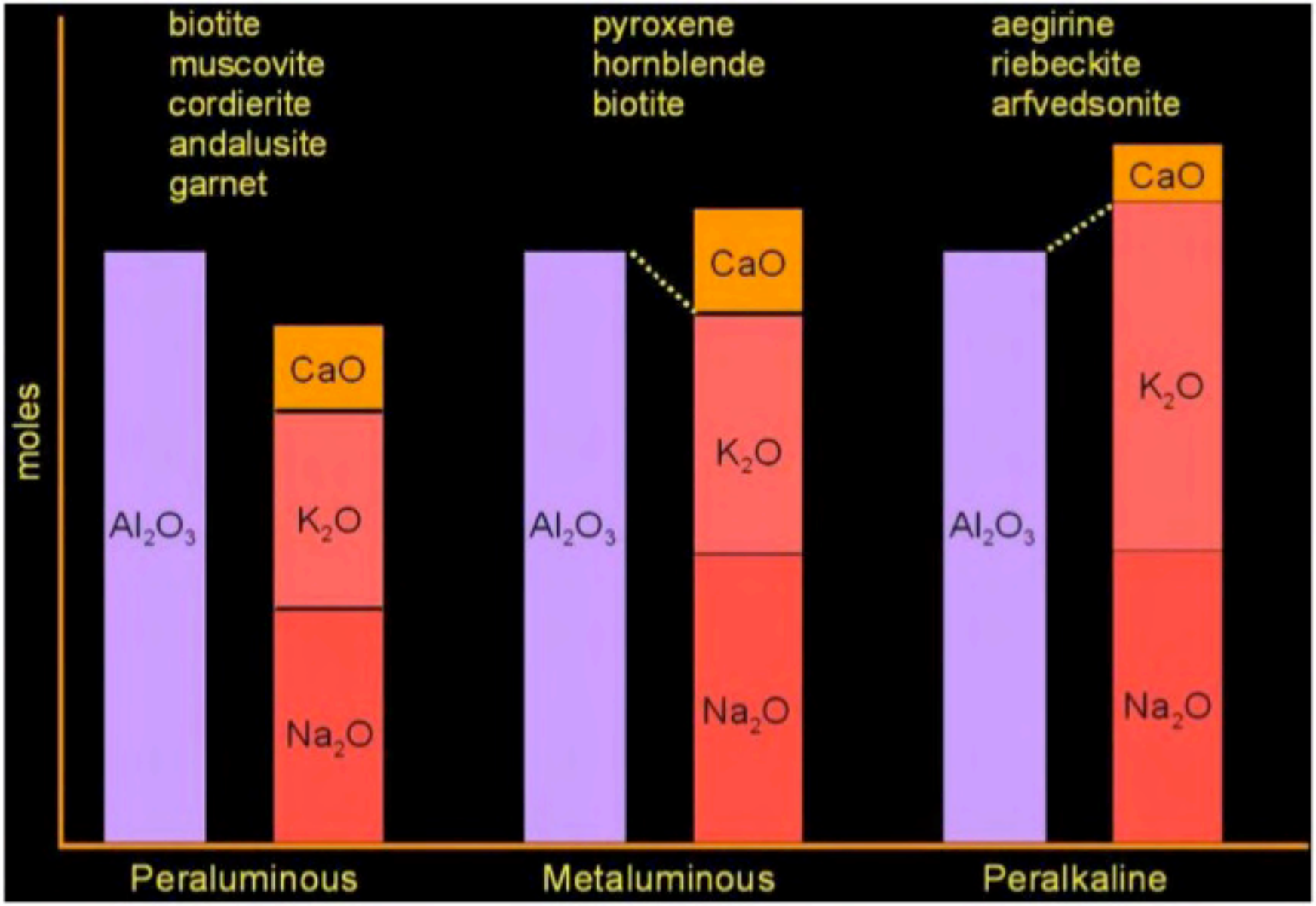


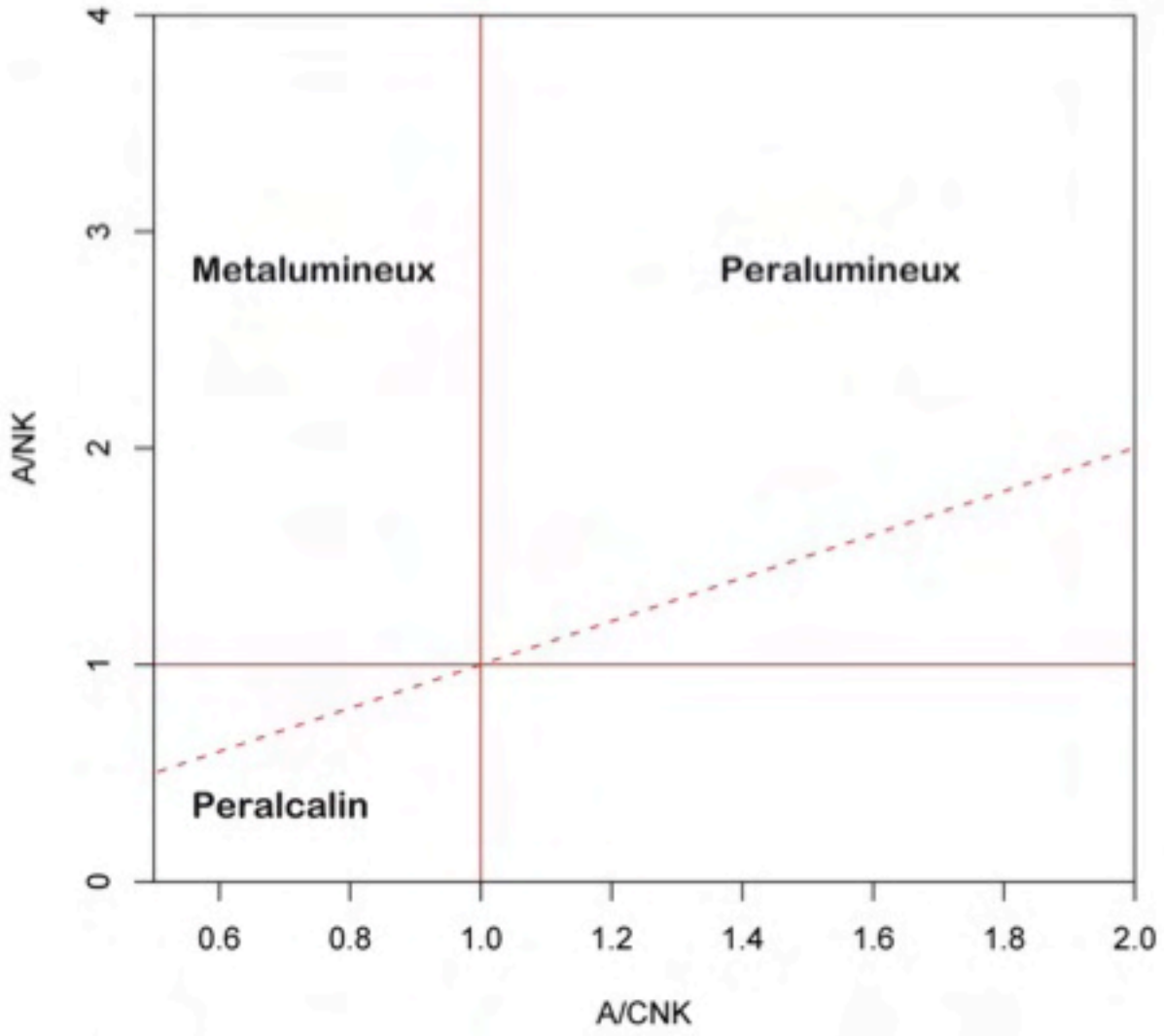


Magma « sursaturé » en Ca



Amphibole, cpx…


biotite
muscovite
cordierite
andalusite
garnet
pyroxene
hornblende
biotite
aegirine
riebeckite
arfvedsonite
moles
CaO
K_2O
Na_2O
Al_2O_3
Peraluminous
Metaluminous
Peralkaline


Metalumineux
Peralumineux
Peralcalin
A/NK
A/CNK
0
1
2
3
4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

« L'alphabet des granites »

- Chappel and White (1974) : I and S granites

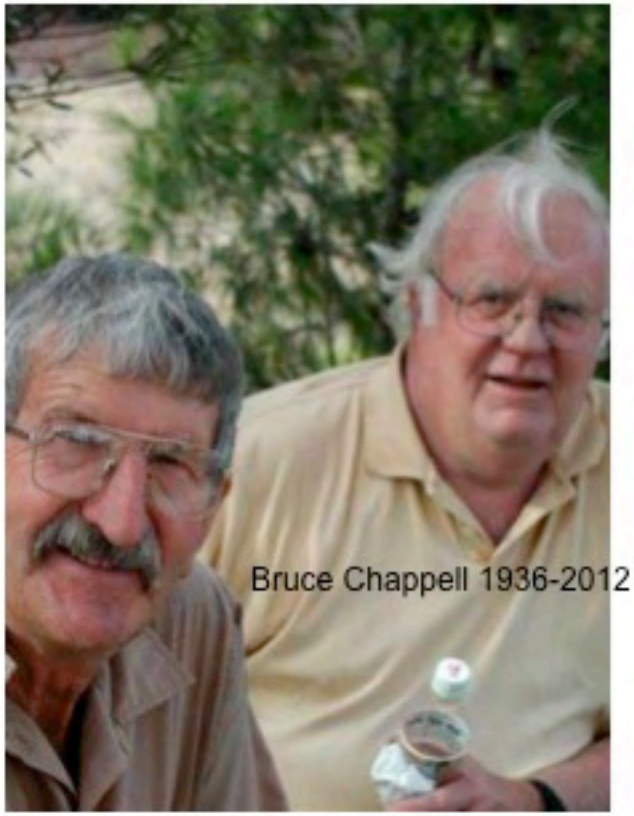
TWO CONTRASTING GRANITE TYPES

B.W. CHAPPELL* and A.J.R. WHITE**

* Australian National University, Canberra, Australia.

** La Trobe University, Bundoora, Melbourne, Australia.

I-types	S-types
Relatively high sodium, Na_2O normally > 3.2% in felsic varieties, decreasing to > 2.2% in more mafic types	Relatively low sodium, Na_2O normally < 3.2% in rocks with approx. 5% K_2O, decreasing to < 2.2% in rocks with approx. 2% K_2O
Mol $Al_2O_3/(Na_2O + K_2O + CaO) < 1.1$	Mol $Al_2O_3/(Na_2O + K_2O + CaO) > 1.1$
C.I.P.W. normative diopside *or* < 1% normative corundum	> 1% C.I.P.W. normative corundum
Broad spectrum of compositions from felsic to mafic	Relatively restricted in composition to high SiO_2 types
Regular inter-element variations within plutons; linear or near-linear variation diagrams	Variation diagrams more irregular



Bruce Chappell 1936-2012

Allan White 1928-2009

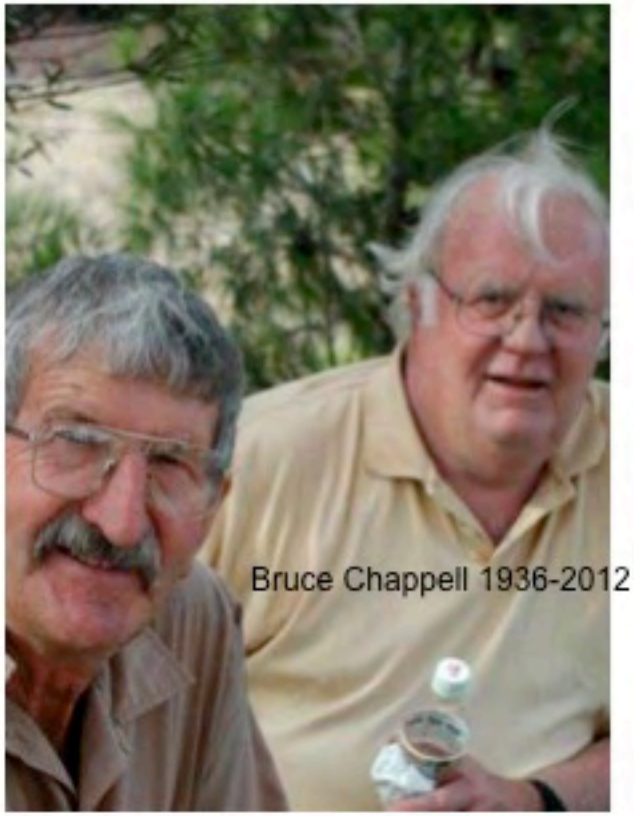
« L'alphabet des granites »

- Chappel and White (1974) : I and S granites

- White 1979 :

The alphabetical classification of granite types, according to White (1979)

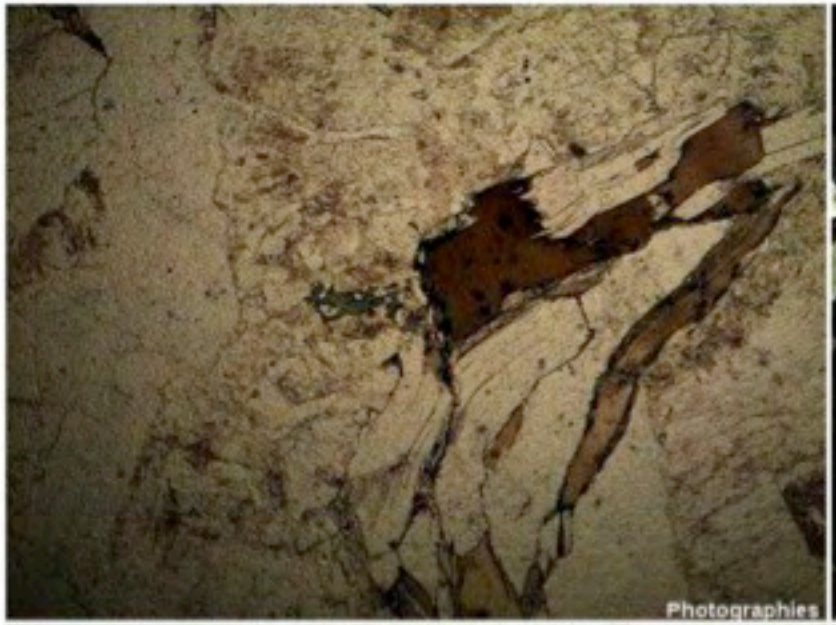
Granite type	Chemical features	Specific minerals	Source rocks
S (1)	Peraluminous ASI ≥ 1.1	Peraluminous mafic minerals (cordierite, garnet, etc.)	Meta-sedimentary sequences
I (1)	Metaluminous ASI < 1.1	No peraluminous mafic minerals occurrence of hornblende	Igneous materials from deep crustal levels
M (2)	Volcanic arc signature		Subducted oceanic crust
No letter attributed (3)	Alkaline affinities and anorogenic	Fe-rich mafic silicates	Granulitic residue from a previous melting event

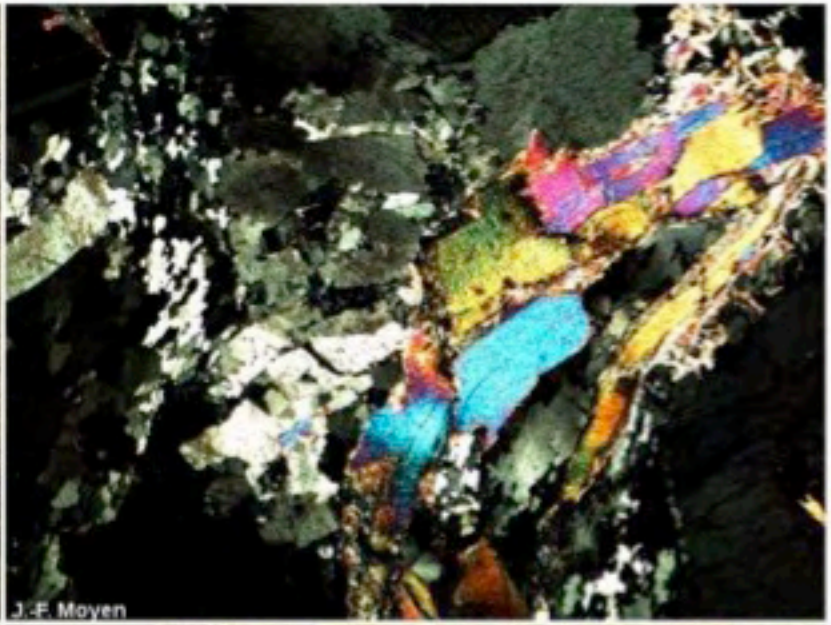


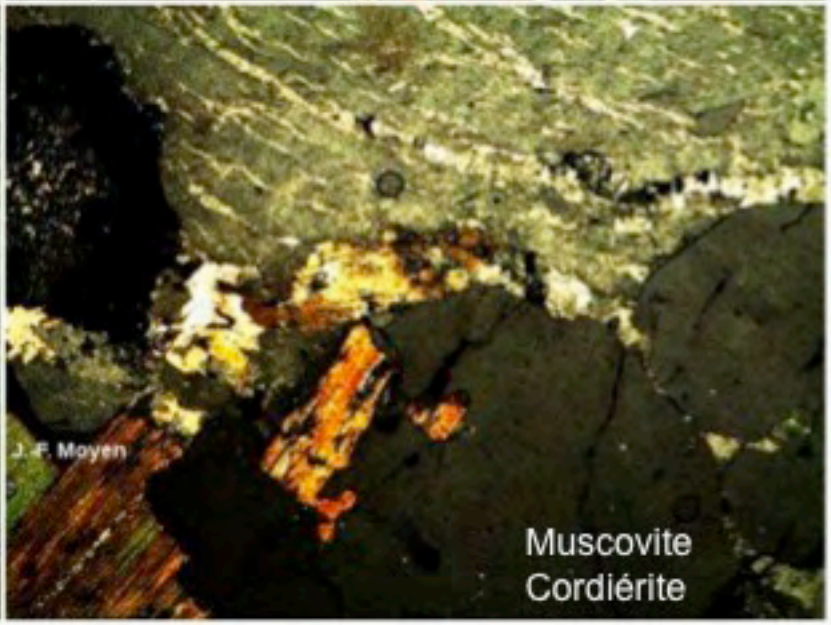
Bruce Chappell 1936-2012

Allan White 1928-2009

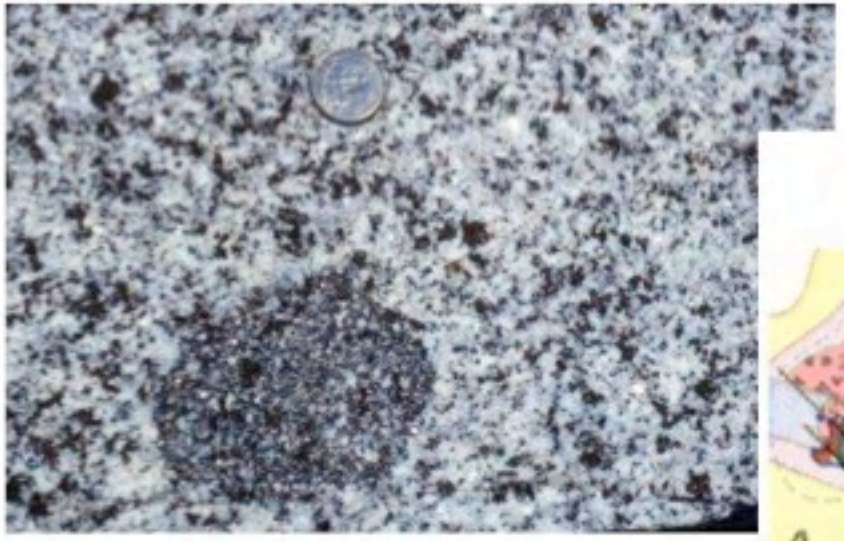
Granites peralumineux (S)

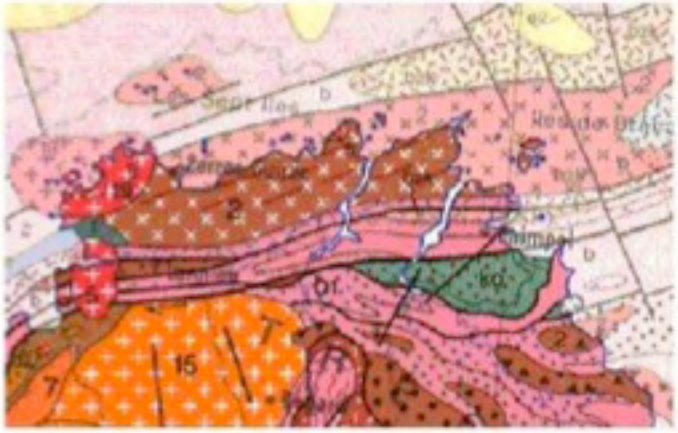




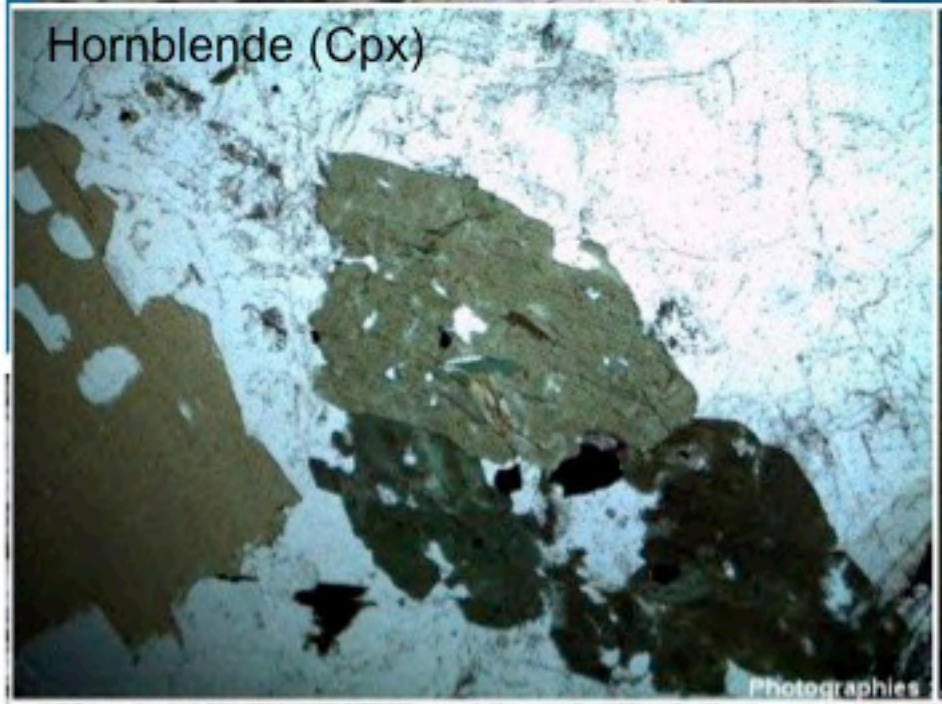


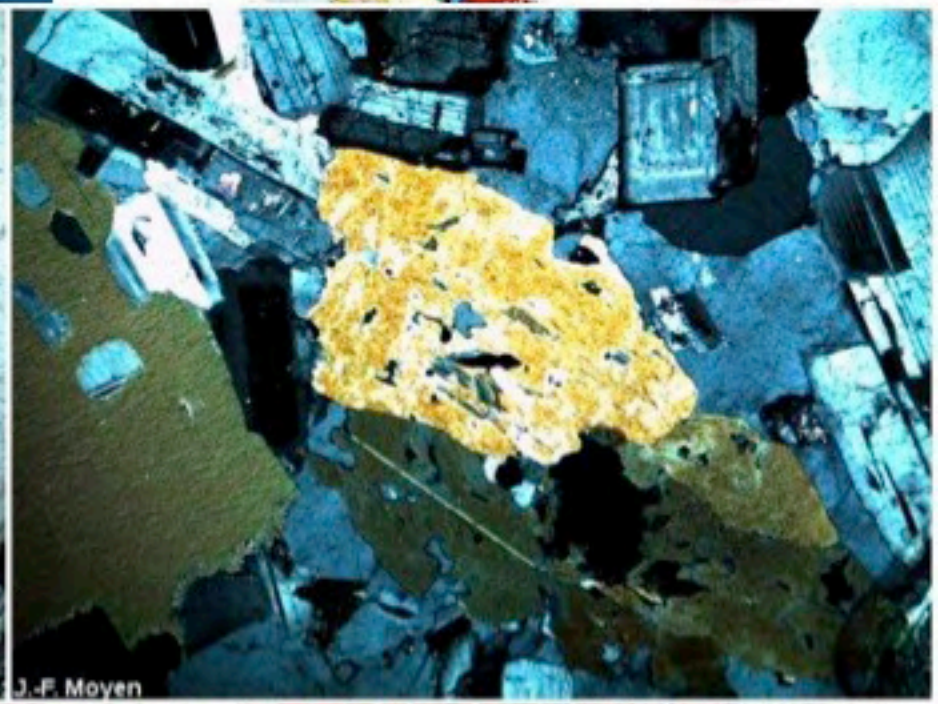
Granites métalumineux (I)

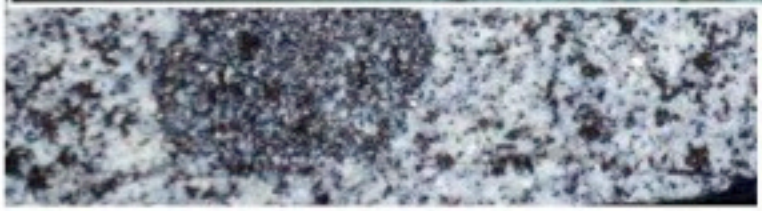




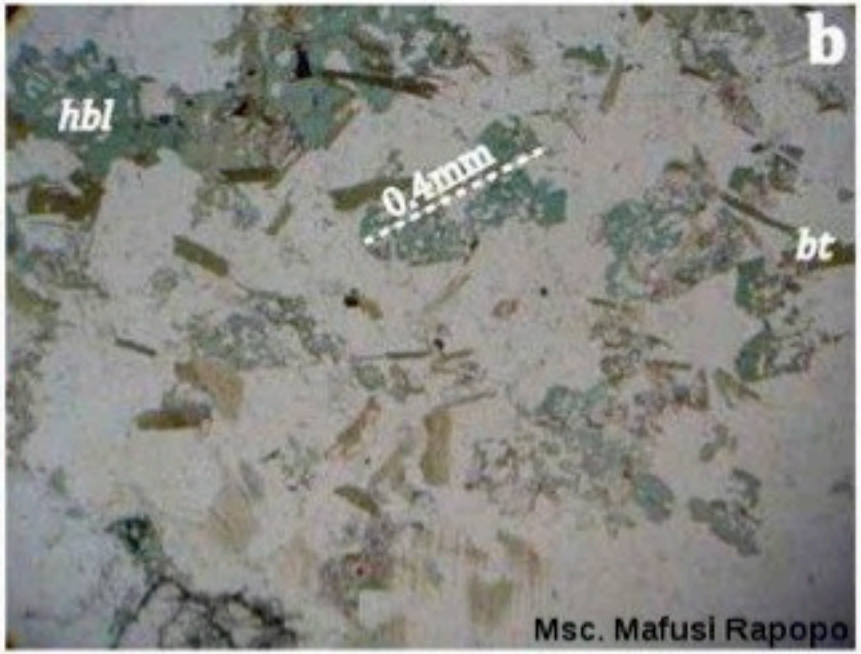
Granites métalumineux (I)



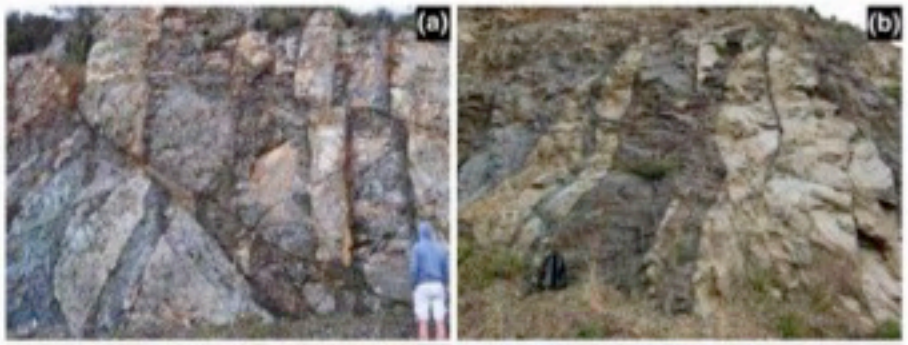


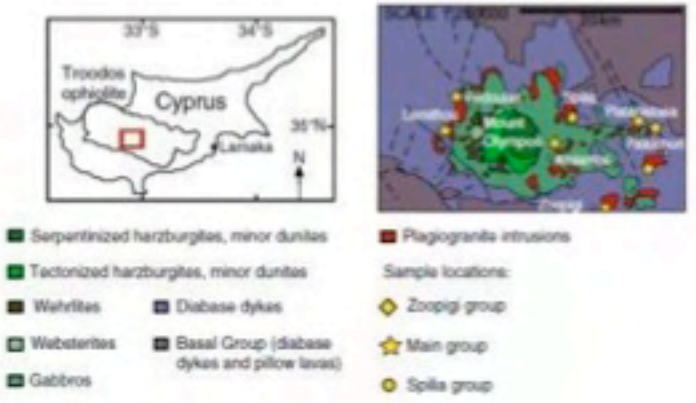


Granites I aussi !



Granites M (plagiogranites)

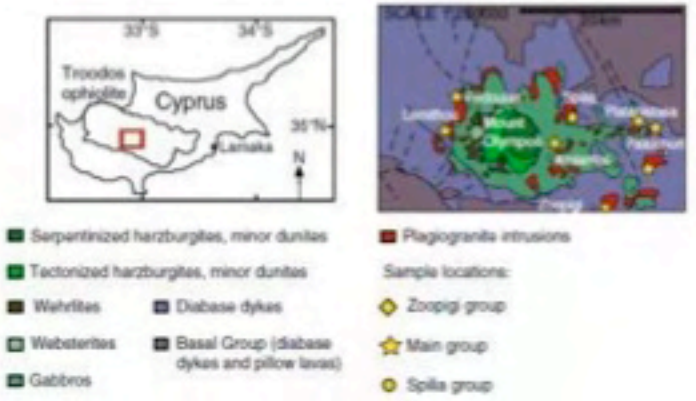




Plagioclase abondant

Freund et al. 2014

Granites M (plagiogranites)



Plagioclase abondant

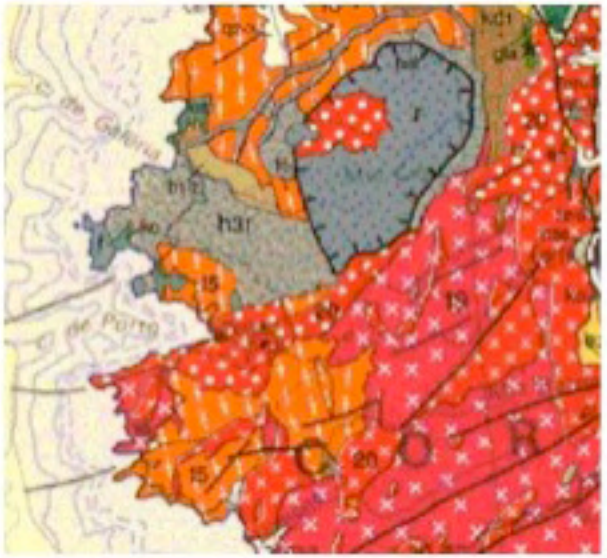
Freund et al. 2014

Granites M (plagiogranites)

Plagioclase abondant

Freund et al. 2014

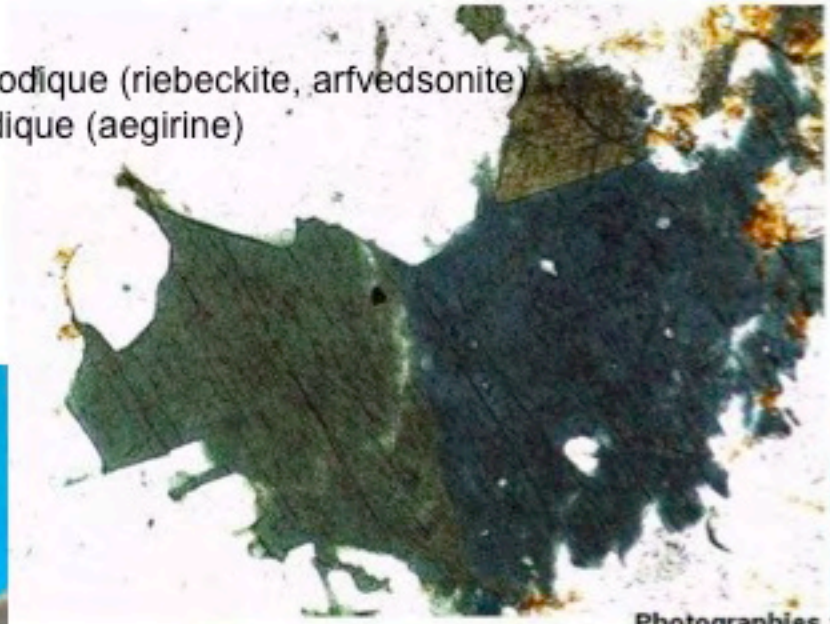
Granites per-alcalins (A)

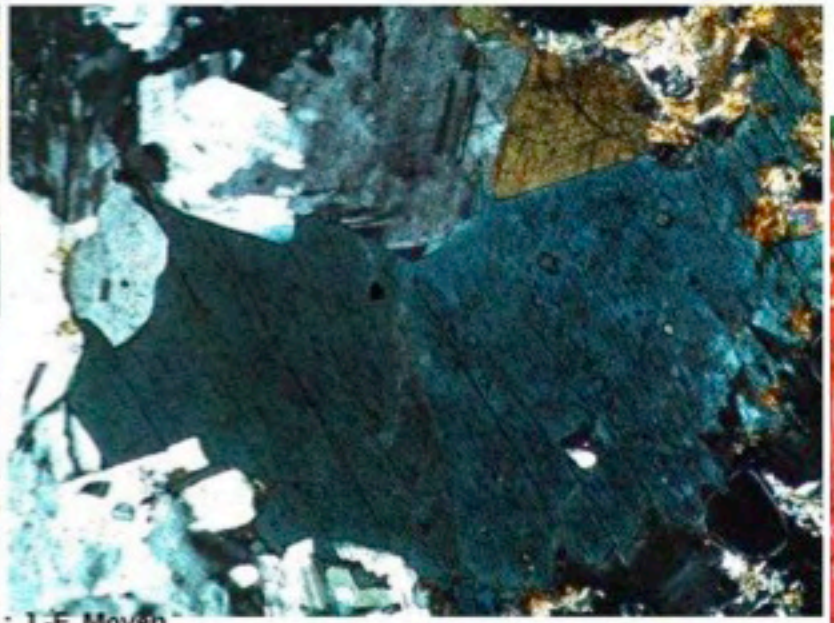


Granites permiens de Corse

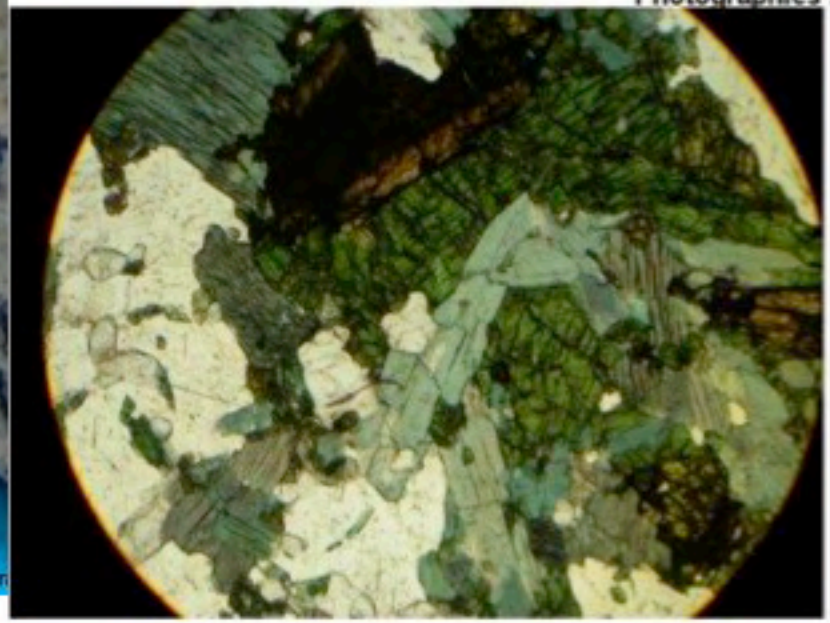
Granites per-alcalins (A)

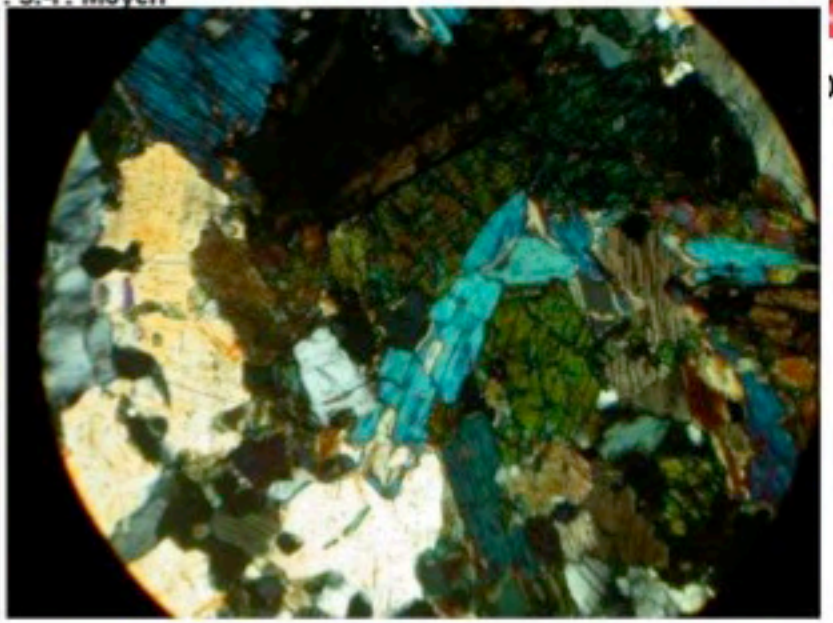
Amp sodique (riebeckite, arfvedsonite)
Px sodique (aegirine)

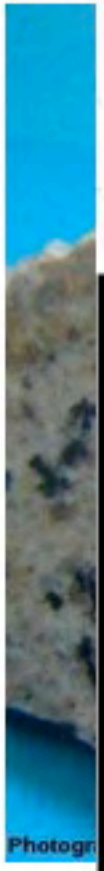




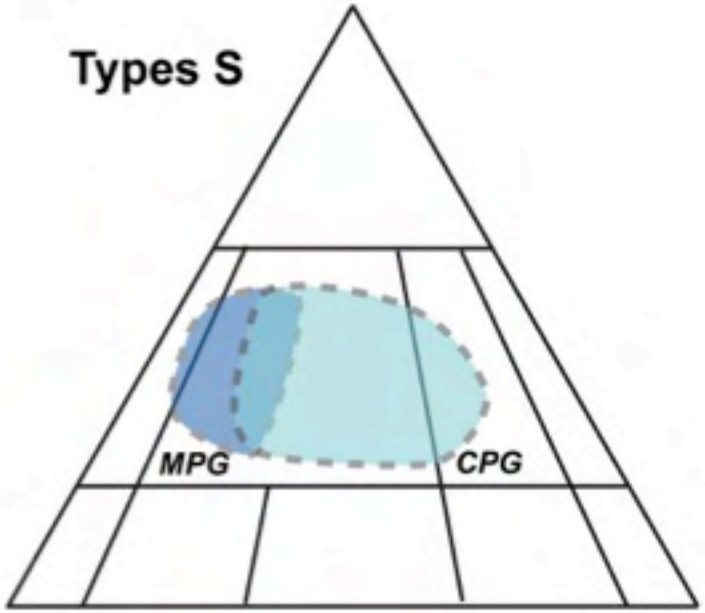
Photographies : J.-F. Moyen

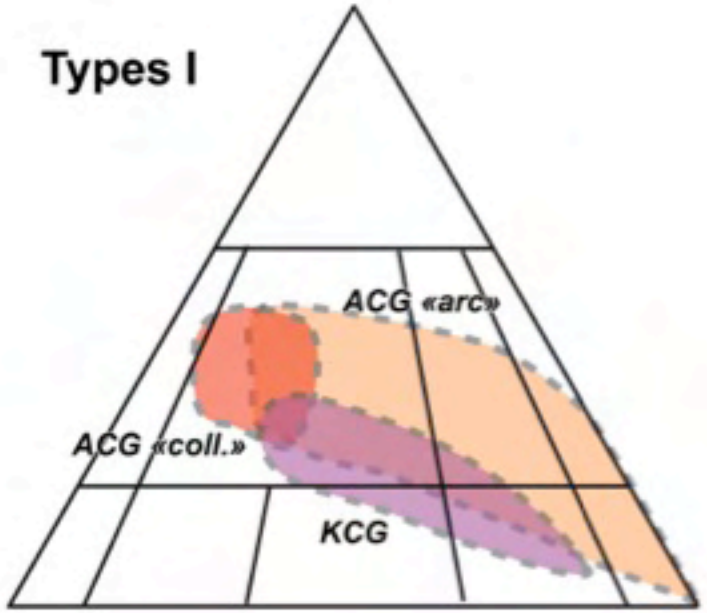


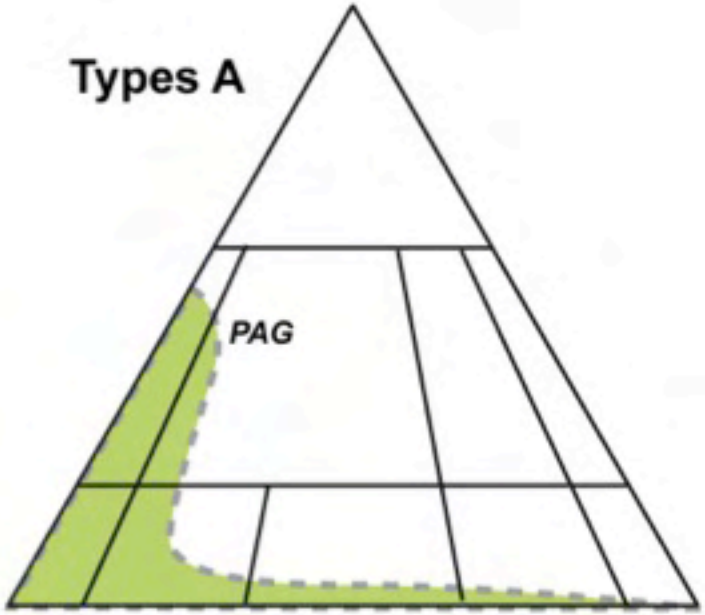


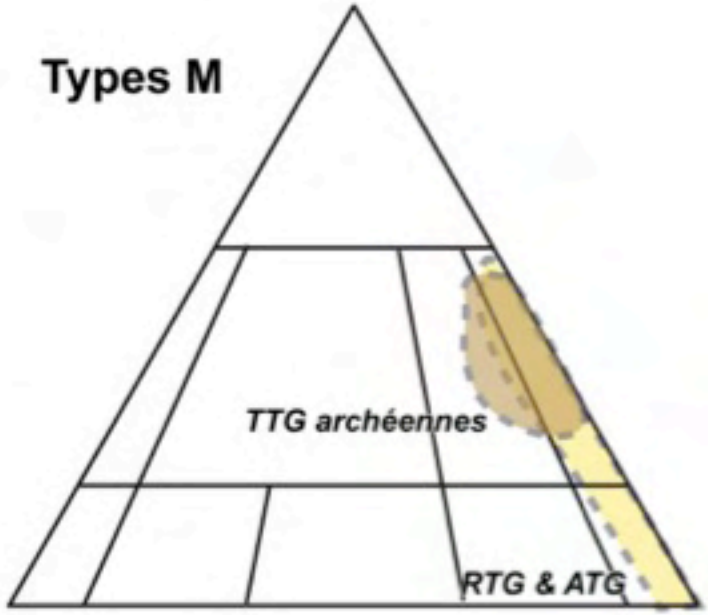


rse


Types S
MPG
CPG


Types I
ACG «arc»
ACG «coll.»
KCG


Types A
PAG


Types M
TTG archéennes
RTG & ATG

Barbarin (1999)

	S	I	M	A

PETROGRAPHY	MPG	CPG	KCG	ACG	RTG	PAG
Petrographic types	Leucogranites (Granites)	(Leucogranites) Granites Granodiorites (Qz diorites)	(Leucogranites) Granites Granodiorites Qz diorites	(Granites) Granodiorites Tonalites Gabbros	Plagiogranites Trondhjemites Tonalites Gabbros	Alk. granites Alk. syenites Syenites Granites (Gabbros) (Anorthosites)
Associated rocks						
Metamorphic	o	Migmatites Anatexites	o	o	o	o
Volcanic	o	o	Acid lavas ("Tuffs")	Andesites & Dacites	Olivine-bearing Tholeiites	Alkaline lavas
Mafic	o	Qz diorites (Vaugnerites)	Qz diorites Gabbros (Appinites)	Gabbros (in large amounts)	Gabbros (in large amounts)	Gabbros (in large amounts)
Enclaves						
Xenoliths	x	o - x	x	x	x	x
Restites	x	x x x	x	o	o	o
Felsic M. E.	x	o - x	x	x	x	x
Mafic M. E.	o	x	x x	x x x	x x x	x
Differentiation processes	fractional crystallization	fractional crystallization or restite unmixing	fractional crystallization and magma mixing	strong fractional crystallization and magma mixing	extreme fractional crystallization	extreme fractional crystallization and subsolidus interactions

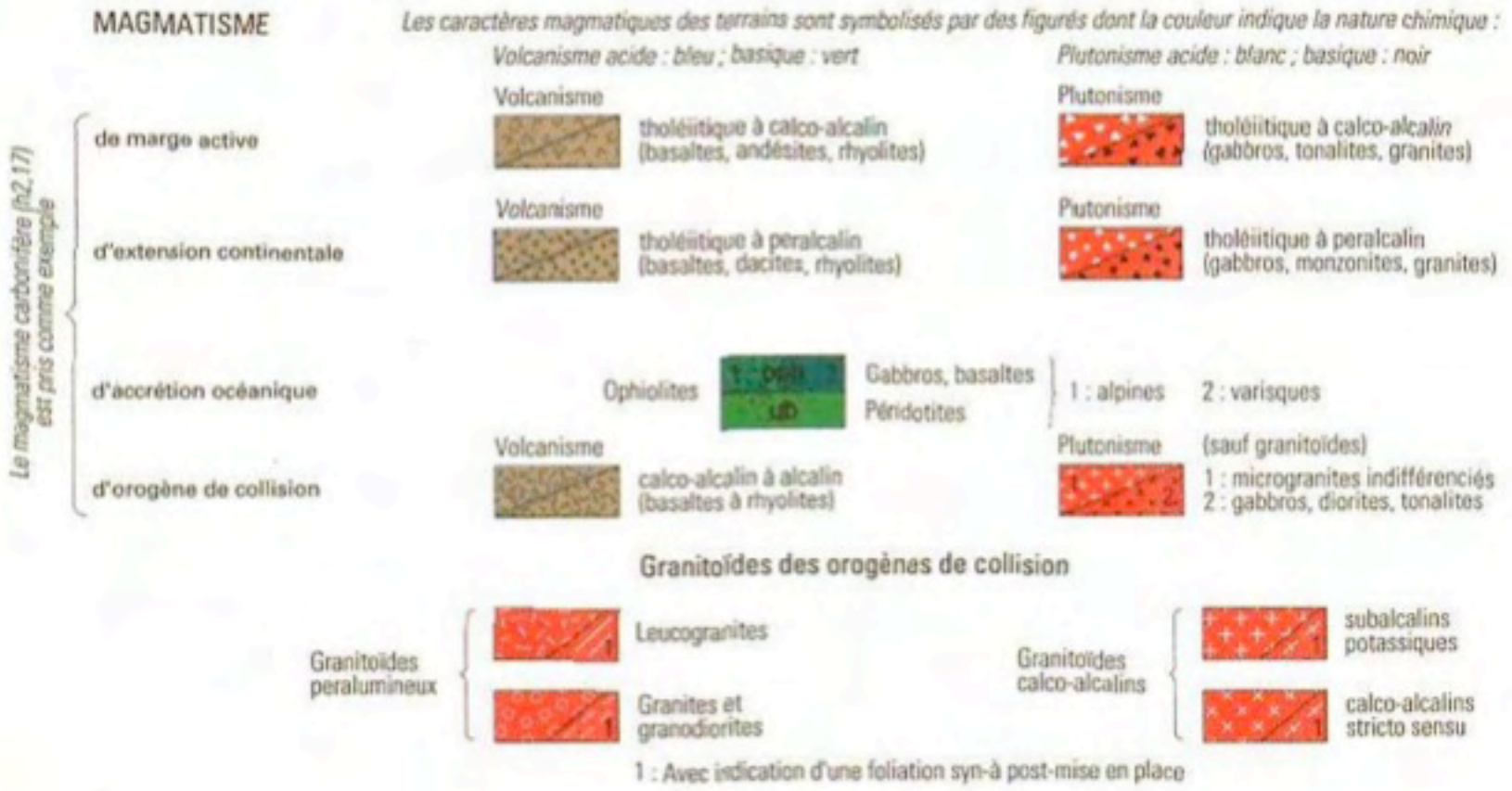
(o : absent; x : rare; xx : common; xxx : abundant)

(Barbarin, Lithos, 1999)

MINERALS	MPG	CPG	KCG	ACG	RTG	PAG
Biotite	x	x x x	x x x	x x	x	x x
Muscovite	x x x	x	x	o	o	x
Cordierite	o	x x	o	o	o	o
Sill.-And.	o	x	o	o	o	o
Amphibole	o	o	x	x x x	x x x	alk. amph.
Pyroxene	o	o	o	x x	x x	alk. pyr.
Apatite	x x x	x x x	x x	x x	x x	x x
Zircon	x	x x	x x x	x x x	x x x	x x x
Monazite	x	x	o	o	o	o
Garnet	x x	x	o	o	o	x
Tourmaline	x x x	x x	o	o	o	o
Allanite	o	x	x x	x x	x	x x
Titanite	o	o	x x	x x x	x	x
Ilmenite	x	x	x	x	x	x x
Magnetite	o	o	x	x x	x x	x x
Plag.-An%	0 - 20	15 - 40	15 - 30	20 - 50	20 - 50	0 - 10

(o : absent; x : rare; xx : common; xxx : abundant)

Sur la carte au 1/1 000 000



Carte au 1/1.000.000			Caractéristiques principales	Barbarin (1999)	Alphabet des granites	Géodynamique
 tholéiitique à peralcalin (gabbros, monzonites, granites)	d'extension continentale		Peralcalins Granites alcalins À amphibole et pyroxène sodique Associés à gabbros, monzonites, etc. de la série alcaline	PAG	A	Rift continental, intraplaque
(pas représentés, cachés dans les ophiolites)			Métalumineux Plagiogranites Associés à basaltes de la série tholéiitique	RTG	M	Dorsale océanique
 tholéiitique à calco-alcalin (gabbros, tonalites, granites)	de marge active		Métalumineux Tonalites et trondhjémites (= plagiogranites) Associés à gabbros de la série tholéiitique	ATG		Subduction (arc océanique)
Granitoïdes des orogénèses de collision	Indifférenciés		-	MPG, CPG, KCG ou ACG	S ou I	-
	Peralumineux	 Leucogranites	Peralumineux Granites s.s. À muscovite, parfois tourmaline, grenat Pas de roches associées	MPG	S	Collision et effondrement
		 Granites et granodiorites	Peralumineux Granodiorites et granites À cordiérite, parfois grenat Pas de roches associées	CPG		
	Calco-alcalins	 subalcalins potassiques	Métalumineux Granodiorites surtout Généralement porphyriques Parfois à hornblende, sphène, épidote Associés à des diorites potassiques	KCG	I	Effondrement, post-collision
		 calco-alcalins stricto sensu	Métalumineux Granodiorites À hornblende, parfois clino-pyroxène Associés à gabbros, diorites de la série calco-alcaline	ACG		Subduction (arc continental)
			Métalumineux Granites et granodiorites Hornblende rare Pas de roches associées			Collision

Les granites

2. Origine des magmas granitiques

a. La fusion crustale

Jean-François Moyen

Université de Lyon

Université Jean Monnet Saint-Étienne

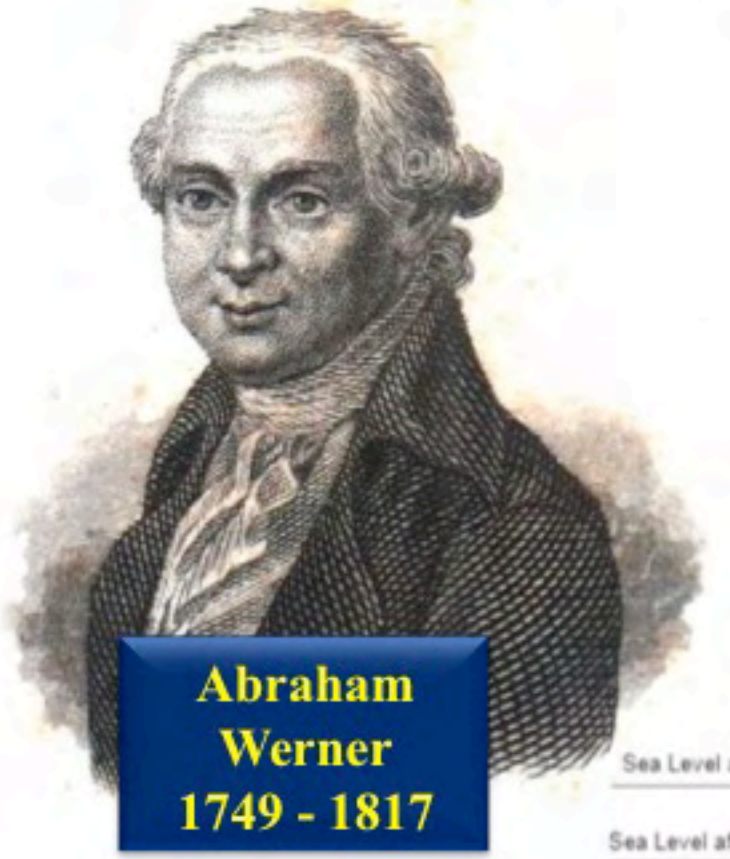
Laboratoire Magmas & Volcans

Perspective historique

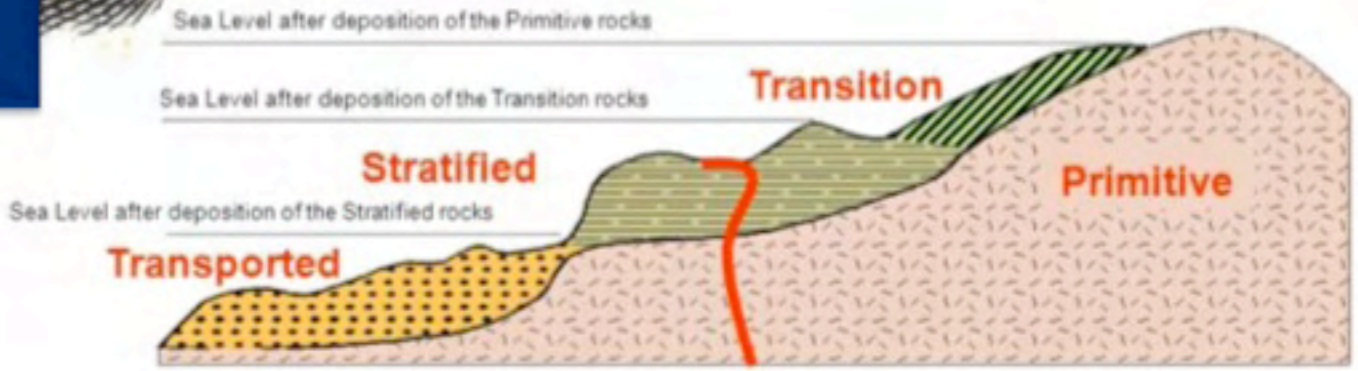
XVIII^{e} – XIX^{e} siècle

Neptunistes
Plutonistes

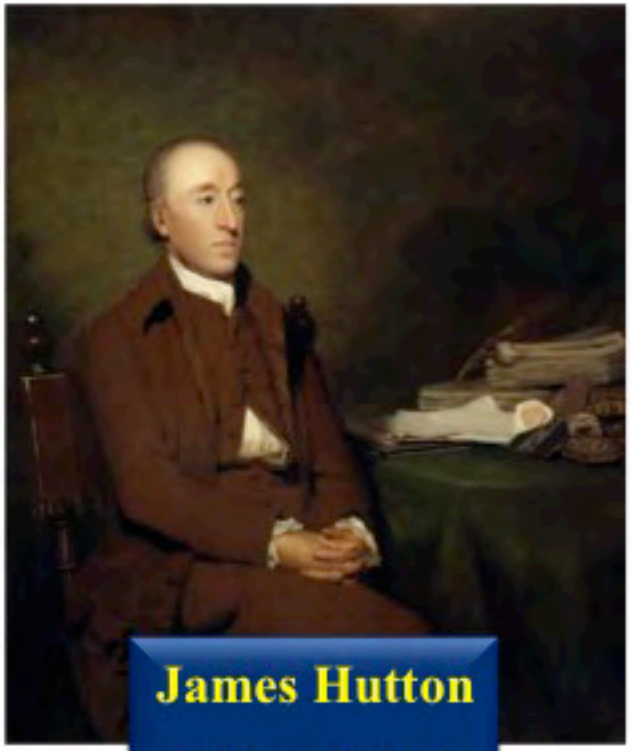
Werner et le Neptunisme



"This basalt, this wacke, this clay, and this sand, are all one and the same formation; that they are all the effect of a precipitation by the wet way…"
(1791)



Hutton et le Plutonisme



James Hutton

1726 - 1797

...the well defined feldspars had formed first, thus determining the shape of the quartz that formed next. ... there is sufficient evidence of this body having been consolidated by means of fusion, and in no other manner.

Fig. 2.

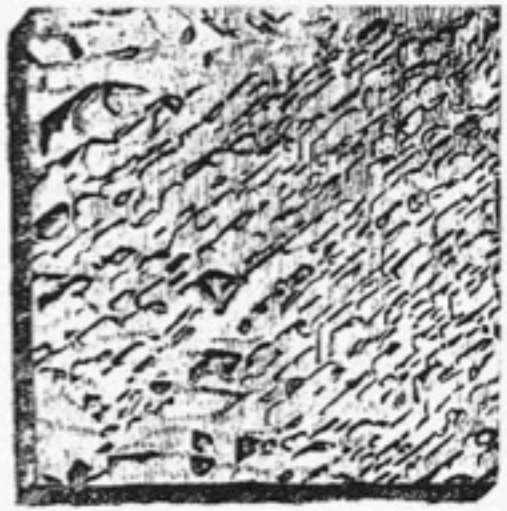
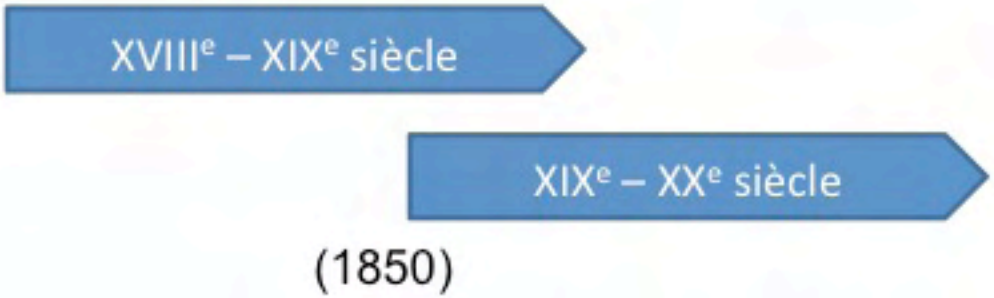


Fig. 3.

Perspective historique



~~Neptunistes~~
Plutonistes

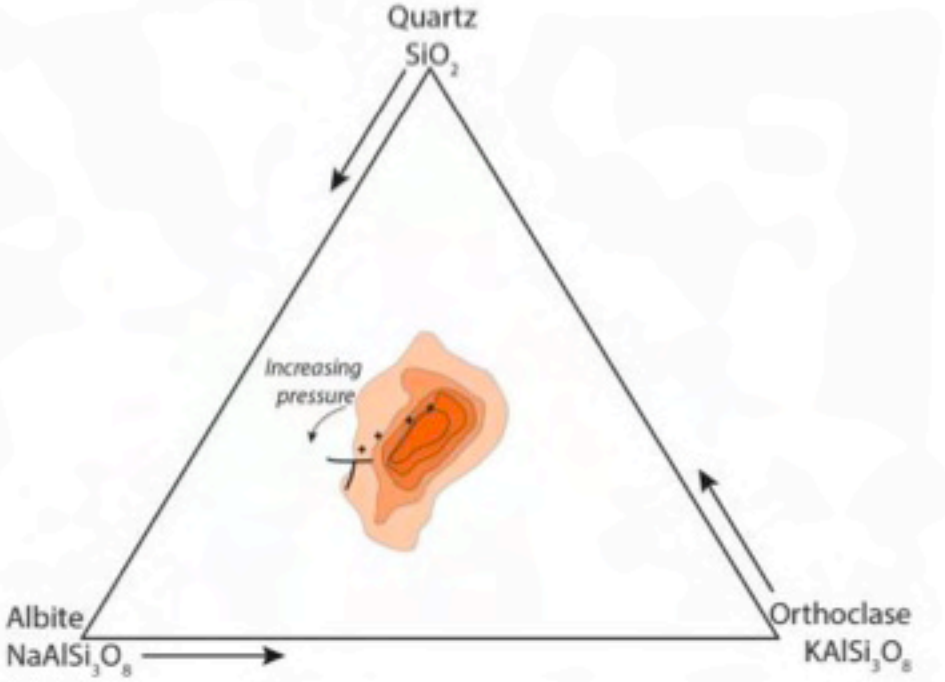
Transformistes
Magmatistes

Les « magmatistes »

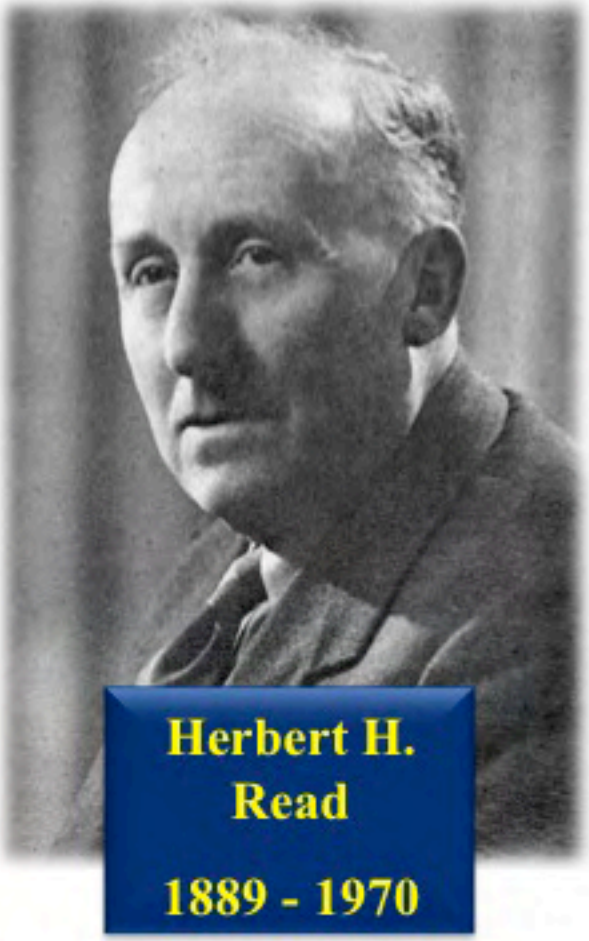
Norman L. Bowen

1887 - 1956

"The difference between the 'pontiff' and the 'soak' is that the latter must have his liquor in lavish quantities on all occasions, but the former handles his liquor like a gentleman."
(1947)

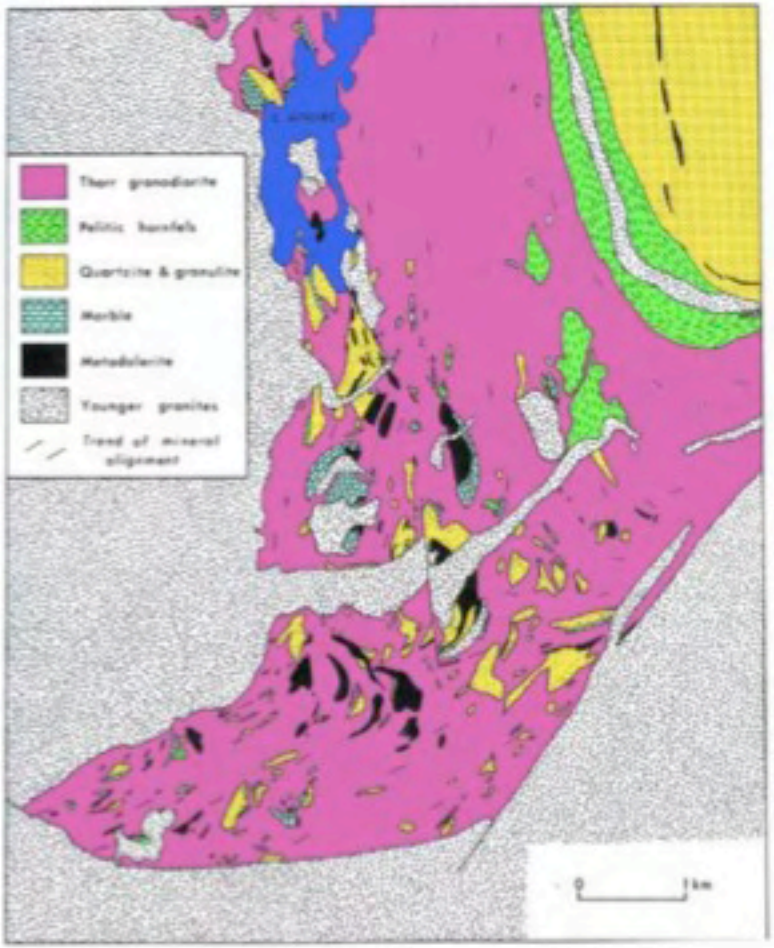


Les « transformistes »



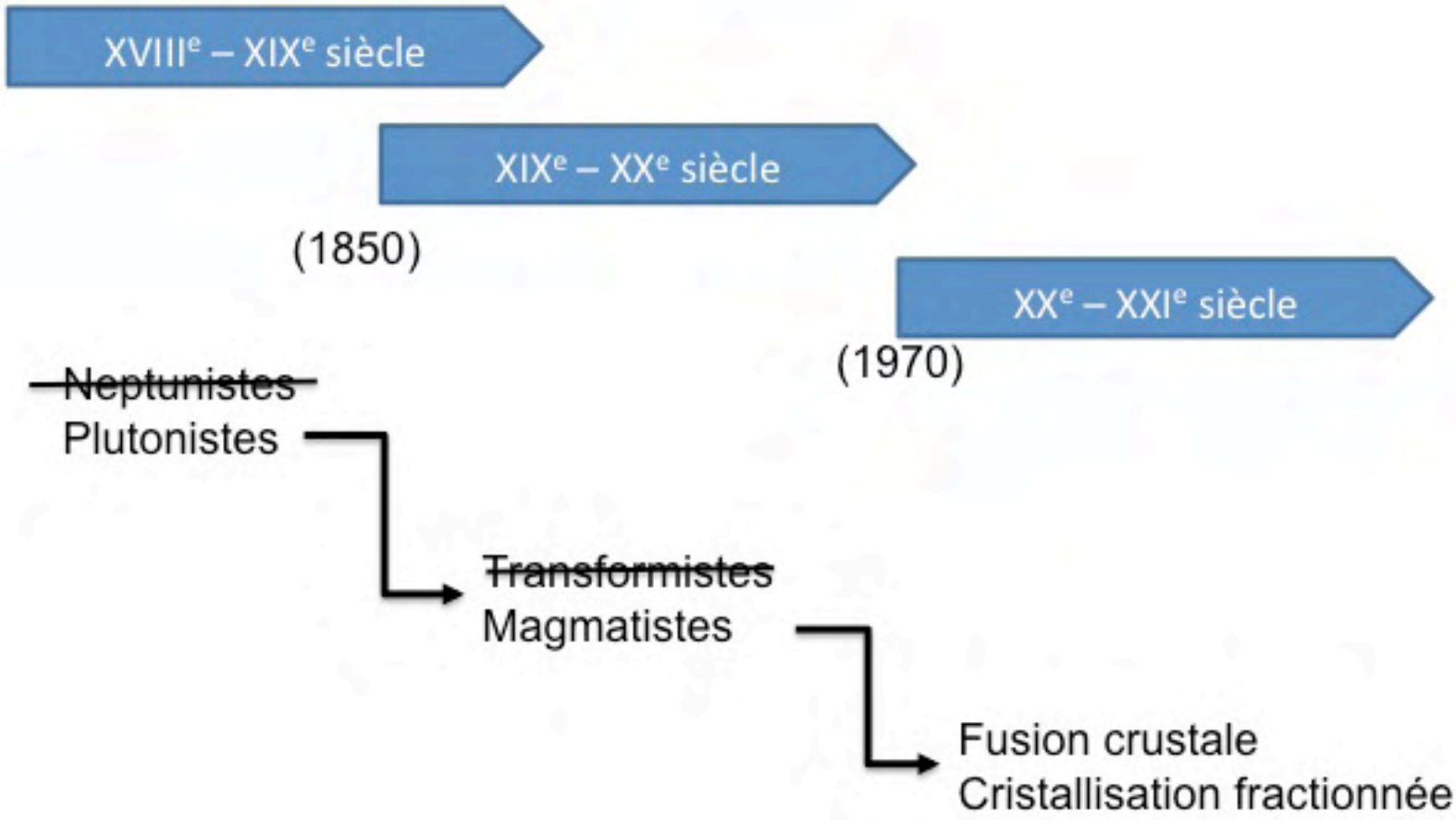
(Mais aussi l'école Française : Roubault, etc.)

"The best geologist is the one who has seen the most rocks." (1940)



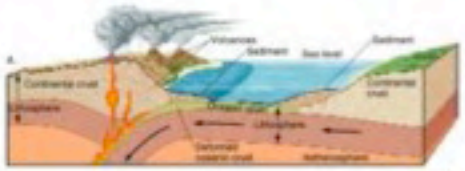
« Ghost Stratigraphy »

Perspective historique



Frac. cryst of mantle melts

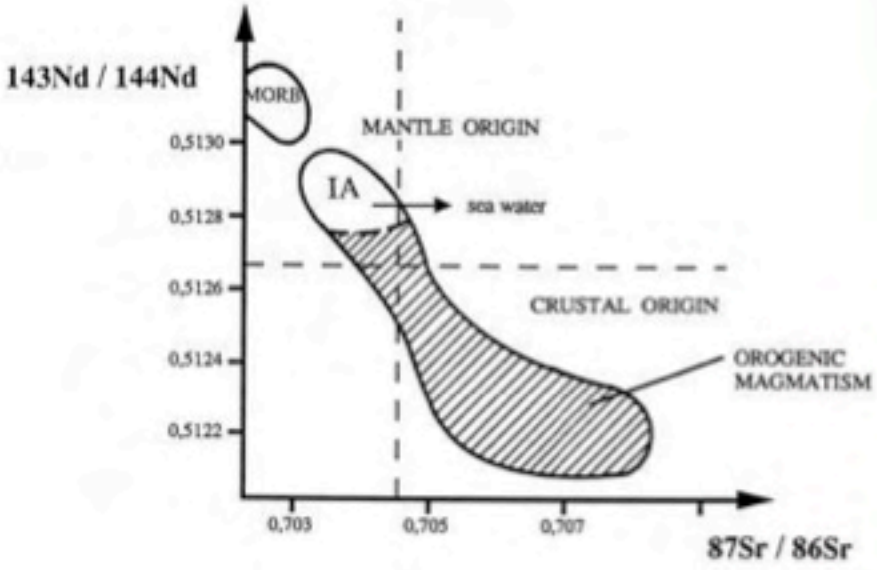
Crustal melting



« arc » people

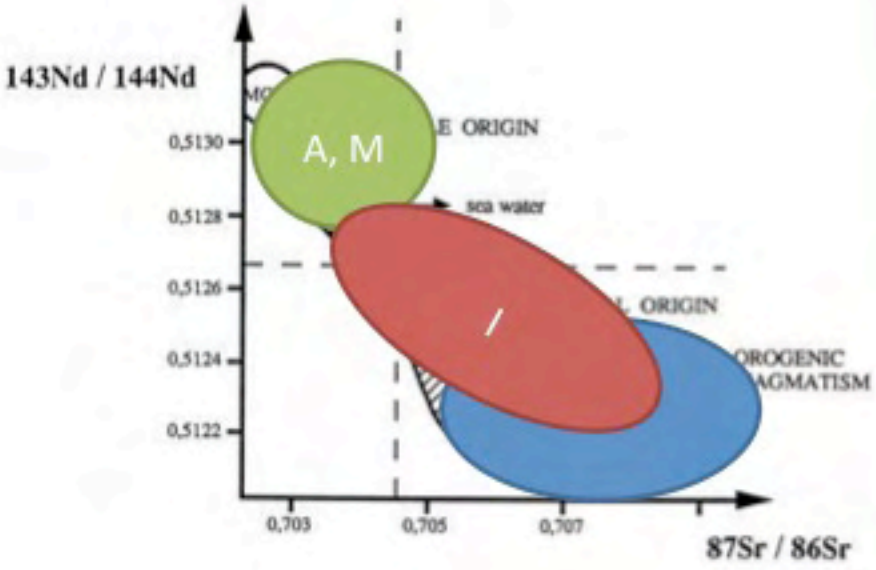
« Collision » people

Granites crustaux / mantelliques



Winter, after Kistler 1990; Miller and Barton 1990; Armstrong 1990

Granites crustaux / mantelliques



Winter, after Kistler 1990; Miller and Barton 1990; Armstrong 1990

Des granites crustaux différents…

- Ca dépend de ce qui fond … et à quelle température

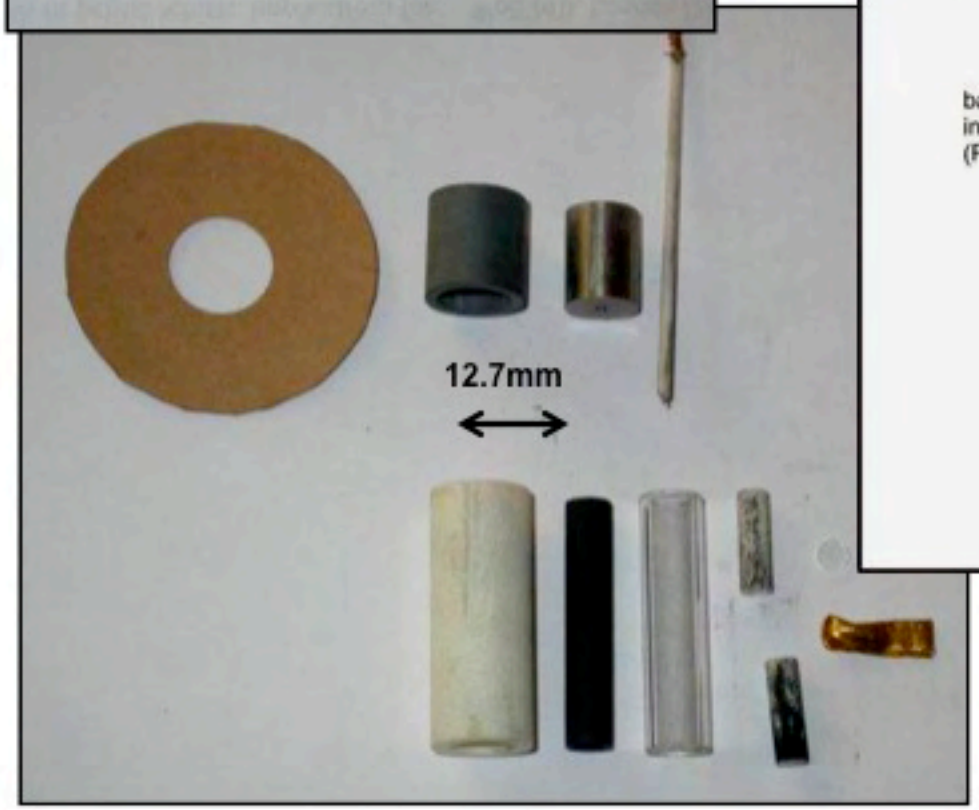
… une amphibolite
(Amp+Pg)

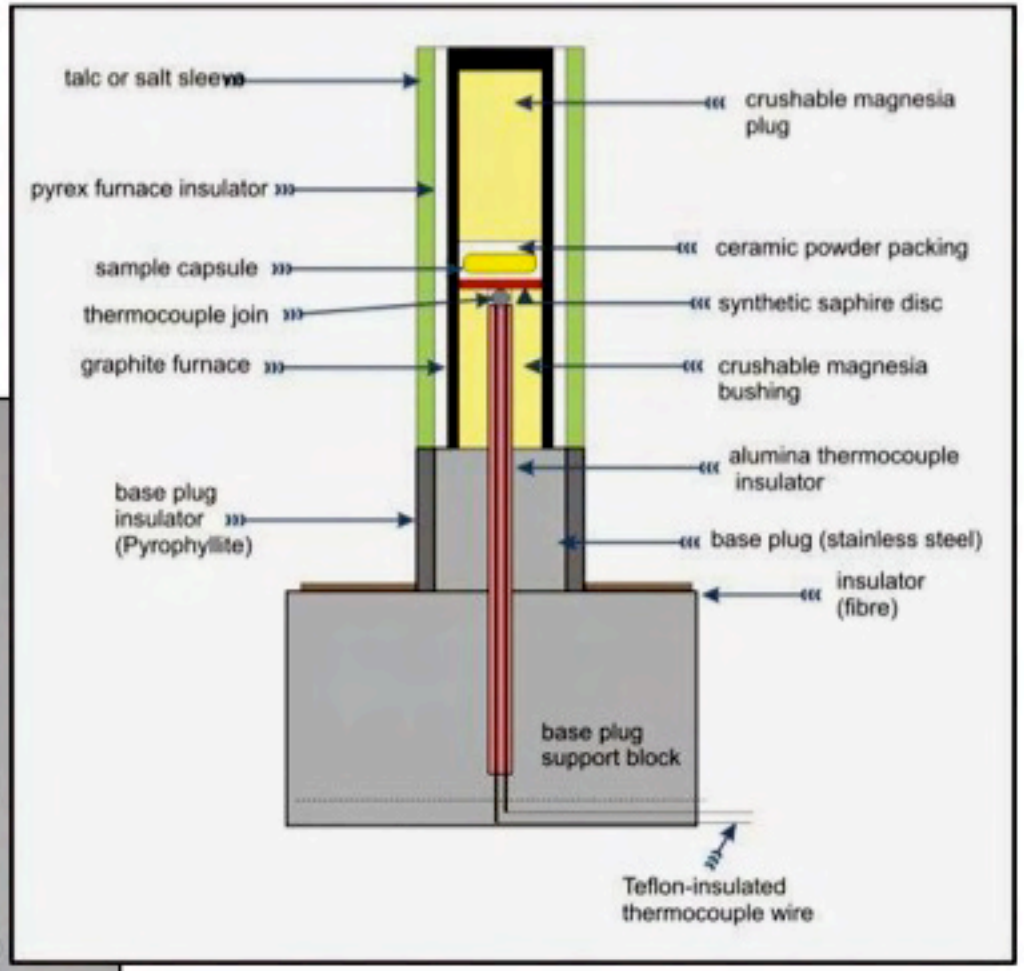
… un ancien sédiment
(Bt+Pg+Qz)

Ce qui importe, c'est la *réaction de fusion*

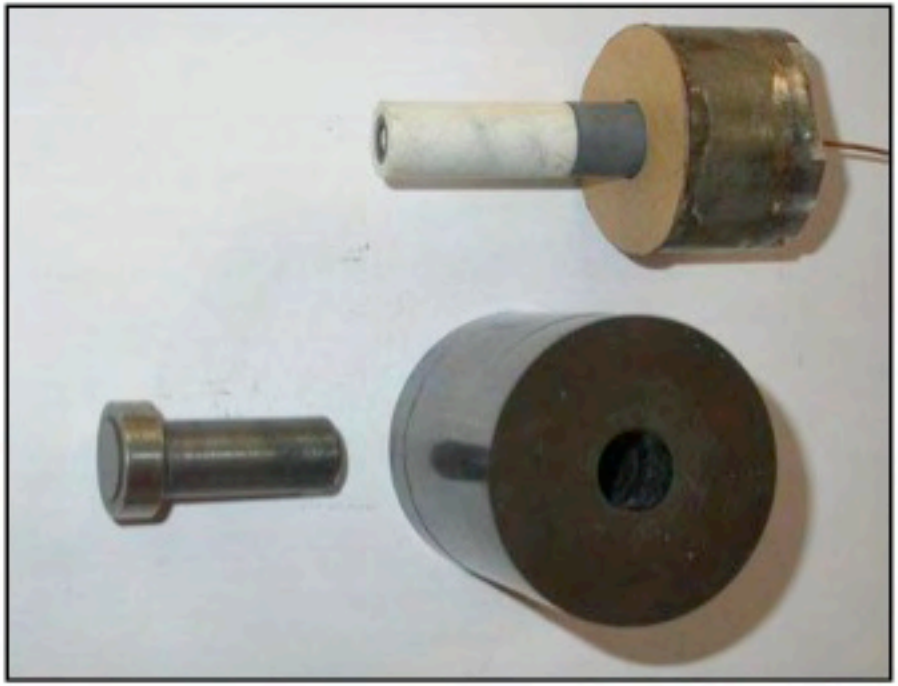
- Avec des réactifs et des produits
- Des coefficients stœchiométriques
- Un emplacement dans l'espace PT

Approche expérimentale

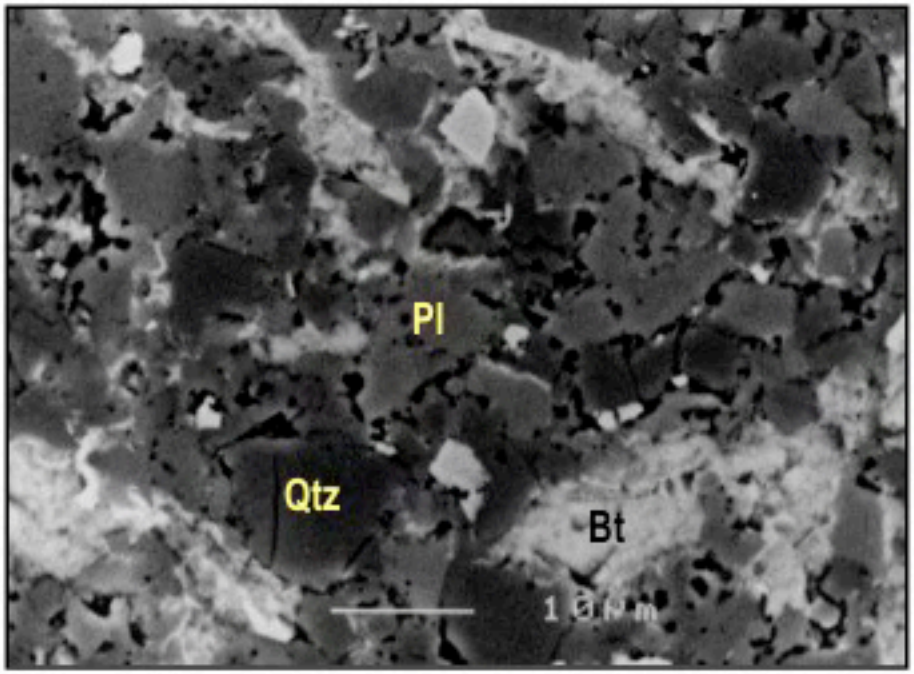


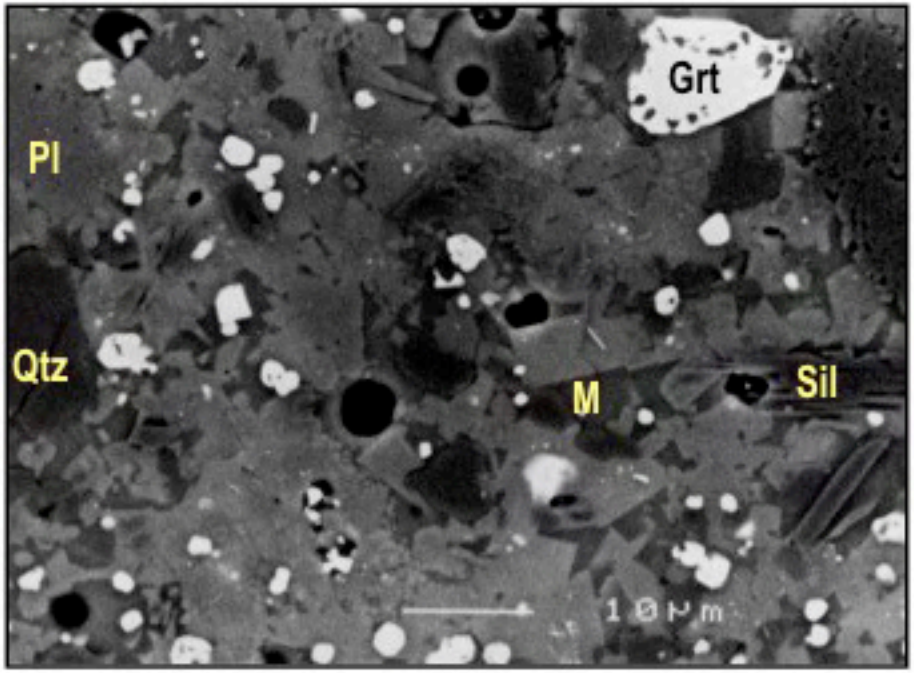


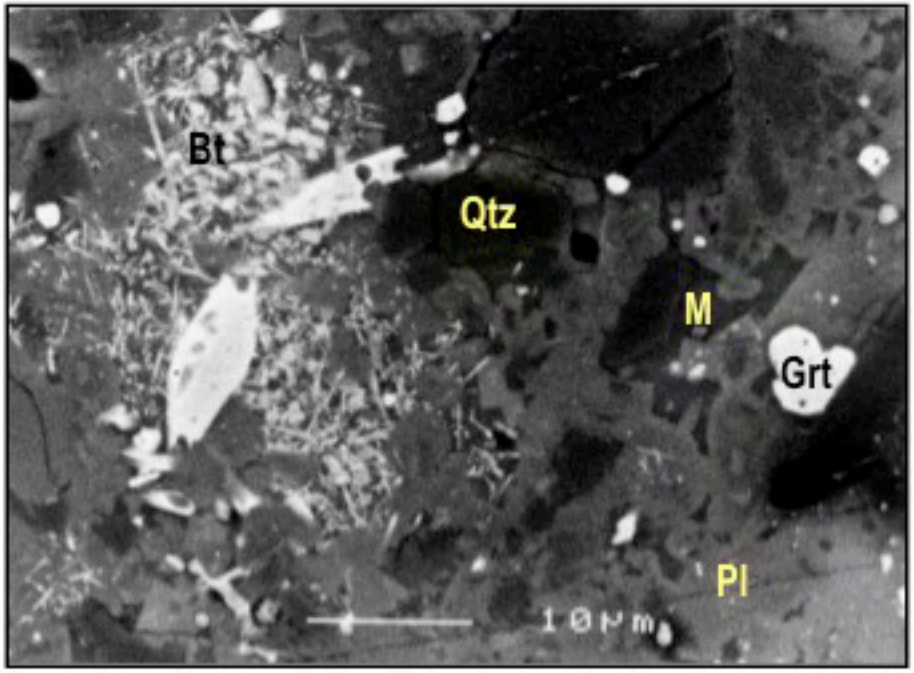
G. Stevens

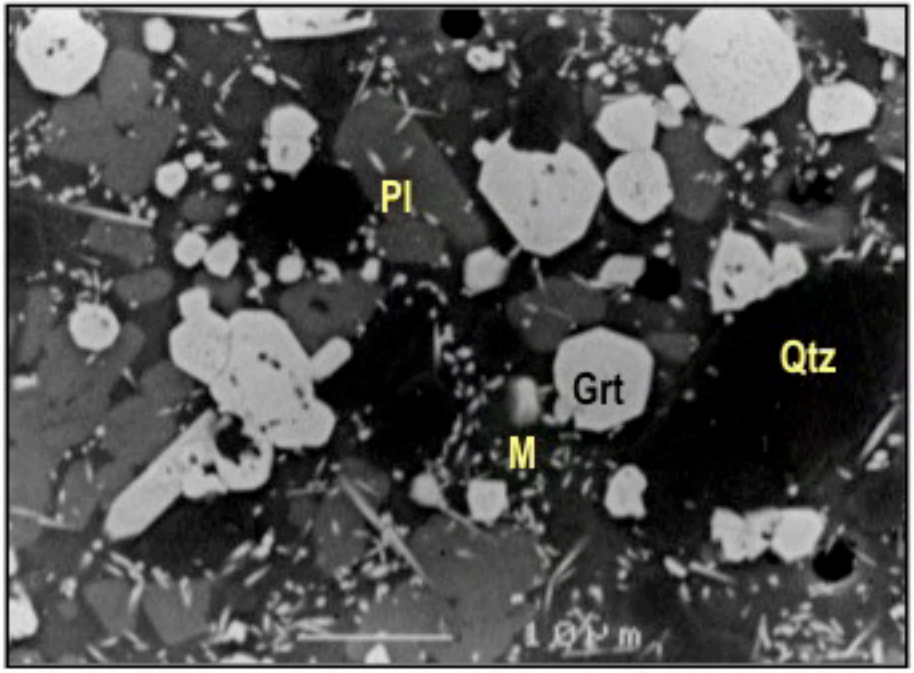


G. Stevens

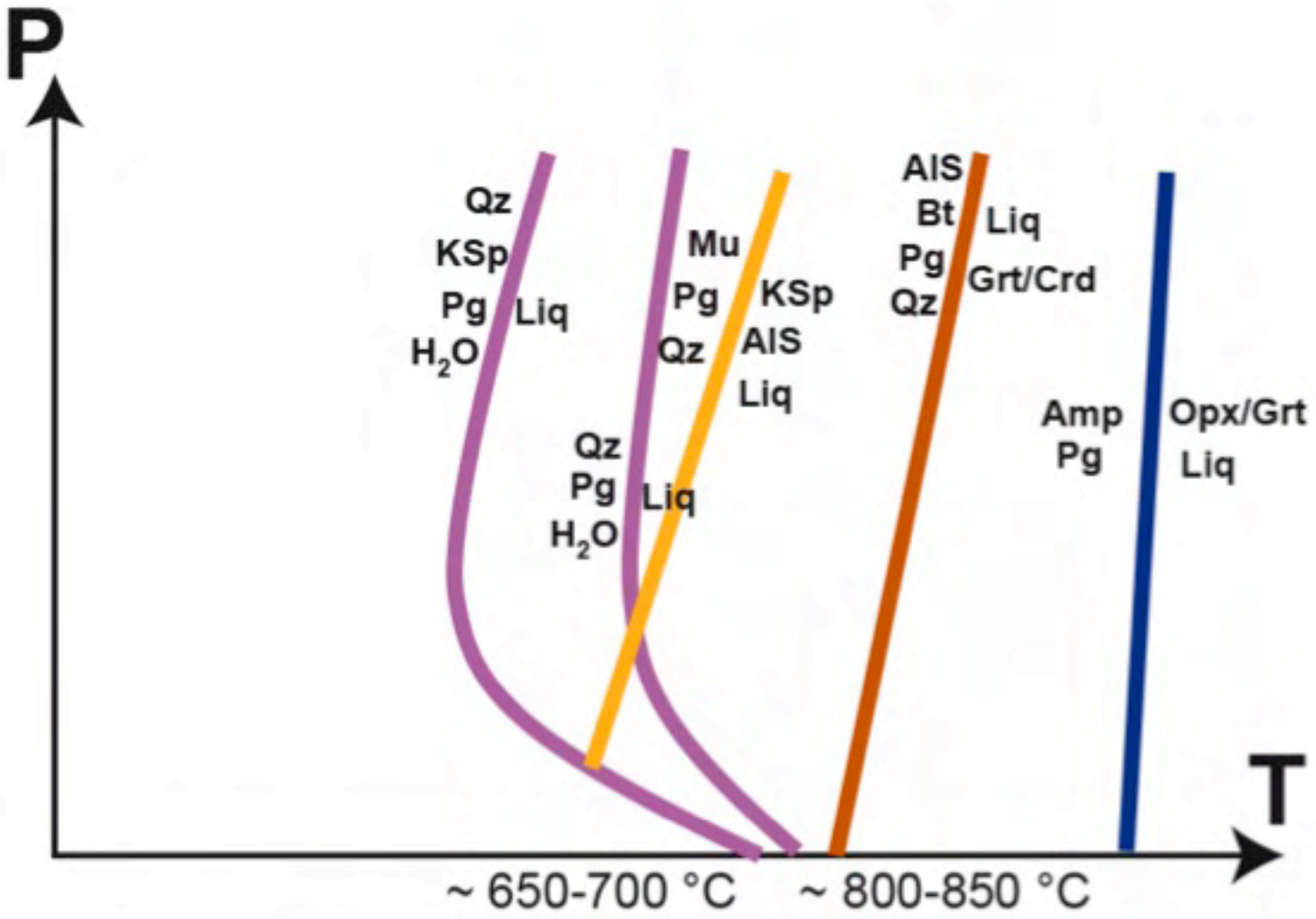

Pl
Qtz
Bt
10μm


Grt
Pl
Qtz
M
Sil
10μm


Bt
Qtz
M
Grt
Pl
10μm

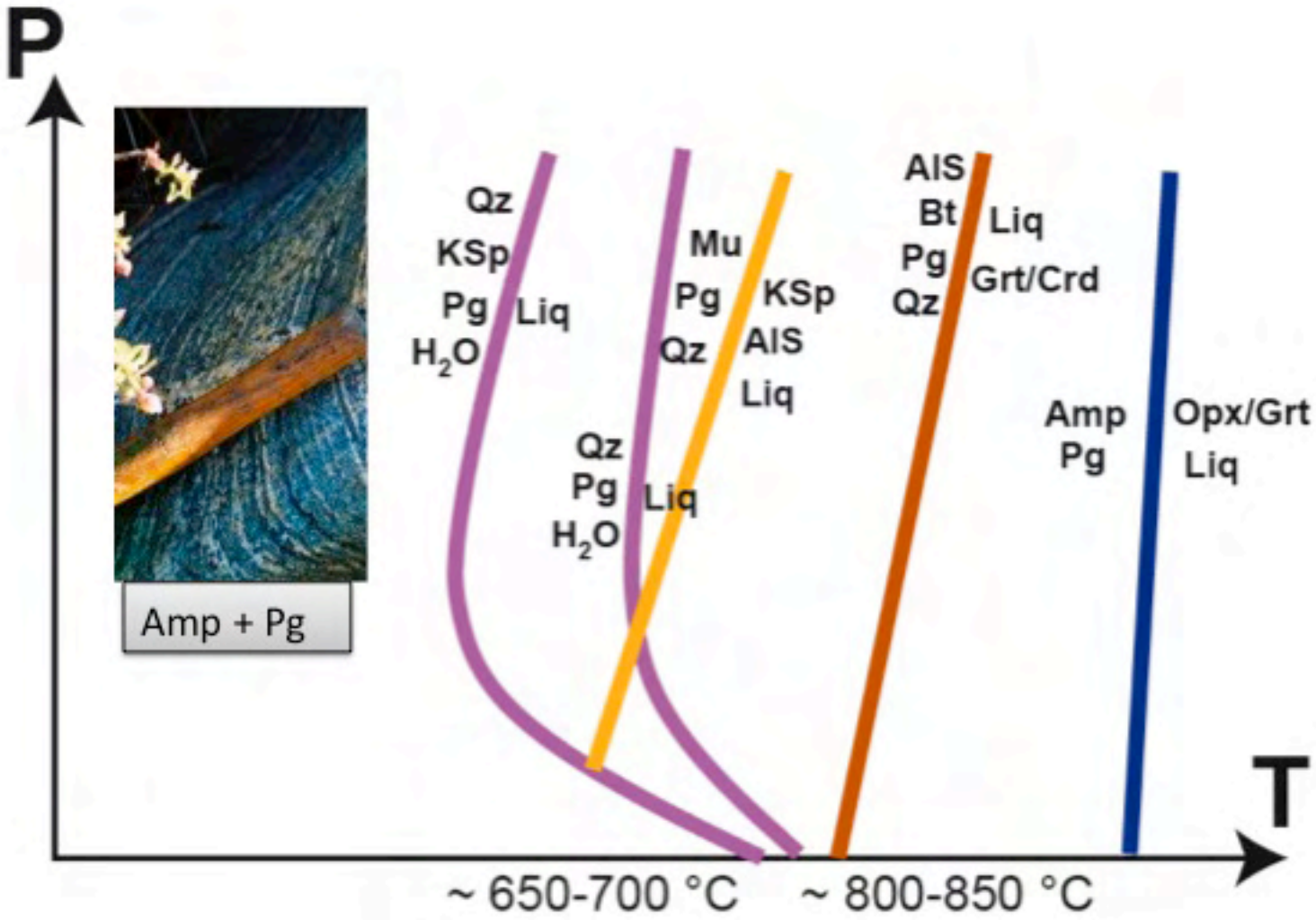

Pl
Qtz
Grt
M

G. Stevens

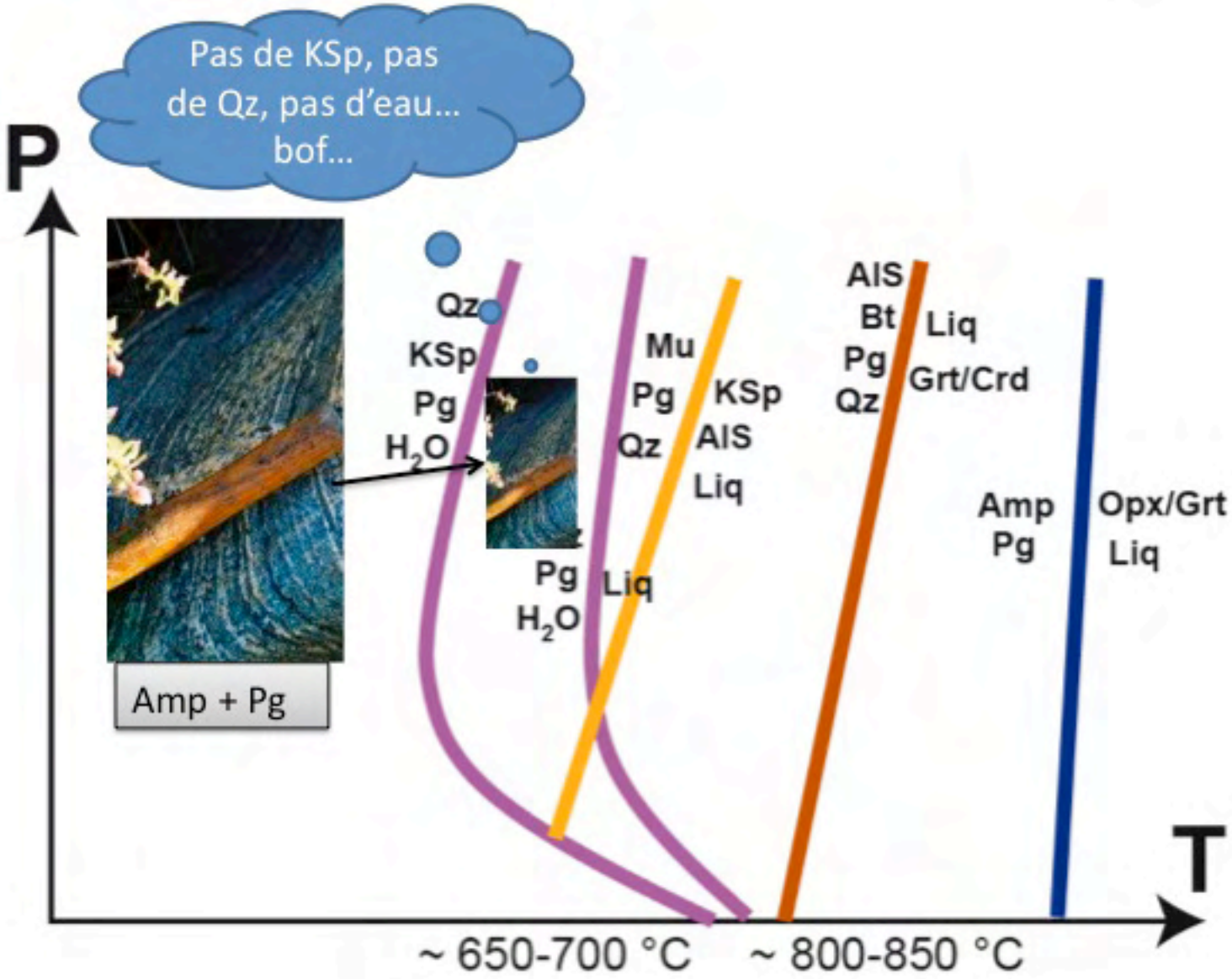


- C’est le bazar ? Oui, mais pour qu’une réaction ait lieu il faut que ses réactifs soient là !!

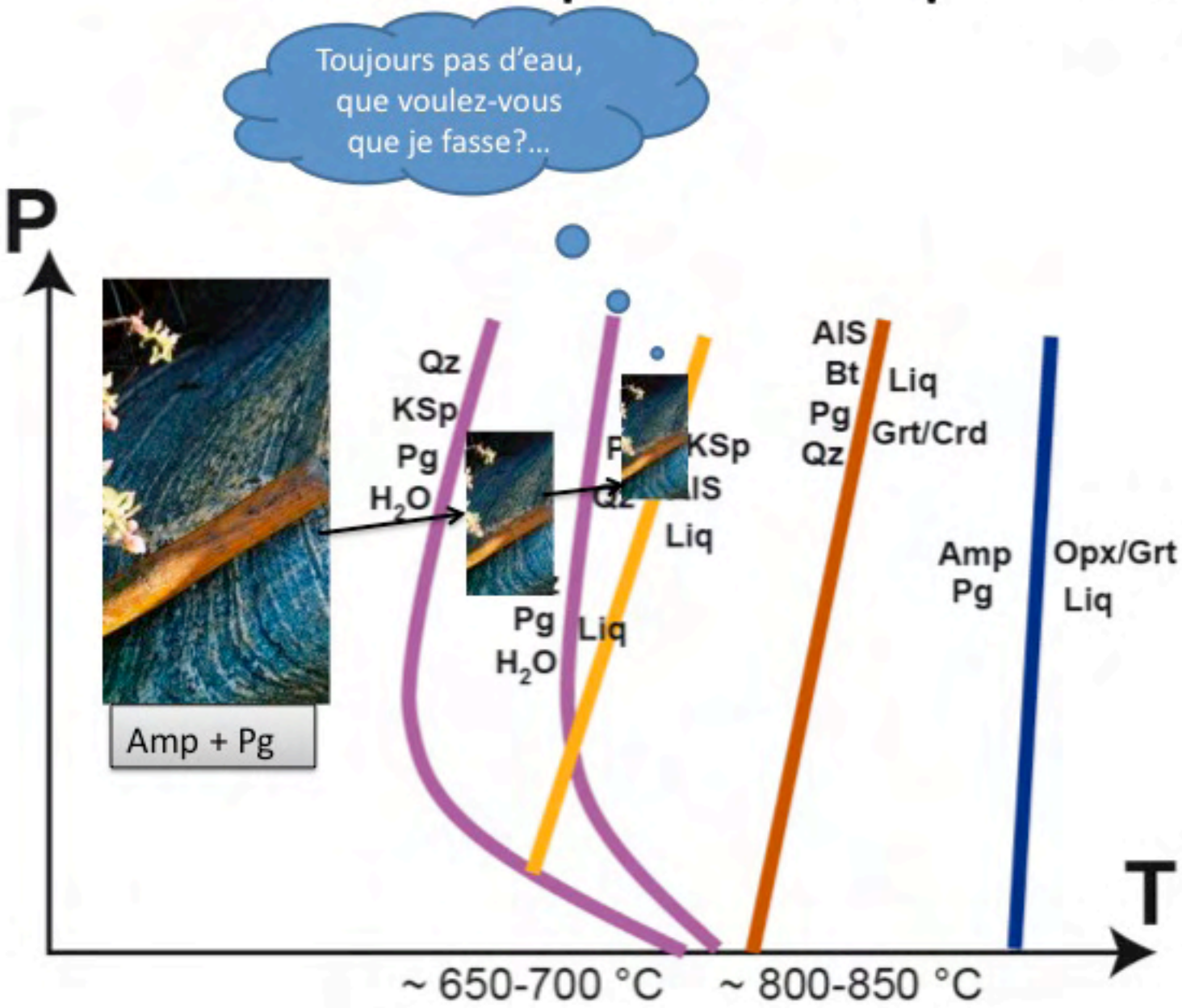
Une amphibolite parle…



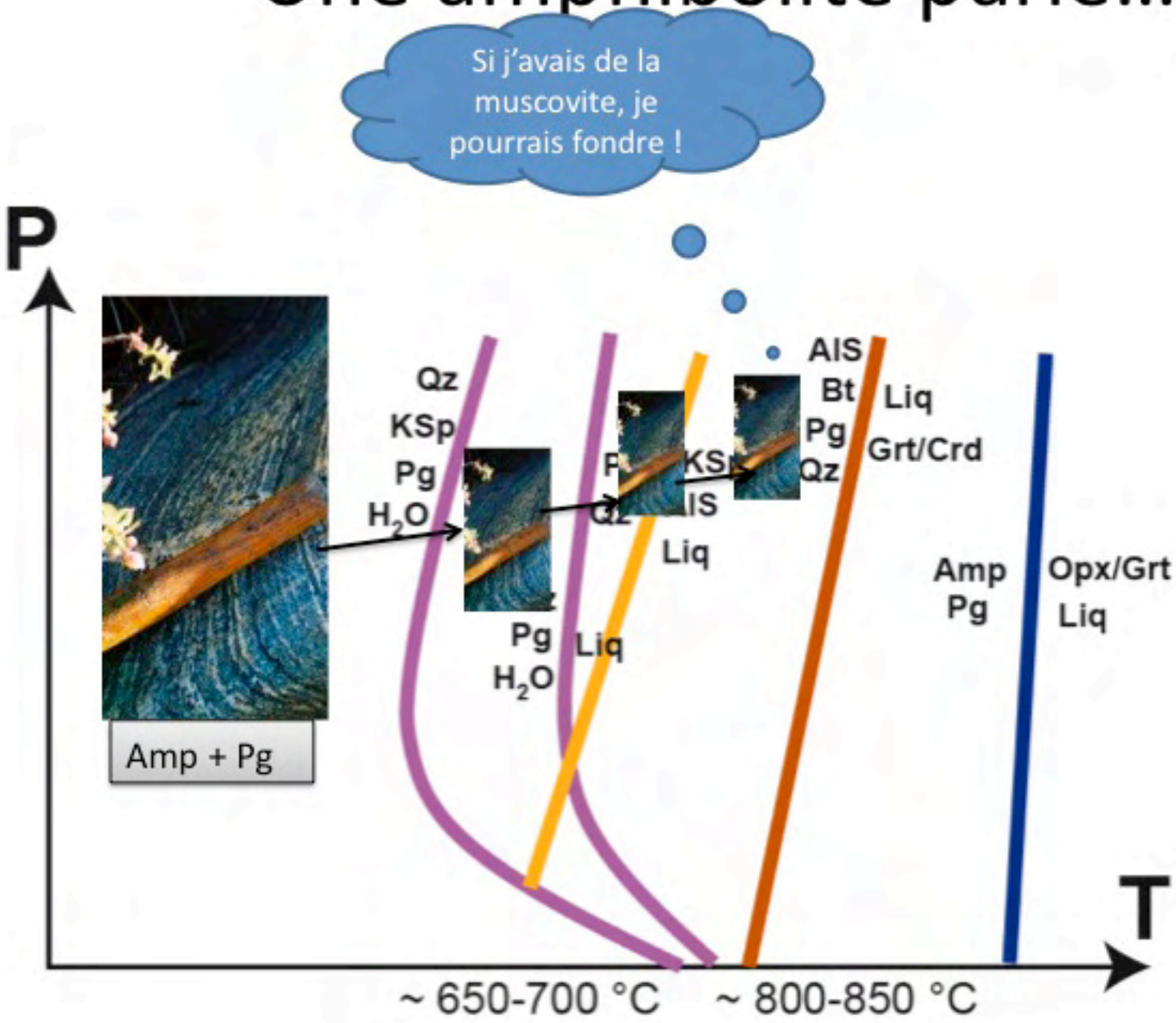
Une amphibolite parle…



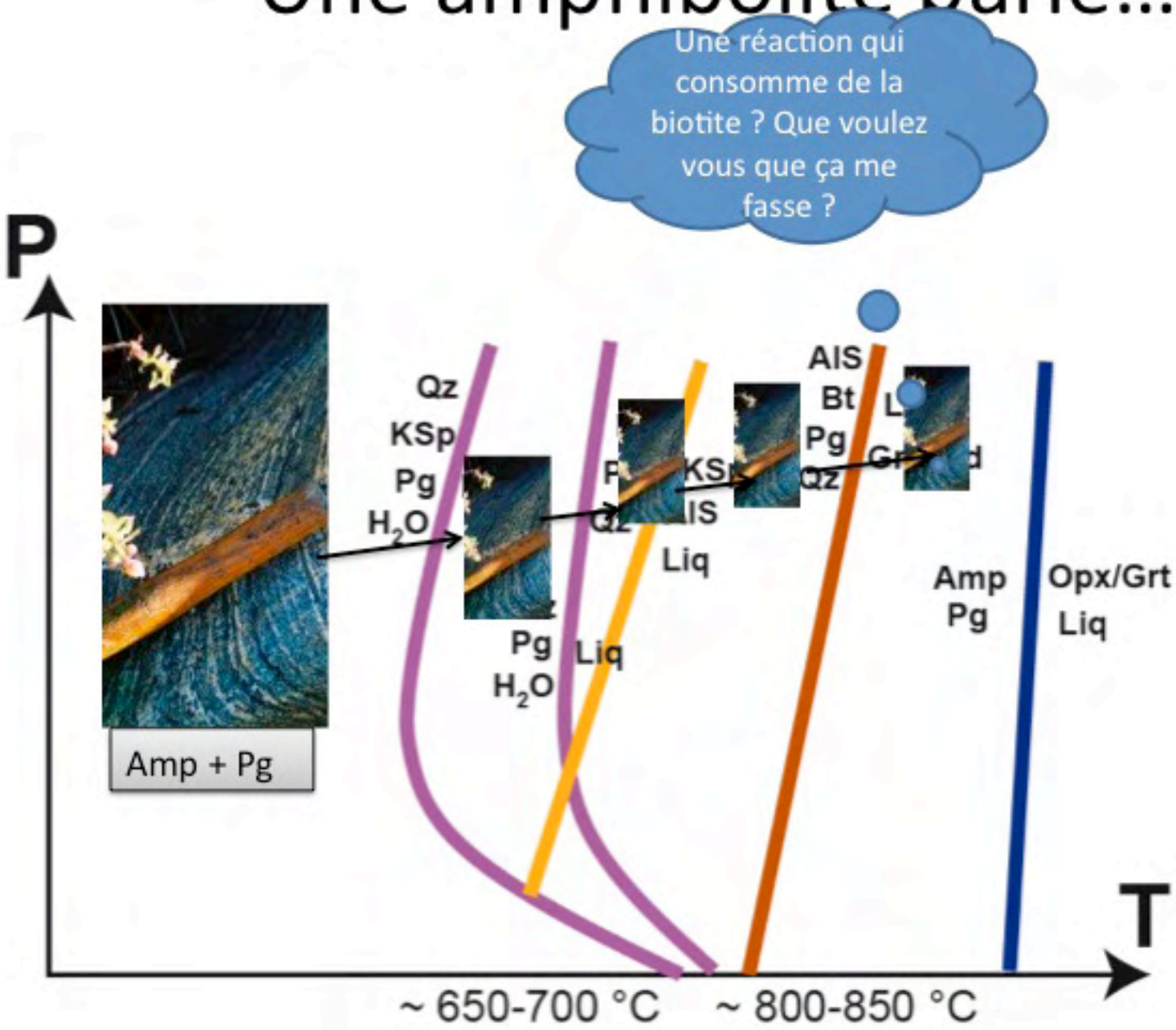
Une amphibolite parle…



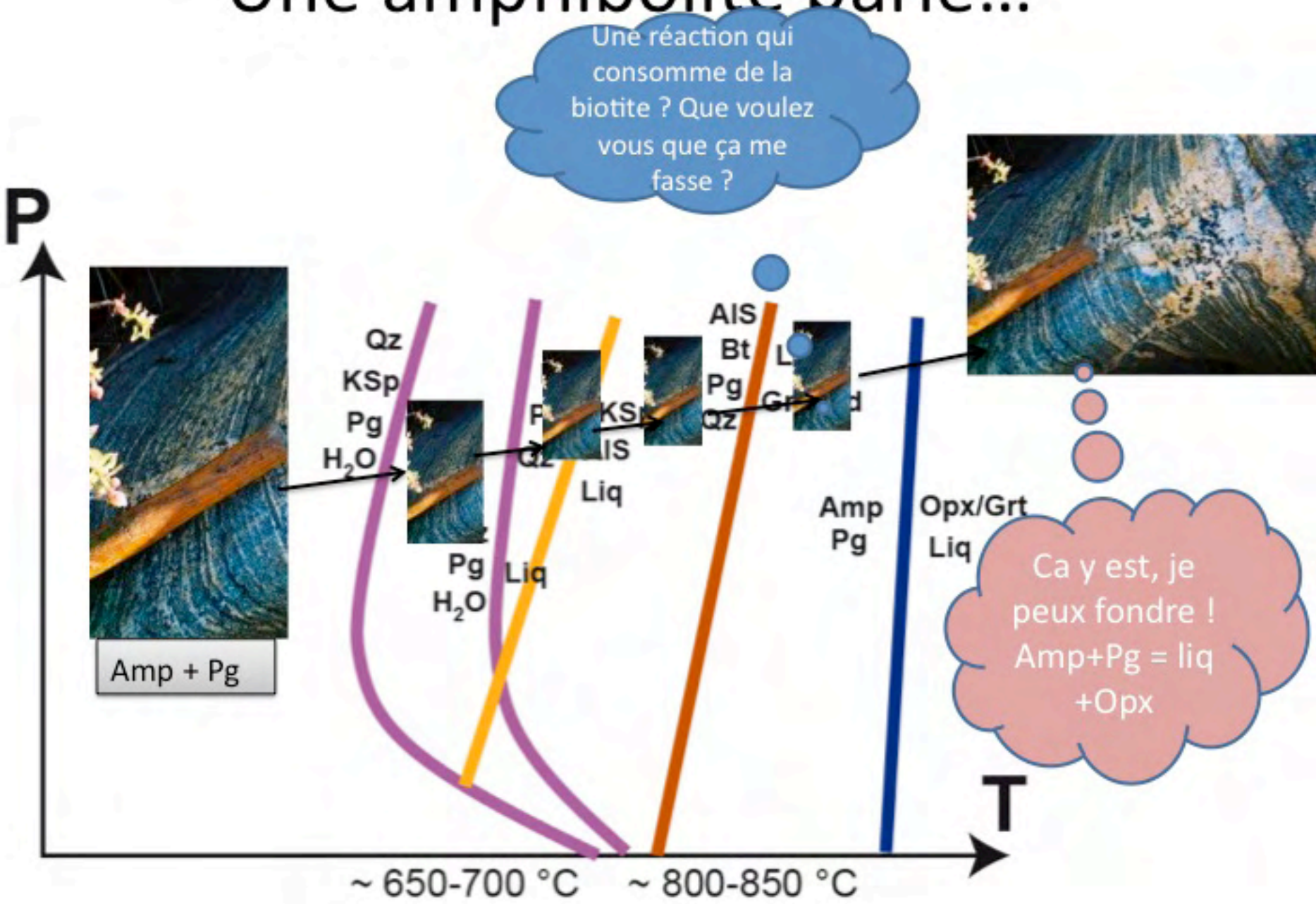
Une amphibolite parle…



Une amphibolite parle…



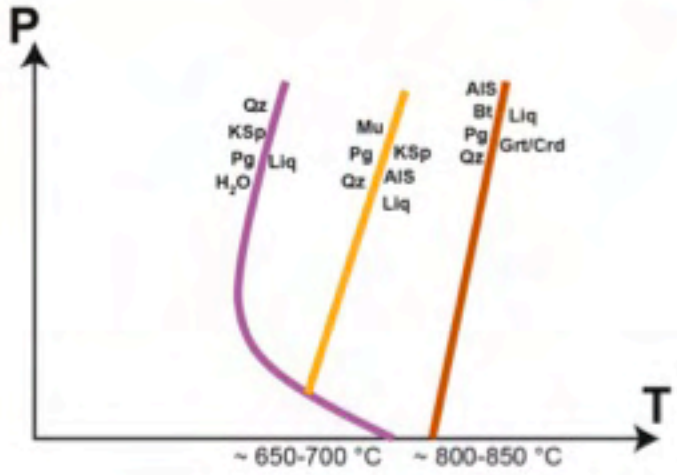
Une amphibolite parle…



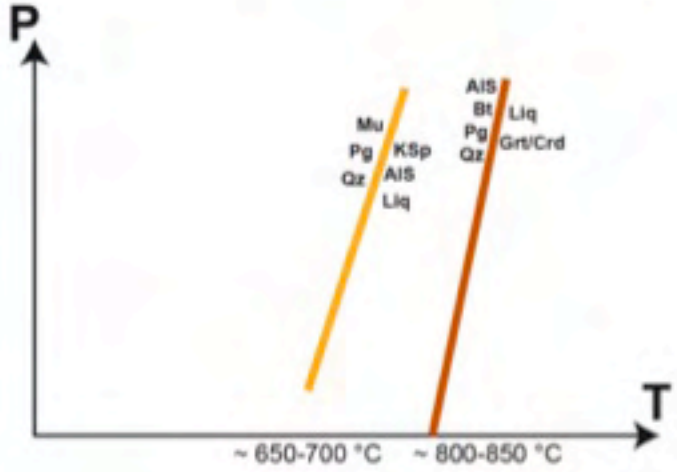
Ce que « voient » différentes roches

Des métasédiments (ici, à Ms)

Avec eau libre



Sans eau libre

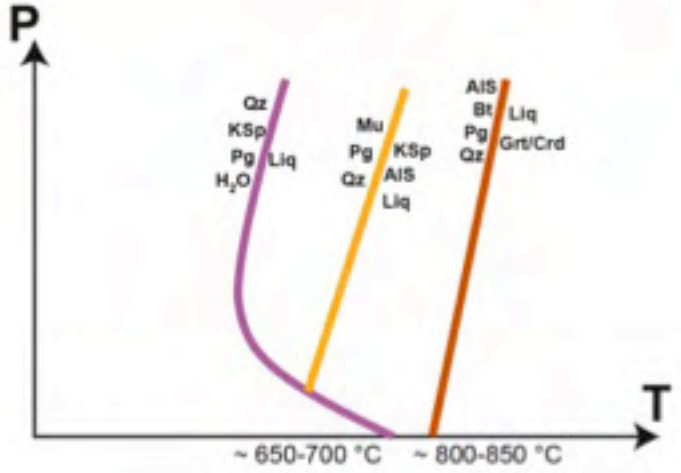


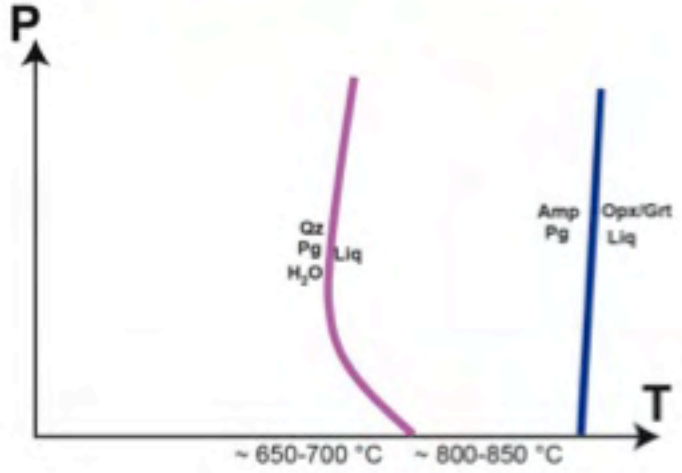
Ce que « voient » différentes roches

Des métasédiments (ici, à Ms)

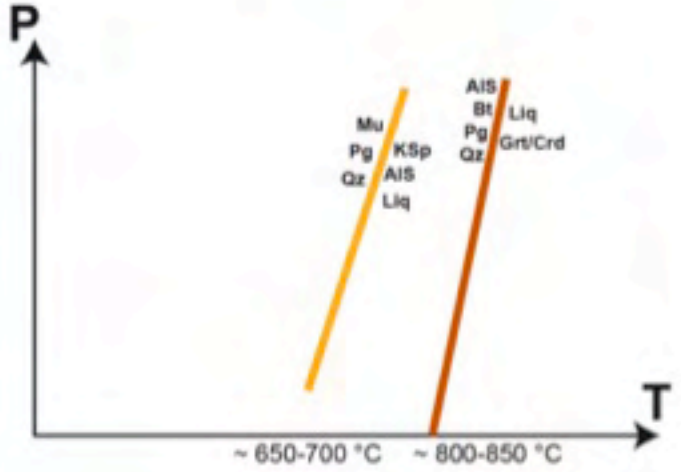
Des amphibolites

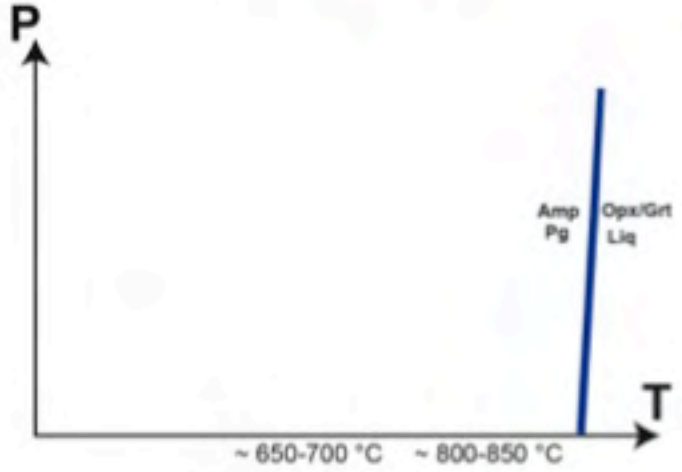
Avec eau libre



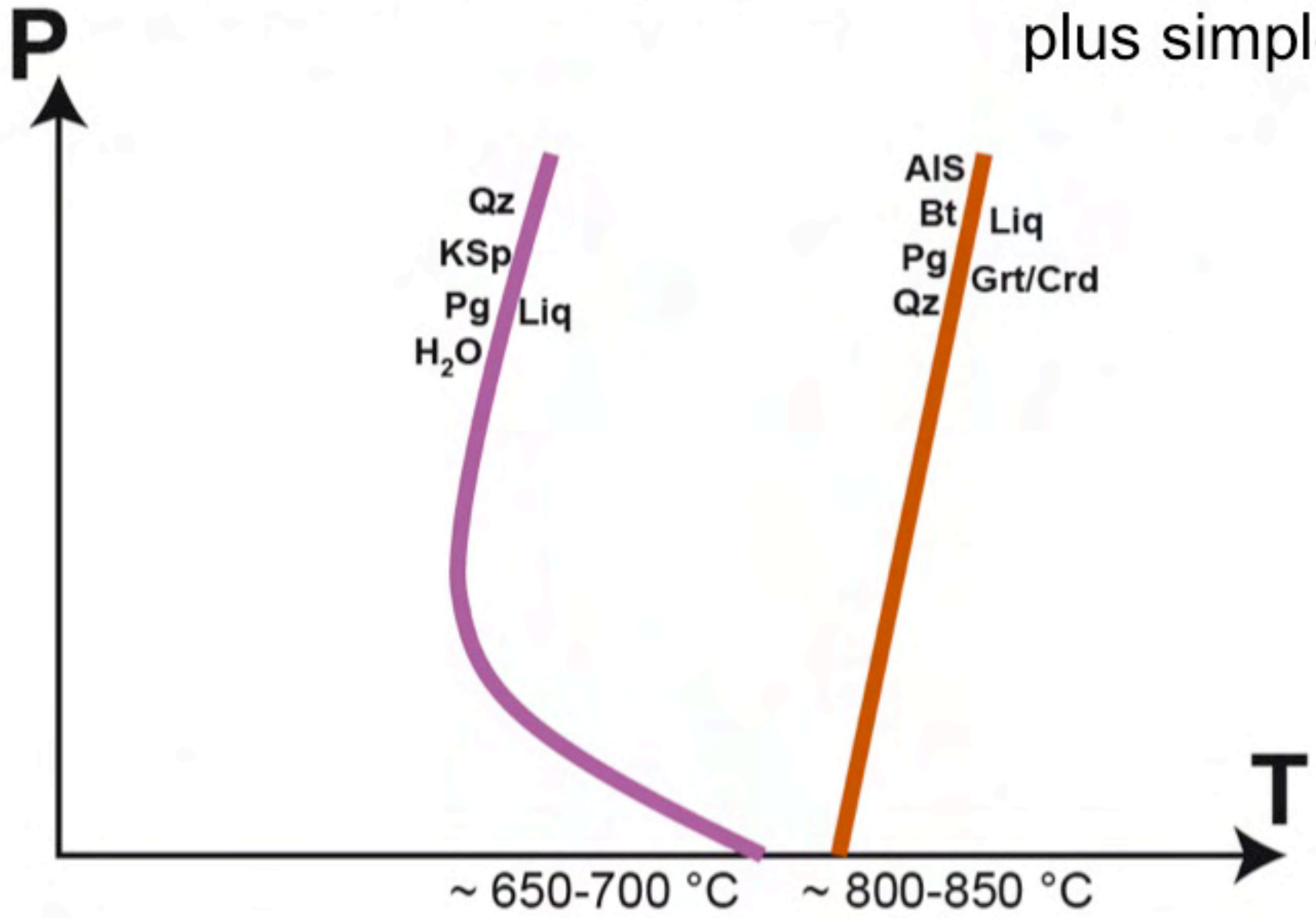


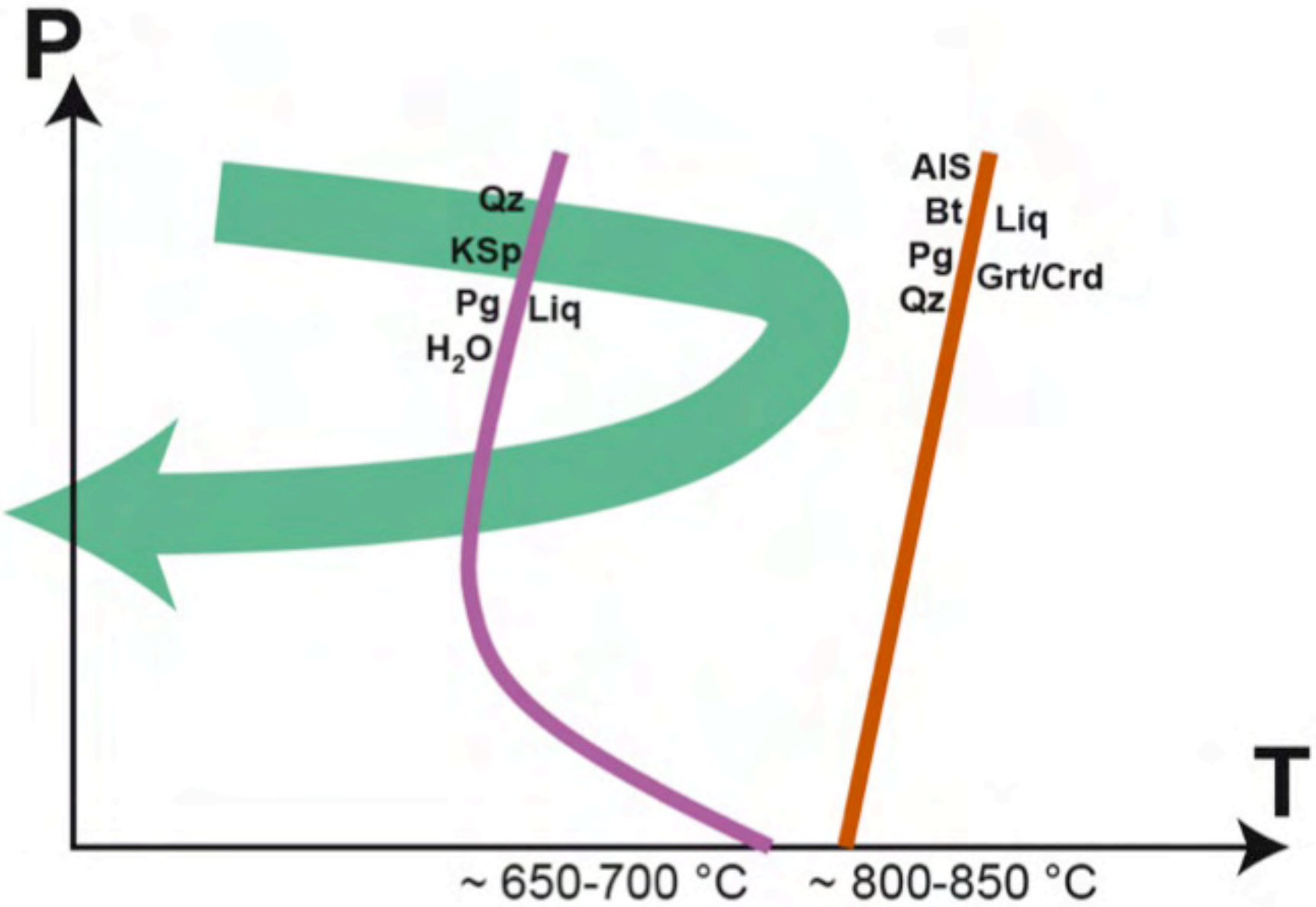
Sans eau libre

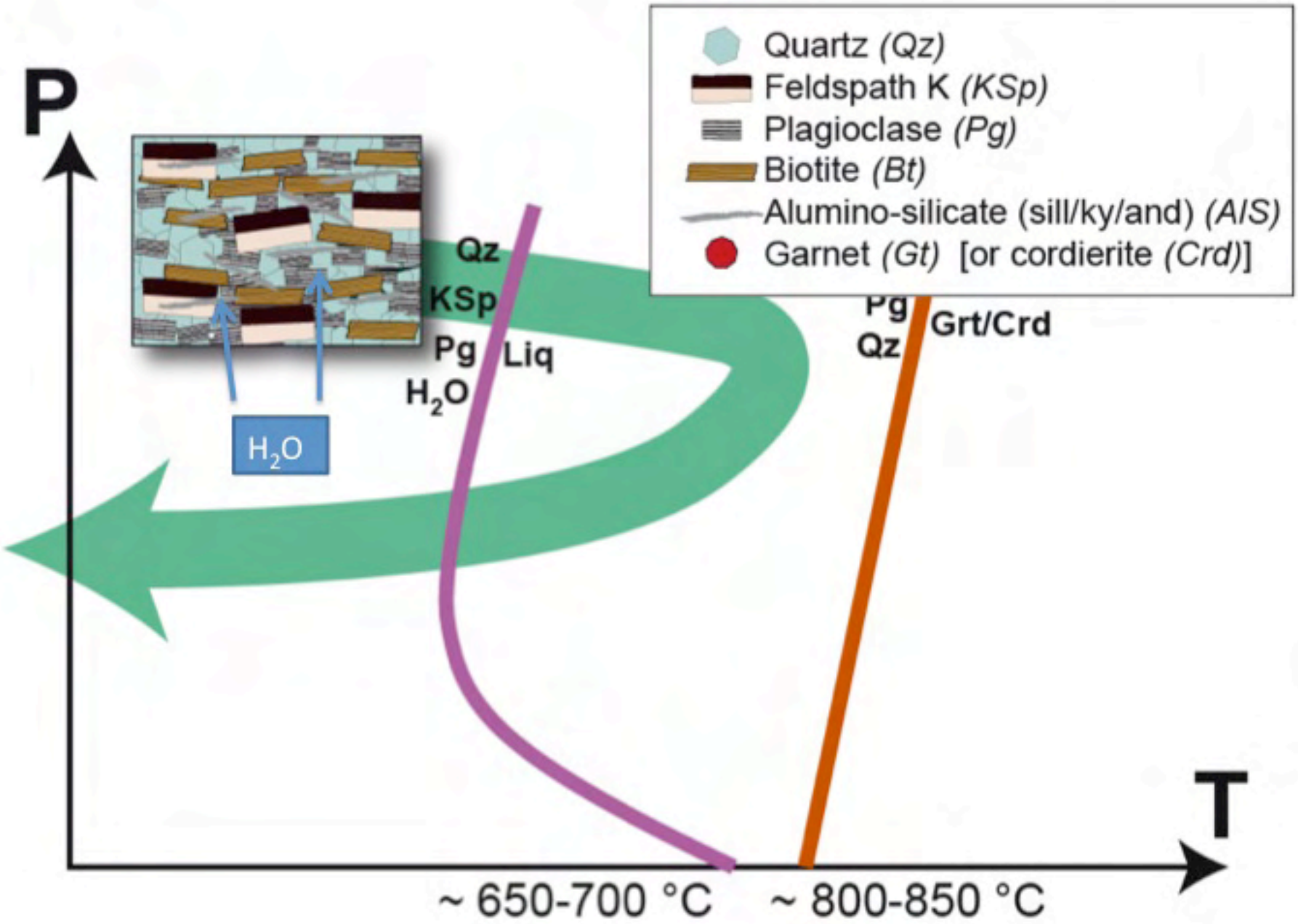


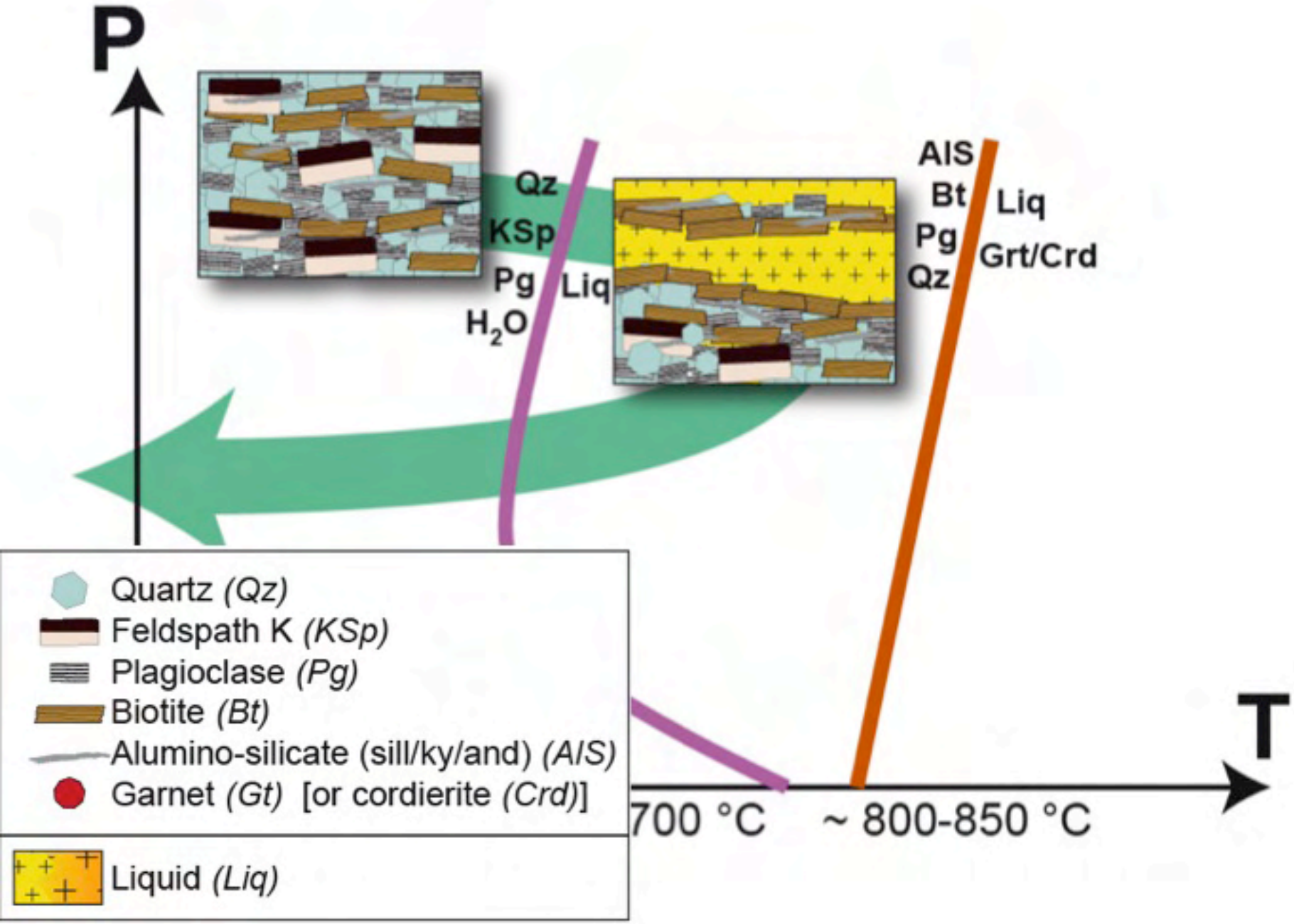


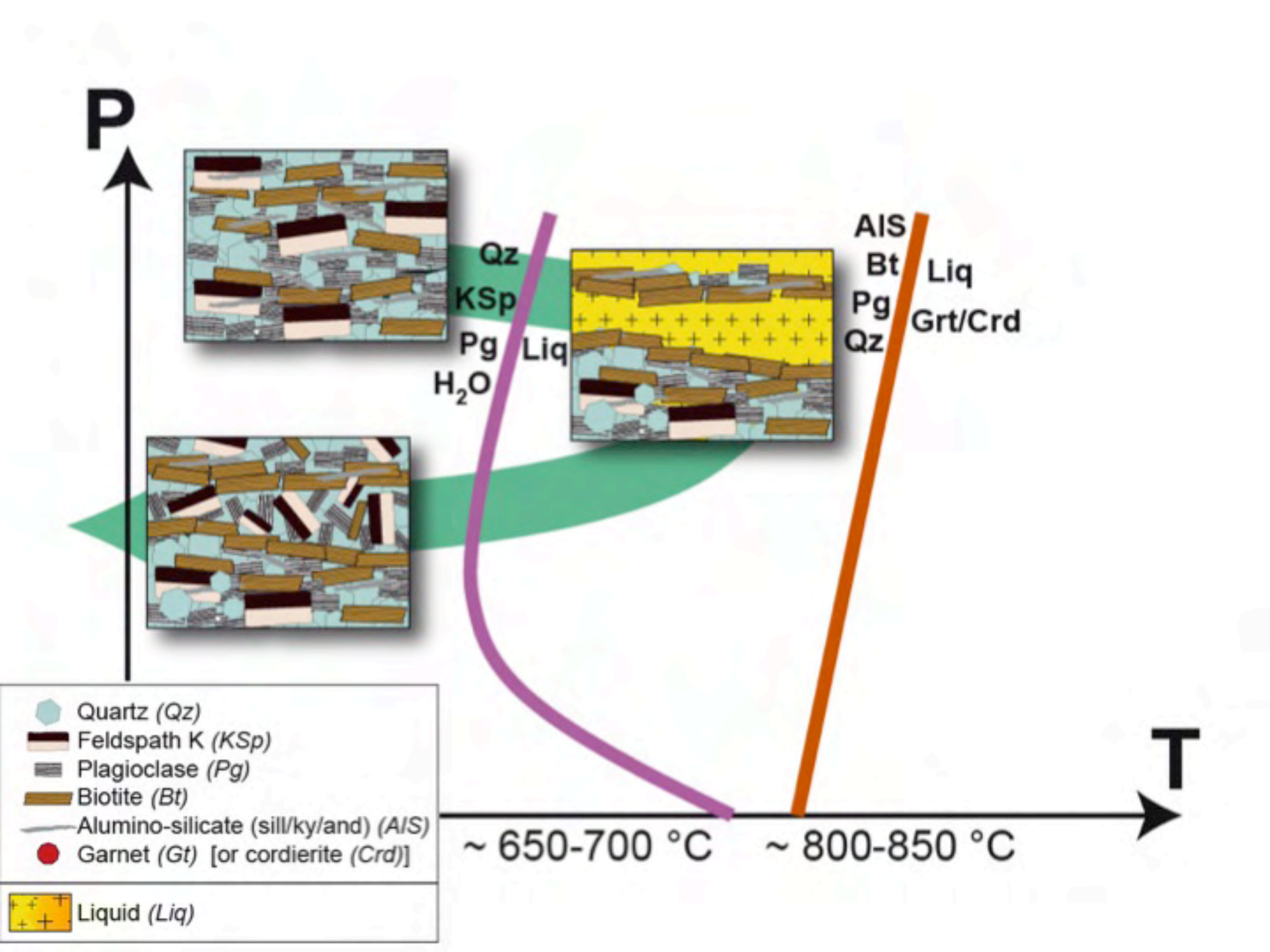
La vie d'un métasédiment (sans muscovite, c'est plus simple)



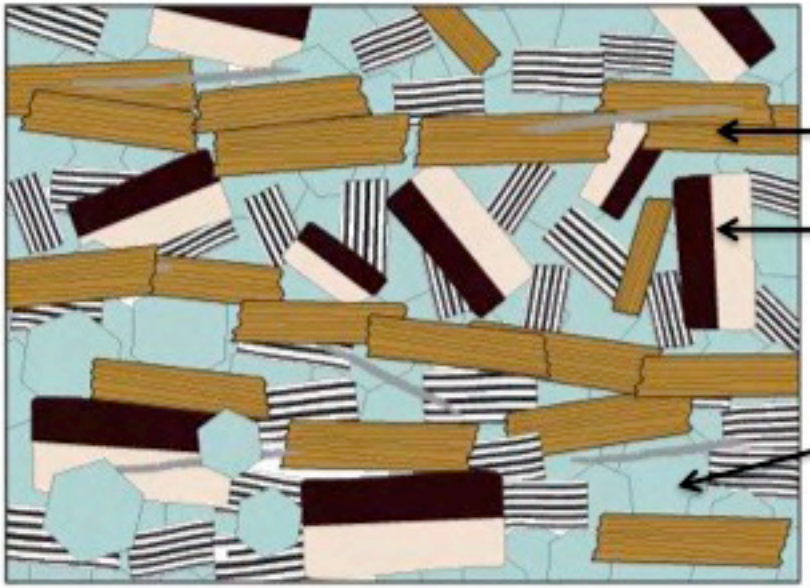

P
T
Qz
KSp
Pg
Liq
H2O
AlS
Bt
Liq
Pg
Grt/Crd
Qz
~ 650-700 °C
~ 800-850 °C


Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
P
T
Qz
KSp
Pg
Liq
H2O
H2O
Pg
Qz
Grt/Crd
~ 650-700 °C
~ 800-850 °C


P
Qz
KSp
Pg
H_2O
Liq
AlS
Bt
Pg
Qz
Liq
Grt/Crd
T
700 °C
~ 800-850 °C
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)


P
T
Qz
KSp
Pg
H_2O
Liq
AlS
Bt
Pg
Qz
Liq
Grt/Crd
~ 650-700 °C
~ 800-850 °C
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)

Une migmatite



Ce qu'on voit…

Partie sombre = ***mélanosome***

Partie claire = ***leucosome***

Partie intermédiaire = ***mésosome***

Ce qu'on imagine…

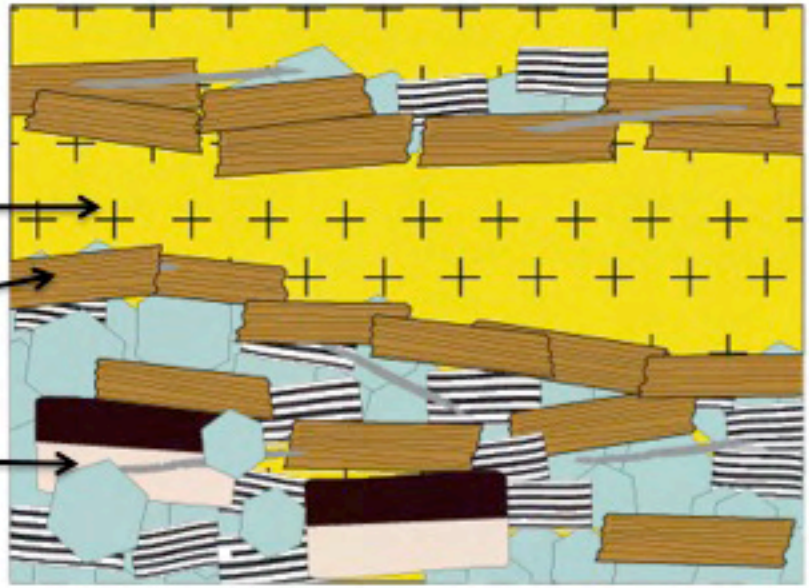
Néosome

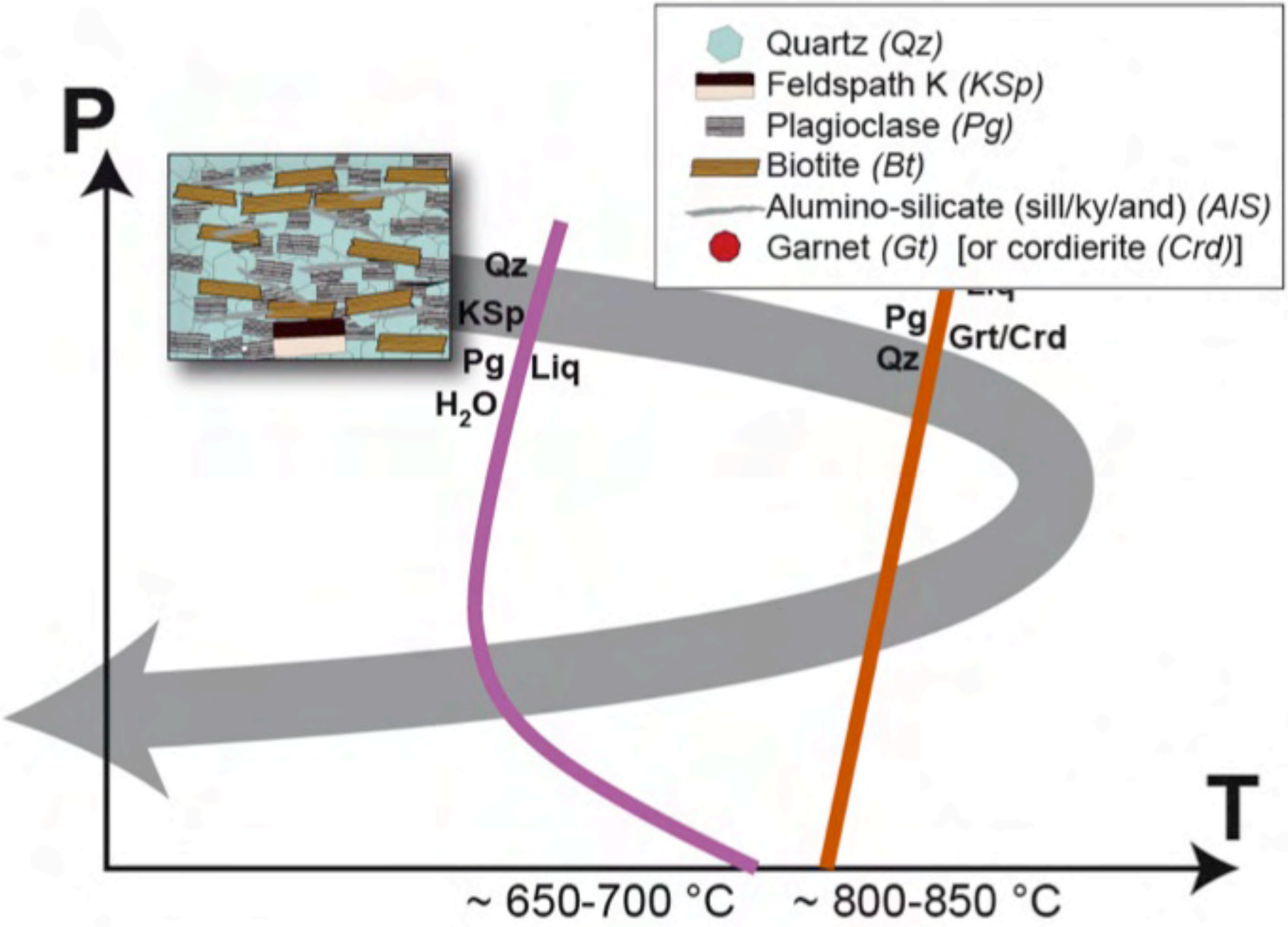
Ancien liquide

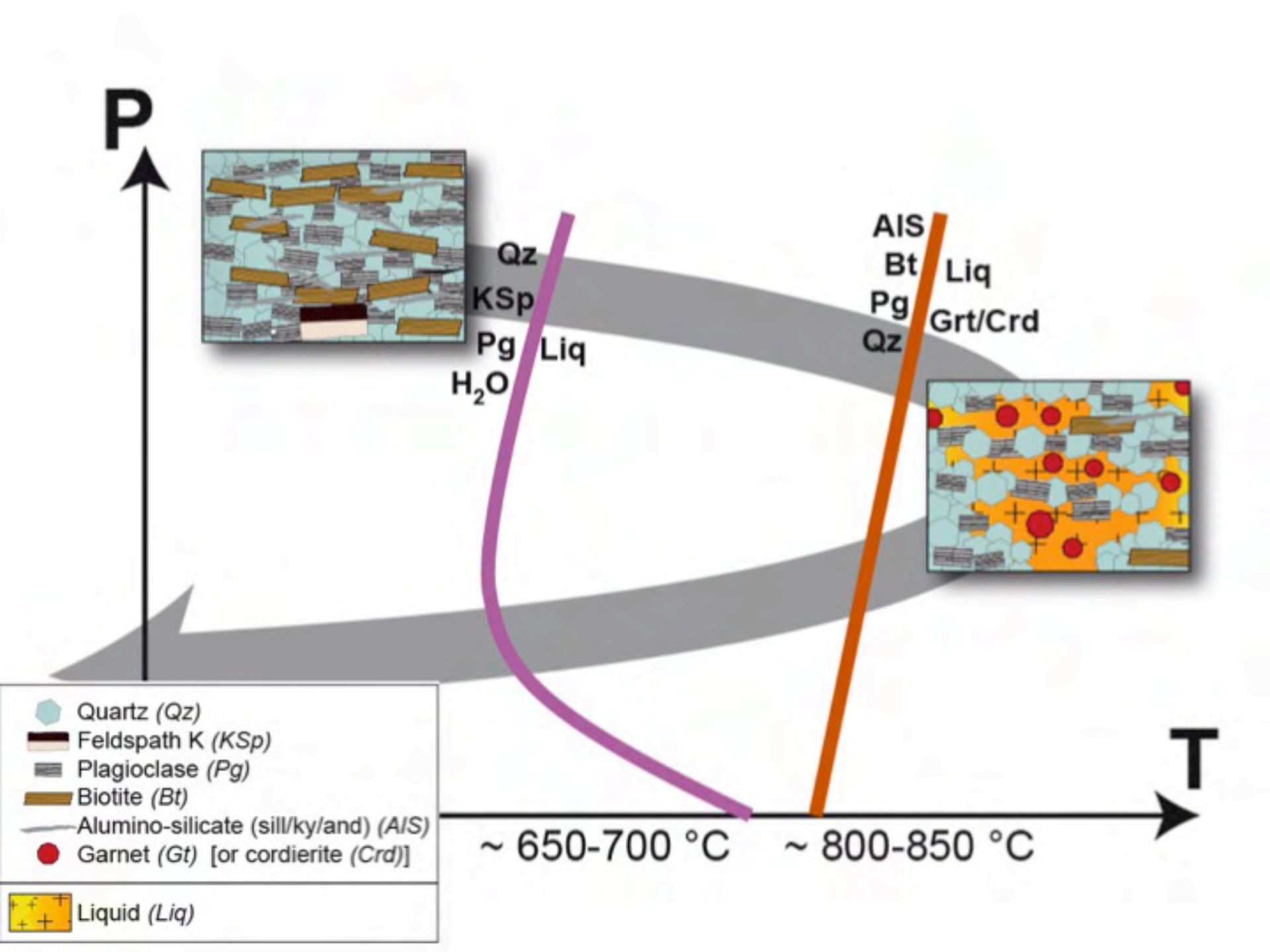
Résidu de fusion

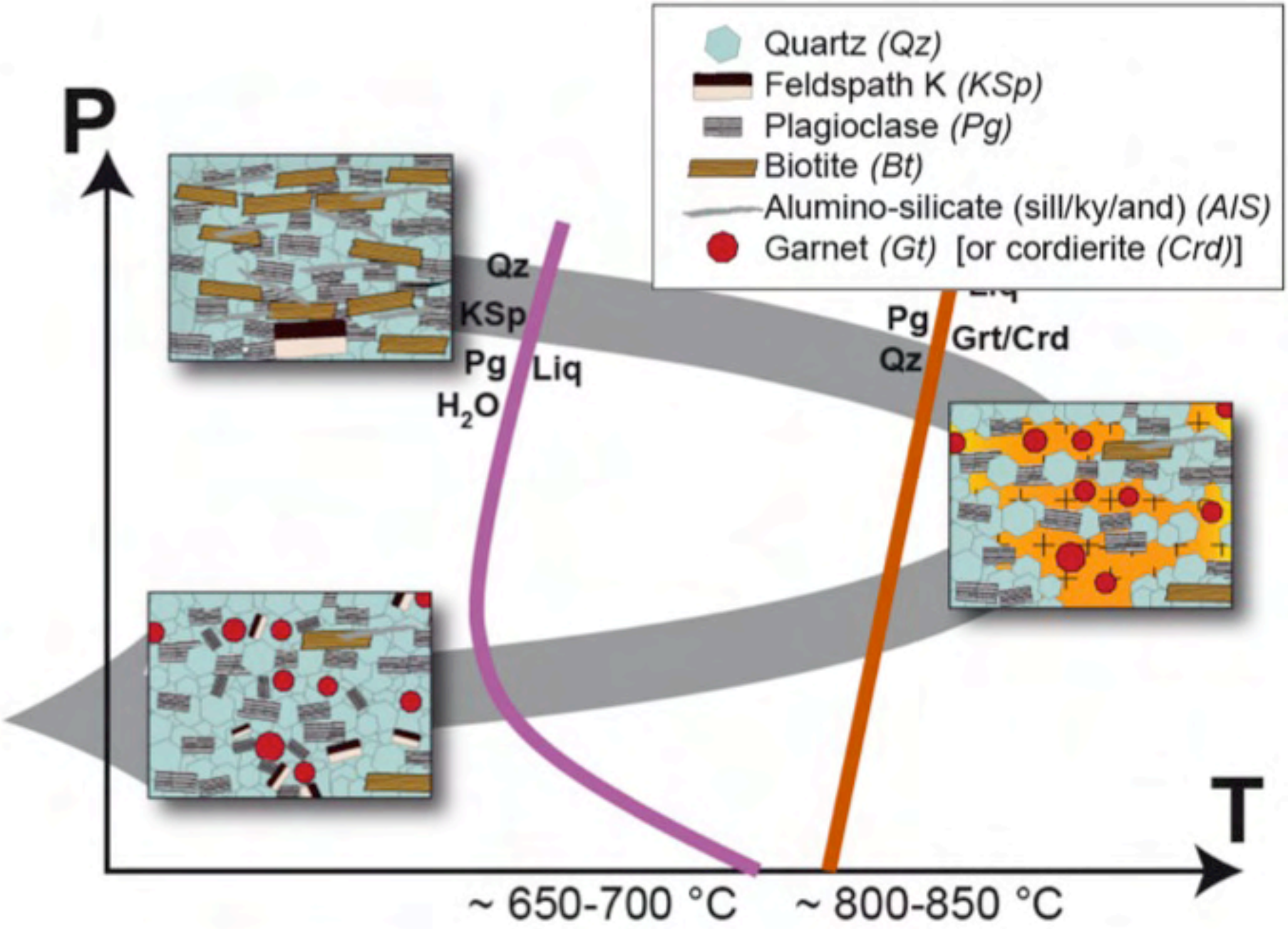
Paléosome

Partie non fondue

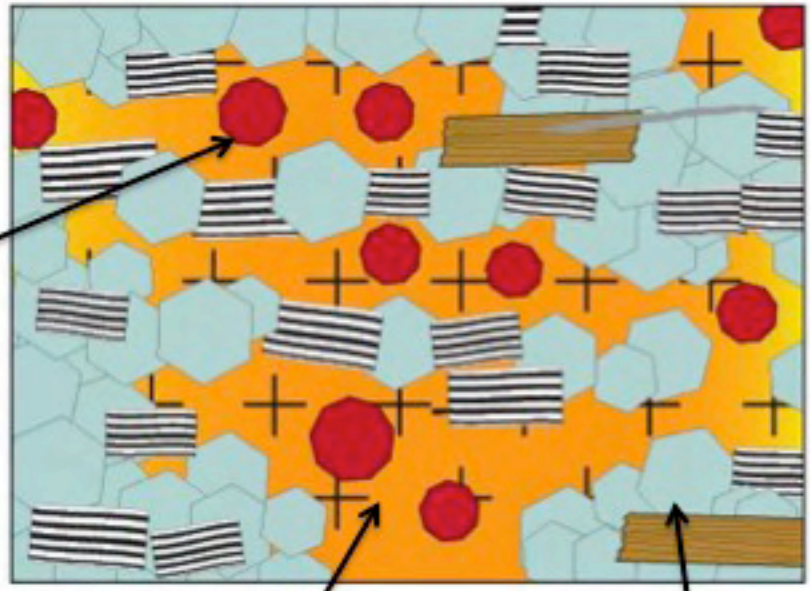



Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
P
T
Qz
KSp
Pg
Liq
H2O
Pg
Qz
Grt/Crd
~ 650-700 °C
~ 800-850 °C


P
T
Qz
KSp
Pg
Liq
H2O
AlS
Bt
Pg
Qz
Liq
Grt/Crd
~ 650-700 °C
~ 800-850 °C
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)

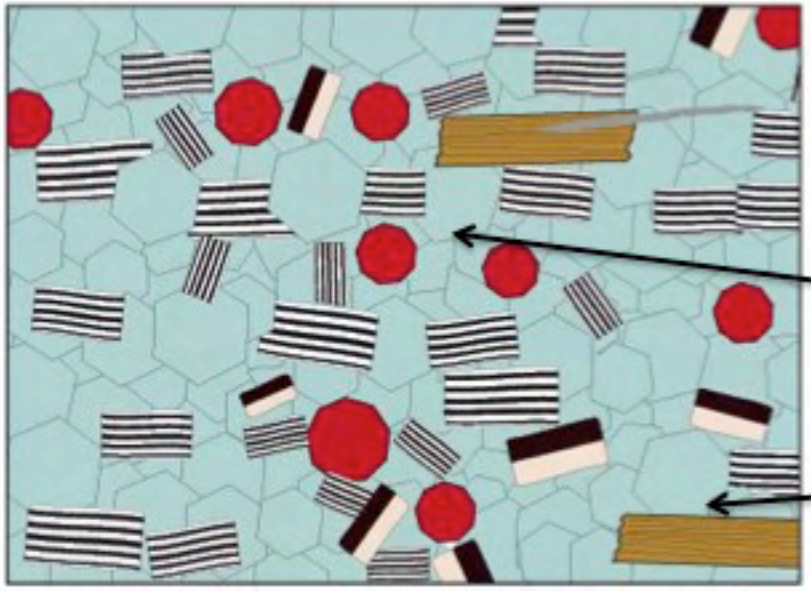

Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
P
T
Qz
KSp
Pg
Liq
H2O
Pg
Qz
Grt/Crd
~ 650-700 °C
~ 800-850 °C

Ce qu'on imagine…



Minéraux formés par la réaction de fusion (« péritectiques »)

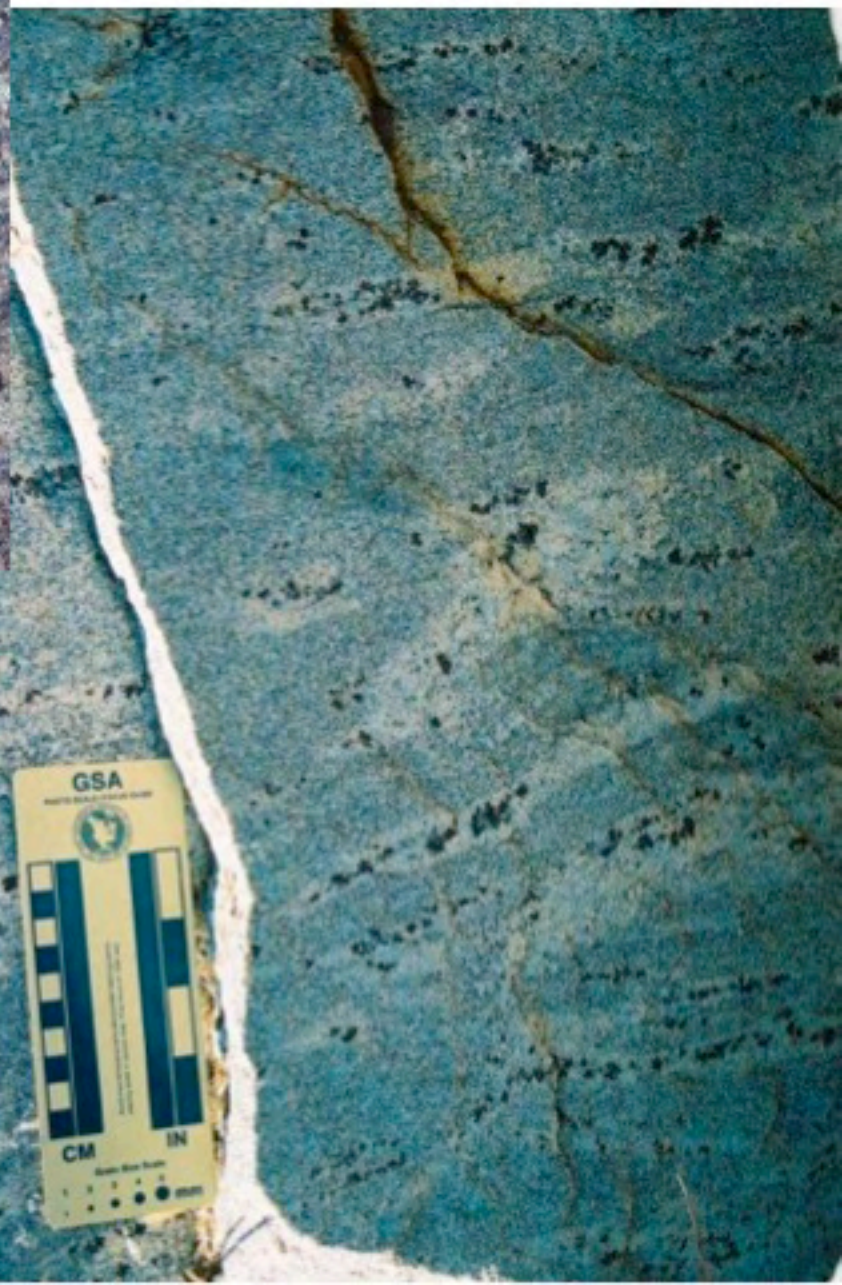
Ce qu'on voit…



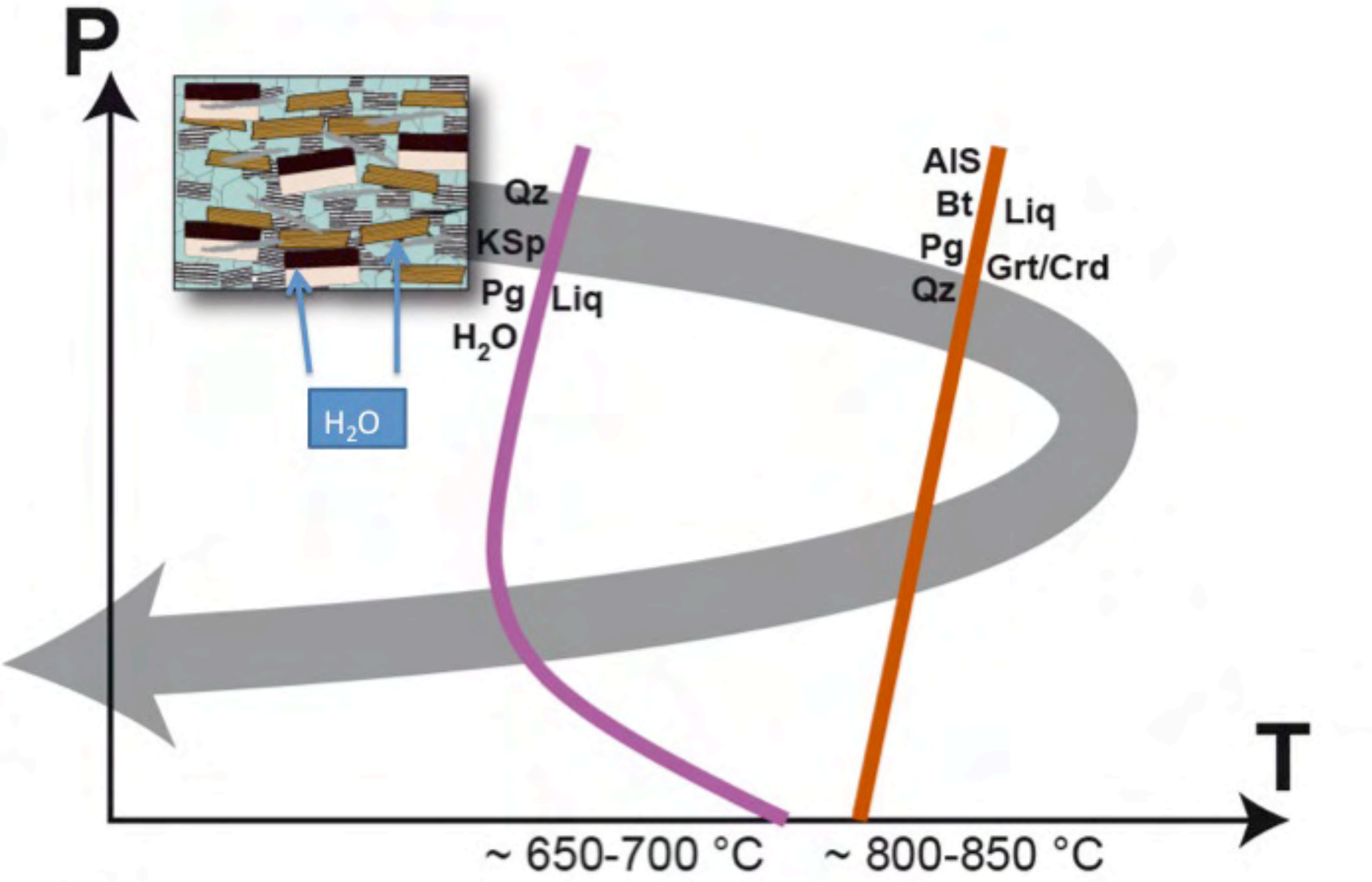
Ancien liquide

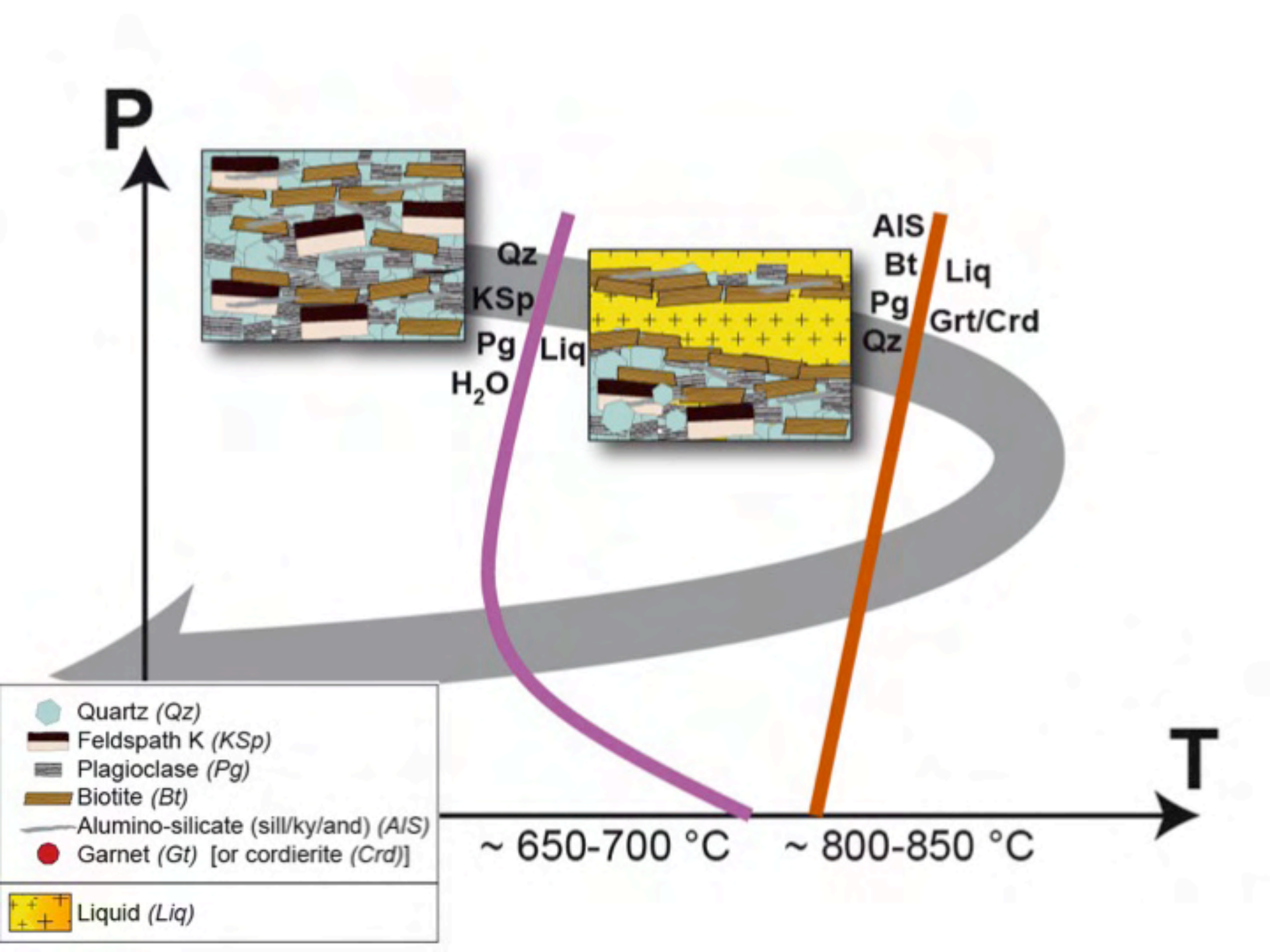
Partie claire = ***leucosome***

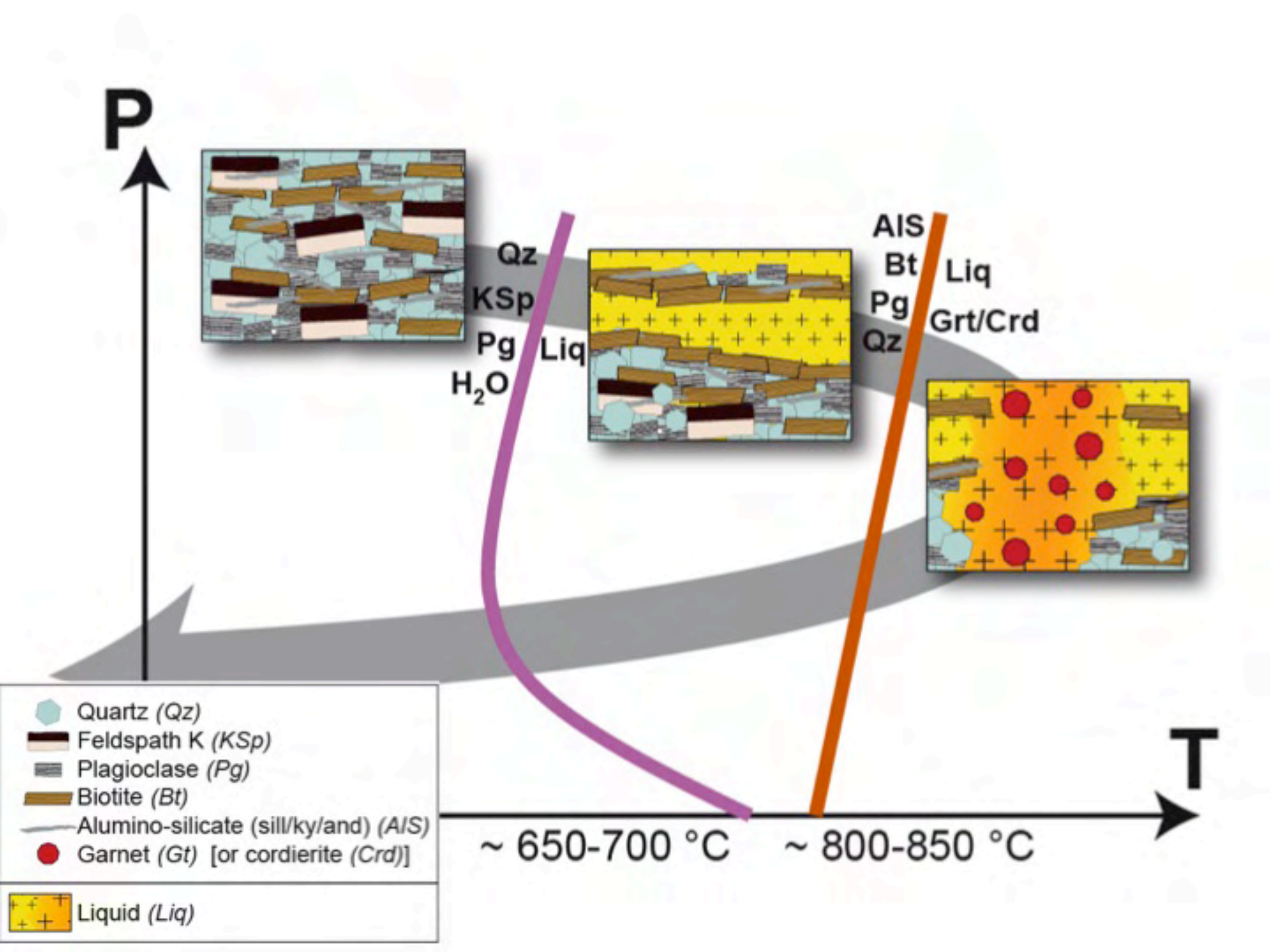
Mésosome non fondu ??

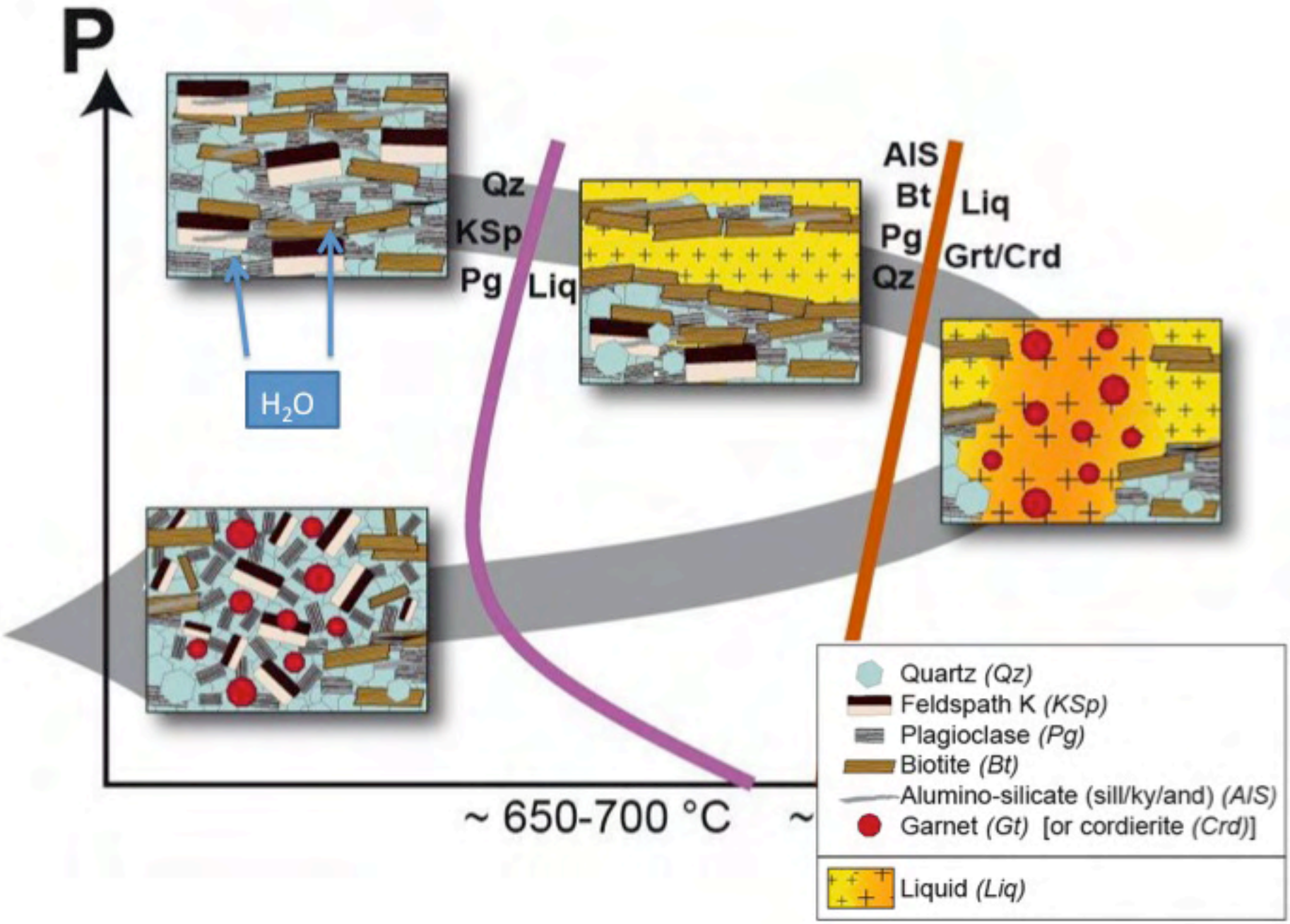

GSA
CM
IN

Dans le Velay, on voit les deux!


P
T
Qz
KSp
Pg
Liq
H2O
H2O
Als
Bt
Pg
Qz
Liq
Grt/Crd
~ 650-700 °C
~ 800-850 °C


P
T
Qz
KSp
Pg
H_2O
Liq
AlS
Bt
Pg
Qz
Liq
Grt/Crd
~ 650-700 °C
~ 800-850 °C
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)


P
T
Qz
KSp
Pg
H_2O
Liq
AlS
Bt
Pg
Qz
Liq
Grt/Crd
~ 650-700 °C
~ 800-850 °C
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)

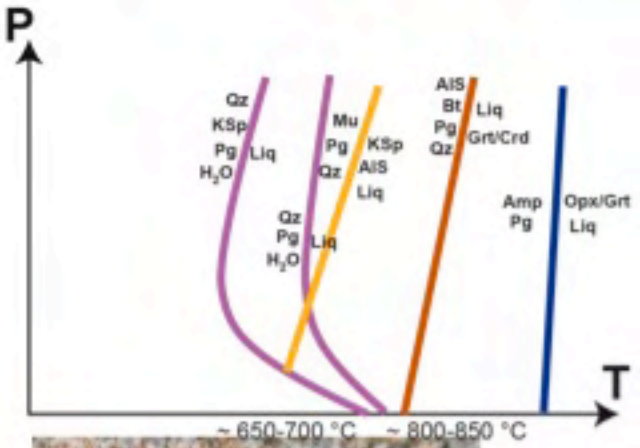

P
Qz
KSp
Pg
Liq
AlS
Bt
Pg
Qz
Liq
Grt/Crd
H_2O
~ 650-700 °C
~
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)

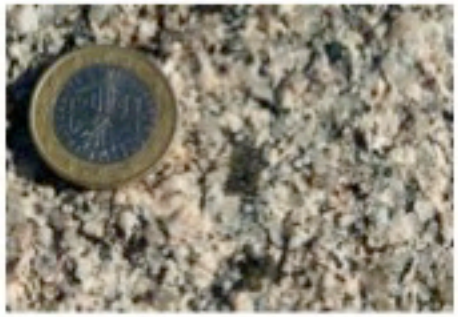
Evidemment, chaque réaction forme des liquides différents…

- Qz+KSp+Pg+H2O = Liq: un liquide hydraté, assez alumineux, pauvre en Fe+Mg

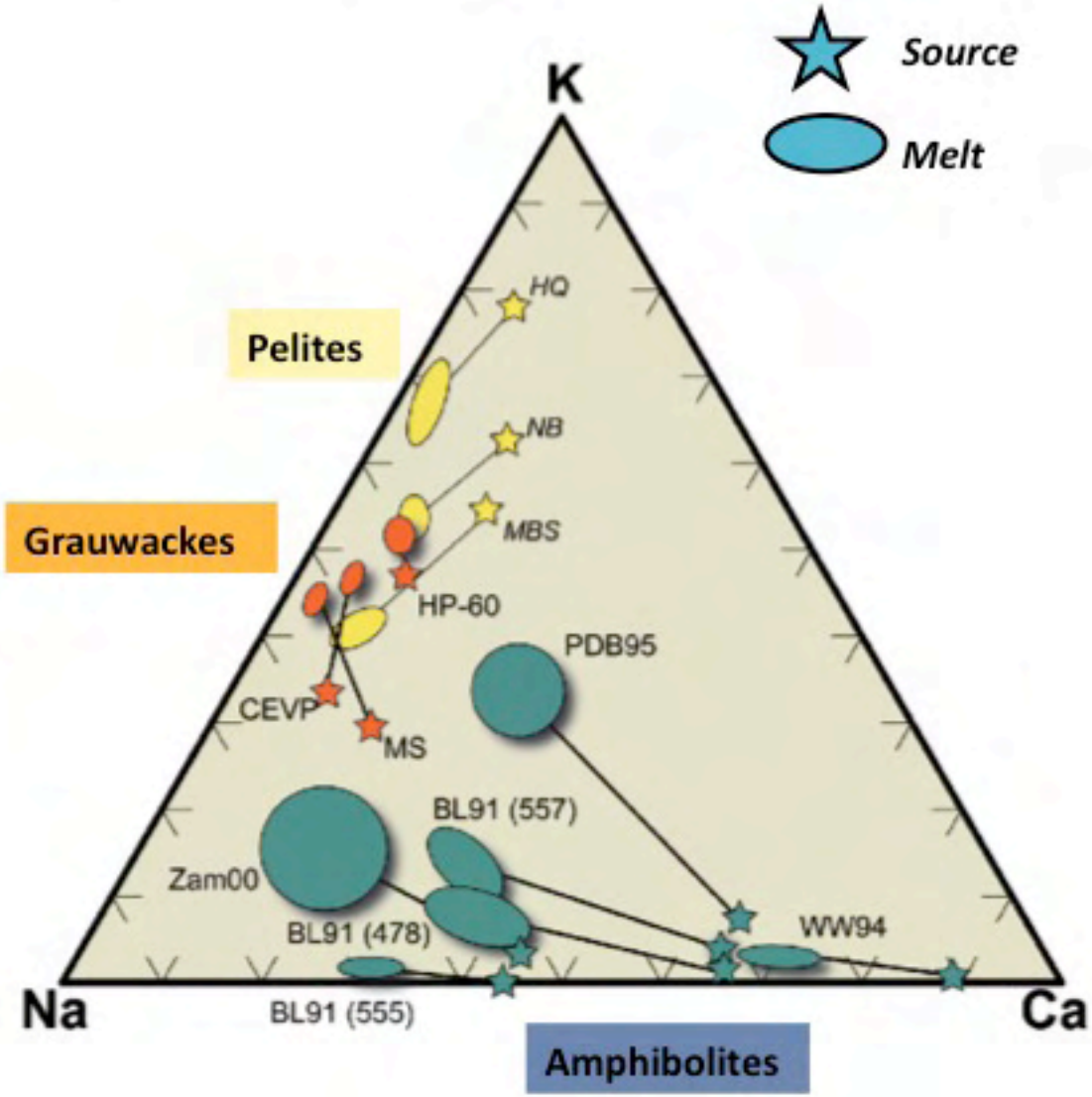
- AlS+Bt+Pg+Qz = Crd+Liq : un liquide riche en Al, moins hydraté, plus mafique

- Amp+Pg=Liq+Opx = un liquide moins alumineux, peu hydraté, calcique





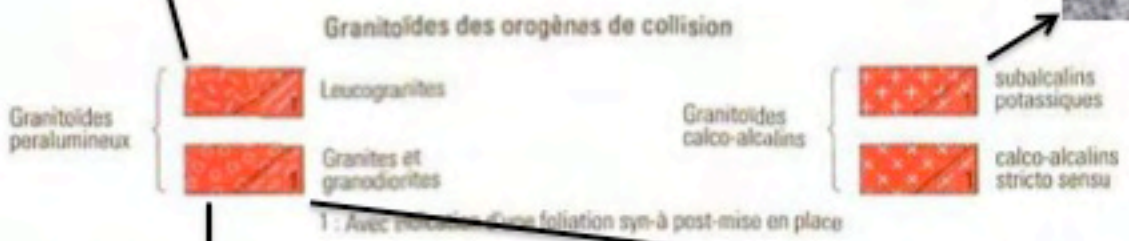
On voit aussi ça dans les expériences…



Moyen, 2011

Gr. de Chambles
Bt+Ms

Gr. De Borne
Parfois amphibole, abondantes enclaves basiques

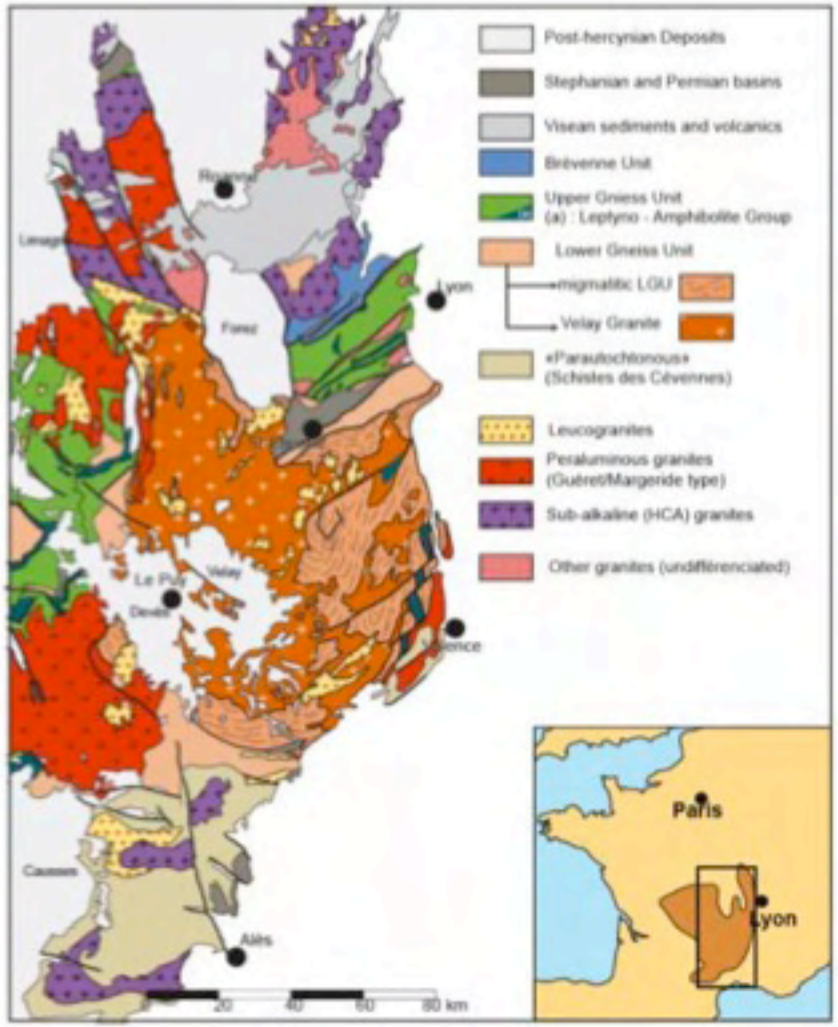


Qz, Fsp alcalin, plagioclase
(sinon c'est pas un granite !)

Gr. de Finiels
Bt+Crd

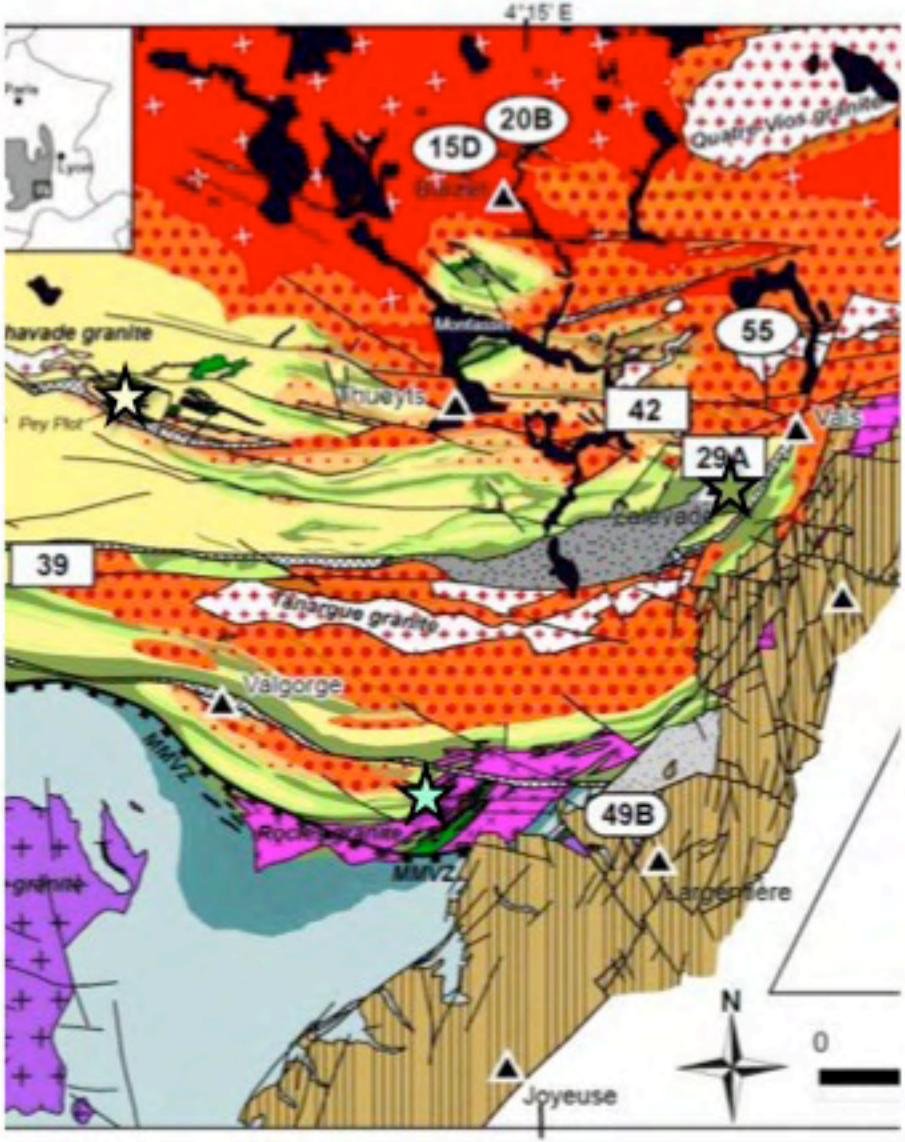
Gr. de Tournon
Bt seule

Qu’est-ce qui fond ?



Un peu tout sans doute…

D'ailleurs ça se voit !



Les granites

3. De la source au pluton

Jean-François Moyen

Université de Lyon

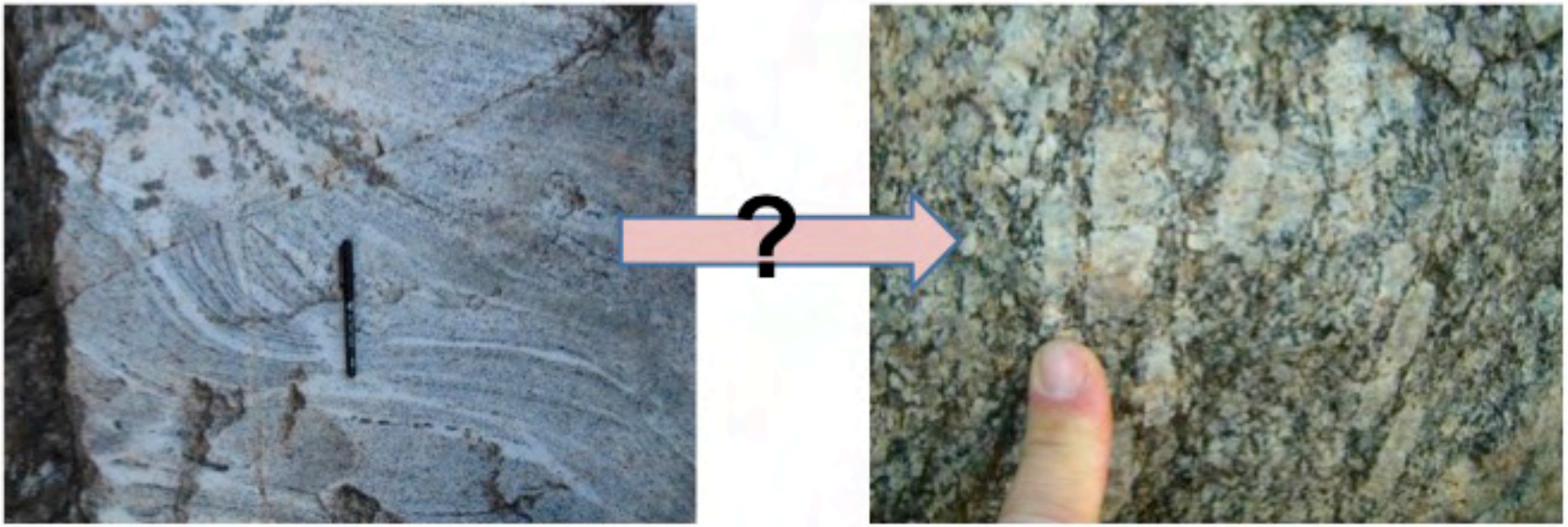
Université Jean Monnet Saint-Étienne

Laboratoire Magmas & Volcans

Pour le moment on n'a formé que des migmatites …

… pas encore des granites !

… pas encore des granites !

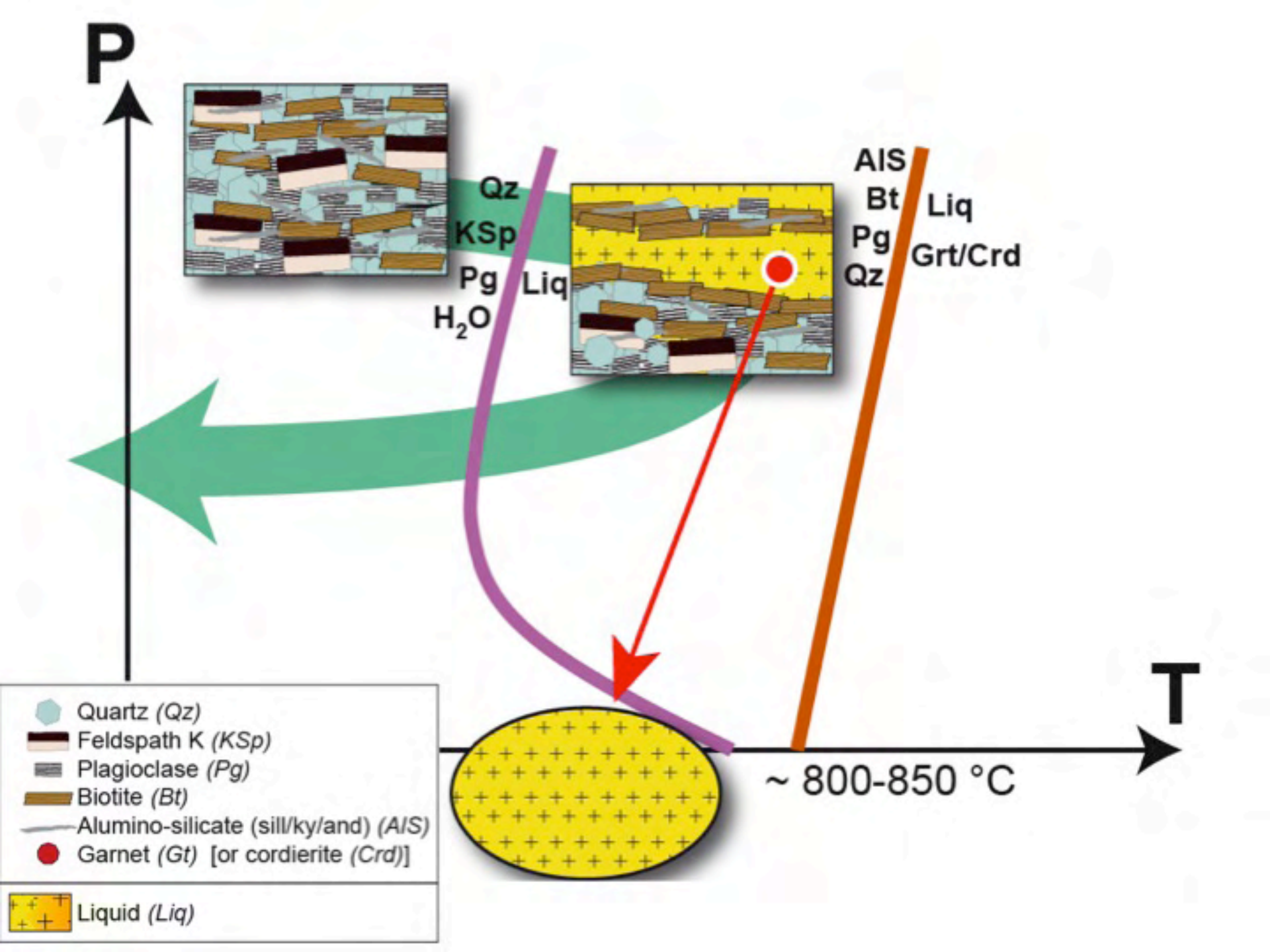


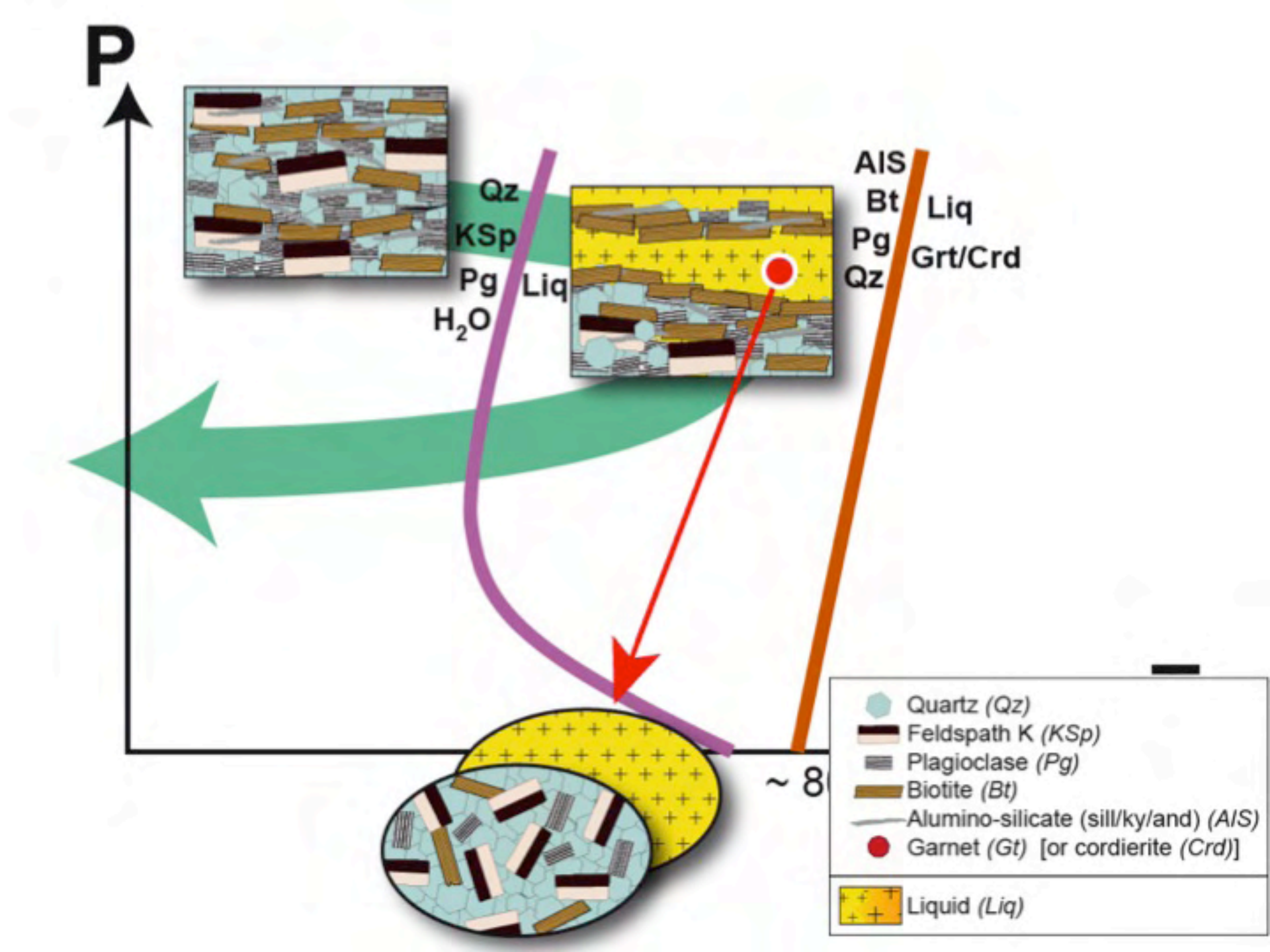
Il faut ***extraire*** le liquide

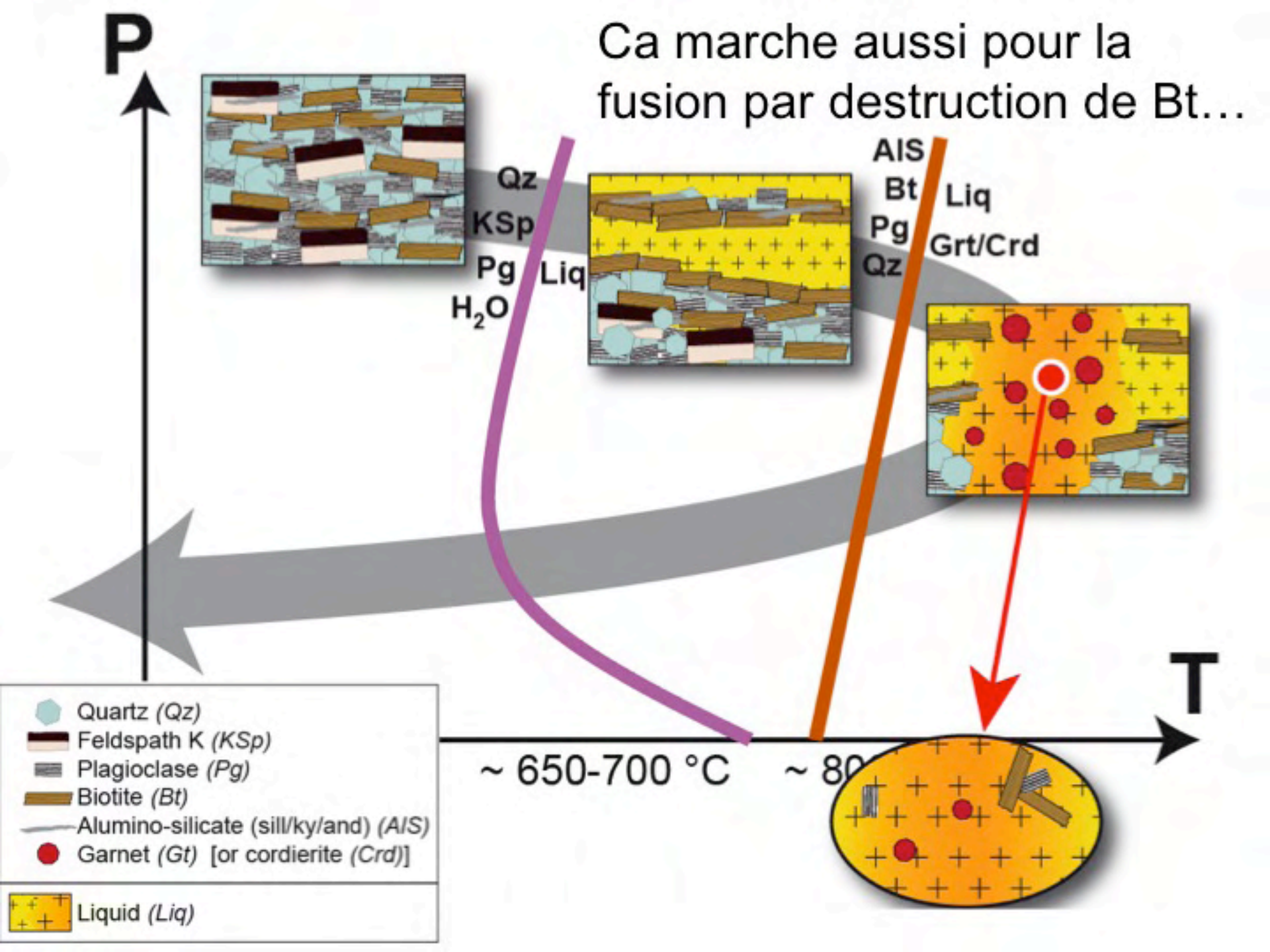
(ici dans l'exemple des migmatites, mais ce serait pareil avec la cristallisation…)

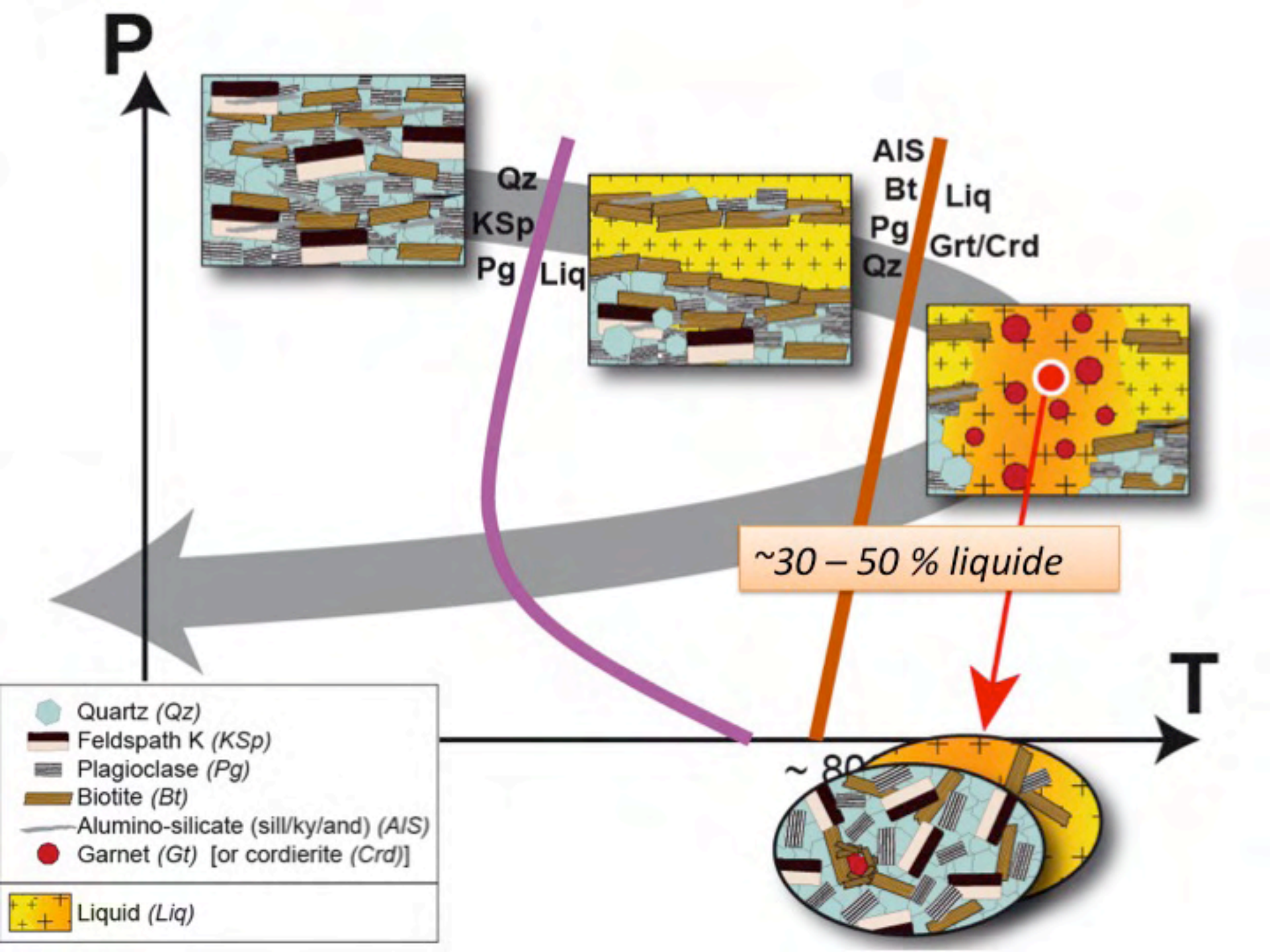
Extraction de liquide d'un « mush » qui cristallise

P. Bouilhol


P
T
Qz
KSp
Pg
Liq
H_2O
AlS
Bt
Pg
Qz
Liq
Grt/Crd
~ 800-850 °C
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)


P
Qz
KSp
Pg
Liq
H2O
AlS
Bt
Pg
Qz
Liq
Grt/Crd
~ 8
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)

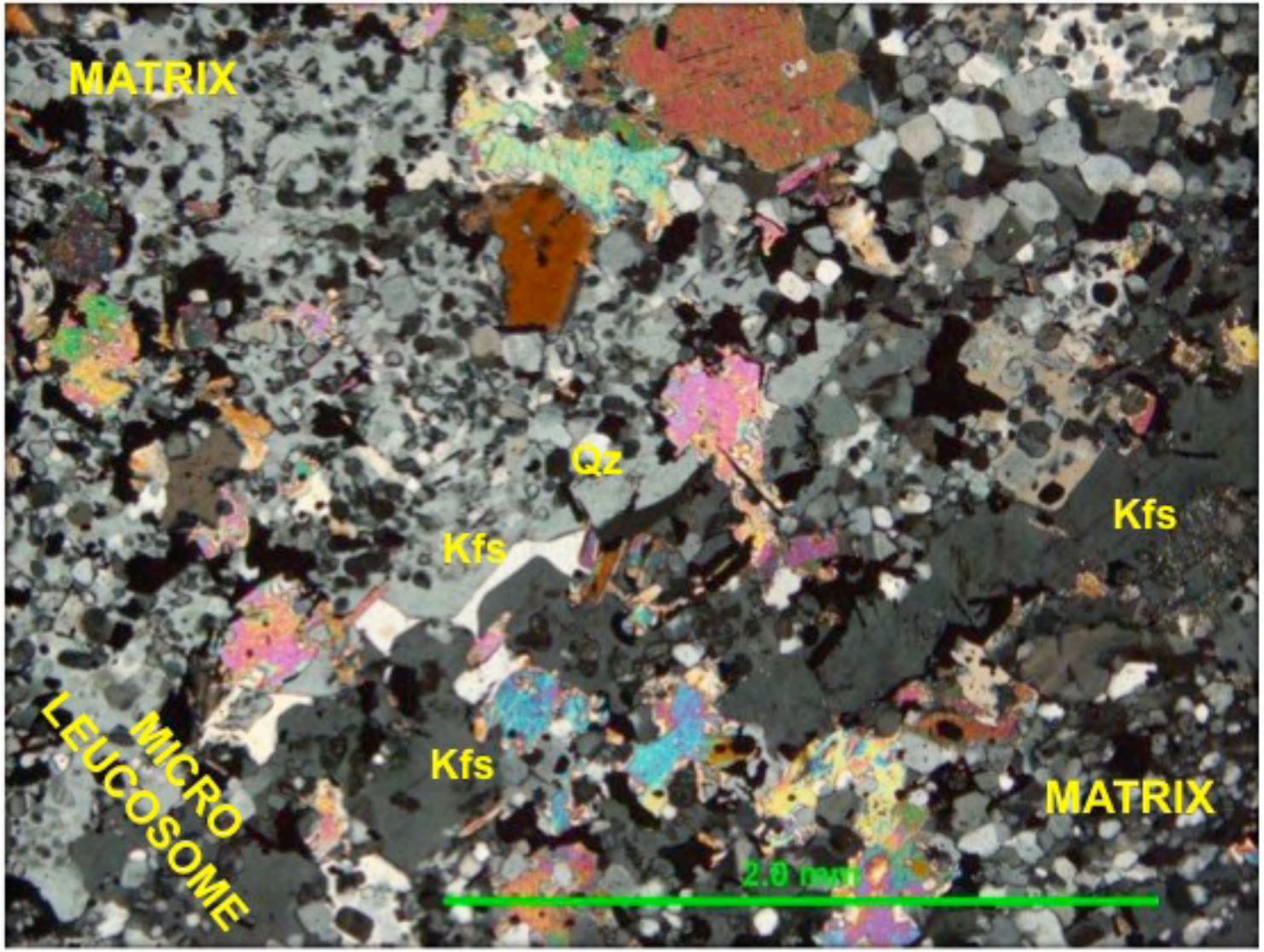

P
Ca marche aussi pour la fusion par destruction de Bt…
Qz
KSp
Pg
H_2O
Liq
AlS
Bt
Pg
Qz
Liq
Grt/Crd
T
~ 650-700 °C
~ 80
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)


P
T
Qz
KSp
Pg
Liq
AlS
Bt
Pg
Qz
Liq
Grt/Crd
~30 – 50 % liquide
~ 80
Quartz (Qz)
Feldspath K (KSp)
Plagioclase (Pg)
Biotite (Bt)
Alumino-silicate (sill/ky/and) (AlS)
Garnet (Gt) [or cordierite (Crd)]
Liquid (Liq)

Les migmatites perdent du liquide !

P. Bons, R. Ward

Micro-leucosome in unfoliated contact aureole migmatite



M. Brown, E. Sawyer

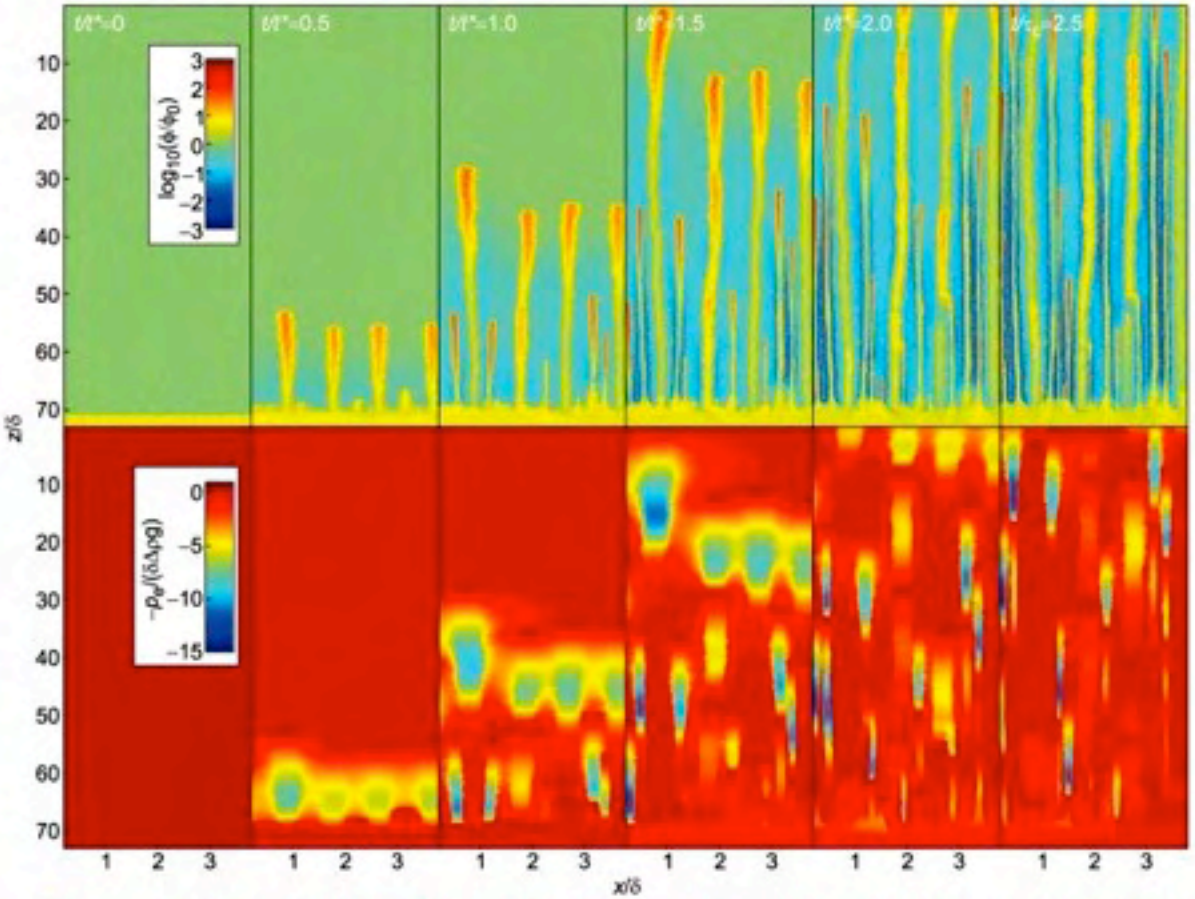
Imprégnations de liquide

Paragneiss Velay

O. Vanderhaeghe

Compaction-generated flow instabilities

Connolly & Podladchikov (2012) have shown that rheological asymmetry between compaction and decompaction in viscous materials leads to formation of mechanical flow channeling instabilities (porosity waves) that nucleate from small perturbations to a uniform porosity.



2-d numerical simulation of fluid flow through a matrix with decompaction weakening as it evolves from a layer with elevated porosity bounded from above and below by regions with an order of magnitude lower porosity.

Top: Porosity in the uppermost portion of the layer and in the overlying region.

Bottom: corresponding distribution of fluid underpressure.

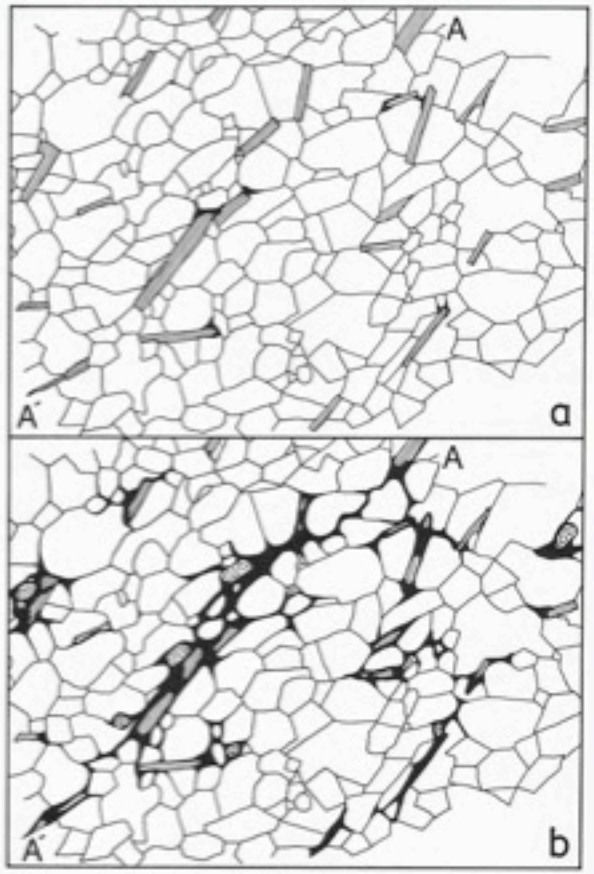
The 3-d expression of the channels would be pipe-like structures.

However, in the presence of far field stress, kinematic effects would flatten the tubes in the direction of the minimum horizontal stress.

Pervasive migration of melt may be the physical expression of compaction-generated flow instabilities as a driver for melt ascent through the crust.

Segregation: from grain boundaries to leucosomes

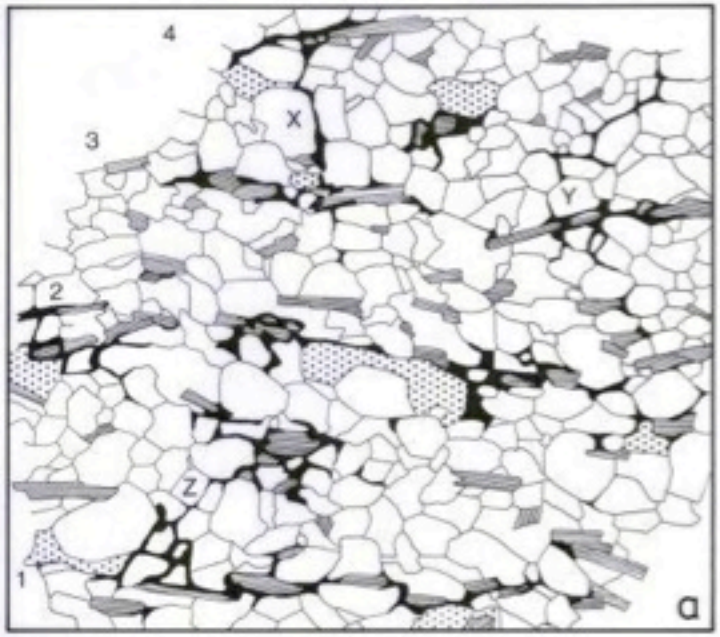
Stage 1 (below). Melting begins at grain junctions.



Stage 2 (above). In foliated rocks, melt forms micro-leucosomes parallel to foliation.

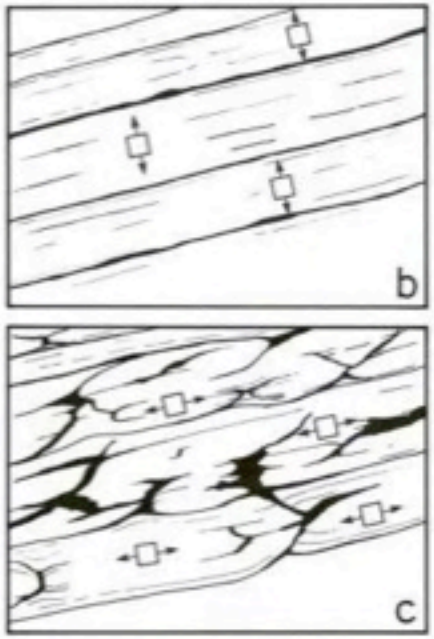
Sawyer (2001) JMG

Stage 3 (below). Even with loss of melt, the distribution of residual melt is still controlled by the fabric.



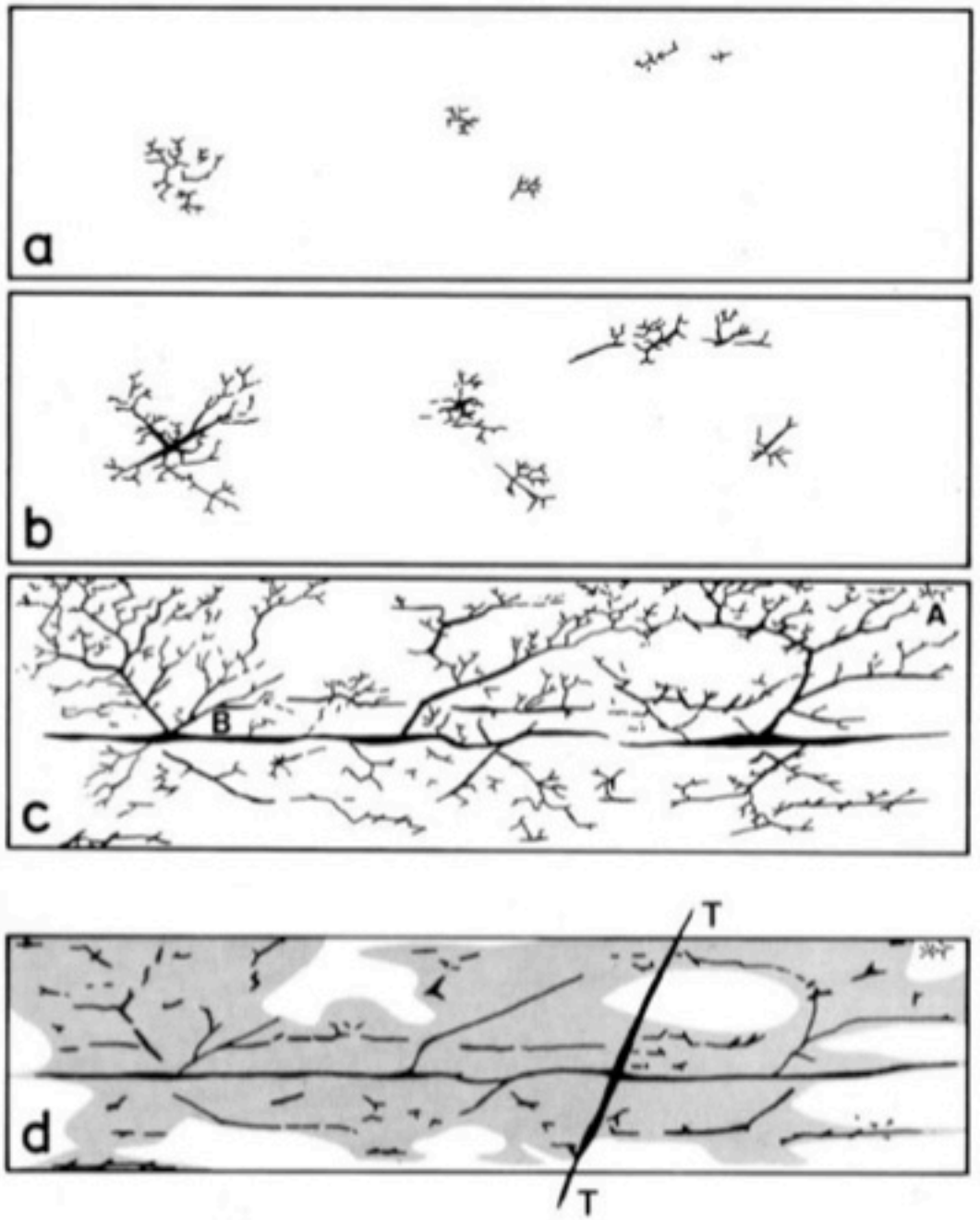
Where does melt drain to?

Melt drains to foliation planes, along lineations and into dilatant deformation bands.



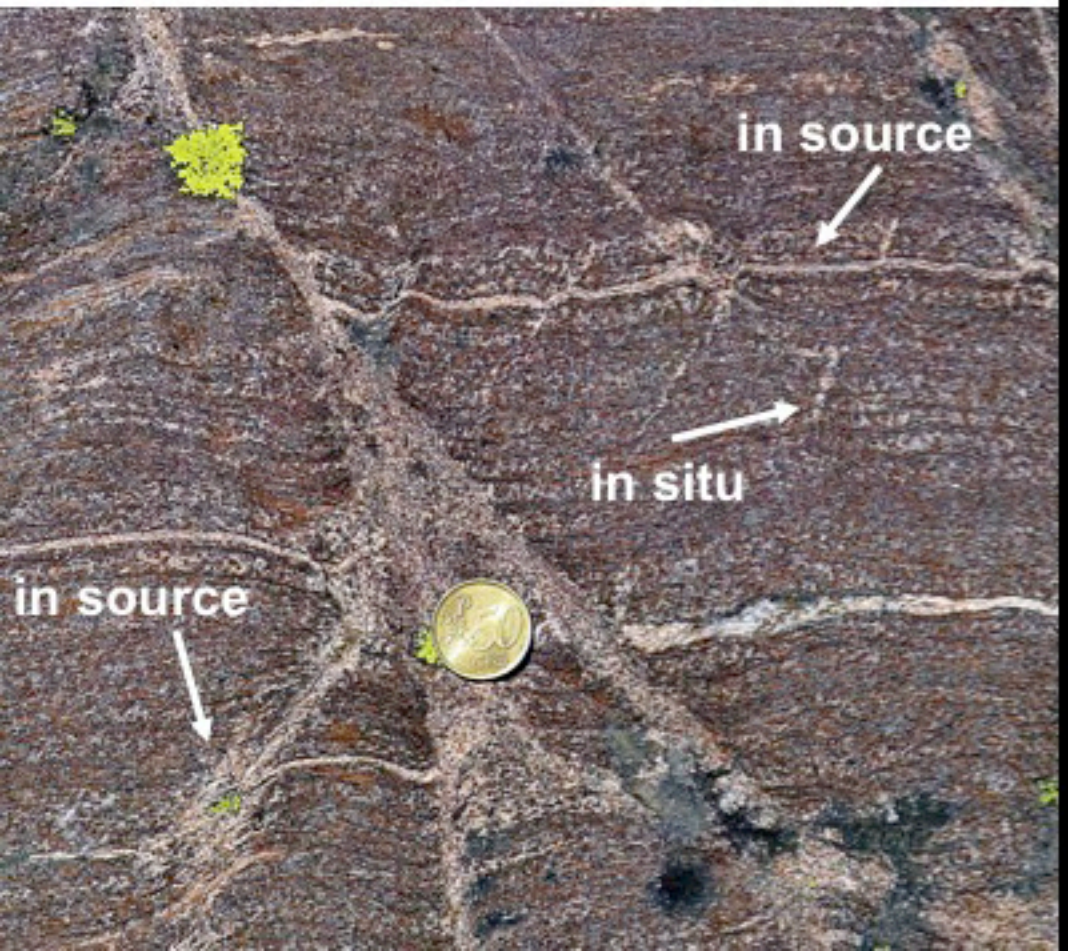
Guernina & Sawyer (2003) JMG

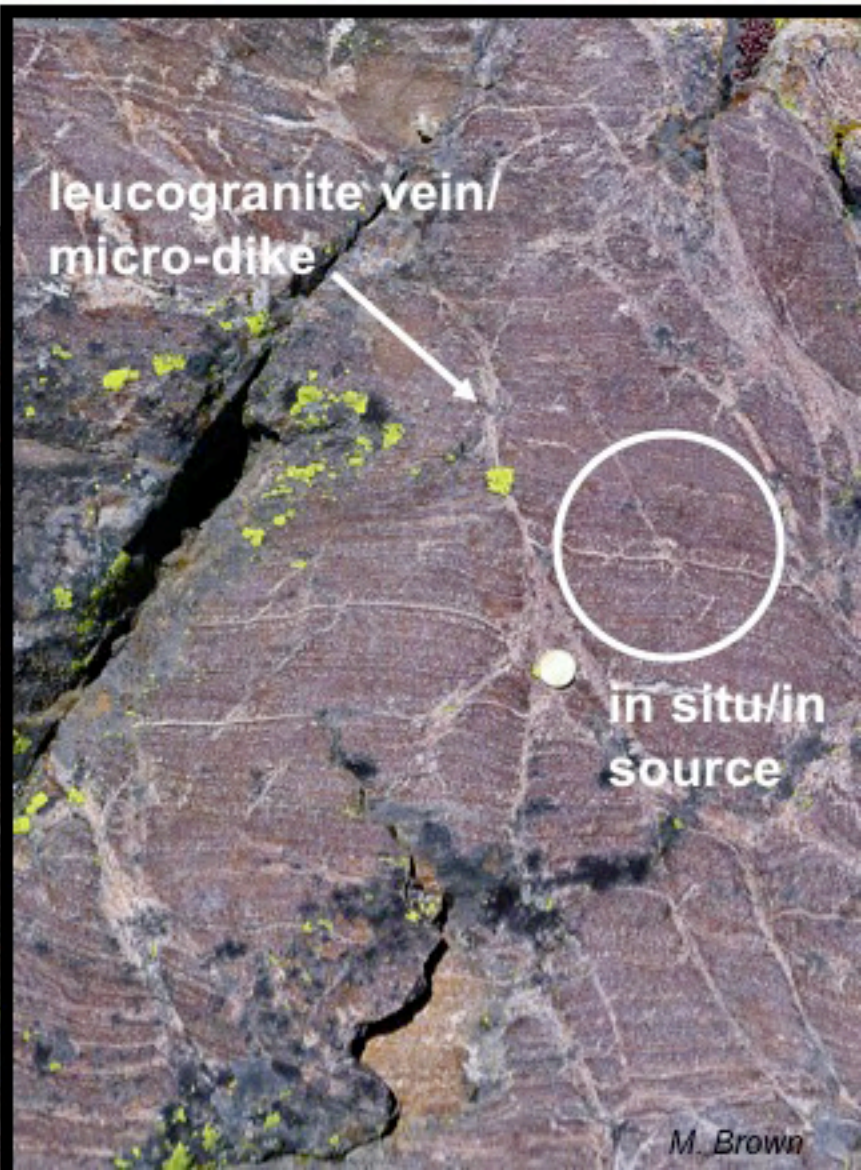
Melt depletion



Outcrop scale leucosome hierarchies forming drainage networks in a contact aureole migmatite

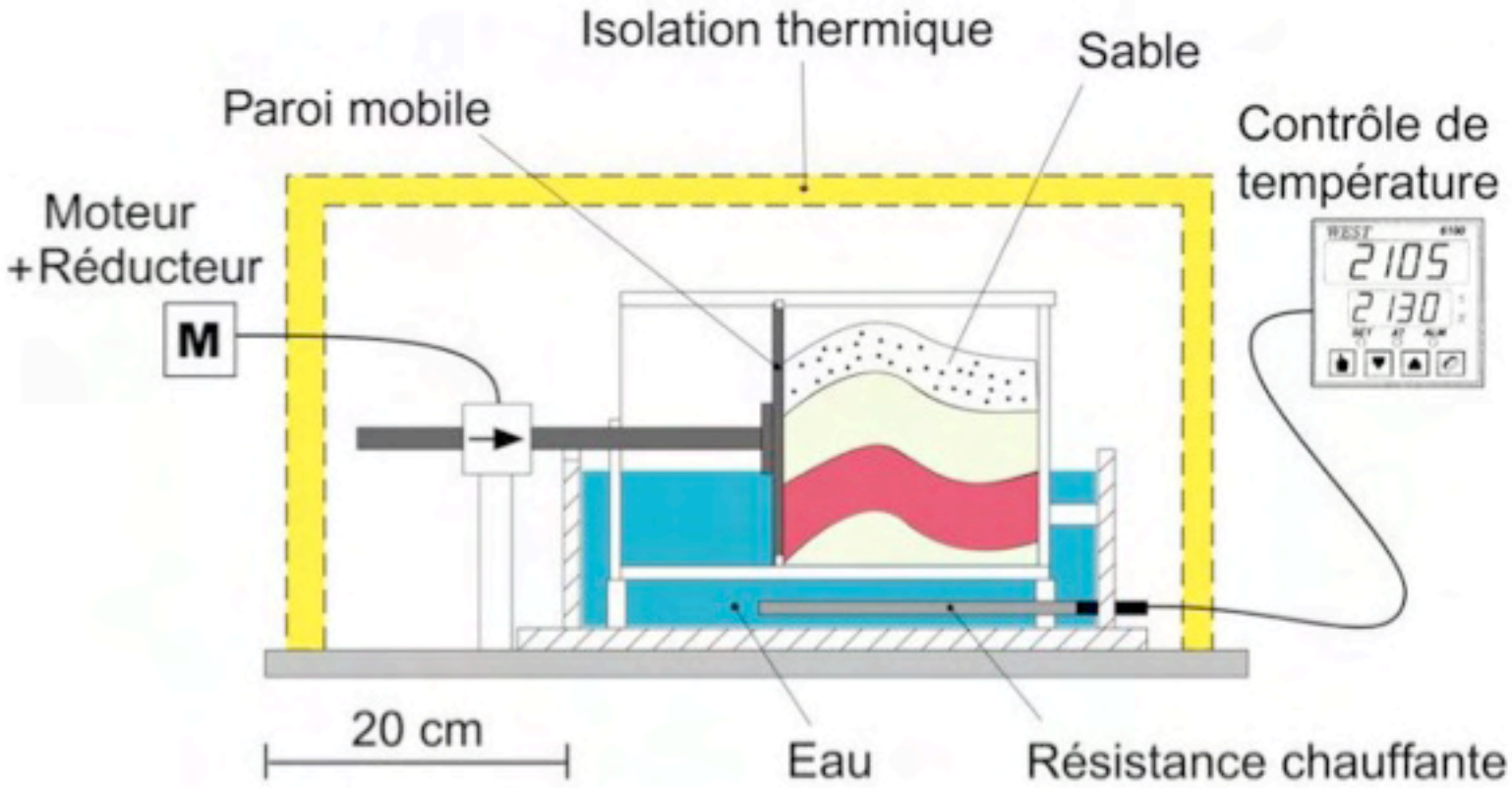
Increase in scale from in situ micro-leucosomes to in source leucosomes to leucogranite veins or micro-dikes.





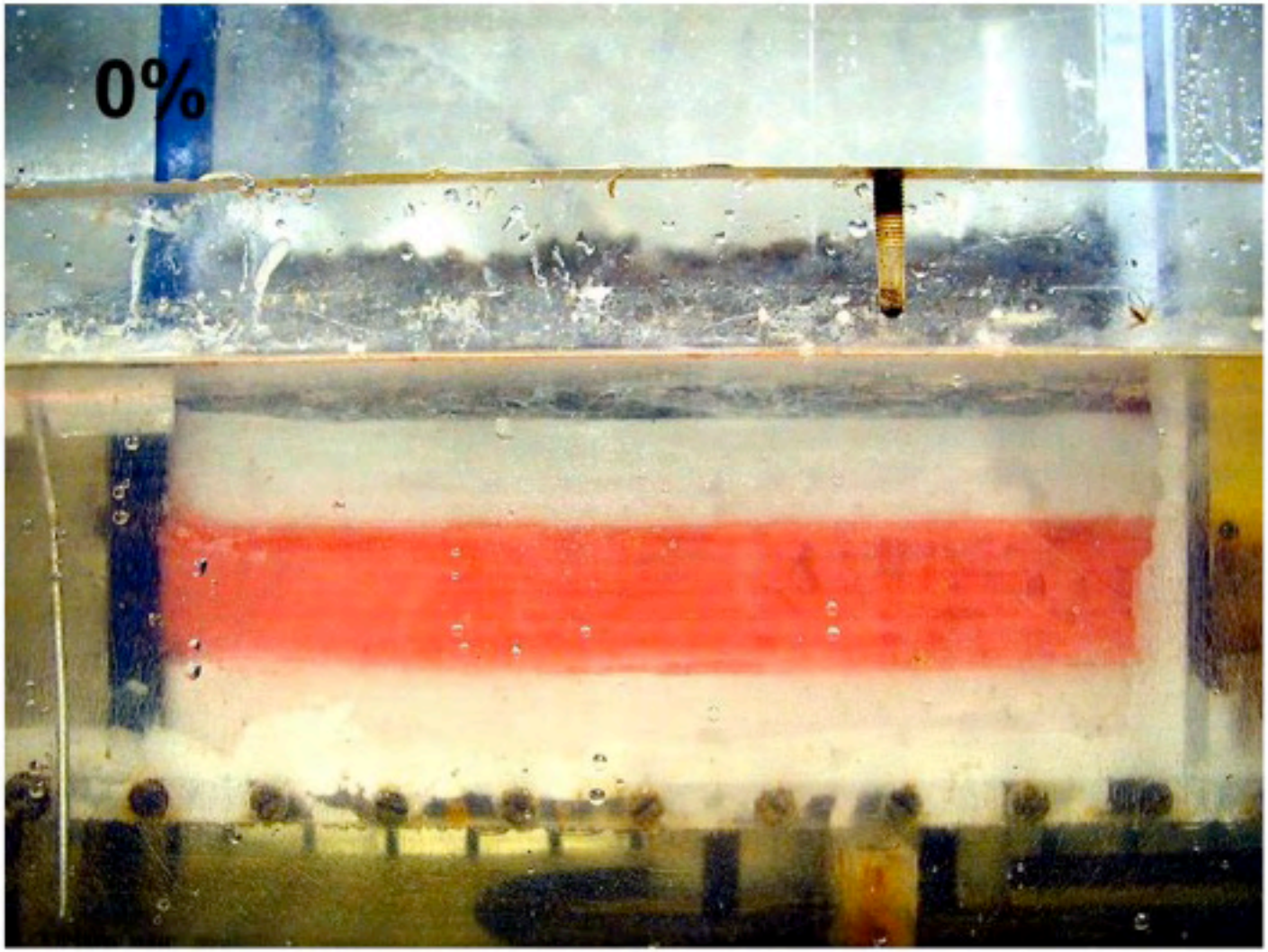
In a regional migmatite we see the ‘birth’ of a micro-dike

Appareil expérimental

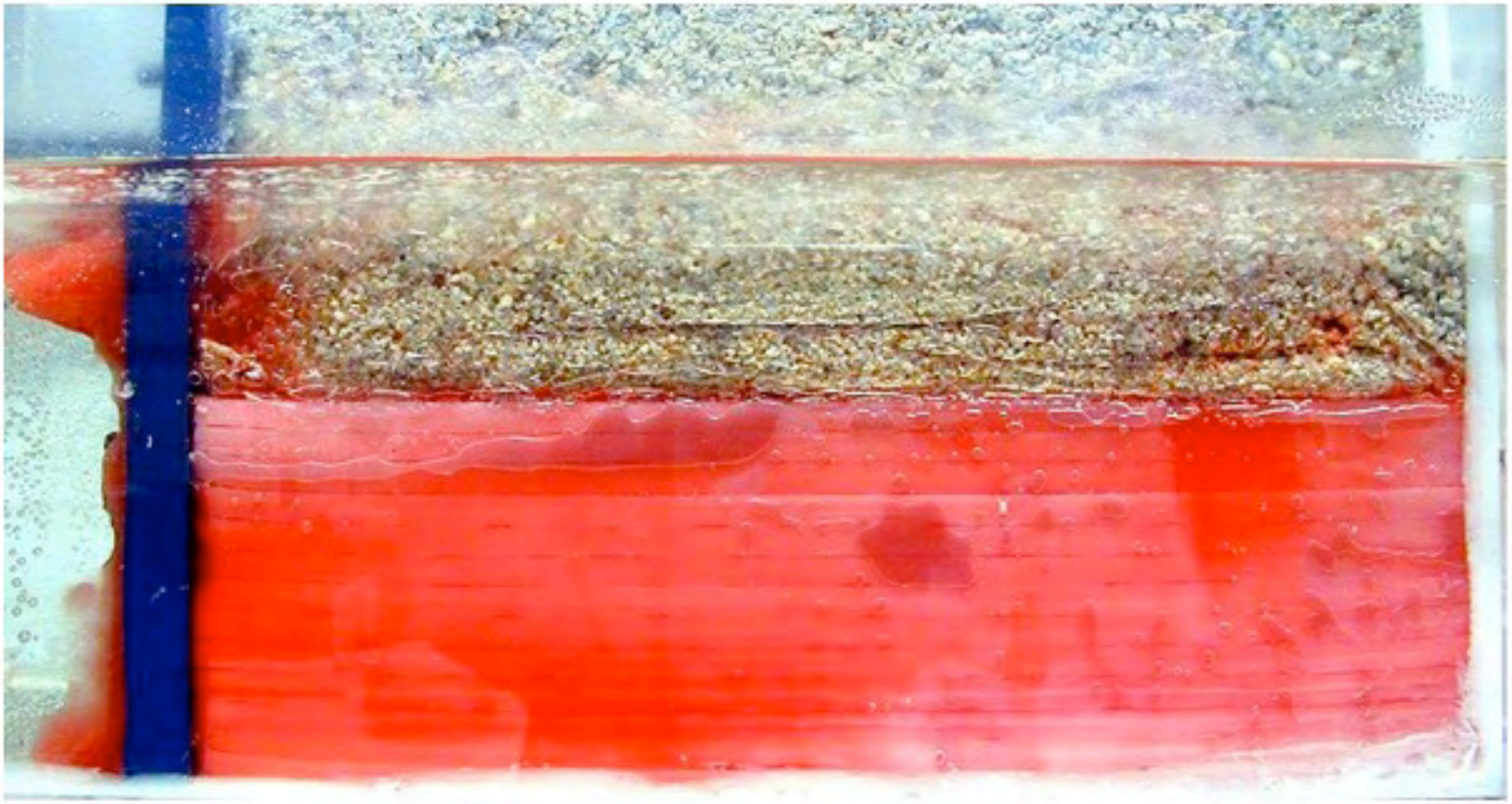


La vitesse du mur mobile est 2.4 mm/h

J. Barraud, Thèse Lyon, 2001

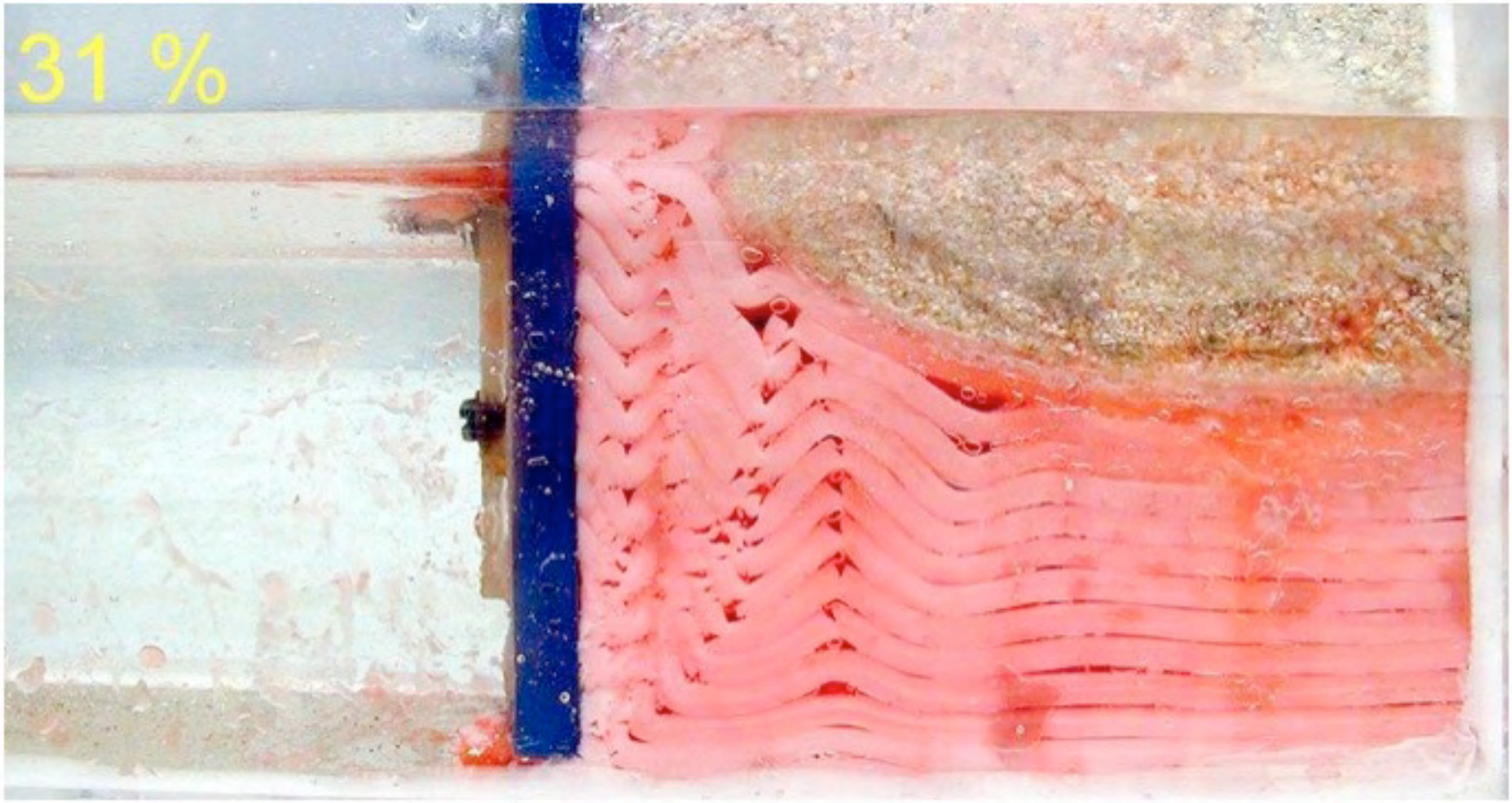


J. Barraud, Thèse Lyon, 2001



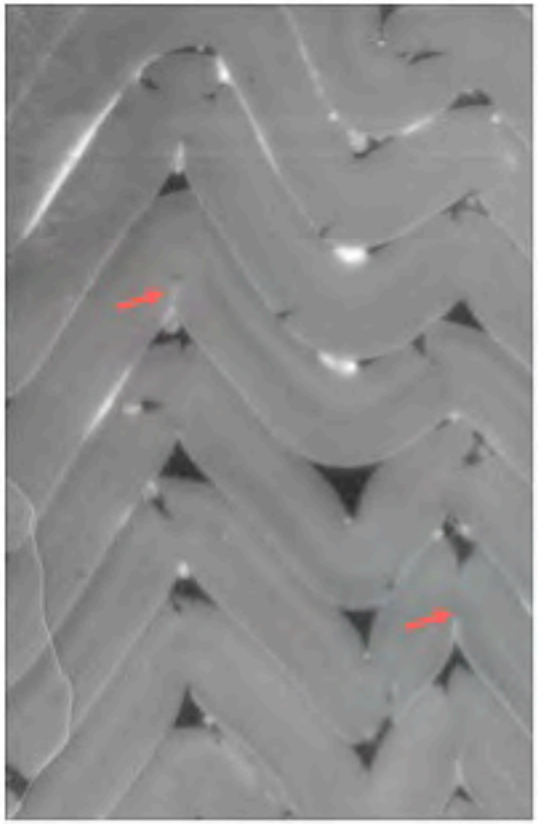
J. Barraud, Thèse Lyon, 2001

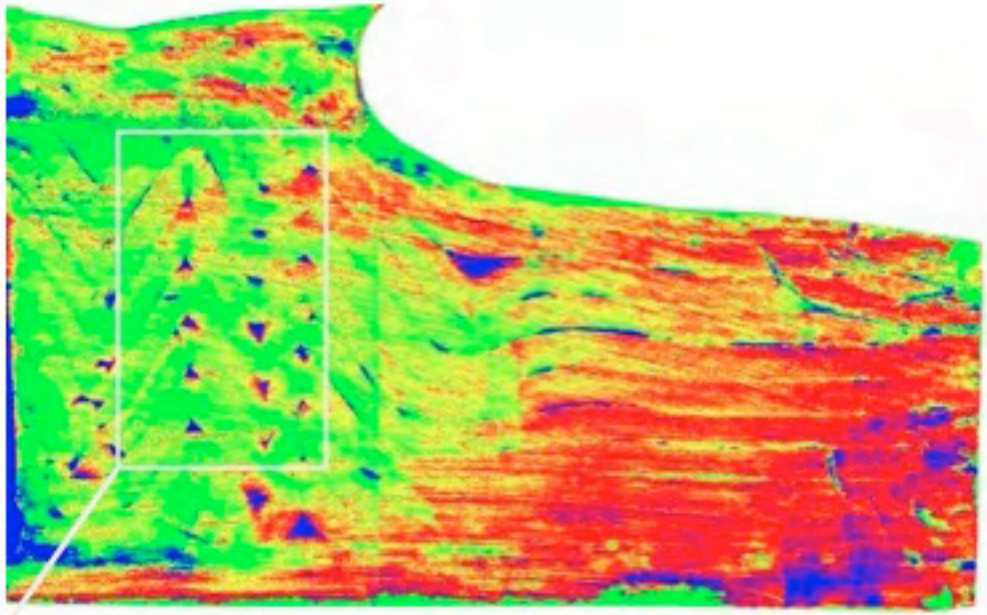
J. Barraud, Thèse Lyon, 2001



J. Barraud, Thèse Lyon, 2001

Mécanismes de ségrégation





Cire riche en liquide

Cire appauvrie en liquide

Liquide pur

Cire intermédiaire

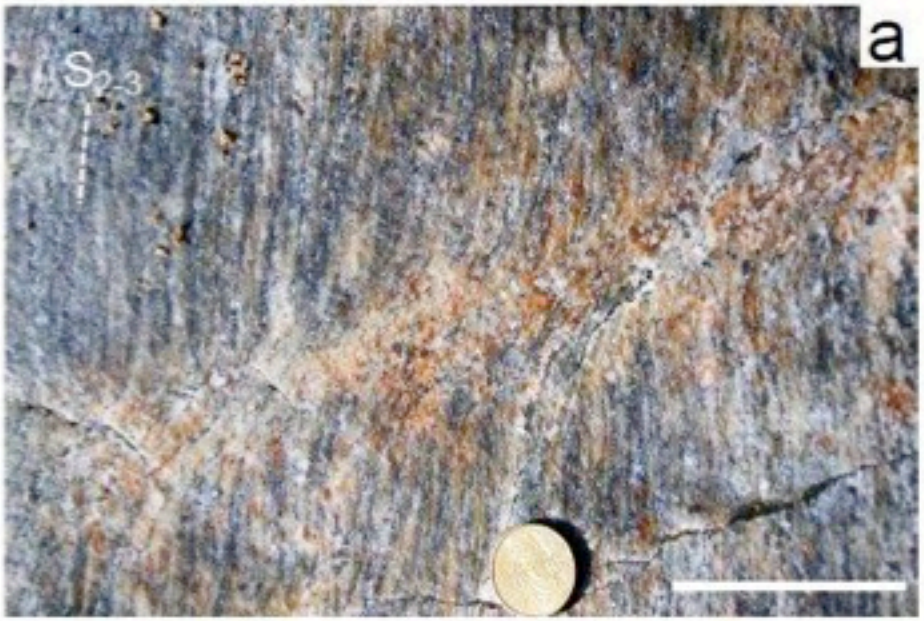
Liens entre plissement et ségrégation

J. Barraud, Thèse Lyon, 2001

Perte de liquide par ascension gravitaire

R. Weinberg

Contrôle structural



Barbey et al. 2015; R. Weinberg

Petrographic continuity

Modal mineralogy and microstructure of leucosome in host indistinguishable from granite in dikes, suggesting they hosted a continuous melt-bearing network and material in leucosomes and dikes underwent final crystallization at the same time.

Dike of leucodiatexite in a deformation band; the leucosome in the dike links continuously with leucosomes in the host migmatite. The weak continuity of fabric, defined by the mafic minerals, across the dike diagonally from lower right to upper left suggests magma movement was out of the screen.

M. Brown

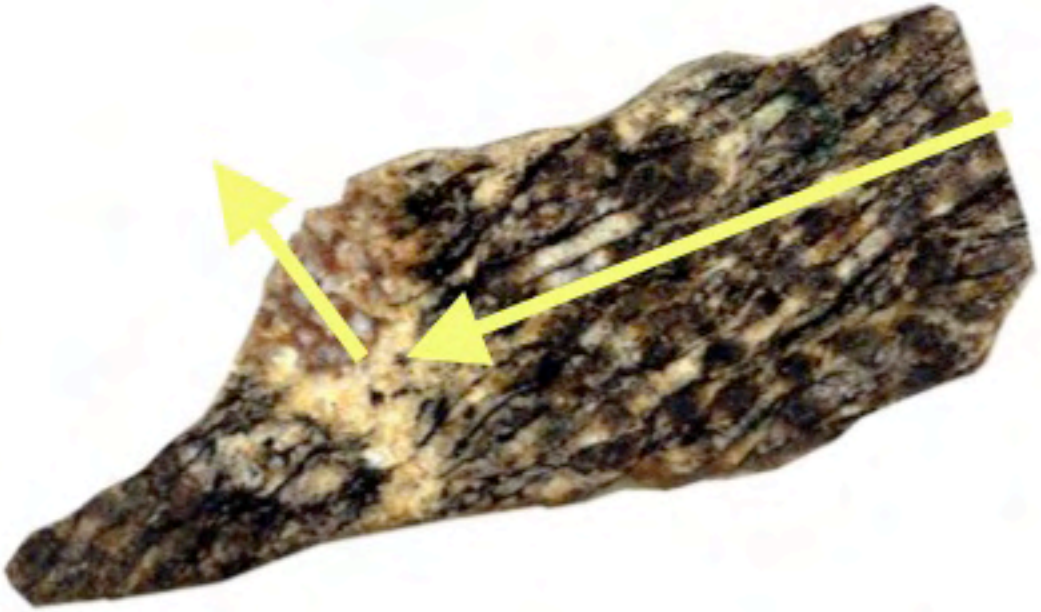
In regional-scale migmatite–granite complexes, how do melt ascent conduits form?

- Melt ascent is postulated to occur by either 1. ductile fracture, or 2. pervasive migration through suprasolidus crust.

- In each case the ascent conduits evolve to brittle–elastic fracture (diking) through the subsolidus crust.

M. Brown

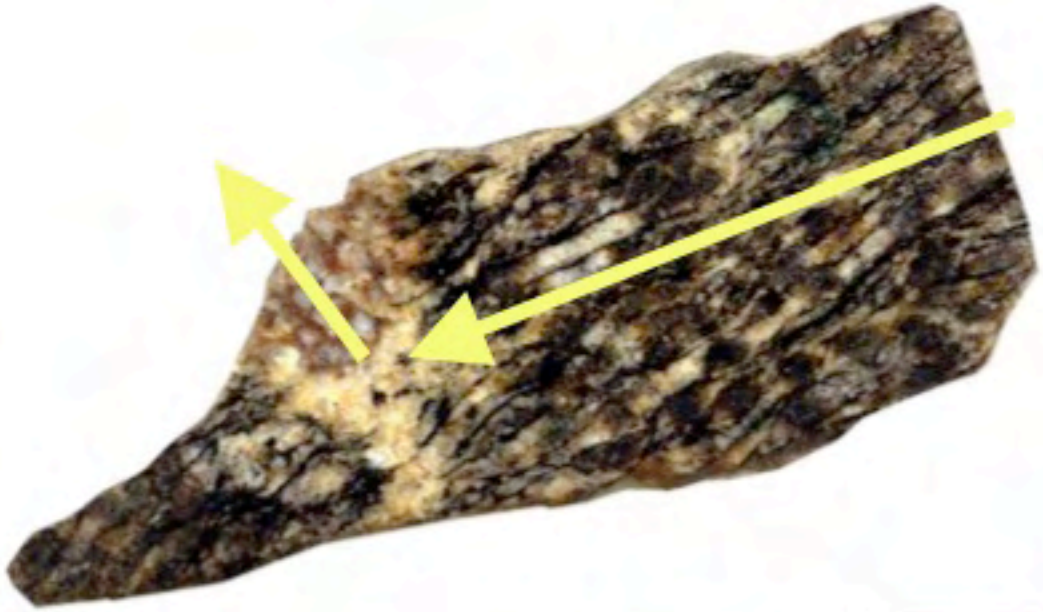
R. Weinberg

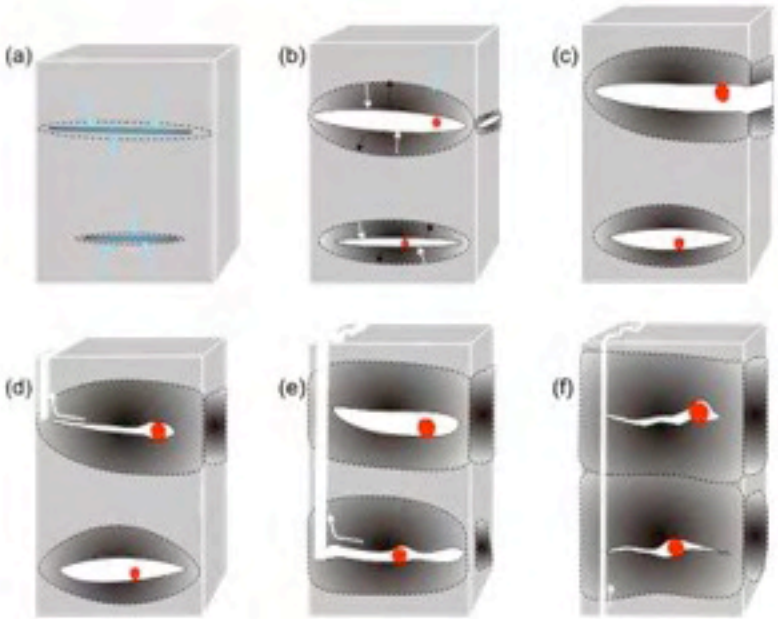


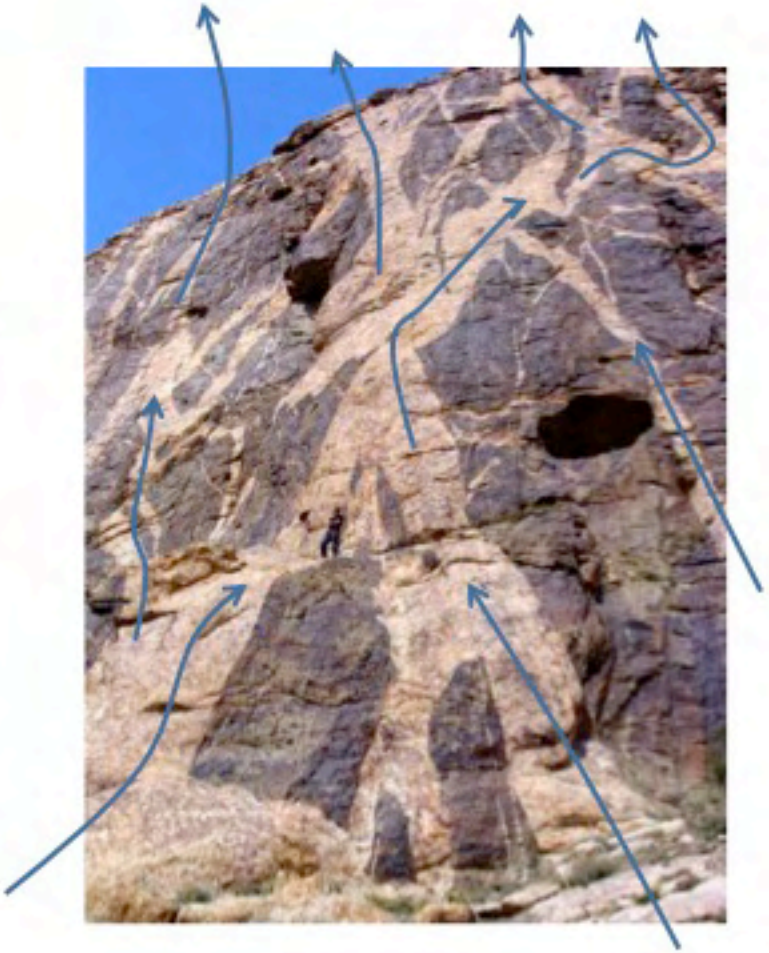
De la source au pluton…

R. Ward, R. Weinberg

De la source au pluton…

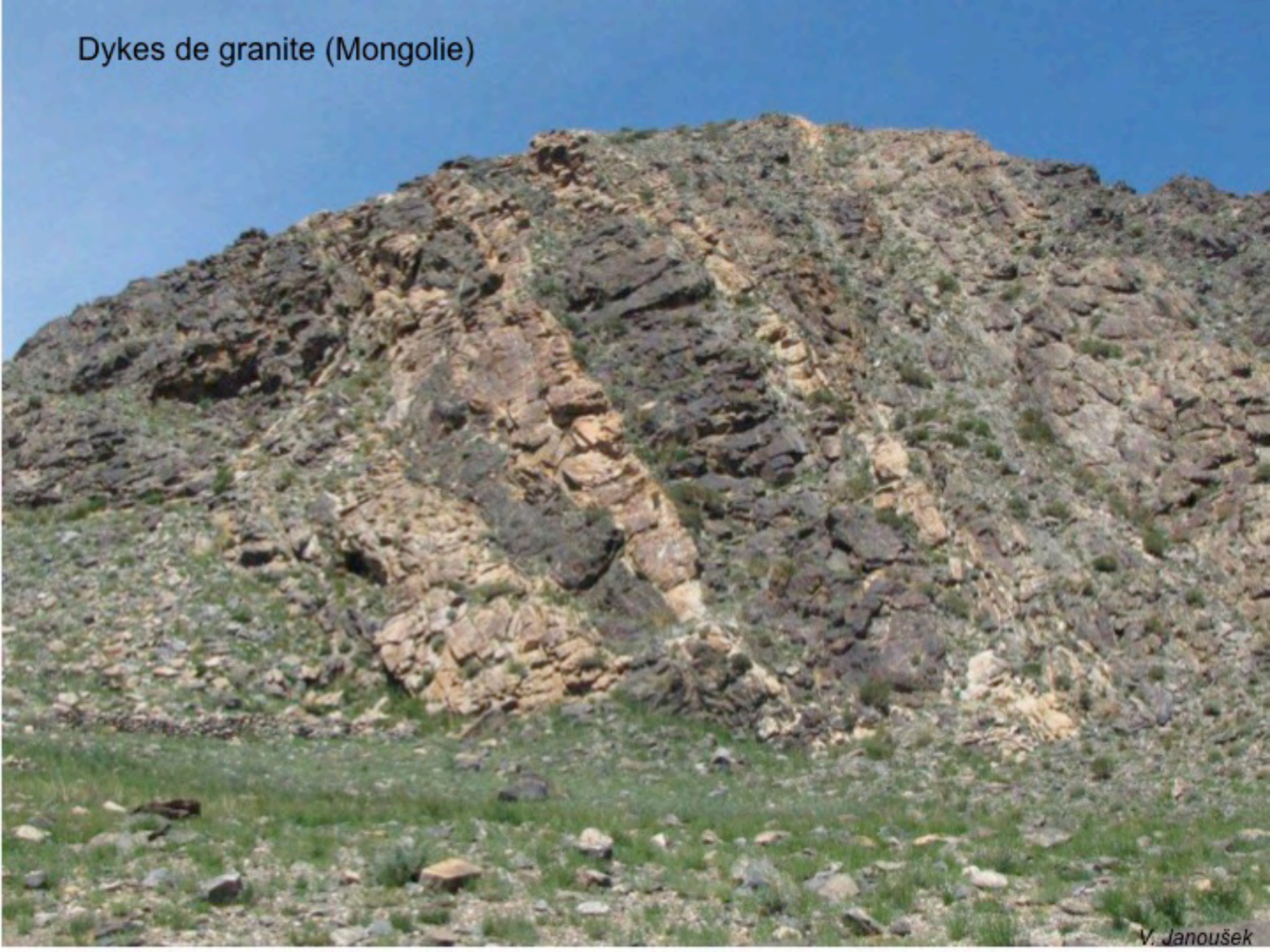






R. Ward, R. Weinberg

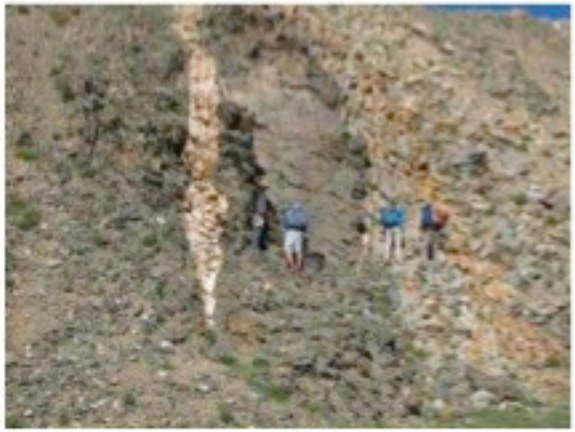
Dykes de granite (Mongolie)



V. Janoušek

V. Janoušek

Les dykes ne sont pas des tuyaux !



… mais des poches de liquide qui migrent dans la croûte partiellement fondue (en collectant les liquides présents)

V. Janoušek, M. Brown, R. Ward

Pièges structuraux

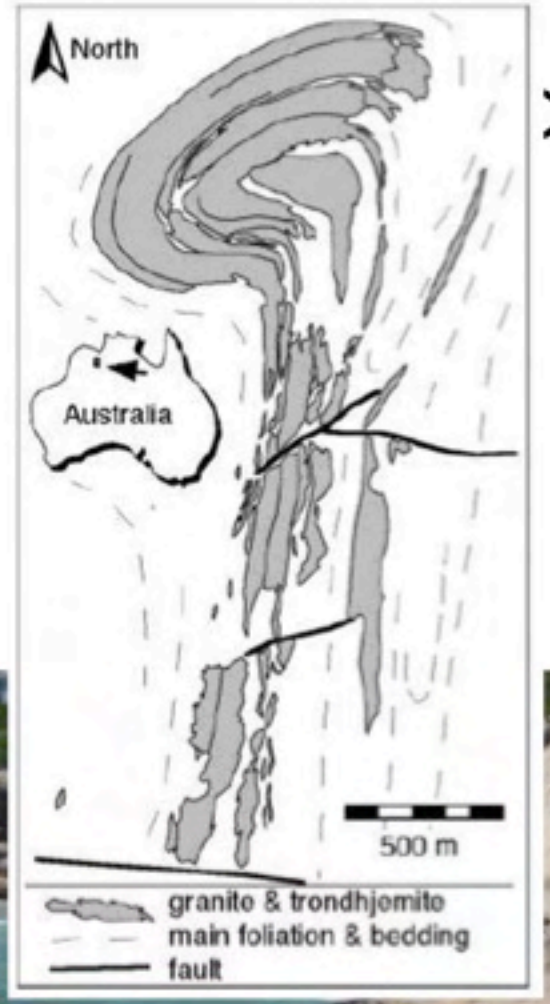
Karakorum (W. Himalaya)

R. Weinberg

V. Janoušek

Des traces d'une construction par « batchs »?

:es d’une construction par « batchs »?

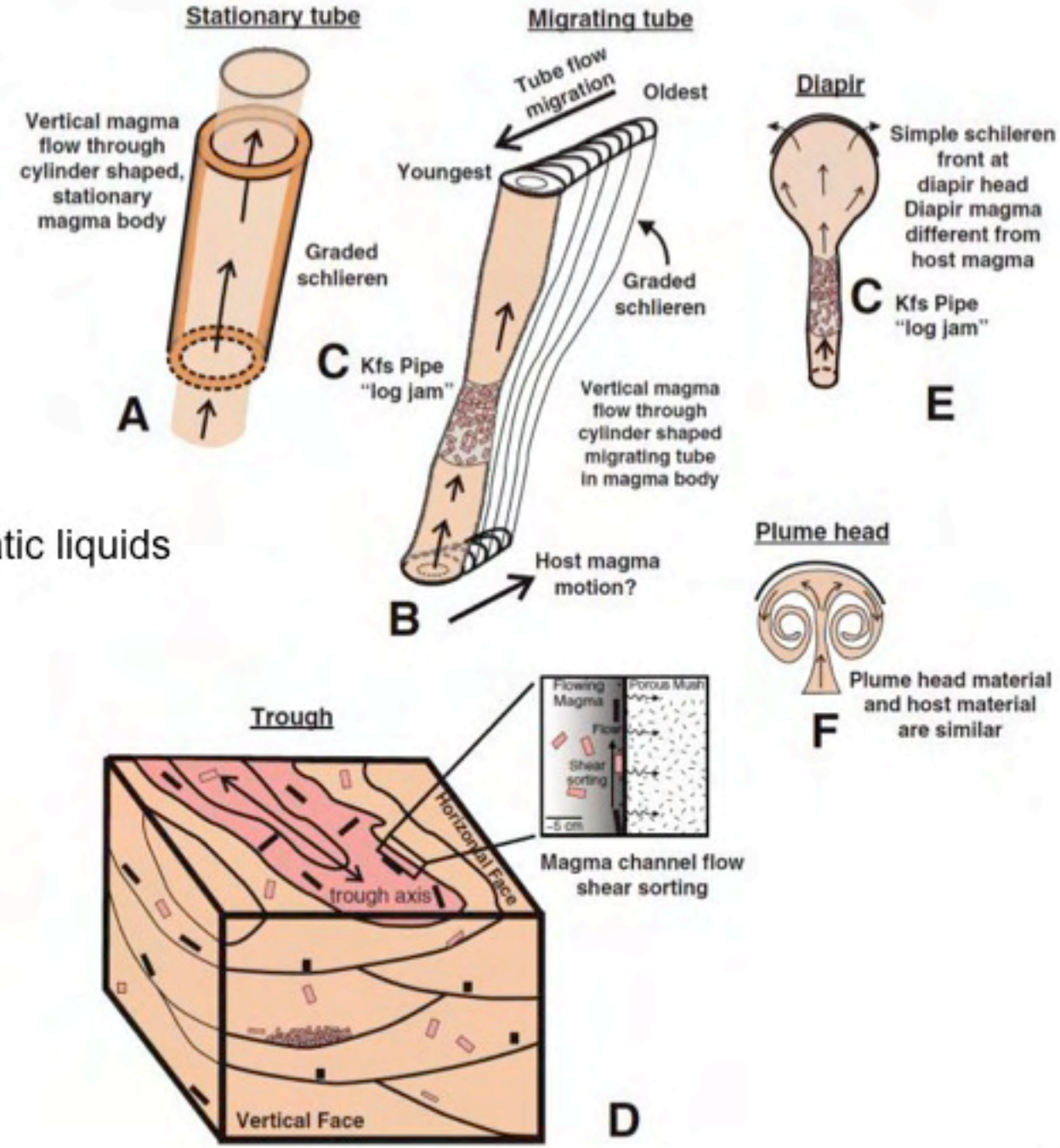


« ellipsoids », « snail structures », « diapirs »

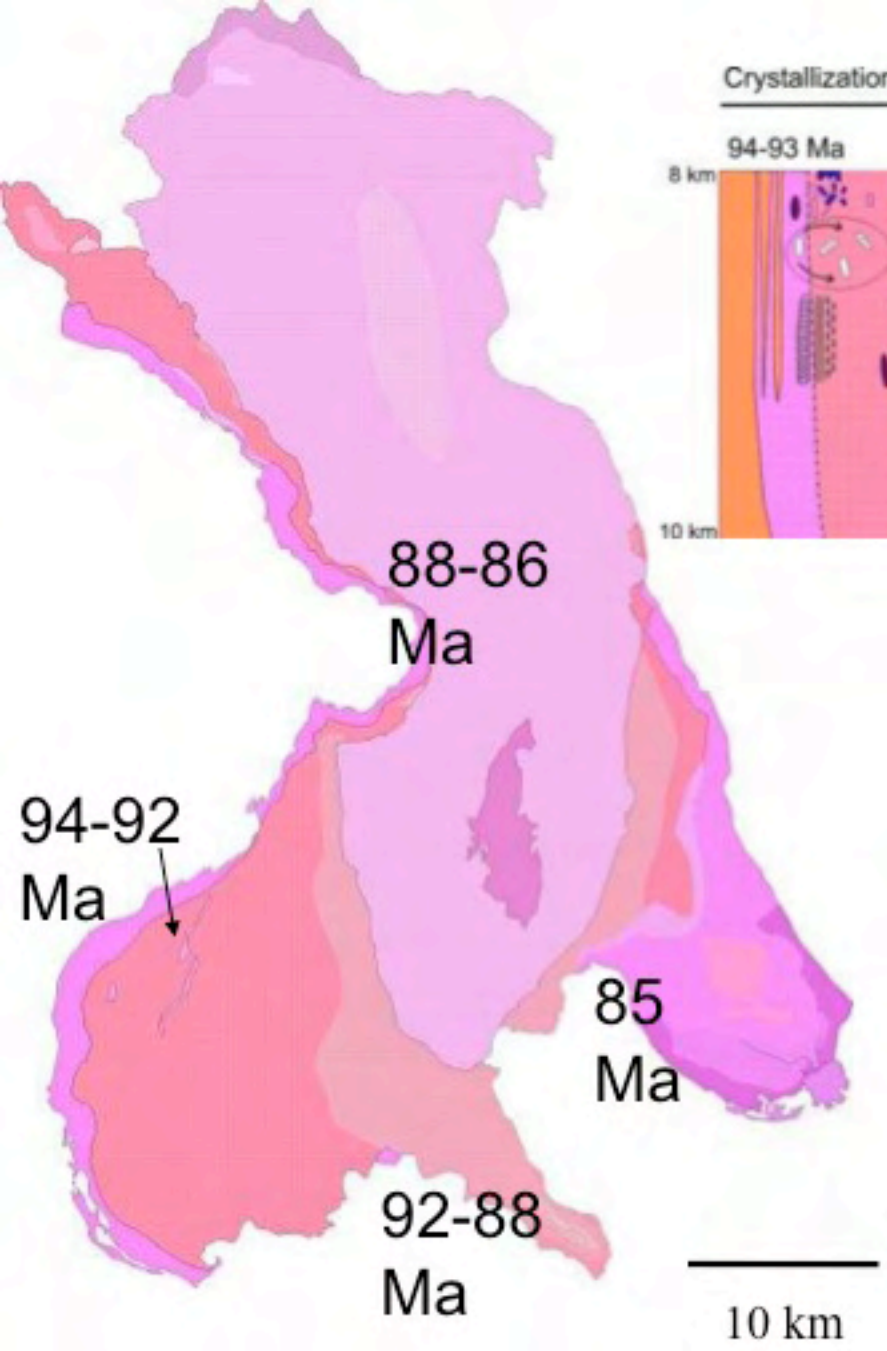
www.earth.monash.edu.au/~weinberg

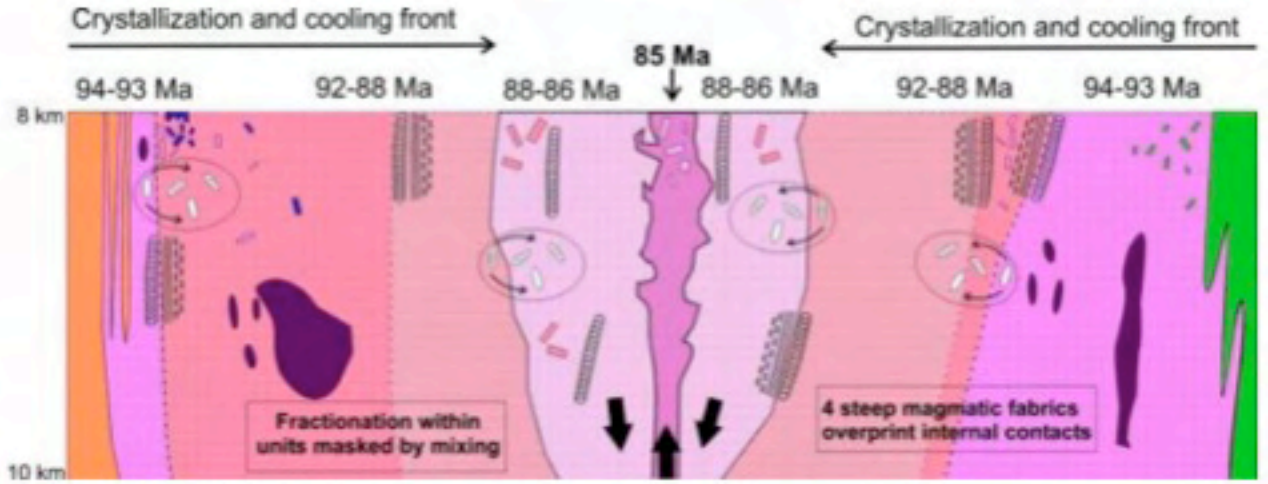
R. Weinberg

Pipes of late magmatic liquids in the mush



R. Weinberg

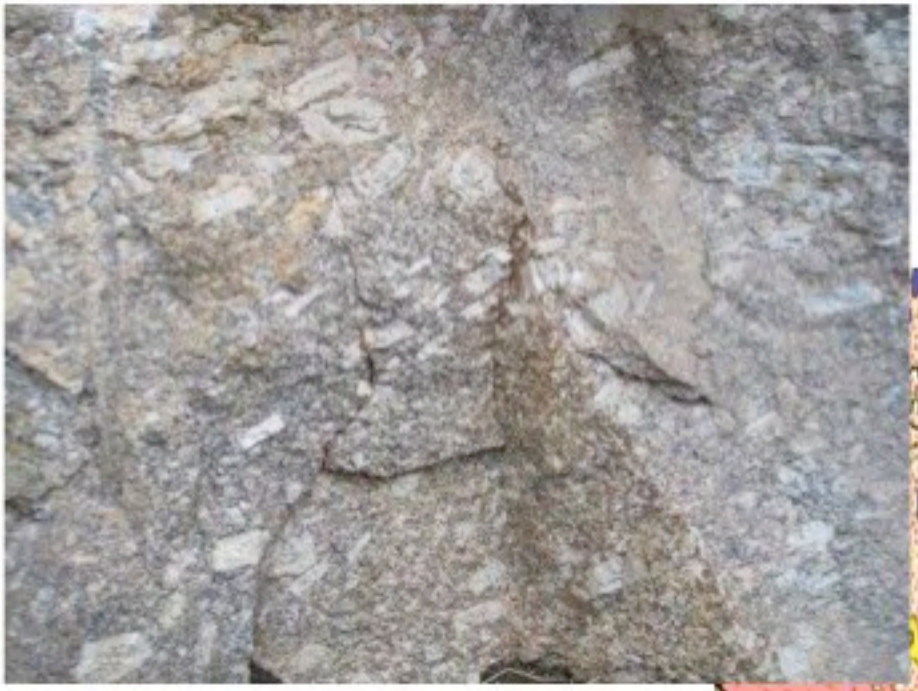


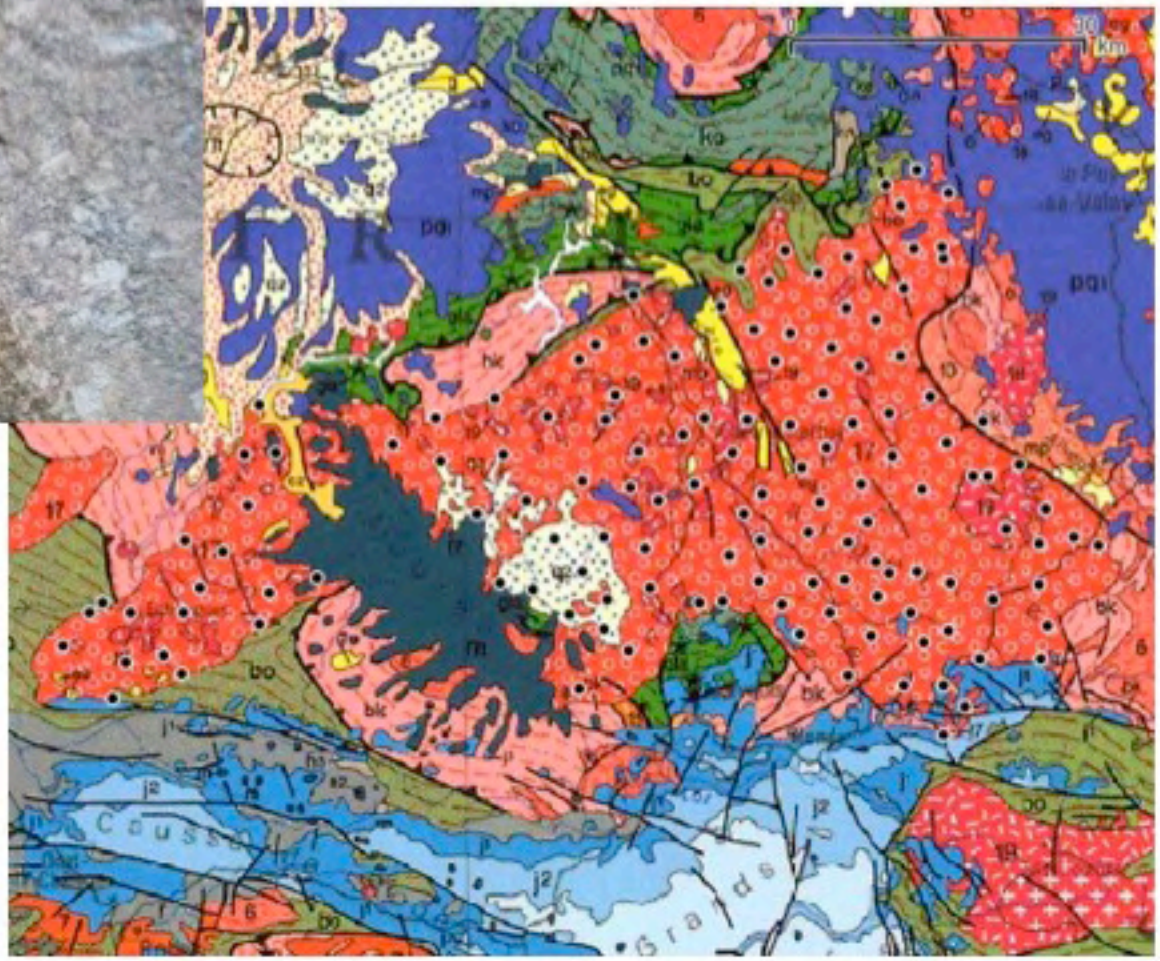


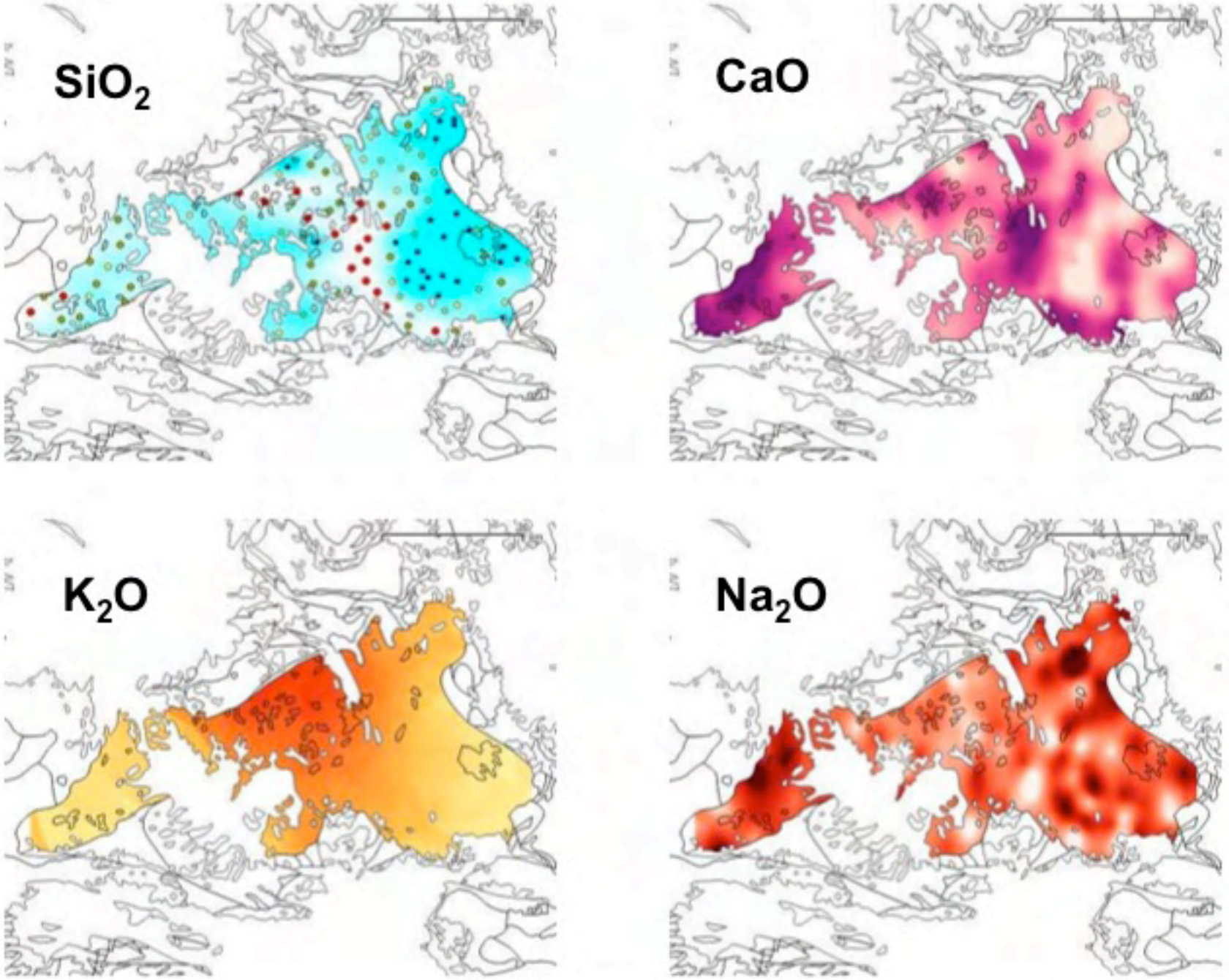
Tuolumne Batholith

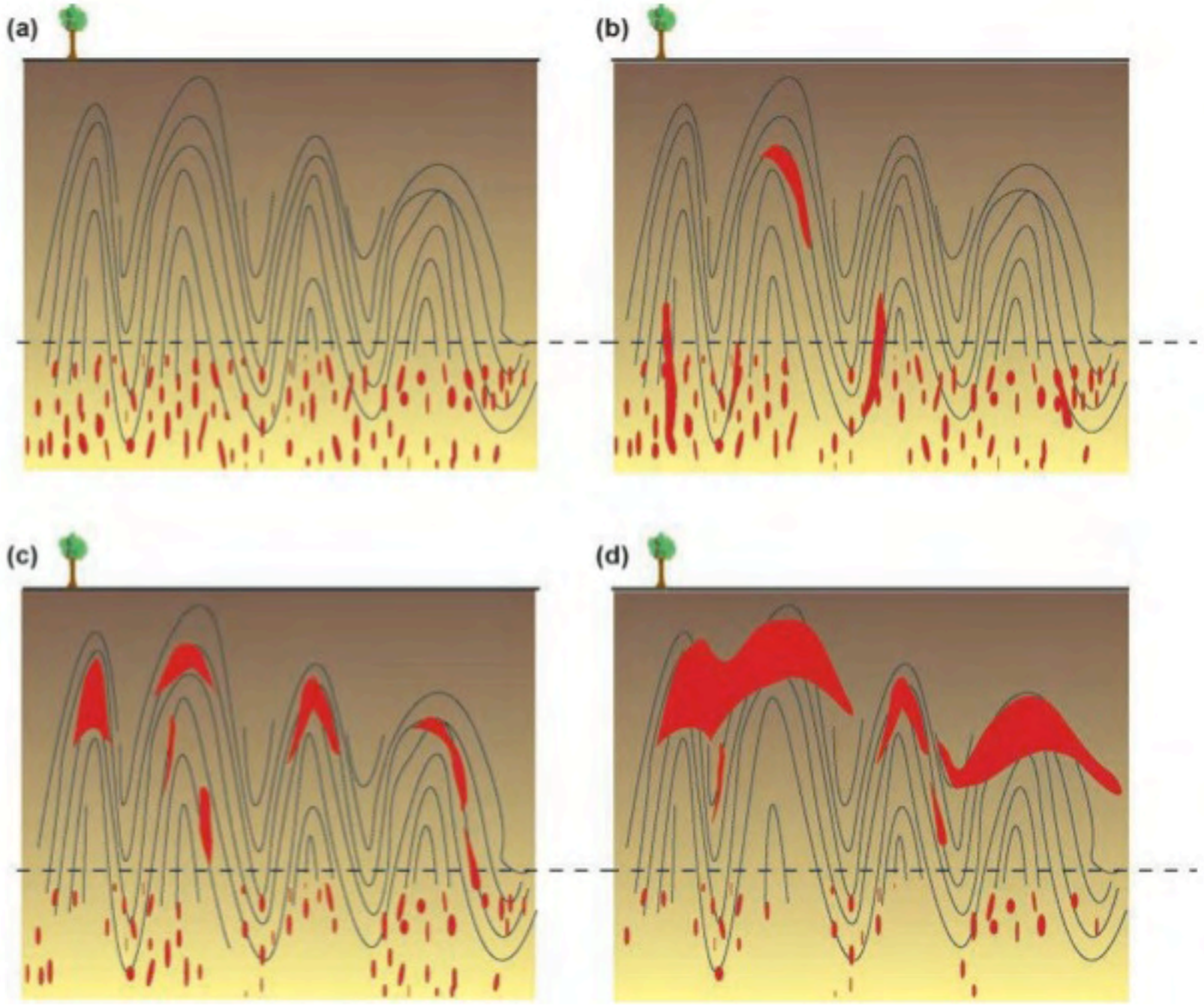
V. Memeti

Granite de Margeride

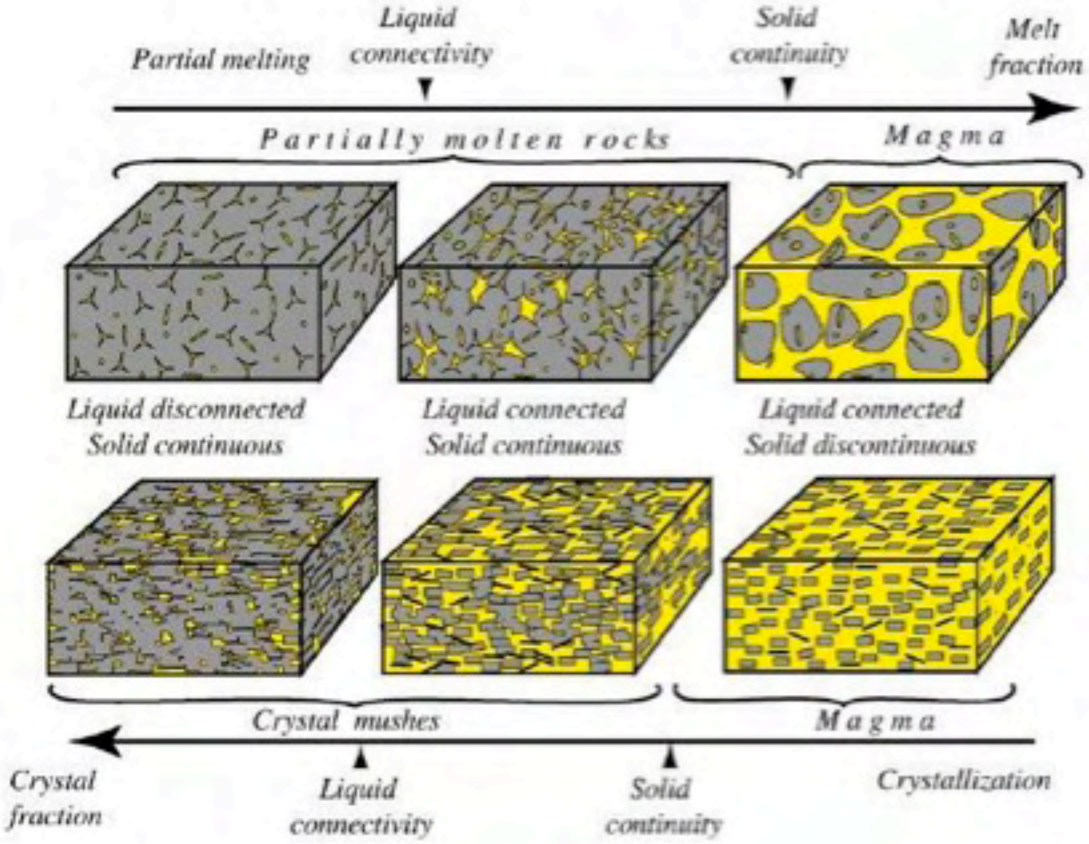




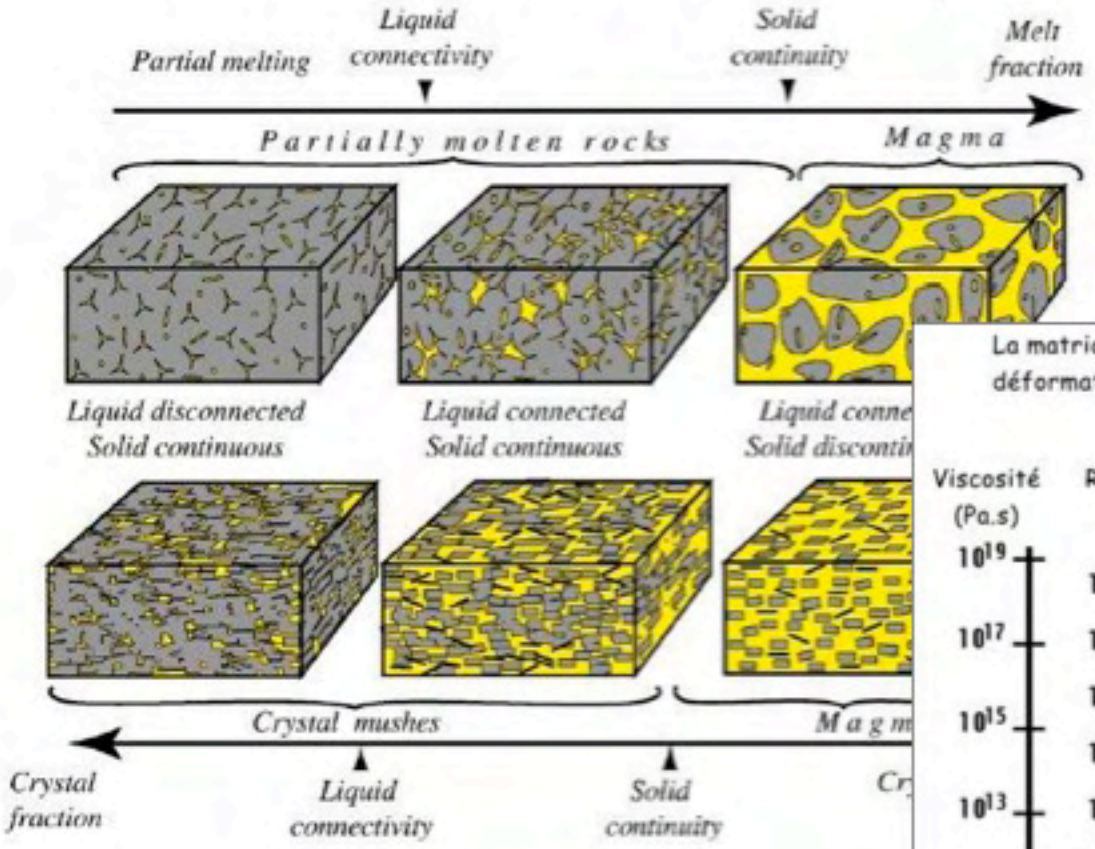

SiO_2
CaO
K_2O
Na_2O

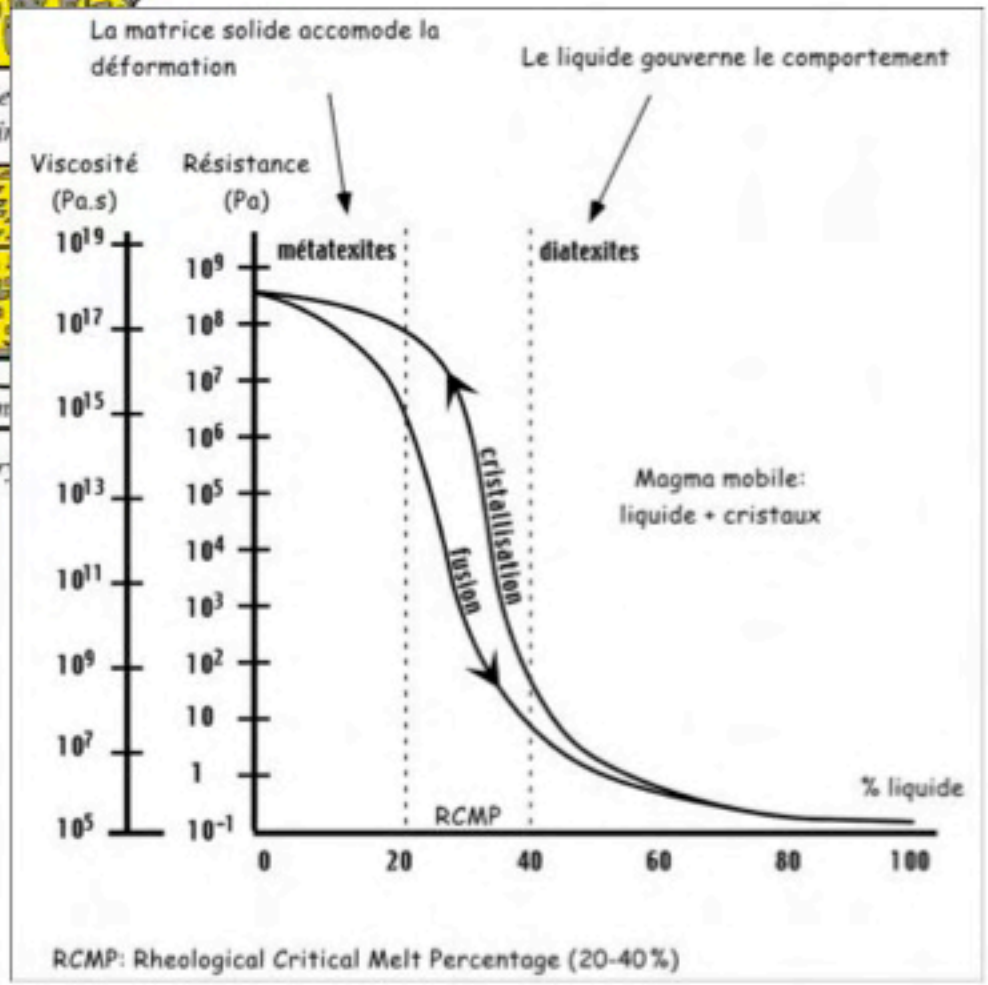

(a)
(b)
(c)
(d)

Rhéologie des roches partiellement fondues

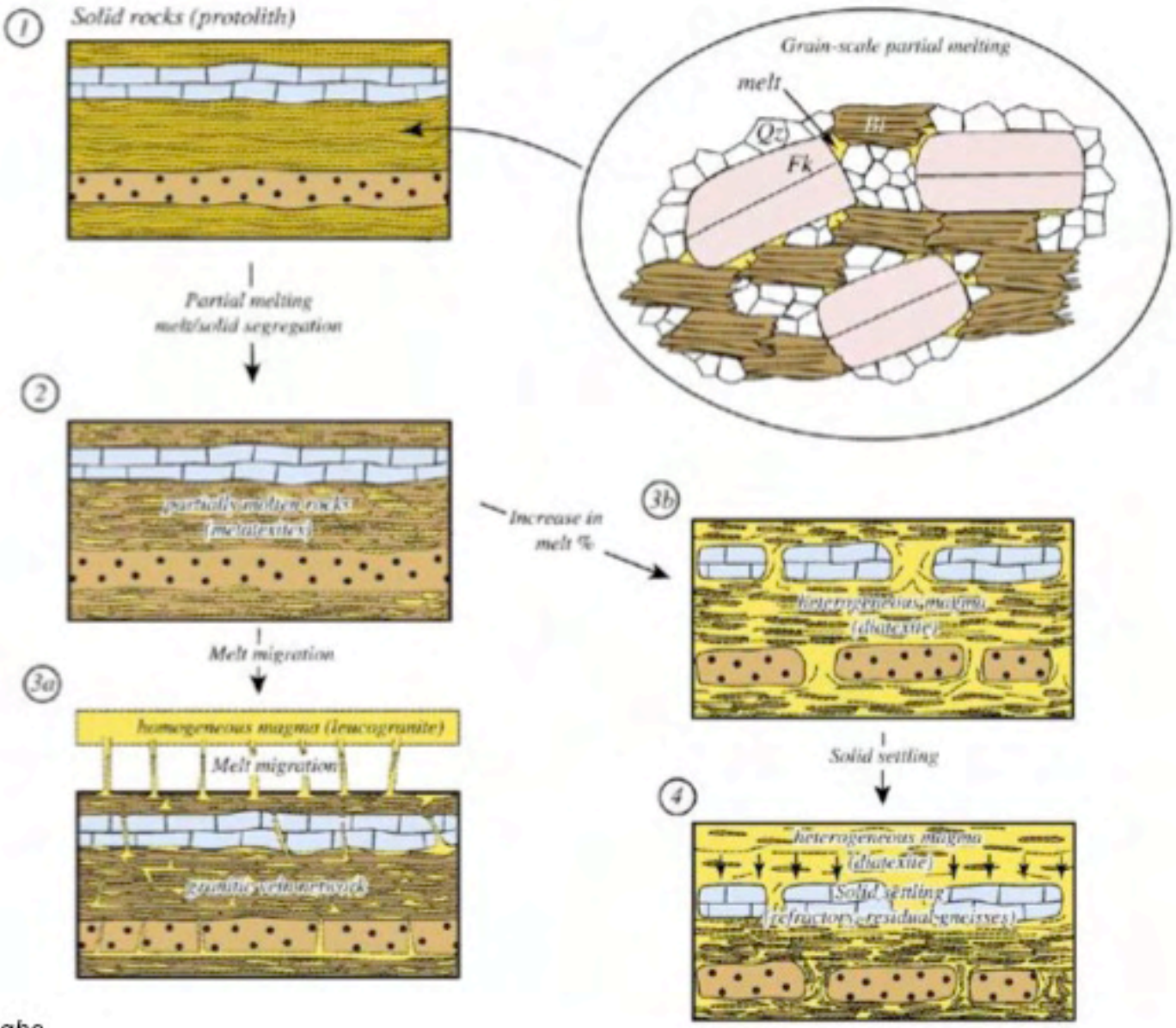


Rhéologie des roches partiellement fondues



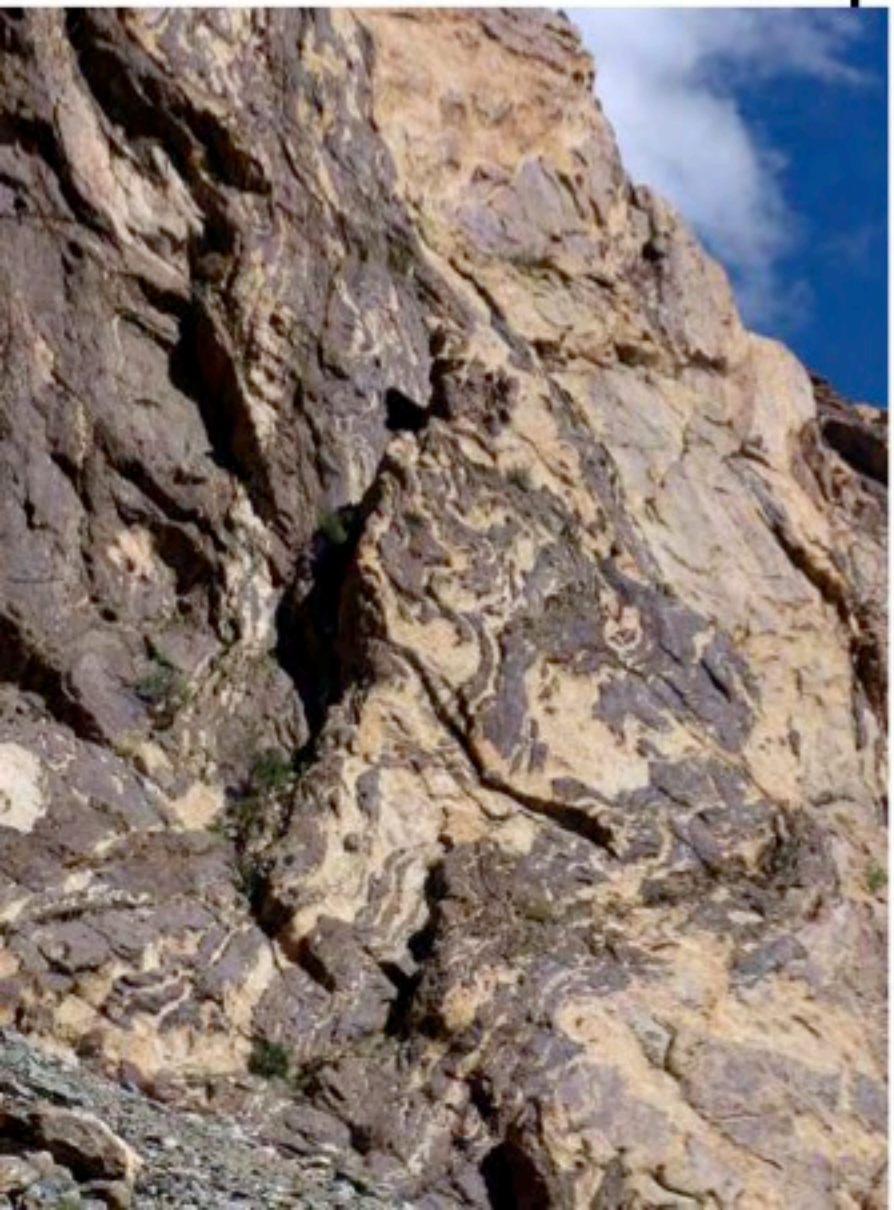


Deux modes d'extraction de liquide



O. Vanderhaeghe

Des « diatexites », des roches qui ont bcp fondu



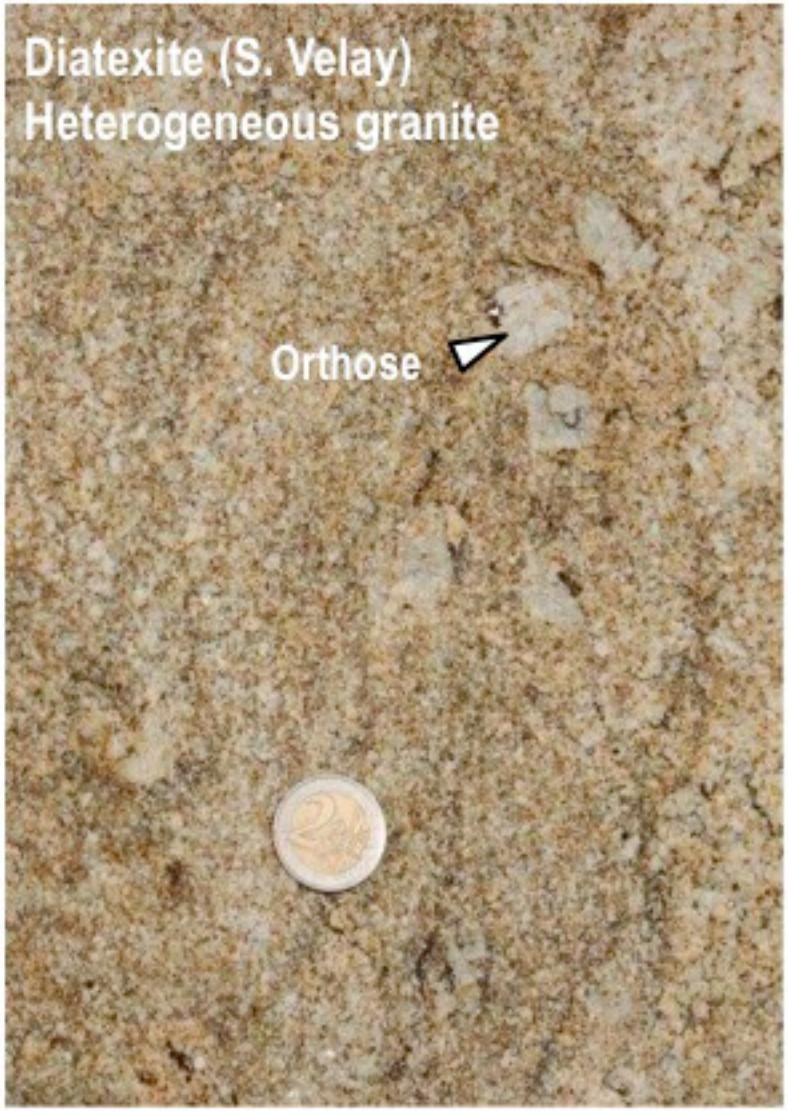
Hortavaer igenous complex, central Norway

Karakorum (W. Himalayas).
Photo R. Weinberg.

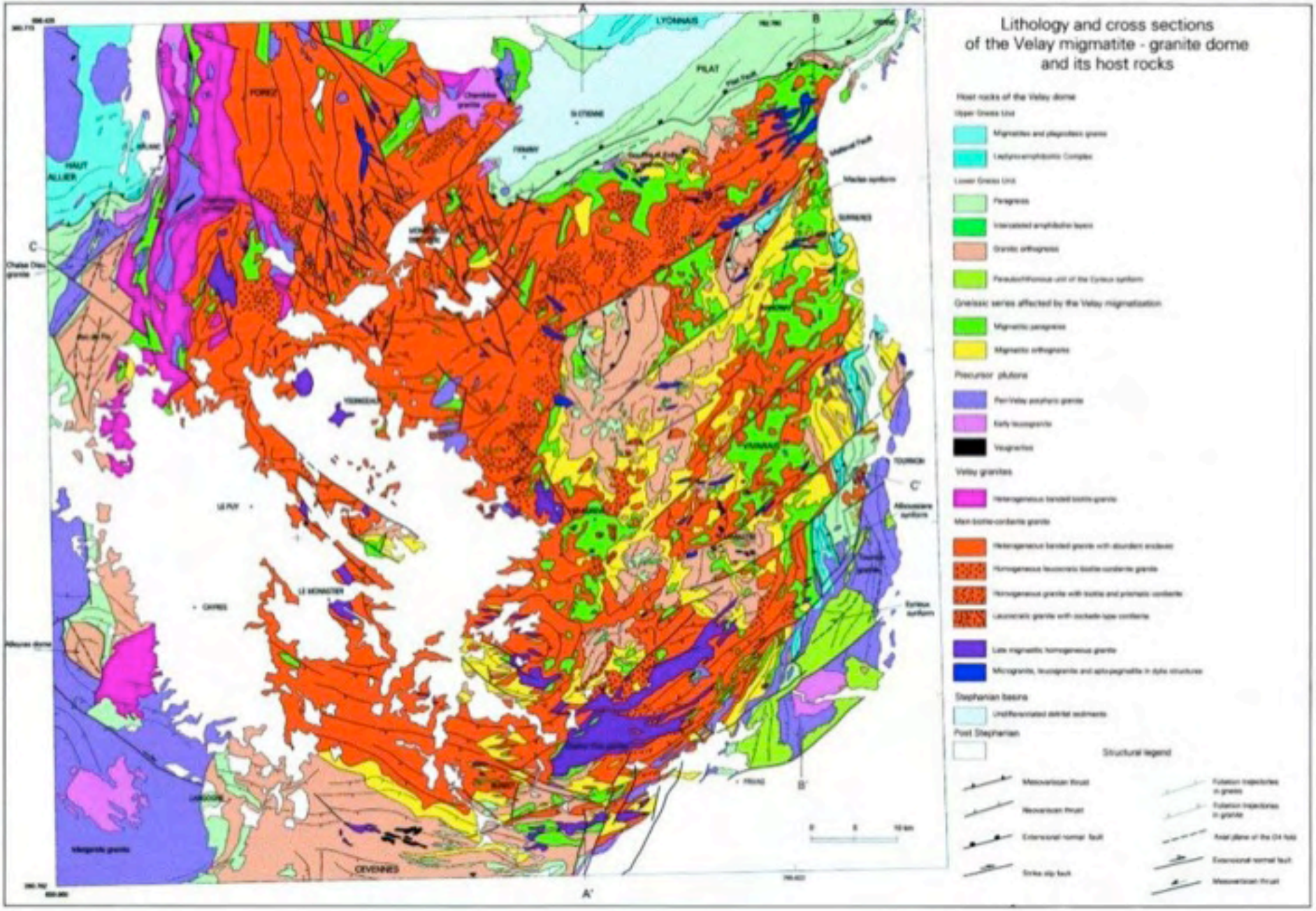
… et qui perdent leur cohérence mécanique

R. Weinberg

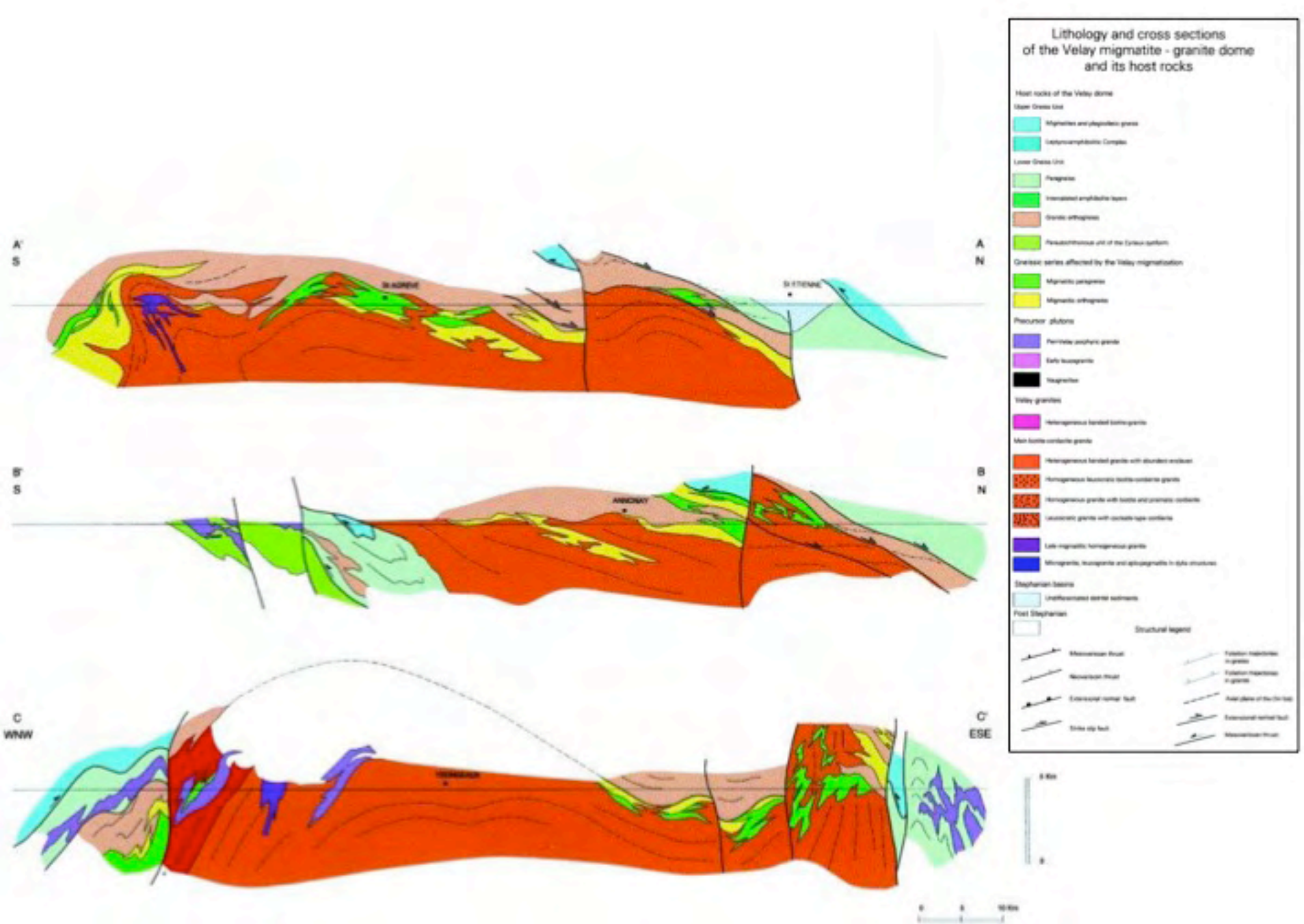
« Granites sales »



O. Vanderhaeghe

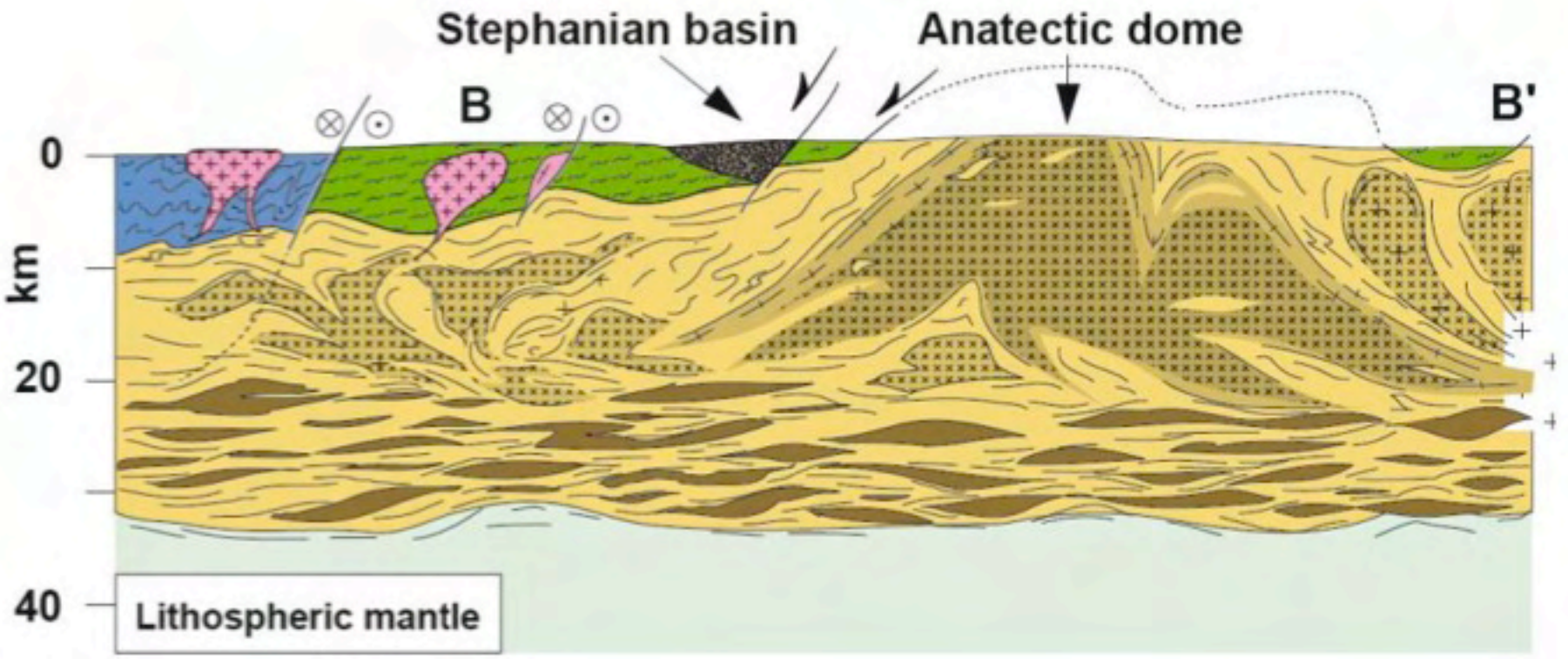


Ledru et al. 2001



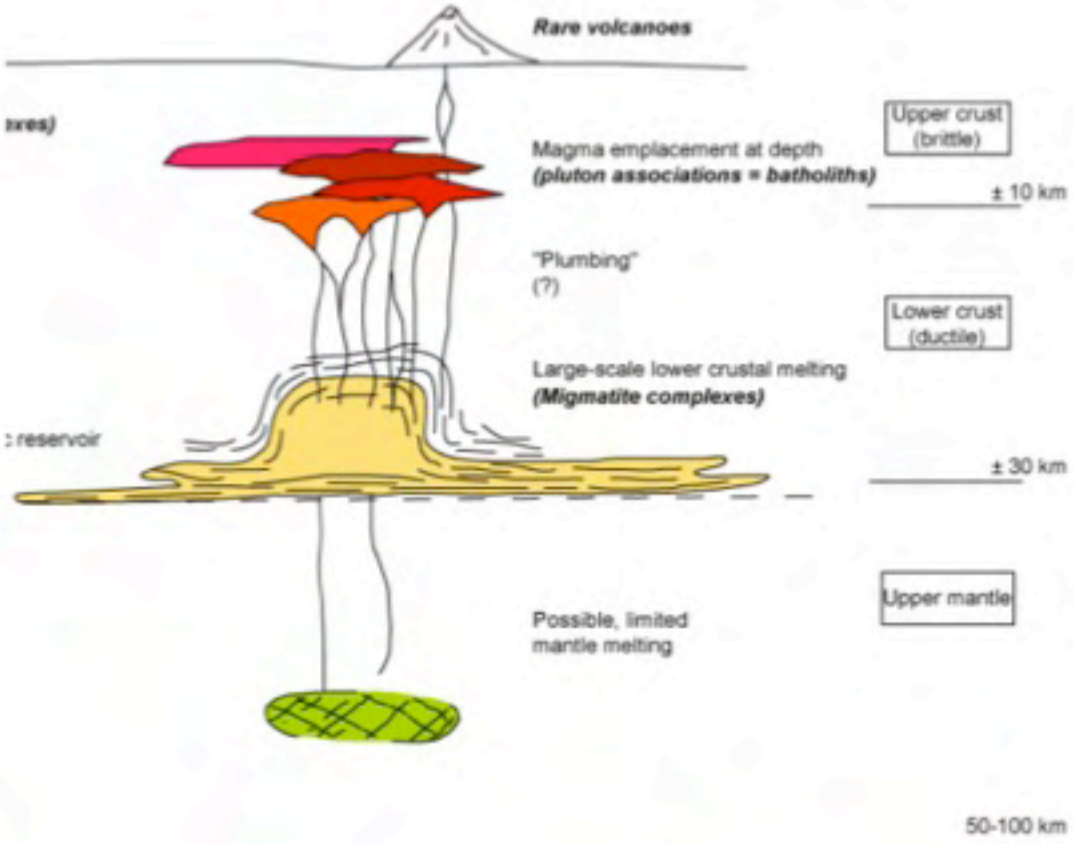
Ledru et al. 2001

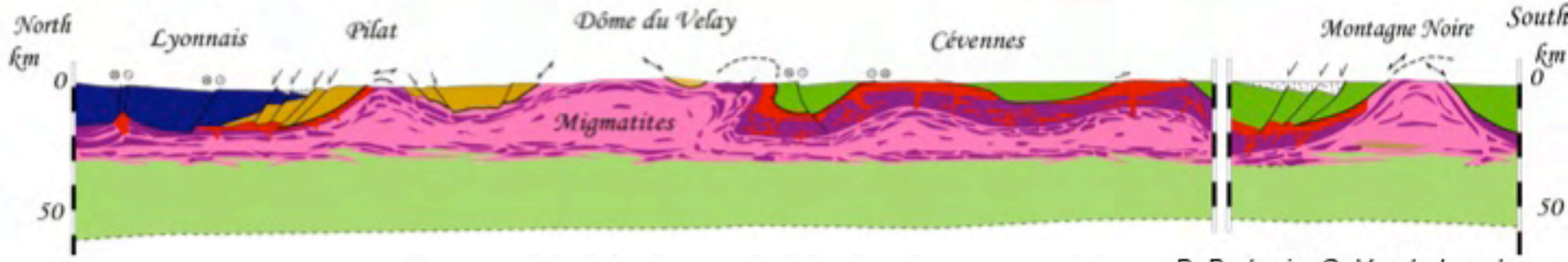
Au Carbonifère: fusion généralisée



Rey, 1997

Construction des plutons

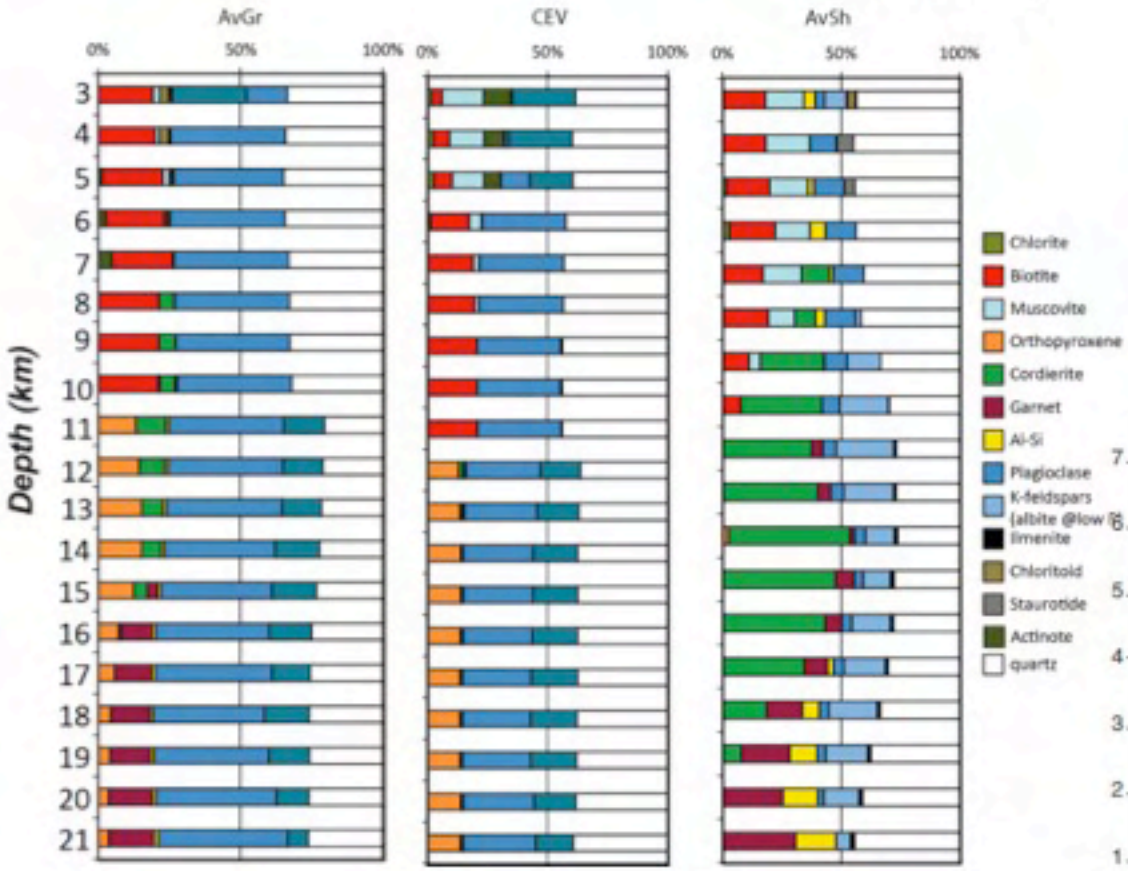


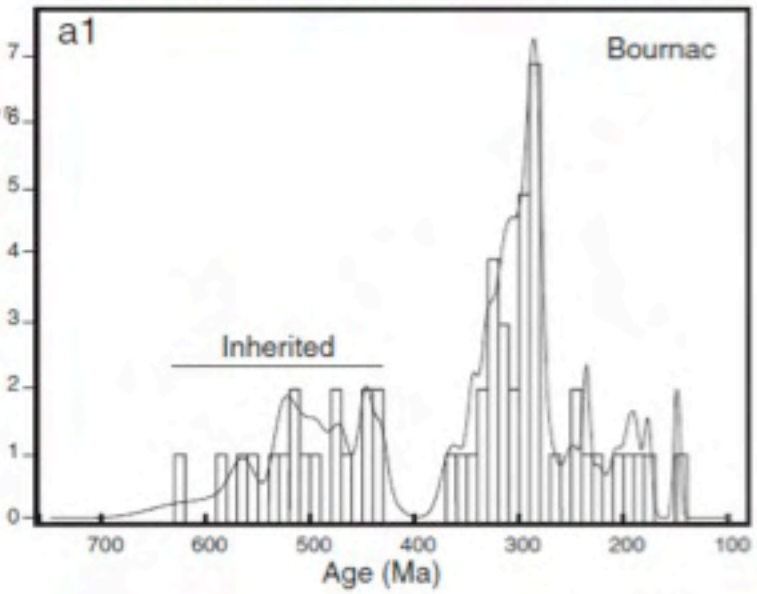


B. Barbarin, O. Vanderhaeghe

Si on enlève des granites, il reste…

Enclaves à Bournac
(Miocène)



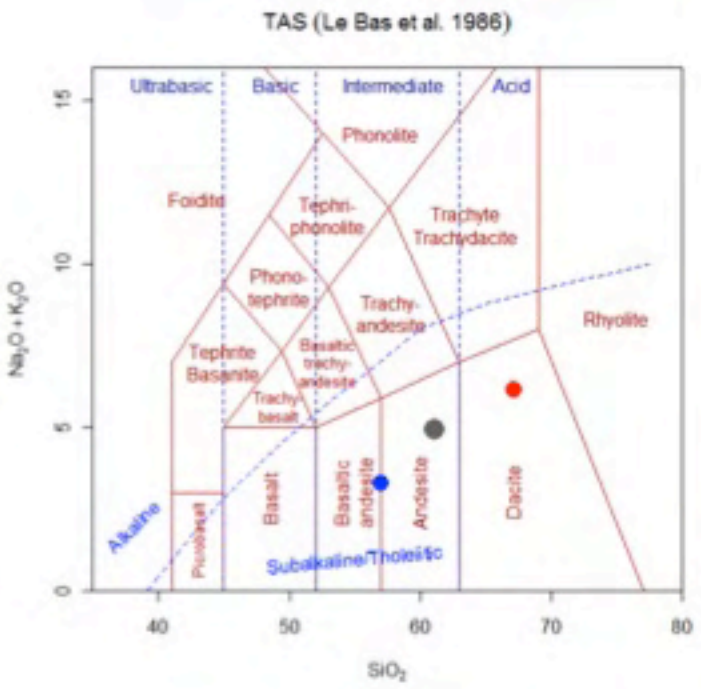


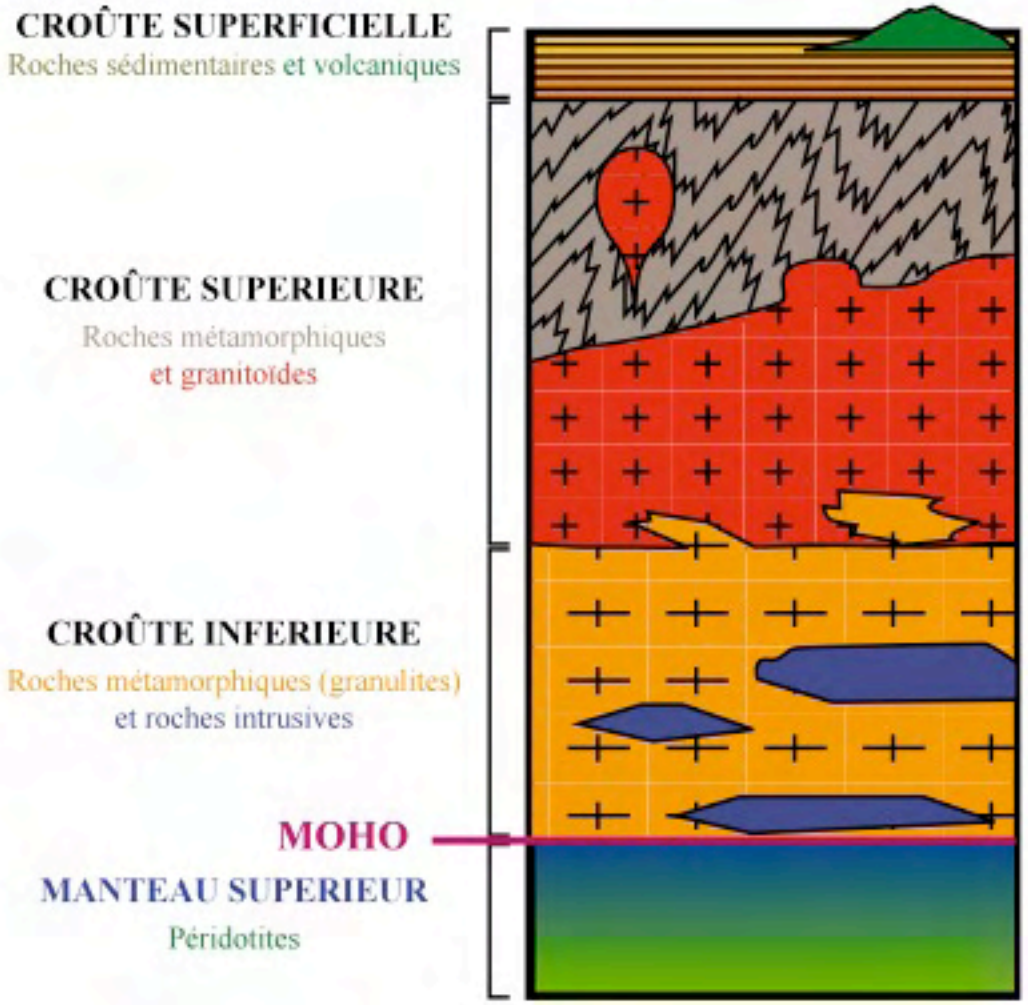
Rossi et al 2006

A. Villaros

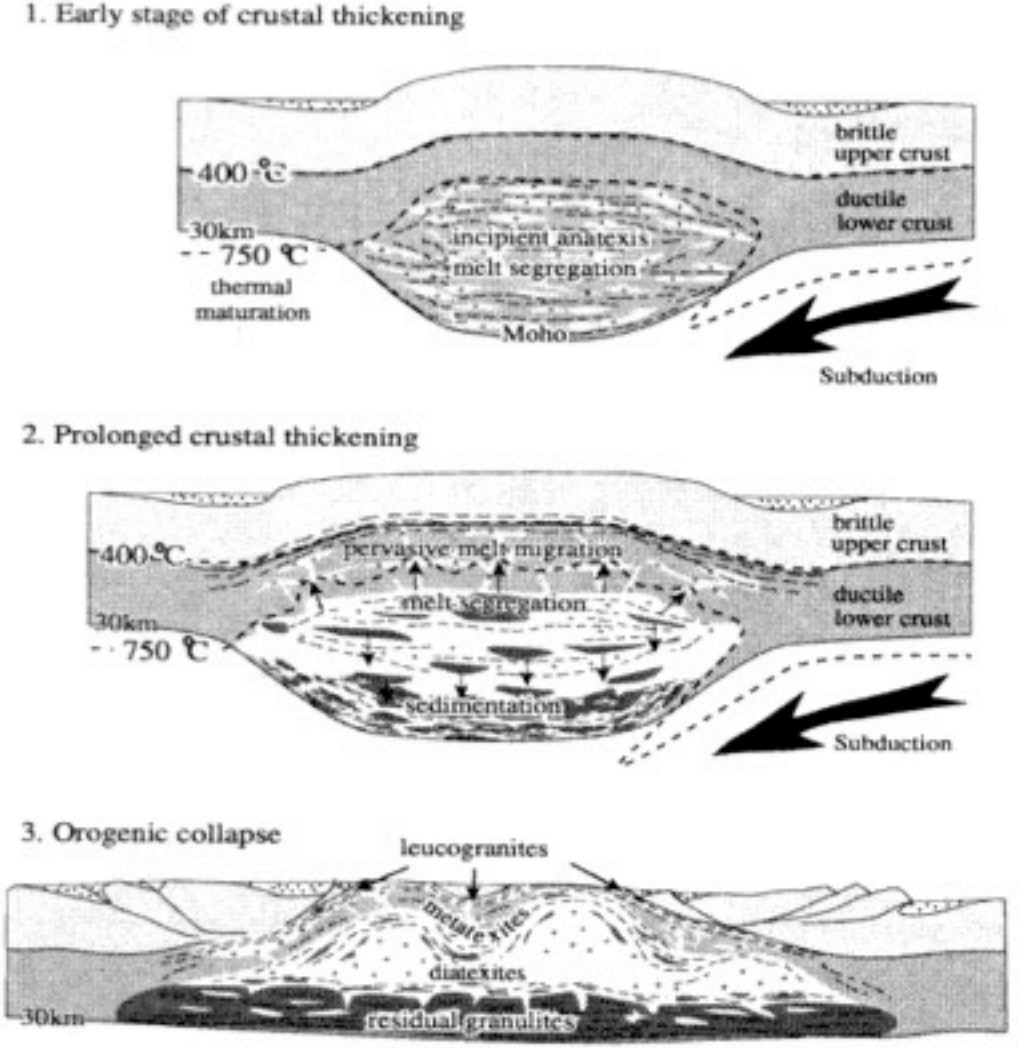
oxydes pds %	Crt sup	Crt inf	Crt globale
SiO2	66.6	54.33	60.60
Al2O3	15.4	15.30	15.90
FeO	5.04	10.60	6.70
MgO	2.48	3.50	4.66
CaO	3.59	8.49	6.40
Na2O	3.27	2.80	3.07
K2O	2.8	0.34	1.81

Mnx normati fs	Crt sup	Crt inf	Crt globale
Q	21.26	7.48	11.17
C	0.46	0.00	0.00
Or	16.55	2.01	10.70
Ab	27.67	23.69	25.98
An	17.81	28.18	24.26
Di	0.00	11.85	6.21
Hy	15.43	22.16	20.83



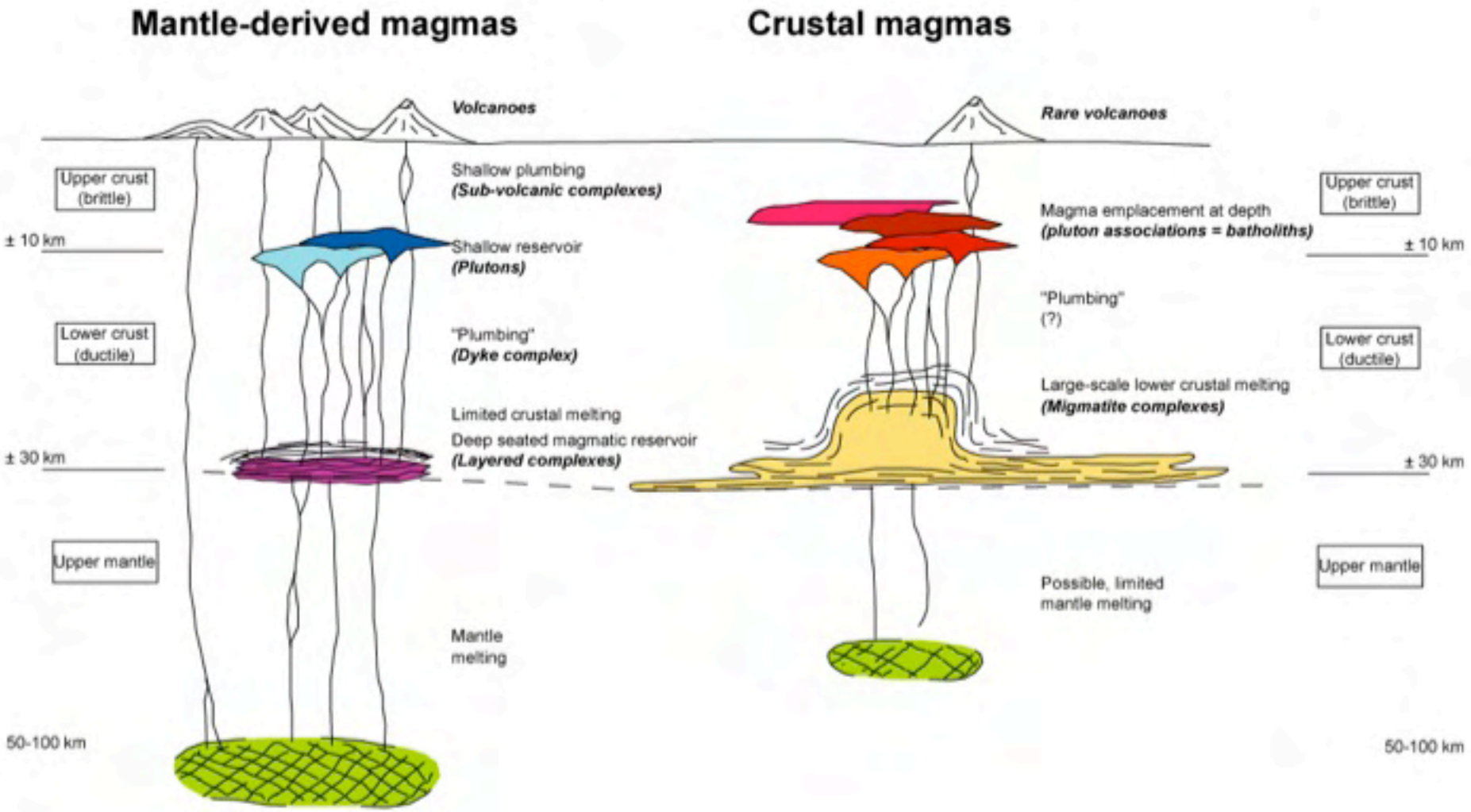


Les granites, agents de la différentiation crustale



Vanderhaeghe 2001

Deux systèmes granitiques



(JFM 06, modified from an original drawing by B. Barbarin)

Les granites

2. Origine des magmas granitiques

b. La cristallisation fractionnée

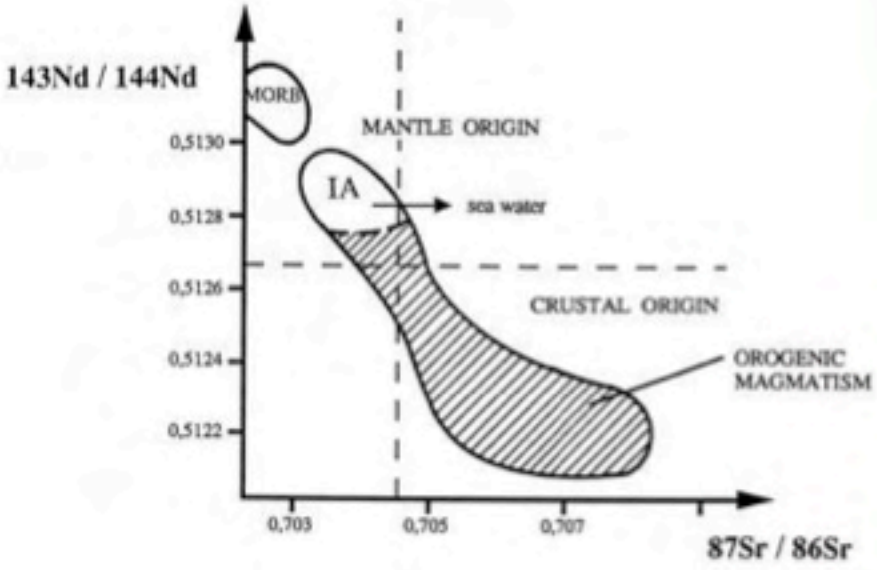
Jean-François Moyen

Université de Lyon

Université Jean Monnet Saint-Étienne

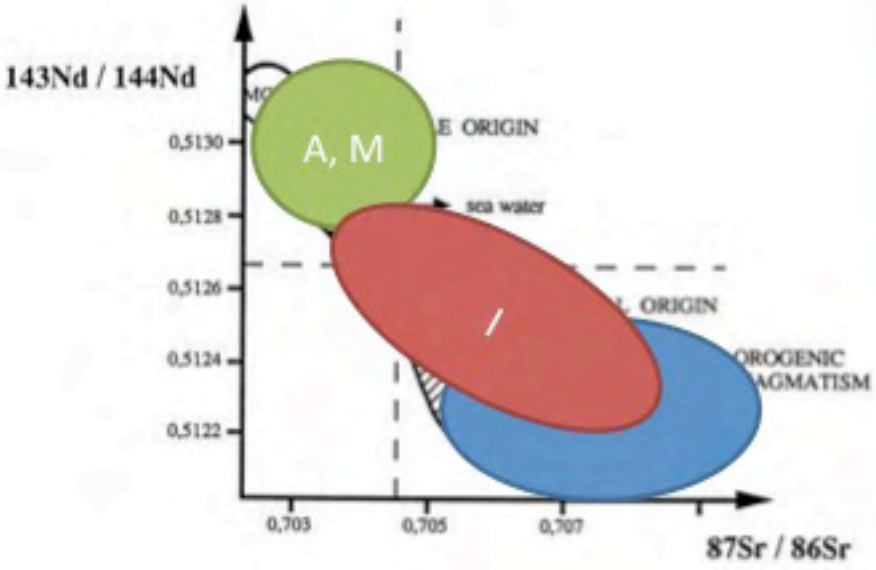
Laboratoire Magmas & Volcans

Granites crustaux / mantelliques



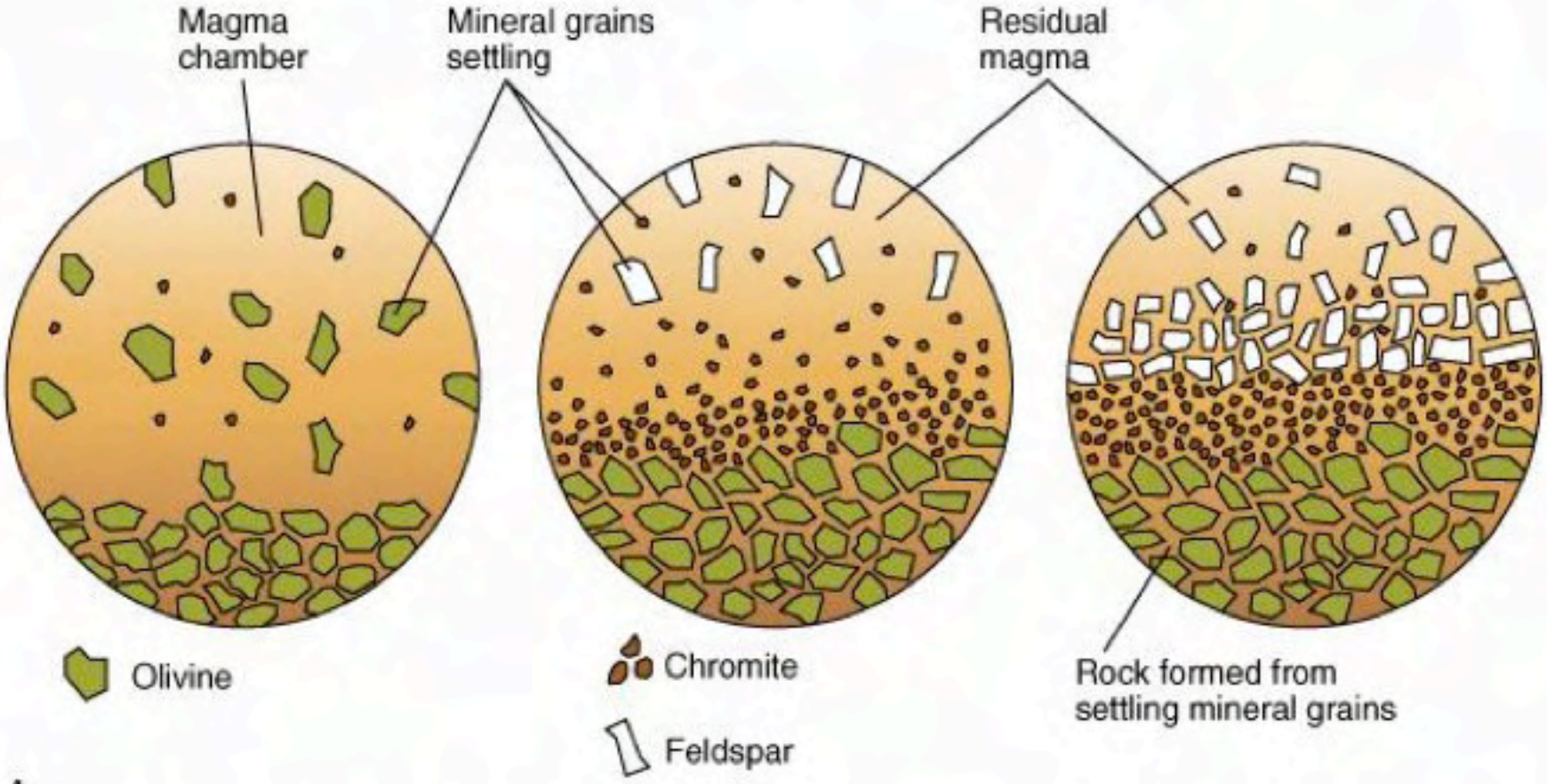
Winter, after Kistler 1990; Miller and Barton 1990; Armstrong 1990

Granites crustaux / mantelliques



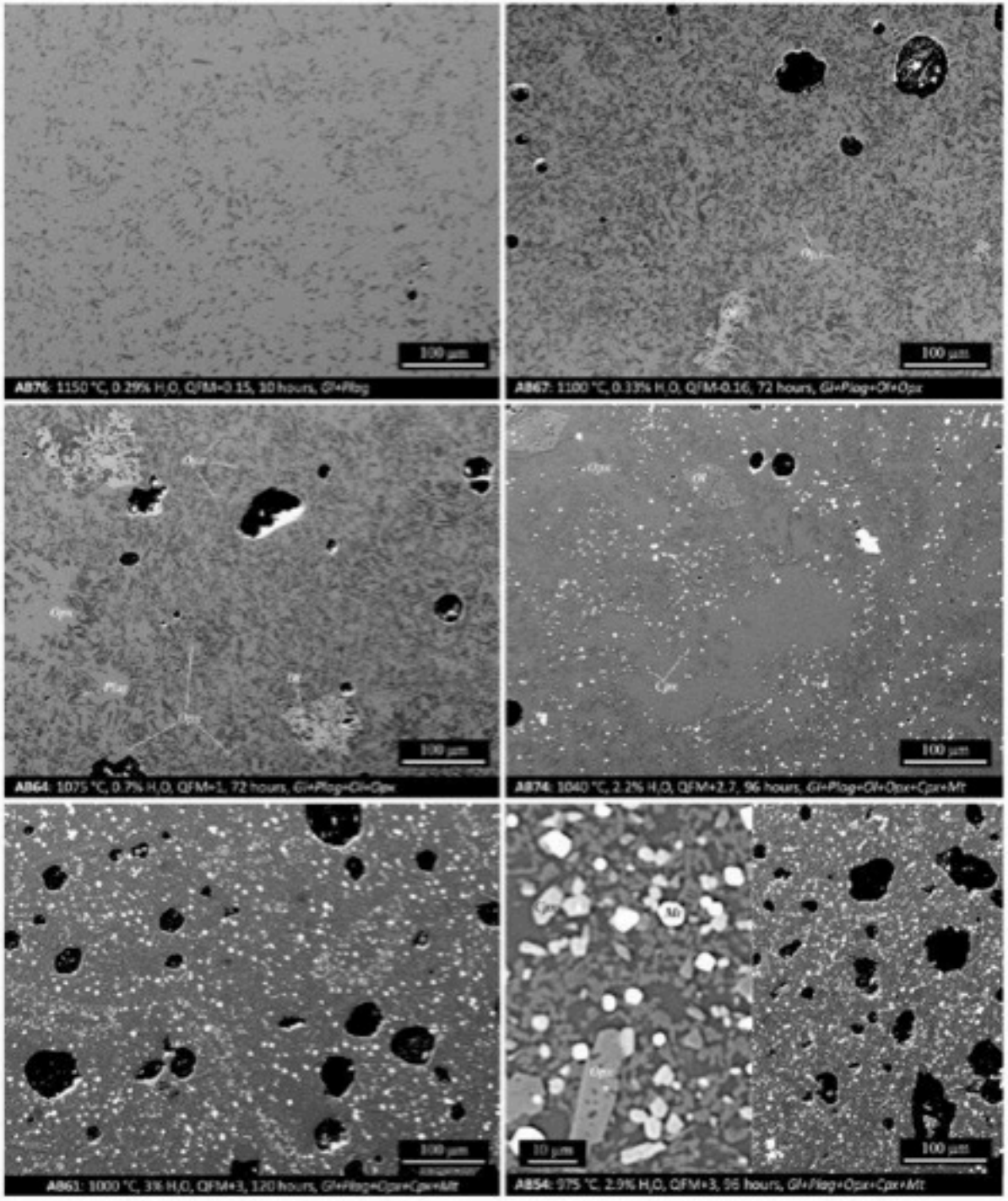
Winter, after Kistler 1990; Miller and Barton 1990; Armstrong 1990

Cristallisation fractionnée

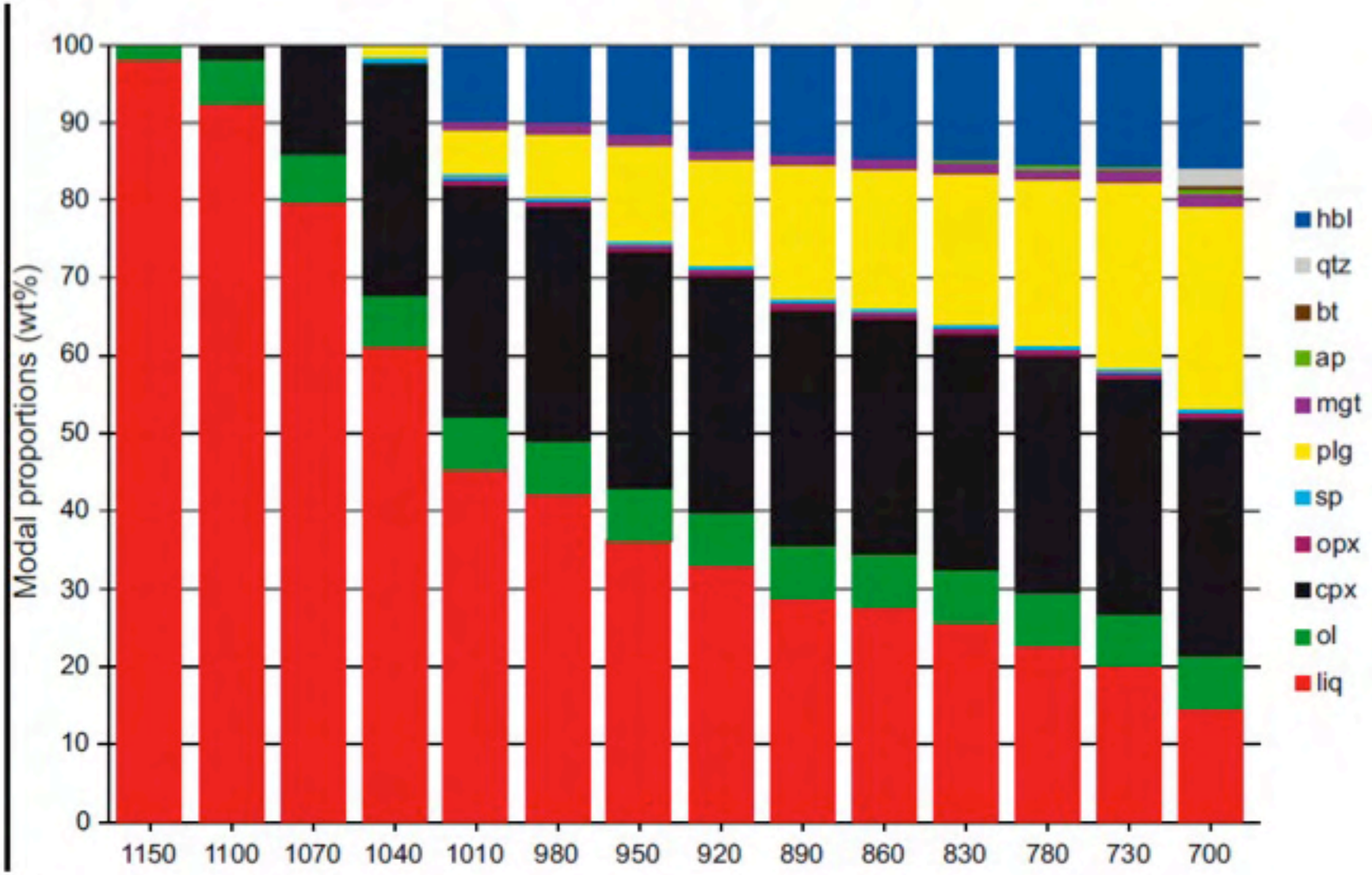


Cumulats

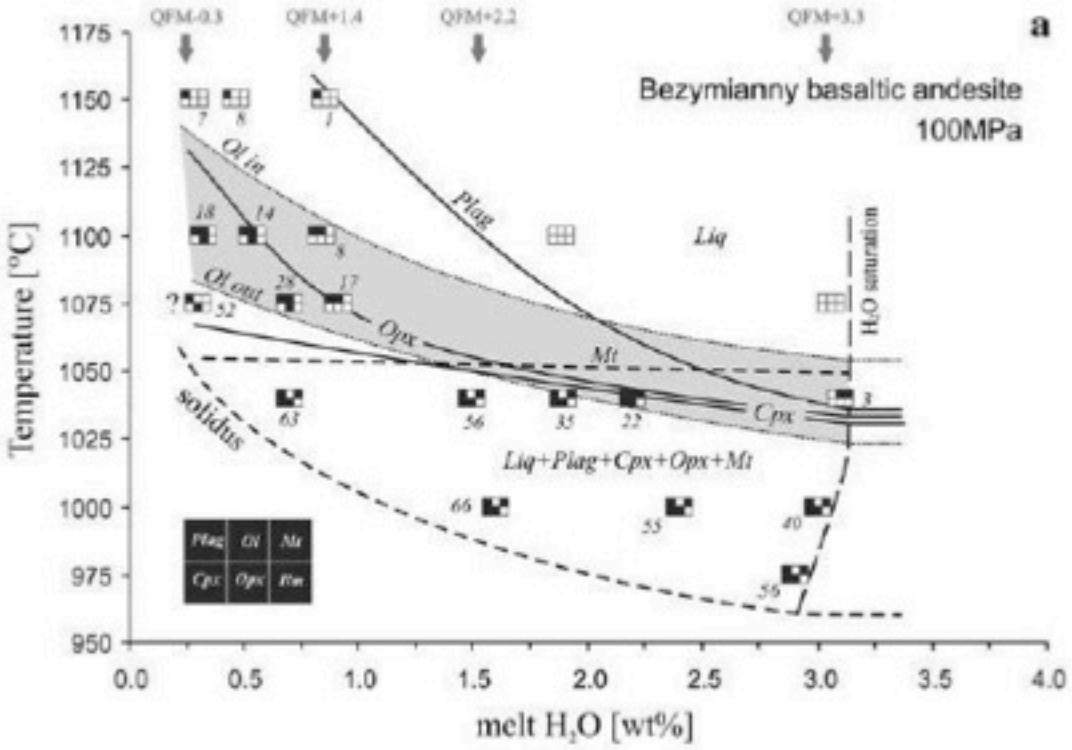
Des granites par cristallisation fractionnée de basaltes (riches en eau)



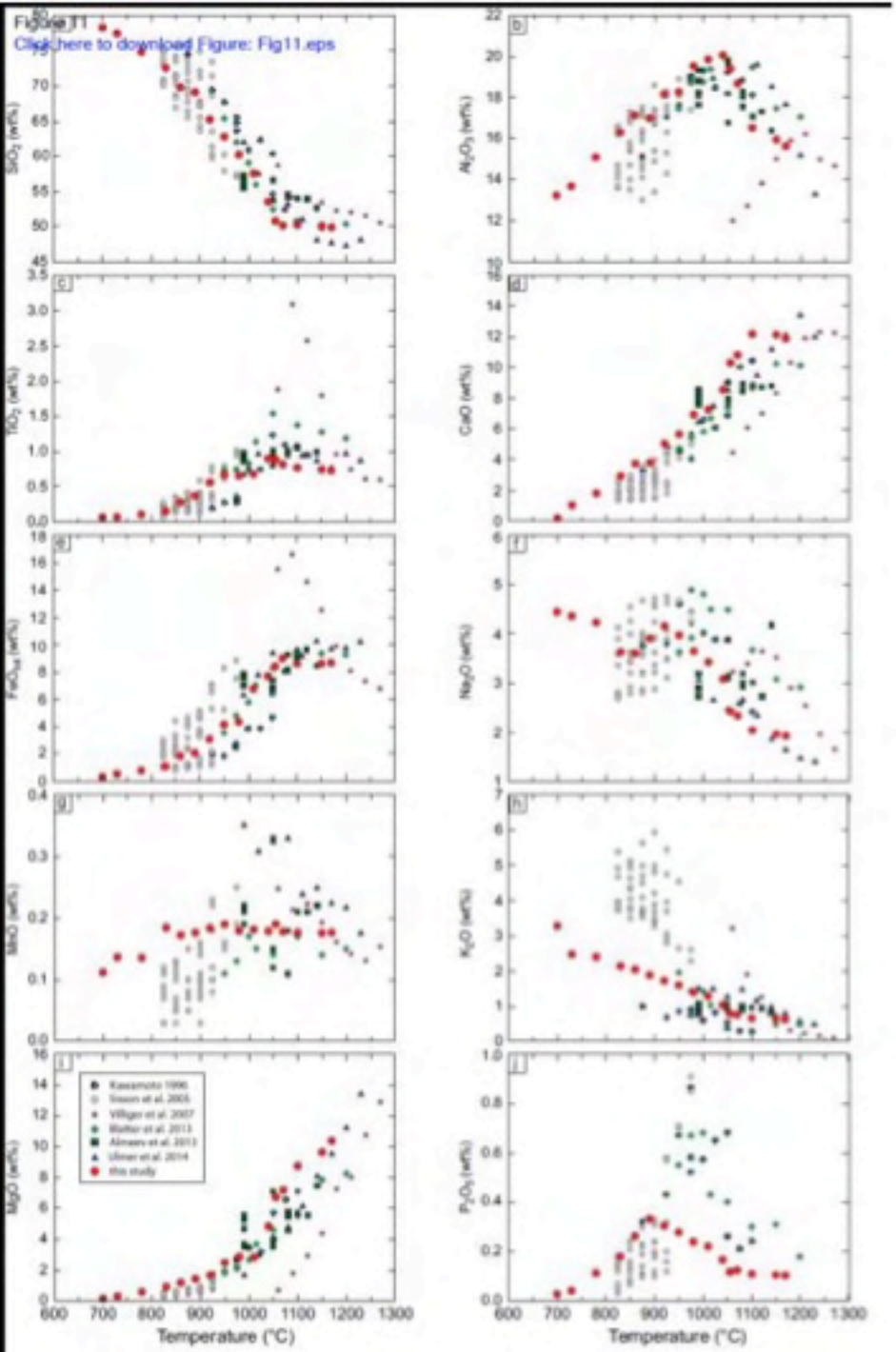
Almeev et al. 2013



Nandedkar et al. 2014



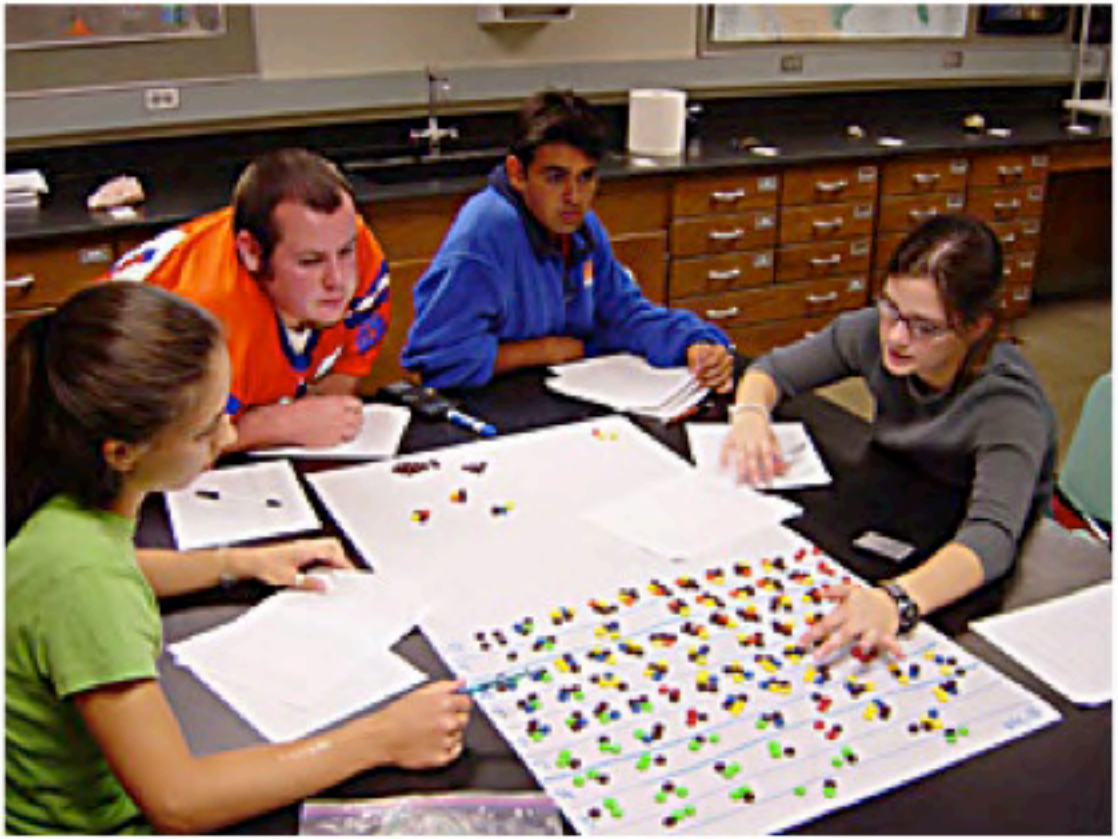
Almeev et al. 2013



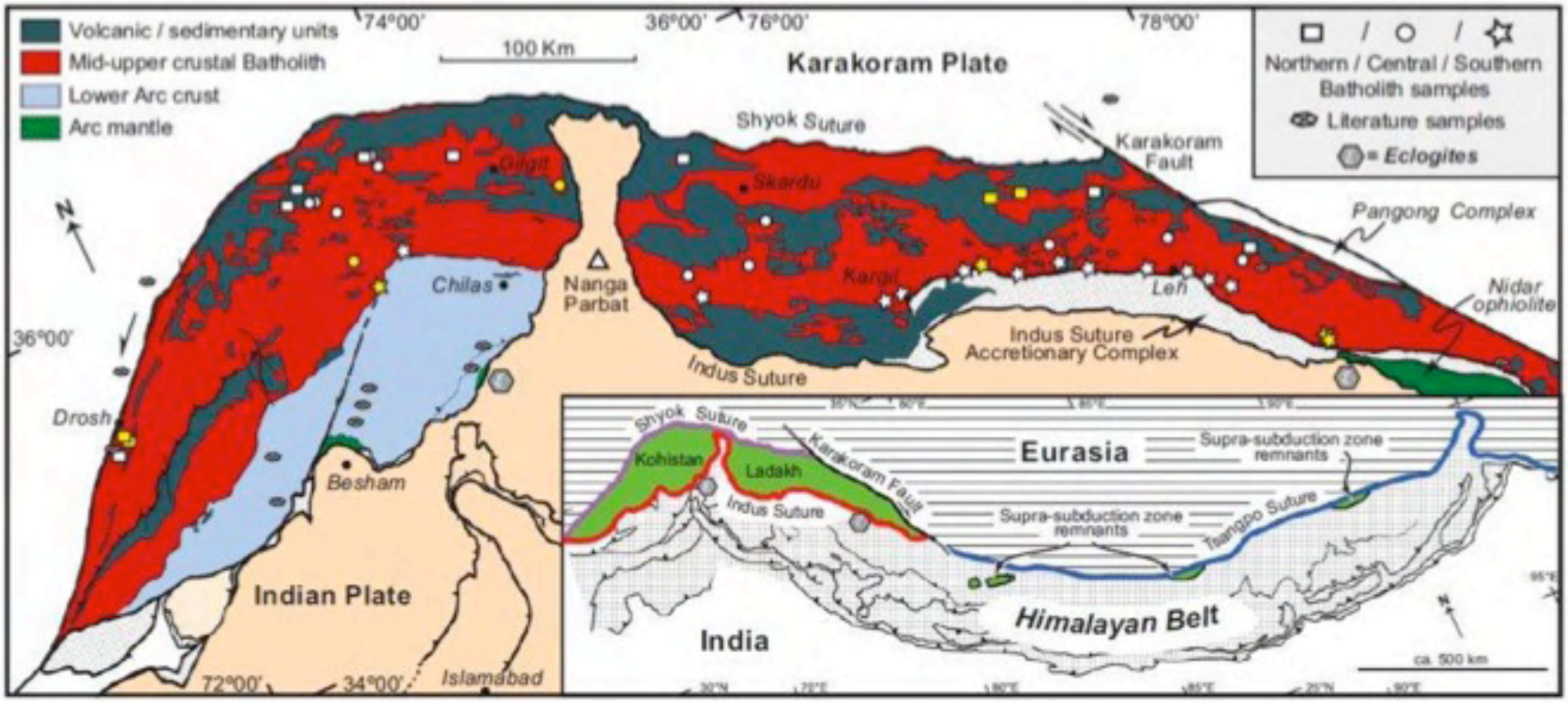
Evolution des liquides

Nandedkar et al. 2014

TP

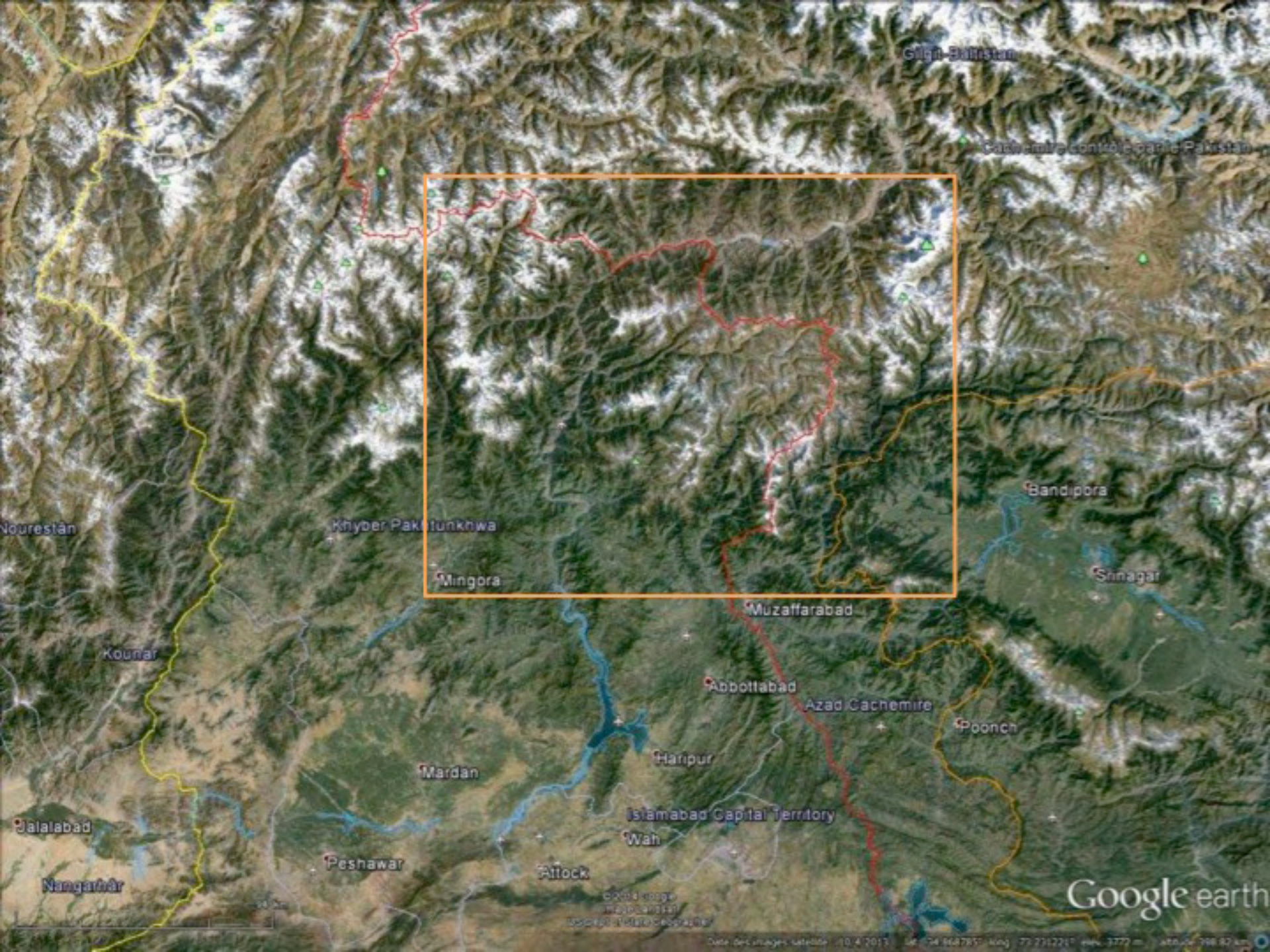


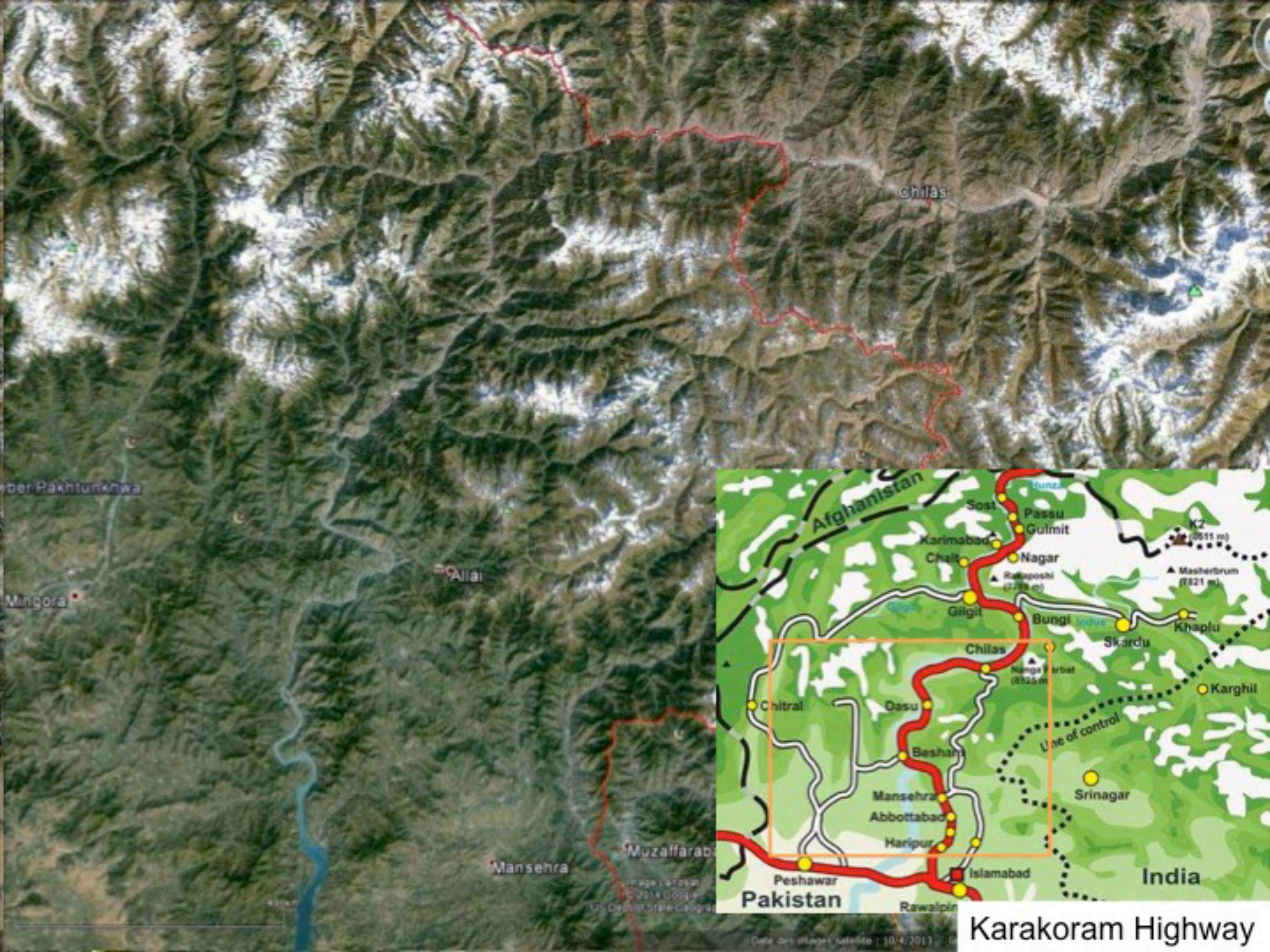
Le (paléo)arc du Kohistan, Pakistan



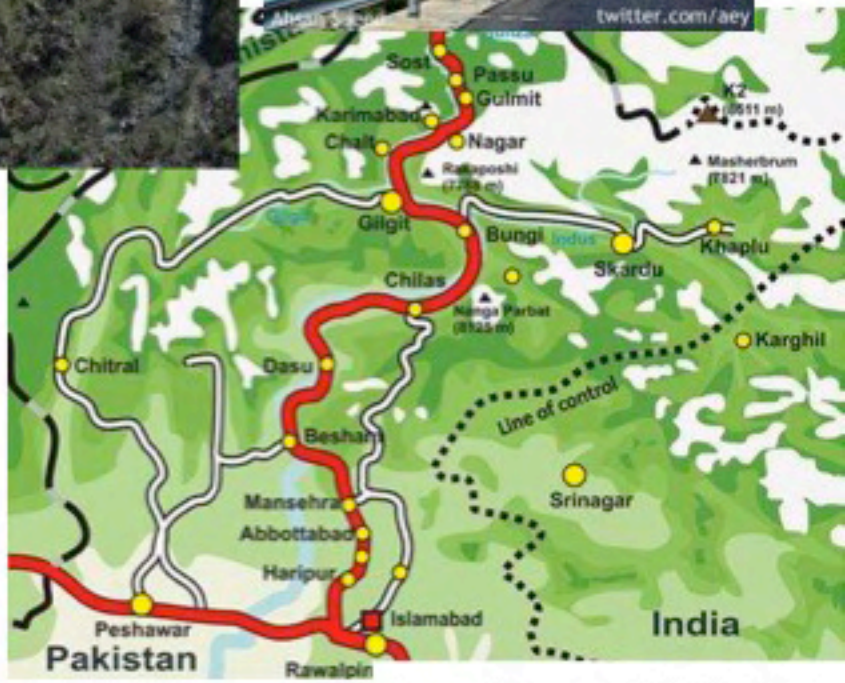
Bouilhol et al. 2013


Bichkek
Kirghizistan
Tachkent
Ouzbékistan
Tadjikistan
Douchanbé
Kaboul
Afghanistan
Pakistan
Pendjab
Chandigarh
Haryana
Delhi
Uttar Pradesh
Rajasthan
Bihar
Jharkhand
Bengale-Occidental
Odisha
Madhya Pradesh
Chhattisgarh
Népal
Katmandou
Bhoutan
Thimphou
Inde
Google earth

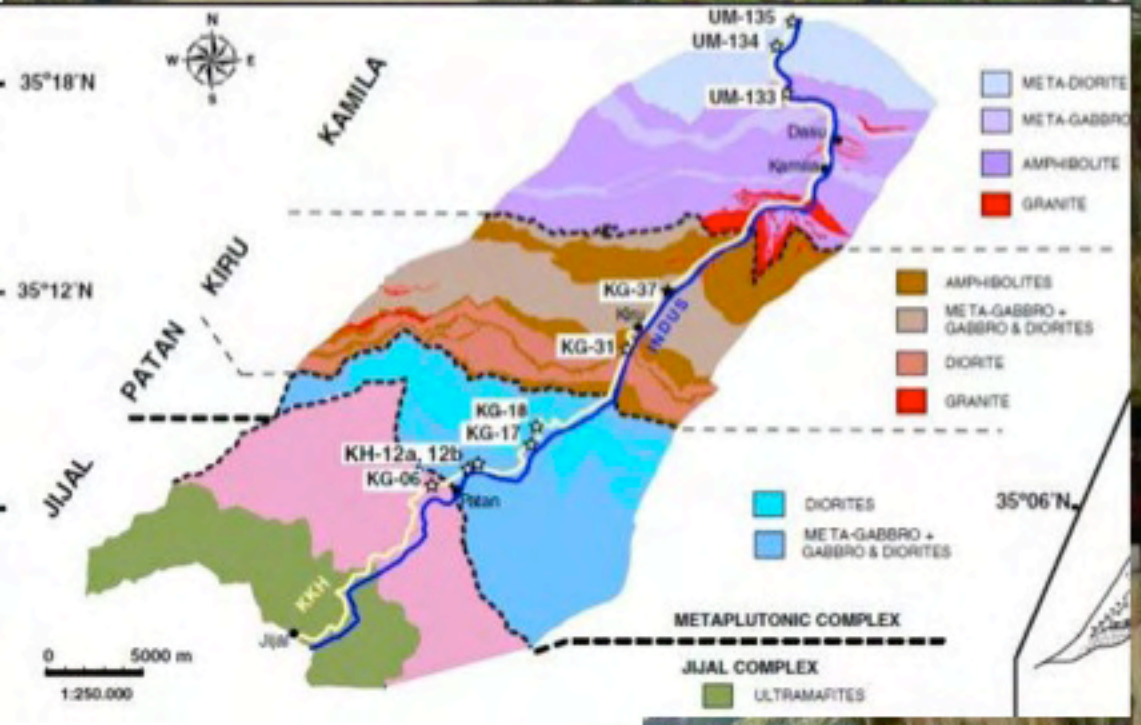

Gilgit-Baltistan
Bandipora
Srinagar
Nouristan
Khyber Pakhtunkhwa
Mingora
Muzaffarabad
Kounar
Abbottabad
Azad Kashmir
Poonch
Haripur
Mardan
Islamabad Capital Territory
Wah
Jalalabad
Peshawar
Attock
Nangarhar
Google earth



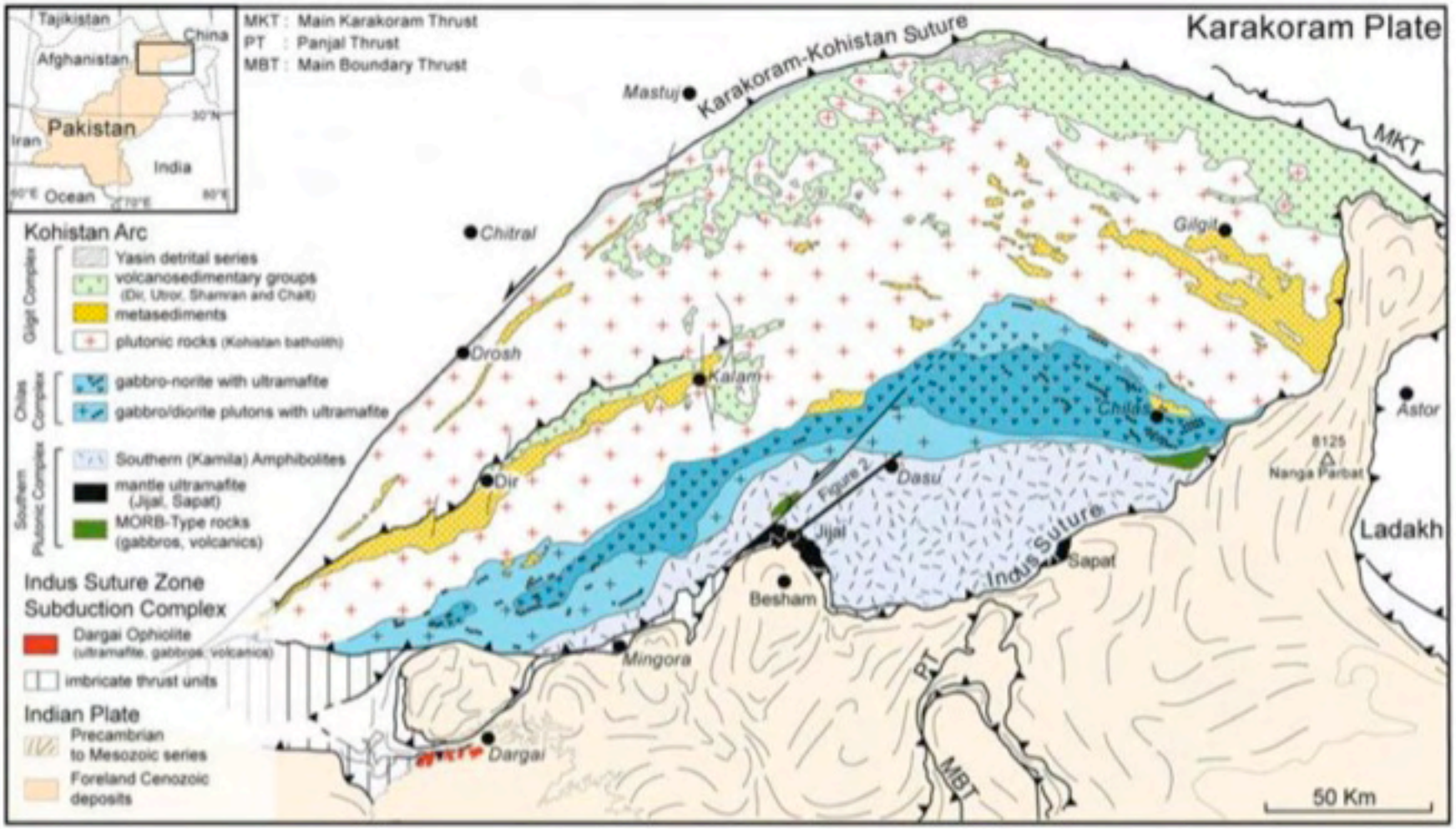
Karakoram Highway



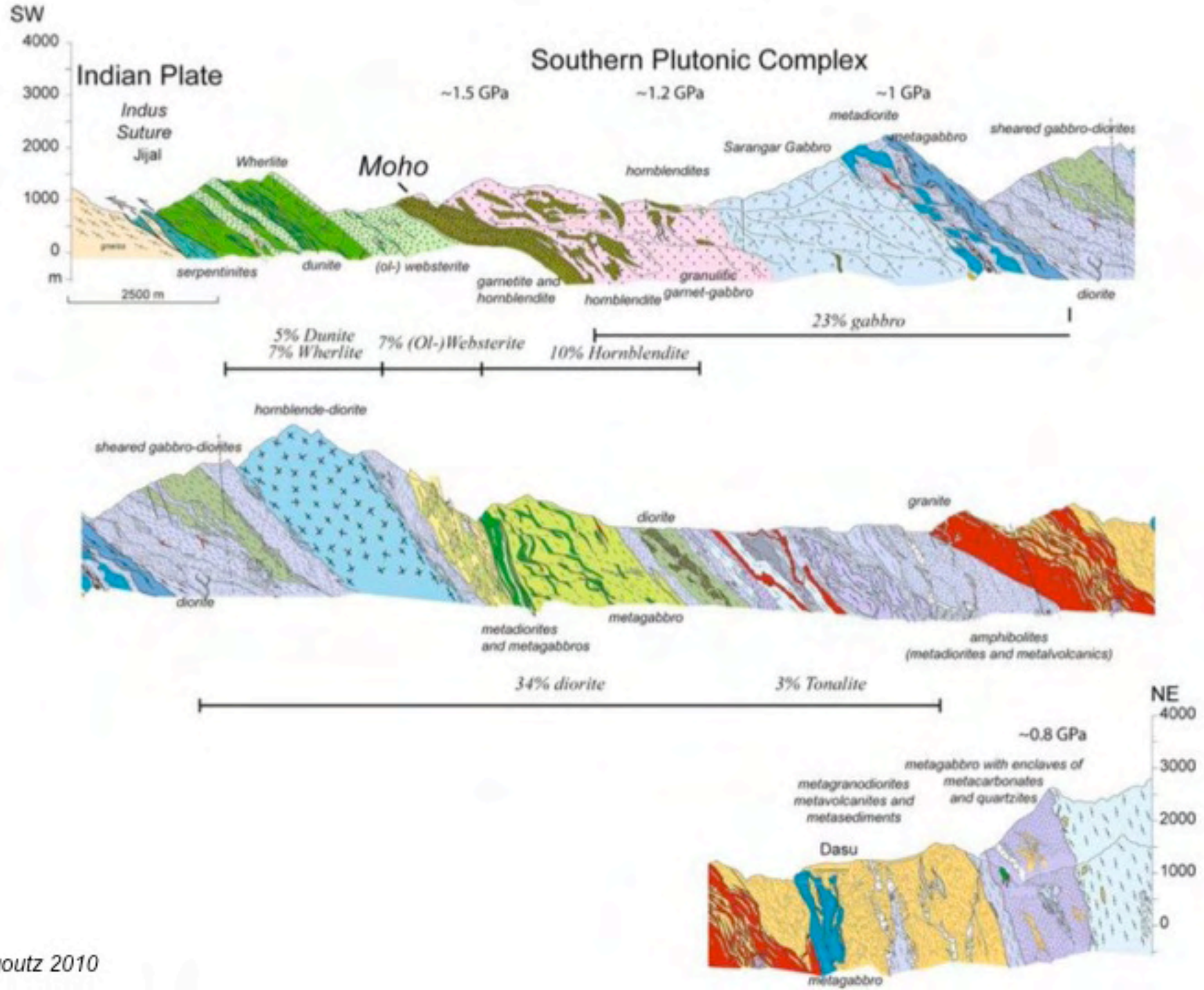
Karakoram Highway


N
W
E
S
35°18'N
35°12'N
35°06'N
KAMILA
KIRU
PATAN
JIJAL
UM-135
UM-134
UM-133
Daku
Kamila
KG-37
KG-31
INDUS
KG-18
KG-17
KH-12a, 12b
KG-06
Patan
KKH
Jijal
0
5000 m
1:250.000
META-DIORITE
META-GABBRO
AMPHIBOLITE
GRANITE
AMPHIBOLITES
META-GABBRO + GABBRO & DIORITES
DIORITE
GRANITE
DIORITES
META-GABBRO + GABBRO & DIORITES
METAPLUTONIC COMPLEX
JIJAL COMPLEX
ULTRAMAFITES

Le (paléo)arc Crétacé du Kohistan, Pakistan



Jagoutz 2010



Jagoutz 2010

Datation des roches du Kohistan

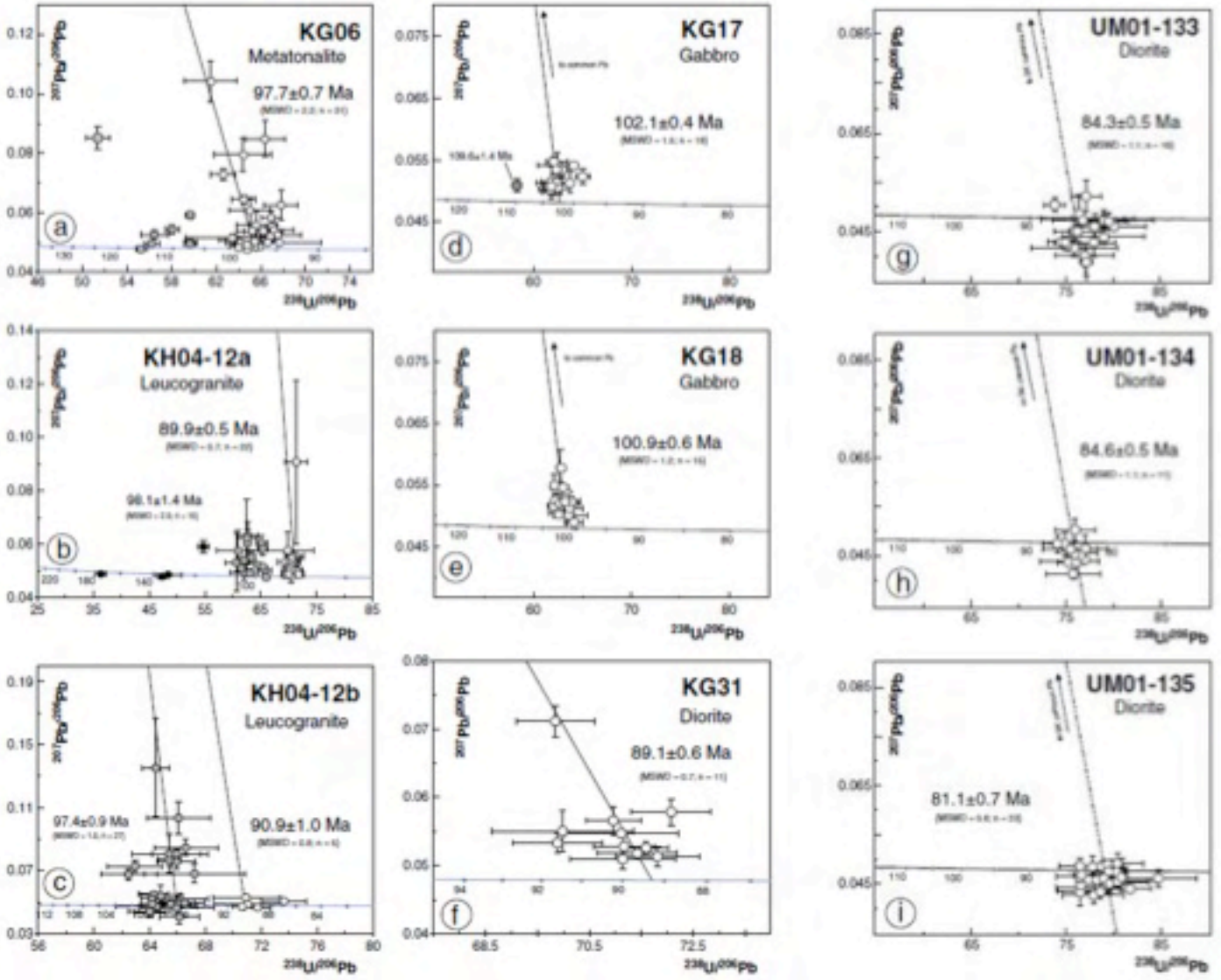


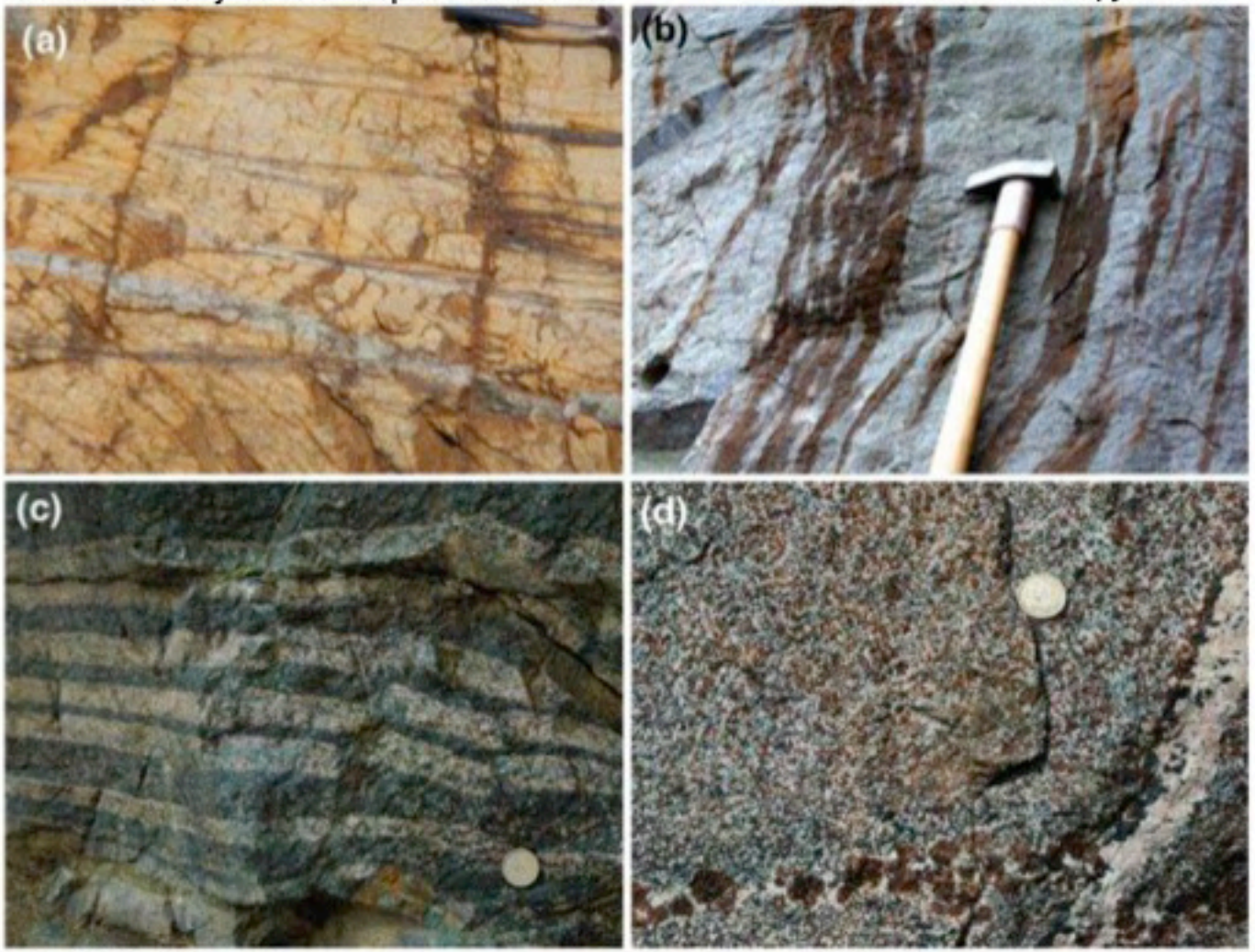
Fig. 2 (Continued).

Bosch et al. 2011

Les roches du Kohistan

Couches de chromitite et dykes de Cr-diopside dans dunite

« flammes » de dunite dans pyroxenite



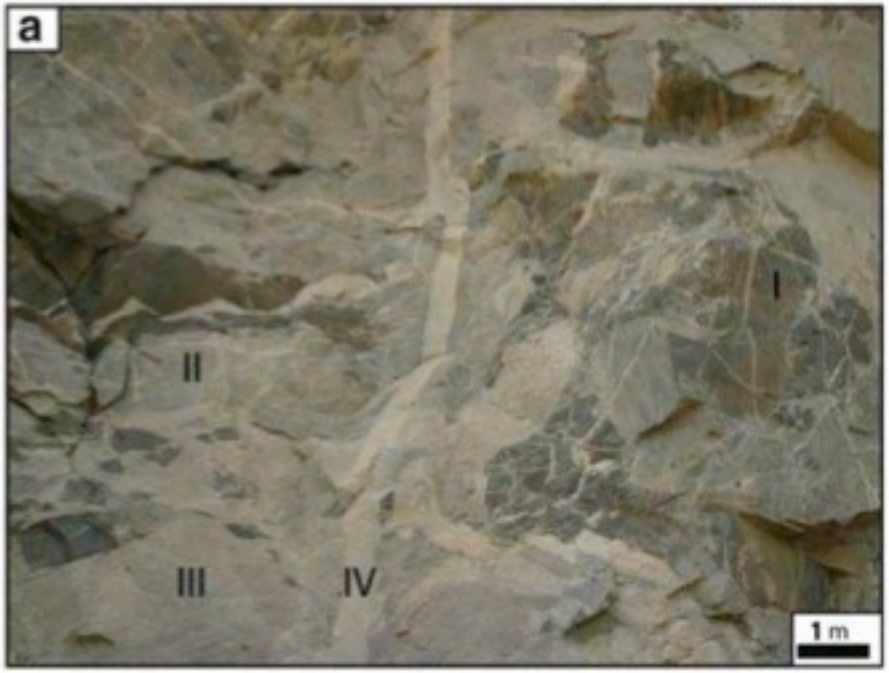
Cumulat à grt et hbl

Gabbro à grt

Jagoutz 2010

Diorite et tonalite

Granodiorite, granite



Jagoutz 2010

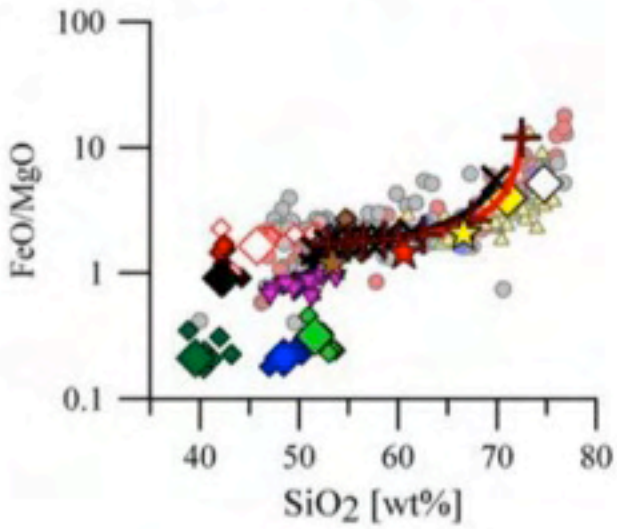
Cumulats

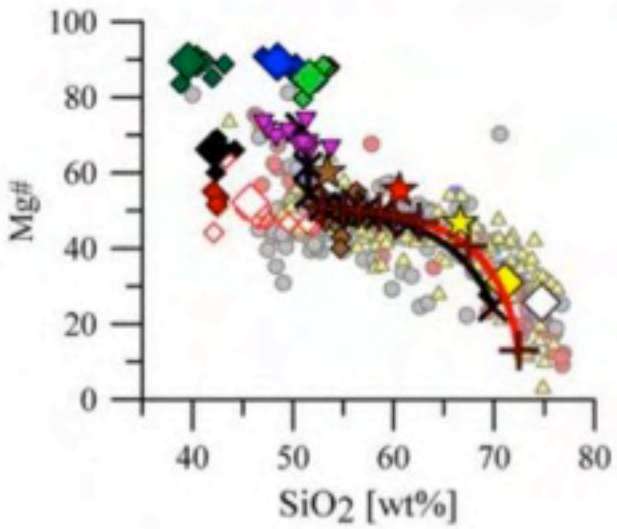
Jagoutz 2010

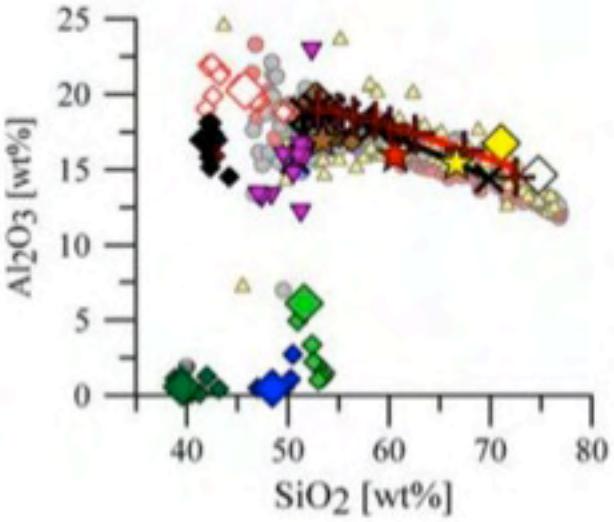
Percolation de liquide gabbroïque dans roches UM

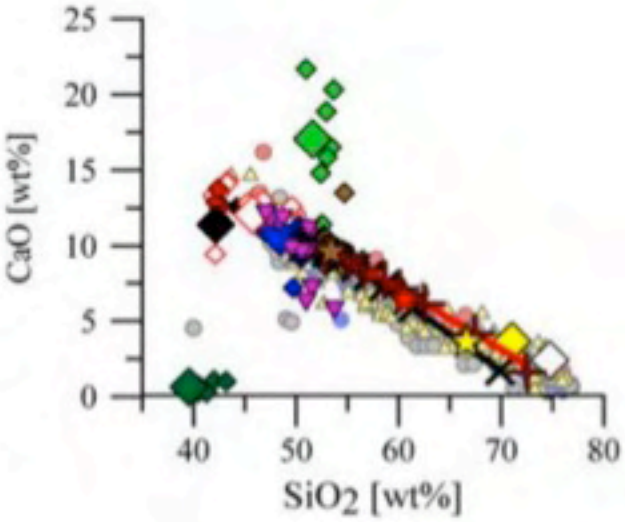
P. Bouilhol

Différentiation de la croûte d'arc au Kohistan



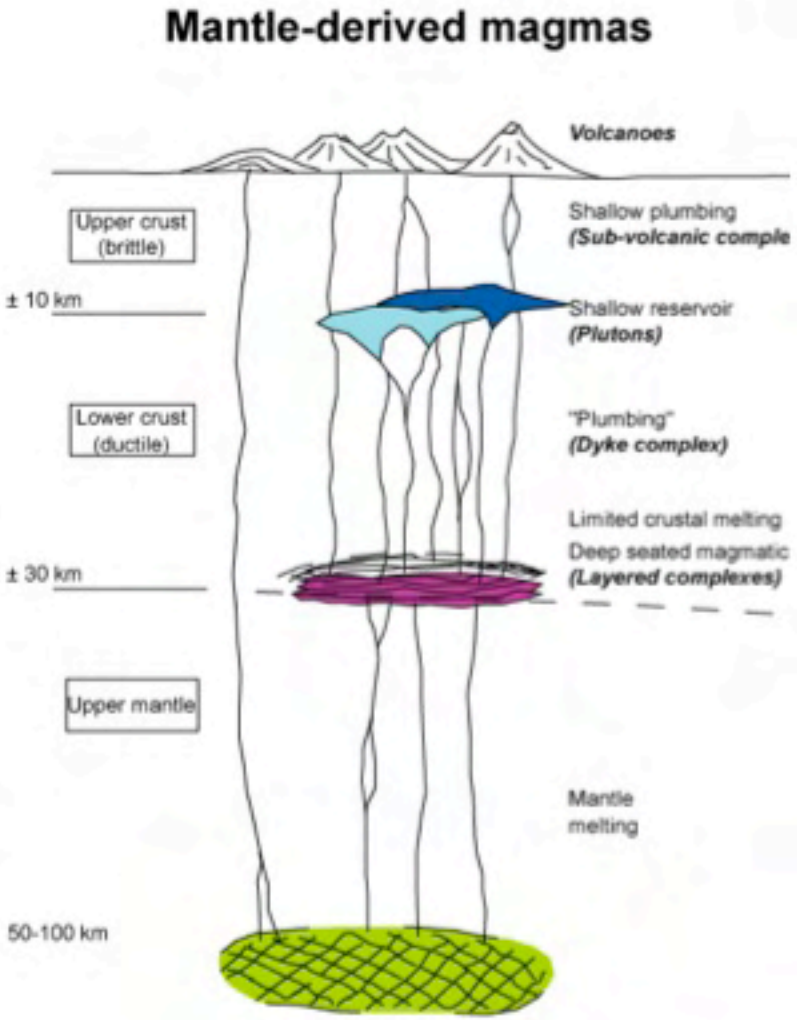






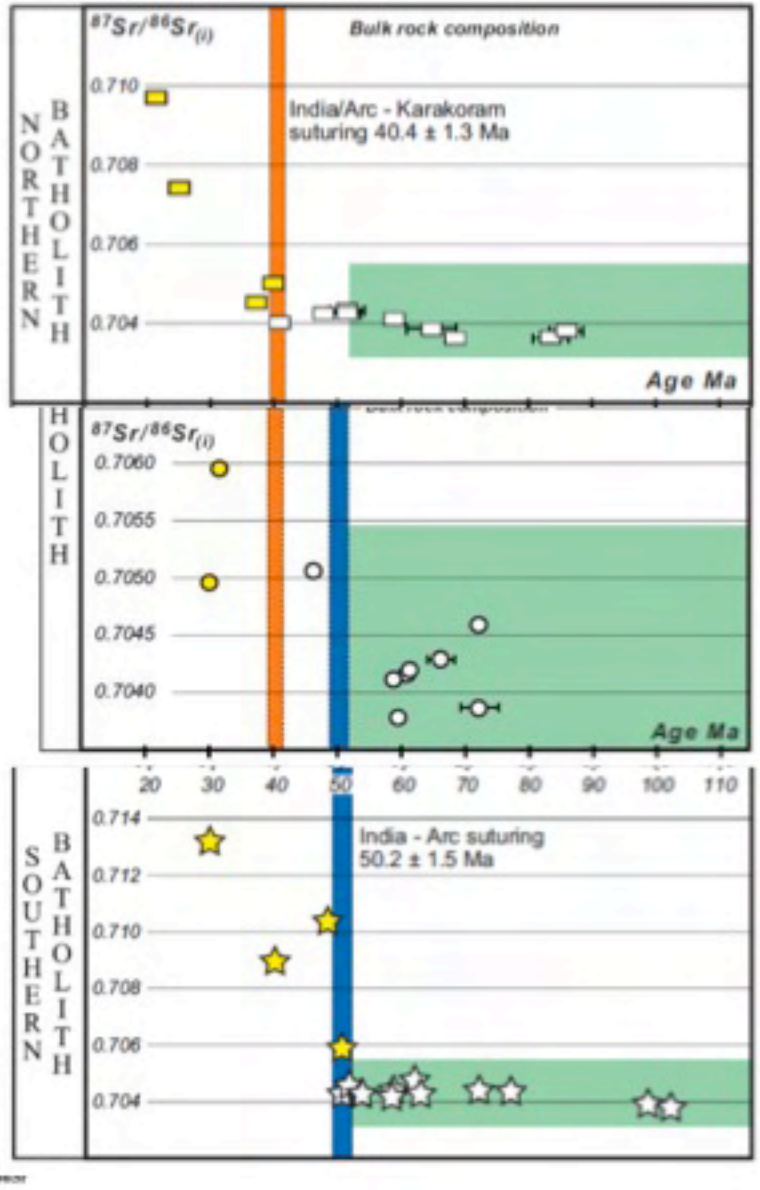
Jagoutz 2010

Un système type Kohistan



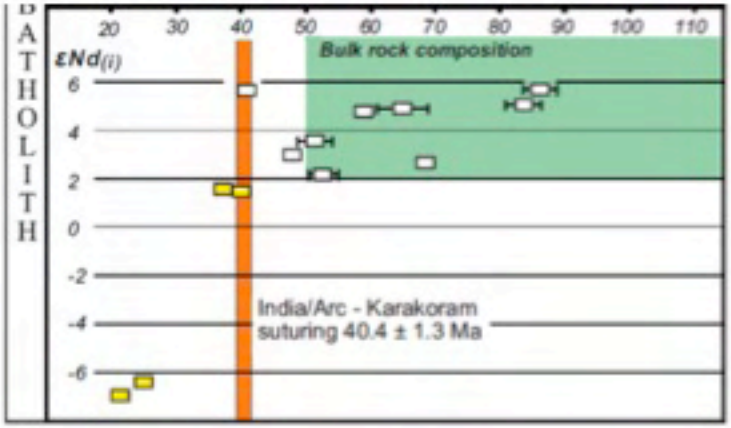
(JFM 06, modified from an original drawing by B. Barbarin)

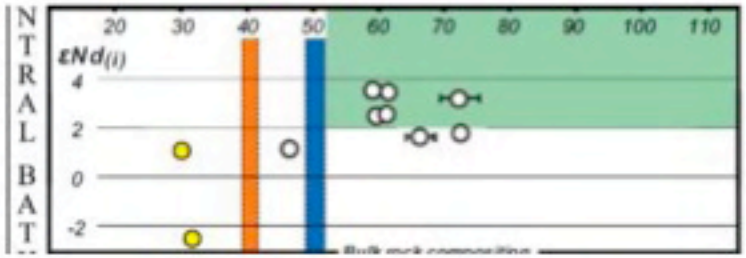
De la subduction à la collision

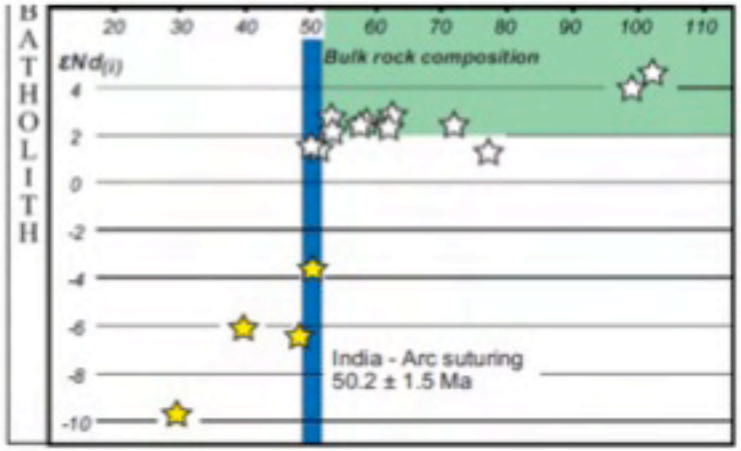


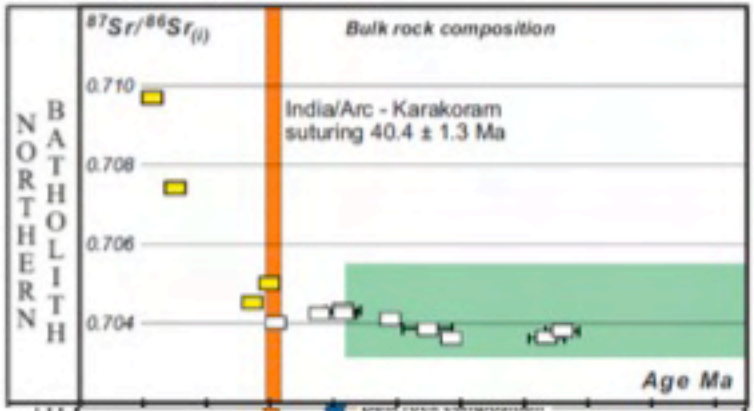
Bouilhol et al. 2013

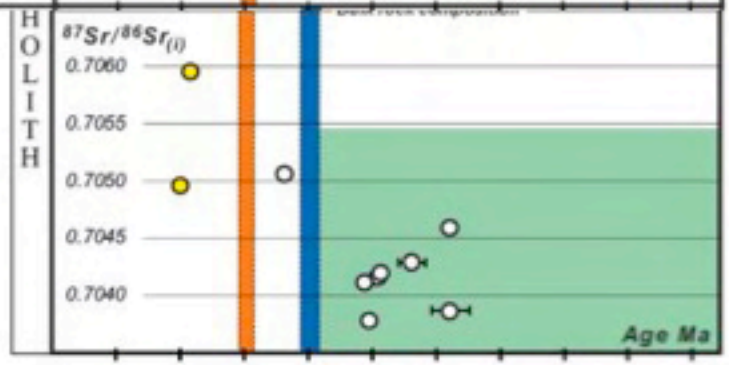
De la subduction à la collision

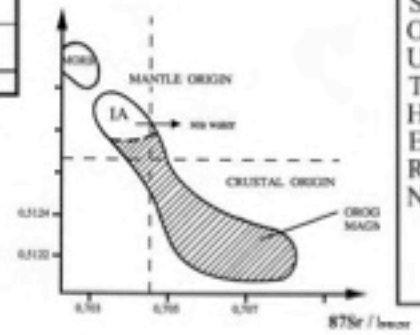












Bouilhol et al. 2013

Les granites

4. Granites et cycle orogénique

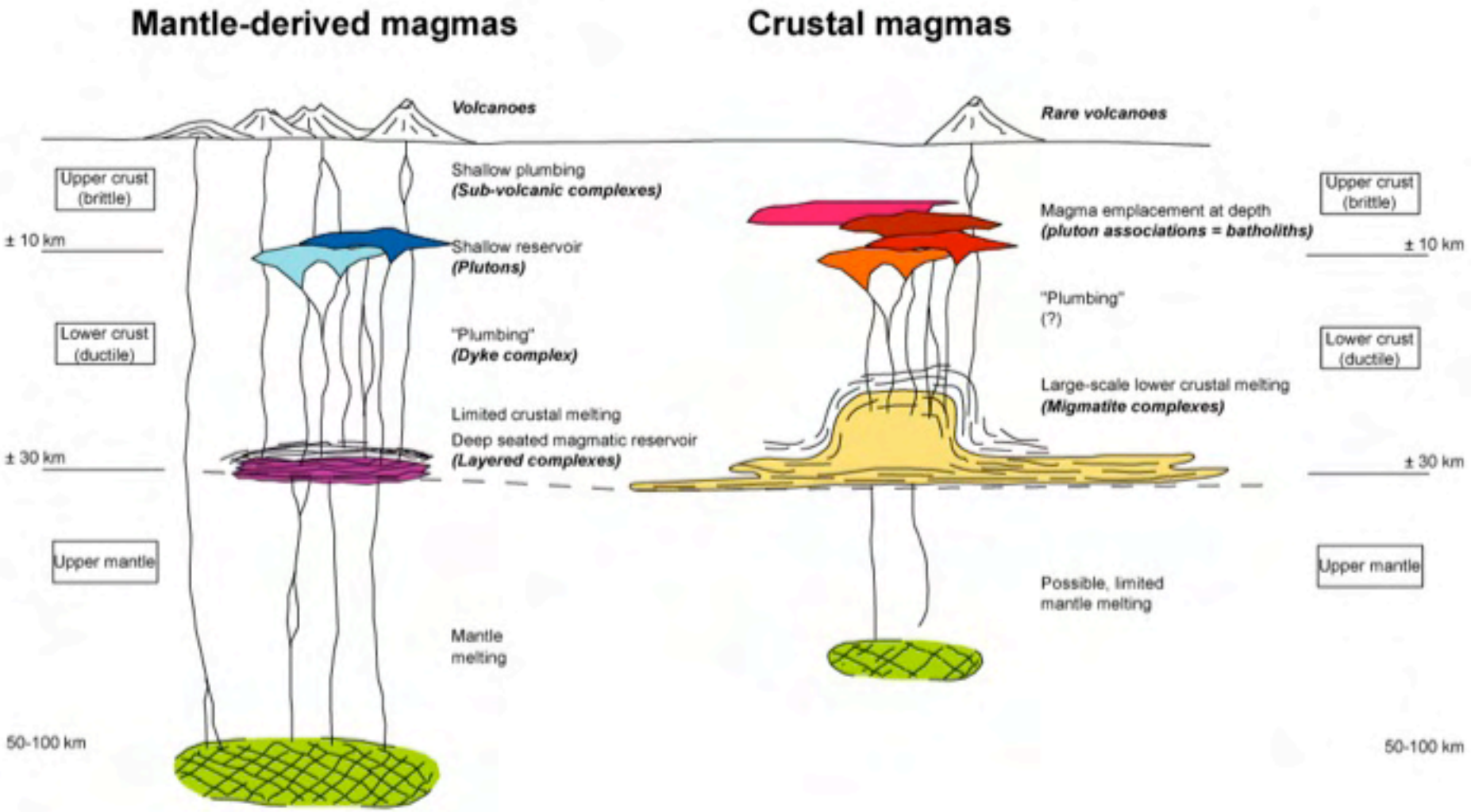
Jean-François Moyen

Université de Lyon

Université Jean Monnet Saint-Étienne

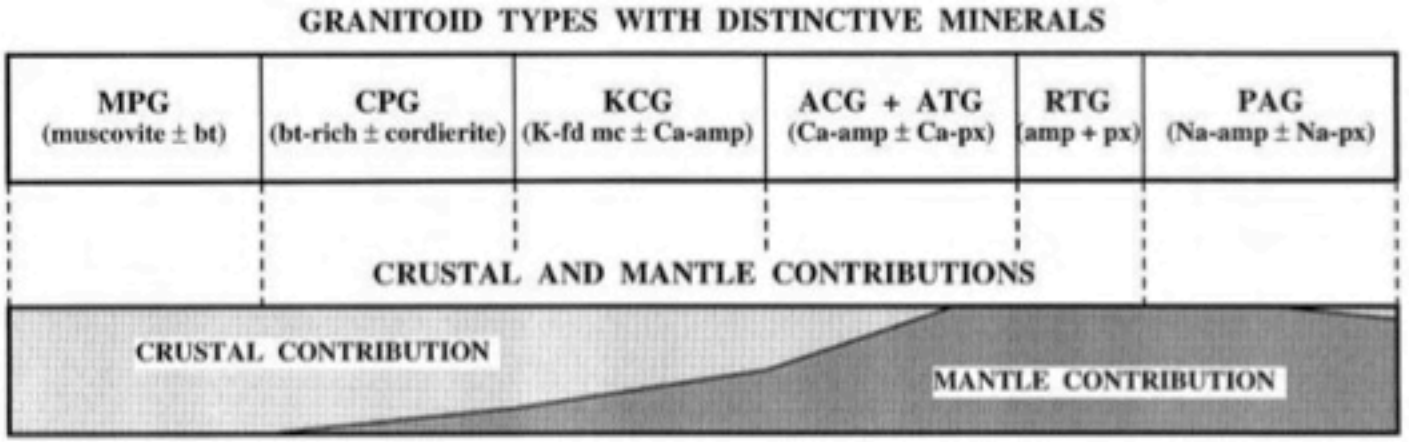
Laboratoire Magmas & Volcans

Deux systèmes granitiques

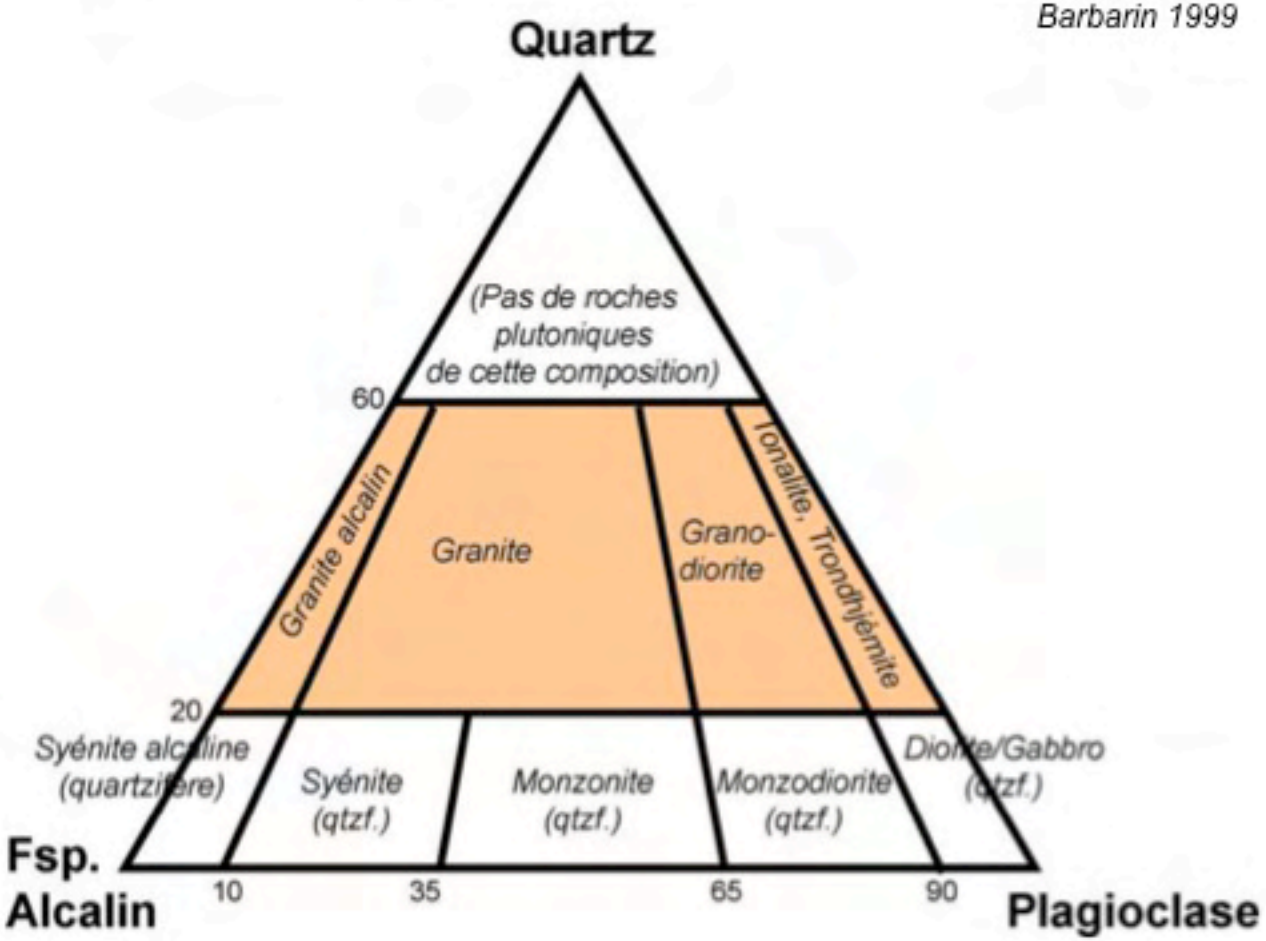


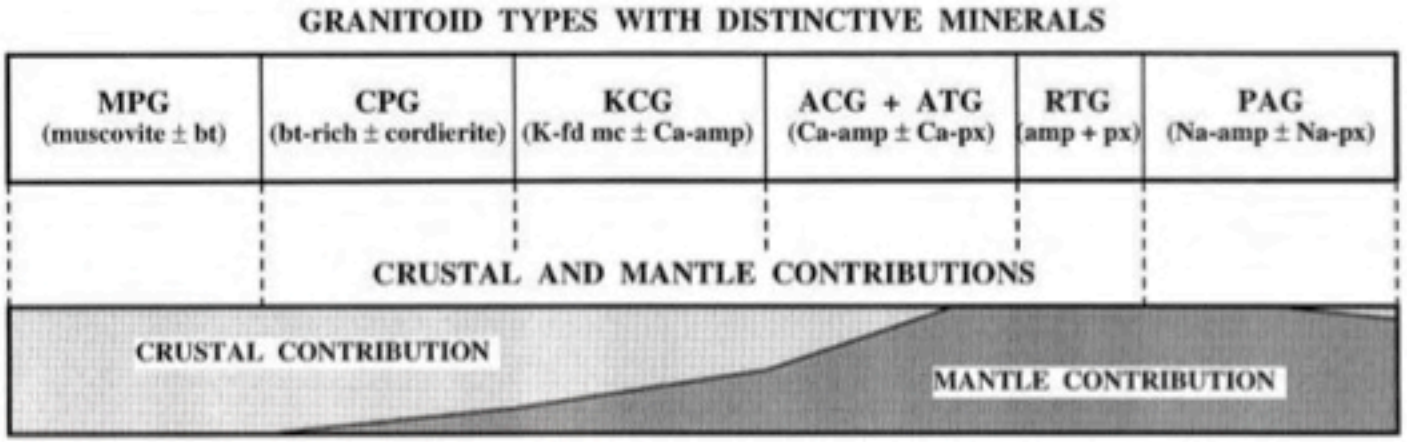
(JFM 06, modified from an original drawing by B. Barbarin)

	GRANITES ALUMINEUX (froid et hydraté)	GRANITES CALCO-ALC. et ALC. (chaud et sec)
[1] PRODUCTION DU MAGMA	• Fusion crustale (anatexie) • Collection du magma	• Chambre magmatique profonde • Différenciation magmatique • Fusion crustale (anatexie) • Mélanges de magmas
[2] TRANSFERT DU MAGMA MISE EN PLACE	• Transfert limité ou nul • Montée diapirique	• Transfert important • Utilisation d'un réseau de conduits • Gonflement ("Ballooning") • Subsidence souterraine • Abbattage ("stoping")
[3] FORMATION DU PLUTON REFROIDISSEMENT	• Métamorphisme de contact faible ou nul • Cristallisation • Diaclasage • Hydrothermalisme	• Métamorphisme de contact souvent très important • Chambre magmatique superficielle • Différenciation in situ • Homogénéisation isotopique • Cristallisation • Diaclasage • Hydrothermalisme
[4] DEFORMATION	• Déformation magmatique, ductile ou cassante	• Déformation magmatique, ductile ou cassante



Barbarin 1999

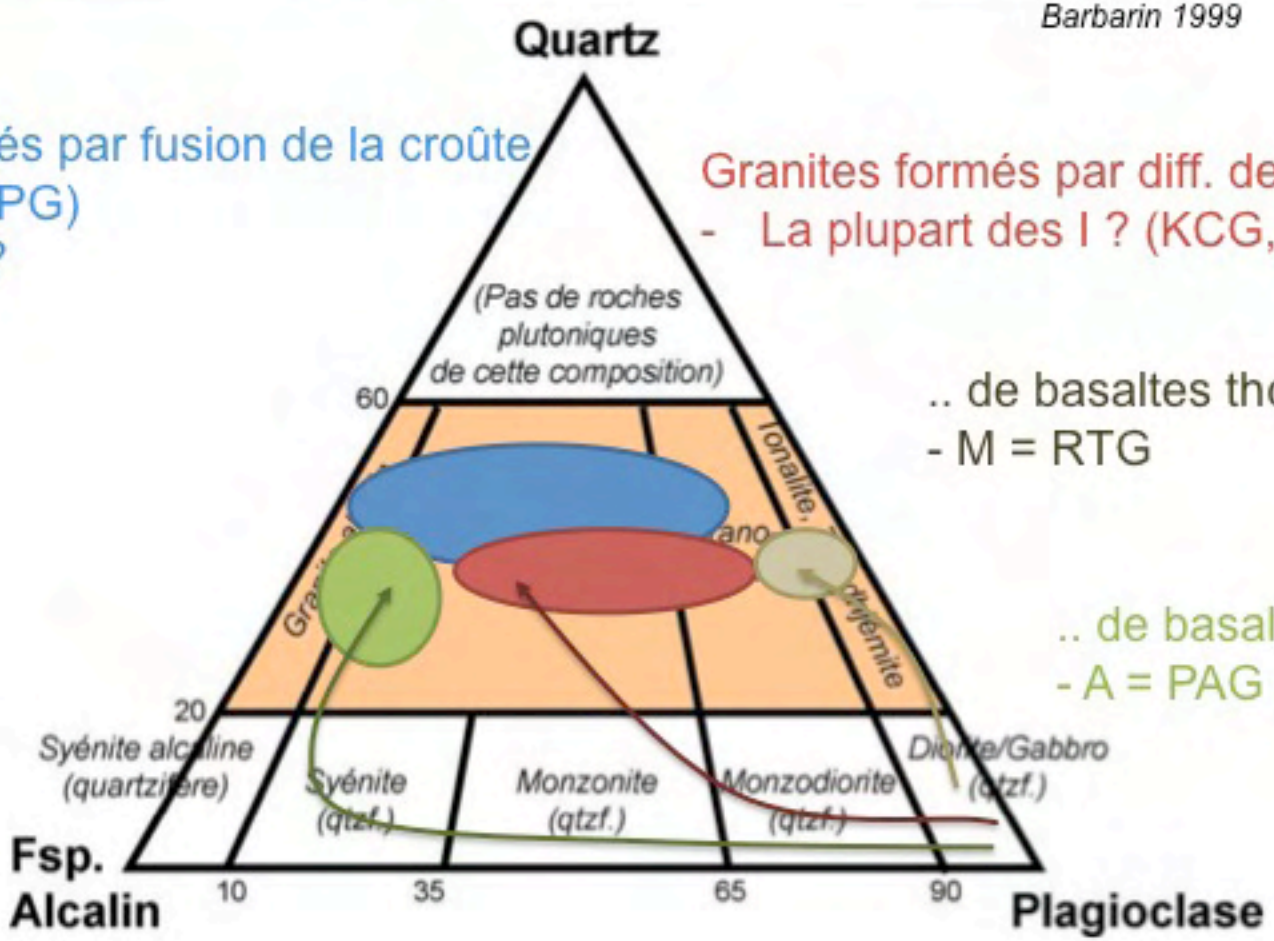




Barbarin 1999

Granites formés par fusion de la croûte
- S (MPG, CPG)
- Certains I ?

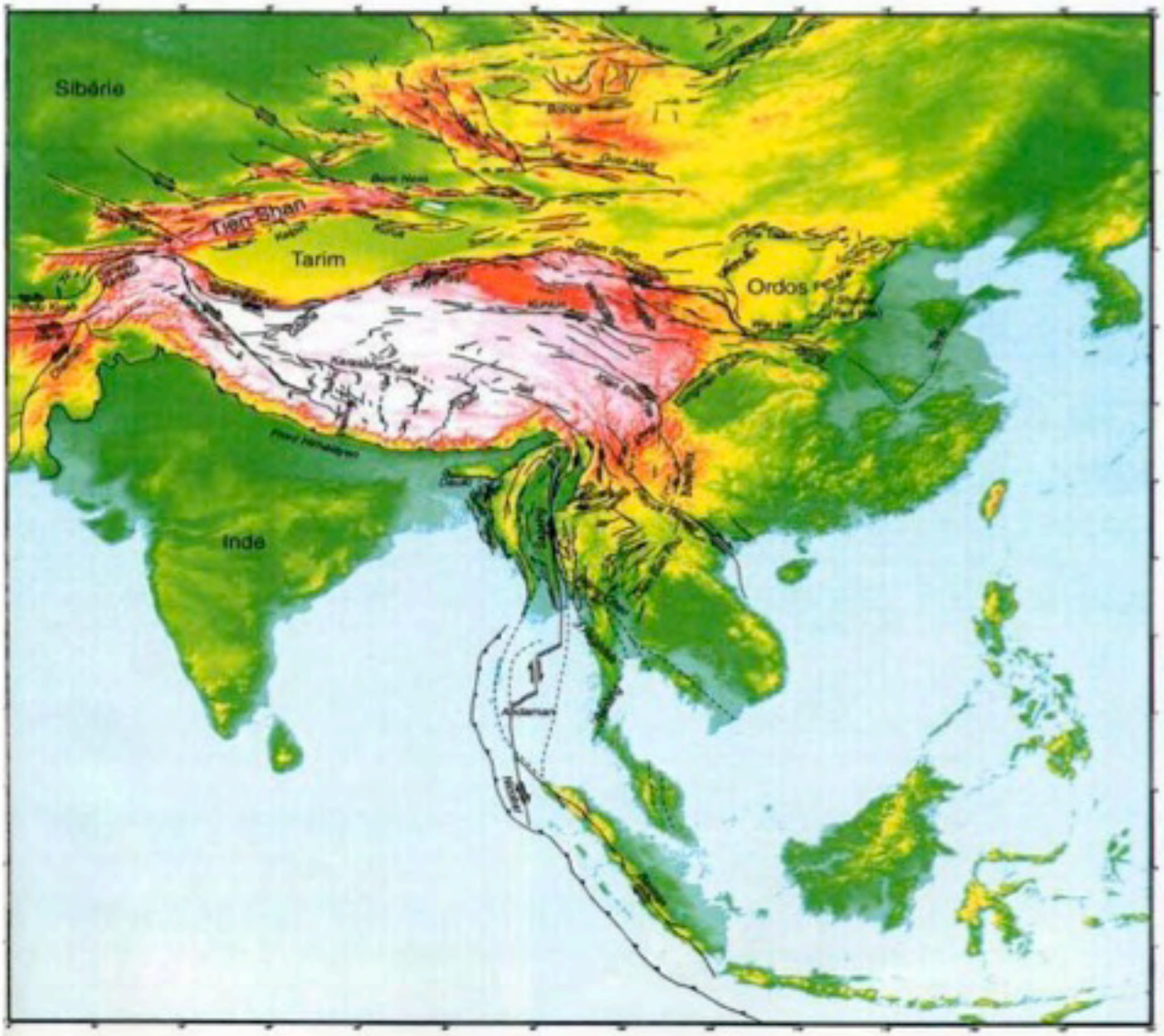
Granites formés par diff. de basaltes d'arc
- La plupart des I ? (KCG, ACG, ATG)

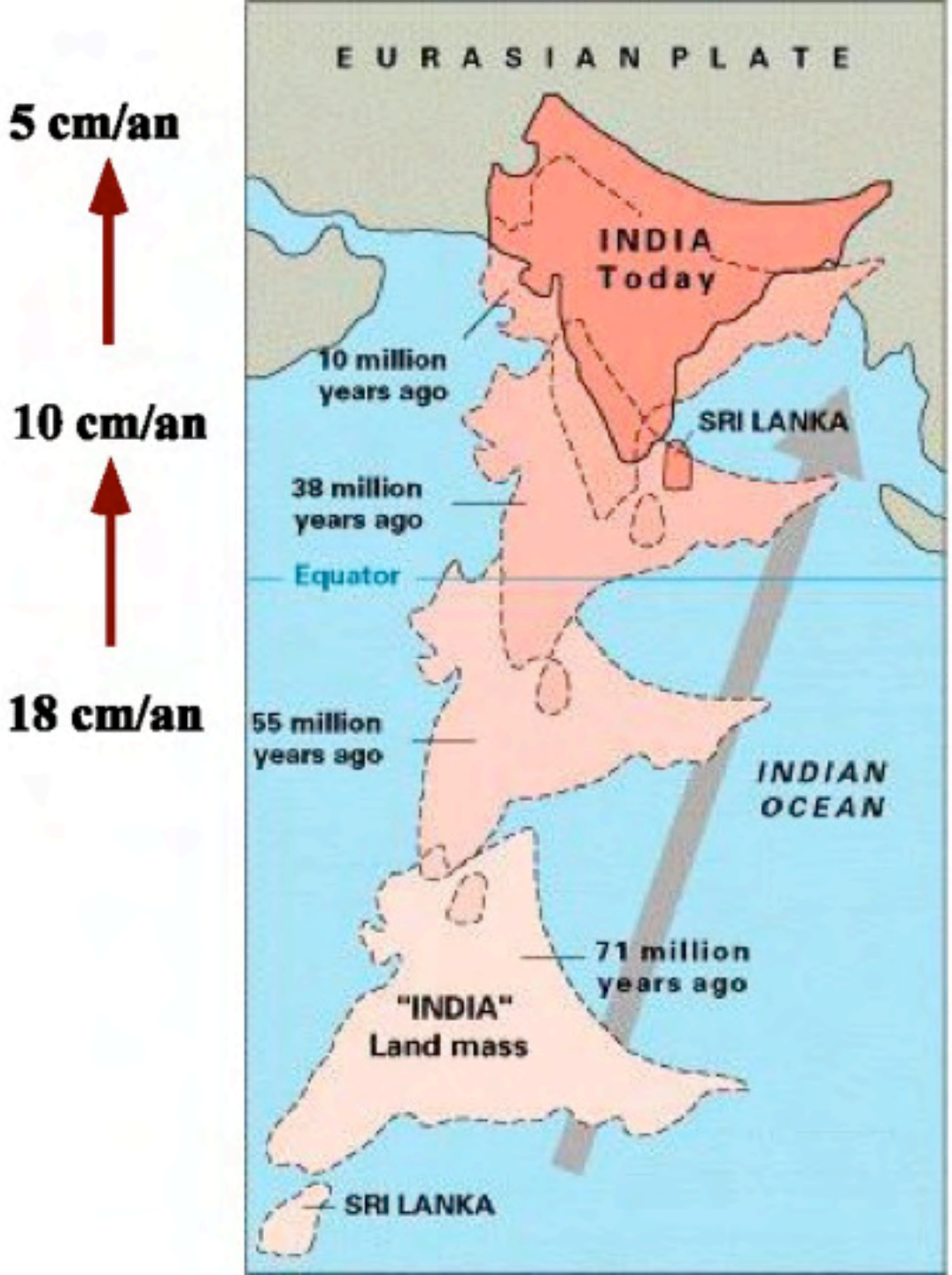


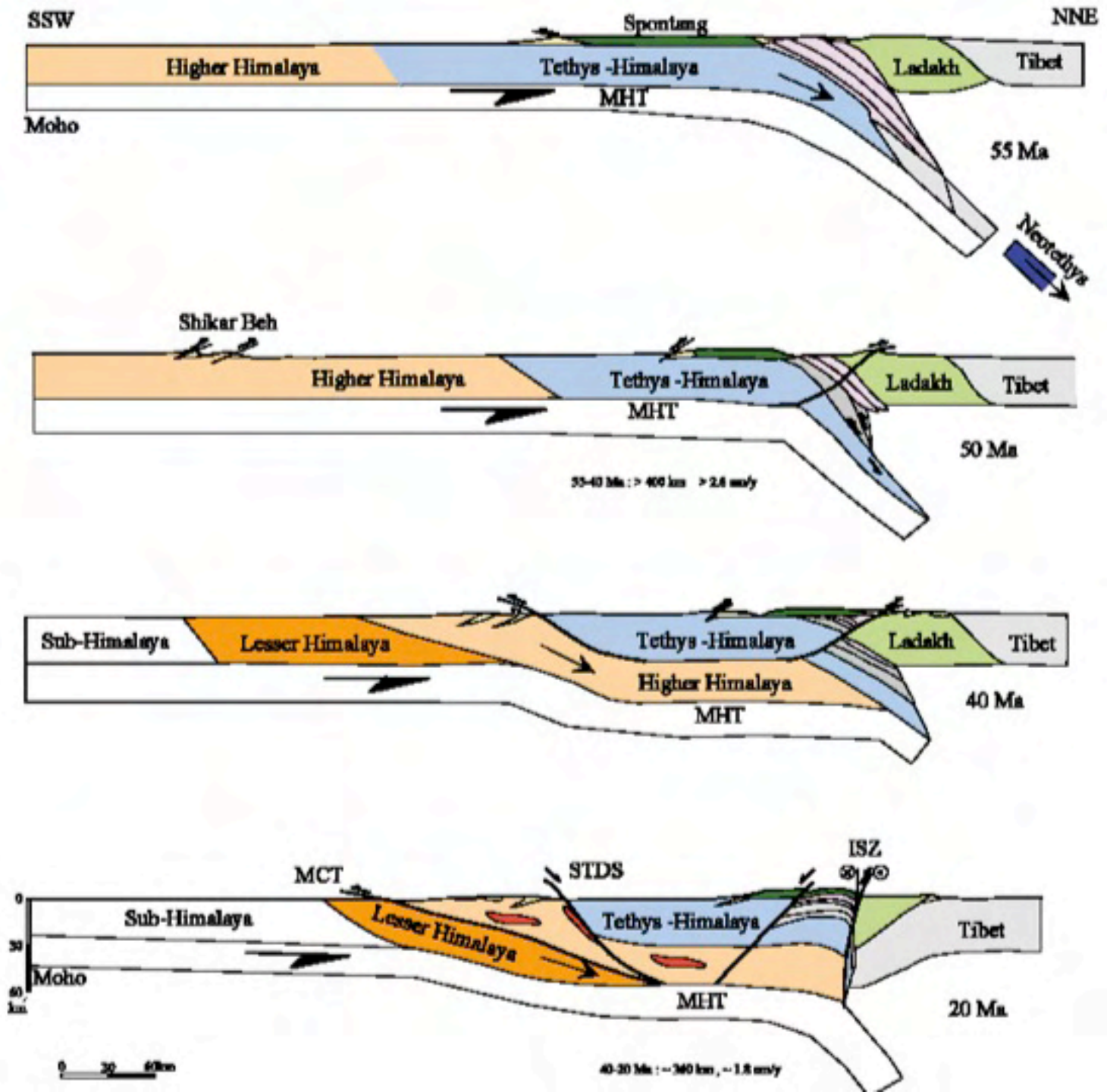
.. de basaltes tholéitiques
- M = RTG

.. de basaltes alcalins
- A = PAG (quoi que…)

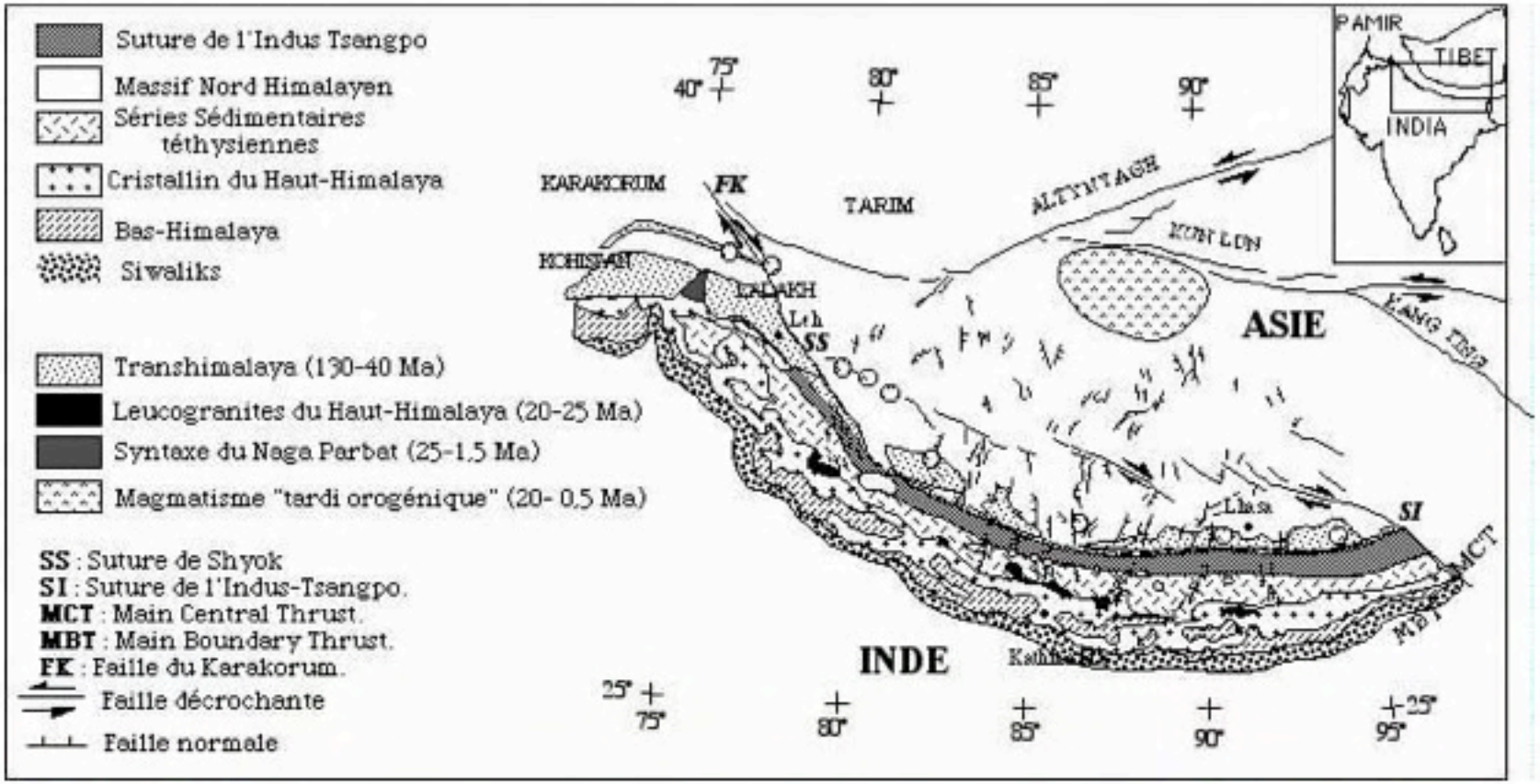
Exemple de l'Himalaya




5 cm/an
10 cm/an
18 cm/an
EURASIAN PLATE
INDIA
Today
10 million
years ago
SRI LANKA
38 million
years ago
Equator
55 million
years ago
INDIAN
OCEAN
71 million
years ago
"INDIA"
Land mass
SRI LANKA

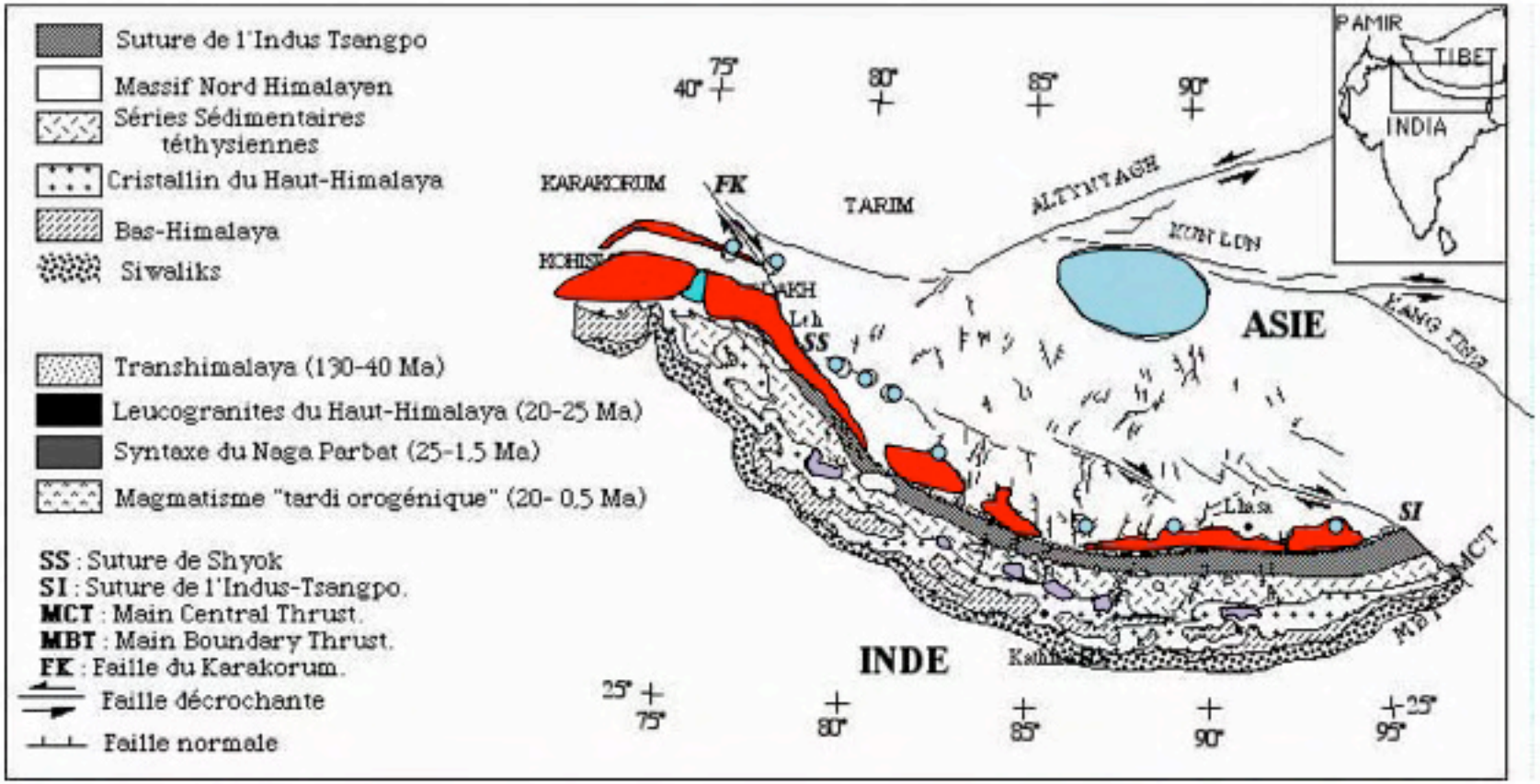

SSW
Spontang
NNE
Higher Himalaya
Tethys -Himalaya
Ladakh
Tibet
MHT
Moho
55 Ma
Neotethys
Shikar Beh
Higher Himalaya
Tethys -Himalaya
Ladakh
Tibet
MHT
50 Ma
Sub-Himalaya
Lesser Himalaya
Tethys -Himalaya
Ladakh
Tibet
Higher Himalaya
MHT
40 Ma
ISZ
MCT
STDS
Sub-Himalaya
Lesser Himalaya
Tethys -Himalaya
Tibet
Moho
MHT
20 Ma

Plusieurs associations granitiques



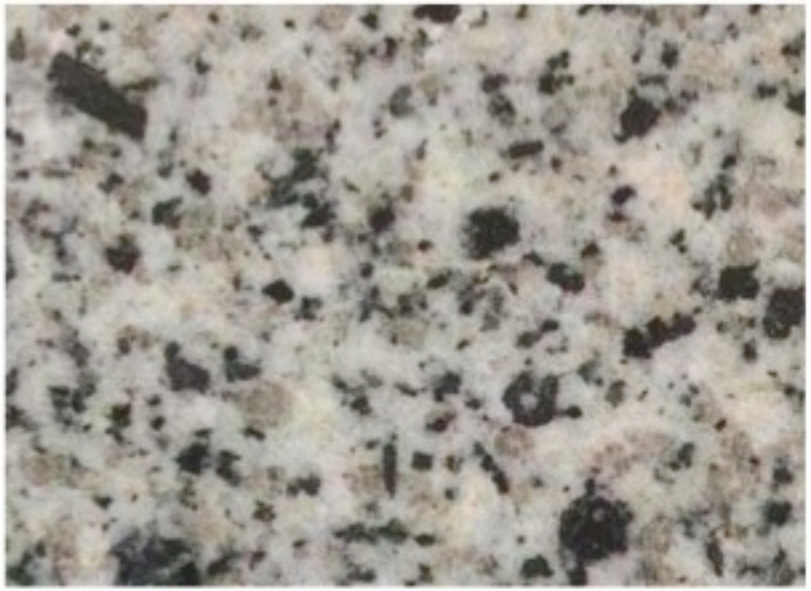
150 125 100 75 50 25 0 tps (Ma)

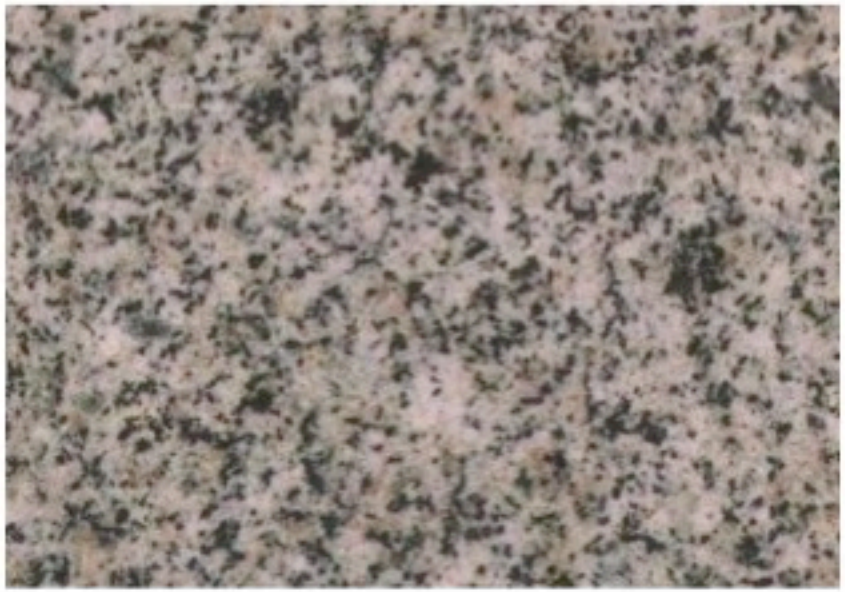
Plusieurs associations granitiques

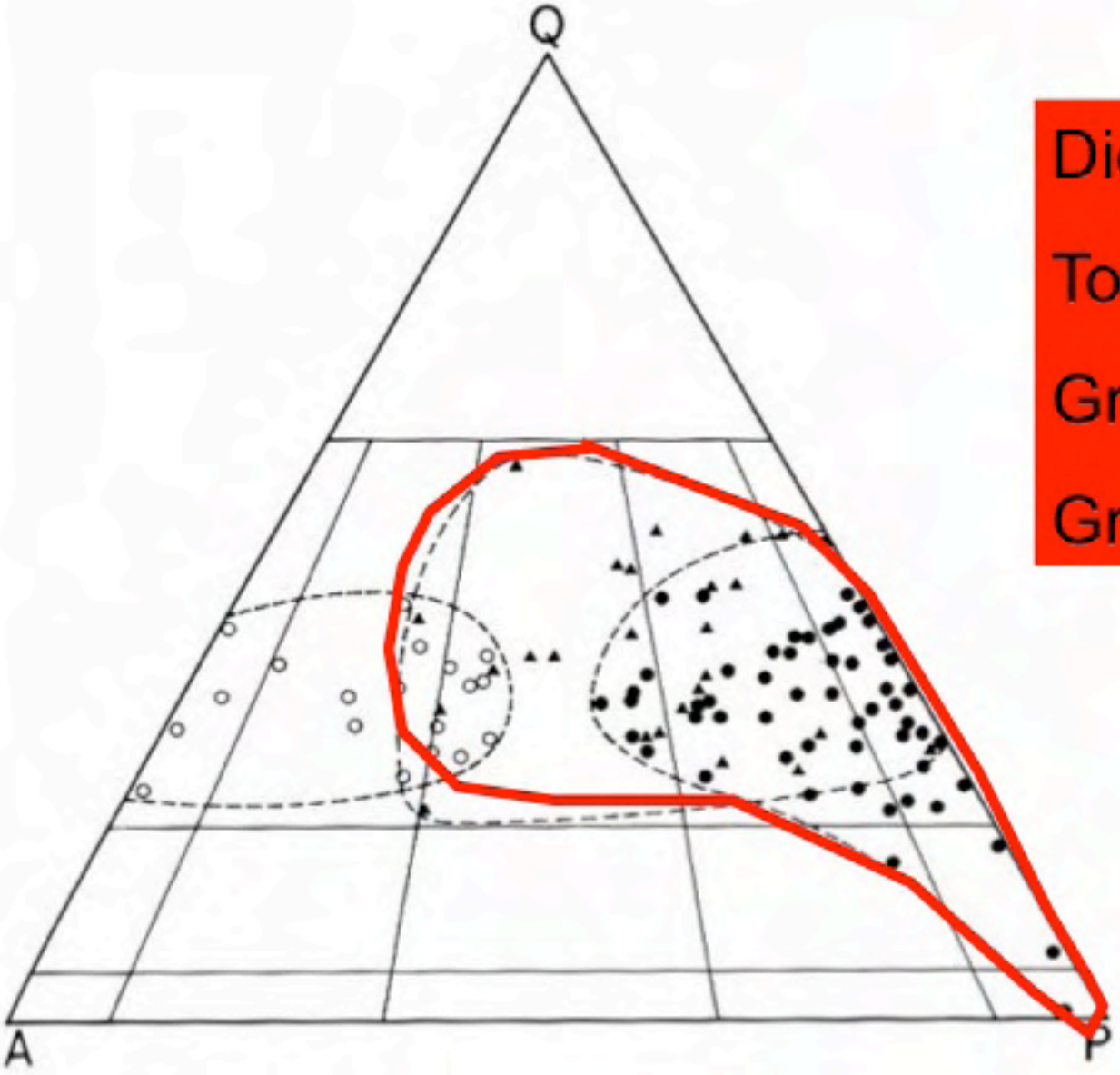


Subduction

- Batholithe trans-Himalayen (Crétacé à Eoccène), similaire aux plutons Andins actuels





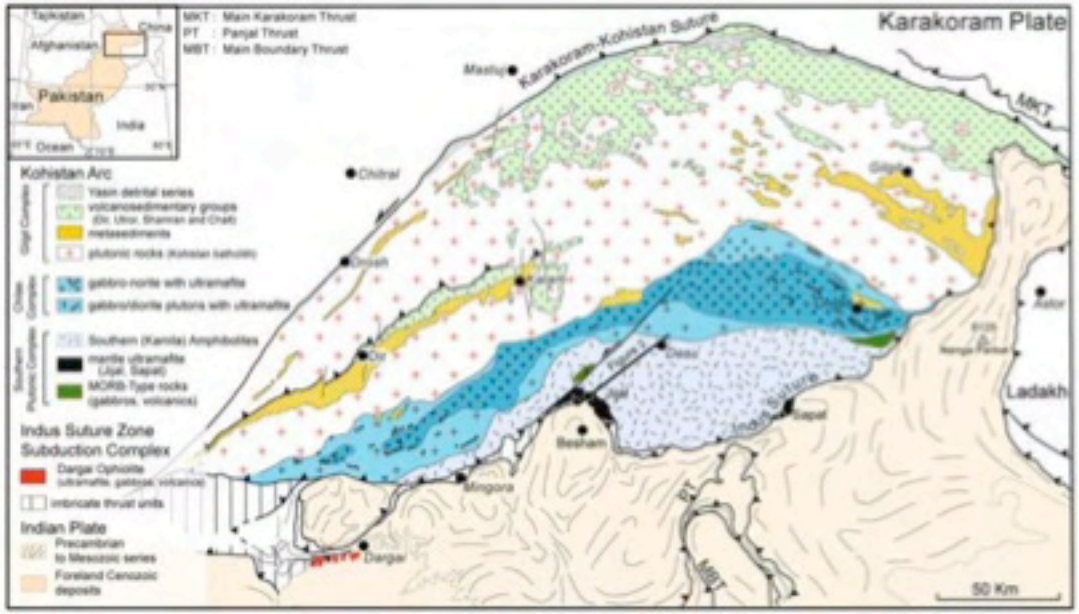


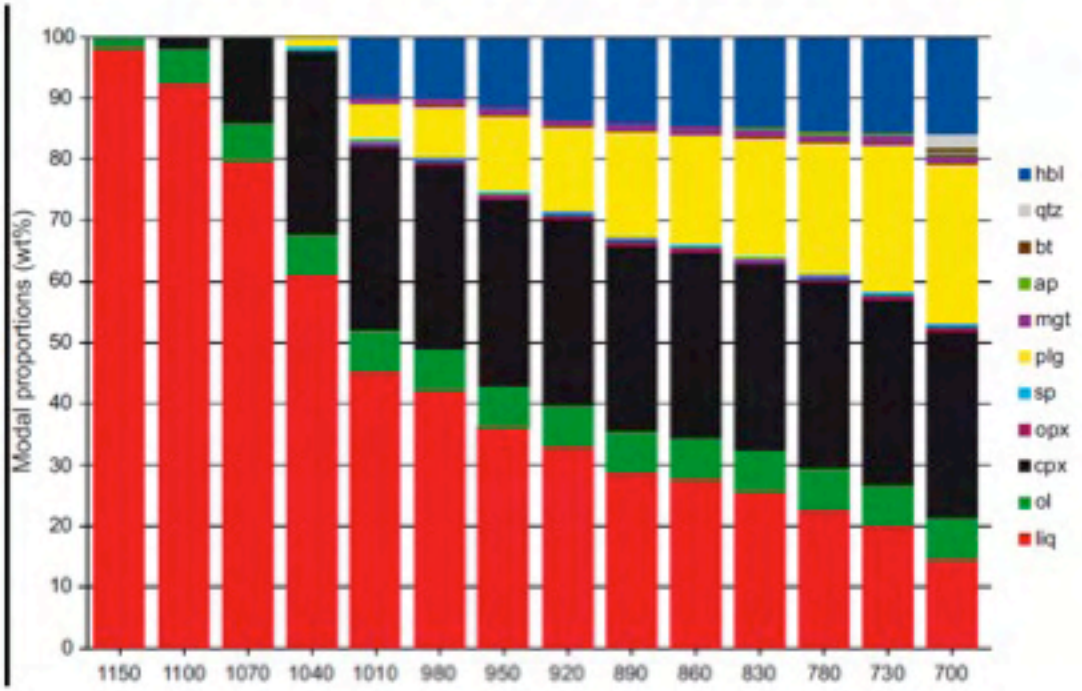
Diorites

Tonalites

Granodiorites

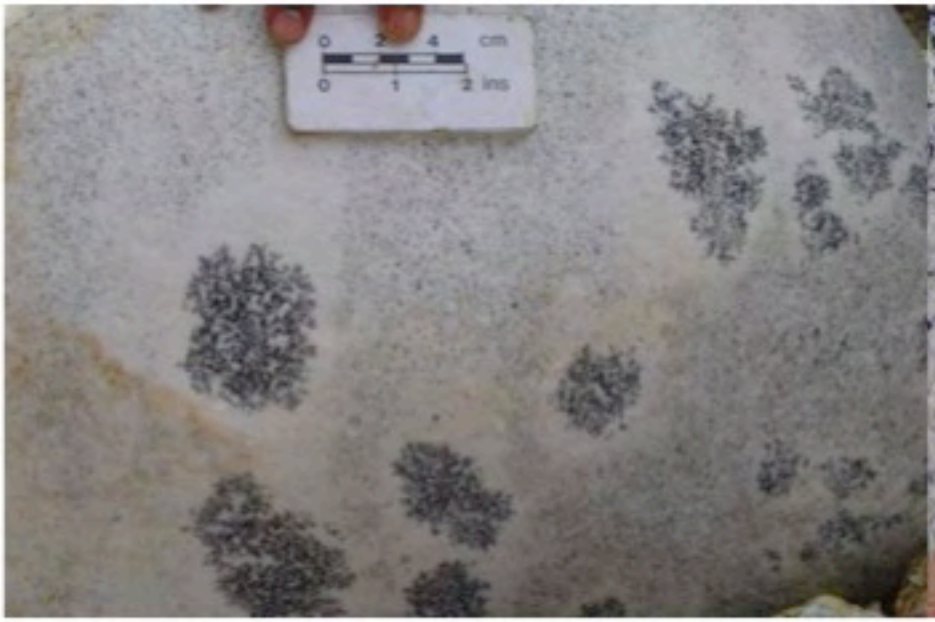
Granites

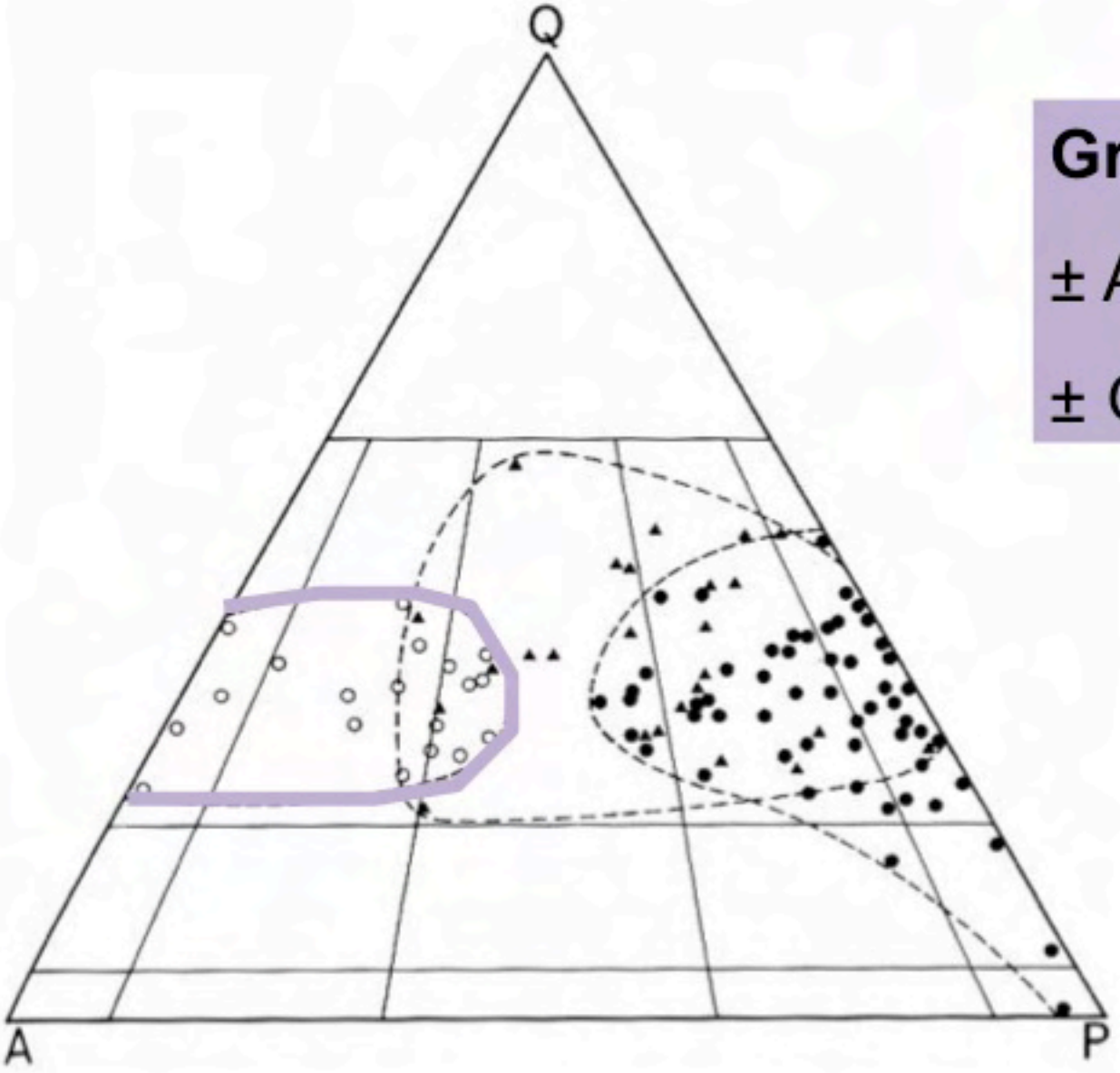

Karakoram Plate
MKT : Main Karakoram Thrust
PT : Panjal Thrust
MBT : Main Boundary Thrust
Tajikistan
China
Afghanistan
Pakistan
India
Iran
Ocean
Karakoram-Kohistan Suture
Mastuj
Chitral
Gilgit
Astor
Ladakh
Besham
Mingora
Dargai
Kohistan Arc
Yasin detrital series
volcanosedimentary groups
metasediments
plutonic rocks (Kohistan batholith)
gabbro-norite with ultramafite
gabbro/diorite plutonis with ultramafite
Southern (Kamila) Amphibolites
mantle ultramafite
MORB-Type rocks
Indus Suture Zone
Subduction Complex
Dargai Ophiolite
intricate thrust units
Indian Plate
Precambrian
to Mesozoic series
Foreland Cenozoic
deposits
50 Km


Modal proportions (wt%)
0
10
20
30
40
50
60
70
80
90
100
1150
1100
1070
1040
1010
980
950
920
890
860
830
780
730
700
hbl
qtz
bt
ap
mgt
plg
sp
opx
cpx
ol
liq

Collision

- Leucogranites du Haut-Himalaya (Miocène)

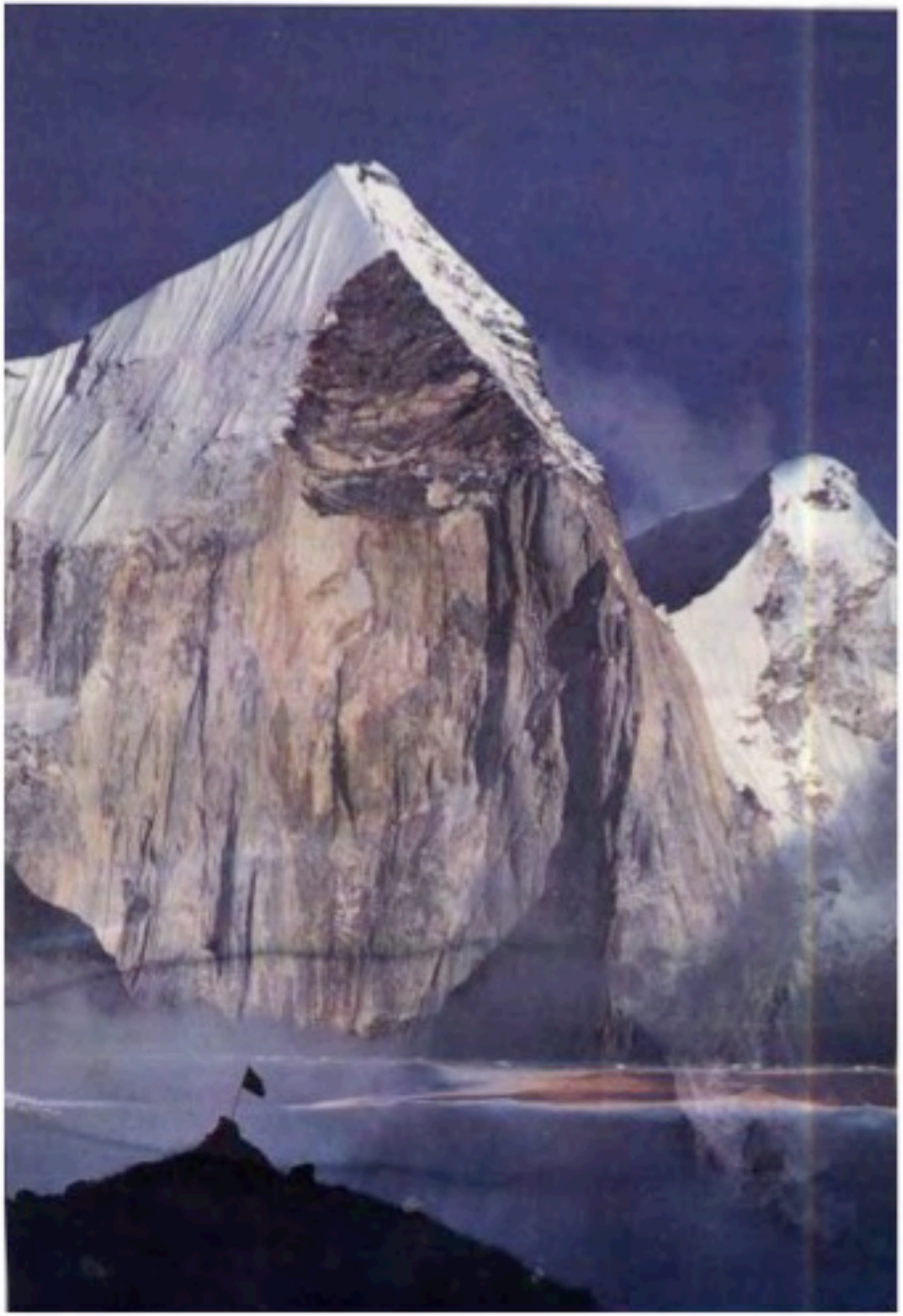


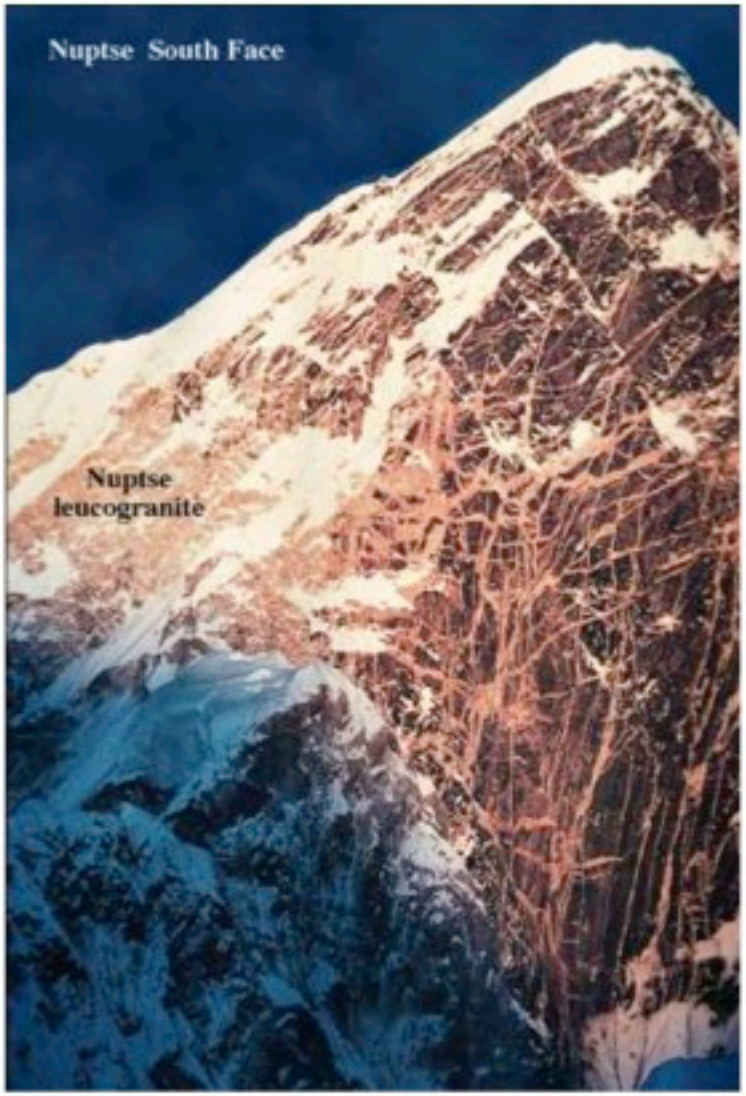


Granites

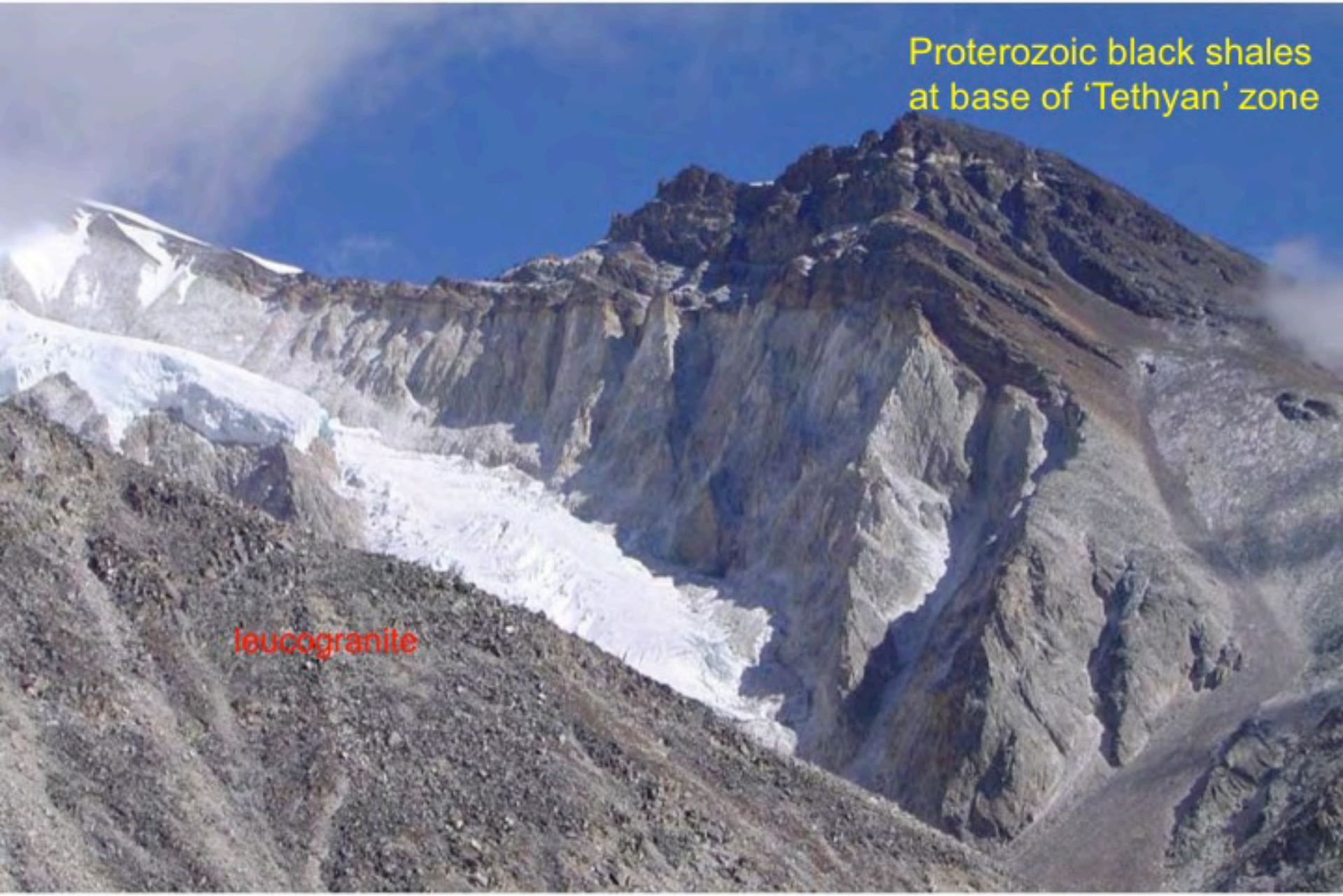
± Alk. Granites

± Granodiorites

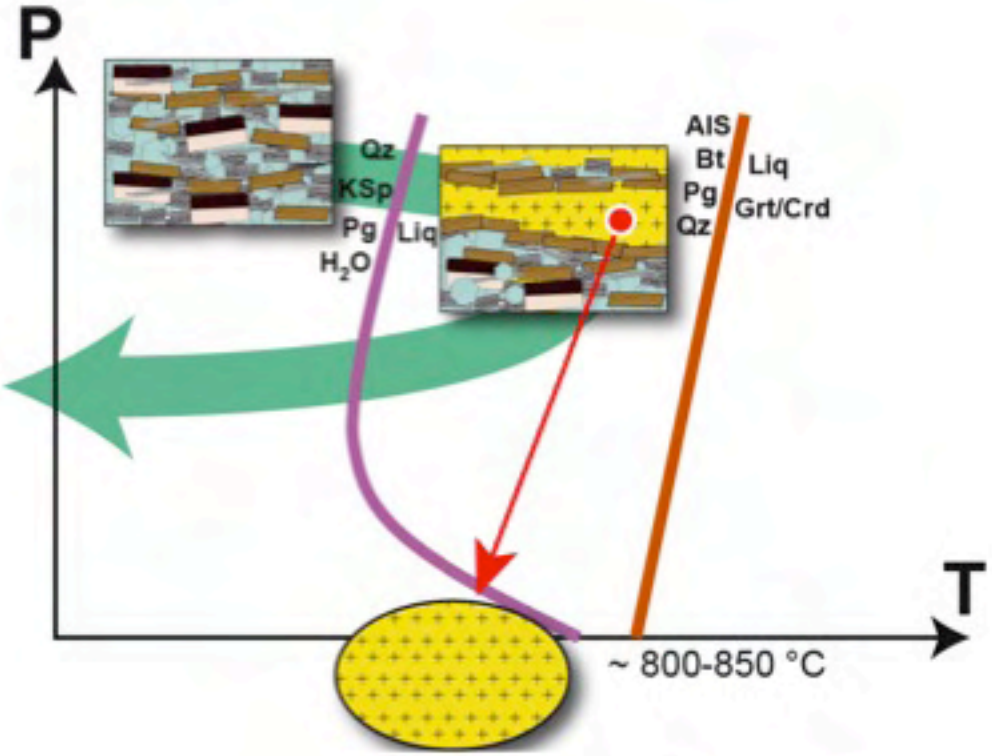


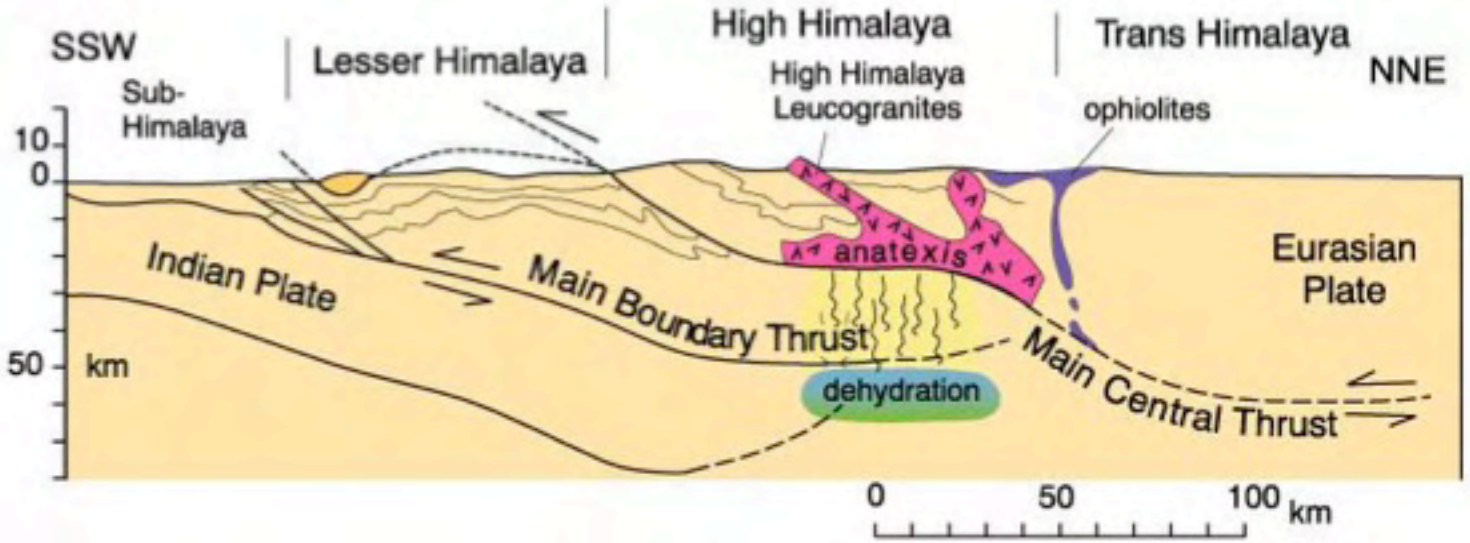

Nuptse South Face
Nuptse
leucogranite

Manaslu leucogranite



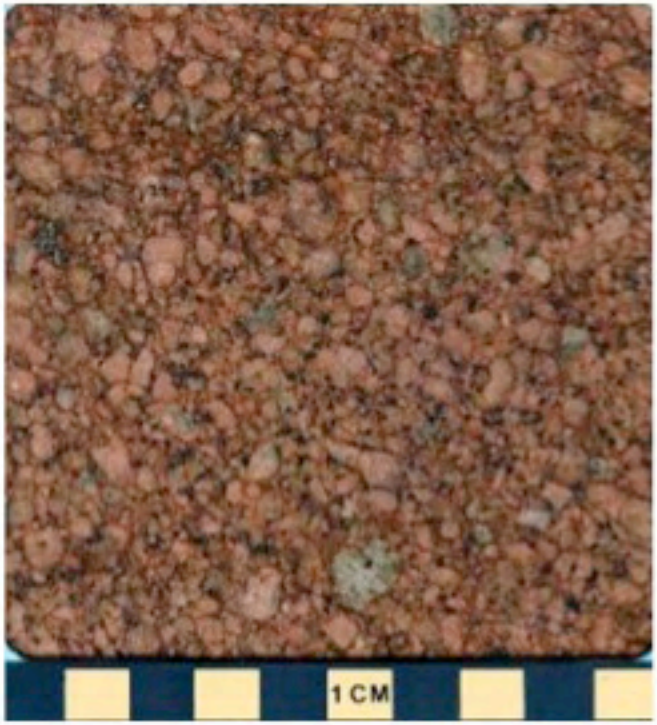
Bhagirathi leucogranite

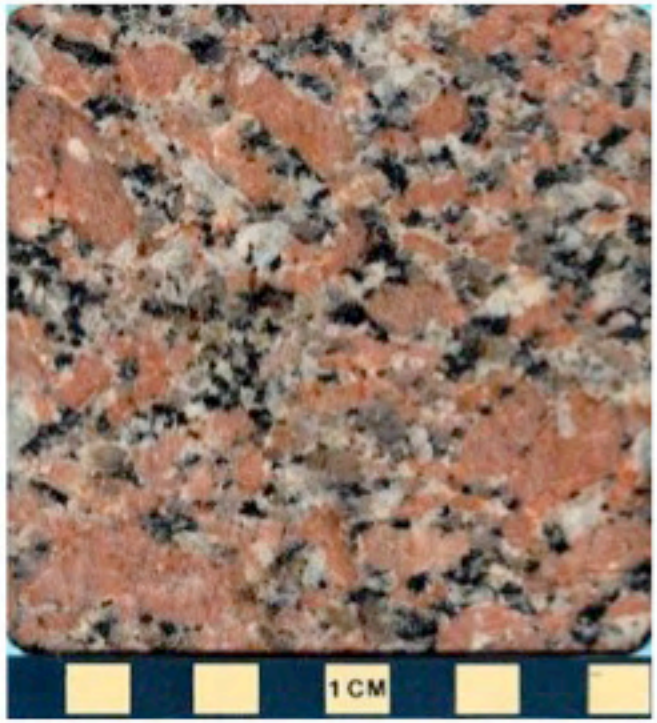

P
T
Qz
KSp
Pg
H_2O
Liq
AIS
Bt
Pg
Qz
Liq
Grt/Crd
~ 800-850 °C


SSW
Sub-
Himalaya
Lesser Himalaya
High Himalaya
High Himalaya
Leucogranites
Trans Himalaya
ophiolites
NNE
10
0
50
km
Indian Plate
Main Boundary Thrust
anatexis
dehydration
Main Central Thrust
Eurasian
Plate
0
50
100 km

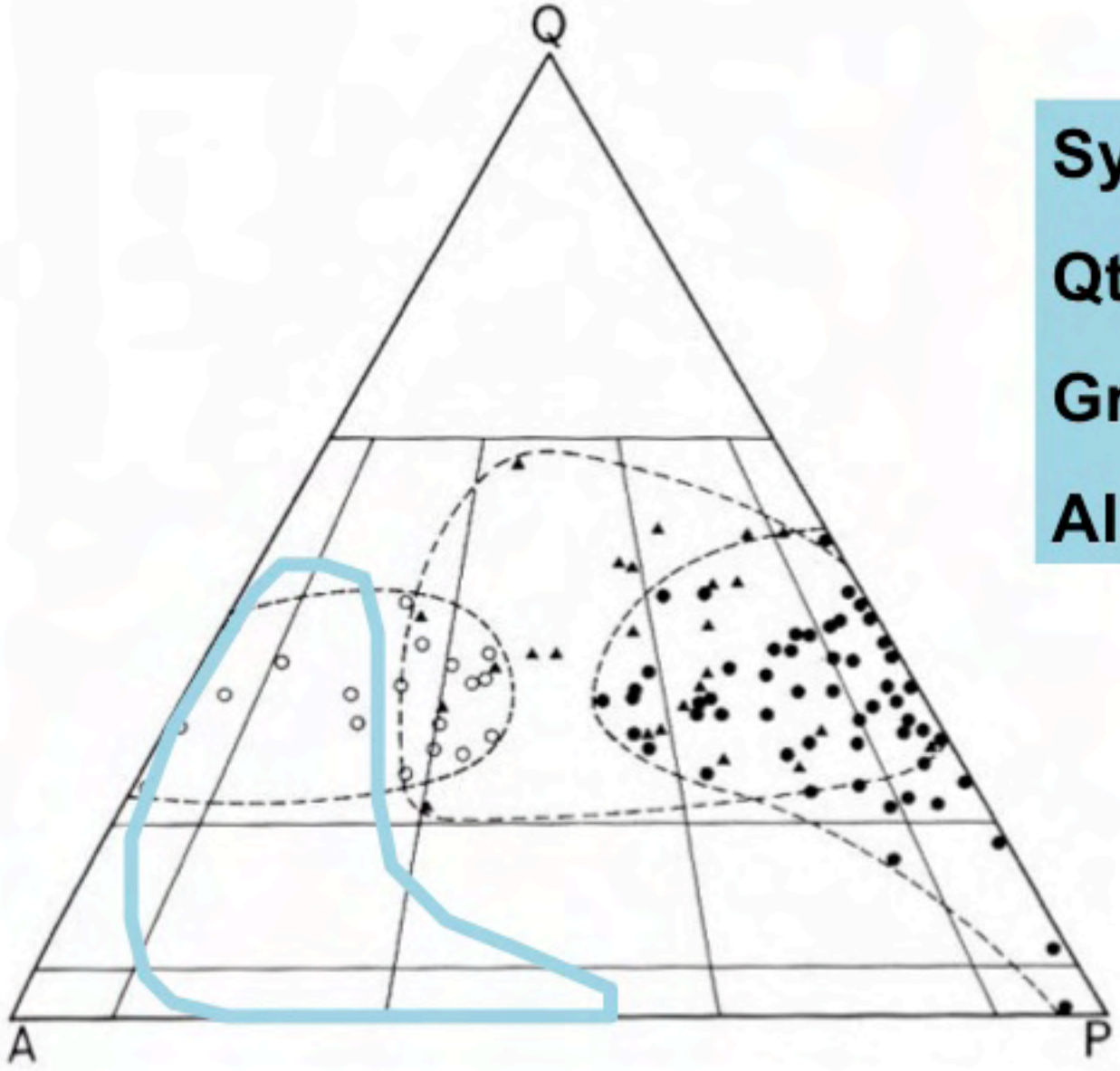
Tardi-collision

- Syénites et granites alcalins (Miocène – actuel) + lamprophyres, etc.






1 CM



Syenites

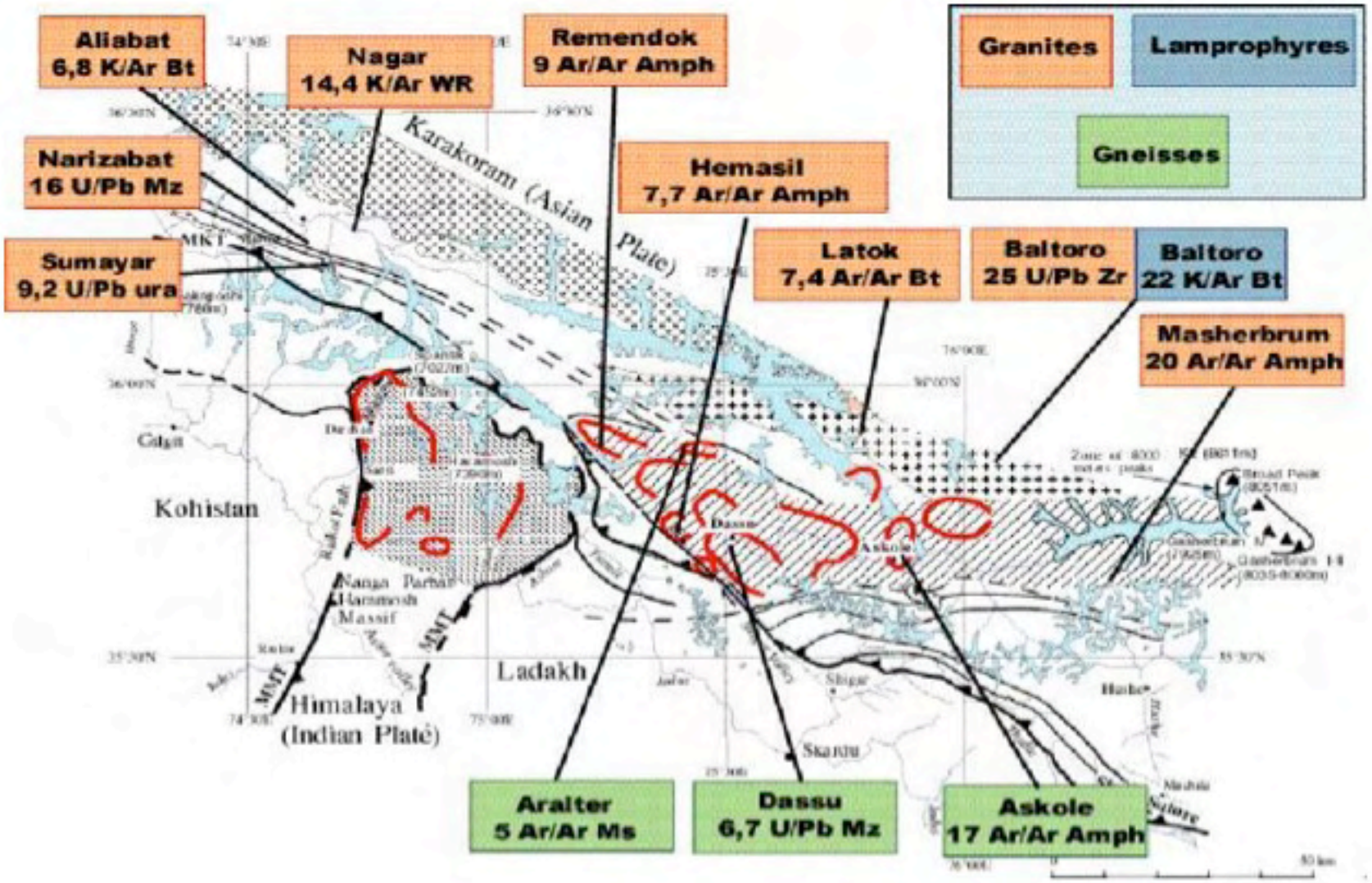
Qtz. Syenites

Granites

Alk. granites

Le magmatisme « post-collisionel » himalayen

Cas du magmatisme Néogène du Sud Karakorum

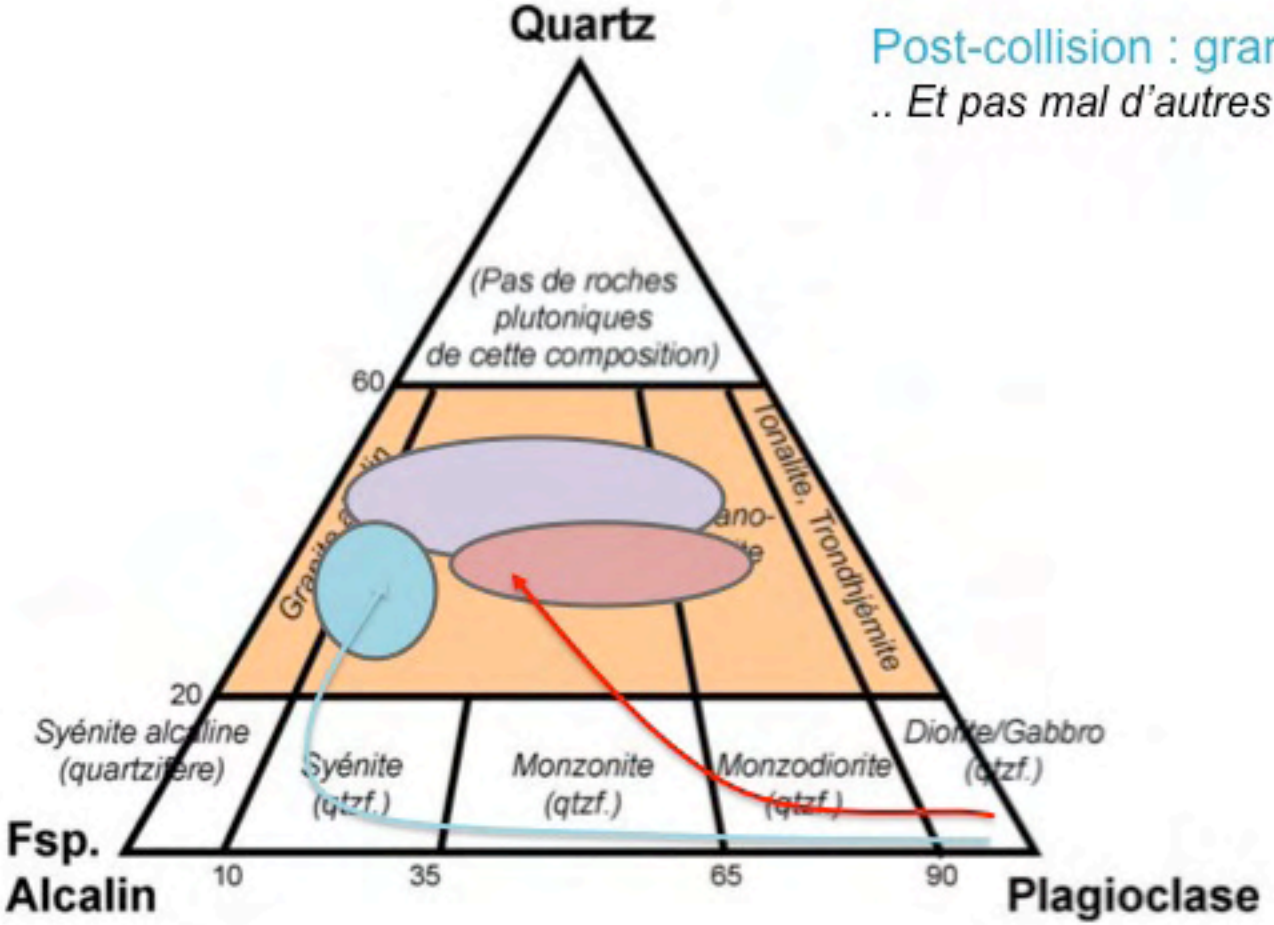


Subduction: granites « I », différentiation de basaltes d'arc

Collision : granites « S », fusion de la croûte

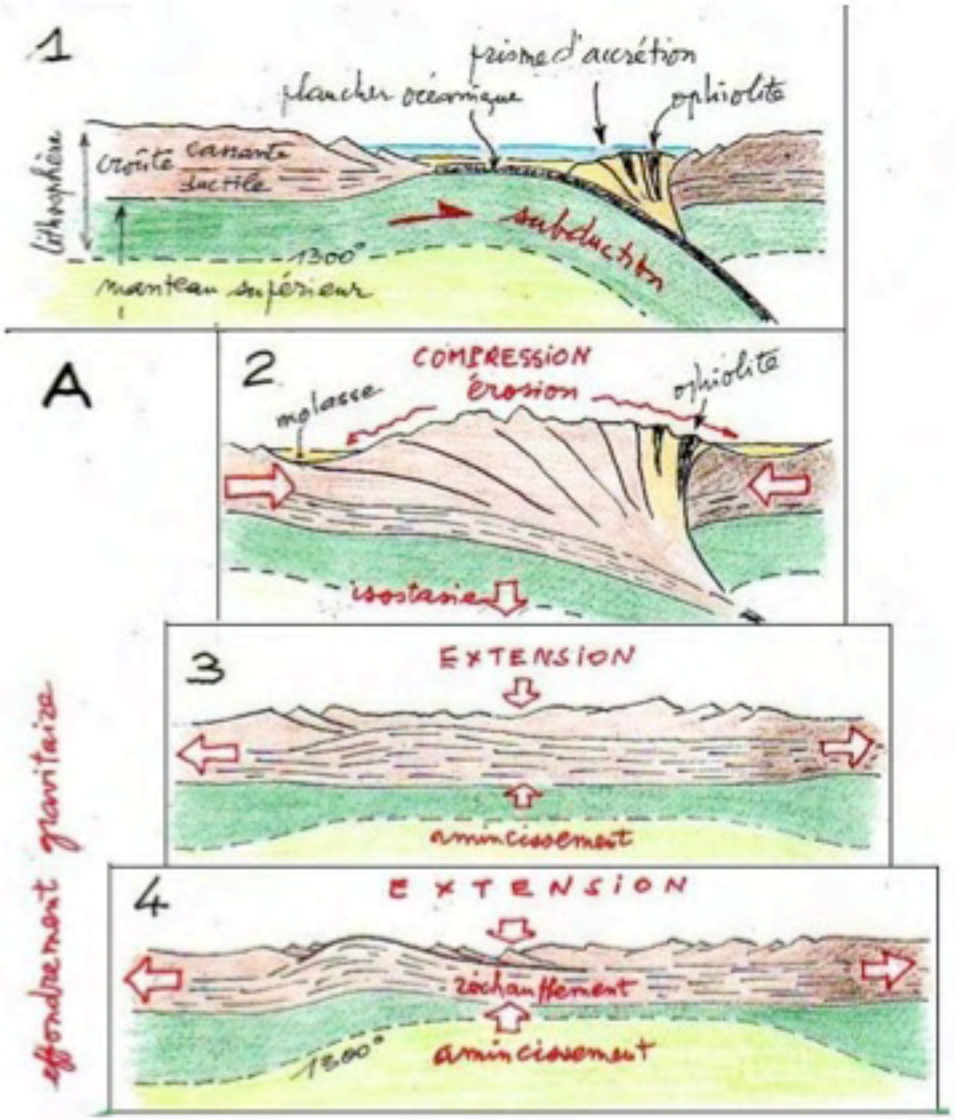
Post-collision : granites « A » (?)

.. Et pas mal d'autres choses



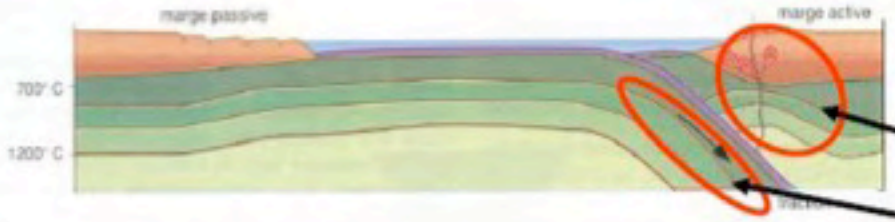
Barbarin 1999

Et après la collision ?



- Effondrement orogénique (pas visible en Himalaya !)

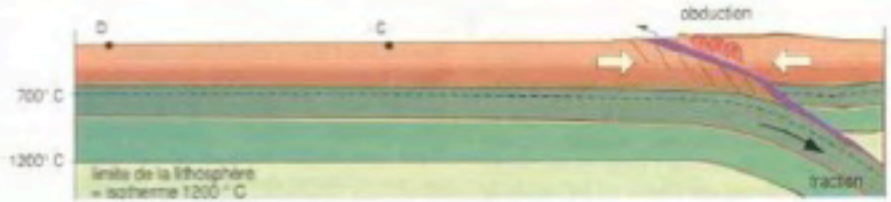
Évolution du métamorphisme au cours de la collision continentale



Métamorphisme pré-collision de marge active

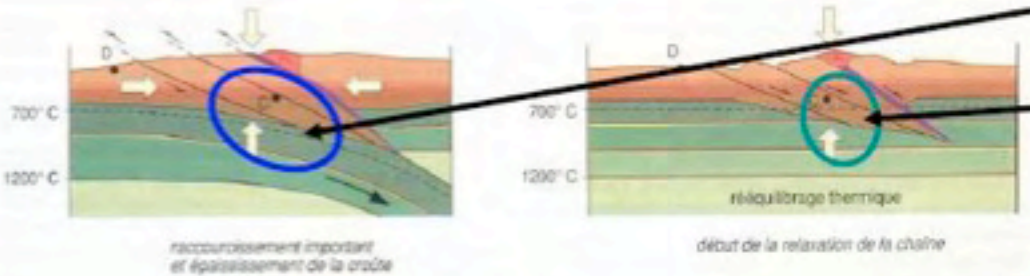
HT-BP

HP-BT



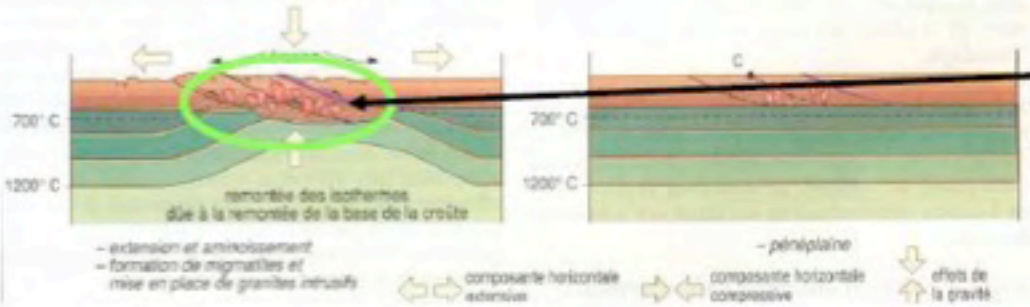
Métamorphisme syn-collision

- en cours d'épaississement HP-BT
- épaississement maximum MP-MT

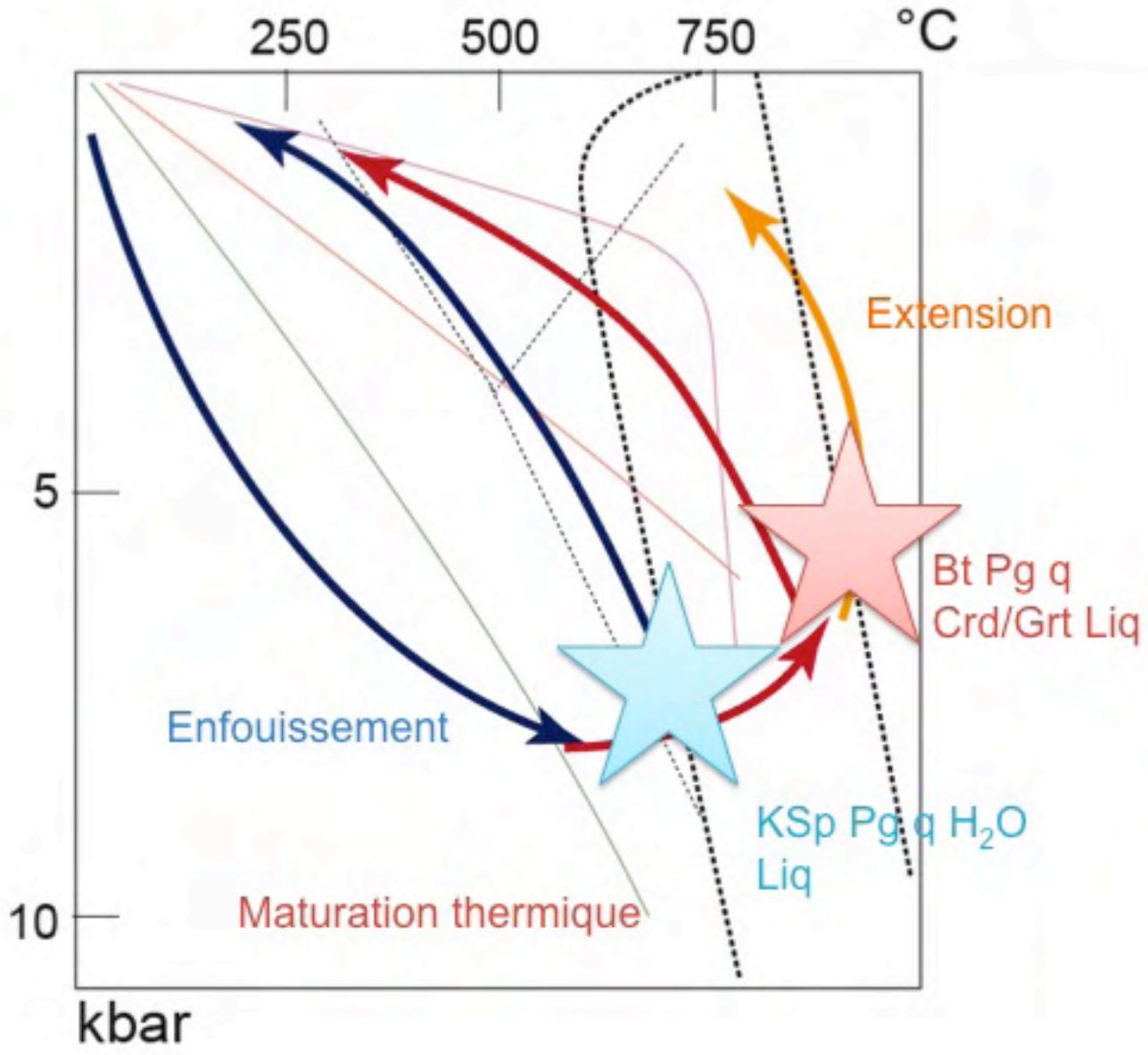


Métamorphisme post-collision

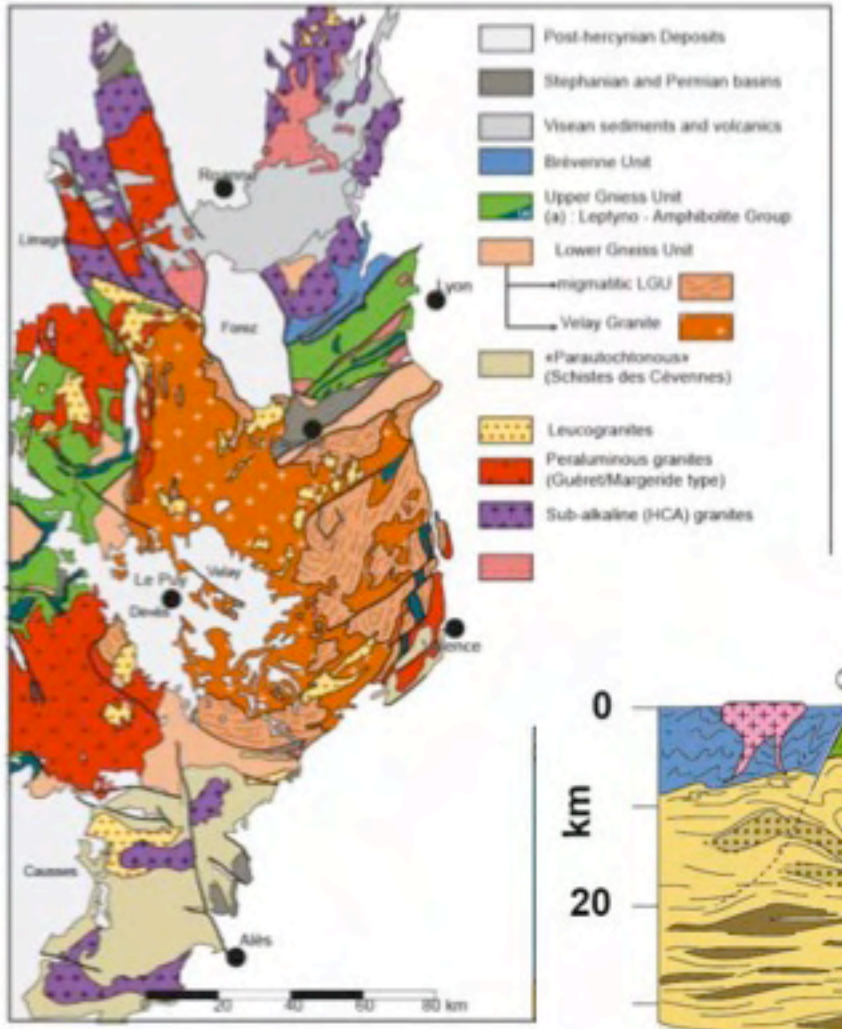
- amincissement lithosphérique HT-BP

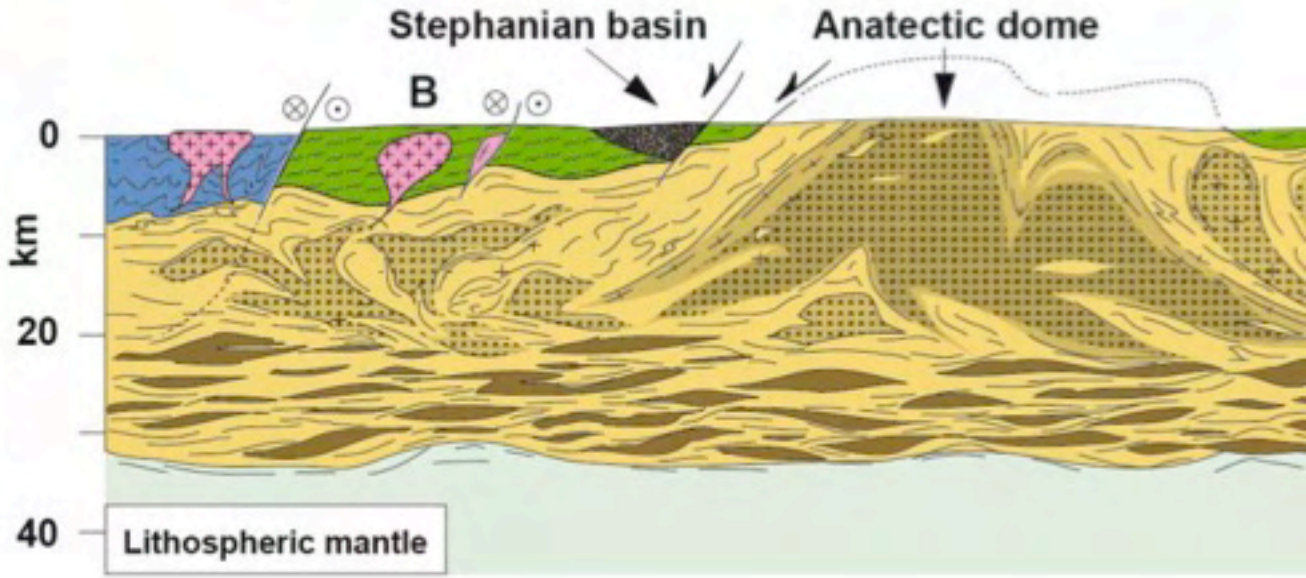


Géothermes de la collision à l ’effondrement

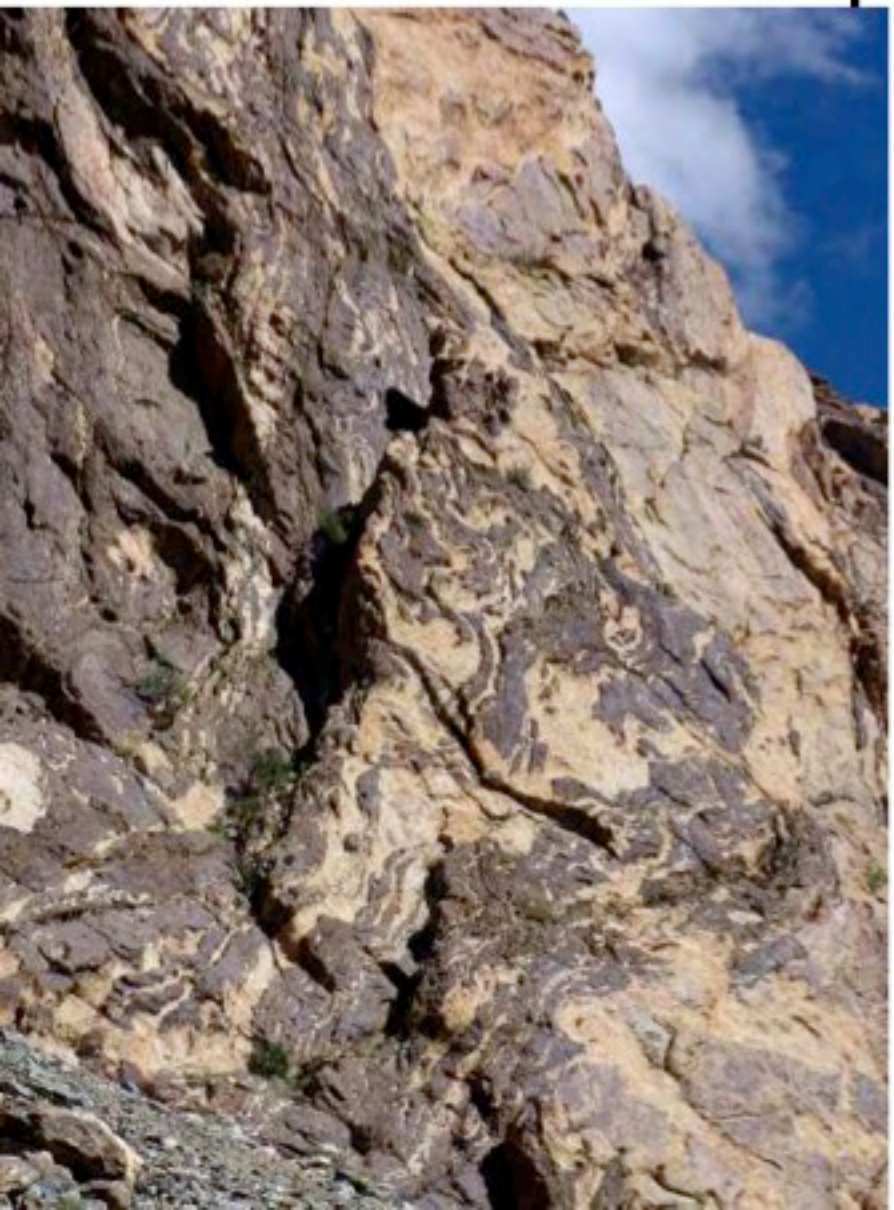


Le magmatisme post-collisionel du Massif Central





Des « diatexites », des roches qui ont bcp fondu



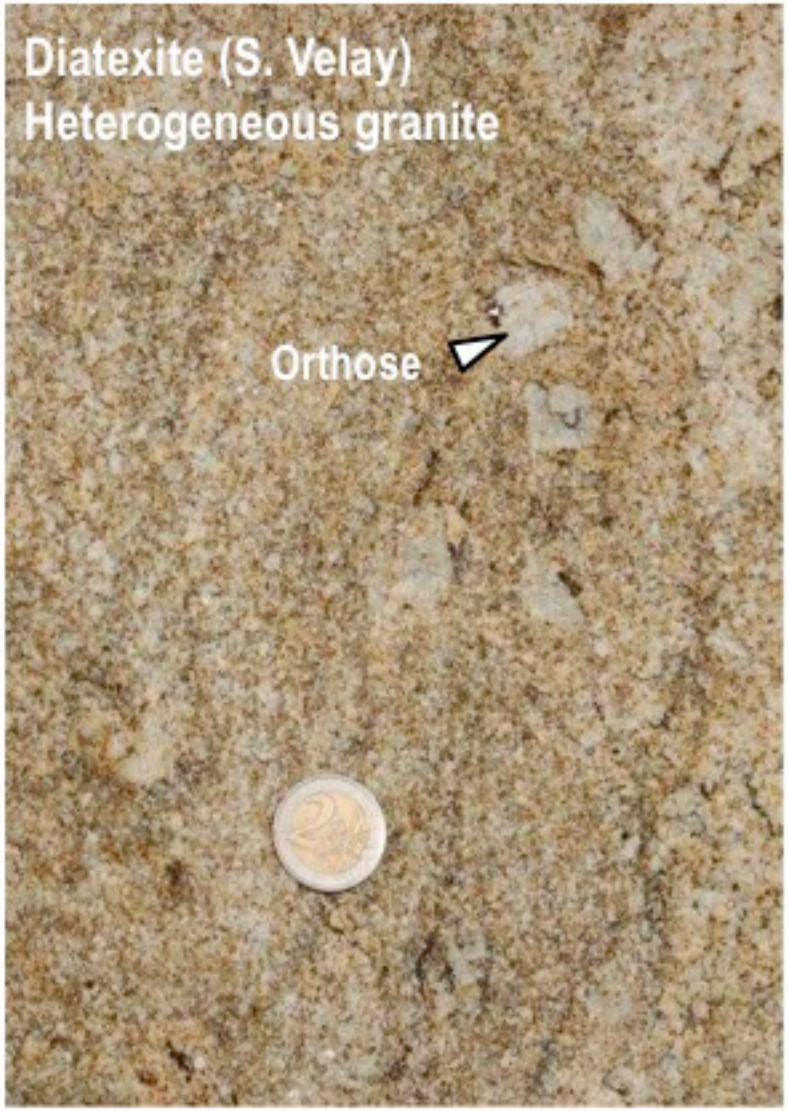
Hortavaer igenous complex, central Norway

Karakorum (W. Himalayas).
Photo R. Weinberg.

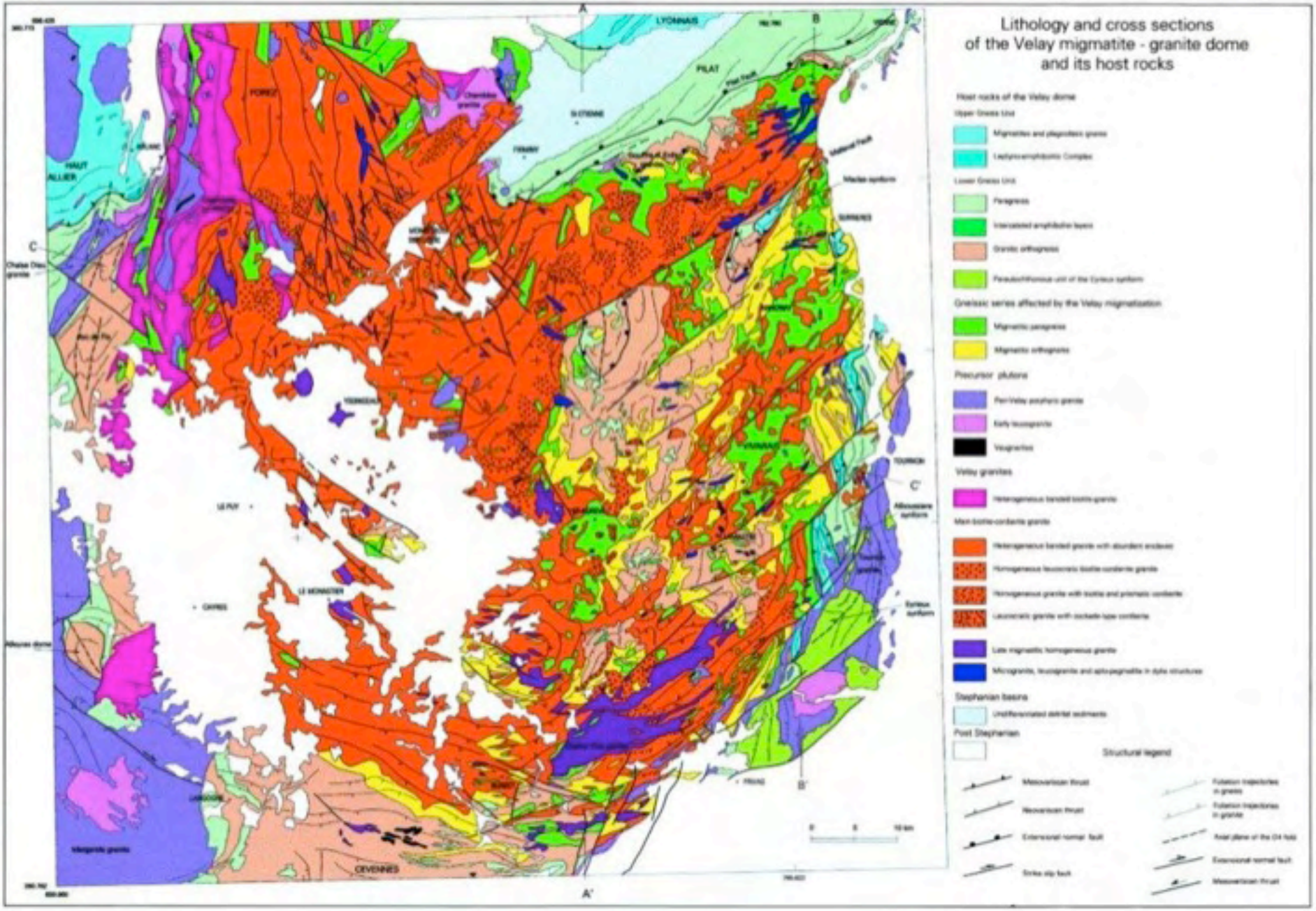
… et qui perdent leur cohérence mécanique

R. Weinberg

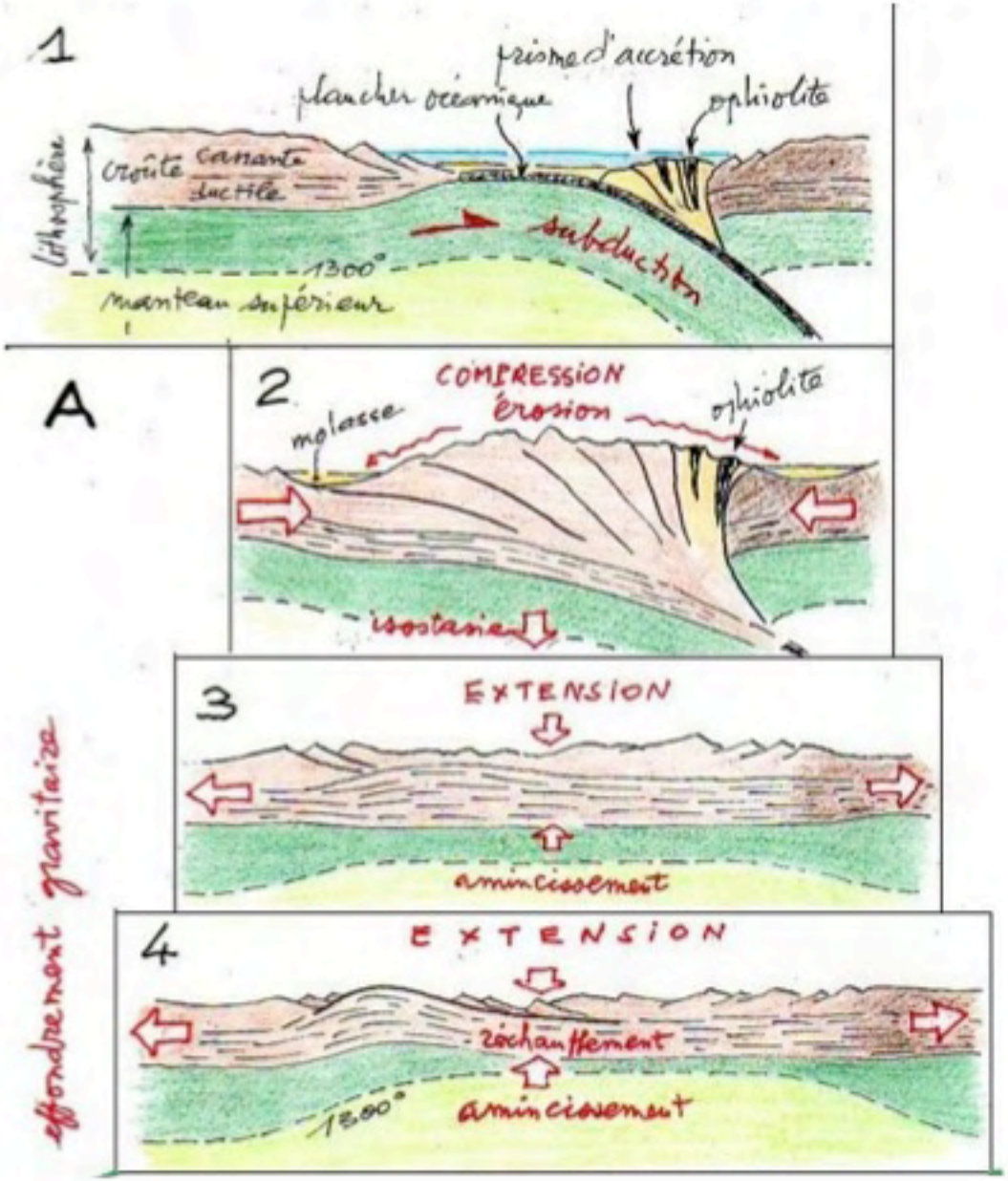
« Granites sales »

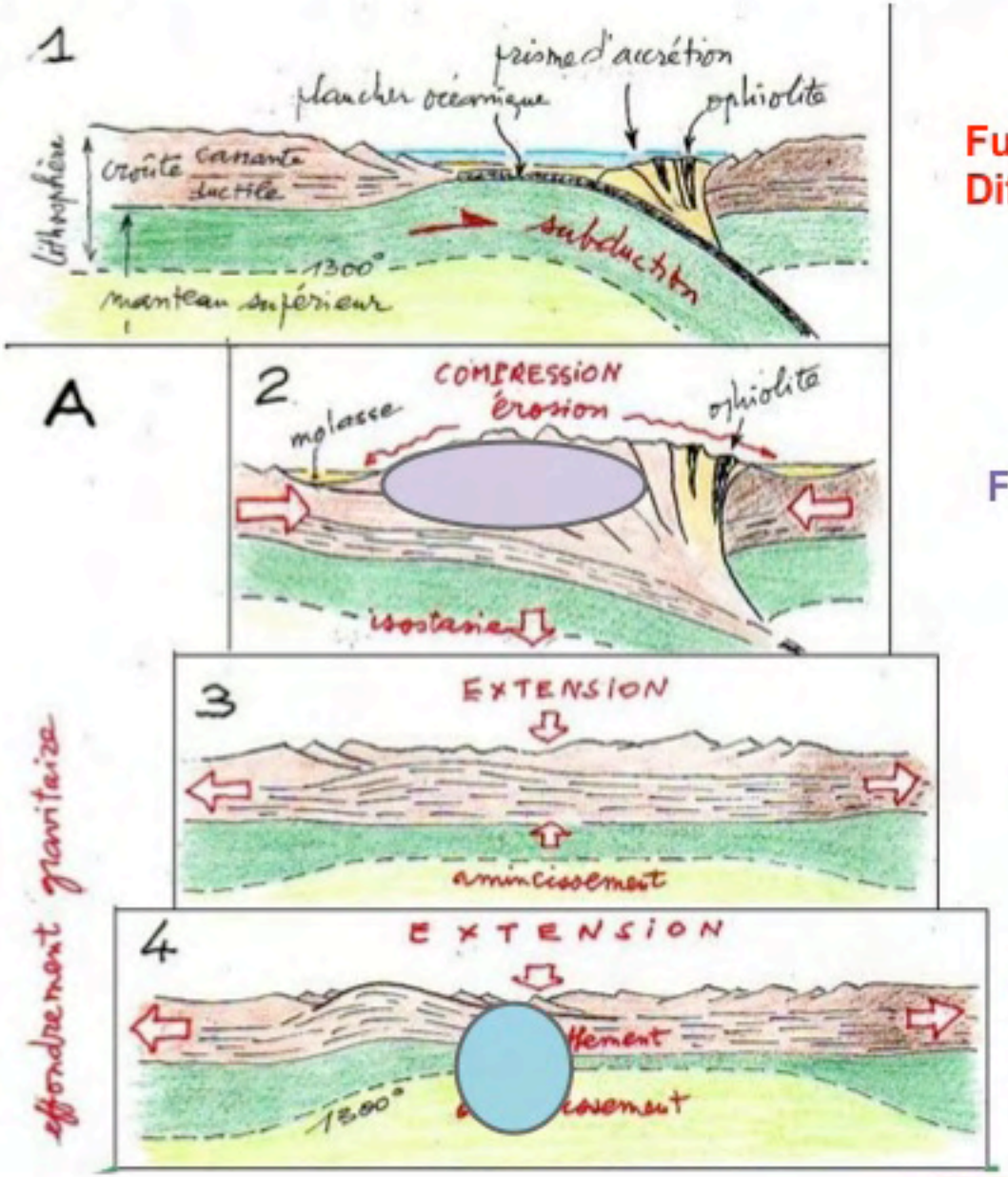


O. Vanderhaeghe



Ledru et al. 2001


1
prisme d'accrétion
plancher océanique
ophiolite
croûte
manteau
ductile
lithosphère
subduction
1300°
manteau supérieur
A
2
COMPRESSION
érosion
molasse
ophiolite
isostasie
3
EXTENSION
amincissement
4
EXTENSION
réchauffement
amincissement
1200°
effondrement gravitaire



Fusion du manteau d'arc
Différentiation

calco-alcalins stricto sensu (I_{ACG})

Fusion de la pile crustale

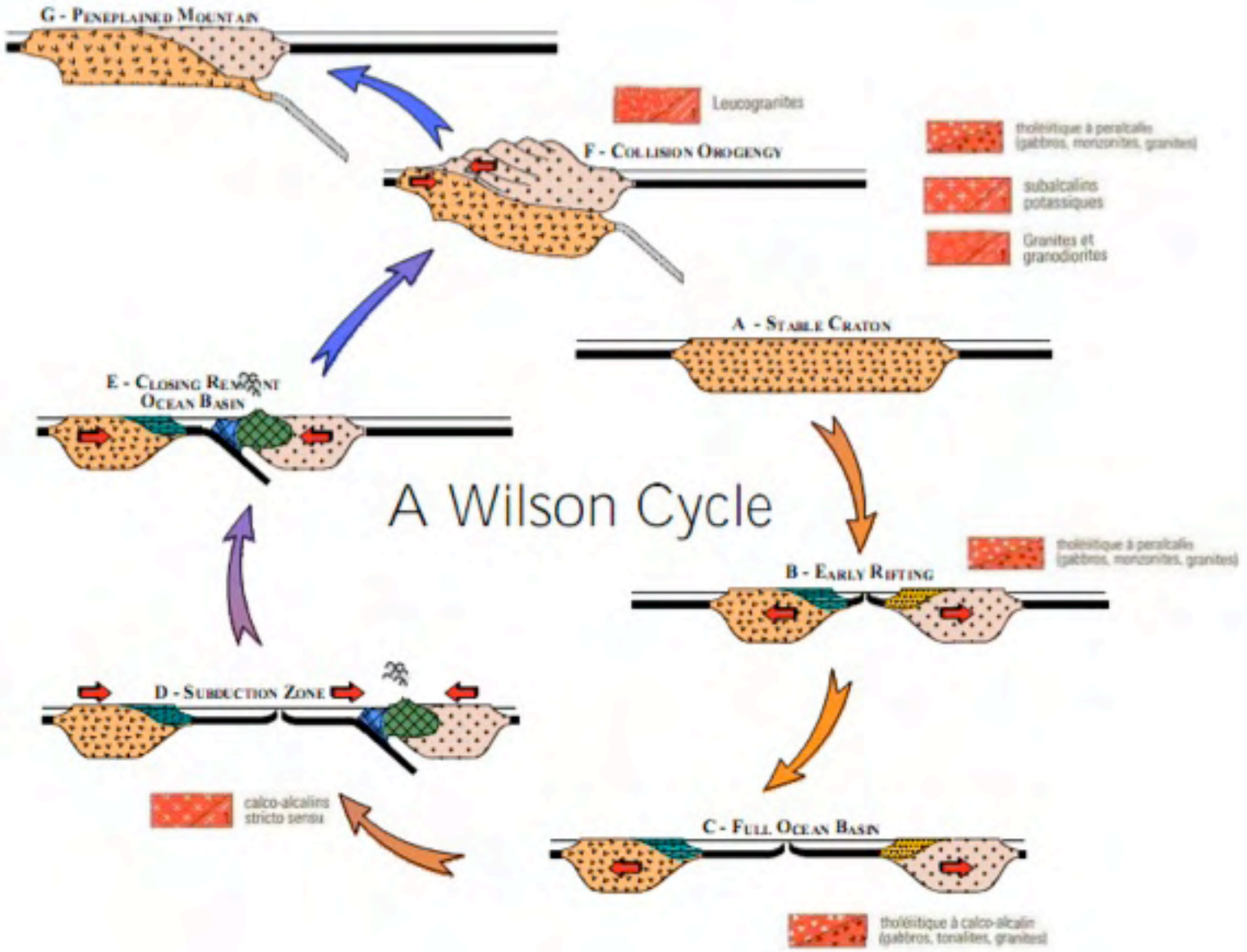
Leucogranites (S_{MPG})

Fusion de tout ce qui passe par là…

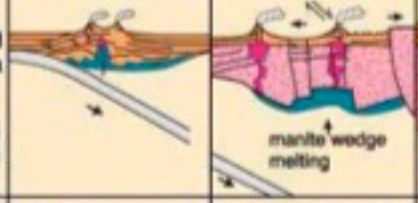
- Manteau enrichi
- Croûte

(I_{KCG}, S_{CPG}, A…)

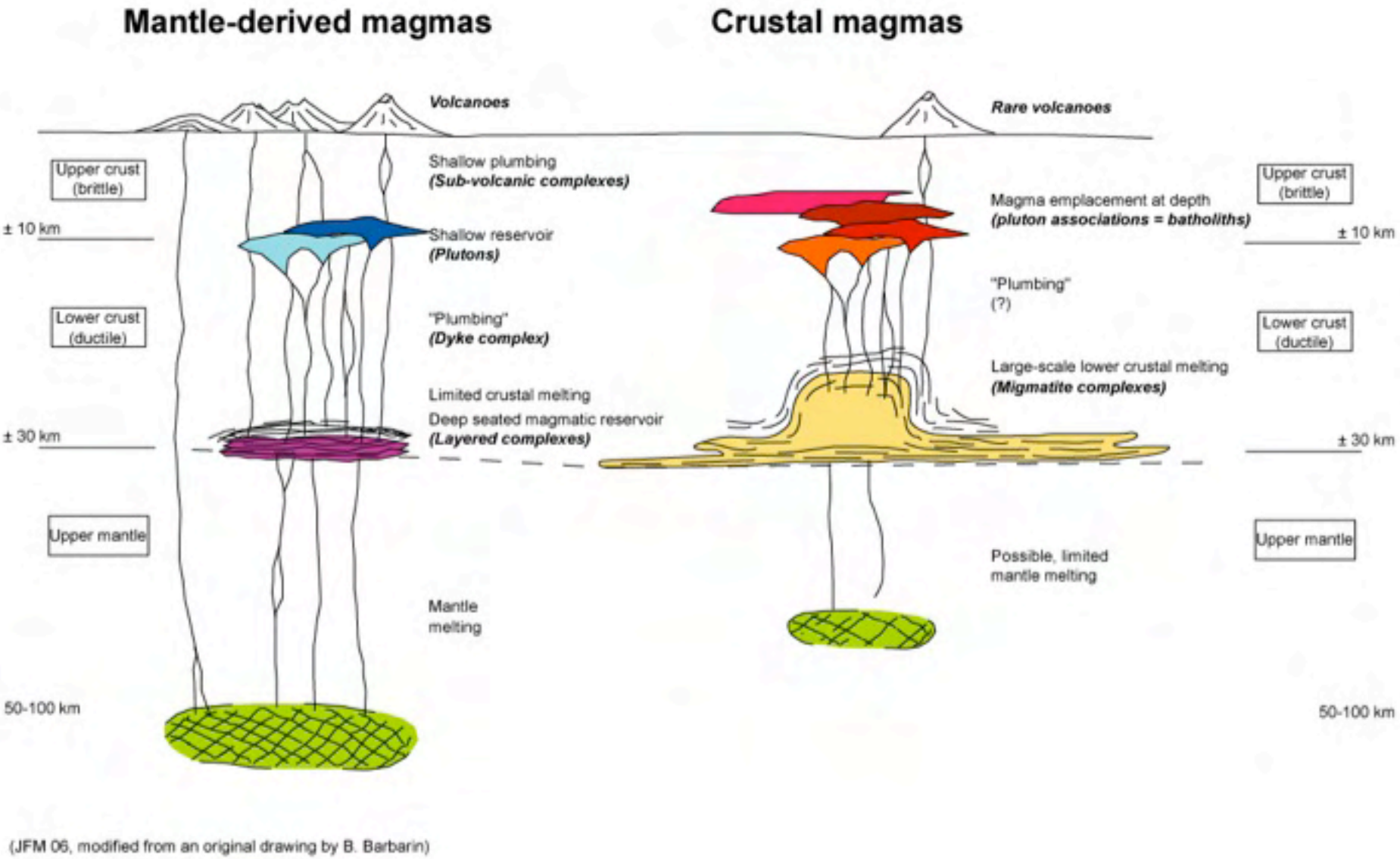
subalcalins potassiques — Granites et granodiorites — tholéiitique à peralcalin (gabbros, monzonites, granites)


G - Peneplained Mountain
Leucogranites
F - Collision Orogengy
tholéiitique à peralcalin (gabbros, monzonites, granites)
subalcalins potassiques
Granites et granodiorites
A - Stable Craton
E - Closing Remnant Ocean Basin
A Wilson Cycle
B - Early Rifting
tholéiitique à peralcalin (gabbros, monzonites, granites)
D - Subduction Zone
calco-alcalins stricto sensu
C - Full Ocean Basin
tholéiitique à calco-alcalin (gabbros, tonalites, granites)

Granites dans leur contexte

	OROGENIC			TRANSITIONAL	ANOROGENIC	
	Oceanic Island Arc	Continental Arc	Continental Collision	Post-Orogenic Uplift/Collapse	Continntal Rifting, Hot Spot	Mid-Ocean Ridge, Ocean Islands
						
Examples	Bougainville, Solomon Islands, Papua New Guinea	Mesozoic Cordilleran batholiths of west Americas Gander Terrane	Manaslu and Lhotse of Nepal, Amorican Massif of Brittany	Late Caledonian Plutons of Britain, Basin and Range, late Variscan, early Northern Proterozoic	Nigerian ring complexes, Oslo rift, British Tertiary Igneous Province, Yellowstone hotspot	Oman and Troodos ophiolites; Iceland, Ascension, and Reunion Island intrusives
Geo-chemistry	Calc-alkaline > thol. M-type & I-M hybrid Metaluminous	Calc-alkaline I-type > S-type Met-Al to sl. Per-Al	Calc-alkaline S-type Peraluminous	Calc-alkaline I-type S-type (A-type) Metalum. to Peralum	Alkaline A-type Peralkaline	Tholeiitic M-type Metaluminous
Rock types	qtz-diorite in mature arcs	tonalite & granodior. > granite or gabbro	migmatites & leucogranite	bimodal granodiorite + dirolte-gabbro	Granite, syenite + diorite-gabbro.	Plagiogranite
Associated Minerals	Hbl > Bt	Hbl, Bt	Bt, Ms, Hbl, Grt, Als, Crd	Hbl > Bt	Hbl, Bt, aegirine fayalite, Rbk, arfved.	Hbl
Associated Volcanism	Island-arc basalt to andesite	Andesite and dacite in great volume	often lacking	basalt and rhyolite	alkali lavas, tuffs, and caldera infill	MORB and ocean island basalt
Classification Barbarin (1990)	T_{IA} tholeiite island arc	H_{CA} hybrid calc-alkaline	C_{ST} C_{CA} C_{CI} continental types	H_{LO} hybrid late orogenic	A alkaline	T_{OR} tholeiite ocean ridge
Pearce *et al. (1984)*	VAG (volcanic arc granites)		COLG (collision granites)		WPG and ORG (within plate and ocean ridge granites)	
Maniar & Piccoli (1989)	IAG island arc granite	CAG contin. arc granite	CCG cont. collision gran.	POG post-orogenic gran.	RRG CEUG rift & aborted/hotspot	OP ocean plagiogranite
Origin	Partial melting of mantle-derived mafic underplate	PM of mantle-derived mafic underplate + crustal contribution	Partial melting of recycled crustal material	Partial melting of lower crust+ mantle and mid-crust contrib	Partial melting of mantle and/or lower crust (anhydrous)	Partial melting of mantle and fractional crystallization
Melting Mechanism	Subduction energy: transfer of fluids and dissolved species from slab to wedge. Melting of wedge, transfer of heat upward		Tectonic thickening plus radiogenic crustal hea	Crustal heat plus mantle heat (rising asthen. + magmas)	Hot spot and/or adiabatic mantle rise	

Winter, after Pitcher (1983, 1993); Barbarin (1990, 1999)



(JFM 06, modified from an original drawing by B. Barbarin)