EENS 1110	Physical Geology
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Metamorphism and Metamorphic Rocks

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Definition of Metamorphism

The word "***Metamorphism***" comes from the Greek: meta = after, morph = form, so metamorphism means the after form. In geology this refers to the changes in mineral assemblage and texture that result from subjecting a rock to pressures and temperatures different from those under which the rock originally formed.

The original rock that has undergone metamorphism is called the ***protolith***. Protolith can be any type of rock and sometimes the changes in texture and mineralogy are so dramatic that is difficult to distinguish what the protolith was.

- Note that diagenesis and weathering are also a changes in form that occur in rocks. In geology, however, we restrict diagenetic processes to those which occur at temperatures below 200^{o}C and pressures below about 300 MPa (MPa stands for Mega Pascals), this is equivalent to about 3,000 atmospheres of pressure.

- Metamorphism therefore occurs at temperatures and pressures higher than 200^{o}C and 300 MPa. Rocks can be subjected to these higher temperatures and pressures as they become buried deeper in the Earth. Such burial usually takes place as a result of tectonic processes such as continental collisions or subduction.

- The upper limit of metamorphism occurs at the pressure and temperature of wet partial melting of the rock in question. Once melting begins, the process changes to an igneous process rather than a metamorphic process.

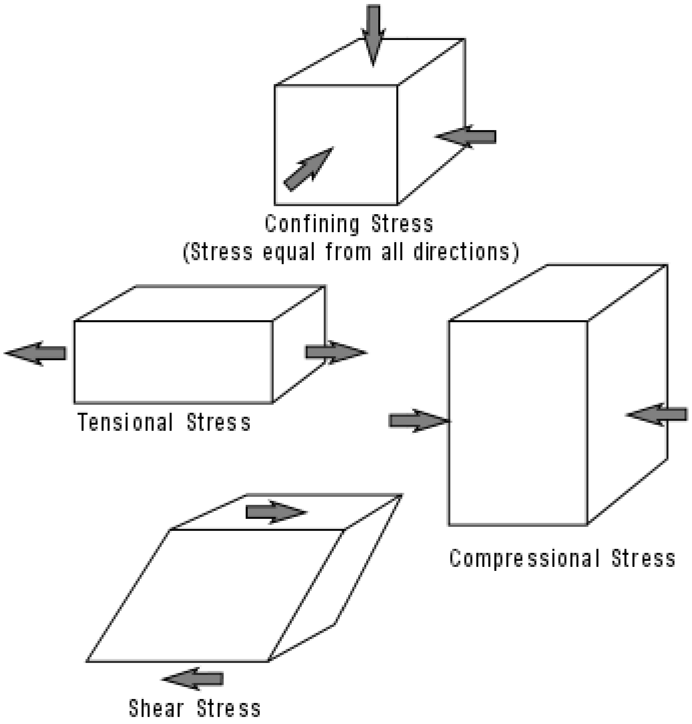
During metamorphism the protolith undergoes changes in texture of the rock and the mineral make up of the rock. These changes take place mostly in the solid state and are caused by changes in physical or chemical conditions, which in turn can be caused by such things as burial, tectonic stress, heating by magma or interactions with fluids.

Factors that Control Metamorphism

Metamorphism occurs because rocks undergo changes in temperature and pressure and may be subjected to differential stress and hydrothermal fluids. Metamorphism occurs because some minerals are stable only under certain conditions of pressure and temperature. When pressure and temperature change, chemical reactions occur to cause the minerals in the rock to change to an assemblage that is stable at the new pressure and temperature conditions. But, the process is complicated by such things as how the pressure is applied, the time over which the rock is subjected to the higher pressure and temperature, and whether or not there is a fluid phase present during metamorphism.

- Temperature
    - Temperature increases with depth in the Earth along the Geothermal Gradient. Thus higher temperature can occur by burial of rock.
    - Temperature can also increase due to igneous intrusion.
- Pressure increases with depth of burial, thus, both pressure and temperature will vary with depth in the Earth. Pressure is defined as a force acting equally from all directions. It is a type of ***stress***, called ***hydrostatic stress***, or ***uniform stress.***

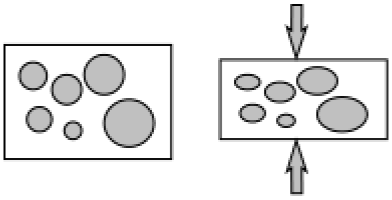
  If the stress is not equal from all directions, then the stress is called a ***differential stress.***



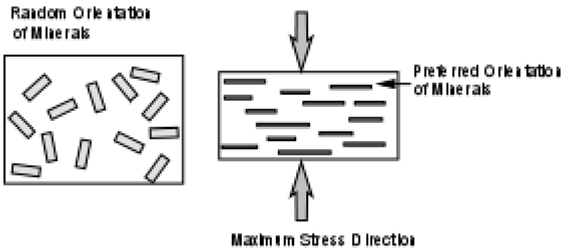
There are two kinds of differential stress. ***Normal stress*** causes objects to be compressed in the direction of maximum principal stress and extended in the direction of minimal stress. If differential stress is present during metamorphism, it can have a profound effect on the texture of the rock. ***Shear stress*** causes objects to be smeared out in the direction of applied stress.

Differential stress if acting on a rocks can have a profound affect on the appearance or texture of the rock.

Rounded grains can become flattened in the direction of maximum stress.



Minerals that crystallize or grow in the differential stress field can have a preferred orientation. This is especially true of the sheet silicate minerals (the micas: biotite and muscovite, chlorite, talc, and serpentine).



These sheet silicates will grow with their sheets orientated perpendicular to the direction of maximum stress. Preferred orientation of sheet silicates causes rocks to be easily broken along approximately parallel sheets. Such a structure is called a ***foliation***.

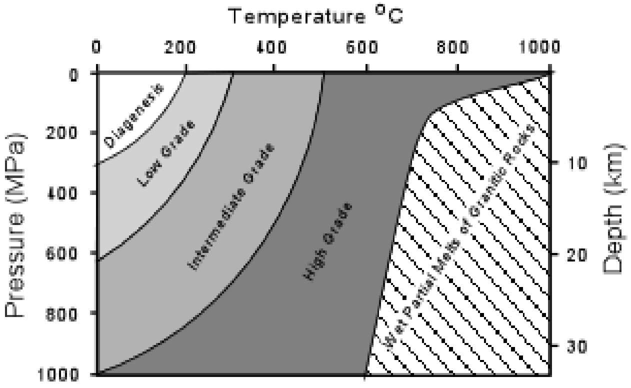
- Fluid Phase.- Any existing open space between mineral grains in a rock can potentially contain a fluid. This fluid is mostly H_2O, but contains dissolved ions. The fluid phase is important because chemical reactions that involve changing a solid mineral into a new solid mineral can be greatly speeded up by having dissolved ions transported by the fluid. If chemical alteration of the rock takes place as a result of these fluids, the process is called ***metasomatism***.

- Time - Because metamorphism involves changing the rock while it is solid, metamorphic change is a slow process. During metamorphism, several processes are at work. Recrystallization causes changes in minerals size and shape. Chemical reactions occur between the minerals to form new sets of minerals that are more stable at the pressure and temperature of the environment, and new minerals form as a result of polymorphic phase transformations (recall that polymorphs are compounds with the same chemical formula, but different crystal structures.

  Laboratory experiments suggest that the the sizes of the mineral grains produced during metamorphism increases with time. Thus coarse grained metamorphic rocks involve long times of metamorphism. Experiments suggest that the time involved is tens of millions of years.

Grade of Metamorphism

Metamorphic grade is a general term for describing the relative temperature and pressure conditions under which metamorphic rocks form. As the temperature and/or pressure increases on a body of rock we say that the rock undergoes ***prograde metamorphism*** or that the grade of metamorphism increases.



- Low-grade metamorphism takes place at temperatures between about 200 to 320°C, and relatively low pressure. Low grade metamorphic rocks are characterized by an abundance of ***hydrous minerals*** (minerals that contain water, H_2O, in their crystal structure).

  - Examples of hydrous minerals that occur in low grade metamorphic rocks:
    - Clay Minerals
    - Serpentine
    - Chlorite
- High-grade metamorphism takes place at temperatures greater than 320^{o}C and relatively high pressure. As grade of metamorphism increases, hydrous minerals become less hydrous, by losing H_2O and non-hydrous minerals become more common.
  - Examples of less hydrous minerals and non-hydrous minerals that characterize high grade metamorphic rocks:
    - Muscovite - hydrous mineral that eventually disappears at the highest grade of metamorphism
    - Biotite - a hydrous mineral that is stable to very high grades of metamorphism.
    - Pyroxene - a non hydrous mineral.
    - Garnet - a non hydrous mineral.

Retrograde Metamorphism

As temperature and pressure fall due to erosion of overlying rock or due to tectonic uplift, one might expect metamorphism to a follow a reverse path and eventually return the rocks to their original unmetamorphosed state. Such a process is referred to as ***retrograde metamorphism***. If retrograde metamorphism were common, we would not commonly see metamorphic rocks at the surface of the Earth. Since we do see metamorphic rocks exposed at the Earth's surface retrograde metamorphism does not appear to be common. The reasons for this include:

- chemical reactions take place more slowly as temperature is decreased
- during prograde metamorphism, fluids such as H_2O and CO_2 are driven off, and these fluids are necessary to form the hydrous minerals that are stable at the Earth's surface.
- chemical reactions take place more rapidly in the presence of fluids, but if the fluids are driven off during prograde metamorphism, they will not be available to speed up reactions during retrograde metamorphism.

Metamorphic Rock Types

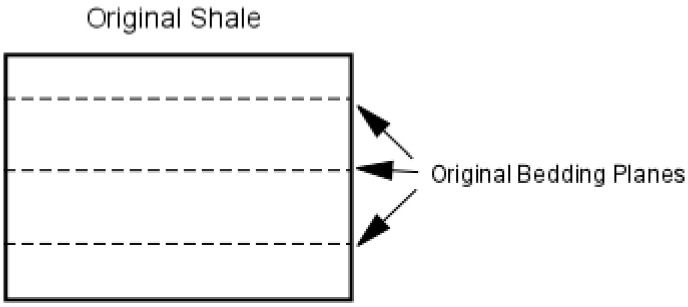
There are two major subdivisions of metamorphic rocks.

1. Foliated – These have a planar foliation caused by the preferred orientation (alignment) of minerals and formed under differential stress.
   They have a significant amount of sheet silicate (platy minerals and are classified by composition, grain size, and foliation type.

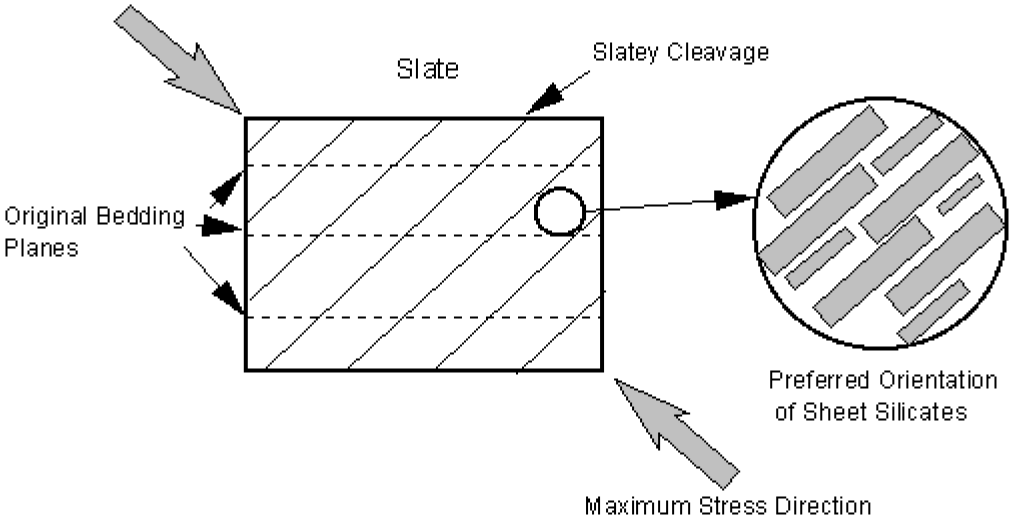
2. Non-foliated – These have no evident planar fabric or foliation, crystallized under conditions where there was no differential stress, and are comprised of equant minerals only. These are classified mainly by the minerals present or the chemical composition of the protolith.

Foliated Metamorphic Rocks

Example - metamorphism of a shale, made up initially of clay minerals and quartz all of clay or silt size.



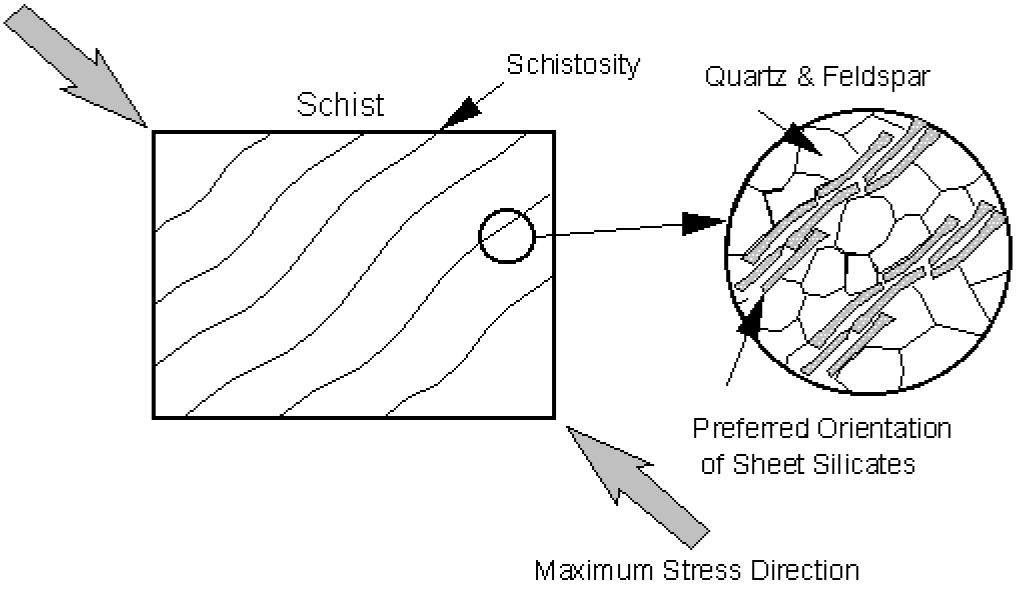
- ***Slate -*** Slates form at low metamorphic grade by the growth of fine grained chlorite and clay minerals. The preferred orientation of these sheet silicates causes the rock to easily break along the planes parallel to the sheet silicates, causing a ***slatey cleavage.*** Note that in the case shown here, the maximum stress is applied at an angle to the original bedding planes, so that the slatey cleavage has developed at an angle to the original bedding.



Because of the nearly perfect breakage along planes, slates are useful for blackboards and shingles.

- ***Phyllite*** - Fine mica-rich rock, formed by low – medium grade metamorphism. In a phyllite, the clay minerals have recrystallized into tiny micas (biotite and muscovite which reflect a satiny luster. Phyllite is between slate and schist.

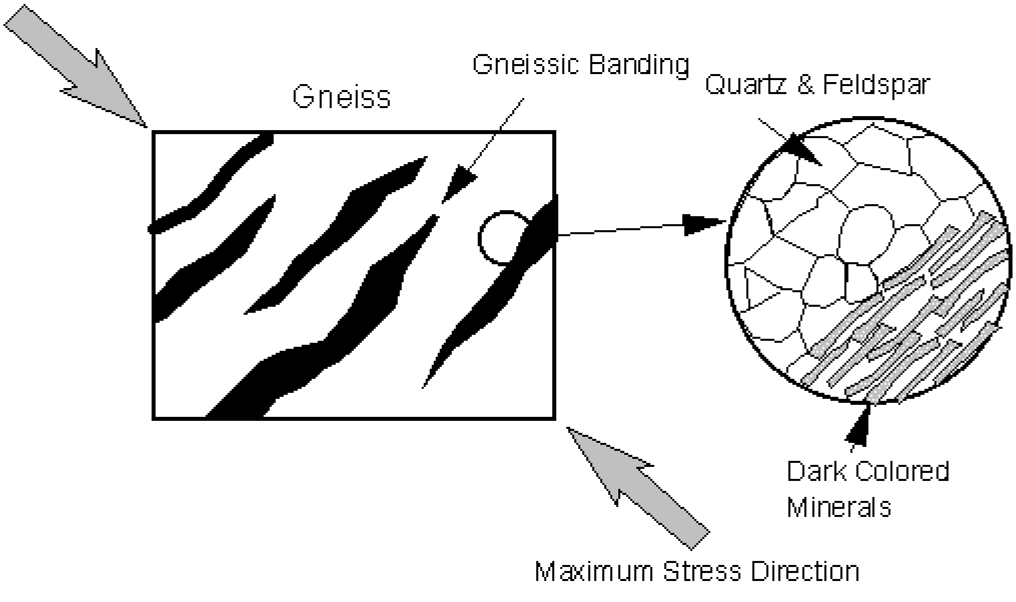
- ***Schist*** - The size of the mineral grains tends to enlarge with increasing grade of metamorphism. Eventually the rock develops a near planar foliation caused by the preferred orientation of sheet silicates (mainly biotite and muscovite). Quartz and Feldspar grains, however show no preferred orientation. The irregular planar foliation at this stage is called ***schistosity***.



Schist often has other minerals besides micas. These include minerals like - Quartz, Feldspars, Kyanite, Garnet, Staurolite, and Sillimanite.

When these non-mica minerals occur with a grain size greater than the rest of the rock, they are called ***pophyroblasts***.

- ***Gneiss*** As metamorphic grade increases, the sheet silicates become unstable and dark colored minerals like hornblende and pyroxene start to grow. These dark colored minerals tend to become segregated in distinct bands through the rock, giving the rock a ***gneissic banding***. Because the dark colored minerals tend to form elongated crystals, rather than sheet- like crystals, they still have a preferred orientation with their long directions perpendicular to the maximum differential stress.



- ***Granulite*** - At the highest grades of metamorphism all of the hydrous minerals and sheet silicates become unstable and thus there are few minerals present that would show a preferred orientation. The resulting rock will have a granulitic texture that is similar to a phaneritic texture in igneous rocks.

- ***Migmatites*** – If the temperature reaches the solidus temperature (first melting temperature), the rock may begin to melt and start to co-mingle with the solids. Usually these melts are felsic with the mafic material remaining metamorphic.

Non-foliated Metamorphic Rocks

Non-foliated rocks lack a planar fabric . Absence of foliation possible for several reasons:

- Rock not subjected to differential stress.

- Dominance of equant minerals (like quartz, feldspar, and garnet).

- Absence of platy minerals (sheet silicates).

Non-foliated rocks are given specific names based on their mineralogy and composition:
Amphibolite - These rocks are dark colored rocks with amphibole (usually hornblende) as their major mineral. They are usually poorly foliated and form at intermediate to high grades of metamorphism of basaltic or gabbroic protoliths.

Hornfels - These are very fine grained rocks that usually form as a result of magma intruding into fined grained igneous rocks or shales. The magma causes a type of metamorphism called contact metamorphism (to be discussed later).

Quartzite - A rock made up almost entirely of quartz. They are formed by metamorphism of quartz arenites (sandstones). Since quartz is stable over a large range of temperatures and pressures, no new minerals are formed during metamorphism, and the only metamorphic effect that occurs is recrystallization of the quartz resulting in interlocking crystals that make up a very hard rock.

Marble - A limestone or dolostone made up only of calcite or dolomite will metamorphose to a marble which is made mostly recrystallized calcite or dolomite. The Recrystallization usually obliterates all fossils. Marbles have a variety of colors and are often complexly banded. They are commonly used as a decorative stone.

Protolith Composition

Although textures and structures of the protolith are usually destroyed by metamorphism, we can still get an idea about the original rock from the minerals present in the metamorphic rock.

Minerals that form, do so because the chemical elements necessary to form them are present in the protolith.

General terms used to describe the chemical composition of both the protolith and the resulting metamorphic rock are:

Pelitic Alumina rich rocks, usually shales or mudstones. These start out originally with clay minerals and as a result of metamorphism, Alumina rich minerals like micas, chlorite, garnet, kyanite, sillimanite and andalusite form. Because of the abundance of sheet silicates, pelitic rocks commonly form slates, phyllites, schists, and gneisses during metamorphism.

Mafic - These are Mg and Fe rich rocks with low amounts of Si. Minerals like biotite, hornblende and plagioclase form during metamorphism and commonly produce amphibolites.

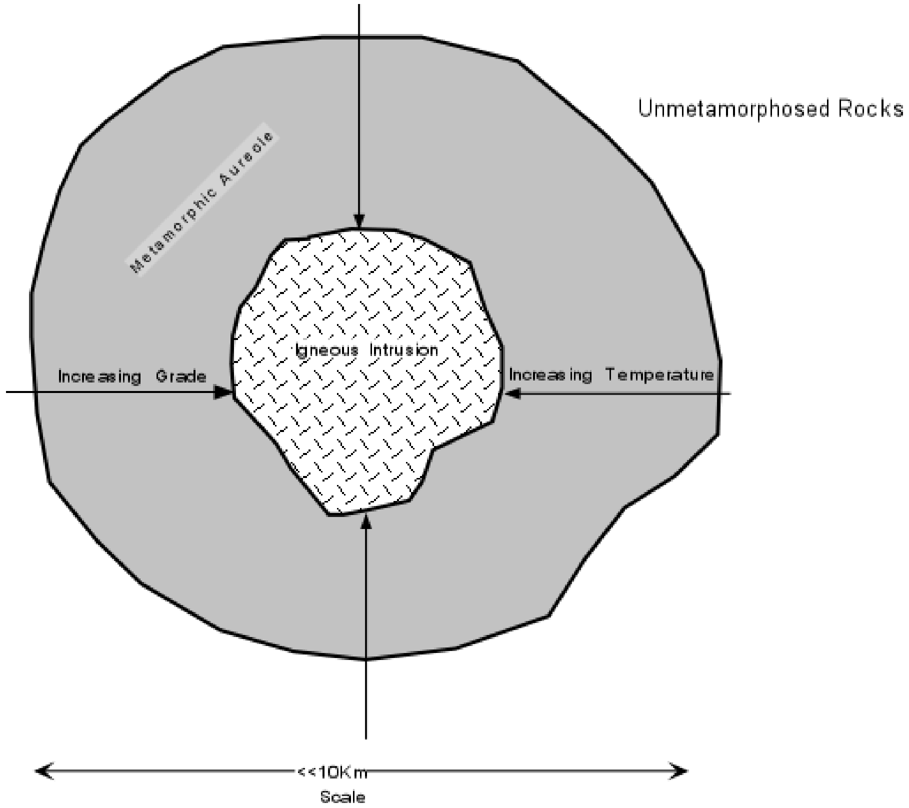
Calcareous - These are calcium-rich rocks usually derived from limestones or dolostones, and thus contain an abundance of Calcite. Marbles are the type of metamorphic rock that results.

Quartzo-Feldspathic - Rocks that contain an abundance of quartz and feldspar fall into this category. Protoliths are usually granites, rhyolites, or arkose sandstones and metamorphism results in gneisses containing an abundance of quartz, feldspar, and biotite.

Types of Metamorphism

Metamorphism can take place in several different environments where special conditions exist in terms of pressure, temperature, stress, conditions, or chemical environments. We here describe several different types of metamorphism that are recognized.

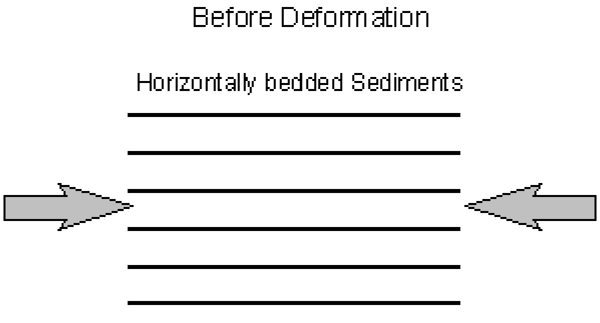
- ***Contact Metamorphism (also called thermal metamorphism)*** - Occurs adjacent to igneous intrusions and results from high temperatures associated with the igneous intrusion. Since only a small area surrounding the intrusion is heated by the magma, metamorphism is restricted to a zone surrounding the intrusion, called a ***metamorphic aureole***. Outside of the contact aureole, the rocks are unmetamorphosed. The grade of metamorphism increases in all directions toward the intrusion. Because temperature differences between the surrounding rock and the intruded magma are larger at shallow levels in the crust, contact metamorphism is usually referred to as high temperature, low pressure metamorphism. The rock produced is often a fine-grained rock that shows no foliation, called a ***hornfels***.

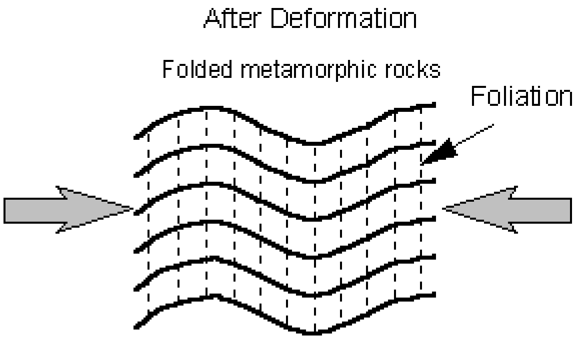


- ***Burial Metamorphism -*** When sedimentary rocks are buried to depths of several hundred meters, temperatures greater than 300°C may develop in the absence of differential stress. New minerals grow, but the rock does not appear to be metamorphosed. The main minerals produced are the Zeolites. Burial metamorphism overlaps, to some extent, with diagenesis, and grades into regional metamorphism as temperature and pressure increase.

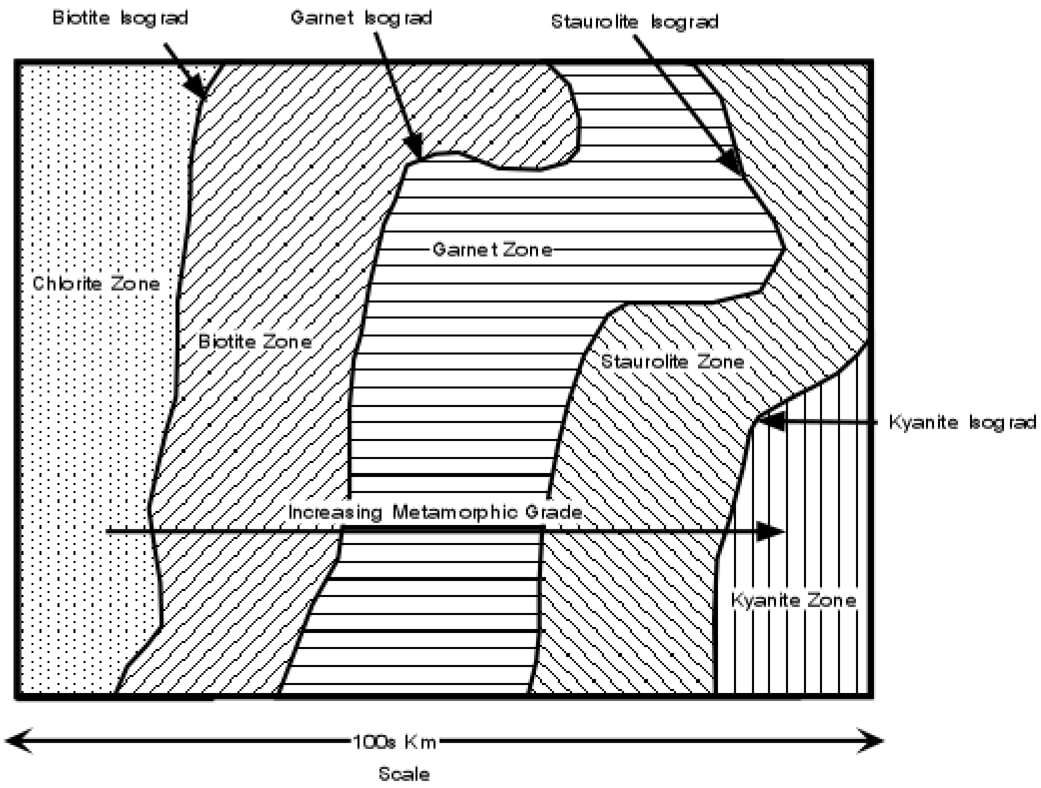
- ***Dynamic Metamorphism*** - This type of metamorphism is due to mechanical deformation, like when two bodies of rock slide past one another along a fault zone. Heat is generated by the friction of sliding along the zone, and the rocks tend to crushed and pulverized due to the sliding. Dynamic metamorphism is not very common and is restricted to a narrow zone along which the sliding occurred. The rock that is produced is called a mylonite.

- ***Regional Metamorphism*** - This type of metamorphism occurs over large areas that were subjected to high degrees of deformation under differential stress. Thus, it usually results in forming metamorphic rocks that are strongly foliated, such as slates, schists, and gneisses. The differential stress usually results from tectonic forces that produce a compression of the rocks, such as when two continental masses collide with one another. Thus, regionally metamorphosed rocks occur in the cores of mountain ranges or in eroded mountain ranges. Compressive stresses result in folding of the rock, as shown here, and results in thickening of the crust which tends to push rocks down to deeper levels where they are subjected to higher temperatures and pressures (See Figure 8.20 in your text).





A map of a hypothetical regionally metamorphosed area is shown in the figure below. Most regionally metamorphosed areas can be divided into zones where a particular mineral, called an ***index mineral,*** is characteristic of the zone. The zones are separated by lines (surfaces in three dimensions) that mark the first appearance of the index mineral. These lines are called ***isograds*** (meaning equal grade) and represent lines (really surfaces) where the grade of metamorphism is equal. A map of a regionally metamorphosed areas are can be seen in figure 8.16 of your text.



Hydrothermal Metamorphism - Near oceanic ridges where the oceanic crust is broken up by extensional faults, sea water can descend along the cracks. Since oceanic ridges are areas where new oceanic crust is created by intrusion and eruption of basaltic magmas, these water-rich fluids are heated by the hot crust or magma and become hydrothermal fluids. The hydrothermal fluids alter the basaltic oceanic crust by producing hydrous minerals like chlorite and talc. Because chlorite is a green colored mineral the rocks hydrothermal metamorphic rocks are also green and often called greenstones.

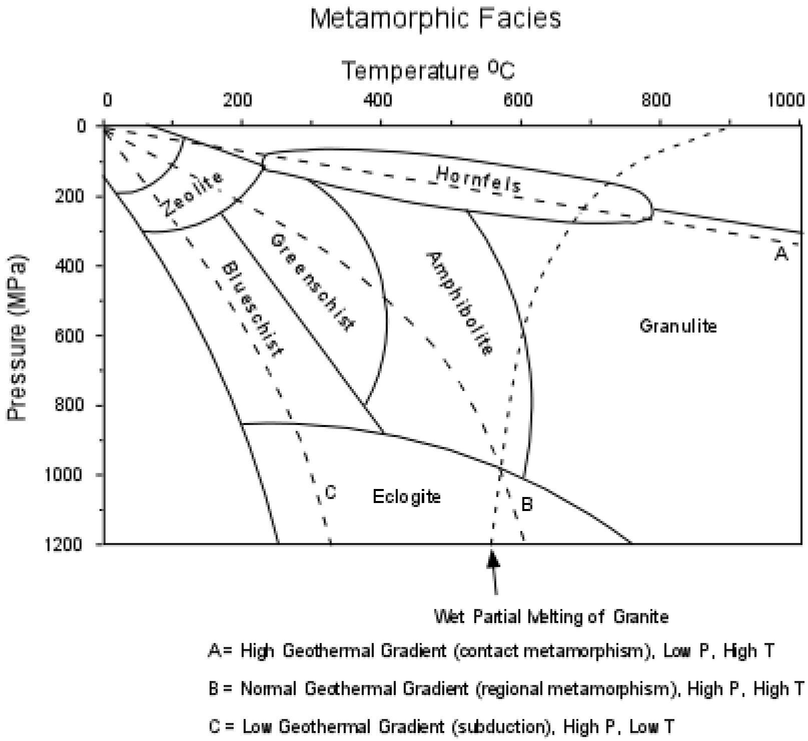
Subduction Related Metamorphism - At a subduction zone, the oceanic crust is pushed downward resulting in the basaltic crust and ocean floor sediment being subjected to relatively high pressure. But, because the oceanic crust by the time it subducts is relatively cool, the temperatures in the crust are relatively low. Under the conditions of low temperature and high pressure, metamorphism produces an unusual blue mineral, glaucophane. Compressional stresses acting in the subduction zone create the differential stress necessary to form schists and thus the resulting metamorphic rocks are called blueschist

Shock Metamorphism - When a large meteorite collides with the Earth, the kinetic energy is converted to heat and a high pressure shock wave that propagates into the rock at the impact site. The heat may be enough to raise the temperature to the melting temperature of the earth rock. The shock wave produces high enough pressure to cause quartz to change its crystal structure to more a dense polymorph like coesite or stishovite. Ancient meteorite impact sites have been discovered on the basis of finding this evidence of shock metamorphism.

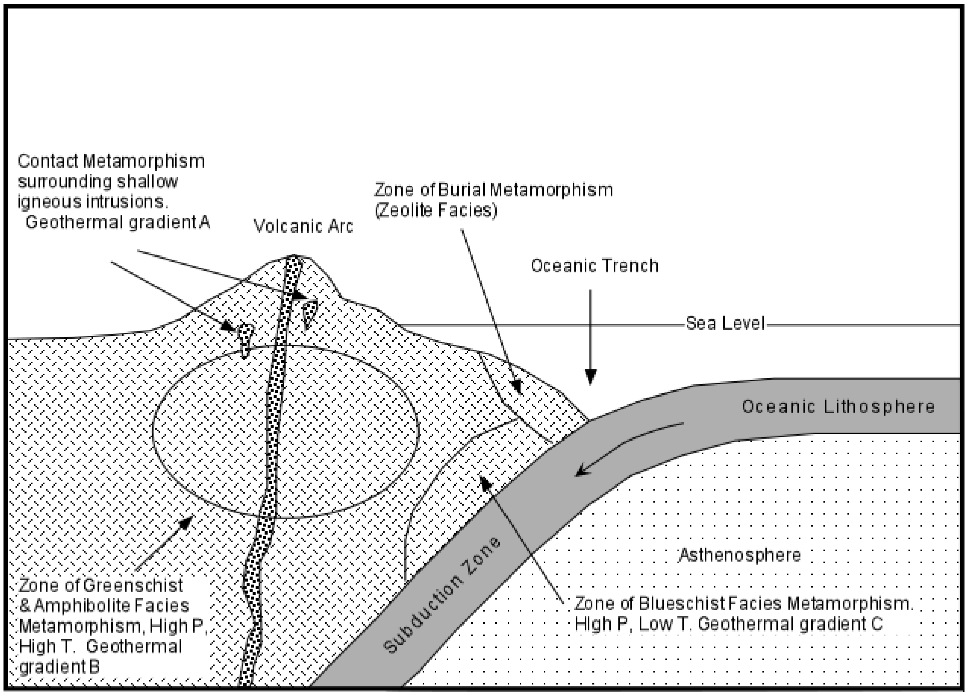
Metamorphic Facies

In general, metamorphic rocks do not undergo significant changes in chemical composition during metamorphism. The changes in mineral assemblages are due to changes in the temperature and pressure conditions of metamorphism. Thus, the mineral assemblages that are observed must be an indication of the temperature and pressure environment that the rock was subjected to. This pressure and temperature environment is referred to as ***Metamorphic Facies.***

The sequence of metamorphic facies observed in any metamorphic terrain, depends on the geothermal gradient that was present during metamorphism. A high geothermal gradient such as the one labeled "A" in the figure shown here, might be present around an igneous intrusion, and would result in metamorphic rocks belonging to the hornfels facies. Under a normal geothermal gradient, such as "B" in the figure, rocks would progress from zeolite facies to greenschist, amphibolite, and eclogite facies as the grade of metamorphism (or depth of burial) increased.



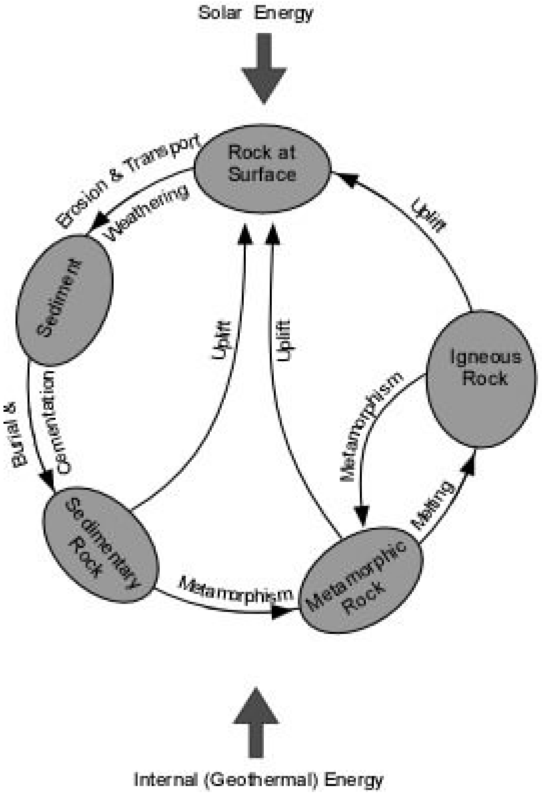
If a low geothermal gradient was present, such the one labeled "C" in the diagram, then rocks would progress from zeolite facies to blueschist facies to eclogite facies. Thus, if we know the facies of metamorphic rocks in the region, we can determine what the geothermal gradient must have been like at the time the metamorphism occurred.



The Rock Cycle

Before moving on to the rest of the course, you should read Interlude C in your textbook (pages 261-268). Now that we have discussed the three types of rocks, it is important to understand how the atoms that make up these rocks cycle through the earth. This cycling involves process that will be discussed in detail throughout the remainder of this course. Since the rock cycle links the rock forming processes to tectonic process and to surface process (most of which will be discussed throughout the rest of the course) , it is important to understand the concept of the rock cycle and the various linkages involved.

- The rock cycle involves cycling of elements between various types of rocks, and thus mostly involves the lithosphere.
- The rock cycle involves the three types of rocks as reservoirs (1) igneous, (2) sedimentary, and (3) metamorphic.
- Chemical elements can reside in each type of rock, and geologic processes move these elements into another type of rock.



- Energy for the parts of the crustal cycle near the Earth's surface is solar and gravitational energy (which control erosion and weathering), whereas
- energy that drives processes beneath the surface is geothermal and gravitational energy (which control uplift, subsidence, melting, and metamorphism).

We here start our discussion with Volcanoes and Volcanic eruptions and processes that are involved in the production of igneous rocks at the earth's surface.

Questions on this material that might be asked on an exam

1. Define the following: (a) geothermal gradient, (b) metamorphism, (c) differential stress, (d) prograde metamorphism, (e) metasomatism (f) protolith, (g) foliation, (i) metamorphic aureole, (j) isograd, (k) greenstone, (l) blueschist.

2. Starting with a shale, describe the textural changes that would occur to the rock during prograde metamorphism with differential stress conditions present.

3. Why is retrograde metamorphism uncommon?
4. Describe the following non-foliated metamorphic rocks (a) amphibolite, (b) quartzite, (c) marble, (d) hornfels.
5. What are the terms used to describe the general chemical composition of metamorphic rocks?. Describe the type of rocks and minerals four nd in each.
6. What are the various types of metamorphism? Describe the rocks produced by each.
7. What is the progression of metamorphic facies that would occur along a high geothermal gradient, a normal geothermal gradient, and a low geothermal gradient.

Return to EENS 1110 Page