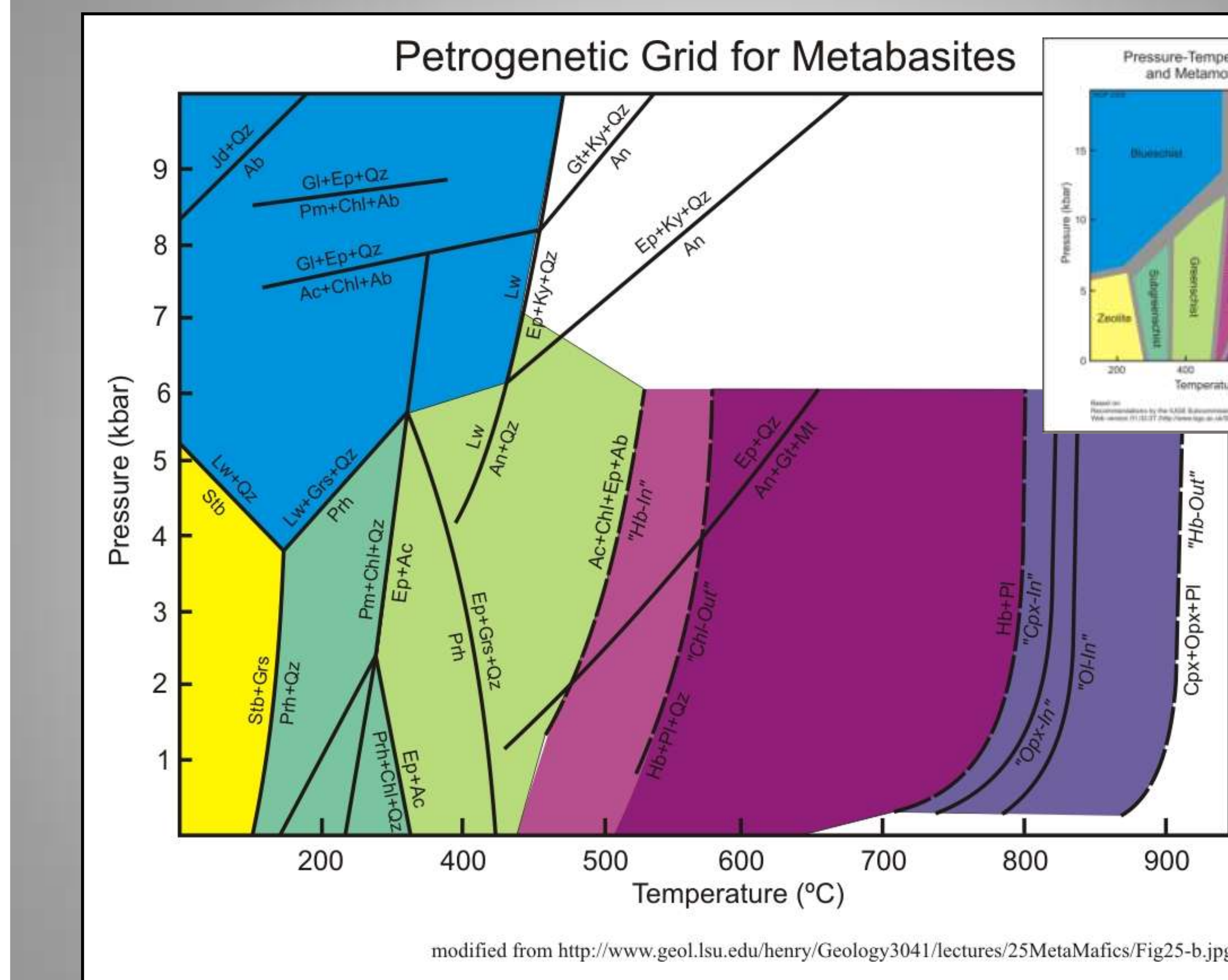
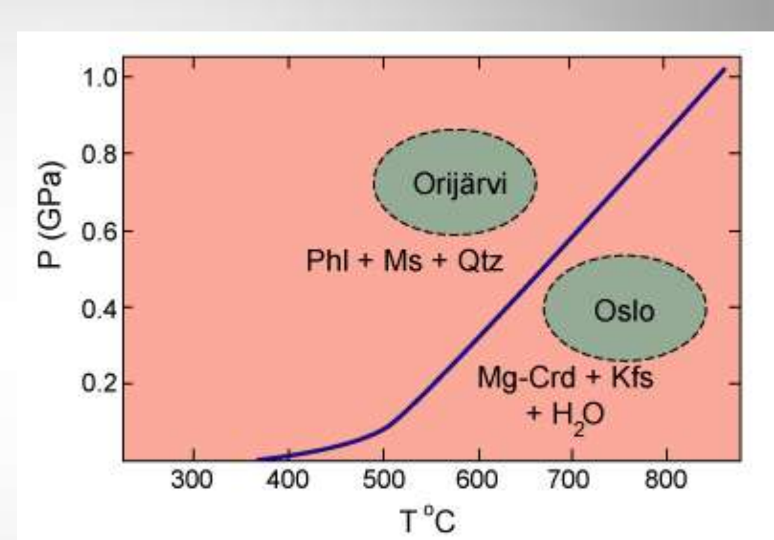
Metamorphic Reactions and Stable Assemblages

Metamorphic Lecture 3



Eskola and Metamorphic Facies

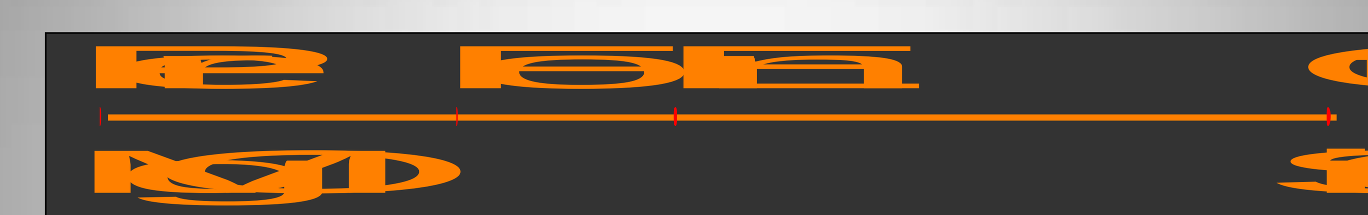
- Eskola (1914, 1915) noted that metapelitic rocks in southern Finland (Orijärvi) contained the assemblage Bt-Ms whereas near Oslo, rocks contained the compositionally equivalent mineral assemblage Kf-Cd
- If rocks are the same composition, then the mineralogical difference must be due to a difference in physical conditions



$$2\ KMg_3AlSi_3O_{10}(OH)_2 + 6\ KAl_2AlSi_3O_{10}(OH)_2 + 15\ SiO_2 \leftrightarrow 3\ Mg_2Al_4Si_5O_{18} + 8\ KAlSi_3O_8 + 8\ H_2O$$

Reactions and Chemographics

- Any two phases in a binary system can react to from a phase that lies between them



- Fo + Qtz = En — $Mg_2SiO_4 + SiO_2 = Mg_2Si_2O_6$
- En + Per = Fo — $Mg_2Si_2O_6 + 2\ MgO = 2\ Mg_2SiO_4$
- Per + Qtz = Fo
- Per + Qtz = En

- Chemographics can help to determine if a reaction is possible

Reactions and Chemographics

- What reaction does this ternary system allow?

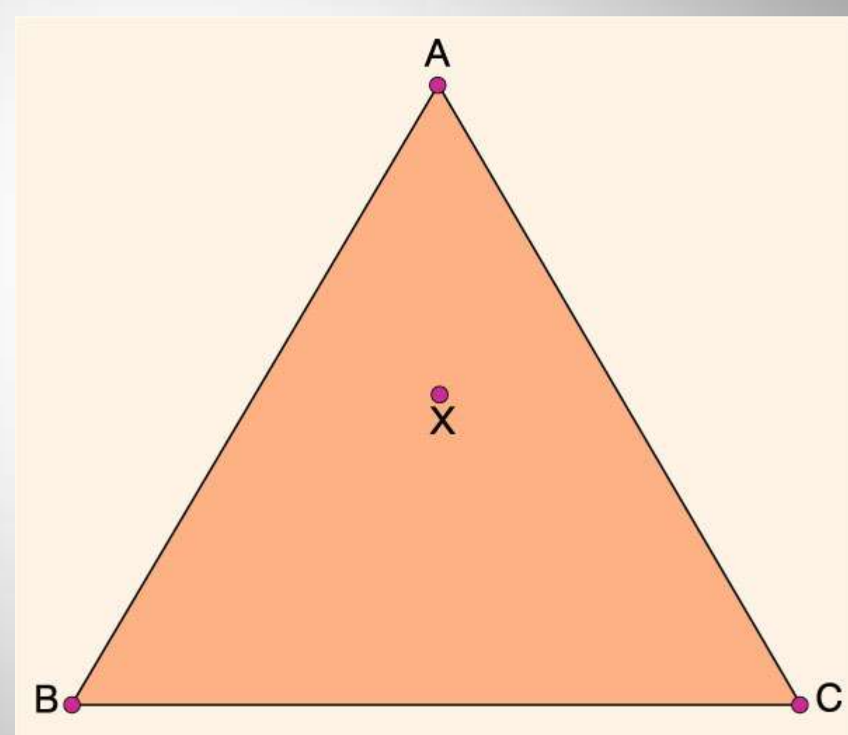
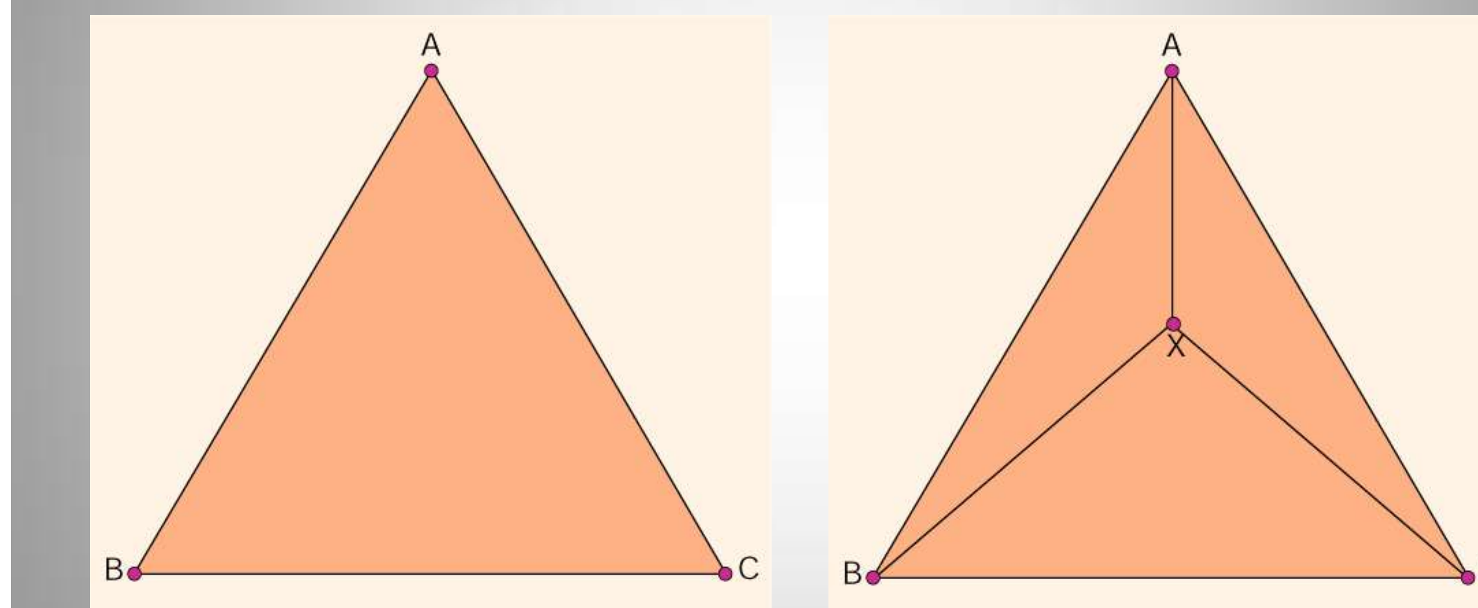


Fig. 26-12. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Reactions and Chemographics

A + B + C = X



Below x-in isograd

Above x-in isograd

Reactions and Chemographics

- What reaction is possible between A-B-C-D?

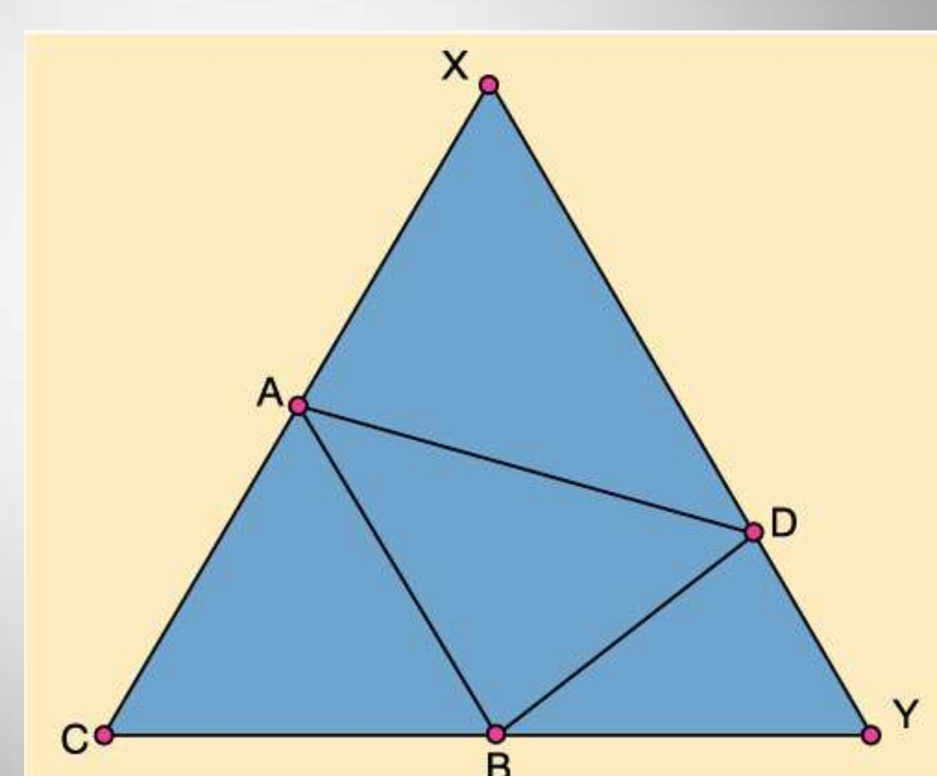


Fig. 26-14a. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

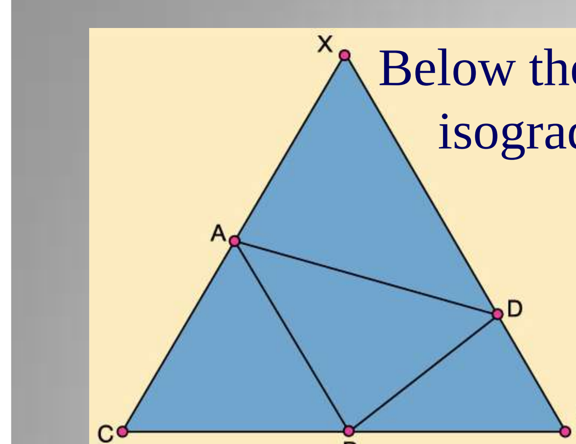
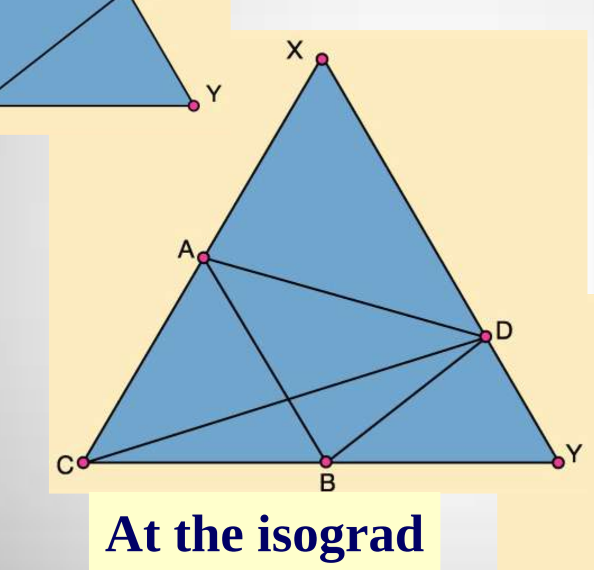
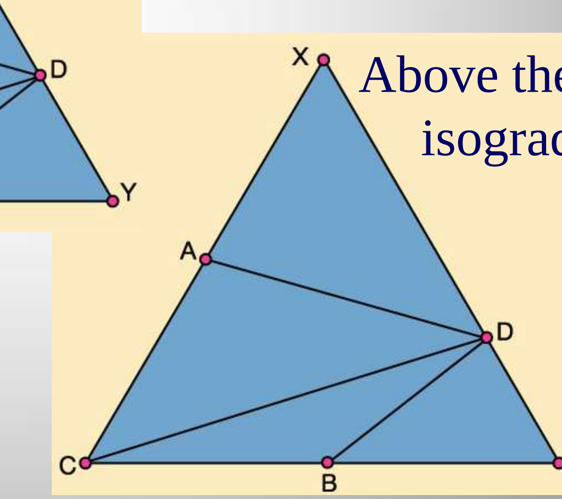


Fig. 26-14. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

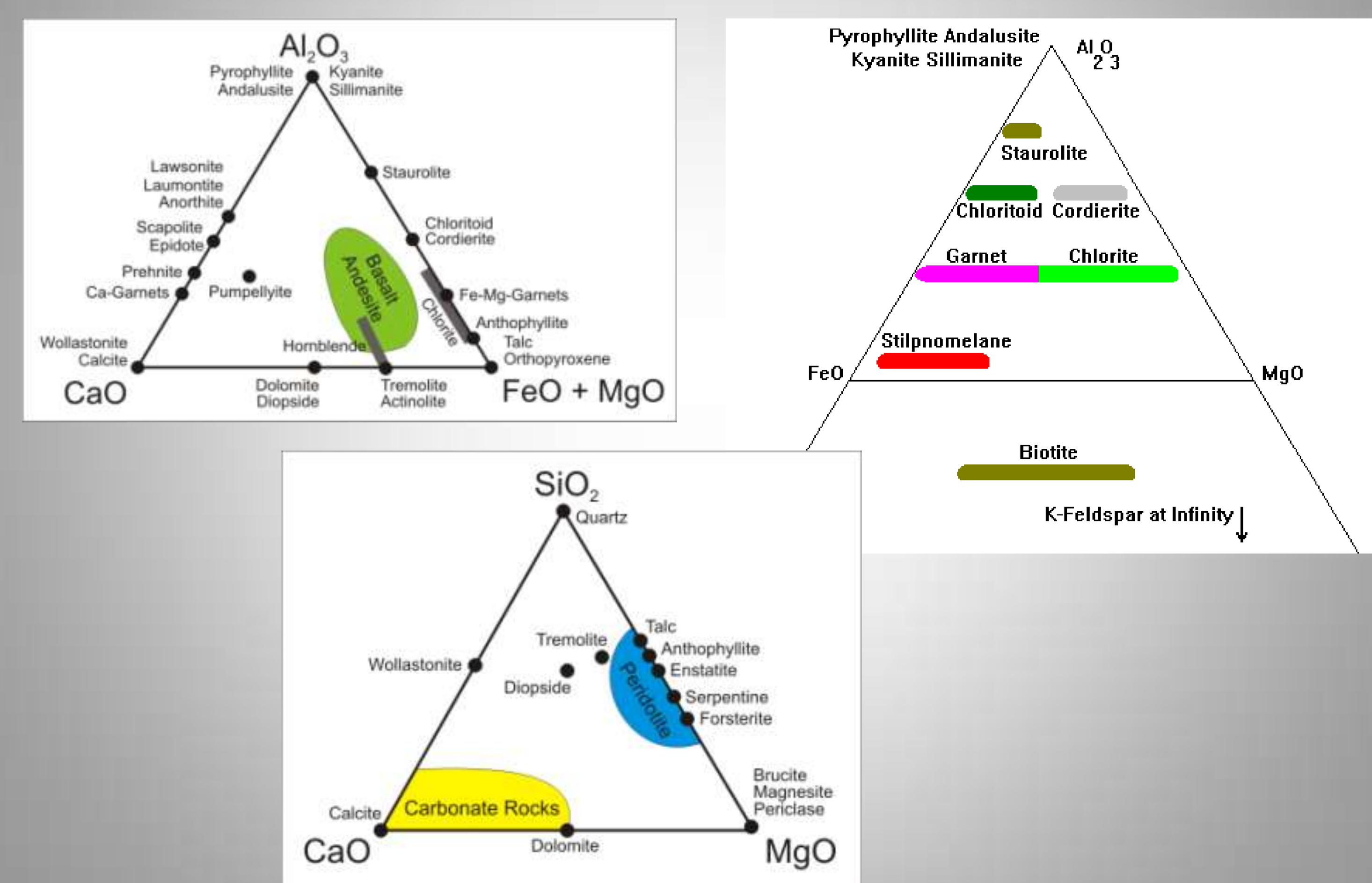
A + B = C + D



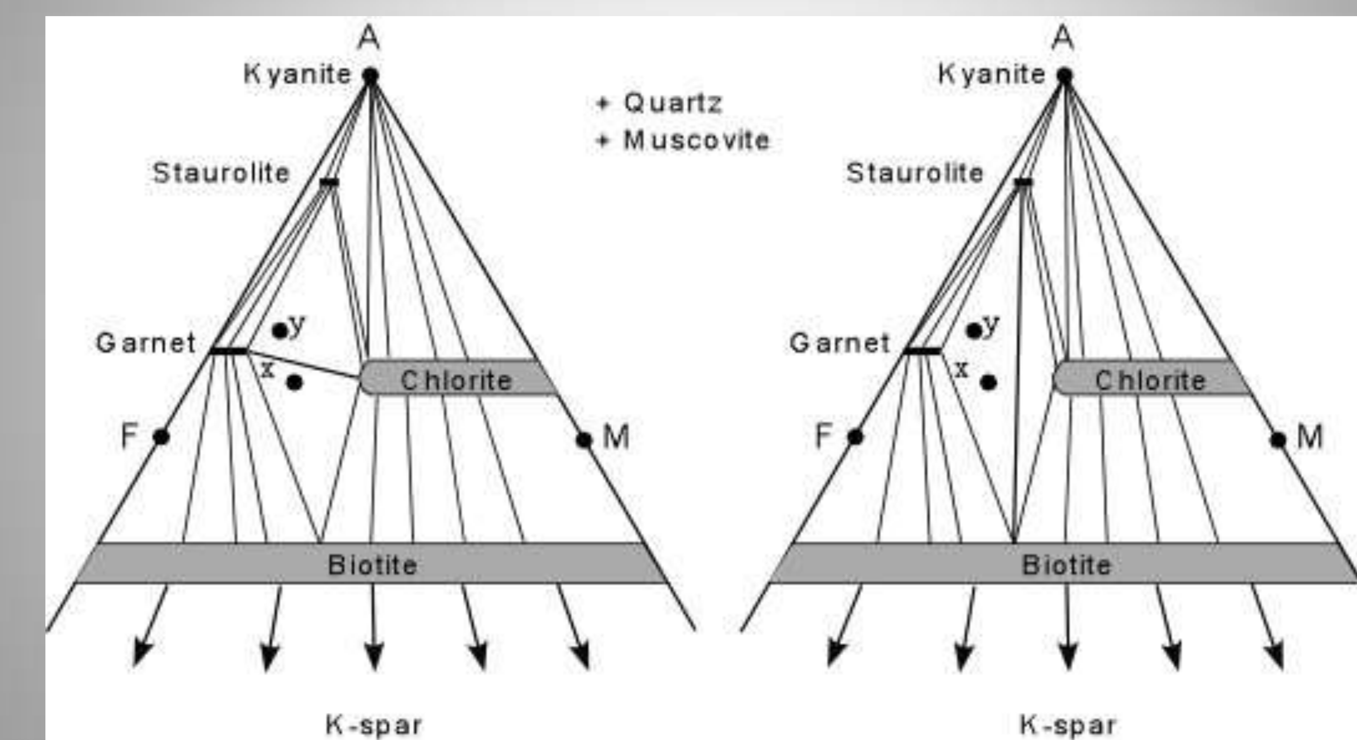


This is called a tie-line flip, and results in new groupings in the next metamorphic zone

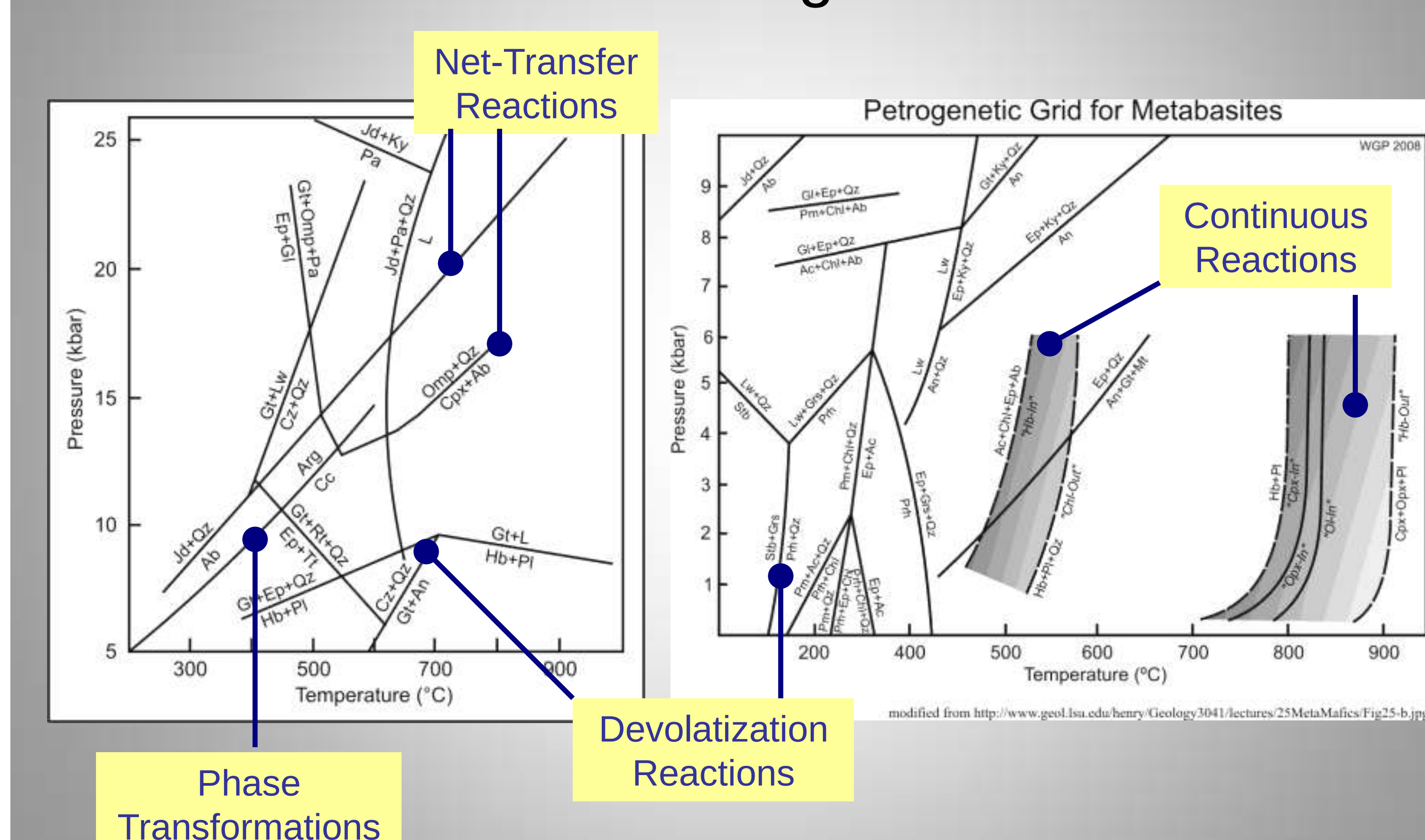
Mineral Compatibility Diagrams



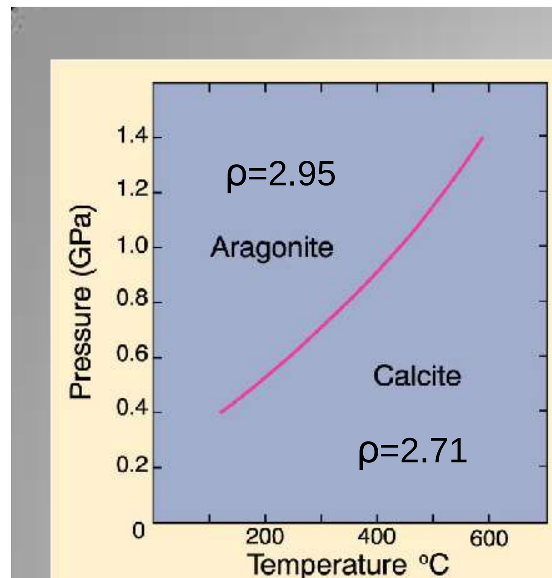
Mineral Compatibility Diagrams

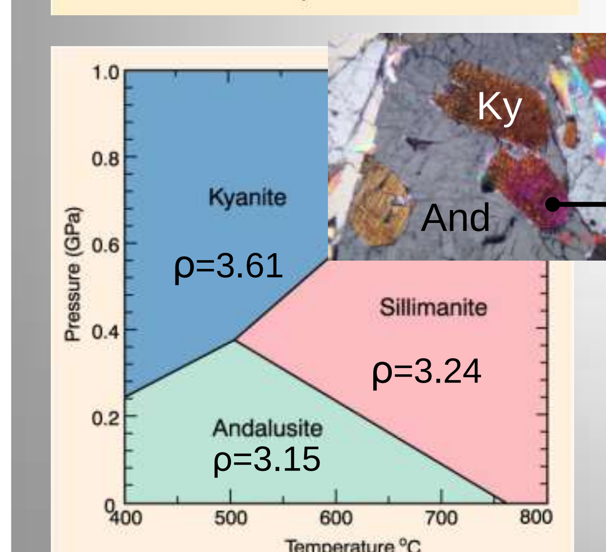


Reactions and Metabasite Petrogenetic Grids

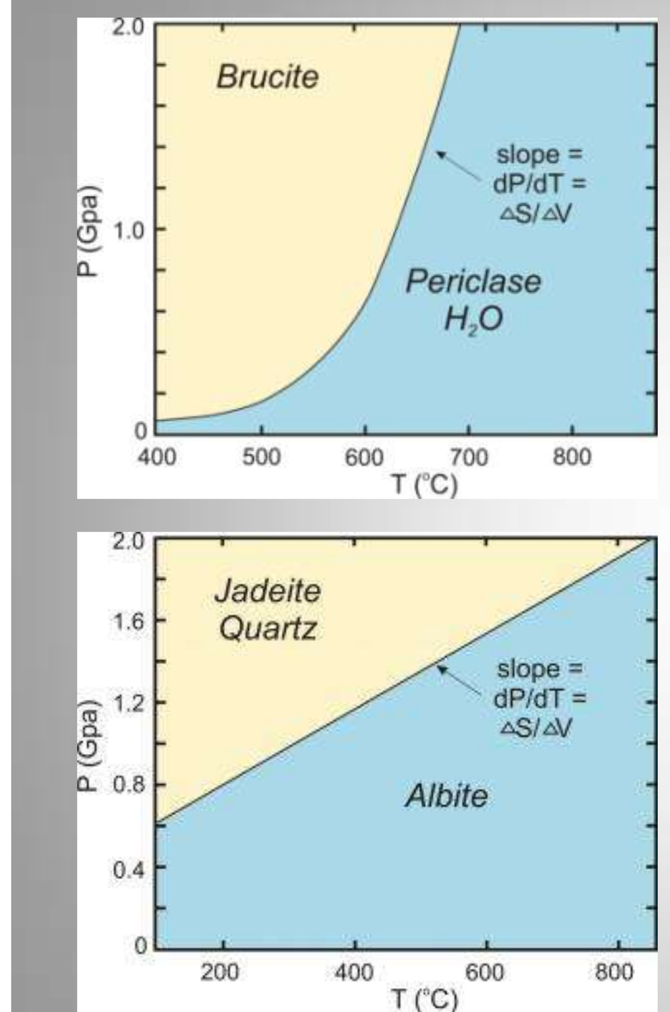


Phase Transformations (Polymorphic Reactions)





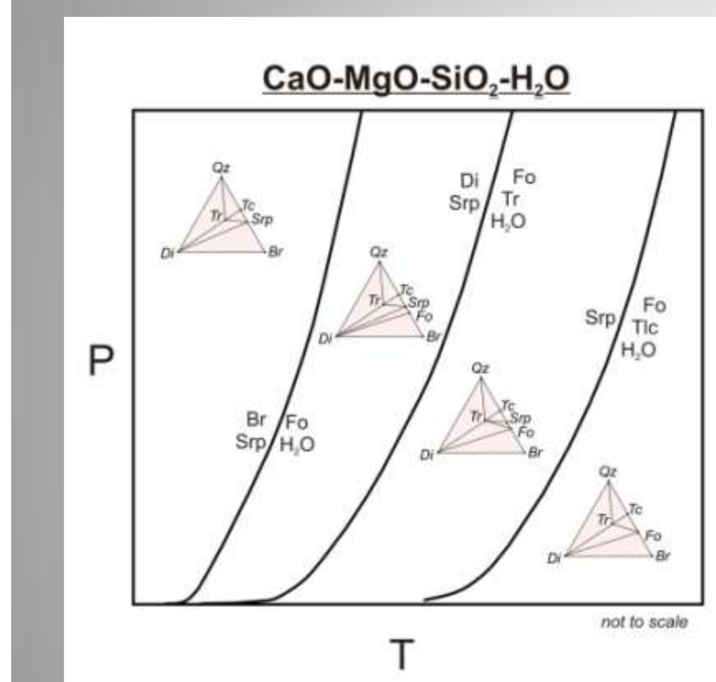
- **Polymorphic reactions** are a special type of solid-solid reaction that involves phases of identical composition.
- Very sluggish reactions
  - Reactant may continue to exist as a metastable phase
- Most solid-solid reactions plot on a P-T diagram as essentially straight lines.



Clapeyron Equation

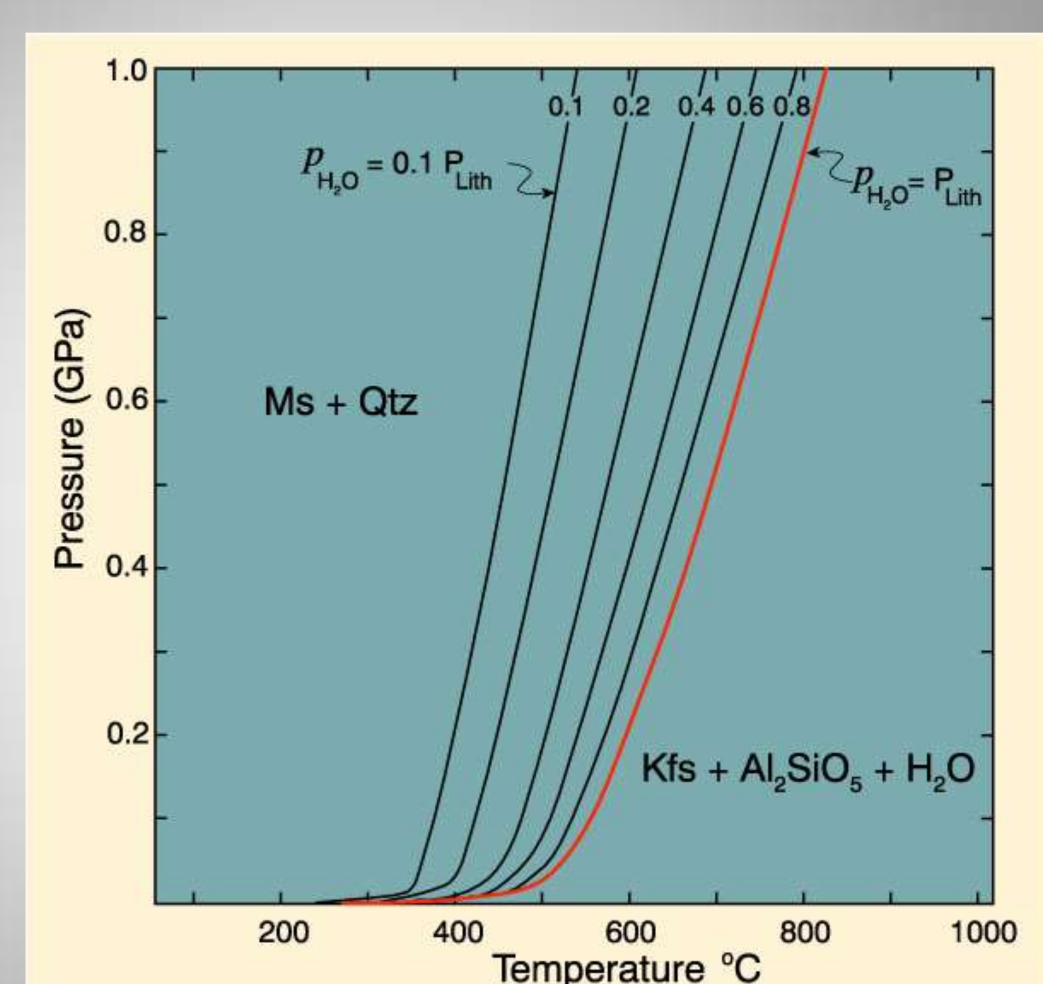
- The Clapeyron equation relates the slope of a reaction line on a phase diagram to fundamental thermodynamic properties.
  - $dP/dT = \Delta S/\Delta V$
- For solid-solid reactions, such as kyanite = sillimanite or albite = jadeite + quartz, the ratio $\Delta S/\Delta V$ is constant or nearly so, and so the equilibrium plots as a straight line in P-T space.
- For reactions involving a gas or fluid phase (such as H_2O and/or CO_2), the ratio $\Delta S/\Delta V$ varies with P and T. This is because of increasing entropy as a gas is produced, and the extreme compressibility of the fluid.

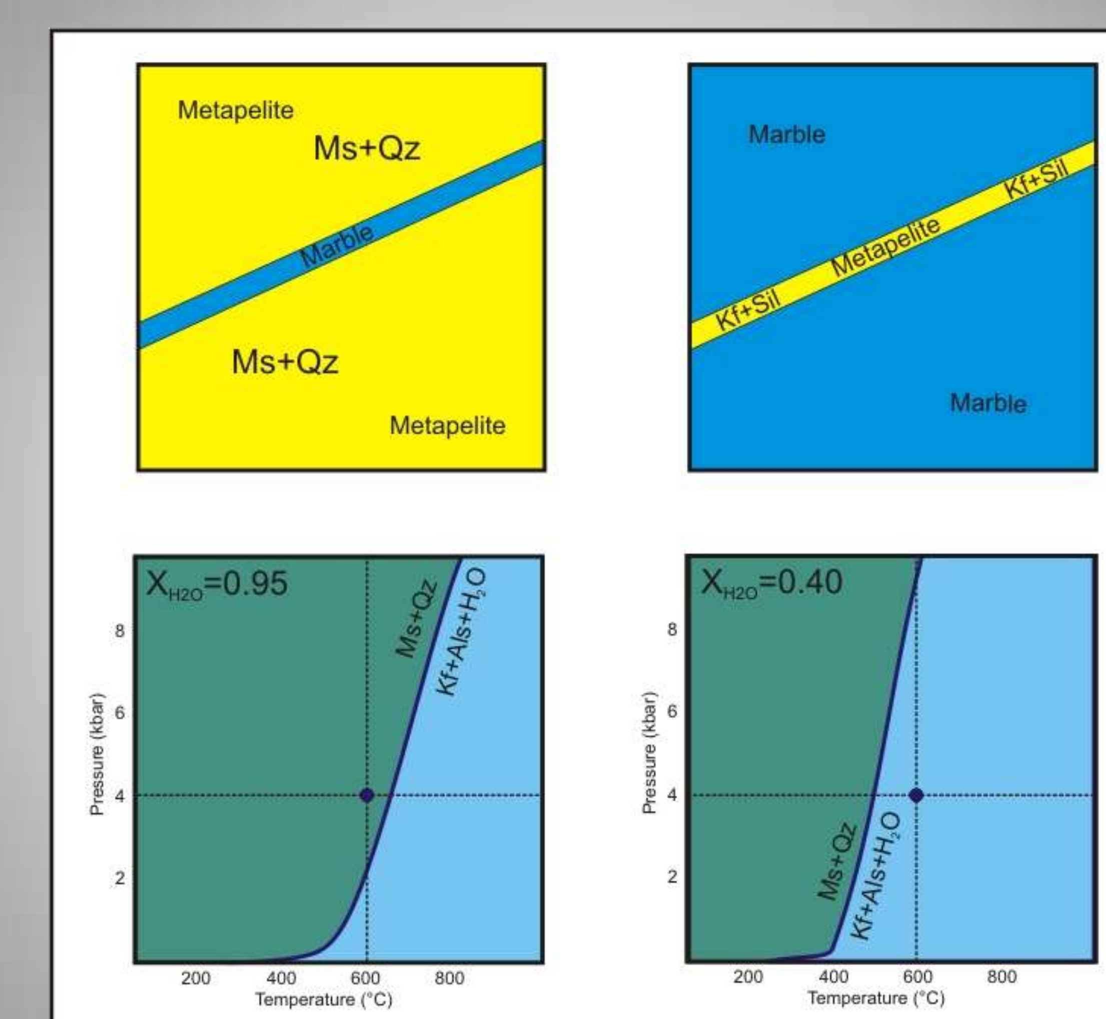
Devolatalization Reactions

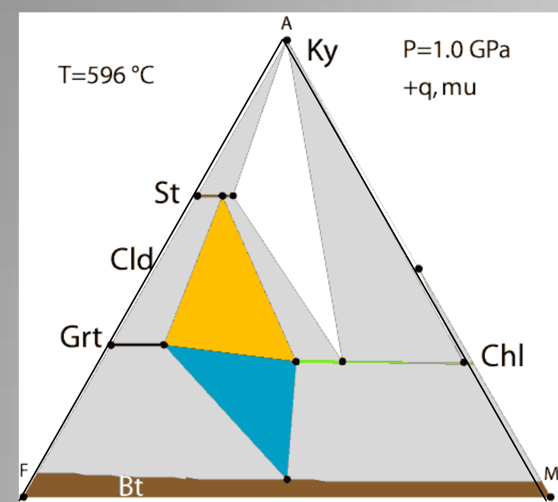


- **Devolatilization reactions** are **net-transfer** reactions that involve the liberation of a volatile phase (H_2O for **dehydration reactions** or CO_2 for **decarbonation reactions**).
- Fluids appear on the high-temperature side of most such reactions.
- The curves for devolatalization reactions on a P-T diagram will have shallower slopes at low pressure because the volume of a fluid phase is much larger than that of solid phases.

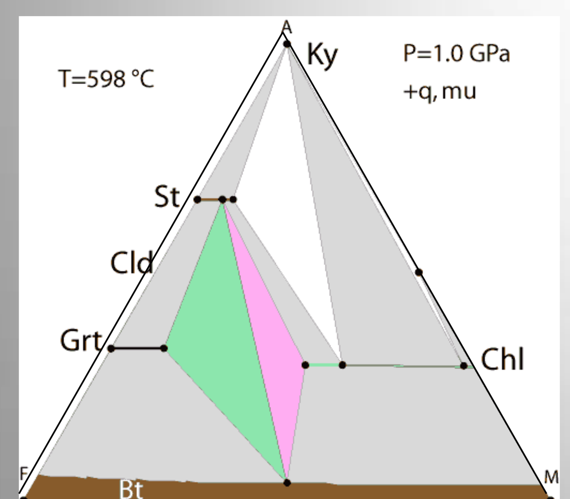
Figure 26-2. P-T phase diagram for the reaction Ms + Qtz = Kfs + Al_2SiO_5 + H_2O showing the shift in equilibrium conditions as p_{H2O} varies (assuming ideal H_2O-CO_2 mixing). Calculated using the program TWQ by Berman (1988, 1990, 1991). Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.







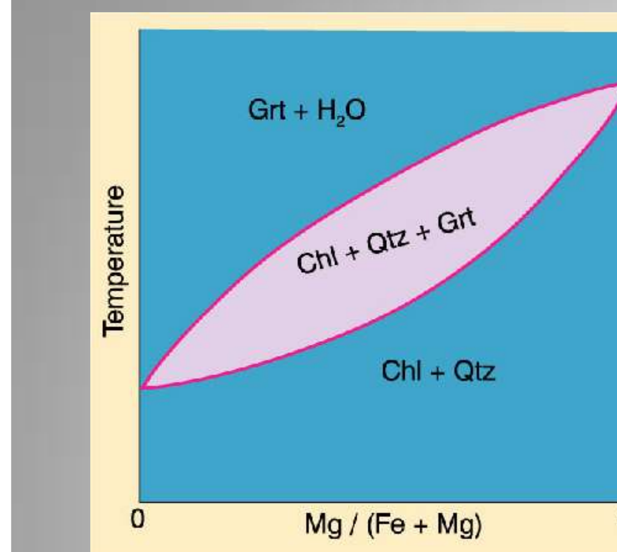
Gt + Chl ↔ St + Bt

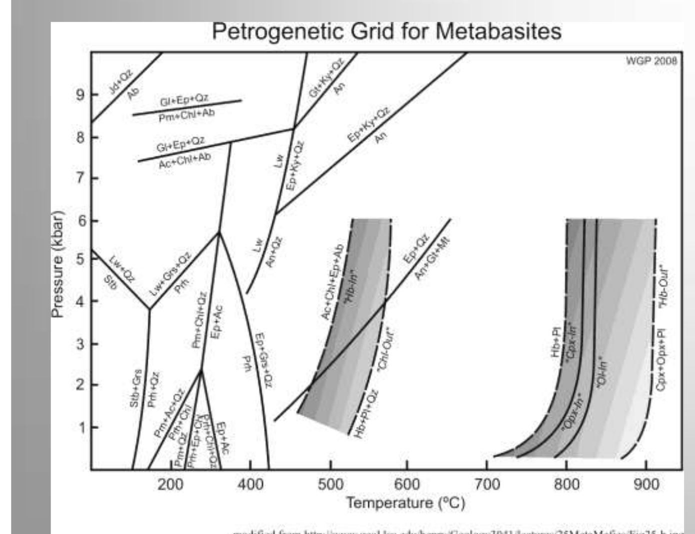


Net-Transfer Reactions

- **Net-transfer reactions** involve chemical components being "transferred" from one phase or set of phases to others
- New minerals are produced as old ones disappear

Tie line flip reactions involve two phases becoming stable together that were previously unstable together, and vice versa

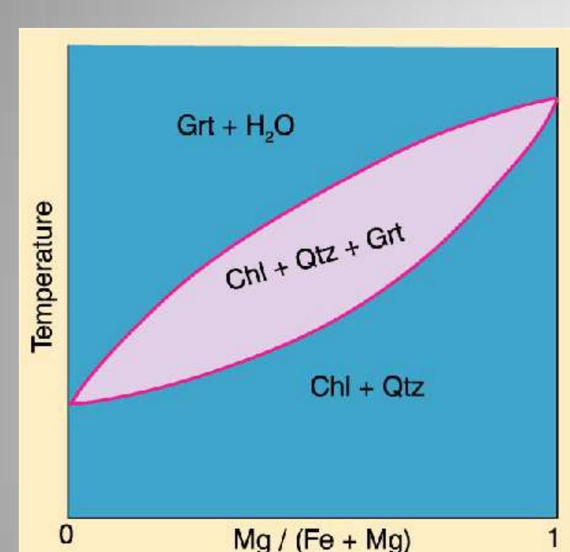


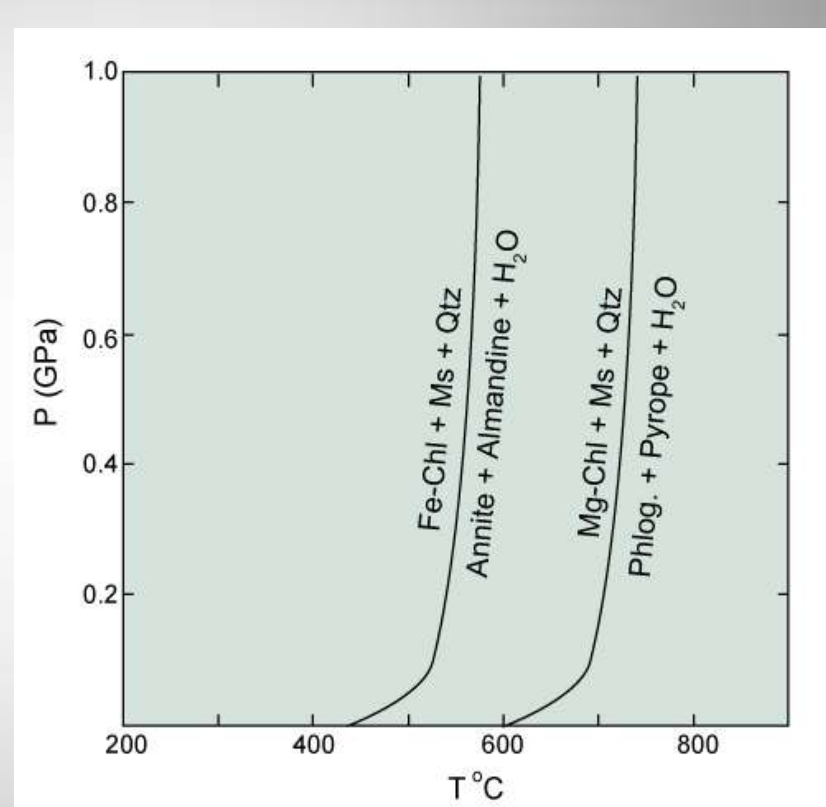


Continuous Reactions

- **Continuous reactions** involve phases that vary in composition
- Continuous reactions occur over a range of PT, so the products and reactants coexist stably over a range of PT
- The compositions of the phases change systematically as conditions change
- Continuous reactions may be net-transfer reactions or ion exchange reactions

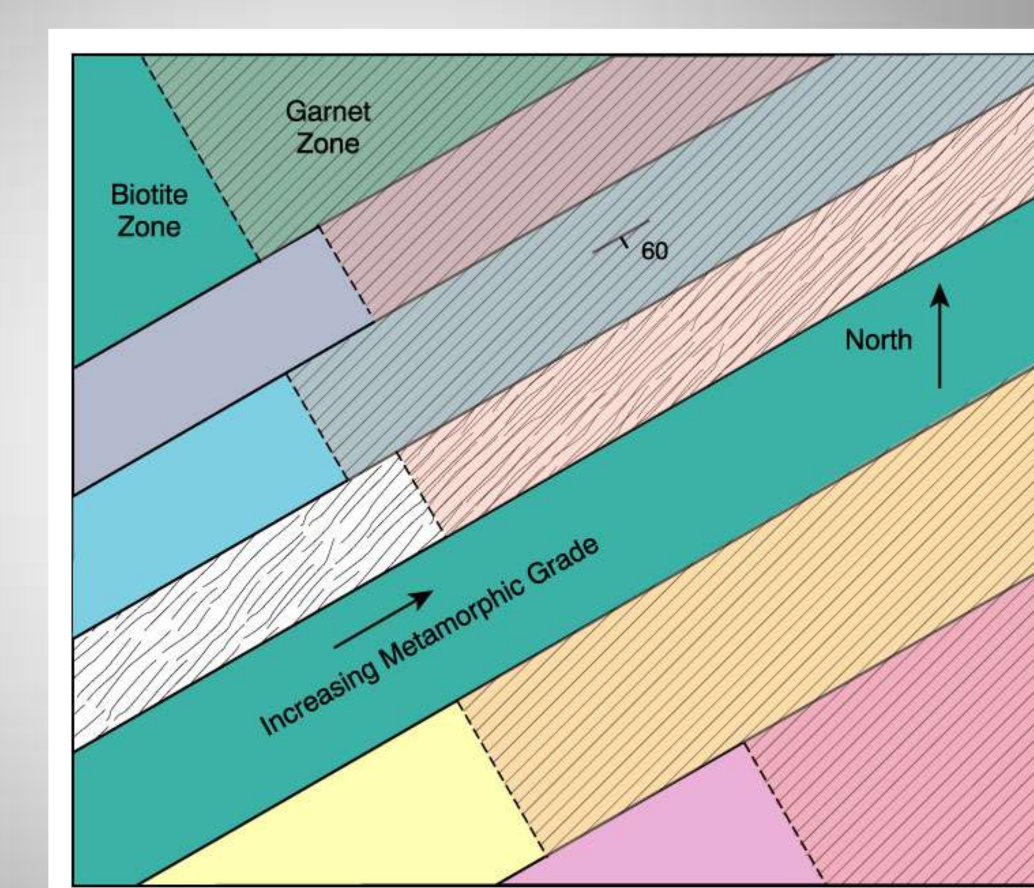
Continuous Reactions



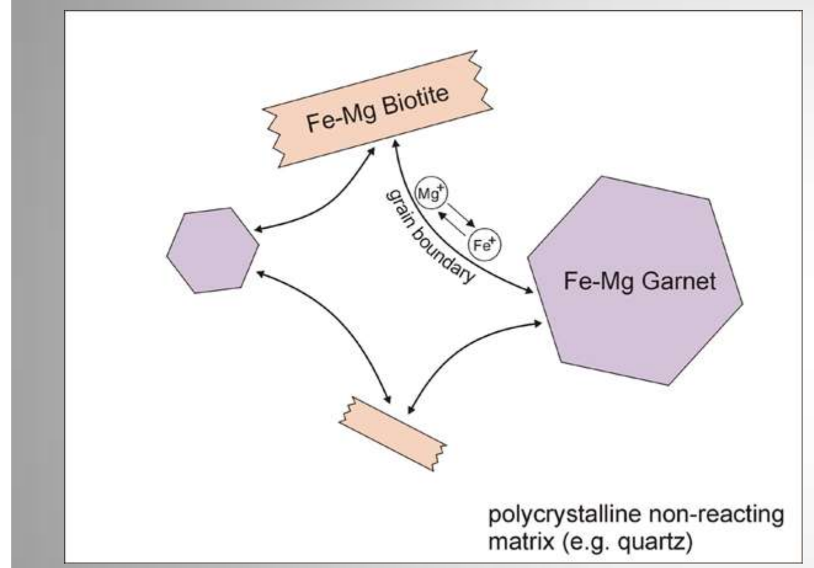


Continuous Reactions

Figure 26-8. Geologic map of a hypothetical field area in which metamorphosed pelitic sediments strike directly up metamorphic grade. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



Ion Exchange Reactions



- **Ion Exchange Reactions** involve chemical components being exchanged between phases, so compositions change, but modes remain the same
- No minerals disappear and no new minerals are produced

Ion Exchange Reactions

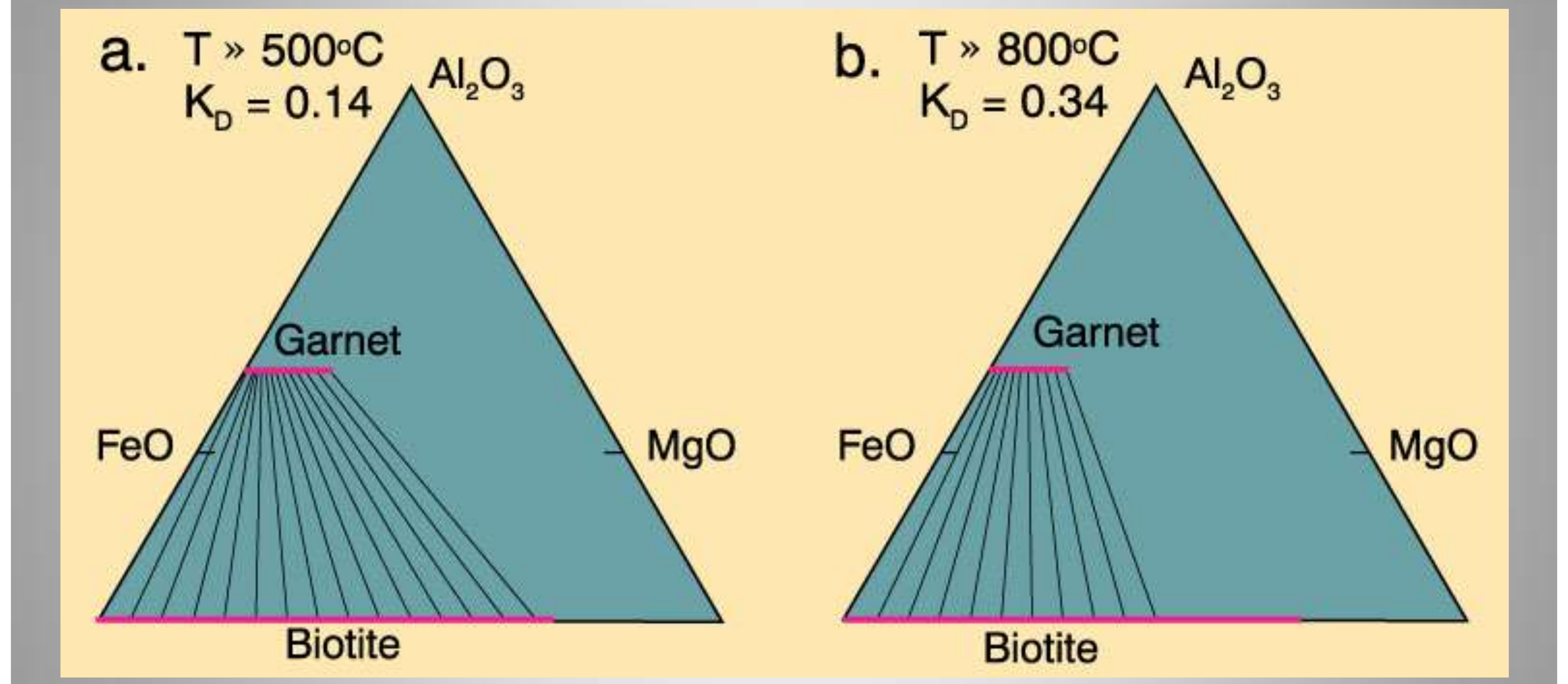
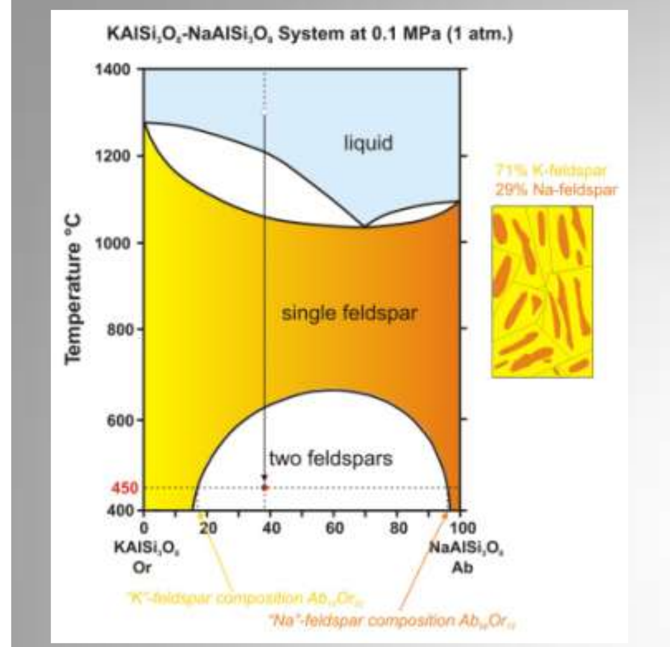
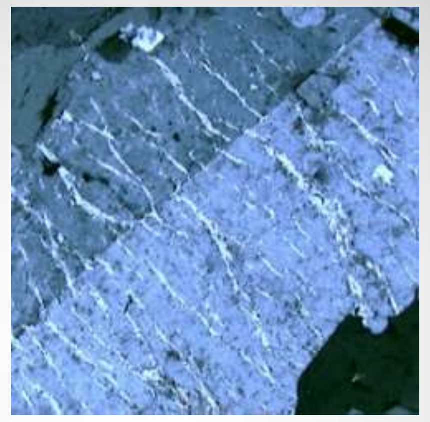


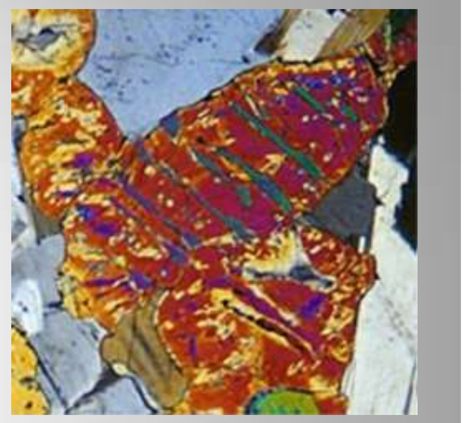
Figure 27-6. AFM projections showing the relative distribution of Fe and Mg in garnet vs. biotite at approximately 500°C (a) and 800°C (b). From Spear (1993) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1. MSA. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



Exsolution Reactions



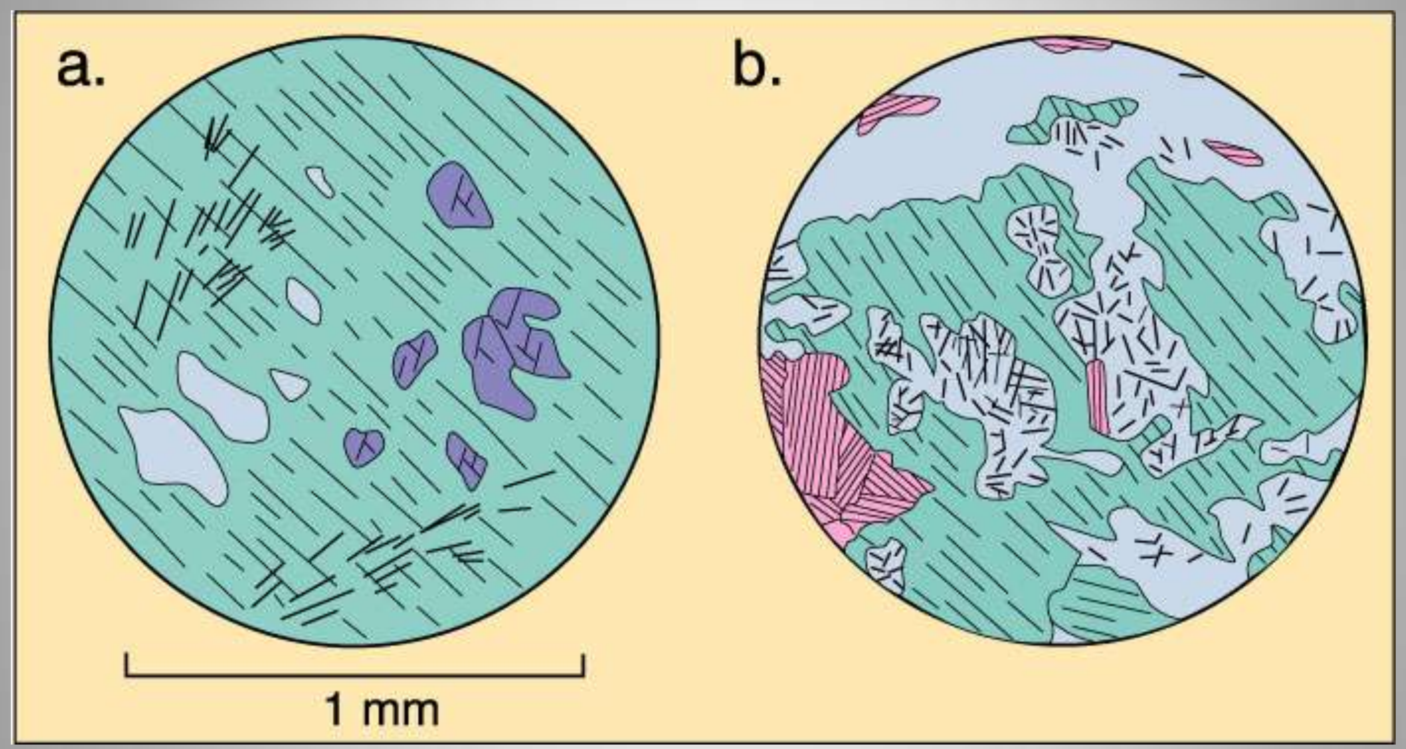
Perthite



Inverted Pigeonite

- Solid solutions frequently are not as compatible at low temperature as they are at high temperature.
- Differences in ionic radius that are accommodated when atoms are highly thermally agitated may result in unstable lattice deformations as the mineral cools.
- In such cases minerals segregate into discrete phases when they cool

Reaction Mechanisms: Ky↔Sil



Sketch from a photomicrograph showing small crystals of kyanite (purple) and quartz (blue) in a larger muscovite grain (green). Small crystals of fibrolitic sillimanite also occur in the muscovite. Glen Cova, Scotland. b. Sillimanite needles in quartz (blue) embaying muscovite (green). Pink crystals are biotite. Donegal, Ireland. After Carmichael (1969). *Contrib. Mineral. Petrol.*, 20, 244-267.

Reaction Mechanisms

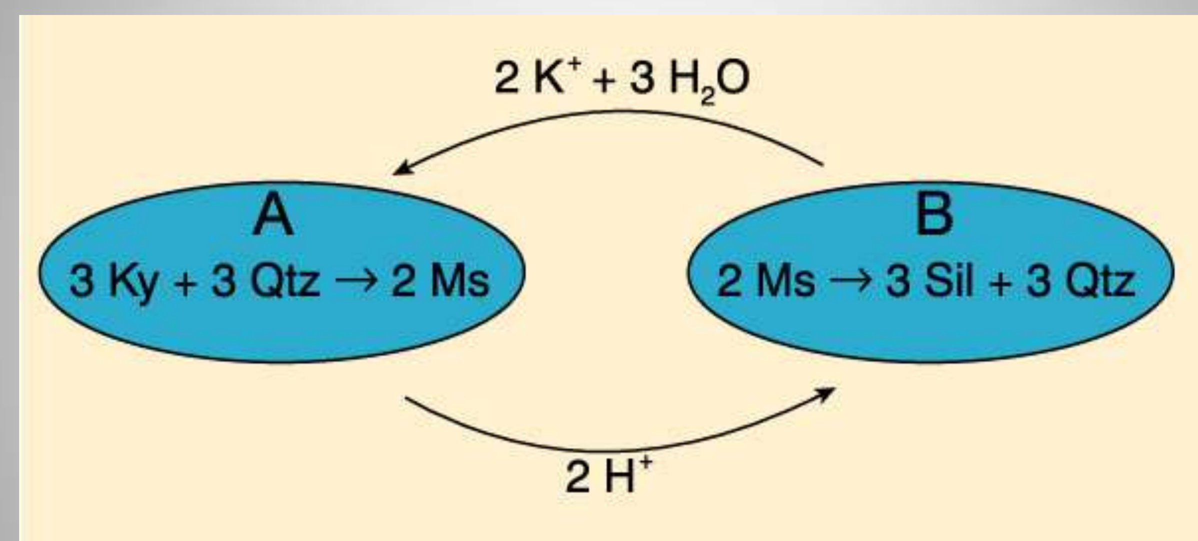


Figure 26-21. **A possible mechanism by which the Ky → Sil reaction can be accomplished while producing the textures illustrated in Figure 26-20a and b. The exchange of ions shown between the two local zones is required if the reactions are to occur. After Carmichael (1969).** ***Contrib. Mineral. Petrol.*****, 20, 244-267.**

Reaction Mechanisms

Figure 26-21. **An alternative mechanism by which the reaction Ky → Sil reaction can be accomplished while producing sillimanite needles associated with biotite with plagioclase occupying embayments in the biotite. The exchange of ions shown between the two local zones is required if the reactions are to occur. After Carmichael (1969).** ***Contrib. Mineral. Petrol.*****, 20, 244-267.**