

Chapter 28: Metamorphism of Pelitic Sediments

- **Mudstones** and **shales**: very fine grained mature clastic sediments derived from continental crust
- Characteristically accumulate in distal portions of a wedge of sediment off the continental shelf/slope
- Grade into coarser graywackes and sandy sediments toward the continental source
- Although begin as humble mud, metapelites represent a distinguished family of metamorphic rocks, because the clays are very sensitive to variations in temperature and pressure, undergoing extensive changes in mineralogy during progressive metamorphism

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- The mineralogy of pelitic sediments is dominated by fine **Al-K-rich phyllosilicates**, such as clays (montmorillonite, kaolinite, or smectite), fine white micas (sericite, paragonite, or phengite) and chlorite, all of which may occur as detrital or authigenic grains
- The phyllosilicates may compose more than 50% of the original sediment
- Fine **quartz** constitutes another 10-30%
- Other common constituents include feldspars (albite and K-feldspar), iron oxides and hydroxides, zeolites, carbonates, sulfides, and organic matter

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- Distinguishing chemical characteristics: **high Al_2O_3** and **K_2O** , and **low CaO**
- Reflect the high **clay** and **mica** content of the original sediment and lead to the dominance of **muscovite** and **quartz** throughout most of the range of metamorphism
- High proportion of micas → common development of **foliated** rocks, such as **slates**, **phyllites**, and **mica schists**
- The chemical composition of pelites can be represented by the system K_2O - FeO - MgO - Al_2O_3 - SiO_2 - H_2O (“KFMASH”)
- If we treat H_2O as mobile, the petrogenesis of pelites is represented well in AKF and A(K)FM diagrams

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Table 28-1. Chemical Compositions* of Shales and Metapelites

	1	2	3	4	5
SiO₂	64.7	64.0	61.5	65.9	56.3
TiO₂	0.80	0.81	0.87	0.92	1.05
Al₂O₃	17.0	18.1	18.6	19.1	20.2
MgO	2.82	2.85	3.81	2.30	3.23
FeO	5.69	7.03	10.0	6.86	8.38
MnO	0.25	0.10			0.18
CaO	3.50	1.54	0.81	0.17	1.59
Na₂O	1.13	1.64	1.46	0.85	1.86
K₂O	3.96	3.86	3.02	3.88	4.15
P₂O₅	0.15	0.15			
Total	100.00	100.08	100.07	99.98	96.94

* Reported on a volatile-free basis (normalized to 100%) to aid comparison.

1. "North American Shale Composite". Gromet *et al.* (1984). 2. Average of ~100 published shale and slate analyses (Ague, 1991). 3. Ave. pelite-pelagic clay (Carmichael, 1989). 4. Ave. of low-grade pelitic rocks, Littleton Fm, N.H. (Shaw, 1956). 5. Ave. of ~150 amphibolite facies pelitic rocks

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- Integrate principles and concepts we covered in previous chapters
- Important to keep in mind that first appearance and final disappearance of a particular mineral during progressive metamorphism in pelites is due to reactions that occur within the broader stability range of that mineral
- The ultimate stability (of a mineral) is governed by the bulk composition of the rock (typically the Al content or the Fe/Mg ratio) and reflect either continuous or discontinuous reaction

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- Examine progressive metamorphism of pelites at Medium P/T path – typical “Barrovian Sequence”
- Begin with chlorite zone of greenschist facies

Metamorphic Grade →

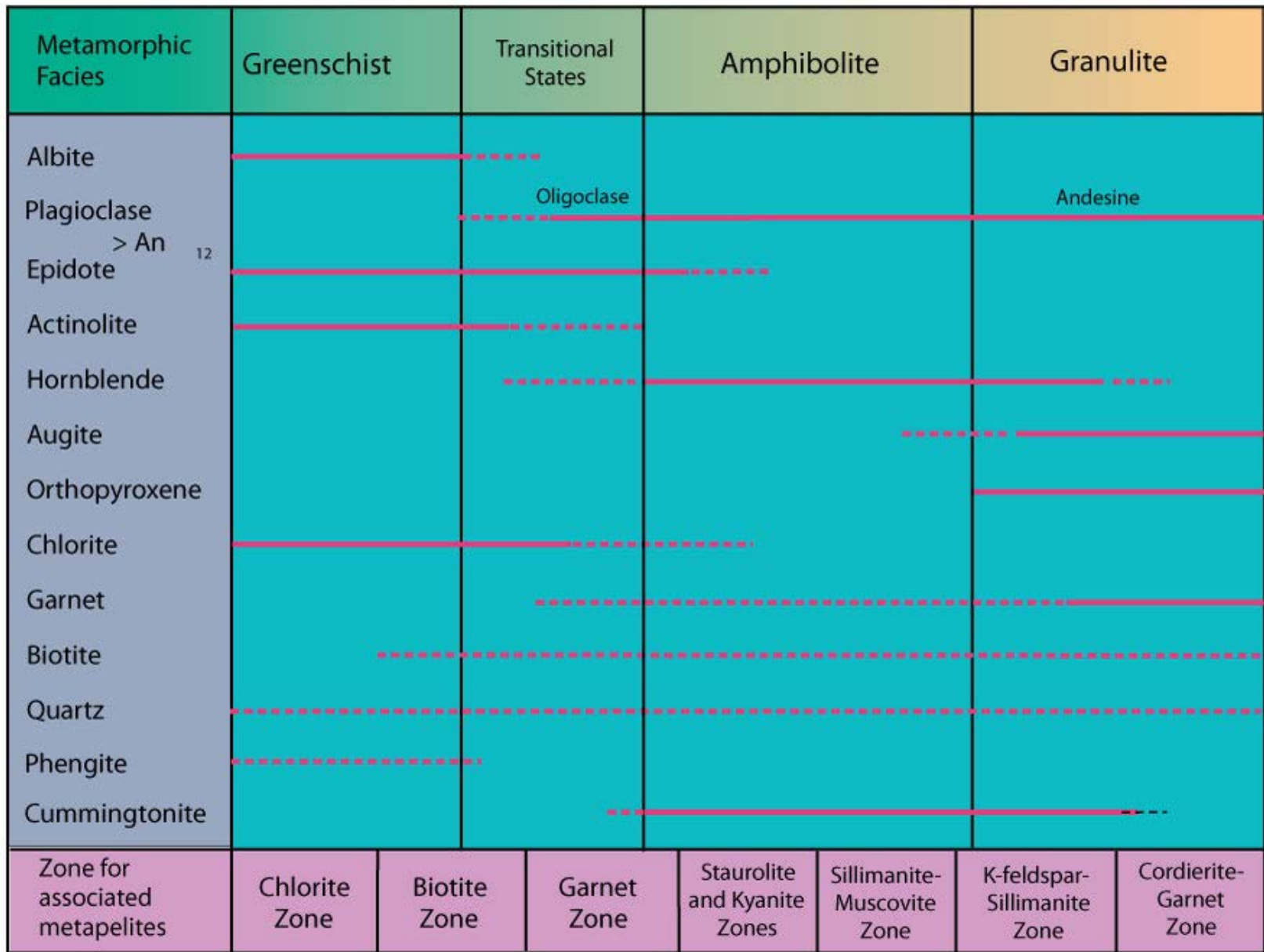


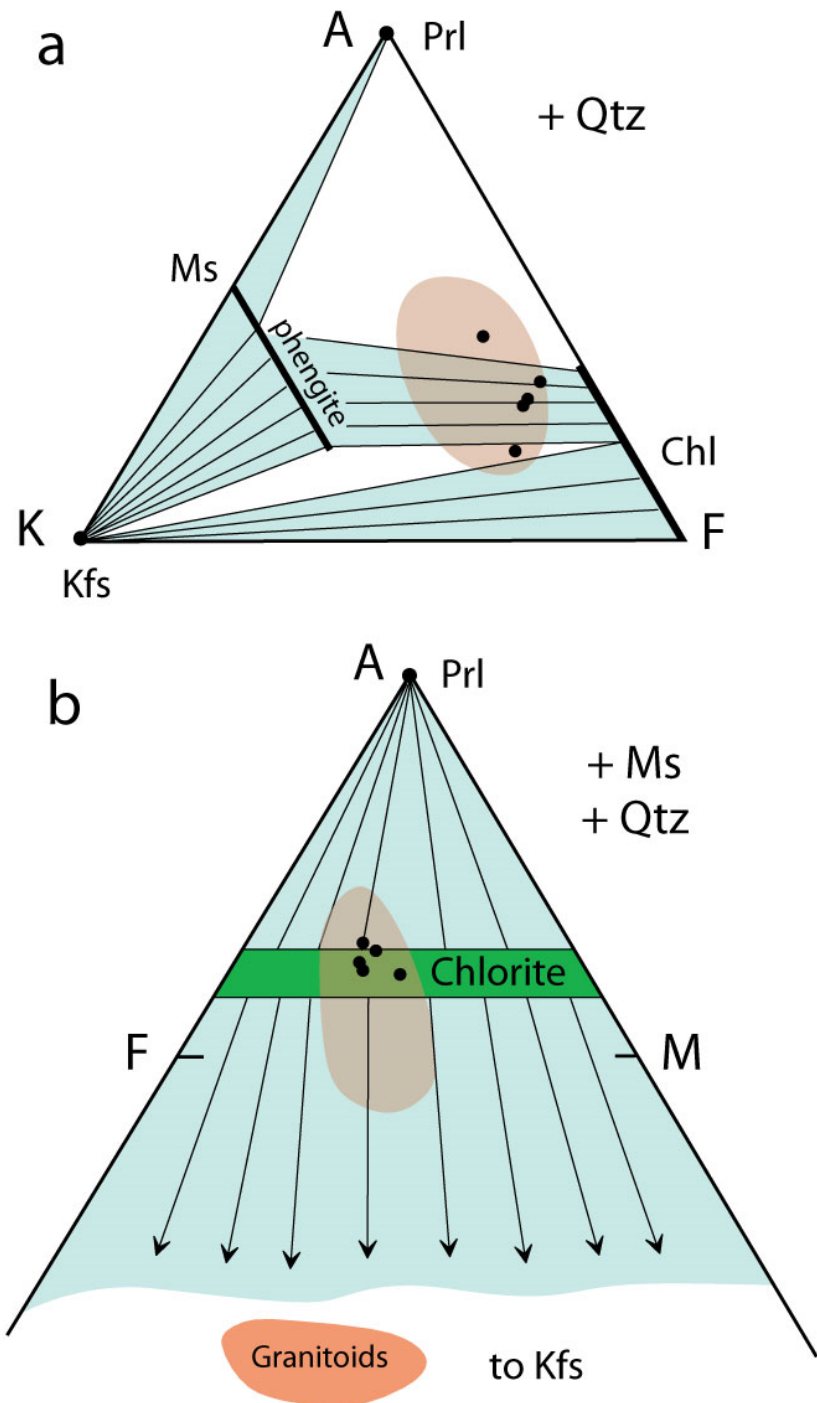
Fig. 25.10. Typical mineral changes that take place in metabasic rocks during progressive metamorphism in the medium P/T facies series. The approximate location of the pelitic zones of Barrovian metamorphism are included for comparison. Winter (2010) An Introduction to Igneous and Metamorphic Petrology.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

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- Chlorite zone – Greenschist Facies
- Difficult to attain equilibrium in experiments, so P-T conditions are not certain
- Temperature range is believed to be 350 – 450 ° C range

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Figure 28.1. AKF (using the Spear, 1993, formulation) and (b) AFM (projected from Ms) compatibility diagrams for pelitic rocks in the chlorite zone of the lower greenschist facies. Shaded areas represent the common range of pelite and granitoid rock compositions. Small black dots are the analyses from Table 28.1.



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- **Chlorite zone – Greenschist Facies**
- Based on the information provided in Figure 28.1, what are the common metamorphic mineral assemblages for pelites within the chlorite zone of the greenschist facies?
- Chlorite + Phengitic Muscovite + Quartz
- Chlorite + K-feldspar + Quartz (only stable for low Al-bearing rocks)
- Chlorite + Phengitic Muscovite + Pyrophyllite + Quartz (occurs in more Al-rich rocks)

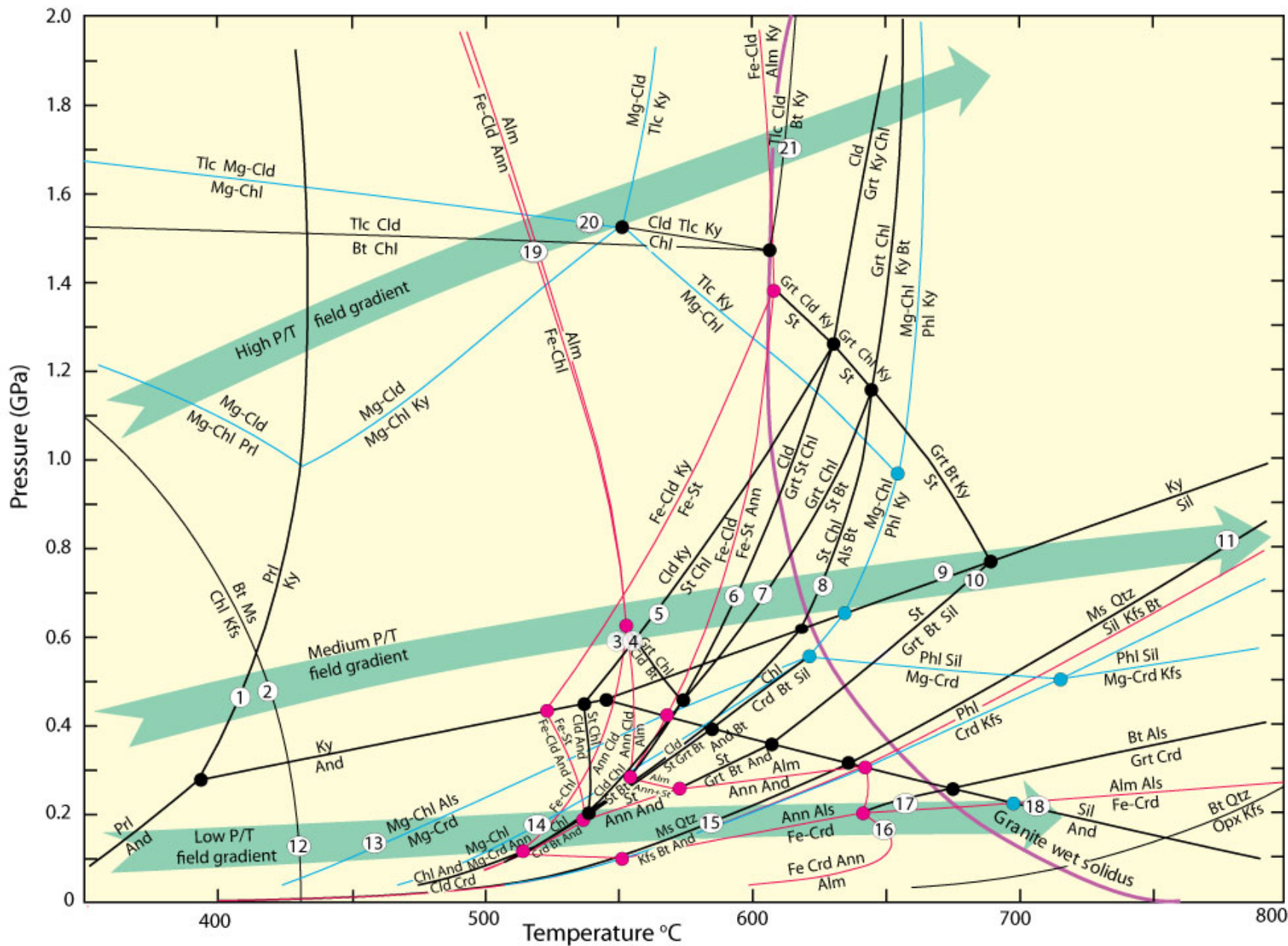


Fig. 28.2. Petrogenetic grid for the system KFMASH at $p_{H_2O} = p_{Total}$.

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- What is the reaction at point #1 in Fig. 28.2?
- Pyrophyllite = Kyanite
- $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2 = \text{Al}_2\text{SiO}_5$
- $\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2 = \text{Al}_2\text{SiO}_5 + 3\text{SiO}_2 + \text{H}_2\text{O}$
- Pyrophyllite = Kyanite + Quartz + Water

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- However, classical ‘Kyanite isograd’ occurs at much higher grades....
- Thus, Kyanite *can* occur in unusually Al-rich pelites at lower grades
- This feature reaffirms two critical points:
 - If we understand the reactions responsible for the isogrades and illustrate the mineral development with the use of appropriate compatibility diagrams, we are able to understand the nature of the mineralogical changes associated with metamorphism
 - The grade at which a mineral first appears in the field can vary, and need not conform to the classical ‘Barrovian Sequence’ in the Scottish Highlands

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- **The Biotite Zone – Greenschist Facies:**

Metamorphic Grade →

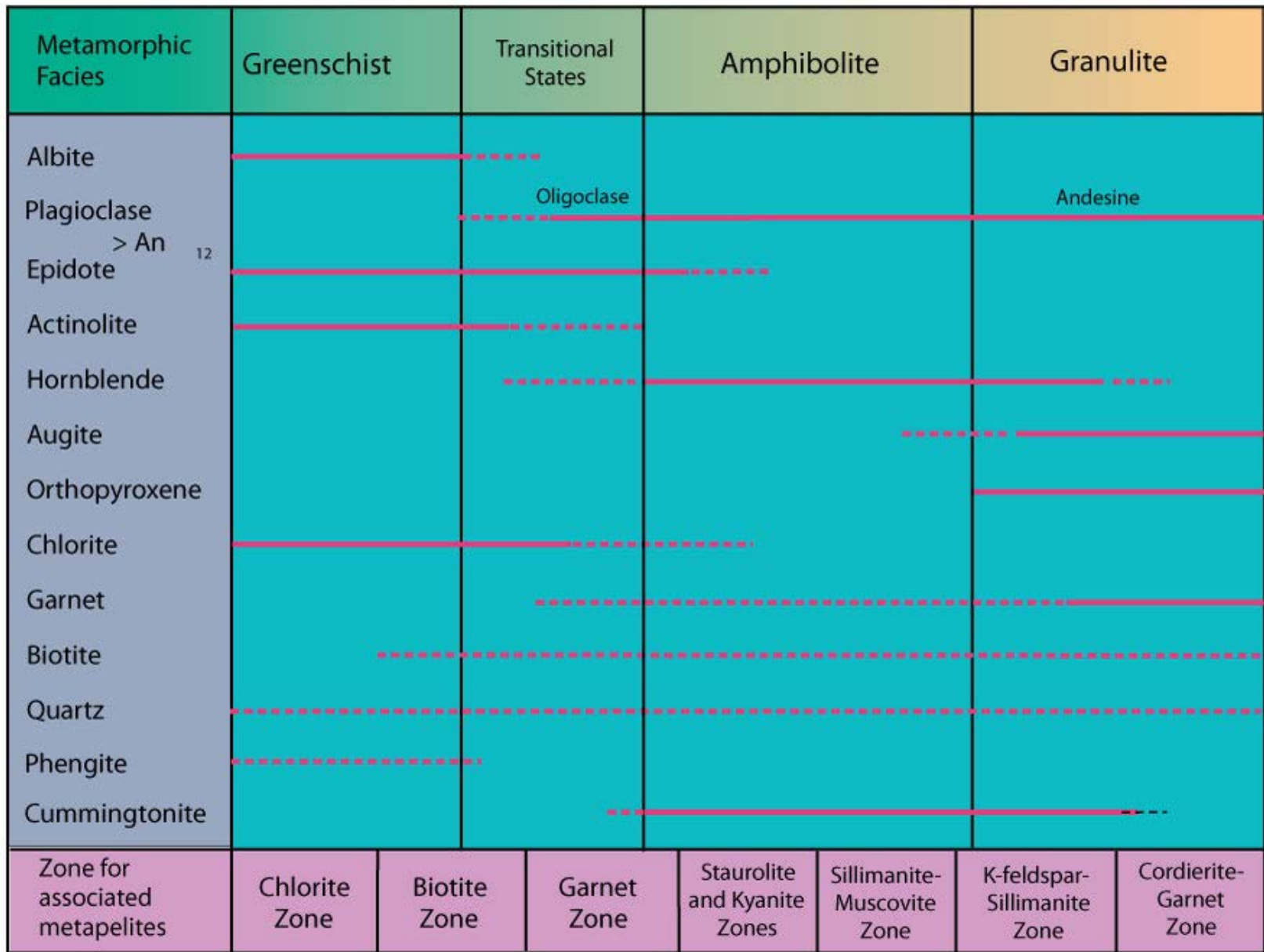


Fig. 25.10. Typical mineral changes that take place in metabasic rocks during progressive metamorphism in the medium P/T facies series. The approximate location of the pelitic zones of Barrovian metamorphism are included for comparison. Winter (2010) An Introduction to Igneous and Metamorphic Petrology.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

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- **The Biotite Zone – Greenschist Facies:**
- Many reactions produce biotite

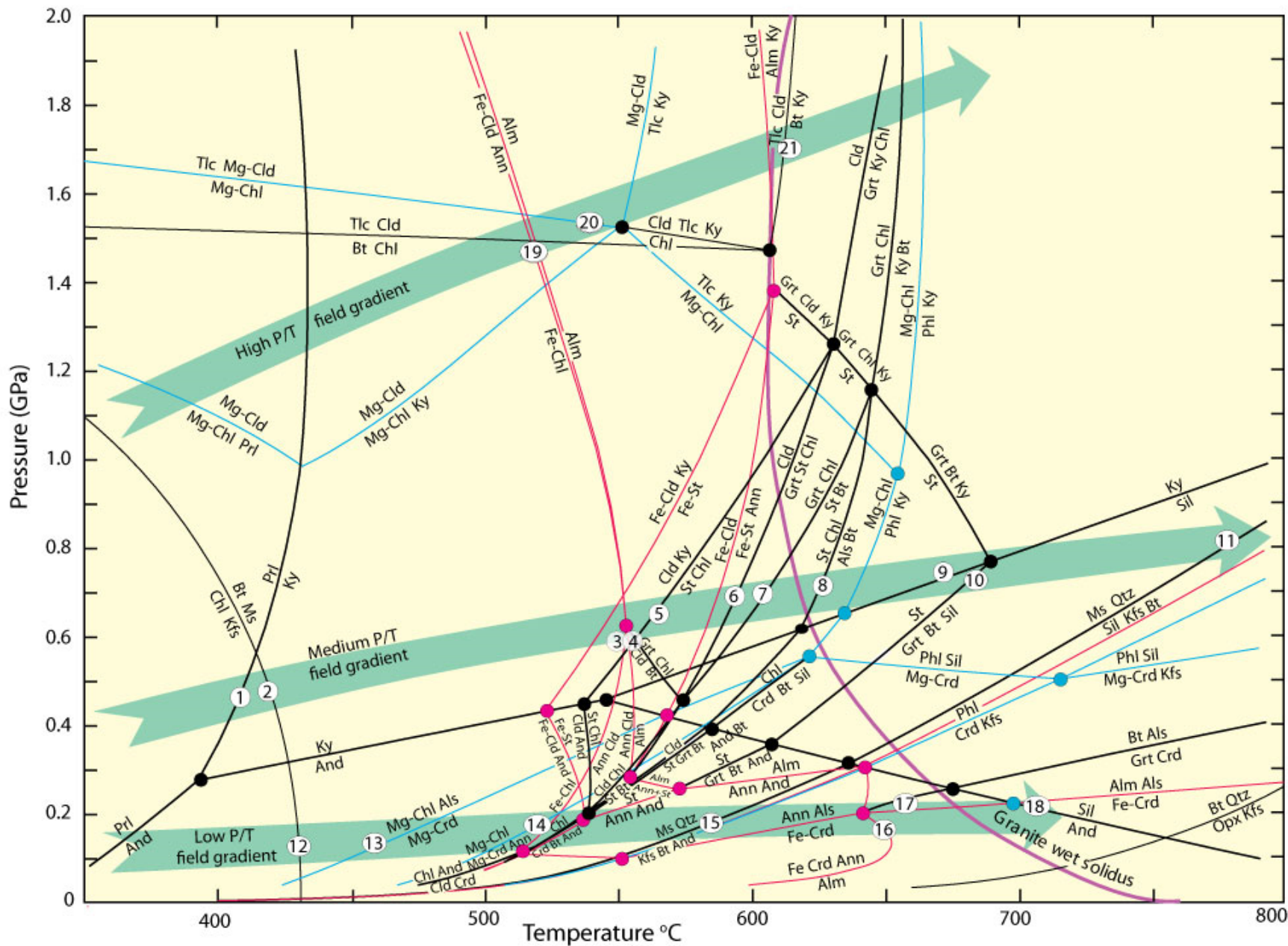


Fig. 28.2. Petrogenetic grid for the system KFMASH at $p_{H_2O}=p_{Total}$.

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- **The Biotite Zone – Greenschist Facies:**
- Reaction at point #2?
- Chlorite + K-feldspar = Biotite + Muscovite +
(Quartz + H₂O)

Typically, more chlorite is present than K-spar, so this reaction typically marks the loss of K-spar

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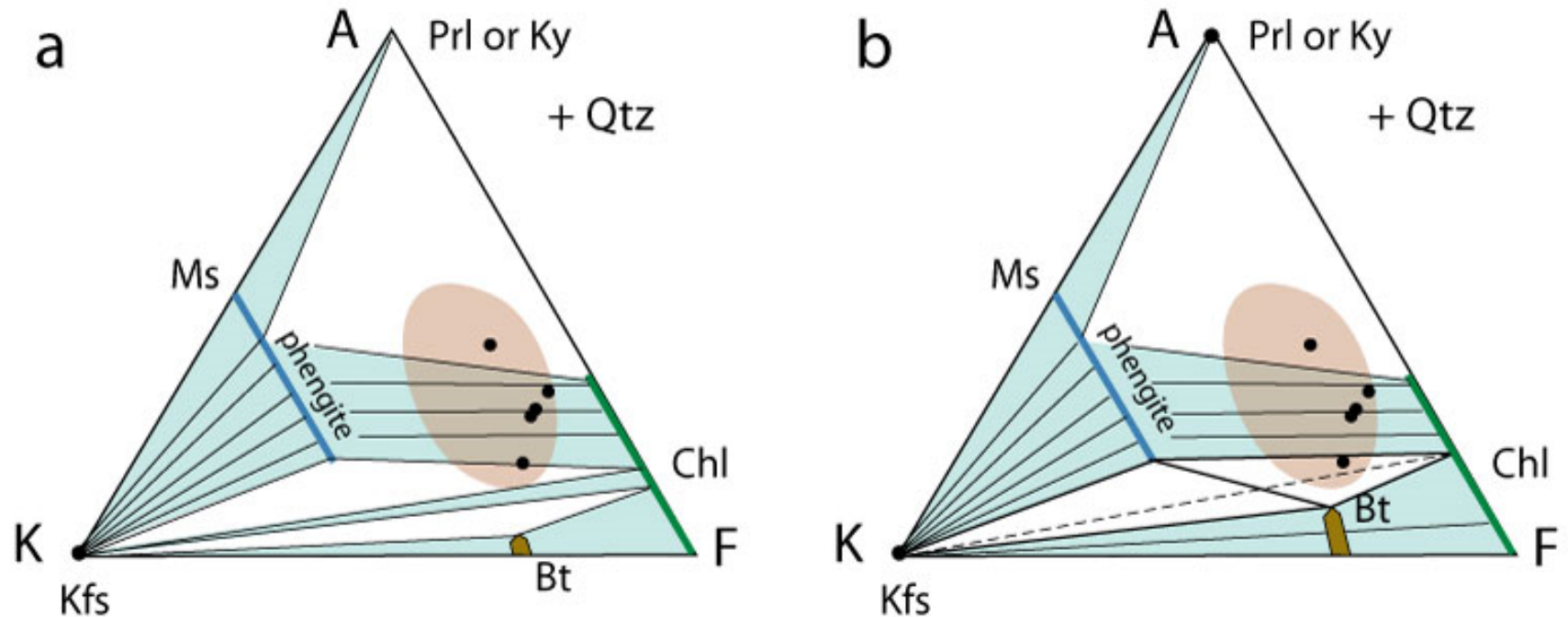


Figure 28.3. Greenschist facies AKF compatibility diagrams (using the Spear, 1993, formulation) showing the biotite-in isograd reaction as a “tie-line flip.” In (a), below the isograd, the tie-lines connecting chlorite and K-Feldspar shows that the mineral pair is stable. As grade increases the Chl-Kfs field shrinks to a single tie-line. In (b), above the isograd, biotite + phengite is now stable, and chlorite + K-feldspar are separated by the new biotite-phengite tie-line, so they are no longer stable together. Only the most Al-poor portion of the shaded natural pelite range is affected by this reaction. Note (Fig. 28.2) that Prl or Ky may be stable, depending on pressure. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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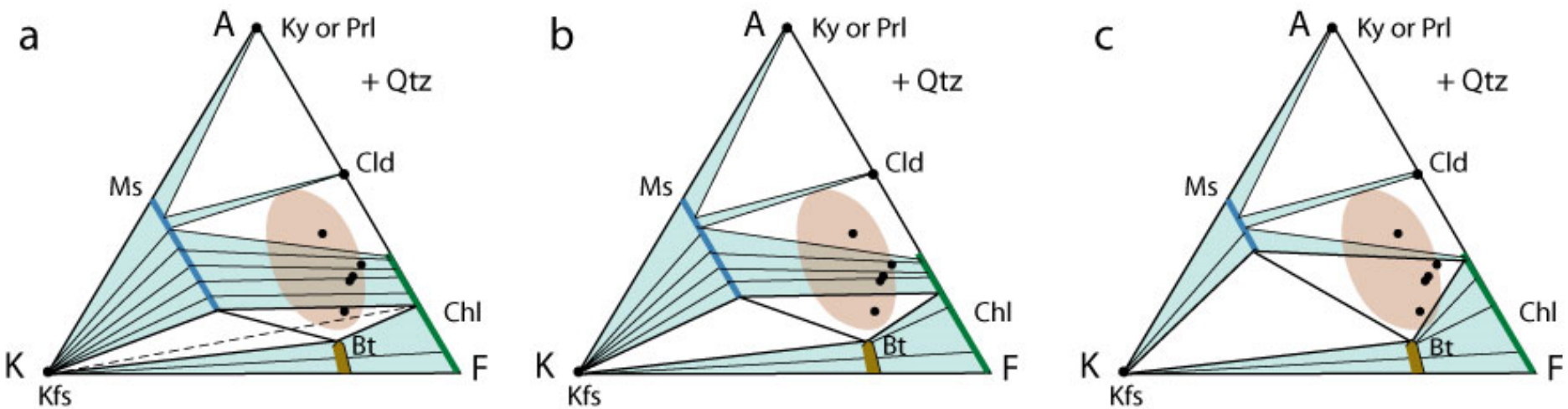


Figure 28.4. A series of AKF compatibility diagrams (using the Spear, 1993, formulation) illustrating the migration of the Ms-Bt-Chl and Ms-Kfs-Bt sub-triangles to more Al-rich compositions via continuous reactions in the **biotite zone of the greenschist facies** above the biotite isograd. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **The Biotite Zone – Greenschist Facies:**
- Stability of Chloritoid (Cld) (+kyanite) over that of chlorite is preferable in rocks with **high-Al** and **high Fe/Mg ratio**
- Chloritoid not present in Scottish Highlands but common phase in pelites elsewhere
- Reaction at point #3 in Fig. 28.2:
- $\text{Fe-Chl (+Ms)} = \text{Annite} + \text{Fe-Cld (+Qtz + H}_2\text{O)}$

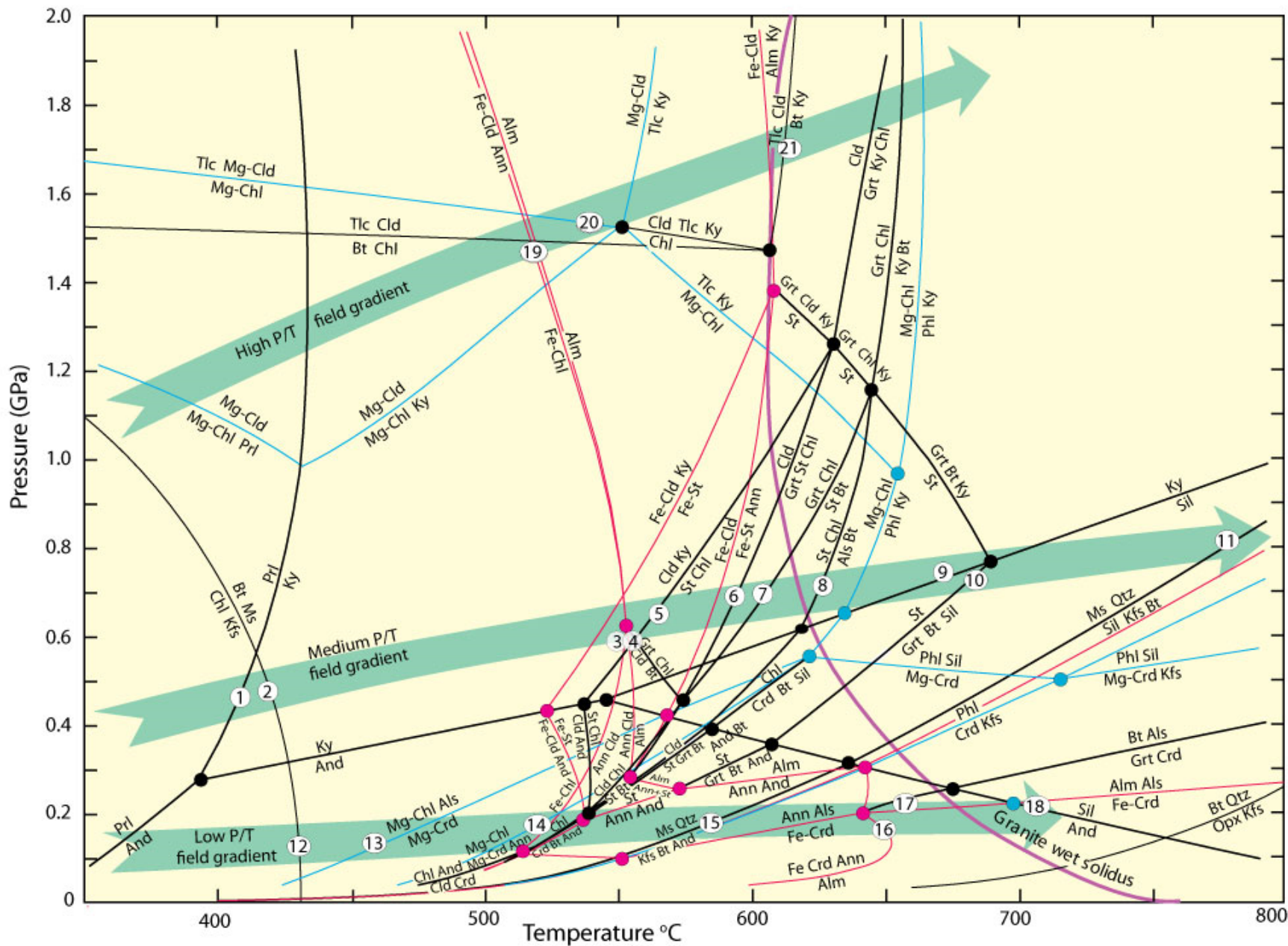


Fig. 28.2. Petrogenetic grid for the system KFMASH at $p_{H_2O}=p_{Total}$.

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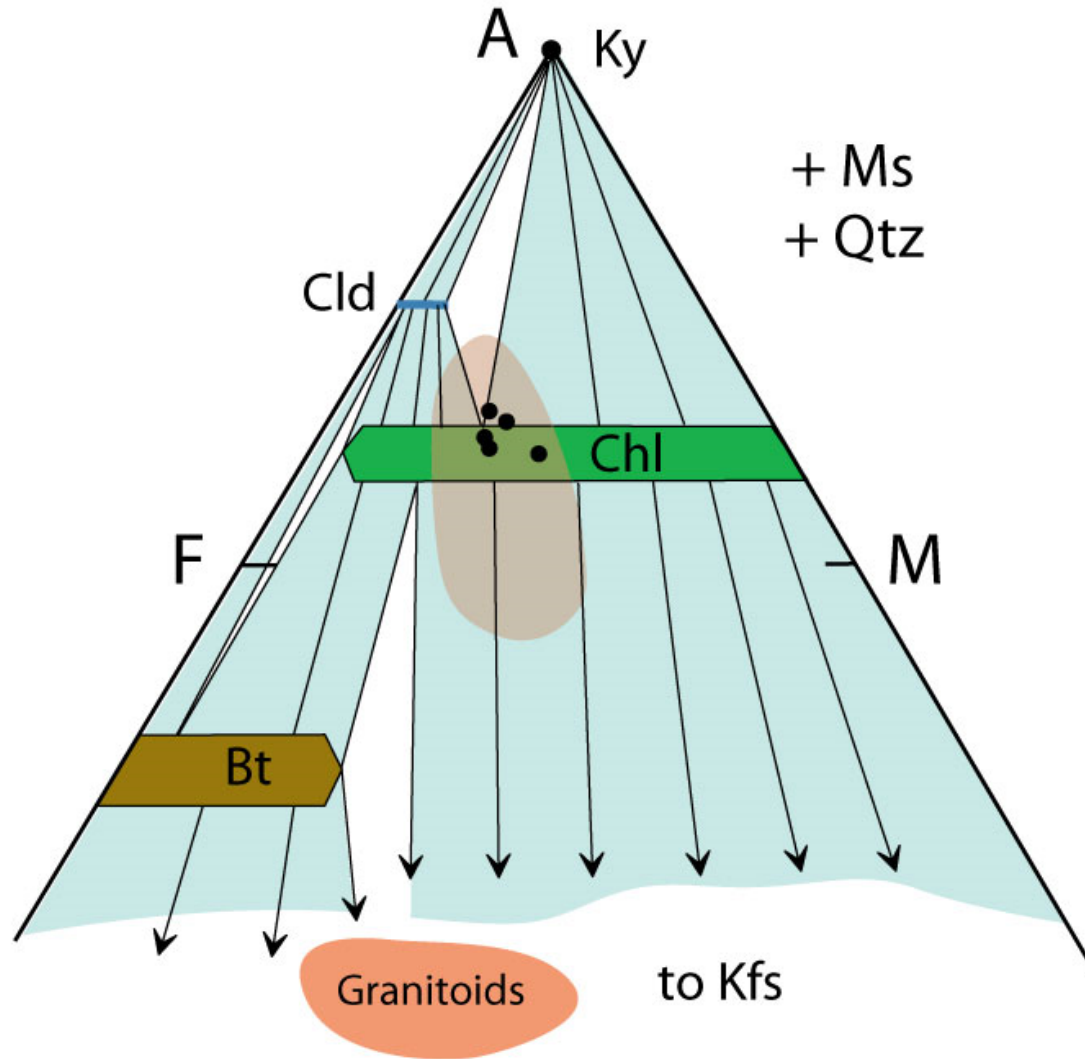


Figure 28.5. AFM compatibility diagram (projected from Ms) for the biotite zone, greenschist facies, above the chloritoid isograd. The compositional ranges of common pelites and granitoids are shaded. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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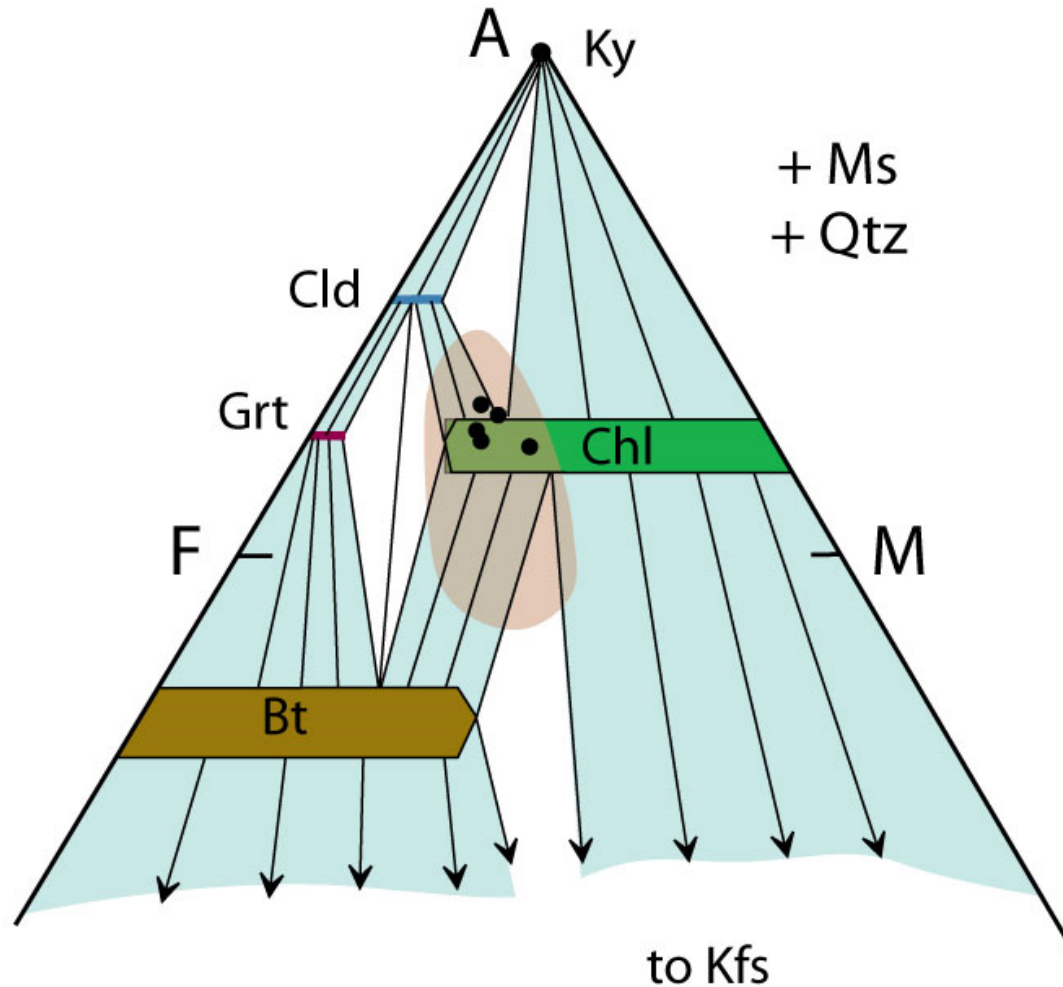


Figure 28.6. AFM compatibility diagram (projected from Ms) for the **upper biotite zone, greenschist facies**. Although garnet is stable, it is limited to unusually Fe-rich compositions, and does not occur in natural pelites (shaded). Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **The Garnet Zone – Transitional-Amphibolite Facies:**

Metamorphic Grade →

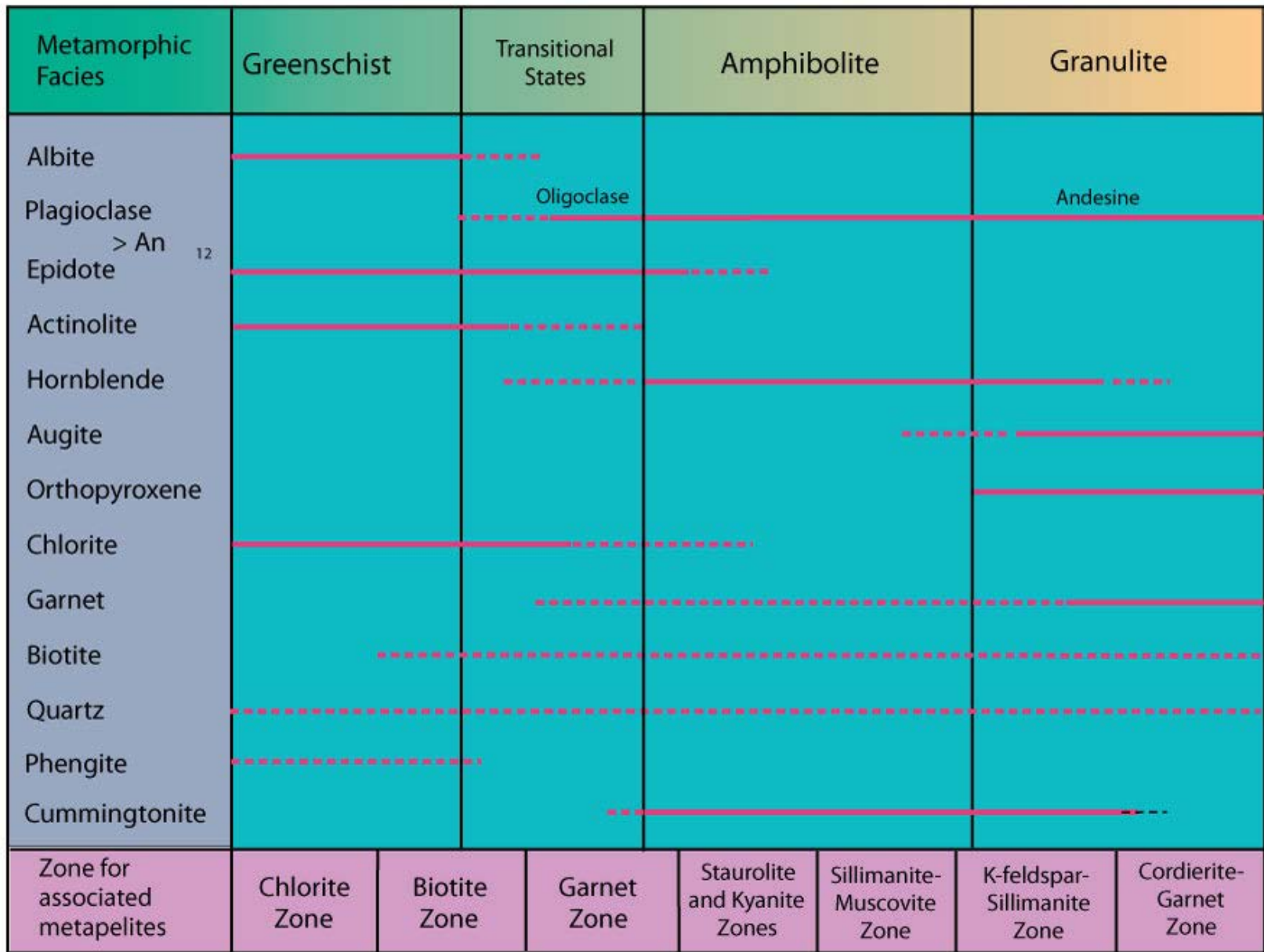


Fig. 25.10. Typical mineral changes that take place in metabasic rocks during progressive metamorphism in the medium P/T facies series. The approximate location of the pelitic zones of Barrovian metamorphism are included for comparison. Winter (2010) An Introduction to Igneous and Metamorphic Petrology.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

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- **The Garnet Zone – Transitional-Amphibolite Facies:**
- The reaction for the breakdown of Fe-chlorite to Fe-garnet (almandine) (+ H₂O)– near reaction #3 on petrogenetic grid (Fig. 28.2)
- Fe-(low-Al)-Chl (+ Ms + Qz) = Alm + Annite (+ H₂O)
- If Chloritoid is present, then almandine may be created by the reaction:
- Fe-Cld + Ann (+ Qtz) = Alm (+ Ms + H₂O)

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- **The Garnet Zone – Transitional-Amphibolite Facies:**
- Garnet may also develop in some natural pelites due to the reaction:
 - $\text{Cld} + \text{Bt} (+ \text{Qtz} + \text{H}_2\text{O}) = \text{Grt} + \text{Chl} (+\text{Ms})$
- Depicted at point #4 in Fig. 28.2, and this marks the garnet isograd for some Fe-rich natural pelites in which chloritoid is present
- This reaction represents an *unusual prograde hydration* reaction

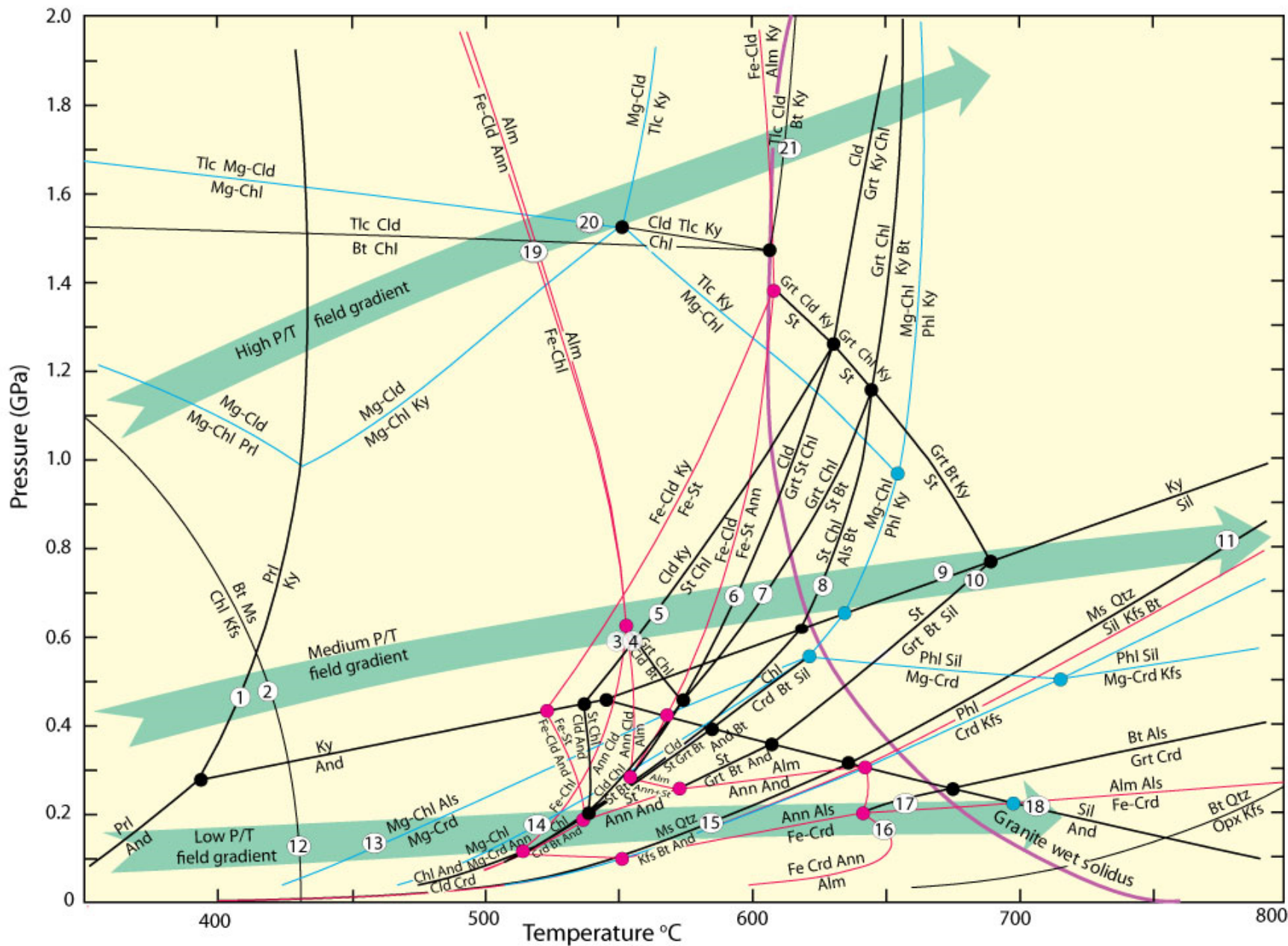


Fig. 28.2. Petrogenetic grid for the system KFMASH at $p_{H_2O}=p_{Total}$.

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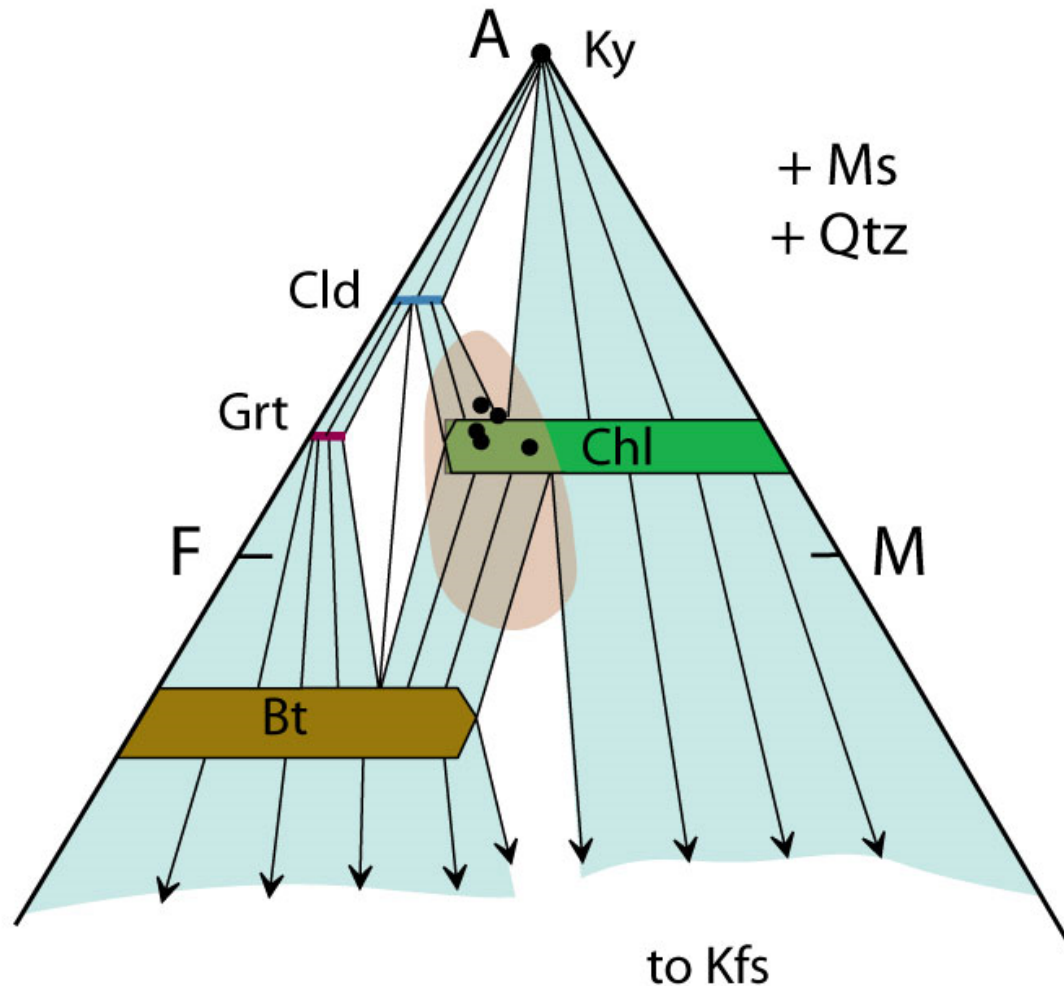


Figure 28.6. AFM compatibility diagram (projected from Ms) for the **upper biotite zone, greenschist facies**. Although garnet is stable, it is limited to unusually Fe-rich compositions, and does not occur in natural pelites (shaded). Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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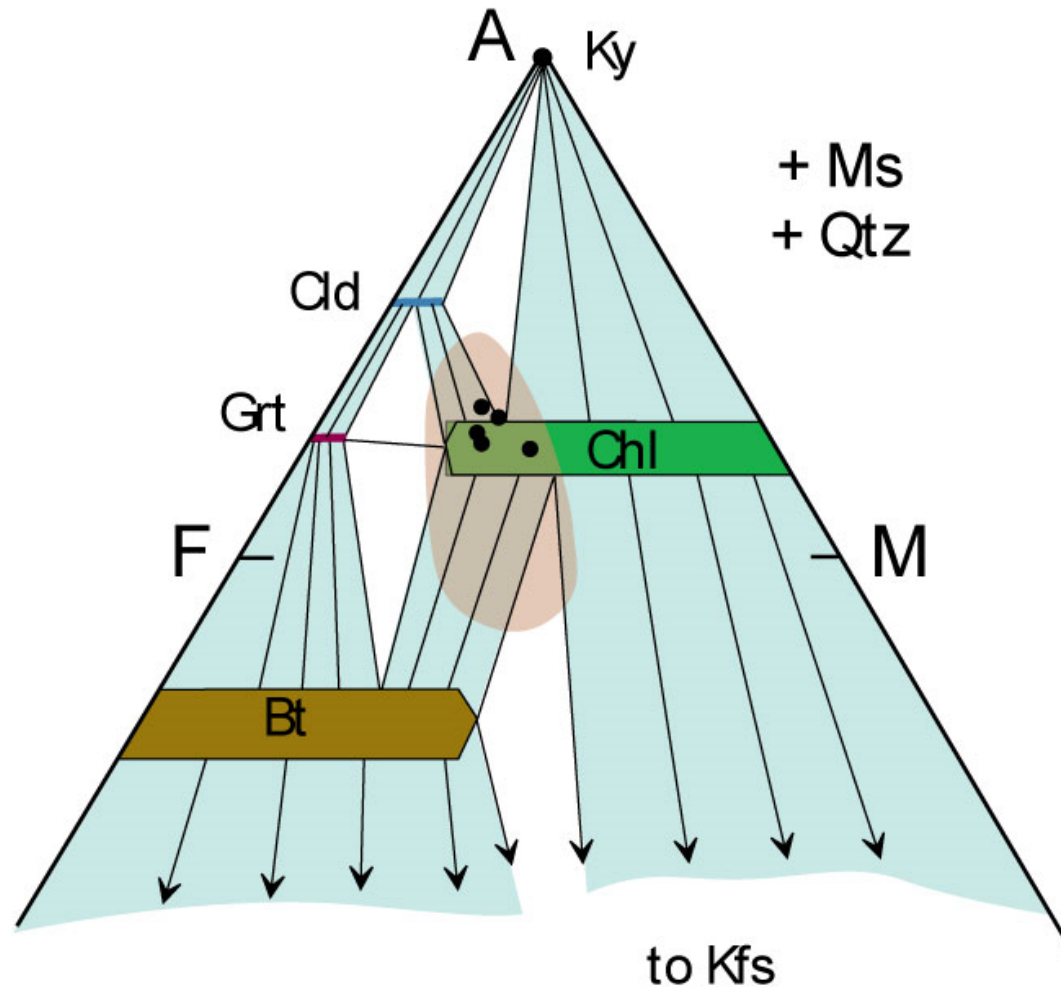


Figure 28.7. AFM compatibility diagram (projected from Ms) for the **garnet zone**, transitional to the amphibolite facies, showing the tie-line flip associated with reaction (28.8) (compare to Figure 28.6) which introduces garnet into the more Fe-rich types of common (shaded) pelites. After Spear (1993) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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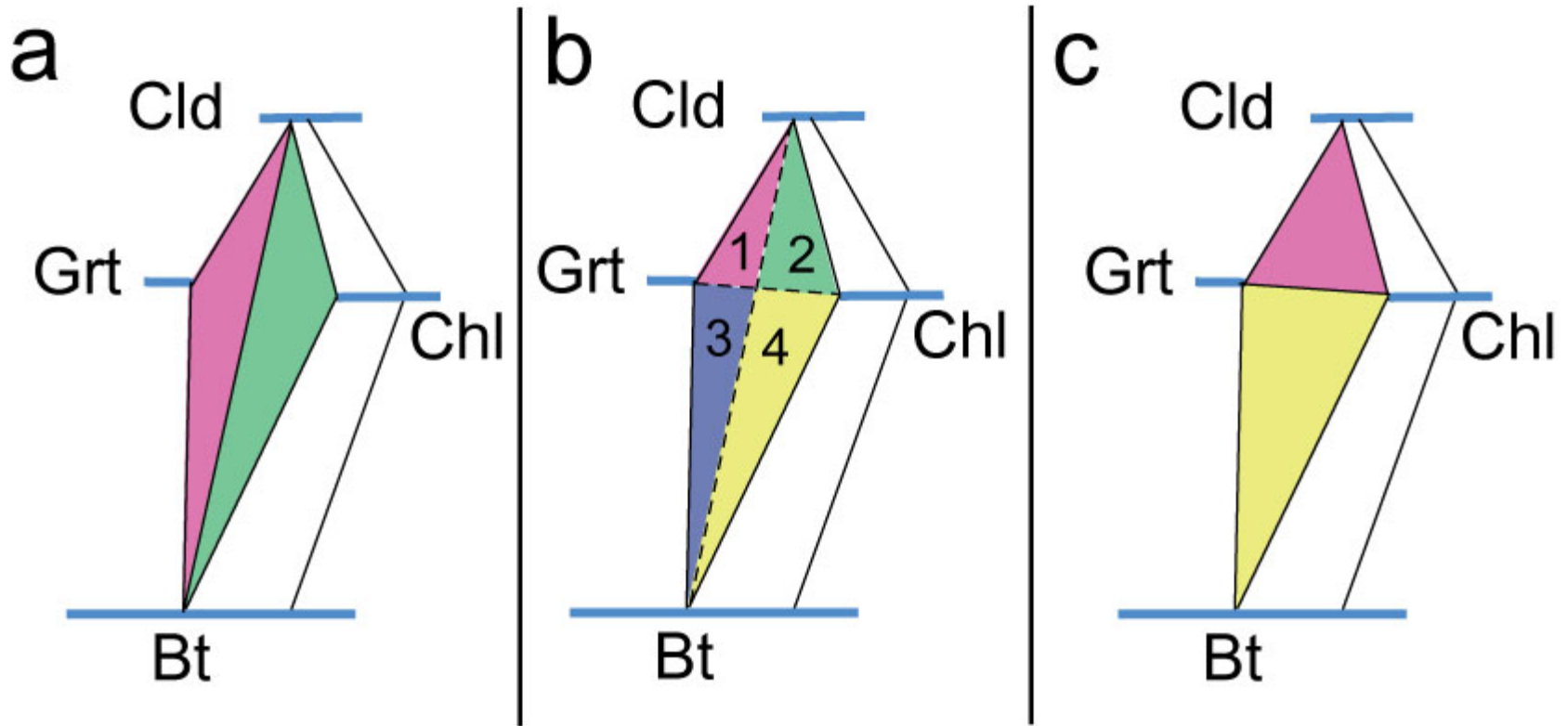


Figure 28.8. An expanded sketch of the Grt-Cld-Chl-Bt quadrilateral from Figures 28.6 and 28.7 illustrating the tie-line flip of reaction (28.7). **a.** Before flip. **b.** During flip (at the isograd). **c.** After flip (above the isograd). Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **The Garnet Zone – Transitional-Amphibolite Facies:**
- **Important point***** - *The minerals that are developed or lost in a rock at the isograd thus depend upon the bulk composition, and do not reflect the absolute stability limit of any mineral involved.*

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- **The Staurolite Zone – Amphibolite Facies:**
- Fe-staurolite (Fe-St) – becomes stable by a reaction between Fe-chloritoid and kyanite – just above point #4 in Figure 28.2
- In KFMASH, staurolite is produced by the next reaction that is crossed along the medium P/T trajectory in the petrogenetic grid – i.e., **point #5 in Fig. 28.2**, which is:
 - $\text{Cld} + \text{Ky} = \text{St} + \text{Chl} (+ \text{Qtz} + \text{H}_2\text{O})$ (Rxn 28.9 in textbook)

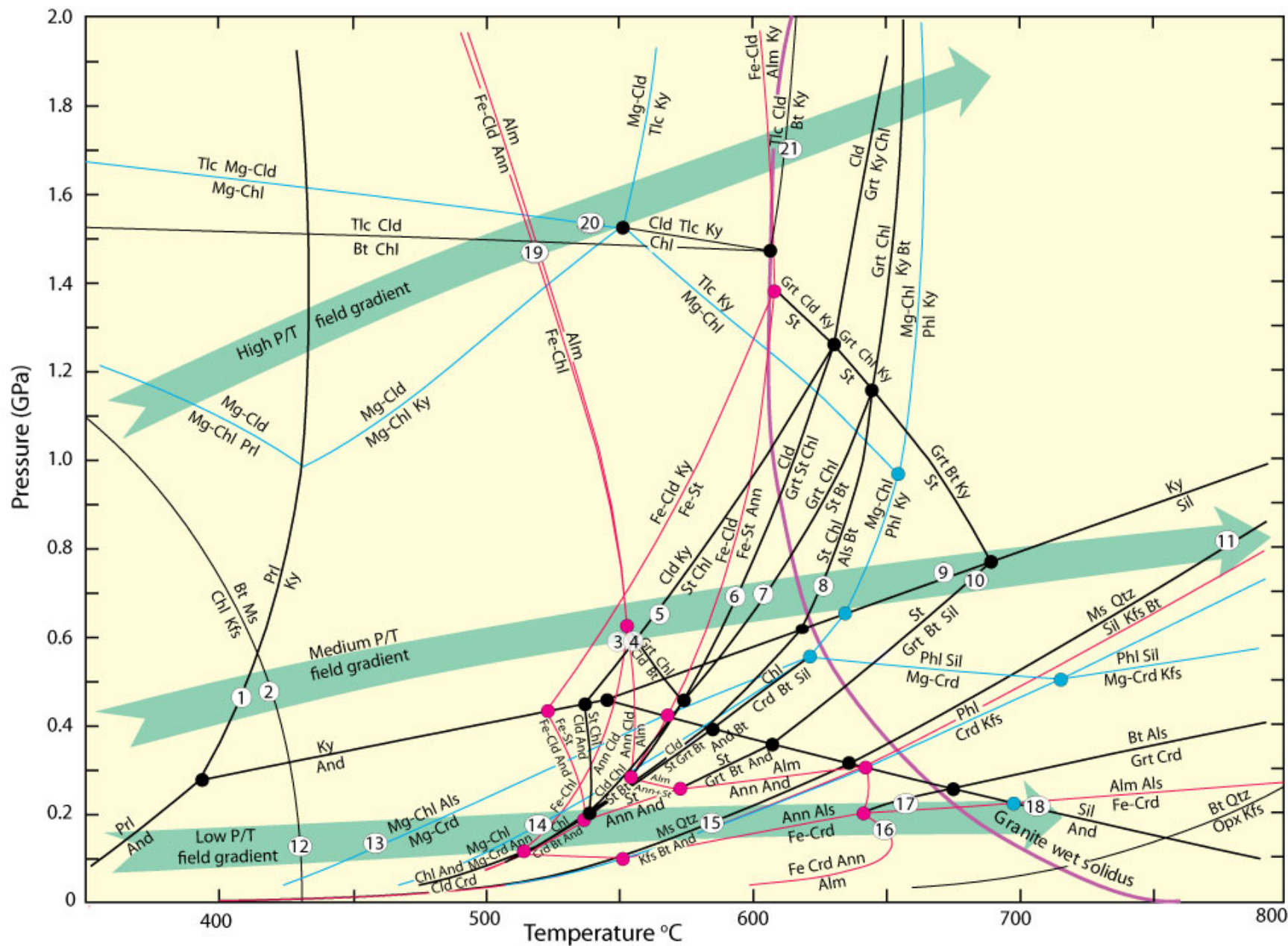


Fig. 28.2. Petrogenetic grid for the system KFMASH at $p_{H_2O} = p_{Total}$.

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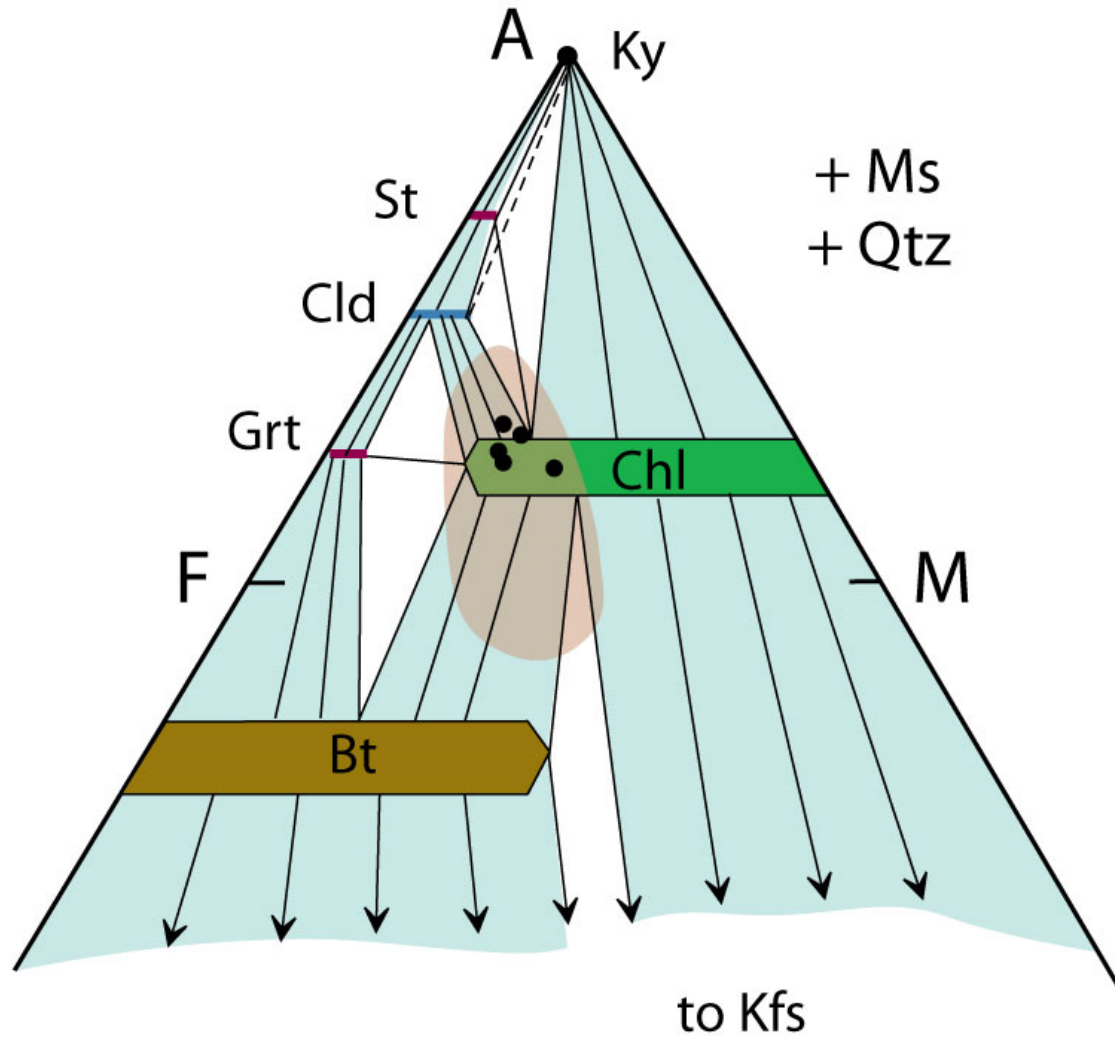


Figure 28.9. AFM compatibility diagram (projected from Ms) in the **lower staurolite zone of the amphibolite facies**, showing the change in topology associated with reaction (28.9) in which the lower-grade Cld-Ky tie-line (dashed) is lost and replaced by the St-Chl tie-line. This reaction introduced staurolite to only a small range of Al-rich metapelites. After Spear (1993) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **The Stauroilite Zone – Amphibolite Facies:**
- However, stauroilite may not form if pelites are Al-poor, and then technically still in garnet zone
- Continue prograde metamorphism, and at **point #6 in Fig. 28.2**, which is:
 - $\text{Cld (+ Qtz)} = \text{Grt} + \text{Chl} + \text{St} + \text{H}_2\text{O}$ (Rxn 28.11 in textbook)

(chloritoid is consumed)

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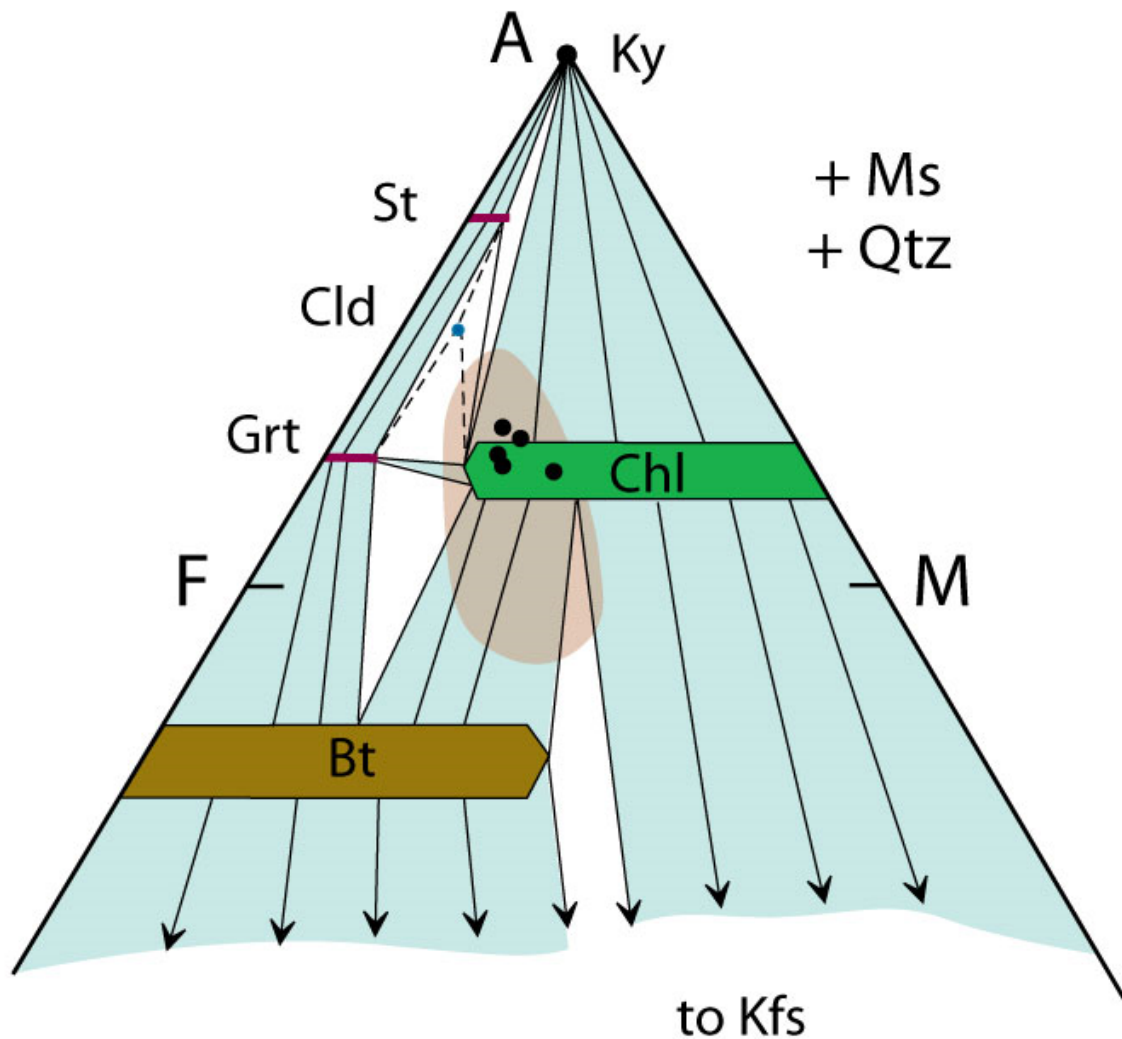


Figure 28.10. AFM compatibility diagram (projected from Ms) in the **staurolite zone of the amphibolite facies**, showing the change in topology associated with the terminal reaction (28.11) in which chloritoid is lost (lost tie-lines are dashed), yielding to the Grt-St-Chl sub-triangle that surrounds it. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **The Staurolite Zone – Amphibolite Facies:**
- Reactions that lose a phase entirely from a compatibility diagram, rather than simply rearrange (flip) tie-lines, are referred to as *terminal* reactions. Thus, rxn 28.11 is a terminal reaction for chloritoid.
- However, please remember that quartz must be present in excess for chloritoid to be terminated; however, this is usually not a problem since quartz is generally plentiful in metapelites!

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- **The Staurokite Zone – Amphibolite Facies:**
- Staurokite can also be introduced into most pelites by the reaction:
- $\text{Grt} + \text{Chl} (+ \text{Ms}) = \text{St} + \text{Bt} (+ \text{Qtz} + \text{H}_2\text{O})$ (Rxn 28.12 in textbook)
- This is encountered at **point #7 in Figure 28.2** (~610 ° C).
- This produces a tie-line ‘flip’ in AFM diagram (Fig. 28.11).

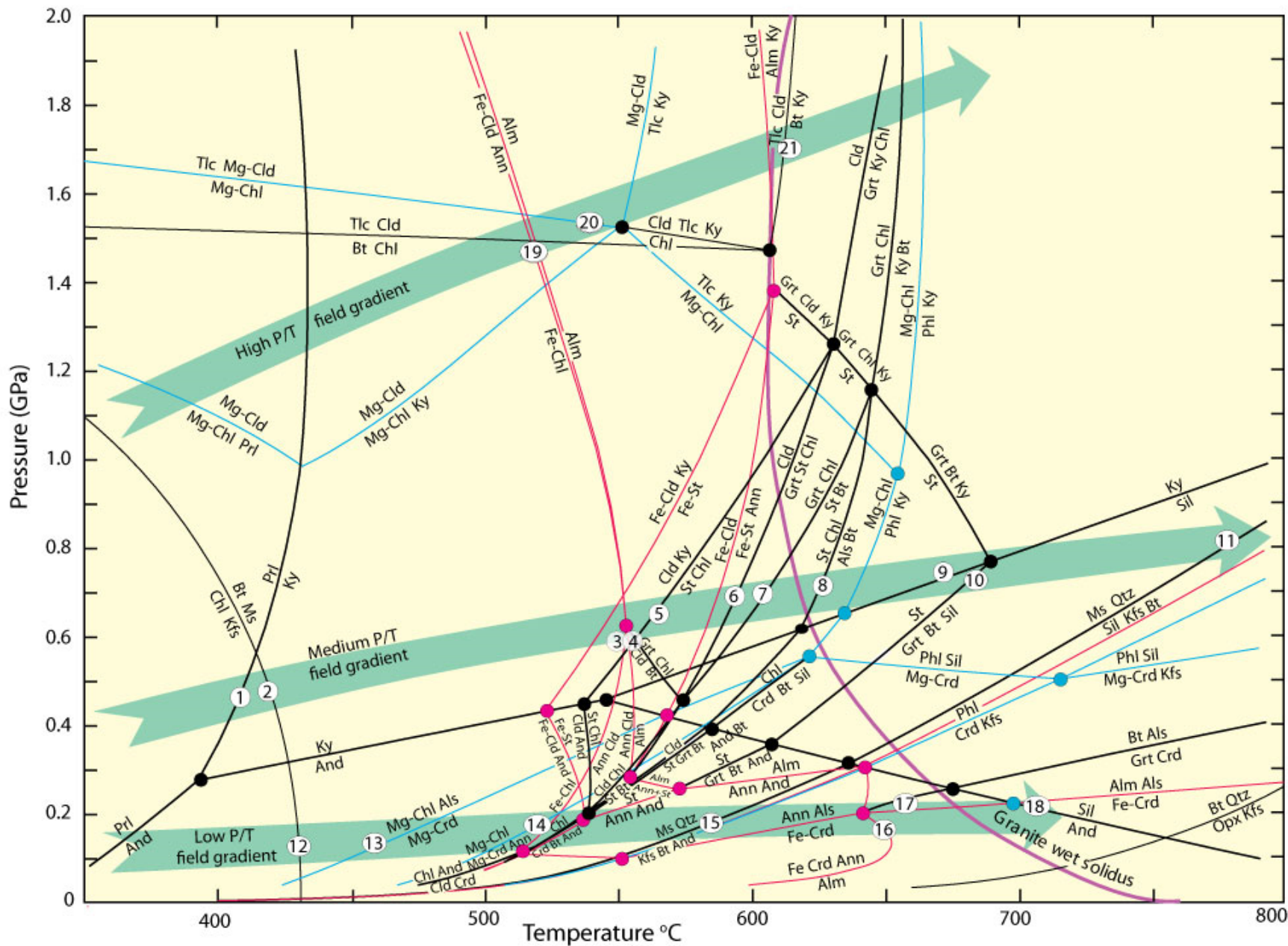


Fig. 28.2. Petrogenetic grid for the system KFMASH at $p_{H_2O} = p_{Total}$.

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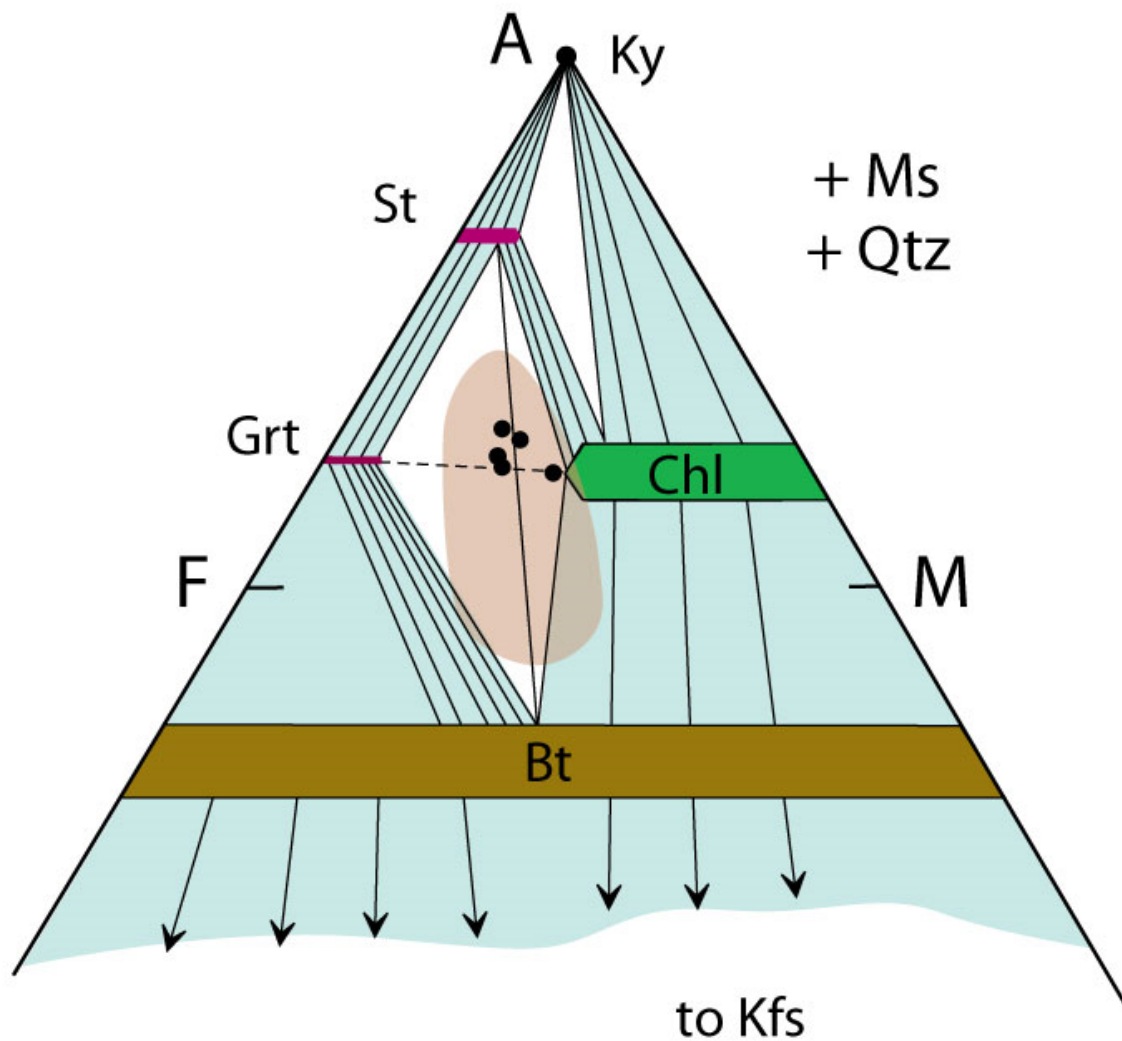


Figure 28.11. AFM compatibility diagram (projected from Ms) for the **staurolite zone, amphibolite facies**, showing the tie-line flip associated with reaction (28.12) which introduces staurolite into many low-Al common pelites (shaded). After Carmichael (1970) *J. Petrol.*, 11, 147-181. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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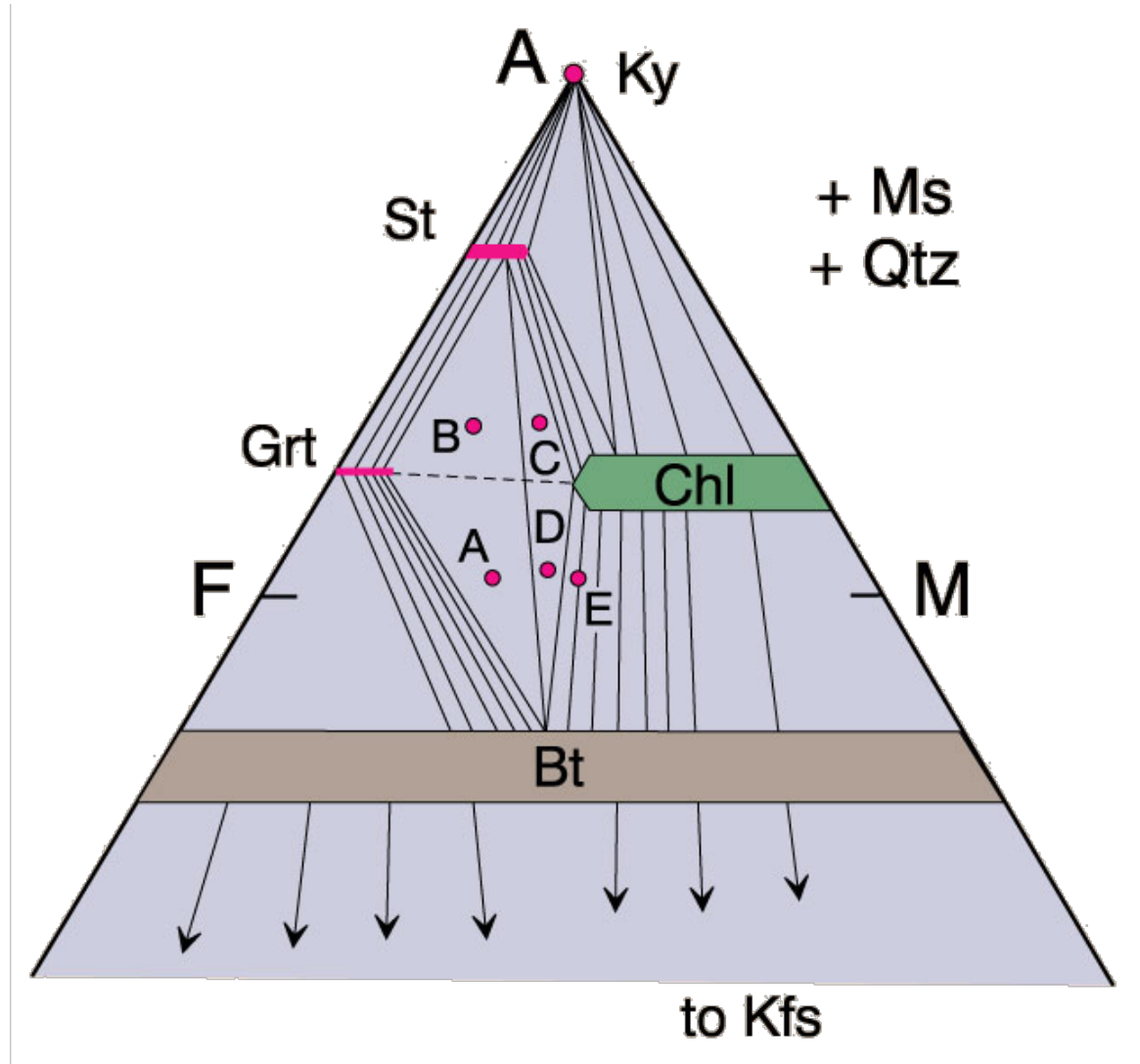


Figure 28.11. AFM compatibility diagram (projected from Ms) for the **staurolite zone, amphibolite facies**, showing the tie-line flip associated with reaction (28.12) which introduces staurolite into many low-Al common pelites (shaded). After Carmichael (1970) *J. Petrol.*, 11, 147-181. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **The Kyanite Zone – Amphibolite Facies:**
- As we continue the medium P-T field gradient in Fig. 28.2, the next reaction encountered **at point #8, ~630° C**, is:
 - $\text{St} + \text{Chl} (+ \text{Ms} + \text{Qtz}) = \text{Ky} + \text{Bt} (+ \text{H}_2\text{O})$

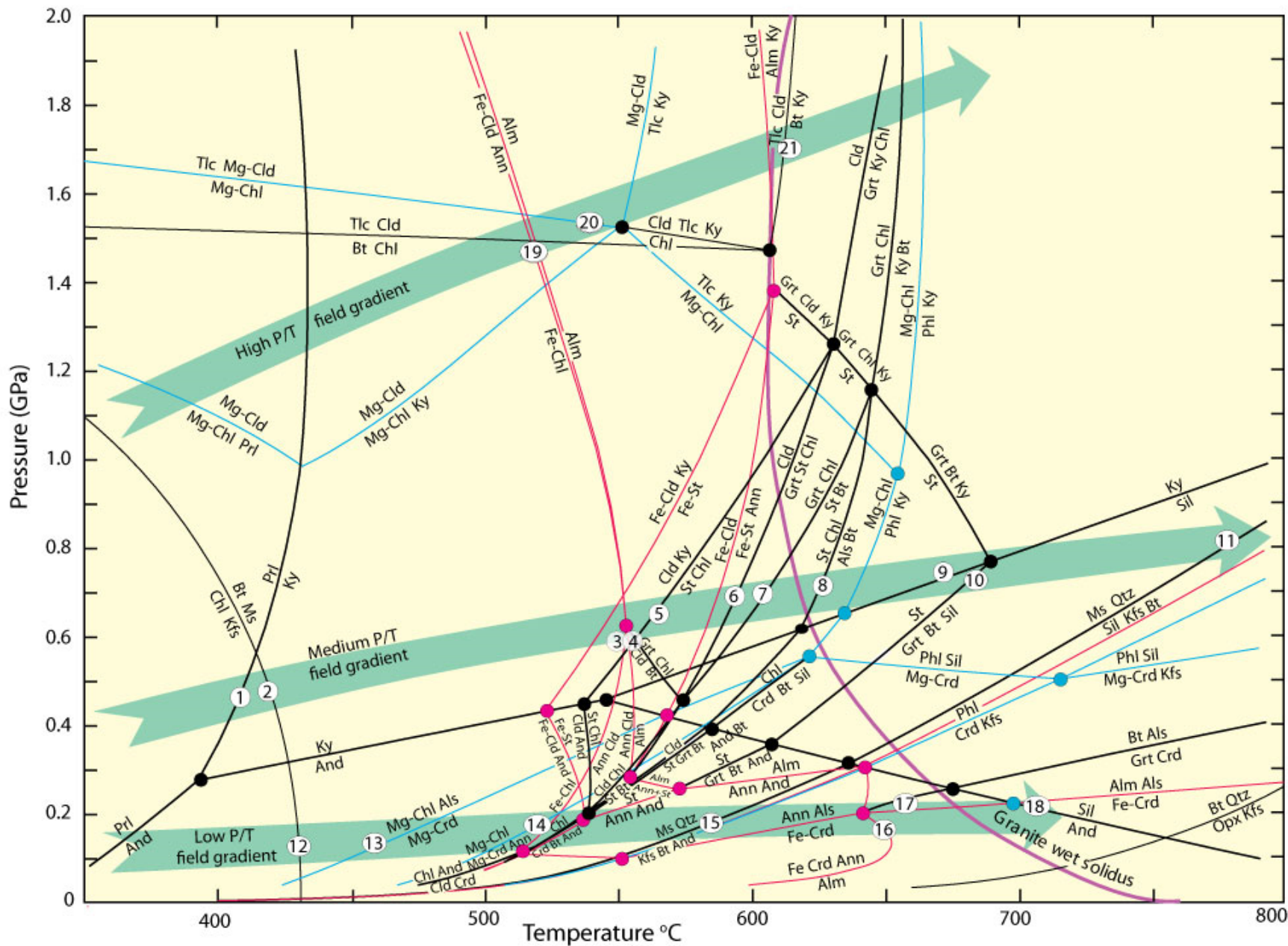


Fig. 28.2. Petrogenetic grid for the system KFMASH at $p_{H_2O} = p_{Total}$.

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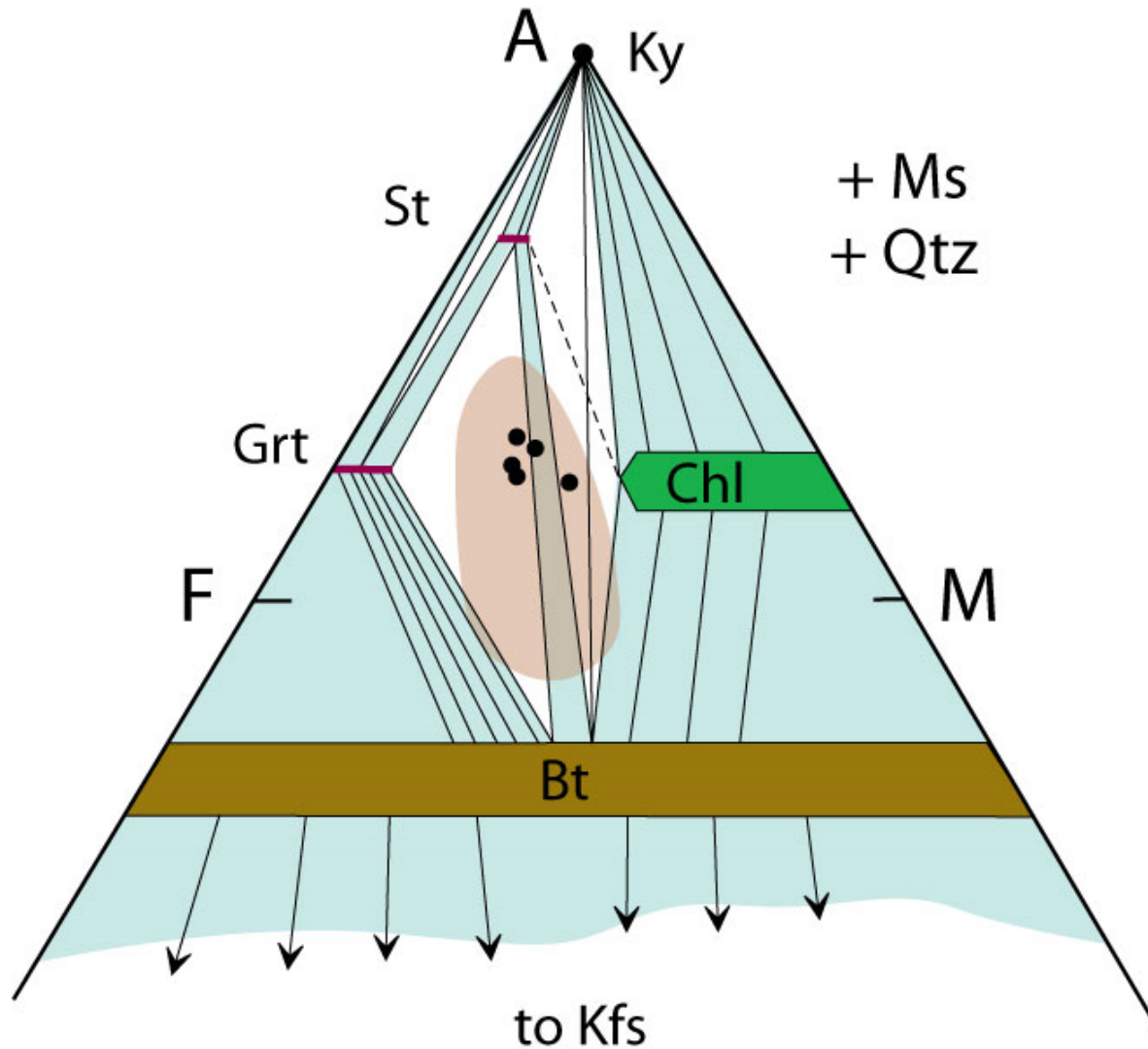


Figure 28.15. AFM compatibility diagram (projected from Ms) for the **kyanite zone, amphibolite facies**, showing the tie-line flip associated with reaction (28.15) which introduces kyanite into many low-Al common pelites (shaded). After Carmichael (1970) *J. Petrol.*, 11, 147-181. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **The Kyanite Zone – Amphibolite Facies:**
- The solidus curve for H₂O-saturated granitic compositions is also encountered in Fig. 28.2 at approx. this metamorphic grade
- Rocks containing quartz, plagioclase, and K-feldspar, if excess H₂O is available, will begin to melt.
- Mg-Chlorite disappears just above point #8 (blue reaction line), $\text{Mg-Chl} = \text{Phl} + \text{Ky}$
- “Staurolite-out” isograd is common in pelites, and due to rxn: $\text{St} (+\text{Ms} + \text{Qtz}) = \text{Grt} + \text{Bt} + \text{Als} + \text{H}_2\text{O}$ (**point #9 in Fig. 28.2**)

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- **The Sillimanite Zone – Upper Amphibolite Facies:**
- The sillimanite isograd is encountered along P-T-t path **at point #10 in Figure 28.2** ($\sim 690^{\circ}$ C), which is a *polymorphic* transformation
 - (Kyanite = Sillimanite)

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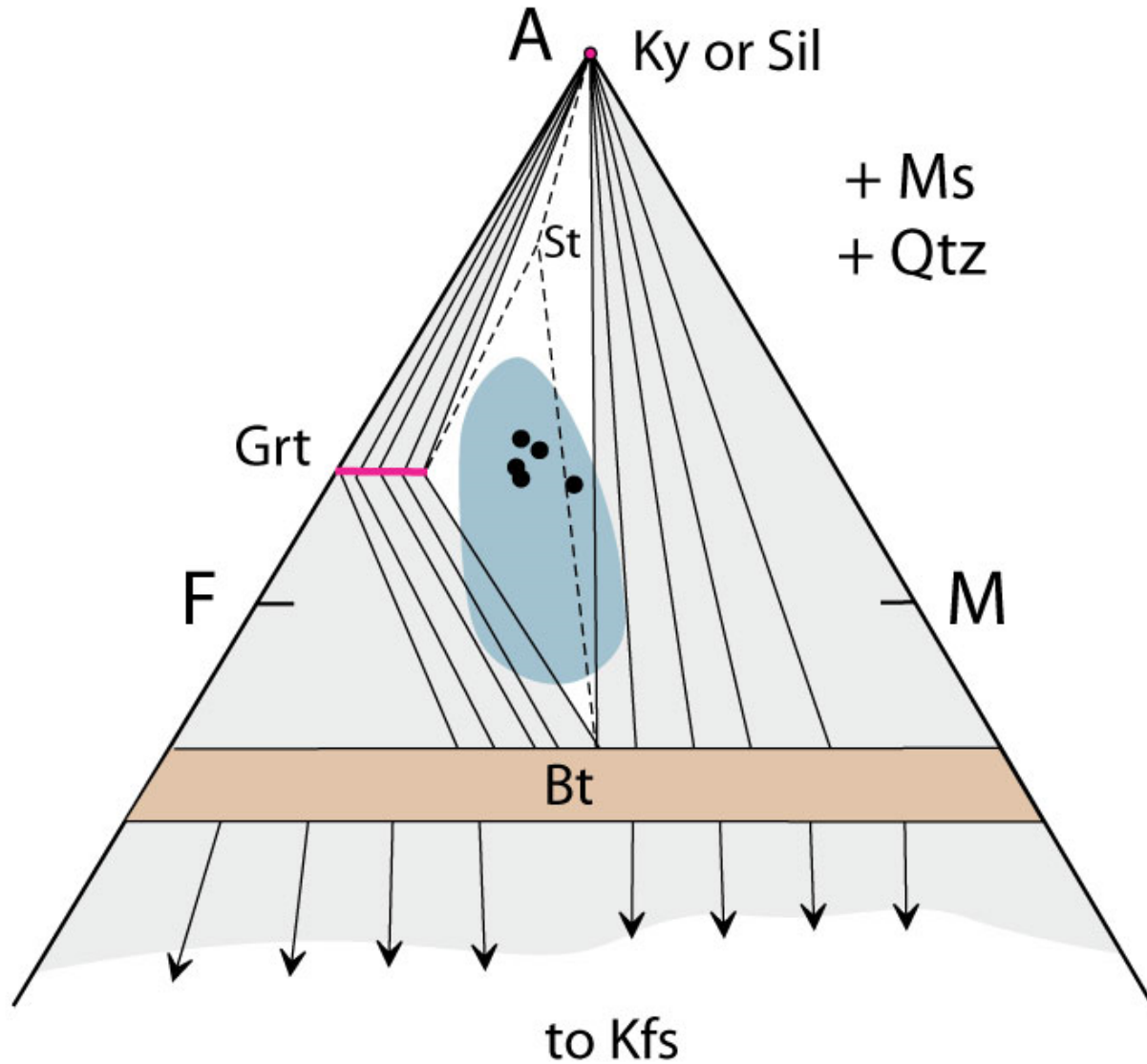


Figure 28.16. AFM compatibility diagram (projected from Ms) above the sillimanite and “stauroilite-out” isograds, **sillimanite zone, upper amphibolite facies**. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **Changes above the Kyanite – Sillimanite Isograd; Granulite Facies:**
- At point #11 in Figure 28.2 (~790° C), the medium P/T gradient intersects the important high-grade pelitic reaction:
- $\text{Ms} + \text{Qtz} = \text{Kfs} + \text{Sil} + \text{H}_2\text{O}$ (Rxn. 28.19) – considered by some petrologists to be transition from amphibolite to granulite facies
- At higher temperatures, we get the following reactions:
 - $\text{Phl} + \text{Sil} (+ \text{Qtz}) = \text{Mg-Crd} (+ \text{Kfs} + \text{H}_2\text{O})$ (Rxn. 28.20)
 - $\text{Bt} + \text{Sil} = \text{Grt} + \text{Crd} + \text{H}_2\text{O}$ (Rxn. 28.21)
 - $\text{Bt} + \text{Qtz} = \text{Opx} + \text{Kfs} + \text{H}_2\text{O}$ (Rxn. 28.22)

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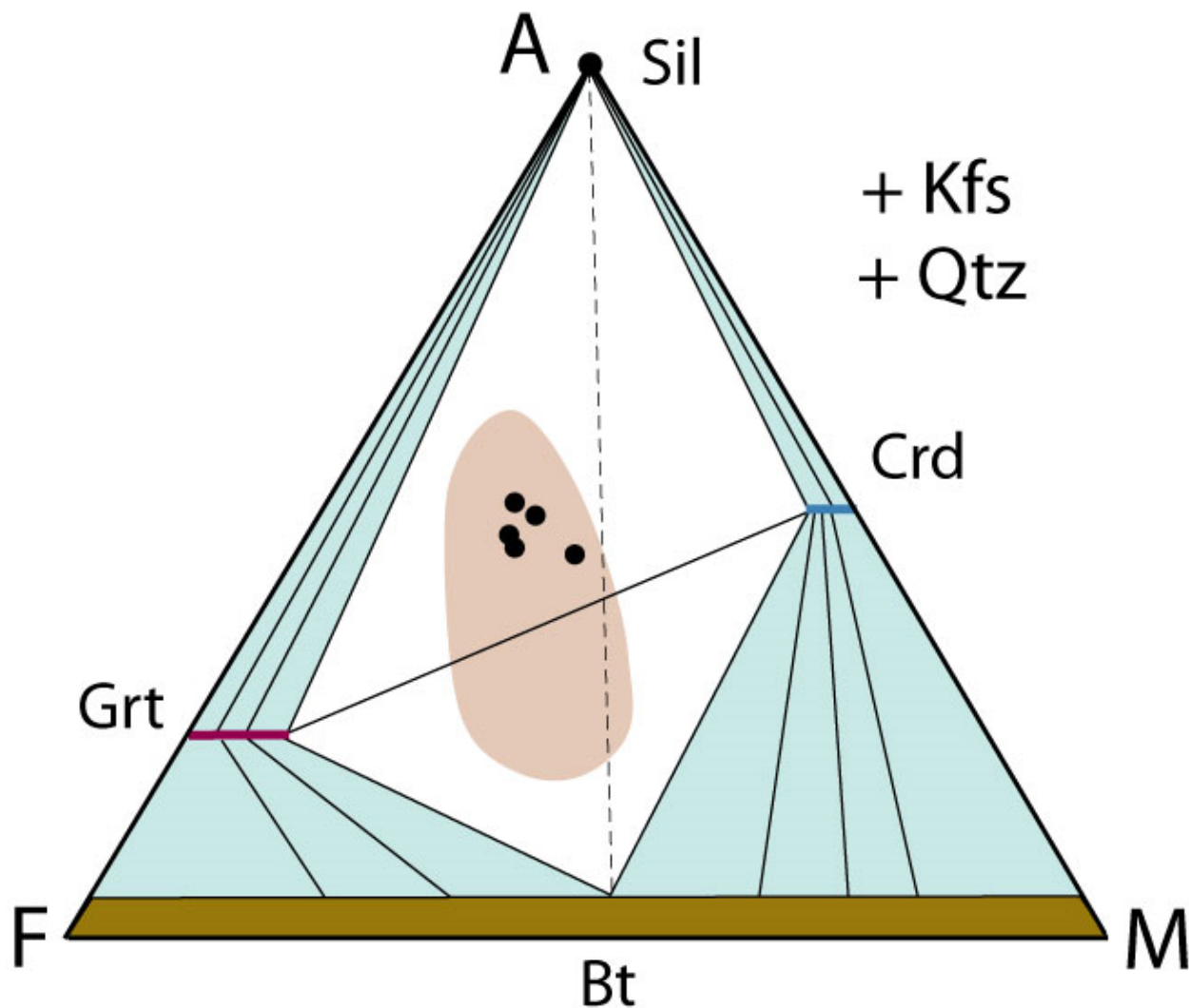


Figure 28.17. AFM compatibility diagram (projected from K-feldspar) above the cordierite-in isograds, **granulite facies**. Cordierite forms first by reaction (28-20), and then the dashed Sil-Bt tie-line is lost and the Grt-Crd tie-line forms as a result of reaction (28.21). Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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- **Migmatites:**
- At high metamorphic grades, many rocks develop *felsic segregations* and are called migmatites
- The term means “mixed rock”, referring to a mixture of apparently igneous and metamorphic component
- Dark schistose component – **Melanosome**
- Light colored, coarser-grained, centimeter-sized layers, veins, pods - **Leucosome**

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- **Migmatites:**
- **Paleosome** (mesosome) – material in migmatites that is intermediate in character between melanosome and leucosome – original rock?
- Represent culmination of metamorphism under more hydrous conditions, and best developed in metapelites (but can occur in other rocks)

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- **Migmatites – Origin:**
- Their origin is somewhat controversial, and there are 3 principal theories:
- 1- Form by injection of granitic leucosome into dark, high-grade schistose rocks;
- 2- Form by localized partial melting (anatexis). The leucosome represent the melts (granitic in composition), the melanosome represents the restite (refractory residuum);
- 3- Created by metamorphic differentiation, or metasomatic growth of the leucosome – i.e., no melt involved;

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Figure 28.20. Veins developed in pelitic hornfels within a few meters of the contact with diorite. The vein composition contrasts with that of the diorite, and suggests that the veins result from localized partial melting of the hornfels. Onawa aureole, Maine. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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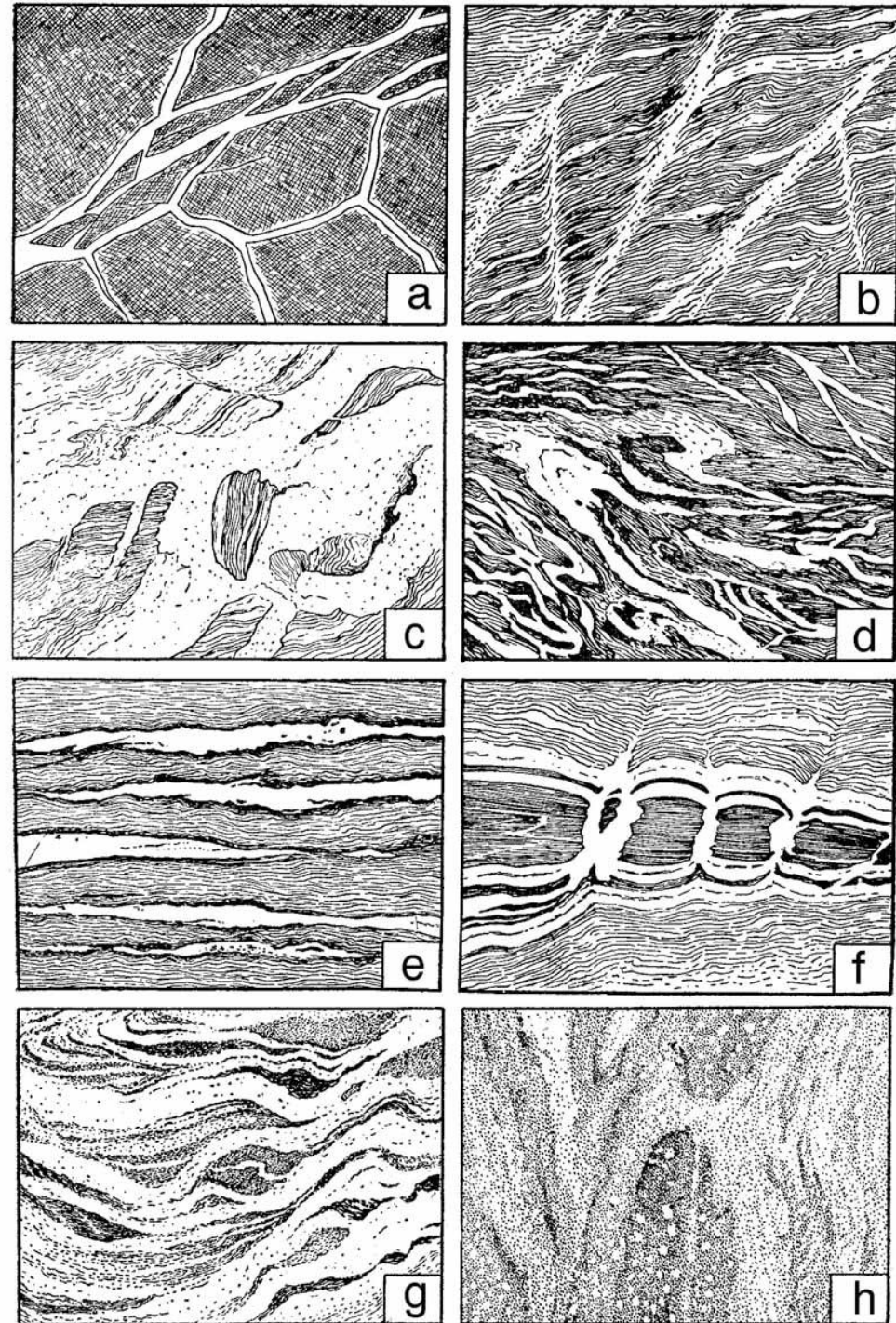


Figure 28.26. Some textures of migmatites. **a.** Breccia structure in agmatite. **b.** Net-like structure. **c.** Raft-like structure. **d.** Vein structure. **e.** Stromatic, or layered, structure. **f.** Dilation structure in a boudinaged layer. **g.** Schleiren structure. **h.** Nebulitic structure. From Mehnert (1968) *Migmatites and the Origin of Granitic Rocks*. Elsevier. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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Figure 28.27. Complex migmatite textures including multiple generations of concordant bands and cross-cutting veins. Angmagssalik area, E. Greenland. Outcrop width ca. 10 m. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

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More complex migmatic textures.



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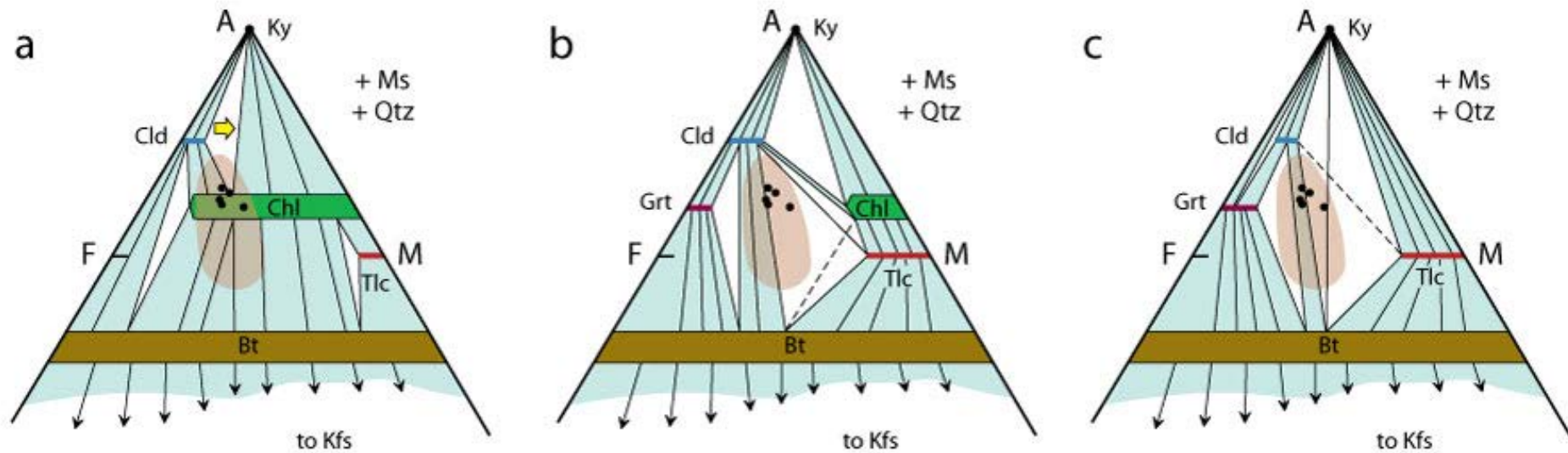


Figure 28.28. AFM compatibility diagrams (projected from muscovite) for the eclogite facies of high P/T metamorphism of pelites. **a.** Talc forms between biotite and chlorite along the Mg-rich side of the diagram via reaction (28.35). **b.** At a higher grade the Chl-Bt tie-line flips to the Tlc-Cld tie-line via reaction (28.36). **c.** After chlorite breaks down the kyanite forms in many metapelites via reaction (28.36). After Spear (1993) *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*. Mineral. Soc. Amer. Monograph 1. Winter (2010) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.