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
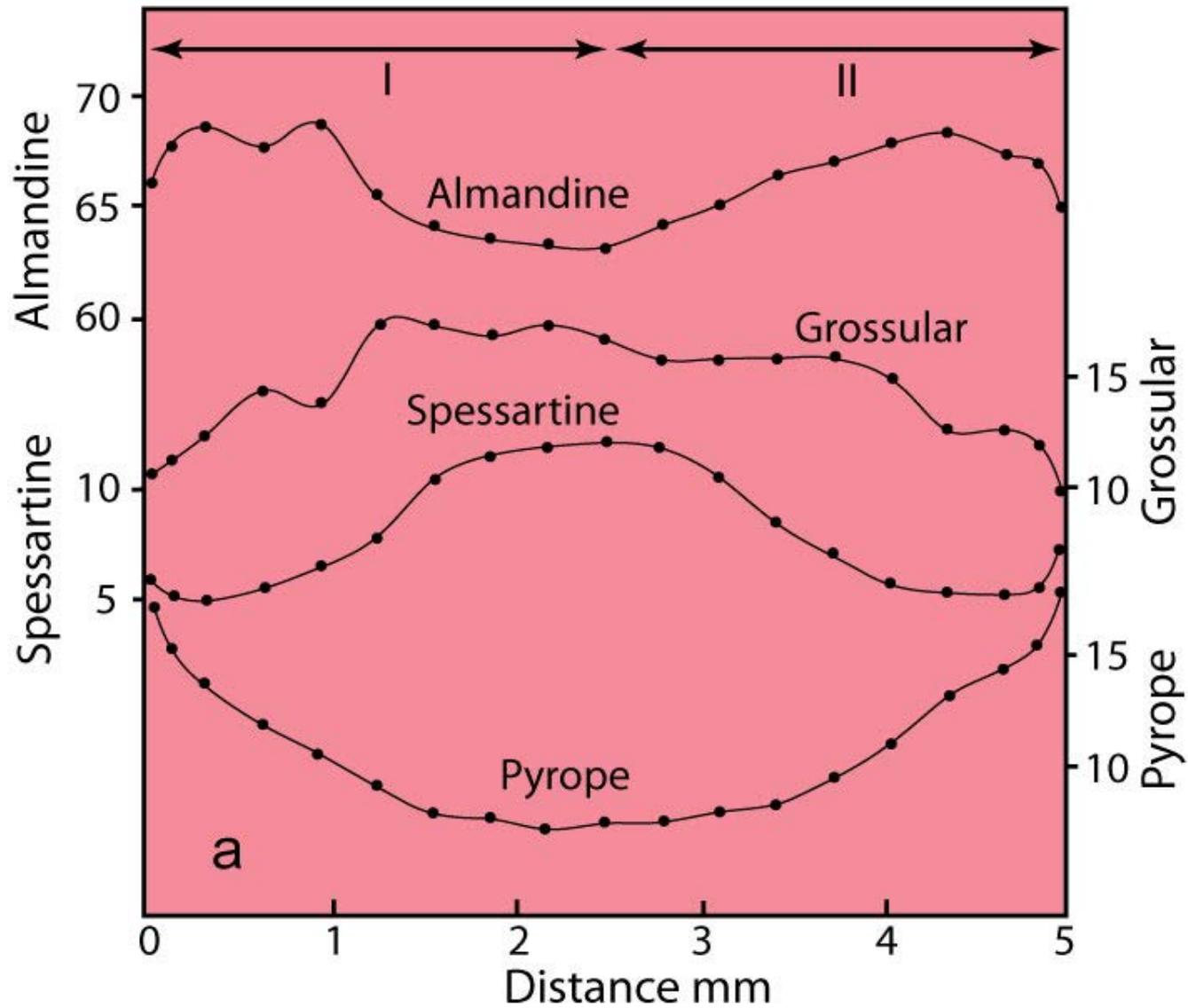
Fig. 25.16a. Chemical zoning profiles across a garnet from the Tauern Window. After Spear (1989)
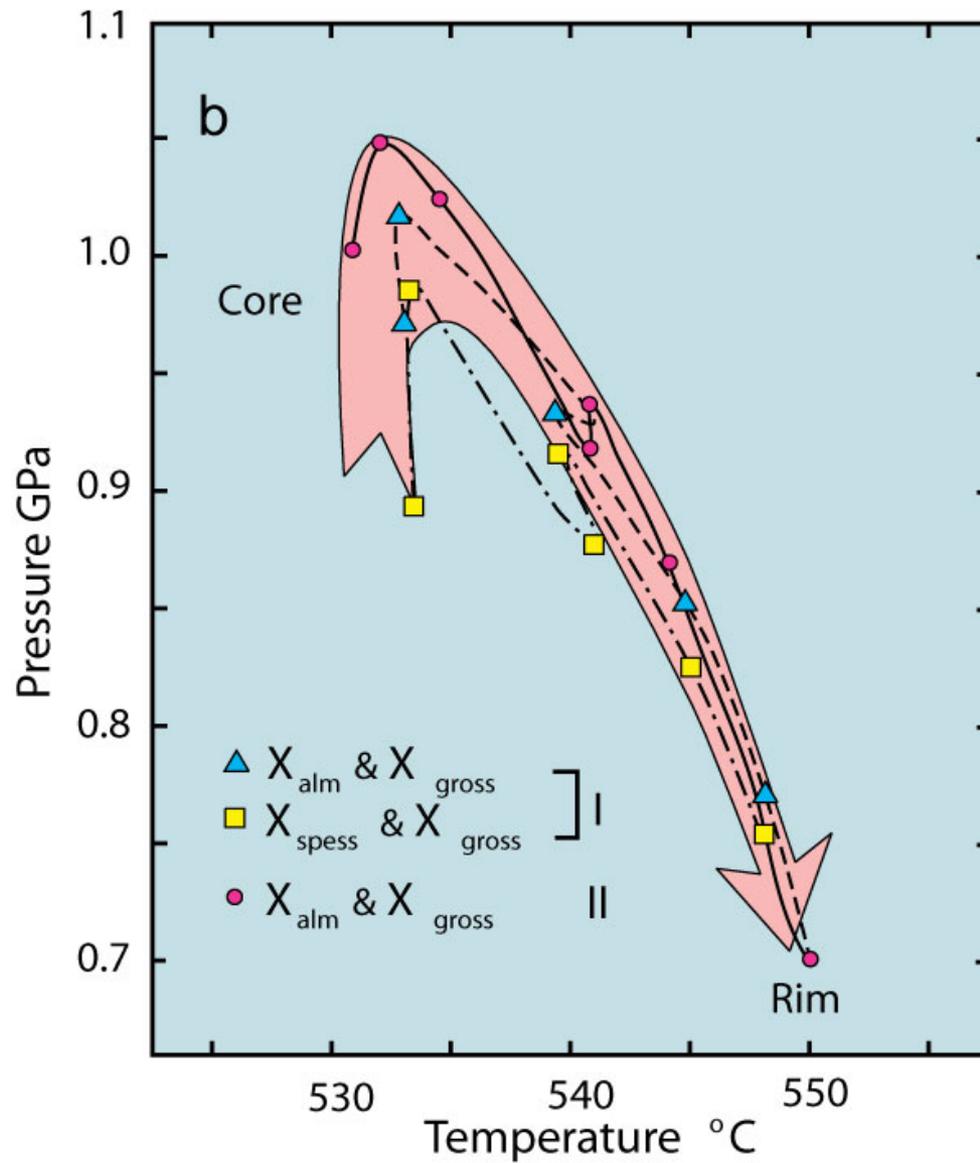
Fig. 25.16b. Conventional P-T diagram (pressure increases upward) showing three modeled "clockwise" P-T-t paths computed from the profiles using the method of Selverstone *et al.* (1984) *J. Petrol.*, 25, 501-531 and Spear (1989). After Spear (1989) *Metamorphic Phase Equilibria and Pressure-Temperature-Time 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
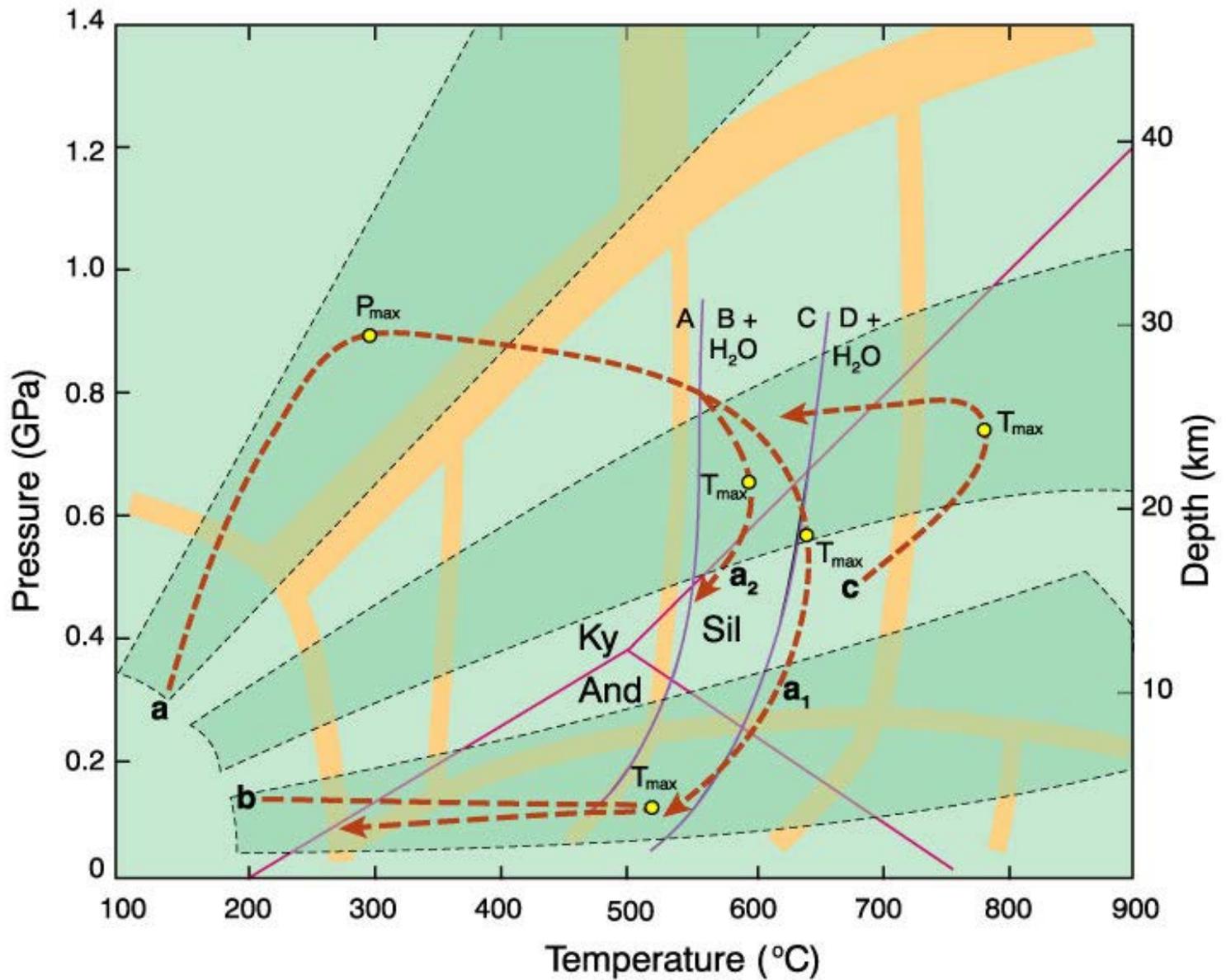
Fig. 25.15. Schematic pressure-temperature-time paths based on heat-flow models. The Al_2SiO_5 phase diagram and two hypothetical dehydration curves are included. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Fig. 25.15a. Schematic pressure-temperature-time paths based on a crustal thickening heat-flow model. The Al$_2$SiO$_5$ 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.
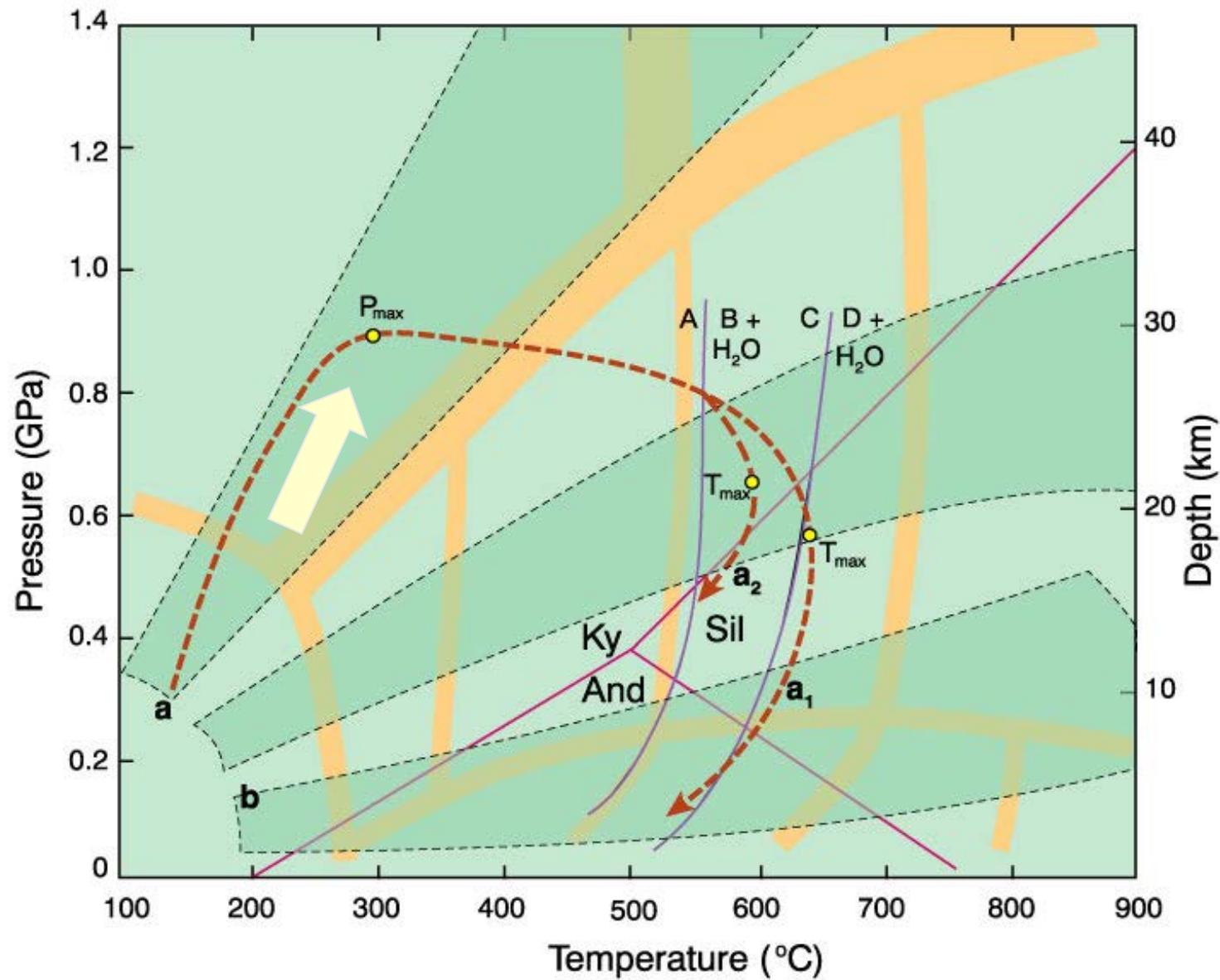
Pressure-Temperature-Time (P-T-t) Paths

- 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
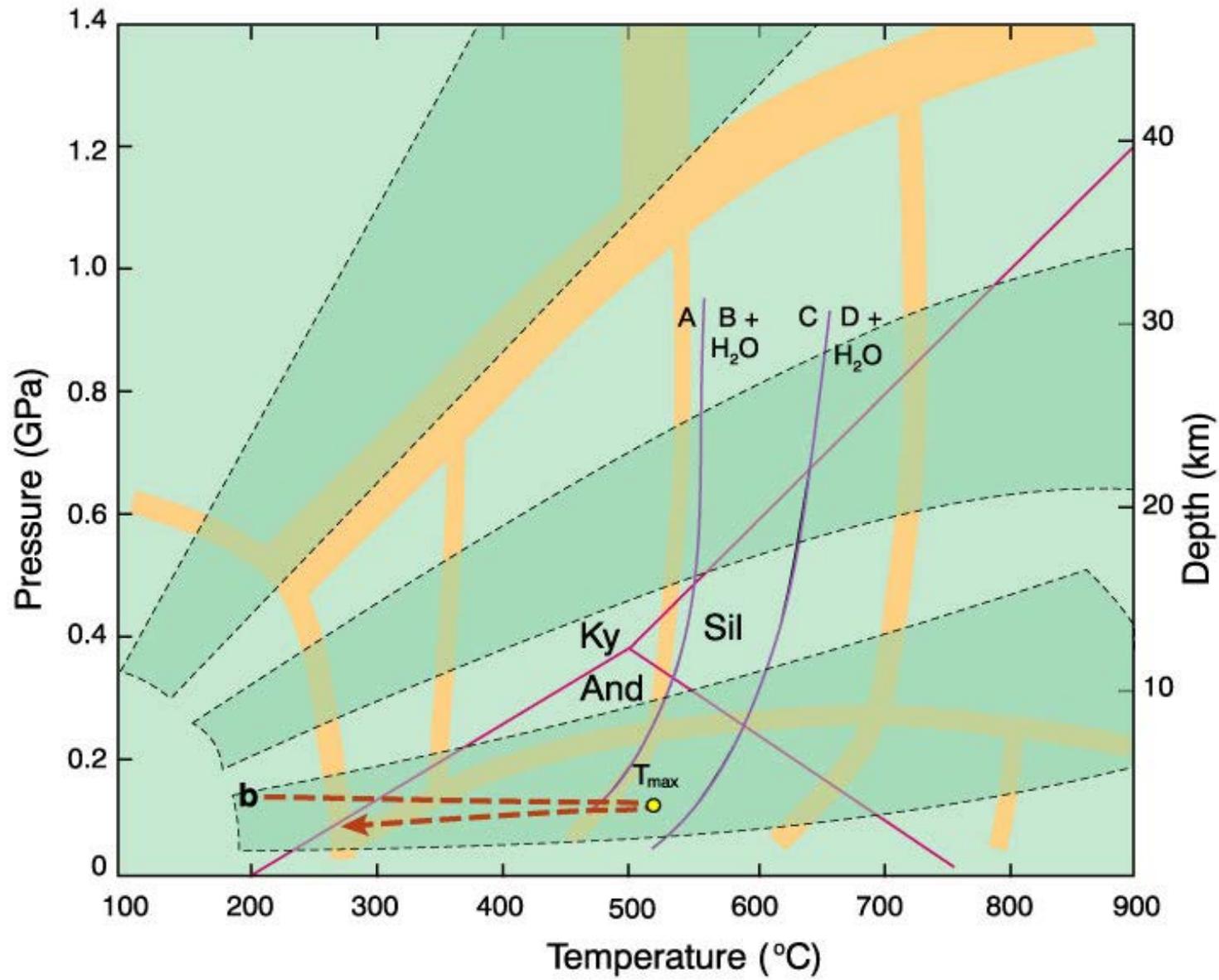
11

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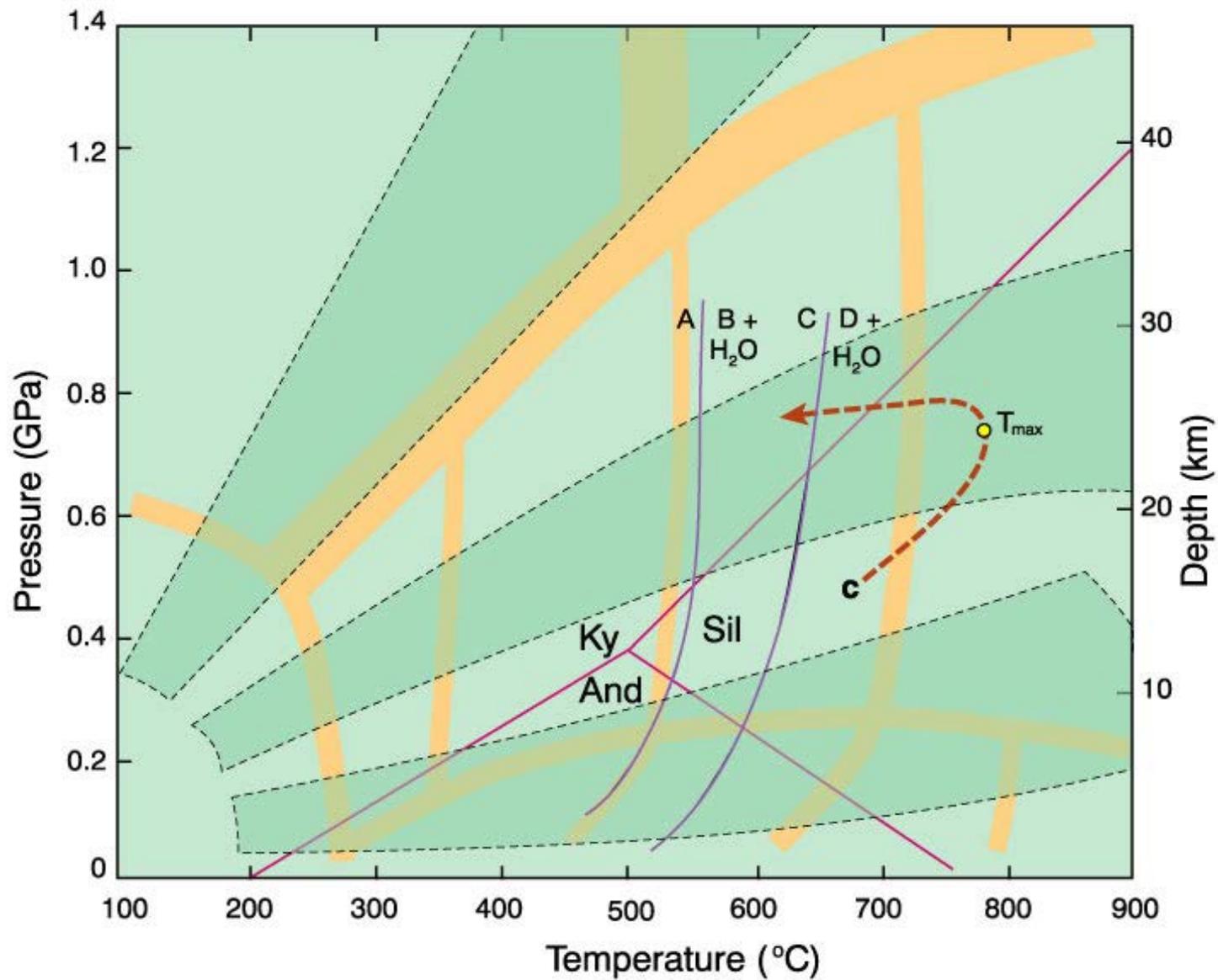
Pressure-Temperature-Time (P-T-t) Paths

- 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 $\rightarrow$ sillimanite transition is generally considered a prograde transition (as in path a_1), but path a_2 crosses the kyanite $\rightarrow$ sillimanite transition as temperature is decreasing. This may result in only minor replacement of kyanite by sillimanite during such a retrograde process
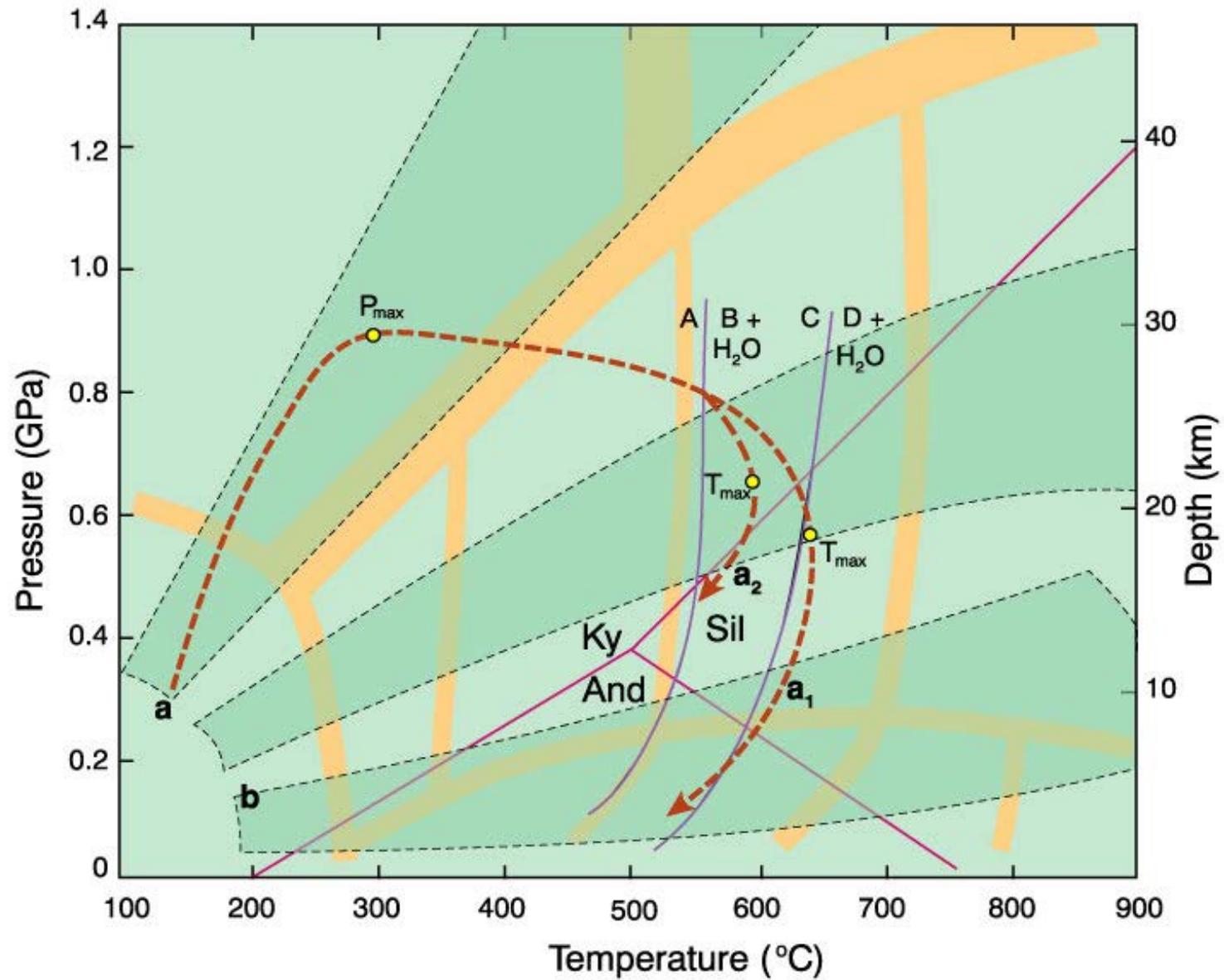
Fig. 25.15a. Schematic pressure-temperature-time paths based on a crustal thickening heat-flow model. The Al_2SiO_5 phase diagram and two hypothetical dehydration curves are included. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

18

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)
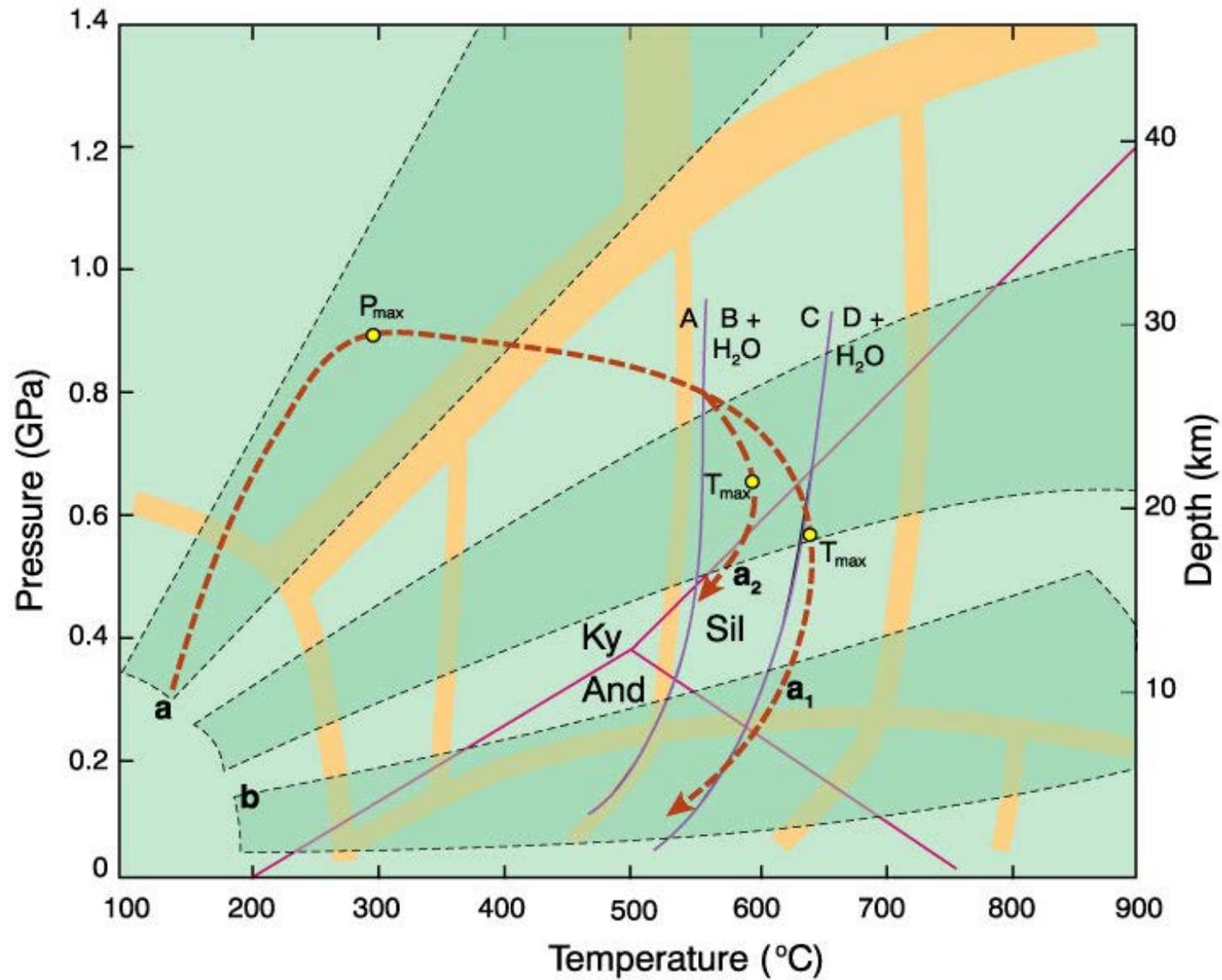
Fig. 25.15a. Schematic pressure-temperature-time paths based on a crustal thickening heat-flow model. The Al_2SiO_5 phase diagram and two hypothetical dehydration curves are included. Facies boundaries, and facies series from Figs. 25.2 and 25.3. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.
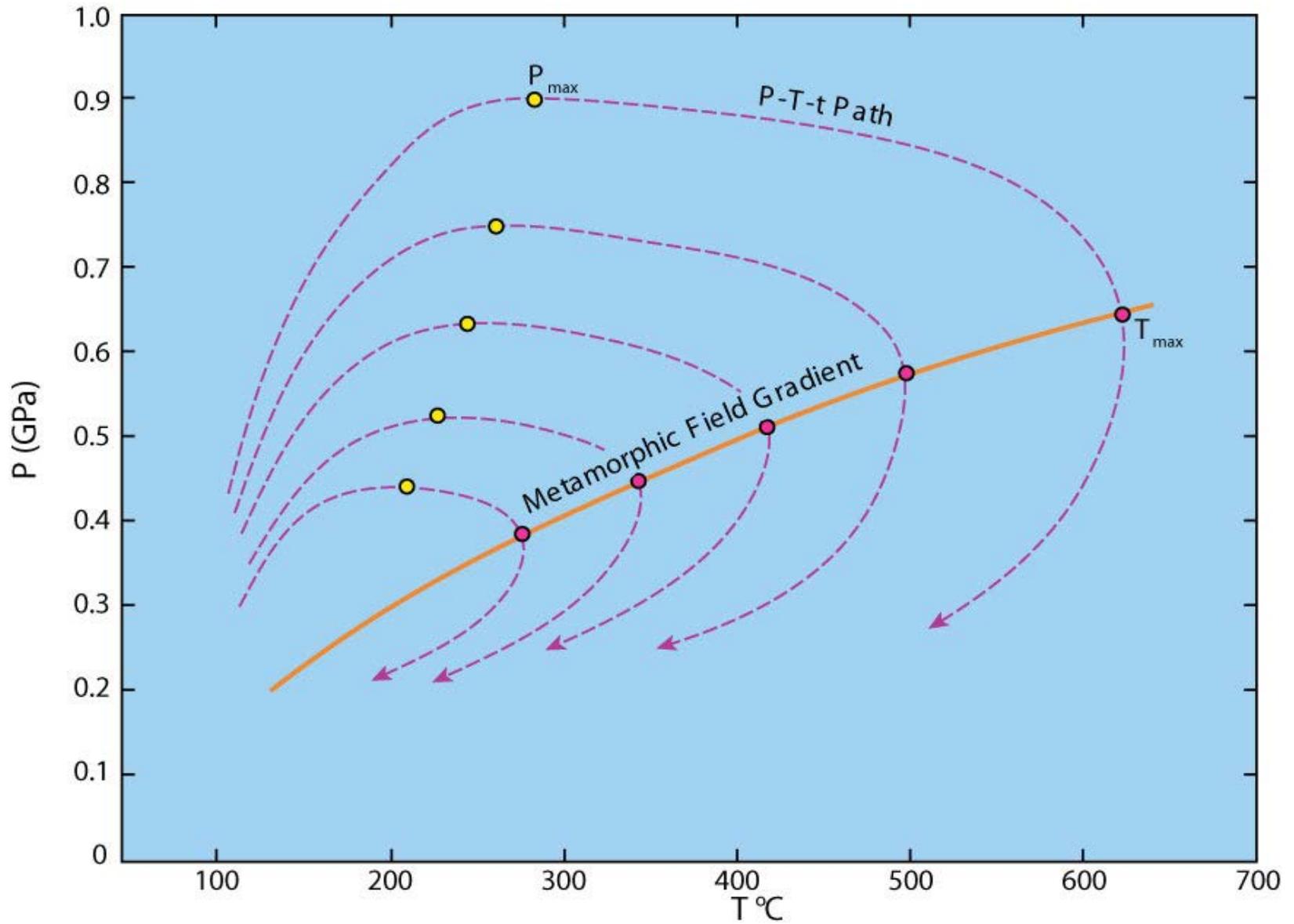
Fig. 25.17. A typical Barrovian-type metamorphic field gradient and a series of metamorphic P-T-t paths for rocks found along that gradient in the field. Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Chapter 24. Stable Mineral Assemblages in Metamorphic Rocks

- Equilibrium Mineral Assemblages
- At **_equilibrium_**, the mineralogy (and the composition of each mineral) is determined by T, P, and X
- "Mineral paragenesis" refers to such an equilibrium mineral assemblage
- Relict minerals or later alteration products are excluded unless specifically stated

Phase equilibrium and Gibbs Phase Rule

- Capable of analyzing 'systems' in a way that allows us to grasp the dynamics of each and to account for the contribution of each chemical constituent to the variations

- Understand how the introduction of additional constituents affects a system – helps us better comprehend new systems and more complex systems in nature

- In other words, it helps us represent and interpret natural systems (e.g., rocks) by **graphical** means (phase diagrams), so that we can evaluate mineral assemblages, e.g., whether these are at equilibrium conditions, or thermodynamically evaluate mineral reactions

The Gibbs Phase Rule

$$F = C - \phi + 2$$

F = # degrees of freedom

> The number of <u>independently</u> **intensive** <u>parameters</u> that must be <u>specified</u> in order to completely determine the system at *equilibrium conditions*

> Consist of properties of the substances that compose a system (e.g., mineral assemblage)

> Examples: Pressure, Temperature, density, molar volume

The Gibbs Phase Rule

$$F = C - \phi + 2$$

F = # degrees of freedom

> The number of independently intensive parameters that must be specified in order to completely determine the system system at ***equilibrium conditions***

ϕ = # of phases

> phases are mechanically separable constituents

> Examples: Mineral, liquid, gas, or an amorphous solid such as glass

The Gibbs Phase Rule

$$F = C - \phi + 2$$

F = # degrees of freedom

> The number of dependently intensive parameters that must be specified in order to completely determine the system at *equilibrium conditions*

ϕ = # of phases

> phases are mechanically separable constituents

C = **<u>minimum</u>** # of components (chemical constituents that must be specified in order to define all phases)

Example: H_2O – treat as one component, not two (H, O)

Plagioclase – normally described as two components –**Albite & Anorthite**

The Gibbs Phase Rule

$$F = C - \phi + 2$$

F = # degrees of freedom

The number of independently intensive parameters that must be specified in order to completely determine the system

ϕ = # of phases

phases are mechanically separable constituents

C = minimum # of components (chemical constituents that must be specified in order to define all phases)

2 = 2 intensive parameters

Usually = temperature and pressure for us geologists

The Phase Rule in Metamorphic Systems

If $F \geq 2$ is the most common situation, then the phase rule may be adjusted accordingly:

$$F = C - \phi + 2 \ \geq 2$$

$$\phi \ \leq C \ (Eq \ 24.1)$$

Goldschmidt's mineralogical phase rule, or simply the mineralogical phase rule

The Phase Rule in Metamorphic Systems

Suppose we have determined C for a rock
Consider the following three scenarios:
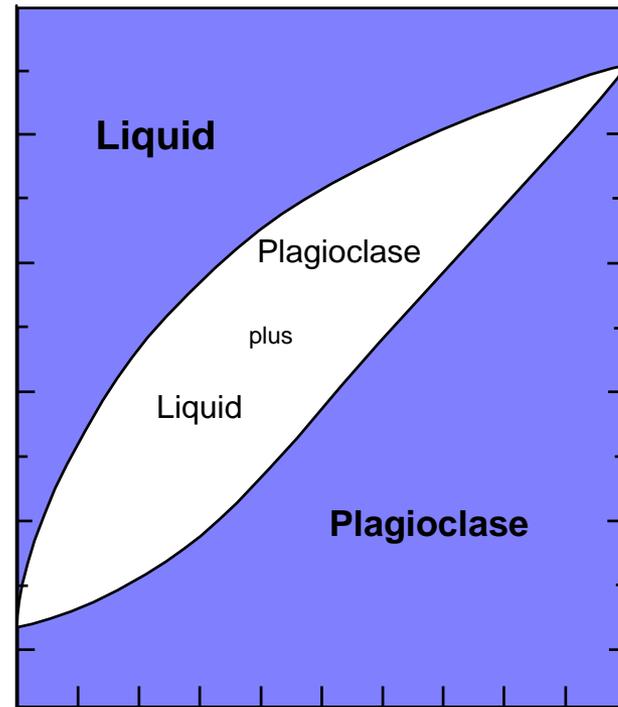
a) $\phi = C$

The standard divariant situation

The rock probably represents an equilibrium mineral assemblage from within a metamorphic zone

The Phase Rule in Metamorphic Systems

b) $\phi < C$

Common with mineral systems that exhibit solid solution

The Phase Rule in Metamorphic Systems

c) $\phi > C$

A more interesting situation, and at least one of three situations must be responsible:

1) $F < 2$

The sample is collected from a location right on a **univariant reaction curve (isograd) or invariant point**

The Phase Rule in Metamorphic Systems

Consider the following three scenarios:

$C = 1$

$\phi = 1$ common

$\phi = 2$ rare

$\phi = 3$ only at the specific P-T conditions of the invariant point
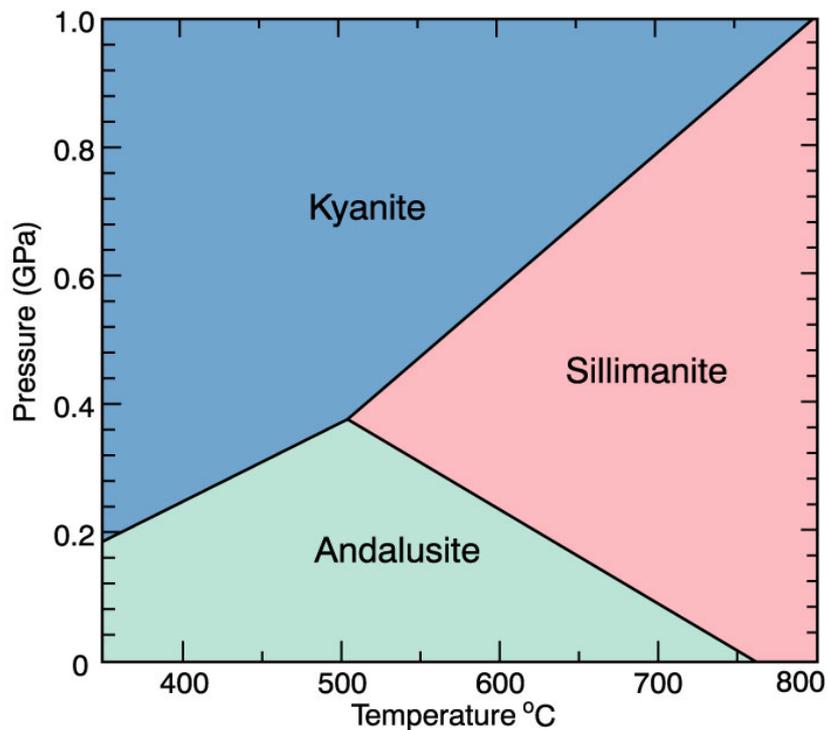
(~ 0.37 GPa and 500ºC)

Figure 21.9. The P-T phase diagram for the system Al_2SiO_5 calculated using the program TWQ (Berman, 1988, 1990, 1991). Winter (2010) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.