Metamorphic Rocks
Reminder notes:

- Metamorphism
- Metasomatism
- Regional metamorphism
- Contact metamorphism
- Protolith
- Prograde
- Retrograde
- Fluids – dewatering and decarbonation – volatile flux
- Chemical change vs textural changes
- Mud to gneiss
Metamorphism – changes in mineralogy and texture of a rock due to changes in pressure and temperature. The bulk chemical composition of the rock doesn’t change.

Metasomatism – changes in mineralogy and texture of a rock due to changes in pressure, temperature, and chemistry. Chemically active fluids move ions from one place to another which changes the bulk chemistry of the rock. These fluids come from the breakdown of hydrous and carbonate minerals.
Contact versus Regional metamorphism
Metamorphic Facies

**FIGURE 15-1** Idealized geologic map of a model metamorphic terrane containing two protoliths, sandstone (stippled) and shale (lined). These rocks were folded and faulted prior to metamorphism. The shale was converted to a muscovite schist and the sandstone to a quartzite during metamorphism. The intensity of metamorphism increases from west to east, with four metamorphic zones being developed (Roman numerals), each with its own characteristic mineral assemblages, as shown on the map. The boundaries between zones, which are called isograds, mark the intersection of reaction surfaces in $P-T$-$\mu$$_{H_2O}$ space with the erosion surface. The isograds are labeled with the new mineral or mineral assemblage appearing on the high-temperature side of the isograd.

**FIGURE 15-2** Minerals present in the metapelite and metasandstone in the four different metamorphic zones of the area shown in Figure 15-1.
Plotting metamorphic mineral diagrams

(A) 

(B) 

(C)
FIGURE 15-3  (a) Tetrahedral mole fraction plot of the mineral assemblages in zone I of the model metamorphic terrane shown in Figure 15-1. Muscovite plots on the back face of the tetrahedron. (b) Projection of the composition of muscovite across the back face of the tetrahedron onto the water-free join AlO$_{3/2}$–KAlSi$_3$O$_8$. (c) Mineral facies diagrams for each of the metamorphic zones. Compositions within the tetrahedron of (a) are projected onto the triangular face AlO$_{3/2}$–KAlSi$_3$O$_8$–SiO$_2$ from the water apex, assuming that the activity of water was buffered at some fixed value by the environment. The bulk composition of the metapelite is indicated by the point marked mp and the metasandstone by ms.
Barrovian metamorphic sequences
Thermodynamics and Gibbs free energy

- Reactions take place in a direction that lowers Gibbs free energy
- Equilibrium is achieved only when Gibbs free energy reaches a minimum
- At equilibrium, temperature, pressure, and chemical potentials of all components must be the same throughout
- Equilibrium thermodynamics and kinetics. Thermodynamics tells us what can happen, kinetics tells us if it does happen

**ENTROPY AND GIBBS FREE ENERGY**

How are entropy and enthalpy related?

\[ \Delta G^0 = \Delta H^0 - T \Delta S^0 \]

**Gibbs free energy** is the energy that is available to do useful work.

A reaction will spontaneously occur if \( \Delta G < 0 \) (exergonic reaction)

A reaction will NOT spontaneously occur if \( \Delta G > 0 \) (endergonic reaction)
Petrogenetic Grid
AKFM diagram for pelitic rocks
Petrogenetic grid – reactions in metapelites for greenschist and amphibolite facies
Assemblages in metapelites as a function of metamorphic grade
Role of Fluids in Metamorphism

$$\text{CaCO}_3 + \text{SiO}_2 = \text{CaSiO}_3 + \text{CO}_2 \text{ (fluid)}$$
\[ \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2 + 3\text{CaCO}_3 = 4\text{CaMgSi}_2\text{O}_6 + \text{CaMg(CO}_3)_2 + \text{H}_2\text{O} + \text{CO}_2 \]

tremolite  
calcite  
diopside  
dolomite  
fluid
Metamorphic grade, index minerals, isograds, and metamorphic facies
<table>
<thead>
<tr>
<th>Facies</th>
<th>Mafic protolith</th>
<th>Pelitic protolith</th>
<th>Carbonate protolith</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zeolite</td>
<td>Chlorite, serpentine, clay minerals, zeolites, analcite, albite, quartz, prehnite, pumpellyte, calcite, dolomite</td>
<td>Chlorite, illite, clay minerals, quartz, albite, calcite, dolomite</td>
<td>Calcite, dolomite, quartz, chlorite, illite, clay minerals, albite</td>
</tr>
<tr>
<td>Prehnite- pumpellyte</td>
<td>Chlorite, serpentine, prehnite, pumpellyte, quartz, albite, calcite, dolomite</td>
<td>Chlorite, muscovite, clay minerals, quartz, albite, calcite dolomite</td>
<td>Calcite, dolomite, quartz, clay minerals, albite</td>
</tr>
<tr>
<td>Blueschist</td>
<td>Glauconphane, lawsonite (or epidote), quartz, garnet</td>
<td>Glauconphane, Si-rich muscovite, lawsonite (or epidote), quartz, garnet</td>
<td>Aragonite, dolomite, glauconphane, epidote, albite</td>
</tr>
<tr>
<td>Greenschist</td>
<td>Chlorite, actinolite, epidote, albite, quartz</td>
<td>Chlorite zone: chlorite, muscovite, quartz, albite</td>
<td>Calcite, dolomite, muscovite, quartz, albite</td>
</tr>
<tr>
<td>Biotite zone: chlorite, muscovite, biotite, quartz, albite, garnet zone: muscovite, biotite, garnet, quartz, albite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Albite-Epidote hornfels</td>
<td>Albite, pyrophyllite, epidote, actinolite, chlorite, quartz</td>
<td>Muscovite, chlorite, biotite, albite, quartz, pyrophyllite</td>
<td>Calcite, epidote, actinolite, quartz</td>
</tr>
<tr>
<td>Amphibolite</td>
<td>Hornblende, plagioclase, quartz, garnet</td>
<td>Staurolite zone: muscovite, biotite, quartz, garnet, staurolite, plagioclase</td>
<td>Calcite, dolomite, quartz, biotite, amphibole, diopside, K-feldspar, wollastonite</td>
</tr>
<tr>
<td>Kyanite zone: muscovite, biotite, quartz, garnet, kyanite, staurolite, plagioclase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sillimanite zone: muscovite, biotite, quartz, garnet, sillimanite, plagioclase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hornblende-hornfels</td>
<td>Cordierite, plagioclase, anthropophyllite, hornblende, diopside, garnet, quartz</td>
<td>Andalusite, muscovite, cordierite, quartz, biotite</td>
<td>Calcite, diopside, grossular, biotite, quartz</td>
</tr>
<tr>
<td>Pyroxene hornfels</td>
<td>Diopside, orthopyroxene, plagioclase, biotite, quartz</td>
<td>Andalusite, cordierite, orthoclase, biotite, quartz</td>
<td>Wollastonite, grossularite, diopside, biotite, quartz</td>
</tr>
<tr>
<td>Granulite</td>
<td>Clinopyroxene, orthopyroxene, plagioclase, garnet, quartz</td>
<td>Quartz, K-feldspar, plagioclase, sillimanite, garnet, biotite, orthopyroxene, cordierite</td>
<td>Calcite, dolomite, quartz, diopside, wollastonite, K-feldspar, forsterite</td>
</tr>
<tr>
<td>Sanidinite</td>
<td>Sanidine, clinopyroxene, orthopyroxene, plagioclase, quartz</td>
<td>Sillimanite or mullite, spinel, sanidine, quartz</td>
<td>Monticellite, melilit, diopside, calcite</td>
</tr>
<tr>
<td>Eclogite</td>
<td>Pyrope-rich garnet, jadeite-rich pyroxene, quartz, kyanite, rutile</td>
<td>Si-rich muscovite, quartz, jadeite-rich pyrope, pyrope-rich garnet, kyanite, rutile</td>
<td>Aragonite, dolomite, jadeite-rich pyrope, epidote, quartz, Si-rich muscovite, pyrope-rich garnet</td>
</tr>
</tbody>
</table>
Textures of metamorphic rocks

- Excess energy present in deformed crystals (elastic), twins, surface free energy
- Growth of new grains leads to decreasing free energy – release elastic energy, reduce surface to volume ratio (increase grains size, exception occurs in zones of intense shearing where a number of nuclei are formed).
- Activation energy is provided by heating and deformation.
- Minerals with high surface free energy recrystallize before minerals with lower surface free energy. This leads to the Crystalloblastic series. Minerals with higher surface free energy form euhedral crystal faces relative to minerals with lower surface free energy.

**Table 14.2 Crystalloblastic series.**

<table>
<thead>
<tr>
<th>Surface Free Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite, rutile, titanite, pyrite</td>
</tr>
<tr>
<td>Sillimanite, kyanite, garnet, staurolite, tourmaline</td>
</tr>
<tr>
<td>Andalusite, epidote, zoisite, forsterite, lawsonite</td>
</tr>
<tr>
<td>Amphibole, pyroxene, wollastonite</td>
</tr>
<tr>
<td>Mica, chlorite, talc, prehnite, stilpnomelane</td>
</tr>
<tr>
<td>Calcite, dolomite, vesuvianite</td>
</tr>
<tr>
<td>Cordierite, feldspar, scapolite</td>
</tr>
<tr>
<td>Quartz</td>
</tr>
</tbody>
</table>
Textures contact metamorphic rocks - Hornfels

Cordierite and spinel

Law of sines $\gamma = \text{surface tension}$

Marble showing $120^\circ$ grain boundary junctures

Law of sines: $\frac{\gamma_1}{\sin \theta_1} = \frac{\gamma_2}{\sin \theta_2} = \frac{\gamma_3}{\sin \theta_3}$
Deformation and textures of regional metamorphic rocks

Slaty cleavage dips to the left. Bedding near vertical.
Boudinage
Solution cleavage planes in limestone

Axial plane solution cleavage in marble
Development of two cleavage directions
Helicitic texture - bands of inclusions that indicate original bedding or schistosity of the parent rock and cut through later-formed crystals of the metamorphic rock.
Plagioclase-hornblende mylonite

Black veins of pseudotachylite
Migmatites

Incipient melting of metamorphic rocks. Diagram below shows melting conditions relative metamorphic facies. A broad zone of Hbl → pyx + H₂O separates amphibolite and granulite facies and provides the water for melting
Geothermometers and Geobarometers

GARB – used to calculate temperature (Exchange reaction)

\[
\begin{align*}
\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12} + \text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2 & \leftrightarrow \text{Mg}_3\text{Al}_3\text{O}_{12} + \text{KFe}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2 \\
almandine & \quad \text{phlogopite} \\
pyrobe & \quad \text{annite}
\end{align*}
\]

\[
52,110 - 19.51^*T(K) + 0.238^*P(\text{bar}) + RT \ln K = 0
\]

where \( K = \frac{X_{\text{Mg}}^{\text{gar}} X_{\text{Fe}}^{\text{bio}}}{X_{\text{Fe}}^{\text{gar}} X_{\text{Mg}}^{\text{bio}}} \) which is an exchange reaction
GASP – used to calculate pressure (Net-transfer reaction)

Net-transfer reactions cause phases to appear or disappear (in this case anorthotite)

\[ 3\text{CaAl}_2\text{Si}_2\text{O}_8 = \text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12} + 2\text{Al}_2\text{SiO}_5 + \text{SiO}_2 \]

anorthite = grossular + kyanite + quartz

\[-48,357 + 150.66 \, T(K) - 6.608 \, P \, (\text{bar}) + RT \ln K = 0\]
A Complete Example

Let's suppose you analyze a group of minerals that are in equilibrium and find the following compositions:

- Garnet: $\text{Ca}_{0.42}\text{Mg}_{0.51}\text{Fe}_{2.04}\text{Mn}_{0.03}\text{Al}_2\text{Si}_3\text{O}_{12}$
- Biotite: $\text{K}\text{Mg}_{1.62}\text{Fe}_{1.38}\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_2$
- Plagioclase: $\text{Na}_{0.64}\text{Ca}_{0.36}\text{Al}_{1.36}\text{Si}_2\text{O}_8$
- Kyanite
- Quartz

Let's determine the equilibrium $P$ and $T$.

Determine mole fractions

$$X_{\text{grs}} = 0.14$$
$$X_{\text{prp}} = 0.17$$
$$X_{\text{alm}} = 0.68$$
$$X_{\text{ann}} = 0.46$$
$$X_{\text{phi}} = 0.54$$
$$X_{\text{an}} = 0.36$$

Determine activities, assuming ideal behavior

$$a_{\text{grs}} = 0.14^3 = 0.0027$$
$$a_{\text{prp}} = 0.17^3 = 0.0049$$
$$a_{\text{alm}} = 0.68^3 = 0.31$$
$$a_{\text{ann}} = 0.46^3 = 0.097$$
$$a_{\text{phi}} = 0.54^3 = 0.16$$
$$a_{\text{an}} = 0.36$$

Calculate equilibrium constants:

$$K_{\text{GASP}} = \frac{a_{\text{grs}}}{a_{\text{an}}^3} = \frac{0.0027}{0.36^3} = 0.054$$
$$K_{\text{GARB}} = \frac{(a_{\text{prp}}a_{\text{ann}})}{(a_{\text{alm}}a_{\text{phi}})} = \frac{(0.0049 \times 0.097)}{(0.31 \times 0.16)} = 0.0096$$

Calculate $P$ and $T$:

GASP: $P (\text{bar}) = \frac{-48,357 + 150.66 \times T(\text{K}) + RT \ln K}{6.608}$
GARB: $P (\text{bar}) = \frac{52,110 - 19.51 \times T(\text{K}) + RT \ln K}{-0.238}$

Choose $T = 873 \text{ K}$:
GASP: $P = 1.7 \text{ kbar}$
GARB: $P = -7.7 \text{ kbar}$

Choose $T = 1073 \text{ K}$:
GASP: $P = 13.2 \text{ kbar}$
GARB: $P = 40.6 \text{ kbar}$

These two lines intersect at $\sim 955 \text{ K}$ and $10.9 \text{ kbar}$. 
Pressure-temperature-time (P-T-t) paths

Radiometric dating – application of different systems to metamorphic rocks.
Summary of Geologic Setting and Metamorphic Facies

- Midocean ridge
  - Ocean water circulating through hot rock causes zeolite facies metamorphism

- High-P, High-T metamorphism

- High-P, Low-T metamorphism

- High-T, Low-P metamorphism

- Greenschist
- Amphibolite

- Delamination of base of crust
- Rise of fluids

- Asthenosphere
- Moho
- Prehnite-Pumpellyite
- Bluerchist
- Eclogite
- Lithosphere