Migmatitos e Granulitos

Migmatitos

- O termo **migmatito** foi introduzido por Sederholm (1907) que sugeriu que estas rochas são formadas por combinação de fusão incipiente, metamorfismo e intrusão de material granítico

- A definição mais moderna (e simples) é de Sawyer (2008): **migmatito** é a rocha formada por fusão parcial *in situ* (**anatexia**)

Terminologia

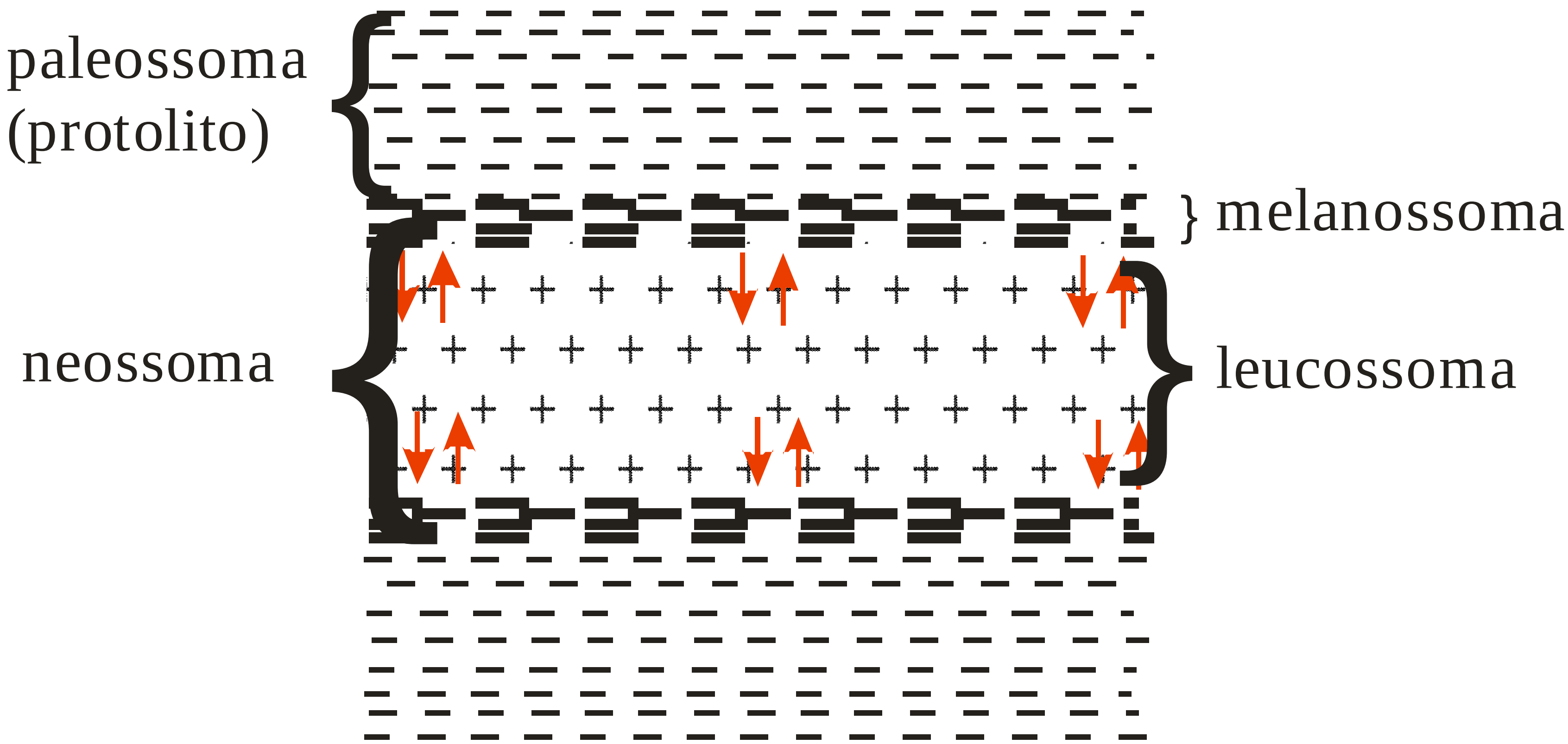
- Mehnert (1968) – As seguintes partes podem ser reconhecidas em migmatitos (termos descritivos):

- **Paleossoma** – a parte não "alterada" da rocha (preservada da fusão), ou que foi modificada levemente, ou ainda a rocha encaixante

- **Neossoma** – a parte nova formada durante a fusão
  - **Leucossoma** – parte clara onde predominam minerais félsicos (quartzo e feldspato). Formado pela segregação do material félsico (fundido)
  - **Melanossoma** – parte escura onde predominam minerais máficos (biotita, hornblenda, granada, cordierita). Formado pelo resíduo sólido após a segregação do material félsico

Mehnert (1968)

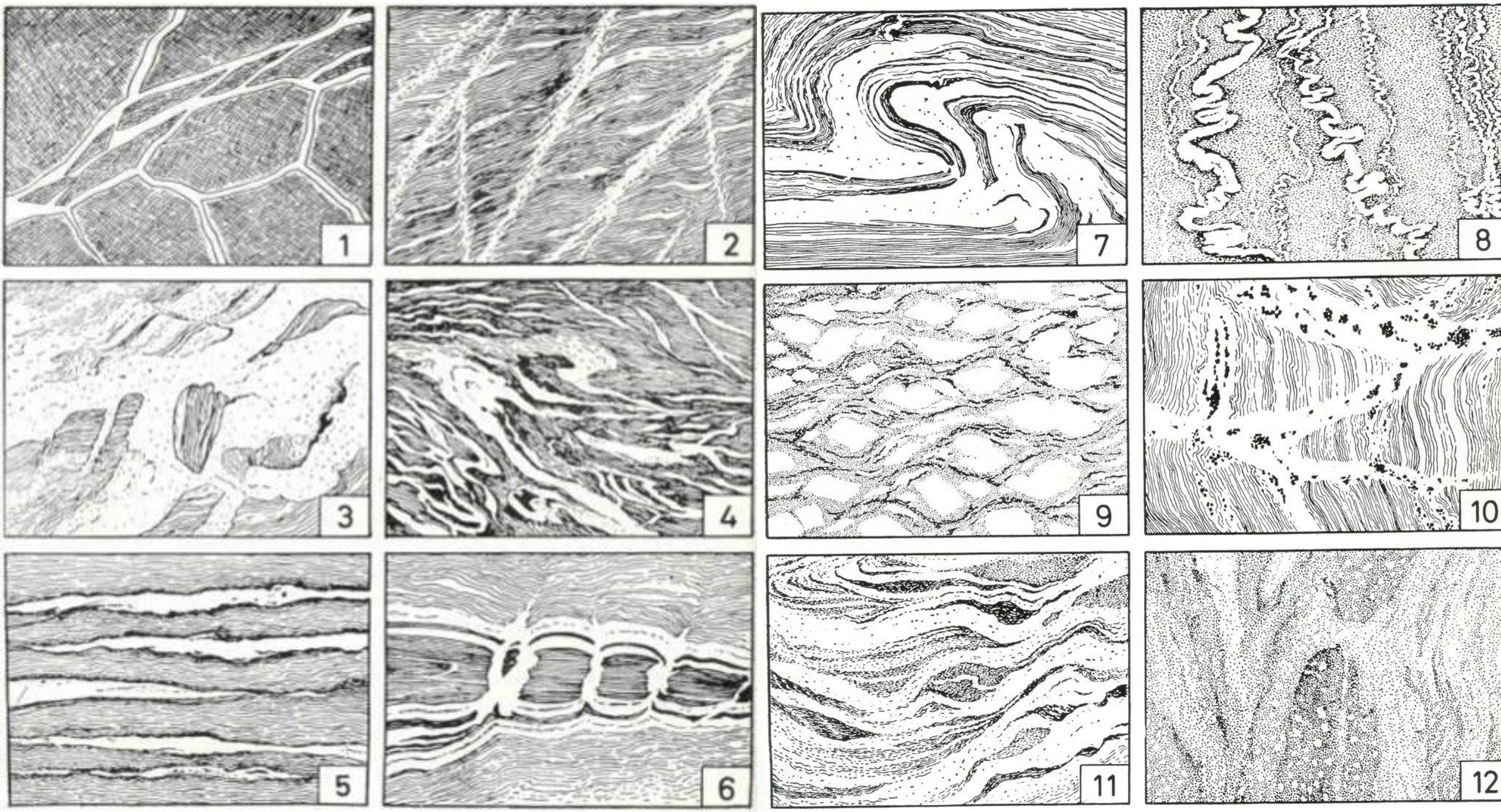
Fusão parcial e diferenciação



paleossoma = leucossoma + melanossoma

sistema precisa ser fechado e o protolito homogêneo

Classificação estrutural de Mehnert



1 – agmatito (brecha)
3 – schollen (jangada)
5 - estromático

2 – diktionítica (veios)
4 – flebítica (veios)
6 – dilatacional (boudin)

7 – dobrada
9 – augen
11 – schlieren

8 – pitigmática
10 – estictolítica (manchada)
12 – nebulítica

agmatito

(brecha)


OLYMPUS
diktionítica


schollen (raft)

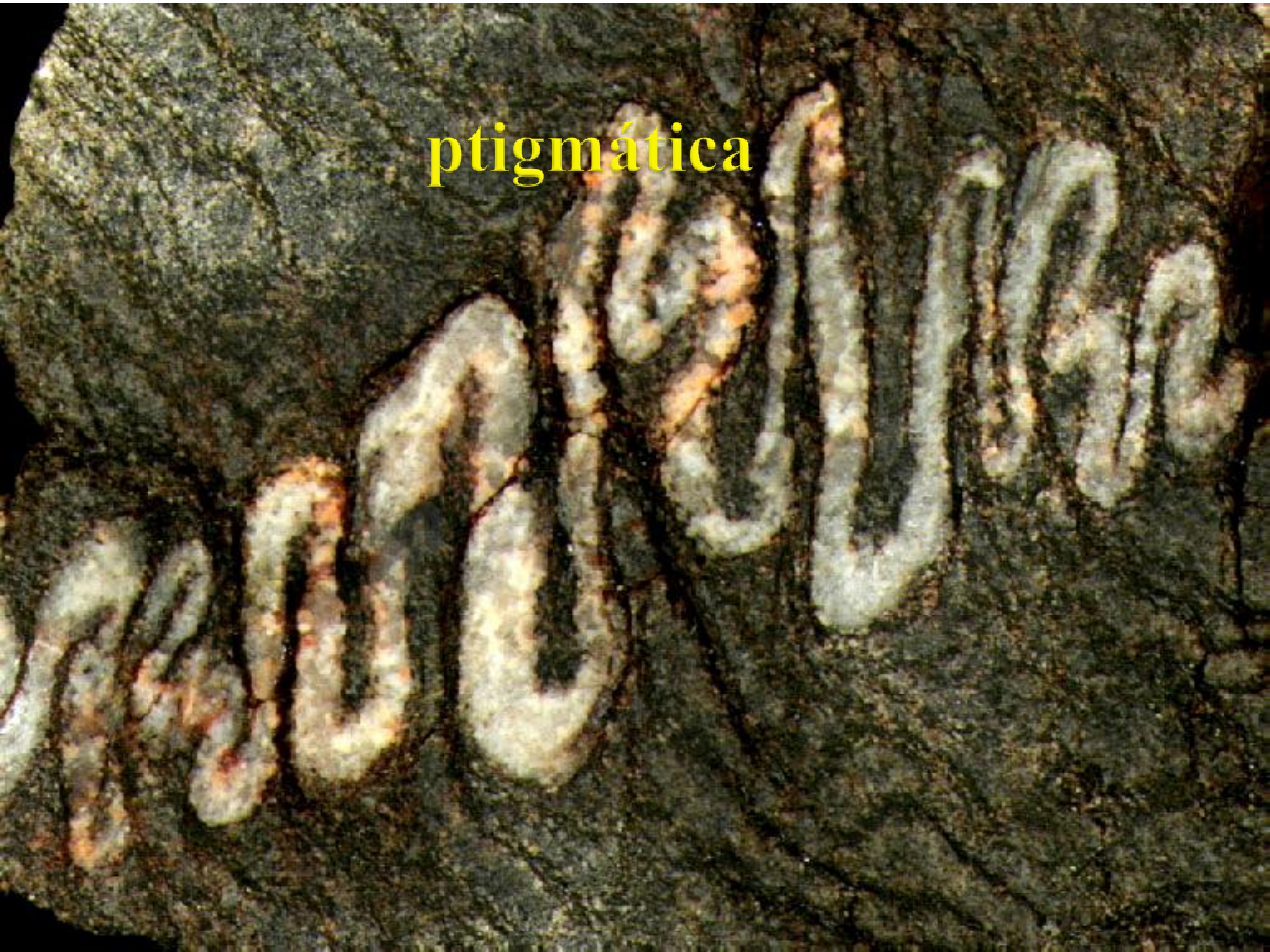

flebitica
(veios)


estromática


dobrada

surreitica
dilatacional
boudins

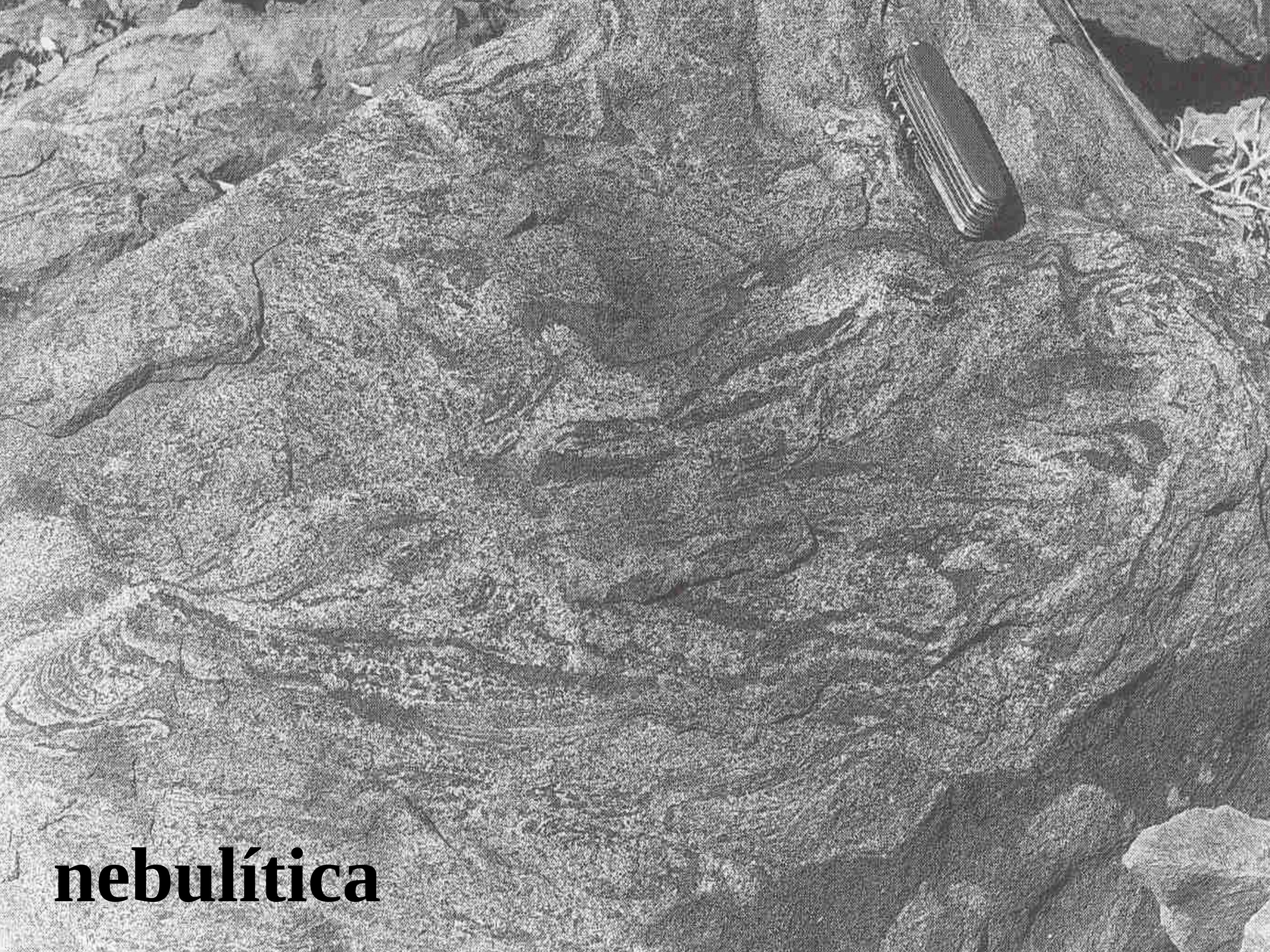
boudins


ptigmática


augen
isso é migmatito??????????


10 cm
manchada

schlieren



nebulítica


nebulítica

Problemas na terminologia de Mehnert

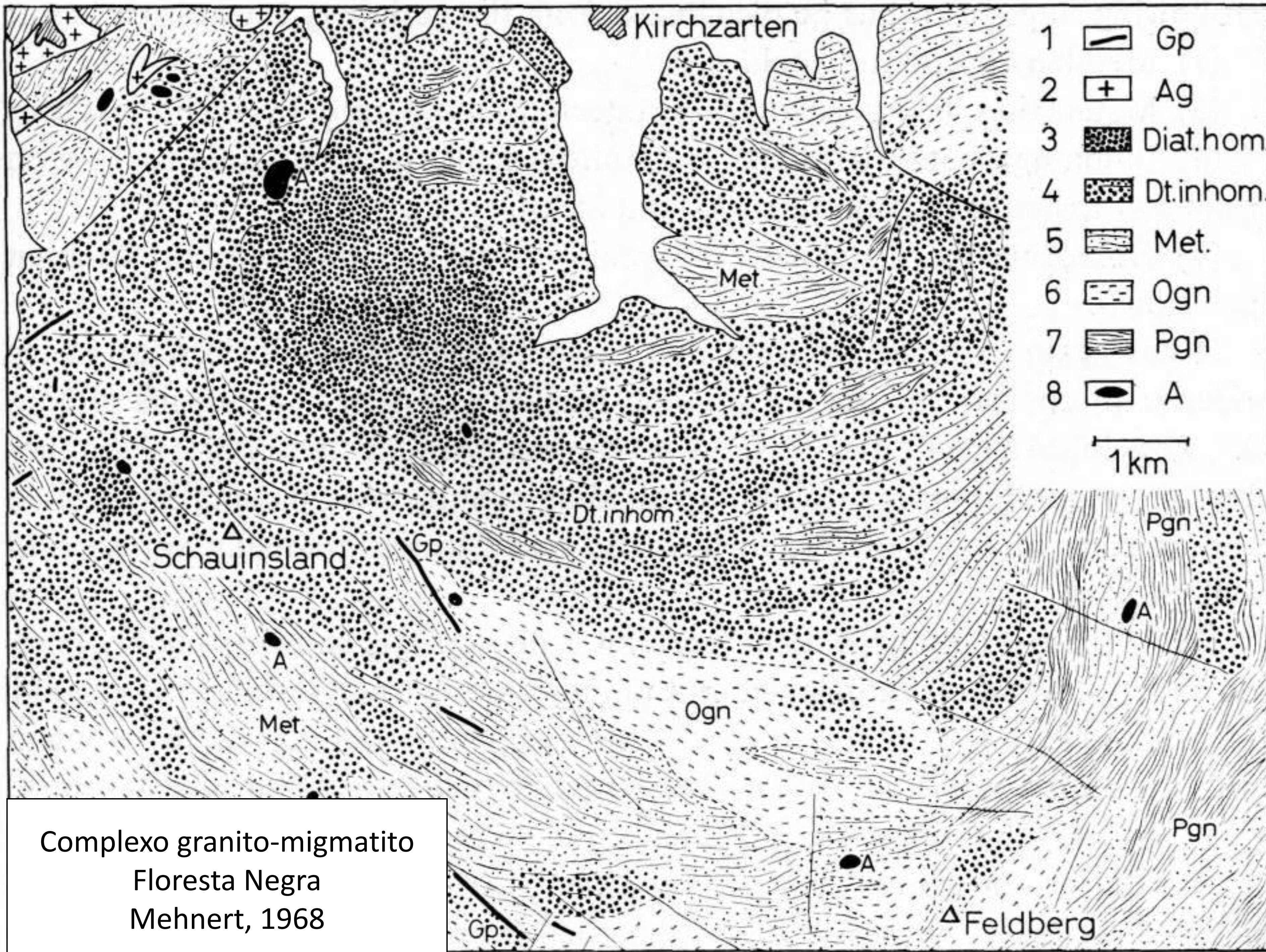
- Os termos **paleossoma** e **neossoma** são interpretativos e não descritivos como sugerido, mas são essenciais na definição de migmatito
- O **paleossoma** só existe como definido por Mehnert em baixas taxas de fusão. Quando altas taxas de fusão são alcançadas, a rocha parental (ou protolito) é bastante modificada e deve ganhar outro nome (neossoma mesocrático?)
- O termo **mesossoma** foi inventado para tentar cobrir esse problema, mas é infeliz, pois geneticamente não diz nada

Brown, 1973

- **Metatexito**: migmatito heterogêneo na escala de afloramento
- estruturas pré-fusão ainda são coerentes e preservadas
- leucossoma bem desenvolvido
- separação clara entre leucossoma e melanossoma

Brown, 1973

- **Diatexito**: migmatito em que o neossoma predomina
- fusão ocorreu de forma homogênea no protolito
- estruturas primárias são raras e substituídas por estruturas de fluxo sin-anatéticas (*schlieren* ou foliação magmática)
- paleossoma pode estar presente como enclaves ou *rafts*



Complexo granito-migmatito
Floresta Negra
Mehnert, 1968


NMV-69
0 1 2 3 4 5 6 7 cm

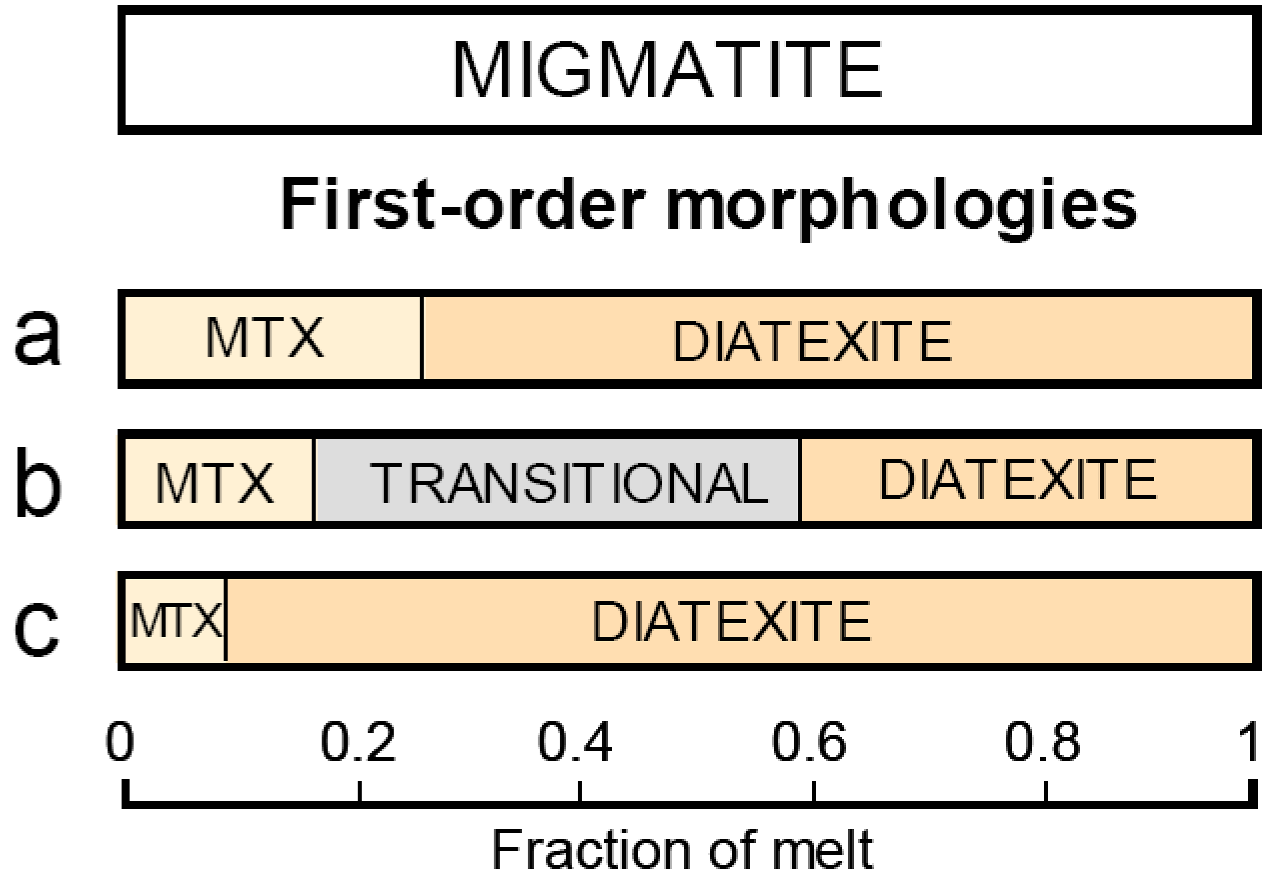

NMV-58
0 1 2 3 4 5 6 7 cm

Classificação de Sawyer (2008)

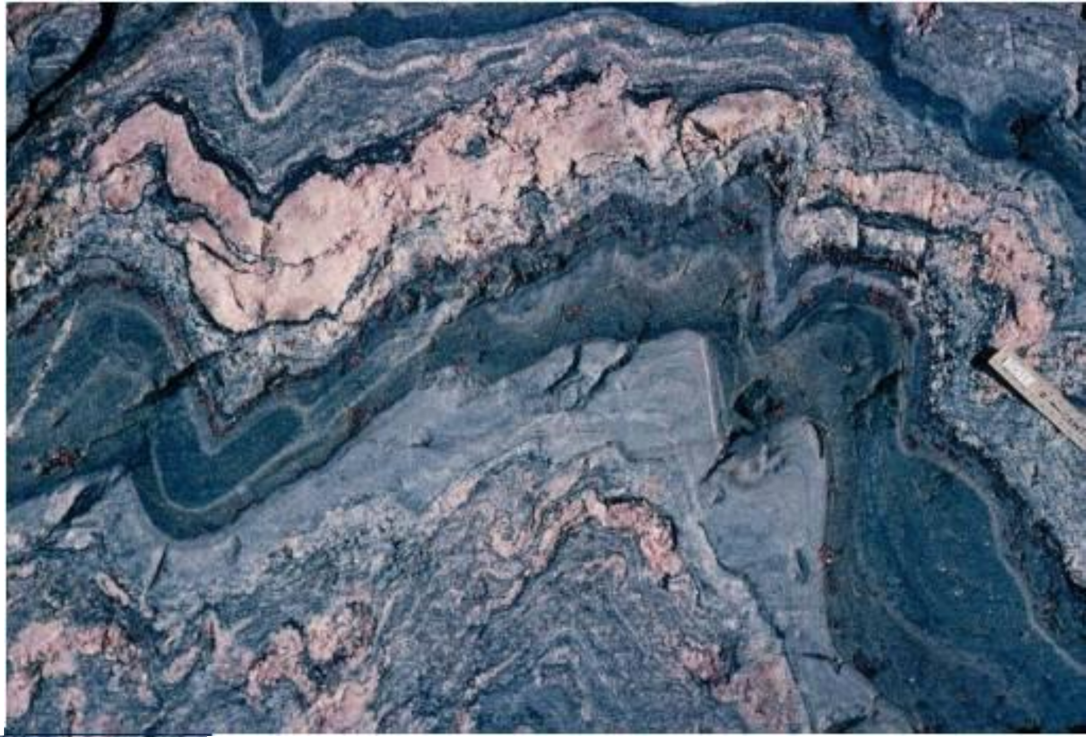
- Classificação leva em conta:
  - taxa de fusão
  - textura original da rocha (forma dos grãos)
  - deformação *vs.* fusão *vs.* cristalização
  - Usam-se os termos de Mehnert:
    - neossoma (leucossoma e melanossoma)
    - paleossoma: porção não fundida (não é o protolito)
  - A classificação é dividida em duas ordens
    - primeira ordem
      - metatexito
      - diatexito
    - segunda ordem
      - estrutura predominante

Divisão de primeira ordem

- Relacionada com a taxa de fusão e proporção de fundido presente
  - metatexito
  - diatexito



diatexito



metatexito

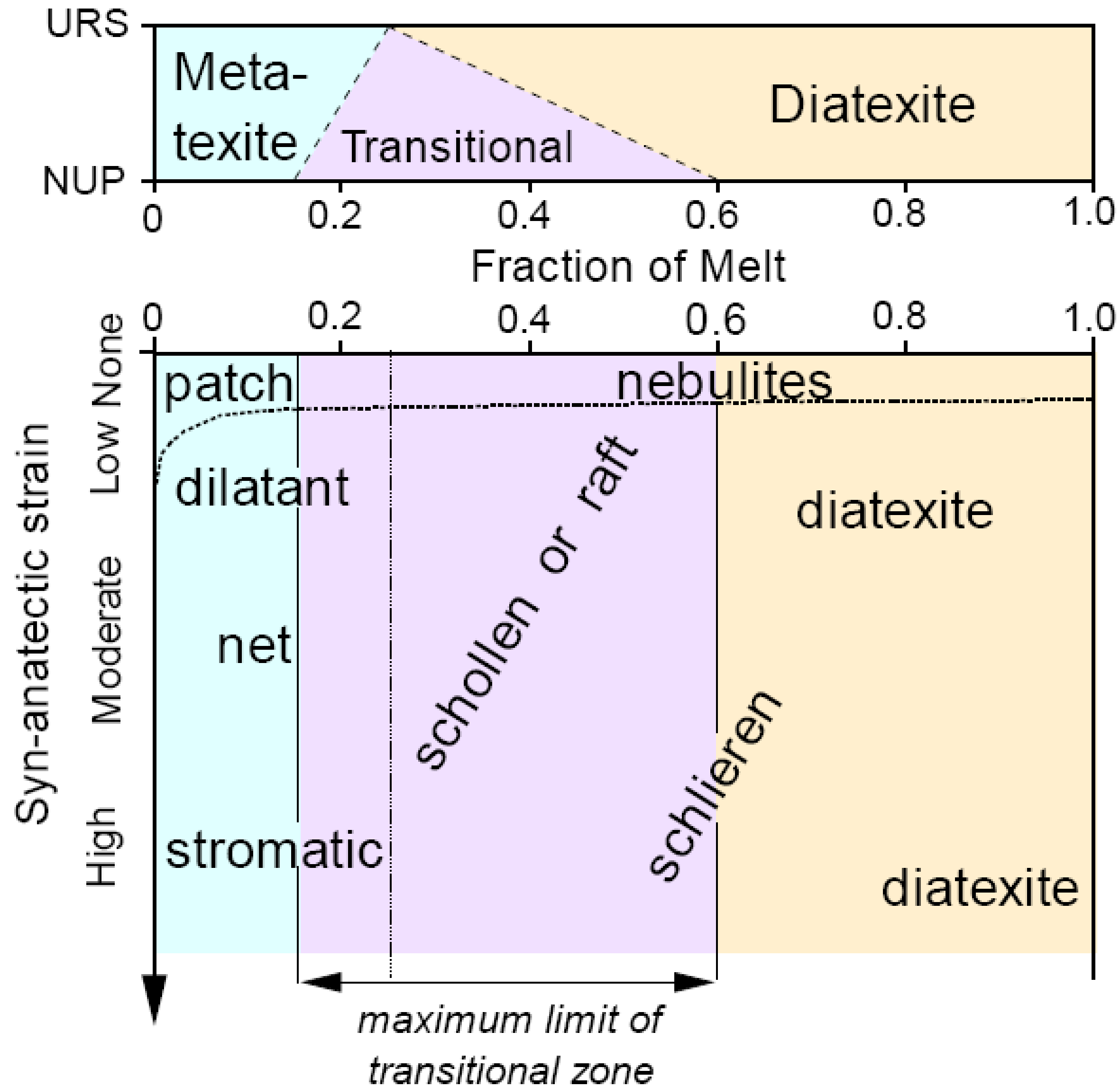
A divisão de primeira ordem está associada com a proporção de fusão no migmatito e, portanto, com *T* e composição da rocha

Divisão de segunda ordem

Divisão de segunda ordem diz respeito à morfologia do migmatito

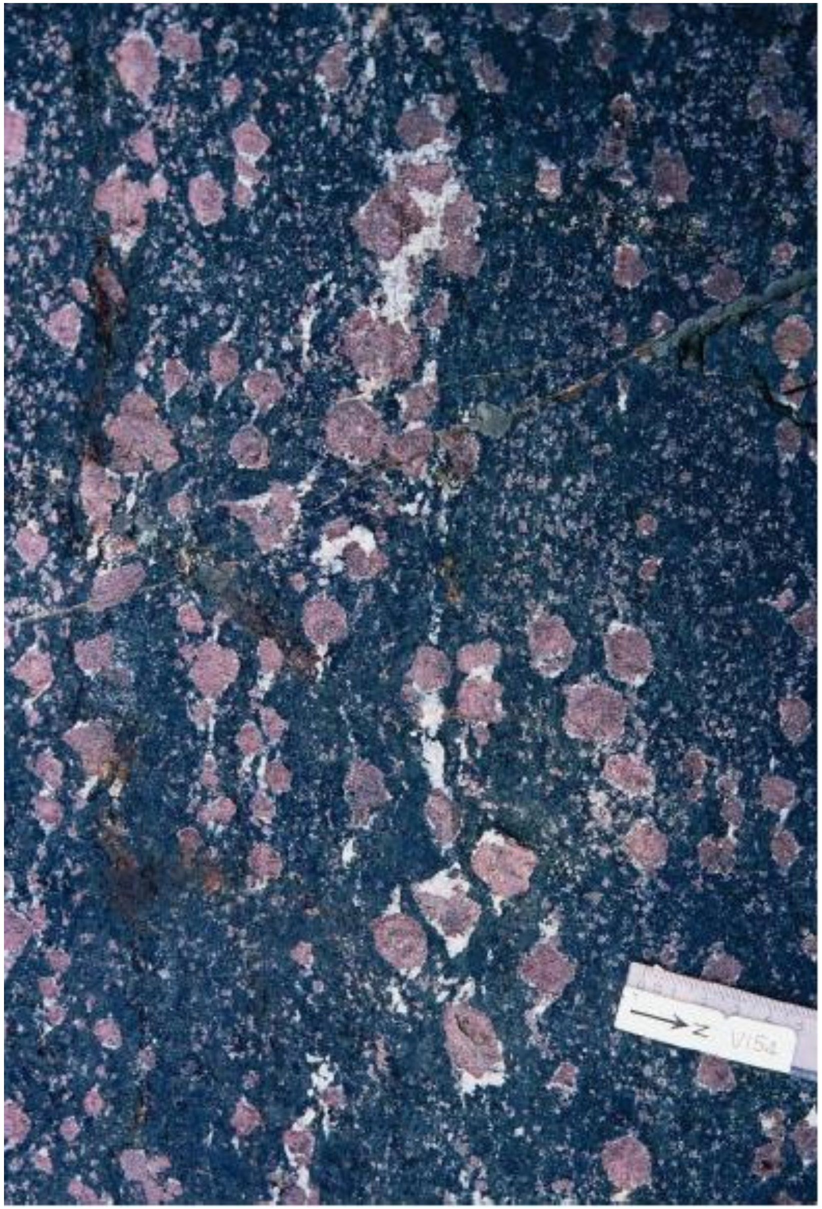
Está relacionada à proporção de fusão e estruturas

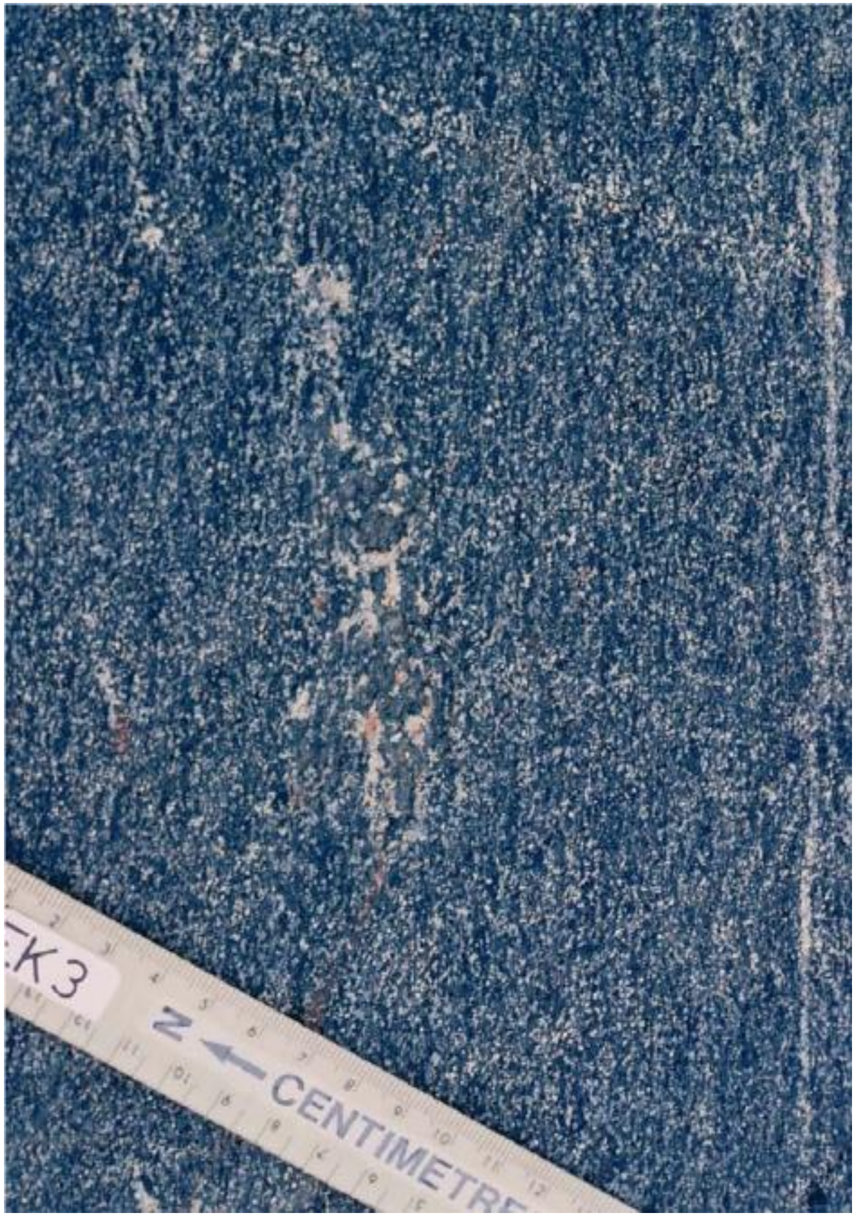
URS – *uniform regular spheres*
NUP – *non-uniform in size and shape*



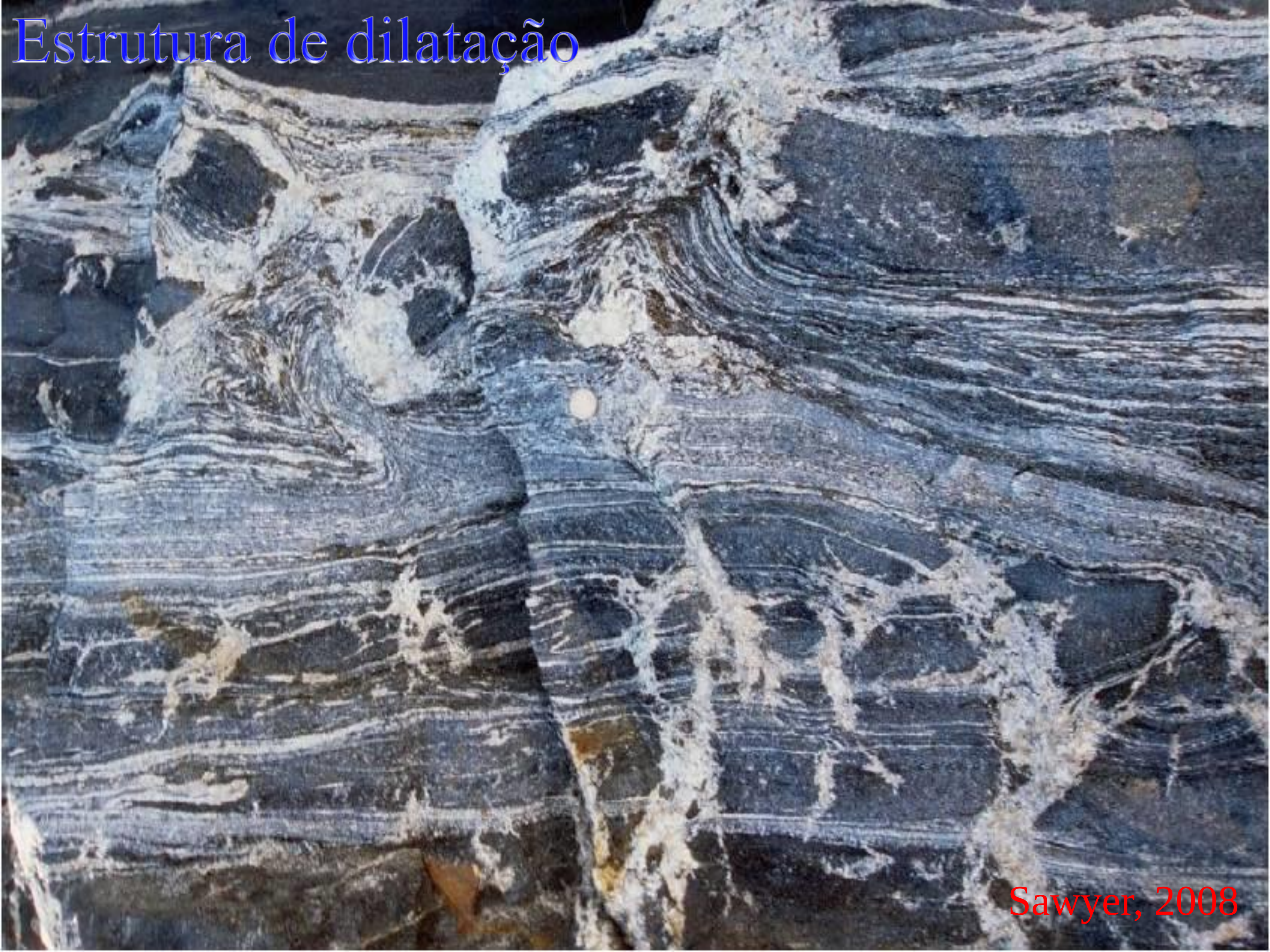
Migmatização incipiente (*patch*)

Sawyer, 2008





Estrutura de dilatação

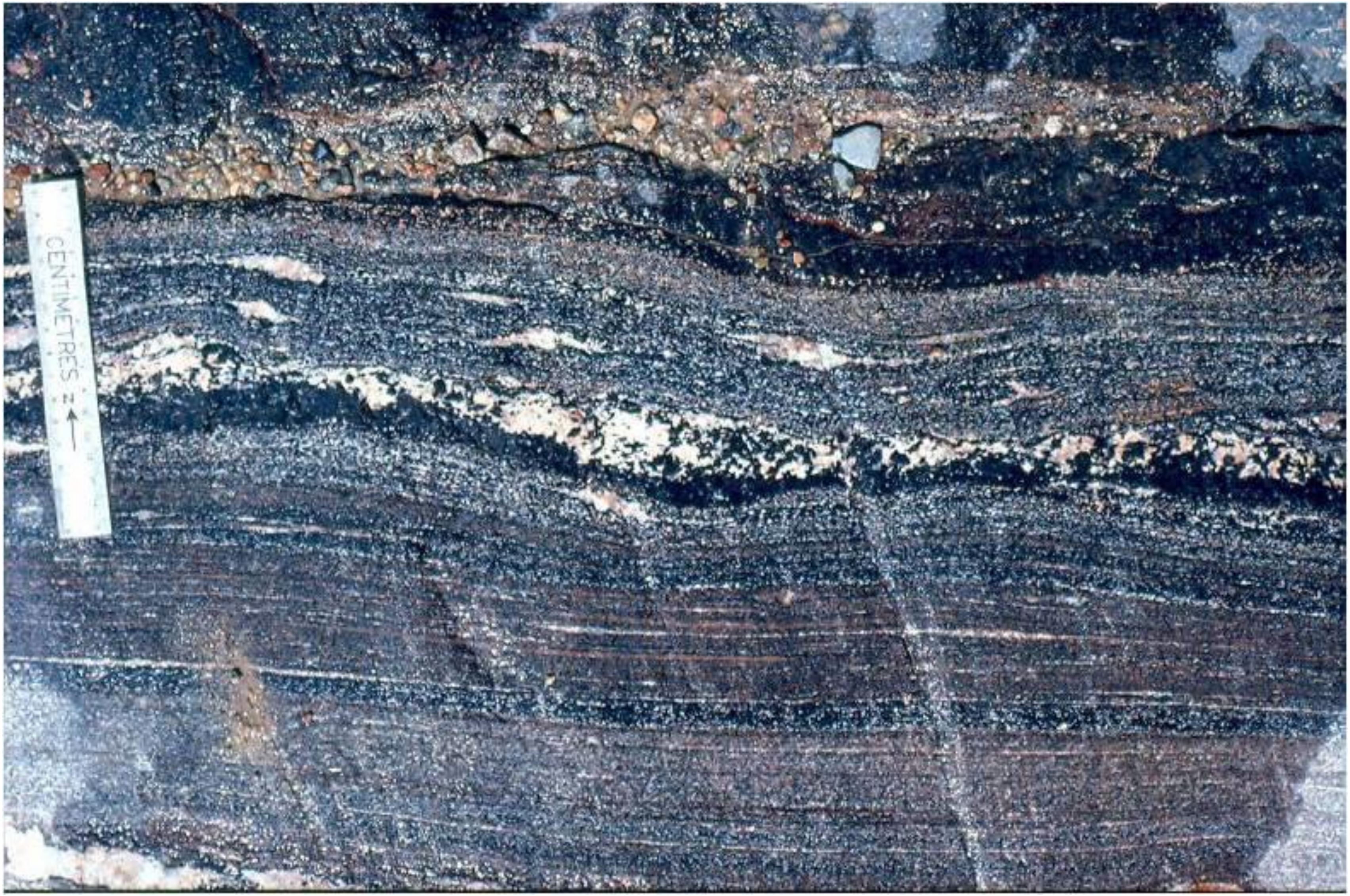


Sawyer, 2008

Metatexito com leucossoma em rede

Sawyer, 2008

Metatexito estromático



Sawyer, 2008

Diatexito nebulítico

Sawyer, 2008

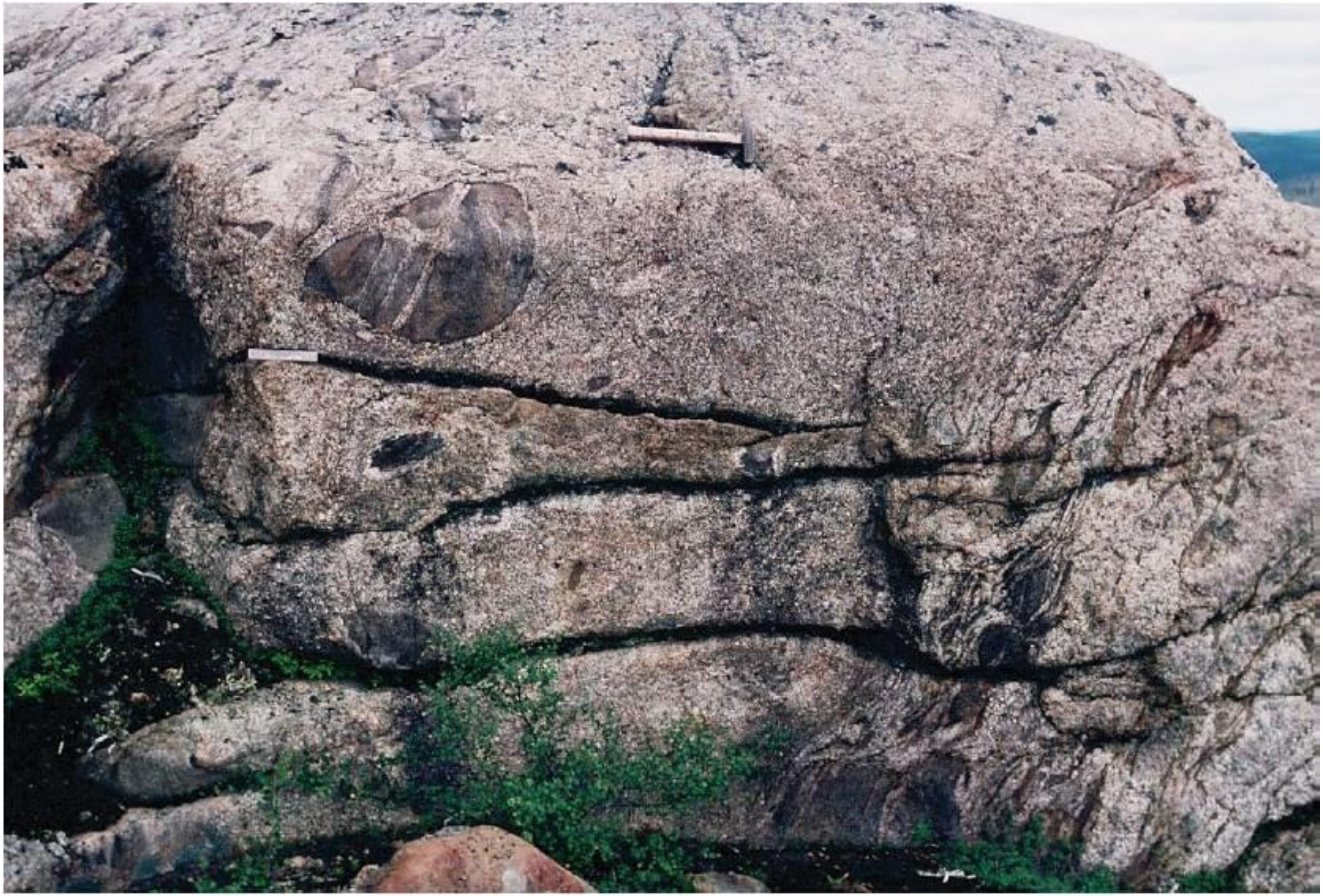
Diatexito com *schölen* ou *raft*

Sawyer, 2008

Diatexito uniforme

Sawyer, 2008

Diatexito heterogêneo

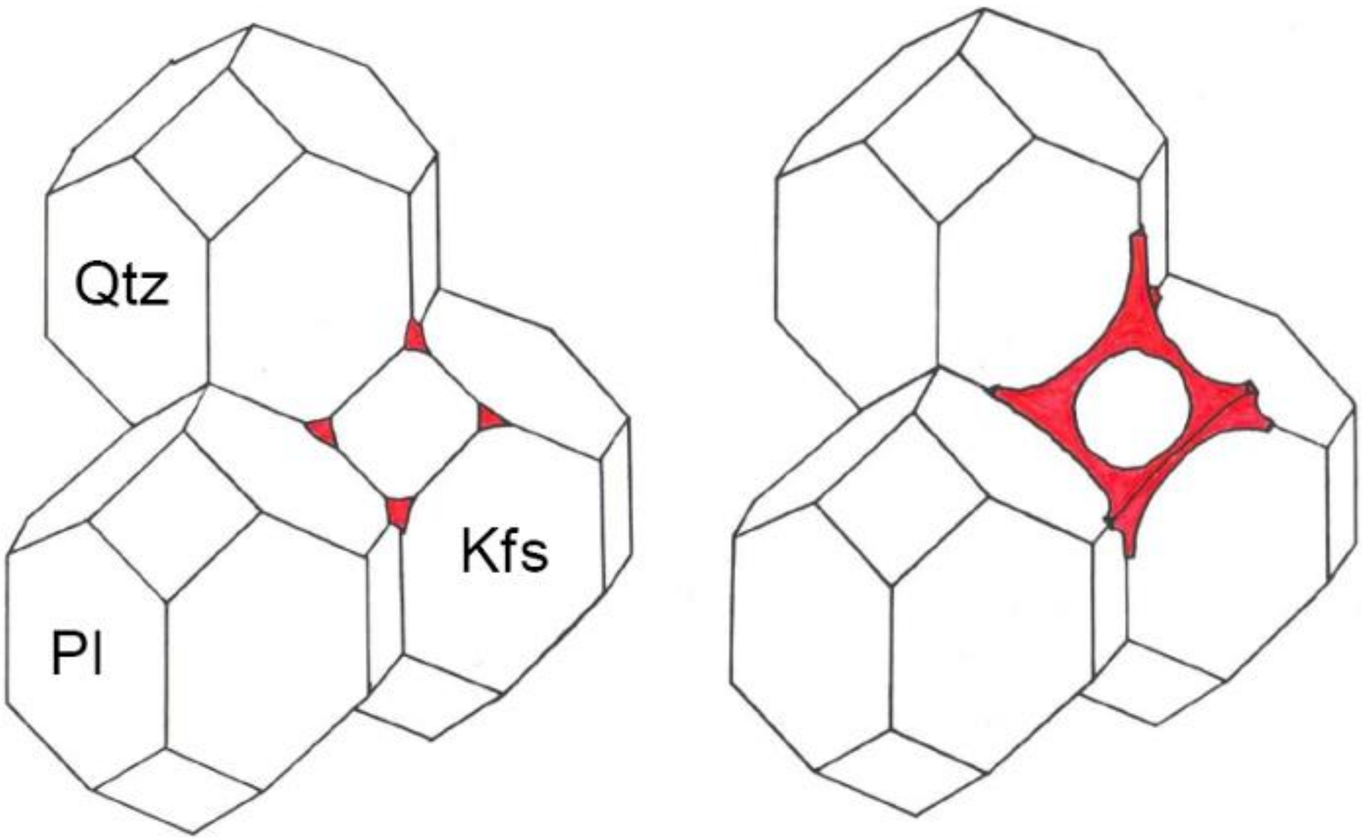


Sawyer, 2008

Fusão parcial (anatexia)

- Como as rochas são materiais heterogêneos, a fusão ocorre de forma parcial e dentro de certo intervalo de temperatura
- A fusão é parcial porque a rocha funde apenas onde todos reagentes estão em contato e quase sempre há geração de resíduo sólido

Onde começa a fusão?



- a fusão começa no contato dos grãos que participam da reação de fusão
- a avanço da fusão interliga as gotas de fundido

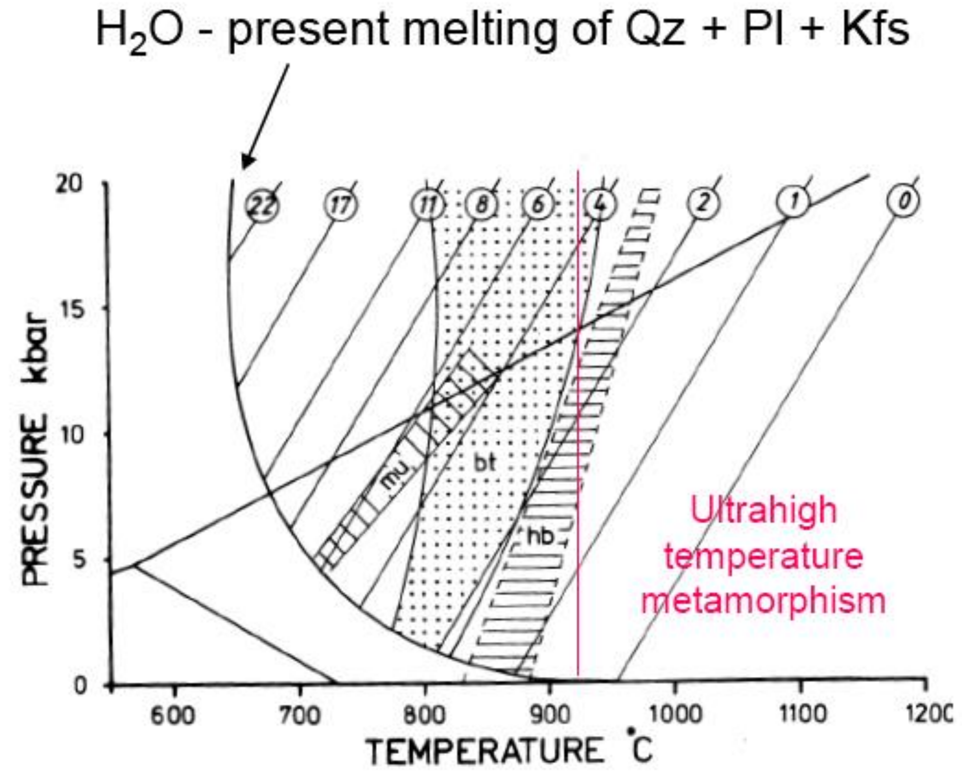
Reações de fusão

- Reações com excesso de H_2O – fusão total e líquido saturado em vapor

- Reações sem excesso de H_2O – produção de líquido mais poucas fases peritéticas

- Reações de fusão por desidratação – líquido insaturado em H_2O + fases peritéticas

- Reações de fusão de fases anidras – líquido insaturado em H_2O + fases peritéticas



Contrib Mineral Petrol (1999) 134: 17–32

Frank S. Spear · Matthew J. Kohn · John T. Cheney

P-T paths from anatectic pelites

Received: 5 March 1998 / Accepted: 7 August 1998

Abstract A relatively simple petrogenetic grid for partial melting of pelitic rocks in the NCKFMASH system is presented based on the assumption that the only H_2O available for melting is through dehydration reactions. The grid includes both discontinuous and continuous Fe-Mg reactions; contours of Fe/(Fe+Mg) for continuous reactions define *P-T* vectors along which continuous melting will occur. For biotite-bearing assemblages (garnet + biotite + sillimanite + K-feldspar + liquid and garnet + biotite + cordierite + K-feldspar + liquid), Fe/(Fe+Mg) contours have negative slopes and melting will occur with increasing temperature or pressure. For biotite-absent assemblages (garnet + cordierite + sillimanite + K-feldspar + liquid or garnet + cordierite + orthopyroxene + K-feldspar + liquid) Fe/(Fe + Mg) contours have flat slopes and melting will occur only with increasing pressure. The grid predicts that abundant matrix K-feldspar should only be observed if rocks are heated at $P < 3.8$ kbar, that abundant retrograde muscovite should only be observed if rocks are cooled at $P > 3.8$ kbar, and that generation of late biotite + sillimanite replacing garnet, cordierite, or as selvages around leucosomes should be common in rocks in which melt is not removed. There is also a predicted field for dehydration melting of staurolite between 5 and 12 kbar. Textures in migmatites from New Hampshire, USA, suggest that prograde dehydration melting reactions are very nearly completely reversible during cooling and crystallization in rocks in which melt is not removed. Therefore, many reaction textures in "low grade" migmatites may represent retrograde rather than prograde reactions.

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M.J. Kohn

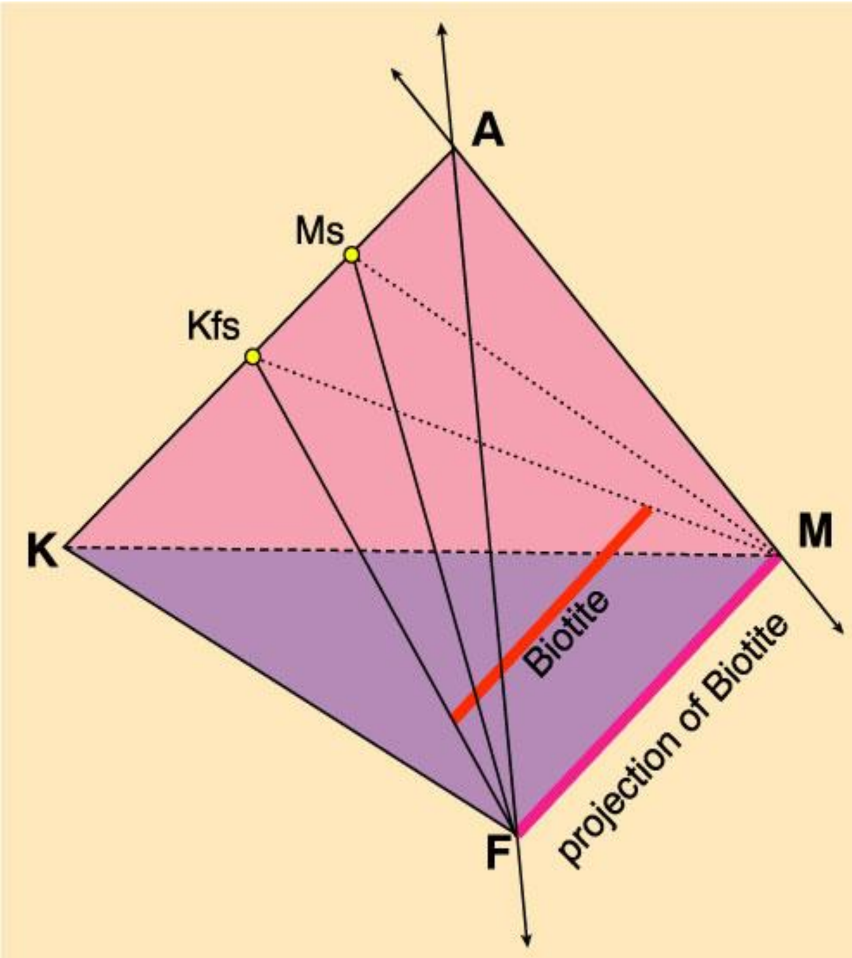
Introduction

Partial melting of pelites involves reactions that are predictable within the context of a petrogenetic grid. Accordingly, reaction textures produced during partial melting and associated mineral zoning can provide powerful clues about a rock's *P-T* evolution.

Numerous experimental studies have constrained the *P-T* conditions for many of the melting reactions important to pelites (e.g., Huang and Wyllie 1973, 1974, 1975, 1981; Huang et al. 1973; Le Breton and Thompson 1988; Gardien et al. 1995; Patiño Douce and Johnston 1991; Vielzeuf and Holloway 1988; Vielzeuf and Clemens 1992). In addition, several petrogenetic grids have been presented for pelites in the melting region, and some of these have considered the implications of vapor-saturated, $P_{fluid} < P_{total}$, and vapor-absent melting reactions (e.g., Thompson and Algor 1977; Thompson and Tracy 1979; Thompson 1982; Grant 1985a, b; Powell and Downes 1990; Carrington and Harley 1995; Thompson and Connolly 1995).

The purpose of this paper is to present a relatively simple petrogenetic grid for partial melting of low variance pelitic rocks that can be used to help interpret reaction textures with respect to their *P-T* significance.

AFM projetado do Kfs



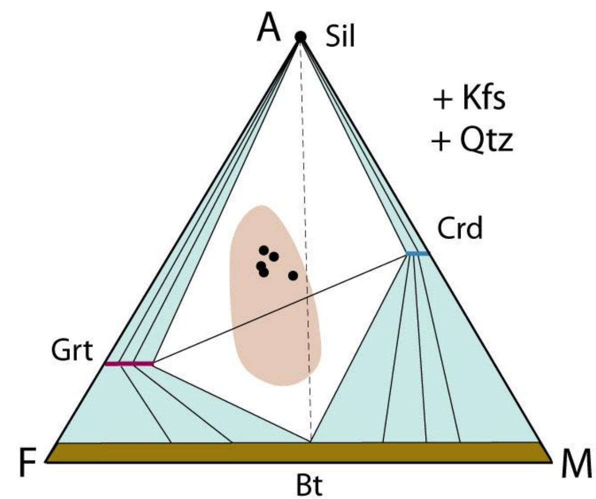
Feldspato potássico: $KAlSi_3O_8$

$0{,}5\ K_2O : 0{,}5\ Al_2O_3 : 3\ SiO_2$

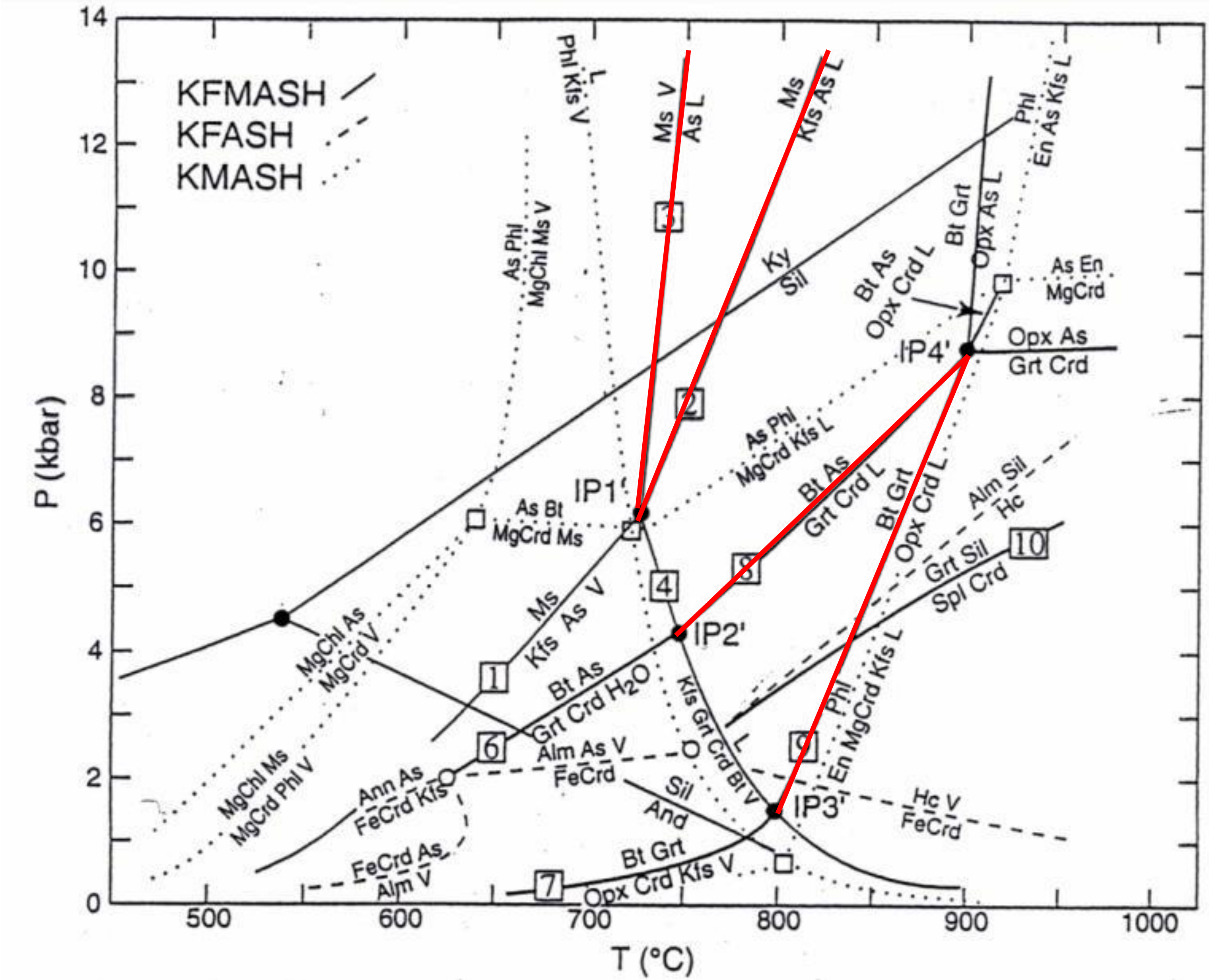
K_2O – feldspato potássico – em excesso em metapelitos de fácies anfibolito superior a granulito

$$A = \frac{Al_2O_3 - K_2O}{Al_2O_3 - K_2O + FeO + MgO}$$

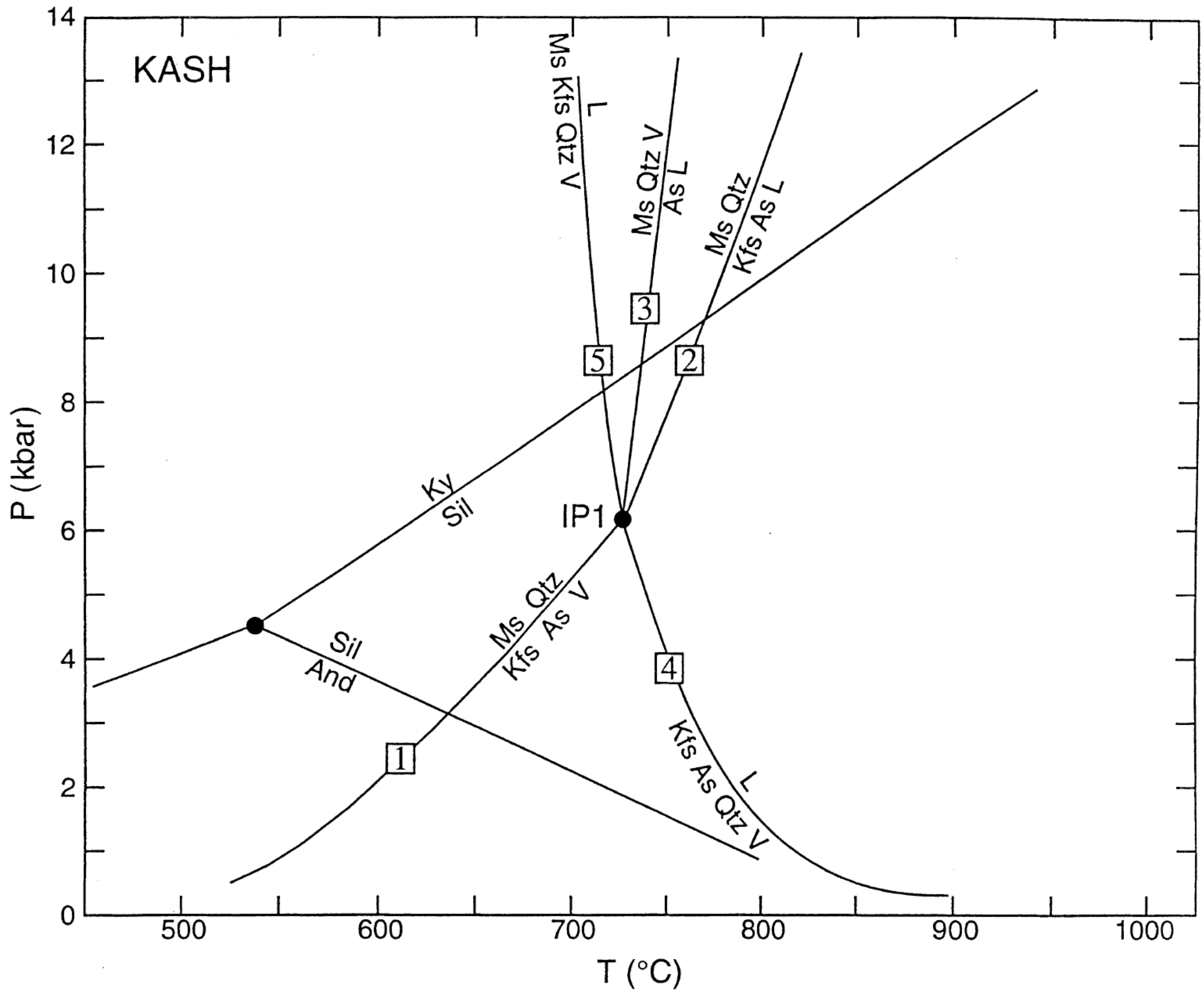
$$X_{Mg} = \frac{MgO}{FeO + MgO}$$



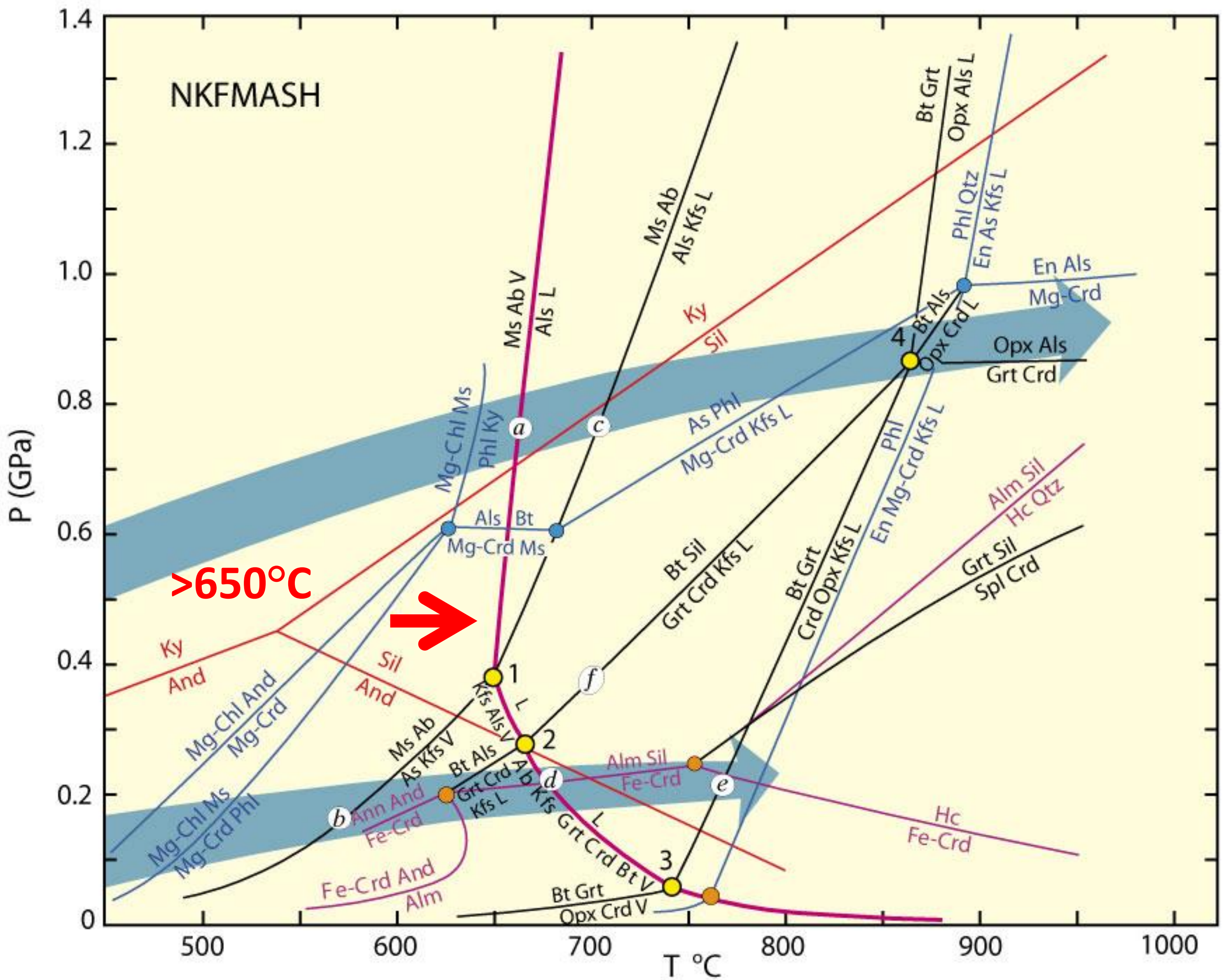
De que *T* estamos falando?



Um muscovita-quartzito pode fundir?



Adicionando Na no sistema (fusão em menor temperatura)

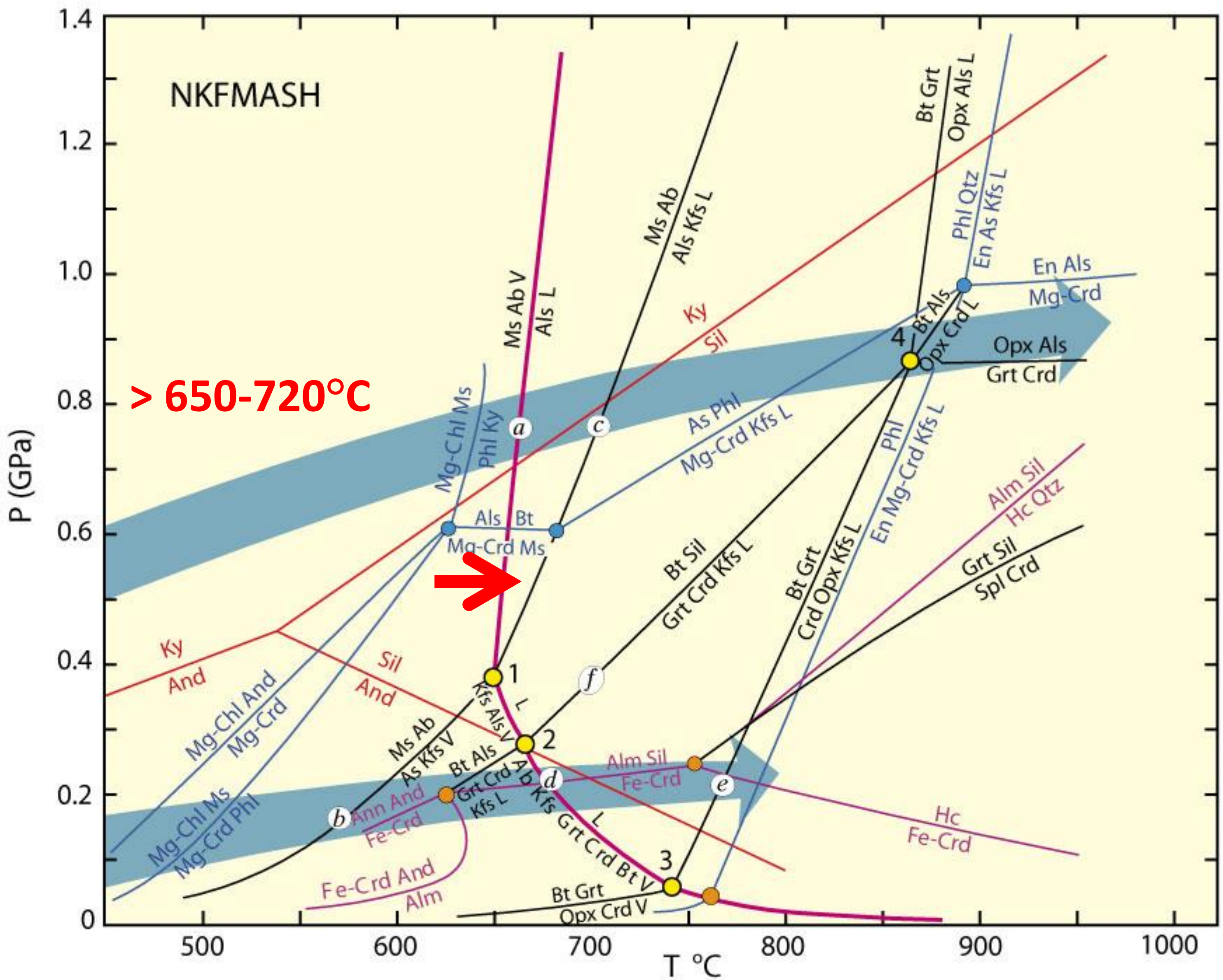


Winter (2010) Principles of Igneous and Metamorphic Petrology 2nd edition. Prentice Hall.
(Adaptado de Spear et al., 1999)

Segunda Isógrada da Sillimanita

Como não é esperado água livre disponível para produzir um grande volume de fundido por reações saturadas em água, a fusão deve ocorrer principalmente pela quebra de minerais hidratados (Ms, Bt, Hbl) que liberam água, que por sua vez é dissolvida no fundido silicático:

Ms + Qtz = Kfs + Sil + fundido silicático



Winter (2010) Principles of Igneous and Metamorphic Petrology 2nd edition. Prentice Hall.
(Adaptado de Spear et al., 1999)

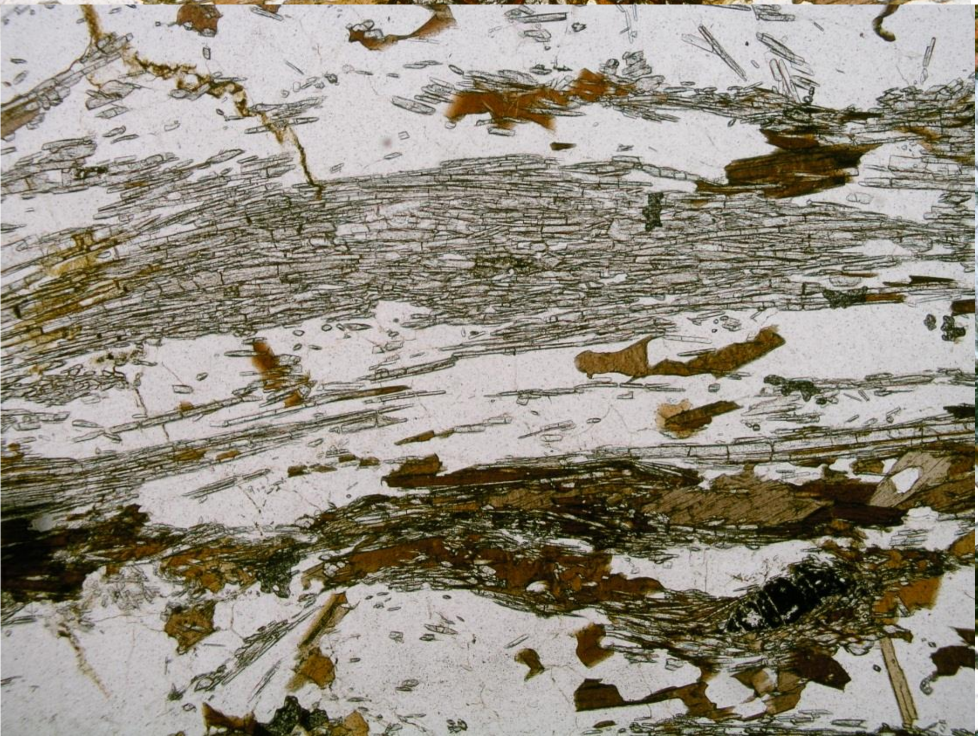
Zona Sillimanita-Feldspato Potássico

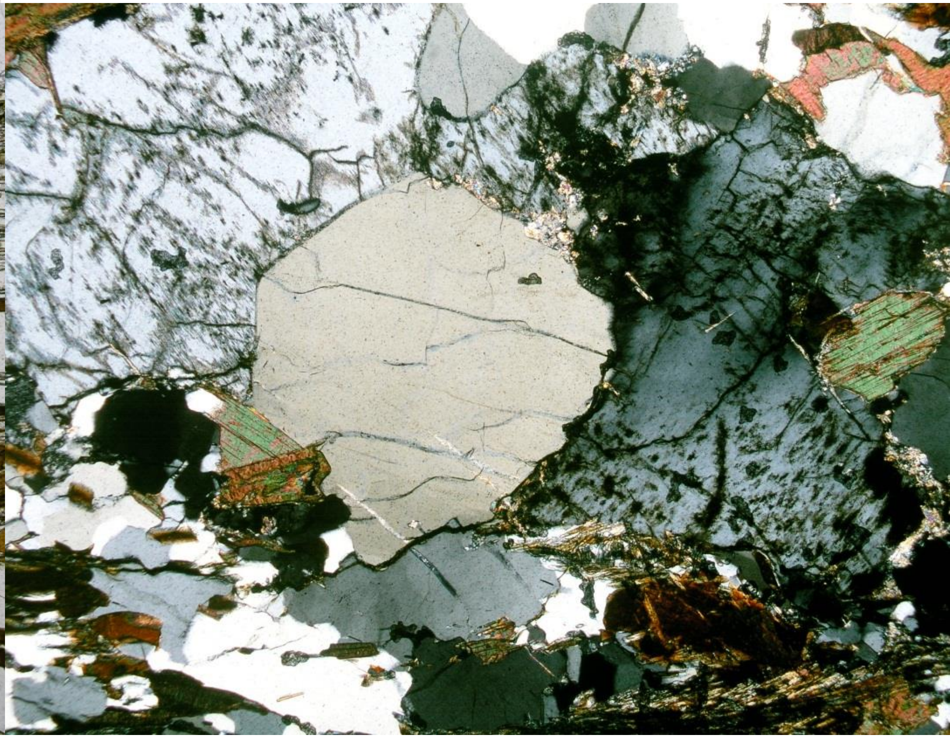
Associação:

Grt + Bt + Sil + Kfs + Qtz ± Pl
(Ms ausente)

Formação Turvo-Cajati (Criogeniano),
Cinturão Ribeira Meridional, Cajati (SP)

Faleiros (2008). Tese de Doutorado. IGc-USP.





E rochas quartzo-feldspáticas?

Lithos 116 (2010) 273–286

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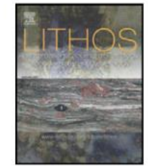

Migmatites formed by water-fluxed partial melting of a leucogranodiorite protolith: Microstructures in the residual rocks and source of the fluid

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ABSTRACT

The Opatica Subprovince in the Canadian Shield is a late Archaean (2761–2702 Ma) plutonic arc formed above a north-dipping subduction zone. Anatexis (2690–2677 Ma) of leucogranodiorite and leucotonalite orthogneisses in the Opatica generated migmatites in an area of north-vergent back thrusts visible at the surface and in Lithoprobe seismic profile 48. Schollen diatexite migmatites occur in the thrusts and metatexite migmatites between them.

The modal mineralogy, microstructure, and whole rock major, trace and oxygen isotope compositions of the protolith and migmatites were investigated to; 1) determine the melting reaction, 2) find microstructural criteria for identifying residual rocks in leucocratic systems where there is no melanosome, and 3) to determine the source of the fluid involved in anatexis.

Partial melting of the protolith did not change the mineral assemblage, but the abundance of quartz and microcline both declined and plagioclase and biotite increased in the residual rocks. Quartz, plagioclase and microcline show evidence for dissolution and biotite does not. Thus, water-fluxed melting of quartz + plagioclase + microcline occurred. A mass balance indicates 25–30% partial melting. The melting reaction consumed the microcline and created essentially monomineralic domains of plagioclase. Extraction of 80–90% of the melt left a thin film of melt on the grain boundaries, and crystallization of these in the plagioclase domains created diagnostic microstructures. Microcline fills the last remaining pore space and forms high-aspect ratio crystals between plagioclases or triangular crystals at grain junctions. Quartz shows a range of morphologies, from high-aspect ratio films through the “string of beads” to isolated rounded grains, as the microstructure progressively equilibrated after crystallisation.

Most accessory phases, including zircon, remained in the residuum. However, almost all the schollen migmatites have high contents of Th, U, Nb, Ta and REE relative to the protolith, due to contamination by accessory phases derived from mafic rocks. Disaggregation of the mafic rocks may have been facilitated by the high strain in the back thrusts where the schollen diatexites formed.

Average whole rock $\delta^{18}O$ for the protolith and migmatites are similar (ca 8.2‰), and the small difference between melt-rich (8.6‰) and residuum-rich rocks (8.0‰) is consistent with fractionation. Thus, the fluid that caused melting was probably of metamorphic origin with $\delta^{18}O$ similar to the protolith. The seismic profile shows several reflectors extending to a present depth of 20 km (ca. 40 km in the late Archaean) under the migmatites; these are the paths along which the metamorphic fluid migrated and generated the migmatites now at the surface. A new type of neosome reported in this study may have formed along fractures that the fluids migrated along, however, these are peripheral pathways in the metatexites adjacent to the back thrusts and schollen diatexites.

E rochas quartzo-feldspáticas?

Lithos 212–215 (2015) 158–188

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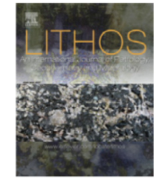

Invited review article

Water-fluxed melting of the continental crust: A review

CrossMark

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ABSTRACT

Water-fluxed melting, also known as fluid- or water-present melting, is a fundamental process in the differentiation of continents but its importance has been underestimated in the past 20 years during which research efforts focused mostly on dehydration melting reactions involving hydrate phases, in the absence of a separate aqueous phase. The presence of a free aqueous phase in anatectic terranes influences all major physical and chemical aspects of the melting process, from melt volumes, viscosity and ability to segregate from rock pores, to melt chemical and isotopic composition. A review of the literature shows that melting due to the fluxing of aqueous fluids is a widespread process that can take place in diverse tectonic environments. Active tectono-magmatic processes create conditions for the release of aqueous fluids and deformation-driven, transient high permeability channels, capable of fluxing high-temperature regions of the crust where they trigger voluminous melting. Water-fluxed melting can be either congruent in regions at the water-saturated solidus, or incongruent at suprasolidus, P–T conditions. Incongruent melting reactions can give rise to peritectic hornblende, or to nominally anhydrous minerals such as garnet, sillimanite or orthopyroxene. In this case, the presence of an aqueous phase is indicated by a mismatch between the large melt fraction generated and the much smaller fractions predicted in its absence.

The relatively small volumes of aqueous fluids compared to that of rocks imply that melting reactions are generally rock buffered. Fluids tend to move upwards and down temperature. However, there are cases in which pressure gradients drive fluids up temperature, potentially fluxing suprasolidus terranes. Crustal regions at conditions equivalent to the water-saturated solidus represent a natural impediment to the up-temperature migration of aqueous fluids because they are consumed in melting reactions. In this case, continued migration into supra-solidus terranes take place through the migration of water-rich melts. Thus, melts become the transport agent of water into supra-solidus terranes and responsible for water-fluxed melting. Other processes, such as the relatively rapid fluid migration through fractures, also allow regional aqueous fluids to by-pass the water-saturated solidus fluid trap and trigger melting above solidus conditions. When aqueous fluids or hydrous melts flux rocks at supra-solidus conditions, they equilibrate with the surroundings through further melting, decreasing water activity and giving rise to undersaturated melts. It is in these conditions that hornblende or anhydrous peritectic phases are stabilized. Unlike dehydration melting, the melt fraction generated in this case is not limited by the water contained in hydrous minerals but by the volume of water added to the system. Unlike melting at the water-saturated solidus, these melts are capable of rising without freezing and do give rise to upper crustal granitic bodies.

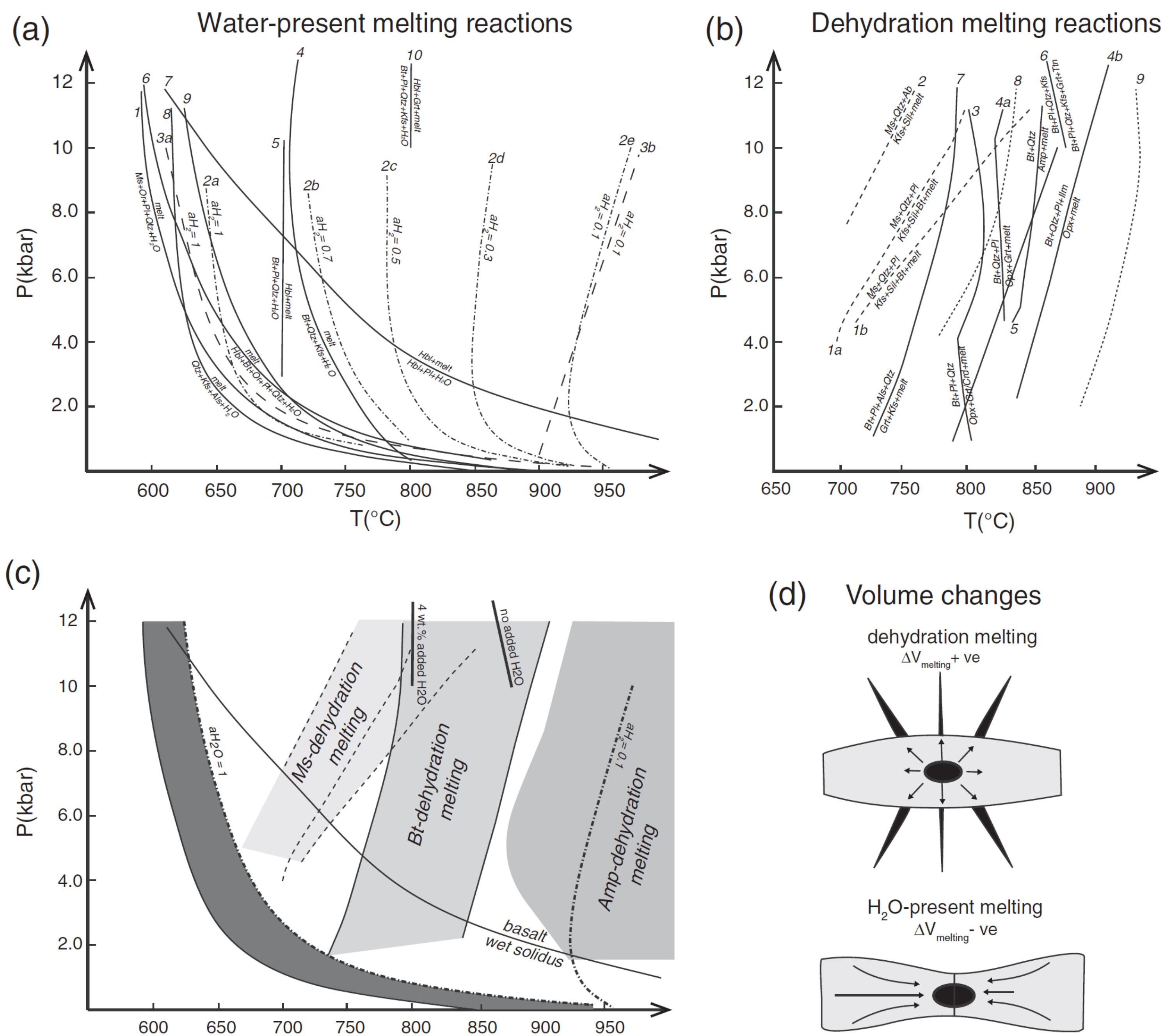

(a)
Water-present melting reactions
P(kbar)
T(°C)
Ms+Or+Pl+Qtz+H2O
melt
aH2=1
aH2=1
aH2=0.7
aH2=0.5
aH2=0.3
aH2=0.1
aH2=0.1
Bt+Pl+Qtz+H2O
Hbl+melt
Bt+Qtz+Kfs+H2O
melt
Hbl+Grt+melt
Bt+Pl+Qtz+Kfs+H2O
Hbl+melt
Hbl+Pl+H2O
Hbl+Bt+Or+Pl+Qtz+H2O
melt
Qtz+Kfs+Als+H2O
melt
(b)
Dehydration melting reactions
P(kbar)
T(°C)
Ms+Qtz+Ab
Kfs+Sil+melt
Ms+Qtz+Pl
Kfs+Sil+Bt+melt
Ms+Qtz+Pl
Kfs+Sil+Bt+melt
Bt+Pl+Als+Qtz
Grt+Kfs+melt
Bt+Pl+Qtz
Opx+Grt/Crd+melt
Bt+Qtz+Pl
Opx+Grt+melt
Bt+Qtz
Amp+melt
Bt+Pl+Qtz+Kfs
Bt+Pl+Qtz+Kfs+Grt+Ttn
Bt+Qtz+Pl+Ilm
Opx+melt
(c)
P(kbar)
T(°C)
aH2O=1
Ms-dehydration melting
4 wt.% added H2O
no added H2O
Bt-dehydration melting
aH2=0.1
Amp-dehydration melting
basalt wet solidus
(d)
Volume changes
dehydration melting
ΔVmelting+ ve
H2O-present melting
ΔVmelting- ve

Table 1
Key dehydration melting reactions. For comparison see Table 2 where water-present melting reactions are listed.

	Peritectic mineral	Melt composition	PT conditions	Protolith type	Reference
Ms-dehydration melting					
Ms + Pl + Qtz = Als + Kfs + melt	Als, Kfs	Kfs-rich melt	MP MT	metapelite	Thompson, 1983; Pëto, 1976; Spear, 1993
Bt-dehydration melting					
Bt + Als + Qtz = Grt/ Crd + Kfs + melt	Grt, Crd, Kfs	Kfs-rich melt	Crd will form at LP, Grt at HP, both at intermediate T	metapelite (no Pl)	Le Breton and Thompson, 1988; Spear, 1993
Bt + Pl + Als + Qtz = Grt/ Crd + Kfs + melt	Grt, Crd, Kfs	Kfs + Pl in melt	Crd will form at LP, Grt at HP, both at intermediate T	metapelite	Le Breton and Thompson, 1988; Spear, 1993
Bt + Pl + Qtz = Opx (+Cpx + Grt) + melt	Opx, Cpx, Grt (depends on rock composition)	Kfs + Pl in melt	variable, type of peritectic mineral depends on rock composition and PT	metapsammite, metagranitoids, metatonalite	Thompson, 1982; Vielzeuf and Holloway, 1988; Vielzeuf and Montel, 1994; Patiño Douce and Beard, 1995, 1996
Amp-dehydration melting					
Hbl + Qtz = Pl + Opx + Cpx (+Grt) + melt Hbl + Pl = Cpx (+Grt + Opx + Amp) + melt	Pl, Opx, Cpx, Grt	Pl-rich melt	variable, type of peritectic mineral depends on rock composition and PT	metabasalt K-poor/Ca-rich amphibolite	Thompson, 2001; Moyen and Stevens, 2006; Wolf and Wyllie, 1994

Abbreviations: MP = medium pressure; MT = medium temperature; HP = high pressure; LP = low pressure; P = pressure; T = temperature

Table 2
Summary of the main water-present melting reactions as determined from experimental and natural studies.

	Melting reaction	P–T conditions	Rock type	Reference
	No peritectic mineral			
[1]	*Qtz + Pl (Ab) + Kfs (Or) + H_2O = melt*			*e.g. Johannes (1985); Ebadi and Johannes (1991); Stevens and Clemens (1993); Sawyer (1998); Vernon et al. (2003)*
[2]	*Bt + Sil + Kfs + Qtz + H_2O = melt*	*650–750°C/4–5.5kbar*	*KFMASH system, pelite*	*Yardley and Barber (1991a)*
[3]	*Kfs + Sil + Bt + Grt + Qtz + H_2O = melt*	*650–750°C/4–5.5kbar*	*KFMASH system, pelite*	*Yardley and Barber (1991a)*
[4]	*Pl + Kfs + Qtz ± Sil + H_2O = melt*	*700°C/4–5kbar*	*Metapelite*	*Jung et al. (2000)*
[5]	*Bt + Qtz + Kfs + H_2O = melt*	*700–720°C/10kbar*	*KMASH*	*Peterson and Newton (1989)*
			Orthogneiss	*Sawyer (2010)*
[6]	*Hbl/Bt + Qtz + Kfs/Pl + H_2O = melt*	*~680–690°C/6kbar*	*TTG*	*Watkins et al. (2007)*
[7]	*Hbl + Bt + Qtz + Or + Pl + H_2O = melt*		*Tonalite*	*Yoder and Tilley (1962)*
[8]	*Qtz + Kfs + Als + H_2O = melt*			*Johannes and Holtz (1996)*
[9]	*Ms + Pl + Qtz + H_2O = melt*	*700–800°C/5–8kbar*	*Metagreywacke, metasedimentary rocks*	*Fornelli et al. (2002)*
		~700–900°C/>6kbar	*Ms–schist (HHC)*	*Patiño Douce and Harris (1998)*
[10]	*Ms + Pl + Kfs + Qtz + H_2O = melt*		*Metapelite*	*Thompson (1990); Huang and Wyllie (1973)*
[11]	*Ms + Sil + Pl + Qtz ± Grt ± Bt + H_2O = melt*		*MnNCKFMASH, metapelite*	*Johnson et al. (2003a)*
[12a]	*Kfs + Pl + Bt + Crd + Qtz + H_2O = melt*	*<700°C/3kbar*	*Metapelite*	*Johnson et al. (2003b)*
[12b]	*Kfs + Pl ± Bt ± Crd ± Grt + Qtz + H_2O = melt*	*~725°C/3kbar*	*Metapelite*	
[13]	*Ms + Bt + Kfs + Pl + Qtz + H_2O = melt*		*Metapelite*	*e.g. Storre and Karotke (1972); Vielzeuf and Schmidt (2001)*
[14]	*Kfs + Qtz ± Pl ± Bt ± Crd + H_2O = melt*	*650–680°C/3kbar*	*Semipelite, pelite*	*Pattison and Harte (1988)*
	Peritectic Hbl			
[15]	*Bt + Pl_1 + Qtz + Ep + H_2O = Hbl + Pl_2 + melt (Kfs rich)*	*670–780°C/8–10kbar*	*TTG*	*Mogk (1992)*
		670°C/7kbar	*Metagranitoid*	*Berger et al. (2008)*
[16]	*Bt + Pl (An_{28}) + Qtz + (H_2O) = Hbl + Pl (An_{32-34}) + Ttn + melt**	*675–750°C/6–8kbar*	*Feldspathic gneiss*	*Lappin and Hollister (1980); Kenah and Hollister (1983)*
		~700°C/6–8kbar	*Calc–alkaline granitoids*	*Reichardt and Weinberg (2012b)*
[17a]	*Bt + Pl + Qtz + H_2O = Hbl + melt*	*750–800°C/9–11kbar*	*Tonalite*	*Büsch et al. (1974)*
		~ 750–850°C/9–12kbar	*Dioritic gneiss*	*Slagstad et al. (2005)*
		675–750°C/4–6kbar	*Dacite*	*Conrad et al. (1988)*
		~ 700°C/5–10kbar >760°C/>10kbar	*CKFMASH, tonalitic gneiss*	*Escuder–Viruete (1999)*
			Gneiss	*McLellan (1988)*
			Amp+Bt gneiss	*Cherneva and Georgieva (2007)*
		675–750°C/6–8kbar	*Calc–alkaline granitoids*	*Reichardt et al. (2010); Reichardt and Weinberg (2012b)*
[17b]	*Bt + Pl + Qtz + H_2O = Hbl + Kfs + melt*	*675–750°C/6–8kbar*	*Calc–alkaline granitoids*	*Reichardt et al. (2010); Reichardt and Weinberg (2012b)*
[18a]	*Bt + Pl + Qtz + Kfs ± Ap ± Ttn ± Ep + H_2O = Hbl + Grt ± Ap ± Ttn + melt*	*<800°C/10kbar*	*Bt+Pl+Qtz banded gneiss*	*Gardien et al. (2000)*
[18b]	*Bt + Pl + Qtz + Kfs ± Ap ± Ttn ± Ep + H_2O = Hbl + Cpx ± Grt ± Ap ± Ttn + melt*	*900°C/20kbar*	*Bt+Pl+Qtz banded gneiss*	*Gardien et al. (2000)*

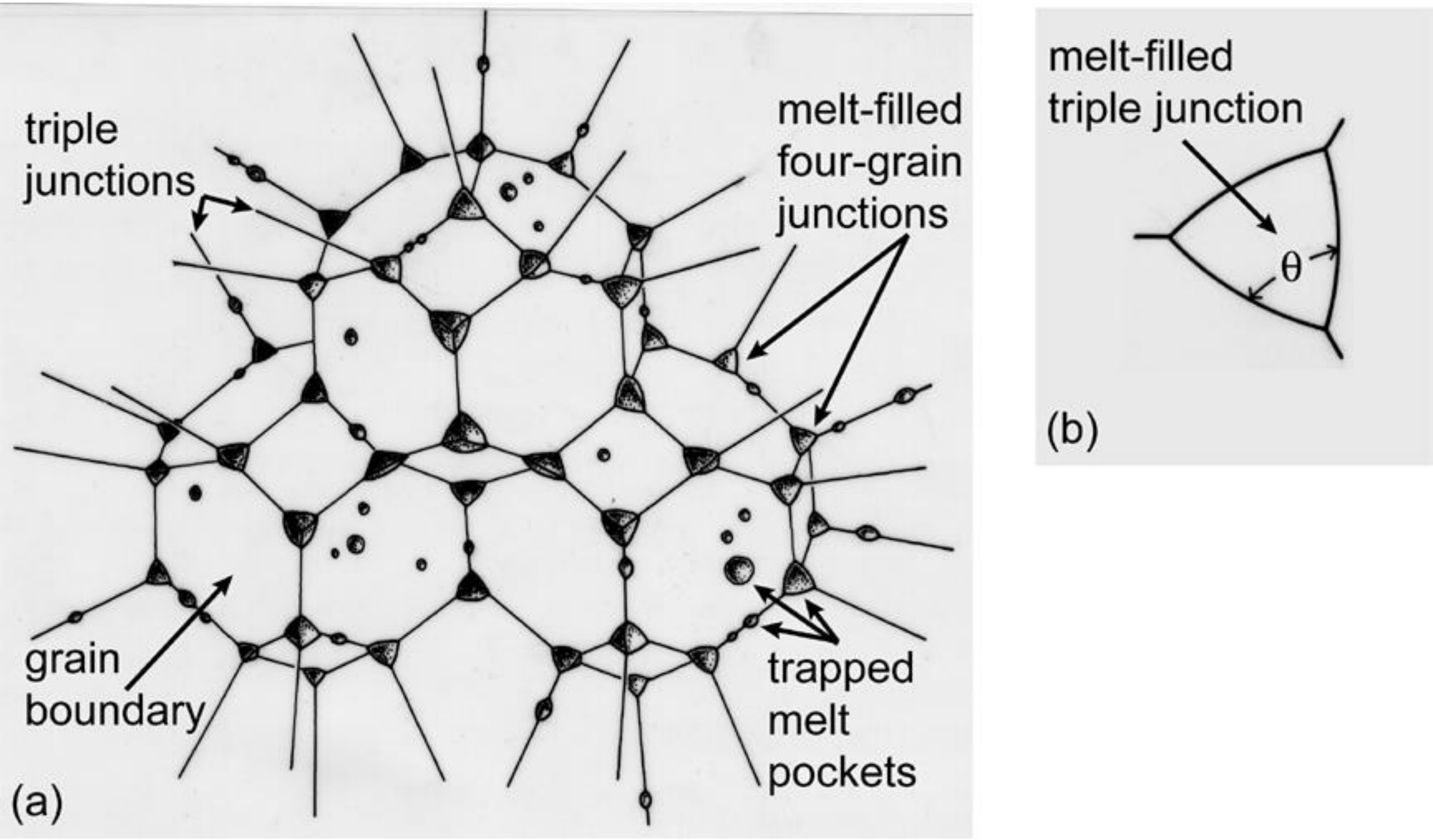
Table 2 (*continued*)

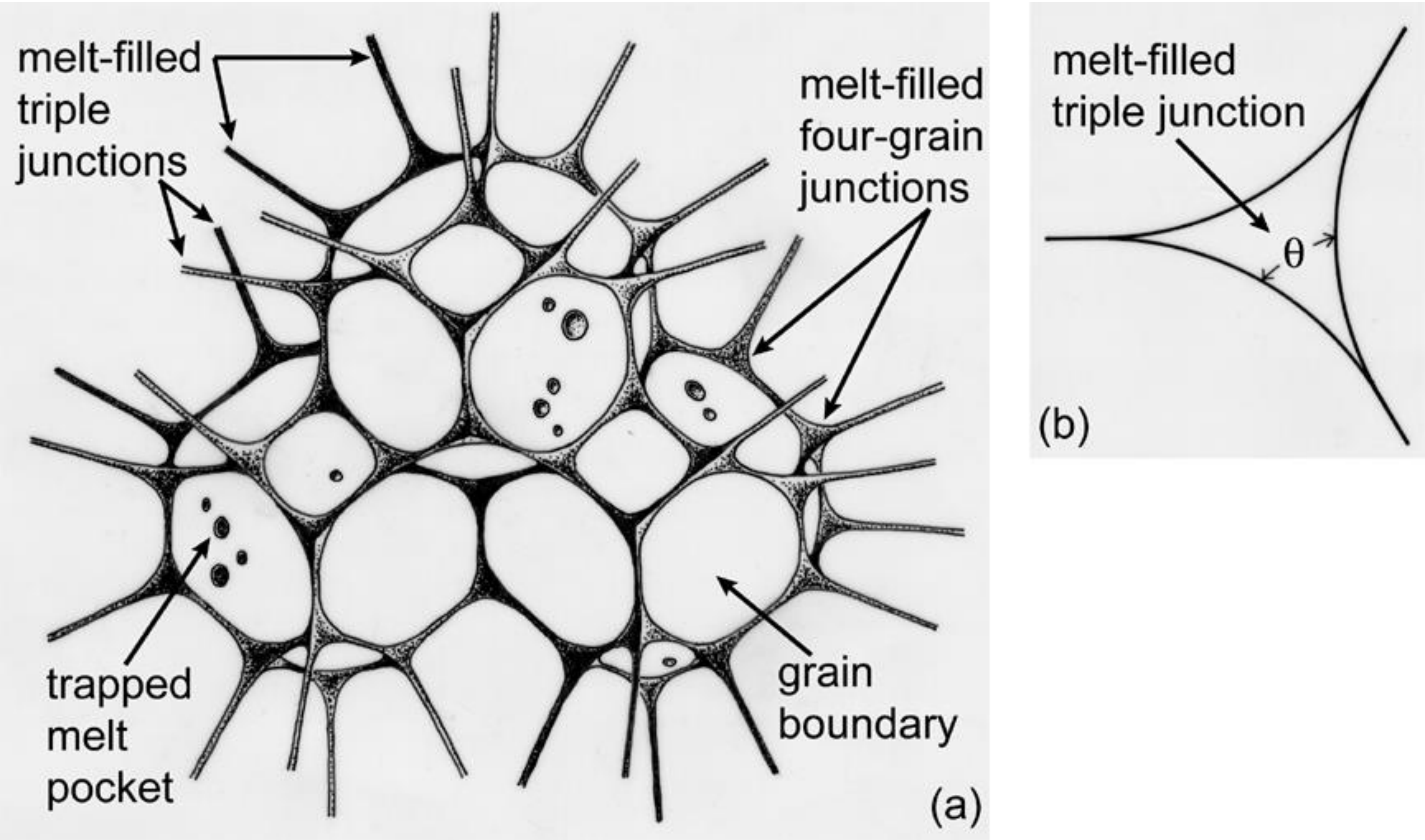
[19]	Pl + Qtz + Bt + H_2O = Amp + Pl ± Ttn + melt		Orthogneiss	Sawyer (2010)
[20]	Amp_1 + Pl + Qtz + H_2O = Hbl + melt	700-730°C/4.7-5.5kbar	Metaigneous rocks	Lee and Cho (2013)
[21a]	Hbl_1+ Pl (An_{40}) + Bt + Qtz (+ H_2O) = Hbl_2 + Pl (An_{48}) + Qtz + melt*	675-750°C/6-8kbar	Amphibolite	Lappin and Hollister (1980); Kenah and Hollister (1983)
[21b]	Hbl + Qtz (+ H_2O) = Hbl + melt*	675-750°C/6-8kbar	Amphibolite	Lappin and Hollister (1980)
	Peritectic Grt and/or Crd			
[22]	Sil + Bt + Qtz + H_2O = Crd + Grt + melt	650-750°C/4-5.5kbar	KFMASH system, pelite	Yardley and Barber (1991a)
[23]	Bt + Qtz + Pl + Als + H_2O = Grt + melt			Stevens and Clemens (1993)
[24]	Qtz + Pl + Bt ± Sil + H_2O = melt ± Kfs + Grt/Crd + Ilm	650-950°C/7-8kbar	Bt-Grt gneiss experiment	Otamendi and Patiño Douce (2001)
[25]	Bt ± Crd + Pl + Sil + Qtz + H_2O = Grt ± Kfs + melt	700°C/4-5kbar	Metapelite	Jung et al. (2000)
[26]	Hbl + Pl + Qtz + H_2O = Grt + Cpx + Ttn + melt	800-850°C/8-10kbar	Amphibolite	Storkey et al. (2005)
[27]	Bt (Mg_{40}) + Als + Pl + H_2O = Grt ± Crd ± Kfs + melt		Metapelite	Clemens (1984)
[28]	Bt + Pl + Qtz + H_2O = Grt + Ms + melt	700°C/10kbar	Ms-schist (HHC) experiment	Patiño Douce and Harris (1998)
[29]	Bt + Sil + Qtz + H_2O = Crd + melt	650-750°C/4-5.5kbar	KFMASH system, pelite	Yardley and Barber (1991)
[30]	Bt + Qtz + Pl + H_2O = Crd + Grt + melt	700-750°C/5kbar	Metasedimentary	Ward et al. (2008); Kisters et al. (2009); Brown (2013)
[31]	Bt + Kfs + Pl + Qtz + H_2O = Grt + melt	690-730°C/4-6kbar	Metaigneous rocks	Jung et al. (2009)
[32]	Kfs + Als + Bt + Qtz + H_2O = Crd + melt	650-750°C/4-5.5kbar 670-730°C/3.5-4kbar	KFMASH system, pelite Metapelite, metapsammite	Yardley and Barber (1991) Ellis and Obata (1992)
[33]	Bt + Qtz + Sil + Pl + H_2O = Crd/Sp + melt		Metapelite	Butler et al. (1997)
	Other peritectic minerals			
[34]	Bt + Qtz + H_2O = En + melt	780-790°C/10kbar	KMASH; experiment	Peterson and Newton (1989)
[35]	Ms + Qtz + Pl + H_2O = Als + melt	750°C/10-12kbar ~625°C/2kbar	Metasediment Metapelites Metapelite	Kalsbeek et al. (2001) Clemens (1984) Icenhower and London (1995)
[36]	Ms + Pl + Qtz + H_2O = Sil + Bt + melt	 <800°C/4-7kbar	 Metasedimentary	Thompson and Tracy (1979) Milord et al. (2001)
[37a]	Hbl + Qtz + H_2O = Cpx + Opx ± Grt + melt	680-700°C/6kbar	TTG	Watkins et al. (2007)
[37b]	Bt + Qtz +Pl + H_2O = Opx ± Grt ± Kfs + melt	680-700°C/6kbar	TTG	
[38]	Bt (Mg_{60}) + Qtz + Pl + H_2O = Opx ± Kfs + melt		Metasedimentary	Clemens (1984)
[39]	Pl + Qtz + Bt + H_2O = Ttn + melt		Orthogneiss	Sawyer (2010)
[40]	Qtz + Kfs + Pl + H_2O = Pl + melt	630-670°C/2-4kbar	Metagreywacke	Genier et al. (2008)

* H_2O in brackets has been added explicitly to the reactions. The original assumed water was present (P_{H2O} ~ P_{total}).

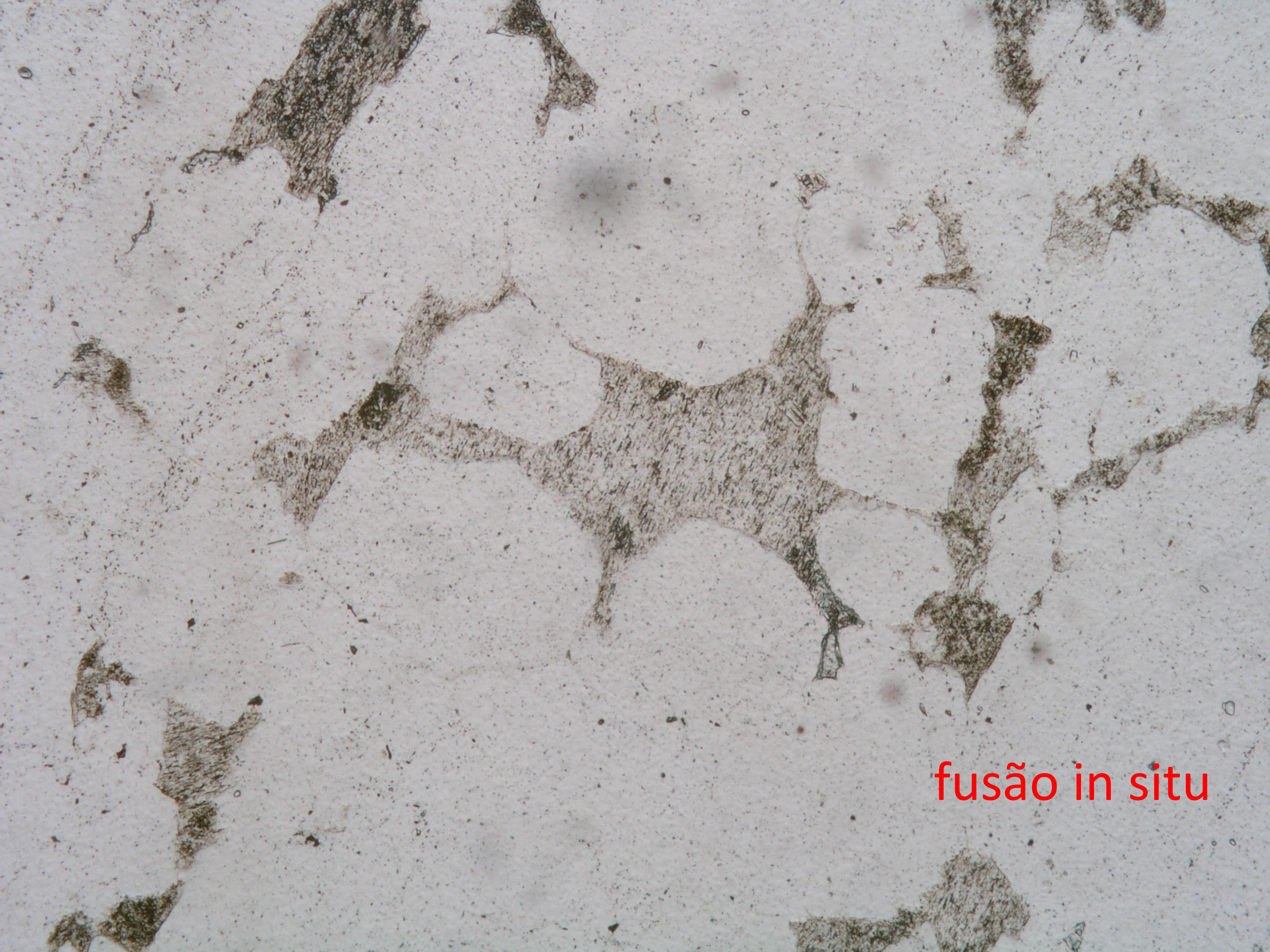
Texturas

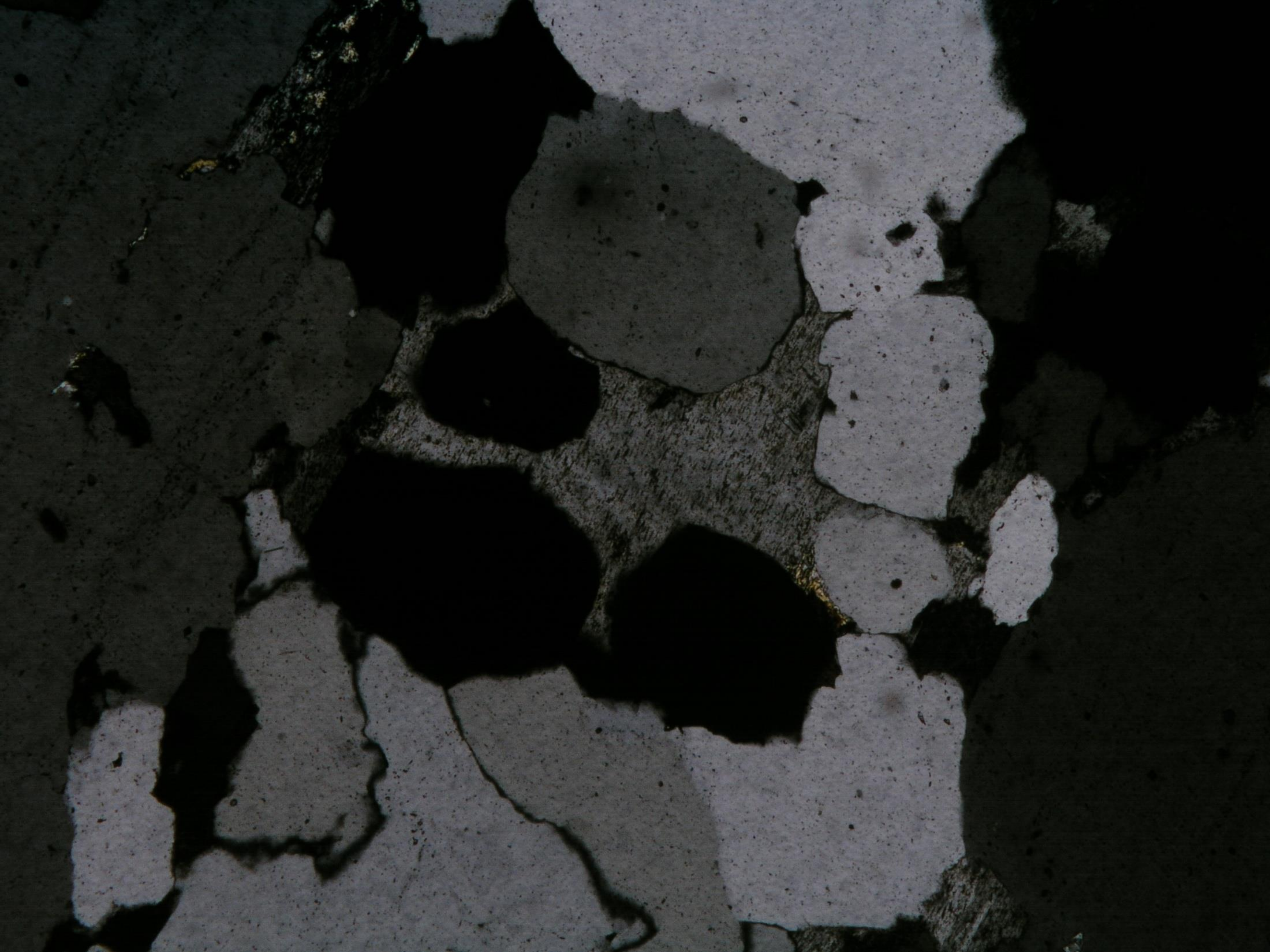
- Existem microestruturas que indicam:
  - fusão (auréolas de contato)
  - cristalização de líquido residual
  - reações de substituição de fases peritéticas

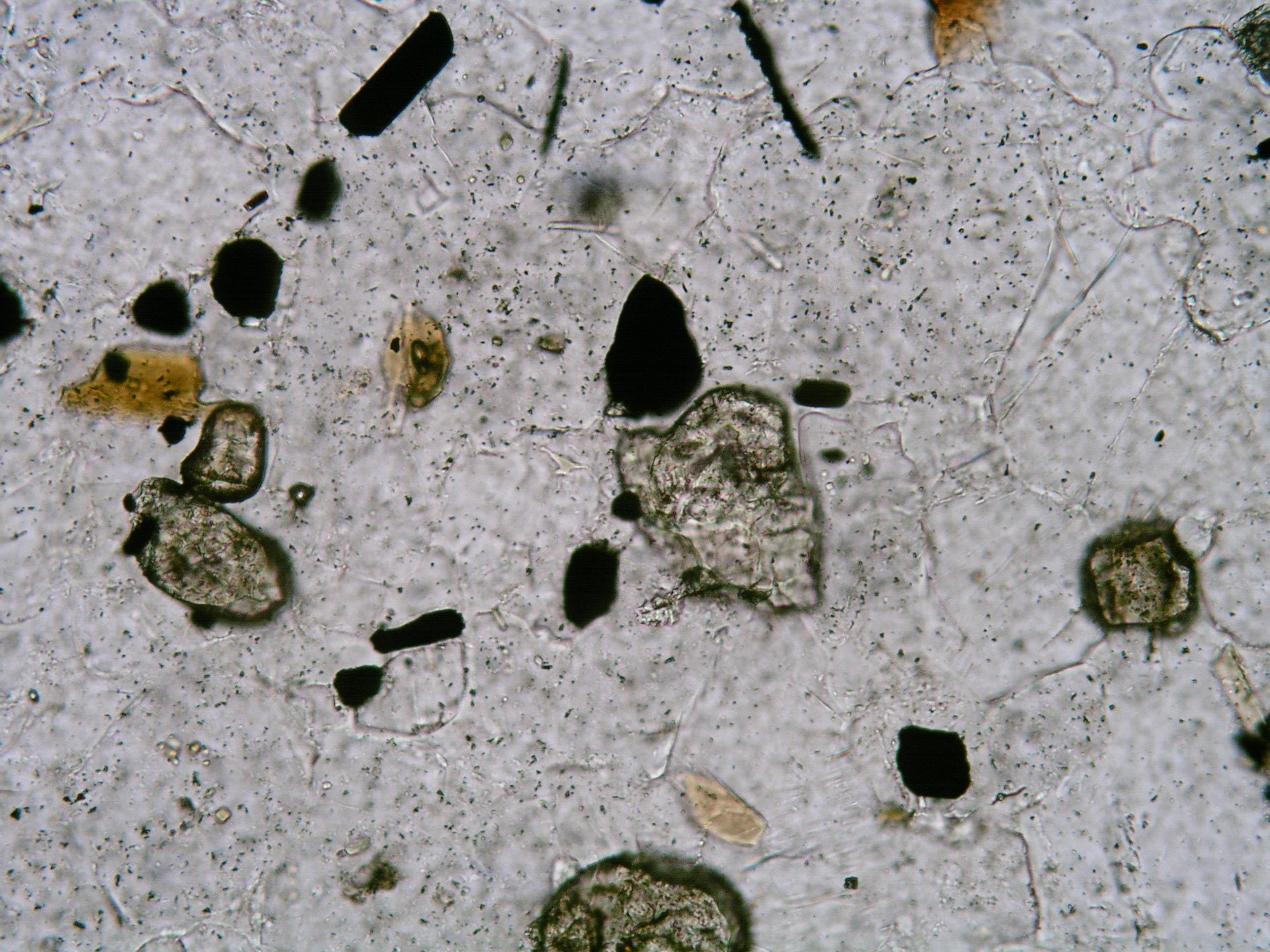

triple
junctions
melt-filled
four-grain
junctions
grain
boundary
trapped
melt
pockets
(a)
melt-filled
triple junction
θ
(b)

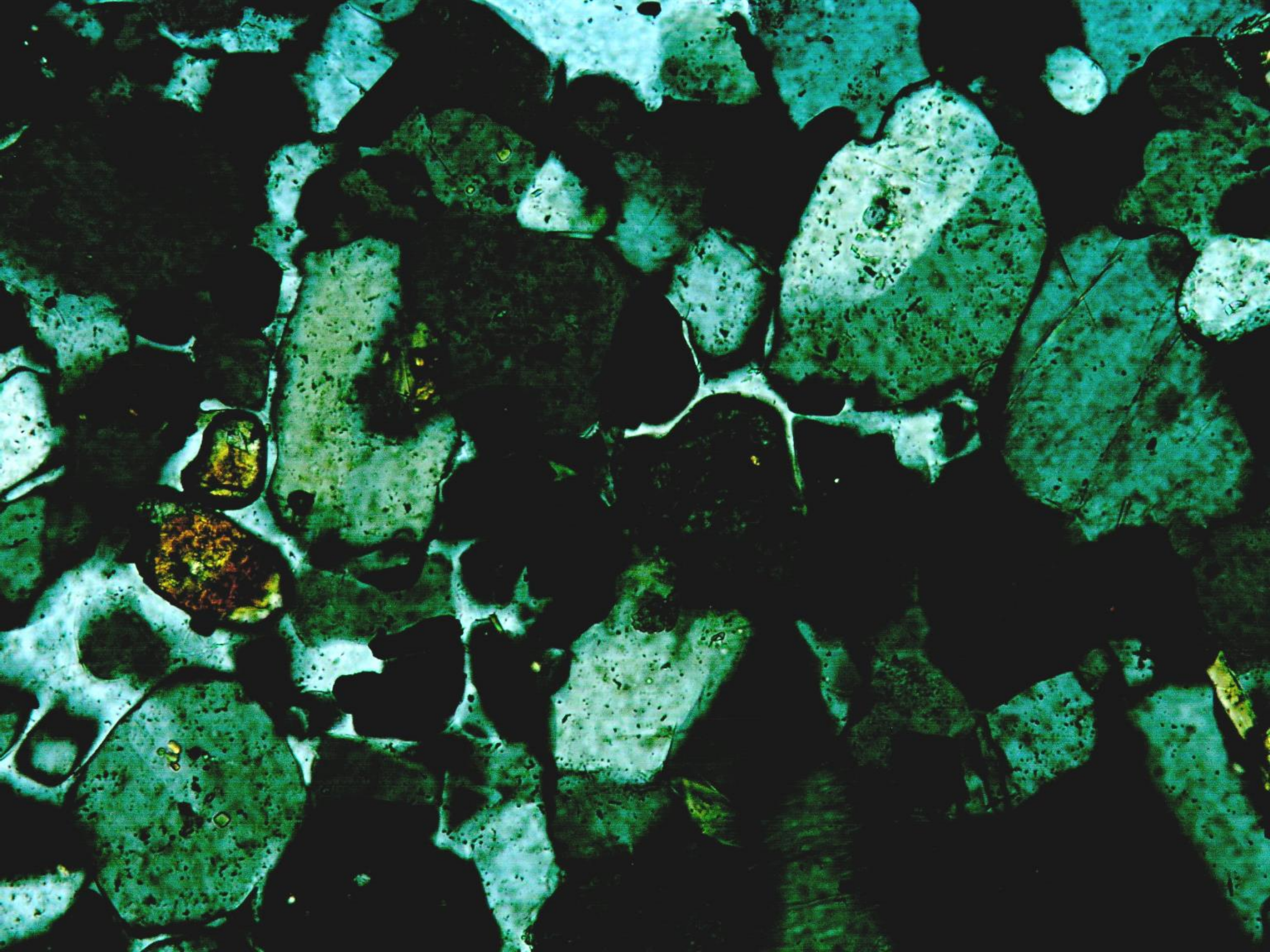


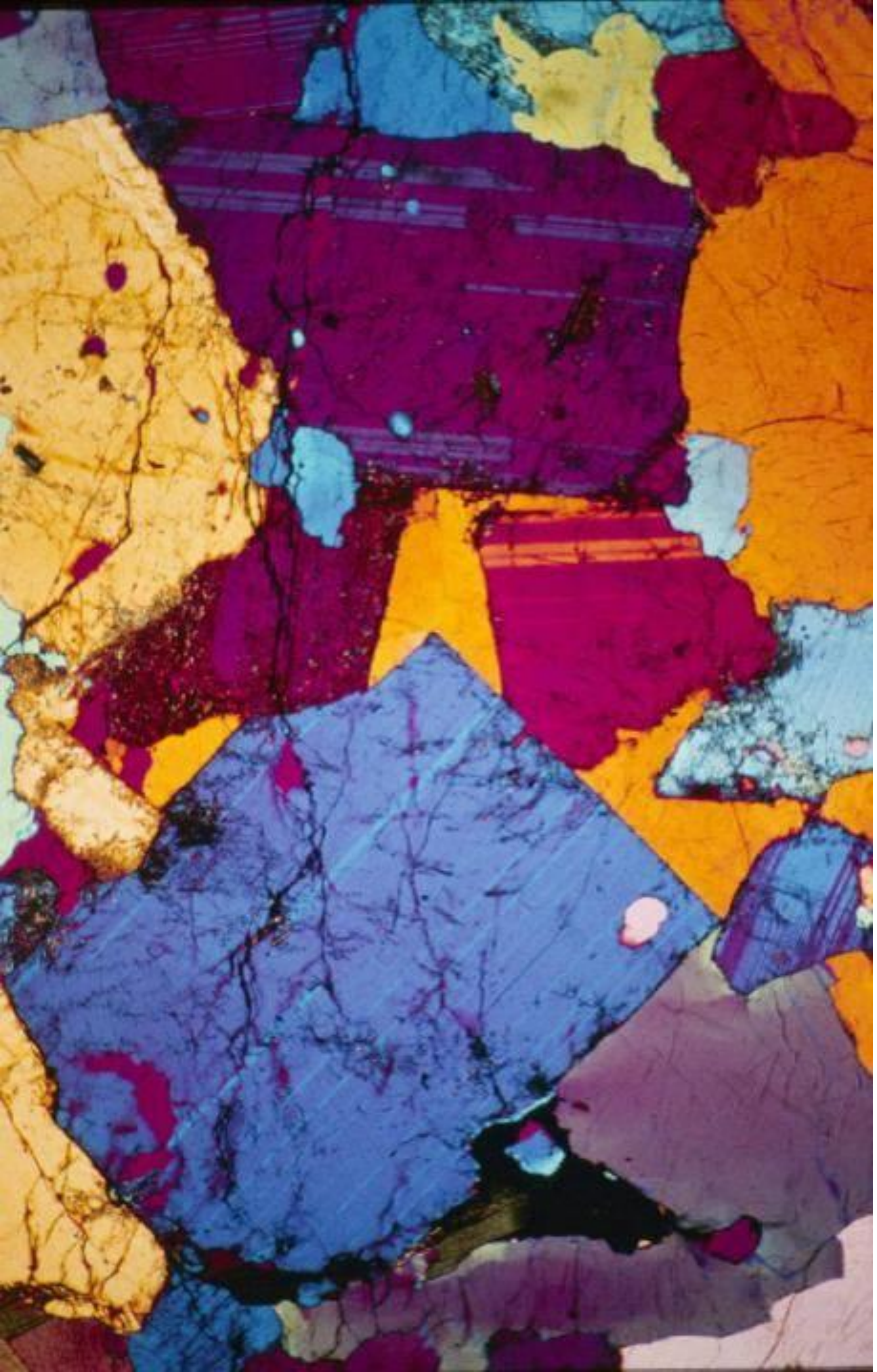
melt-filled
triple
junctions
melt-filled
four-grain
junctions
trapped
melt
pocket
grain
boundary
(a)
melt-filled
triple junction
θ
(b)


fusão in situ





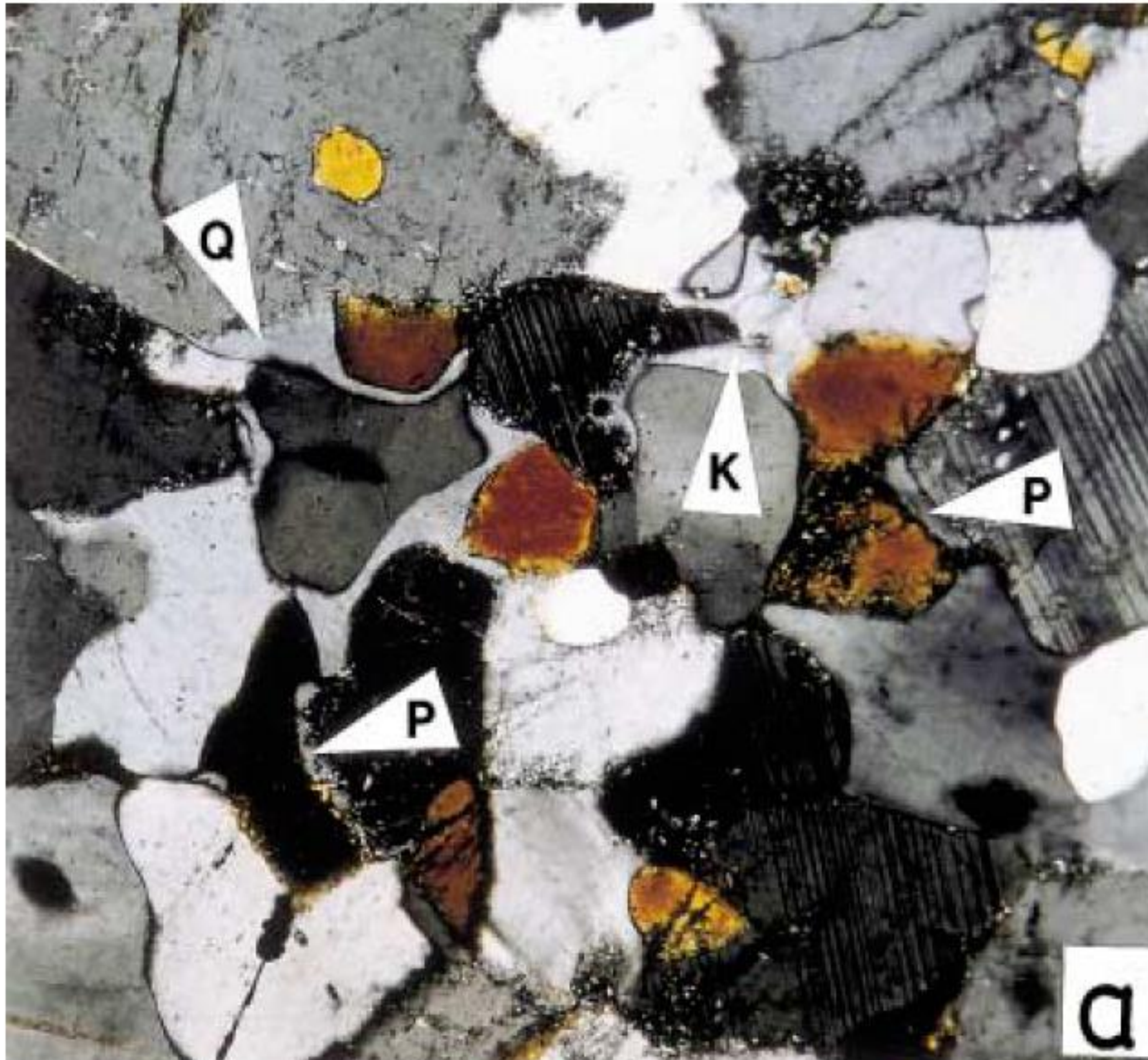




Cristalização do leucossoma

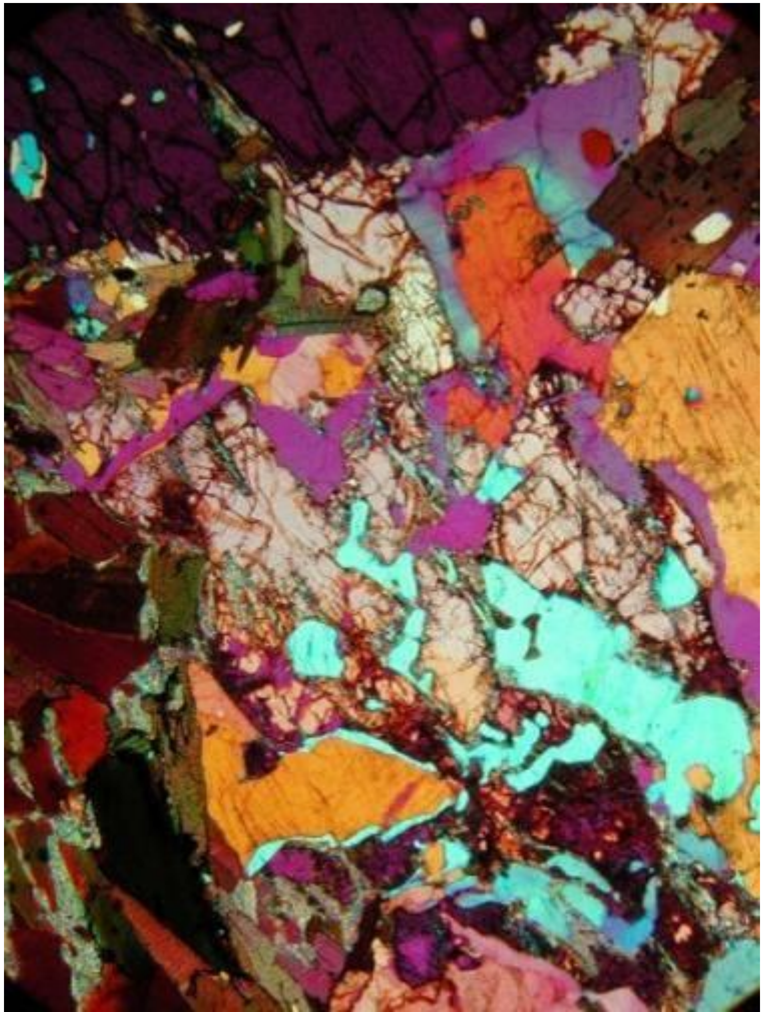
- Notar:
  - plagioclásio euhedral
  - quartzo intersticial
  - textura ígnea

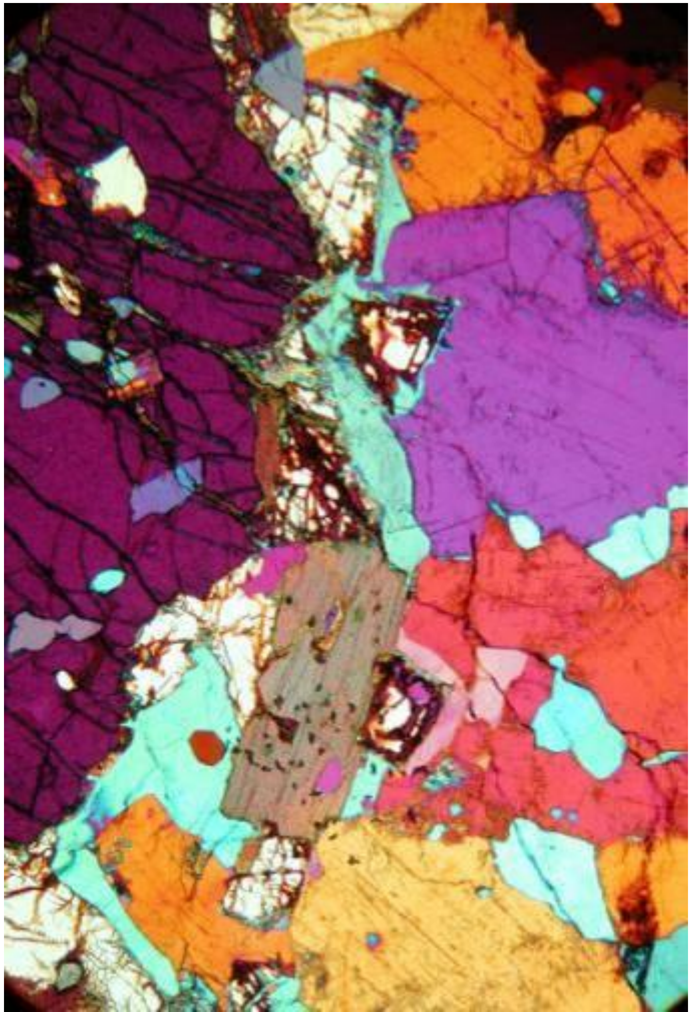
Cristalização de líquido aprisionado



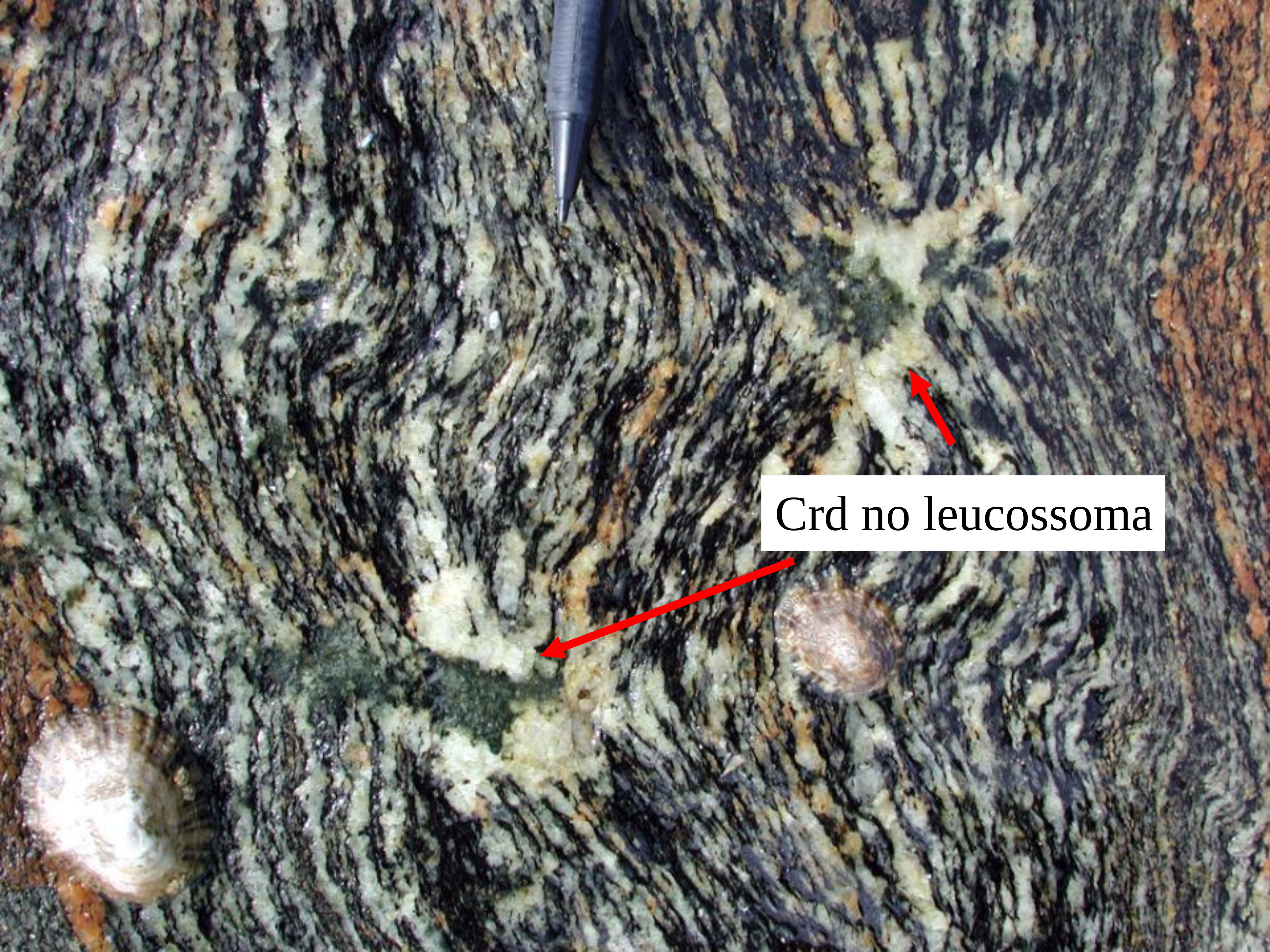
Cristalização de líquido aprisionado

- Notar:
  - quartzo intersticial com orientação cristalográfica contínua

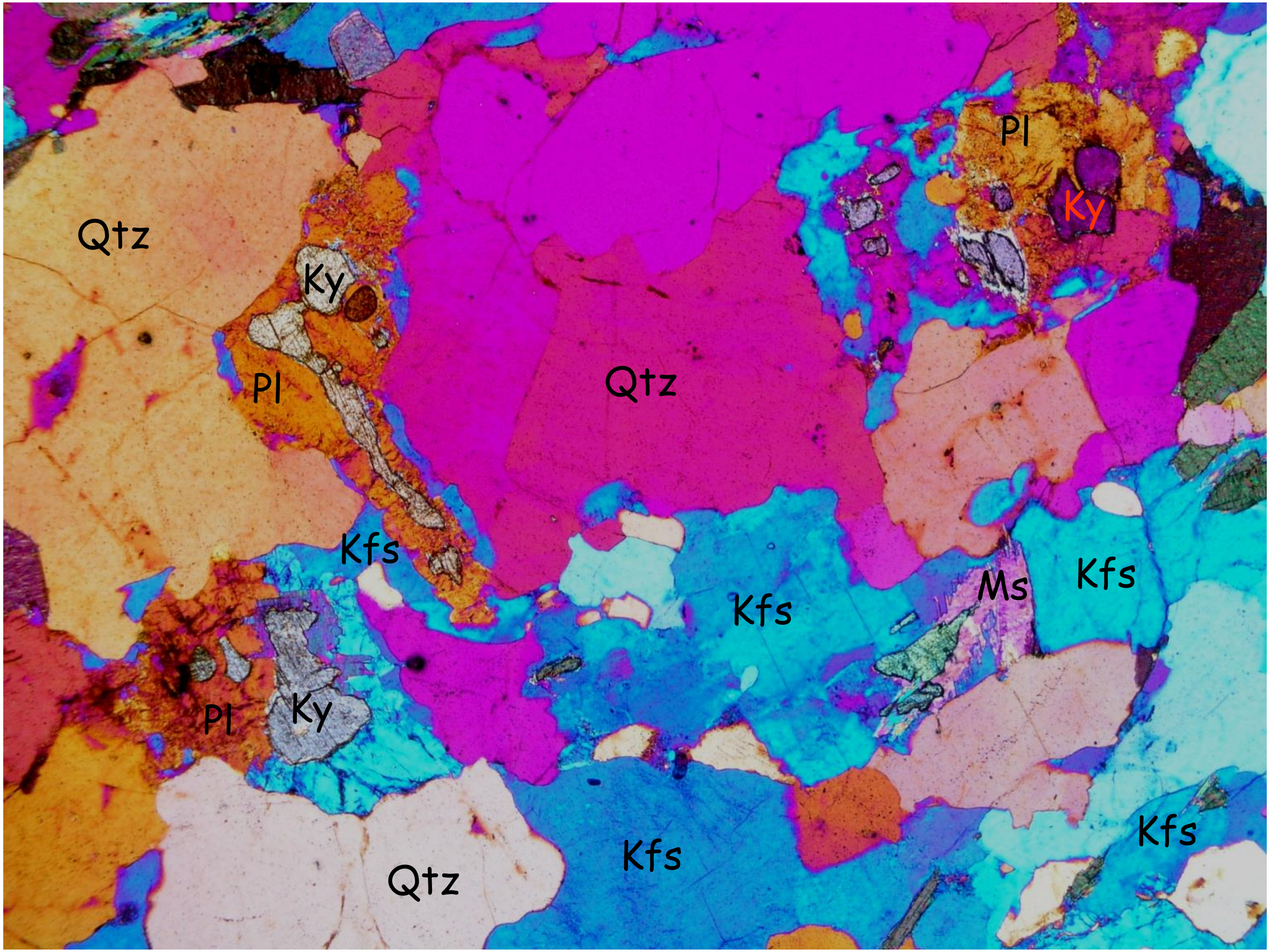




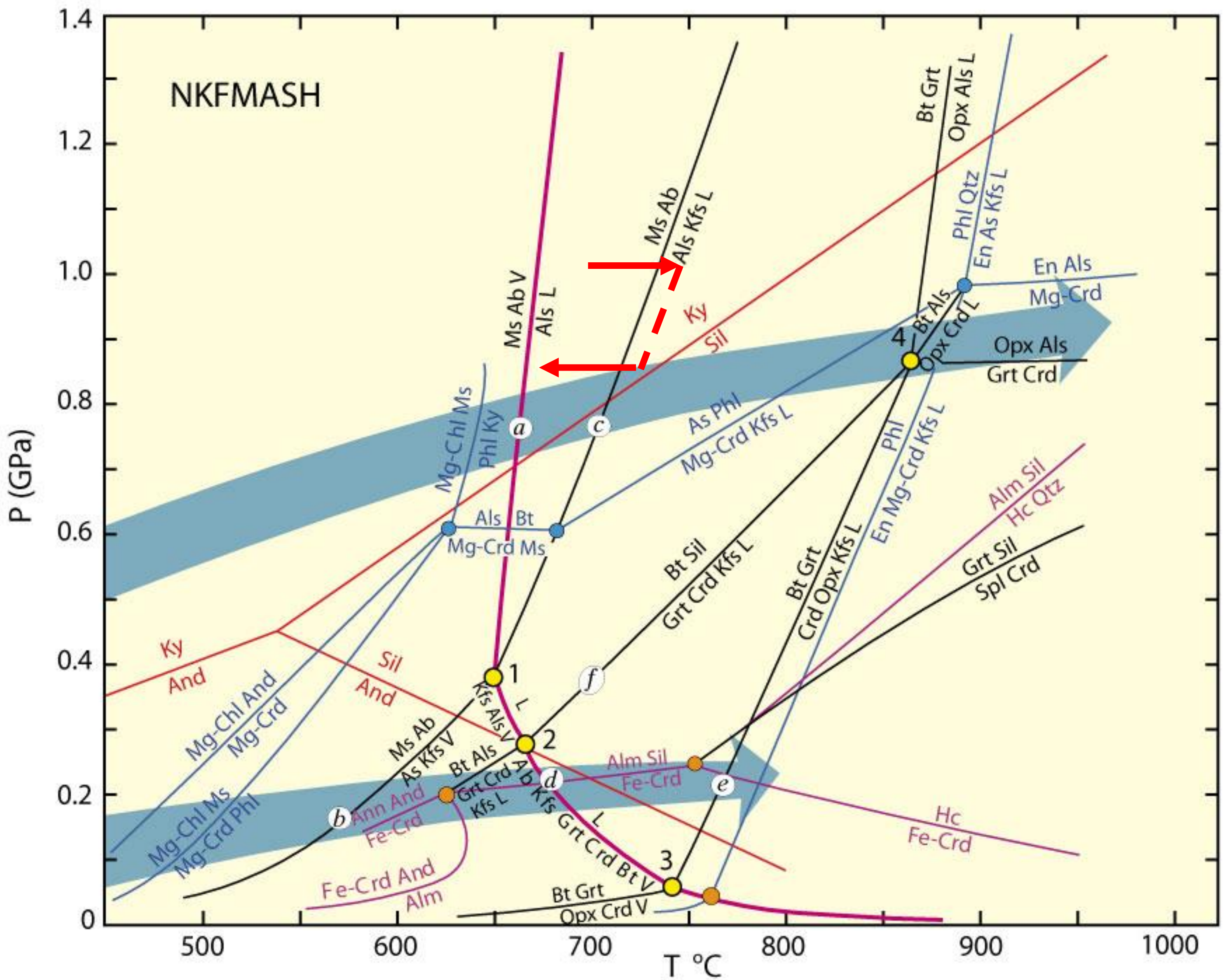
Granada peritética no leucossoma


Crd no leucossoma

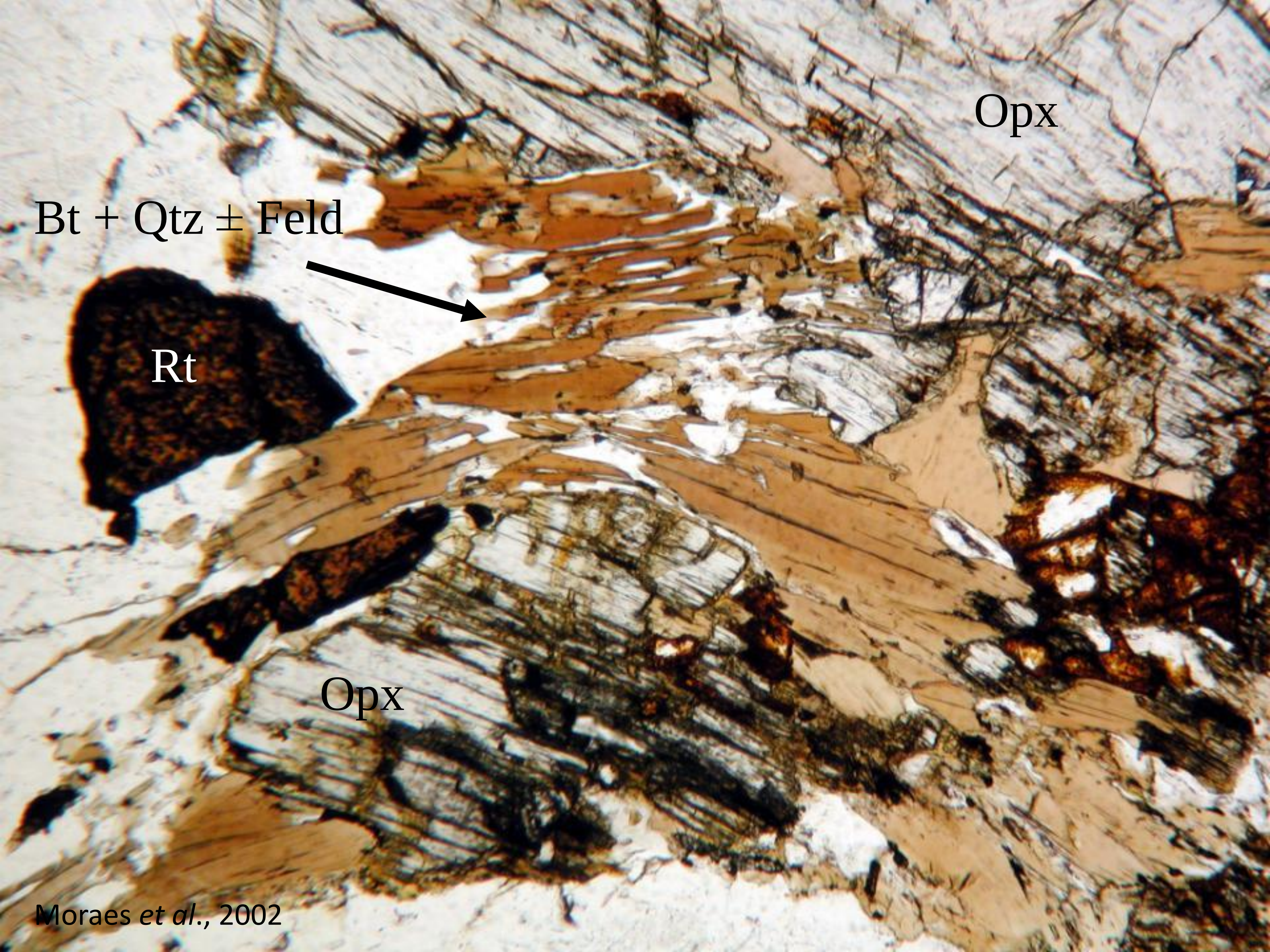
'Reação Reversa' Ms + Pl + Qtz = Ky + Kfs + Fundido



Faleiros (2008). Tese de Doutorado. IGc-USP.



Winter (2010) Principles of Igneous and Metamorphic Petrology 2nd edition. Prentice Hall. (Adaptado de Spear et al., 1999)

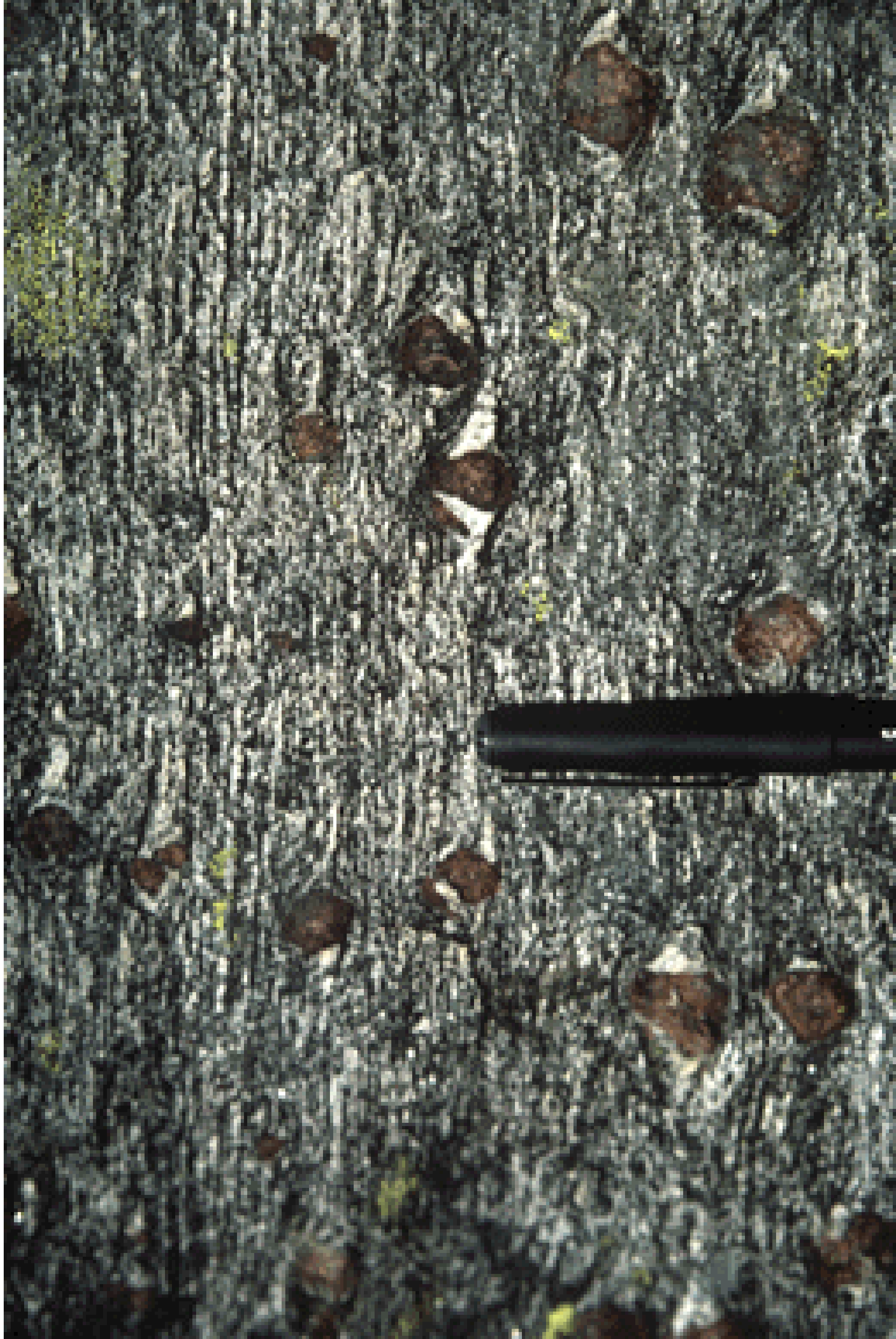

Opx
Bt + Qtz ± Feld
Rt
Opx
Moraes *et al.*, 2002

E quando não ocorre retro-reação?

- Isso implica em perda de fundido (ou seja, a proporção fundido gerado/fases peritéticas mudou)

- aBt + bQtz →

  cKfs + dGrt + eL



Granulitos

- A maior parte dos granulitos são resíduos de fusão, formados por minerais peritéticos preservados após extração do fundido

- O ortopiroxênio é o mineral índice da fácies granulito

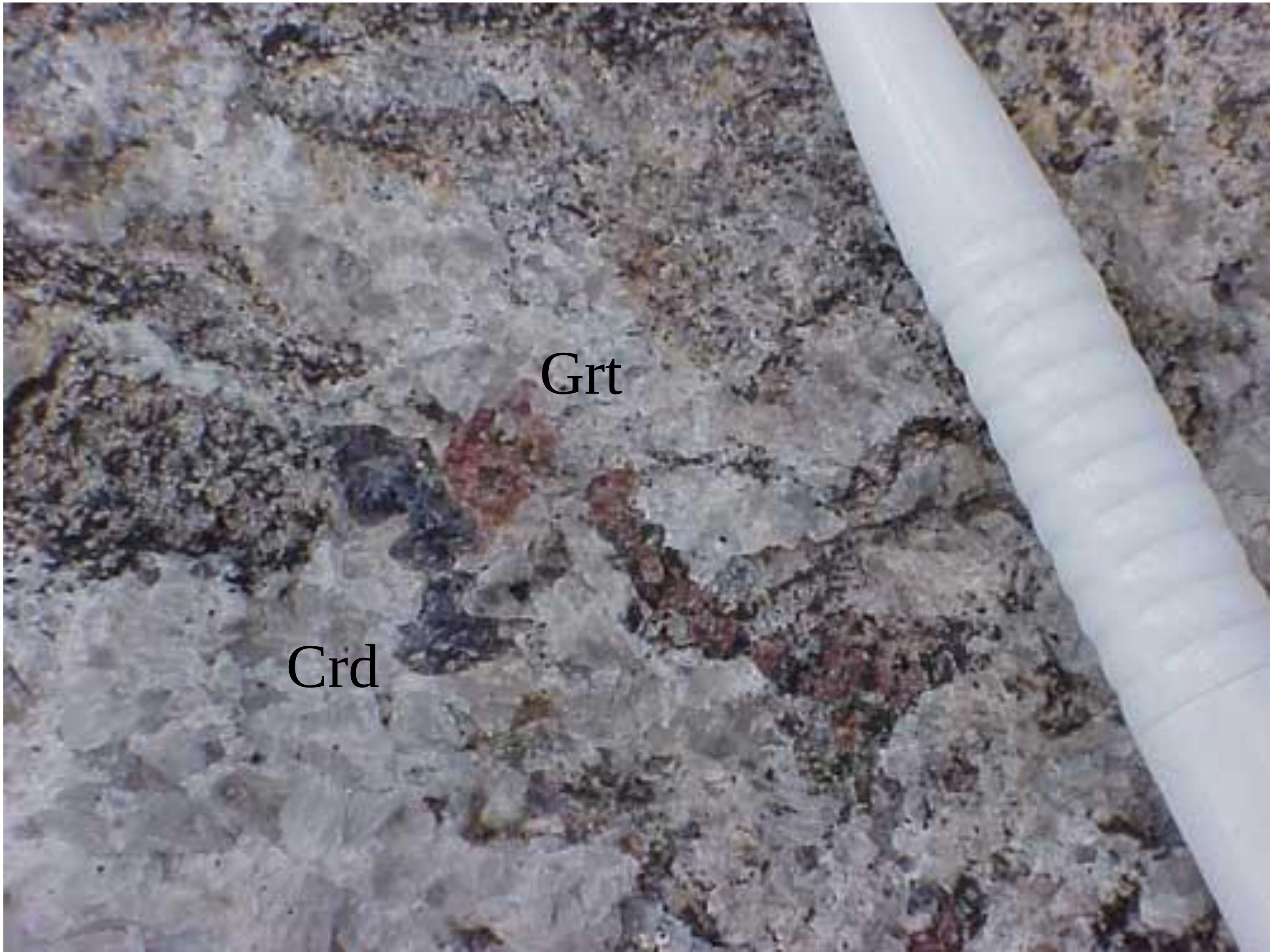
- Rochas com alto ponto de fusão podem sofrer desidratação e recristalização, sem fusão, e serem transformadas em granulitos

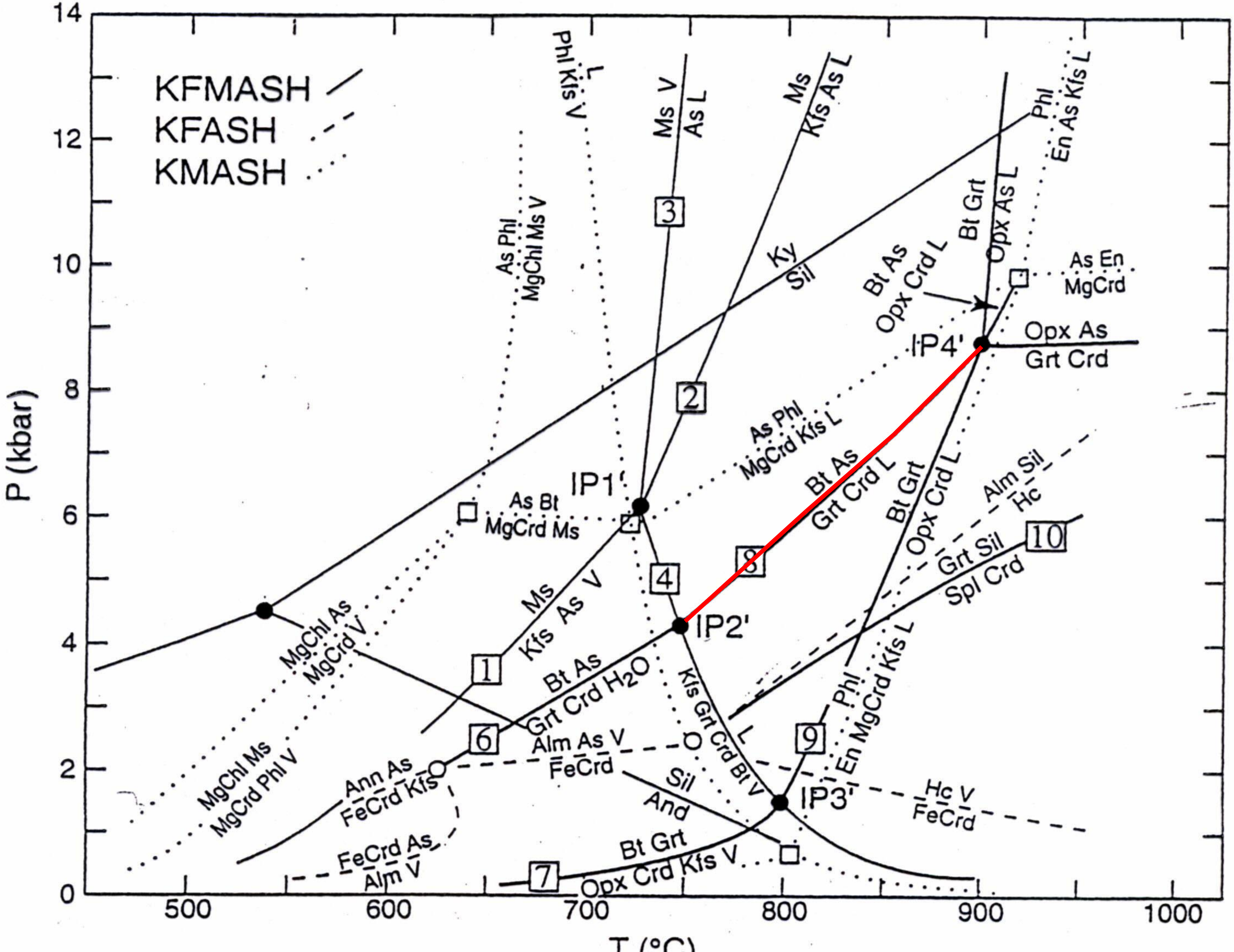
Paragêneses diagnósticas

- Granulito máfico
  - Ol + Opx + Pl ± Hbl (baixa *P*)
  - Opx + Pl ± Grt ± Cpx ± Qtz ± Hbl
  - Cpx + Qtz + Grt ± Pl ± Hbl (alta *P*)
- Granulito félsico
  - Qtz + Opx + Mesopertita ± Grt ± Pl ± Bt
- Granulito aluminoso (pelítico)
  - Qtz + + Mesopertita ± Bt ± Pl
    - + Crd + Grt ± Sil (*T* > 750 °C)
    - + Opx ± Crd ± Grt (*T* > 800 °C)
    - + Grt + Kfs + Ky + Rt (*T* > 800 °C, *P* > 13 kbar)

Granulito félsico ou pelítico

Grt + Crd

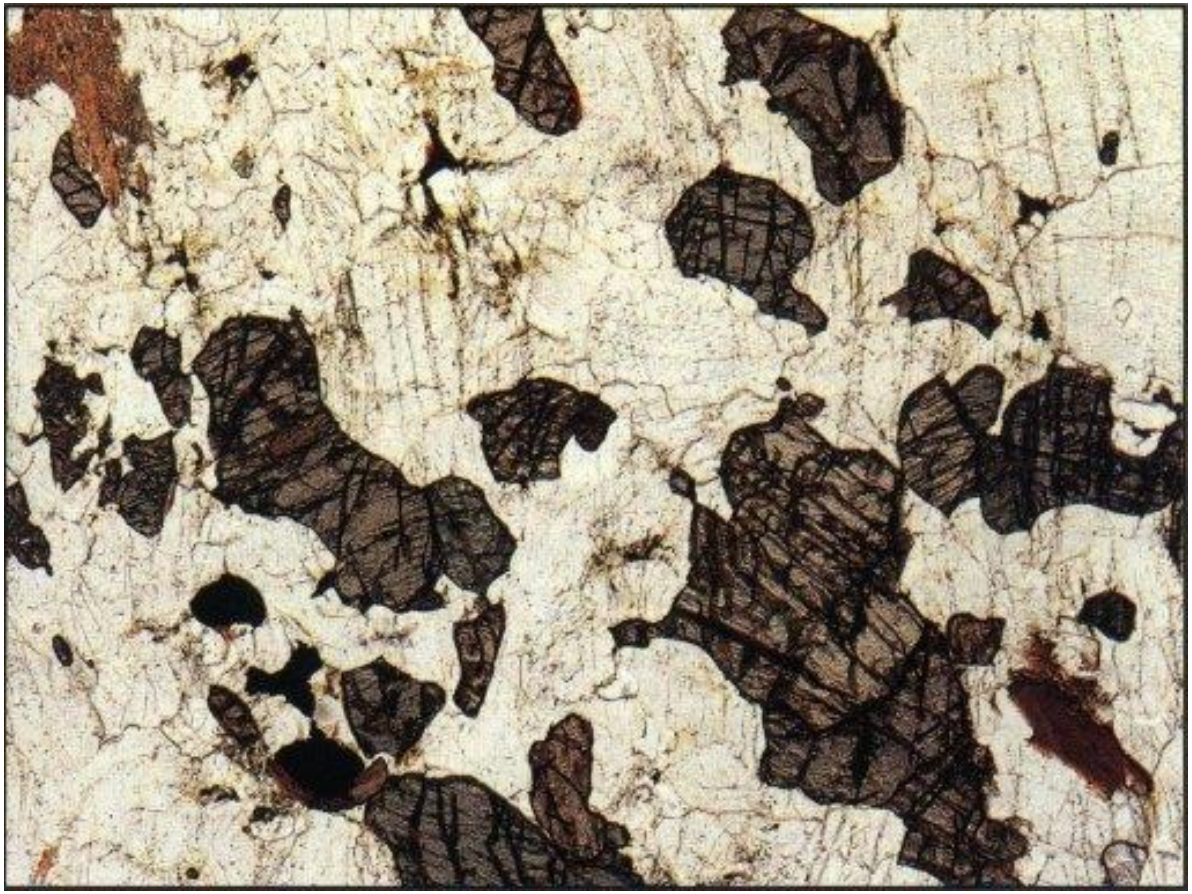




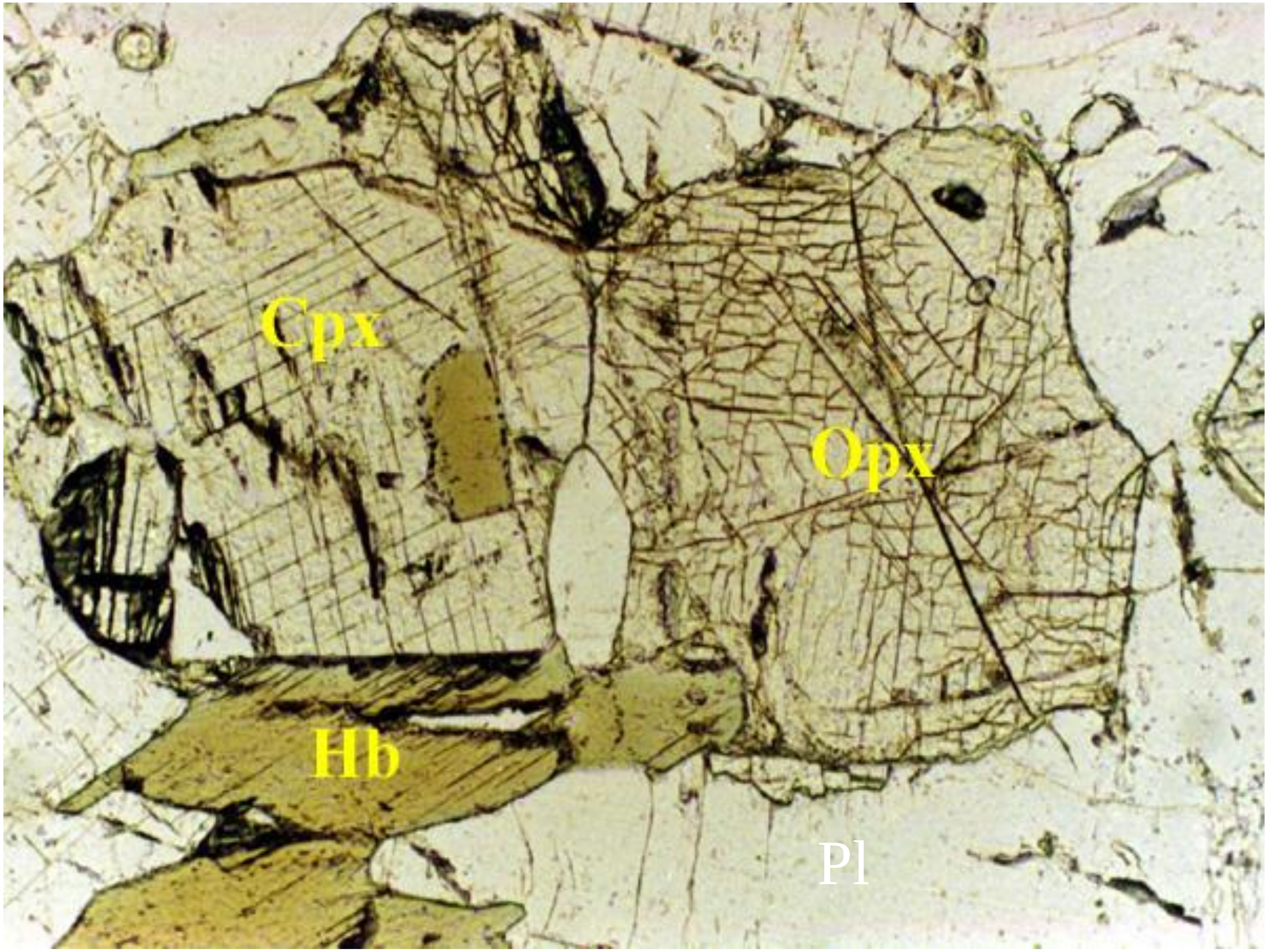
Spear *et al*., 1999

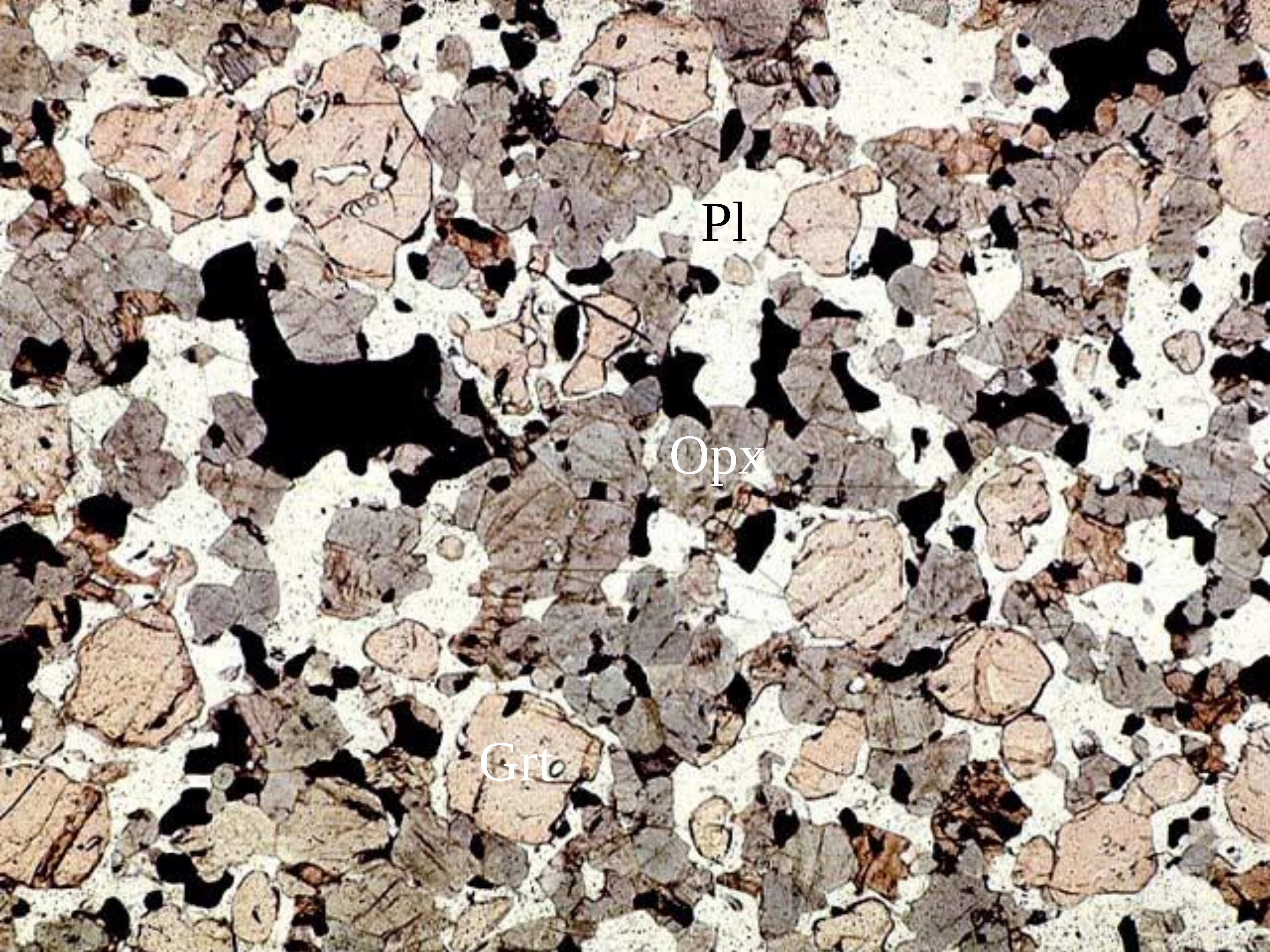
Granulito félsico ou pelítico

Ortopiroxênio



Granulito máfico




Pl
Opx
Grt

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Temperatures of Granulite-facies Metamorphism: Constraints from Experimental Phase Equilibria and Thermobarometry Corrected for Retrograde Exchange

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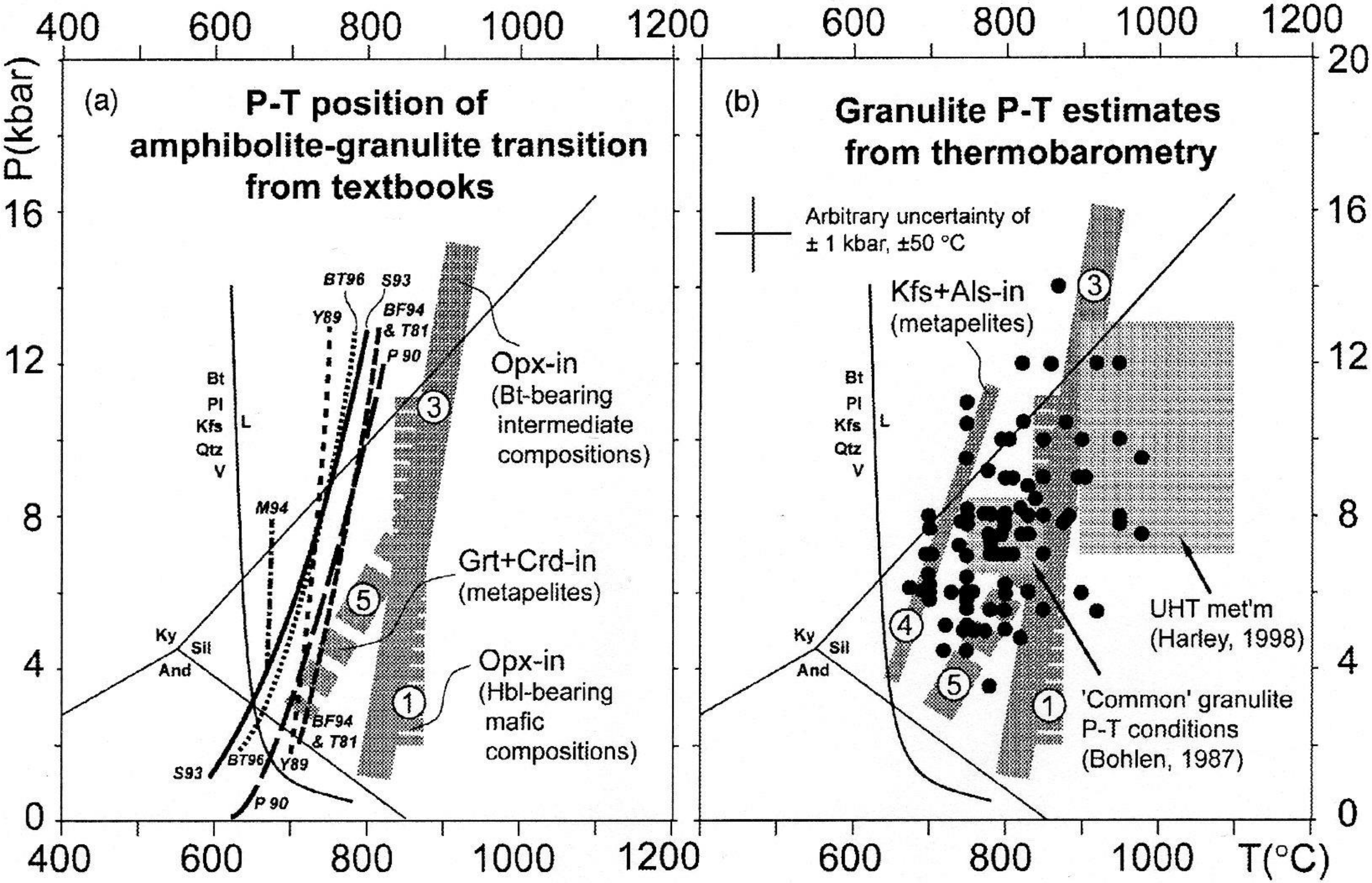
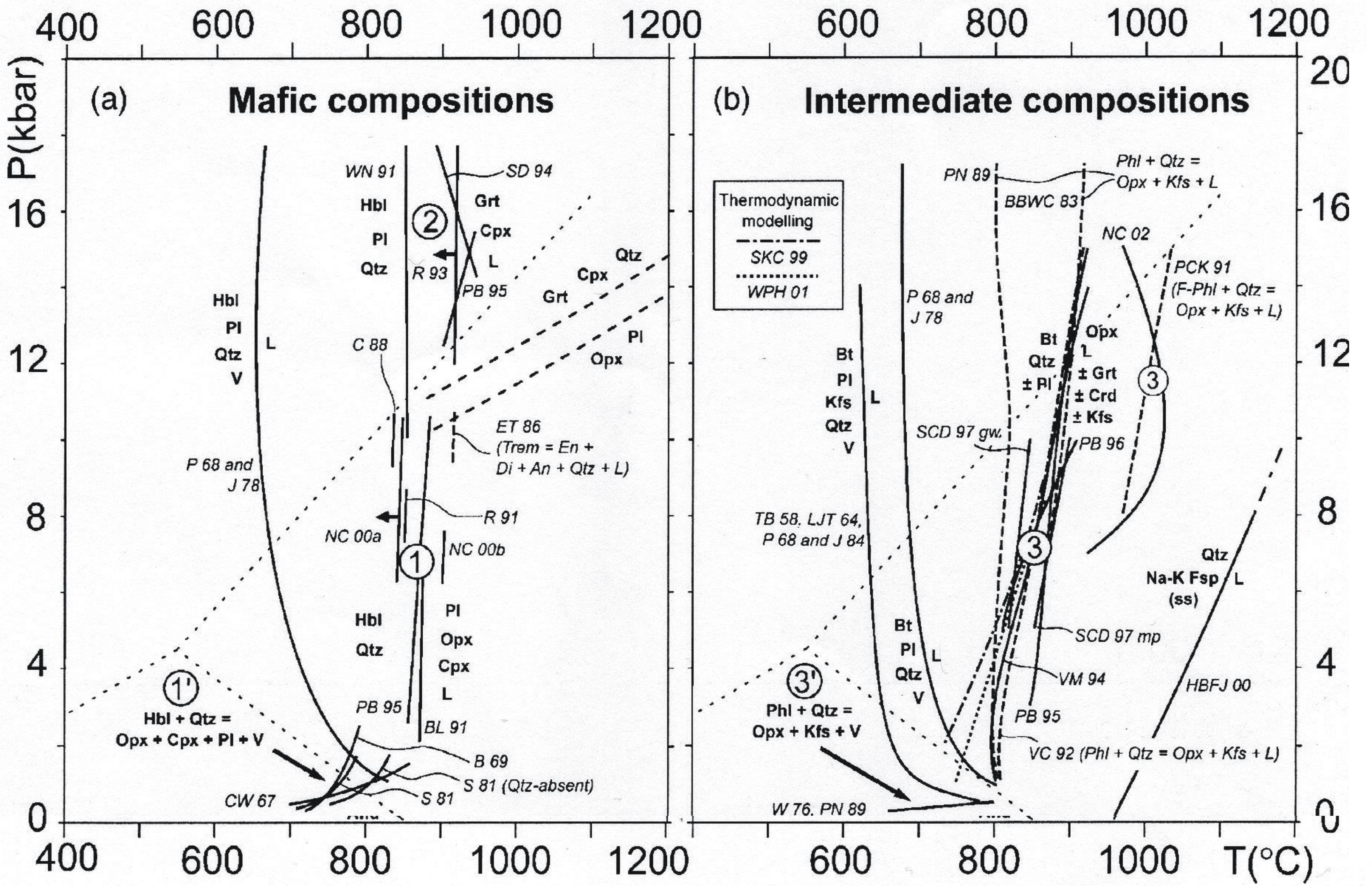
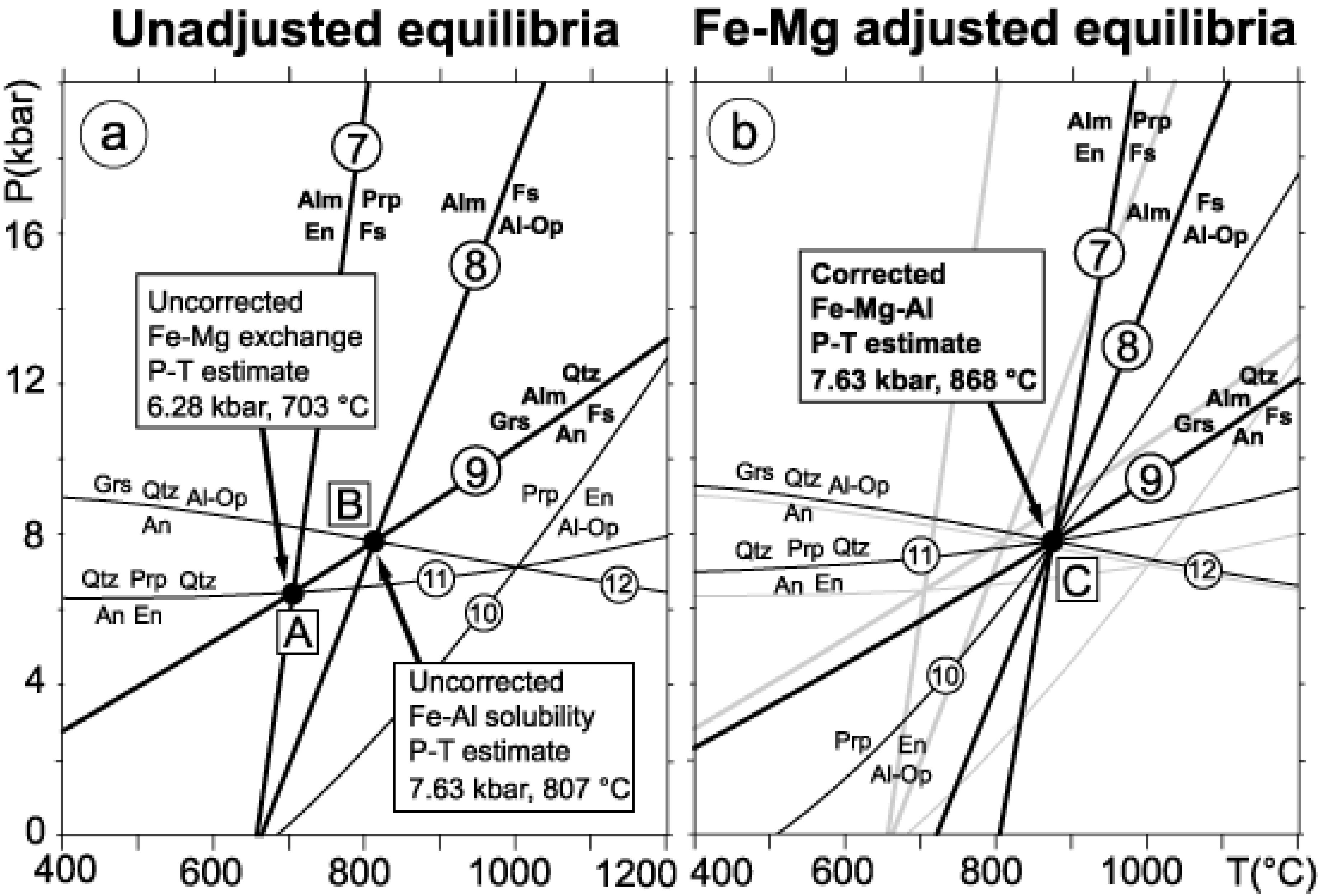


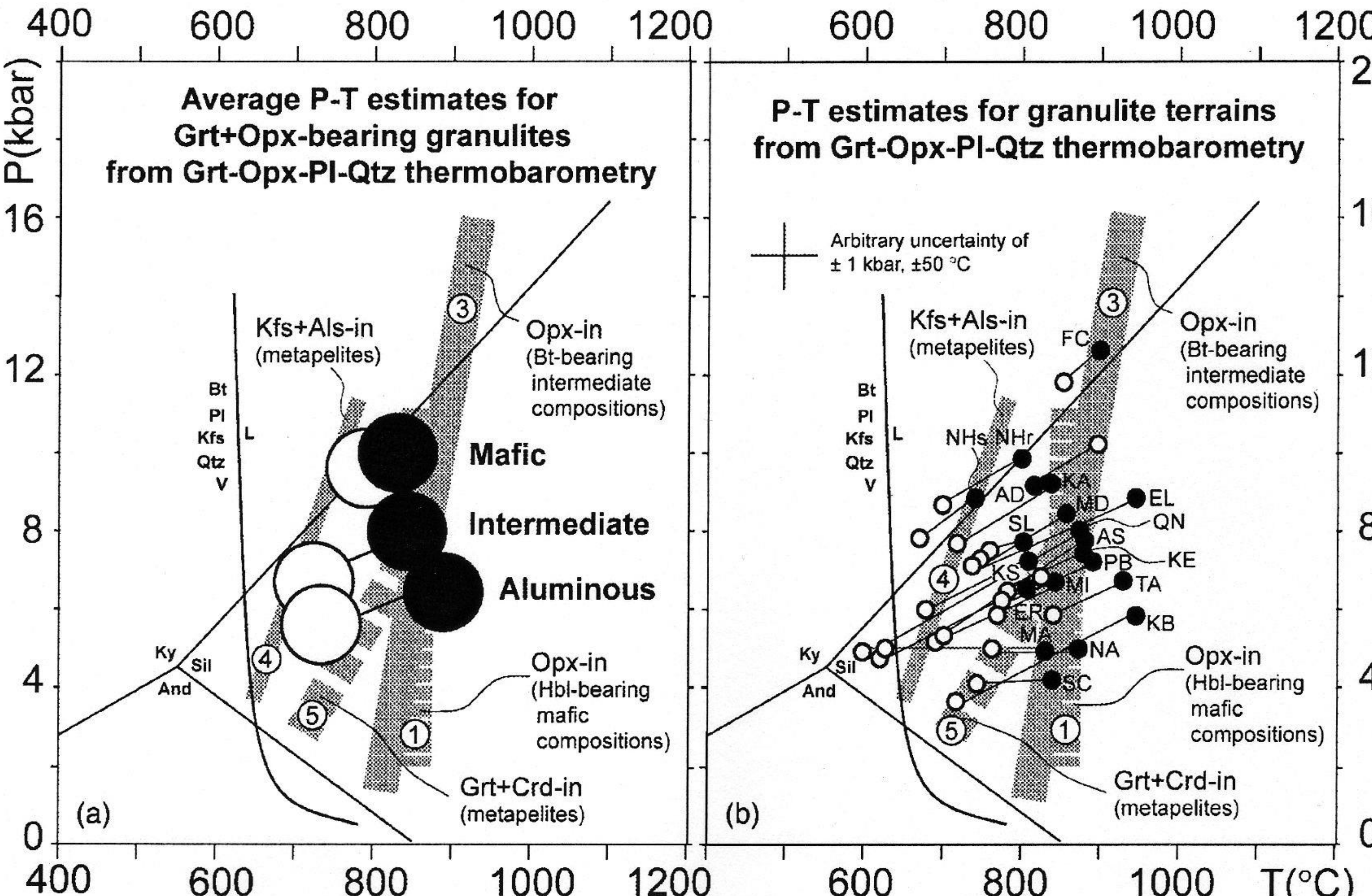
Pattison *et al.*, 2003 - JPET



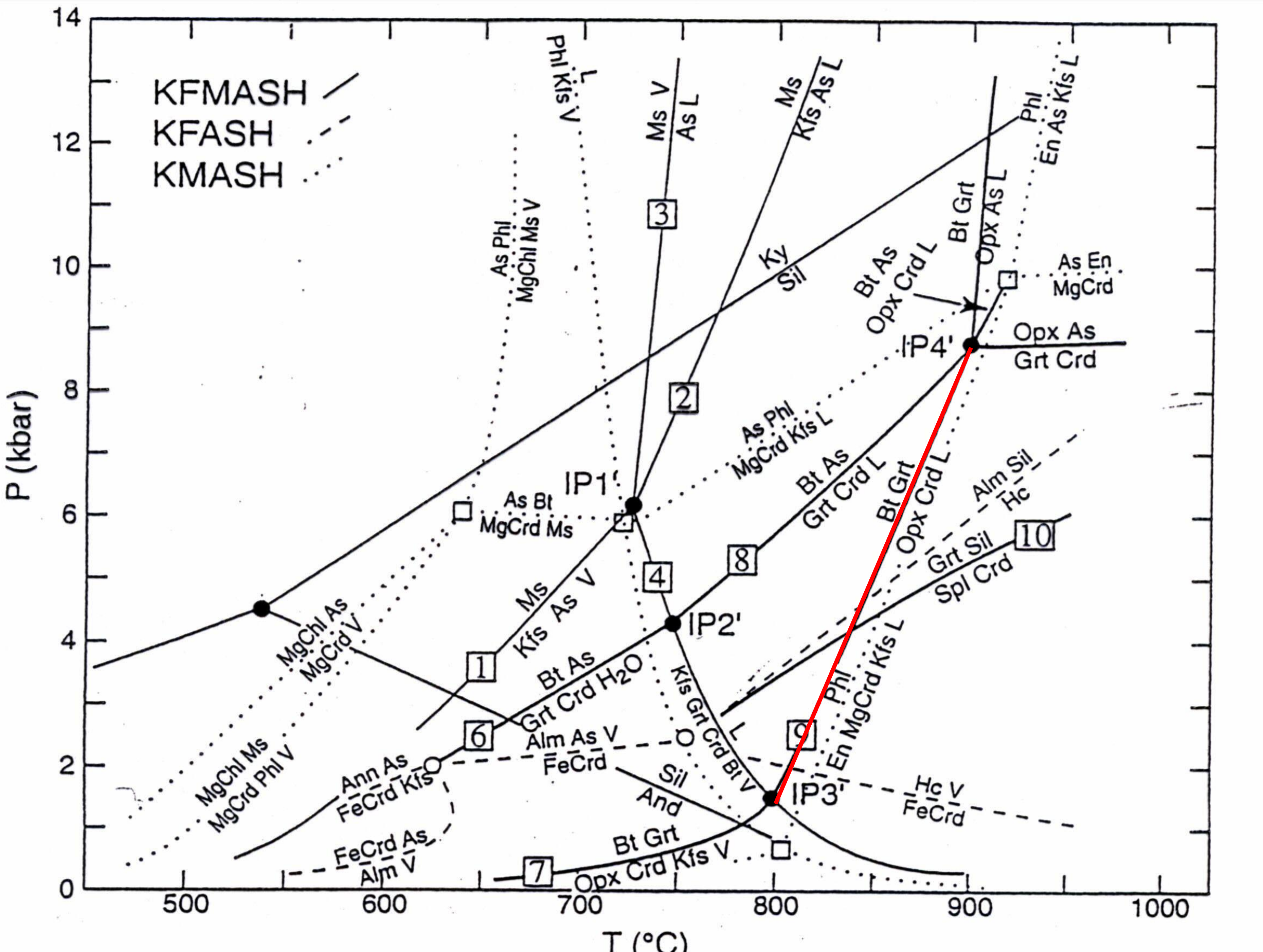
(a) Mafic compositions
(b) Intermediate compositions
P(kbar)
T(°C)
Hbl + Qtz = Opx + Cpx + Pl + V
Phl + Qtz = Opx + Kfs + V
Phl + Qtz = Opx + Kfs + L
Thermodynamic modelling
SKC 99
WPH 01
ET 86 (Trem = En + Di + An + Qtz + L)
PCK 91 (F-Phl + Qtz = Opx + Kfs + L)
VC 92 (Phl + Qtz = Opx + Kfs + L)
S 81 (Qtz-absent)
Na-K Fsp (ss)



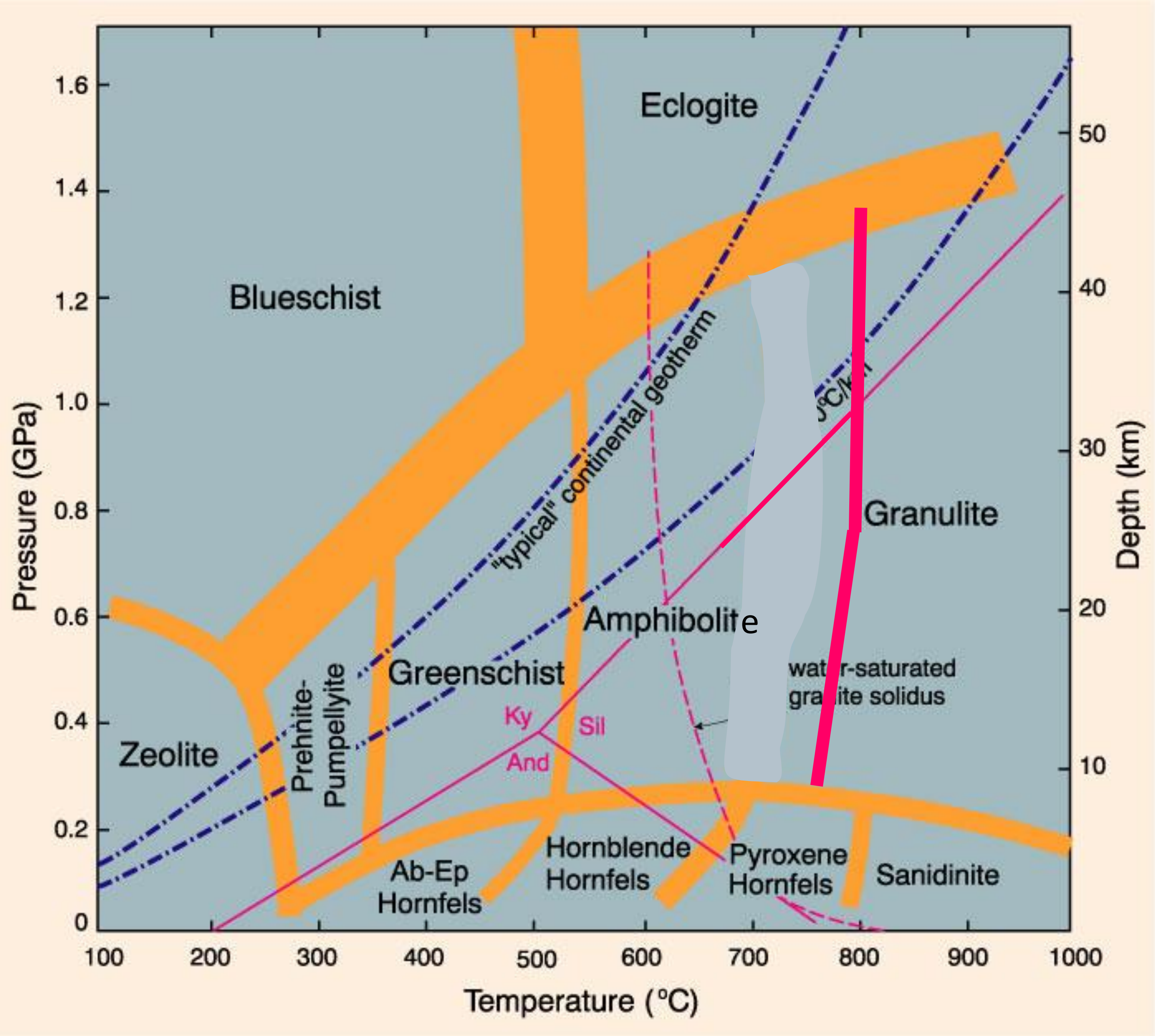
Unadjusted equilibria
Fe-Mg adjusted equilibria
P(kbar)
T(°C)
a
b
Alm Prp
En Fs
Alm Fs
Al-Op
Uncorrected
Fe-Mg exchange
P-T estimate
6.28 kbar, 703 °C
Qtz
Alm
Grs
Fs
An
Grs Qtz Al-Op
An
Prp En
Al-Op
Qtz Prp Qtz
An En
A
B
C
Uncorrected
Fe-Al solubility
P-T estimate
7.63 kbar, 807 °C
Corrected
Fe-Mg-Al
P-T estimate
7.63 kbar, 868 °C
7
8
9
10
11
12
0
4
8
12
16
400
600
800
1000
1200



Average P-T estimates for Grt+Opx-bearing granulites from Grt-Opx-Pl-Qtz thermobarometry
P-T estimates for granulite terrains from Grt-Opx-Pl-Qtz thermobarometry
P(kbar)
T(°C)
Kfs+Als-in (metapelites)
Opx-in (Bt-bearing intermediate compositions)
Opx-in (Hbl-bearing mafic compositions)
Grt+Crd-in (metapelites)
Bt Pl Kfs Qtz V
L
Ky
Sil
And
Mafic
Intermediate
Aluminous
Arbitrary uncertainty of ± 1 kbar, ±50 °C
FC
NHs NHr
KA
AD
MD
EL
QN
SL
AS
KE
PB
KS
MI
TA
ER
MA
KB
NA
SC
(a)
(b)



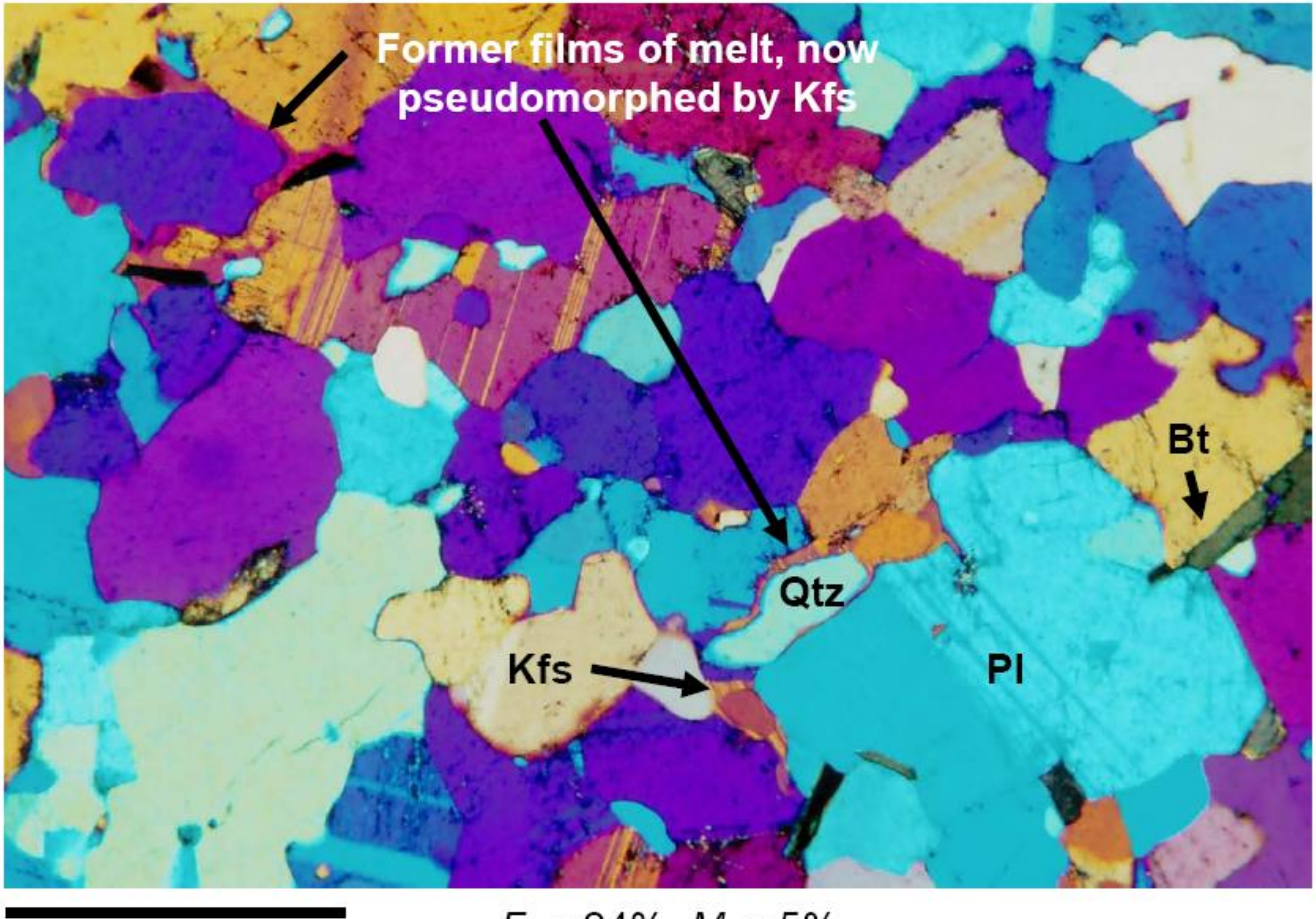
Spear *et al.*, 1999



Eclogite
Blueschist
"typical" continental geotherm
°C/km
Granulite
Amphibolite
water-saturated granite solidus
Greenschist
Prehnite-Pumpellyite
Zeolite
Ky
Sil
And
Ab-Ep Hornfels
Hornblende Hornfels
Pyroxene Hornfels
Sanidinite
Pressure (GPa)
Depth (km)
Temperature (°C)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
50
40
30
20
10
100
200
300
400
500
600
700
800
900
1000

STRONGLY MELT-DEPLETED MIGMATITES

Leucotrondhjemite protolith; H_2O added melting, Opatica Subprovince
quartz + plagioclase + K-feldspar + H_2O = melt



F ~ 24%, M_f ~ 5%

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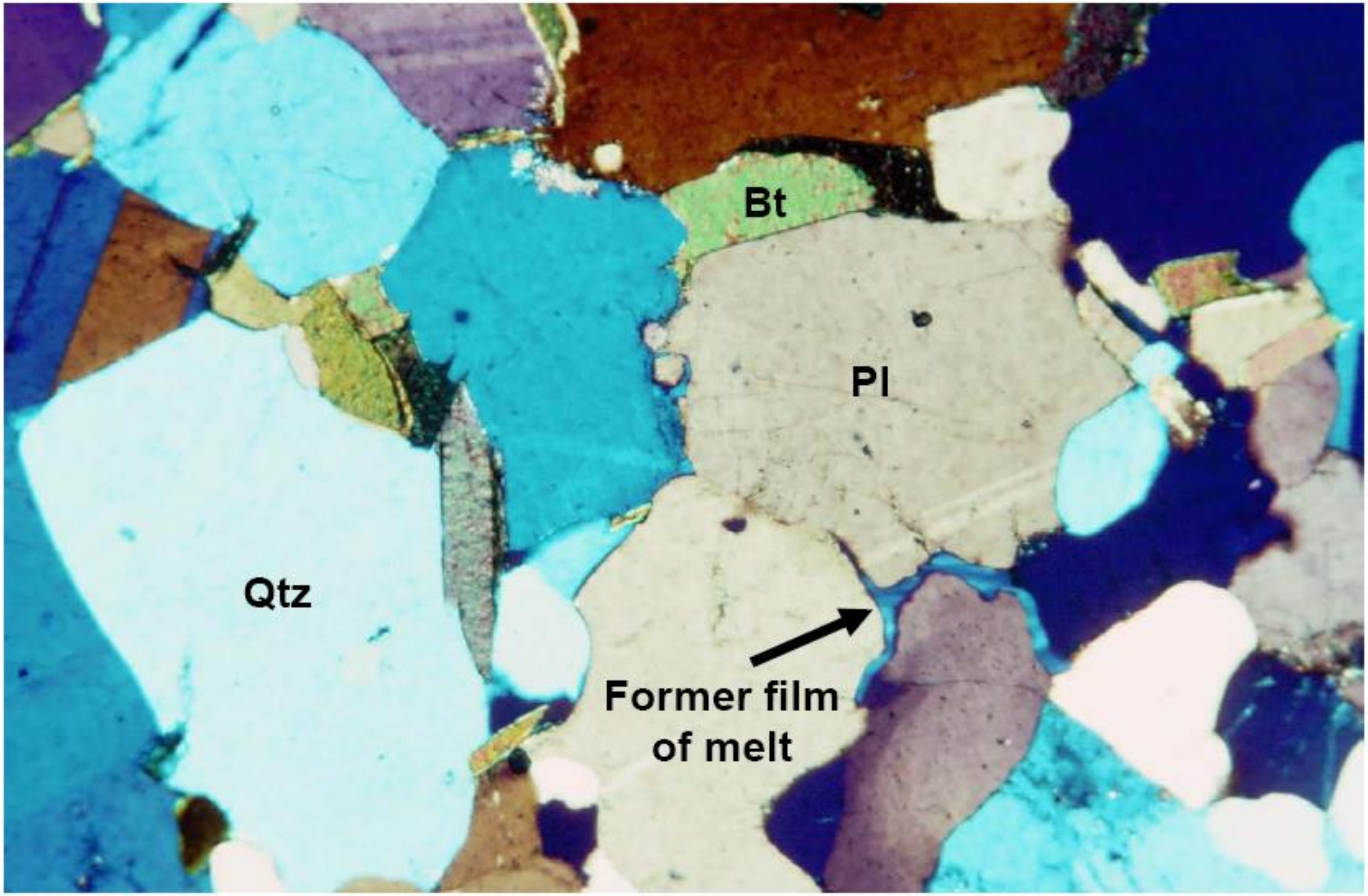
STRONGLY MELT-DEPLETED MIGMATITES

Leucotrondhjemite protolith; H_2O added melting, Opatica Subprovince
quartz + plagioclase + K-feldspar + H_2O = melt



1 mm

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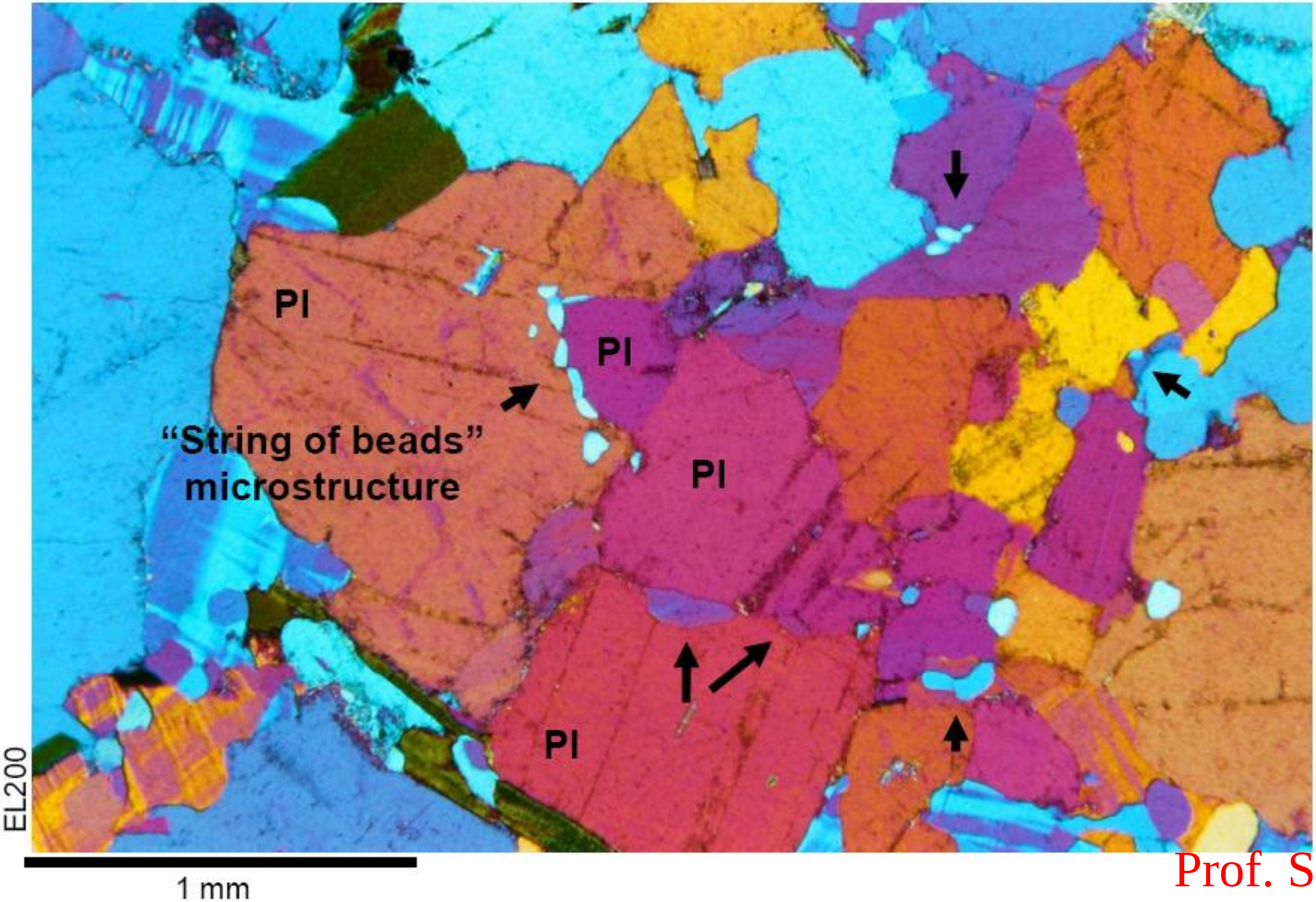
MODIFICATION OF THE FILMS OF MELT AND START OF SUB-SOLIDUS TEXTURAL MODIFICATION

The films of melt on the grain boundaries have "necked down" to form droplets that forms a "string of beads" microstructure



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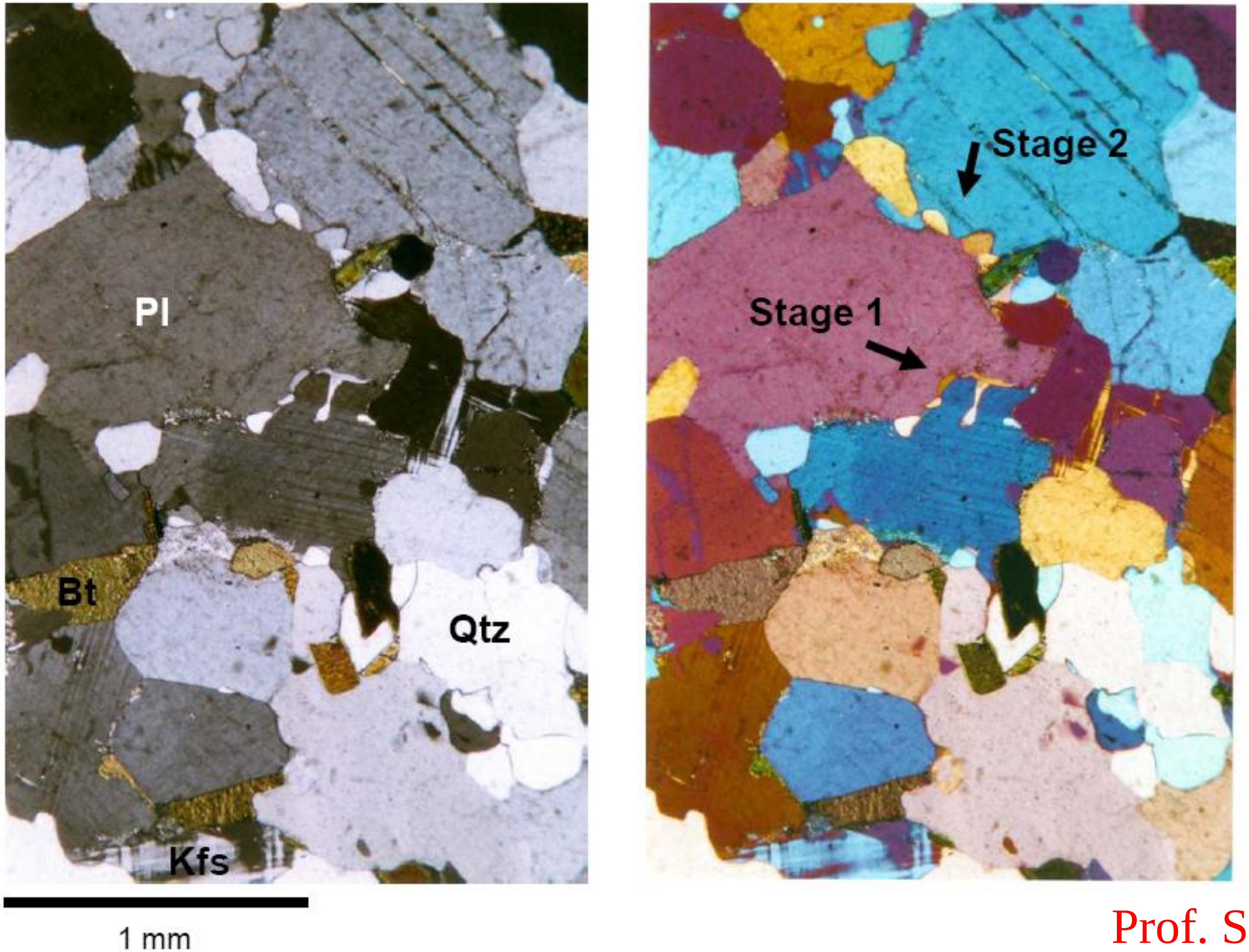
SOLID-STATE MODIFICATION OF STRING OF BEADS MICROSTRUCTURE

Development of higher dihedral angles (θ ~120°)



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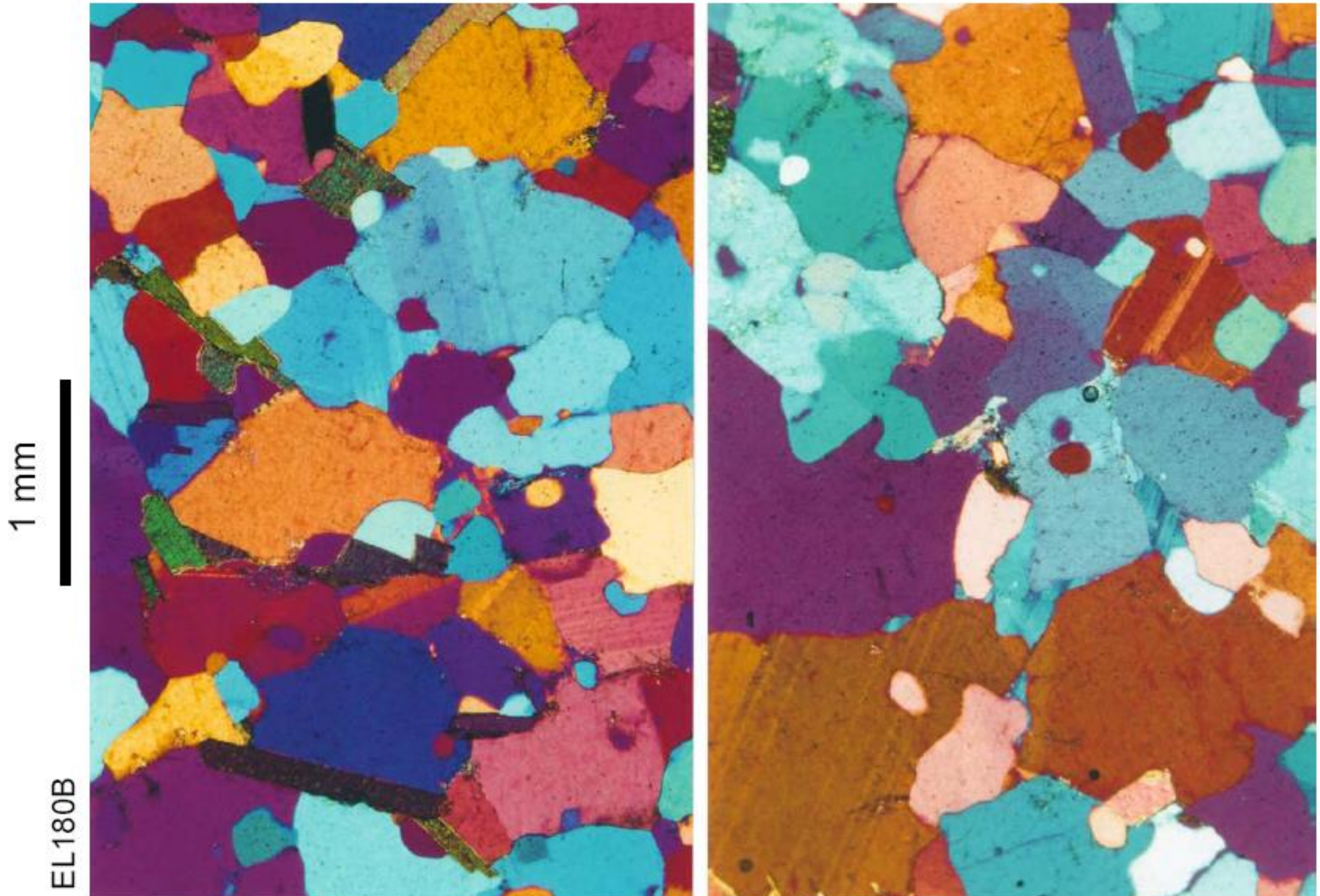
MICROSTRUCTURAL MODIFICATION IN THE SOLID STATE

Polygonal microstructure develops, but some former melt films pseudomorphed by K-feldspar remain evident



Microestruturas em diatexitos

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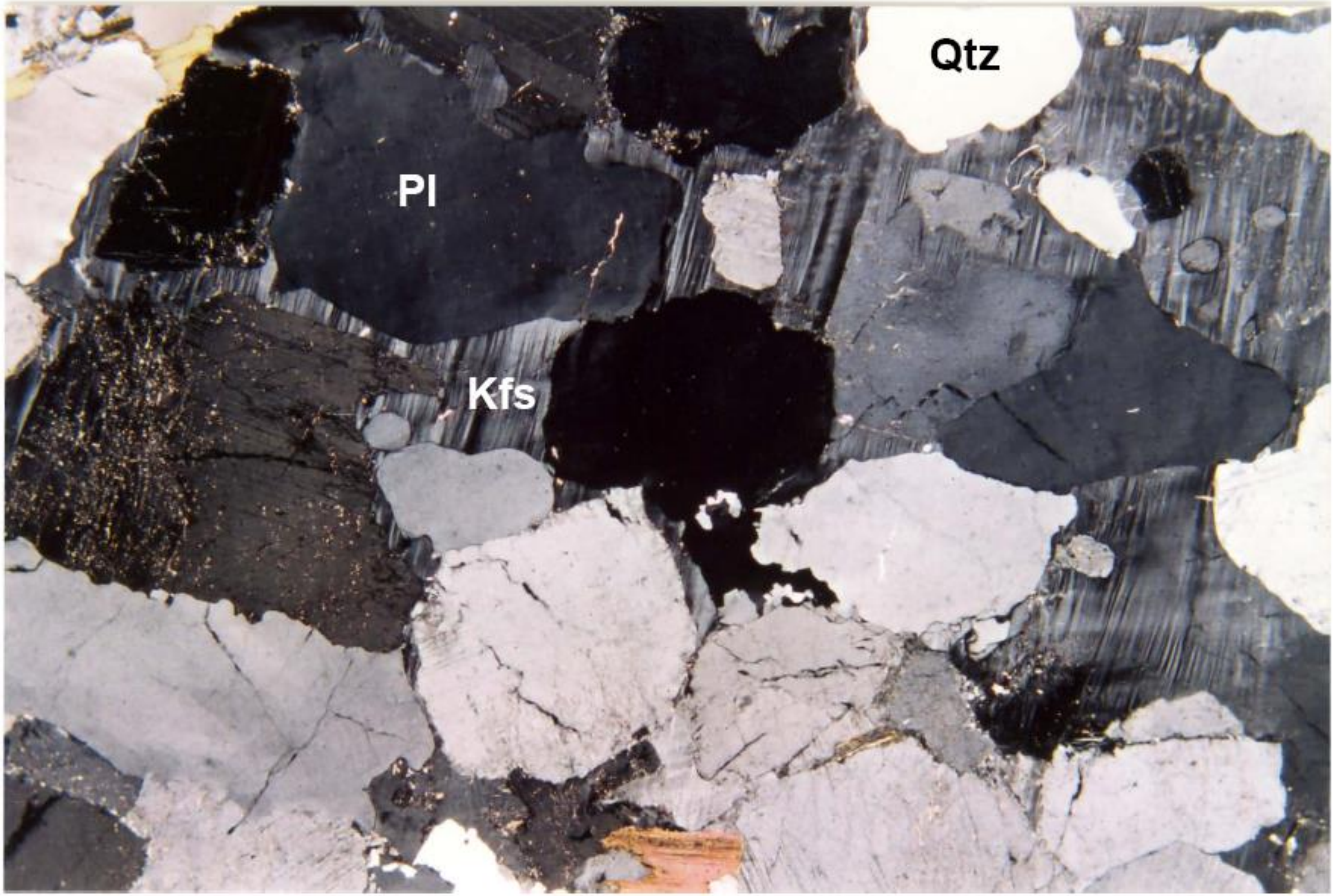

5 mm

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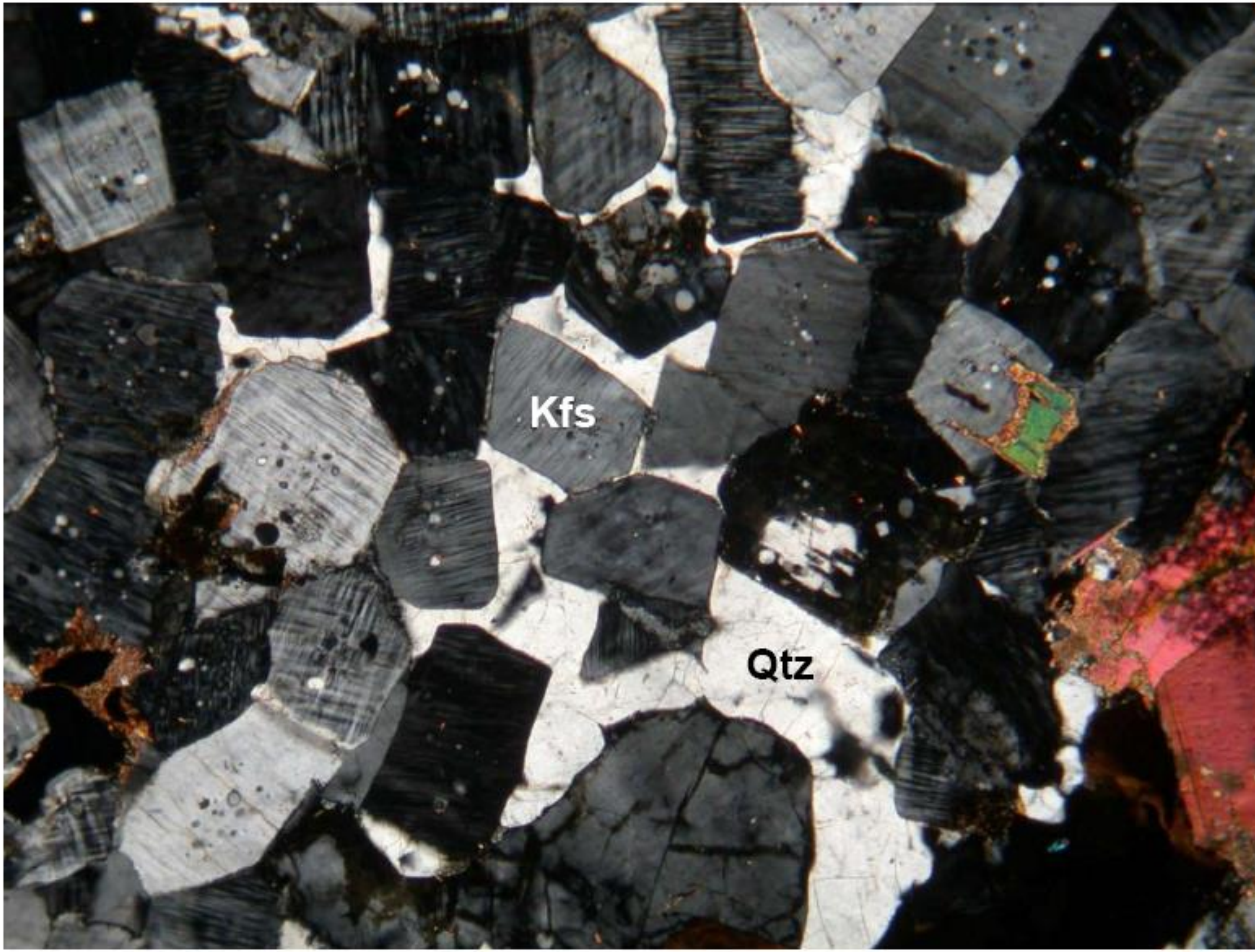

1 mm

Image by Richard White, see White et al., (2001) JPet