Chapter 25. Metamorphic Facies and Metamorphosed Mafic Rocks

V.M. Goldschmidt (1911, 1912a), contact metamorphosed pelitic, calcareous, and hornfelses in the Oslo region

Relatively simple mineral assemblages (< 6 major minerals) in the inner zones of the aureoles around granitoid intrusives

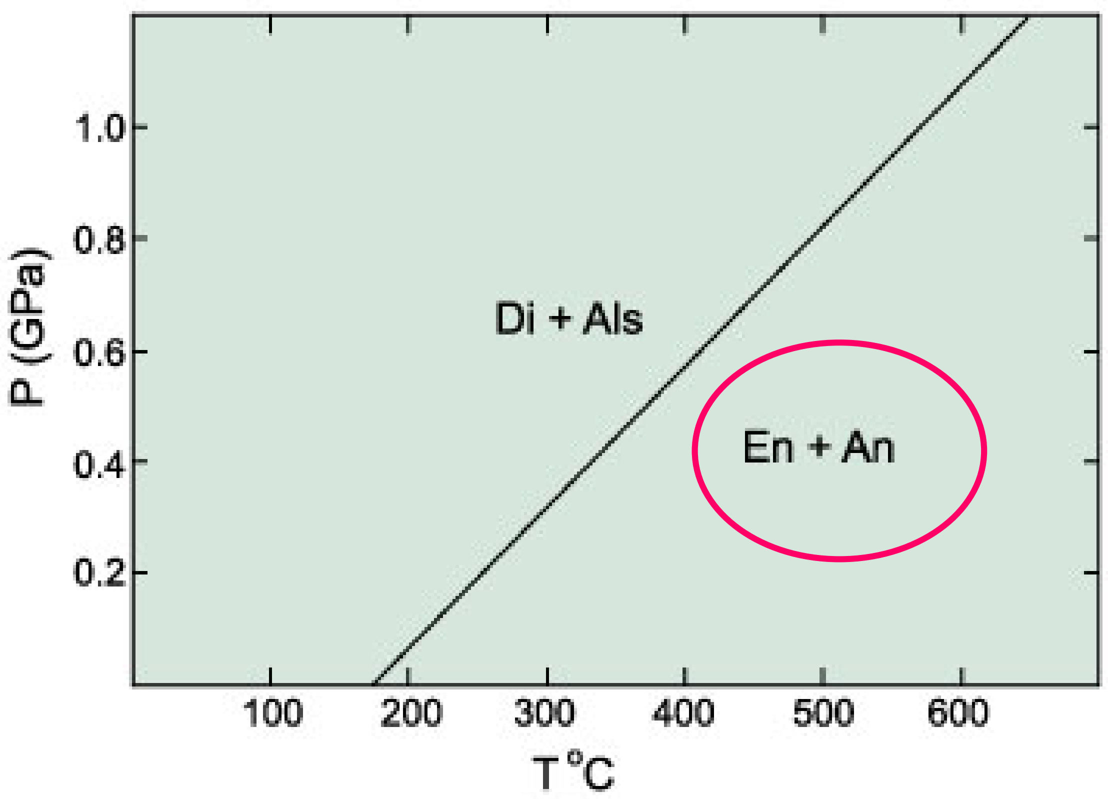
Equilibrium mineral assemblage related to X_{bulk}

Metamorphic Facies

- Certain mineral pairs (e.g. anorthite + hypersthene) were consistently present in rocks of appropriate composition, whereas the compositionally equivalent pair (diopside + andalusite) was not
- If two alternative assemblages are X-equivalent, we must be able to relate them by a reaction
- In this case the reaction is simple:

$$MgSiO_3 + CaAl_2Si_2O_8 = CaMgSi_2O_6 + Al_2SiO_5$$

En An Di Als


1.0
0.8
0.6
0.4
0.2
P (GPa)
Di + Als
En + An
100
200
300
400
500
600
T °C

Metamorphic Facies

Pentii Eskola (1914, 1915) Orijärvi, S. Finland

Rocks with K-feldspar + cordierite at Oslo contained the compositionally equivalent pair biotite + muscovite at Orijärvi

Eskola: difference must reflect differing physical conditions

Finnish rocks (more hydrous and lower volume assemblage) equilibrated at lower temperatures and higher pressures than the Norwegian ones

Metamorphic Facies

Oslo: Ksp + Cord

Orijärvi: Bi + Mu

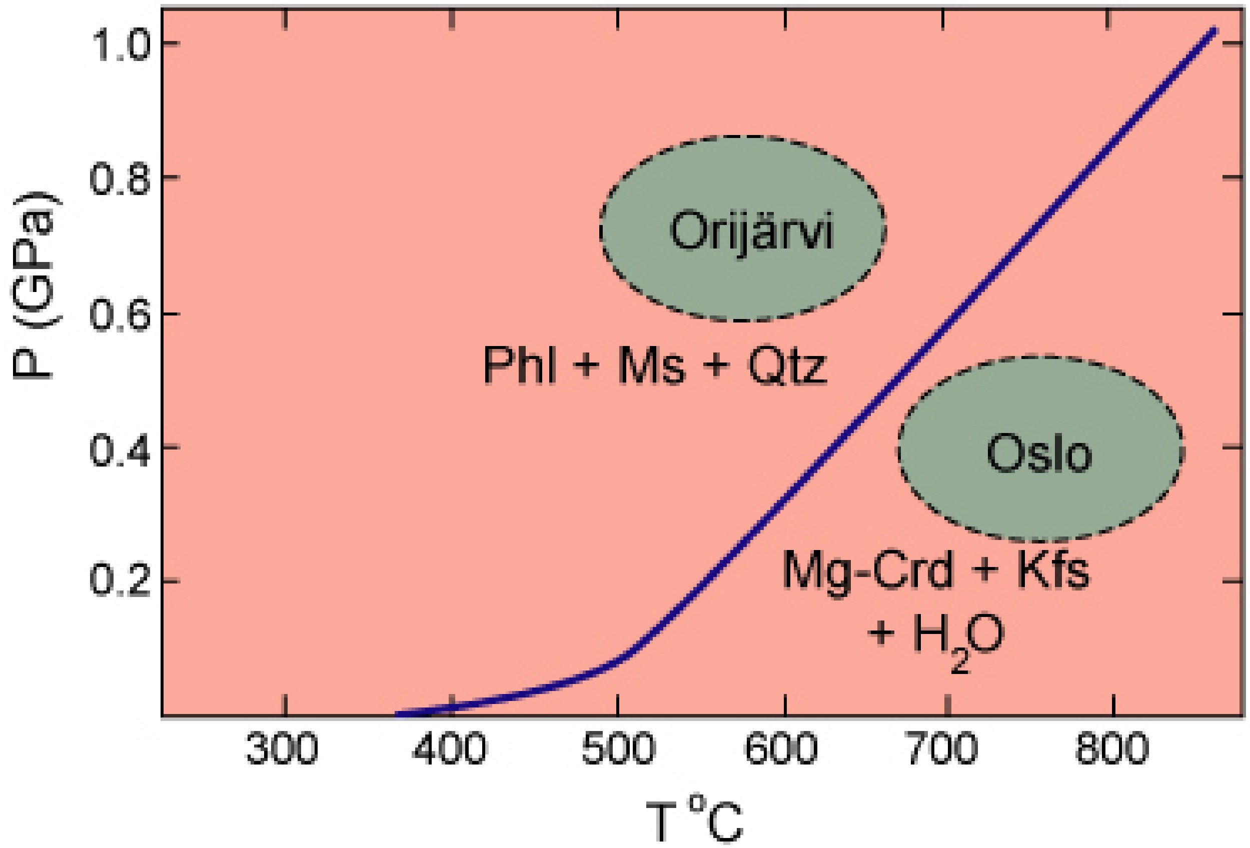
Reaction:

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

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)
300
400
500
600
700
800
T °C
Orijärvi
Phl + Ms + Qtz
Oslo
Mg-Crd + Kfs
+ H2O

Metamorphic Facies

Eskola (1915) developed the concept of **metamorphic facies:**

> "In any rock or metamorphic formation which has arrived at a chemical equilibrium through metamorphism at constant temperature and pressure conditions, the mineral composition is controlled only by the chemical composition. We are led to a general conception which the writer proposes to call metamorphic facies."

Metamorphic Facies

Dual basis for the facies concept

1. Descriptive: relationship between the X_{bulk} & mineralogy
   - A fundamental feature of Eskola's concept
   - A metamorphic facies is then a set of repeatedly associated metamorphic mineral assemblages
   - If we find a specified assemblage (or better yet, a group of compatible assemblages covering a range of compositions) in the field, then a certain facies may be assigned to the area

Metamorphic Facies

2. Interpretive: the range of temperature and pressure conditions represented by each facies

- Eskola aware of the P-T implications and correctly deduced the relative temperatures and pressures of facies he proposed
- Can now assign relatively accurate temperature and pressure limits to individual facies

Metamorphic Facies

Eskola (1920) proposed 5 original facies:

- Greenschist
- Amphibolite
- Hornfels
- Sanidinite
- Eclogite

Easily defined on the basis of mineral assemblages that develop in mafic rocks

Metamorphic Facies

In his final account, Eskola (1939) added:

- Granulite
- Epidote-amphibolite
- Glaucophane-schist (now called Blueschist)

... and changed the name of the hornfels facies to the pyroxene hornfels facies

Metamorphic Facies

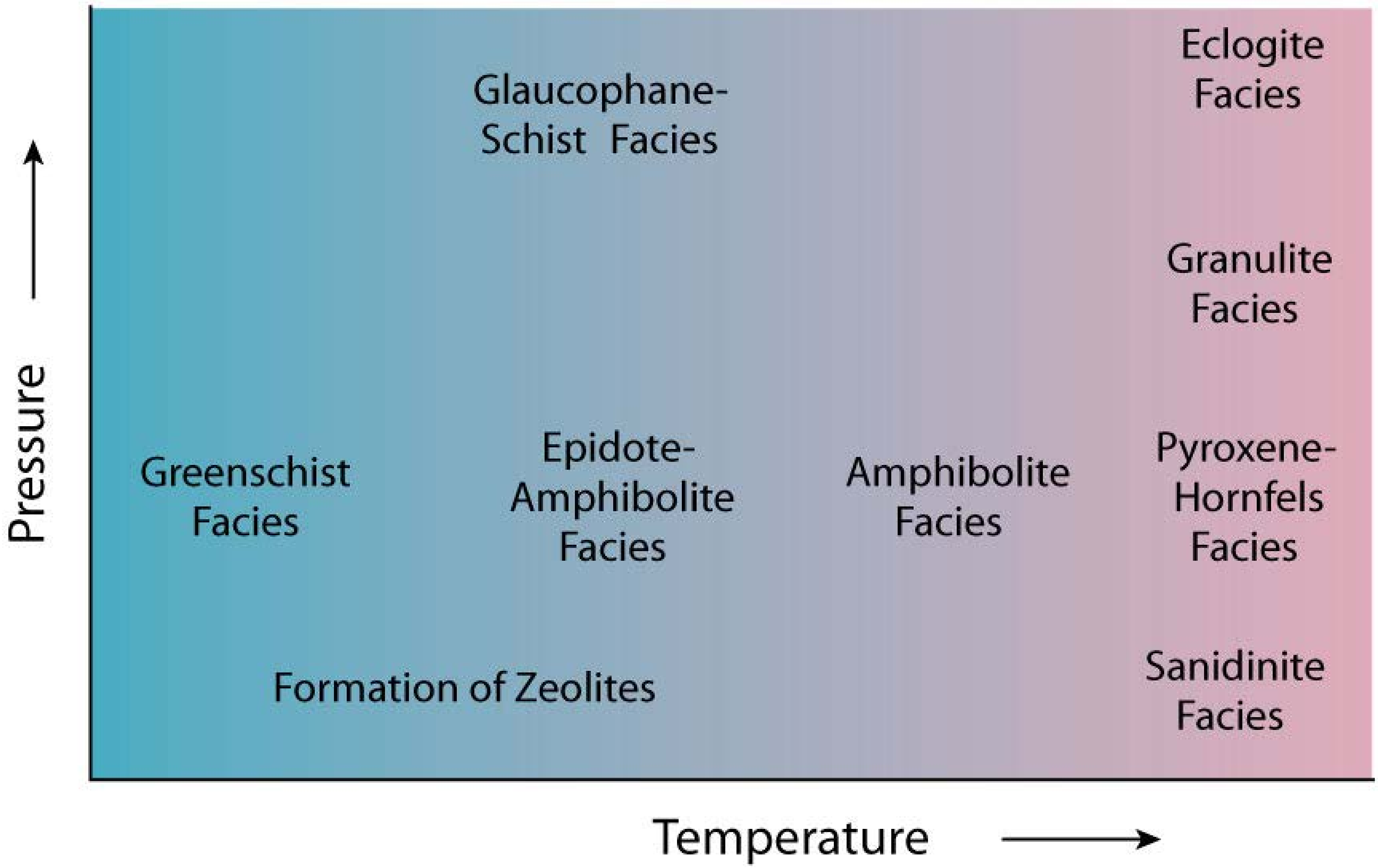


Fig. 25.1 The metamorphic facies proposed by Eskola and their relative temperature-pressure relationships. After Eskola (1939) *Die Entstehung der Gesteine*. Julius Springer. Berlin.

Metamorphic Facies

Several additional facies types have been proposed. Most notable are:

- Zeolite
- Prehnite-pumpellyite

...from Coombs in the "burial metamorphic" terranes of New Zealand

Fyfe *et al*. (1958) also proposed:

- Albite-epidote hornfels
- Hornblende hornfels

Metamorphic Facies

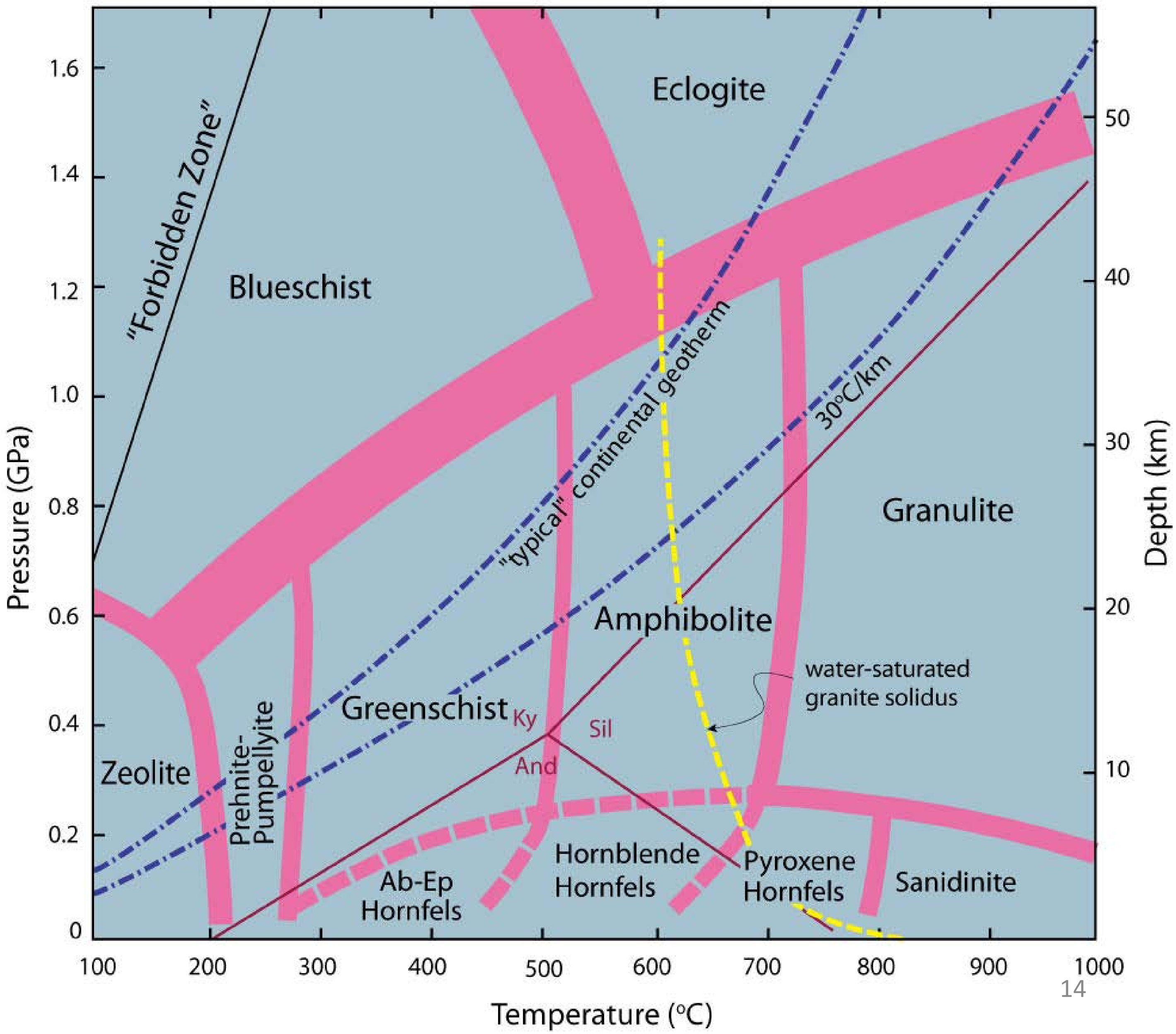


Fig. 25.2. Temperature-pressure diagram showing the generally accepted limits of the various facies used in this text. Boundaries are approximate and gradational. The "typical" or average continental geotherm is from Brown and Mussett (1993). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Metamorphic Facies

Table 25.1. The definitive mineral assemblages that characterize each facies (for mafic rocks).

Table 25-1. Definitive Mineral Assemblages of Metamorphic Facies

Facies	Definitive Mineral Assemblage in Mafic Rocks
Zeolite	zeolites: especially laumontite, wairakite, analcime
Prehnite-Pumpellyite	prehnite + pumpellyite (+ chlorite + albite)
Greenschist	chlorite + albite + epidote (or zoisite) + quartz ± actinolite
Amphibolite	hornblende + plagioclase (oligoclase-andesine) ± garnet
Granulite	orthopyroxene (+ clinopyrixene + plagioclase ± garnet ± hornblende)
Blueschist	glaucophane + lawsonite or epidote (+albite ± chlorite)
Eclogite	pyrope garnet + omphacitic pyroxene (± kyanite)
Contact Facies	Mineral assemblages in mafic rocks of the facies of contact meta-morphism do not differ substantially from that of the corresponding regional facies at higher pressure.

After Spear (1993)

It is convenient to consider metamorphic facies in **4 groups**:

1) Facies of high pressure

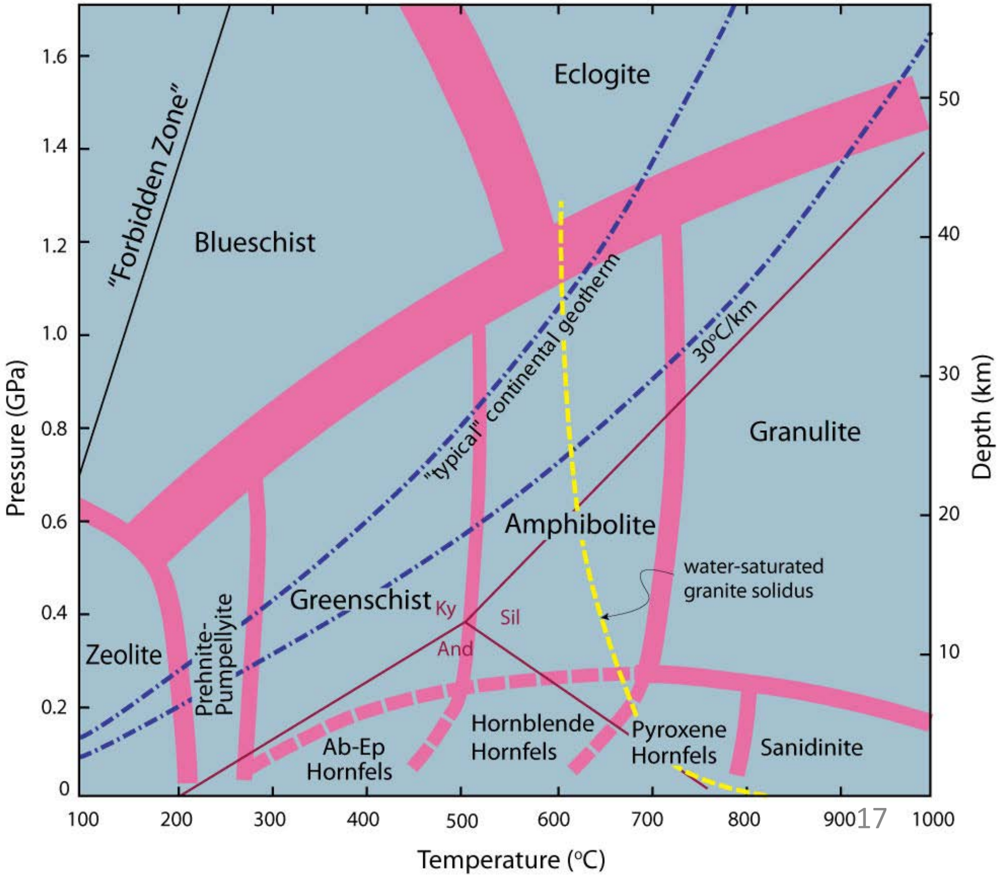
- The blueschist and eclogite facies: low molar volume phases under conditions of high pressure
- Blueschist facies- areas of low T/P gradients: subduction zones
- Eclogites: stable under normal geothermal conditions

  Deep crustal chambers or dikes, sub-crustal magmatic underplates, subducted crust that is redistributed into the mantle

Metamorphic Facies

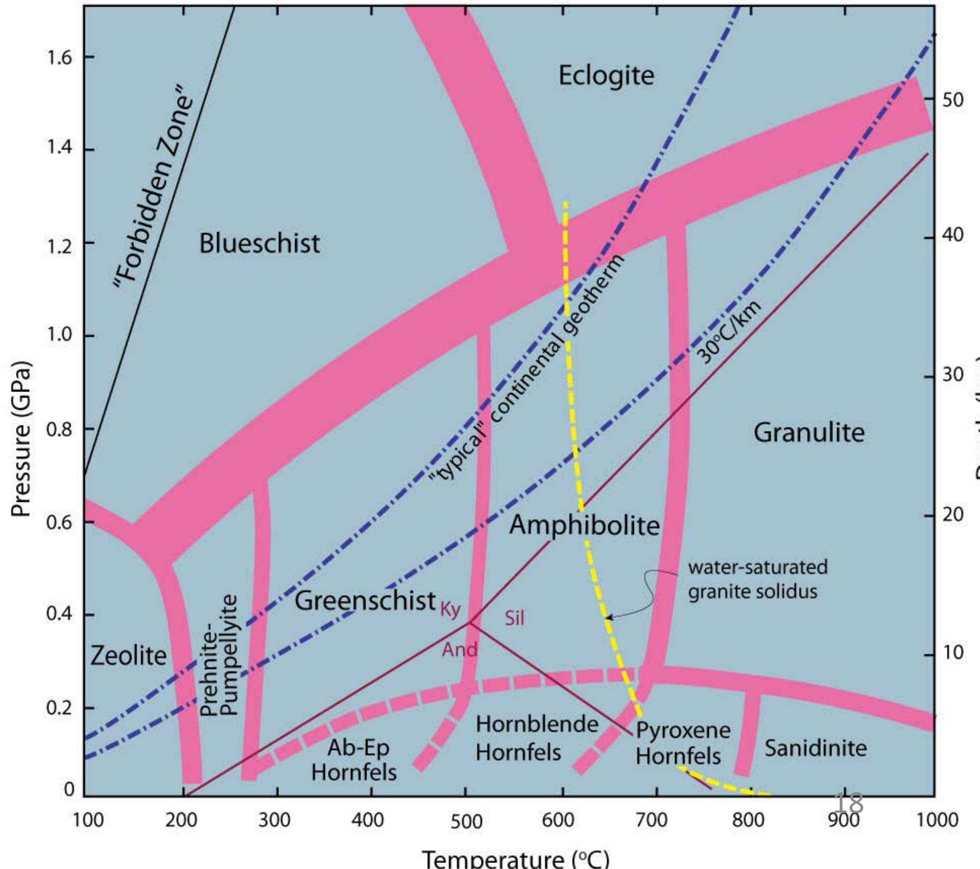
2) Facies of medium pressure

- Most exposed metamorphic rocks belong to the greenschist, amphibolite, or granulite facies
- The greenschist and amphibolite facies conform to the "typical" geothermal



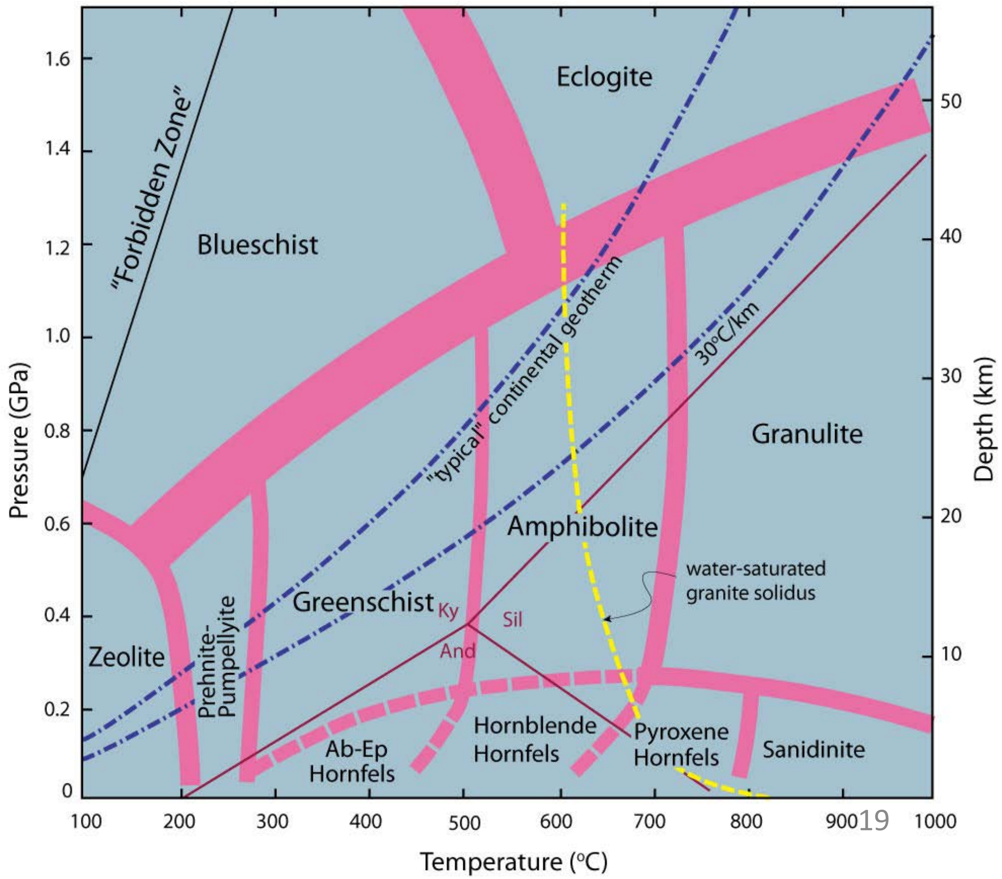
Metamorphic Facies

- **3) Facies of low pressure**
  - Albite-epidote hornfels, hornblende hornfels, and pyroxene hornfels facies: contact metamorphic terranes and regional terranes with very high geothermal gradient.
  - Sanidinite facies is rare- limited to xenoliths in basic magmas and the innermost portions of some contact aureoles adjacent to hot basic intrusives



Metamorphic Facies

- **4) Facies of low grades**
  - Rocks may fail to recrystallize thoroughly at very low grades, and equilibrium not always attained
  - Zeolite and prehnite-pumpellyite facies not always represented, and greenschist facies may be the lowest grade developed in many regional terranes



Metamorphic Facies

Combine the concepts of **isograds**, **zones**, and **facies**

- Examples: "chlorite zone of the greenschist facies," the "staurolite zone of the amphibolite facies," or the "cordierite zone of the hornblende hornfels facies," etc.
- Metamorphic maps typically include isograds that define zones and ones that define facies boundaries
- Determining a facies or zone is most reliably done when several rocks of varying composition and mineralogy are available

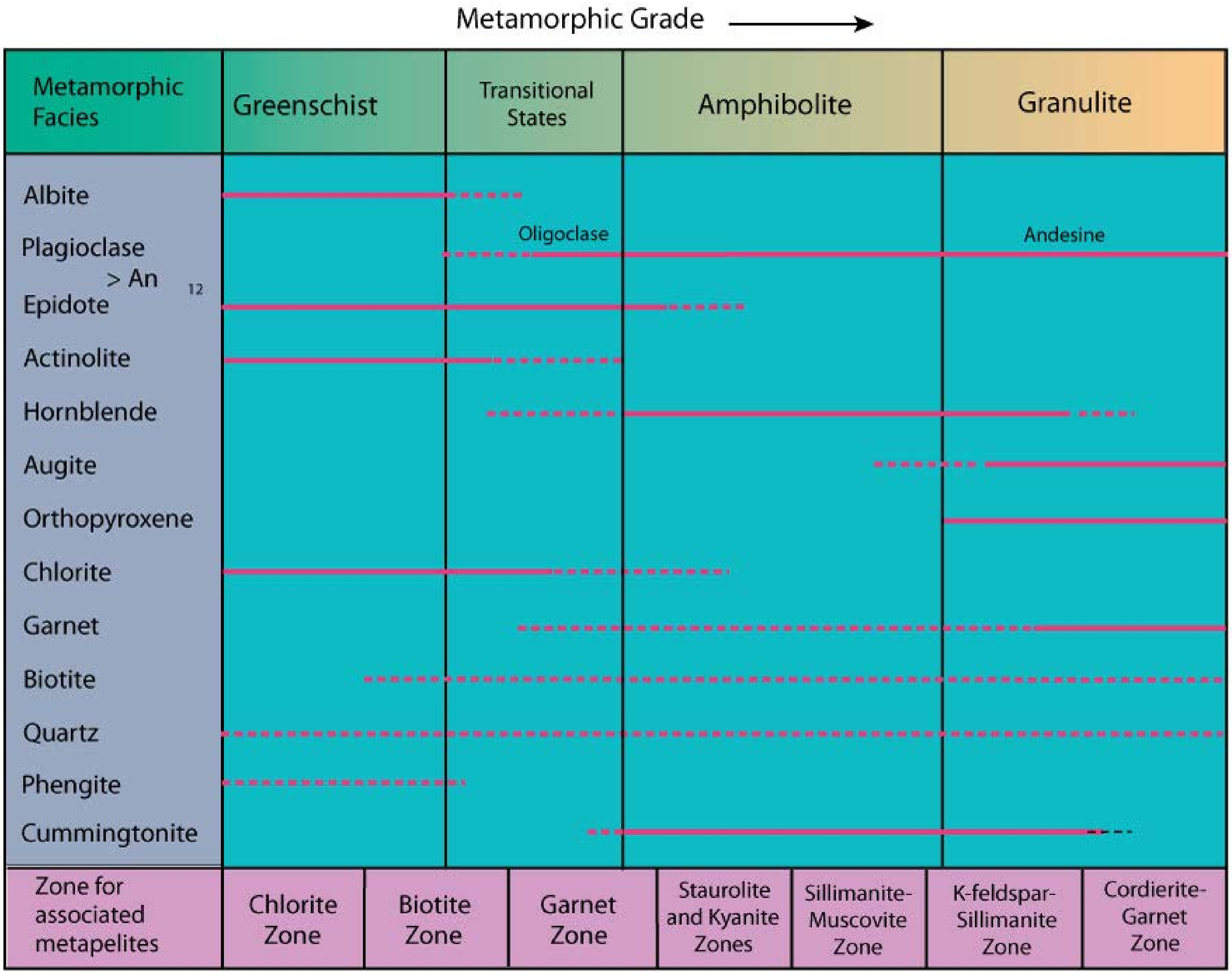


Fig. 25.10. Typical mineral changes that take place in metabasic rocks during progressive metamorphism in the medium P/T facies series. The approximate location of the pelitic zones of Barrovian metamorphism are included for comparison. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Facies Series

A traverse up grade through a metamorphic terrane should follow one of several possible metamorphic field gradients (Fig. 21.1), and, if extensive enough, cross through a sequence of facies

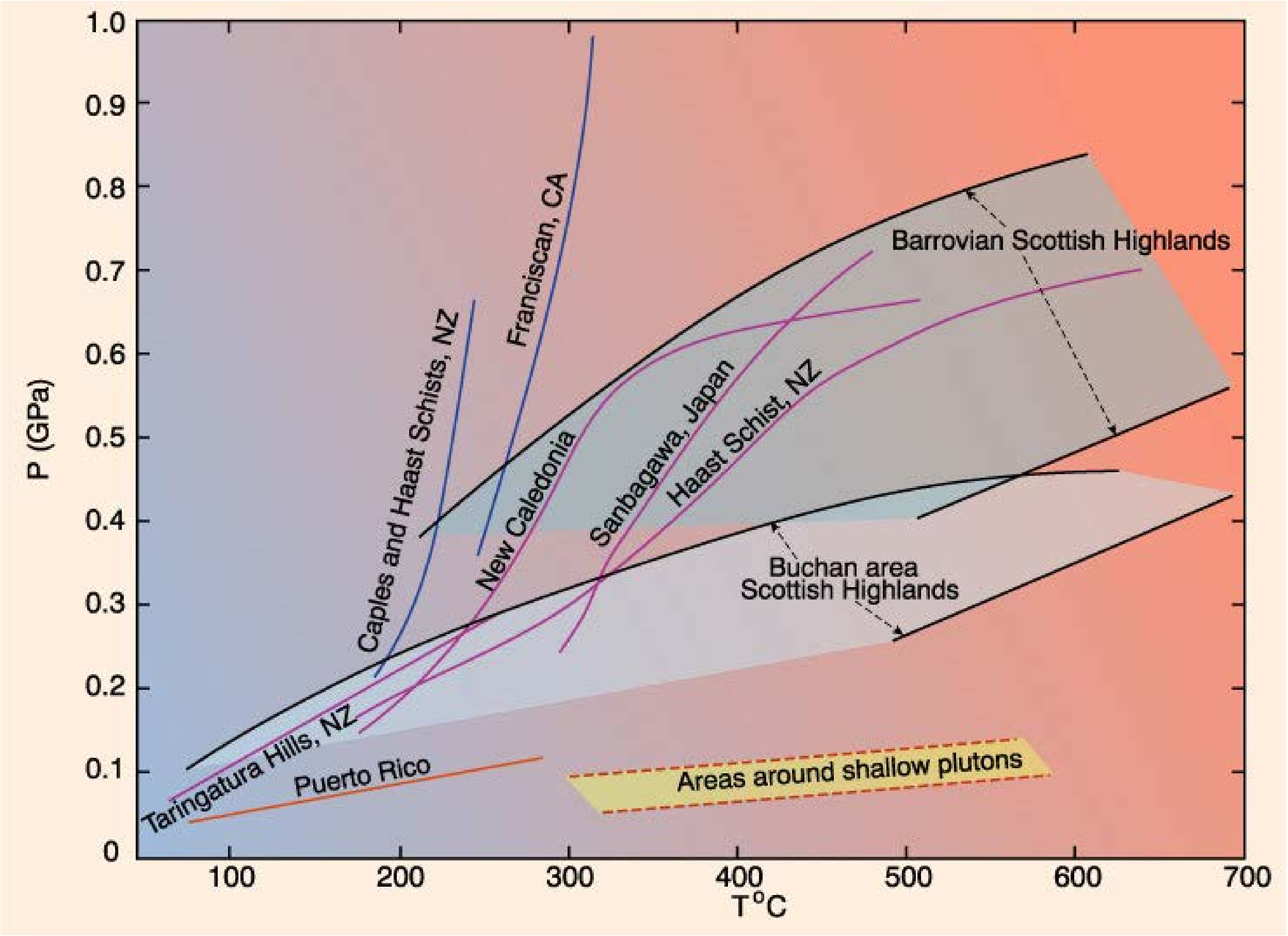


Figure 21.1. Metamorphic field gradients (estimated P-T conditions along surface traverses directly up metamorphic grade) for several metamorphic areas. After Turner (1981). *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill.

Facies Series

Miyashiro (1961) proposed five facies series, most of them named for a specific representative "type locality" The series were:

1. Contact Facies Series (very low-P)
2. Buchan or Abukuma Facies Series (low-P regional)
3. Barrovian Facies Series (medium-P regional)
4. Sanbagawa Facies Series (high-P, moderate-T)
5. Franciscan Facies Series (high-P, low T)

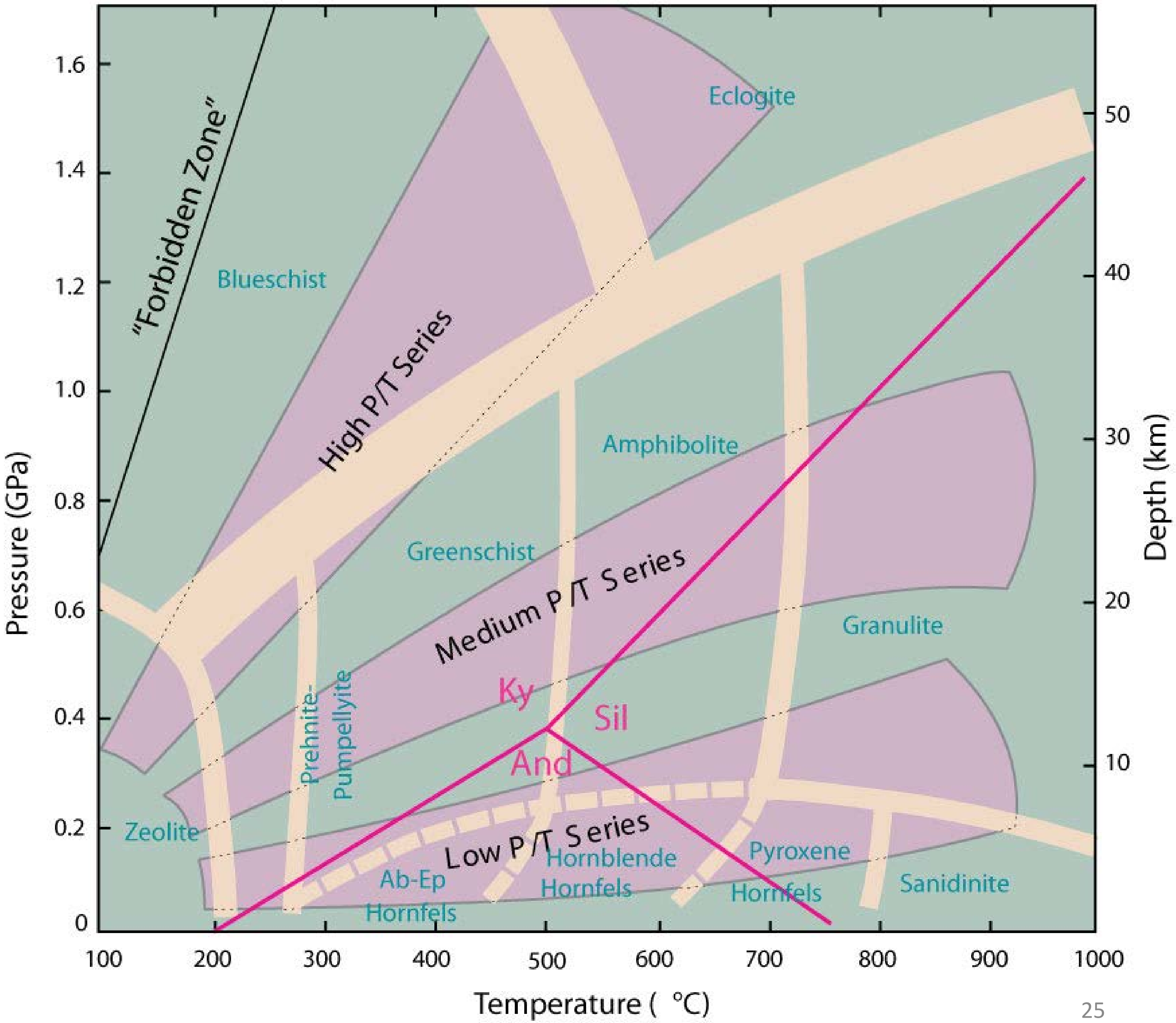


Fig. 25.3. Temperature-pressure diagram showing the three major types of metamorphic facies series proposed by Miyashiro (1973, 1994). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Metamorphic Facies

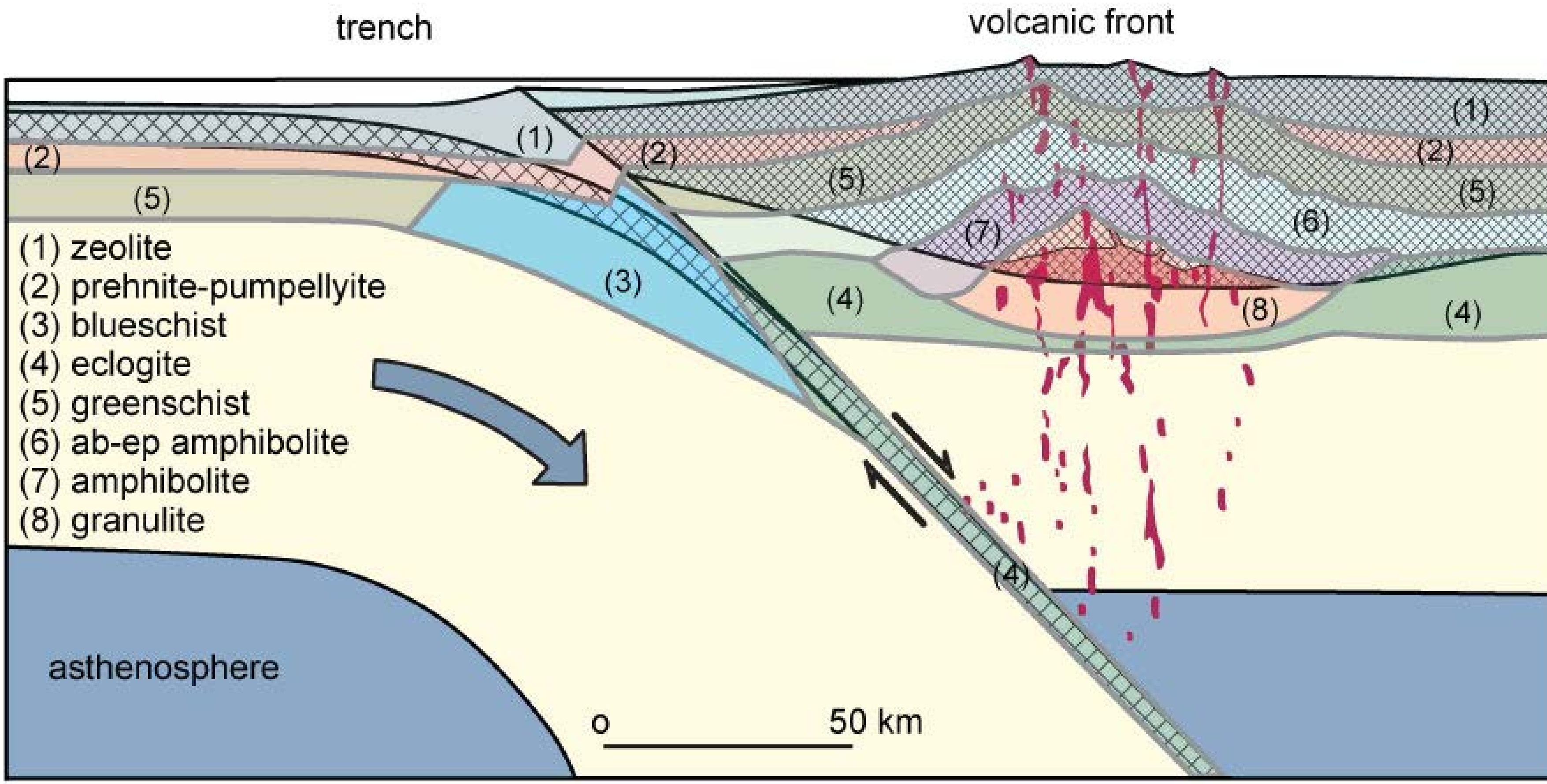


Figure 25.4. Schematic cross-section of an island arc illustrating isotherm depression along the outer belt and elevation along the inner axis of the volcanic arc. The high P/T facies series typically develops along the outer paired belt and the medium or low P/T series develop along the inner belt, depending on subduction rate, age of arc and subducted lithosphere, etc. From Ernst (1976).

Metamorphism of Mafic Rocks

Mineral changes and associations along T-P gradients characteristic of the three facies series

- Hydration of original mafic minerals generally required
- If water unavailable, mafic igneous rocks will remain largely unaffected, even as associated sediments are completely re-equilibrated
- Coarse-grained intrusives are the least permeable and likely to resist metamorphic changes
- Tuffs and graywackes are the most susceptible

Metamorphism of Mafic Rocks

Plagioclase:

- Ca-rich plagioclase progressively unstable as T lowered
- General correlation between temperature and *maximum* An-content of stable plagioclase
  - Low metamorphic grades: albite (An_{0-3})
  - Upper-greenschist facies oligoclase becomes stable.
  - Andesine and more calcic plagioclase stable in the upper amphibolite and granulite facies

- The excess Ca and Al $\rightarrow$ calcite, an epidote mineral, sphene, or amphibole, etc. (depending on P-T-X)

Metamorphism of Mafic Rocks

- Clinopyroxene → various mafic minerals.
- Chlorite, actinolite, hornblende, epidote, a metamorphic pyroxene, etc.
- The mafics that form are commonly diagnostic of the grade and facies

Mafic Assemblages at Low Grades

- Zeolite and prehnite-pumpellyite facies
- Do not always occur - typically require unstable protolith
- Boles and Coombs (1975) showed that metamorphism of tuffs in NZ accompanied by substantial chemical changes due to circulating fluids, and that these fluids played an important role in the metamorphic minerals that were stable
- The classic area of burial metamorphism thus has a strong component of hydrothermal metamorphism as well

Mafic Assemblages of the Medium P/T Series: Greenschist, Amphibolite, and Granulite Facies

- The greenschist, amphibolite and granulite facies constitute the most common facies series of regional metamorphism
- The classical Barrovian series of pelitic zones and the lower-pressure Buchan-Abukuma series are variations on this trend

Greenschist, Amphibolite, Granulite Facies

- Metamorphism of mafic rocks first evident in the greenschist facies, which correlates with the chlorite and biotite zones of associated pelitic rocks
  - Typical minerals include chlorite, albite, actinolite, epidote, quartz, and possibly calcite, biotite, or stilpnomelane
  - Chlorite, actinolite, and epidote impart the green color from which the mafic rocks and facies get their name

Greenschist, Amphibolite, Granulite Facies

Greenschist → **Amphibolite** facies transition involves two major mineralogical changes

1. Albite → oligoclase

2. Actinolite → hornblende (amphibole accepts increasing aluminum and alkalis at higher T)

Both transitions occur at approximately the same grade, but have different P/T slopes

Greenschist, Amphibolite, Granulite Facies

Greenschist, Amphibolite, Granulite Facies

- Mafic rocks generally melt at higher temperatures
- If water is removed by the earlier melts the remaining mafic rocks may become depleted in water
- Hornblende decomposes and orthopyroxene + clinopyroxene appear
- This reaction occurs over a T interval > 50°C

Greenschist, Amphibolite, Granulite Facies

Origin of granulite facies rocks is complex and controversial. There is general agreement, however, on two points

1) Granulites represent unusually hot conditions

- Temperatures > 700^{o}C (geothermometry has yielded some very high temperatures, even in excess of 1000^{o}C)
- Average geotherm temperatures for granulite facies depths should be in the vicinity of 500^{o}C, suggesting that granulites are the products of crustal thickening and excess heating

Greenschist, Amphibolite, Granulite Facies

2) Granulites are dry

- Rocks don't melt due to lack of available water
- Granulite facies terranes represent deeply buried and dehydrated roots of the continental crust
- Fluid inclusions in granulite facies rocks of S. Norway are CO_2-rich, whereas those in the amphibolite facies rocks are H_2O-rich

Mafic Assemblages of the Low P/T Series: Albite-Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite Facies

- Mineralogy of low-pressure metabasites not appreciably different from the med.-P facies series
- Albite-epidote hornfels facies correlates with the greenschist facies into which it grades with increasing pressure
- Hornblende hornfels facies correlates with the amphibolite facies, and the pyroxene hornfels and sanidinite facies correlate with the granulite facies

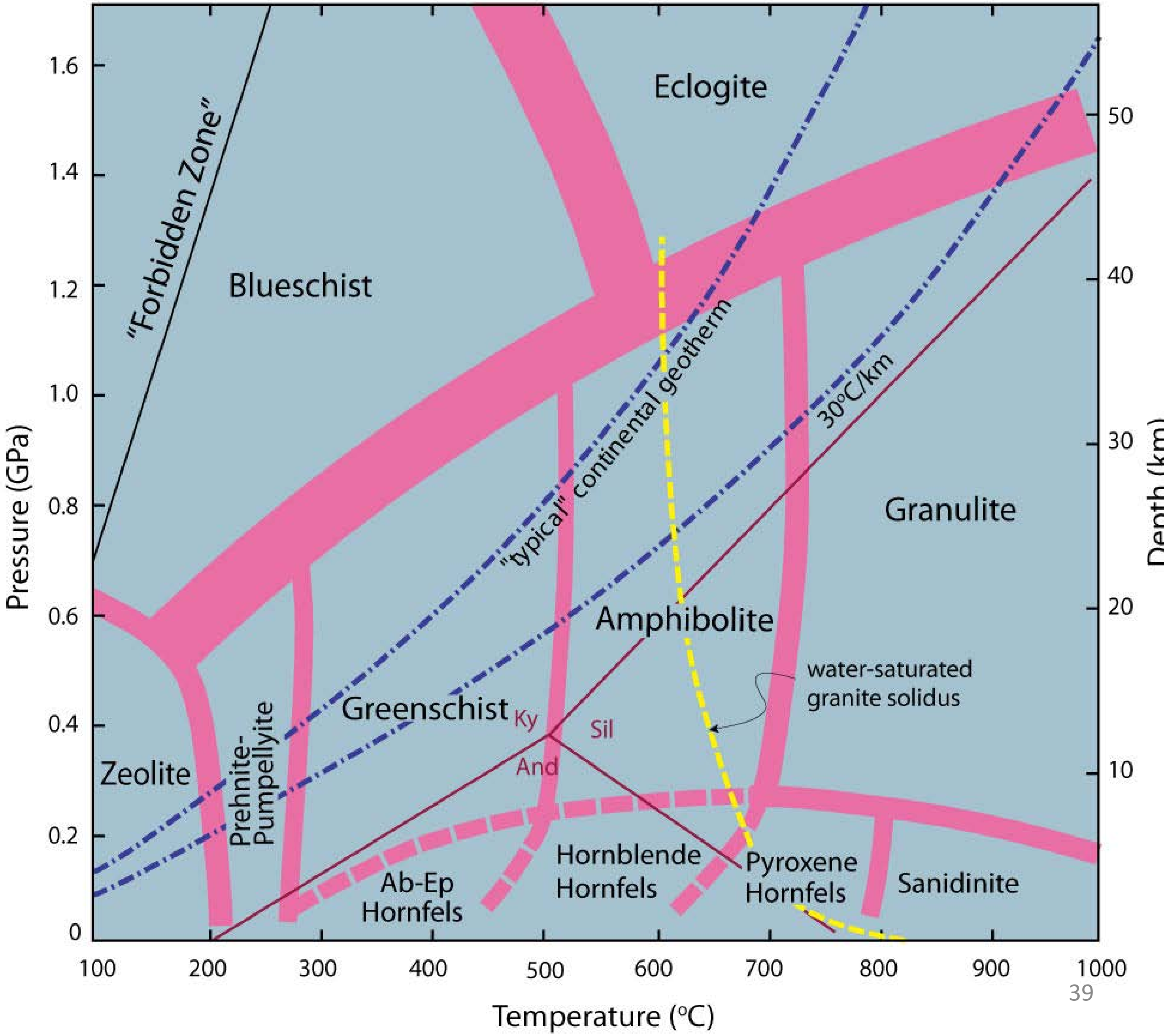


Fig. 25.2. Temperature-pressure diagram showing the generally accepted limits of the various facies used in this text. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Mafic Assemblages of the Low P/T Series: Albite-Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite Facies

Facies of contact metamorphism are readily distinguished from those of medium-pressure regional metamorphism on the basis of:

- Presence of andalusite and cordierite - metapelites
- Textures and field relationships
- Mineral thermobarometry

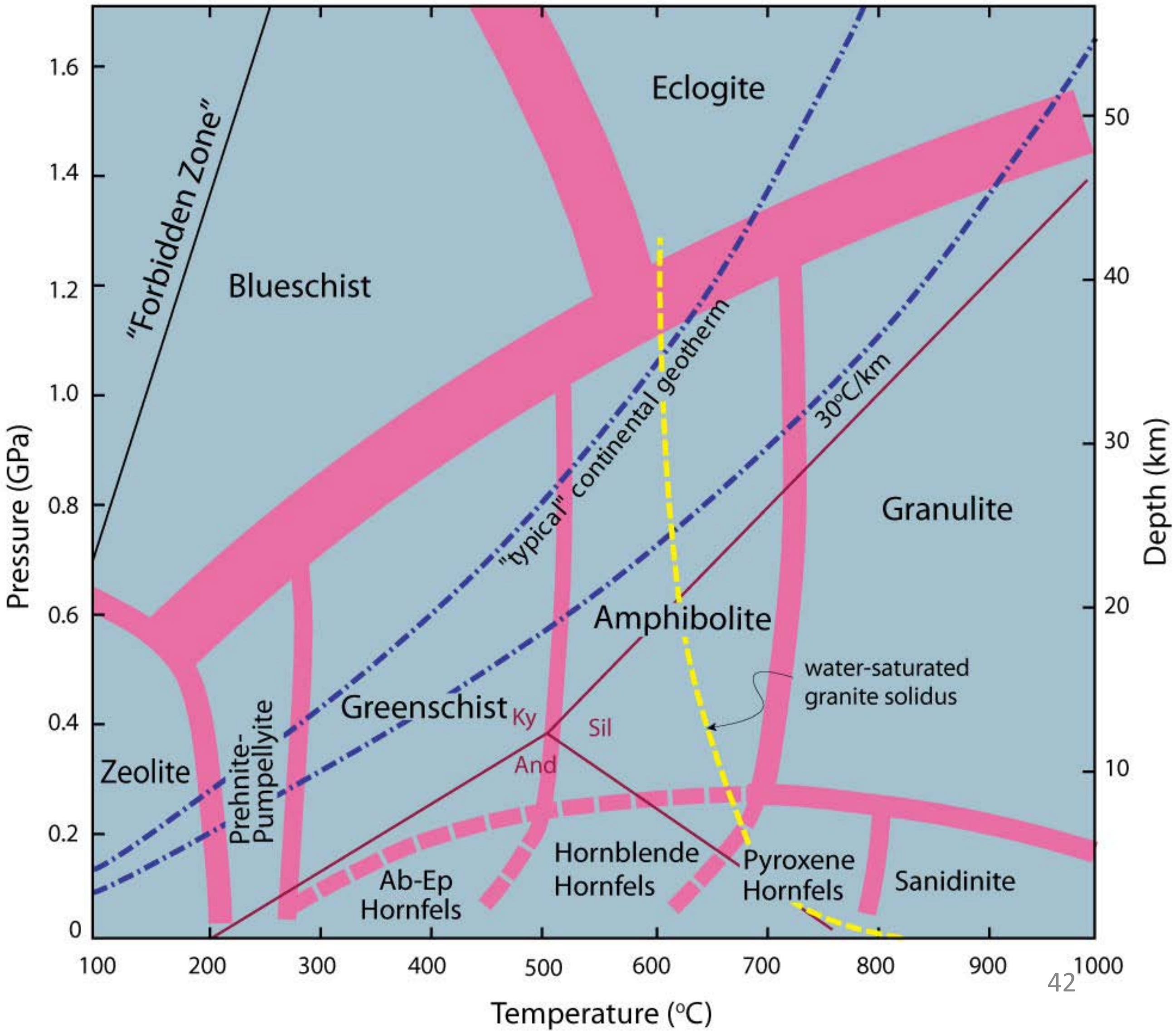
Mafic Assemblages of the High P/T Series: Blueschist and Eclogite Facies

- Mafic rocks (not pelites) develop definitive mineral assemblages under high P/T conditions
- High P/T geothermal gradients characterize subduction zones
- Mafic blueschists are easily recognizable by their color, and are useful indicators of ancient subduction zones
- The great density of eclogites: subducted basaltic oceanic crust becomes more dense than the surrounding mantle

Blueschist and Eclogite Facies

Alternative paths to the blueschist facies

Fig. 25.2. Temperature-pressure diagram showing the generally accepted limits of the various facies used in this text. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



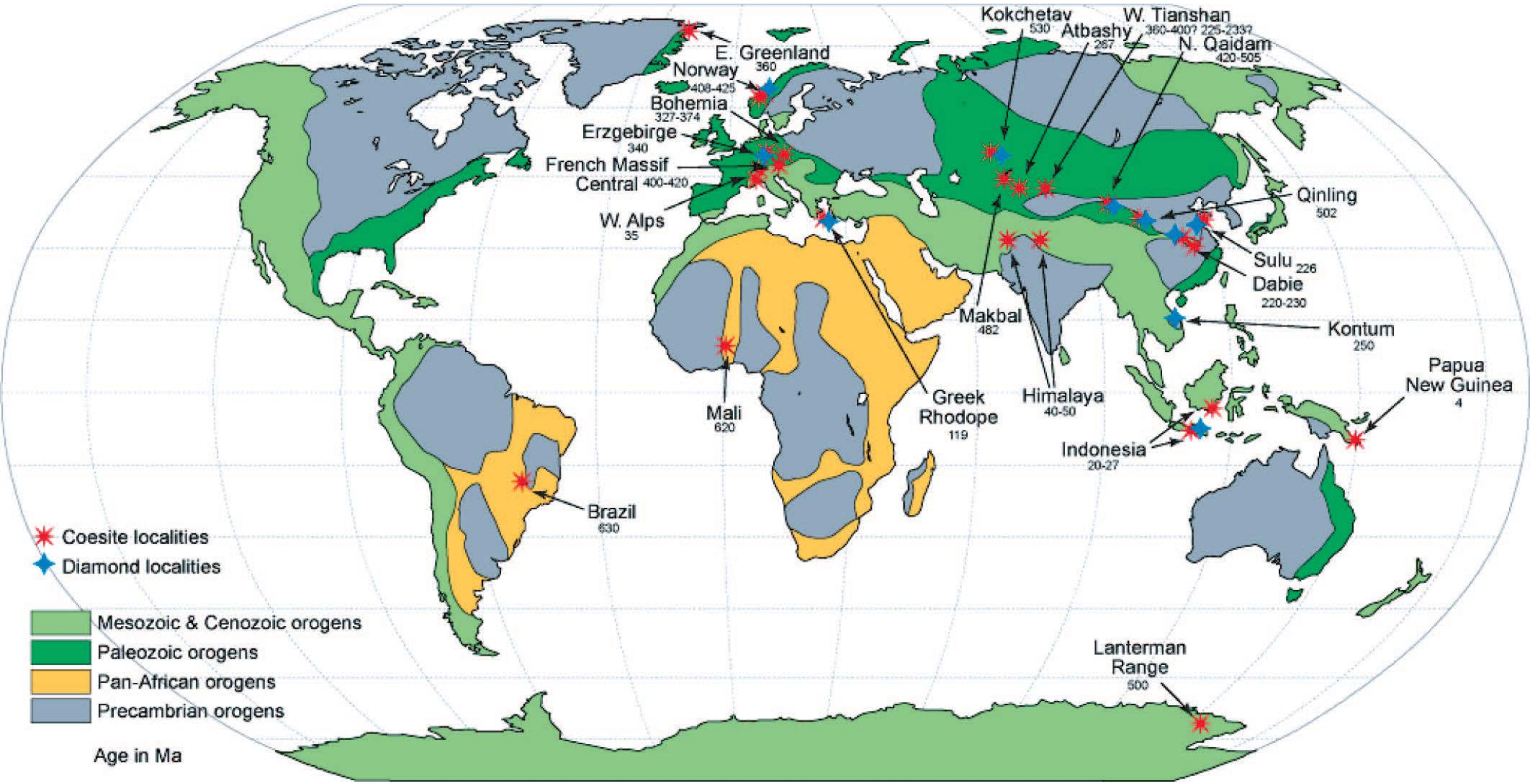
Blueschist and Eclogite Facies

- The blueschist facies is characterized in metabasites by the presence of a sodic blue amphibole stable only at high pressures (notably glaucophane, but some solution of crossite or riebeckite is possible)
- The association of glaucophane + lawsonite is diagnostic. Crossite is stable to lower pressures, and may extend into transitional zones
- Albite breaks down at high pressure by reaction to jadeitic pyroxene + quartz:

$NaAlSi_3O_8 = NaAlSi_2O_6 + SiO_2$ (reaction 25.3)

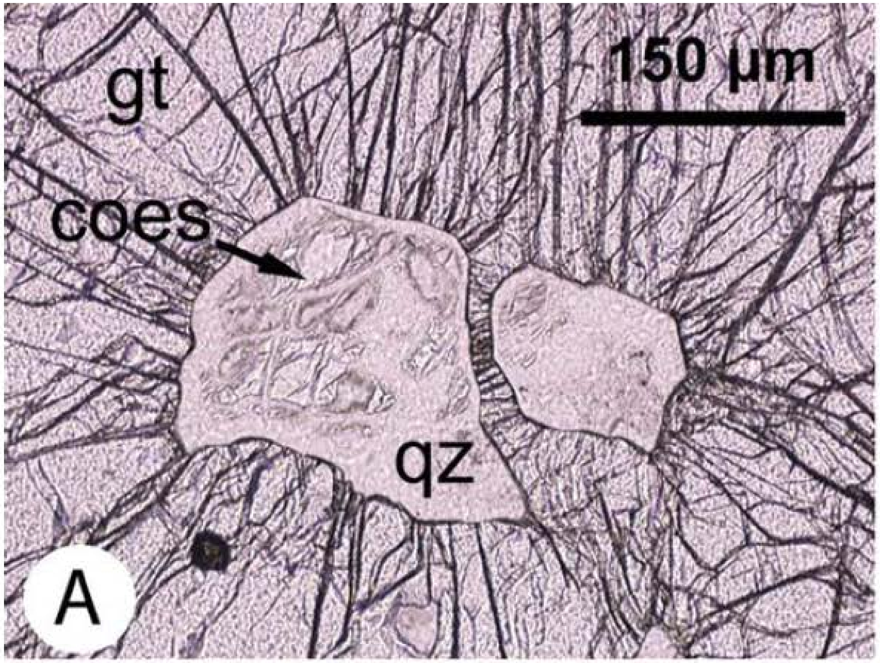
Ab = Jd + Qtz

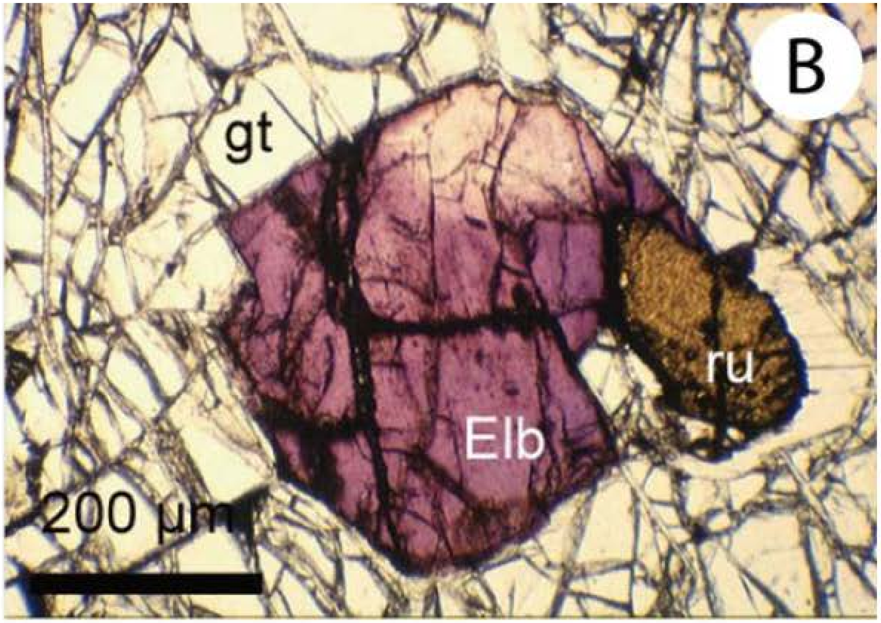
Ultra-high Pressure Metamorphism



Map of UHP localities and corresponding metamorphic ages from Liou et al. (2007).

Ultra-high Pressure Metamorphism



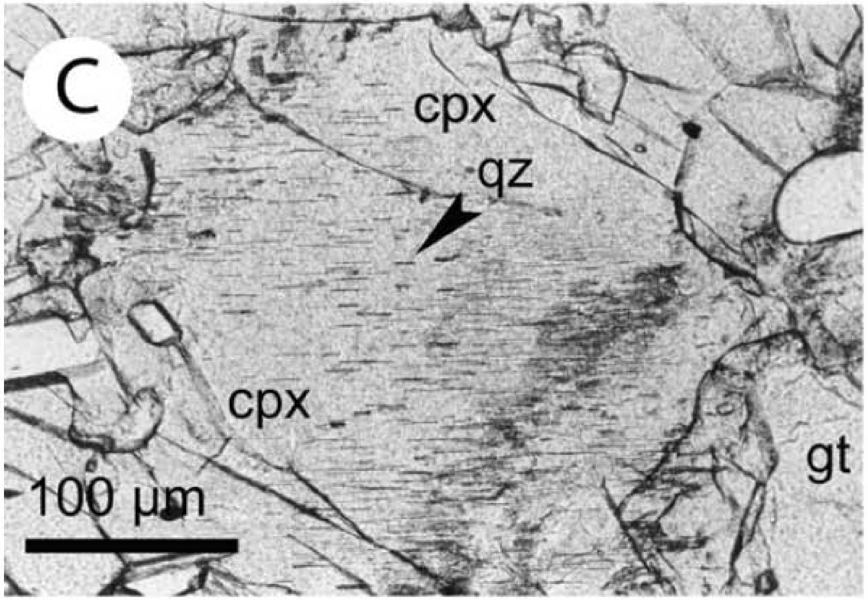


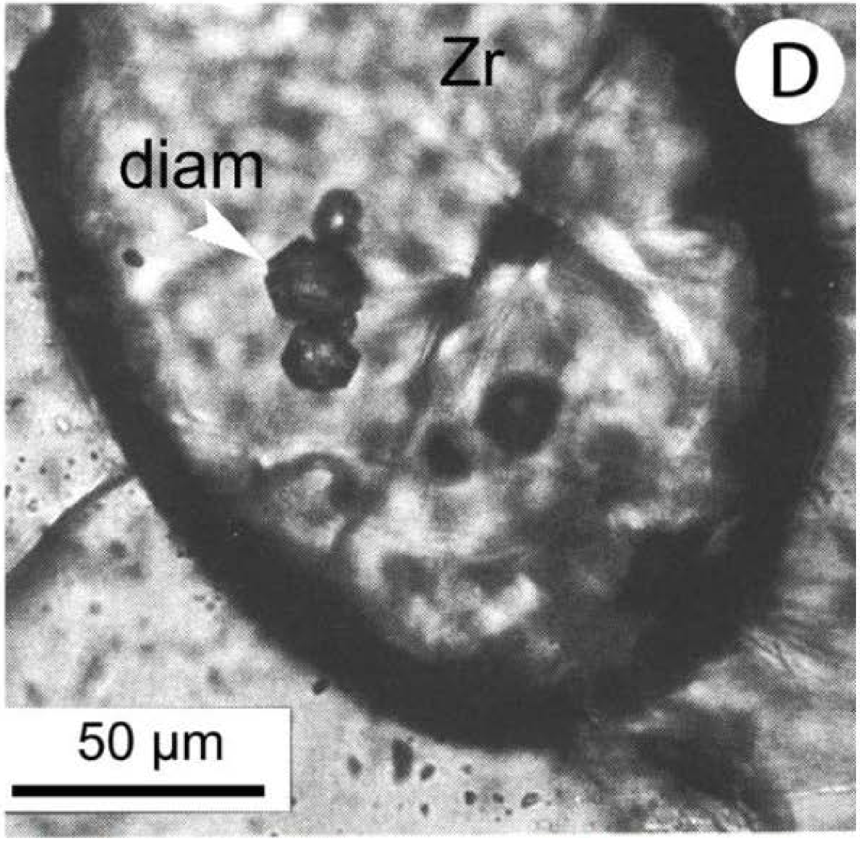
A. Coesite inclusion in garnet (partly transformed to quartz upon uplift, producing radial cracks in host due to volume increase).

B. Ellenbergerite ($Mg_6TiAl_6Si_8O_{28}(OH)_{10}$ – stable only at pressure >2.7 GPa and T <725^{o}C) and rutile in garnet.

Both samples from Dora Maira massif, N. Italy. Chopin (2003).

Ultra-high Pressure Metamorphism



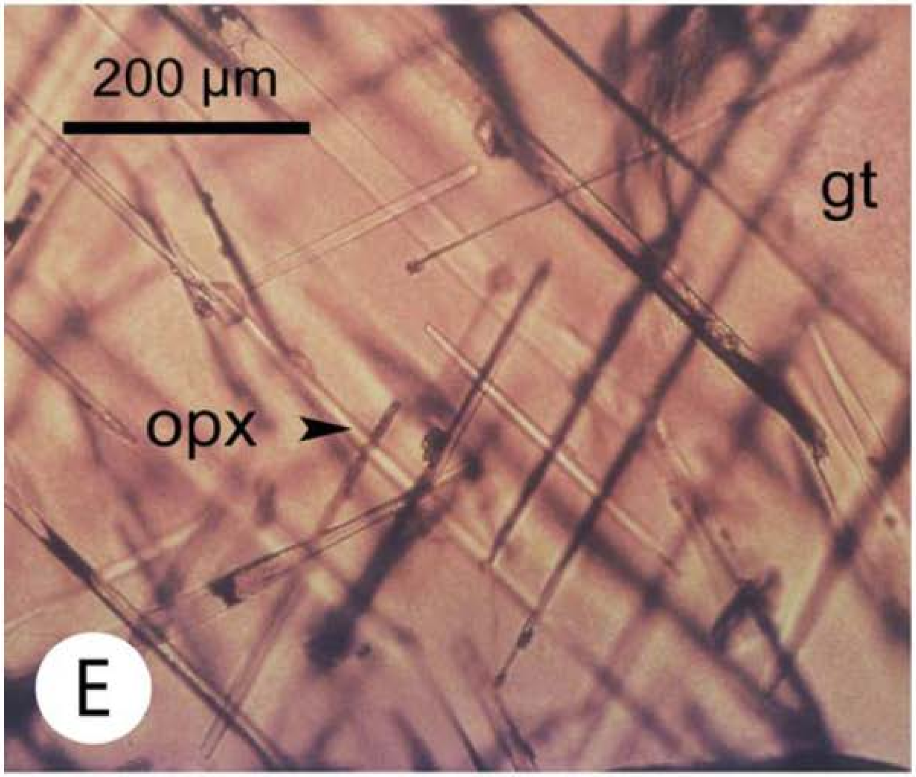


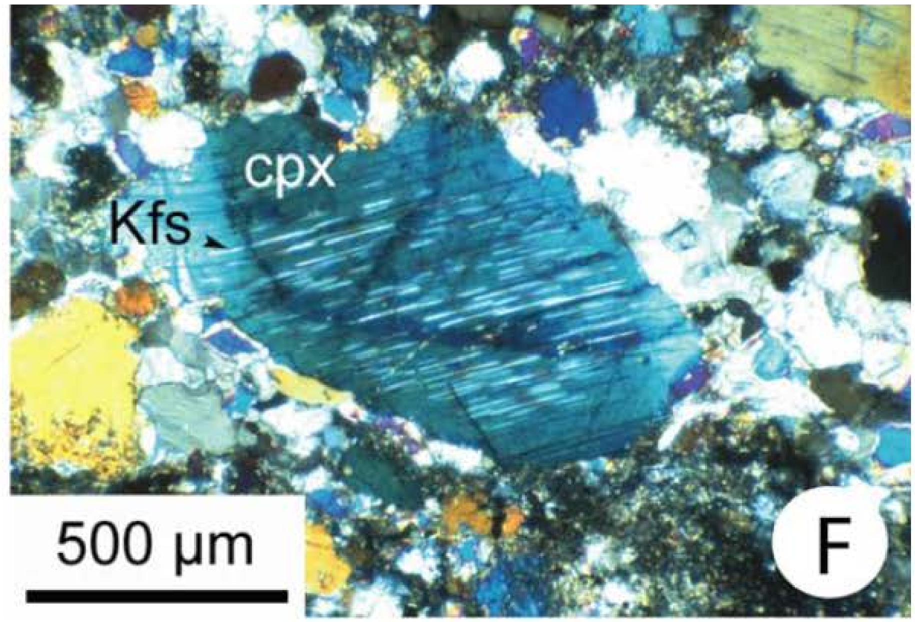
C. Quartz needles exsolved from clinopyroxene . High-SiO_2 pyroxenes are high-pressure phases.

D. Microdiamond inclusions within zircon in garnet gneiss.

Both samples from Erzgebirge, N. Germany. Chopin (2003).

Ultra-high Pressure Metamorphism





E. Orthopyroxene needles exsolved high-P-high SiO_2 majoritic garnet, Otrøy, W. Norway.

F. K-feldspar exsolved from clinopyroxene , Kokchetav massif, N. Kazakhstan. Chopin (2003).

Mineral transformations vs. Metamorphic Facies

Original Minerals	Zeolite Facies	Prehnite-Pumpellyite Facies	Greenschist
Orthopyroxene Augite	→ Chlorite	→ Pumpellyite Ca	→ Actinolite Al
Olivine Al Ca	→ Chlorite	→ Chlorite	→ Chlorite
Anorthite Al	→ Laumontite	→ Prehnite → Epidote	→ Epidote
Albite	→ Albite Analcime at v. low T	→ Albite	→ Albite
Other	± Quartz ± Calcite	± Quartz ± Calcite	± Quartz

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Mineral transformations vs. Metamorphic Facies

Original Minerals	Greenschist Facies	Amphibolite Facies	Granulite Facies
Orthopyroxene Augite	Actinolite	olive brown Hornblende Al	Orthopyroxene Hornblende Augite
Olivine	Chlorite		Olivine (v. hi T)
Anorthite	Al Epidote	Plagioclase	Plagioclase
Albite	Albite	(transition is P-dependent)	
Other	± Quartz	± Quartz ± Garnet (at high P)	± Quartz ± Garnet (at high P)

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Mineral transformations vs. Metamorphic Facies

Original Minerals	Greenschist Facies	Blueschist Facies	Eclogite Facies
Orthopyroxene Augite	Actinolite	increasing P deep purple → lavender Na-amphibole	
Olivine	Na Chlorite	(low P) (high P) Garnet	Garnet
Al Anorthite	Epidote	Epidote Lawsonite (hi P, low T)	Epidote (low T)
Albite	Albite	Na Pyroxene	Na Pyroxene
Other	± Quartz	± Quartz	± Quartz ± Kyanite ± Muscovite

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