EENS 212	Petrology
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Metamorphic Reactions, Isograds, and Reaction Mechanisms

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Types of Metamorphic Reactions

Chemical reactions that take place during metamorphism produce mineral assemblages stable under the new conditions of temperature and pressure. Thus, in order to understand the mineral assemblages and what they mean in terms of the pressure and temperature of metamorphism, we must first explore the various types of metamorphic reactions. A metamorphic reaction is an expression of how the minerals got to their final state, but a reaction does not necessarily tell us the path that was actually taken to arrive at this state. Sometimes it is possible to deduce the path by means of a reaction mechanism. Thus, we will also explore reaction mechanisms.

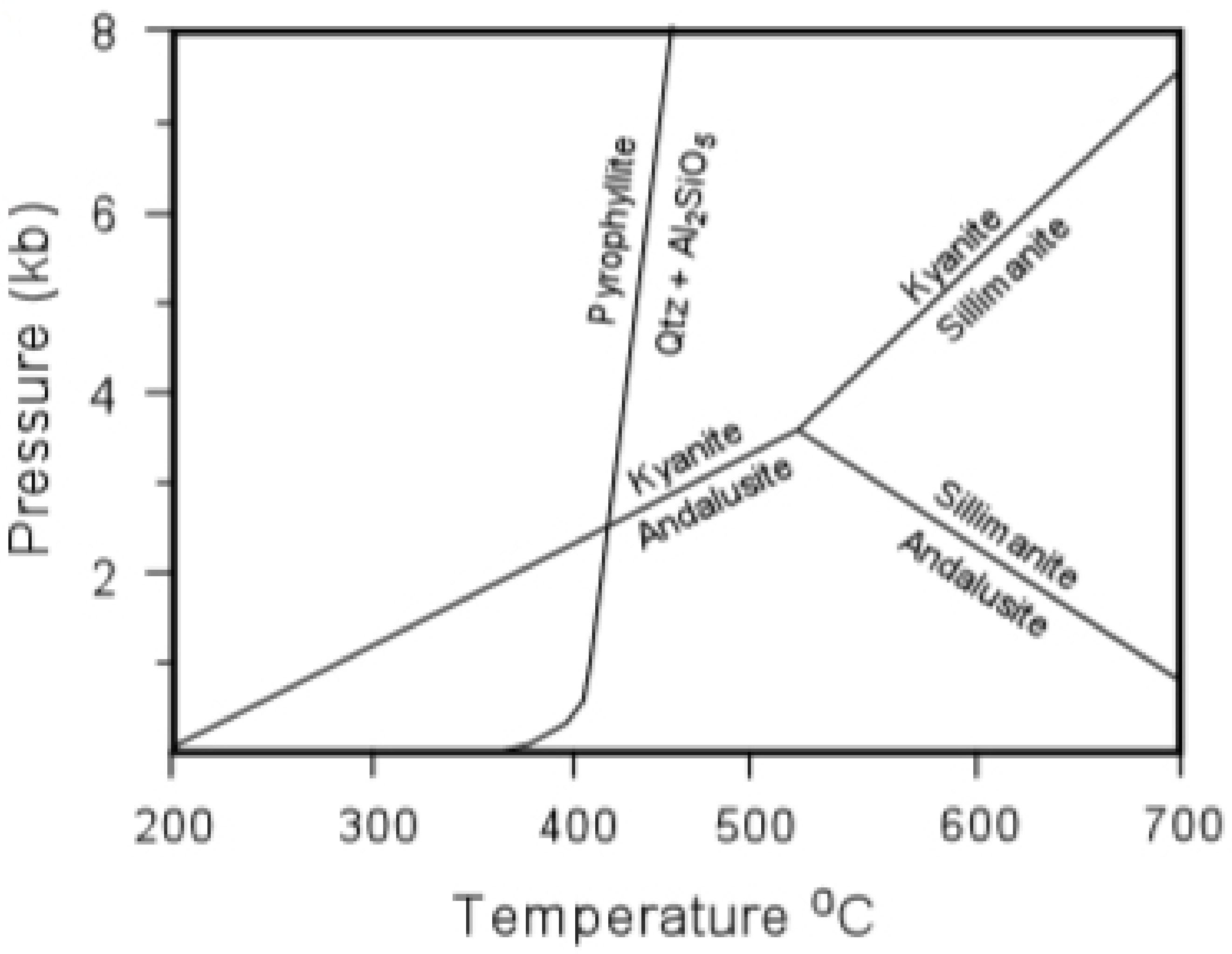
If we are considering a rock of fixed chemical composition, then a metamorphic reaction states the principles of equilibrium. In other words, if we can write a reaction expressing equilibrium between the minerals we see in the rock, we expect that the reaction must have been taking place during metamorphism. We will first look at various types of metamorphic reactions.

Univariant Reactions

For a given rock composition, a univariant reaction is one that plots as a line or curve on a pressure-temperature diagram. If all phases in the reaction are present in the rock, then we know that the rock must have been metamorphosed at some pressure and temperature along the reaction boundary Consider for example the simple Al_2SiO_5 system with excess SiO_2 and H_2O. In low grade metamorphic in this system, the reaction:

$$\underset{\text{Pyrophyllite}}{Al_2Si_4O_{10}(OH)_2} \Leftarrow\!\Rightarrow \underset{\text{Ky or Andal}}{Al_2SiO_5} + \underset{\text{Qtz}}{3SiO_2} + \underset{\text{fluid}}{H_2O}$$

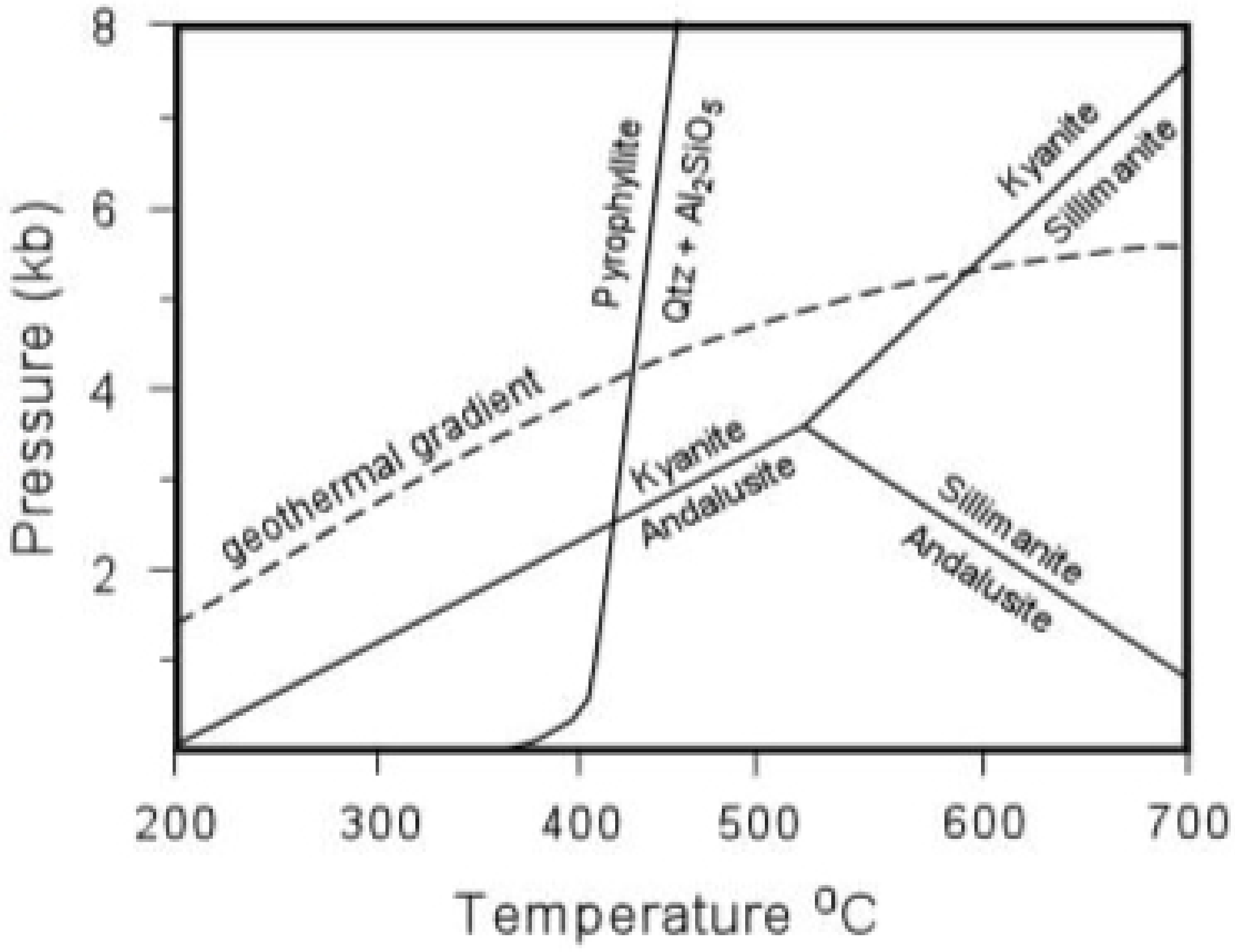
defines a reaction boundary on a P-T diagram. This boundary can be determined experimentally or can be calculated using thermodynamic properties of the phases involved. If we find a rock that contains pyrophyllite, quartz, and an Al_2SiO_5 mineral, then we know that metamorphism took place somewhere along the trajectory of the reaction boundary. Furthermore, combining this with the knowledge of the stability fields of the Al_2SiO_5 minerals, we could place boundaries on the conditions of metamorphism.



For example, if the mineral is andalusite, then we know the rock was metamorphosed at a pressure less than about 2.5 kilobars. If the mineral is kyanite, then we know that the pressure was greater than about 2.5 kilobars.

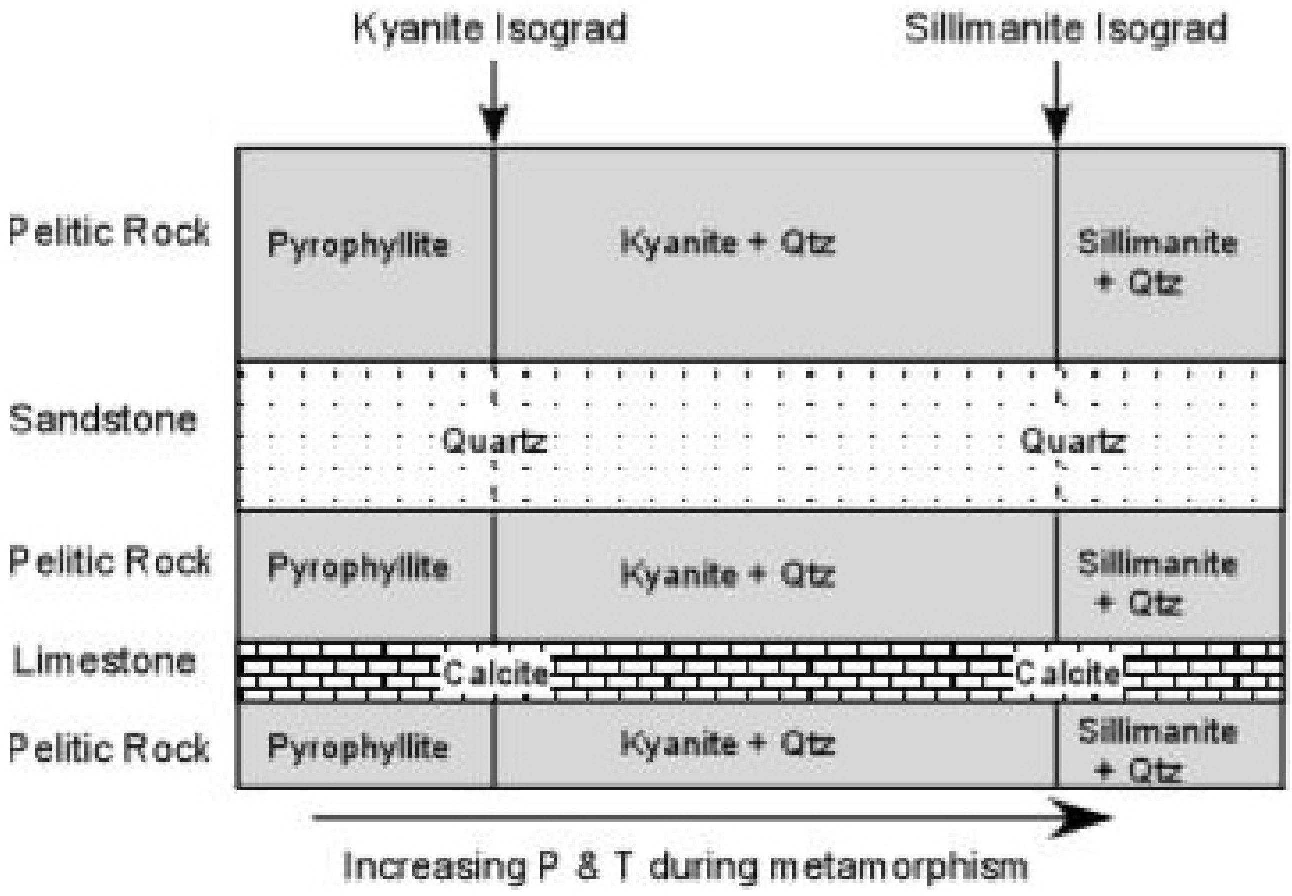
Combinations of other such reactions could further constrain the pressure and temperature conditions of metamorphism. The example above, however, is probably too simple for a real rock.

Although simple, we can use the diagram to illustrate another point. Imagine that a group of rocks are buried along the geothermal gradient shown in the diagram to the right. Rocks buried to a pressure less than about 4 kb and a temperature less than about 420 °C should have pyrophyllite so long as they have the right composition. Rocks buried to pressures between about 4 and 5 kb and temperatures between 420 and about 600 °C should have kyanite + quartz, and rocks buried to pressures along the geothermal gradient greater than about 5 kb and temperatures greater than about 600 °C should have Sillimanite + Quartz.



Now imagine that these rocks are brought back to the surface of the Earth and that retrograde metamorphism did not occur on the reverse path back to the surface. Furthermore, they are fortuitously exposed so that the strike direction of the rocks is coincident with the direction along which temperature and pressure increased along the geothermal gradient during the metamorphic event.

If we walk along the outcrop along the strike direction (coincident with the direction that pressure and temperature increased during metamorphism) we see that in pelitic rocks the low P & T end of the outcrop has a mineral assemblage consisting of only pyrophyllite. Walking further along strike, we suddenly come to a place where the mineral assemblage changes to Kyanite + Quartz. Note that if were making a geologic map, we could draw a line on the map that separates the pelitic rocks containing only Pyrophyllite from those containing Kyanite + Quartz. Such a line (a surface in 3 dimensions) is called an isograd (iso - same, grad - grade).



In this case, since it represents the first appearance of Kyanite, we call it the Kyanite Isograd.

Notice that the isograd represents the point on the phase diagram, above where the geothermal gradient intersects the boundary for the reaction:

$$\underset{\text{Pyrophyllite}}{Al_2Si_4O_{10}(OH)_2} <=> \underset{\text{Kyanite}}{Al_2SiO_5} + \underset{\text{Qtz}}{3SiO_2} + \underset{\text{fluid}}{H_2O}$$

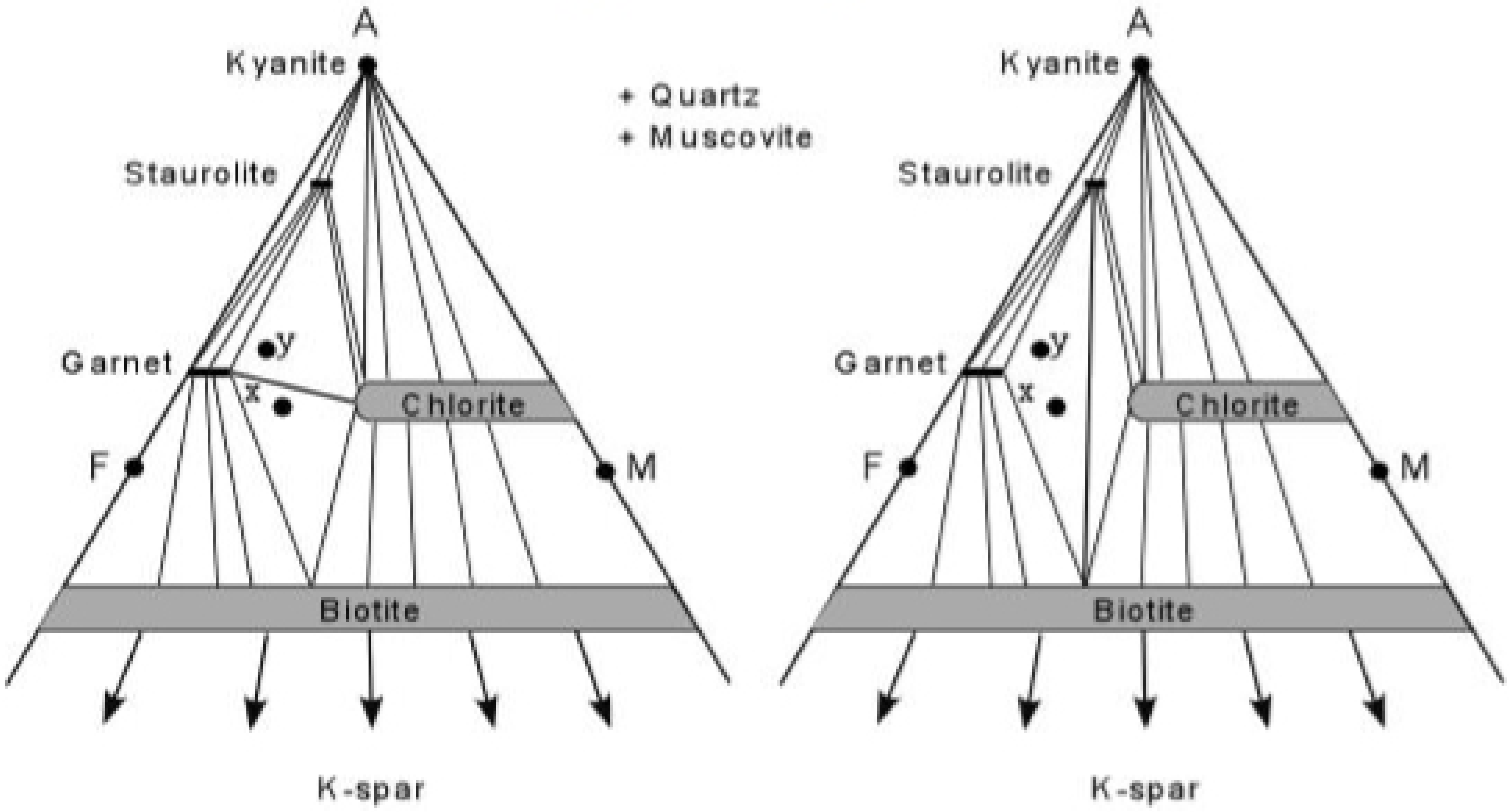
Also notice that if were were walking along an outcrop of the sandstone or the limestone, that we would not be able to map this isograd in these rocks. The reason of course is that the sandstone, made of pure grains of quartz, and the limestone, made of pure grains of calcite, do not have the necessary chemical constituents to form minerals like Pyrophyllite and Kyanite.

If we continue walking along the direction that T & P increased in these rocks during metamorphism, we would eventually come to another place where in the pelitic rocks the mineral assemblage changes. This time the change is from Kyanite + Quartz to Sillimanite + Quartz. Again, we can draw a line on the map that indicates this change in mineral assemblage, this time calling it the Sillimanite Isograd. Just like before, this represents the point on the phase diagram, above, where the geothermal gradient intersected the boundary for the reaction:

$$\underset{\text{Kyanite}}{Al_2SiO_5} <=> \underset{\text{Sillimanite}}{Al_2SiO_5}$$

Because the sandstone and the limestone do not contain Kyanite, the isograd does not appear in these rocks, but we can still extrapolate its position across the map or outcrop.

On mineral compatibility diagrams, univariant reactions may show up as flipping tie lines. To illustrate this we will use the AFM diagram for metapelites.



In the diagrams, the average pelitic rock is shown as composition x. At low grade, the stable mineral assemblage is Garnet + Chlorite + Biotite + Muscovite + Quartz. As temperature and pressure are raised, this assemblage becomes unstable and the tie line connecting Garnet and Chlorite is replaced by one connecting Staurolite + Biotite.