Fácies metamórficas

Conceito, isógradas, minerais índices, fácies e zonas metamórficas, série de fácies metamórficas

Prof. Renato de Moraes
GMG0332 - Petrologia Metamórfica
Aula 2 - Fácies

Divisões do campo *P-T* do metamorfismo

- As rochas metamórficas são geradas em condições *P-T* variadas dentro da crosta terrestre
- Como sabemos que uma rocha sofreu metamorfismo mais "intenso" que outra?
- É possível comparar o metamorfismo de duas rochas de composições diferentes?
- Podemos perceber essas variações no campo?
- Podemos atribuir valores de *P* e *T* para as condições do metamorfismo que afetou uma rocha?
- Como podemos dividir o campo *P-T* do metamorfismo?

Metamorfismo progressivo

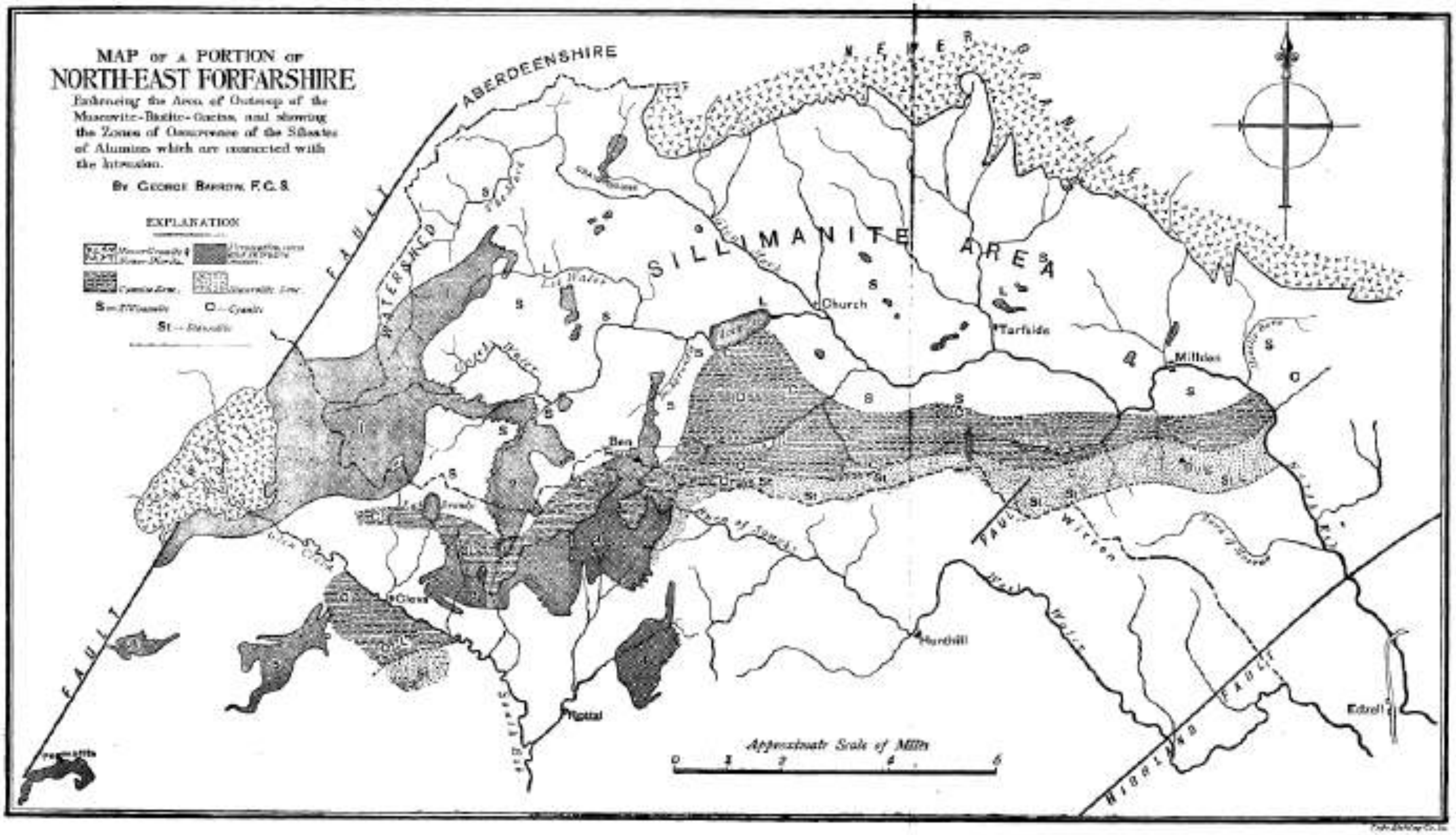
- Primeiros estudos de **metamorfismo progressivo** foram feitos por George Barrow (1893, 1912) nas terras altas (*highlands*) da Escócia
- Barrow identificou **zonas metamórficas**, caracterizadas por **minerais índices**, inicialmente atribuídas ao metamorfismo de contato em torno de granito
  - clorita
  - biotita
  - granada
  - **estaurolita**
  - **cianita (+biotita)**
  - **sillimanita (+biotita)**

29. *On an* Intrusion *of* Muscovite-biotite Gneiss *in the* South-eastern Highlands *of* Scotland, *and its* accompanying Metamorphism.

By George Barrow, Esq., F.G.S. (Communicated by permission of the Director-General of the Geological Survey. Read March 22nd, 1893.)

[Plates XV. & XVI.]

Contents.


MAP OF A PORTION OF
NORTH-EAST FORFARSHIRE
By George Barrow, F.C.S.
EXPLANATION
ABERDEENSHIRE
SILLIMANITE AREA
FAULT
WATERSHED
Church
Tarfside
Millden
Edzell
HIGHLAND FAULT
Approximate Scale of Miles

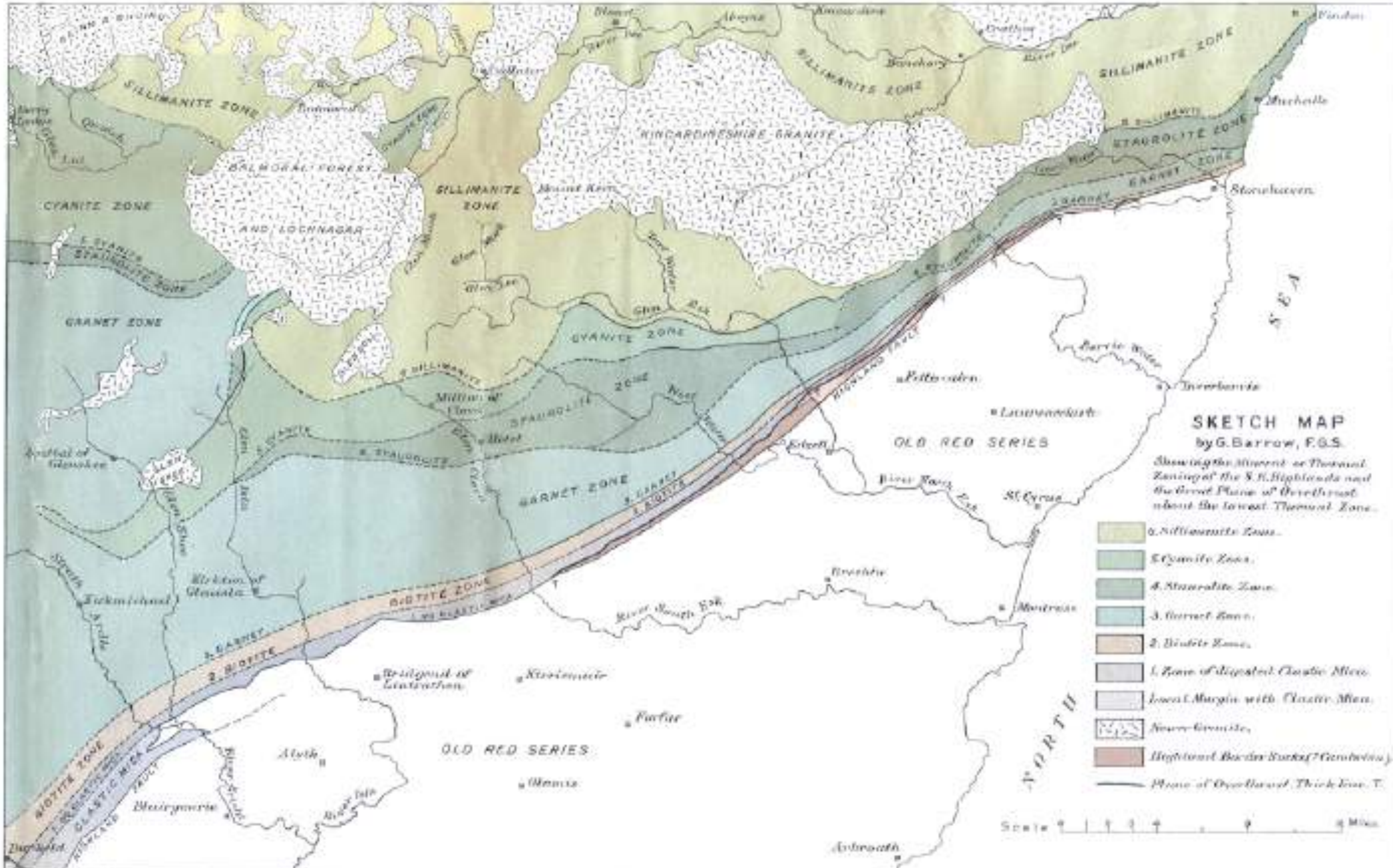
Barrow (1893)

ON THE GEOLOGY OF LOWER DEE-SIDE AND THE SOUTHERN HIGHLAND BORDER.

By GEORGE BARROW, F.G.S.

THE Excursion of the Association to the west of Scotland in September, 1912, was undertaken in order to enable the Members to examine two portions of the great mass of more or less crystalline rocks that cover so large a part of the north of Scotland and of the north-west of Ireland. As it is now well known that the same metamorphosed sediments occur in both countries it will be convenient to call these rocks the Highland series. The object of this examination was to get a true insight into the nature of this great mass of crystalline material; into the cause, in part at least, of its crystallisation, and to study the phenomena occurring along the margins of the mass where it ceases to be crystalline.

I.—The Nature of the Highland Rocks.


SKETCH MAP
by G. Barrow, F.G.S.
SILLIMANITE ZONE
KINCARDINESHIRE GRANITE
BALMORAL FOREST
AND LOCHNAGAR
CYANITE ZONE
STAUROLITE ZONE
GARNET ZONE
BIOTITE ZONE
OLD RED SERIES
NORTH
SEA
Stonehaven

Barrow, 1912

Isógrada, mineral índice e paragênese

- Cecil .F. **Tilley** (1924a, 1925) confirmou e estendeu as zonas de Barrow por toda a região do Dalradiano
- **Mineral índice** caracteriza uma zona metamórfica (Tilley, 1924b)
- O limite de cada zona mineral é marcado por **isógradas** - linha que marca o **primeiro aparecimento** ou **desaparecimento** do mineral índice
  - isógrada da biotita (**Bt in**)
  - isógrada do desaparecimento da muscovita (**Ms out**)
- O termo **isógrada** foi cunhado por Tilley (1924b)

1924 a

4. Contact-Metamorphism in the Comrie Area of the Perthshire Highlands. By Cecil Edgar Tilley, Ph.D., B.Sc., F.G.S. (Read June 6th, 1923.)

(Plate IV.)

Contents.

1925

5. A Preliminary Survey of Metamorphic Zones in the Southern Highlands of Scotland. By Cecil Edgar Tilley, Ph.D., B.Sc., F.G.S. (Read June 4th, 1924.)

(Plate IX—Map.)

Contents.

I. Introduction.

Thirty-one years ago, Mr. George Barrow (1)[1] presented to this Society his classic account of the intrusion phenomena of a group of 'Older Granites' in the Forfarshire area of the South-Eastern Highlands. That paper is distinguished by reason of the clear enunciation of the two outstanding conclusions to which the author was led. In the one was illustrated for the first time the effect of crustal stresses on the differentiation course of igneous magmas, a process which plays so important a part in present-day theories of petrogenesis; in the other, also for the first time, was indicated the subdivision of a group of highly-metamorphosed sediments into metamorphic zones characterized by the presence of critical index-minerals. So far as I am aware, his paper represents the first attempt in petrological literature to bring precision to the study of regional metamorphism, by laying upon a map zonal lines indicative of varying grades of metamorphism.

1924 b

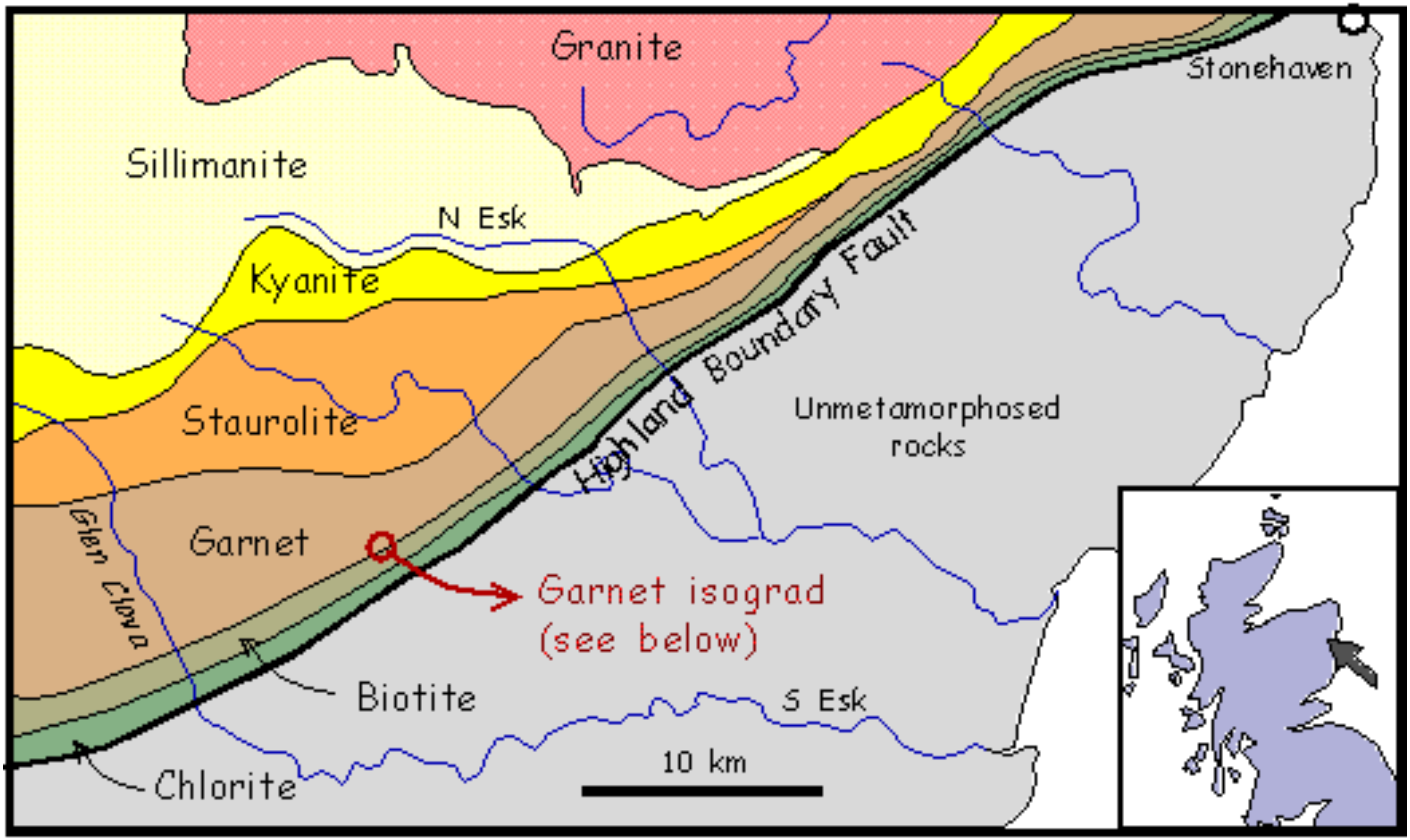
The Facies Classification of Metamorphic Rocks.

By C. E. Tilley.

THE diversity in mineral composition of metamorphic rocks can be regarded as the resultant of two independent variables, first of the ultimate composition of the rocks, and secondly of the grade of metamorphism, or the particular pressure-temperature conditions under which the rocks have arisen. It is clear that these two variables may well form the basis of a classification of rocks of metamorphic origin.

In Grubenmann's well-known classification of the crystalline schists [1] these two variables occupy the dominant positions, and are the foundation upon which his classification is erected. Thus the twelve groups adopted by Grubenmann represent the composition-variable, and his three-fold division of depth zones—epi, meso, and kata—is an attempt to express the variation induced by the imposition of varying physical environment, in other words the grade.

Whatever may be said of the chemical part of Grubenmann's classification, there can be few who would regard the division into three zones as satisfactory or at all adequate to express the diversity of rock types brought about by their subjection to varying grades of metamorphism. Moreover, Grubenmann has no well-defined place for rocks which have arisen under the conditions prevailing in contact metamorphism, and for any classification to be adequate, such rock types cannot be ignored.



Metamorphic mineral zones in NE Scotland, after Barrow and Tilley

Isógrada, mineral índice e paragênese

- **Isógrada** é a linha em mapa que marca o aparecimento ou desaparecimento de um mineral índice

- **Paragênese** é a associação mineral estável na rocha durante o **pico do metamorfismo**

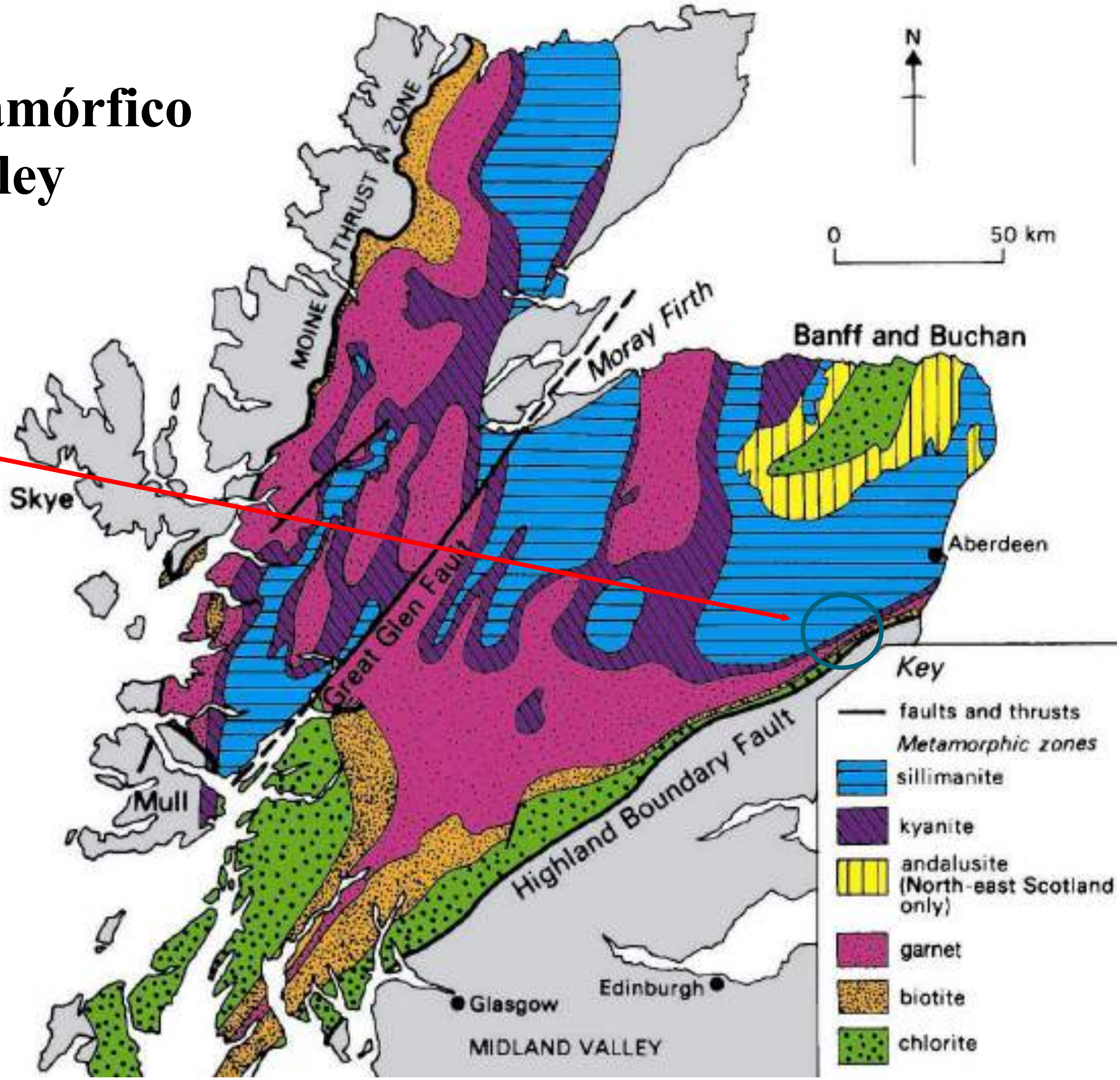
- **Pico metamórfico** é a condição de mais alta temperatura alcançada pela rocha e pressão associada

Metamorfismo (tipo) barroviano

- Barrow observou que entre as zonas da clorita e sillimanita ocorre aumento do tamanho do grão; ele associou o fato ao efeito do aumento de temperatura – daí a ideia de **metamorfismo progressivo**
- Com o aumento do metamorfismo as rochas ficam mais "cristalinas" e perdem as características sedimentares originais
- Na Escócia, o denominado **metamorfismo barroviano** gera a sequência de minerais índices **Chl, Bt, Grt, St, Ky, Sil**
- A sequência de minerais pode mudar com a composição da rocha ou com variações nas condições *P-T* (diferentes das rochas da Escócia)

Mapa metamórfico de Tilley

Área em que Barrow trabalhou



rocha da zona da biotita, Escócia
Foto: Renato Moraes

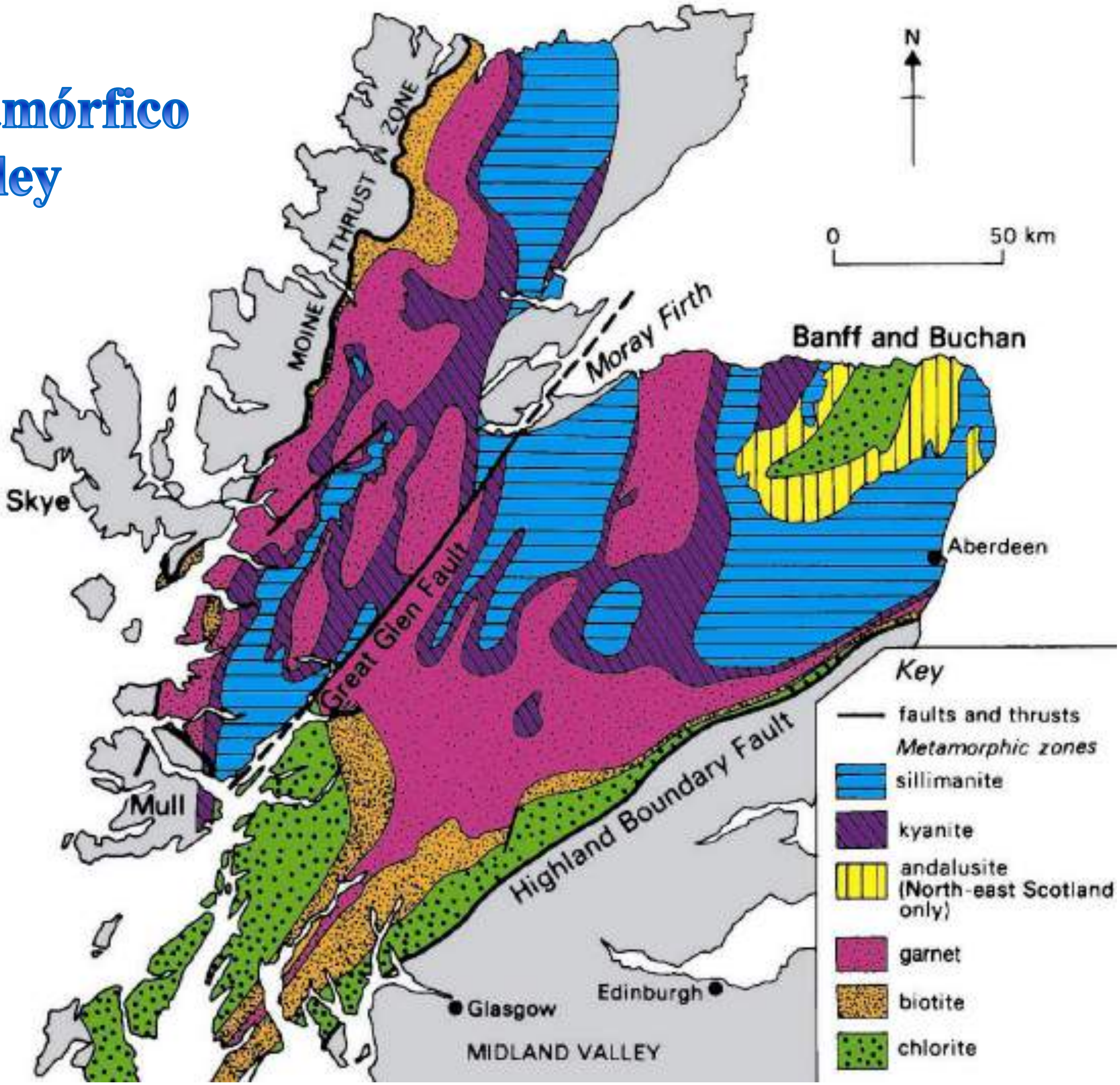
Metamorfismo tipo barroviano e buchan

- Na região a NE da Escócia, distritos de Buchan e Banff, **Tilley** descobriu que pelitos de composição idêntica aos estudados por Barrow podem apresentar sequência de minerais - índice diferente:

clorita – biotita – cordierita – andaluzita - sillimanita

- Razão da diferença da sequência de minerais-índices: condições de *P*-*T* (*P* mais baixa) durante o metamorfismo

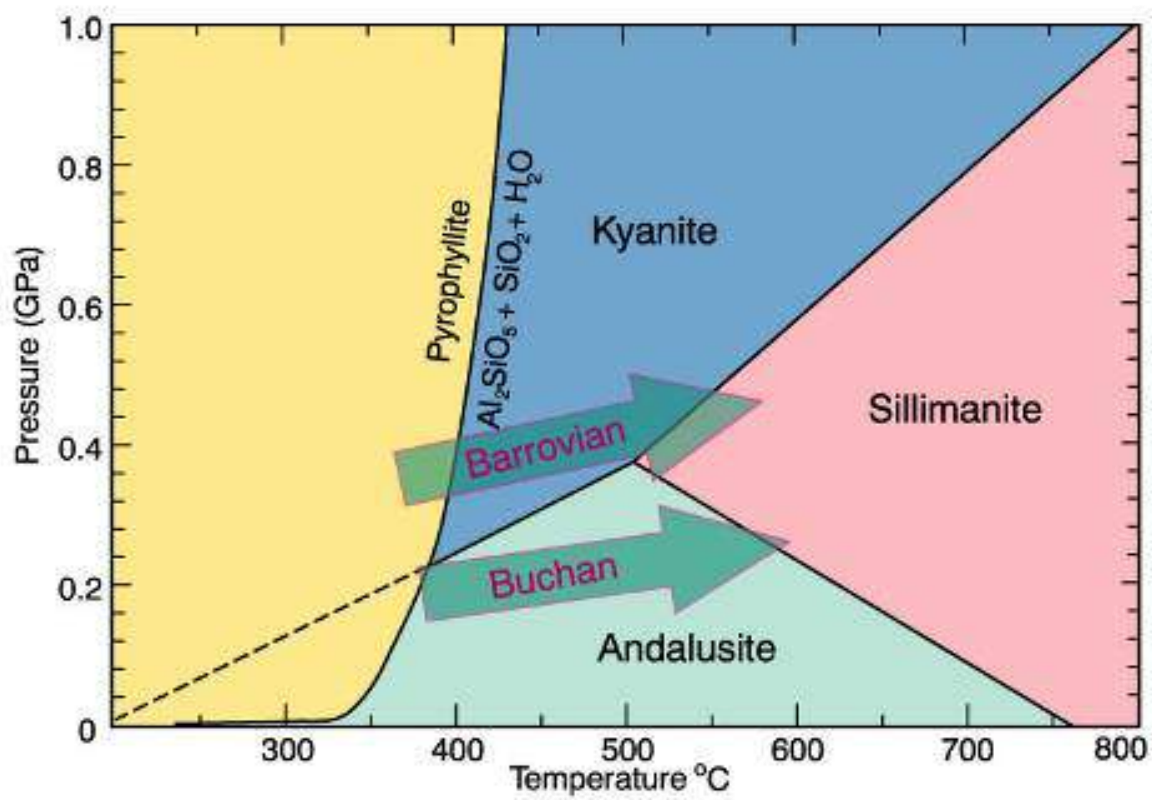
Mapa metamórfico de Tilley



Metamorfismo barroviano e buchan

- Então duas coisas determinam a sequência dos minerias metamórficos:
  - *P* e *T*
  - composição

  da rocha



Termodinâmica e o metamorfismo

- **Victor Moritz Goldschmidt** (1911, 1912a) foi o primeiro petrólogo a ver as rochas como sistemas químicos e aplicar os conceitos da termodinâmica às rochas, principalmente o conceito de **equilíbrio químico** e a **regra das fases**

- Ele estudou a auréola de metamorfismo de contato na região de Oslo, Noruega. No contato são observadas **paragêneses** em rochas pelíticas, calcárias e psamíticas

- **Em cada rocha, a paragênese que ocorre em cada zona da auréola de contato é quimicamente equivalente à paragênese das outras zonas**

- A **paragênese** (associação mineral) reflete **condições de equilíbrio** e está relacionada à *P, T*, composição da rocha e do fluido

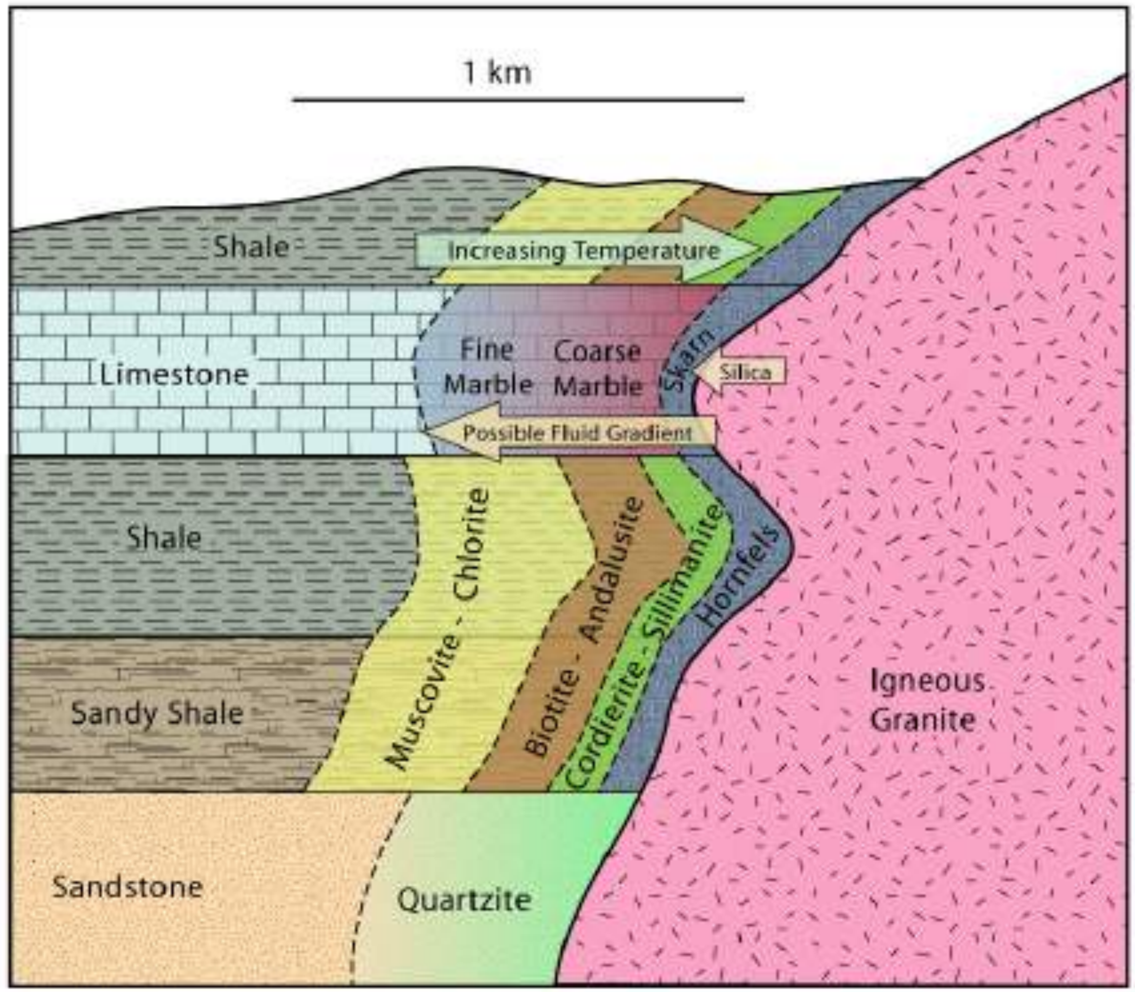
Paragêneses observadas na auréola de contato perto de Oslo, Noruega

Pelito

1 – Qtz + Ms + And + Bt
2 – Qtz + Kfs + And + Crd (Bt)
3 – Qtz + Kfs + And + Crd + Pl (Bt)
4 – Qtz + Kfs + Sil + Crd + Pl (Bt)
5 – Qtz + Kfs + Pl + Crd + Opx

Calcário

1 – Pl + Di + Grs + Cc + Qtz
2 – Di + Grs + Ves + Cc + Qtz
3 – Di + Grs + Wo + Ves + Cc



Termodinâmica e o metamorfismo

- **Goldschmidt** é responsável por um dos maiores avanços no entendimento do metamorfismo quando começou a tratar as rochas como **sistemas químicos** e com base na **termodinâmica**
  - Ele entendeu que sob o efeito da temperatura, a rocha é submetida ao metamorfismo e que a paragênese define um momento de **equilíbrio químico**
  - Ele provou que o **eclogito** nada mais é do que **gabro** (ou basalto) metamorfizado; ele comparou a composição e o volume molar da associação **plagioclásio + augita** com as das fases quimicamente equivalentes, **onfacita + piropo,** e concluiu que o eclogito era o gabro submetido a **altas pressões!**

Fácies metamórficas

- **Pentii Eskola** (1914, 1915) estudou a auréola da região de Orijärvi, Finlândia
- Em Oslo foram observadas rochas com **feldspato potássico + cordierita**, mas em Orijärvi ocorre o par equivalente **biotita + muscovita**
- Através da comparação das várias associações minerais, Eskola concluiu que as diferenças devem refletir condições físicas (*P*-*T*) diferentes durante a formação das auréolas de contato, já que as composições das rochas são semelhantes
- Concluiu ainda que as rochas da Finlândia, que apresentam associação hidratada e de menor volume molar, foram formadas em condições de *T* mais baixa e *P* mais alta do que as rochas da Noruega

Fácies metamórficas

Pentti Eskola

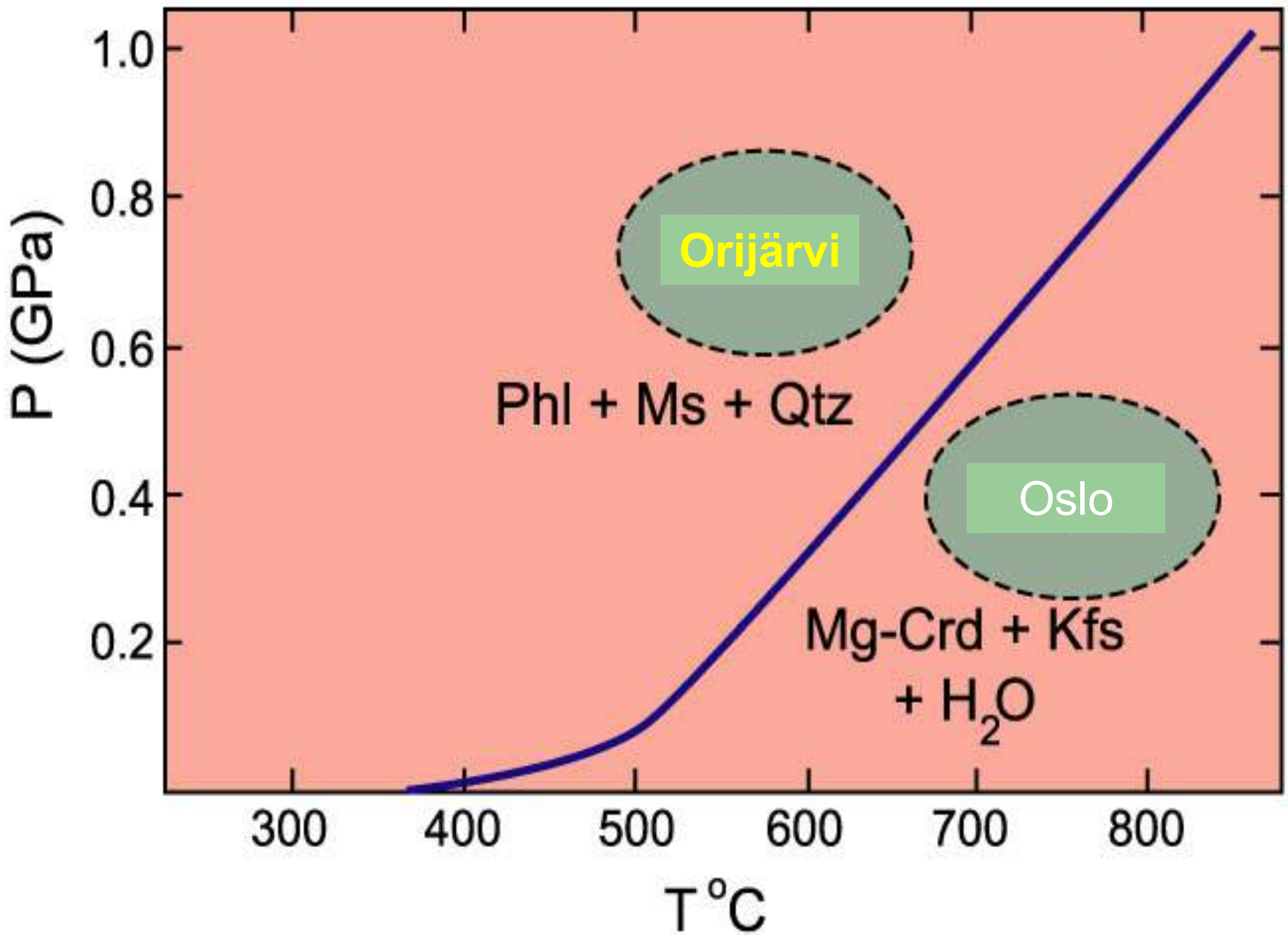
Oslo	Orijärvi
Kfs + And	Ms + Qtz
Kfs + Crd	Bt + Ms
Kfs + Opx + Pl	Bt + Hbl
Opx	Ath

$$2\ KMg_3AlSi_3O_{10}(OH)_2 + 6\ KAl_2AlSi_3O_{10}(OH)_2 + 15\ SiO_2$$

Bt Ms Qtz

$$= 3\ Mg_2Al_4Si_5O_{18} + 8\ KAlSi_3O_8 + 8\ H_2O$$

Crd Kfs



1.0
0.8
0.6
0.4
0.2
P (GPa)
Orijärvi
Phl + Ms + Qtz
Oslo
Mg-Crd + Kfs
+ H2O
300
400
500
600
700
800
T °C

Fácies metamórficas

Baseado nas observações das duas auréolas de contato Eskola (1915, 1920) desenvolveu o conceito de **fácies metamórfica**:

- Duas rochas de composições semelhantes produzem sequências de associações metamórficas diferentes se submetidas a condições *P-T* diferentes

- Se a rocha atingiu o equilíbrio químico em dada condição *P-T* do metamorfismo, sua mineralogia é controlada pela composição da rocha

- A evolução para a petrologia metamórfica é o entendimento da **associação mineral (paragênese)** como resultado do **equilíbrio químico** alcançado durante o metamorfismo, ao invés de considerar só os **minerais - índices**

Fácies metamórficas

- Nome das fácies é proveniente do nome da **rocha máfica** característica daquelas condições *P-T* (ex: xisto verde, xisto azul, eclogito, anfibolito)

  - os limites das fácies são definidos por mudanças na associação mineral ou na química dos minerais das rochas máficas
  - os limites das fácies não são absolutos pois dependem de H_2O/CO_2 e da composição da rocha
  - os limites são faixas e podem ser representados por reações contínuas

- A fácies metamórfica é dada pela paragênese (associação mineral) formada no pico do metamorfismo (T_{max})

Fácies metamórficas

- **basalto –** augita + plagioclásio (An_{50})

- **xisto verde** – clorita ou epidoto + actinolita + albita $\pm$ granada
- **anfibolito** – hornblenda + plagioclásio (An > 17) $\pm$ granada
- **granulito** – ortopiroxênio + clinopiroxênio + plagioclásio $\pm$ granada
- **xisto azul** – glaucofâna + epidoto ou lawsonita + albita $\pm$ granada $\pm$ clorita
- **eclogito** – onfacita + piropo

Fácies metamórficas

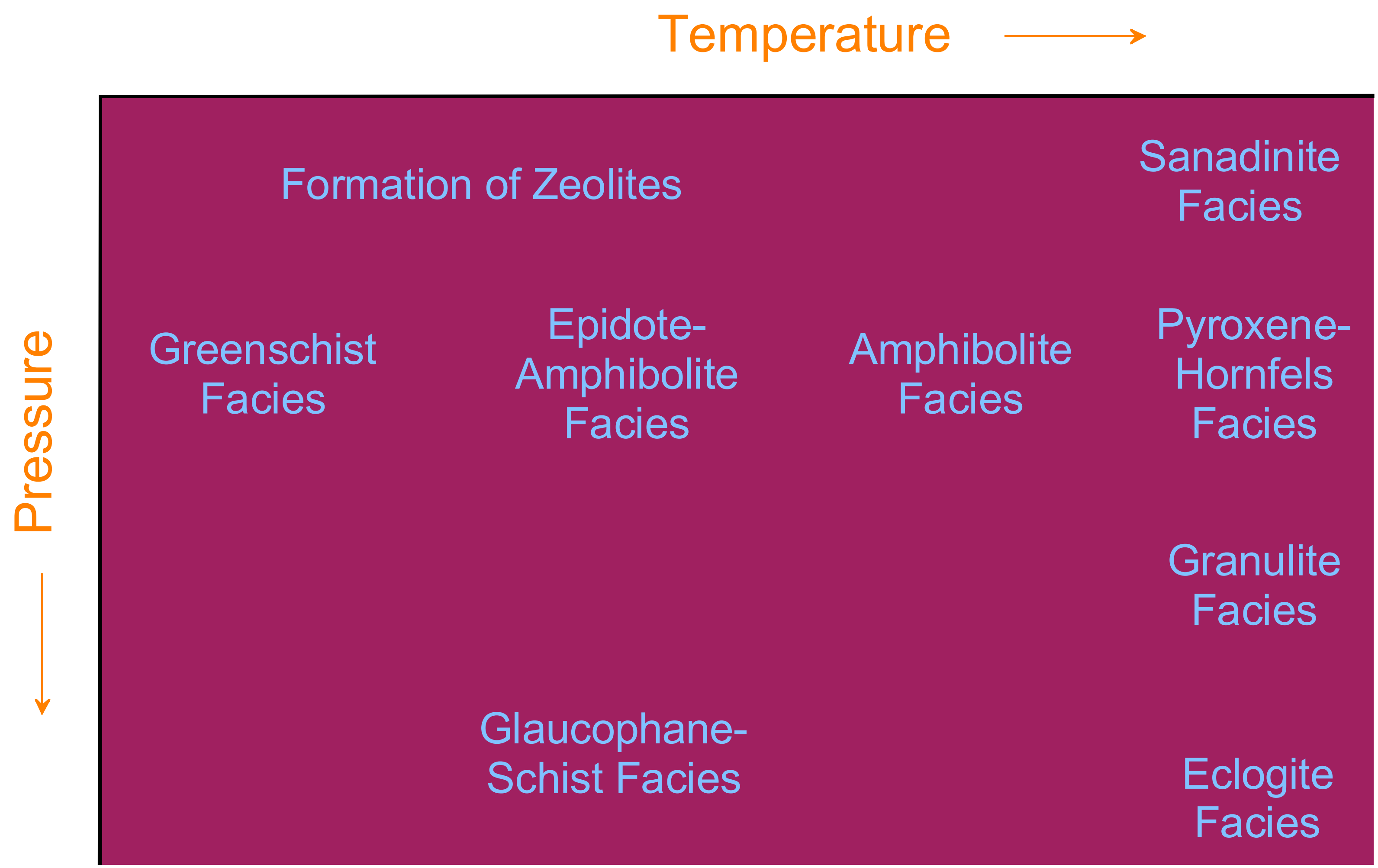


Fig. 25-1 The metamorphic facies proposed by Eskola and their relative temperature-pressure relationships. After Eskola (1939) *Die Entstehung der Gesteine*. Julius Springer. Berlin.

Contr. Mineral. and Petrol. 12, 354—364 (1966)

Reappraisal of the Metamorphic Facies Concept

W. S. Fyfe and F. J. Turner

Department of Geology, Manchester University, and Department of Geology, University of California

Received February 28, 1966

Abstract. Eskola's concept of metamorphic facies, now 50 years old, is reappraised in the light of current knowledge and usage among petrologists. Facies should be defined solely in terms of observable geologic criteria. Like Eskola, we continue to view each facies as a set of mineral assemblages that approximate equilibrium within a definite range of temperature; but this is inference and must be excluded from the definition of facies.

Mutual boundaries between facies are transitional. Division into subfacies has proved unacceptable to many writers, and has led to confusion in the physical interpretation of metamorphic parageneses. We propose henceforth not to recognize subfacies.

Eleven facies are recognized in this paper and their terminology has been adapted as nearly as possible to current general usage:

A. Low-pressure facies commonly but not exclusively of contact metamorphism. In order of increasing temperature:

(1) Albite-epidote hornfels.

(2) Hornblende-hornfels.

(3) Pyroxene-hornfels.

(4) Sanidinite.

B. High-pressure low-temperature facies of regional metamorphism. In order of increasing pressure:

(5) Zeolitic.

(6) Greenschist.

(7) Glaucophane-lawsonite-schist.

C. High-pressure medium- to high-temperature facies of regional metamorphism. In order of increasing temperature:

(8) Albite-epidote-amphibolite.

(9) Amphibolite.

(10) Granulite.

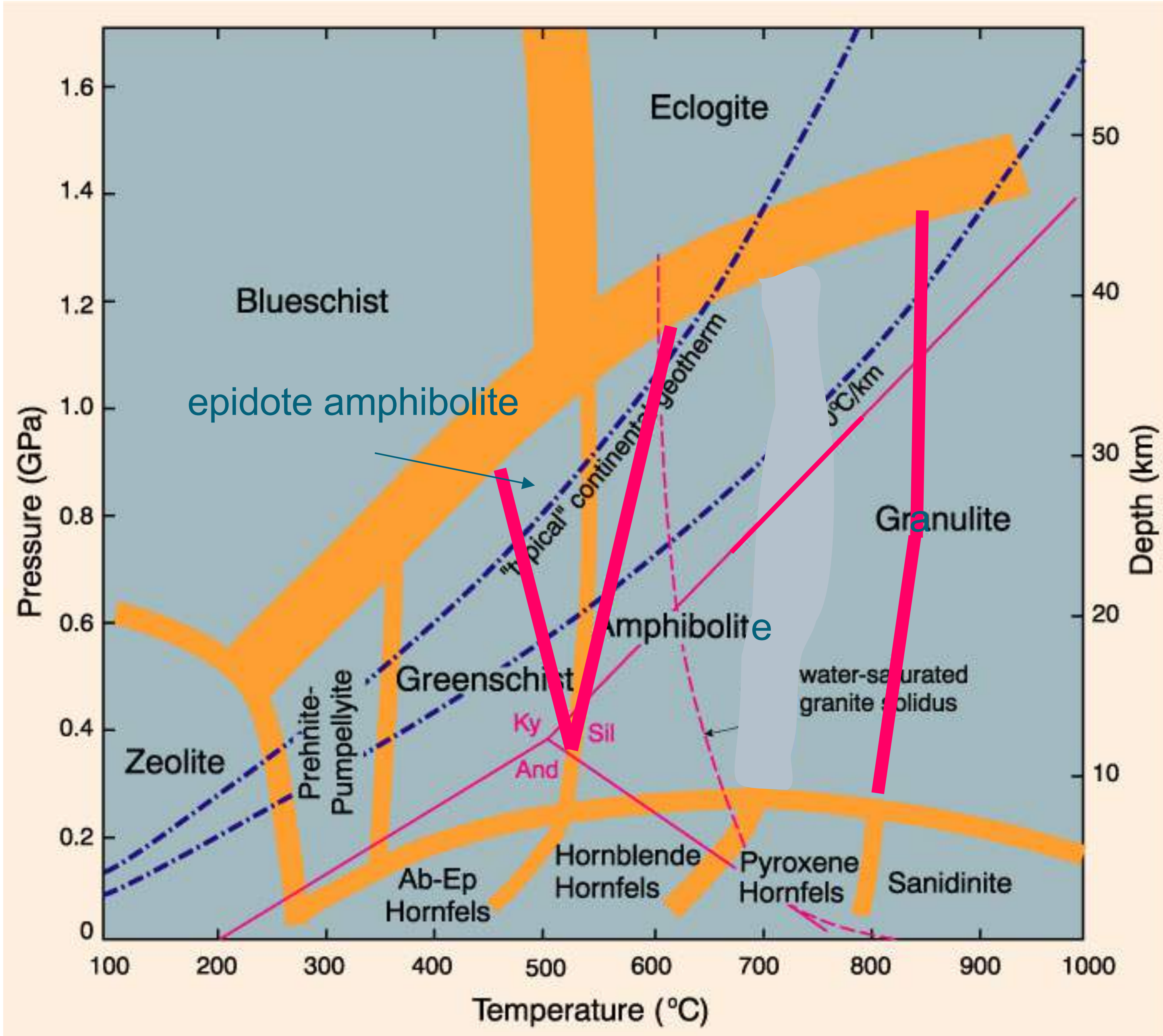
D. Facies of extreme pressure and wide temperature range:

(11) Eclogite.

Fácies metamórficas

Definição apresentada por Turner (1981):

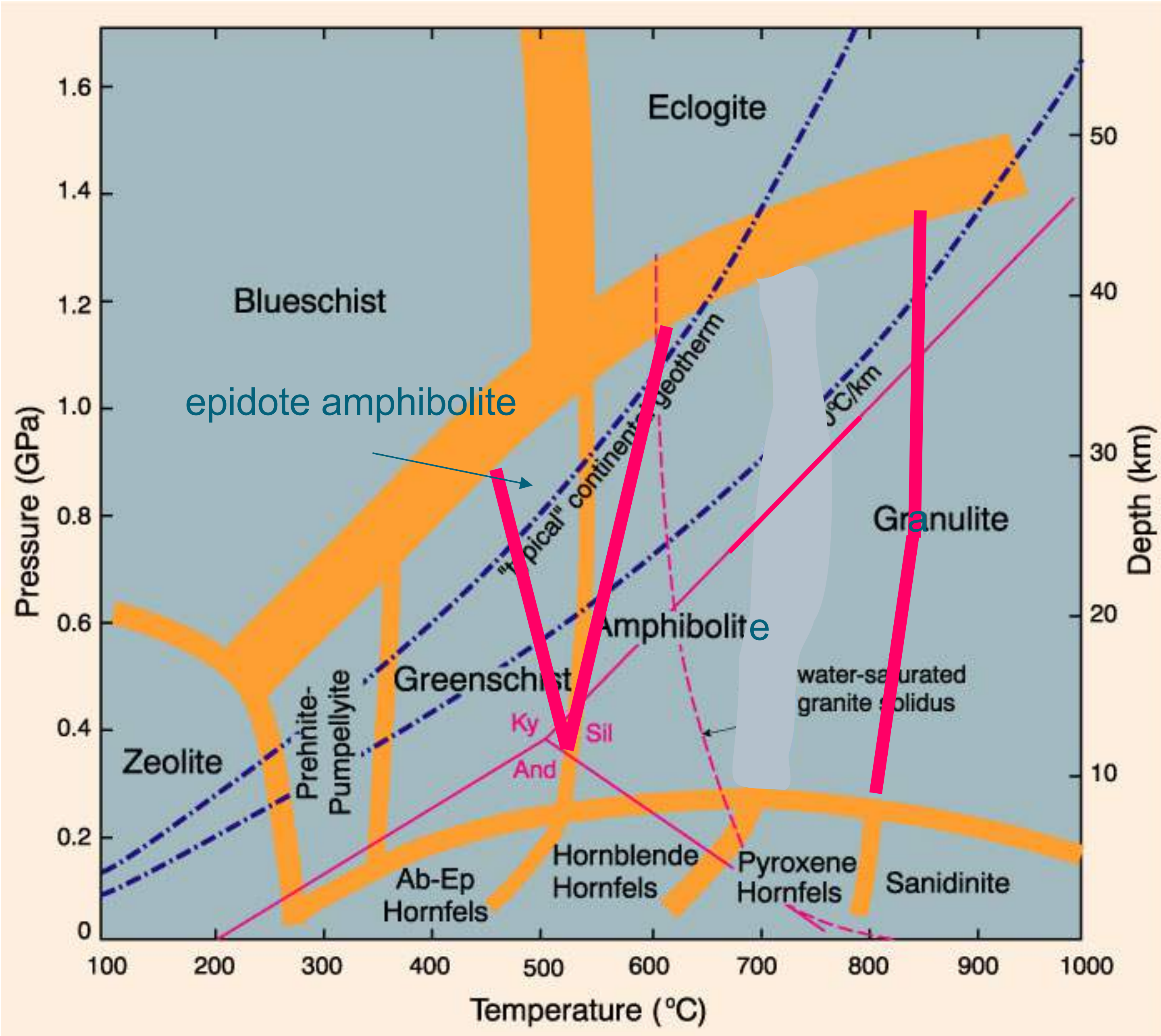
A fácies metamórfica é o conjunto de associações de minerais metamórficos, que ocorrem repetidamente no espaço e no tempo, de modo que exista relação constante e previzível entre a composição mineral, a composição da rocha (e as condições *P*-*T*)



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

Fácies metamórficas por Moraes (2020)

- **Fácies metamórfica** é definida por grupos de paragêneses que ocorrem em rochas diferentes e que definem um mesmo campo no espaço *P-T*
- Dada uma composição de rocha, paragêneses diferentes implicam em condições *P-T* diferentes e paragêneses iguais implicam em condições *P-T* semelhantes
- A mudança de paragênese é controlada pela composição da rocha, do fluido e pelas condições *P-T*
- A mudança de uma paragênese para outra é vinculada a uma reação metamórfica, logo pelas condições *P-T* do metamorfismo



Eclogite
Blueschist
epidote amphibolite
"typical" continental geotherm
°C/km
Granulite
Amphibolite
Greenschist
water-saturated granite solidus
Ky
Sil
And
Zeolite
Prehnite-Pumpellyite
Ab-Ep Hornfels
Hornblende Hornfels
Pyroxene Hornfels
Sanidinite
Pressure (GPa)
Depth (km)
Temperature (°C)

Fácies metamórficas

- Embora o nome das **fácies metamórficas** seja escolhido pelo tipo de rocha metamórfica proveniente do metamorfismo de **basalto**, o nome das **zonas metamórficas** (**minerais - índices**) são provenientes do metamorfismo de **pelitos** e isso pode ser combinado
  - facies xisto verde
    - zonas da clorita, biotita e granada
  - fácies anfibolito
    - zonas da estaurolita, cianita e sillimanita

Relação composição da rocha minerais

- Existe relação direta entre a composição da rocha e os possíveis minerais gerados durante o metamorfismo

- As rochas metamórficas derivadas de basalto (e afins) são dominadas por minerais ferro-magnesianos, com ou sem cálcio (e sódio), e por plagioclásio, ou outro mineral aluminoso

- O metamorfismo de pelitos gera minerais ricos em alumínio, alguns com potássio, outros ferro-magnesianos

Composição média de basalto e pelito

basalto

SiO_2 — 49.97

TiO_2 — 1.87

Al_2O_3 — 15.99

Fe_2O_3 — 3.85

FeO — 7.24

MnO — 0.20

MgO — 6.84

CaO — 9.62

Na_2O — 2.96

K_2O — 1.12

P_2O_5 — 0.35

pelito

SiO_2 — 60.78

TiO_2 — 0.8

Al_2O_3 — 16.88

FeO — 6.87

MnO — 0.13

MgO — 3.44

CaO — 1.21 (~ 0)

Na_2O — 1.65 (~ 0)

K_2O — 3.70

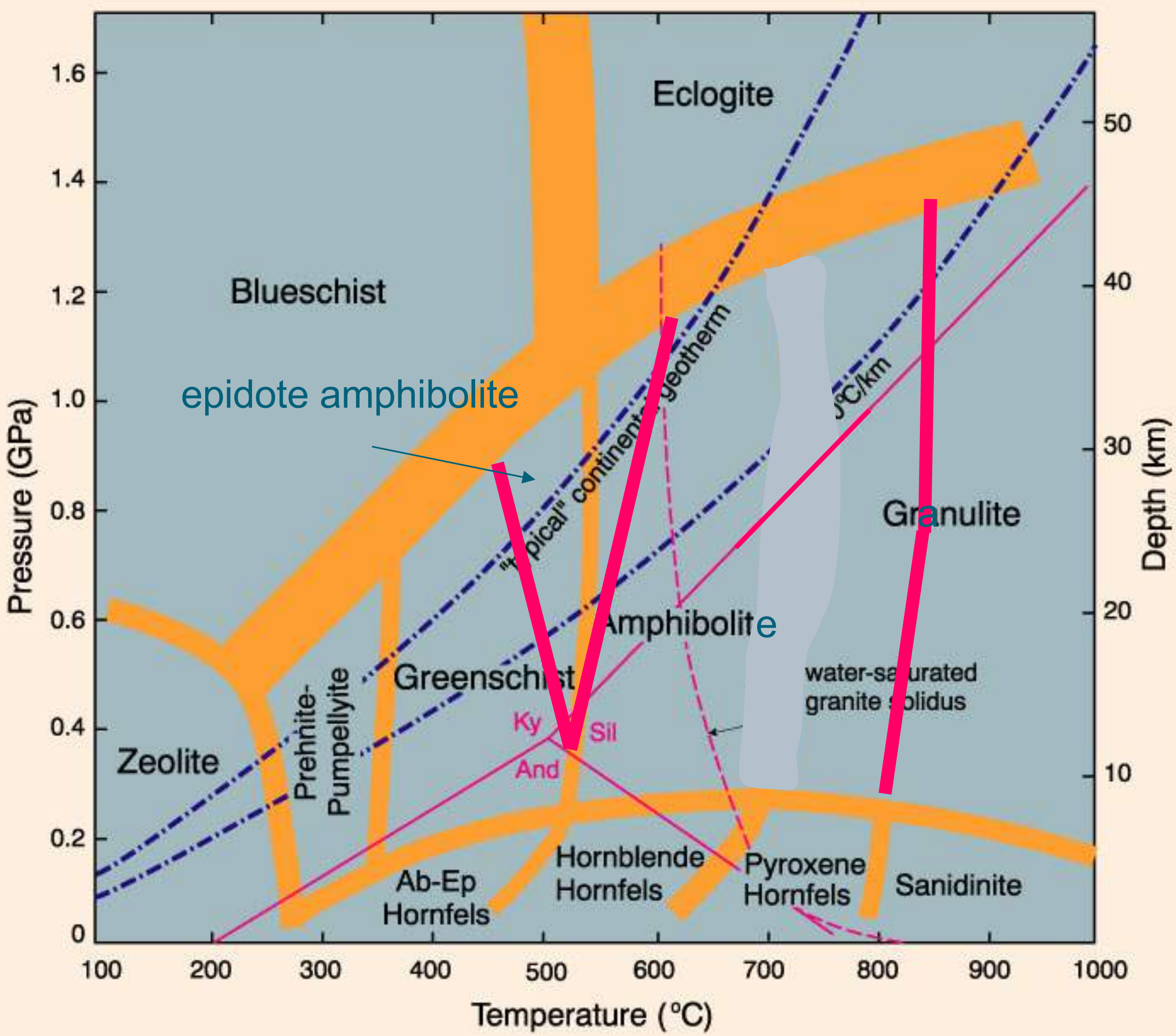
P_2O_5 — 0.15

Rochas máficas	**Pelitos**	**Rochas calciossilicáticas**
Fácies xisto verde	**Zona da clorita** Qtz + Ms + Chl	Talco + flogopita
(Act+Chl+Ep+Ab)	**Zona da biotita** Qtz + Ms + Chl + Bt	
Fácies epidoto-anfibolito (Act + Pl + Ep + Hbl)	**Zona da granada** Qtz + Ms + Chl + Bt +Grt	Tremolita-Actinolita +
Fácies anfibolito (Hbl + Pl ($An_{>17}$) ± Grt)	**Zona da estaurolita** Qtz +Ms +Bt+Grt+St	Epidoto + Zoisita
Hbl + Pl ± Grt	**Zona da cianita** Qtz +Ms +Bt+Grt+Ky	Diopsídio
(Hbl+ Pl ± Cpx ± Grt)	**Zona da Sil +Kfs** Qtz +Kfs +Bt+Grt+Sil+Liq **Zona da Crd + Grt** Qtz +Kfs +Crd+Grt+Sil+Liq	Grossulária, escapolita
Fácies granulito Opx + Cpx + Pl ± Grt	**Zona do Opx + Crd ± Grt** Qtz +Kfs +Opx Crd+Grt+Liq	Forsterita

Rochas máficas	**Pelitos**
Fácies xisto azul	
(Glc + Ep ou Lw ± Ab)	Ky + Ctd ± St
Fácies eclogito	Ctd + Ky + Chl / Tlc + Ky + Grt + Ms
Omp + Prp (sem Pl)	Kfs + Grt + Ky + Rt

Fácies metamórficas e condições *P-T*

- Inicialmente a ideia original de **Goldschmidt** e de **Eskola** era apenas de se fazer a ligação entre paragêneses e a composição da rocha, embora eles soubessem que a consequência direta era a ligação com as condições *P-T*
  - *Fácies eclogito* – metamorfismo de basalto resultando em rocha com piroxênio sódico e granada magnesiana
- Hoje o conceito de fácies está diretamente relacionado com o campo *P-T* em que a associação mineral é estável
  - *Fácies eclogito* – implica em condições *P-T* específicas para formar o eclogito – rocha com piroxênio sódico e granada magnesiana – ($T > 500$ °C e $P > 12$ kbar)



Eclogite
Blueschist
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°C/km
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And
Zeolite
Prehnite-
Pumpellyite
Ab-Ep
Hornfels
Hornblende
Hornfels
Pyroxene
Hornfels
Sanidinite
Pressure (GPa)
Depth (km)
Temperature (°C)

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Focus paper

The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics

CrossMark

Michael Brown

Laboratory for Crustal Petrology, Department of Geology, University of Maryland, College Park, MD 20742, USA

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Rayleigh–Taylor instabilities
Stagnant lid
Subduction

ABSTRACT

In the early 1980s, evidence that crustal rocks had reached temperatures >1000 °C at normal lower crustal pressures while others had followed low thermal gradients to record pressures characteristic of mantle conditions began to appear in the literature, and the importance of melting in the tectonic evolution of orogens and metamorphic–metasomatic reworking of the lithospheric mantle was realized. In parallel, new developments in instrumentation, the expansion of in situ analysis of geological materials and increases in computing power opened up new fields of investigation. The robust quantification of pressure (*P*), temperature (*T*) and time (*t*) that followed these advances has provided reliable data to benchmark geodynamic models and to investigate secular change in the thermal state of the lithosphere as registered by metamorphism through time. As a result, the last 30 years have seen significant progress in our understanding of lithospheric evolution, particularly as it relates to Precambrian geodynamics.

Eoarchean–Mesoarchean crust registers uniformly high *T*/*P* metamorphism that may reflect a stagnant lid regime. In contrast, two contrasting types of metamorphism, eclogite–high-pressure granulite metamorphism, with apparent thermal gradients of 350–750 °C/GPa, and granulite–ultrahigh temperature metamorphism, with apparent thermal gradients of 750–1500 °C/GPa, appeared in the Neoarchean rock record. The emergence of paired metamorphism is interpreted to register the onset of one-sided subduction, which introduced an asymmetric thermal structure at these developing convergent plate margins characterized by lower *T*/*P* in the subduction channel and higher *T*/*P* in the overriding plate. During the Paleoarchean to Paleoproterozoic the ambient mantle temperature was warmer than at present by ~300–150 °C. Although the thermal history of Earth is only poorly constrained, it is likely that prior to ca. 3.0 Ga heating from radioactive decay would have exceeded surface heat loss, whereas since ca. 2.5 Ga secular cooling has dominated the thermal history of the Earth. The advent of paired metamorphism is consistent with other changes in the geological record during the Neoarchean that are best explained as the result of a transition from a stagnant lid to subduction and a global plate tectonics regime by ca. 2.5 Ga. This interpretation is supported by results from 2-D numerical experiments of oceanic subduction that demonstrate a change to one-sided subduction is plausible as upper mantle temperature declined to <200 °C warmer than at present during the late Neoarchean–Paleoproterozoic. This is the beginning of the Proterozoic plate tectonics regime.

At 1.0 Ga the ambient mantle temperature was still ~150–100 °C warmer than at present. Continued secular cooling caused a transition to cold subduction registered in the crustal record of metamorphism by the first appearance of blueschist and high to ultrahigh pressure metamorphism during the Neoproterozoic. Results of 2-D numerical experiments of continental collision demonstrate a transition from

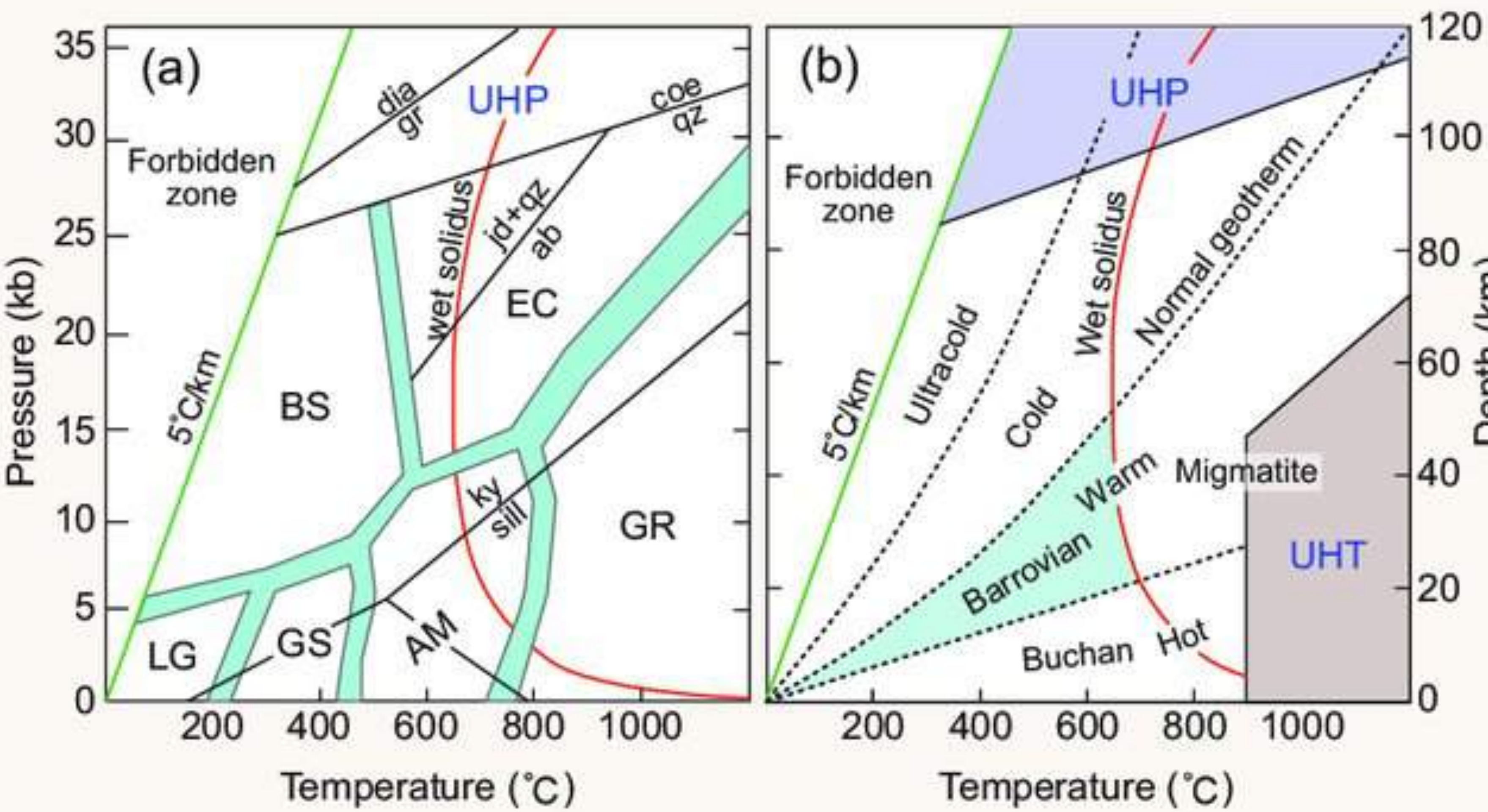
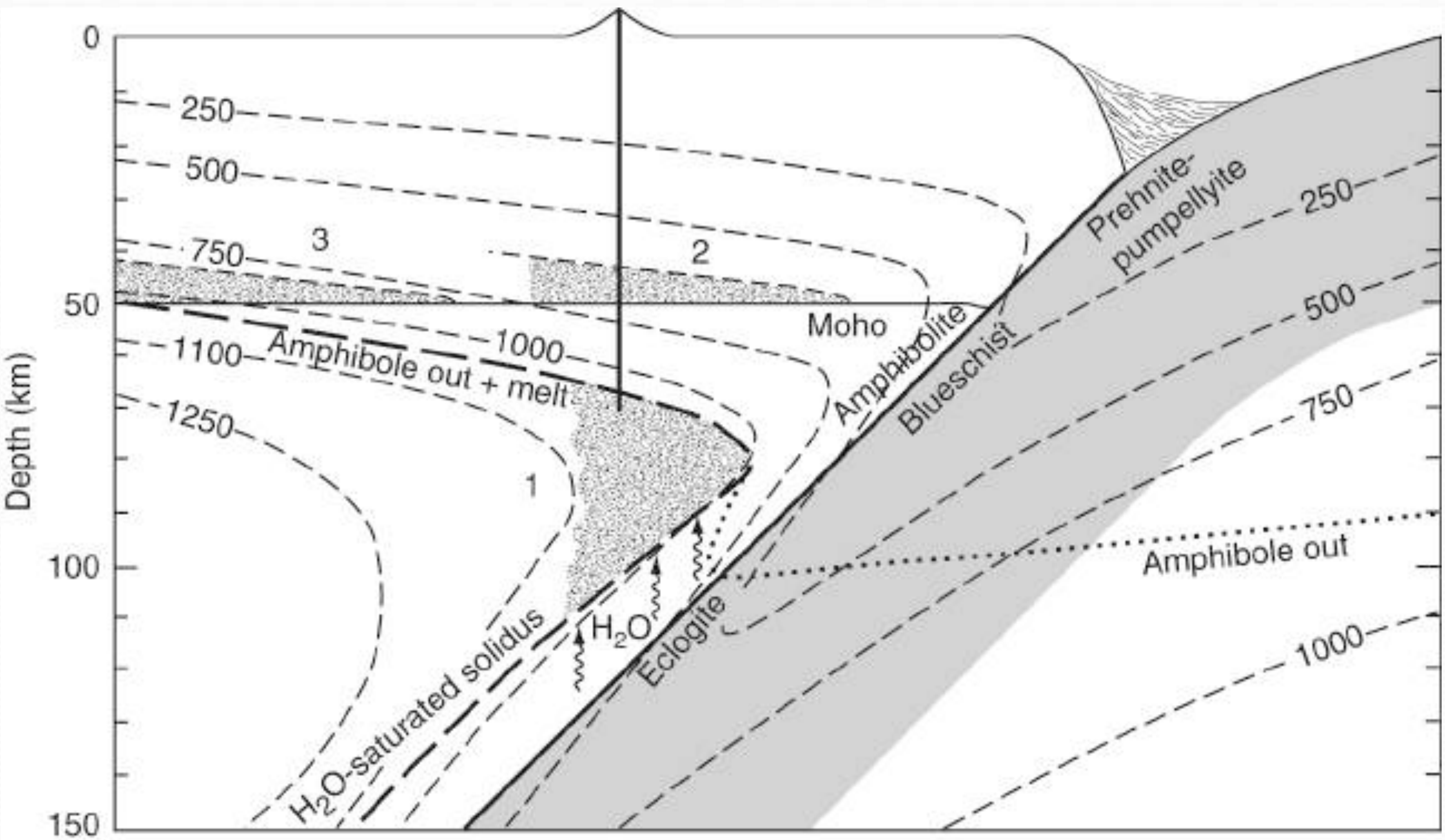


Figure 1. To show the contrasting views of P–T space as viewed by the petrologist (a) and the geodynamicist (b); modified after Stüwe (2007, Fig. 7.1; subject to copyright, published with kind permission of Springer Science + Business Media). The pressure to depth conversion is based in an average density of ~3000 kg m^{-3} (i.e. 3 GPa ≈ 100 km). (a) Shows the principal metamorphic facies in their simplest form. At pressures below coesite stability the facies boundaries are transitional to indicate the control of bulk composition on the change in mineral assemblages from one facies to another. Low-to-moderate pressure facies are: Lg, low-grade metamorphism, includes the zeolite facies; Gr, greenschist facies; Am, amphibolite facies; Gn, granulite facies; and, UHT, ultrahigh temperature metamorphism, which is the part of the granulite facies at $T > 900$ °C. High-to-ultrahigh pressure facies are: Bl, blueschist facies; E-HPG, eclogite–high-pressure granulite facies, which is the part of the eclogite facies where plagioclase remains stable in some bulk compositions but not in others at common P–T conditions; and, UHP, ultrahigh pressure metamorphism, which is the part of the eclogite facies at P above quartz stability. (b) P–T space divided in relation to a normal geotherm, where the normal geotherm is drawn to pass through 500 °C at ~33 km depth and 1200 °C at ~105 km depth. Thus, there are tectonic settings that may have either lower or higher T/P gradients than normal. On contemporary Earth, one example of where both tectonic settings occur in close proximity is along a convergent plate boundary, where the subduction zone has lower T/P and the arc–backarc higher T/P, respectively.

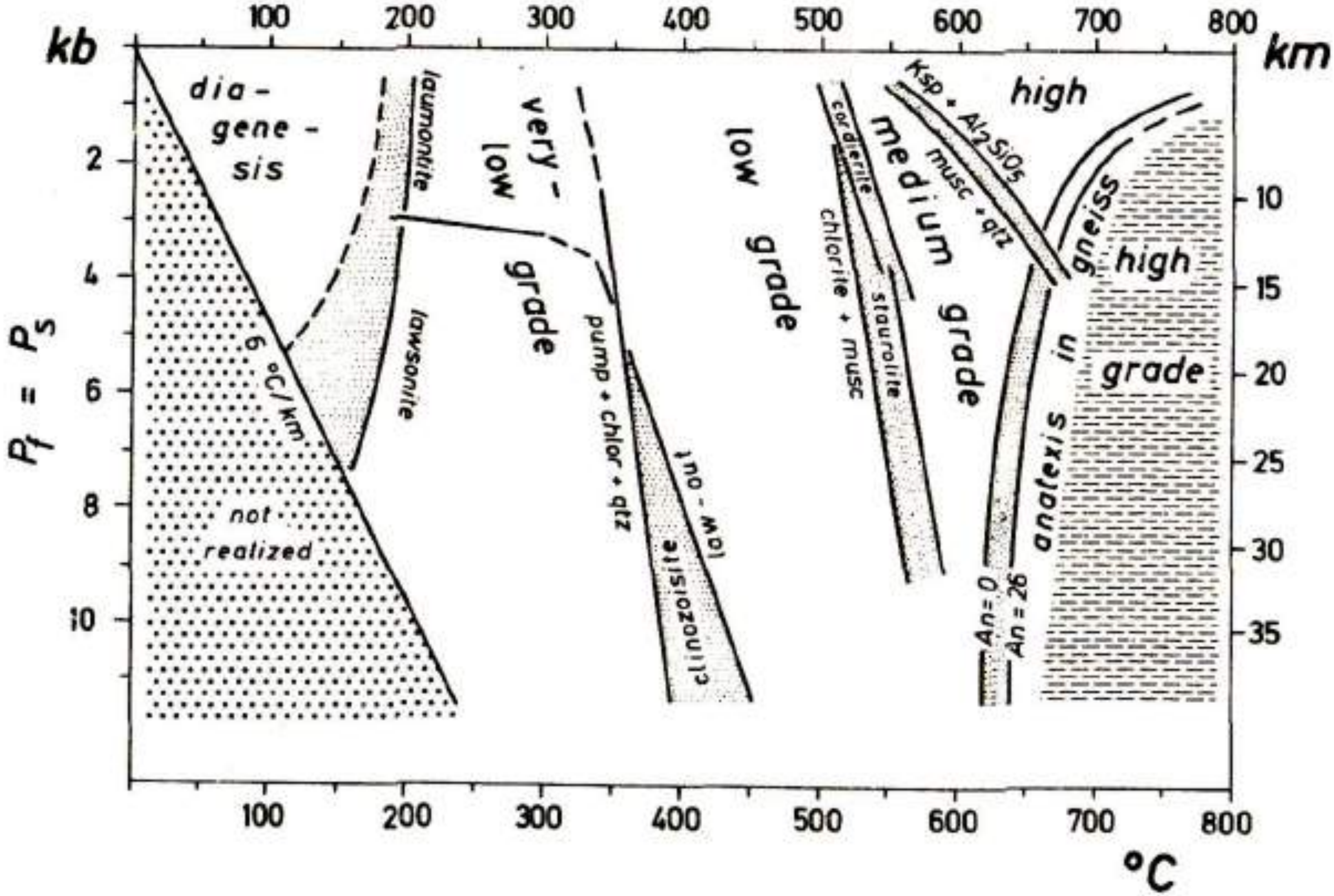


Philpotts & Ague, 2010

Grau metamórfico e iso-reação

- Winkler no final da década de 1960 descontente com variações no crescente número de sub-fácies, propôs que as fácies metamórficas fossem substituídas por 4 subdivisões de **grau metamórfico**
- grau muito baixo (ou incipiente)
- grau baixo
- grau médio
- grau alto

- Ainda propôs o conceito de **iso-reação**, em que devemos mapear reações e não isógradas



kb
km
°C
$P_f = P_s$
dia-
gene-
sis
not
realized
°C/km
laumontite
lawsonite
very-
low
grade
pump + chlor + qtz
clinozoisite
low - out
low
grade
cordierite
chlorite + musc
staurolite
medium
grade
Ksp + Al_2SiO_5
musc + qtz
high
gneiss
high
grade
anatexis
in
An=0
An=26

Grau metamórfico e iso-reação

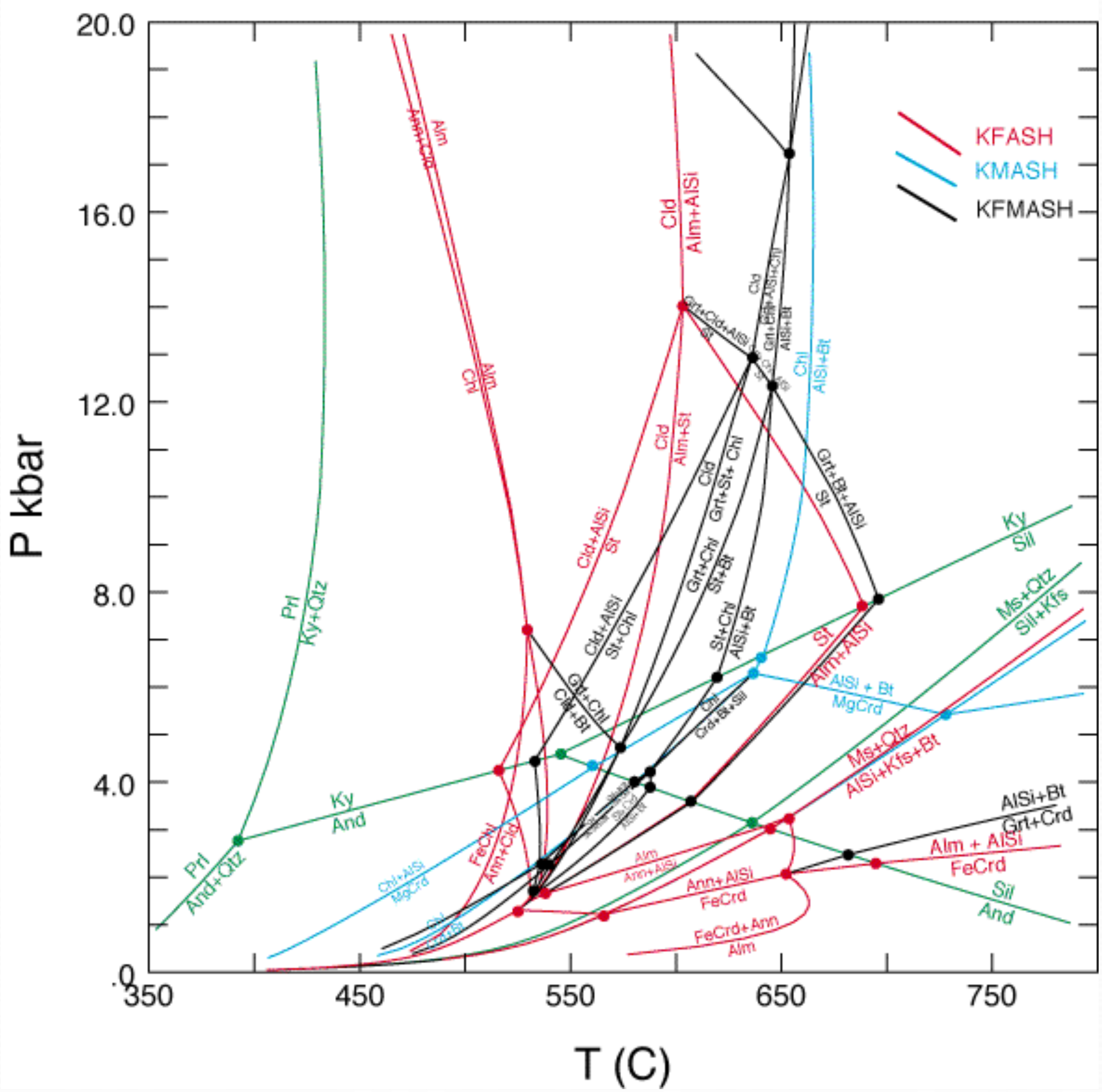
- Embora Winkler tenha usado o termo **grau metamórfico** em substituição às **fácies metamórficas** de um modo formal, ***grau metamórfico*** comumente é usado de uma maneira informal, para dizer se as rochas sofreram **metamorfismo mais ou menos intenso** em relação à **temperatura**

Grade Petrogenética

iso-reação - mapeamento de reações metamórficas no campo e não do mineral índice

veja que mais de uma reação pode gerar estaurolita, com o conceito de mineral índice isso é perdido

Spear & Cheney (unpublished)



Séries de fácies metamórficas

- Miyashiro (1961) reconheceu duas **séries de fácies metamórficas** em terrenos metamórficos do Japão que são diferentes das propostas por Barrow
  - zeólita / prehnita-pumpellyita / xisto azul / eclogito
  - xisto verde / anfibolito com **And – Sil** (baixa *P*)
- Cinturões metamórficos emparelhados
- Identificou as séries de fácies (séries faciais, ou tipos báricos)

Evolution of Metamorphic Belts

by AKIHO MIYASHIRO

Geological Institute, Faculty of Science, University of Tokyo, Japan

ABSTRACT

The metamorphic facies series in regional metamorphism may be classified into the following categories according to an order of increasing rock pressure: (1) andalusite–sillimanite type, (2) low-pressure intermediate group, (3) kyanite–sillimanite type, (4) high-pressure intermediate group, and (5) jadeite–glaucophane type.

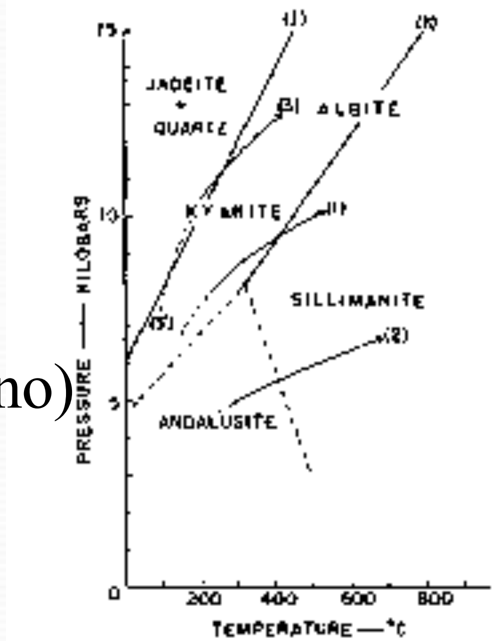
In Japan and other parts of the circum-Pacific region, a metamorphic belt of the andalusite–sillimanite type and/or low-pressure intermediate group and another metamorphic belt of the jadeite–glaucophane type and/or high-pressure intermediate group run side by side, forming a pair. The latter belt is always on the Pacific Ocean side. They were probably formed in different phases of the same cycle of orogeny. Their origin is discussed.

Regional metamorphism under higher rock pressures appears to have taken place in later geological times.

The metamorphic facies series of contact metamorphism are briefly discussed.

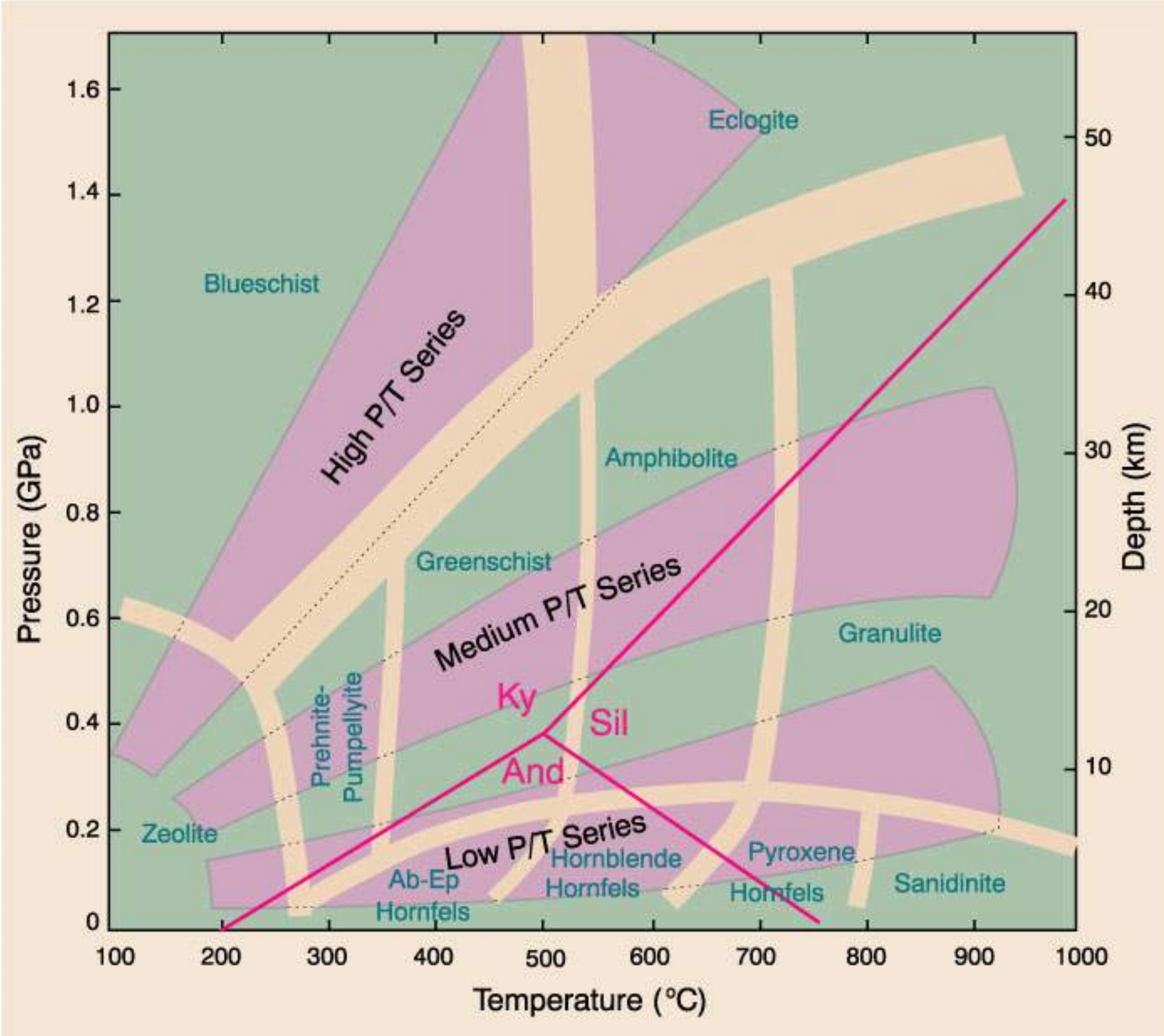
[Journal of Petrology, Vol. 2, Part 3, pp. 277–311, 1961]

Séries de fácies metamórficas



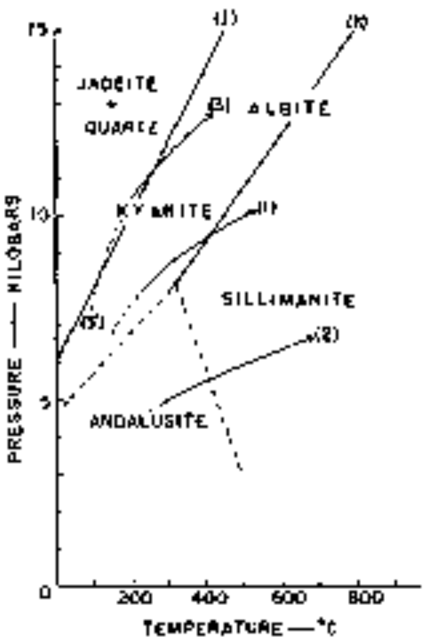
- Identificou 3 séries de fácies
  - razão *P/T* alta – glaucofano – jadeíta
  - razão *P/T* intermediária – Ky – Sil (barroviano)
  - razão *P/T* baixa – And – Sil

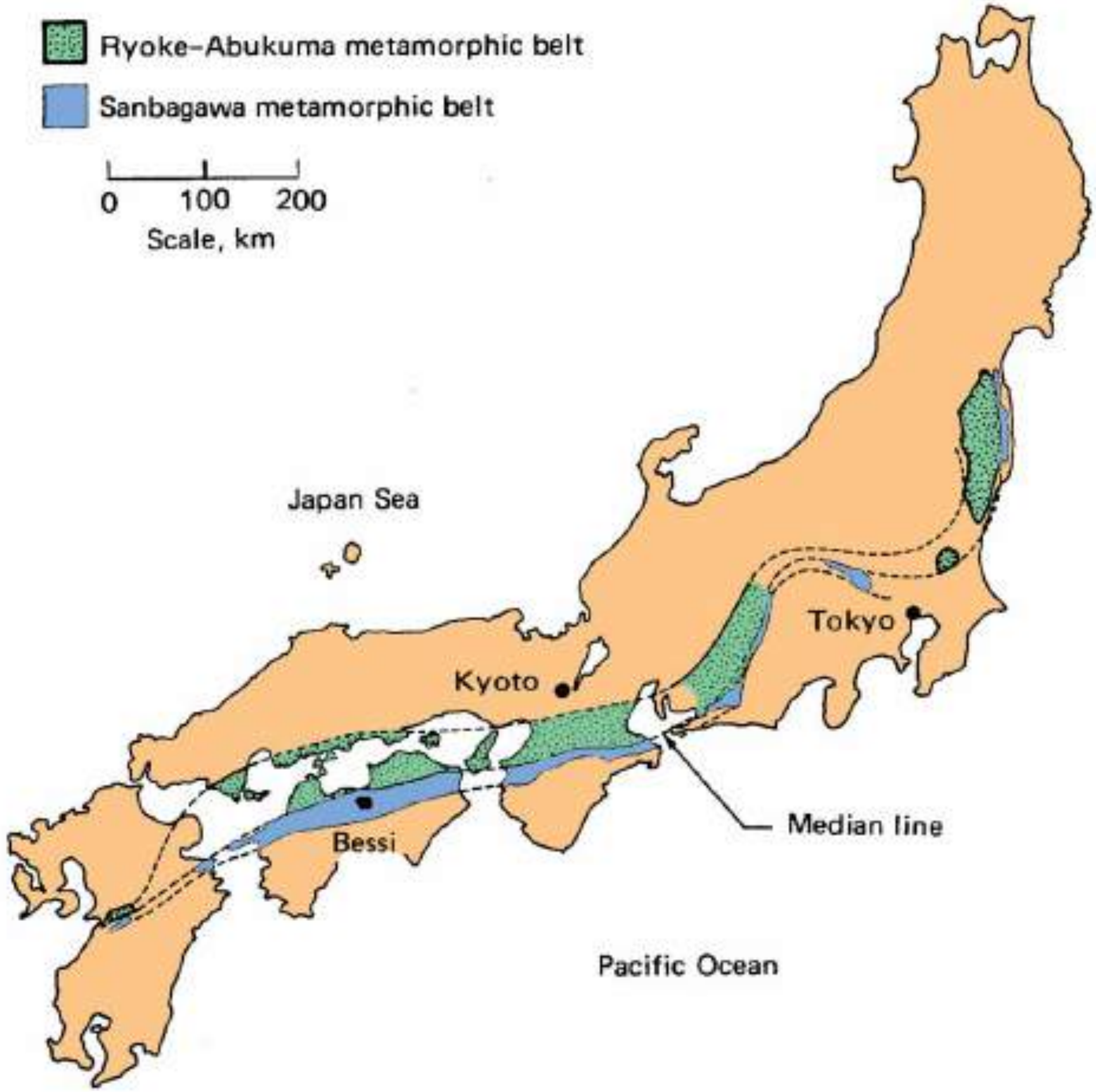
- razão *P/T* alta – metamortismo sambagawa
- razão *P/T* intermediária – metamorfismo barroviano
- razão *P/T* baixa – metamorfismo buchan, abukuma, ryoke



Pressure (GPa)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Depth (km)
50
40
30
20
10
Temperature (°C)
100
200
300
400
500
600
700
800
900
1000
Eclogite
Blueschist
High P/T Series
Amphibolite
Greenschist
Medium P/T Series
Granulite
Prehnite-
Pumpellyite
Ky
Sil
And
Zeolite
Low P/T Series
Ab-Ep
Hornfels
Hornblende
Hornfels
Pyroxene
Hornfels
Sanidinite

Cinturões Metamórficos Emparelhados

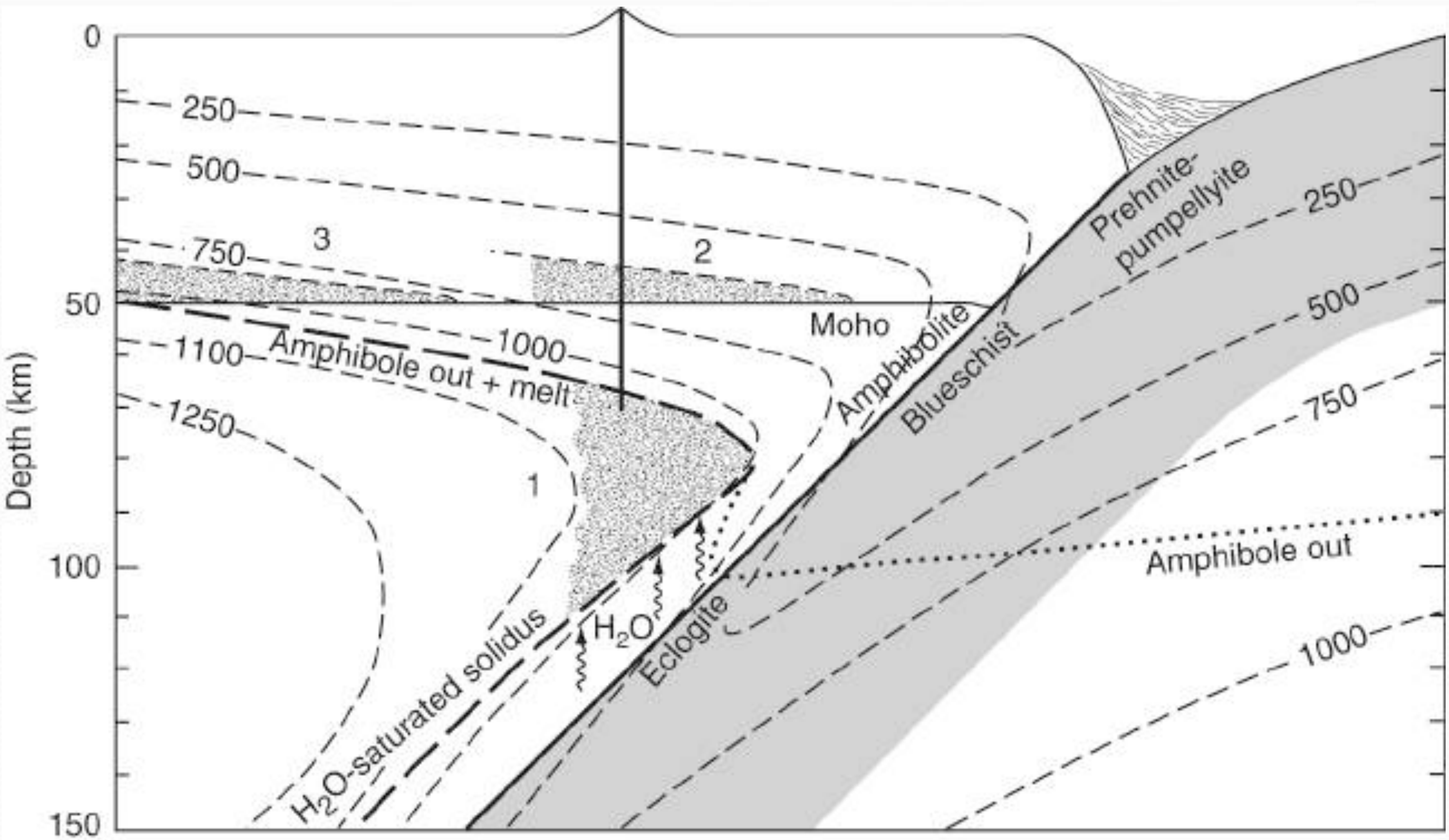




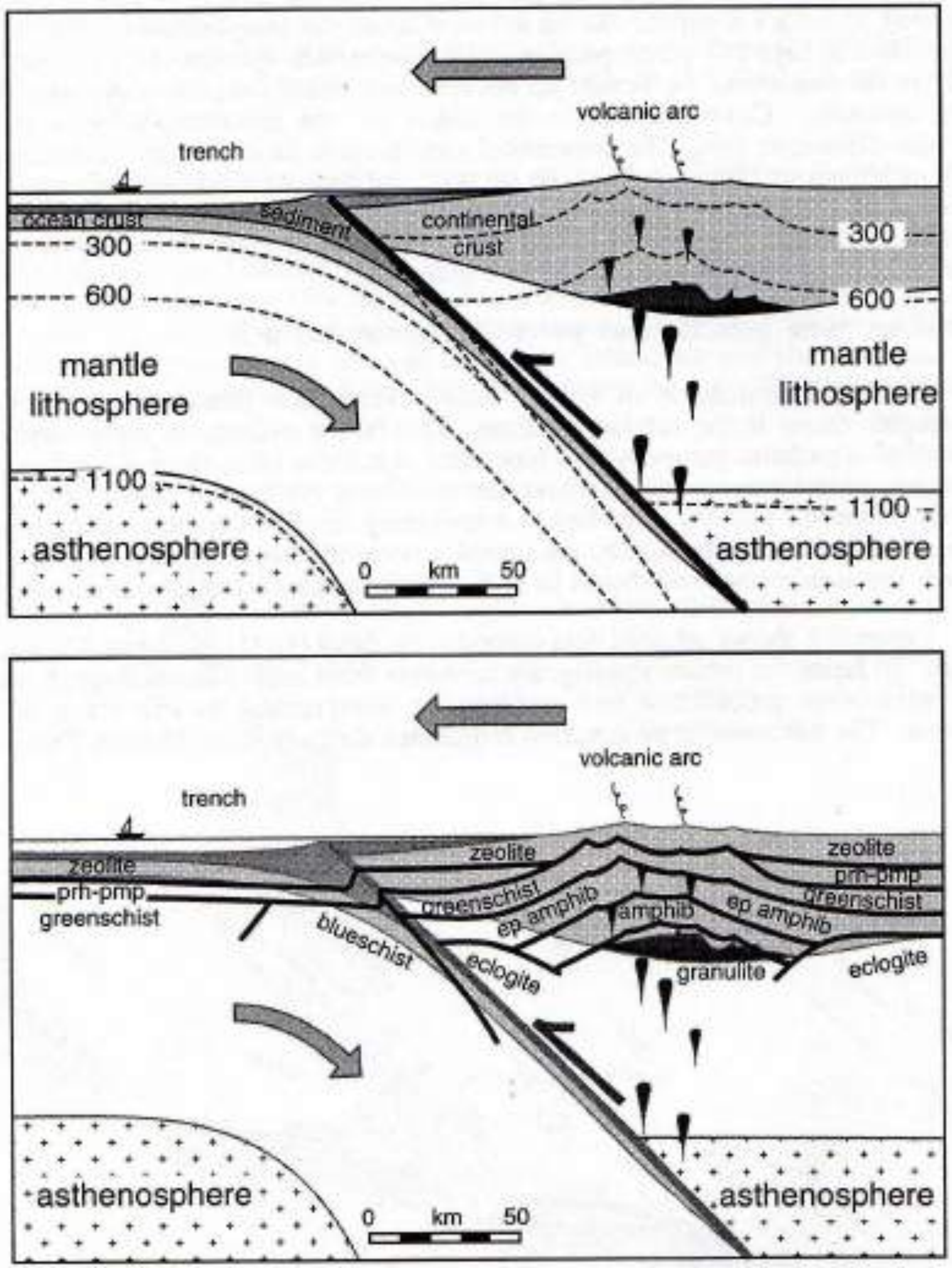
Séries de fácies e ambientes tectônicos

- Ambientes colisionais – arcos de ilha e zonas de colisão continental
- Arcos de ilha - repressão das isotermas em virtude da placa fria descendente e alçamento das isotermas na zona de arco magmático
- Cinturões Metamórficos Emparelhados
  - razão *P/T* alta – glaucofana-jadeíta (zona de subducção)
  - razão *P/T* baixa – And-Sil (arcos de ilha)

Cinturões metamórficos emparelhados

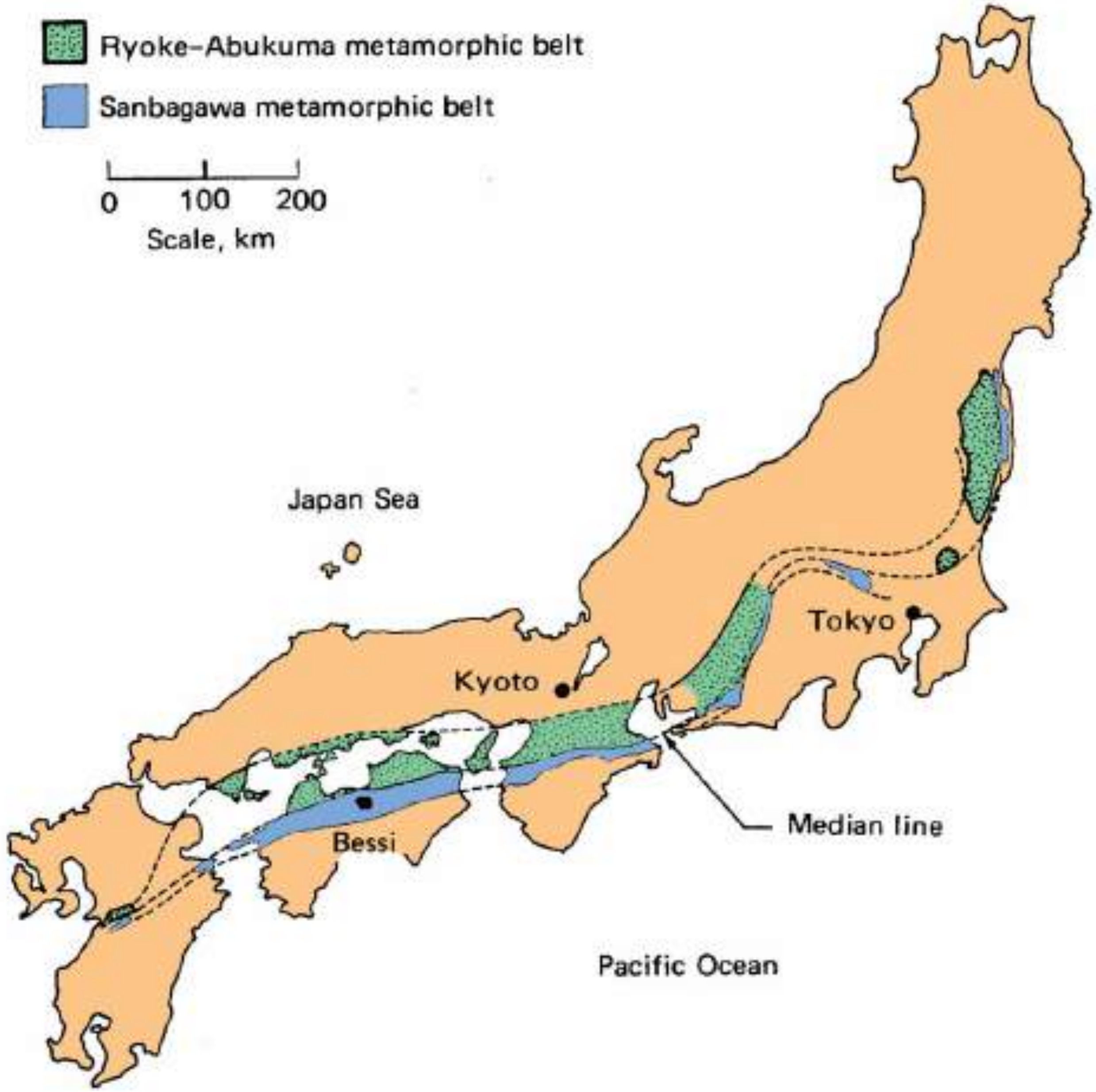


Philpotts & Ague, 2010

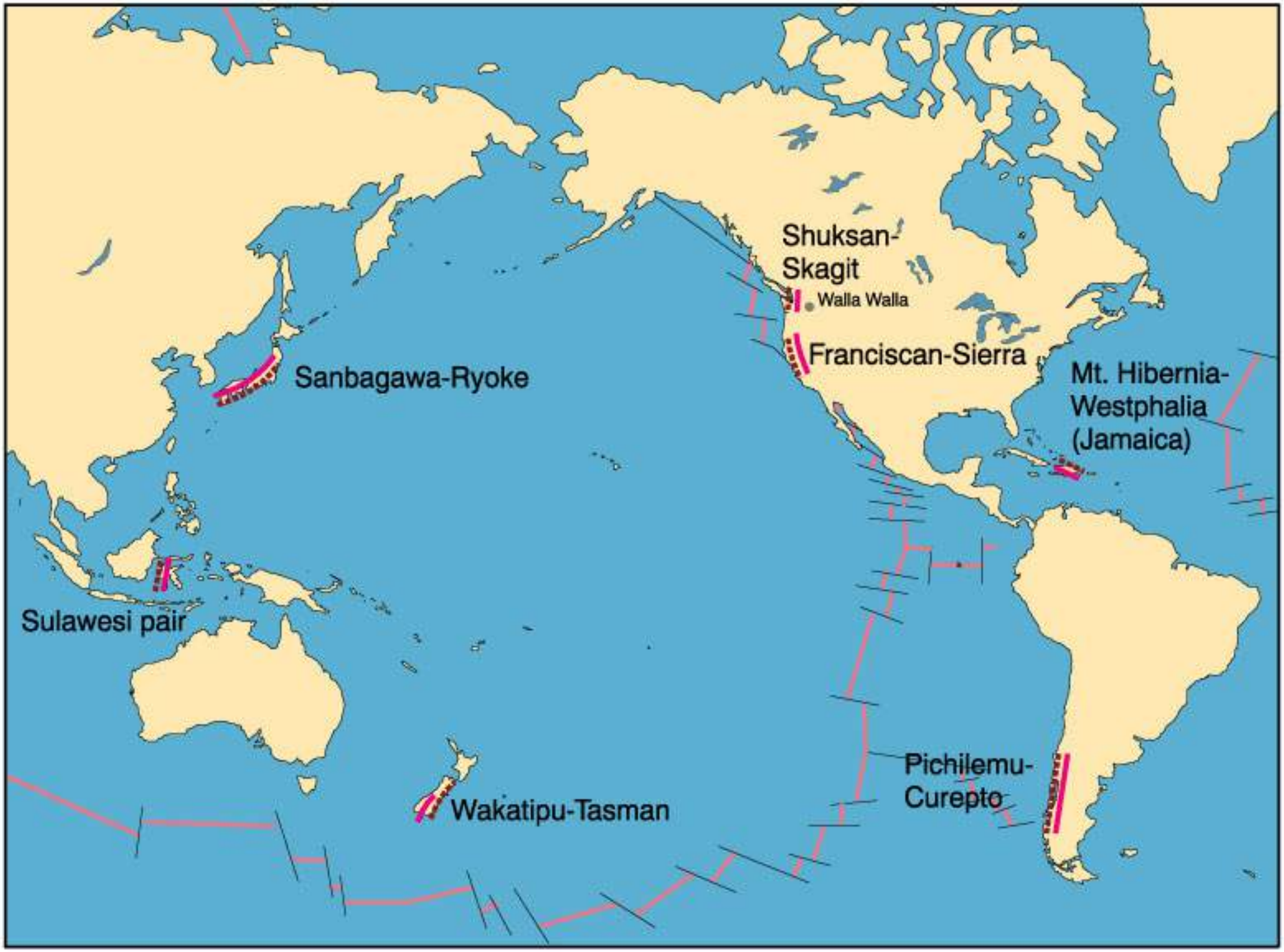


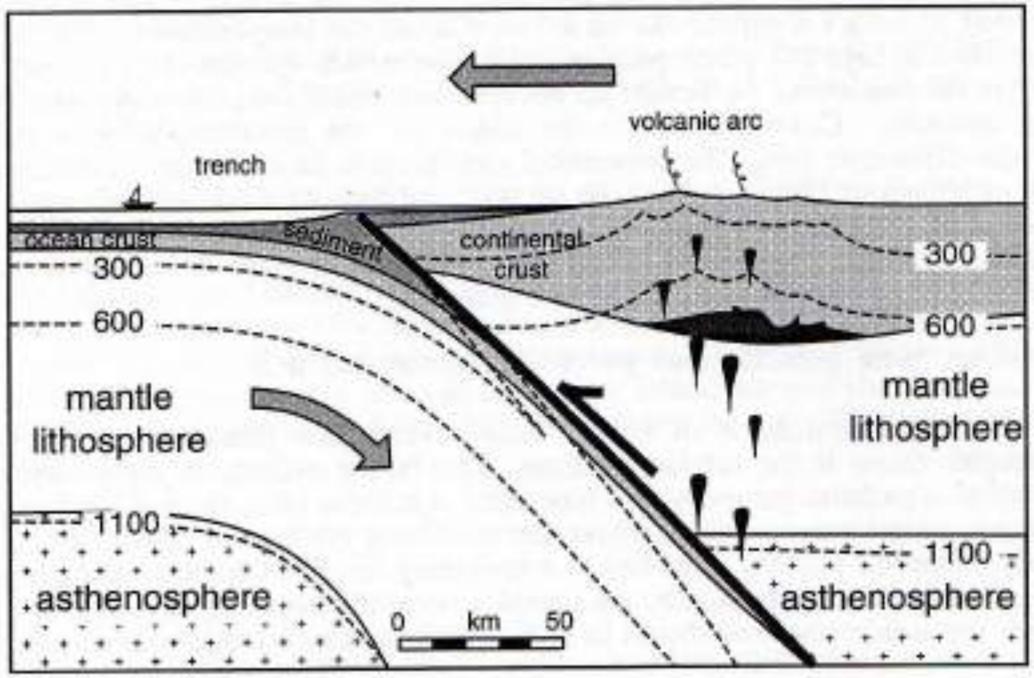
volcanic arc
trench
ocean crust
sediment
continental
crust
300
600
mantle
lithosphere
1100
asthenosphere
0 km 50
volcanic arc
trench
zeolite
prh-pmp
greenschist
blueschist
eclogite
ep amphib
amphib
granulite
asthenosphere
0 km 50

Cinturões Metamórficos Emparelhados

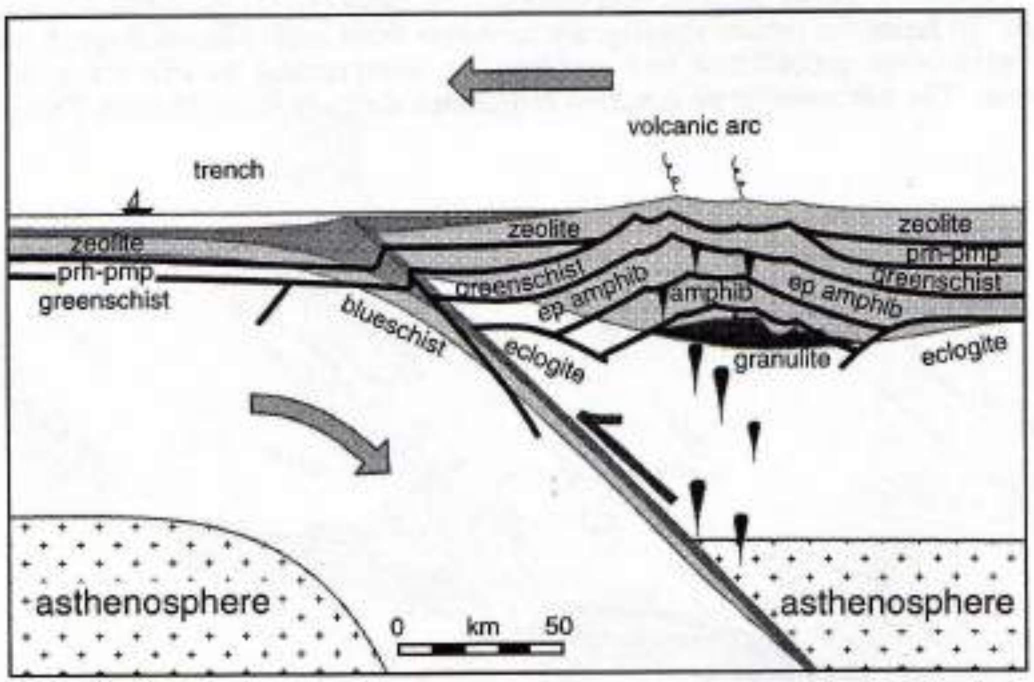


Miyashiro (1961, 1973) sugeriu que a ocorrência de cinturões metamórficos emparelhados e contemporâneos, um cinturão externo de alta razão *P/T*, e outro interno de baixa razão *P/T*, deve ser de ocorrência comum em várias zonas de subducção, modernas e antigas.


Shuksan-
Skagit
Walla Walla
Franciscan-Sierra
Sanbagawa-Ryoke
Mt. Hibernia-
Westphalia
(Jamaica)
Sulawesi pair
Pichilemu-
Curepto
Wakatipu-Tasman



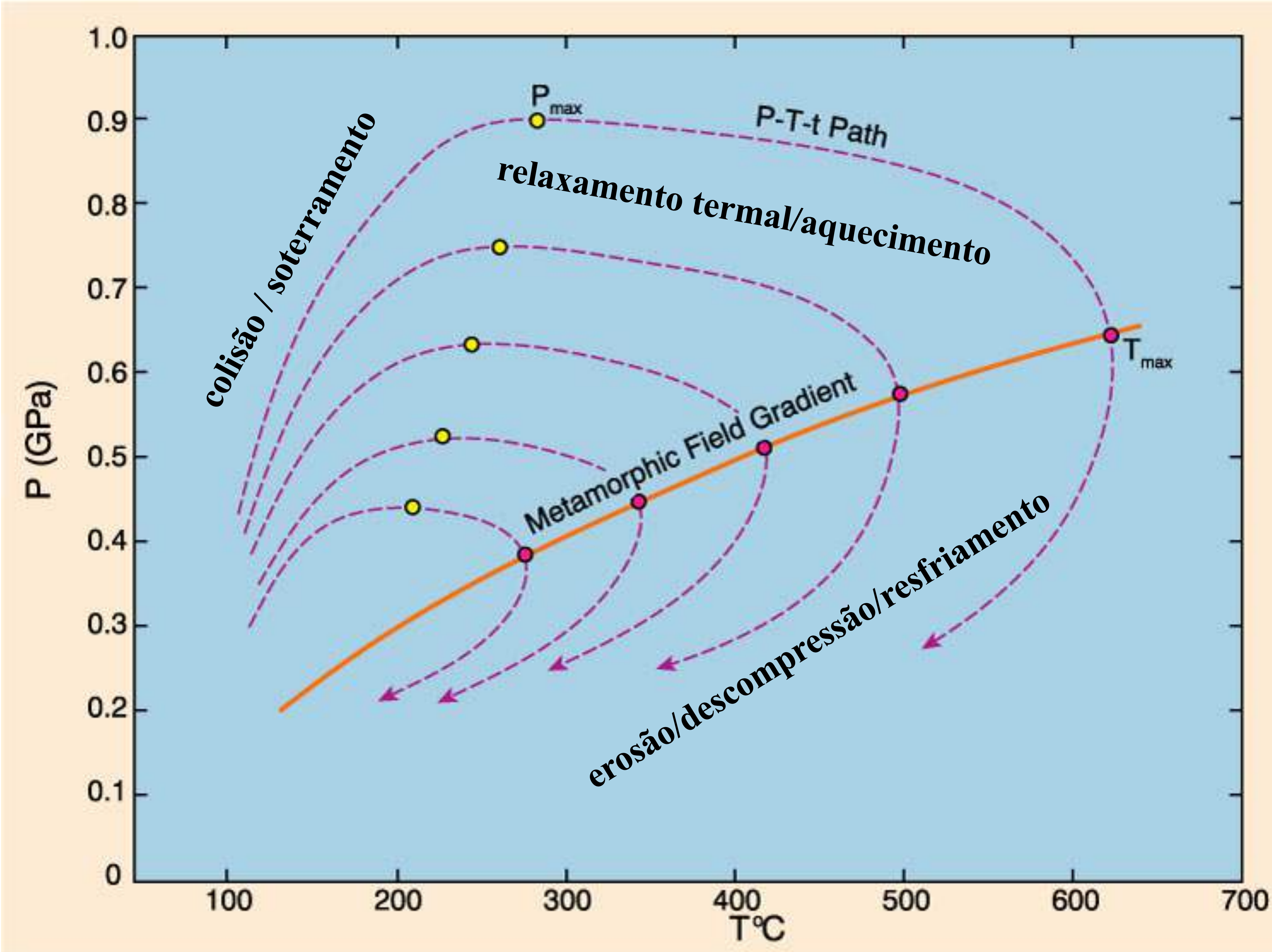
volcanic arc
trench
ocean crust
sediment
continental
crust
300
600
mantle
lithosphere
mantle
lithosphere
1100
asthenosphere
asthenosphere
0 km 50



volcanic arc
trench
zeolite
prh-pmp
greenschist
zeolite
zeolite
prh-pmp
greenschist
greenschist
ep amphib
amphib
ep amphib
blueschist
eclogite
granulite
eclogite
asthenosphere
asthenosphere
0 km 50

Trajetórias *P-T*-t

- O tempo relativo de três processos controla a forma da trajetória *P-T*-t
  - duração da colisão
  - duração do re- equilíbrio termal da crosta (relaxamento termal)
  - duração da exumação
- Trajetória *P-T* horária em cinturões colisionais
- England & Richardson (1978):
  - duração da colisão - estágio mais rápido < 10 Ma
  - relaxamento termal e exumação – dezenas de Ma



P (GPa)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
600
700
T°C
P max
P-T-t Path
T max
Metamorphic Field Gradient
colisão / soterramento
relaxamento termal/aquecimento
erosão/descompressão/resfriamento

Trajetórias *P-T* horárias

- P_{max} antece T_{max} (estágio de alta *P*)
- T_{max} é alcançada durante a descompressão
- Quanto mais rápido acontecer o início da erosão após a colisão, menor vai ser a diferença entre P_{max} e P_{pico} e menor vai ser T_{max}

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

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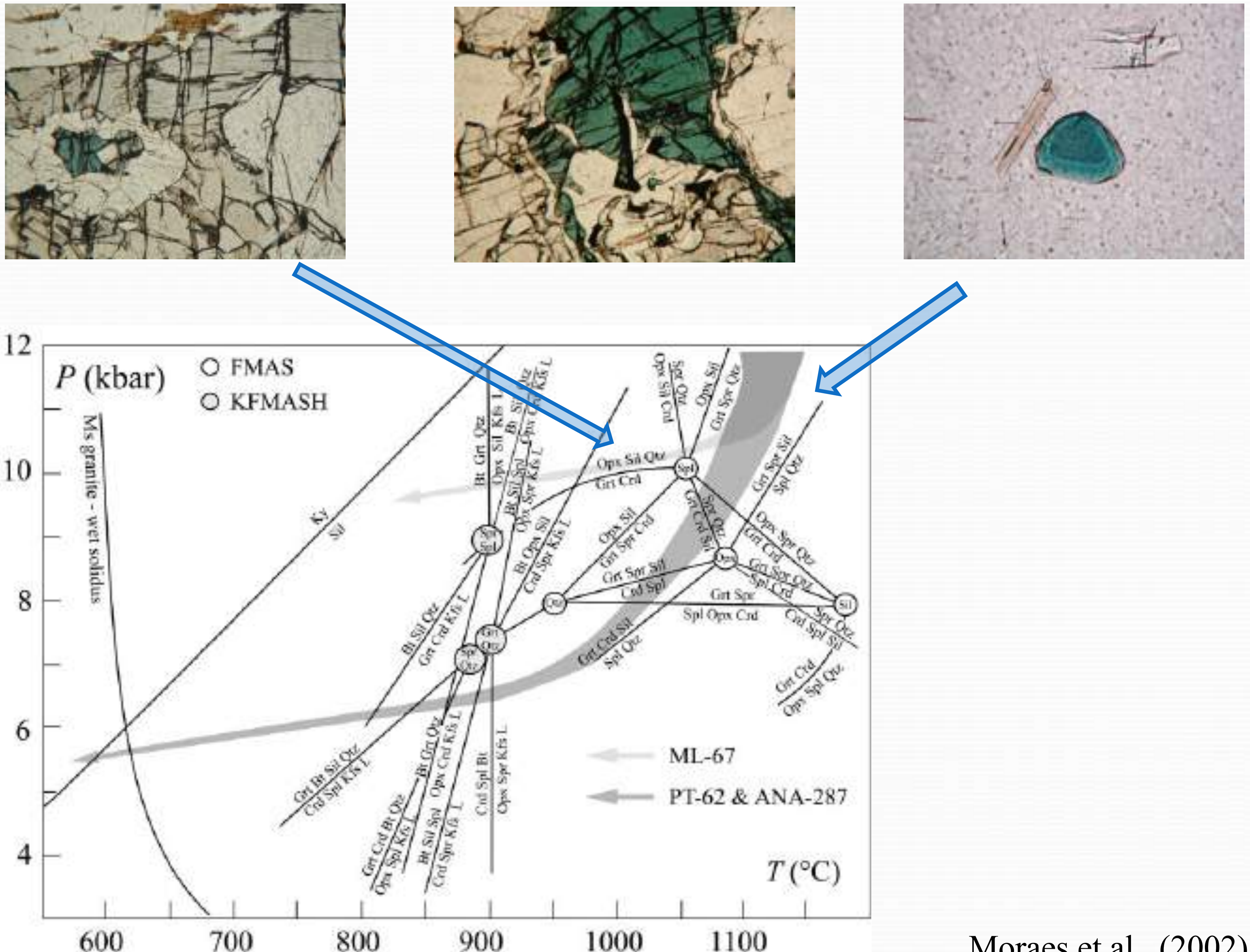
RECEIVED SEPTEMBER 10, 2001; REVISED TYPESCRIPT ACCEPTED MARCH 8, 2002

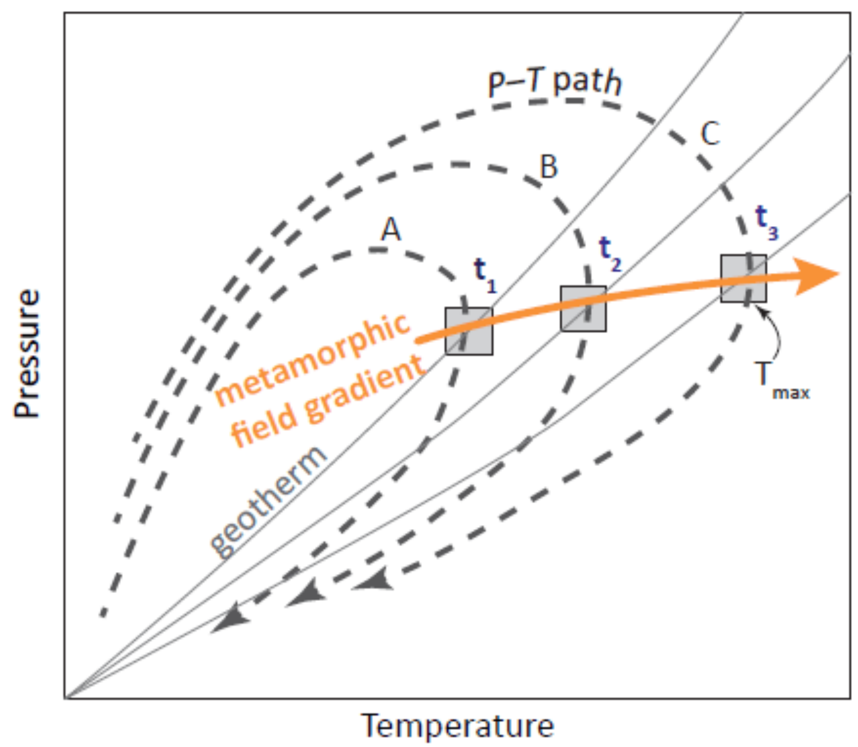


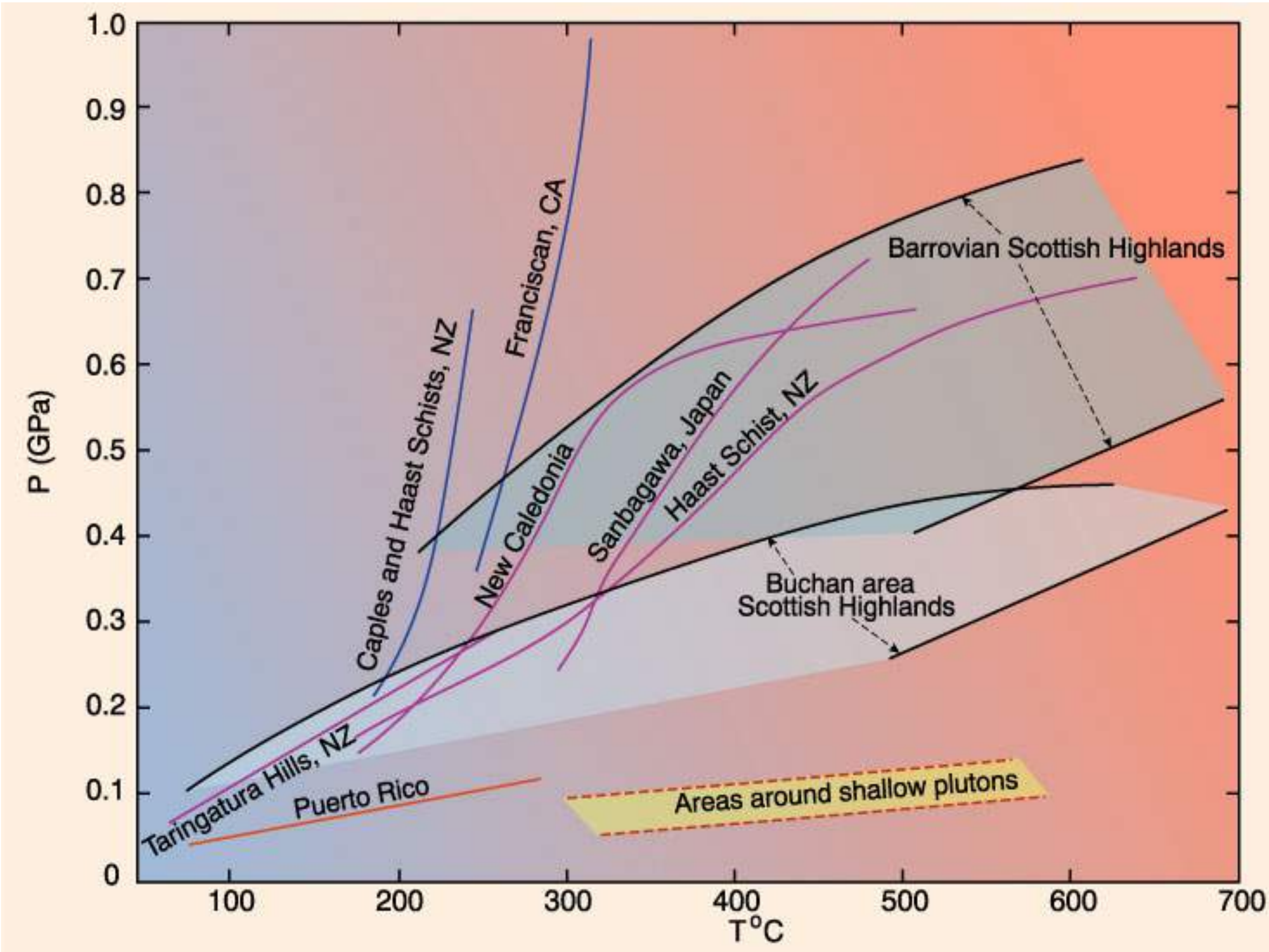
Moraes et al., (2002)

Gradiente metamórfico de campo (*Metamorphic Field Gradient*)

- Linha no espaço *P-T* que une os pontos de T_{max} (e correspondente *P*) da região

- Linha ou série *PT*
- Gradiente metamórfico de campo





P (GPa)
T °C
Barrovian Scottish Highlands
Franciscan, CA
Caples and Haast Schists, NZ
New Caledonia
Sanbagawa, Japan
Haast Schist, NZ
Buchan area
Scottish Highlands
Taringatura Hills, NZ
Puerto Rico
Areas around shallow plutons

Int J Earth Sci (Geol Rundsch)
DOI 10.1007/s00531-016-1436-7

ORIGINAL PAPER

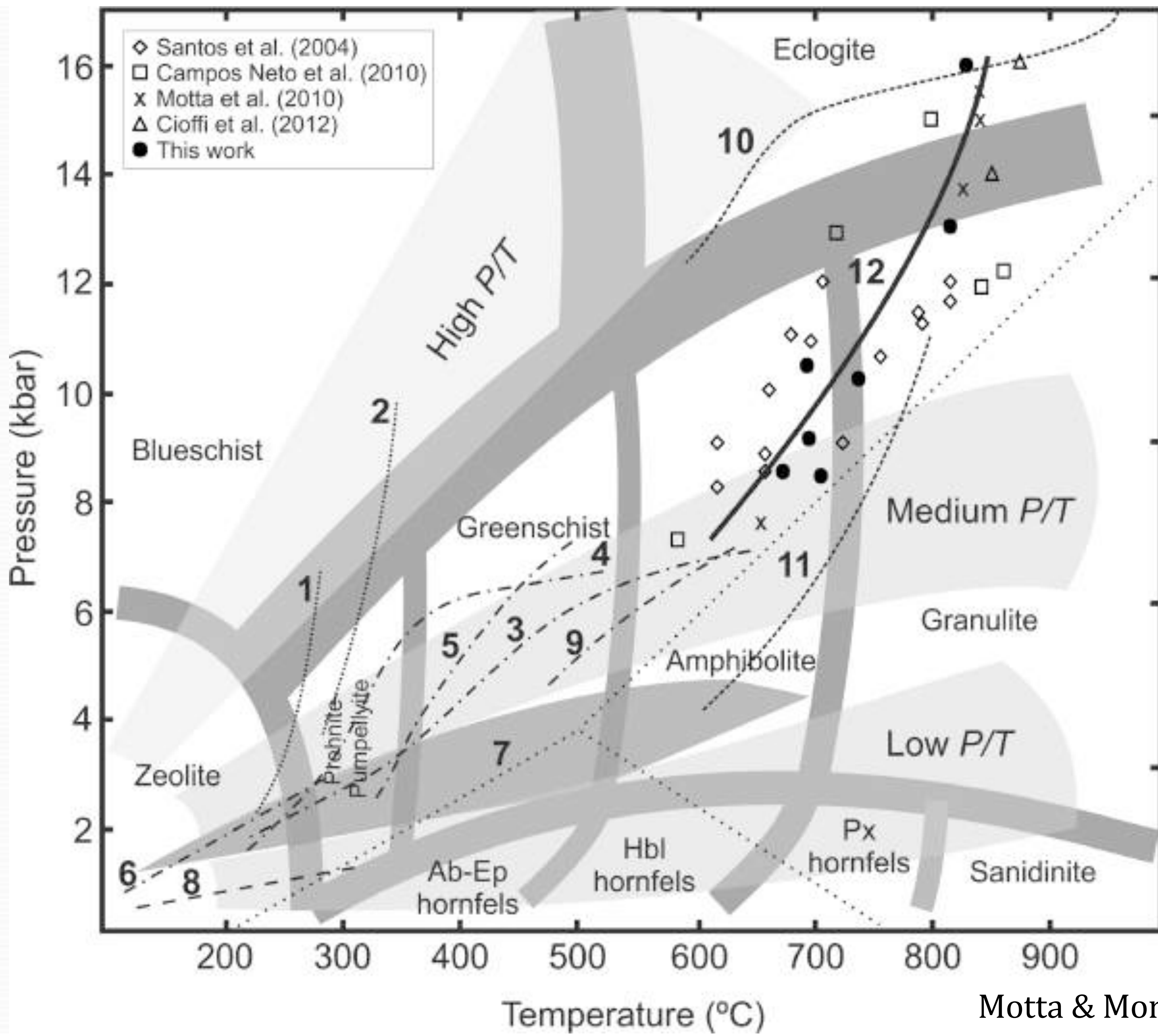
Pseudo- and real-inverted metamorphism caused by the superposition and extrusion of a stack of nappes: a case study of the Southern Brasília Orogen, Brazil

Rafael Gonçalves da Motta[1] · Renato Moraes[1]

Received: 4 March 2016 / Accepted: 14 December 2016

Abstract The Southern Brasília Orogen is a Neoproterozoic belt that occurs along the southernmost border of the São Francisco Craton where the Andrelândia Nappe System represents the subducted sedimentary domain and is divided into three allochthonous groups, of which the ages and *P–T* conditions of metamorphism are studied here. The basal unit, the Andrelândia Nappe, exhibits an inverted metamorphic pattern. The base of the structure, composed of staurolite, garnet, biotite, kyanite, quartz, and muscovite, marks the metamorphic peak, whereas at the top, the association of the metamorphic peak does not contain staurolite. The Liberdade Nappe, the middle unit, presents a normal metamorphic pattern; its base, close to the Andrelândia (622.3 ± 7.6 Ma). The upper unit, the Serra da Natureza Klippe, bears a typical high-pressure granulite mineral assemblage that is composed of kyanite, garnet, K-feldspar, rutile, and leucosome, as well as a metamorphic peak at 604.5 ± 6.1 Ma. This tectonic assembly, with inverted and non-inverted metamorphic patterns and generation of klippen structures, is consistent with exhumation models and a strong indentor located in the lower continental crust.

Keywords Brasília Orogen · High-pressure granulite · Inverted metamorphism · Metamorphic field gradient · Monazite dating · Exhumation model



Motta & Moraes, 2017

Precambrian Research 345 (2020) 105766

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

Tectonic implications of juxtaposed high- and low-pressure metamorphic field gradient rocks in the Turvo-Cajati Formation, Curitiba Terrane, Ribeira Belt, Brazil

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A R T I C L E I N F O

Keywords:
Detrital zircon U–Pb ages
Metamorphic field gradients
Paired metamorphic belts
Pseudosection modeling
Ribeira Belt
Neoproterozoic

A B S T R A C T

The Turvo-Cajati Formation (TCF) is an important unit forming the Curitiba Terrane, a major segment of the southern Ribeira Belt, SE Brazil. It is composed of rocks of greenschist (LTCF), amphibolite (MTCF) and granulite (HTCF) facies conditions. Previous studies in the HTCF indicate that the unit underwent extensive partial melting under high-pressure conditions (670–810 °C and 9.5–12 kbar), within the kyanite stability field. In this paper, a study of the metamorphic zoning within the LTCF and MTCF is undertaken using pseudosection modeling in the NCKFMASHTO and MnNCKFMASHTO model systems coupled with detrital zircon U–Pb geochronology. Four metamorphic zones are recognized for the LTCF and MTCF: biotite, garnet, staurolite and sillimanite zones, with predominance of sillimanite zone and pressures lower than 8 kbar, as staurolite breaks down straight to sillimanite, without formation of a kyanite zone. Pseudosections yielded metamorphic peak conditions of ~530–560 °C and ~6–7.5 kbar (garnet zone) and ~660–690 °C and ~6–7.5 kbar (sillimanite zone). The metamorphic field gradient is flat and of low to medium pressure, below the typical Barrovian-type baric regime, and different from the HTCF. Available petrological and geochronological data suggest that the TCF comprises a paired low-*P* and high-*P* metamorphic belt, associated with a major Ediacaran suture zone in the southern Ribeira Belt. Probability density plots from detrital zircon U–Pb ages indicate late-Cryogenian-Ediacaran arc-related and Rhyacian sources for all TCF sub-units. This scenario suggests that the TCF is made up of a collisional juxtaposition of an accretionary wedge (HTCF) and a back-arc basin (LTCF and MTCF) on the border of a microplate, which includes a Rhyacian basement microcontinent, the Atuba Complex. It is inferred the high metamorphic gradient recorded in the LTCF and MTCF was related with asthenospheric upwelling in the back-arc region, which also produced extensive partial melting in the Atuba Complex basement.

1. Introduction

The Barrovian-type metamorphism has been described in multiple places all over the World since it was characterized in the Scottish Highlands by George Barrow (1912), such as in Iberian Massif (Catalán et al., 2003), between Canada and EUA (Brown and Walker, 1993), in Andes (García et al., 2005), in Alps (Burg and Gerya, 2005), among others. Now, it is known to represent a common type of orogenic regional metamorphism (e.g. England & Thompson, 1984). In recent decades, advances in Metamorphic Petrology, such as geothermobarometry, pseudosection modeling and development of software such as THERMOCALC (Powell & Holland, 1988), Perple_X (Connolly, 2005), Theriak/Domino (de Capitani & Brown 1987; de Capitani 1994) and Gibbs (Spear et al., 2001), allowed the increase of knowledge in mechanisms and processes operating during metamorphism. Also, the relationship with large-scale tectonic processes is better understood with these advances. One interesting tool that allows comparing tectonic regimes of different metamorphic terranes is the metamorphic field gradient (Turner, 1981), a line defined by the metamorphic peak conditions of a rock pile that underwent the same metamorphic event, but with rocks at different depths. Its inclination defines the metamorphic facies series, as well as the dT/dP regime of the terrane and has a direct connection with the tectonic setting of metamorphism (Turner, 1981; Philpotts & Ague, 2009).

The Southern Ribeira Belt, in southeast Brazil, is formed by several different metamorphic terranes (Basei et al., 1992; Faleiros et al.,

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