EENS 212	Petrology
Prof. Stephen A. Nelson	Tulane University

Metamorphic Rocks- Classification, Field Gradients, & Facies

This document last updated on 31-Mar-2004

Metamorphism is defined as follows:

> **The mineralogical and structural adjustment of solid rocks to physical and chemical conditions that have been imposed at depths below the near surface zones of weathering and diagenesis and which differ from conditions under which the rocks in question originated.**

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

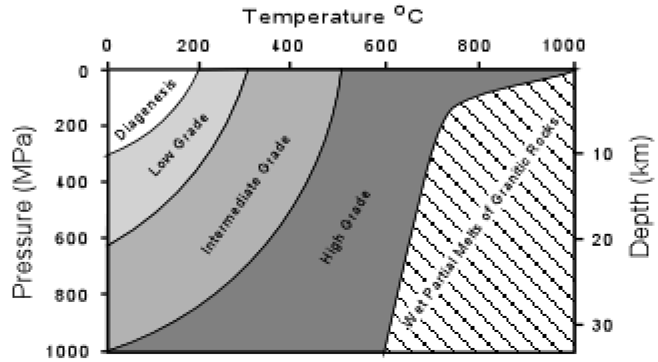
- Note that ***Diagenesis*** is also a change in form that occurs in sedimentary rocks. In geology, however, we restrict diagenetic processes to those which occur at temperatures below 200^{o}C and pressures below about 300 MPa (MPa stands for Mega Pascals), this is equivalent to about 3 kilobars of pressure (1kb = 100 MPa).
- 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 are 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 where melting of the rock in question begins. Once melting begins, the process changes to an igneous process rather than a metamorphic process.

Grade of Metamorphism

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

- Low-grade metamorphism takes place at temperatures between about 200 to 320^{o}C, and relatively low pressure. Low grade metamorphic rocks are generally characterized by an abundance of hydrous minerals**.**

With increasing grade of metamorphism, the hydrous minerals begin to react with other minerals and/or break down to less hydrous minerals.



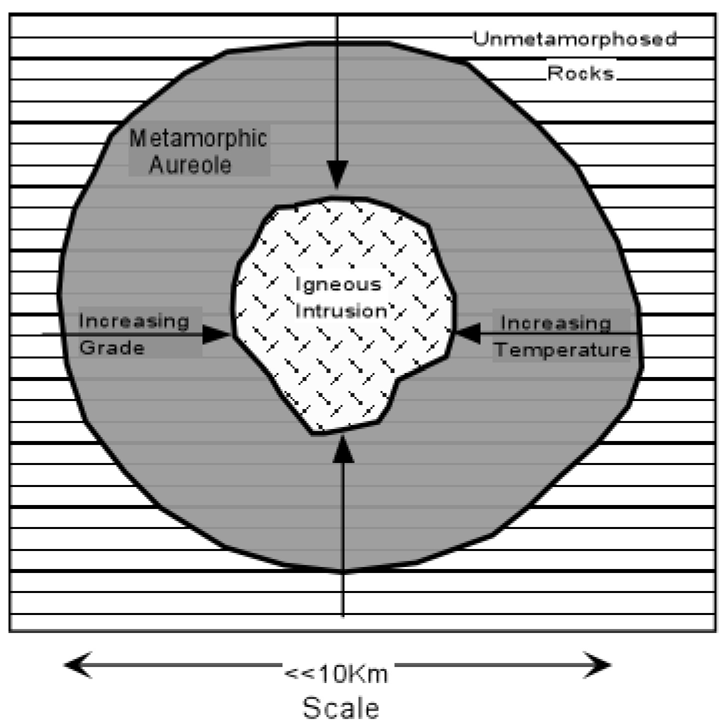
- High-grade metamorphism takes place at temperatures greater than 320°C and relatively high pressure. As grade of metamorphism increases, hydrous minerals become less hydrous, by losing H_2O, and non-hydrous minerals become more common.

Types of Metamorphism

Contact Metamorphism

Contact 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 the zone surrounding the intrusion, called a ***metamorphic*** or ***contact aureole***. Outside of the contact aureole, the rocks are not affected by the intrusive event. The grade of metamorphism increases in all directions toward the intrusion. Because the temperature contrast between the surrounding rock and the intruded magma is larger at shallow levels in the crust where pressure is low, contact metamorphism is often referred to as high temperature, low pressure metamorphism. The rock produced is often a fine-grained rock that shows no foliation, called a ***hornfels***.



Regional Metamorphism

Regional metamorphism occurs over large areas and generally does not show any relationship to igneous bodies. Most regional metamorphism is accompanied by deformation under nonhydrostatic or differential stress conditions. Thus, regional metamorphism usually results in forming metamorphic rocks that are strongly foliated, such as slates, schists, and gniesses. The differential stress usually results from tectonic forces that produce compressional stresses in the rocks, such as when two continental masses collide. Thus, regionally metamorphosed rocks occur in the cores of fold/thrust mountain belts or in eroded mountain ranges. Compressive stresses result in folding of rock and thickening of the crust, which tends to push rocks to deeper levels where they are subjected to higher temperatures and pressures.

Cataclastic Metamorphism

Cataclastic metamorphism occurs as a result of 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 such a shear zone, and the rocks tend to be mechanically deformed, being crushed and pulverized, due to the shearing. Cataclastic metamorphism is not very common and is restricted to a narrow zone along which the shearing occurred.

Hydrothermal Metamorphism

Rocks that are altered at high temperatures and moderate pressures by hydrothermal fluids are hydrothermally metamorphosed. This is common in basaltic rocks that generally lack hydrous minerals. The hydrothermal metamorphism results in alteration to such Mg-Fe rich hydrous minerals as talc, chlorite, serpentine, actinolite, tremolite, zeolites, and clay minerals. Rich ore deposits are often formed as a result of hydrothermal metamorphism.

Burial Metamorphism

When sedimentary rocks are buried to depths of several hundred meters, temperatures greater than 300^oC 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 often the Zeolites. Burial metamorphism overlaps, to some extent, with diagenesis, and grades into regional metamorphism as temperature and pressure increase.

Shock Metamorphism (Impact Metamorphism)

When an extraterrestrial body, such as a meteorite or comet impacts with the Earth or if there is a very large volcanic explosion, ultrahigh pressures can be generated in the impacted rock. These ultrahigh pressures can produce minerals that are only stable at very high pressure, such as the SiO_2 polymorphs coesite and stishovite. In addition they can produce textures known as shock lamellae in mineral grains, and such textures as shatter cones in the impacted rock.

Classification of Metamorphic Rocks

Classification of metamorphic rocks is based on mineral assemblage, texture, protolith, and bulk chemical composition of the rock. Each of these will be discussed in turn, then we will summarize how metamorphic rocks are classified.

Texture
In metamorphic rocks individual minerals may or may not be bounded by crystal faces. Those that are bounded by their own crystal faces are termed ***idioblastic***. Those that show none of their own crystal faces are termed ***xenoblastic***. From examination of metamorphic rocks, it has been found that metamorphic minerals can be listed in a generalized sequence, known as the ***crystalloblastic series***, listing minerals in order of their tendency to be idioblastic. In the series, each mineral tends to develop idioblastic surfaces against any mineral that occurs lower in the series. This series is listed below:

- rutile, sphene, magnetite
- tourmaline kyanite, staurolite, garnet, andalusite
- epidote, zoisite, lawsonite, forsterite
- pyroxenes, amphiboles, wollastonite
- micas, chlorites, talc, stilpnomelane, prehnite
- dolomite, calcite
- scapolite, cordierite, feldspars
- quartz

This series can, in a rather general way, enable us to determine the origin of a given rock. For example a rock that shows euhedral plagioclase crystals in contact with anhedral amphibole, likely had an igneous protolith, since a metamorphic rock with the same minerals would be expected to show euhedral amphibole in contact with anhedral plagioclase.

Another aspect of the crystalloblastic series is that minerals high on the list tend to form ***porphyroblasts*** (the metamorphic equivalent of phenocrysts), although K-feldspar (a mineral that occurs lower in the list) may also form porphyroblasts. Porphyroblasts are often riddled with inclusions of other minerals that were enveloped during growth of the porphyroblast. These are said to have a ***poikioblastic texture***.

Most metamorphic textures involve foliation. Foliation is generally caused by a preferred orientation of sheet silicates. If a rock has a slatey cleavage as its foliation, it is termed a ***slate***, if it has a phyllitic foliation, it is termed a ***phyllite***, if it has a shistose foliation, it is termed a ***schist***. A rock that shows a banded texture without a distinct foliation is termed a ***gneiss***. All of these could be porphyroblastic (i.e. could contain porhyroblasts).

A rock that shows no foliation is called a ***hornfels*** if the grain size is small, and a ***granulite***, if the grain size is large and individual minerals can be easily distinguished with a hand lens.

Protolith
Protolith refers to the original rock, prior to metamorphism. In low grade metamorphic rocks, original textures are often preserved allowing one to determine the likely protolith. As the grade of metamorphism increases, original textures are replaced with metamorphic textures and other clues, such as bulk chemical composition of the rock, are used to determine the protolith.

Bulk Chemical Composition
The mineral assemblage that develops in a metamorphic rock is dependent on

- The pressure and temperature reached during metamorphism
- The composition of any fluid phase present during metamorphism, and

- The bulk chemical composition of the rock.

Just like in igneous rocks, minerals can only form if the necessary chemical constituents are present in the rock (i.e. the concept of silica saturation and alumina saturation applies to metamorphic rocks as well). Based on the mineral assemblage present in the rock one can often estimate the approximate bulk chemical composition of the rock. Some terms that describe this general bulk chemical composition are as follows:

- ***Pelitic***. These rocks are derivatives of aluminous sedimentary rocks like shales and mudrocks. Because of their high concentrations of alumina they are recognized by an abundance of aluminous minerals, like clay minerals, micas, kyanite, sillimanite, andalusite, and garnet.

- ***Quartzo-Feldspathic.*** Rocks that originally contained mostly quartz and feldspar like granitic rocks and arkosic sandstones will also contain an abundance of quartz and feldspar as metamorphic rocks, since these minerals are stable over a wide range of temperature and pressure. Those that exhibit mostly quartz and feldspar with only minor amounts of aluminous minerals are termed quartzo-feldspathic.

- ***Calcareous.*** Calcareous rocks are calcium rich. They are usually derivatives of carbonate rocks, although they contain other minerals that result from reaction of the carbonates with associated siliceous detrital minerals that were present in the rock. At low grades of metamorphism calcareous rocks are recognized by their abundance of carbonate minerals like calcite and dolomite. With increasing grade of metamorphism these are replaced by minerals like brucite, phlogopite (Mg-rich biotite), chlorite, and tremolite. At even higher grades anhydrous minerals like diopside, forsterite, wollastonite, grossularite, and calcic plagioclase.

- ***Basic.*** Just like in igneous rocks, the general term basic refers to low silica content. Basic metamorphic rocks are generally derivatives of basic igneous rocks like basalts and gabbros. They have an abundance of Fe-Mg minerals like biotite, chlorite, and hornblende, as well as calcic minerals like plagioclase and epidote.

- ***Magnesian.*** Rocks that are rich in Mg with relatively less Fe, are termed magnesian. Such rocks would contain Mg-rich minerals like serpentine, brucite, talc, dolomite, and tremolite. In general, such rocks usually have an ultrabasic protolith, like peridotite, dunite, or pyroxenite.

- ***Ferriginous.*** Rocks that are rich in Fe with little Mg are termed ferriginous. Such rocks could be derivatives of Fe-rich cherts or ironstones. They are characterized by an abundance of Fe-rich minerals like greenalite (Fe-rich serpentine), minnesotaite (Fe-rich talc), ferroactinolite, ferrocummingtonite, hematite, and magnetite at low grades, and ferrosilite, fayalite, ferrohedenbergite, and almandine garnet at higher grades.

- ***Manganiferrous.*** Rocks that are characterized by the presence of Mn-rich minerals are termed manganiferrous. They are characterized by such minerals as Stilpnomelane and spessartine.

Classification

Classification of metamorphic rocks depends on what is visible in the rock and its degree of metamorphism. Note that classification is generally loose and practical such that names can be adapted to describe the rock in the most satisfactory way that conveys the important characteristics. Three kinds of criteria are normally employed. These are:

1. Mineralogical - The most distinguishing minerals are used as a prefix to a textural term. Thus, a schist containing biotite, garnet, quartz, and feldspar, would be called a biotite-garnet schist. A gneiss containing hornblende, pyroxene, quartz, and feldspar would be called a hornblende-pyroxene gneiss. A schist containing porphyroblasts of K-feldspar would be called a K-spar porphyroblastic schist.

2. Chemical - If the general chemical composition can be determined from the mineral assemblage, then a chemical name can be employed. For example a schist with a lot of quartz and feldspar and some garnet and muscovite would be called a garnet-muscovite quartzo-feldspathic schist. A schist consisting mostly of talc would be called a talc-magnesian schist.
3. Protolithic - If a rock has undergone only slight metamorphism such that its original texture can still be observed then the rock is given a name based on its original name, with the prefix meta- applied. For example: metabasalt, metagraywacke, meta-andesite, metagranite.

In addition to these conventions, certain non-foliated rocks with specific chemical compositions and/or mineral assemblages are given specific names. These are as follows:

- ***Amphibolites***: These are medium to coarse grained, dark colored rocks whose principal minerals are hornblende and plagioclase. They result from metamorphism of basic igneous rocks. Foliation is highly variable, but when present the term schist can be appended to the name (i.e. amphibolite schist).
- ***Marbles***: These are rocks composed mostly of calcite, and less commonly of dolomite. They result from metamorphism of limestones and dolostones. Some foliation may be present if the marble contains micas.
- ***Eclogites***: These are medium to coarse grained consisting mostly of garnet and green clinopyroxene called omphacite, that result from high grade metamorphism of basic igneous rocks. Eclogites usually do not show foliation.

Quartzites: Quartz arenites and chert both are composed mostly of SiO_2. Since quartz is stable over a wide range of pressures and temperatures, metamorphism of quartz arenites and cherts will result only in the recrystallization of quartz forming a hard rock with interlocking crystals of quartz. Such a rock is called a quartzite.

Serpentinites: Serpentinites are rocks that consist mostly of serpentine. These form by hydrothermal metamorphism of ultrabasic igneous rocks.

Soapstones: Soapstones are rocks that contain an abundance of talc, which gives the rock a greasy feel, similar to that of soap. Talc is an Mg-rich mineral, and thus soapstones from ultrabasic igneous protoliths, like peridotites, dunites, and pyroxenites, usually by hydrothermal alteration.

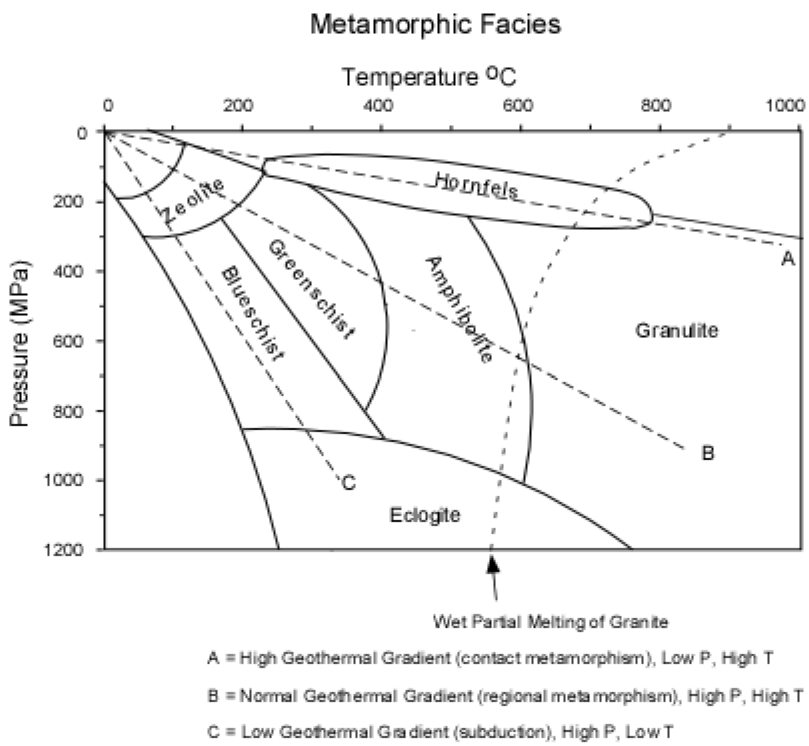
Skarns: Skarns are rocks that originate from contact metamorphism of limestones or dolostones, and show evidence of having exchanged constituents with the intruding magma. Thus, skarns are generally composed of minerals like calcite and dolomite, from the original carbonate rock, but contain abundant calcium and magnesium silicate minerals like andradite, grossularite, epidote, vesuvianite, diopside, and wollastonite that form by reaction of the original carbonate minerals with silica from the magma. The chemical exchange is that takes place is called ***metasomatism.***

- ***Mylonites:*** Mylonites are cataclastic metamorphic rocks that are produced along shear zones deep in the crust. They are usually fine-grained, sometimes glassy, that are streaky or layered, with the layers and streaks having been drawn out by ductile shear.

Metamorphic Facies

In general, metamorphic rocks do not drastically change chemical composition during metamorphism, except in the special case where metasomatism is involved (such as in the production of skarns, as discussed above). 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.*** (This is similar to the concept of sedimentary facies, in that a sedimentary facies is also a set of environmental conditions present during deposition). 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" , might be present around an igneous intrusion, and would result in metamorphic rocks belonging to the hornfels facies. Under a normal to high geothermal gradient, such as "B", 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.



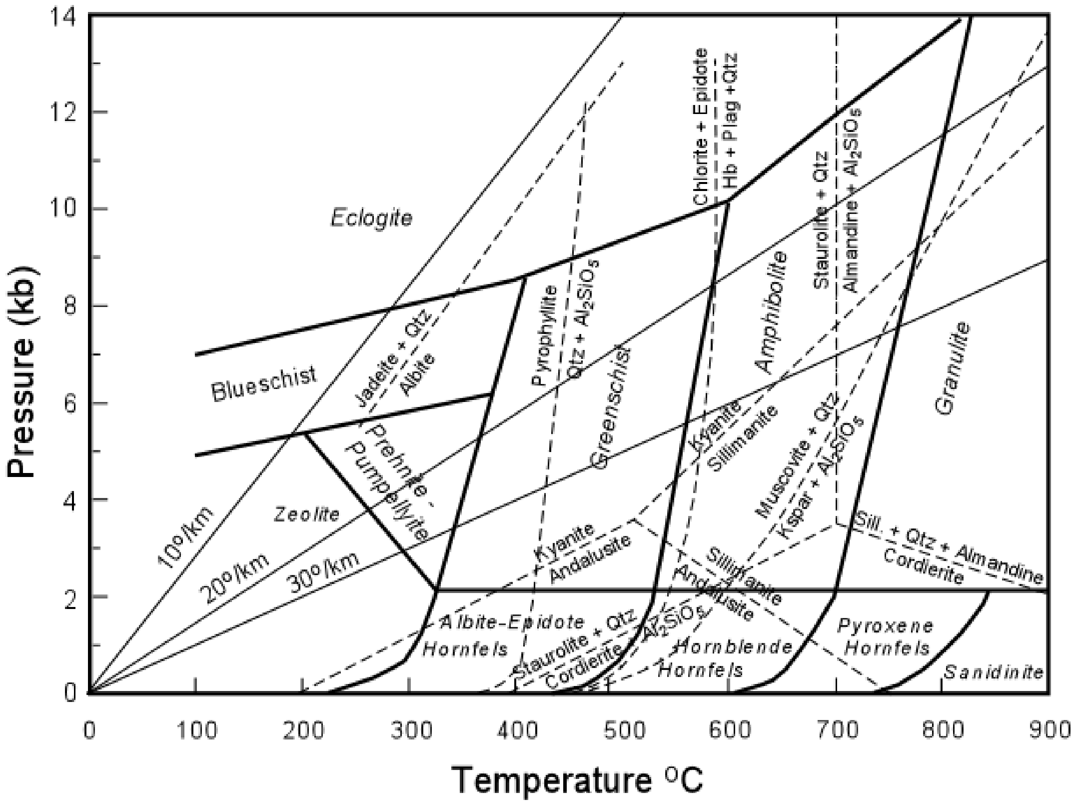
Thus, if we know the facies of metamorphic rocks in the region, we can determine what the geothermal gradient must have been like at the time the metamorphism occurred. This relationship between geothermal gradient and metamorphism will be the central theme of our discussion of metamorphism.

The facies concept was developed by Eskola in 1939. The names of Eskola's facies are based on mineral assemblages found in metabasic basic rocks.

- Thus, since basic rocks metamorphosed to the greenschist facies contain the green minerals, chlorite and actinolite, along with other minerals like plagioclase, biotite, and garnet, the rocks were called greenschists.
- Basic rocks metamorphosed to the blueschist facies contain the blue sodic amphibole, gluacophane (along with garnet and lawsonite) are thus blueschists.
- Basic rocks metamorphosed to the amphibolite facies are amphibolites, containing mostly hornblende and plagioclase.
- Basic rocks metamorphosed to the eclogite facies are eclogites, containing the green sodic pyroxene called omphacite and garnet.
- The granulite and hornfels facies were named after the textures of the rocks, with hornfels being the rocks commonly found in contact metamorphic aureoles (high temperature, low pressure environments) and granulites being coarse grained rocks with a granulitic texture and being generally free of hydrous minerals.
- The Zeolite facies was introduced well after Eskola first developed the facies concept, but, was its name is consistent with Eskola's original concept in that zeolite facies metamorphic rocks include basic rocks containing zeolite minerals.

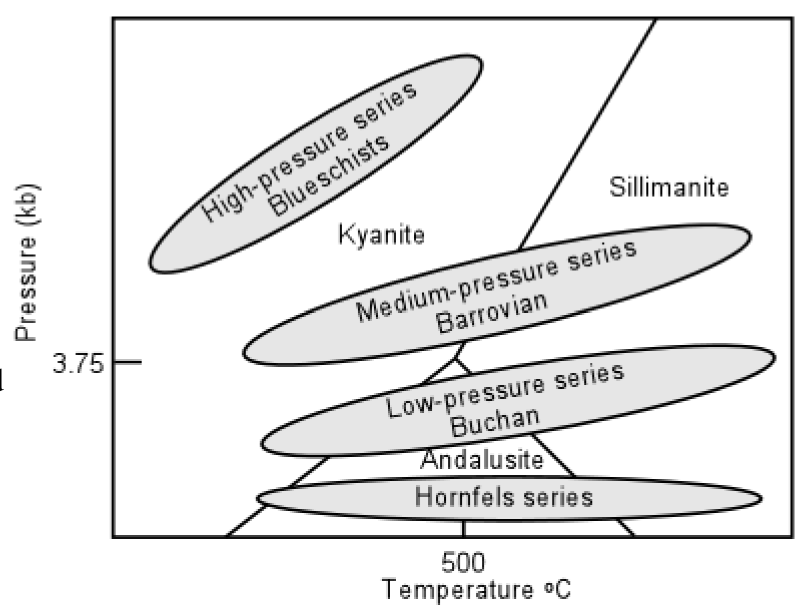
Estimating Pressure and Temperature of Metamorphism

Using combinations of reactions that have likely taken place during metamorphism, petrologists have been able over the years to determine the pressure and temperature of metamorphism in a variety of rocks, and in so doing have been able to place constraints on the fields of temperature and pressure for the various metamorphic facies. Some of these reactions that have been determined experimentally, are shown in the diagram below with reaction boundaries superimposed over the facies diagram.



The diagram also shows various geothermal gradients that would control the succession of facies encountered during prograde metamorphism if the rocks were pushed down into the Earth along one of these geothermal gradients.

- A low geothermal gradient of around 10^{o}/km would cause prograde metamorphism to occur along a sequence of facies from zeolite to blueschist to eclogite. Such a progression is termed a facies series, and in general terms this would be called a high pressure facies series, as shown in the diagram below. Such a facies series would be expected in areas near subduction zones where cool lithosphere is pushed to higher pressure.
- A geothermal gradient of around 30^{o}/km, expected in areas undergoing an orogenic event, would produce a succession of facies from zeolite to prehnite pumpellyite to greenschist to amphibolite to granulite. Note that in pelitic rocks of this series, the Al_2SiO_5 minerals would change from kyanite to sillimanite somewhere in the amphibolite facies. This facies series is termed the Medium pressure series or Barrovian facies series.



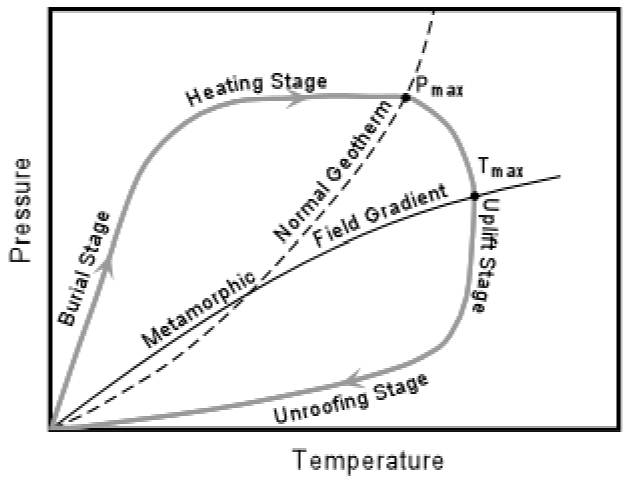
Note that a slightly higher geothermal gradient would produce the same succession of facies, but pelitic rocks would show a change in the Al_2SiO_5 minerals from kyanite to andalusite to sillimanite. This facies series is called the Low-pressure series or Buchan facies series.

- Along very high geothermal gradients, such as might be expected in the vicinity of intruding magmas the succession of facies would increase from the albite-epidote hornfels facies to the hornblende hornfels facies to pyroxene hornfels and sanidinite facies, the facies of contact metamorphism. This facies series is called the hornfels facies series or the contact facies series.

Metamorphic Field Gradients

As rocks are pushed deeper into the Earth as a result of tectonism, they will encounter four stages during which temperature and pressure change in the rock in different ways.

- During the burial stage the effects of increasing pressure are encountered by the rock immediately as depth of burial increases. But increasing temperature will take time, because heat has to be conducted into the rock in order to increase the temperature to that of the surroundings. So, the rock will follow a path resembling a low geothermal gradient.



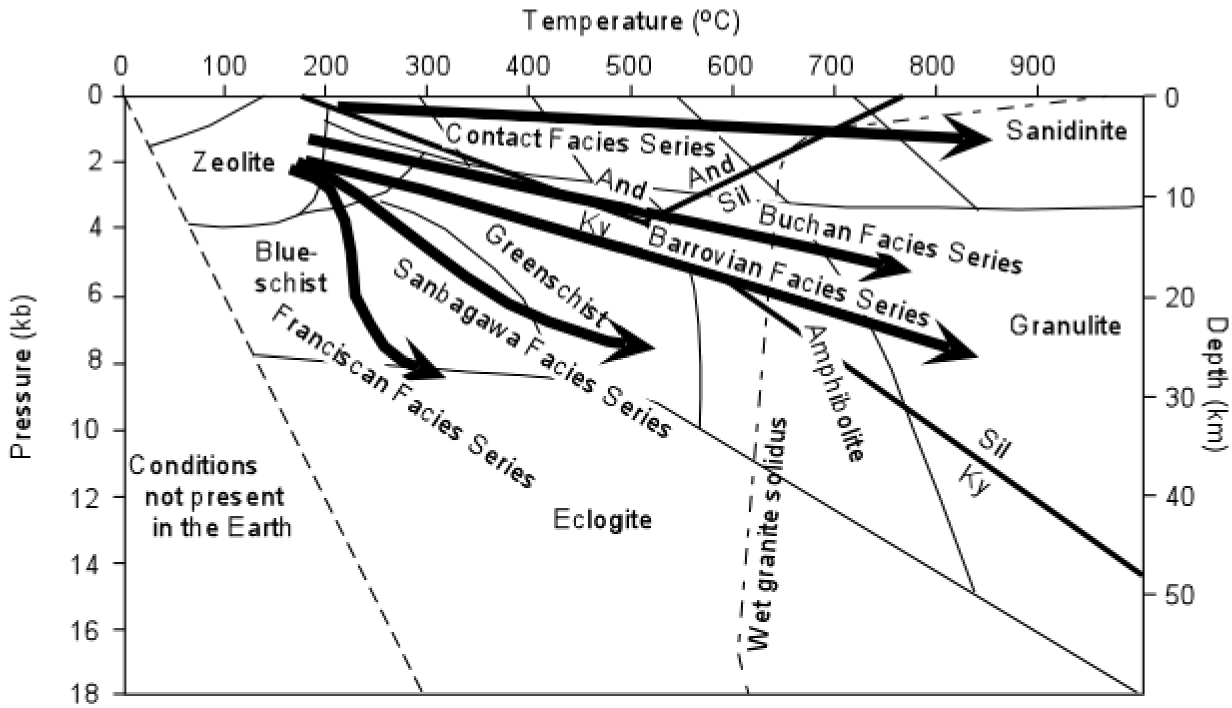
- When the rocks are nearly buried to their maximum depth, heat conducted from below will cause an increase in temperature and the rock will undergo a heating stage at a pressure equivalent to the maximum pressure encountered by the rock. Along this path the rock will encounter the temperature and pressure of the regional geothermal gradient and will also encounter the maximum pressure of metamorphism.

- As rocks heat up, they will decrease in density, and thus there will be an isostatic response to the heating, wherein the rocks will begin to rise resulting in uplift of the overlying rock. Uplift alone will not cause a decrease in pressure, but erosion of the uplifted region will remove material and eventually pressure will start to decrease. During this uplift stage, the rocks will continue to gain temperature because they are expanding and they are carrying heat with them. At some point during this uplift stage, the maximum temperature will be encountered.

- The unroofing stage occurs when erosion rates become high enough that pressure starts to decrease. As rocks move to a lower pressure environment heat will conducted into their surroundings and temperature will decrease to that present on the surface.

Since chemical equilibrium will be controlled more by temperature than by pressure, the mineral assemblages will reflect those stable at the maximum temperature, but not necessarily the maximum pressure. Thus, the geothermal gradient deduced from a series of rocks in any area will reflect a thermal gradient somewhat higher than the true geothermal gradient. To distinguish between the true geothermal gradient and that deduced from the facies series, the deduced geothermal gradient is called the ***metamorphic field gradient***.

Metamorphic field gradients can also be used to define metamorphic facies series for specific metamorphic belts, as shown in the diagram below. Here, in addition to the contact, Buchan, and Barrovian Series, discussed above, are shown the facies series and metamorphic field gradients deduced for the Franciscan rocks in California and the Sanbagawa belt rocks of Japan. These will be discussed in more detail in our lecture on regional metamorphism.



Return to EENS 212 Home Page