Os extremos do metamorfismo de *T* e *P*

As rochas das fácies granulito e eclogito

GMG0332 – Petrologia Metamórfica
Renato de Moraes
rmoraes@usp.br

1

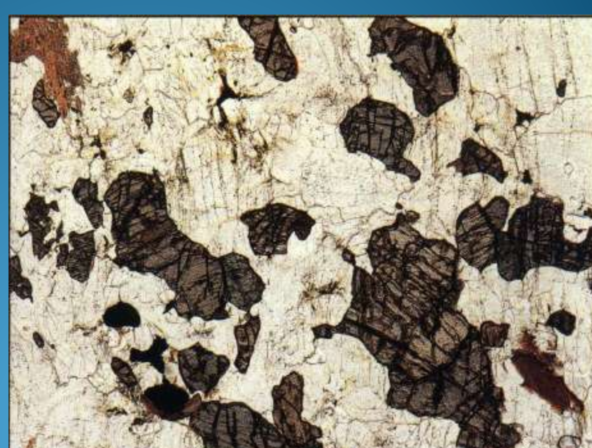
granada granulito félsico com *boudin* de ultra-restito com granada e ortopiroxênio, Varginha, MG

2

eclogito
Hornelen Basin, Noruega
L. Gernigon

3

Granulitos



4

PRESSURE-TEMPERATURE-TIME PATHS AND A TECTONIC MODEL FOR THE EVOLUTION OF GRANULITES[1]

STEVEN R. BOHLEN
Department of Earth and Space Sciences, State University of New York, Stony Brook, New York 11794

ABSTRACT

Petrologic studies and application of well-calibrated mineralogic thermometers and barometers reveal several important features common to many granulite terrains: (1) "Peak" metamorphic pressure and temperature conditions cluster around values of 7.5 ± 1 kbar and 800 ± 50°C, implying average geothermal gradients of 30–35°C/km. (2) In comparison with upper amphibolite facies rocks, especially in paired, amphibolite-granulite terrains, it is evident that granulites are distinguished from amphibolites by the former's higher metamorphic temperatures but *not* higher pressure. (3) Initial cooling of granulite terrains from "peak" conditions is nearly isobaric. For garnet closure temperatures of 600 ± 50°C, the dP/dT retrograde paths inferred from compositionally zoned garnet rims are 2–8 b/°C in most granulites. (4) Primary, coarse sillimanite is found in most granulites, and retrograde kyanite is known in a few. These data suggest that granulites form as a result of anomalous thermal gradients caused by the intrusion of magmas beneath or into a given terrain rather than by increased heating as the result of increased burial. The data also imply that heating occurs before and during tectonic loading, hence an anti-clockwise P-T-time path of metamorphism. This contrasts sharply with the clockwise P-T-time paths (loading before heating) inferred for Phanerozoic fold-thrust mobile belts. An anti-clockwise P-T-time path is likely to be characteristic of magmatically thickened and heated crust such as that observed in an continental arc environment. If so, then the time-honored explanation for the origin of granulites as resulting from continent-continent collision must be revised.

boas ideias,
mas algumas conclusões

[JOURNAL OF GEOLOGY, 1987, vol. 95, p. 617–632]

5

Geol. Mag. **126** (*3*), *1989, pp. 215–247. Printed in Great Britain* 215

The origins of granulites: a metamorphic perspective

S. L. HARLEY*
Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, U.K.

(*Received* 21 June 1988; *accepted* 24 November 1988)

Abstract – Although many recent reviews emphasize a uniformity in granulite pressure–temperature (*P–T*) conditions and paths, granulites in reality preserve a spectrum of important petrogenetic features which indicate diversity in their modes of formation. A thorough survey of over 90 granulite terranes or occurrences reveals that over 50% of them record *P–T* conditions outside the 7.5 ± 1 kbar and 800 ± 50 °C average granulite regime preferred by many authors. In particular, an increasing number of very high temperature (900–1000 °C) terranes are being recognized, both on the basis of distinctive mineral assemblages and geothermobarometry. Petrogenetic grid and geothermobarometric approaches to the determination and interpretation of *P–T* histories are both evaluated within the context of reaction textures to demonstrate that the large range in *P–T* conditions is indeed real, and that both near-isothermal decompression (ITD) and near-isobaric cooling (IBC) *P–T* paths are important. Amphibolite–granulite transitions promoted by the passage of CO_2-rich fluids, as observed in southern India and Sri Lanka, are exceptional and not representative of fluid-related processes in the majority of terranes. It is considered, on the contrary, that fluid-absent conditions are typical of most granulites at or near the time of their recorded thermal maxima.

ITD granulites are interpreted to have formed in crust thickened by collision, with magmatic additions being an important extra heat source. Erosion alone is not, however, considered to be the dominant post-collisional thinning process. Instead, the ITD paths are generated during more rapid thinning (1–2 mm/yr exposure) related to tectonic exhumation during moderate-rate or waning extension. IBC granulites may have formed in a variety of settings. Those which show anticlockwise *P–T* histories are interpreted to have formed in and beneath areas of voluminous magmatic accretion, with or without additional crustal extension. IBC granulites at shallow levels (< 5 kbar) may also be formed during extension of normal thickness crust, but deeper-level IBC requires more complex models. Many granulites exhibiting IBC at deep crustal levels may have formed in thickened crust which underwent *very* rapid (5 mm/yr) extensional thinning subsequent to collision. It is suggested that the preservation of IBC paths rather than ITD paths in many granulites is primarily related to the *rate* and *timescale* of extensional thinning of thickened crust, and that hybrid ITD to IBC paths should also be observed.

Most IBC granulites, and probably many ITD granulites, have not been exposed at the Earth's surface as a result of the tectonic episodes which produced them, but have resided in the middle and lower crust for long periods of time (100–2000 Ma) following these events. The eventual exhumation of most granulite terranes only occur through their incorporation in later tectonic and magmatic events unrelated to their formation.

6

J. metamorphic Geol., 1991, 9, 223–229

On the formation of granulites

S. R. BOHLEN
United States Geological Survey, MS-910, 345 Middlefield Road, Menlo Park, CA 94025, USA

ABSTRACT The tectonic settings for the formation and evolution of regional granulite terranes and the lowermost continental crust can be deduced from pressure–temperature–time (P–T–time) paths and constrained by petrological and geophysical considerations.

P–T conditions deduced for regional granulites require transient, average geothermal gradients of greater than 35° C km^{-1}, implying minimum heat flow in excess of 100 mW m^{-2}. Such high heat flow is probably caused by magmatic heating. Tectonic settings wherein such conditions are found include convergent plate margins, continental rifts, hot spots and at the margins of large, deep-seated batholiths. However, particular P–T–time paths do not allow specific tectonic settings to be distinguished at this time. Under different conditions, both clockwise, CW (P_{max} attained before T_{max}), and anticlockwise, ACW (P_{max} attained slightly after T_{max}), paths are possible in the same tectonic setting. Both CW and ACW end-member paths can yield nearly isobaric cooling, IBC, paths. Such cooling paths are clearly not an artefact of thermobarometry, but can be constrained by solid–solid and devolatilization equilibria and geophysical modelling.

In terms of understanding the evolution of the deep crust, a potentially significant group of regional granulite terranes are those that show evidence for ACW-IBC paths. Such paths are the likely result of: (i) episodic igneous activity resulting in intrusions within all levels of the crust, (ii) thickening of the crust by magmatic underplating, (iii) slow uplift as a result of the formation of a deep, garnet-rich crustal root and (iv) excavation resulting from a later tectonic event unrelated to that resulting in the formation of the granulites. The later event might be triggered by the delamination of the garnet-rich, lowermost crust.

Key words: barometry; crustal evolution; granulite; P–T–t path, thermometry.

7

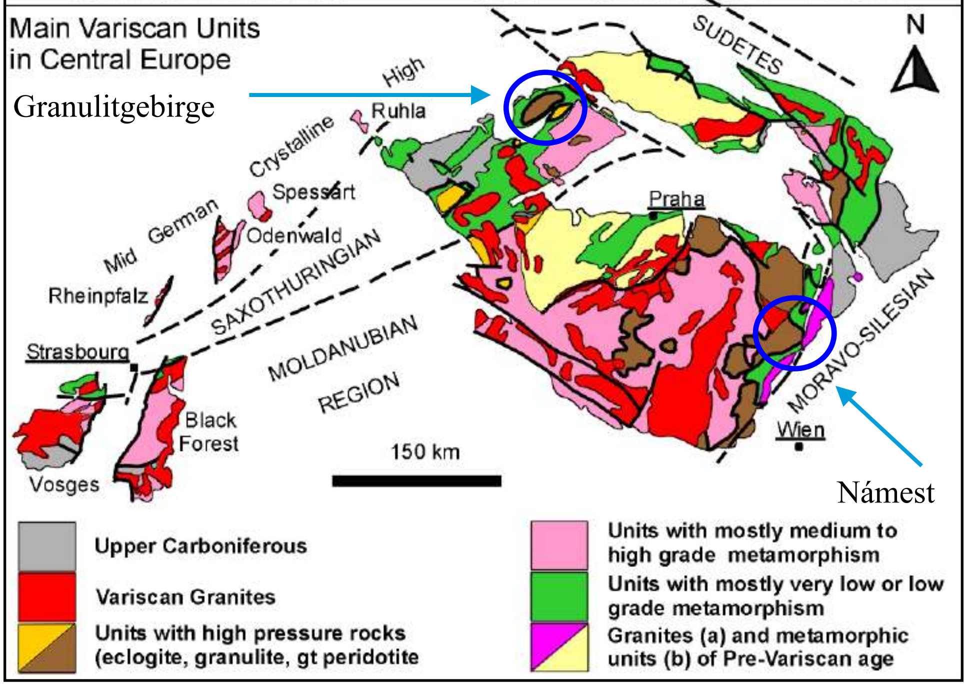
Histórico

- Primeira descrição foi feita há mais de 260 anos atrás (Justi, 1754)
- O termo **granulito** foi inicialmente utilizado para designar rocha quartzo-feldspática (com Ky e Grt) do Erzgebirge, maciço da Saxônia, Europa Central (Weiss, 1803)


Neue
Wahrheiten
Naturkunde
des gesellschaftlichen Lebens
1754.
Nachricht

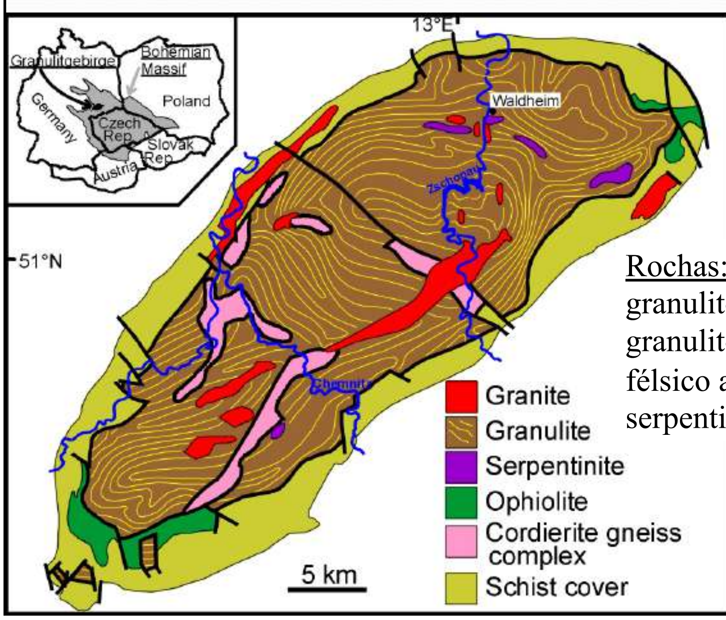
8

Granulito : Weiss (1803) usou para rochas do Granulitgebirge da Saxônia



9

Granulitgebirge: domo de gnaisse em meio a xistos de baixo grau

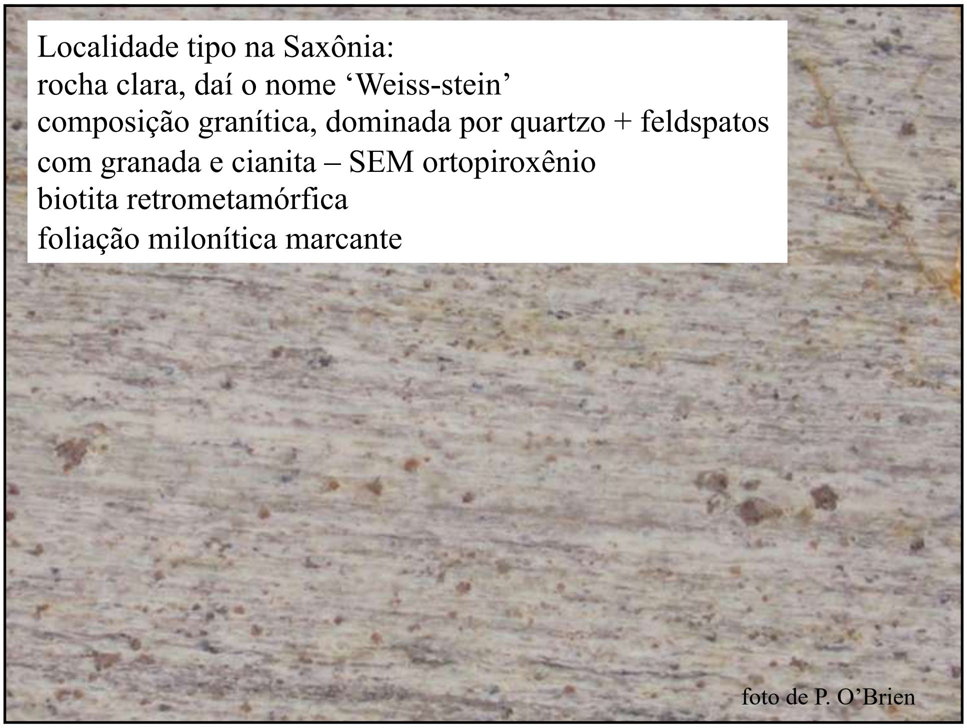


Rochas:
granulito félsico
granulito com piroxênio:
félsico a máfico
serpentinito com granada

figura de P. O'Brien

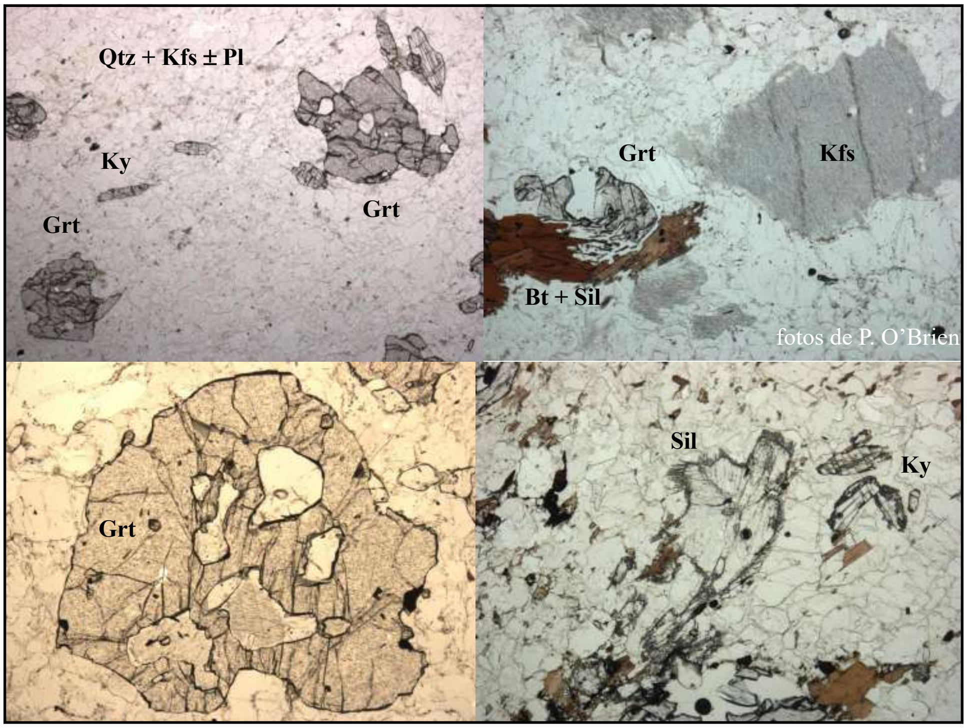
10

Localidade tipo na Saxônia:
rocha clara, daí o nome 'Weiss-stein'
composição granítica, dominada por quartzo + feldspatos
com granada e cianita – SEM ortopiroxênio
biotita retrometamórfica
foliação milonítica marcante



11

12



13

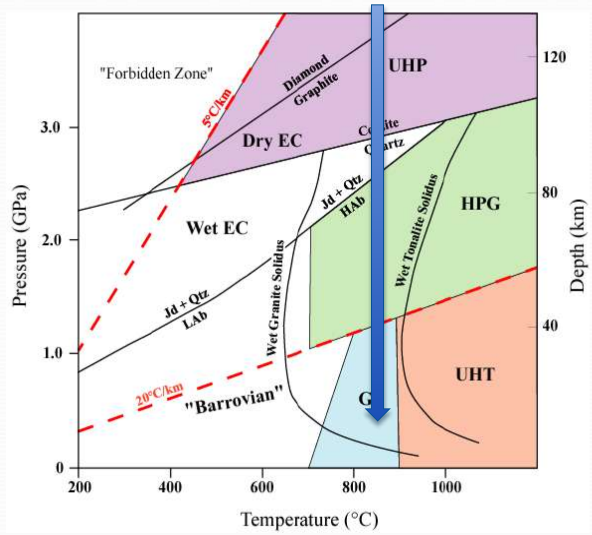
Histórico

- Após a proposição do conceito de fácies metamórfica (Eskola, 1921), alguma confusão foi gerada, pois cada fácies metamórfica foi identificada com o nome da rocha **máfica** típica daquelas condições, *e.g.* xisto verde, anfibolito, xisto azul, eclogito
- Eskola estudou rochas da Lapônia, Finlândia, as quais são portadoras de **ortopiroxênio metamórfico**. Em alguns afloramentos, as rochas são mais deformadas e têm aspecto granular, como as do Maciço da Saxônia
- Assim, ele concluiu que o ortopiroxênio deveria ser o mineral índice da fácies granulito e deturpou o nome **granulito**, mas essa é a definição aceita hoje pela maior parte da comunidade internacional

14

Histórico

- Na região do Erzgebirge, onde o termo granulito foi usado pela primeira vez, as condições do metamorfismo são da fácies eclogito, englobando rochas de pressão ultra-alta, com diamante metamórfico (Massone, 1999)
- Retrometamorfismo da fácies granulito (UH*T*)

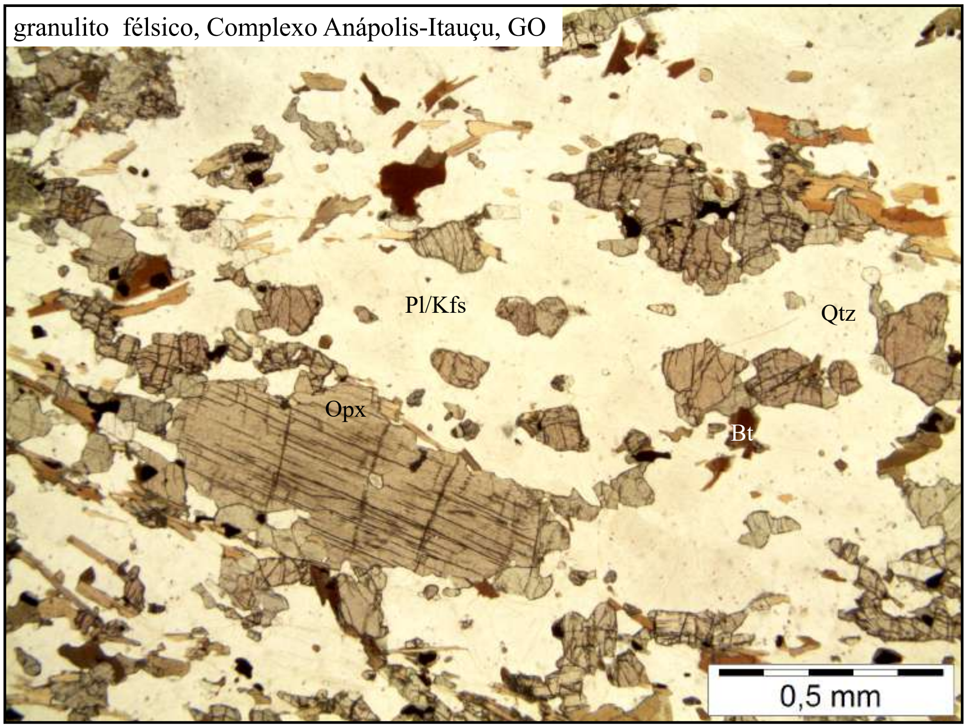


15

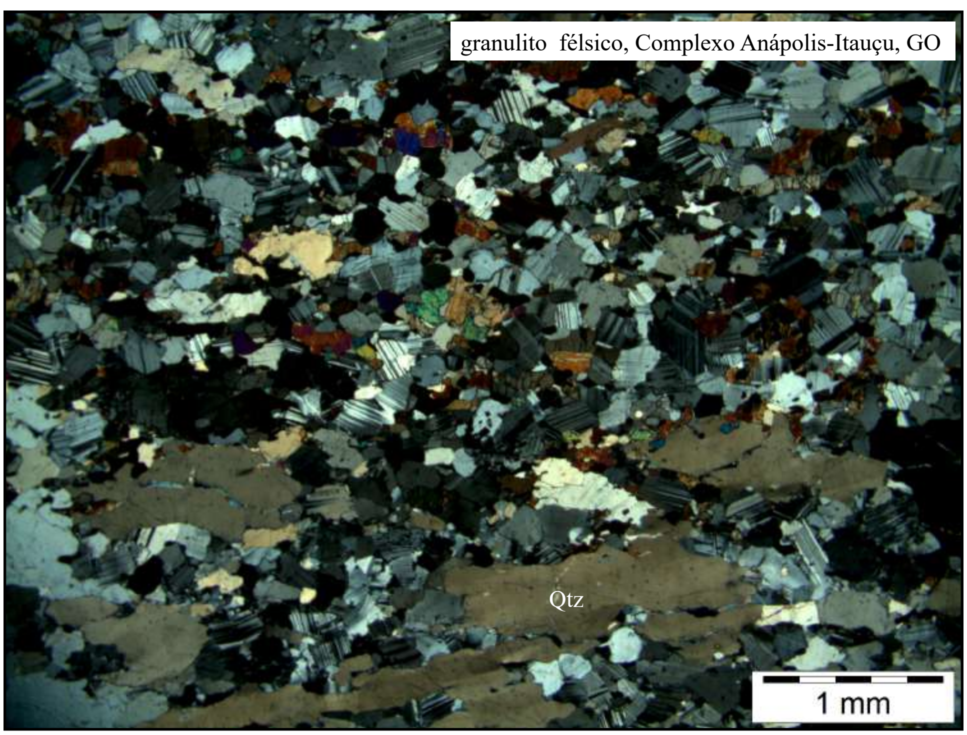
Granulito

- Para Winkler (1976), **o ortopiroxênio é o mineral índice da fácies granulito**
- Rocha contendo mineralogia anidra, com predomínio de feldspatos e fases Fe-Mg, **tais como ortopiroxênio**, granada, clinopiroxênio; quartzo pode ou não estar presente
- O resto da mineralogia depende da composição do protolito
- Rocha com estrutura tipo *flaser* (*ribbon* /*fita* de quartzo)

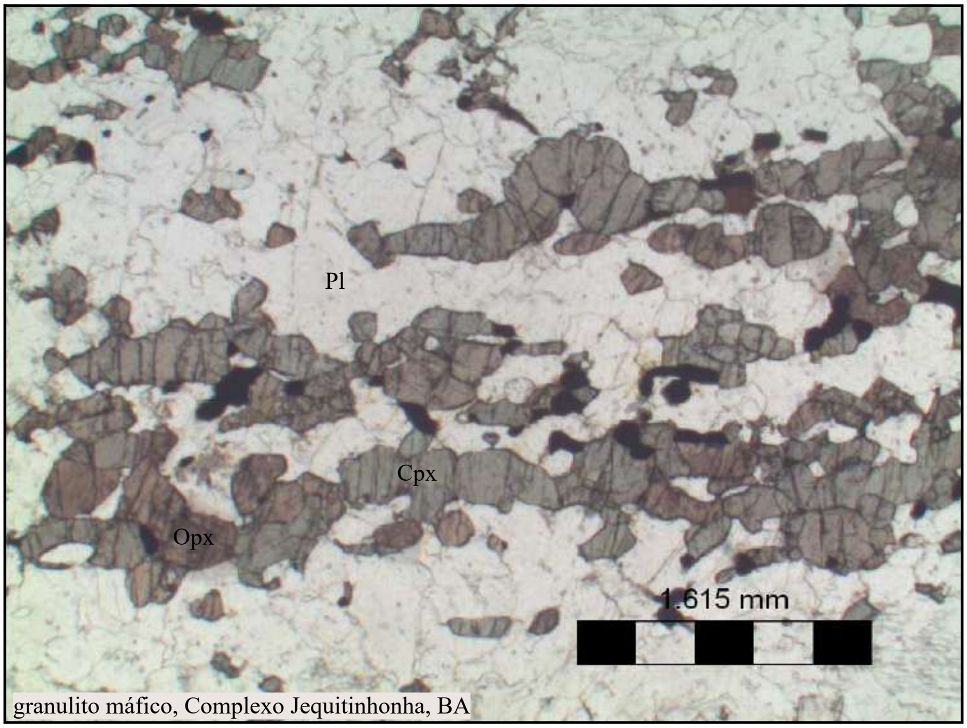
16


granulito félsico, Complexo Anápolis-Itauçu, GO
Pl/Kfs
Qtz
Opx
Bt
0,5 mm

17


granulito félsico, Complexo Anápolis-Itauçu, GO
Qtz
1 mm

18



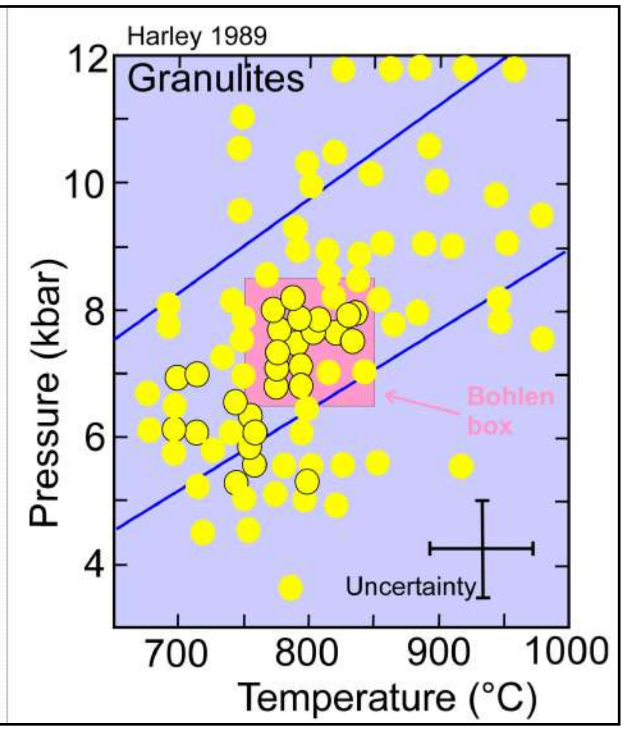
19

De que *T* estamos falando?

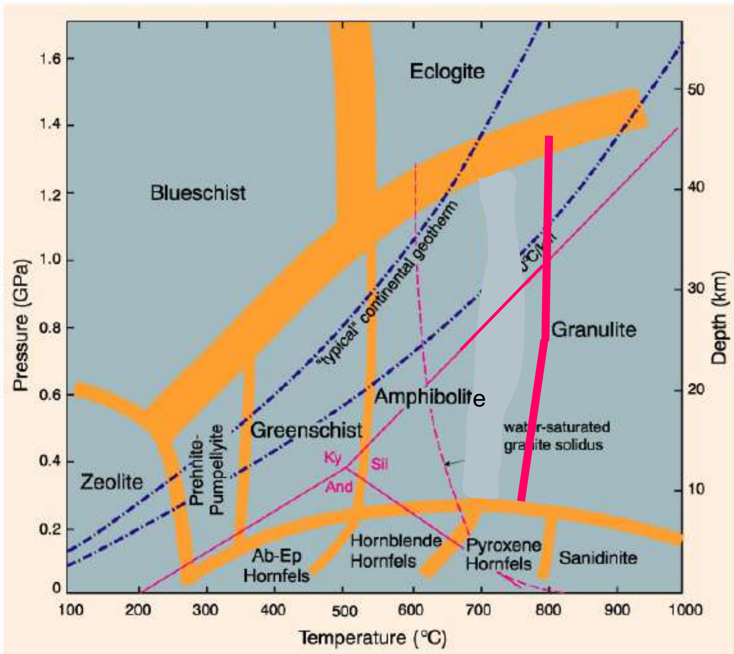
T > 750 - 800 °C

Bohlen (1987)
7.5 ± 1 kbar
800 ± 50 °C
mas......

Harley, 1989



20



Winter, 2011, modificado por Moraes

21

Paragêneses diagnósticas e nomenclatura

- **Granulito máfico**
  - Opx + Ol + Pl ± Hbl (baixa *P*)
  - Opx + Pl + Cpx ± Grt ± Qtz ± Hbl
  - Cpx + Grt + Pl ± Hbl ± Qtz (alta *P*)
- **Granulito félsico**
  - Qtz + Opx + Mesopertita + Pl ± Grt ± Di ± Bt ± Hbl
- **Granulito aluminoso (pelítico)**
  - Qtz + Mesopertita + Opx ± Pl ± Grt ± Crd

- Muitos granulitos tem aspecto de migmatito em campo, apresentam leucossoma!

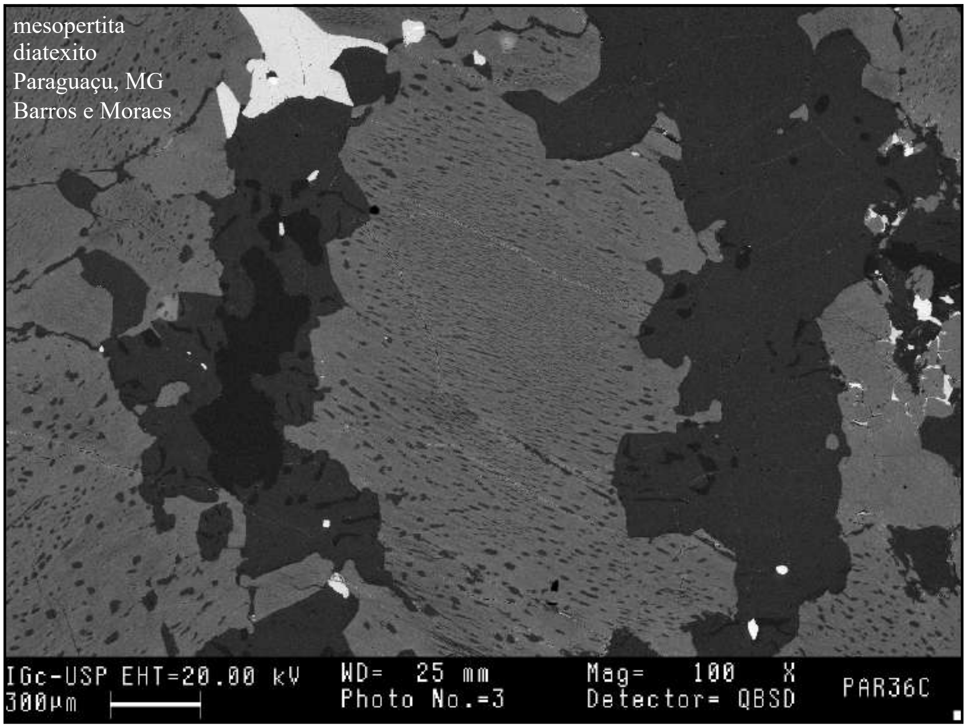
22

contato entre diatexito estromático e granulito félsico. Notar leucossoma dentro do granulito.
sul da Bahia, Complexo Jquitinhonha

23

resíduo granulítico bandado, com bandas ricas em Hbl e bandas máficas, alternadas com leucossoma
Nappe Varginha-Três Pontas, MG

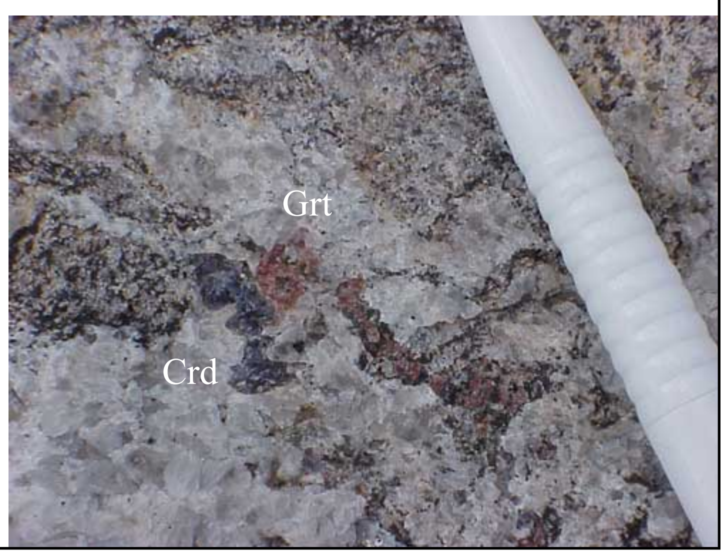
24



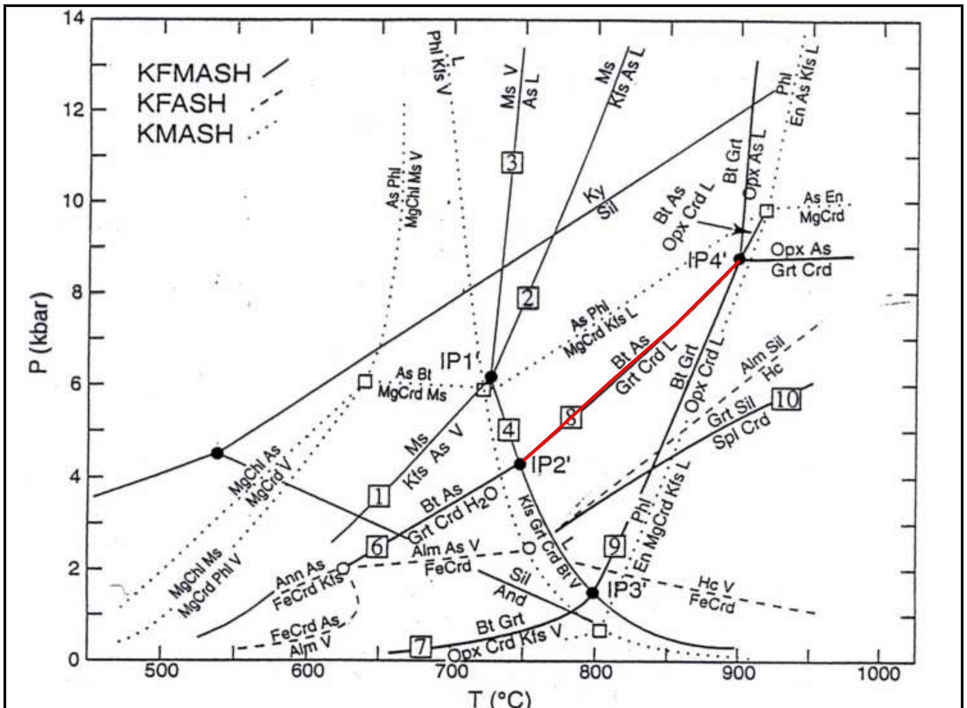
25

Granulito félsico ou pelítico

Grt + Crd



26



Spear *et al.*, 1999

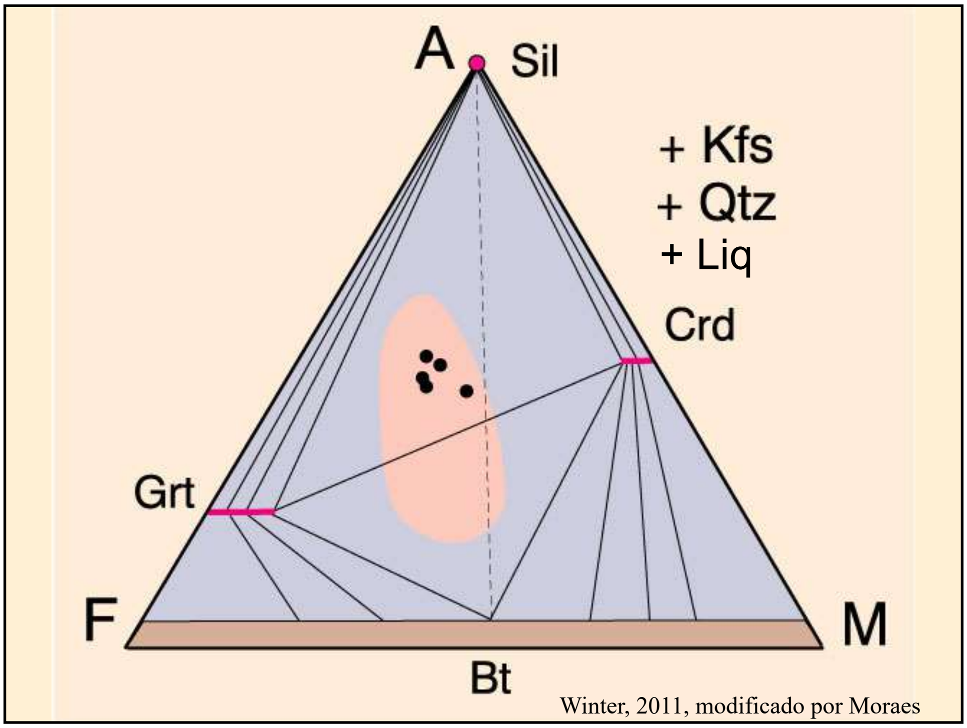
27

Granada + cordierita

- Aspecto da rocha – metatexito ou diatexito
- $T \geq 750°C$, $P \geq 4$ kbar (Spear *et al*., 1999)
- Bt + Al_2SiO_5 + Qtz → Grt + Crd + Kfs + líquido
- Associação típica: Grt + Crd + Kfs + Qtz ± Sil ± Pl ± Bt + leucossoma (com Grt e/ou Crd)
- Kinzigito (Qtz + Grt + Crd + Sil + Kfs + Gph)
- Bt – estabilidade aumenta pela presença de Ti e/ou F (alto X_{Mg})

- Crd + Grt ocorrem na fácies anfibolito superior, atravessam as condições da fácies granulito, mas até onde são estáveis?

28



29

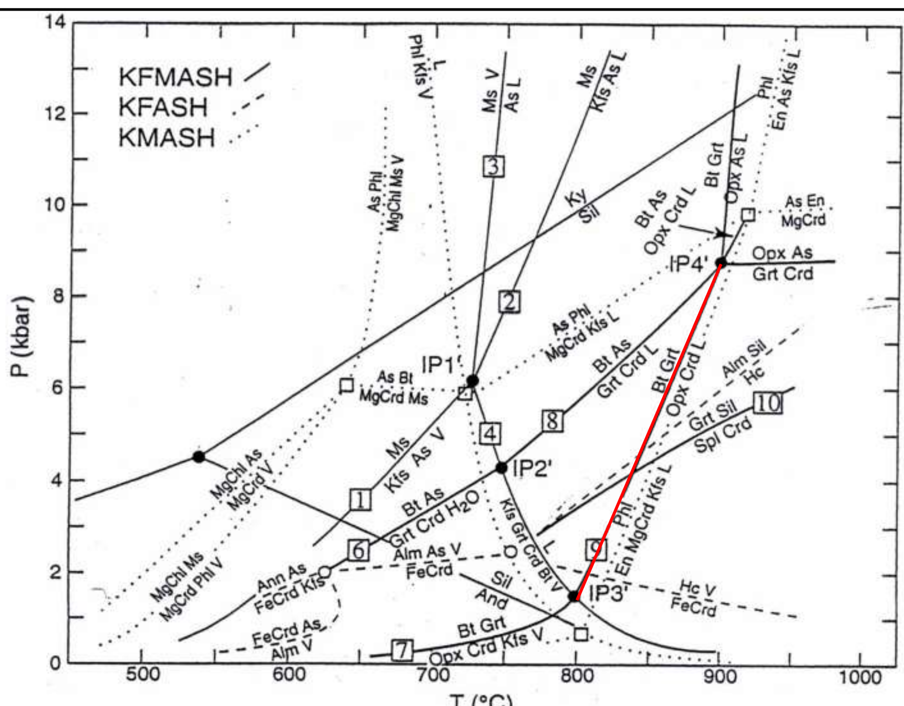
Granulito félsico ou pelítico

ortopiroxênio

30

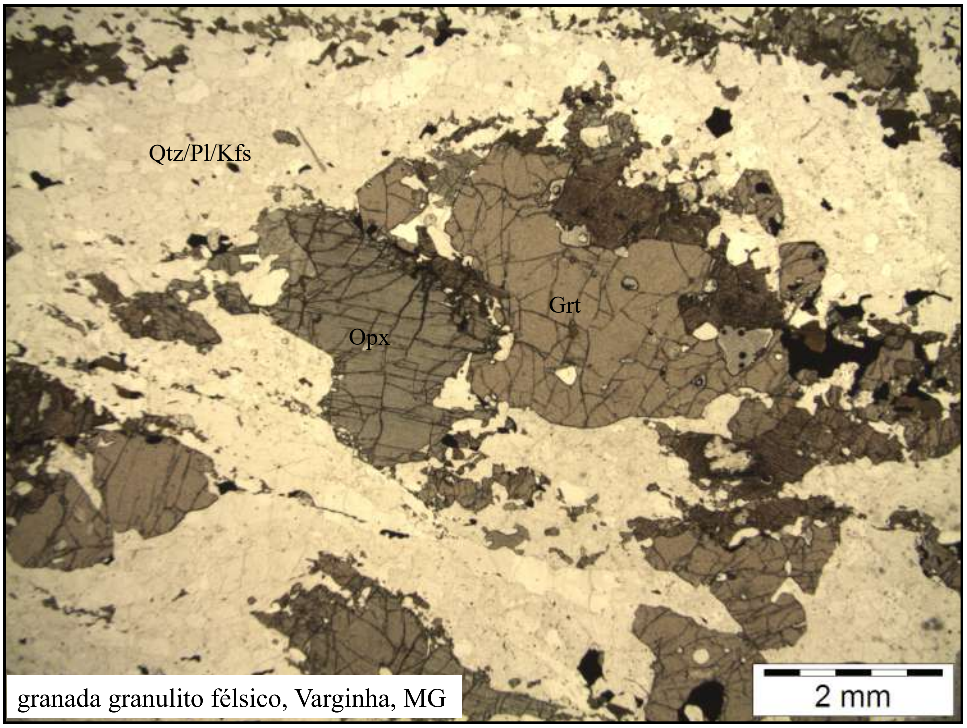
granada granulito félsico com *boudin* de ultra-restito com granada e ortopiroxênio, Varginha, MG

31



Spear *et al.*, 1999

32


Qtz/Pl/Kfs
Opx
Grt
granada granulito félsico, Varginha, MG
2 mm

33

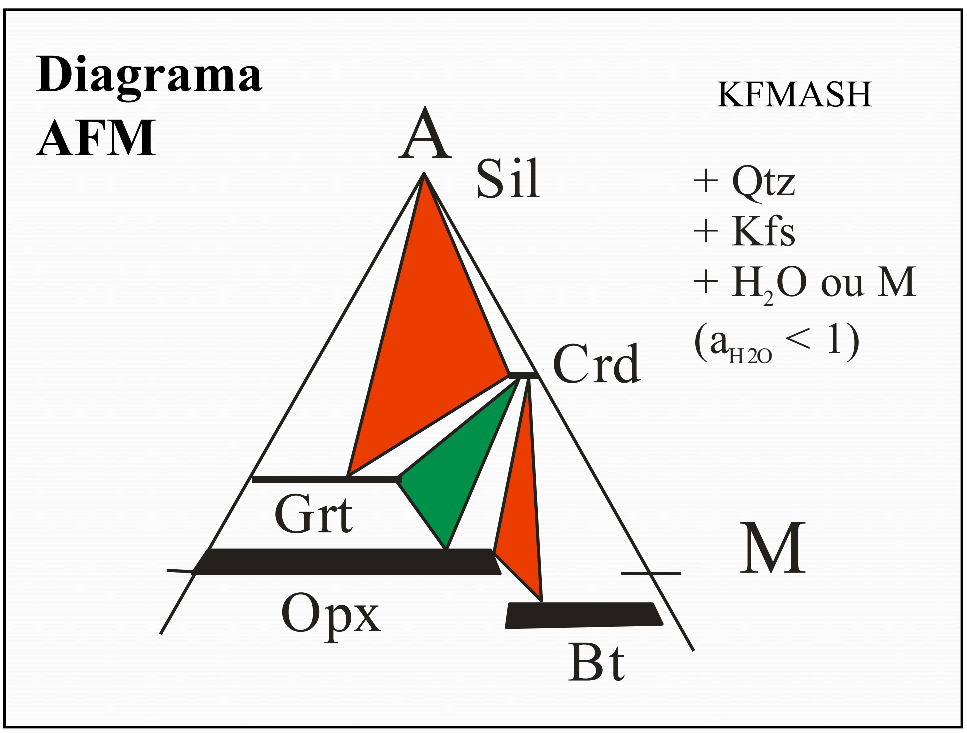


Diagrama AFM
KFMASH
A
Sil
+ Qtz
+ Kfs
+ H2O ou M
(aH2O < 1)
Crd
Grt
M
Opx
Bt

34

Ortopiroxênio

- $T \geq 800$ °C, $P \geq 1{,}5$ kbar (Spear *et al*., 1999)
- Bt + Grt + Qtz → Opx + Crd + Kfs + líquido
- Associação típica pelítica: Opx + Crd + Kfs (mesopertita) ± Pl ± Bt ± Grt + leucossoma (com Opx + Crd)
- Associação típica rocha quartzo-feldspática: Qtz + Kfs + Pl + Opx ± Grt + leucossoma ± Crd

- Se considerarmos o ortopiroxênio como mineral índice da fácies granulito, não seria interessante, então, colocar o início da fácies granulito em 800 °C?

35

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

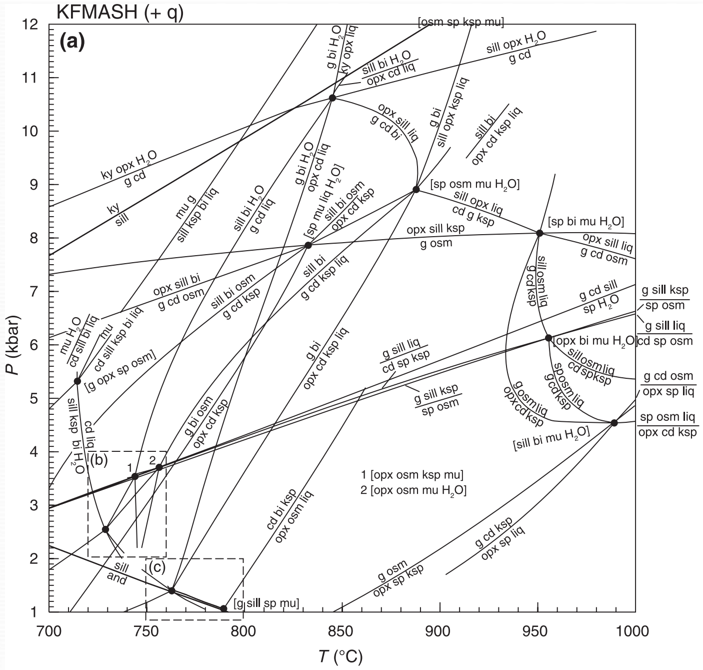
Progress relating to calculation of partial melting equilibria for metapelites

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.

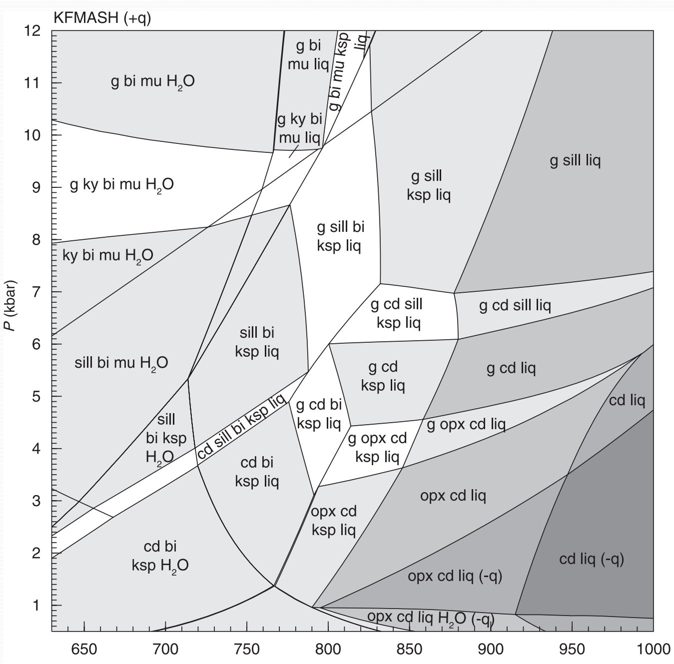
Key words: activity model; mineral equilibria; pseudosection; *P–T* grid; THERMOCALC.

36



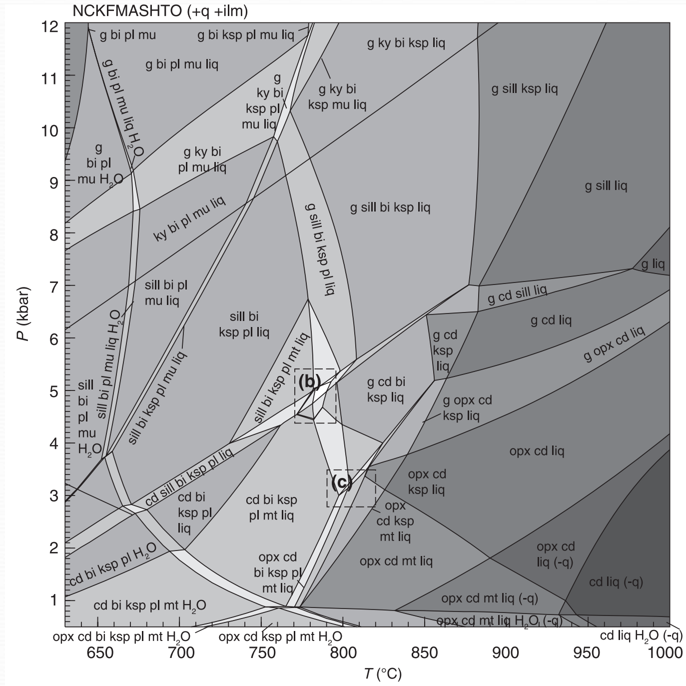
KFMASH (+ q)
(a)
P (kbar)
T (°C)
1 [opx osm ksp mu]
2 [opx osm mu H2O]
[osm sp ksp mu]
[sp osm mu H2O]
[sp bi mu H2O]
[opx bi mu H2O]
[sill bi mu H2O]
[g opx sp osm]
[g sill sp mu]

37



KFMASH (+q)
g bi mu H2O
g ky bi mu H2O
ky bi mu H2O
sill bi mu H2O
g bi mu liq
g ky bi mu liq
g sill bi ksp liq
g sill ksp liq
g sill liq
g cd sill ksp liq
g cd sill liq
sill bi ksp liq
g cd ksp liq
g cd liq
g cd bi ksp liq
g opx cd ksp liq
g opx cd liq
cd liq
cd bi ksp liq
opx cd ksp liq
opx cd liq
cd bi ksp H2O
opx cd liq (-q)
cd liq (-q)
opx cd liq H2O (-q)
P (kbar)
T (°C)

38



39

Qual a *T* mínima da fácies granulito?

- Deve ser aquela que dá condições para formação de ortopiroxênio metamórfico
  - ~ 800 °C

Então por que os livros colocam em *T* do início da fácies granulito entre 700 e 750 °C?

40

Início da fácies granulito

- A temperatura mínima do início da fácies granulito deve ser baseado em dados experimentais ou termobarometria?

- Dados experimentais *vs.* termobarometria
  - Dados experimentais - Opx em T~ 800 °C
  - Termobarometria $T_{calc} \geq 700$ ºC
  - Os primeiros dados de termobarometria em granulitos foram baseados em termometria de dois piroxênios ou granada-ortopiroxênio sem que correções na razão Fe/Mg dos minerais fosse feite e que ocorre durante o resfriamento gerando $T_{calculada}$ mais baixa que a T_{pico}

41

JOURNAL OF PETROLOGY | VOLUME 44 | NUMBER 5 | PAGES 867–900 | 2003

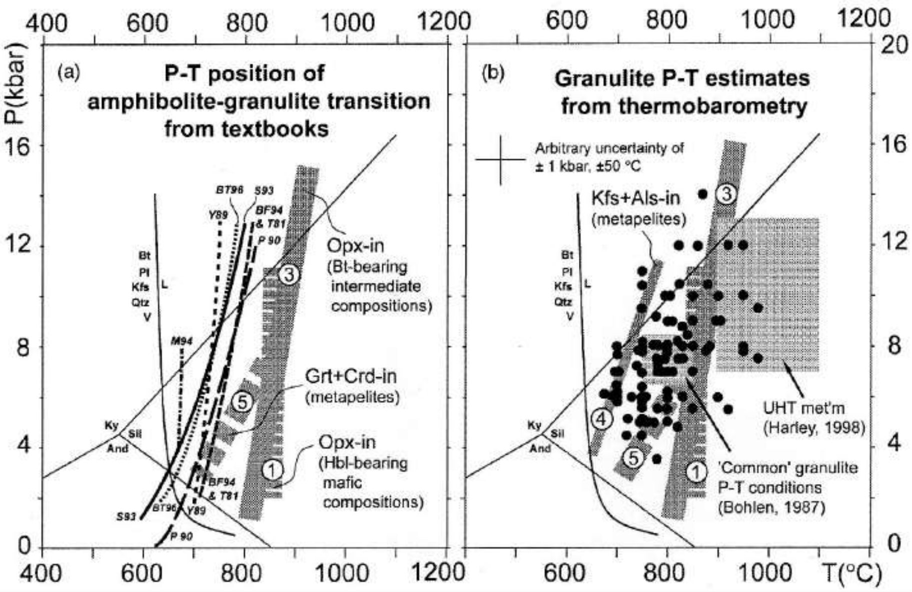
Temperatures of Granulite-facies Metamorphism: Constraints from Experimental Phase Equilibria and Thermobarometry Corrected for Retrograde Exchange

DAVID R. M. PATTISON[1]*, THOMAS CHACKO[2], JAMES FARQUHAR[3] AND CHRISTOPHER R. M. McFARLANE[4]

[1]DEPARTMENT OF GEOLOGY AND GEOPHYSICS, UNIVERSITY OF CALGARY, CALGARY, AB, T2N 1N4, CANADA
[2]DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES, UNIVERSITY OF ALBERTA, EDMONTON, AB, T6G 2E3, CANADA
[3]DEPARTMENT OF GEOLOGY AND EARTH SYSTEM SCIENCE INTERDISCIPLINARY CENTRE, UNIVERSITY OF MARYLAND, COLLEGE PARK, MD 20742, USA
[4]DEPARTMENT OF GEOLOGICAL SCIENCES, THE UNIVERSITY OF TEXAS AT AUSTIN, AUSTIN, TX 78701, USA

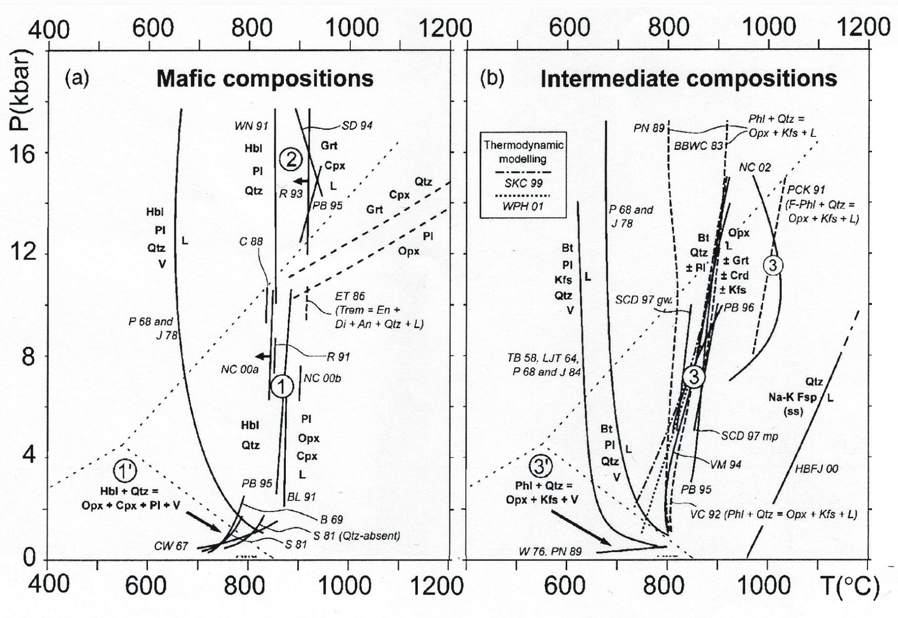
RECEIVED MAY 29, 2002; ACCEPTED NOVEMBER 18, 2002

42

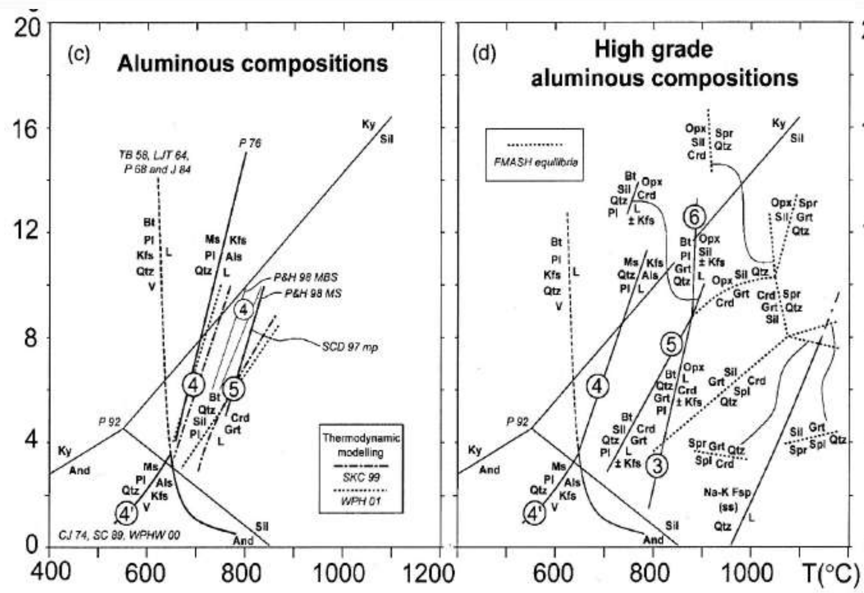


Pattison *et al.*, 2003 - JPET

43



44

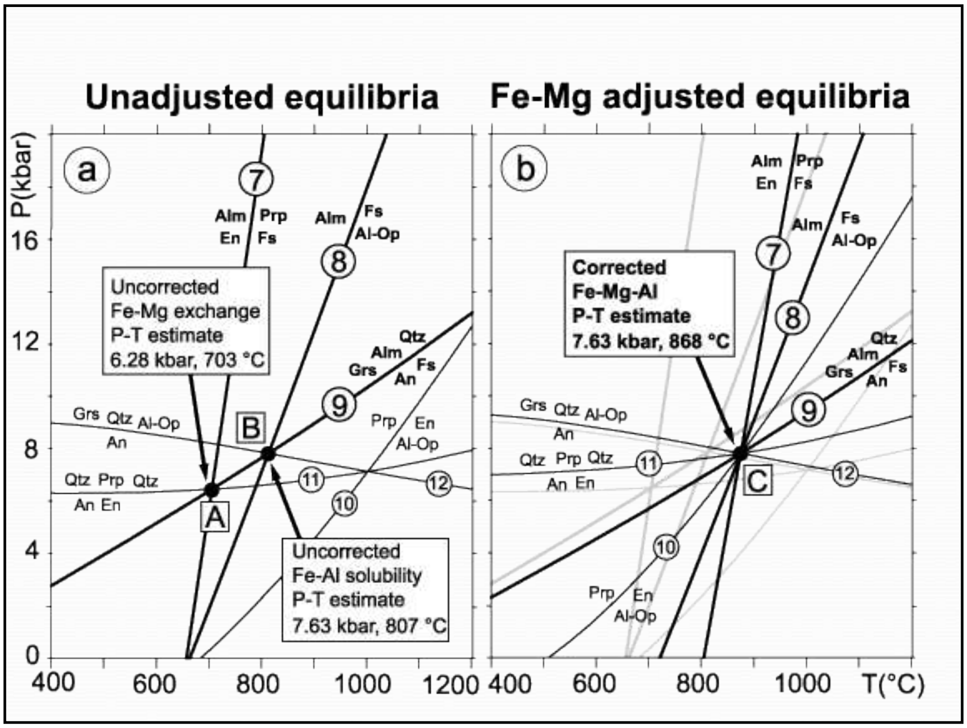


45

T calculada em granulitos

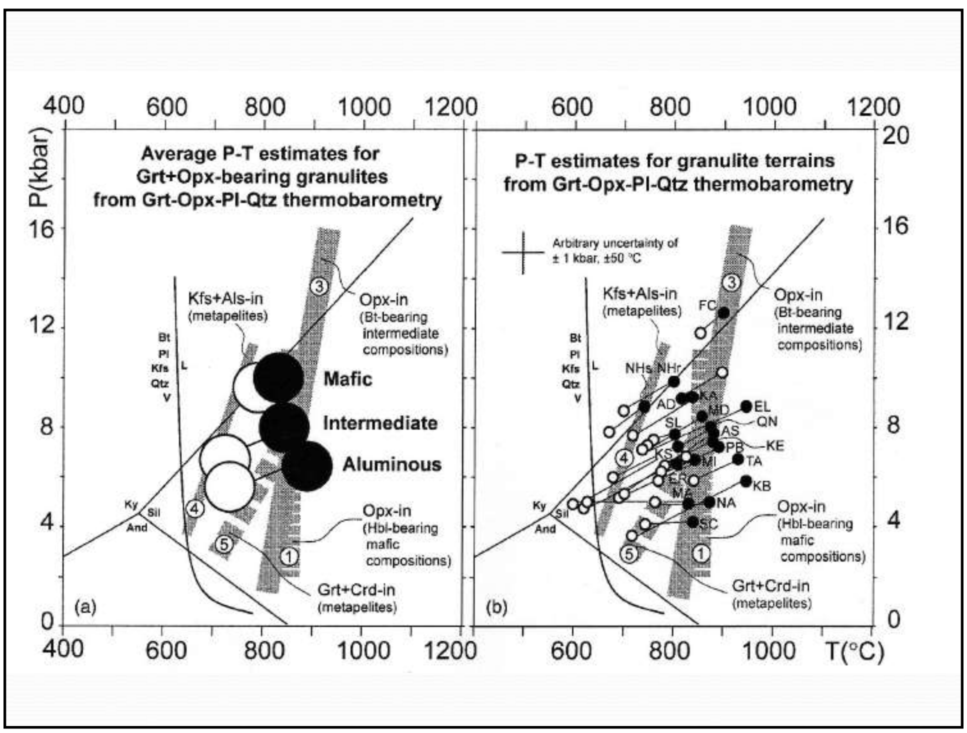
- Investigação em granulitos máficos, félsicos e aluminosos (414)
- Método de cálculo combina resultados de:
  - 2Alm + 1Grs + 3Qtz = 6Fs + 3An
  - 1Alm + 3En = 1Prp = 3Fs
  - 1Alm = 3Fs + AlOpx
  - método é interativo e leva em conta a proporção modal de Grt e Opx

46



Unadjusted equilibria
Fe-Mg adjusted equilibria
P(kbar)
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
Uncorrected
Fe-Al solubility
P-T estimate
7.63 kbar, 807 °C
Corrected
Fe-Mg-Al
P-T estimate
7.63 kbar, 868 °C
C
T(°C)

47



P(kbar)
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
Kfs+Als-in
(metapelites)
Opx-in
(Bt-bearing
intermediate
compositions)
Mafic
Intermediate
Aluminous
Opx-in
(Hbl-bearing
mafic
compositions)
Grt+Crd-in
(metapelites)
Ky
Sil
And
(a)
(b)
Arbitrary uncertainty of
± 1 kbar, ±50 °C
T(°C)

48

Conclusão

- Os experimentos indicam que a temperatura mínima para a formação de ortopiroxênio metamórfico é de ~800 °C para rochas máficas, pelíticas e graníticas
- Quando a correção da composição de granada e ortopiroxênio é aplicada, os dados termobarométricos fornecem temperaturas mínimas da ordem de 800 °C
- A temperatura mínima da fácies granulito deve ser de ~ 800 °C

49

Contr. Mineral. and Petrol. 33, 309–330 (1971)

Experimental Study of the Stability of Cordierite and Garnet in Pelitic Compositions at High Pressures and Temperatures

I. Compositions with Excess Alumino-Silicate

B. J. Hensen * and D. H. Green

Department of Geophysics and Geochemistry, Australian National University

Received October 28, 1971

Abstract. The stability of cordierite and garnet relative to their anhydrous breakdown products, i.e. hypersthene, sapphirine, olivine, spinel, sillimanite and quartz, has been studied experimentally in model pelitic compositions (system MgO–FeO–Al_2O_3–CaO–K_2O–SiO_2). Below 1000° C cordierite breaks down according to the divariant reaction cordierite ⇄ garnet + sillimanite + quartz (1) for most values of the $MgO/MgO + FeO$ ratio (X). At very high values of X (ca. $X > 0.9$) garnet in reaction (1) is replaced by hypersthene. The position and width of the divariant field (in terms of pressure and temperature) in which cordierite and garnet coexist, is a function of the $MgO/MgO + FeO$ ratio. If this ratio is increased then the stability field of garnet is reduced and that of cordierite extended towards higher pressure. Compositions of coexisting cordierite and garnet in divariant equilibrium have been analysed by electron probe micro-analyser. These compositions are unique functions of pressure and temperature. Above ca. 1000° C the breakdown of cordierite involves the phases sapphirine and hercynite-rich spinel in Mg-rich and Fe-rich compositions respectively.

50

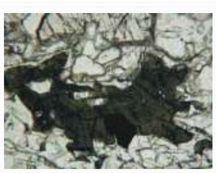
Limite da estabilidade de Grt + Crd

- A investigação do limite superior de estabilidade do par Grt + Crd foi investigado de modo teórico (quimiografia) por Hensen (1970) e de modo experimental por Hensen & Green (1971, 1972, 1973, CPM)
- Os resultados de seus experimentos não foram bem aceitos pela comunidade petrológica por causa das *T* extremamente altas envolvidas (*T* > 900 °C)
- A partir da metade da década de 80 é que os resultados dos experimentos começaram a ser aceitos, quando termômetros que pudessem calcular *T* para essas rochas começaram a se tornar disponíveis

51

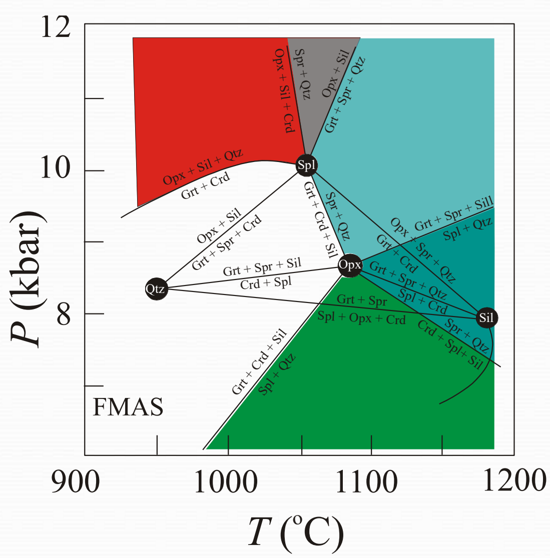
Granulitos UH*T*

Spr + Qtz



Spl + Qtz

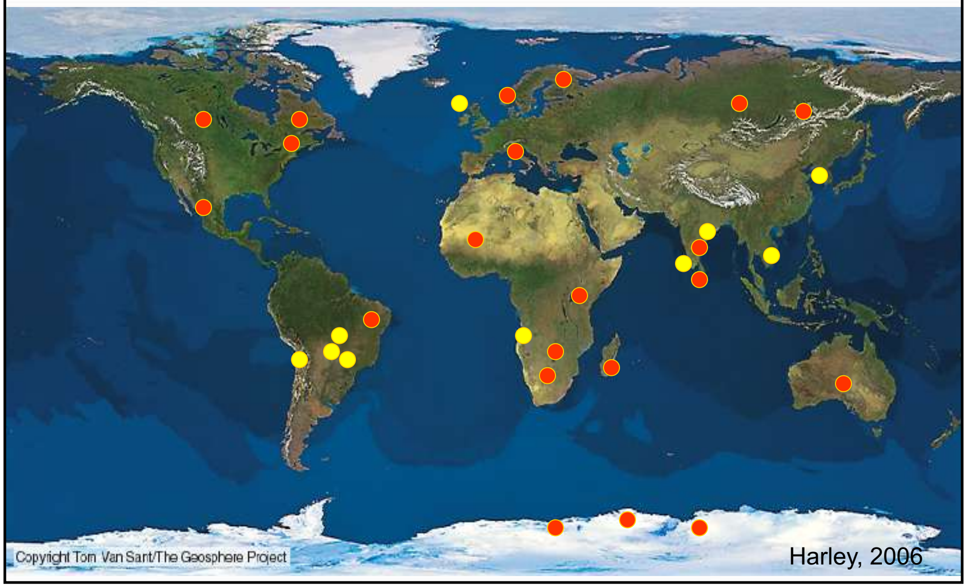
Opx + Sil + Qtz



Harley, 1998

52

Exemplos de terrenos UHT



53

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, 70910-900, BRAZIL

[3]COMPANHIA DE PESQUISA DE RECURSOS MINERAIS (CPRM), RUA S-02, 463 APTO 101, SETOR BELA VISTA GOIÂNIA, GO 74823-430, BRAZIL

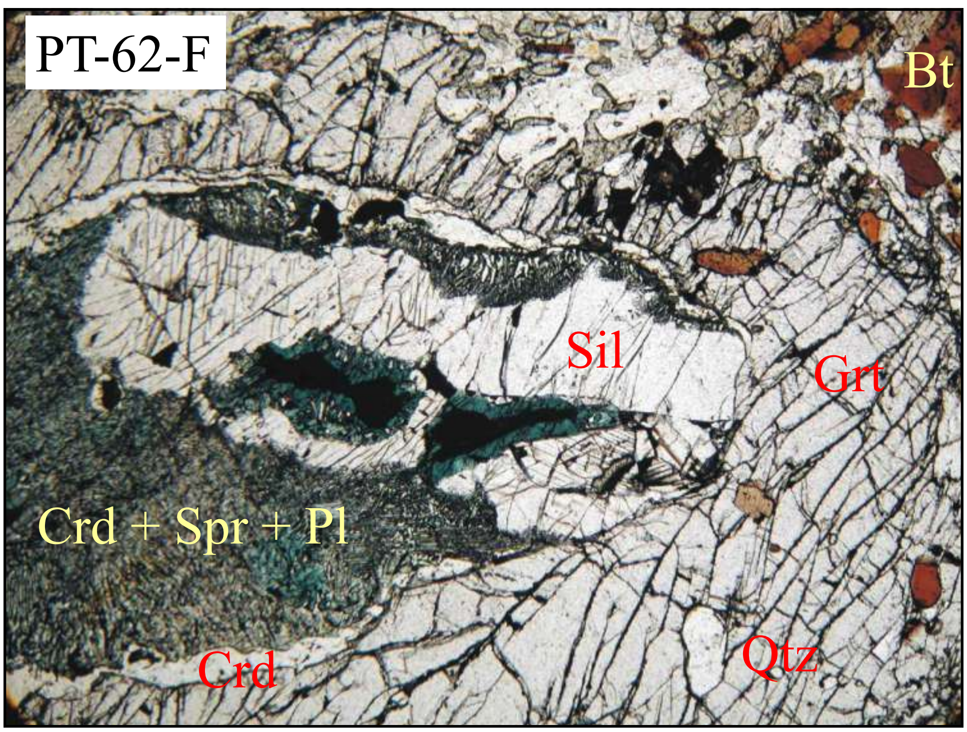
[4]COMPANHIA DE PESQUISA DE RECURSOS MINERAIS (CPRM), SGAN 603 CONJ. 'J', PARTE 'A', 1°, ANDAR BRASÍLIA, DF 70830 030, BRAZIL

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

54

PT-62 – Complexo Anápolis-Itauçu, GO

55



56

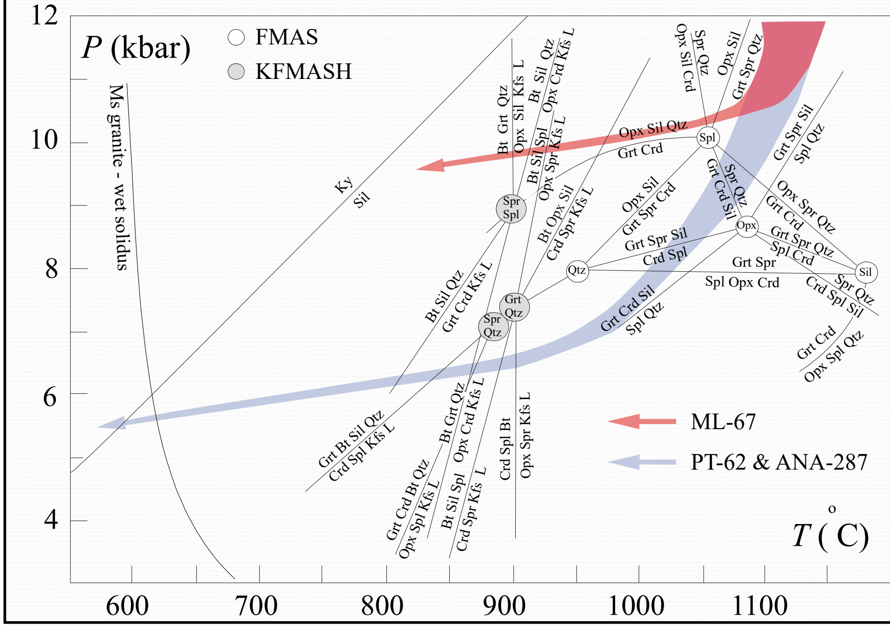
ML-67

57

ML-67

58

Trajetórias *P-T* inferidas



59

On the occurrence and characterization of ultrahigh-temperature crustal metamorphism

SIMON L. HARLEY

Department of Geology and Geophysics, University of Edinburgh, Kings Buildings, West Mains Road, Edinburgh, EH9 3JW, UK

Abstract: Ultrahigh-temperature (UHT) crustal metamorphism is a division of medium-pressure granulite facies metamorphism where peak temperatures of 900–1100°C have been attained at pressures in the range 7–13 kbar. The key indicators of UHT conditions are mineral assemblages involving combinations of sapphirine, garnet, aluminous orthopyroxene, cordierite, sillimanite, spinel and quartz in pelites and quartzites. Experimentally constrained and calculated FMAS and KFMASH petrogenetic grids involving these phases and additional osumilite and melt indicate that sapphirine + quartz is stable only at >1040°C in reduced rocks, that osumilite is restricted to >900°C for pressures greater than 6 kbar and has an ultimate stability limit of 9 kbar in FMAS, and that the orthopyroxene + sillimanite + quartz assemblage is restricted to pressures greater than 8 kbar in KFMASH. These criteria, coupled with the grids isoplethed for the Mg/(Mg + Fe) of garnet and Al-content of orthopyroxene allow the peak pressure–temperature (*P–T*) conditions of several UHT occurrences to be defined and the post-peak *P–T* paths delineated.

UHT conditions are seldom determined from slowly cooled granulites using conventional geothermometry principally because of the propensity of Fe–Mg exchange thermometry to only record closure temperatures of 700–850°C. However, pressure-convergence calculations for several granulites with UHT mineral assemblages yield back-calculated mineral compositions that are consistent with temperatures of 950–1000°C prior to post-peak Fe–Mg re-equilibration. The best compositional indicator of UHT conditions remains the preservation of high Al_2O_3 contents (8–12 wt%) in orthopyroxene coexisting with garnet, sillimanite or sapphirine.

The *P–T* conditions and records preserved in the currently documented UHT localities and terranes are varied. Both types of post-peak *P–T* path isobaric cooling and isothermal decompression (ITD) are recorded from reaction textures in different UHT terranes, and several preserve very similar ITD histories that may reflect the final stage of collisional orogenesis. Although counter-clockwise and clockwise *P–T* paths have been proposed on the basis of textural observation for some terranes, the prograde *P–T* histories of most UHT areas are not known. Such information, and further experimental constraints on quartz-absent assemblages at UHT conditions, are of prime importance to interpret further this extreme form of crustal metamorphism.

HARLEY, S. L. 1998. On the occurrence and characterization of ultrahigh-temperature crustal metamorphism. *In*: TRELOAR, P. J. & O'BRIEN, P. J. (eds) *What Drives Metamorphism and Metamorphic Reactions?* Geological Society, London, Special Publications, **138**, 81–107.

60

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Gondwana Research 13 (2008) 1–29
GR
www.elsevier.com/locate/gr

GR Focus

On ultrahigh-temperature crustal metamorphism

David E. Kelsey *

Continental Evolution Research Group, School of Earth and Environmental Sciences, The University of Adelaide, Adelaide, 5005, Australia

Received 20 February 2007; received in revised form 30 May 2007; accepted 4 June 2007
Available online 13 June 2007

Abstract

Ultrahigh-temperature (UHT) metamorphism is the most thermally extreme type of crustal metamorphism, with the crust capable of withstanding temperatures ≥900 °C. Mineral assemblages diagnostic of UHT metamorphism commonly occur in Mg–Al-rich rock compositions that are unfortunately relatively rare in nature. These include sapphirine + quartz, orthopyroxene + sillimanite ± quartz and osumilite. However, UHT metamorphism has been diagnosed using more common garnet + aluminous orthopyroxene assemblages, as well as ternary feldspars and metamorphic pyroxenes. The worldwide number of UHT localities exceeds 40, and may continue to increase as petrologists apply new retrieval methods for extracting information from mineral assemblages in conjunction with mineral chemistry, e.g. the aluminium content of orthopyroxene, and calculated phase equilibria, based on thermodynamic datasets that continue to be refined and improved. This contribution presents a review of UHT metamorphism, including: 1) the history of experiments that have ultimately lead to the precise *P–T* constraints we can now place on the generation and evolution of UHT mineral assemblages; 2) the diagnostic assemblages; 3) the age distribution of UHT metamorphism; 4) the use of calculated phase equilibria to constrain the evolution of UHT rocks; 5) the duration of UHT metamorphic episodes, which is a very active field of research at present; and, 6) the tectonic scenarios that have been proposed for the generation of UHT conditions in the deep crust. The two fundamental types of orogenic systems, namely accretionary and collisional, have been proposed to be potential sites for UHT metamorphism. In contrast to current geodynamic models that are typically unable to account for UHT metamorphic conditions in the deep crust, it may be possible that UHT metamorphism can occur during 'normal' tectonic events. If UHT metamorphism can occur on a regional scale during 'normal' tectonism, it is important to understand all aspects of UHT metamorphism and the implications it has for lithospheric rheology, crust–mantle interactions and the geodynamics of granulite facies metamorphism.

Keywords: UHT granulite; Mineral assemblage; Calculated phase diagrams; Zircon; Tectonic setting

61

Geoscience Frontiers xxx (2014) 1–40

HOSTED BY
ELSEVIER
Contents lists available at ScienceDirect
China University of Geosciences (Beijing)
Geoscience Frontiers
journal homepage: www.elsevier.com/locate/gsf
GEOSCIENCE FRONTIERS

Focus paper

On ultrahigh temperature crustal metamorphism: Phase equilibria, trace element thermometry, bulk composition, heat sources, timescales and tectonic settings

David E. Kelsey *, Martin Hand

Department of Geology and Geophysics, School of Physical Sciences, The University of Adelaide, South Australia 5005, Australia

A R T I C L E I N F O

Article history:
Received 5 July 2014
Received in revised form
16 September 2014
Accepted 22 September 2014
Available online xxx

Keywords:
Sapphirine + quartz
P–T pseudosections
Zr-in-rutile
Ti-in-zircon
U–Pb geochronology
Subduction

A B S T R A C T

Ultrahigh temperature (UHT) metamorphism is the most thermally extreme form of regional crustal metamorphism, with temperatures exceeding 900 °C. UHT crustal metamorphism is recognised in more than 50 localities globally in the metamorphic rock record and is accepted as 'normal' in the spectrum of regional crustal processes. UHT metamorphism is typically identified on the basis of diagnostic mineral assemblages such as sapphirine + quartz, orthopyroxene + sillimanite ± quartz and osumilite in Mg–Al-rich rock compositions, now usually coupled with pseudosection-based thermobarometry using internally-consistent thermodynamic data sets and/or Al-in-Orthopyroxene and ternary feldspar thermobarometry. Significant progress in the understanding of regional UHT metamorphism in recent years includes: (1) development of a ferric iron activity–composition thermodynamic model for sapphirine, allowing phase diagram calculations for oxidised rock compositions; (2) quantification of UHT conditions via trace element thermometry, with Zr-in-rutile more commonly recording higher temperatures than Ti-in-zircon. Rutile is likely to be stable at peak UHT conditions whereas zircon may only grow as UHT rocks are cooling. In addition, the extent to which Zr diffuses out of rutile is controlled by chemical communication with zircon; (3) more fully recognising and utilising temperature-dependent thermal properties of the crust, and the possible range of heat sources causing metamorphism in geodynamic modelling studies; (4) recognising that crust partially melted either in a previous event or earlier in a long-duration event has greater capacity than fertile, unmelted crust to achieve UHT conditions due to the heat energy consumed by partial melting reactions; (5) more strongly linking U–Pb geochronological data from zircon and monazite to *P–T* points or path segments through using Y + REE partitioning between accessory and major phases, as well as phase diagrams incorporating Zr and REE; and (6) improved insight into the settings and factors responsible for UHT metamorphism via geodynamic forward models. These models suggest that regional UHT metamorphism is, principally, geodynamically related to subduction, coupled with elevated crustal radiogenic heat generation rates.

62

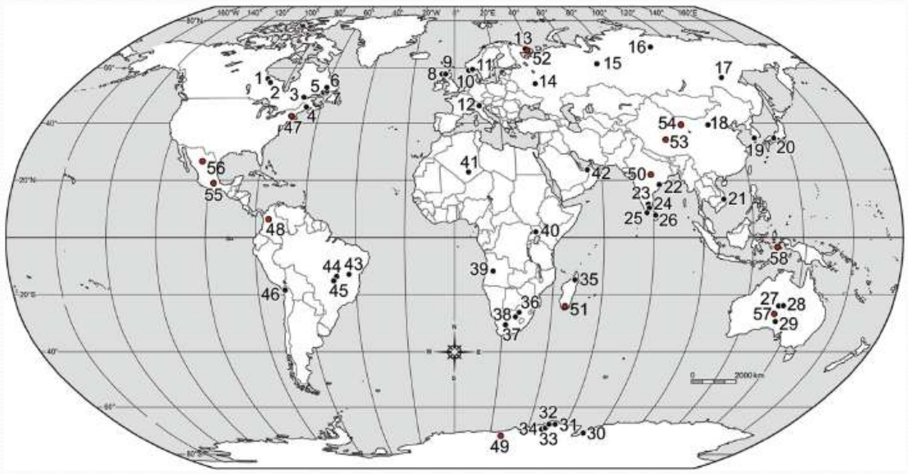
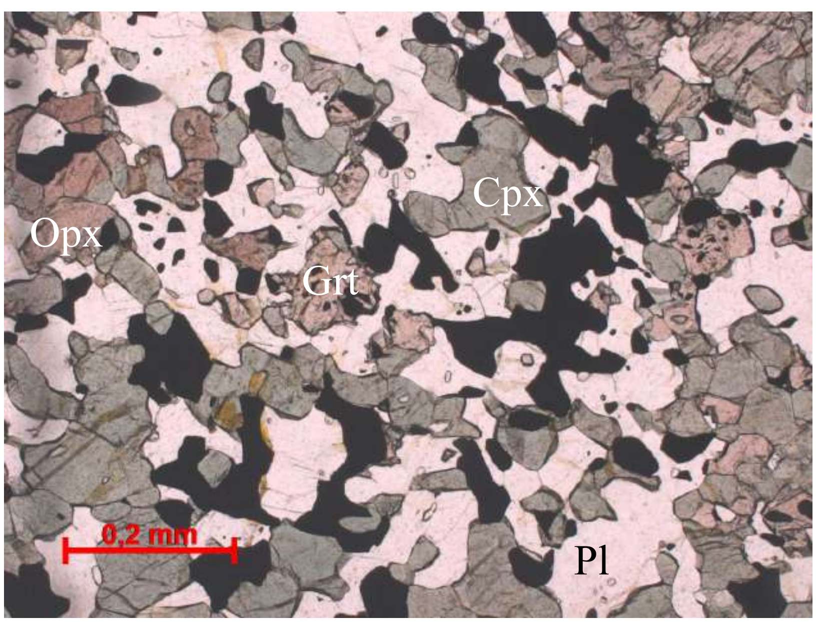


Figure 2. World map of exposed ultrahigh temperature metamorphic rocks (including xenoliths in some cases). The red filled circles denote newly found localities and localities not included in Kelsey (2008). The black filled circles represent localities reported in Kelsey (2008). See Table 1 herein and table 1 in Kelsey (2008) for the studies conducted for each locality.

63

Granulito máfico



granada granulito máfico , *Nappe* Socorro-Guaxupé, Paraguaçu, MG

64

65

Granulito máfico

- Granulito máfico
  - Opx + Ol + Pl ± Hbl (baixa *P*)
  - Opx + Pl + Cpx ± Grt ± Qtz ± Hbl
  - Cpx + Grt + Pl **± Hbl ± Qtz** (alta *P*)
- Ortopiroxênio é o mineral característico
- Associação mineral típica é Opx + Cpx + Pl ± Grt ± Hbl ± Rt ± Ilm
- Reação

  Hbl ± Qtz → Opx + Pl + Cpx + H_2O (ou fusão)

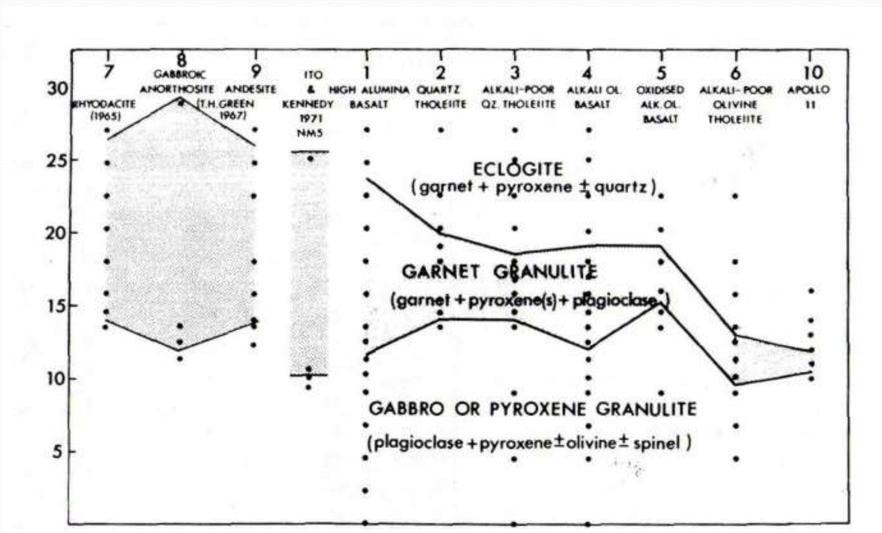
  se o protolito for gabro – só a recristalização em alta *T* é necessária

66

Granulito máfico

- Paragêneses de alta *P* com Qtz + Di + Pl + Grt
- **cuidado com o livro do Yardley (1989)**
- Alguns livros baseiam-se nos trabalhos experimentais de Green & Ringwood (1967, 1972) e Ito & Kennedy (1971) para discussão das paragêneses da fácies granulito e da sua transição para a fácies eclogito

67



Ringwood, 1975

68

Granulito máfico

- Baseado nesses trabalhos, cujo "reagente" nos experimentos é **gabro anidro, sem hornblenda**, em alta *P* temos Cpx + Qtz + Grt ± Pl
- Em rocha com hornblenda (anfibolito) o metamorfismo é diferente, a hornblenda pode entrar em fusão junto com quartzo e plagioclásio; o quartzo é consumido antes da hornblenda, tornando sua coexistência com diopsídio improvável
- A transição para a fácies granulito é dependente da composição da rocha, se quartzo toleíito ou se olivina toleíito

69

rochas com Hbl + Pl + Qtz fundem
anfibolito Cafelândia, migmatito em que Qtz não estava presente no estado sólido no pico metamórfico - Moraes (1997) ou Lima (2006, 2010)

70

Rochas de outras composições na fácies granulito

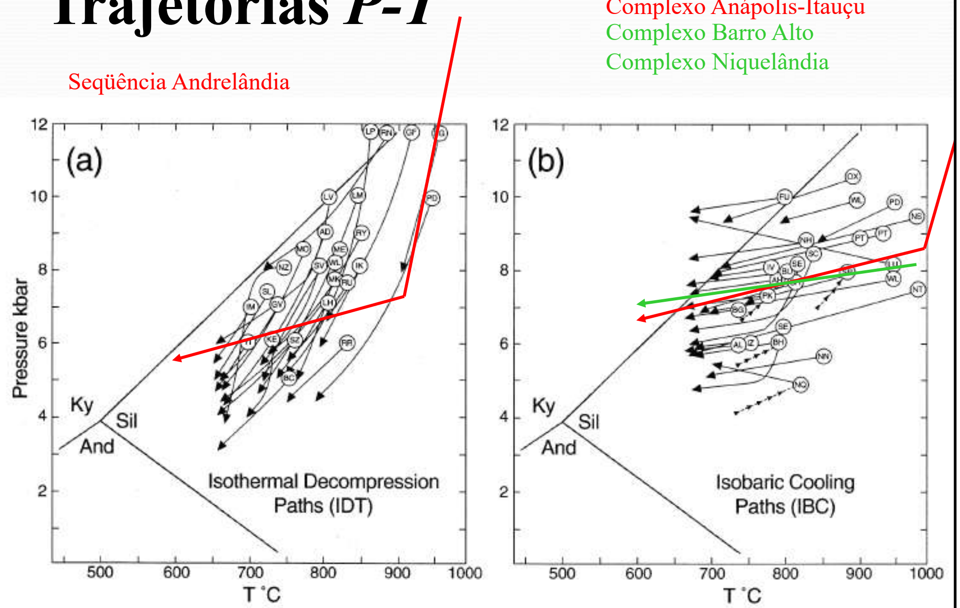
- rochas ultramáficas
  - Di + En + Fo
- rochas ultramáficas com Al_2O_3
  - En + Fo + Spl ± Hbl
- rochas calcissilicáticas
  - Fo + Di
  - Wol + Cc (ou Qtz) ± Cpx
  - Wol + Scp (se *P* > 9 kbar *T* > 900°C)

71

Trajetórias *P-T*

Complexo Anápolis-Itauçu
Complexo Barro Alto
Complexo Niquelândia

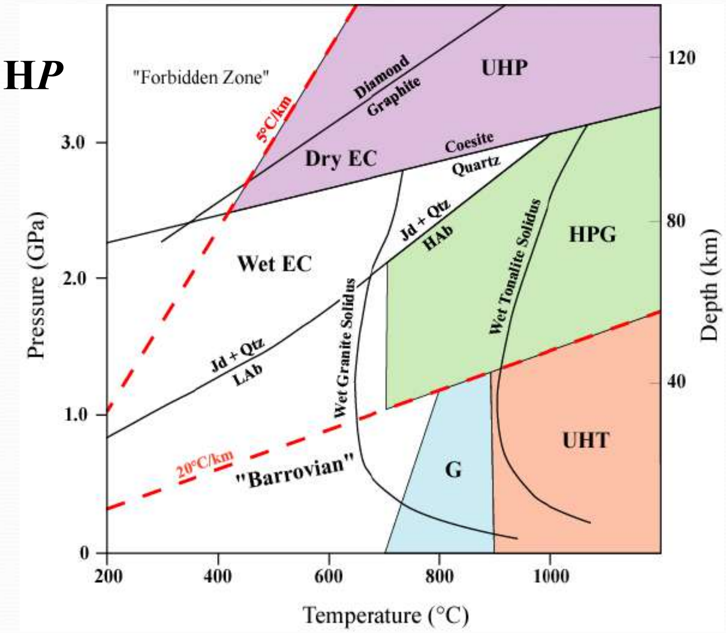
Seqüência Andrelândia



Harley, 1989

72

Granulitos H*P*

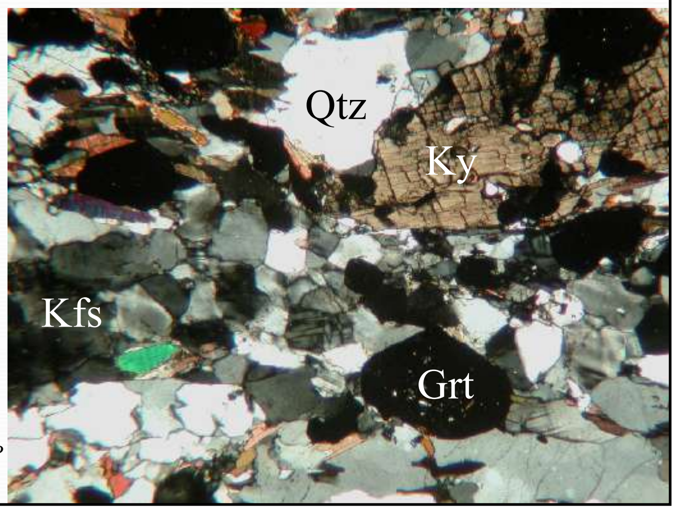


73

74

Granulitos H*P*

- Qtz + Ky + Grt + Kfs (ou feldspato ternário)
- diamante
- coesita

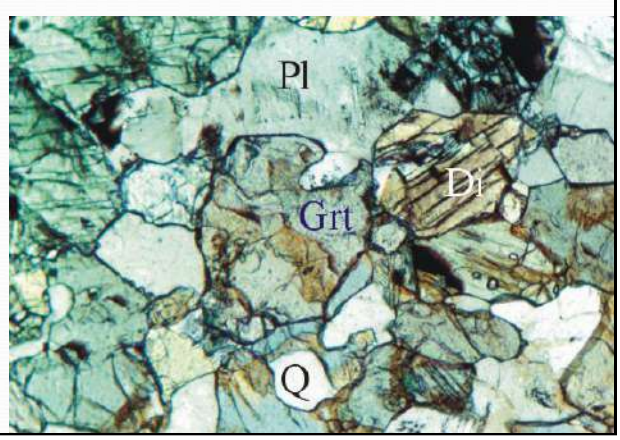


Rt-Grt-Ky-Kfs granulito de alta *P*
Três Pontas, MG

75

Granulitos H*P*

- Grt + Cpx + Pl ± Qtz ± Hbl
- Podem ocorrer eclogitos e peridotitos associados



76

77

Eclogito

- Haüy (1822) rocha formada por granada e clinopiroxênio
  - composição – basalto
  - onfacita (Cpx rico em jadeita, alto Al^{VI} e Na)
  - granada rica em piropo
  - plagioclásio não ocorre como fase primária
  - Rt, Qtz, Opx e Ky são fases adicionais mais comuns
  - fases hidratadas comuns: Hbl, Gln, Ms (fengita), Phl, Tc, Zo
  - Diamante, coesita e aragonita indicam *P* extremamente altas

78

R. G. COLEMAN
D. E. LEE
L. B. BEATTY
W. W. BRANNOCK
U. S. Geological Survey, Menlo Park, Calif.

Eclogites and Eclogites: Their Differences and Similarities

Abstract: Eclogites are divisible into three groups based on mode of occurrence: Group A, inclusions in kimberlites, basalts, or layers in ultramafic rocks; Group B, bands or lenses within migmatite gneissic terrains; Group C, bands or lenses within alpine-type metamorphic rocks. The compositions range from olivine basalt for Group A to tholeiitic basalts for Group C. New analytical data on six eclogites from glaucophane schist terrains in California and New Caledonia now permit comparisons among the three eclogite types. The pyrope content of the garnets is distinctive for each group as follows: Group A, greater than 55 per cent py; Group B, 30–55 per cent py; Group C, less than 30 percent py. Pyroxenes coexisting with these garnets also reflect a compositional change related to their occurrence. The jadeite content progressively increases from Group A through Group B, whereas the diopside content decreases. A comparison of eclogites from different geologic occurrences but with similar bulk compositions demonstrates variation in Ca-Mg partition between coexisting garnet and pyroxene. The Ca/Mg ratio increases in garnet and decreases in pyroxene from Group A through Group B eclogites. This obvious difference in the Ca-Mg partition between coexisting garnet-pyroxene in eclogites of the same bulk composition indicates a broad range of pressure-temperature conditions obtained during crystallization. Experimental synthesis of eclogite-like material at high pressures and temperatures demonstrates that some eclogites may form in the earth's mantle, but naturally occurring Group C eclogites have coexisting garnet-pyroxene with distinct Ca/Mg ratios when compared to Group A or B eclogites of similar bulk composition. This difference in the Ca/Mg ratio must reflect the pressure-temperature conditions characterizing the glaucophane schist facies.

The formation of eclogites within different metamorphic facies is strong evidence of the divergent pressure-temperature conditions that allow basalts to recrystallize into garnet-pyroxene rocks. In view of the rather compelling field evidence, it would seem advisable to discontinue the concept of an eclogite metamorphic facies.

Geological Society of America Bulletin, v. 76, p. 483–508, 12 figs., May 1965

79

LT, MT, HT eclogites

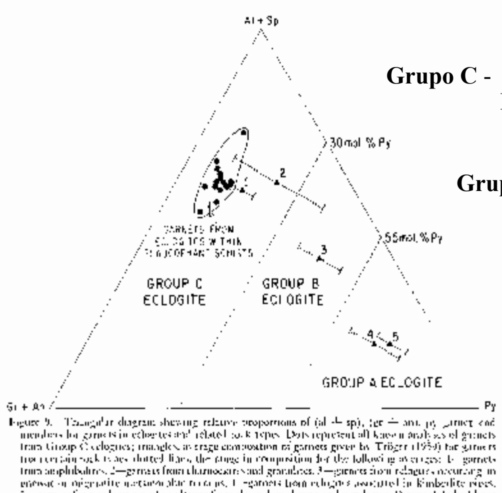


Figure 9. Triangular diagram showing relative proportions of (al + sp), (gr + an), py garnet end members for garnets in eclogites and related rock types. Dots represent all known analyses of garnets from Group C eclogites; triangles, average composition of garnets given by Tröger (1959) for garnets from certain rock types; dotted lines, the range in composition for the following averages: 1—garnets from amphibolites; 2—garnets from charnockites and granulites; 3—garnets from eclogites occurring in gneissic or migmatitic metamorphic terrains; 4—garnets from eclogites associated in kimberlite pipes; 5—garnets from eclogites within ultramafic rocks such as dunite and peridotite. Diagonal dashed lines set off compositional ranges based on the pyrope content of the garnet as related to the geological groupings of the eclogites.

Grupo C - lentes em xistos azuis
LT - $T \sim 600$ °C

Grupo B - lentes em granulitos e migmatitos
MT - $T \sim 900$ °C

Grupo A - xenólitos em basaltos, kimberlitos ou camadas em rochas ultramáficas (algumas lentes de manto)

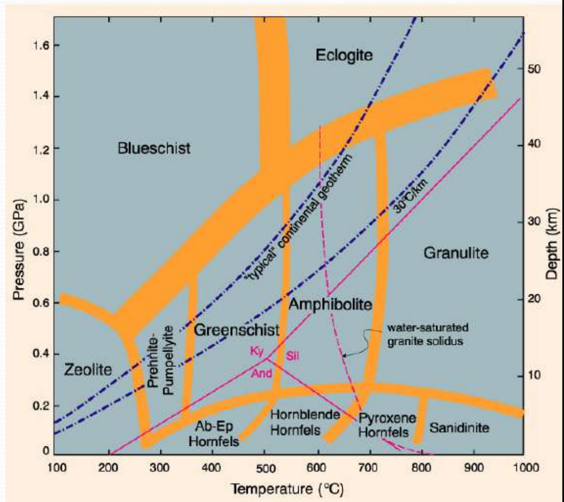
HT - $T > 900$ °C

Coleman, 1965

80

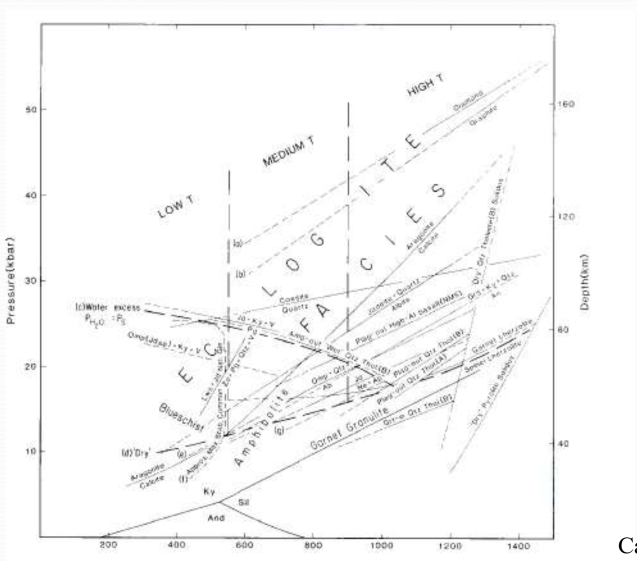
Condições *P-T*

- Equilavente de alta *P* das fácies anfibolito e granulito
  - 550 °C ~ 12 kbar
  - 800 °C ~ 14 kbar



81

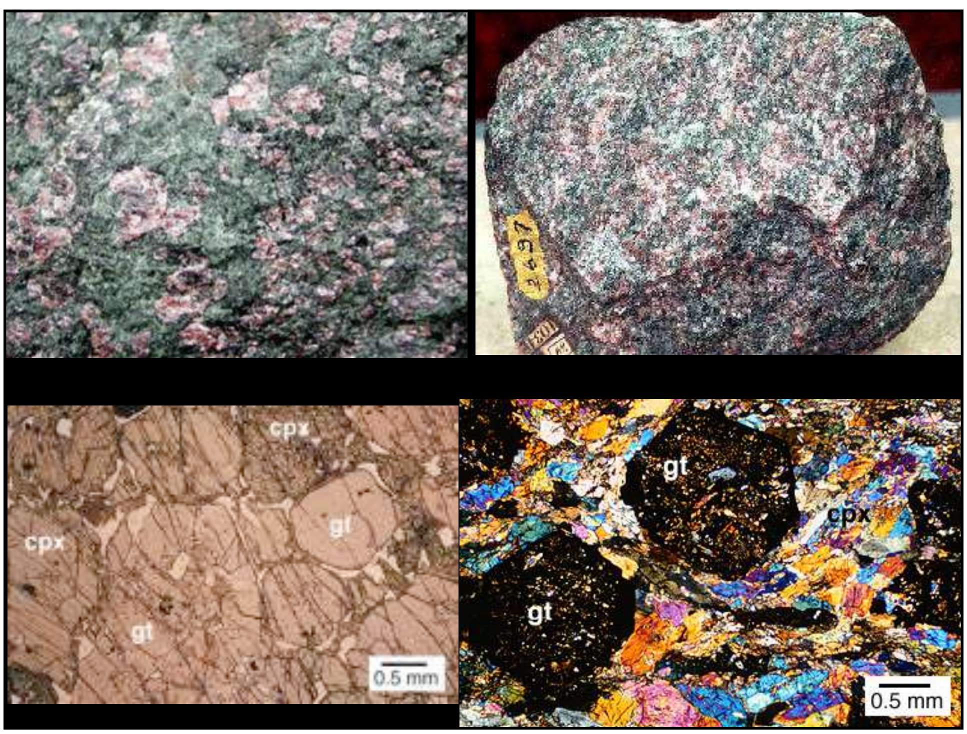
Fácies eclogito



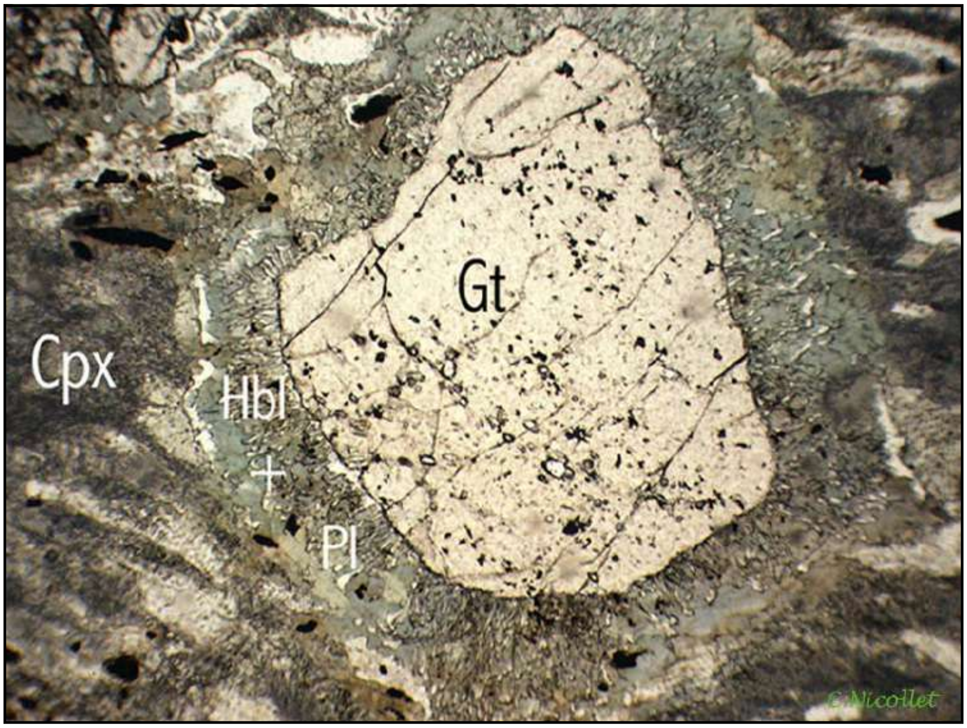
Carswell, 1990

82

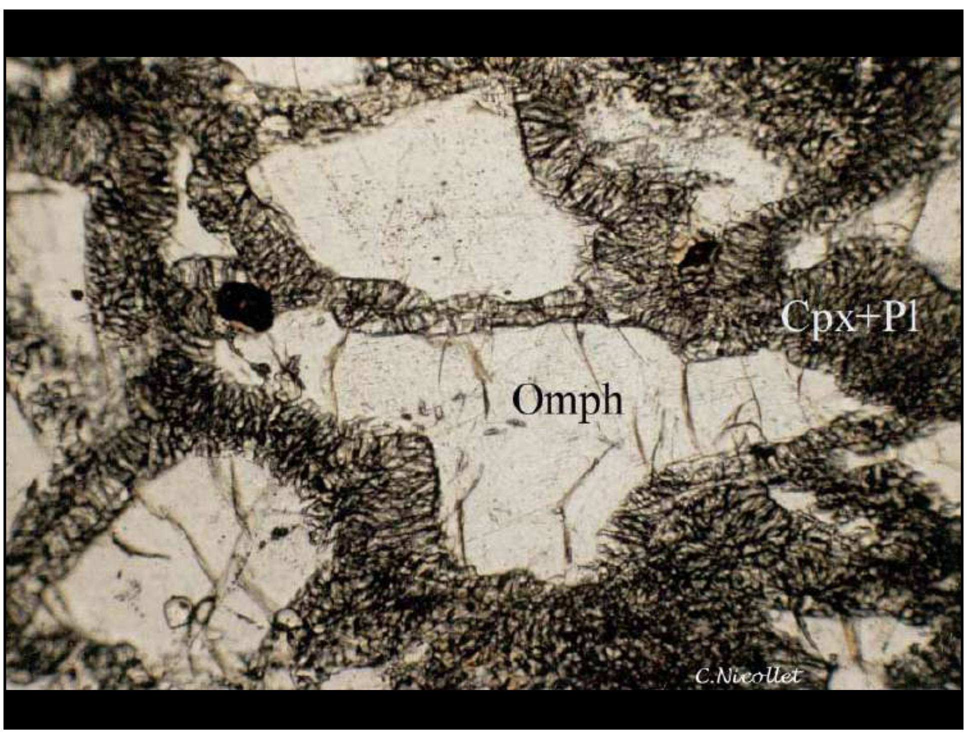
83



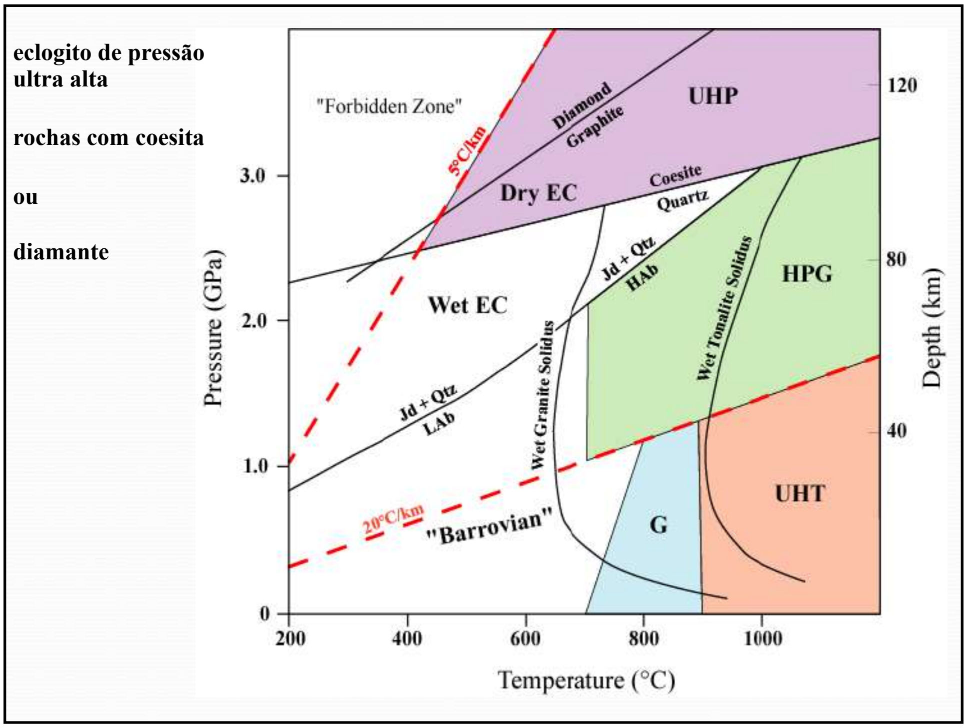
84



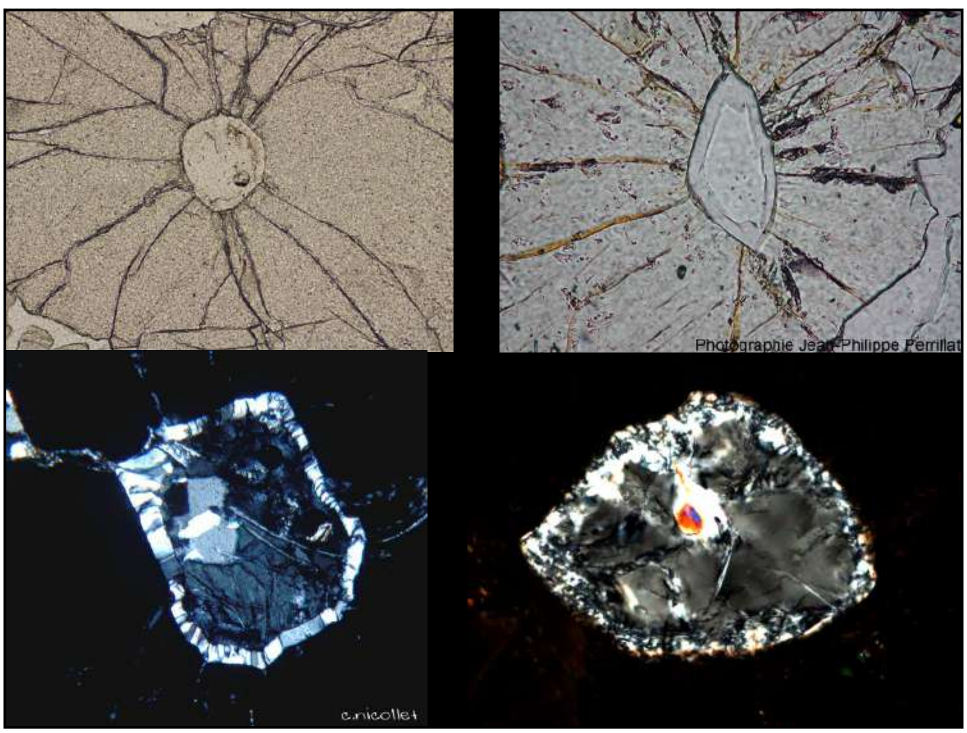
85



86

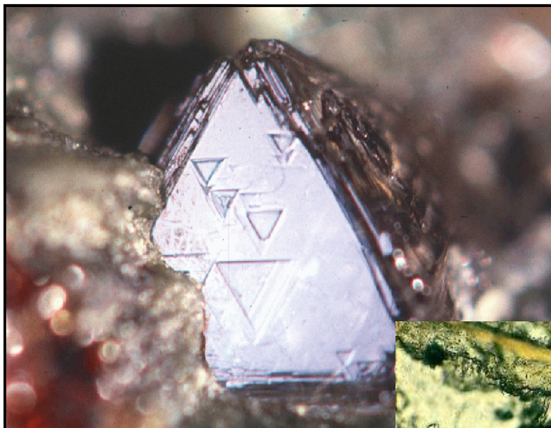

eclogito de pressão ultra alta
rochas com coesita
ou
diamante
"Forbidden Zone"
5°C/km
Diamond
Graphite
UHP
Dry EC
Coesite
Quartz
Jd + Qtz
HAb
Wet EC
Jd + Qtz
LAb
Wet Granite Solidus
Wet Tonalite Solidus
HPG
20°C/km
"Barrovian"
G
UHT
Pressure (GPa)
0
1.0
2.0
3.0
Depth (km)
40
80
120
200
400
600
800
1000
Temperature (°C)

87


Photographie Jean-Philippe Perrillat
c.nicollet

88

micro-diamante metamórfico



89

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. B1, 2029, doi:10.1029/2001JB001127, 2003

Subduction factory
1. Theoretical mineralogy, densities, seismic wave speeds, and H_2O contents

Bradley R. Hacker
Department of Geological Sciences, University of California, Santa Barbara, California, USA

Geoffrey A. Abers
Department of Earth Sciences, Boston University, Boston, Massachusetts, USA

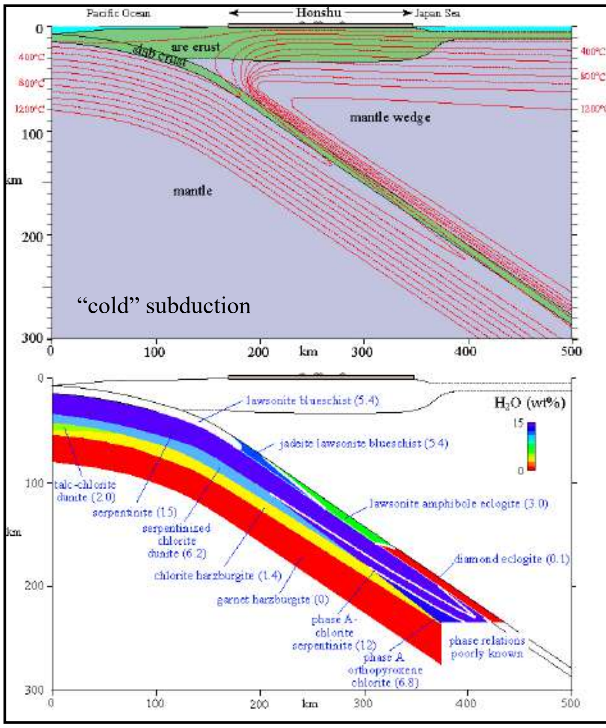
Simon M. Peacock
Department of Geological Sciences, Arizona State University, Tempe, Arizona, USA

Received 27 August 2001; revised 11 June 2002; accepted 18 July 2002; published 18 January 2003.

[1] We present a new compilation of physical properties of minerals relevant to subduction zones and new phase diagrams for mid-ocean ridge basalt, lherzolite, depleted lherzolite, harzburgite, and serpentinite. We use these data to calculate H_2O content, density and seismic wave speeds of subduction zone rocks. These calculations provide a new basis for evaluating the subduction factory, including (1) the presence of hydrous phases and the distribution of H_2O within a subduction zone; (2) the densification of the subducting slab and resultant effects on measured gravity and slab shape; and (3) the variations in seismic wave speeds resulting from thermal and metamorphic processes at depth. In considering specific examples, we find that for ocean basins worldwide the lower oceanic crust is partially hydrated (<1.3 wt % H_2O), and the uppermost mantle ranges from unhydrated to ~20% serpentinized (~2.4 wt % H_2O). Anhydrous eclogite cannot be distinguished from harzburgite on the basis of wave speeds, but its ~6% greater density may render it detectable through gravity measurements. Subducted hydrous crust in cold slabs can persist to several gigapascals at seismic velocities that are several percent slower than the surrounding mantle. Seismic velocities and V_P/V_S ratios indicate that mantle wedges locally reach 60–80% hydration. *INDEX TERMS:* 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 3660 Mineralogy and Petrology: Metamorphic petrology; 3919 Mineral Physics: Equations of state; 5199 Physical Properties of Rocks: General or miscellaneous; 8123 Tectonophysics: Dynamics, seismotectonics; *KEYWORDS:* subduction, seismic velocities, mineral physics, H_2O

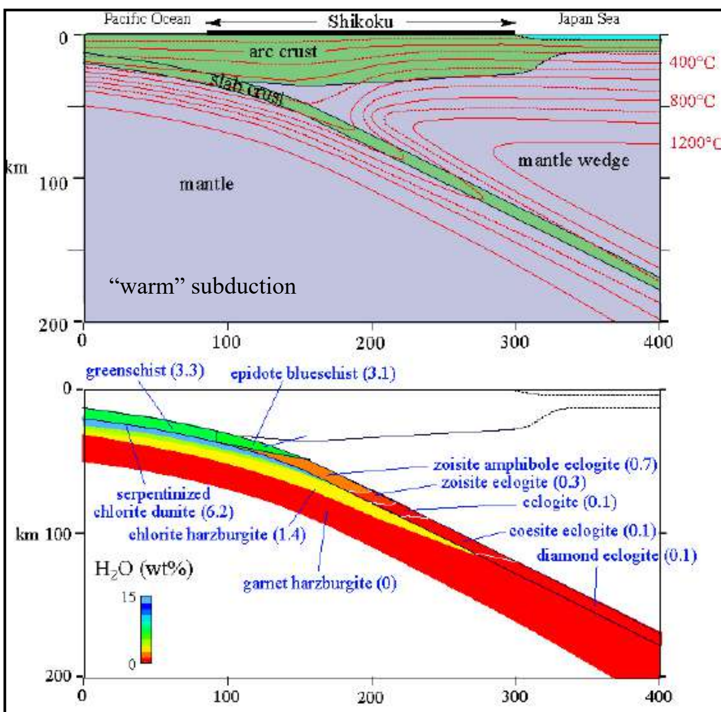
Citation: Hacker, B. R., G. A. Abers, and S. M. Peacock, Subduction factory, 1, Theoretical mineralogy, densities, seismic wave speeds, and H_2O contents, *J. Geophys. Res.*, *108*(B1), 2029, doi:10.1029/2001JB001127, 2003.

90



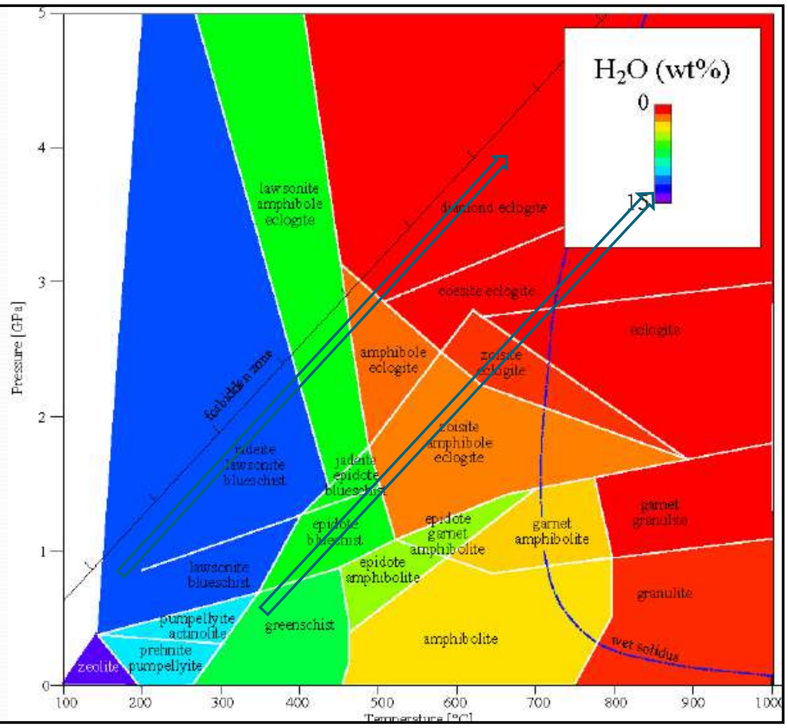
Site do Prof. Bradley Hacker

91



Site do Prof.
Bradley Hacker

92

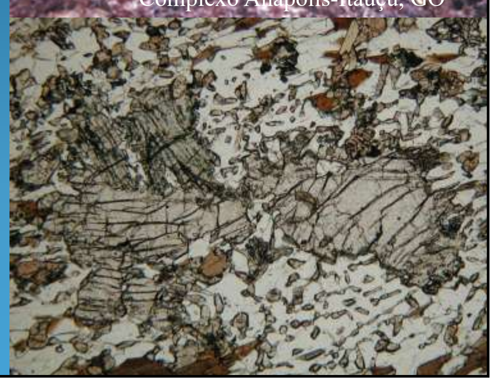


Site do Prof.
Bradley Hacker

93

Granulitos: resíduos de fusão

Preservação das paragêneses da facies granulito



94


Rt-Grt-Ky-Kfs granulito de alta *P*
Três Pontas, MG

95


Leucossoma com Opx em granulito máfico
Complexo Acaiaca, MG

96


Leucossoma com Opx em granulito máfico
Complexo Acaiaca, MG

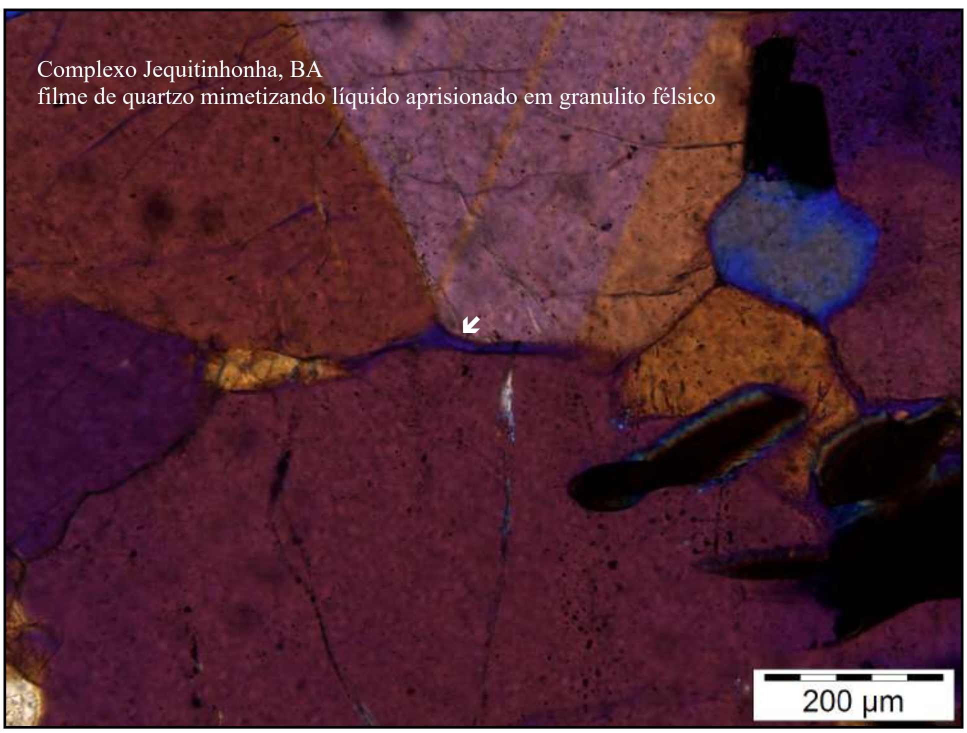
97


Leucossoma praticamente todo exaurido/extraído
com Opx peritético deixado para trás em granulito máfico
Complexo Acaiaca, MG

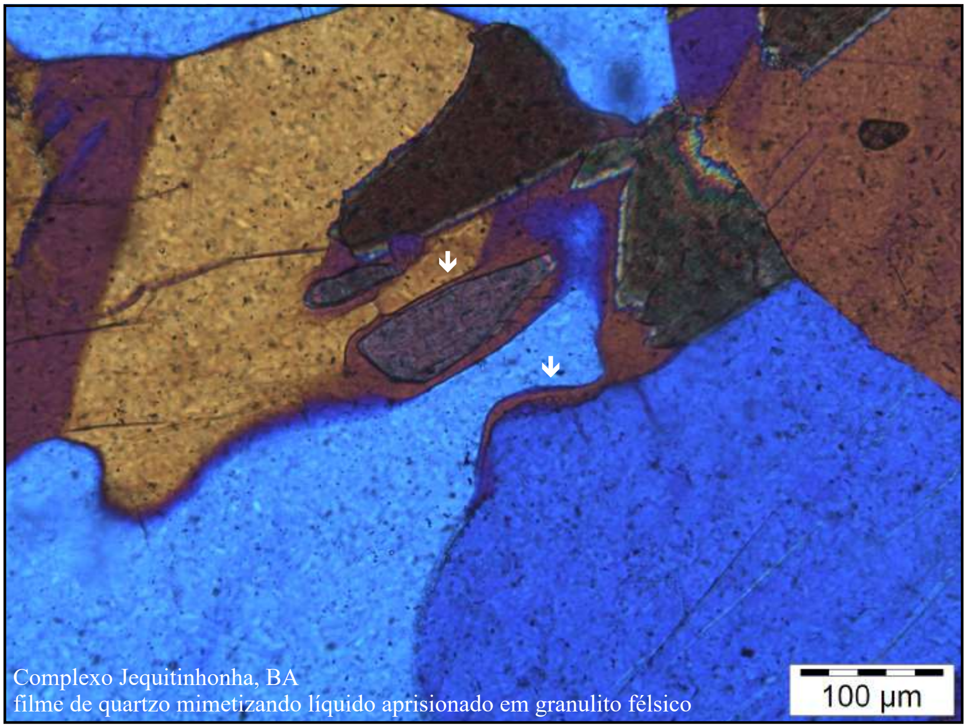
98


Leucossoma praticamente todo exaurido/extraído
com Opx peritético deixado para trás em granulito máfico
Complexo Acaiaca, MG

99


Complexo Jequitinhonha, BA
filme de quartzo mimetizando líquido aprisionado em granulito félsico
200 μm

100



101

Características gerais

- Anatexia se inicia na fácies anfibolito, com fusão da muscovita (com ou sem excesso de H_2O)
- Granulitos são formados por reações de fusão por desidratação de biotita ou hornblenda
  - fusão incongruente – líquido insaturado em H_2O + resíduo sólido
- Granulitos - produtos *in situ* de reações de fusão
- A geração de granulitos esta ligada com a diferenciação da crosta continental
  - crosta superior fértil e rica material granítico
  - crosta inferior exaurida e pobre em elementos produtores de calor

102

Características gerais

- O granulito é formado pelo resíduo do protolito (fases em excesso das reações de fusão) + fases peritéticas (Opx, Grt, Crd, etc)
- Em muitos casos não há melanossoma algum (principalmente de Bt), pois as fases peritéticas podem estar misturadas no resíduo
- A rocha é intensamente recristalizada, raras texturas associadas à fusão são preservadas e algumas poucas de cristalização de líquido aprisionado podem ser observadas
- A preservação das paragêneses requer a separação/perda do fundido do resíduo

103

granada granulito félsico com *boudin* de ultra-restito com granada e ortopiroxênio, Varginha, MG

104

105

J. metamorphic Geol., 2002, **20**, 621–632

Melt loss and the preservation of granulite facies mineral assemblages

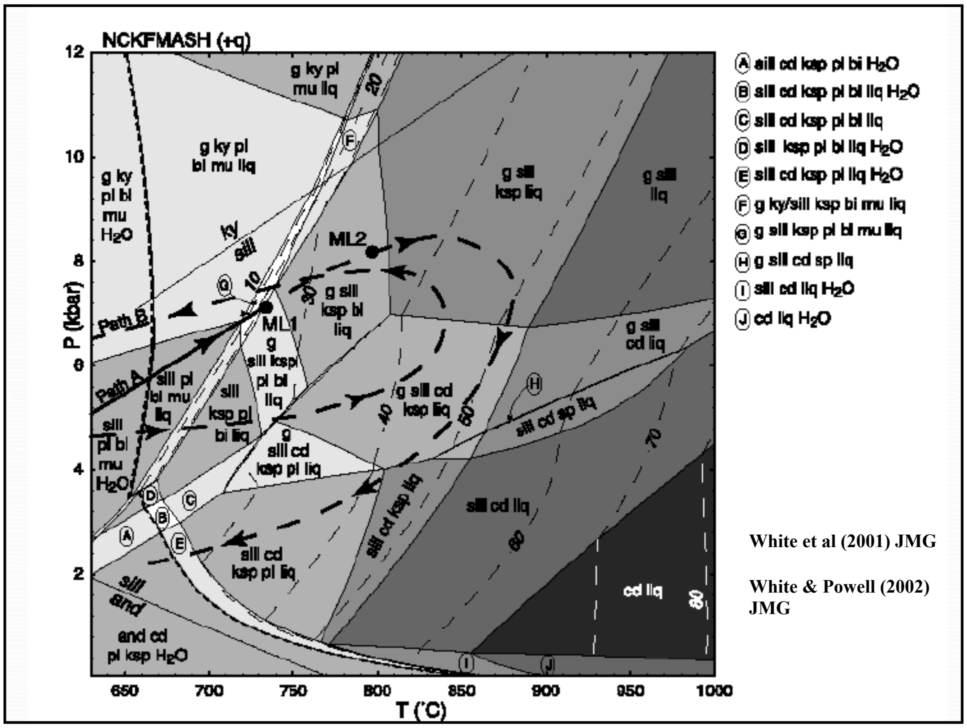
R. W. WHITE AND R. POWELL
School of Earth Sciences, University of Melbourne, Parkville, Victoria 3052, Australia
(r.white@earthsci.unimelb.edu.au)

ABSTRACT The loss of a metamorphic fluid via the partitioning of H_2O into silicate melt at higher metamorphic grade implies that, in the absence of open system behaviour of melt, the amount of H_2O contained within rocks remains constant at temperatures above the solidus. Thus, granulite facies rocks, composed of predominantly anhydrous minerals and a hydrous silicate melt should undergo considerable retrogression to hydrous upper amphibolite facies assemblages on cooling as the melt crystallizes and releases its H_2O. The common occurrence of weakly retrogressed granulite facies assemblages is consistent with substantial melt loss from the majority of granulite facies rocks. Phase diagram modelling of the effects of melt loss in hypothetical aluminous and subaluminous metapelitic compositions shows that the amount of melt that has to be removed from a rock to preserve a granulite facies assemblage varies markedly with rock composition, the number of partial melt loss events and the P–T conditions at which melt loss occurs. In an aluminous metapelite, the removal of nearly all of the melt at temperatures above the breakdown of biotite is required for the preservation of the peak mineral assemblage. In contrast, the proportion of melt loss required to preserve peak assemblages in a subaluminous metapelite is close to half that required for the aluminous metapelite. Thus, if a given proportion of melt is removed from a sequence of metapelitic granulites of varying composition, the degree of preservation of the peak metamorphic assemblage may vary widely.

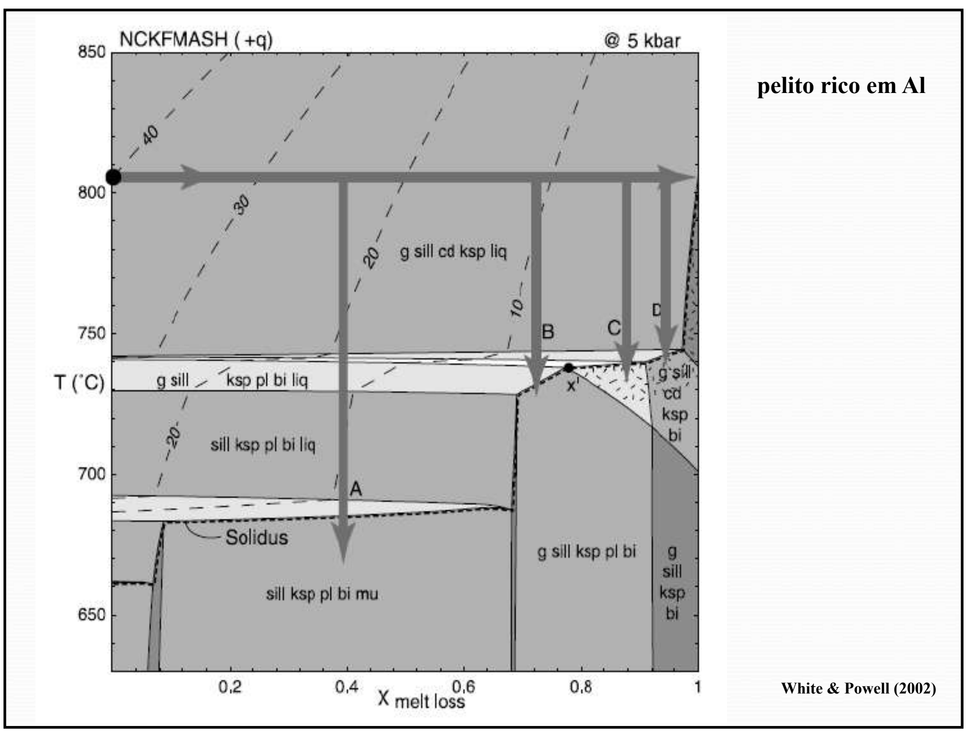
Key words: granulites; melt loss; melting; metapelite.

Mineral abbreviations: quartz, q; garnet, g; sillimanite, sill; cordierite, cd; K-feldspar, ksp; plagioclase, pl; biotite, bi; muscovite, mu; silicate melt, liq.

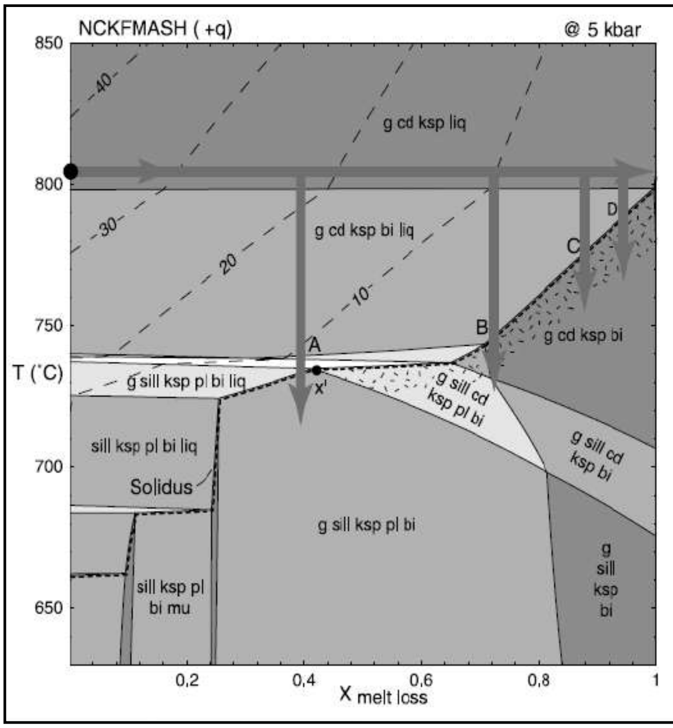
106


NCKFMASH (+q)
P (kbar)
T (˚C)
12
10
8
6
4
2
650
700
750
800
850
900
950
1000
g ky pl mu liq
g ky pl bi mu liq
g ky pl bi mu H2O
ky
sill
sill and
Path B
Path A
ML2
ML1
g sill ksp bi liq
g sill ksp pl bi liq
sill pl bi mu liq
sill ksp pl bi liq
sill pl bi mu H2O
g sill cd ksp pl liq
g sill cd ksp liq
sill cd ksp pl liq
g sill ksp liq
g sill liq
g sill cd liq
sill cd sp liq
sill cd ksp liq
sill cd liq
cd liq
and cd pl ksp H2O
10
20
30
40
50
60
70
80
A sill cd ksp pl bi H2O
B sill cd ksp pl bi liq H2O
C sill cd ksp pl bi liq
D sill ksp pl bi liq H2O
E sill cd ksp pl liq H2O
F g ky/sill ksp bi mu liq
G g sill ksp pl bi mu liq
H g sill cd sp liq
I sill cd liq H2O
J cd liq H2O
White et al (2001) JMG
White & Powell (2002) JMG

107


NCKFMASH (+q)
@ 5 kbar
pelito rico em Al
T (˚C)
850
800
750
700
650
0,2
0,4
0,6
0,8
1
X melt loss
40
30
20
10
g sill cd ksp liq
g sill ksp pl bi liq
sill ksp pl bi liq
Solidus
sill ksp pl bi mu
g sill ksp pl bi
g sill ksp bi
g sill cd ksp bi
A
B
C
D
x
White & Powell (2002)

108



pelito pobre em Al

White & Powell (2002)

109

leucossoma (cinza claro) que reagiu com resíduo granulítico (cinza escuro) gerando zona de reação (*selvedge*, cinza médio)

leucossoma (cinza claro) cristalizado após perda de parte do fundido, que modificou a razão líquido/resíduo impedindo a reação com o resíduo granulítico (cinza escuro)

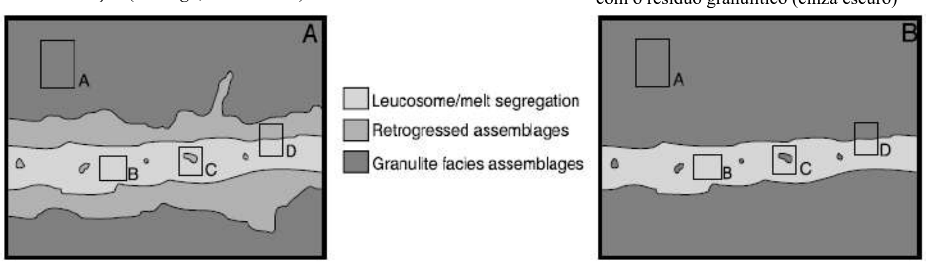


Fig. 5. (a–b). Sketches of two melt segregation/melt loss scenarios. The boxes labelled A–D in both sketches show different amounts of melt–rock interaction (see text for explanation). (a) Sketch showing the possible outcome of melt segregation but no melt loss. In this scenario melt can interact with part of the source rock (b) Sketch showing the preservation of mineral assemblages adjacent to the melt segregation (leucosome). The preservation of the peak metamorphic mineral assemblages adjacent to the melt segregation in this example reflects melt loss from the leucosome.

White & Powell (2002)

110

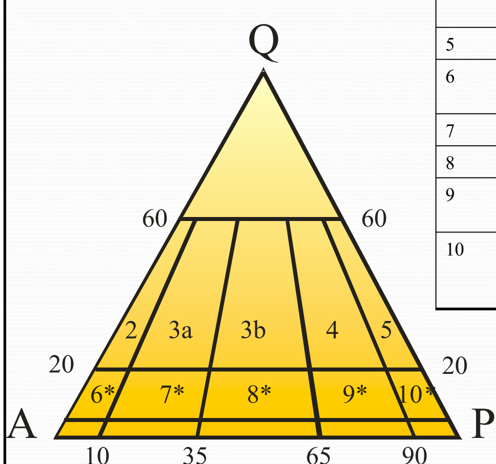
Charnockito

- Charnockitos são rochas ígneas, granitóides, (Qtz, Kfs, Pl) portadoras de ortopiroxênio
- Apresentam contatos intrusivos
- Apresentam microestruturas ígneas (são rochas isotrópicas)
- Nomenclatura proposta por Streckeisen (1974)

111

Charnockito

campo	termo geral	nome
2	hiperstênio feldspato-alcalino granito	feldspato-alcalino chanockito
3	hiperstênio granito	chanockito (3b farsundito)
4	hiperstênio granodiorito	opdalito or charno-enderbito
5	hiperstênio tonalite	enderbito
6	hiperstênio alkali feldspar sienito	
7	hiperstênio syenito	
8	hiperstênio monzonito	mangerito
9	monzonorito (hiperstênio monzodiorito)	jotunito
10	norito (hiperstênio diorito), anortosito (M<10)	

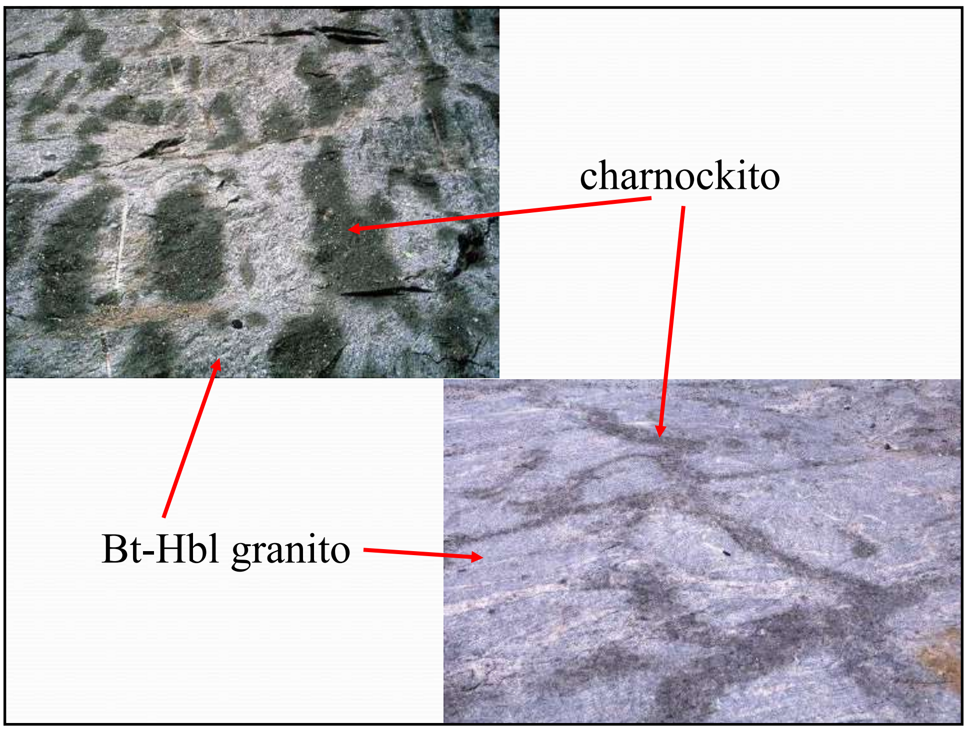


112

Charnockitos, granulitos e o papel do CO_2

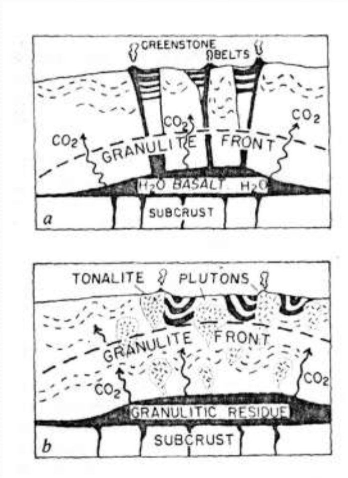
- Comum a ocorrência de charnoquitos sintectônicos
  - são transformados em produtos deformados, gerando confusão na distinção entre charnockito e granulito
- Na Índia e em outros locais do planeta onde ocorrem charnoquitos é comum a ocorrência de granitos "charnockitizados"
- Nas décadas de 1970 e 1980 foi muito difundido o modelo de frentes de CO_2 provenientes do manto para explicar tal feição
- Isso se deve ao fato de que as porções charnockíticas ocorrem apenas inclusões fluidas ricas em CO_2

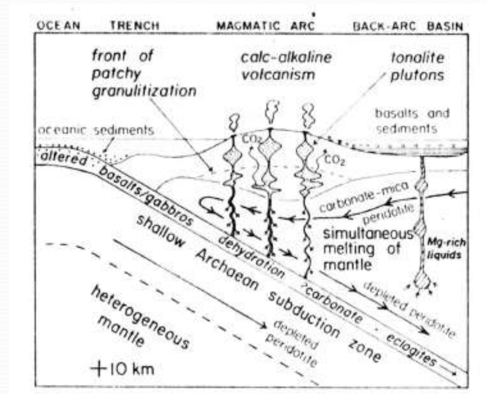
113



114

Modelo de Newton *et al.* (1980)





Modelo *hot spot* Modelo tectônica de placas

115

Problema do CO_2 e dos granulitos

- Em muitos granulitos foi demonstrado que as inclusões de CO_2 são aprisionadas após o pico metamórfico
- Hoje muitos pesquisadores defendem que o mais importante na formação de granulitos é a baixa quantidade de água, formando sistema praticamente anidro

116

Bohlen, S.R. & Mezger, K. 1989. Origin of granulite terranes and the formation of the lowermost continental crust. *Science*. 244:326 - 329.
Bohlen, S.R. 1987. Pressure-temperature time paths and a tectonic model for the evolution of granulites. *Journal of Geology* 95, 617-632.
Bohlen, S.R. 1991. On the formation of Granulites. *Journal of Metamorphic Geology* 9, 223-229.
Ellis, D.J. (1987). Origin and evolution of granulites in normal and thickened crusts. *Geology* 15, 167-170.
Harley, S.L 1989. The origins of granulites: a metamorphic perspective. *Geological Magazine*, 126 (3): 215 - 247.
Kelsey, D.E., 2008, On ultrahigh-temperature crustal metamorphism. *Gondwana Research*, 13, 1-29.
Moraes, R. 2010. O que é granulito? Memórias Del XIX Congreso Geológico Boliviano, Tarija, Bolívia. 167 – 170.
Newton, R.C; Smith, J.V; Windley, B.F. 1980. Carbonic metamorphism, granulites and crustal growth. *Nature*, 288: 45-50.
White, R.W. & Powell, R. 2002. Melt loss and the preservation of granulite facies mineral assemblages. *Journal of Metamorphic Geology* 20, 621-632.
White, R.W. & Powell, R. 2010. Retrograde melt–residue interaction and the formation of near-anhydrous leucosomes in migmatites, *Journal of Metamorphic Geology* 28: 579–597.

117