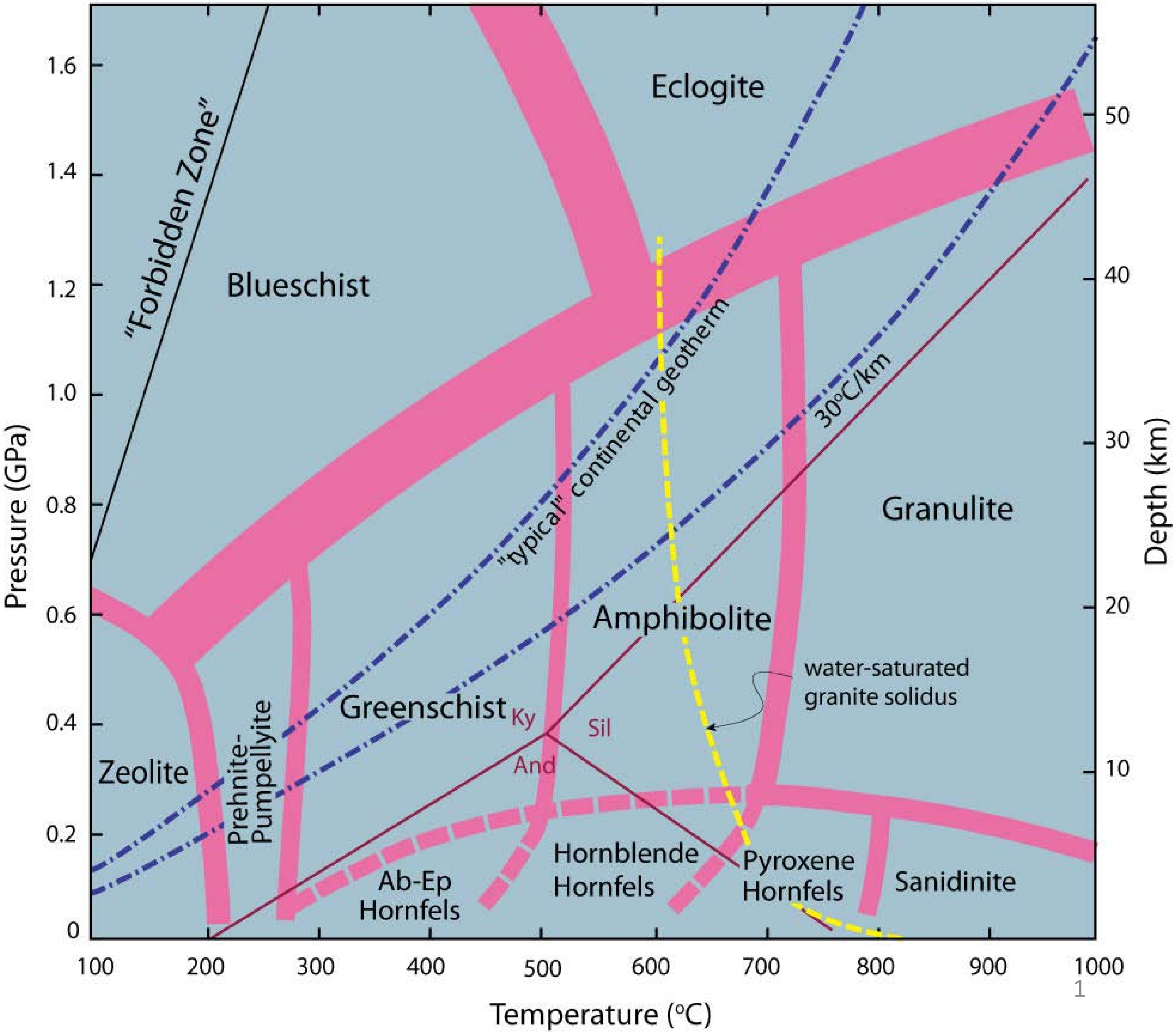
Metamorphic Facies

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).

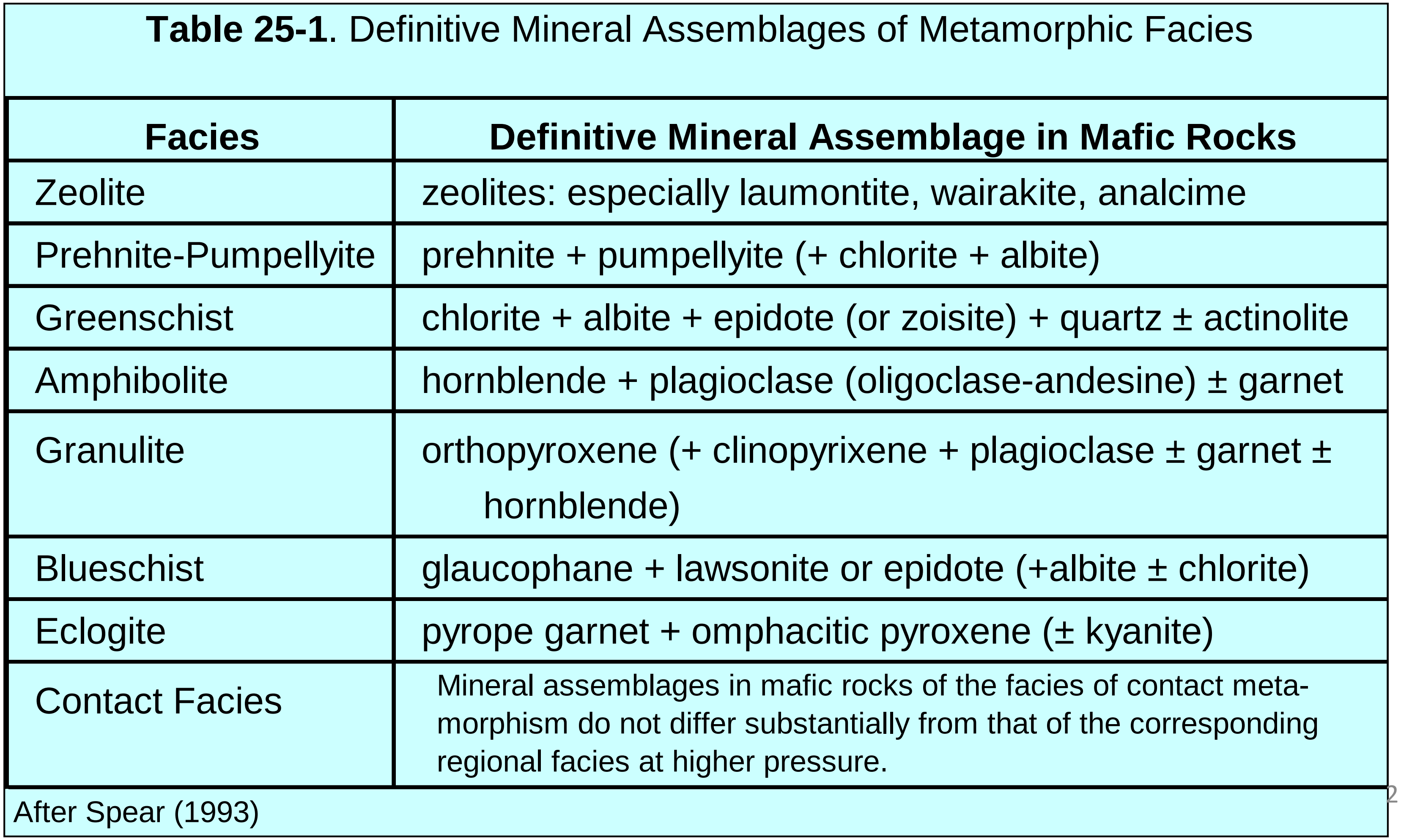


Table 25-1. Definitive Mineral Assemblages of Metamorphic Facies

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 metamorphism 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

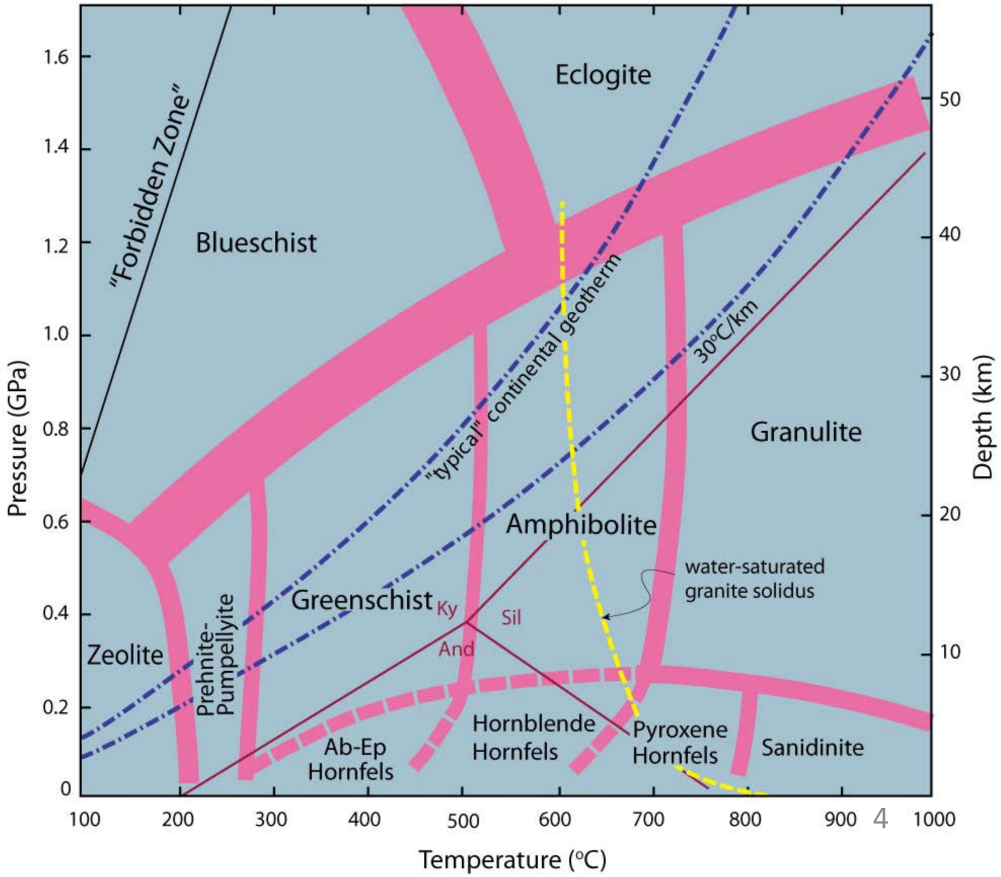
- The blueschist and eclogite facies: low molar volume phases under conditions of high pressure
- Blueschist facies- areas of low T/P gradients: subduction zones
- Eclogites: stable under normal geothermal conditions

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

Metamorphic Facies

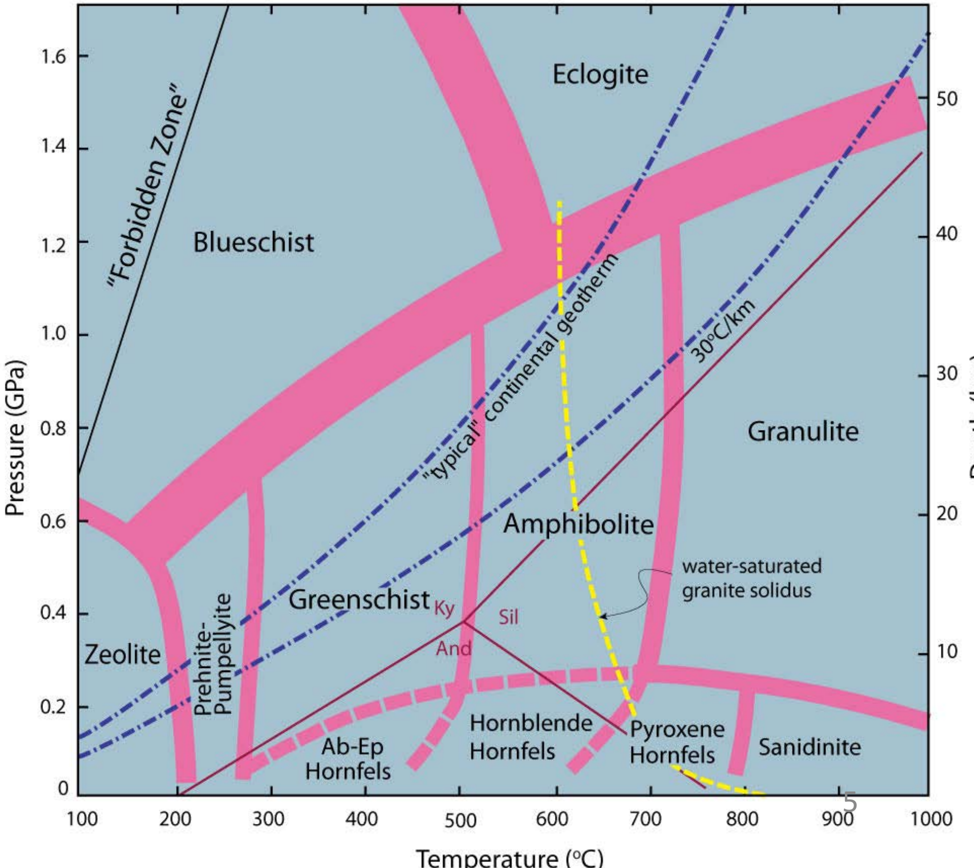
2) Facies of medium pressure

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



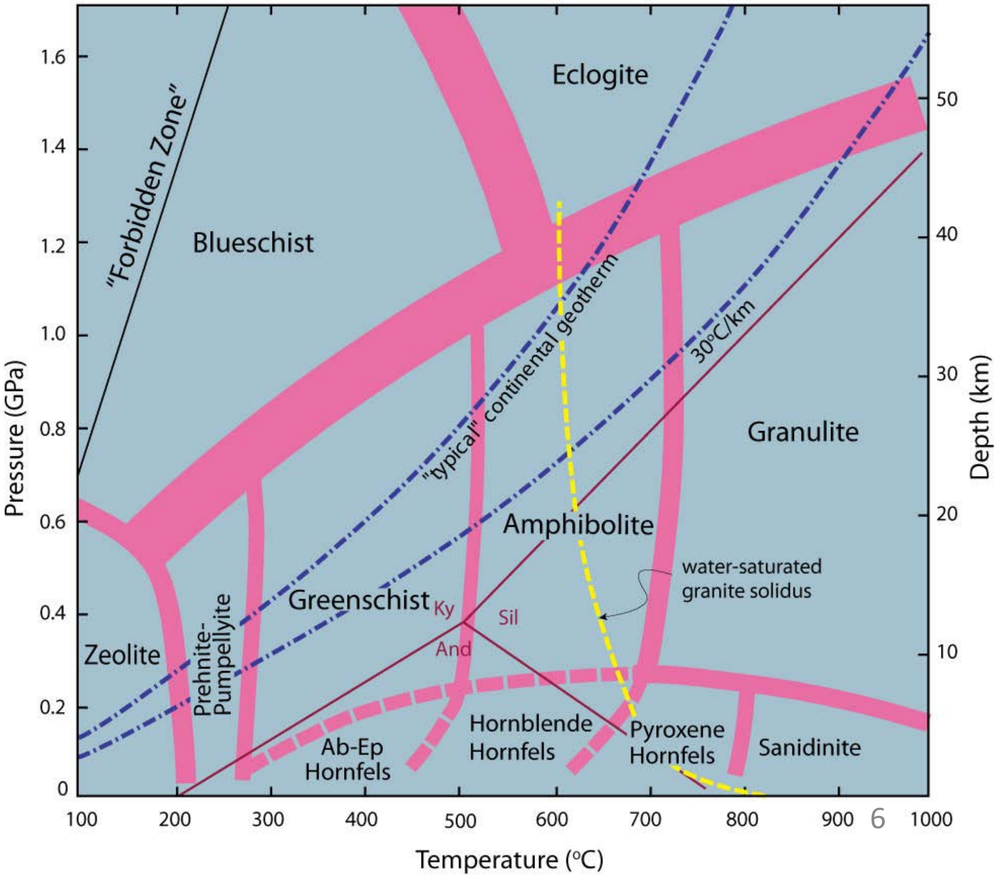
Metamorphic Facies

- **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

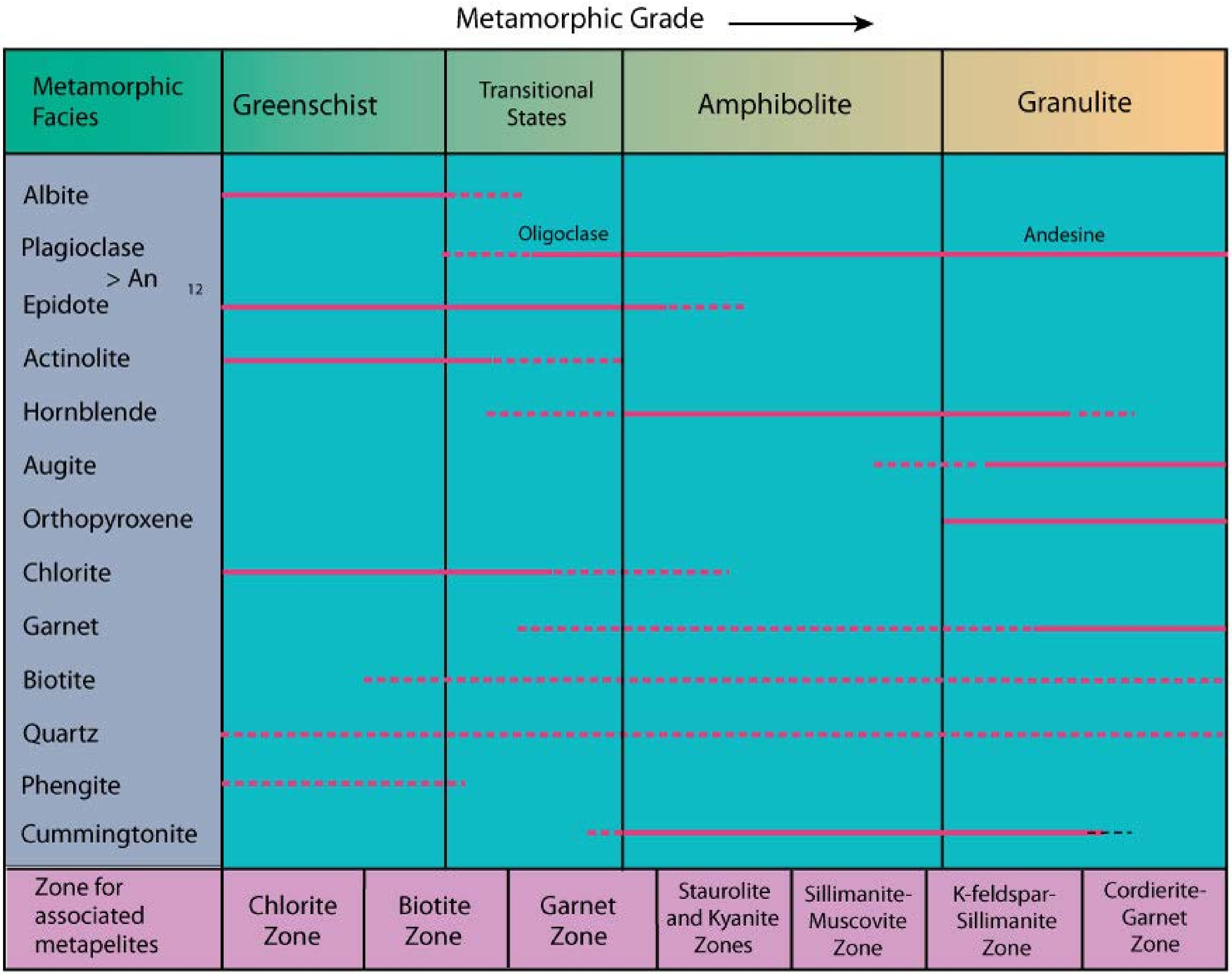


Fig. 25.10. Typical mineral changes that take place in metabasic rocks during progressive metamorphism in the medium P/T facies series. The approximate location of the pelitic zones of Barrovian metamorphism are included for comparison. Winter (2010) An Introduction to Igneous and Metamorphic Petrology.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

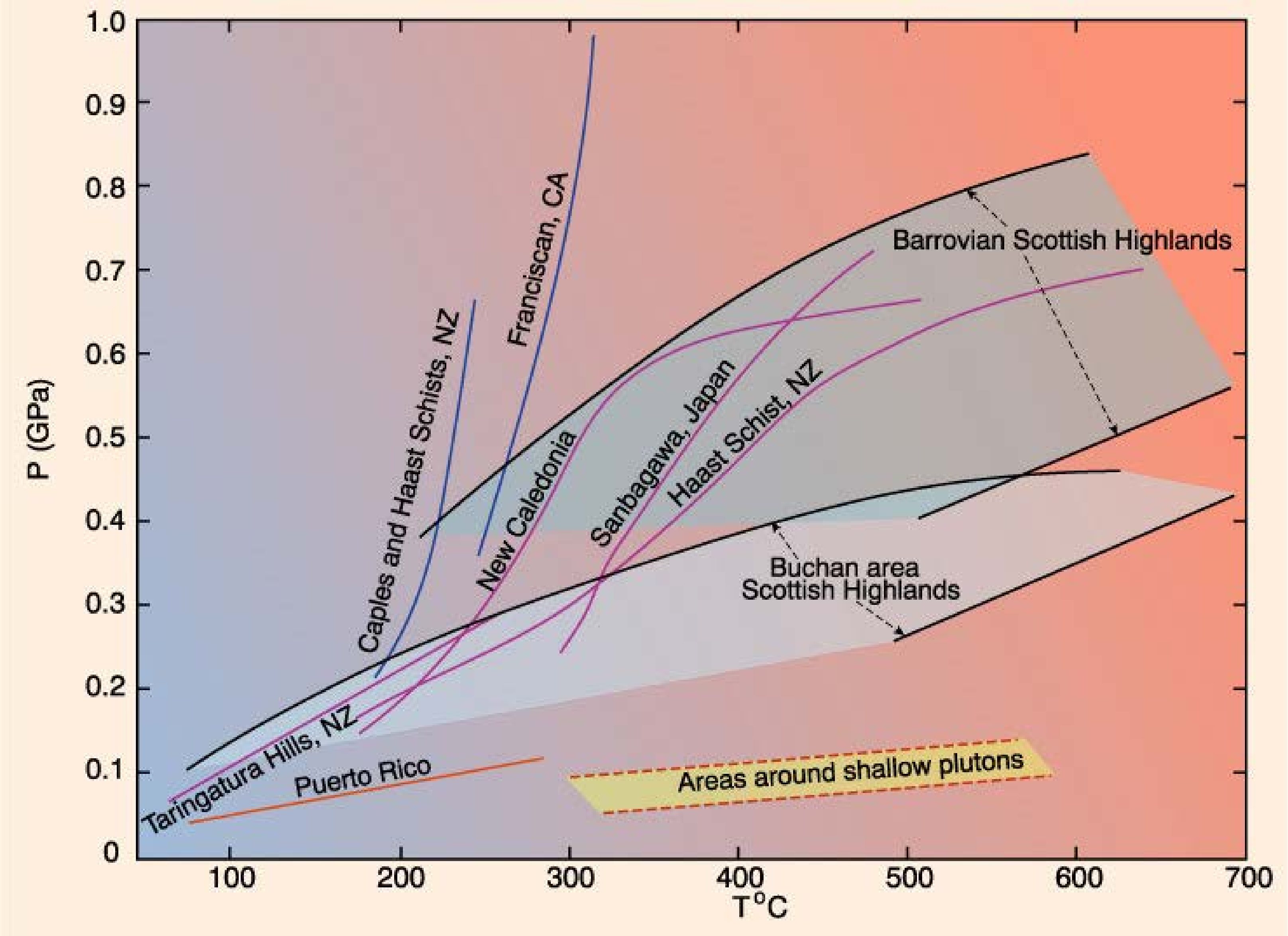


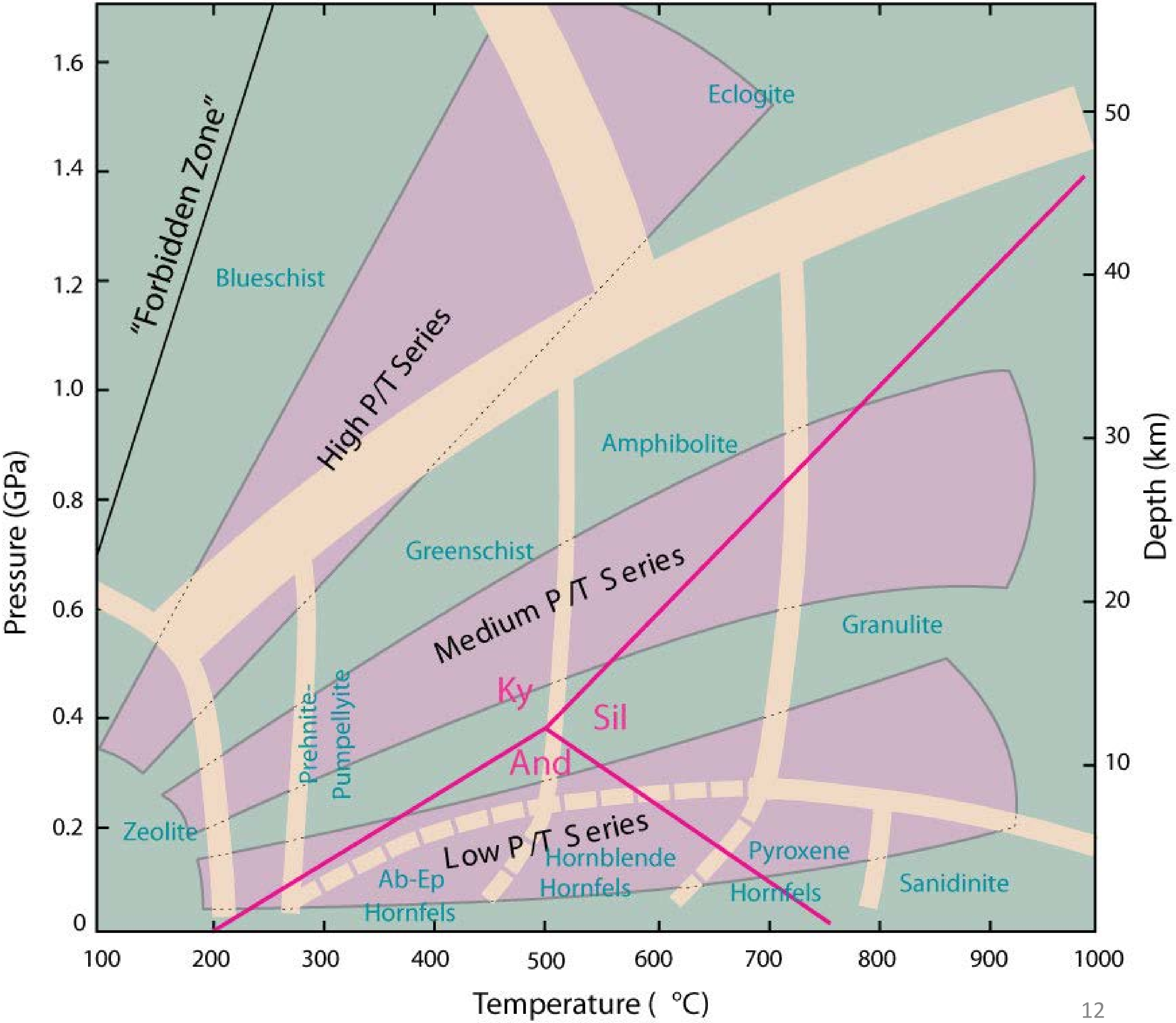
Figure 21.1. Metamorphic field gradients (estimated P-T conditions along surface traverses directly up metamorphic grade) for several metamorphic areas. After Turner (1981). *Metamorphic Petrology: Mineralogical, Field, and Tectonic Aspects*. McGraw-Hill.

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

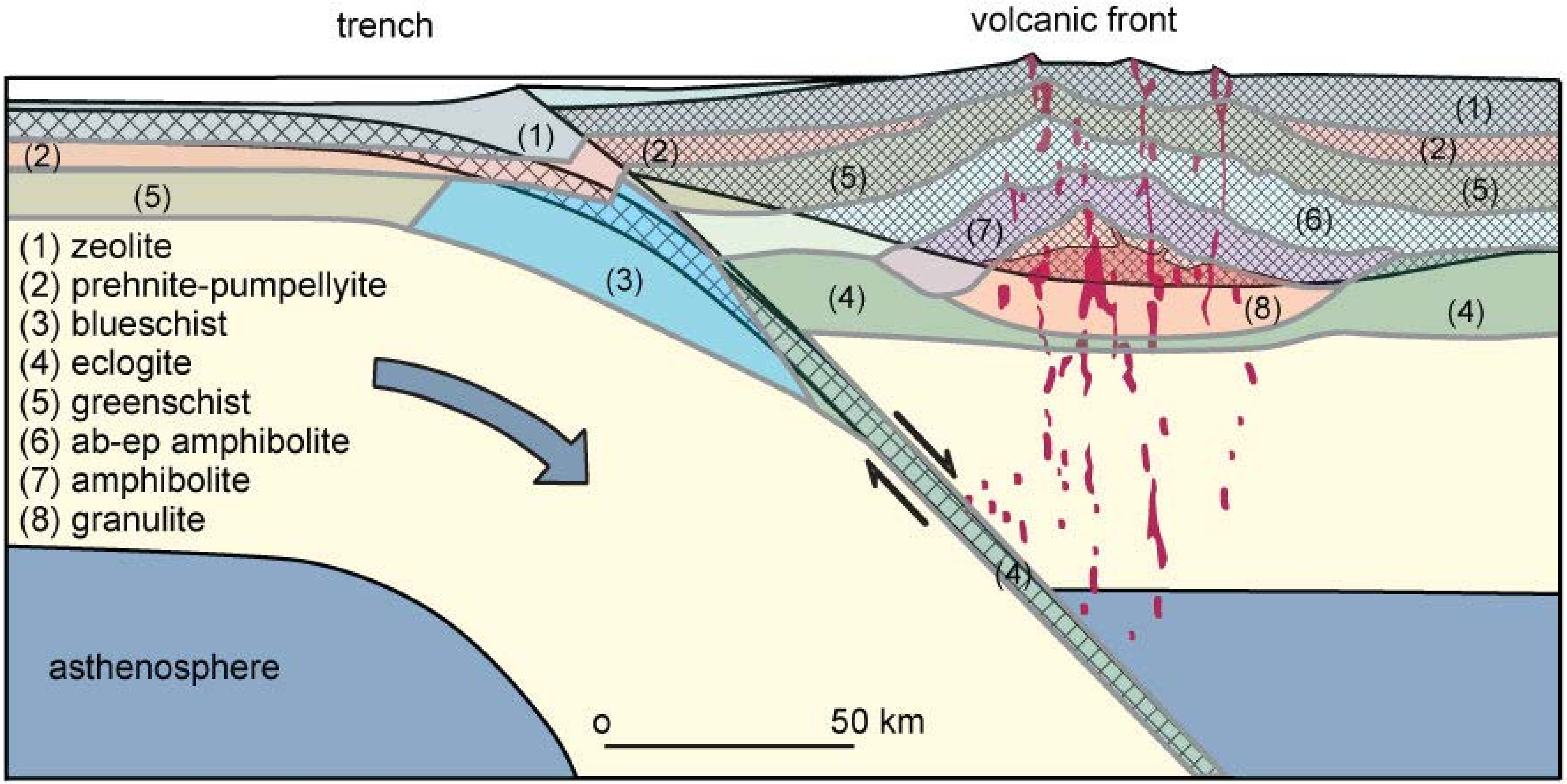


Figure 25.4. Schematic cross-section of an island arc illustrating isotherm depression along the outer belt and elevation along the inner axis of the volcanic arc. The high P/T facies series typically develops along the outer paired belt and the medium or low P/T series develop along the inner belt, 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 ($An_{0\text{-}3}$)
  - Upper-greenschist facies oligoclase becomes stable.
  - Andesine and more calcic plagioclase stable in the upper amphibolite and granulite facies

- The excess Ca and Al → 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

- Amphibolite → granulite facies ~ 650-700^{o}C
- If aqueous fluid, associated pelitic and quartzo-feldspathic rocks (including granitoids) begin to melt in this range at low to medium pressures → migmatites and melts may become mobilized
- As a result not all pelites and quartzo-feldspathic rocks reach the 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^{o}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

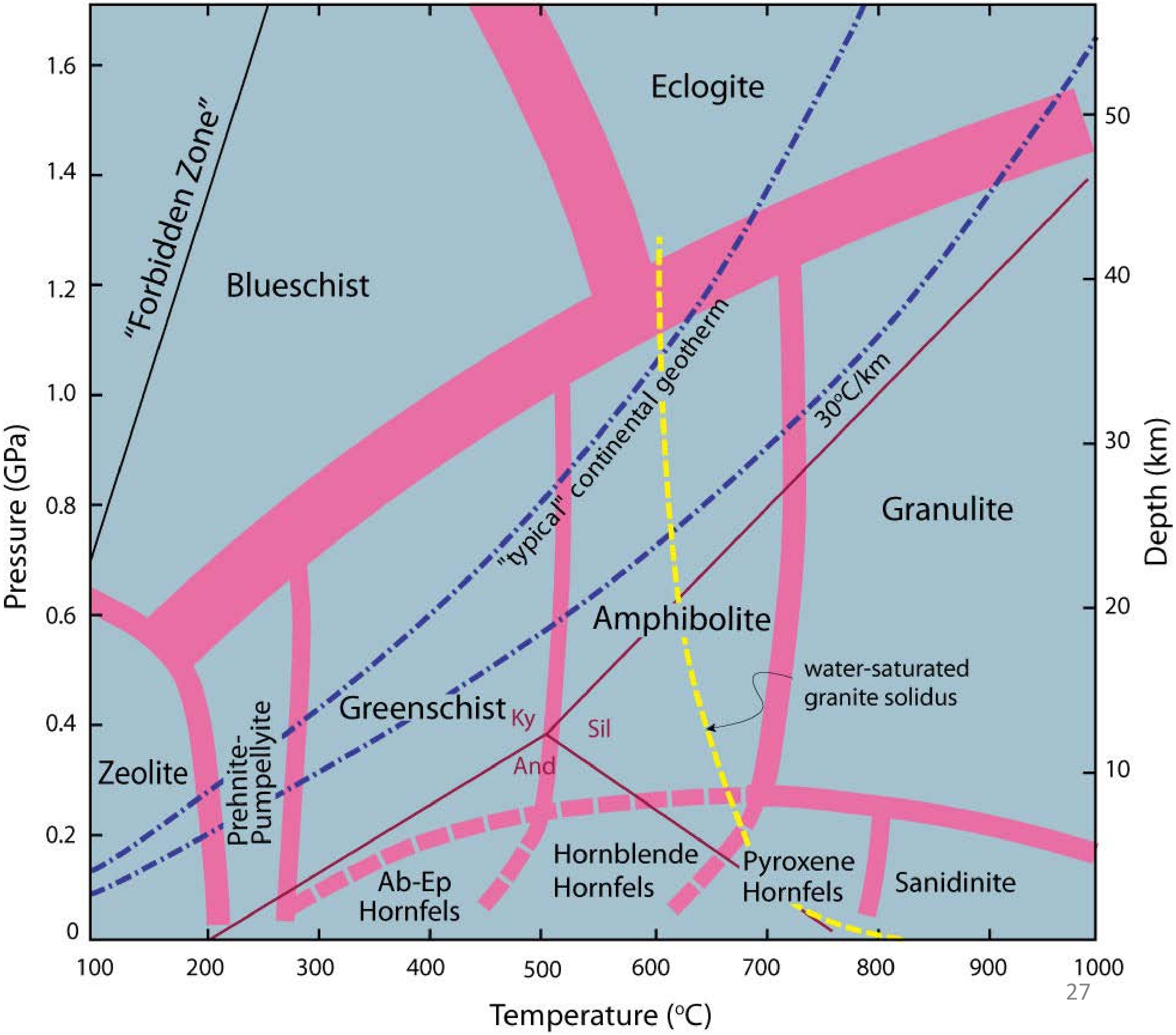
2) Granulites are dry

- 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:

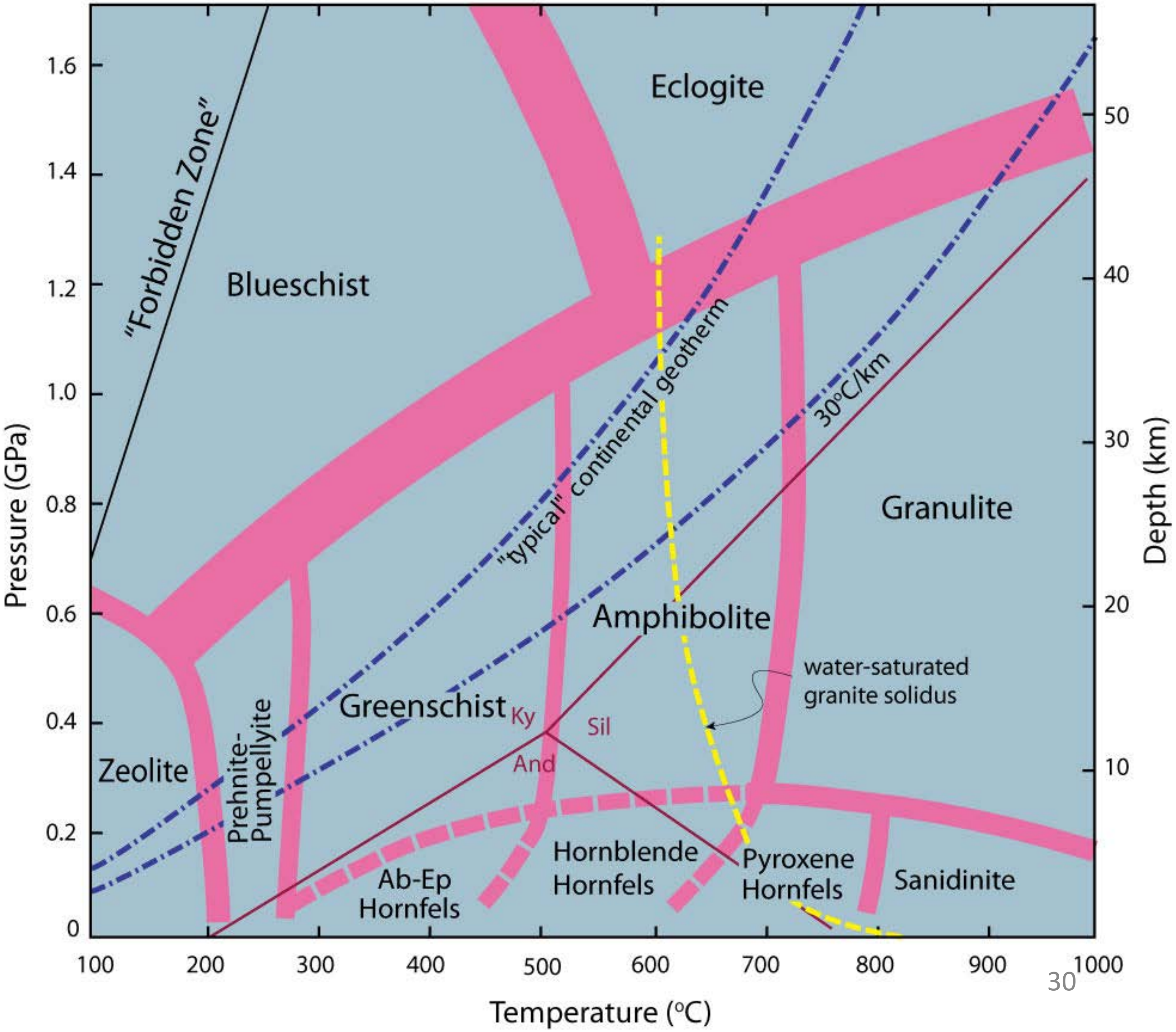
Blueschist and Eclogite Facies

- 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.



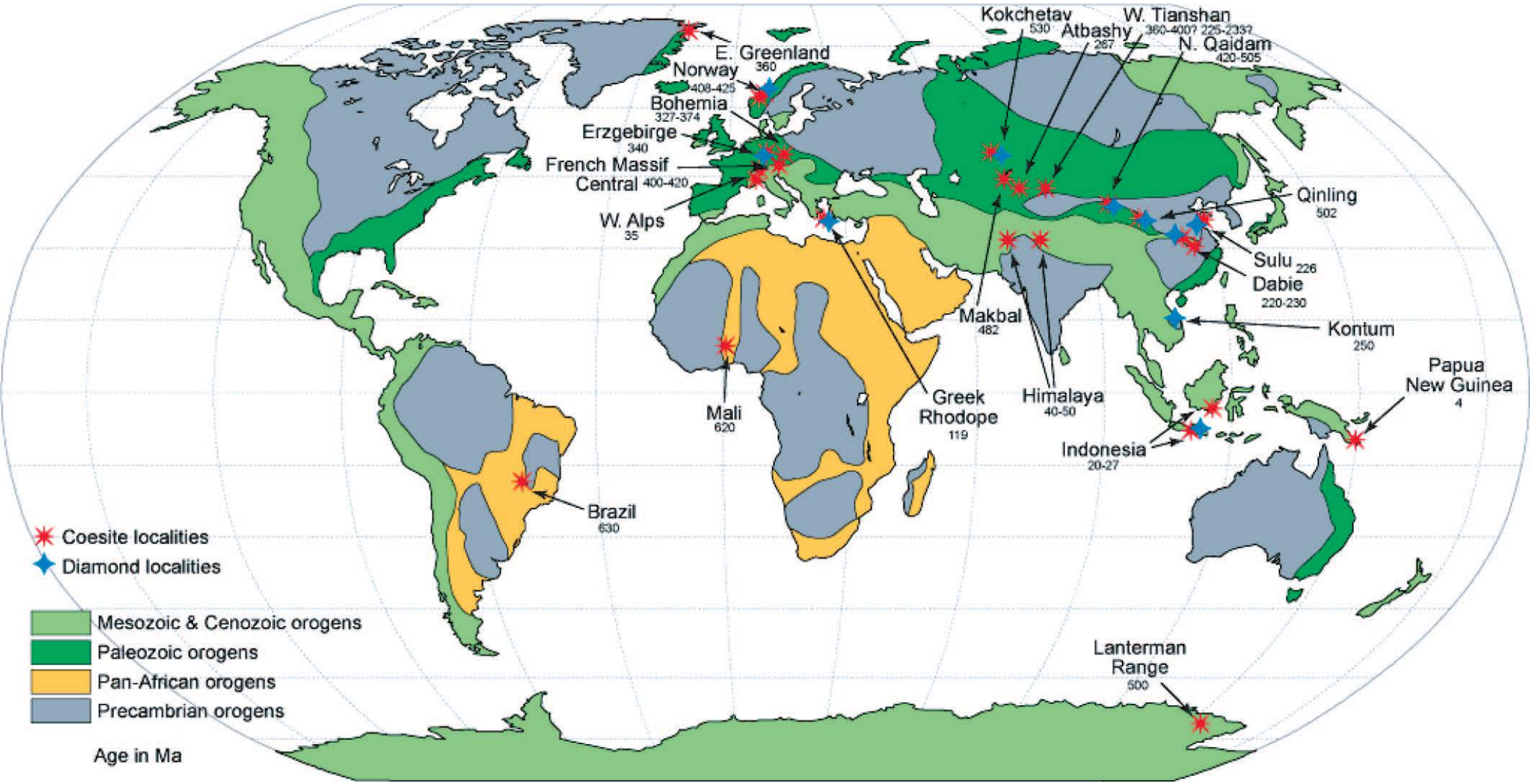
Blueschist and Eclogite Facies

- 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)

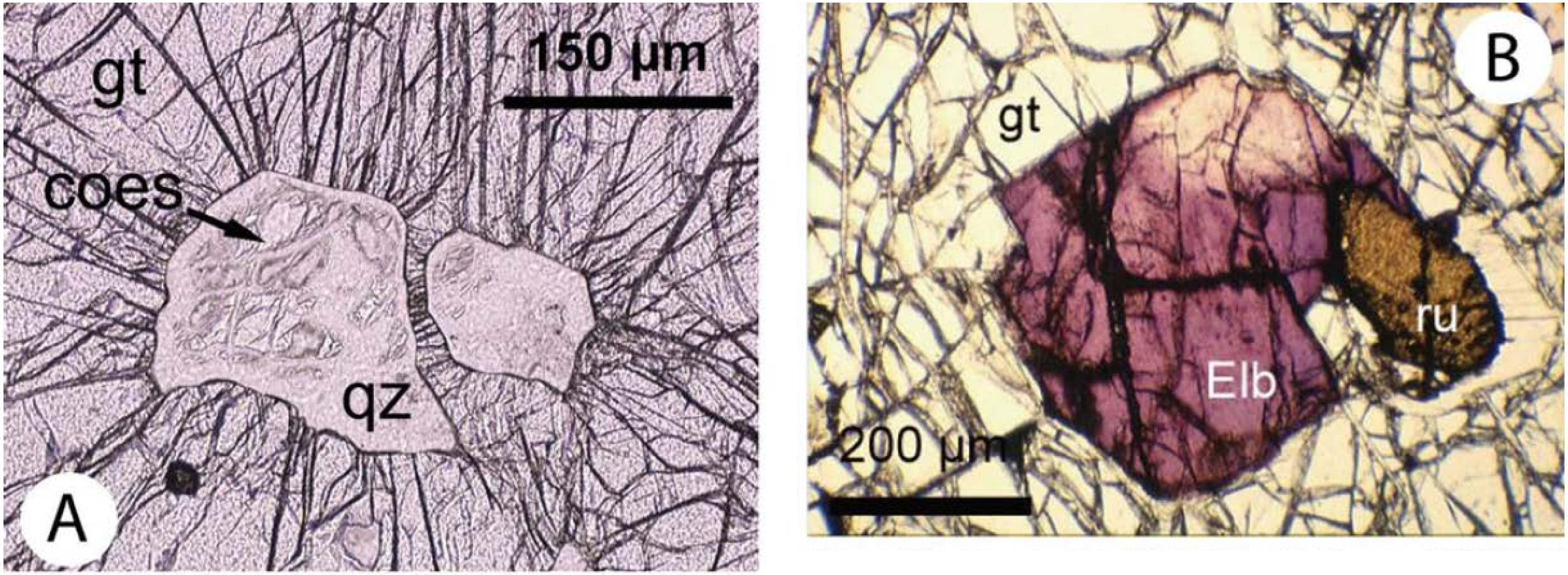
Ab = Jd + Qtz

Ultra-high Pressure Metamorphism



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

Ultra-high Pressure Metamorphism

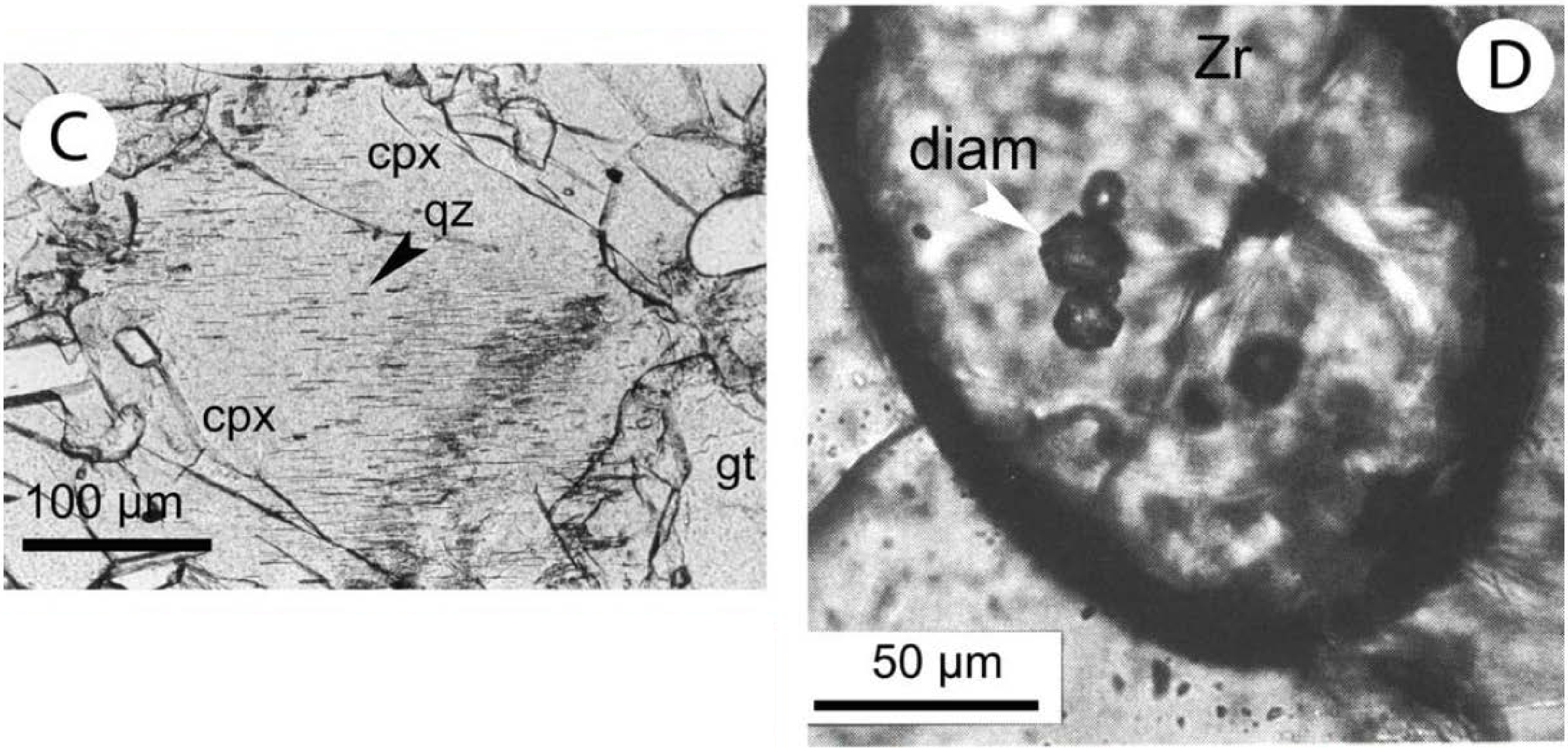


A. Coesite inclusion in garnet (partly transformed to quartz upon uplift, producing radial cracks in host due to volume increase).

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

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

Ultra-high Pressure Metamorphism

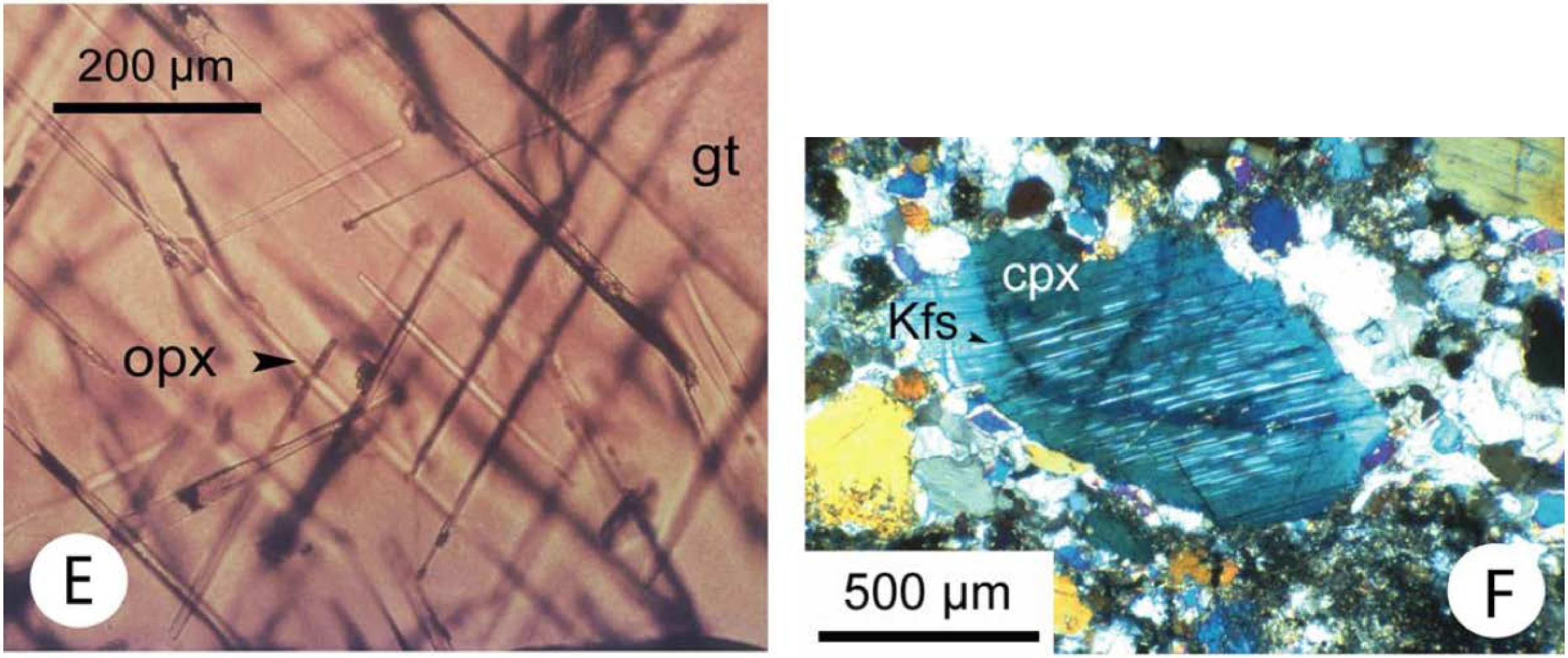


C. Quartz needles exsolved from clinopyroxene . High-SiO_2 pyroxenes are high-pressure phases.

D. Microdiamond inclusions within zircon in garnet gneiss.

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

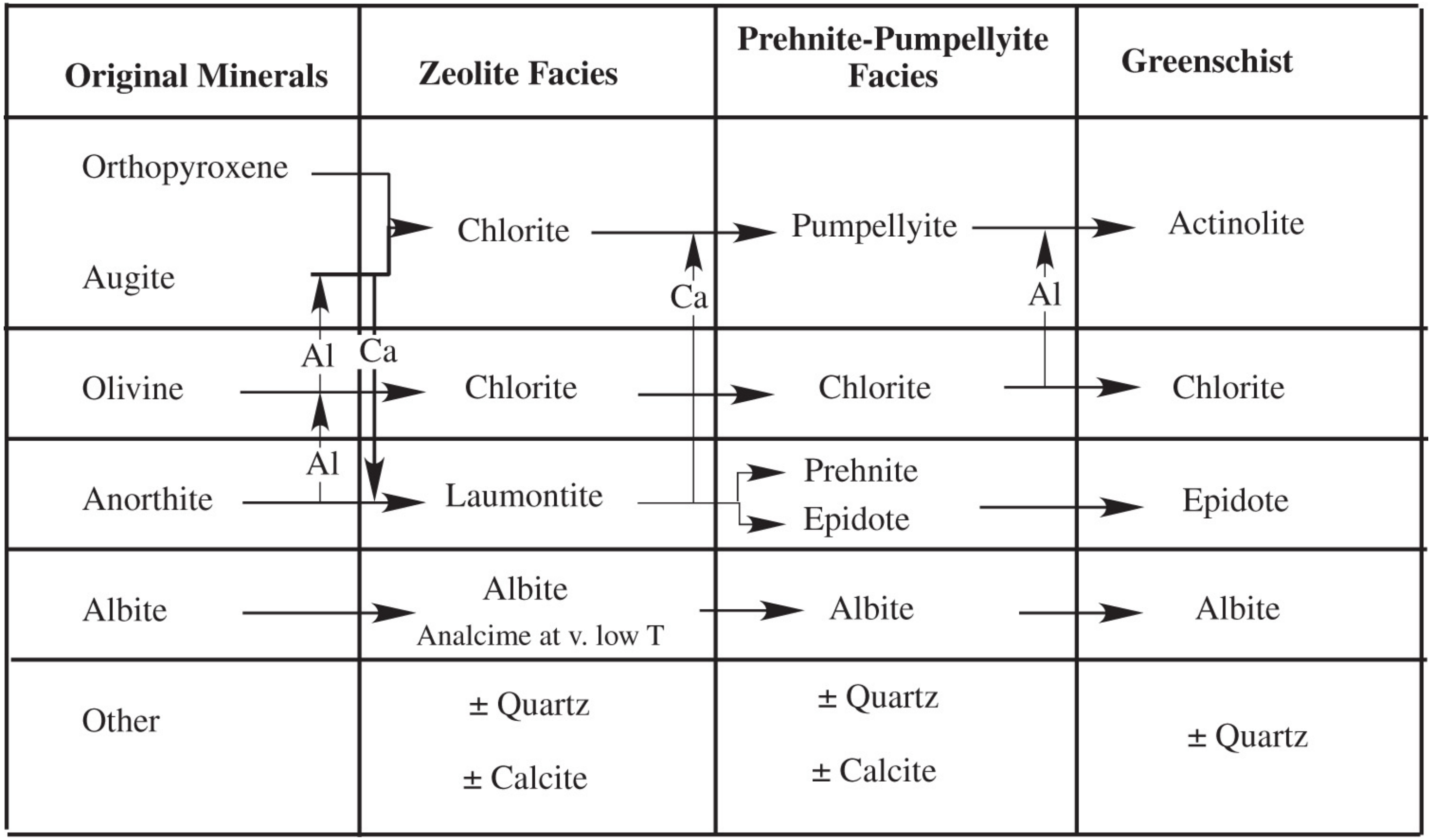
Ultra-high Pressure Metamorphism



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).

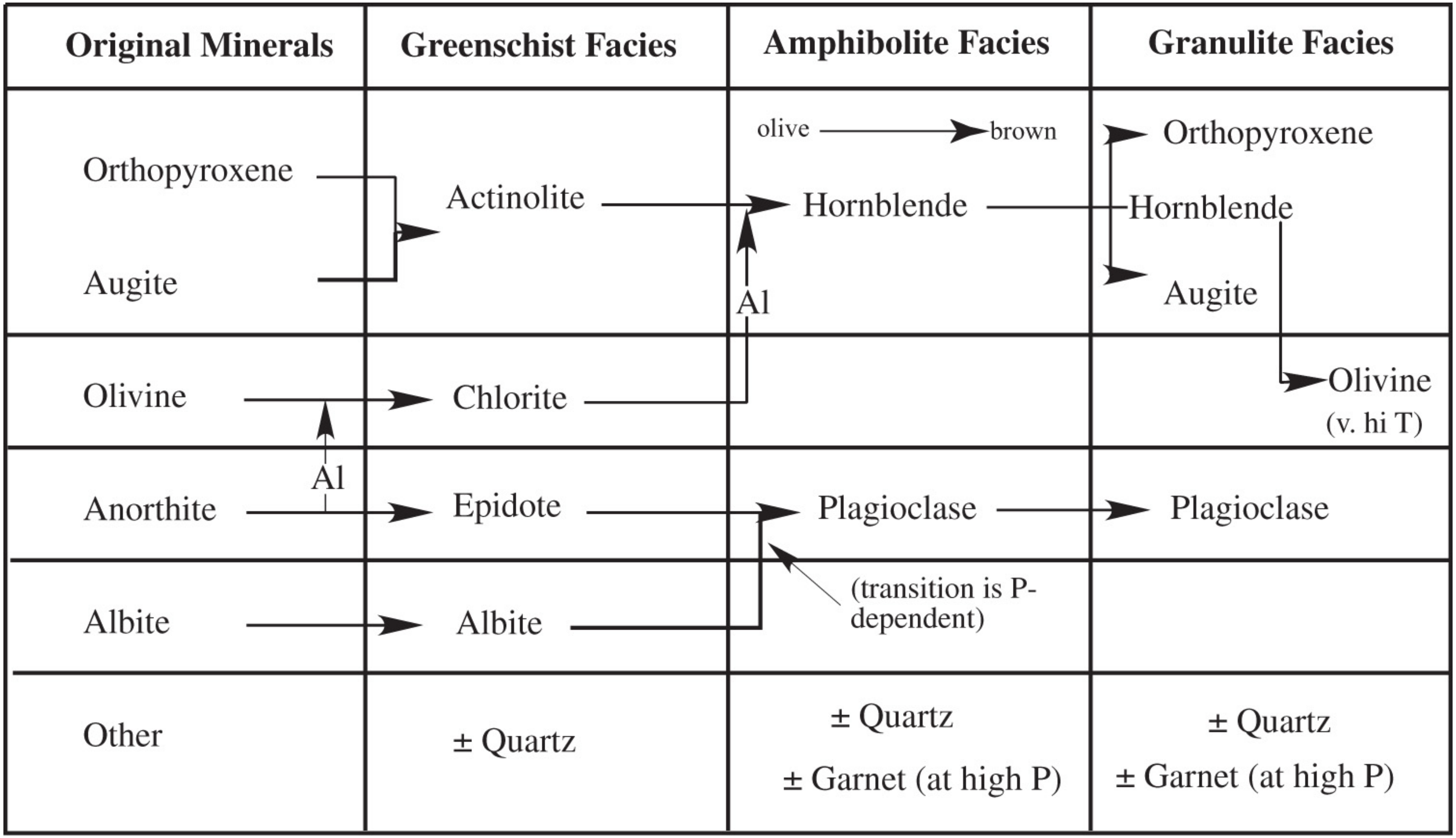
Mineral transformations vs. Metamorphic Facies



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

Frost_Tbl. 13_2

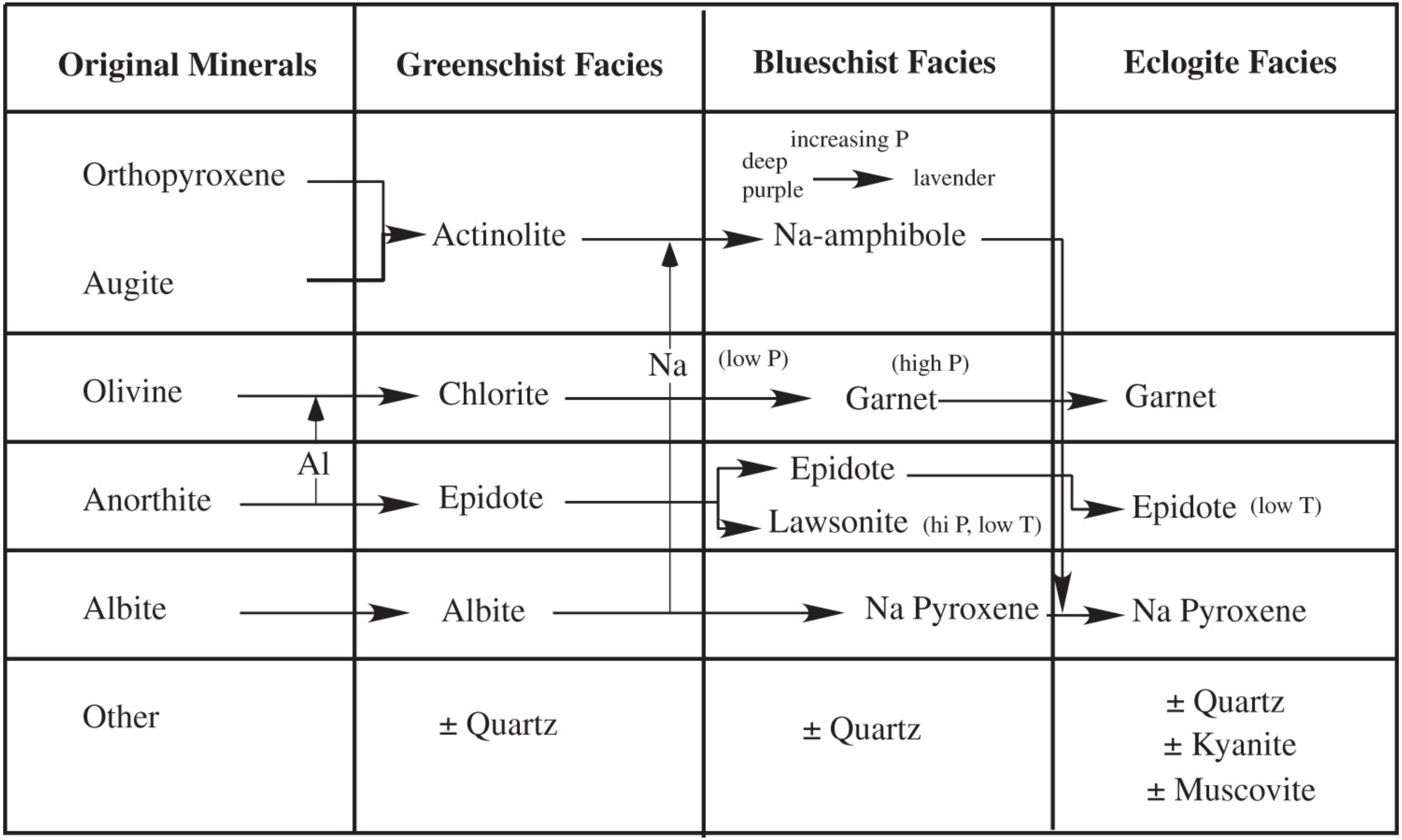
Mineral transformations vs. Metamorphic Facies



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

Frost_Tbl. 13_3

Mineral transformations vs. Metamorphic Facies



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

Frost_Tbl. 13_4

Pressure-Temperature-Time (P-T-t) Paths

The facies series concept suggests that a traverse up grade through a metamorphic terrane should follow a metamorphic field gradient, and may cross through a sequence of facies (spatial sequences)

Progressive metamorphism: rocks pass through a series of mineral assemblages as they continuously equilibrate to increasing metamorphic grade (temporal sequences)

However, do all metamorphic rocks within a region of study undergo the ***same*** temporal and spatial mineralogical changes?

Pressure-Temperature-Time (P-T-t) Paths

The complete set of T-P conditions that a rock may experience during a metamorphic cycle from burial to metamorphism (and orogeny) to uplift and erosion is called a pressure-temperature-time path, or P-T-t path

Pressure-Temperature-Time (P-T-t) Paths

Metamorphic P-T-t paths may be addressed by:

1) Observing partial overprints of one mineral assemblage upon another

   - The relict minerals may indicate a portion of either the prograde or retrograde path (or both) depending upon when they were created

Pressure-Temperature-Time (P-T-t) Paths

Metamorphic P-T-t paths may be addressed by:

2) Apply geothermometers and geobarometers to the core vs. rim compositions of chemically zoned minerals to document the changing P-T conditions experienced by a rock during their growth

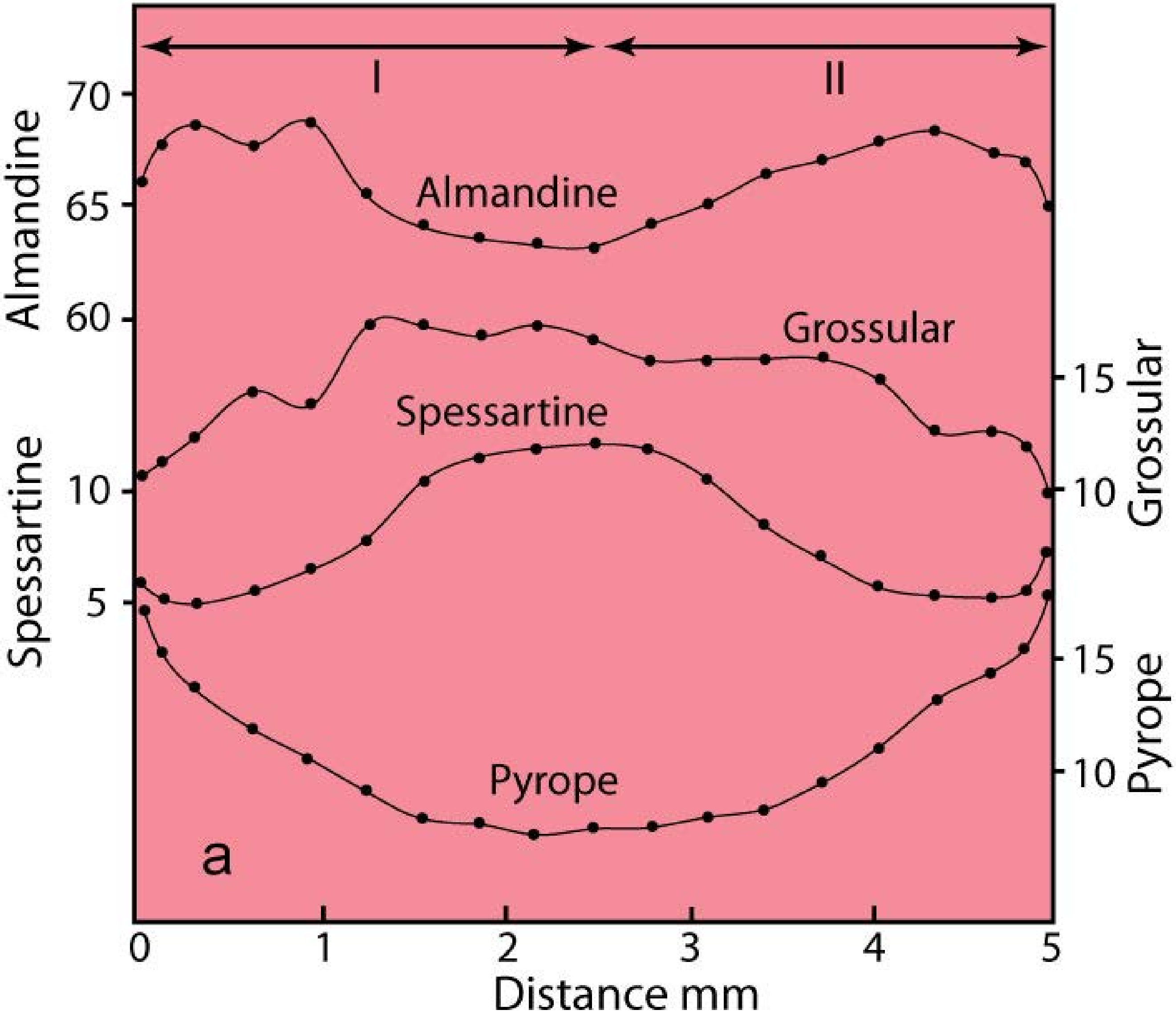


Fig. 25.16a. Chemical zoning profiles across a garnet from the Tauern Window. After Spear (1989)

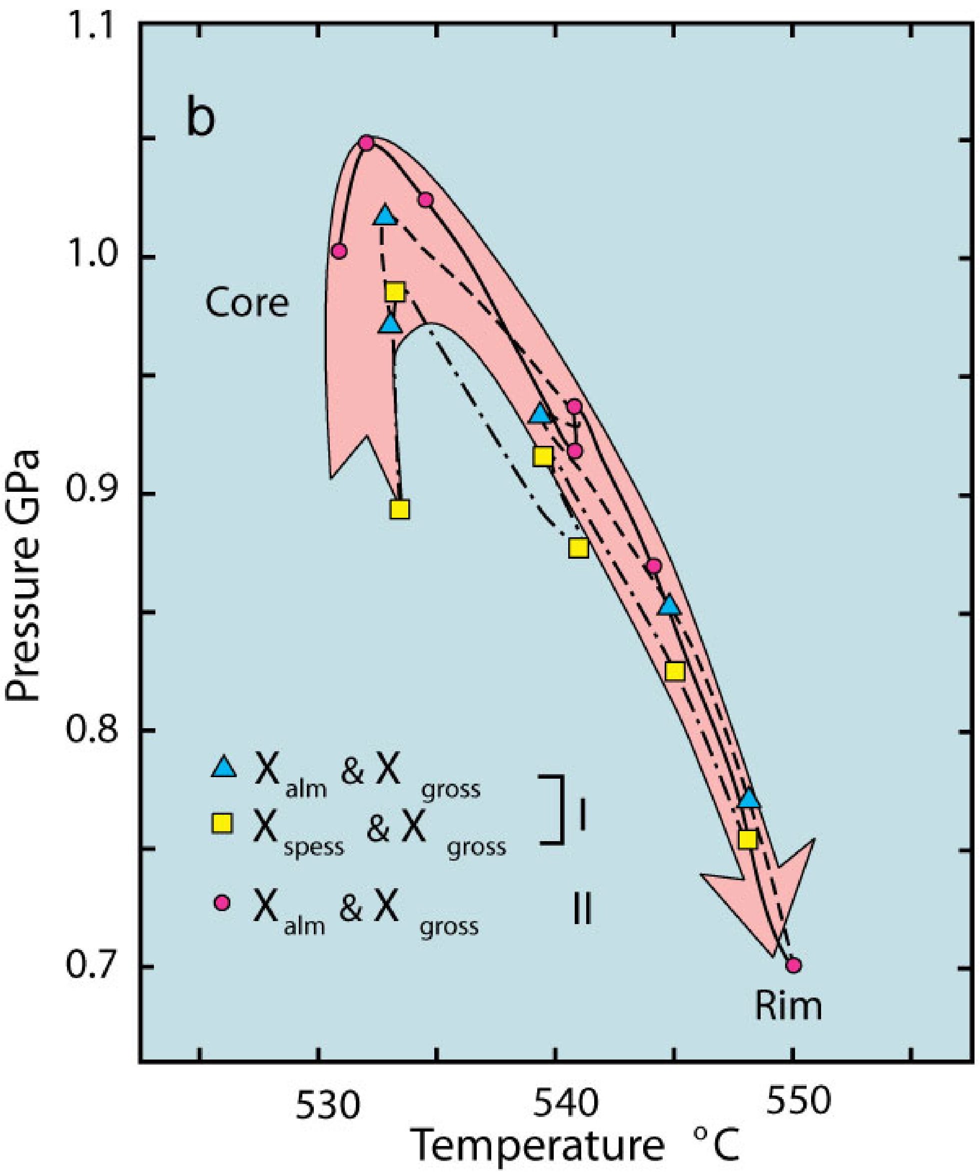


Fig. 25.16b. Conventional P-T diagram (pressure increases upward) showing three modeled “clockwise” P-T-t paths computed from the profiles using the method of Selverstone *et al*. (1984) *J. Petrol.*, 25, 501-531 and Spear (1989). After Spear (1989) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1.

Pressure-Temperature-Time (P-T-t) Paths

Even under the best of circumstances (1) overprints and (2) geothermobarometry can usually document only a small portion of the full P-T-t path

3) We thus rely on “forward” **heat-flow models** for various tectonic regimes to compute more complete P-T-t paths, and evaluate them by comparison with the results of the backward methods

Pressure-Temperature-Time (P-T-t) Paths

- Classic view: regional metamorphism is a result of deep burial or intrusion of hot magmas
- Plate tectonics: regional metamorphism is a result of crustal thickening and heat input during orogeny at convergent plate boundaries (not simple burial)
- **Heat-flow models** have been developed for various regimes, including burial, progressive thrust stacking, crustal doubling by continental collision, and the effects of crustal anatexis and magma migration
  - **Higher than the normal heat flow** is required for typical greenschist-amphibolite medium P/T facies series
  - **Uplift and erosion** has a fundamental effect on the geotherm and must be considered in any complete model of metamorphism

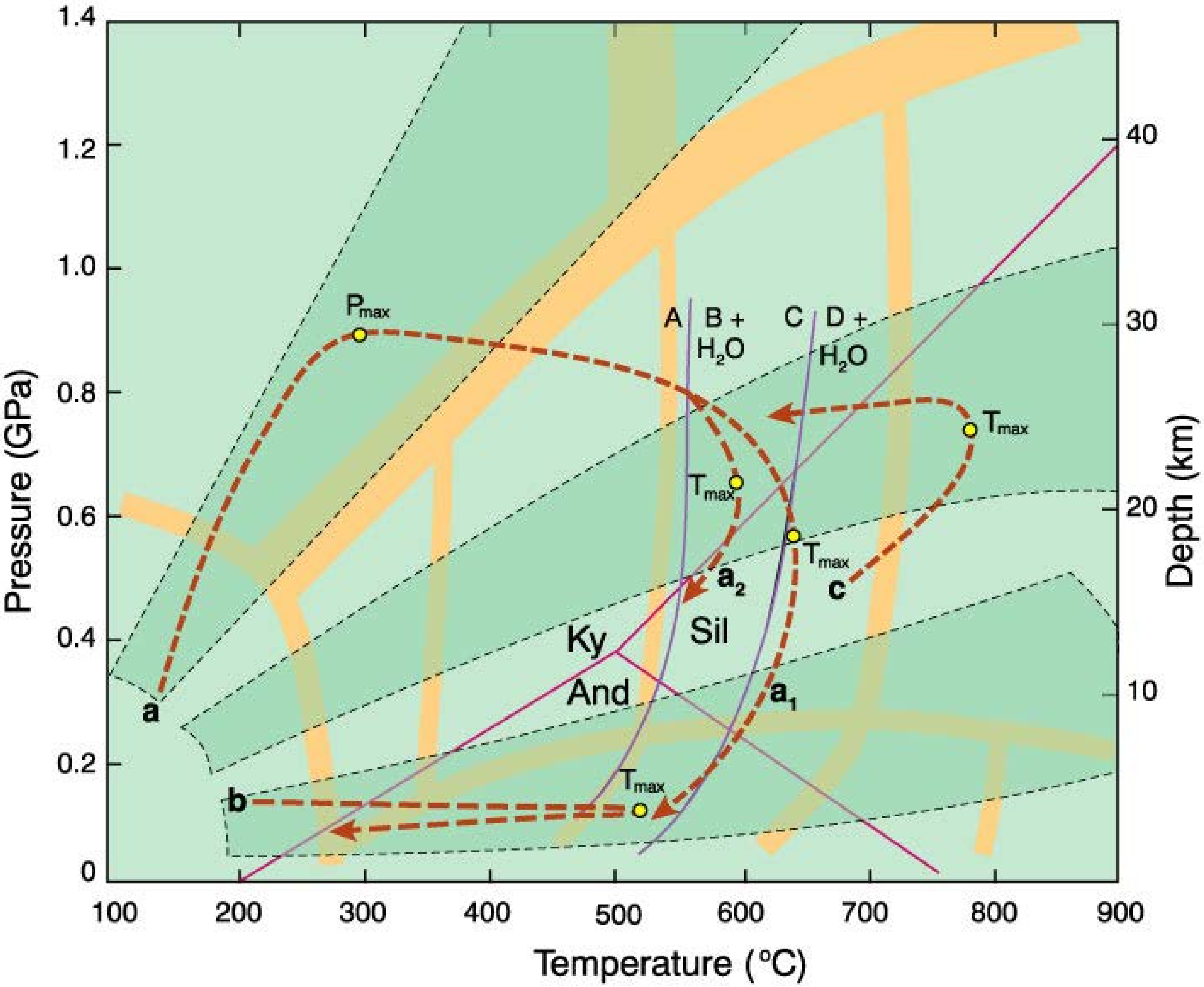


Fig. 25.15. Schematic pressure-temperature-time paths based on heat-flow models. The Al_2SiO_5 phase diagram and two hypothetical dehydration curves are included. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

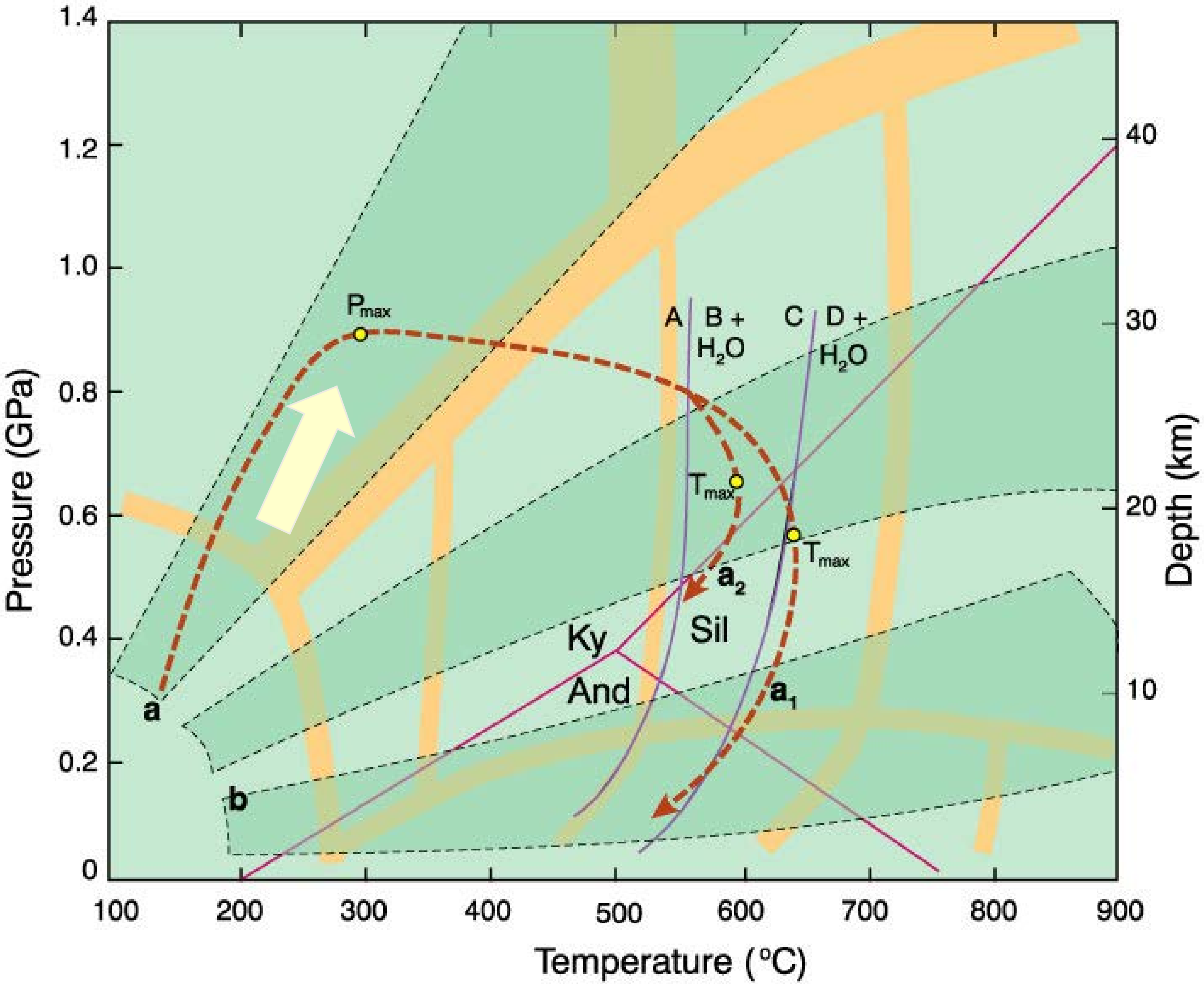


Fig. 25.15a. Schematic pressure-temperature-time paths based on a crustal thickening heat-flow model. The Al_2SiO_5 phase diagram and two hypothetical dehydration curves are included. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Pressure-Temperature-Time (P-T-t) Paths

- Most examples of crustal thickening have the same general looping shape, whether the model assumes homogeneous thickening or thrusting of large masses, conductive heat transfer or additional magmatic rise
- Paths such as (a) are called "clockwise" P-T-t paths in the literature, and are considered to be the norm for regional metamorphism

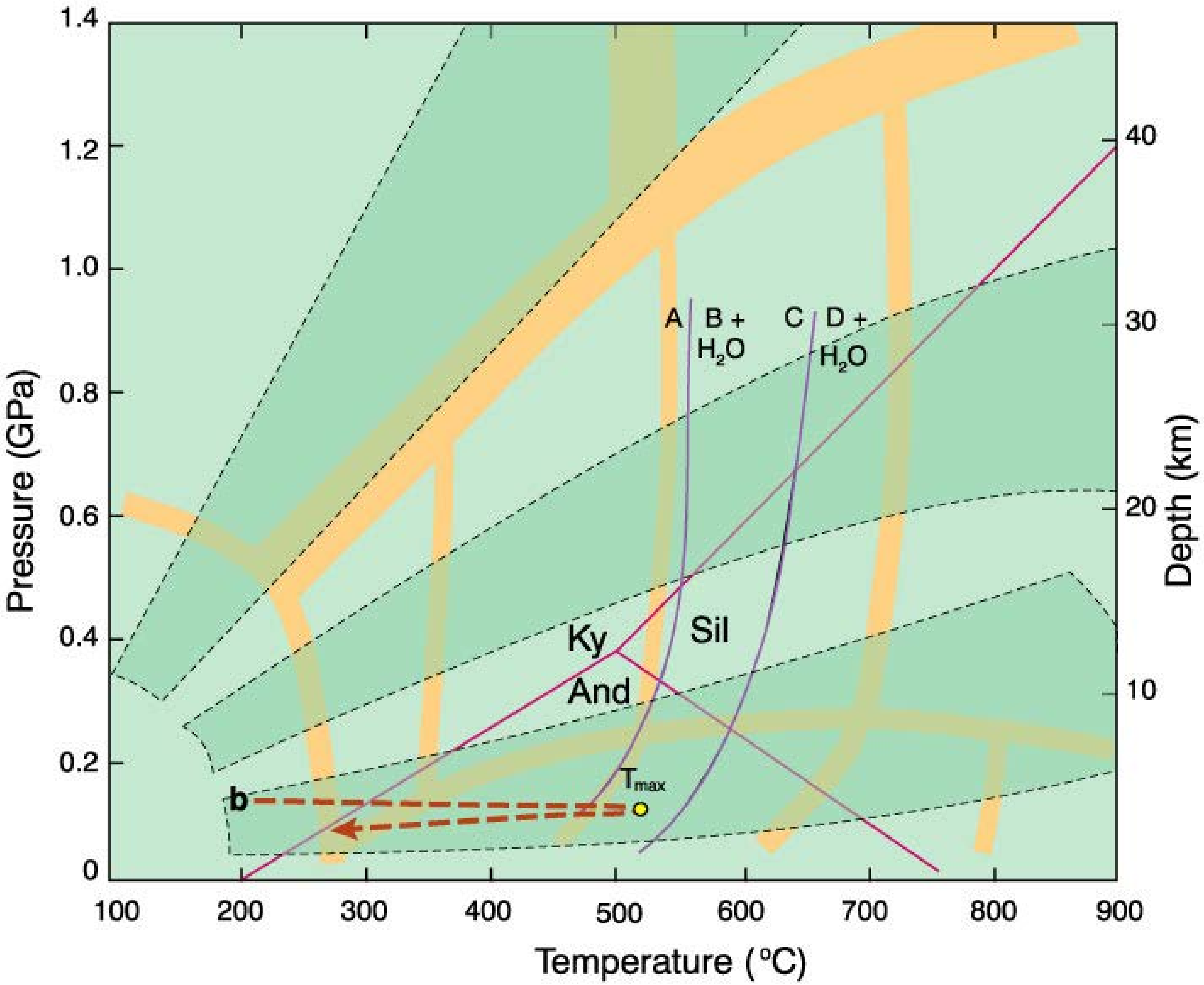


Fig. 25.15b. Schematic pressure-temperature-time paths based on a shallow magmatism heat-flow model. The Al_2SiO_5 phase diagram and two hypothetical dehydration curves are included. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

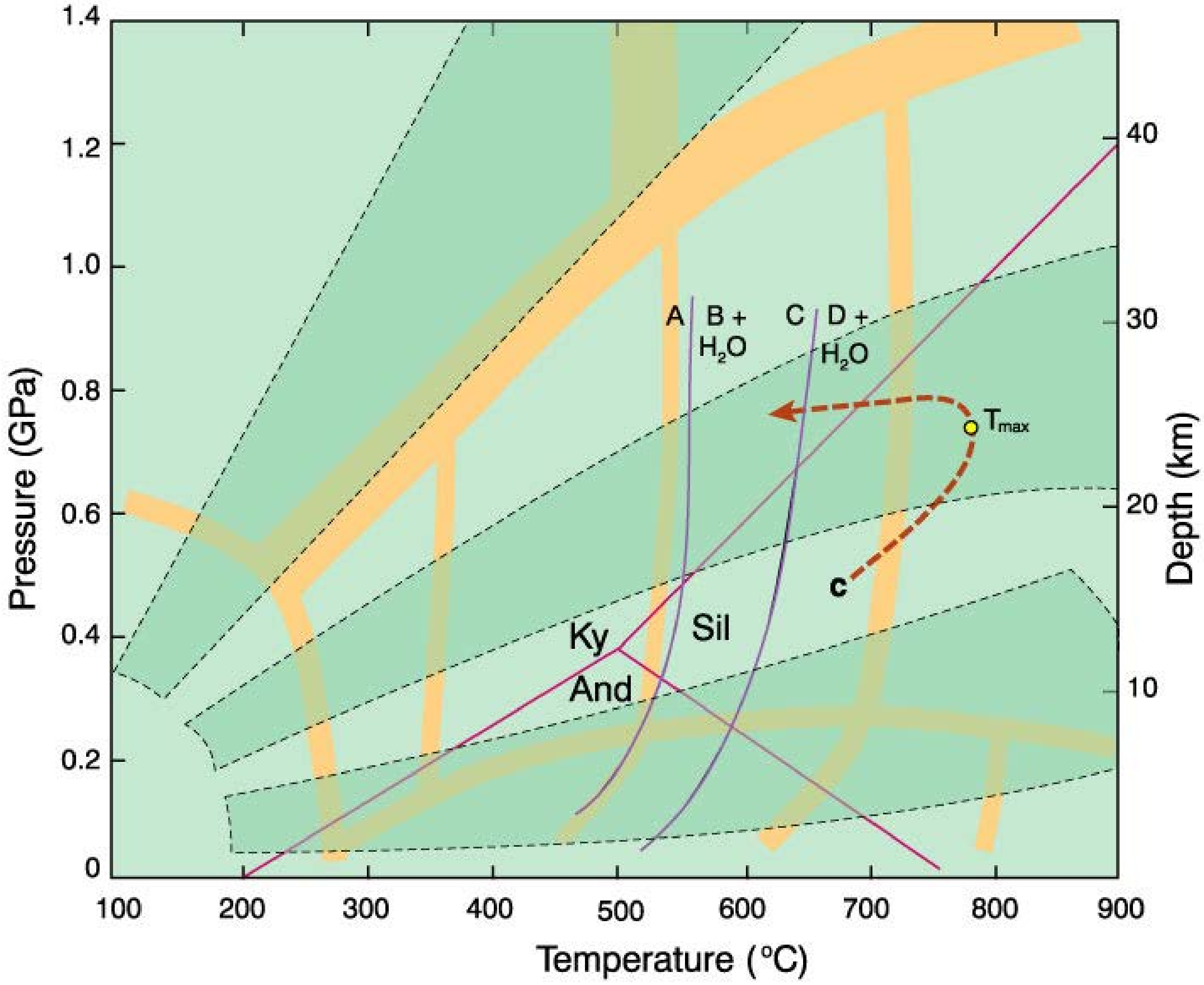


Fig. 25.15c. Schematic pressure-temperature-time paths based on a heat-flow model for some types of granulite facies metamorphism. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Pressure-Temperature-Time (P-T-t) Paths

- Broad agreement between the forward (model) and backward (geothermobarometry) techniques regarding P-T-t paths
- The general form of a path such as (a) therefore probably represents a typical rock during orogeny and regional metamorphism

Pressure-Temperature-Time (P-T-t) Paths

1. Contrary to the classical treatment of metamorphism, temperature and pressure do not both increase in unison as a single unified "metamorphic grade."

Their relative magnitudes vary considerably during the process of metamorphism

Pressure-Temperature-Time (P-T-t) Paths

2. P_{max} and T_{max} do not occur at the same time

- In the usual "clockwise" P-T-t paths, P_{max} occurs much earlier than T_{max}.
- T_{max} should represent the maximum grade at which chemical equilibrium is "frozen in" and the metamorphic mineral assemblage is developed
- This occurs at a pressure well below P_{max}, which is uncertain because a mineral geobarometer should record the pressure of T_{max}
- "Metamorphic grade" should refer to the temperature and pressure at T_{max}, because the grade is determined via reference to the equilibrium mineral assemblage

Pressure-Temperature-Time (P-T-t) Paths

3. Some variations on the cooling-uplift portion of the "clockwise" path (a) indicate some surprising circumstances

   - For example, the kyanite → sillimanite transition is generally considered a prograde transition (as in path a_1), but path a_2 crosses the kyanite → sillimanite transition as temperature is decreasing. This may result in only minor replacement of kyanite by sillimanite during such a retrograde process

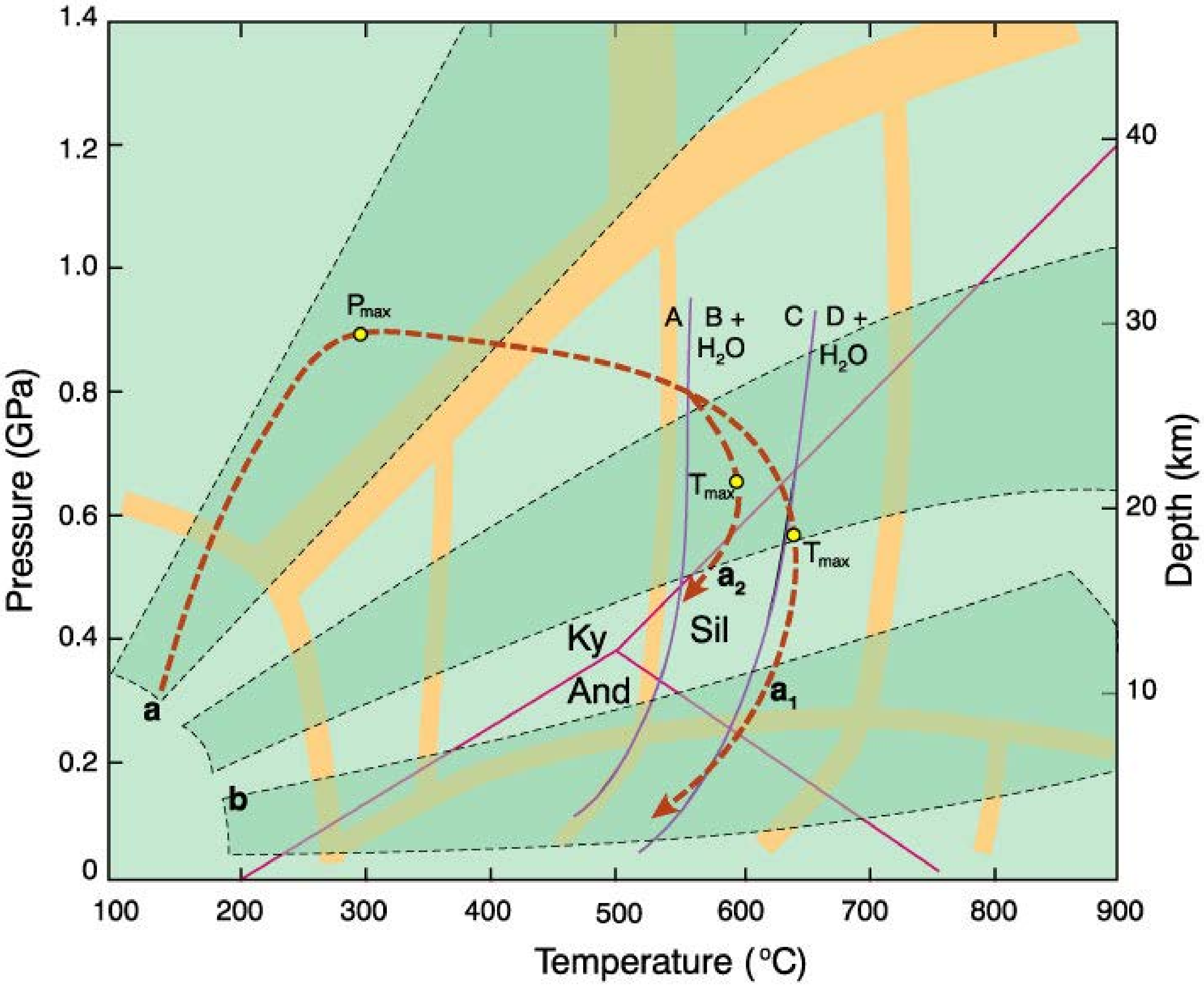


Fig. 25.15a. Schematic pressure-temperature-time paths based on a crustal thickening heat-flow model. The Al_2SiO_5 phase diagram and two hypothetical dehydration curves are included. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Pressure-Temperature-Time (P-T-t) Paths

3. Some variations on the cooling-uplift portion of the "clockwise" path (a) in Fig. 25.12 indicate some surprising circumstances

   - If the P-T-t path is steeper than a dehydration reaction curve, it is also possible that a dehydration reaction can occur with decreasing temperature (although this is only likely at low pressures where the dehydration curve slope is low)

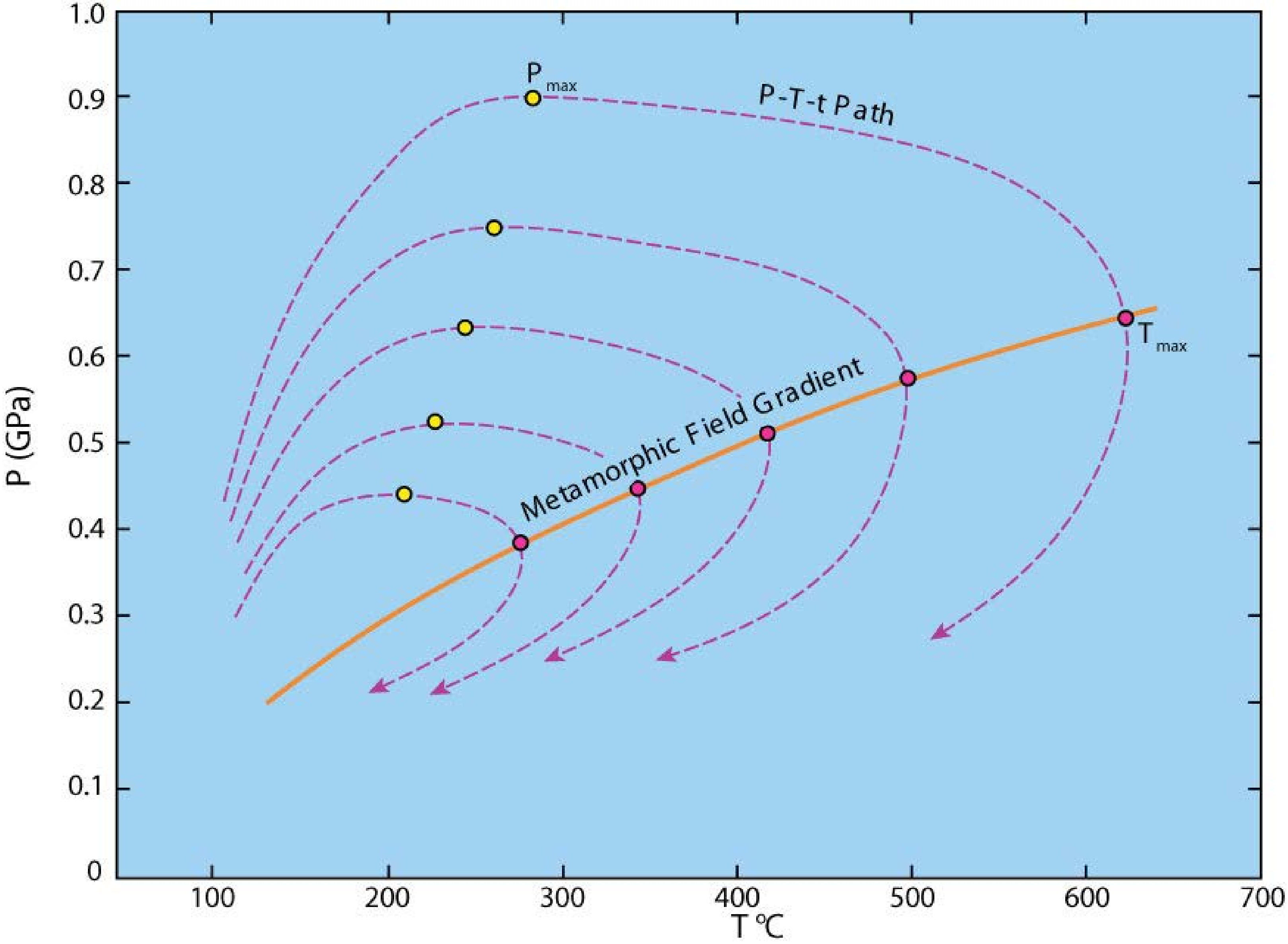


Fig. 25.17. A typical Barrovian-type metamorphic field gradient and a series of metamorphic P-T-t paths for rocks found along that gradient in the field. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.