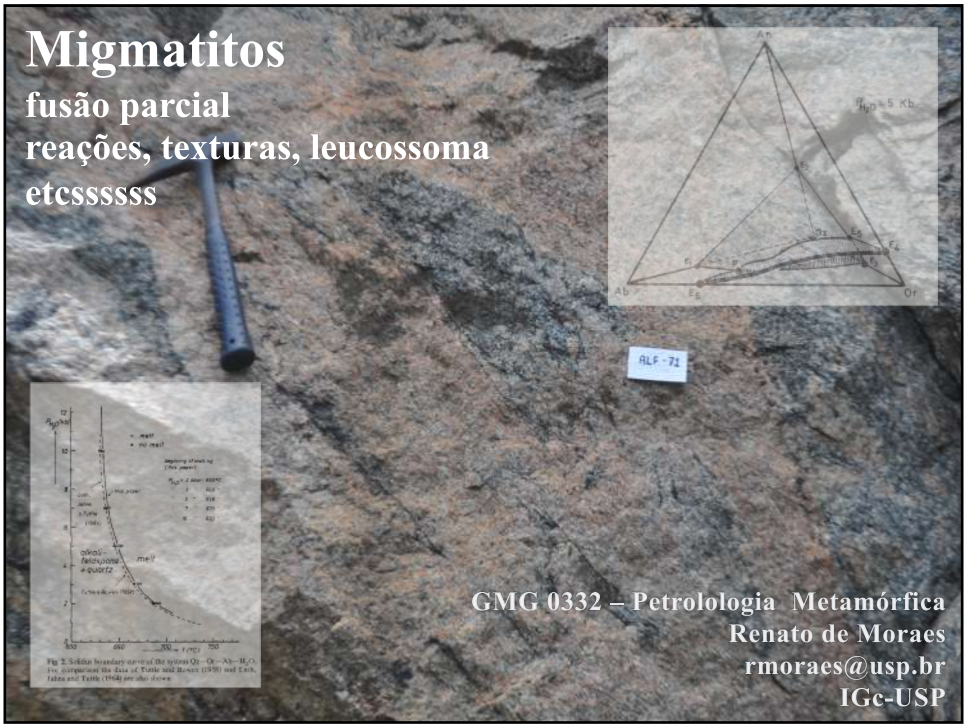
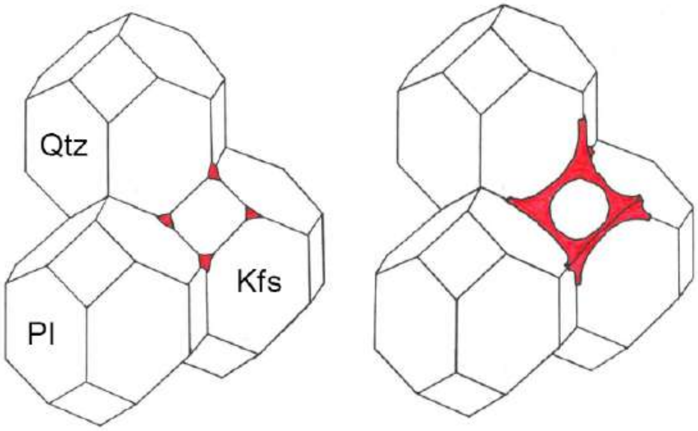


Migmatitos

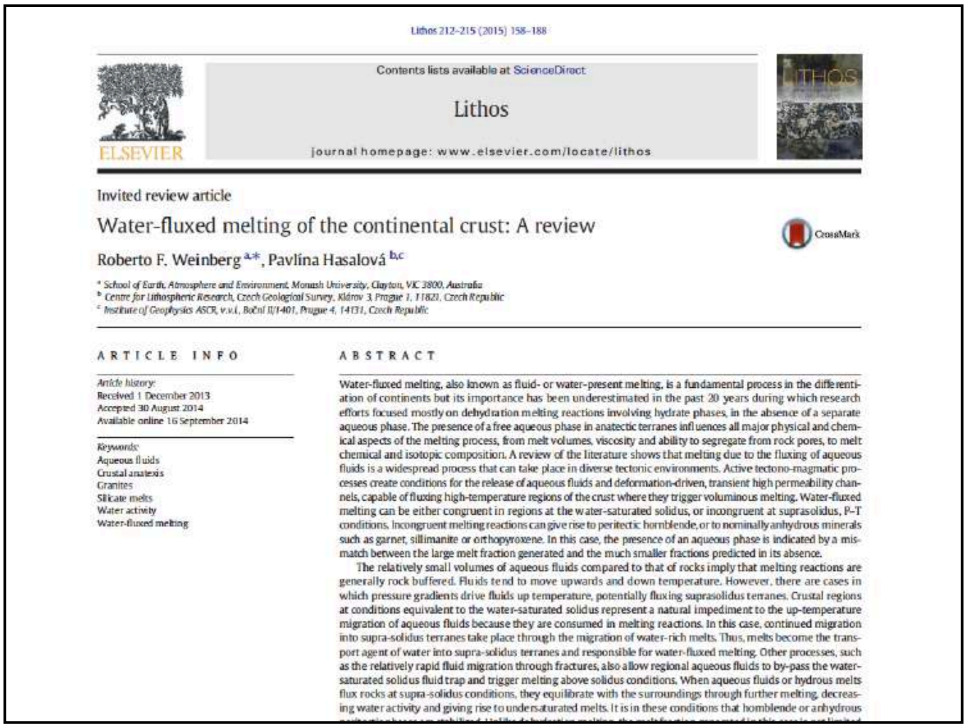
fusão parcial
reações, texturas, leucossoma
etcssssss

GMG 0332 – Petrolologia Metamórfica
Renato de Moraes
rmoraes@usp.br
IGc-USP

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



Lithos 212–215 (2015) 158–188

Contents lists available at ScienceDirect

Lithos

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

Invited review article

Water-fluxed melting of the continental crust: A review

Roberto F. Weinberg [a,*], Pavlína Hasalová [b,c]

[a] School of Earth, Atmosphere and Environment, Monash University, Clayton, VIC 3800, Australia
[b] Centre for Lithospheric Research, Czech Geological Survey, Klárov 3, Prague 1, 11821, Czech Republic
[c] Institute of Geophysics ASCR, v.v.i., Boční II/1401, Prague 4, 14131, Czech Republic

ARTICLE INFO

Article history:
Received 1 December 2013
Accepted 30 August 2014
Available online 16 September 2014

Keywords:
Aqueous fluids
Crustal anatexis
Granites
Silicate melts
Water activity
Water-fluxed melting

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

Fusão parcial (anatexia)

- Como as rochas são materiais heterogêneos, a fusão ocorre de forma parcial e dentro de certo intervalo de temperatura (*T*) e pressão (*P*)
- A fusão é parcial porque a rocha funde apenas onde todos reagentes estão em contato
- Há geração de um fundido e, quase sempre, há geração de resíduo sólido (fase peritética)

- Fusão congruente – fusão total
- Fusão incongruente – fundido + fase(s) peritética(s)

Do que depende a fusão parcial?

- *T*empetura, *P*ressão
- Composição da rocha
- H_2O
- Sistema aberto ou fechado

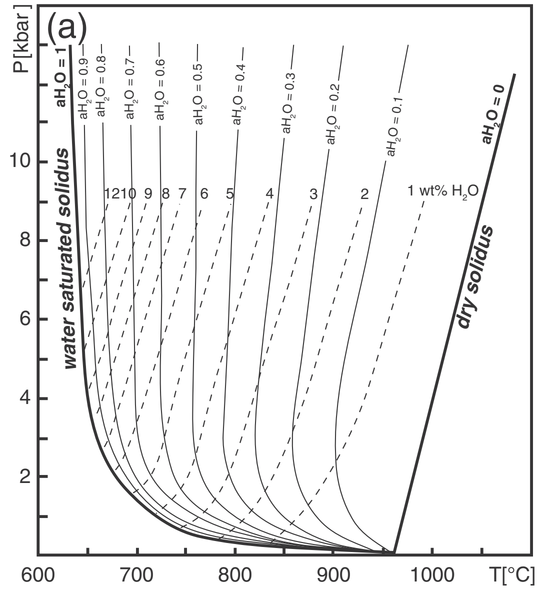
- Em que *T* uma rocha granítica funde?

Definições

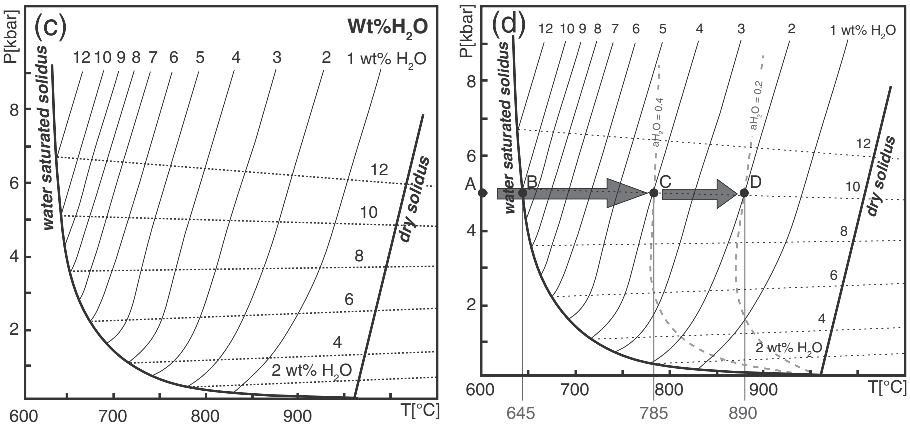
- Sistema haplogranítico – Qtz – Ab – Or – (H_2O)
- *Solidus* – curva de fusão mínima de qualquer sistema (onde a primeira **gota** de fundido ocorre) e isso sempre ocorre na curva com o sistema saturado em H_2O
- *Liquidus* – curvas que representam a quantidade de água em um fundido em equilíbrio com cristais de feldspato e quartzo: se a água cair abaixo deste valor, parte do fundido solidifica para recuperar o valor mínimo; se o teor de água aumenta, ocorre a fusão para recuperar esse valor mínimo
- *Solidus* seco - concide com a fusão total da rocha sem H_2O

Definições

- Fusão saturada em H_2O (*wet solidus*) – fusão que ocorre no *solidus*. Na natureza essa condição é muito restrita, pois a quantidade de H_2O nos poros das rochas é muito baixa. Há necessidade de ocorrer influxo constante de fonte externa para que ocorra fusão em alto volume nessas condições
  - o fundido é saturado em H_2O
  - ou seja ele tem o máximo de H_2O dissolvida
  - quanto **maior** a taxa de fusão, **menor** a quantidade de H_2O que ocorrerá no fundido



Weinberg & Hasalova, 2015

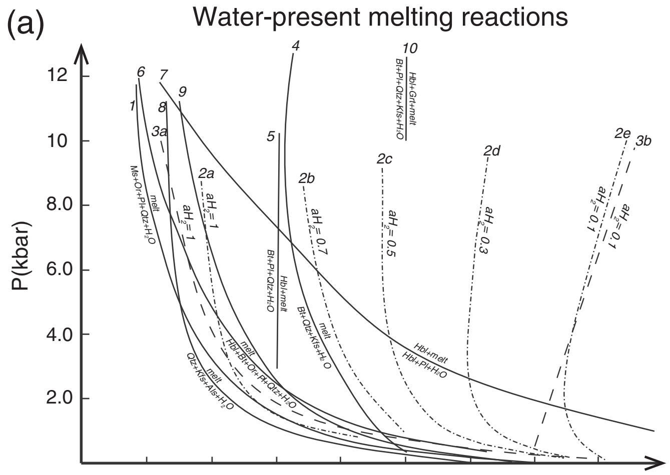


Linhas verticais quantidade de H_2O dissolvida no fundido

Linhas horizontais tracejadas marcam a quantidade máxima de H_2O que pode ser dissolvida no fundido. Abaixo da *P* referida haverá fundido + H_2O se valor indicado for ultrapassado

Fundido saturado em H_2O (B) não pode ascender, mas se for super – aquecido e for insaturado em H_2O, pode (C ou D)

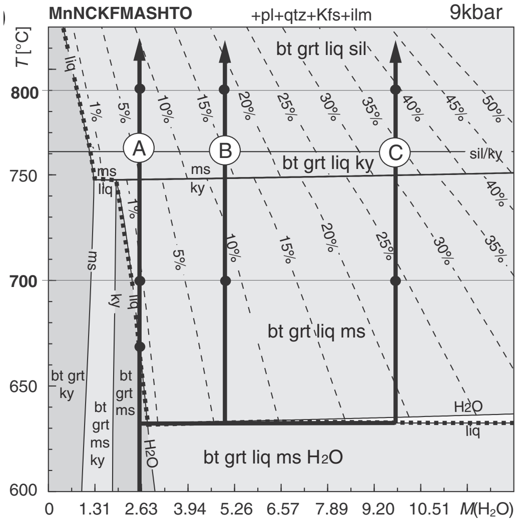
Weinberg & Hasalova, 2015



Fusão com H_2O
Veja que a composição da rocha pouco influencia a *T*
Compare as curvas 1 (Ms-granito) e 6 (Hbl-tonalito)
A inclinação das curvas é negativa

Weinberg & Hasalova, 2015

Efeito da H_2O

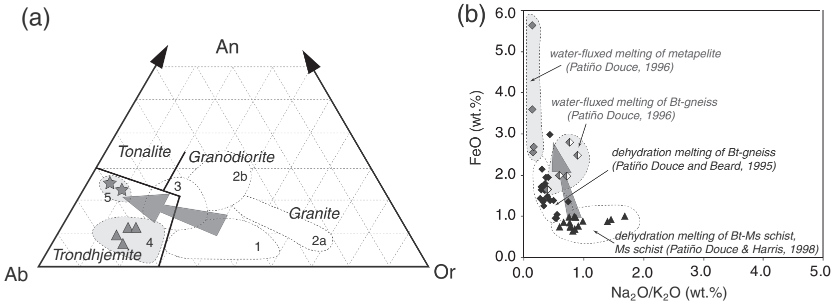


Bt-Ms granito

Weinberg & Hasalova, 2015

Fusão sem H_2O ou com influxo de H_2O

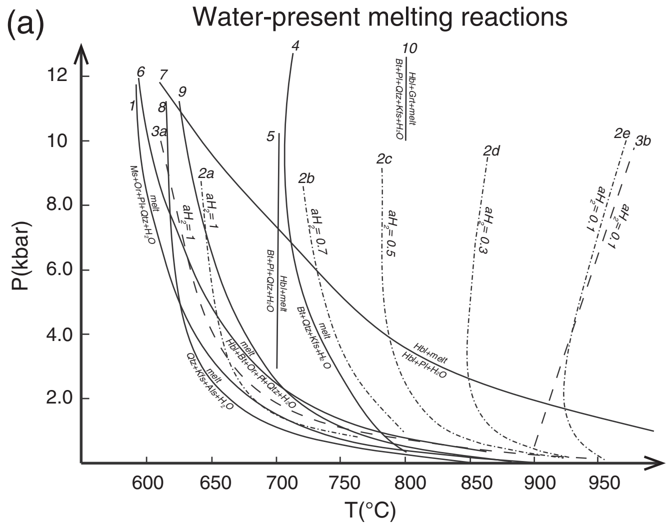
- Fusão por desidratação ou fusão sem fluido – a fusão ocorre pela quebra de fases hidratadas (micas e anfibólio), gerando fundido e fases peritéticas anidras
  - O fundido é sempre insaturado em H_2O
  - A reação de *T* mais baixa é da muscovita, depois da biotita e depois da hornblenda
- Fusão com influxo de H_2O – ocorre quando a rocha está em *T* acima do *solidus* e recebe um influxo de H_2O, fundindo



Campo branco – fusão por desidratação
favorece fusão de Ms, Pl e Kfs

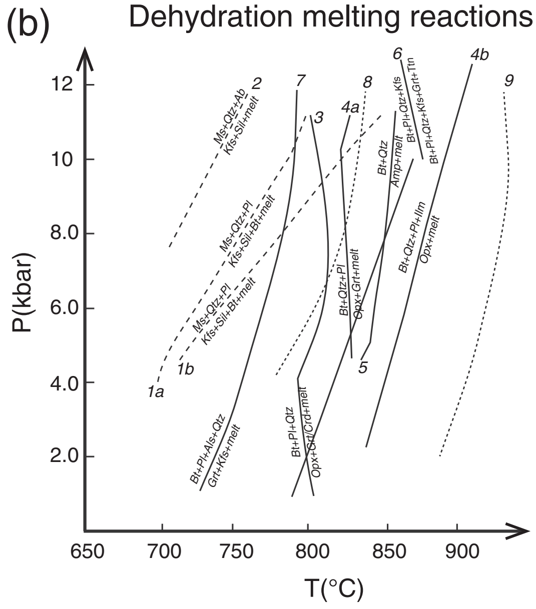
Campos cinza – fusão com influxo de H_2O
enriquece o fundido em Na_2O e FeO

Weinberg & Hasalova, 2015



Fusão com H_2O
Veja que a composição da rocha pouco influencia a *T*
Compare as curvas 1 (Ms-granito) e 6 (Hbl-tonalito)
A inclinação das curvas é negativa

Weinberg & Hasalova, 2015



As reações de fusão por desidratação

T Ms< Bt < Hbl

Sempre produzem fases peritéticas anidras

Inclinações positivas

As reações com influxo de H_2O produzem fases fases peritéticas hidratadas

Weinberg & Hasalova, 2015

Reconhecendo fusão com ou sem H_2O

- Leucossoma com Qtz + Kfsp + Pl ± Bt indica fusão em presença ou introdução de H_2O
- Leucossoma contendo minerais Fe-Mg anidros (Crd, Grt, Opx) são produzidos por fusão incongruente em sistema insaturado em H_2O

$Qtz + Pl + Kfs + H_2O = Liq$

Sawyer, 2008

sem fases peritéticas


resíduo com Pl + Qtz + Bt + Grt + Rt
leucossoma – trondjemito (Qtz + Pl ± Bt ± Grt)
melanossoma – biotita ± granada

metatexito com baixa taxa de fusão parcial, com leucossoma em veios isolados
Grupo Andrelância, Três Corações, MG

$Qtz + Pl + Ms + H_2O = Bt + Liq$

Metatexito estromático na zona de cisalhamento Pernambuco
Hbl peritética

Lucas Tesser

Qtz + Pl + Bt + H2O = Kfs + Hbl + Liq

contato transcional entre leucossoma e resíduo
resíduo – anfibolito
leucossoma – tonalito
fase peritética – hornblenda (cpx?)

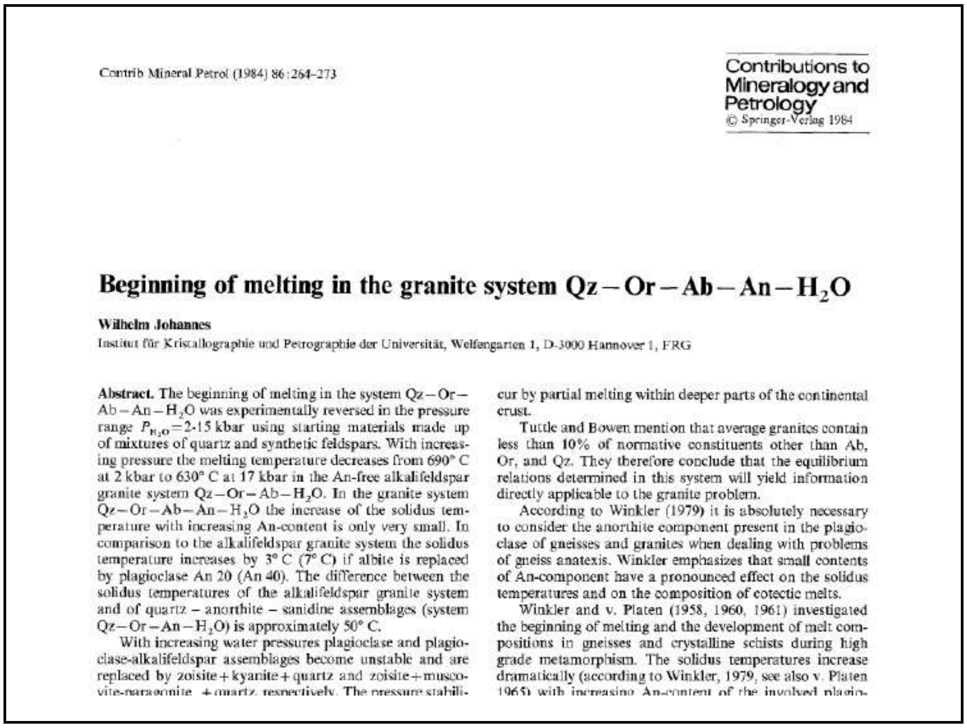
migmatito de anfibolito, córrego Uba, Acaiaca, MG

$\mathrm{Qtz + Pl + Hbl_1 + H_2O = Cpx + Hbl_2 + Liq}$

resíduo com Pl + Opx + Cpx + Ilm
leucossoma – tonalito
melanossoma / fase peritética – Opx

granulito máfico, leucossoma com Opx peritético, Stenigekusten, Província Sveconorwegian, Suécia

Qtz + Pl + Hbl = Opx + liq



Contrib Mineral Petrol (1984) 86:264–273

Contributions to Mineralogy and Petrology

Beginning of melting in the granite system Qz – Or – Ab – An – H_2O

Wilhelm Johannes
Institut für Kristallographie und Petrographie der Universität, Welfengarten 1, D-3000 Hannover 1, FRG

Abstract. The beginning of melting in the system Qz – Or – Ab – An – H_2O was experimentally reversed in the pressure range P_{H_2O} = 2-15 kbar using starting materials made up of mixtures of quartz and synthetic feldspars. With increasing pressure the melting temperature decreases from 690° C at 2 kbar to 630° C at 17 kbar in the An-free alkalifeldspar granite system Qz – Or – Ab – H_2O. In the granite system Qz – Or – Ab – An – H_2O the increase of the solidus temperature with increasing An-content is only very small. In comparison to the alkalifeldspar granite system the solidus temperature increases by 3° C (7° C) if albite is replaced by plagioclase An 20 (An 40). The difference between the solidus temperatures of the alkalifeldspar granite system and of quartz – anorthite – sanidine assemblages (system Qz – Or – An – H_2O) is approximately 50° C.

With increasing water pressures plagioclase and plagioclase-alkalifeldspar assemblages become unstable and are replaced by zoisite + kyanite + quartz and zoisite + muscovite-paragonite + quartz, respectively. The pressure stabili- … cur by partial melting within deeper parts of the continental crust.

Tuttle and Bowen mention that average granites contain less than 10% of normative constituents other than Ab, Or, and Qz. They therefore conclude that the equilibrium relations determined in this system will yield information directly applicable to the granite problem.

According to Winkler (1979) it is absolutely necessary to consider the anorthite component present in the plagioclase of gneisses and granites when dealing with problems of gneiss anatexis. Winkler emphasizes that small contents of An-component have a pronounced effect on the solidus temperatures and on the composition of cotectic melts.

Winkler and v. Platen (1958, 1960, 1961) investigated the beginning of melting and the development of melt compositions in gneisses and crystalline schists during high grade metamorphism. The solidus temperatures increase dramatically (according to Winkler, 1979, see also v. Platen 1965) with increasing An-content of the involved plagio-

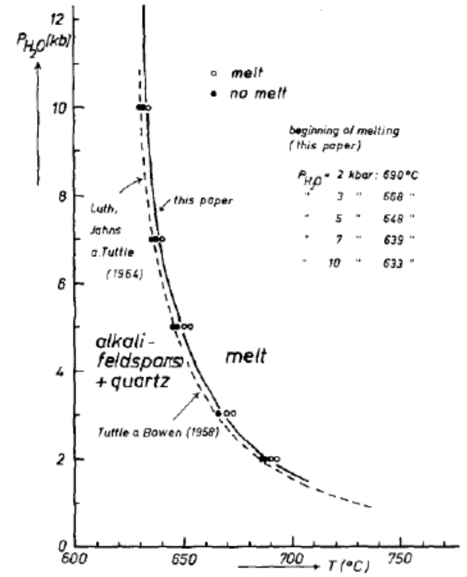


Fig. 2. Solidus boundary curve of the system Qz – Or – Ab – H_2O. For comparison the data of Tuttle and Bowen (1958) and Luth, Jahns and Tuttle (1964) are also shown

23

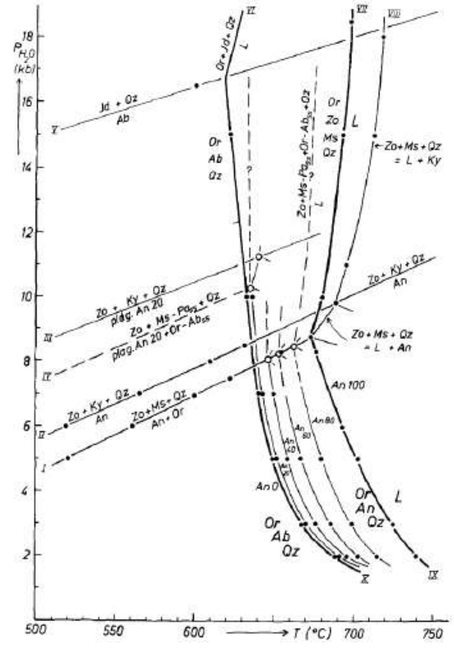


Fig. 7. Melting and subsolidus reactions in the system $Na_2O - K_2O - CaO - Al_2O_3 - SiO_2 - H_2O$. Data sources: I: Johannes (1980b), II: this paper, III: Goldsmith (1982), IV: estimated (see text), V and VI: Huang and Wyllie (1975), VII and VIII: Schliestedt and Johannes (1984), IX: Johannes (1986), X: this paper. For details see text

24

Fases peritéticas

- As fases peritéticas são aquelas fases sólidas formadas como resíduos sólidos das reações de fusão incongruente
  - Qtz + Ms + H_2O = Al_2SiO_5 + Liq
    - A presença de H_2O ajuda a fusão e faz com que haja apenas uma fase peritética
  - Qtz + Ms = Al_2SiO_5 + Kfs + Liq
    - Sem H_2O ocorre número maior de fases peritéticas e aqui nenhuma é máfica!
  - Qtz + Bt + Sil = Grt + Crd + Kfs + Liq
    - A quebra de fase Fe-Mg gera fases peritéticas Fe-Mg

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.

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.

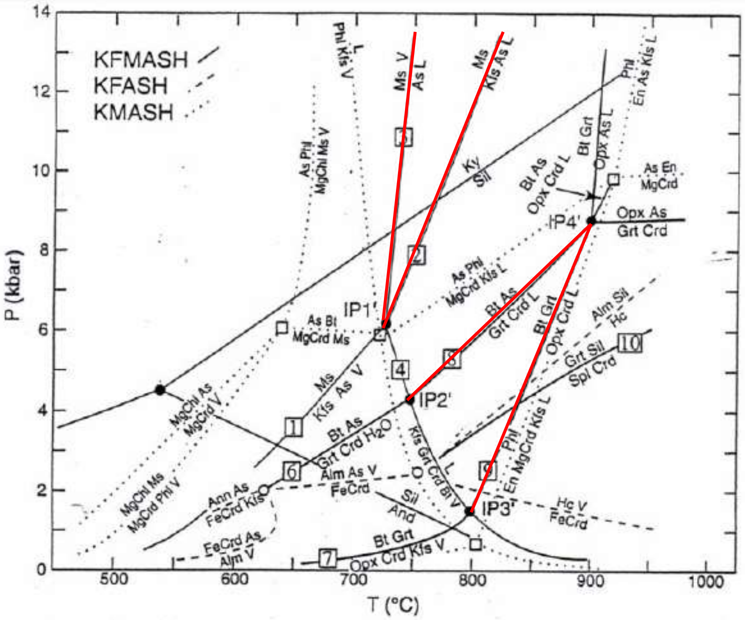
Numerous experimental studies have constrained the *P-T* conditions for many of the melting reactions important to pelites (e.g., Huang and Wyllie 1973, 1974, 1975, 1981; Huang et al. 1973; Le Breton and Thompson 1988; Gardien et al. 1995; Patiño Douce and Johnston 1991; Vielzeuf and Holloway 1988; Vielzeuf 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.

F.S. Spear (✉)
Department of Earth and Environmental Sciences,
Rensselaer Polytechnic Institute, Troy, NY 12180, USA;
E-mail: spearf@rpi.edu

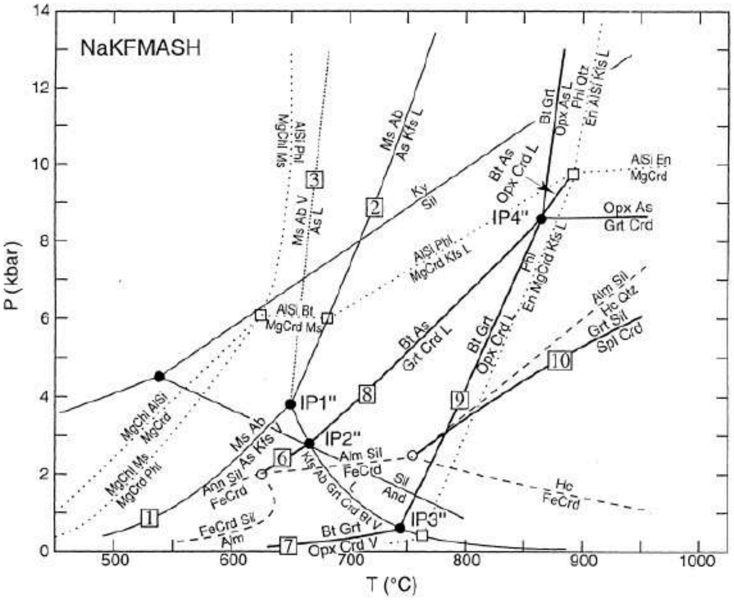
M.J. Kohn

De que *T* estamos falando?



reações 3 e 2 (Ms) e 8 e 9 (Bt) são importantes e ocorrem em diversas composições

27

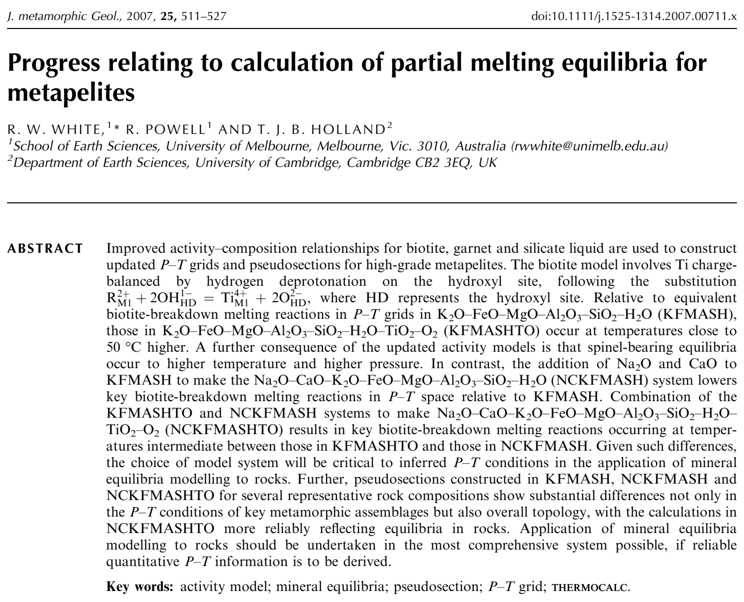


adição de Ab diminui a *T* de fusão, mas a adição de Pl diminui a *T* em menor proporção

28

Do que depende a *T* de fusão?

- Proporção Qtz, Kfs, Pl, Ms, Bt, Sill na rocha (ou seja, a composição da rocha)
- Da quantidade de H_2O e da composição do fluido
- Da composição do plagioclásio (> An, > *T*)
- Da *P* (pressão confinante)



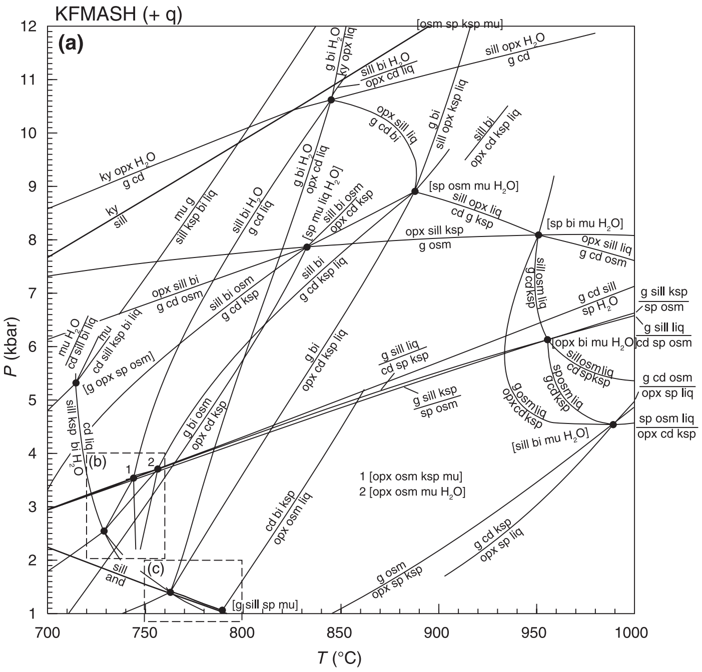
J. metamorphic Geol., 2007, **25**, 511–527 doi:10.1111/j.1525-1314.2007.00711.x

Progress relating to calculation of partial melting equilibria for metapelites

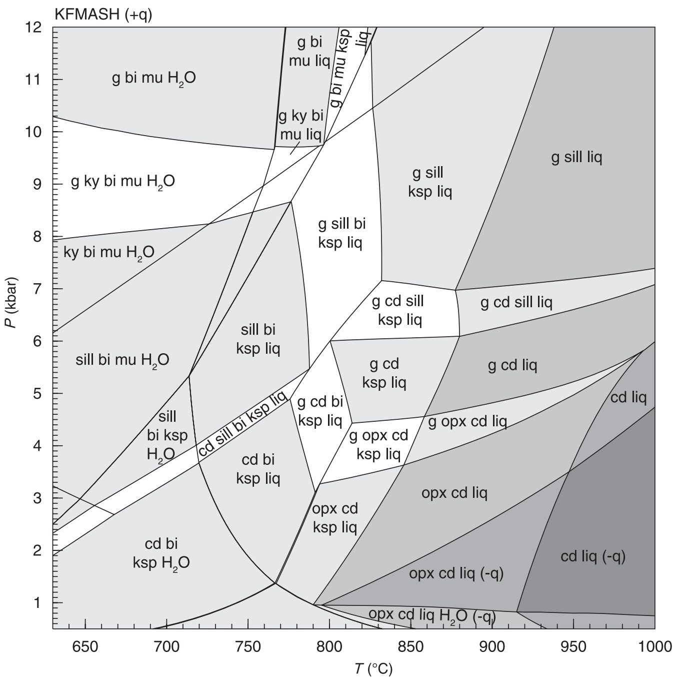
R. W. WHITE,[1]* R. POWELL[1] AND T. J. B. HOLLAND[2]
[1]*School of Earth Sciences, University of Melbourne, Melbourne, Vic. 3010, Australia (rwwhite@unimelb.edu.au)*
[2]*Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK*

ABSTRACT Improved activity–composition relationships for biotite, garnet and silicate liquid are used to construct updated *P–T* grids and pseudosections for high-grade metapelites. The biotite model involves Ti charge-balanced by hydrogen deprotonation on the hydroxyl site, following the substitution $R^{2+}_{M1} + 2OH^{1-}_{HD} = Ti^{4+}_{M1} + 2O^{2-}_{HD}$, where HD represents the hydroxyl site. Relative to equivalent biotite-breakdown melting reactions in *P–T* grids in K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O (KFMASH), those in K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2–O_2 (KFMASHTO) occur at temperatures close to 50 °C higher. A further consequence of the updated activity models is that spinel-bearing equilibria occur to higher temperature and higher pressure. In contrast, the addition of Na_2O and CaO to KFMASH to make the Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O (NCKFMASH) system lowers key biotite-breakdown melting reactions in *P–T* space relative to KFMASH. Combination of the KFMASHTO and NCKFMASH systems to make Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2–O_2 (NCKFMASHTO) results in key biotite-breakdown melting reactions occurring at temperatures intermediate between those in KFMASHTO and those in NCKFMASH. Given such differences, the choice of model system will be critical to inferred *P–T* conditions in the application of mineral equilibria modelling to rocks. Further, pseudosections constructed in KFMASH, NCKFMASH and NCKFMASHTO for several representative rock compositions show substantial differences not only in the *P–T* conditions of key metamorphic assemblages but also overall topology, with the calculations in NCKFMASHTO more reliably reflecting equilibria in rocks. Application of mineral equilibria modelling to rocks should be undertaken in the most comprehensive system possible, if reliable quantitative *P–T* information is to be derived.

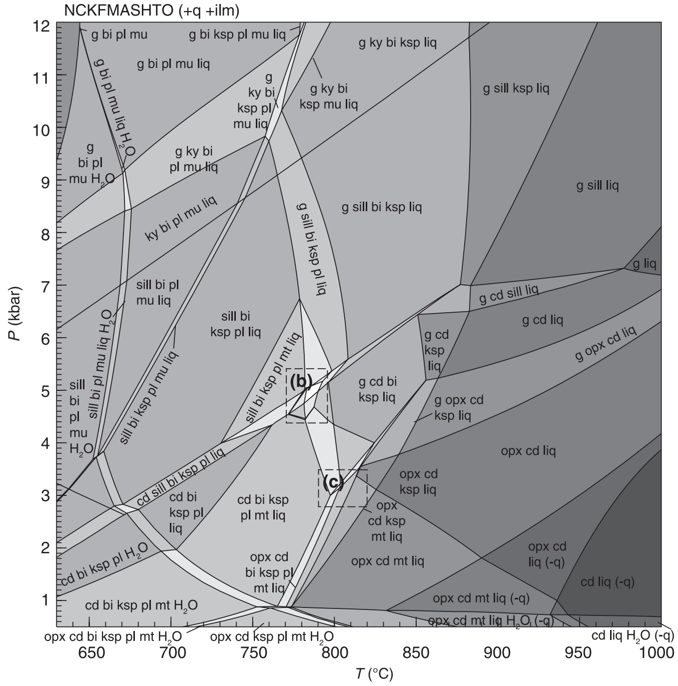
Key words: activity model; mineral equilibria; pseudosection; *P–T* grid; THERMOCALC.


KFMASH (+ q)
(a)
P (kbar)
T (°C)
12
11
10
9
8
7
6
5
4
3
2
1
700
750
800
850
900
950
1000
ky opx H_2O / g cd
ky / sill
mu g / sill ksp bi liq
sill bi H_2O / g cd liq
g bi H_2O / opx cd liq
g bi H_2O / ky opx liq
sill bi H_2O / opx cd liq
[osm sp ksp mu]
sill opx H_2O / g cd
opx sill liq / g cd bi
g bi / sill opx ksp liq
sill bi / opx cd ksp liq
[sp mu liq H_2O]
sill bi osm / opx cd ksp
[sp osm mu H_2O]
sill opx liq / cd g ksp
opx sill ksp / g osm
[sp bi mu H_2O]
opx sill liq / g cd osm
sill bi / g cd ksp liq
opx sill bi / g cd osm
sill bi osm / g cd ksp
mu H_2O / cd sill bi liq
mu / cd sill ksp bi liq
[g opx sp osm]
sill ksp bi H_2O
cd liq
g bi / opx cd ksp liq
g bi osm / opx cd ksp
(b)
1
2
(c)
sill / and
[g sill sp mu]
cd bi ksp / opx osm liq
sill osm liq / g cd ksp
g cd sill / sp H_2O
g sill ksp / sp osm
g sill liq / cd sp osm
[opx bi mu H_2O]
g sill liq / cd sp ksp
g sill ksp / sp osm
sill osm liq / cd sp ksp
sp osm liq / g cd ksp
g osm liq / opx cd ksp
g cd osm / opx sp liq
sp osm liq / opx cd ksp
[sill bi mu H_2O]
1 [opx osm ksp mu]
2 [opx osm mu H_2O]
g osm / opx sp ksp
g cd ksp / opx sp liq

31


KFMASH (+q)
P (kbar)
T (°C)
12
11
10
9
8
7
6
5
4
3
2
1
650
700
750
800
850
900
950
1000
g bi mu H_2O
g bi mu liq
g bi mu ksp
liq
g ky bi mu liq
g ky bi mu H_2O
g sill ksp liq
g sill liq
g sill bi ksp liq
ky bi mu H_2O
g cd sill ksp liq
g cd sill liq
sill bi ksp liq
sill bi mu H_2O
g cd ksp liq
g cd liq
sill bi ksp H_2O
cd sill bi ksp liq
g cd bi ksp liq
cd liq
g opx cd liq
g opx cd ksp liq
cd bi ksp liq
opx cd liq
opx cd ksp liq
cd bi ksp H_2O
opx cd liq (-q)
cd liq (-q)
opx cd liq H_2O (-q)

32



Sistema fechado e aberto

- Sistema fechado – o fundido é mantido junto com sua fonte
- Sistema aberto – o fundido é retirado, separado da sua fonte, em um único episódio ou em episódios. Isso implica em segregação do fundido (e mudança de fertilidade)

The composition of anatectic melt and its complementary residue by forward modelling of closed-system and open-system melting using THERMOCALC

M. Pavan[1,2,3*]; R. Moraes[2], E. W. Sawyer[3]

[1]CPRM – Geological Survey of Brazil, Rua Costa 55, Consolação, CEP 01304-010, São Paulo SP, Brazil.

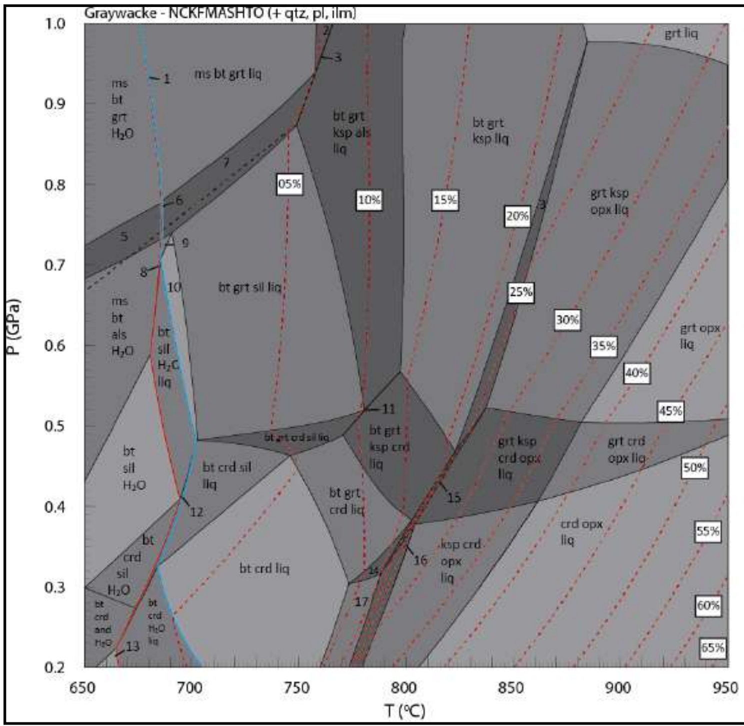
[2]Instituto de Geociências, Universidade de São Paulo, Rua do Lago 562, CEP 05508-080, São Paulo SP, Brazil.

[3]UQAC - Université du Québec à Chicoutimi, 555 Boulevard de l'Université, Chicoutimi, QC, G7H 2B1, Canada

Submitted to Lithos

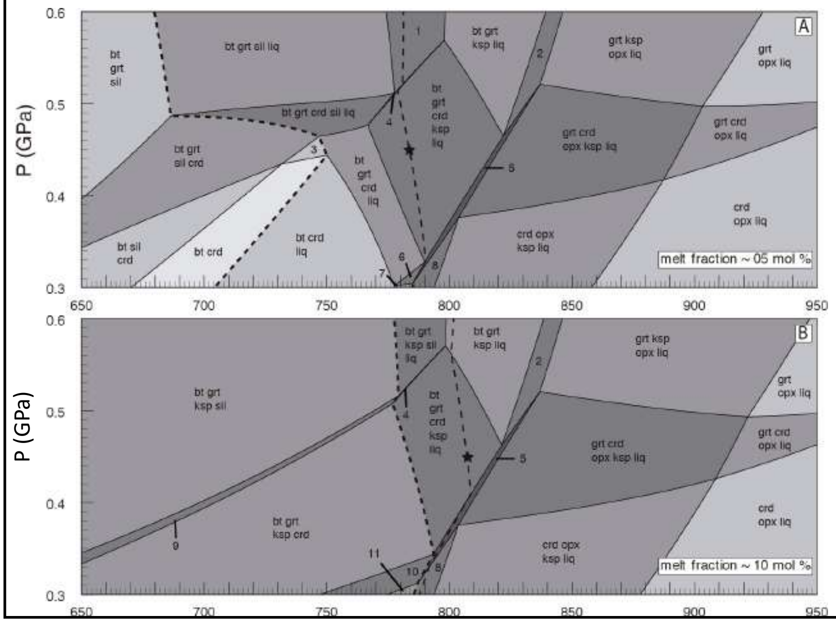
Table 1: Chemical composition of samples used in this work. Values in wt. % were extracted from Condie (1993), converted to mol. % and simplified to NCKFMASHTO chemical system to run the calculations in THERMOCALC. FeOt* corresponds to values converted from Fe_2O_3t.

Samples	Graywacke bulk composition		Shale bulk composition	
oxides	wt. %	mol. %	wt. %	mol. %
SiO_2	66.10	70.22	63.1	68.26
TiO_2	0.77	0.61	0.64	0.52
Al_2O_3	15.00	9.39	17.5	11.15
Fe_2O_3	-	0.10	-	0.10
FeO_T*	5.80	5.15	5.65	4.99
MgO	2.10	3.32	2.2	3.55
CaO	2.60	2.96	0.71	0.82
Na_2O	2.80	2.88	1.06	1.11
K_2O	2.50	1.70	3.62	2.50
H_2O	-	3.67	-	7.00
Sum	97.67	100.00	94.6	100.00

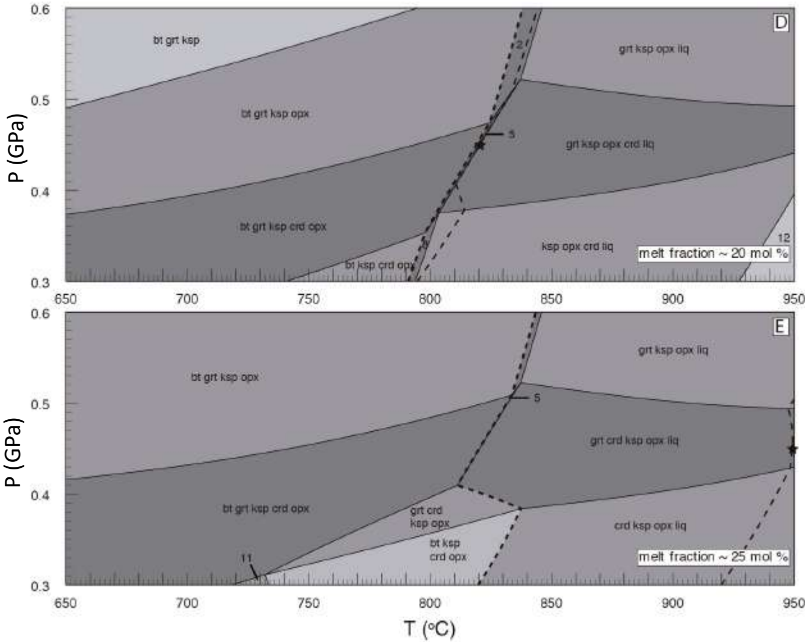


wacke
sistema fechado

wacke - sistema aberto
retirada do fundido em 0,45 GPa

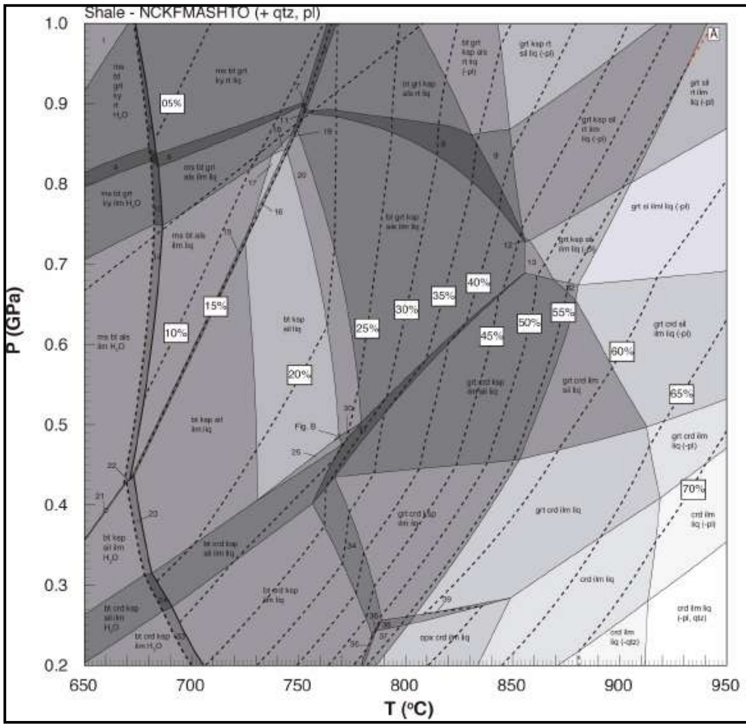


wacke - sistema aberto
retirada do fundido em 0,45 GPa

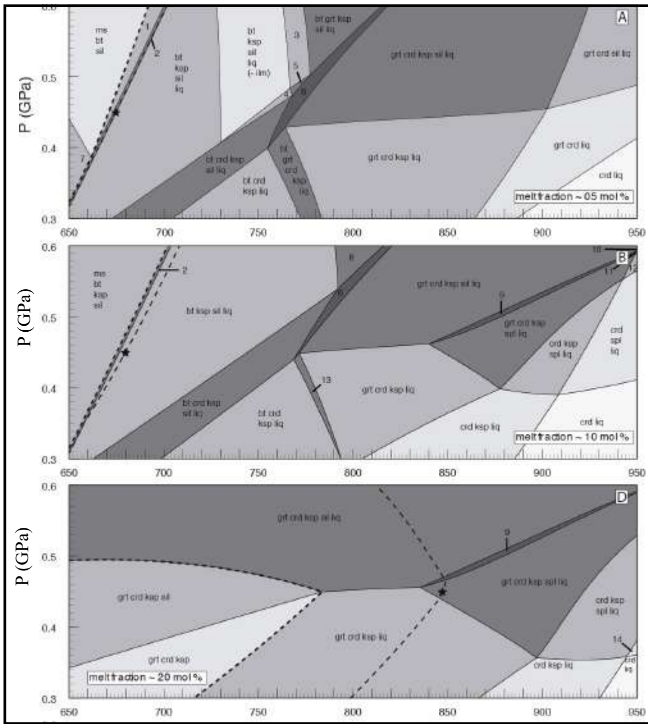


39

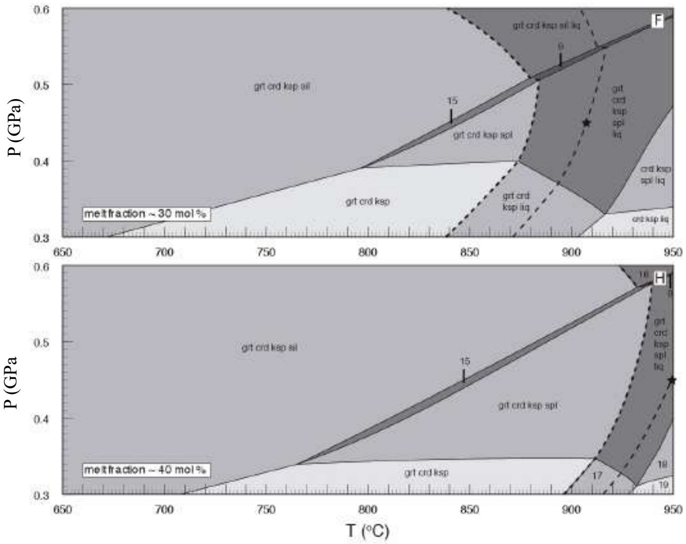
pelito
sistema fechado



40



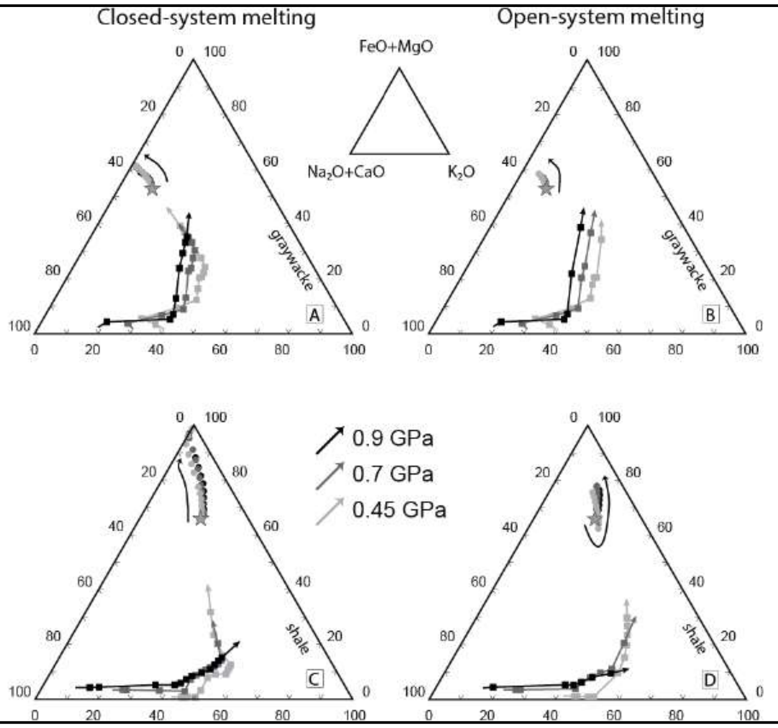
pelito
sistema aberto
retirada do fundido
em 0,45 GPa



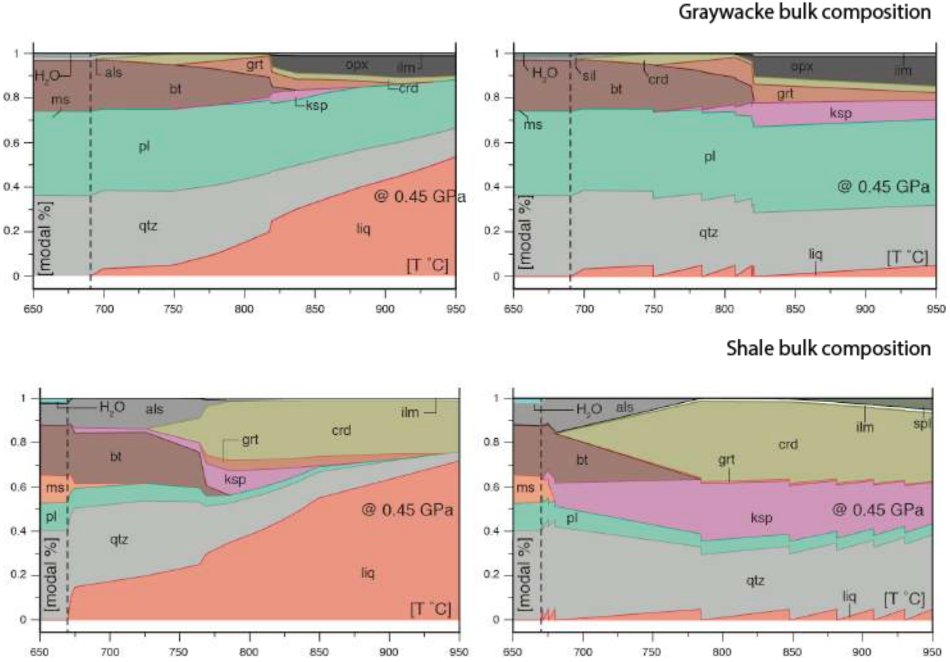
pelito
sistema aberto
retirada do fundido
em 0,45 GPa

● resíduo

■ fundido



Moda mineral do resíduo e porcentagem de fundido



Relação entre composição de rocha, reação de fusão, resíduo, *T,* fase peritética e composição do fundido

- Cada rocha funde intervalo específico de *T*

  em *T* mais baixa (~730 °C) a reação de fusão em um pelito

  – Qtz + Ms + Pl = Kfs + Al_2SiO_5 + Liq

  o fundido é granítico, pois a reação funde Ms, Qtz e Pl

  as fases peritéticas tem K_2O e Al_2O_3, relacionadas à Ms

- Em *T* mais elevada (*T* >750 °C) a reação de fusão em um pelito

  – Qtz + Bt + Sil + Pl = Kfs + Grt + Crd + Liq

  o fundido é granítico a granodiorítico, pois a reação funde Qtz, Pl e Bt (e se soma ao fundido granítico que já estava presente)

  as fases peritéticas tem K_2O, FeO, MgO, Al_2O_3, relacionadas à Bt e Sil

- Em *T* mais elevada (*T* >850 °C) a reação de fusão em um anfibolito
  - Qtz + Pl + Hbl = Cpx + Liq

o fundido é tonalítico, pois a reação funde Qtz, Pl e não há de onde tirar K_2O

a fase peritéticas tem CaO, FeO e MgO relacionadas à Hbl e Pl

Leucossoma

- **Fundido (granito) mínimo** – representa composição do eutético, onde feldspato alcalino (albita - ortoclásio) coexistem com quartzo, Qtz-Ab-Or-H_2O, ou de um ponto em cima da linha cotética em sistema Qtz-Ab-Or-An-H_2O
- Muitos granitos apresentam composição normativa em torno dessa composição
- Leucossoma com essa composição é raro

ARTICLE

DOI: 10.1590/2317-4889201920180066

BJGEO
Brazilian Journal of Geology

Evaluation of the contributions of possible sources to the leucosome of the diatexite of Socorro-Guaxupé Nappe, in the Alfenas Region, MG, Brazil

Lizeth Hernandez Tasco[1], **Renato Moraes**[2*]

Abstract

The Socorro-Guaxupé Nappe crops out in southern Minas Gerais and it has an intermediate unit called Metaxite Unit, dominated by diatexites at its base, with large volumes of leucosome and schollen of stromatic garnet-biotite metatexite. Leucosome within the schollen crystallized via fractional crystallization and is dominated by plagioclase and quartz, although K-feldspar might be present. However, the larger volume of the coarse-grained leucosome, that dominates the unit, has granite, sometimes close to minimum granite composition. So, its formation, after partial melting, involved, segregation, fractional crystallization and accumulation. Proportions of leucosome / residue and leucosome / residue / peritectic phases indicate that the leucosome crystallized from more melt than a pelite source could produce, and probably diatexite worked as a pre-magmatic chamber and stocked melt produced from the granulites sitting at its bottom. Large proportion of biotite crystallized in the residue was formed due to equalization of water chemical potential between residue and leucosome.

KEYWORDS: Leucosome; melt crystallization; melt segregation; partial melting; Socorro-Guaxupé Nappe.

Braz. J. Geol., 49(1):e20180066

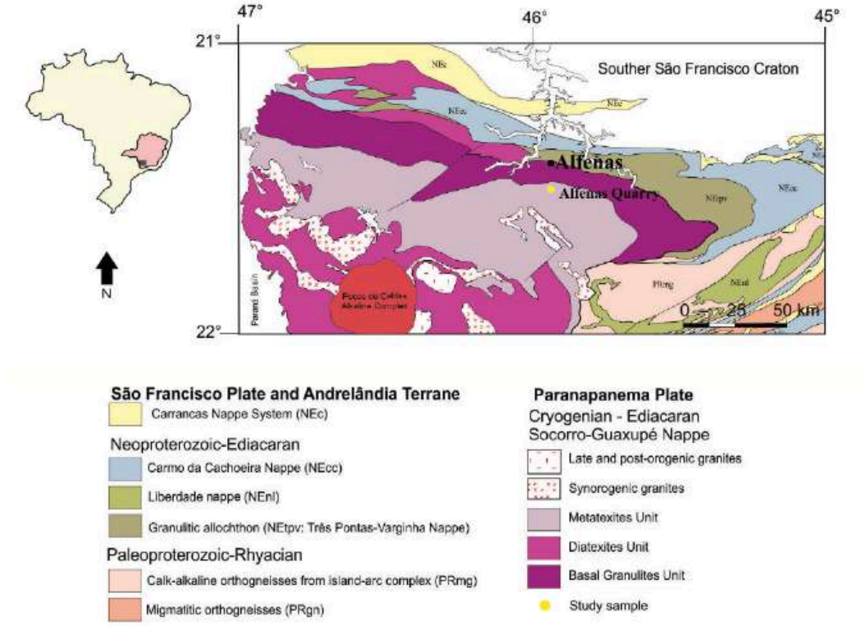


Figure 1. Geological map of the Southern Brasilia Orogen with the location of the study area (cut and modified from Campos Neto *et al.* 2011).

Objetivos

- Comparar:
  - composição do leucossoma dentro do *schollen*
  - composição do leucossoma grosso do diatexito
  - avaliar semelhanças, diferenças de fonte, fusão e o processo de cristalização

Nappe Socorro-Guaxupé, unidade de diatexito, Alfenas, MG


Nappe Socorro-Guaxupé, unidade de diatexito, Alfenas, MG

53

54

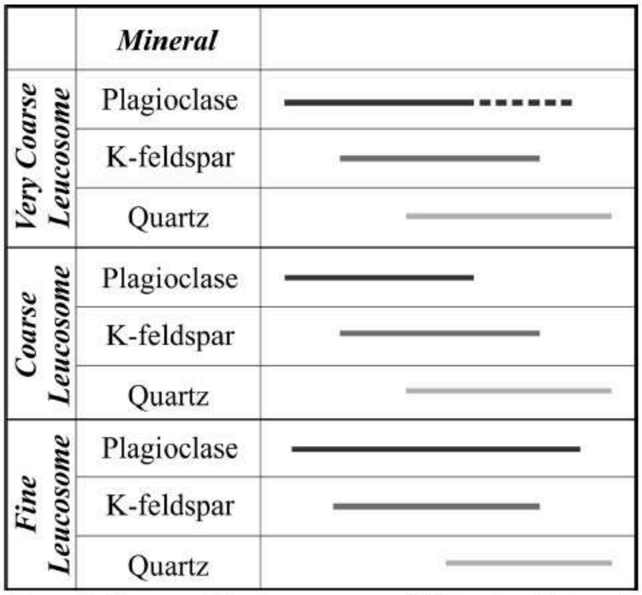


Figure 5. The crystallization sequence of felsic minerals in each leucosome types.

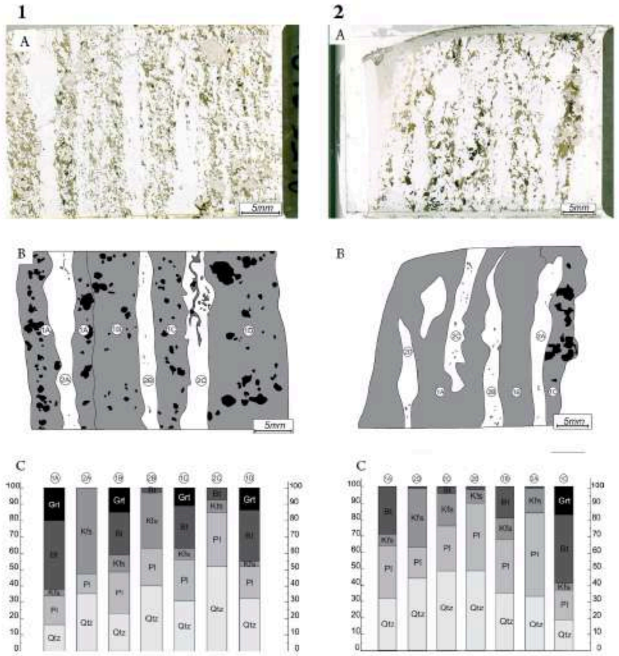


Figure 7. Comparison of the modal proportions between residue and leucosome layers in samples of schollen of stromatic biotite metatexite rich (1 — ALFE-71D1) or poor (2 — DE3-3B1-C) in garnet. In all three images (A) is a scan of the thin section (B) is a drawing of residue and garnet and leucosome (in white) and in (C) the modal proportions of garnet, biotite and felsic minerals from different layers.

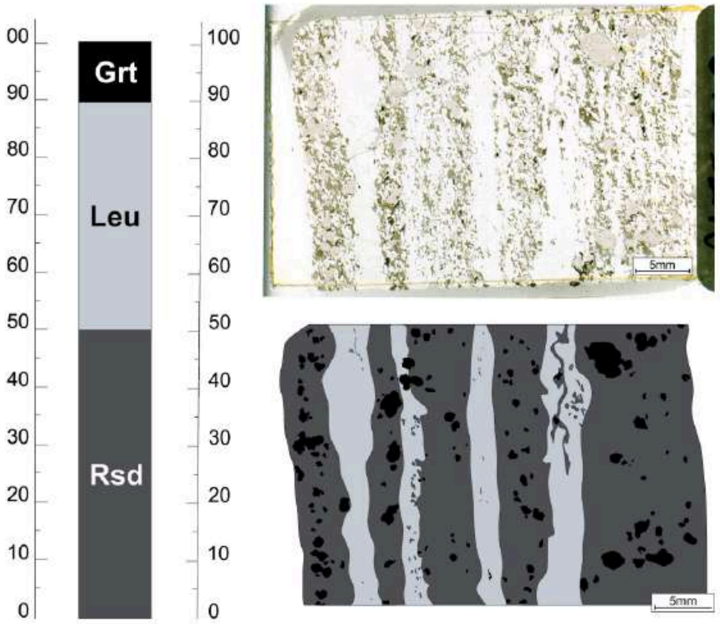


Figure 8. Proportions of the migmatite parts recognized in thin section and normalized to 100%; peritectic garnet (Grt), leucosome (Leu) and residue (Rsd).

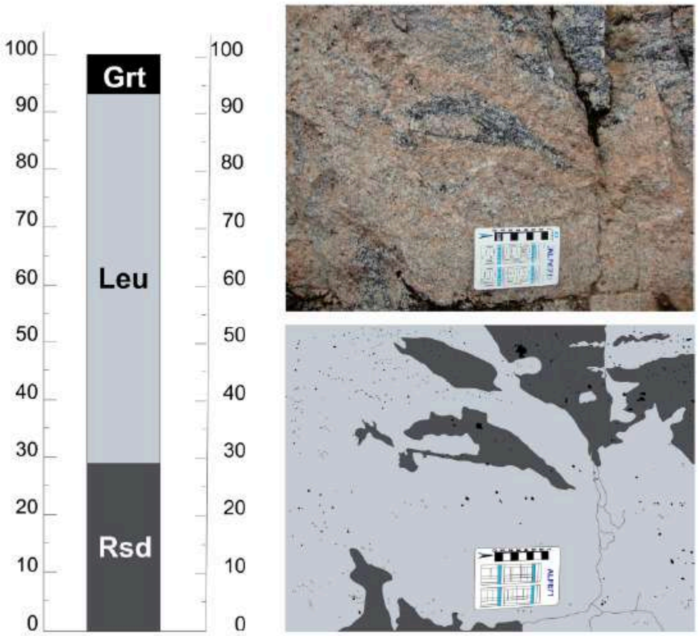


Figure 10. Proportions of the migmatite parts recognized in field and normalized to 100%; peritectic garnet (Grt), leucosome (Leu) and schollen — residue (Rsd).

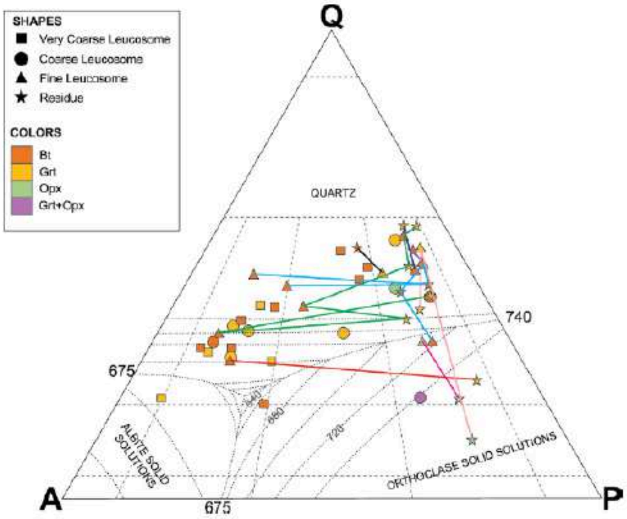


Figure 6. QAP diagram of the mineral modal percentage of in leucosome types and related residues, when available. A tie line connects a residue with leucosome symbols that are from the same thin section. The isolines shows equilibrium diagram for the granite minimum at 10 kb from Luth *et al.* (1964).

Conclusões

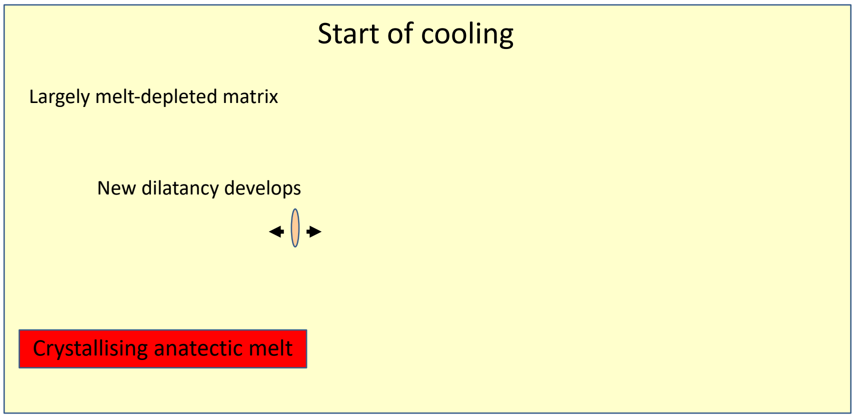
- A investigação do neossoma do diatexito em questão permite concluir que a sua cristalização teve envolvimento de:
  - – segregação do líquido
  - – cristalização na fonte do líquido remanescente
  - – cristalização paulatina do líquido segregado
  - – acúmulo de feldspato potássico
- O volume de fundido observado, se balizado pela proporção de Grt, é muito maior, implicando que pode ter ocorrido adição proveniente de outras unidades

Stolen from Edward Sawyer

- Model for leucosomes!

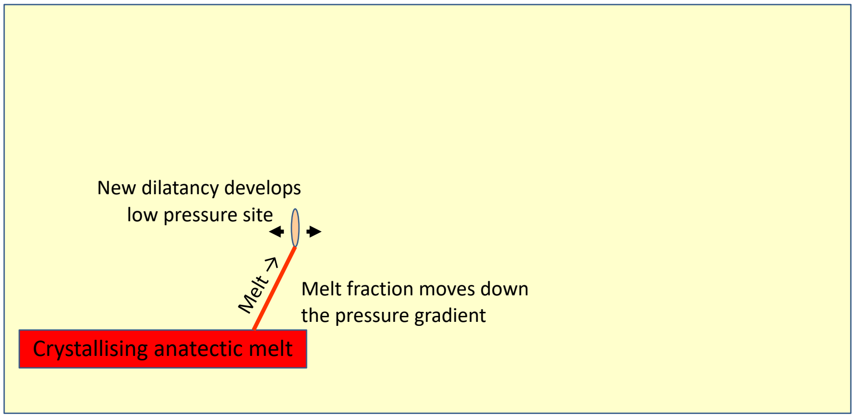
An explanation: segregation during crystallisation of melt

What controls what we see in leucosomes is not so much the prograde stage, but the cooling of migmatites. Most deep regional migmatites cool very slowly and are above the melt solidus temperature (~650ºC) for ~30 My, during this time the melt they contain is slowly crystallising. So there is a low viscosity, low density melt with high viscosity dense crystals; these can be separated from one another.



An explanation: segregation during crystallisation of melt

What controls what we see in leucosomes is not so much the prograde stage, but the cooling of migmatites. Most deep regional migmatites cool very slowly and are above the melt solidus temperature (~650ºC) for ~30 My, during this time the melt they contain is slowly crystallising. So there is a low viscosity, low density melt with high viscosity dense crystals; these can be separated from one another.



New dilatancy develops low pressure site

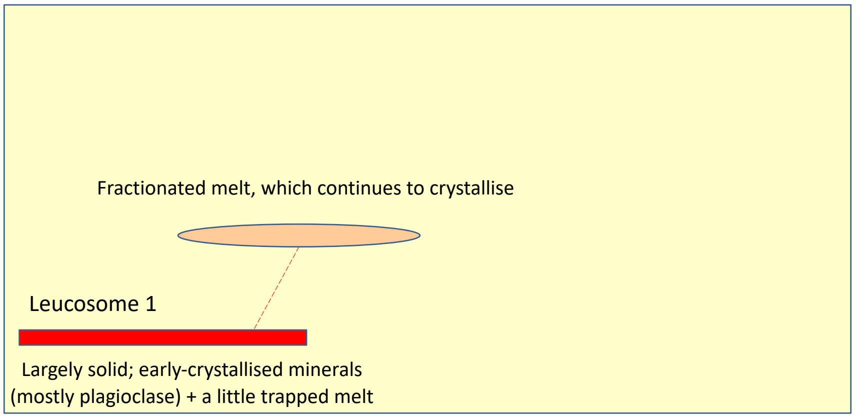
Melt →

Melt fraction moves down the pressure gradient

Crystallising anatectic melt

An explanation: segregation during crystallisation of melt

What controls what we see in leucosomes is not so much the prograde stage, but the cooling of migmatites. Most deep regional migmatites cool very slowly and are above the melt solidus temperature (~650ºC) for ~30 My, during this time the melt they contain is slowly crystallising. So there is a low viscosity, low density melt with high viscosity dense crystals; these can be separated from one another.



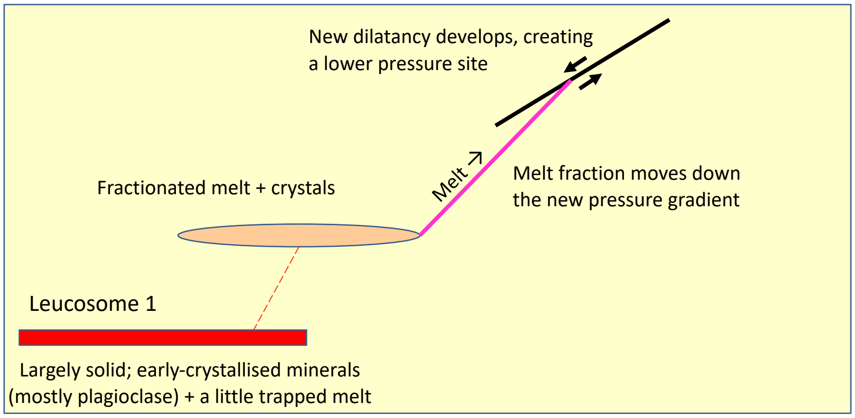
Fractionated melt, which continues to crystallise

Leucosome 1

Largely solid; early-crystallised minerals (mostly plagioclase) + a little trapped melt

An explanation: segregation during crystallisation of melt

What controls what we see in leucosomes is not so much the prograde stage, but the cooling of migmatites. Most deep regional migmatites cool very slowly and are above the melt solidus temperature (~650ºC) for ~30 My, during this time the melt they contain is slowly crystallising. So there is a low viscosity low density melt with high viscosity dense crystals; these can be separated from one another.



New dilatancy develops, creating a lower pressure site

Melt ↗

Melt fraction moves down the new pressure gradient

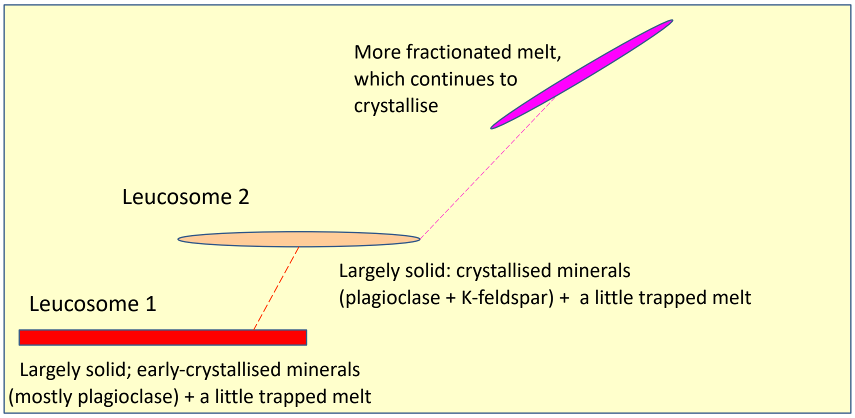
Fractionated melt + crystals

Leucosome 1

Largely solid; early-crystallised minerals (mostly plagioclase) + a little trapped melt

An explanation: segregation during crystallisation of melt

What controls what we see in leucosomes is not so much the prograde stage, but the cooling of migmatites. Most deep regional migmatites cool very slowly and are above the melt solidus temperature (~650ºC) for ~30 My, during this time the melt they contain is slowly crystallising. So there is a low viscosity low density melt with high viscosity dense crystals; these can be separated from one another.



More fractionated melt, which continues to crystallise

Leucosome 2

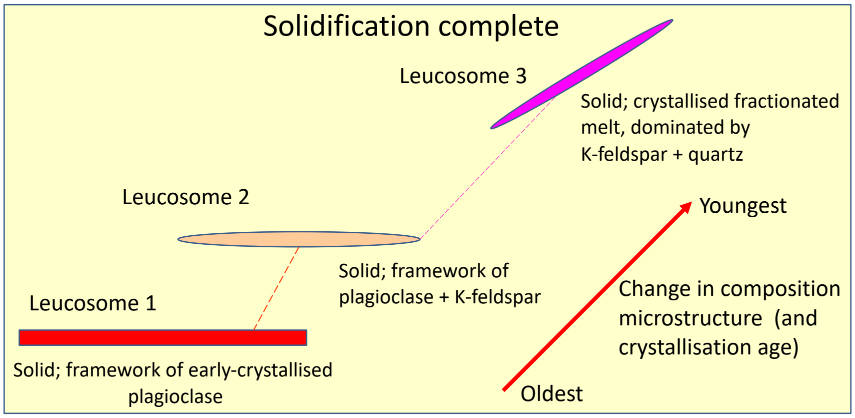
Largely solid: crystallised minerals (plagioclase + K-feldspar) + a little trapped melt

Leucosome 1

Largely solid; early-crystallised minerals (mostly plagioclase) + a little trapped melt

An explanation: segregation during crystallisation of melt

What controls what we see in leucosomes is not so much the prograde stage, but the cooling of migmatites. Most deep regional migmatites cool very slowly and are above the melt solidus temperature (~650ºC) for ~30 My, during this time the melt they contain is slowly crystallising. So there is a low viscosity, low density melt with high viscosity dense crystals; these can be separated from one another.



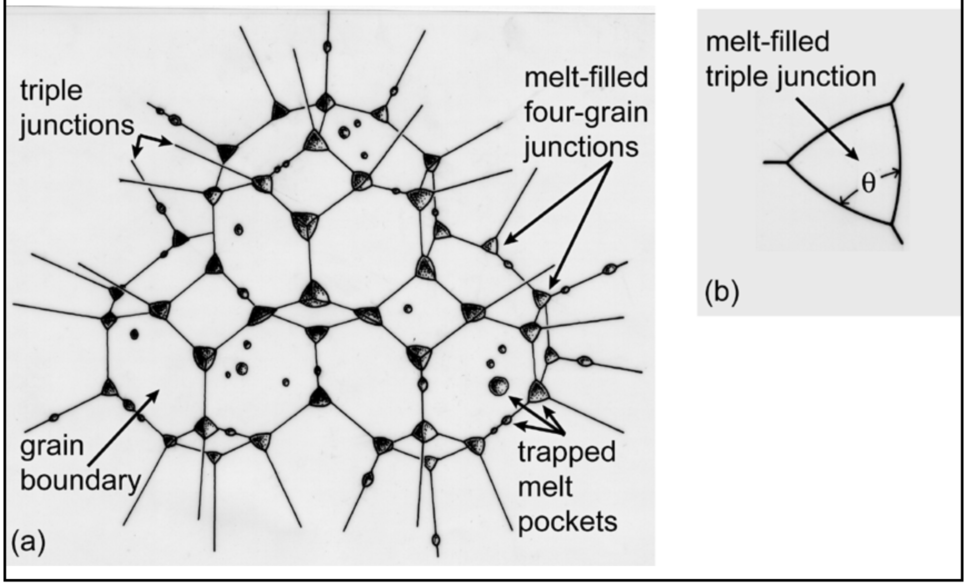
CONCLUSIONS

- Microstructure and compositions of leucosomes are powerful tools for understanding the relationships and processes that occur in migmatites as they cool and solidify.
- But you need to know which part of a migmatite has been sampled; e.g. to demonstrate melting you need the residuum, not the leucosome.
- If you are interested in dating; be aware that leucosomes can have many different morphologies and all come from the same melting event.

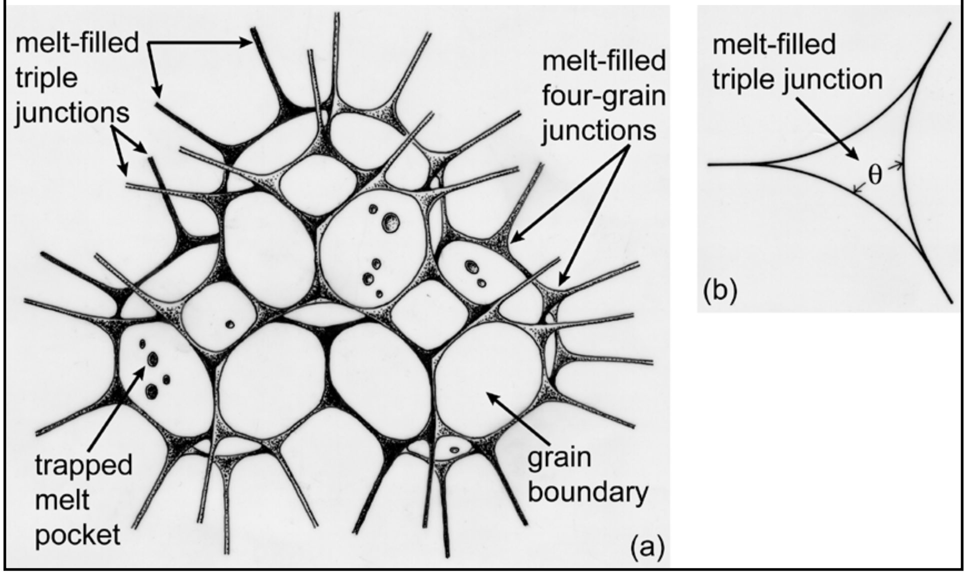
Texturas

- Existem microestruturas que indicam:
  - fusão (auréolas de contato – texturas raras)
  - cristalização de líquido residual (resíduo)
  - cristalização do líquido anatético (leucossoma)
  - recristalização
  - fases peritéticas
  - reações de substituição de fases peritéticas

Início da fusão e o ângulo diedral

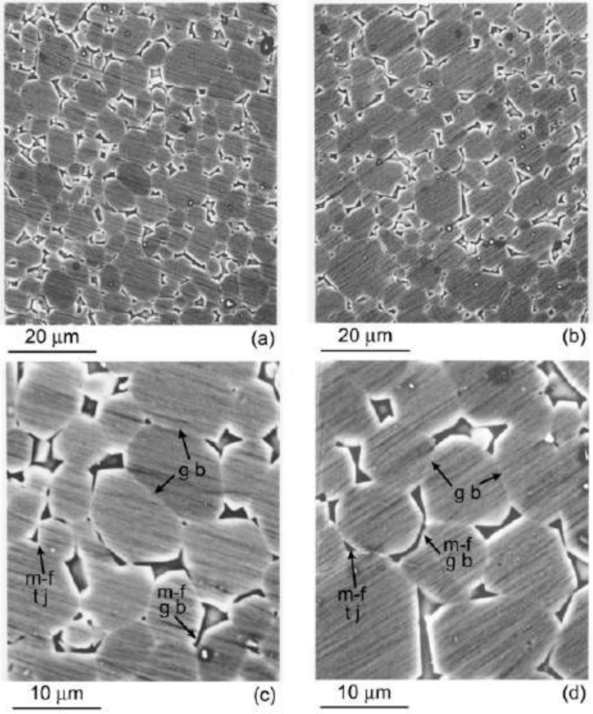


Progressão da fusão e o ângulo diedral

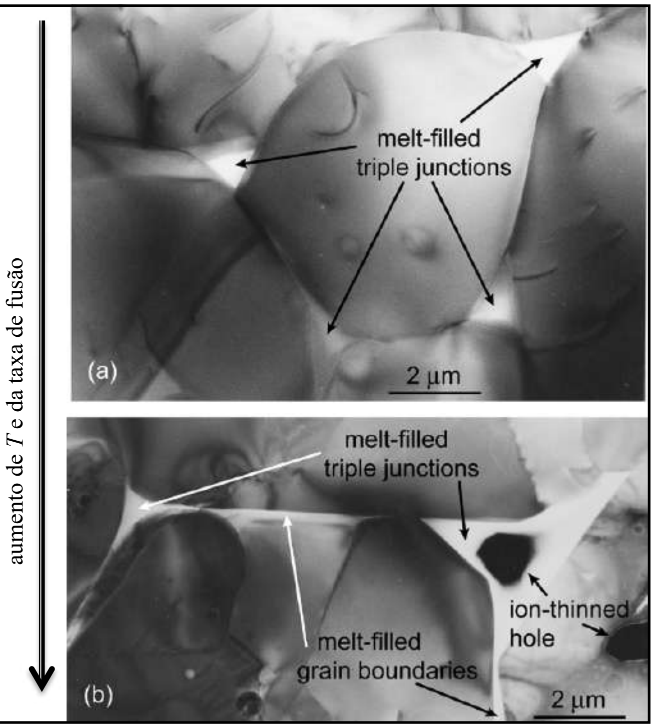


Experimentos de fusão

- Notar forma arredondada dos grãos dissolvidos
- Forma dos instertícios entre os grãos dissolvidos



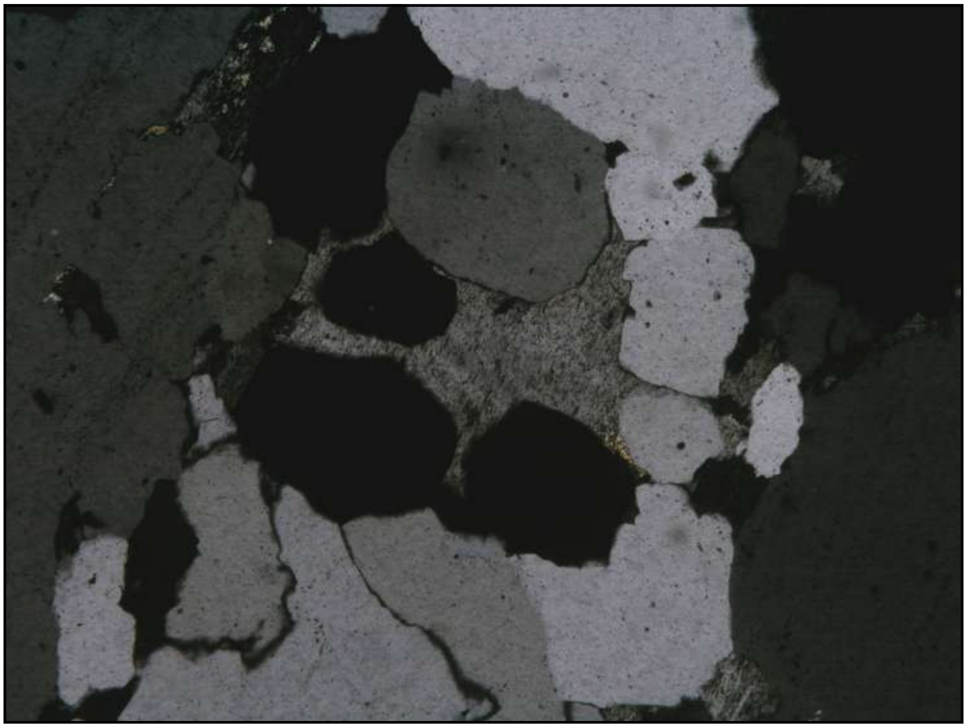
Cristaliazação
de líquido
residual nas
junções
tríplices



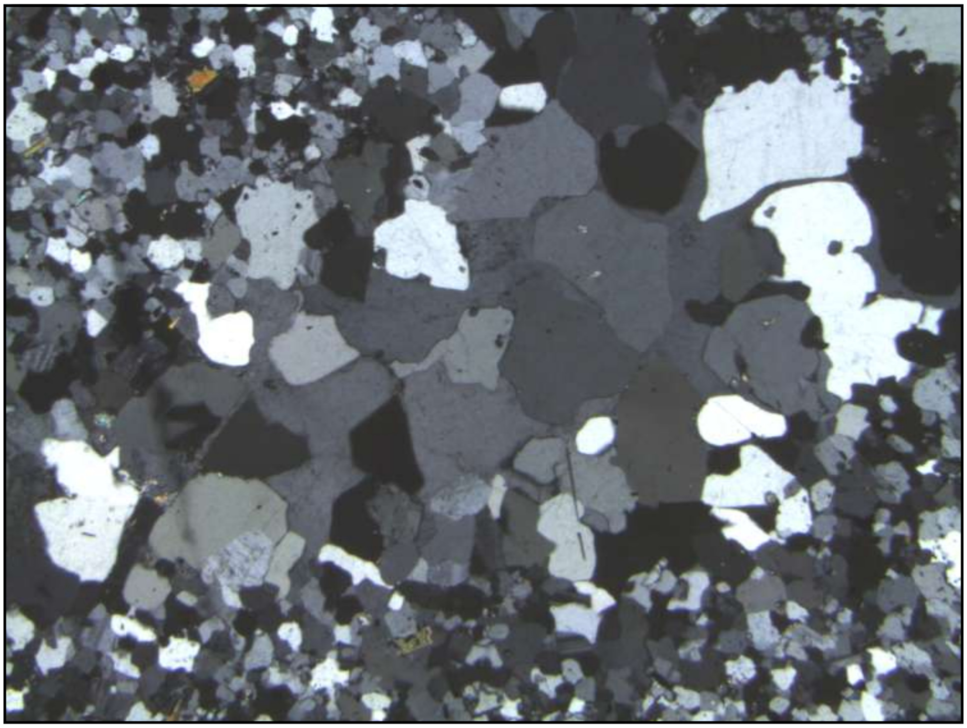
Texturas de fusão parcial

- As texturas de fusão são raras
- Ocorrem em auréolas de contato
- São facilmente destruídas pela deformação e recristalização
- e com o metamorfismo regional?
  - envolve fusão, segregação, deformação
  - formação de migmatitos

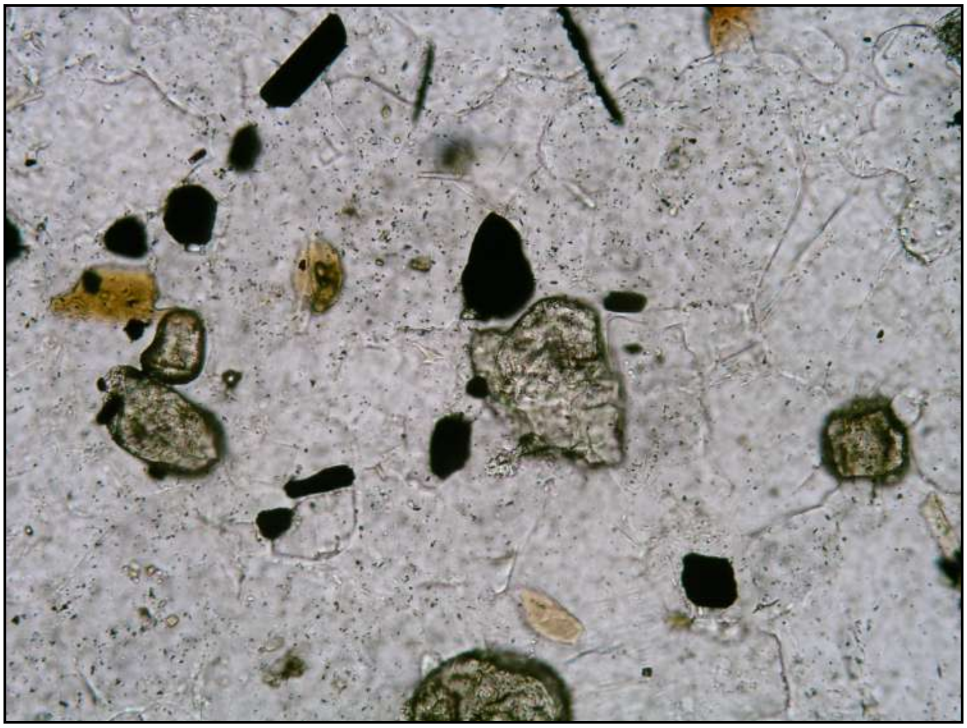
75



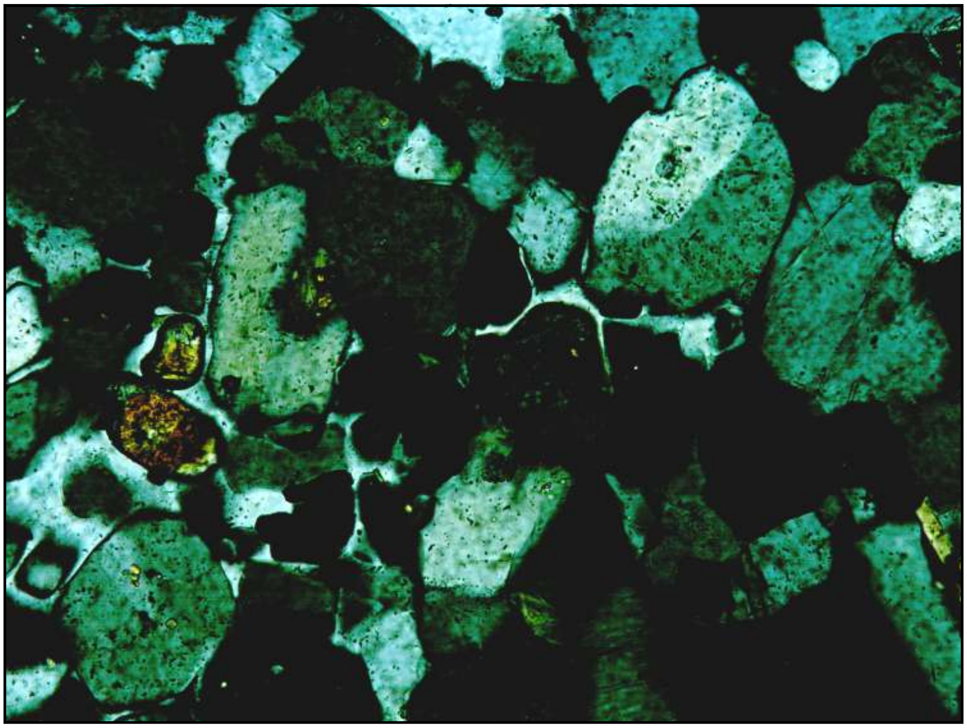
76



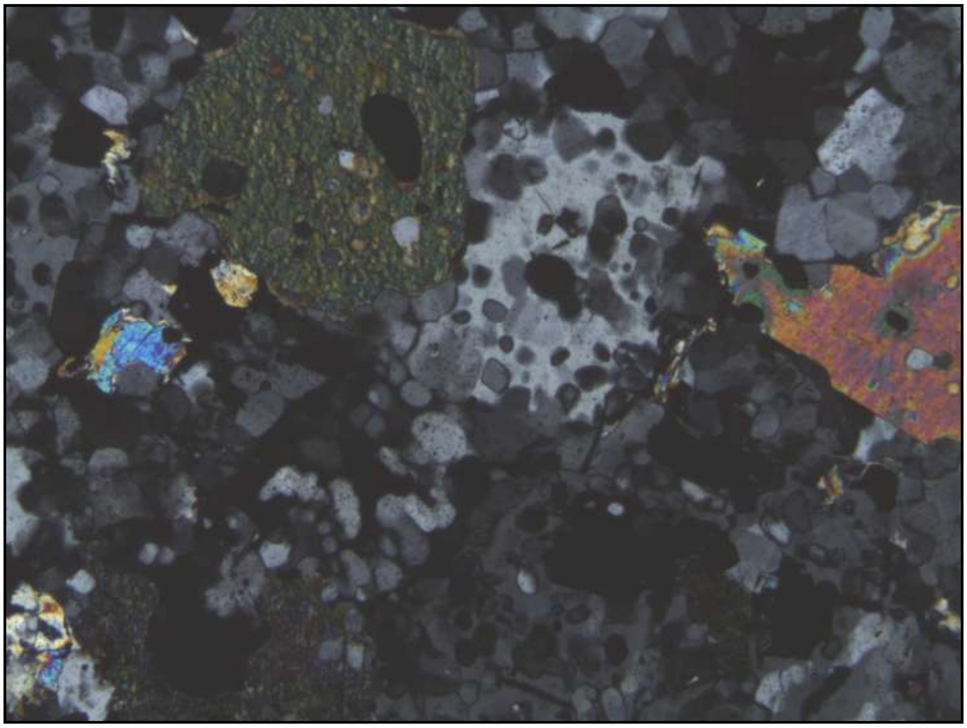
77



78



79

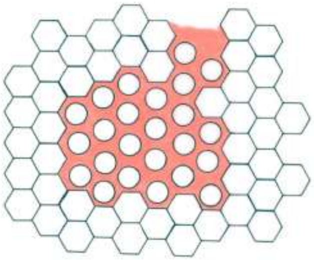


80

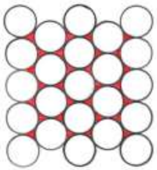
Por que o ângulo diedral é importante?

1° LIMITE – quando uma rede de líquido é gerada pode ocorrer segregação do fundido 5-7% fundido - $\theta < 30°$
transição da conectividade de fundido

começo da fusão
T ~700 °C – $\theta > 60°$



T >800 °C

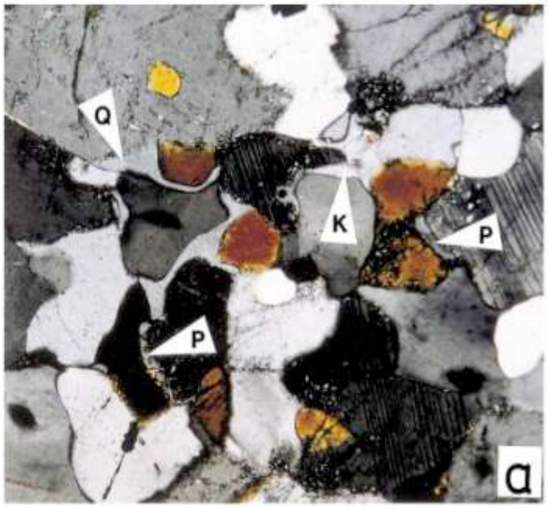


Até uns 23% de fusão, ainda ocorre contato físico entre as bordas dos grãos

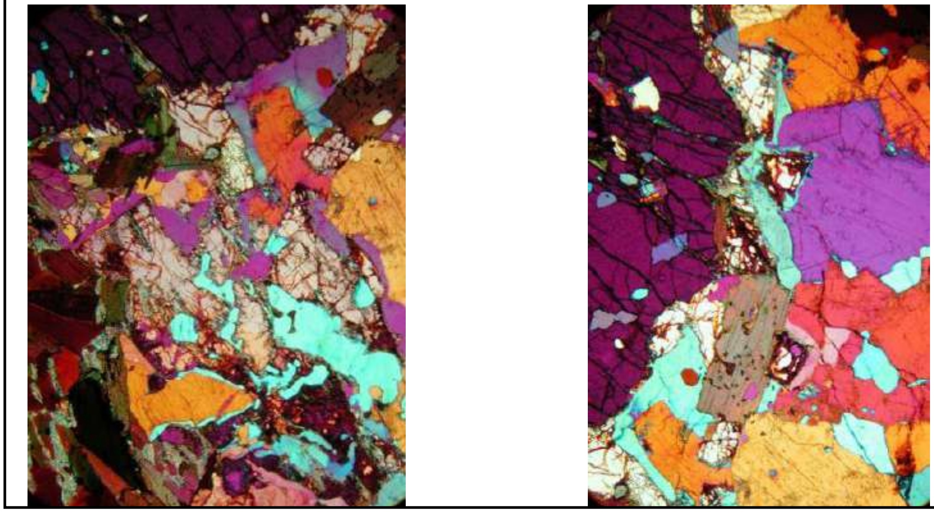
2° LIMITE – acima de 23% de fusão (valor maior quando ocorre maior proporção de minerais placóides), os grãos perdem o contato e a rocha pode fluir – **transição sólido para líquido**

Cristalização de líquido residual dentro do resíduo (neossoma não segregado)

- Comumente formada por filmes de quartzo e ou feldspatos cristalizados entre as fases residuais e com continuidade óptica



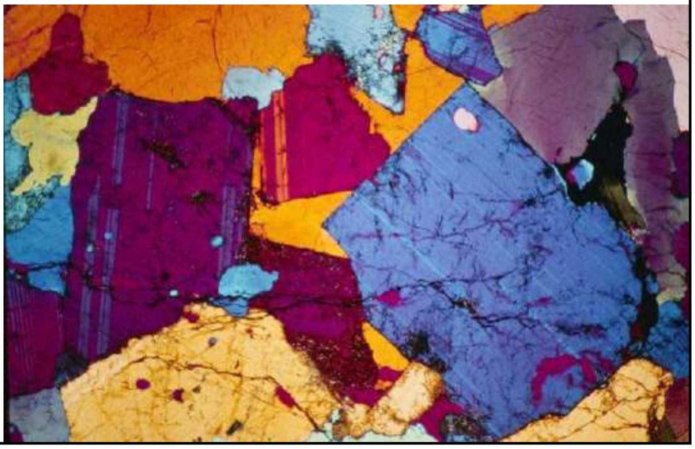
- Notar:
  - quartzo intersticial com orientação cristalográfica contínua



Leucossoma

- Cristalização do leucossoma produz texturas ígneas que podem ser subsequentemente modificadas por recristalização

- Notar:
  - plagioclásio euhedral
  - quartzo intersticial



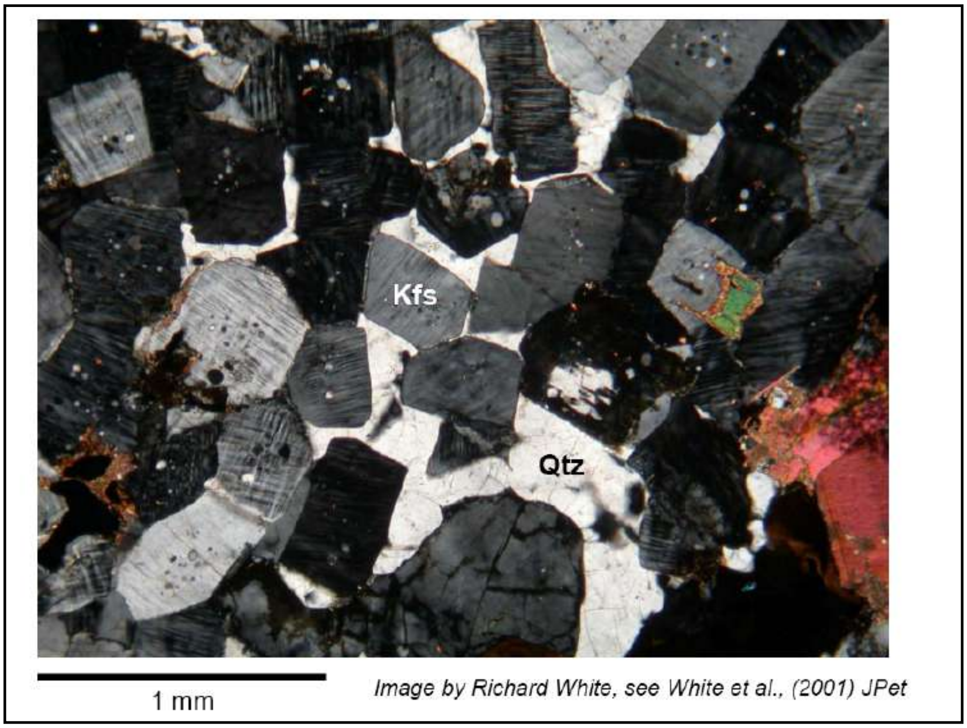
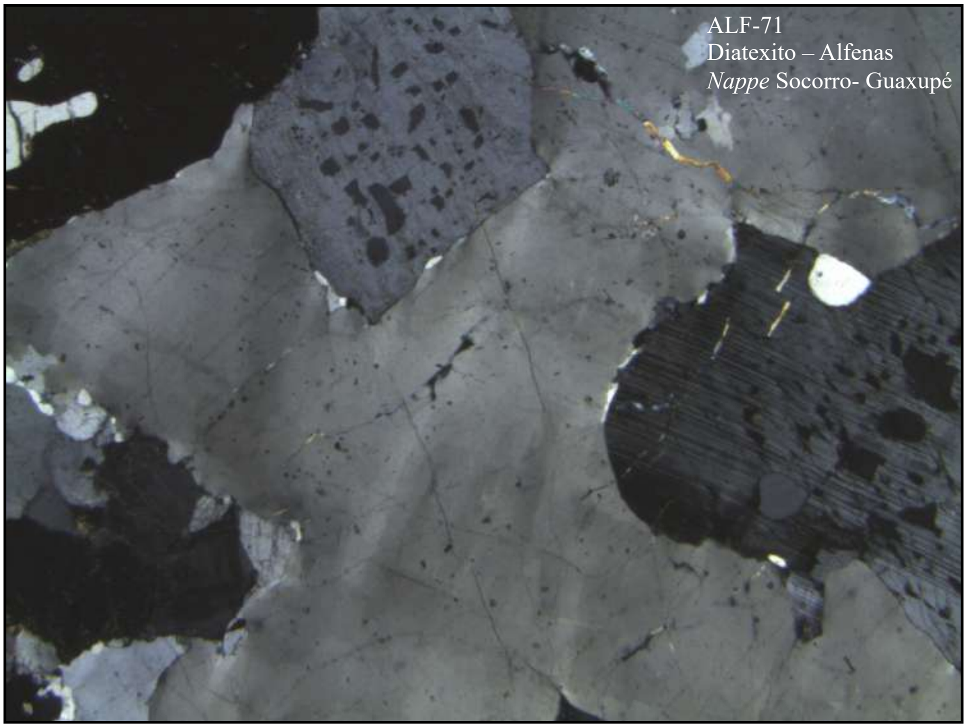
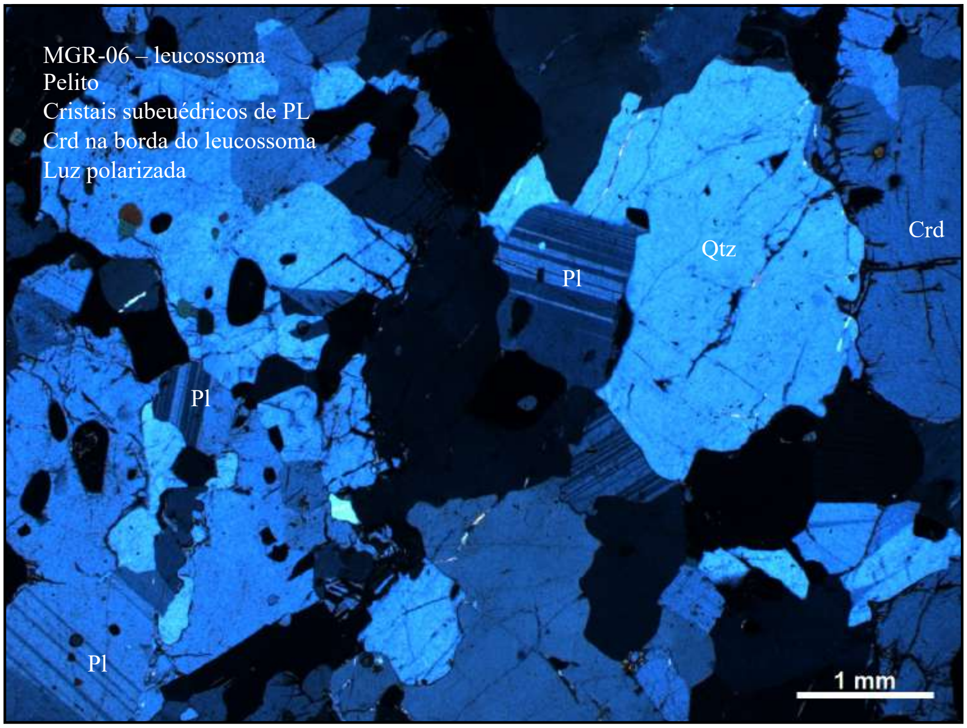


Image by Richard White, see White et al., (2001) JPet

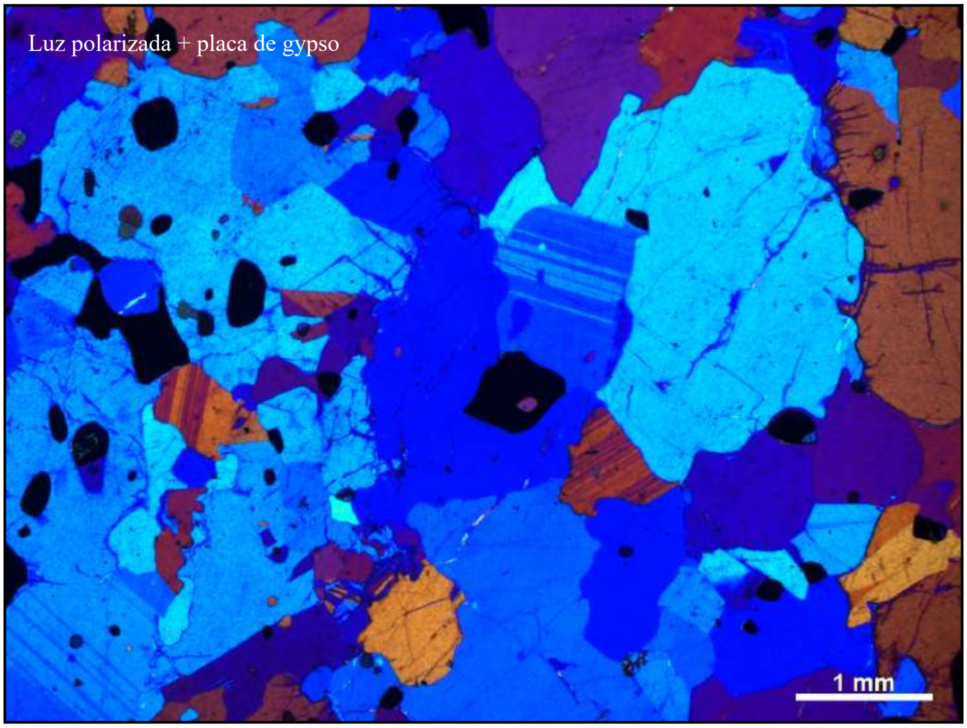
85


ALF-71
Diatexito – Alfenas
Nappe Socorro- Guaxupé

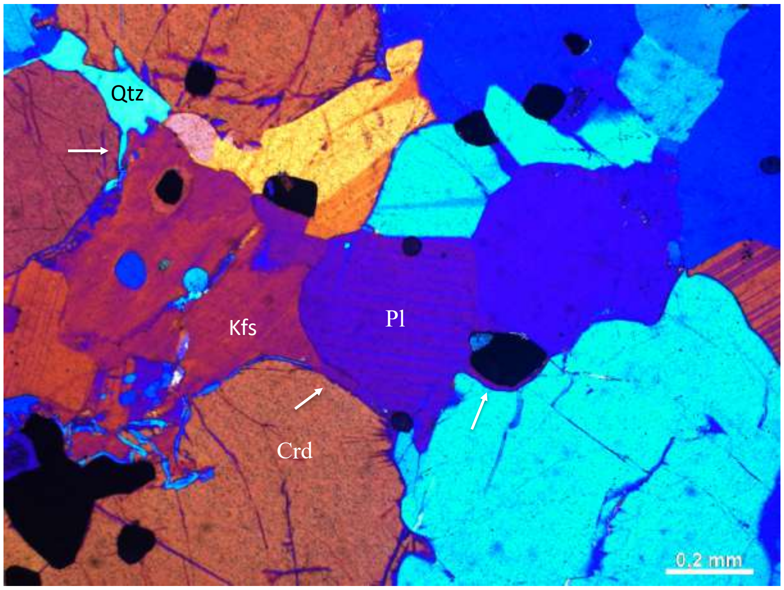
86



MGR-06 – leucossoma
Pelito
Cristais subeuédricos de PL
Crd na borda do leucossoma
Luz polarizada

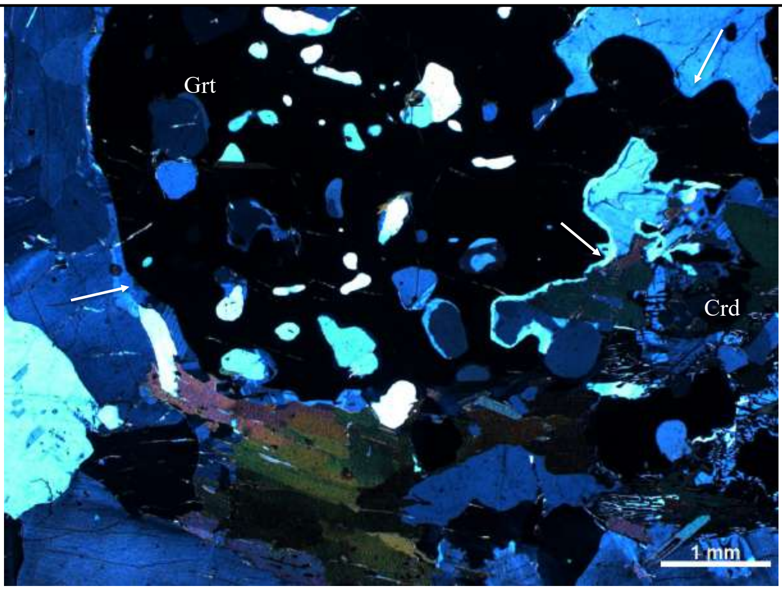


Luz polarizada + placa de gypso



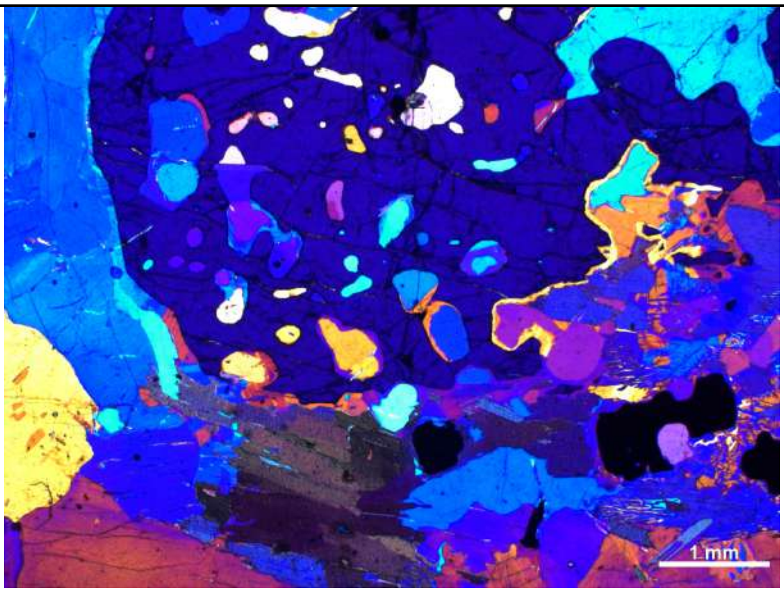
MGR-06 – resíduo de pelito
Crd na borda do leucossoma
Luz polarizada + placa de gypso

Notar as terminações em cunha e reentrencias do Pl, Kfs e do Qtz – isso é cristalização de fundido!



MGR-06 – resíduo de pelito
Crd na borda do leucossoma
Luz polarizada

Notar os filmes de Pl, Kfs e do Qtz em torno da Grt e Crd - isso é cristalização de fundido!



MGR-06 – resíduo de pelito
Crd na borda do leucossoma
Luz polarizada

Notar os filmes de Pl, Kfs e do Qtz em torno da Grt e Crd - isso é cristalização de fundido!

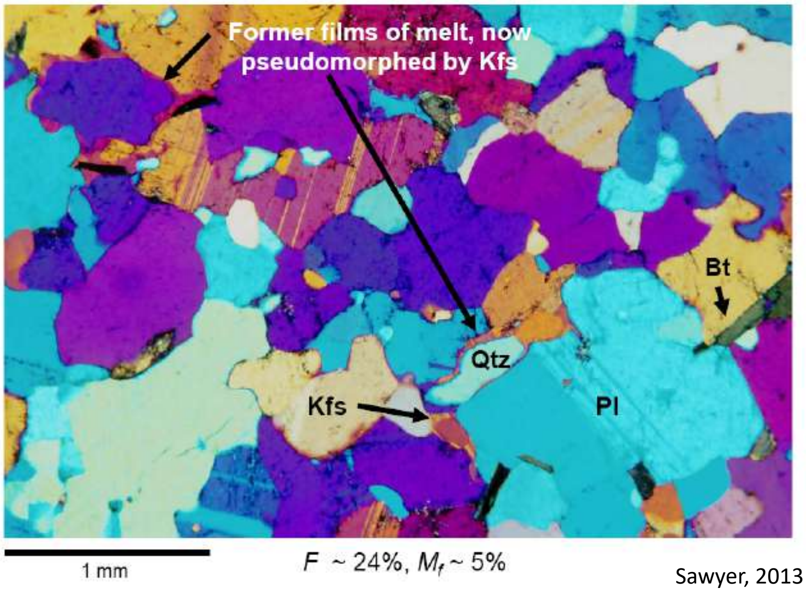
Recristalização

- Texturas formadas pela cristalização de líquido aprisionado (intersticial) podem ser recristalizadas pela deformação
  - ângulos diedrais menores que 30^o são substituídos por 120^o

STRONGLY MELT-DEPLETED MIGMATITES

Leucotrondhjemite protolith; H_2O added melting, Opatica Subprovince

quartz + plagioclase + K-feldspar + H_2O = melt



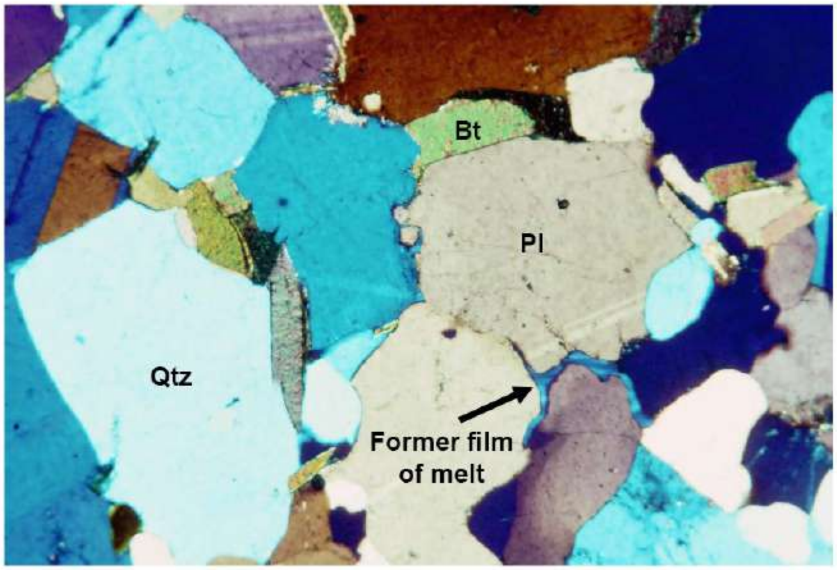
F ~ 24%, M_f ~ 5%

Sawyer, 2013

STRONGLY MELT-DEPLETED MIGMATITES

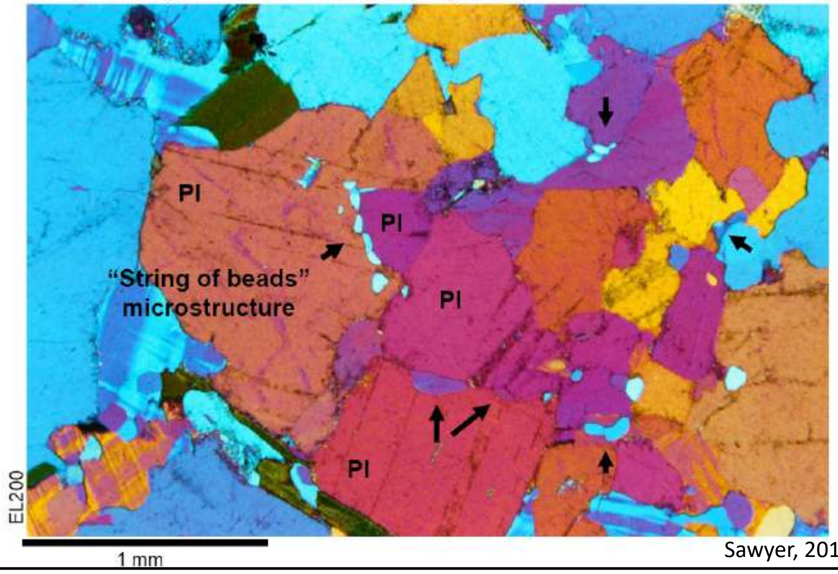
Leucotrondhjemite protolith; H_2O added melting, Opatica Subprovince

quartz + plagioclase + K-feldspar + H_2O = melt



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

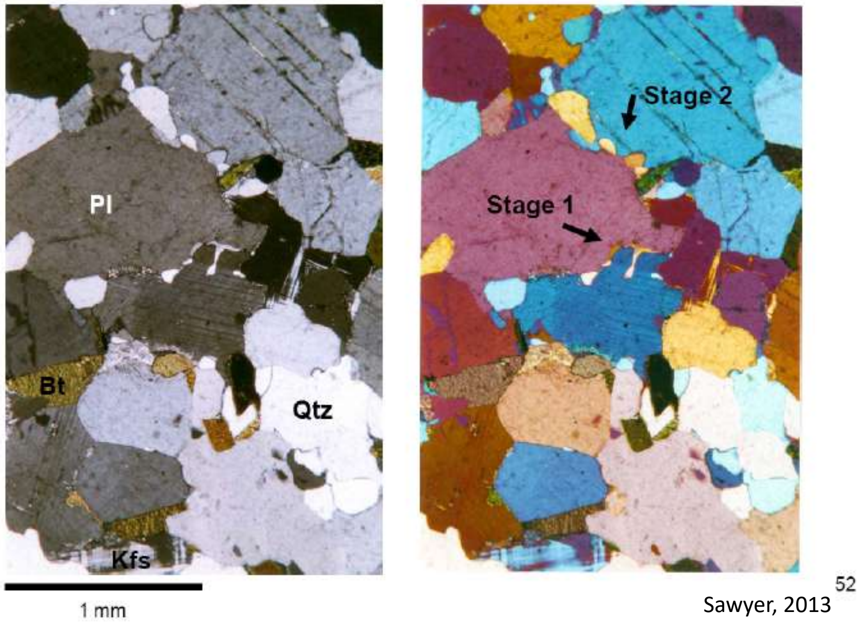
The films of melt on the grain boundaries have "necked down" to form droplets that forms a "string of beads" microstructure



Sawyer, 2013

SOLID-STATE MODIFICATION OF STRING OF BEADS MICROSTRUCTURE

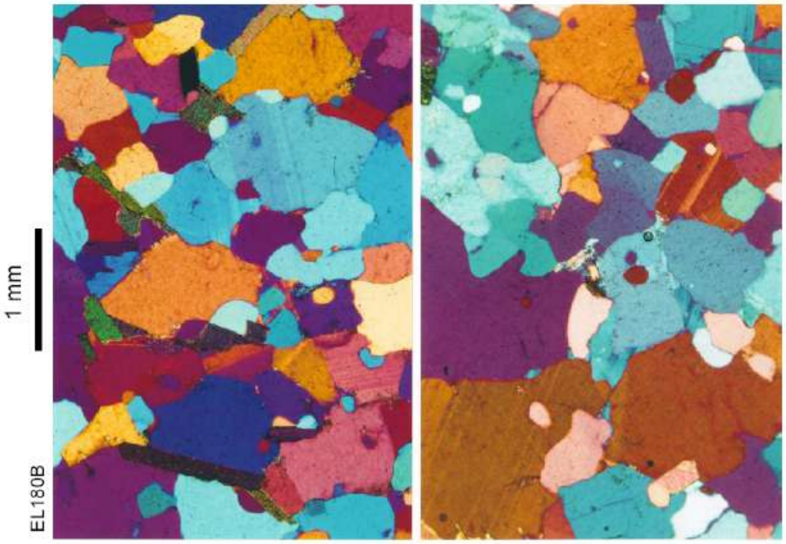
Development of higher dihedral angles (θ ~120°)



Sawyer, 2013

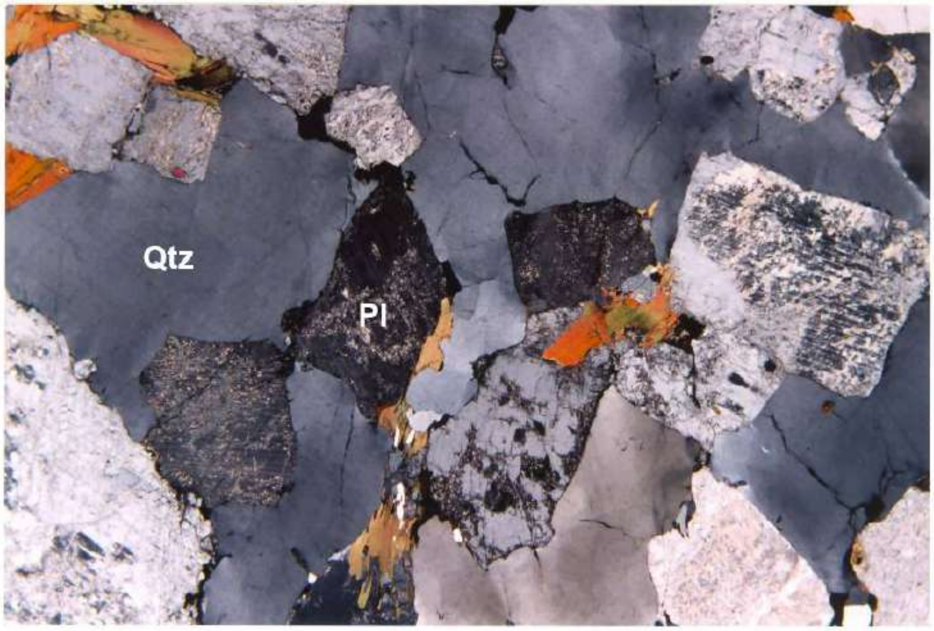
MICROSTRUCTURAL MODIFICATION IN THE SOLID STATE

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

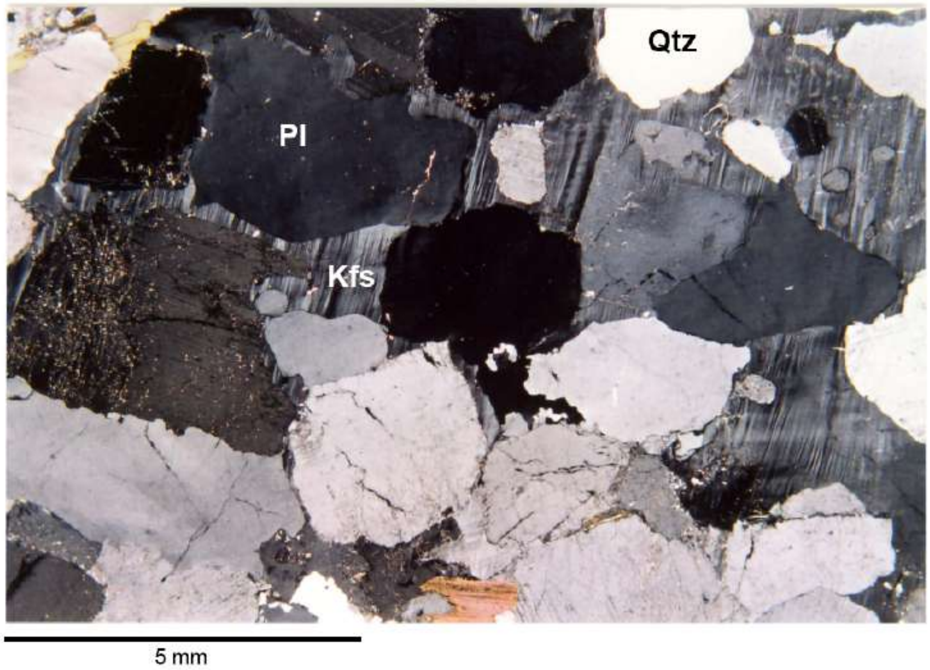


54

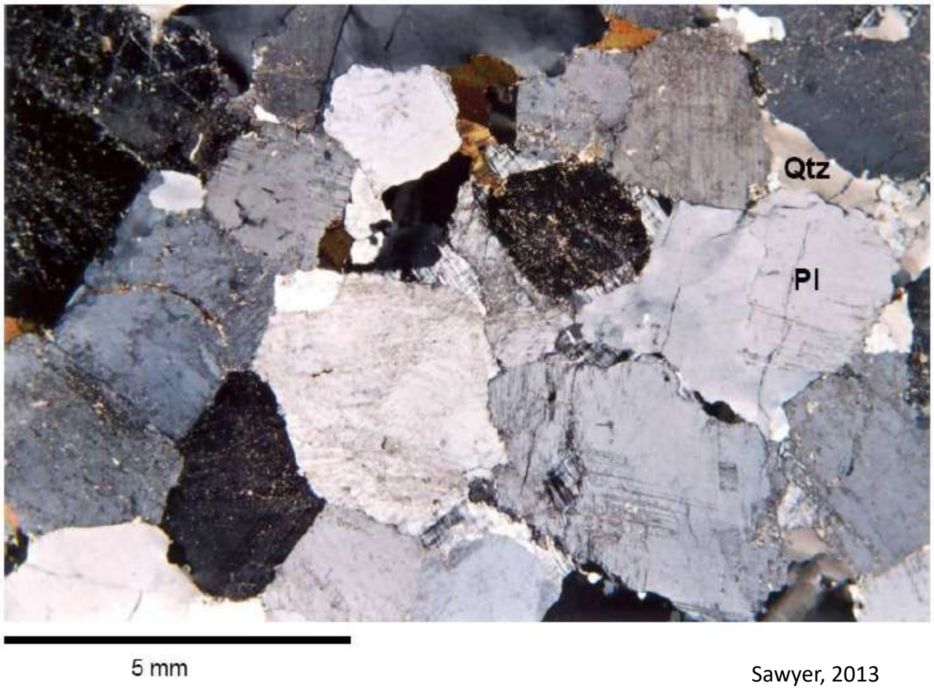
Sawyer, 2013



Microestruturas em diatexitos



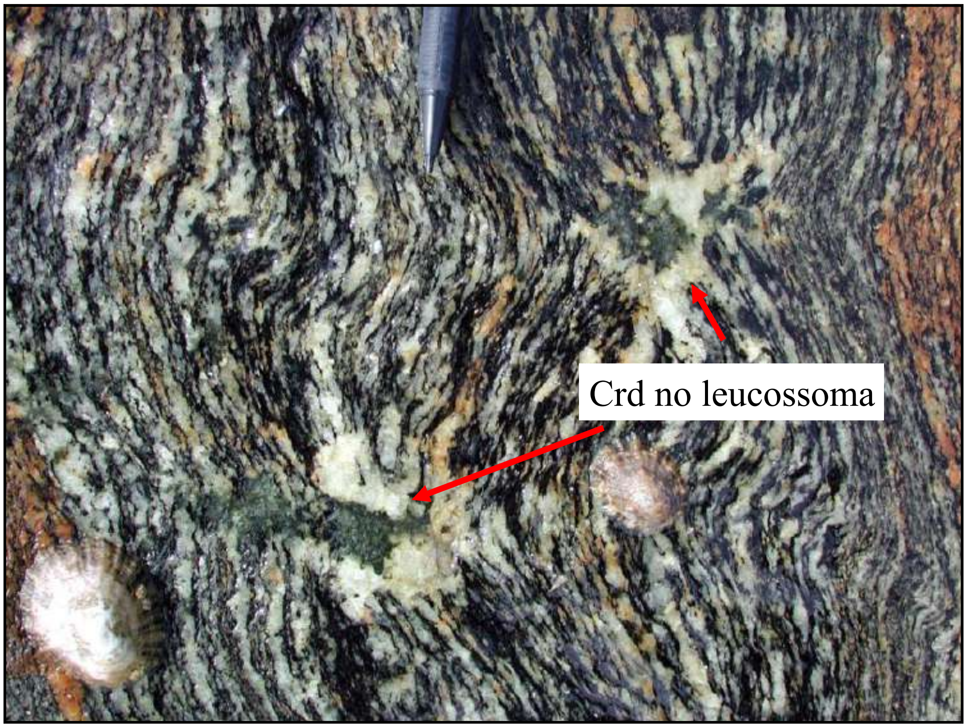
Sawyer, 2013



Sawyer, 2013

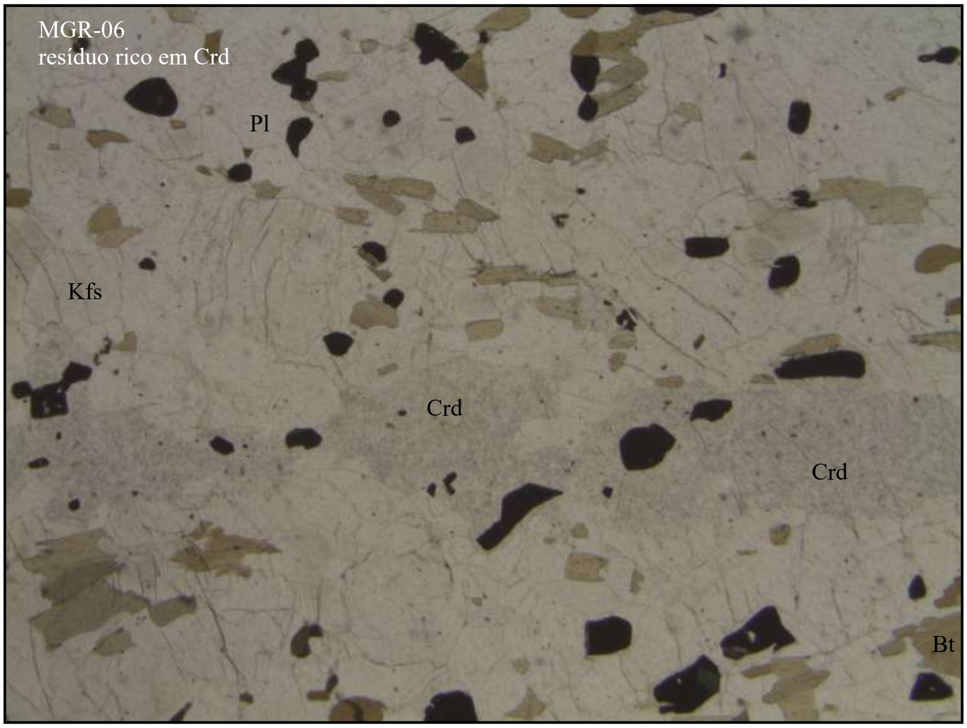
Granada peritética no leucossoma

101

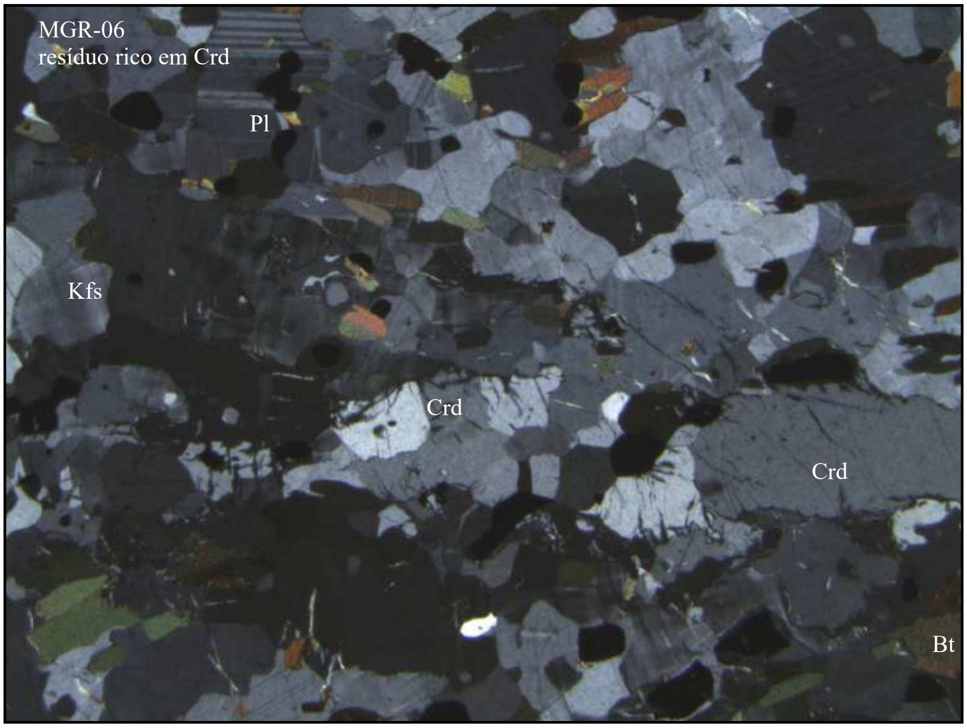


Crd no leucossoma

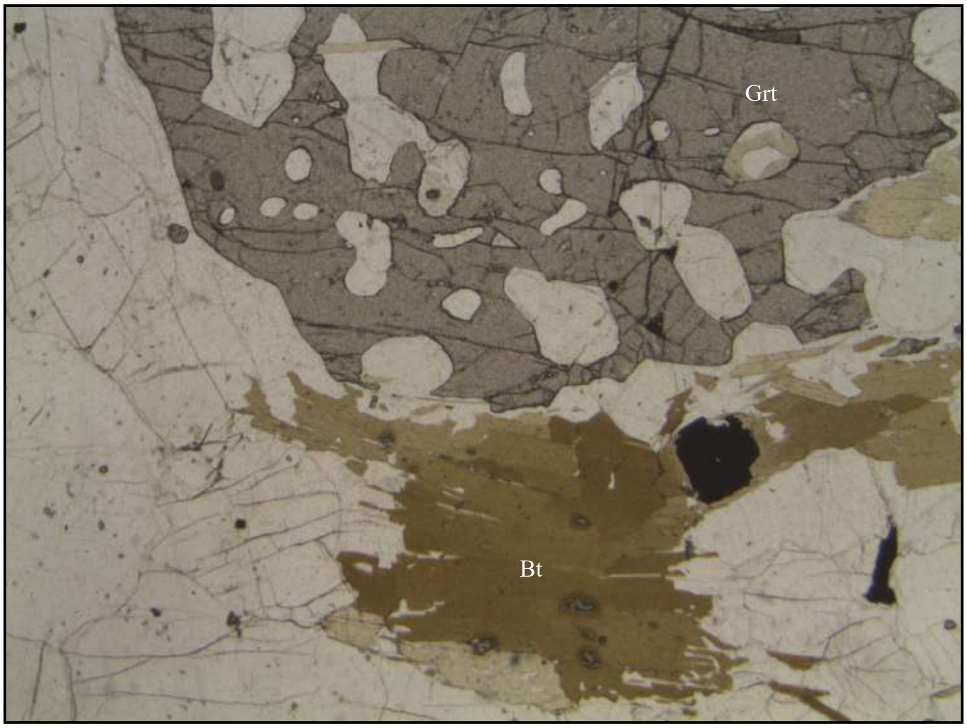
102


MGR-06
resíduo rico em Crd
Pl
Kfs
Crd
Crd
Bt

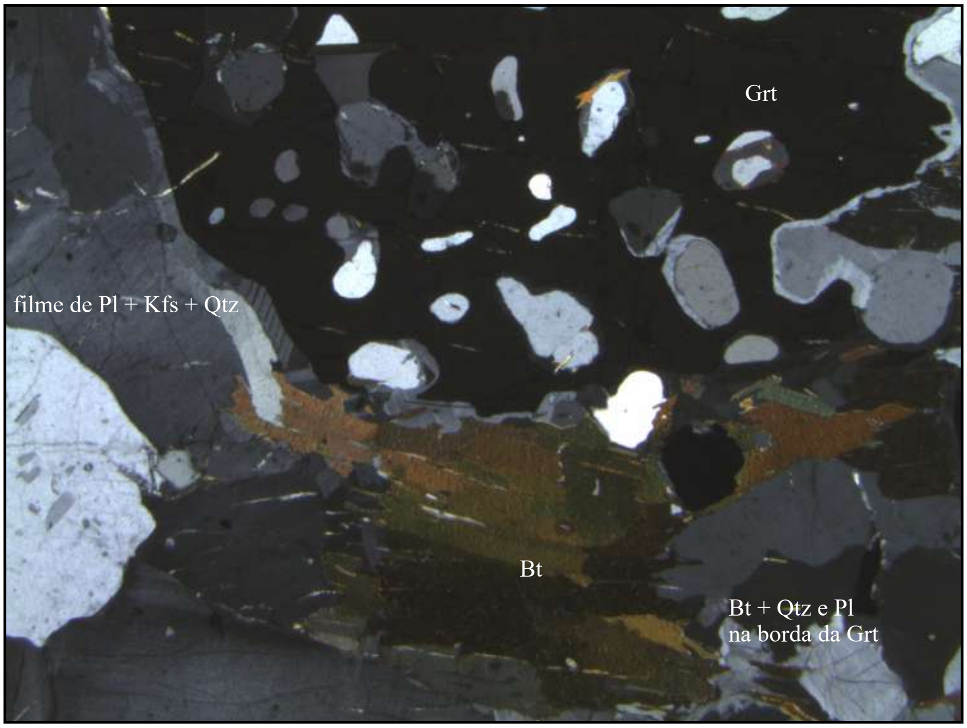
103


MGR-06
resíduo rico em Crd
Pl
Kfs
Crd
Crd
Bt

104



105

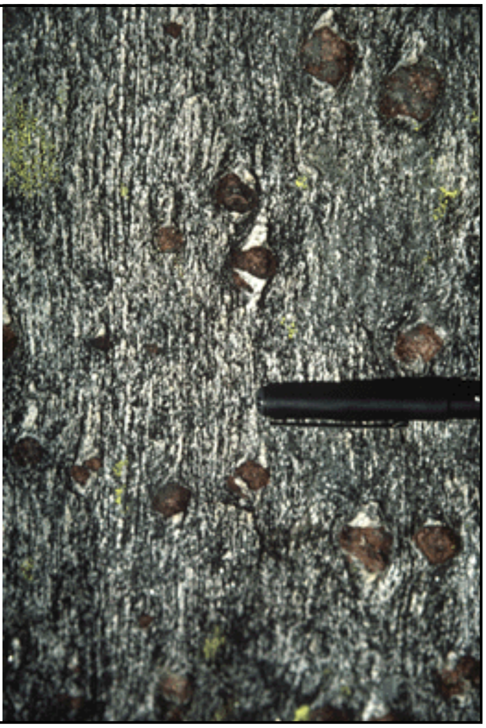


106

E quando não ocorre retro-reação?

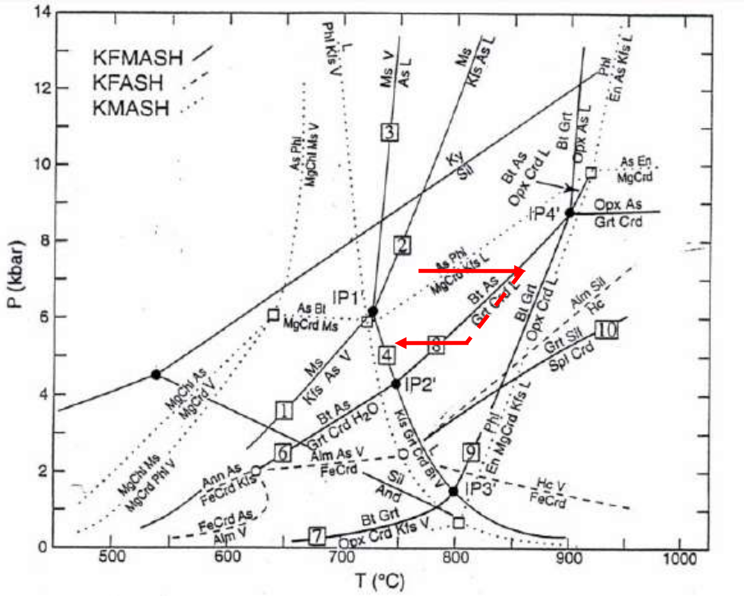
- Isso implica em perda de fundido (ou seja, a proporção fundido gerado/fases peritéticas mudou)

- $a\mathrm{Bt} + b\mathrm{Qtz} \rightarrow c\mathrm{Kfs} + d\mathrm{Grt} + e\mathrm{L}$

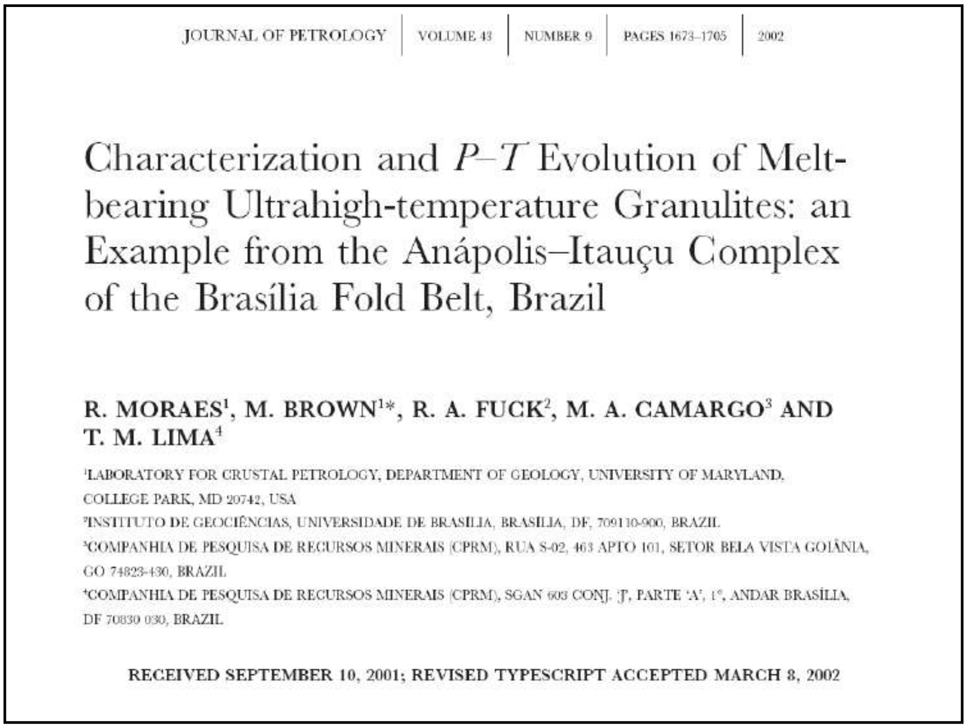


107

Retro reação (*back-reaction*)



108



JOURNAL OF PETROLOGY | VOLUME 43 | NUMBER 9 | PAGES 1673–1705 | 2002

Characterization and *P–T* Evolution of Melt-bearing Ultrahigh-temperature Granulites: an Example from the Anápolis–Itauçu Complex of the Brasília Fold Belt, Brazil

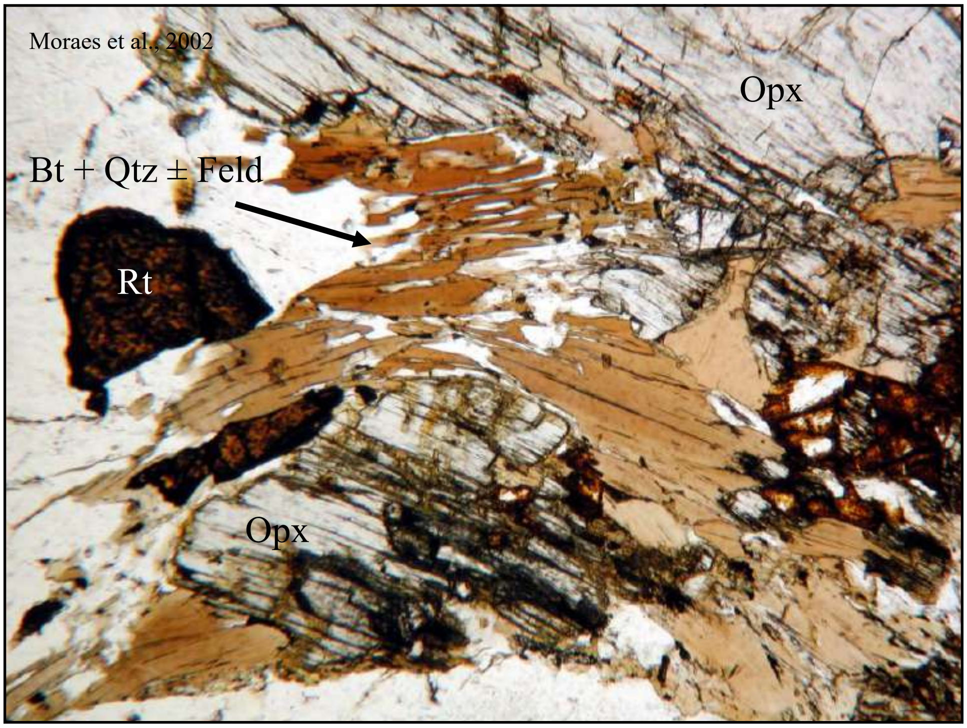
R. MORAES[1], M. BROWN[1]*, R. A. FUCK[2], M. A. CAMARGO[3] AND T. M. LIMA[4]

[1] LABORATORY FOR CRUSTAL PETROLOGY, DEPARTMENT OF GEOLOGY, UNIVERSITY OF MARYLAND, COLLEGE PARK, MD 20742, USA
[2] INSTITUTO DE GEOCIÊNCIAS, UNIVERSIDADE DE BRASÍLIA, BRASÍLIA, DF, 709110-900, BRAZIL
[3] COMPANHIA DE PESQUISA DE RECURSOS MINERAIS (CPRM), RUA S-02, 463 APTO 101, SETOR BELA VISTA GOIÂNIA, GO 74823-430, BRAZIL
[4] COMPANHIA DE PESQUISA DE RECURSOS MINERAIS (CPRM), SGAN 603 CONJ. 'J', PARTE 'A', 1°, ANDAR BRASÍLIA, DF 70830 030, BRAZIL

RECEIVED SEPTEMBER 10, 2001; REVISED TYPESCRIPT ACCEPTED MARCH 8, 2002

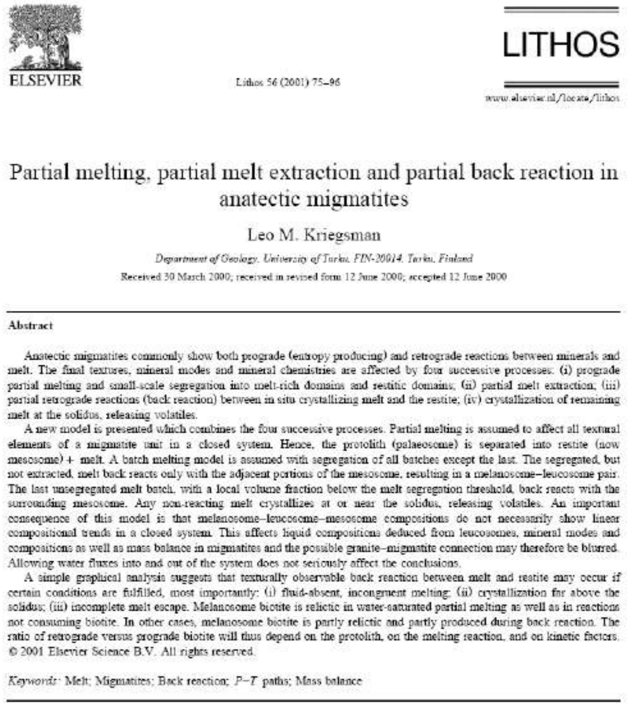
Moraes et al., 2002


Moraes et al., 2002


Moraes et al., 2002

Texturas - conclusão

- A textura do migmatito:
  - leucossoma – textura ígnea + fases petitéticas
    - pode ser alterada por deformação tardia com recristalização
  - resíduo – textura metamórfica + cristalização do líquido aprisionado
    - pode mudar por rescristalização + deformação
    - colar de pérolas, grãos recristalizados, contatos 120 °
    - textura de consumo parcial das fases peritéticas por reação com o líquido
  - diatexito – predomina textura ígnea + fases peritéticas
    - pode mudar por rescristalização + deformação, gerando grãos recristalizados e contatos de 120 °



ELSEVIER

Lithos 56 (2001) 75–96

LITHOS

www.elsevier.nl/locate/lithos

Partial melting, partial melt extraction and partial back reaction in anatectic migmatites

Leo M. Kriegsman

Department of Geology, University of Turku, FIN-20014, Turku, Finland

Received 30 March 2000; received in revised form 12 June 2000; accepted 12 June 2000

Abstract

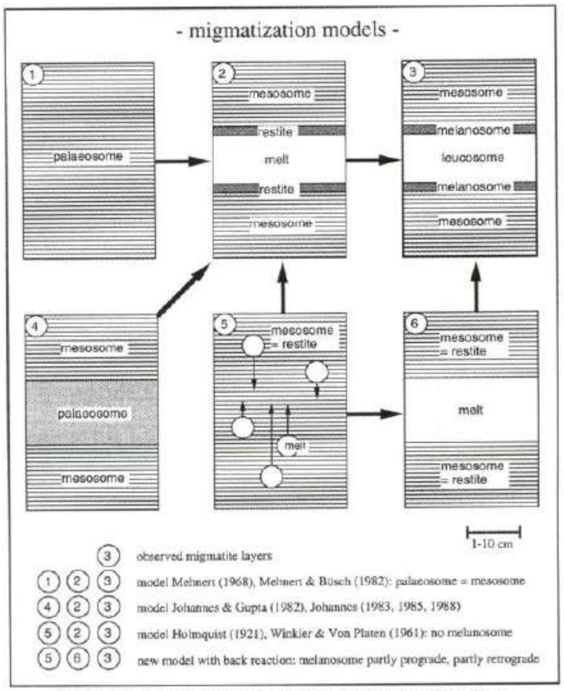
Anatectic migmatites commonly show both prograde (entropy producing) and retrograde reactions between minerals and melt. The final textures, mineral modes and mineral chemistries are affected by four successive processes: (i) prograde partial melting and small-scale segregation into melt-rich domains and restitic domains; (ii) partial melt extraction; (iii) partial retrograde reactions (back reaction) between in situ crystallizing melt and the restite; (iv) crystallization of remaining melt at the solidus, releasing volatiles.

A new model is presented which combines the four successive processes. Partial melting is assumed to affect all textural elements of a migmatite unit in a closed system. Hence, the protolith (palaeosome) is separated into restite (now mesosome) + melt. A batch melting model is assumed with segregation of all batches except the last. The segregated, but not extracted, melt back reacts only with the adjacent portions of the mesosome, resulting in a melanosome–leucosome pair. The last unsegregated melt batch, with a local volume fraction below the melt segregation threshold, back reacts with the surrounding mesosome. Any non-reacting melt crystallizes at or near the solidus, releasing volatiles. An important consequence of this model is that melanosome–leucosome–mesosome compositions do not necessarily show linear compositional trends in a closed system. This affects liquid compositions deduced from leucosomes, mineral modes and compositions as well as mass balance in migmatites and the possible granite–migmatite connection may therefore be blurred. Allowing water fluxes into and out of the system does not seriously affect the conclusions.

A simple graphical analysis suggests that texturally observable back reaction between melt and restite may occur if certain conditions are fulfilled, most importantly: (i) fluid-absent, incongruent melting; (ii) crystallization far above the solidus; (iii) incomplete melt escape. Melanosome biotite is relictic in water-saturated partial melting as well as in reactions not consuming biotite. In other cases, melanosome biotite is partly relictic and partly produced during back reaction. The ratio of retrograde versus prograde biotite will thus depend on the protolith, on the melting reaction, and on kinetic factors.

Keywords: Melt; Migmatites; Back reaction; *P–T* paths; Mass balance

Modelo dinâmico para formação de migmatito



③ observed migmatite layers

① ② ③ model Mehnert (1968), Mehnert & Büsch (1982): palaeosome = mesosome

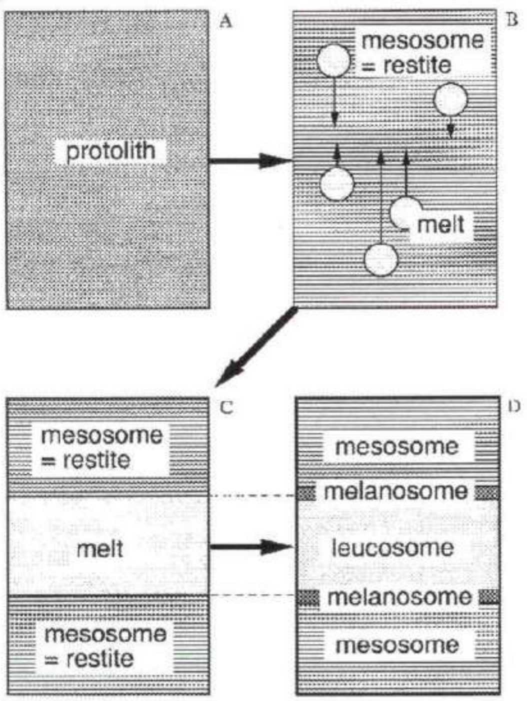
④ ② ③ model Johannes & Gupta (1982), Johannes (1983, 1985, 1988)

⑤ ② ③ model Holmquist (1921), Winkler & Von Platen (1961): no melanosome

⑤ ⑥ ③ new model with back reaction: melanosome partly prograde, partly retrograde

Fig. 4. Schematic representation of published migmatite models and the new model proposed in this paper.

Kriegsman, 2001



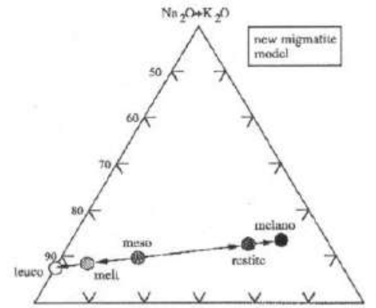


Fig. 7. Same migmatite compositional diagram as Fig. 2, but explained by new model.

Kriegsman, 2001

descrição	leucossoma (neossoma)	melanossoma (neossoma)	resíduo (neossoma)	paleossoma	*selvedge*	mesossoma
Mehnert (1967)	porção leucocrática Qtz + Kfs + Pl	porção melanocrática Bt, Grt, Crd, Hbl, Px	porção da rocha que sobrou da fusão após segregação do fundido	- porção da rocha pouco ou não modificada pela fusão -rocha encaixante - protolito		
Brown (1973)	porção leucocrática Qtz + Kfs + Pl	porção melanocrática Bt, Grt, Crd, Hbl, Px	porção da rocha que sobrou da fusão após segregação do fundido	porção da rocha que sobrou da fusão após segregação do fundido		
Johannes & Gupta (1982)	porção leucocrática Qtz + Kfs + Pl	porção melanocrática Bt, Grt, Crd, Hbl, Px	porção da rocha que sobrou da fusão após segregação do fundido			resíduo **mesocrático** de qualquer rocha bandada
Sawyer (2008)	porção leucocrática Qtz + Kfs + Pl	porção melanocrática Bt, Grt, Crd, Hbl, Px fases peritéticas das reações de fusão	porção da rocha que sobrou da fusão após segregação do fundido	rocha que não fundiu (algo **totalmente** diferente do protolito)	porção máfica que separa duas porções diferentes do migmatito	
Kriegsman (2000)	porção leucocrática Qtz + Kfs + Pl	porção melanocrática Bt, Grt, Crd, Hbl, Px	porção da rocha que sobrou da fusão após segregação do fundido	várias definições	porção máfica tardia (confunde com a definição de melanossoma)	

origem	leucossoma (neossoma)	melanossoma (neossoma)	resíduo (neossoma)	paleossoma	*selvedge*	mesossoma
Mehnert (1967)	cristalização do fundido após segregação	fases residuais da fusão parcial	rocha que sobra após fusão e segregação de fundido	termo mal definido (um enigma), pois a definição muda ao longo livro ~ resíduo do protolito		
Brown (1973)	cristalização do fundido após segregação	fases residuais da fusão parcial	rocha que sobra após fusão e segregação de fundido	resíduo do protolito		
Johannes & Gupta (1982)	cristalização do fundido após segregação	fases residuais da fusão parcial				resíduos mesocráticos de rochas bandadas submetidas à fusão parcial
Sawyer (2008)	cristalização do fundido após segregação com cristalização fracionada ou não	fases residuais (peritéticas) da fusão parcial	rocha que sobra após fusão e segregação de fundido	parte que não fundiu da rocha uma rocha **totalmente** diferente do protolito do migmatito	porção máfica formada por reação entre o fundido e uma porção adjacente, normalmente resíduo, durante o resfriamento	
Kriegsman (2000)	cristalização do fundido após segregação	fases residuais (peritéticas) da fusão parcial	rocha que sobra após fusão e segregação de fundido	várias definições	porção máfica tardia gerada por reação entre fundido e porção adjacente **melanossoma**	

Ashworth J.R. and Brown M. (Eds.) 1990. High-Temperature Metamorphism and Crustal Anatexis. The Mineralogical Society Series. 384 p.

Ashworth, J.R. 1985 Migmatites. Kluwer Academic Publishers, 320 p.

Atherton, M.P. & Gribble, C. D. (Eds.) 1983. Migmatites, melting and metamorphism; Proceedings/ Meeting High grade metamorphism, migmatites and melting of the Geochemical Group of the Mineralogical Society of the University of Glasgow. 326 p.

Mehnert, K.R. 1968 Migmatites and the origin of the granitic rocks. Elsevier Publishing Company, Amsterdam, 393 p.

Sawyer, E. W. 2008. Atlas of Migmatites. Special Publications of The Canadian Mineralogist, Vol. 9. 386pg.

Sawyer, E.W. 2010. Migmatites formed by water-fluxed partial melting of a leucogranodiorite protolith: Microstructures in the residual rocks and source of the fluid. Lithos, 116: 273-286.

Vernon, R. H., Clarke, G. 2008. Principles of Metamorphic Petrology. Cambridge University Press. 446p.