Why study metamorphic rocks?

- 6.1 What is metamorphism?
- 6.2 What is the role of temperature in metamorphism?
- 6.3 What is the role of pressure in metamorphism?
- 6.4 What is the role of fluid in metamorphism?
- 6.5 Why do metamorphic rocks exist at the surface?
- 6.6 How do we know … how to determine the stability of minerals?
- 6.7 What were the conditions of metamorphism?
- 6.8 How are metamorphic rocks classified?
- 6.9 What was the rock before it was metamorphosed?
- 6.10 Where does metamorphism occur?
Why study metamorphic rocks?

- 6.1 What is metamorphism?
- 6.2 What is the role of temperature in metamorphism?
- 6.3 What is the role of pressure in metamorphism?
- 6.4 What is the role of fluid in metamorphism?
- 6.5 Why do metamorphic rocks exist at the surface?
- 6.6 How do we know ... how to determine the stability of minerals?
- 6.7 What were the conditions of metamorphism?
- 6.8 How are metamorphic rocks classified?
- 6.9 What was the rock before it was metamorphosed?
- 6.10 Where does metamorphism occur?

Some rocks are not from igneous or sedimentary processes. They show changes in texture, mineral content, or both after they originally formed. Metamorphic rocks are rocks transformed from previously existing rocks.
Why study metamorphic rocks?

Metamorphic rocks
- form almost exclusively beneath Earth’s surface (so metamorphic processes cannot be directly observed).
- are often found exposed in actively forming mountain ranges.
- are always found in eroded ancient mountain belts in continental interiors.
- and the minerals they contain make up such economic materials as talc, graphite, marble, garnet, corundum, and metamorphosed coals.

Objectives: In this chapter you will
- Learn how to identify metamorphic rocks.
- Learn to understand how metamorphic rocks form.
- Examine where metamorphic rocks form.
- Gain an understanding of how geologists use metamorphic rocks to interpret the geologic history of a region.

6.1 What is metamorphism?

From the Greek “meta” (change) and “morph” (form)
- Describes the mineralogical, chemical, and textural changes to preexisting rocks that occur in a (more or less) solid state.

Rocks exhibit two types of change
1. New minerals form at the expense of the old ones
2. Rock texture is altered by changes in size, shape, and orientation of constituent minerals

Significance of the original rock
- Essential to determining what reactions will take place
- By and large, the composition you start with is the composition you end up with

However, presence of chemically active fluids can cause substantial change

Metamorphism = mineralogical, chemical, and textural changes to preexisting rocks in an essentially solid state by changing environmental conditions.

These conditions include changing temperature, changing pressure, and the addition or subtraction of fluid.
6.2 What is the role of temperature in metamorphism?

We see that it takes approximately 12 km of burial to reach minimum metamorphic conditions.

Intrusion of magma alters the local geothermal gradient. This metamorphoses adjacent rock.

6.2 What is the role of temperature in metamorphism?

- Heat drives away water and gases
  - High-temperature metamorphism causes minerals containing water and gases to lose them
    - Dehydration – loss of water
      
      $\text{(HEAT)} \downarrow$
      $$\text{KAl}_3\text{Si}_3\text{O}_{10}\text{(OH)}_2 + \text{SiO}_2 \rightarrow \text{Al}_2\text{SiO}_5 + \text{KAl}_2\text{Si}_3\text{O}_8 + \text{H}_2\text{O}$$
      (muscovite) (quartz) (sillimanite) (K-feldspar) (water)

- Degassing – loss of gas
  
  $\text{(HEAT)}\downarrow$
  $$\text{CaMg(CO}_3\text{)}_2 \rightarrow \text{CaCO}_3 + \text{MgO} + \text{CO}_2 \text{(gas)}$$
  (dolomite) (calcite) (periclase) (carbon dioxide)

6.3 What is the role of pressure in metamorphism?

- Pressure is related to stress

  Magnitude of force divided by the area the force is applied to

  Normal stress – perpendicular to the surface. Results in change in volume and often shape.

  Shear stress – force parallel to the surface. Results in change of shape, but not volume.

  Strain – the deformation of a rock as a result of stress
6.3 What is the role of pressure in metamorphism?

- Recrystallization of minerals into new sizes and shapes
  - The packing of snow into ice is very much like the changes exhibited by minerals under stress

- How rock textures record strain
  - Metamorphic rock with foliation. Arrow indicates mineral lineation.

- Normal stress applied in all directions equally is pressure. At greater depths, increasing pressure causes a change in volume without a changing shape.

- Shear stress acts parallel to surfaces and in opposite directions. This stress changes the shape of the cube but does not affect volume.

- Near surface

- Recrystallization of minerals into new sizes and shapes
  - We can see this plainly as sandstone becomes a quartzite.

- This is an example of texture in which minerals are oriented in a preferred direction. Quartz and feldspar, the most abundant minerals in the rock, are oriented in parallel, forming a foliation or layering that can be seen in the polished surface of the rock.

- Metamorphic rock with foliation. Arrow indicates mineral lineation.
6.3 What is the role of pressure in metamorphism?
- How rock textures record strain

6.4 What is the role of fluid in metamorphism?
- Fluids can participate in two ways
  - React with minerals to form new minerals that contain components of the fluid molecules (water or CO₂)
  - Change the metamorphic rock by delivering and removing dissolved ions. Fluid makes reactions occur faster and more easily.

6.5 Why do metamorphic rocks exist at the surface?
- Most metamorphic rocks form some few to many kilometers underground
- Most get exposed due to mountain uplift and subsequent erosion
- Mountain-building processes uplift and expose metamorphic rocks at the surface as erosion removes overlying rocks.
- Once formed, metamorphic rocks do not revert back to the original minerals at Earth’s surface. There is not sufficient temperature, pressure, fluid, or time to promote the necessary reverse reactions.

6.6 How do we know ... how to determine the stability of minerals?
- Sillimanite crystallizing from dissolved andalusite under experimental conditions. Shows that conditions of stability changed from favoring one to the other.
6.7 What were the conditions of metamorphism?

- Index minerals are those that form in a limited range of conditions. If present, they tell geologists about the metamorphic condition.

6.8 How are metamorphic rocks classified?

- Composition and texture
  - We know that metamorphic processes change the minerals in a rock and often their form. Therefore, texture and composition are the primary criteria for classifying metamorphic rocks.
  - The first characteristic is either foliated or non-foliated. Foliated rocks all share having layered, or otherwise linearly arranged, minerals.

Foliated texture:
- Fine-grained with minerals aligned along planes (rock cleavage). Contains clays, muscovite, biotite, chlorite, quartz. Parent rock: shale, tuff

Foliated texture: fine-grained, minerals have a distinct layering; shiny. Contains muscovite, biotite, chlorite, quartz, garnet, talc, staurolite, others. Parent rock: shale, igneous rocks

Foliated texture: Compositional banding along parallel, often contorted, bands. Contains muscovite, biotite, chlorite, quartz, garnet, talc, staurolite, others. Parent rock: shale, igneous rocks
Changes in rock texture and mineral content take place as the metamorphic grade increases.

So, for foliated metamorphic rocks, the type or degree of foliation is the primary naming characteristic.

Rocks without foliation

For non-foliated metamorphic rocks, composition (mineral content) is the primary naming characteristic.
6.8 How are metamorphic rocks classified?

- The classification of metamorphic rock is based on texture (foliation and grain size) and mineral content.
- The names of foliated metamorphic rocks are based on texture size and the index minerals present.
- Most non-foliated rocks are named on the basis of mineral content.

6.9 What was the rock before it was metamorphosed?

- Possible metamorphic pathways for different parent sedimentary and igneous rocks

<table>
<thead>
<tr>
<th>Parent rock</th>
<th>Metamorphic grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Mafic igneous</td>
<td>Garnet + muscovite</td>
</tr>
<tr>
<td>Intermediate igneous</td>
<td>Garnet + muscovite</td>
</tr>
<tr>
<td>Felsic igneous</td>
<td>Sillimanite</td>
</tr>
<tr>
<td>Limestone/dolomite</td>
<td>Marble</td>
</tr>
<tr>
<td>Sandstone</td>
<td>Quartzite</td>
</tr>
<tr>
<td>Coal</td>
<td>Anhydrite</td>
</tr>
<tr>
<td>Slate</td>
<td>Slate</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Metamorphosed igneous rock
  - Low to med. grade metamorphism of mafic to intermediate igneous rocks gives dark-colored metamorphic rocks with Fe, Mg micas like chlorite and biotite. If foliated, they are generally schists; if not, they are greenstones.
  - Felsic rocks metamorphose to schist if water is present to convert feldspar to muscovite; otherwise, a gneiss may form. Igneous gneisses are less likely to have Al-rich index minerals.

6.10 Where does metamorphism occur?

- The parent rock is interpreted from the mineral composition of the metamorphic rock (as long as fluids were not a major part).
- The major elements in the metamorphic minerals are similar to those found in the parent rock.
- If the parent rock contains primarily one mineral, the metamorphic rock will likely contain a recrystallized metamorphic version such as marble from limestone, or quartzite from sandstone.
6.10 Where does metamorphism occur?

- **Contact metamorphism**
  - Occurs along the boundaries of igneous intrusions, and to a lesser extent, under lava flows.
  - Heat is the dominant factor.
  - Hornfels is the most common contact metamorphic rock.
  - Grade is highest close to the intrusion and less farther away.

- **Hydrothermal metamorphism**
  - Involves migration and reaction of hot, geothermal fluids.
  - Along mid-ocean ridges.

- **Regional metamorphism**
  - Occurs along subduction zones and active mountain-forming zones.
  - Broad, large-scale, pressure-driven in large part.
  - Not tied to single intrusion, mountain, or other singular location.
6.10 Where does metamorphism occur?

There are three primary types of metamorphism—contact, hydrothermal, and regional.
- Contact metamorphism occurs along boundaries of igneous intrusions. It is local and driven by heat.
- Hydrothermal metamorphism is a local-scale type as well for the most part. Occurs widely along ocean ridges. Involves hot fluids and the ions it moves.
- Regional metamorphism involves increasing temperature and pressure over large volumes of crust. Typically occurs at converging plate boundaries.