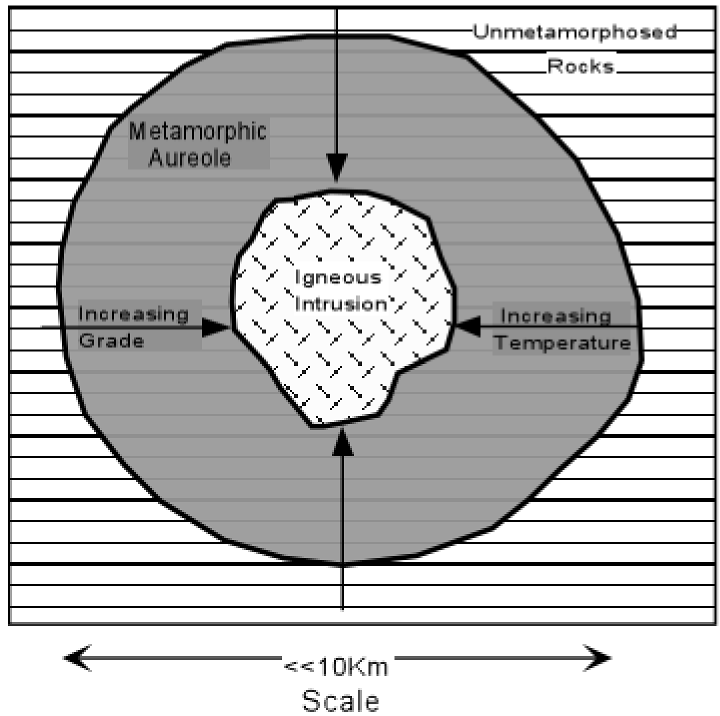
Lecture notes,2nd semester unit-3
Contact Metamorphism and Metamorphic Rocks

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 non-hydrostatic 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^{o}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 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.

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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.

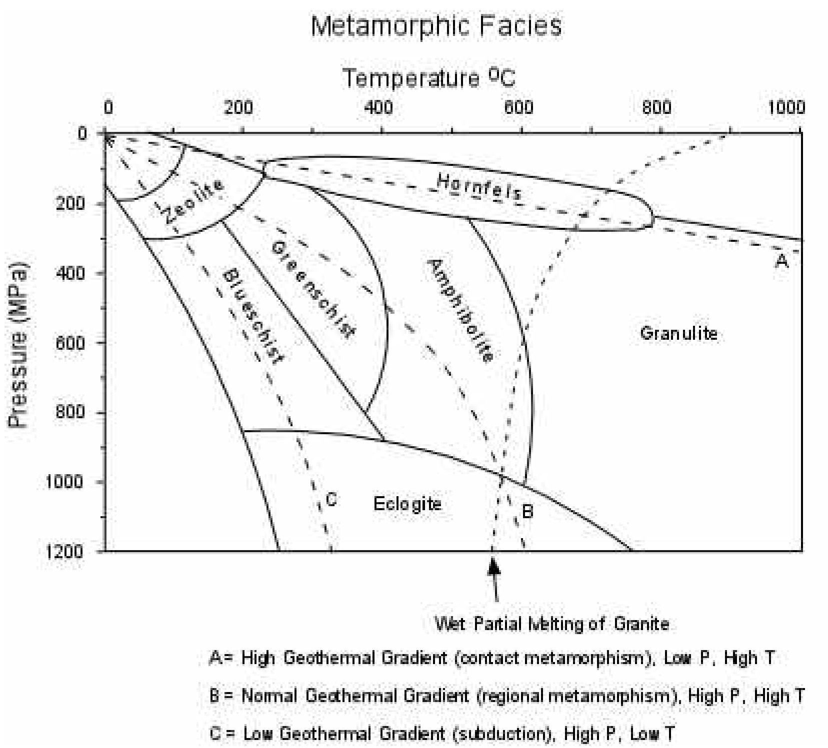
- ***Skarns:*** Skarns are rocks that originate from contact metamorphism of limestones or dolostones, and show evidence of having exchanged constituents with the intruding magma. Thus, skarns are generally composed of minerals like calcite and dolomite, from the original carbonate rock, but contain 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.

(COMPILED BY GDC HANDWARA)

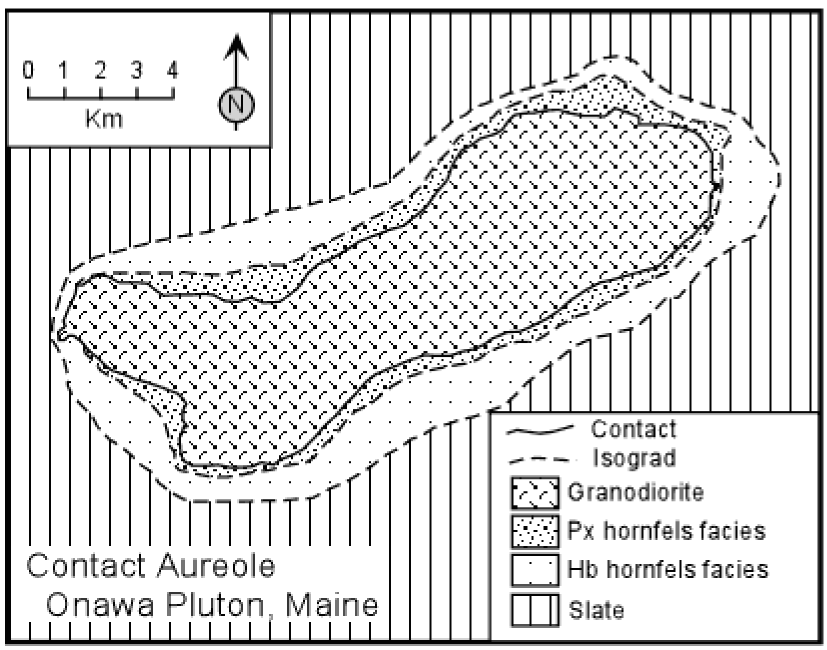
CONTACT METAMORPHISM

As discussed previously, contact metamorphism occurs as a result of a high geothermal gradient produced locally around intruding magma. Contact metamorphism is usually restricted to relatively shallow depths (low pressure) in the Earth because it is only at shallow depths where there will be a large contrast in temperature between the intruding magma and the surrounding country rock. Also, since intrusion of magma does not usually involve high differential stress, contact metamorphic rocks do not often show foliation. Instead, the common rocks types produced are fine grained idioblastic or hypidioblastic rocks called hornfels. The area surrounding an igneous intrusion that has been metamorphosed as a result of the heat released by the magma is called a contact aureole. We will here first discuss contact aureoles, then look at the facies produced by contact metamorphism.

Contact Aureoles

Within a contact metamorphic aureole the grade of metamorphism increases toward the contact with the igneous intrusion.

An example of a contact aureole surrounding the Onawa Pluton in Maine is shown here. The granodiorite pluton was intruded into slates produced by a prior regional metamorphic event. The aureole is a zone ranging in width from about 0.5 to 2.5 km around the intrusion. Two zones representing different contact metamorphic facies are seen within the aureole. The outer zone contains metapelites in the Hornblende Hornfels Facies, and the zone adjacent to the pluton contains metapelites in the Pyroxene Hornfels Facies. The zones are marked by an ***isograd***, which represents a surface along which the grade of metamorphism is equal.



After Philbrick (1936) & Moore, 1960)

The size of a contact aureole depends on a number of factors that control the rate at which heat can move out of the pluton and into the surrounding country rock. Among these factors are:

- The size and temperature of the intrusion. This will control how much heat is available to heat the surrounding country rocks.

- The thermal conductivity of the surrounding rocks. This will control the rate at which heat can be transferred by conduction into the surrounding rocks. In general, the rate of heat flow Q, depends on the thermal conductivity, K, and the temperature gradient, $(\partial T/\partial x)$

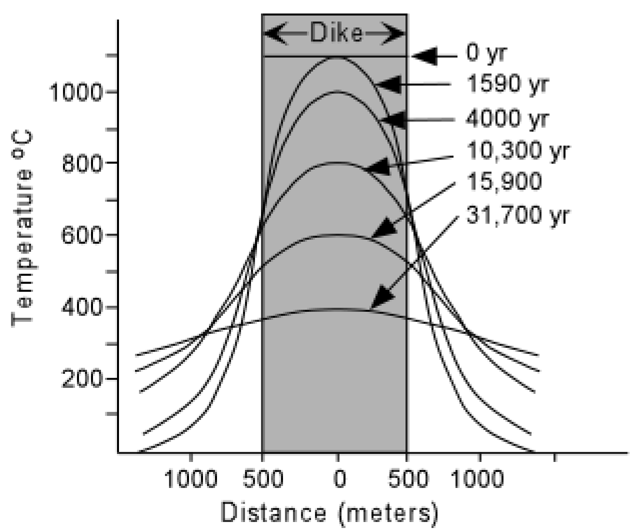
$$Q = K(\partial T/\partial x)$$

Thus, the rate at which heat moves by conduction increases if the thermal conductivity and temperature gradient are higher.

- The initial temperature within the country rock. This, in combination with the temperature of the intrusion, will determine the initial temperature gradient, and thus the rate at which heat can flow into the surrounding country rocks.
- The latent heat of crystallization of the magma. As you recall, the total amount of heat available in a liquid is not only dependent on the temperature, but also involves the heat released due to crystallization. Thus, if the latent heat of crystallization is large, their will be more heat available to heat the surrounding country rocks.
- The heat of metamorphic reactions. In order for a metamorphic reaction to take place some heat is necessary and this heat will be absorbed by the reactions without increasing the temperature in the intrusion.
- The amount of water in and the permeability of the surrounding country rock. If the country rock is permeable and contains groundwater, heat will be able to move by convection.

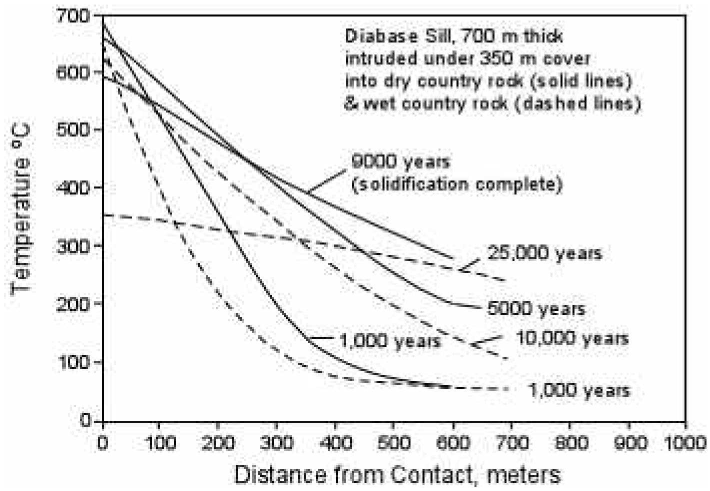
Solutions to the heat equation given above are complicated because most the terms in the equation are functions of temperature, time, and position. Solutions for a simple case are shown below.

In this simple case a basaltic dike is assumed to have intruded at temperature of 1100^{o}C, into dry country rock at a temperature of 0^{o}C. The width of dike is assumed to be 1000 m, and the latent heat of crystallization is assumed to be released between 1100^{o} and 800^{o}. Solidification of the intrusion is thus complete at 800^{o}, after 10,300 years. Note how the temperature of the country rock near the contact reaches a maximum of about 600^{o} after about 1600 years, and how the temperature in the country rock at distances greater than about 700 m from the center of the dike continues to rise, while temperatures near the contact drops.



The model above assumes that all heat moves by conduction. If the country rock is saturated with water or the pluton expels water, and if the country rock is permeable, then the heat will move into the country rock by convection. Water will be heated near the contact and carry heat outward and away where it will eventually cool to return to the contact to carry more heat away.

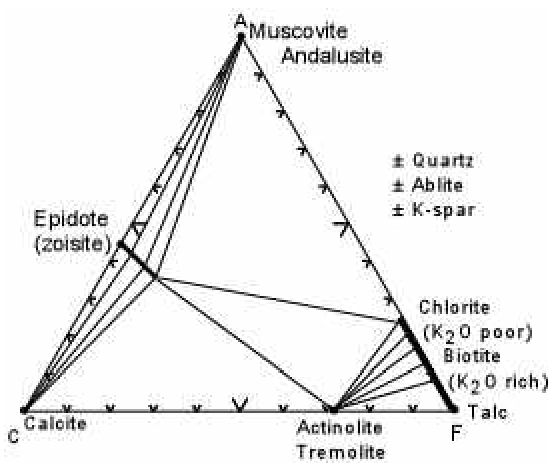
To show these effects, a model was developed for a diabase sill 700 m thick, intruded under 350 m of cover into both dry and wet country rock. The results show that the temperature gradient developed in the country rock will be higher under dry country rock conditions, and the actual temperature attained in the country rock at any position will be slightly less under wet conditions than under dry conditions. Thus, the size of the aureole will be smaller if the heat is removed and distributed by convection.



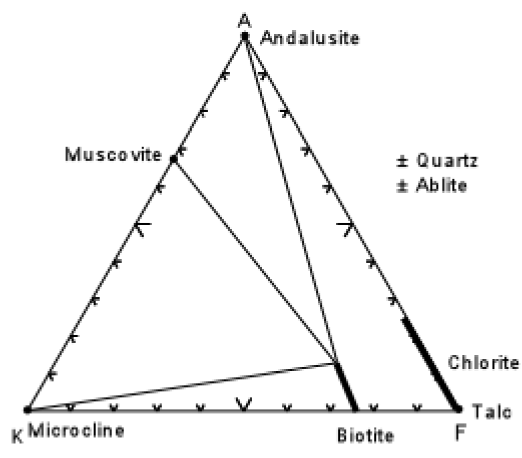
Facies of Contact Metamorphism

The facies of contact metamorphism progress in temperature at relatively low pressure from the Albite-Epidote Hornfels Facies to the Hornblende Hornfels Facies, to the Pyroxene Hornfels Facies. Xenoliths picked up by the magma may be metamorphosed to the Sanidinite Facies, but such rocks are relatively rare. In this lecture we will look at the mineral assemblages that develop in these contact metamorphic facies.

Albite - Epidote Hornfels Facies



Albite-Epidote Hornfels Facies



Albite-Epidote Hornfels Facies

Pelitic rocks will be characterized by an assemblage of

- quartz, albite, epidote, muscovite or andalusite, chlorite, biotite

Quartzo-feldspathic rocks will be characterized by an assemblage of

- microcline, quartz, muscovite, albite, and biotite.

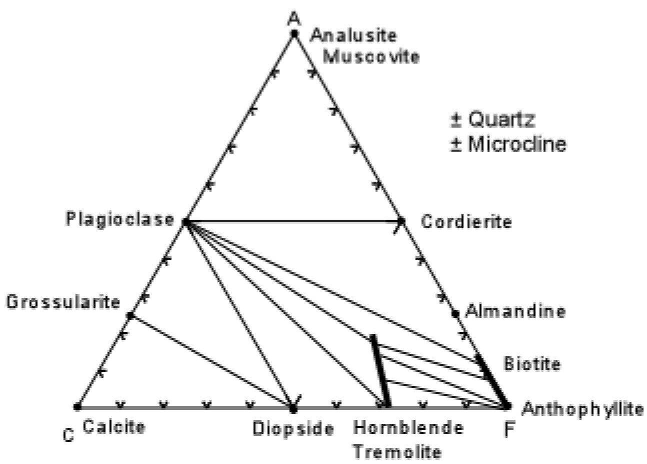
Basic rocks will contain

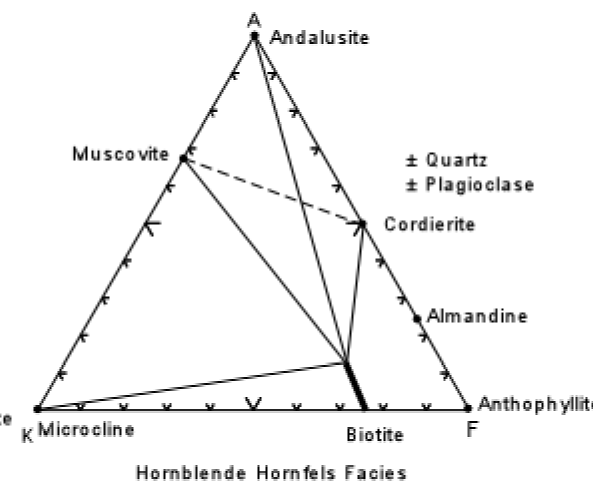
- actinolite, epidote, chlorite, and/or biotite, and possibly talc, and may contain quartz and albite.

Calcareous rocks will consist of

- calcite, epidote and tremolite, with possibly quartz.

Hornblende-Hornfels Facies





Pelitic rocks will be characterized by an assemblage of

- quartz, plagioclase, muscovite or andalusite, cordierite, or
- quartz, plagioclase cordierite, muscovite, and biotite

  Note the absence of epidote and chlorite in these assemblages.

Quartzo-feldspathic rocks will be characterized by an assemblage of

- microcline, quartz, muscovite, plagioclase and biotite and possibly almandine.

Basic rocks will likely contain

- plagioclase, biotite, and possibly almandine, and may contain quartz, anthophyllite & cordierite

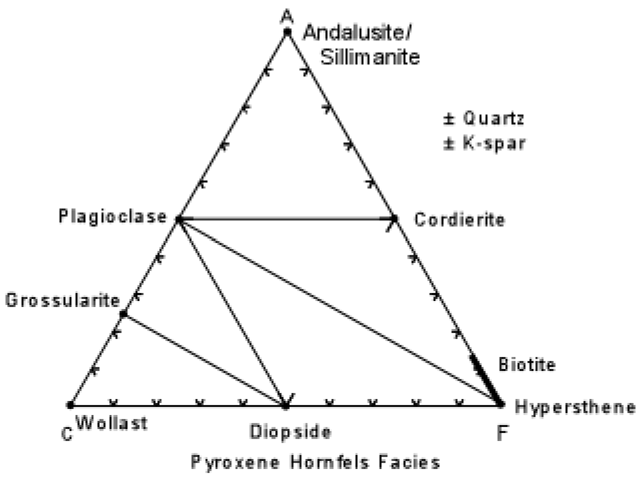
  Note the absence of epidote and actinolite.

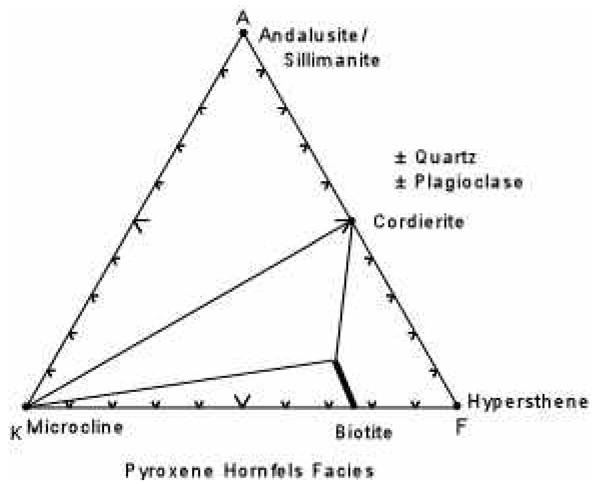
Calcareous rocks will consist of

- plagioclase, grossularite, and tremolite and possibly quartz, or
- calcite, diopside, and grossularite with possibly quartz.

  Note the absence of epidote.

Pyroxene-Hornfels Facies





Pelitic rocks will be characterized by an assemblage of

- quartz, plagioclase, K-spar, andalusite or sillimanite, and cordierite

  Note the absence of muscovite.

Quartzo-feldspathic rocks will be characterized by an assemblage of

- K-spar, quartz, plagioclase and biotite

  Again note the absence of muscovite

Basic rocks will likely contain

- plagioclase, cordierite, and biotite and possibly quartz, or
- plagioclase, hypersthene, biotite, and diopside, and possibly quartz.

  Note the absence of hornblende in the these assemblages.

Calcareous rocks will consist of

- plagioclase, grossularite, and diopside and possibly quartz, or
- wollastonite, diopside, and grossularite with possibly quartz.

  Note the absence of calcite and tremolite in these assemblages.

Sanidinite Facies
The sanidinite facies is relatively rare in contact metamorphic aureoles, although it is somewhat more common in rocks found as xenoliths in igneous rocks. It represents the highest conditions of temperature. The facies is characterized by the absence of hydrous minerals, particularly micas.

- Pelitic and quartzo-feldspathic rocks contain unusual phases like mullite ($3Al_2O_3 \cdot 2SiO_2$), along with sanidine, cordierite, anorthite, hypersthene, and sillimanite or corundum. Sometimes tridymite is present in place of quartz.
- Basic rocks of the sanidinite facies are more common, and are often found along the conduit walls of dikes. Several assemblages have been reported.

  augite, hypersthene, calcic plagioclase, brookite, and tridymite

  olivine, augite, plagioclase, magnetite, and ilmenite (similar to an igneous mineral assemblage)

  hypersthene, plagioclase, magnetite, ilmenite, psuedobrookite

  cordierite, plagioclase, magnetite, hematite, psuedobrookite

  some rare aluminous basic rocks have also been found with
  corundum and hematite

  corundum, mullite, and hematite, sometimes with cristobalite or tridymite

  corundum, mullite, hercynite ($FeAl_2O_4$), sometimes with cordierite and cristobalite or tridymite

- Calcareous rocks contain various assemblages with rare minerals. Among the assemblages observed are:

  wollastonite, anorthite, and diopside

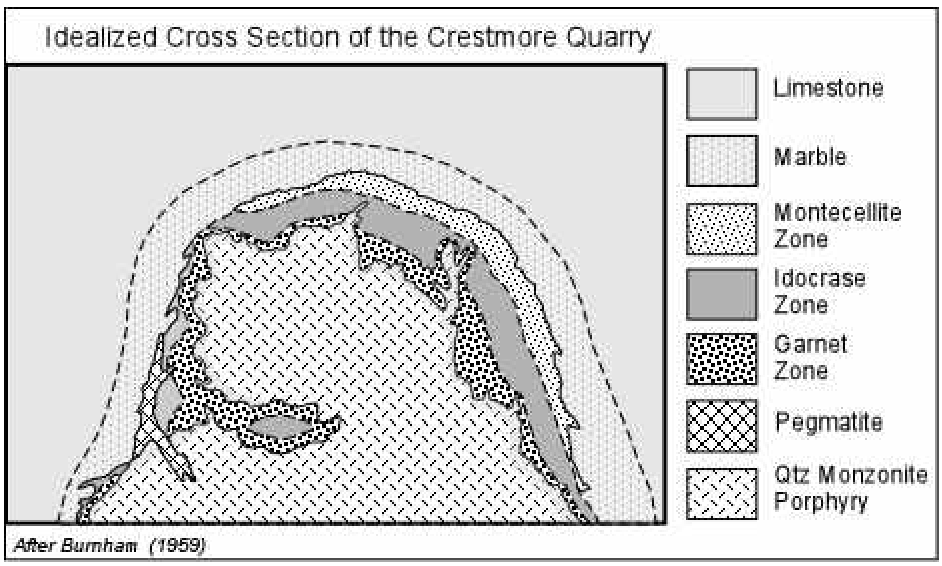
wollastonite, mellilite ($[Ca,Na]_2[Mg,Fe,Al,Si]_3O_7$), and

calcite, larnite (Ca_2SiO_4), along with the rare minerals brownmillerite ($Ca_2[Al,Fe]_2O_5$) and mayenite ($Ca_{12}Al_{14}O_{33}$)

Skarns

Sometimes when a siliceous magma intrudes carbonate rocks like limestone and dolostone, significant chemical exchange (metasomatism) takes place between the magma and the carbonate rock. Such a metasomatized rock is refered to as skarn. An excellent example of a skarn occurs in the Crestmore quarry near San Diego, California.

Here, quartz monzonite intruded an Mg-rich limestone. Metamorphism and metasomatism produced four zones near the contact three ranging in size from 3 cm to 15 m in width. The outer zone consists of calcite marble or calcite - brucite [$MgOH_2$] marble, showing little metasomatism.



Closer to the contact is the montecellite zone. This zone consists of calcite, montecellite [$Ca(Mg,Fe)SiO_4$] and one or more of the minerals clinohumite [$Mg(OH,F)_2 \cdot 4Mg_2SiO_4$], forsterite, mellilite, spurrite [$2Ca_2SiO_4.CaCO_3$], tilleyite [$Ca_3Si_2O_7 \cdot 2CaCO_3$], and merwinite [$Ca_3MgSi_2O_8$]

Interior to the montecellite zone is the idocrase zone, consisting of idocrase [$Ca_{19}(Al,Fe)_{10}(Mg,Fe)_3Si_{18}O_{68}(OH,F)_{10}$] in association with calcite, diopside, wollastonite, phlogopite (Mg-rich biotite), montecellite, and xanthophyllite [$Ca_2(Mg,Fe)_{4.6}Al_{6.9}Si_{2.5}O_{20}(OH)_4$].

Next to the contact is the garnet zone consisting of grossularite garnet, diopside, wollastonite, and miner calcite and quartz.

A thin zone along the contact shows evidence of assimilation of the limestone by the magma.

The ratio of Si to Ca and the concentration of Al all increase toward the contact, indicating that the limestone received these components from the magma.

(COMPILED BY GDC HANDWARA)

Lecture notes,2nd semester,unit-3

METAMORPHISM AND METAMORPHIC ROCKS

Definition of Metamorphism

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 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^oC 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^oC 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.

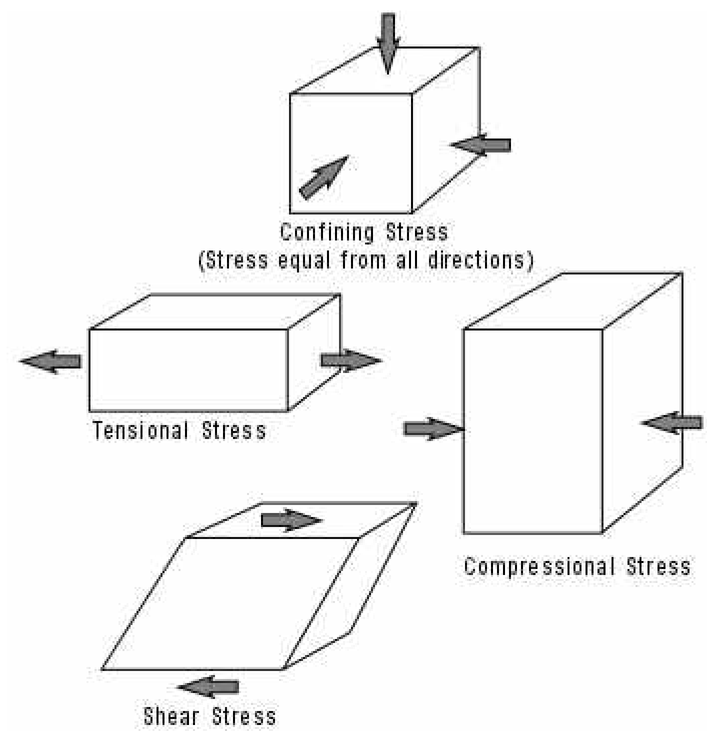
During metamorphism the protolith undergoes changes in texture of the rock and the mineral make up of the rock. These changes take place mostly in the solid state and are caused by changes in physical or chemical conditions, which in turn can be caused by such things as bu srial, tectonic stress, heating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

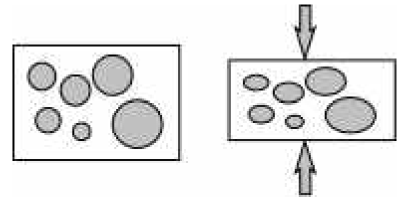
  If the stress is not equal from all directions, then the stress is called a ***differential stress.***



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^{o}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 diff rent 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^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 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 maps of a regionally metamorphosed areas are can be seen in figure 8.15 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 239-245). 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.

(COMPILED BY GDC HANDWARA)

Lecture notes,2nd semester,unit-3

Metamorphic Textures and Structures

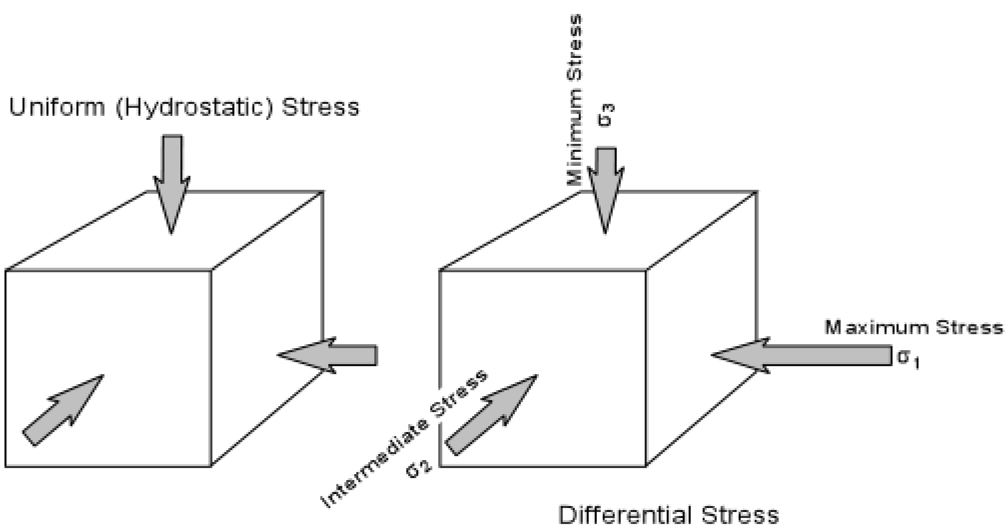
Metamorphic rocks exhibit a variety of textures. These can range from textures similar to the original protolith at low grades of metamorphism, to textures that are purely produced during metamorphism and leave the rock with little resemblance to the original protolith. Textural features of metamorphic rocks have been discussed in the previous lecture. Here, we concentrate on the development of foliation, one of the most common purely metamorphic textures, and on the processes involved in forming compositional layering commonly observed in metamorphic rocks.

Foliation

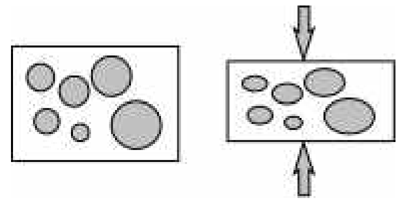
Foliation is defined as a pervasive planar structure that results from the nearly parallel alignment of sheet silicate minerals and/or compositional and mineralogical layering in the rock. Most foliation is caused by the preferred orientation of phylosilicates, like clay minerals, micas, and chlorite. Preferred orientation develops as a result of non-hydrostatic or ***differential stress*** acting on the rock (also called ***deviatoric stress***). We here review the differences between hydrostatic and differential stress.

Stress and Preferred Orientation

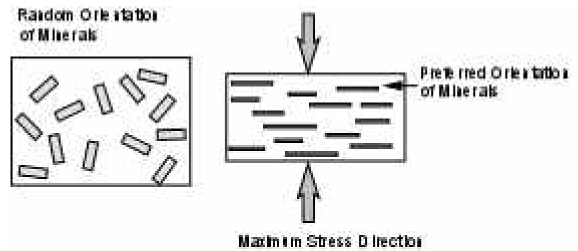
Pressure increases with depth of burial, thus, both pressure and temperature will vary with depth in the Earth. Pressure is defined as a force acting equally from all directions. It is a type of ***stress***, called ***hydrostatic stress*** or ***uniform stress.*** If the stress is not equal from all directions, then the stress is called a ***differential stress.*** Normally geologists talk about stress as compressional stress. Thus, if a differential stress is acting on the rock, the direction along which the maximum principal stress acts is called σ_1, the minimum principal stress is called σ_3, and the intermediate principal stress direction is called σ_2. Note that extensional stress would act along the direction of minimum principal stress.



If differential stress is present during metamorphism, it can have a profound effect on the texture of the rock.



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

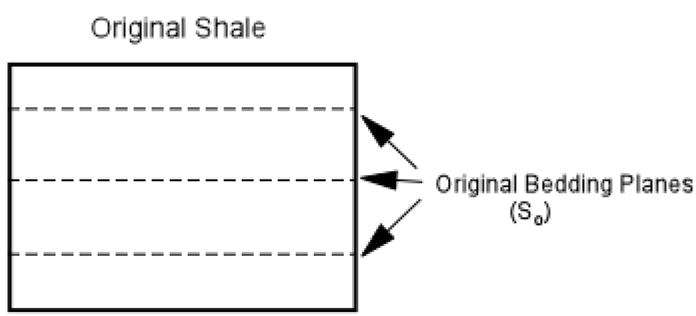


- Minerals that crystallize or grow in the differential stress field may develop a preferred orientation. Sheet silicates and minerals that have an elongated habit will grow with their sheets or direction of elongation orientated perpendicular to the direction of maximum stress.

  This is because growth of such minerals is easier along directions parallel to sheets, or along the direction of elongation and thus will grow along σ_3 or σ_2, perpendicular to σ_1.

  Since most phyllosilicates are aluminous minerals, aluminous (pelitic) rocks like shales, generally develop a foliation as the result of metamorphism in a differential stress field.

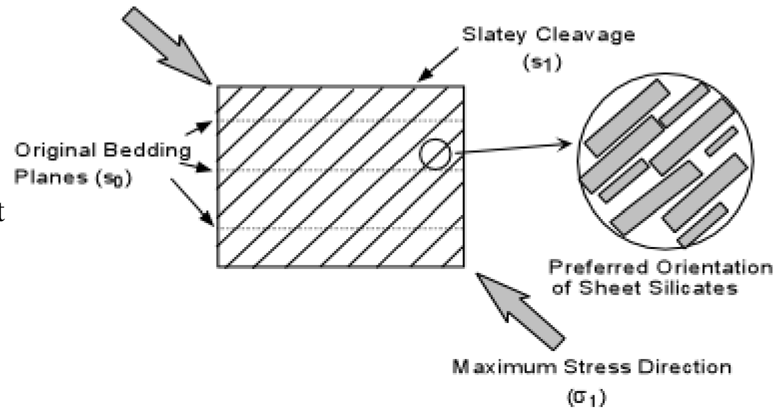
Example - metamorphism of a shale (made up initially of clay minerals and quartz)



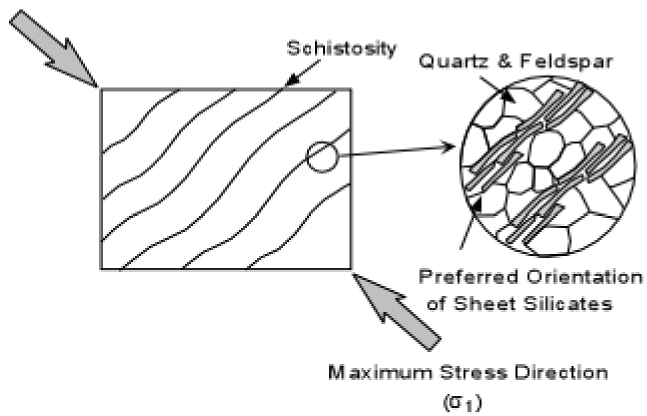
Shales have fissility that is caused by the preferred orientation of clay minerals with their {001} planes orientated parallel to bedding. Metamorphic petrologists and structural geologists refer to the original bedding surface as S_0.

- ***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 planes parallel to the sheet silicates, causing a ***slatey cleavage.***

Note that in the case shown here, the maximum principle stress is oriented at an angle to the original bedding planes so that the slatey cleavage develops at an angle to the original bedding. The foliation or surface produced by this deformation is referred to S_1.

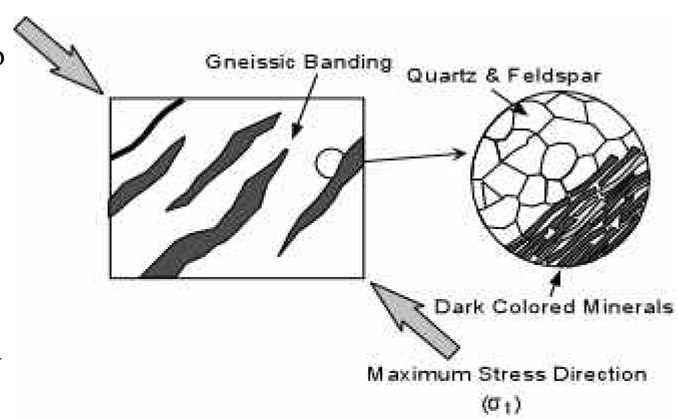


- ***Schist*** - The size of the mineral grains tends to enlarge with increasing grade of metamorphism. Eventually the rock develops a near planar foliation caused by the preferred orientation of sheet silicates (mainly biotite and muscovite). Quartz and feldspar grains, however show no preferred orientation.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

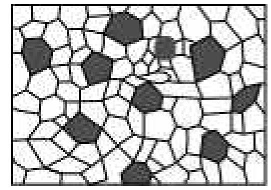


- ***Gneiss*** As metamorphic grade increases, the sheet silicates become unstable and dark colored minerals like hornblende and pyroxene start to grow.

These dark colored minerals tend to become segregated into distinct bands through the rock (this process is called metamorphic differentiation), 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 most 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.



In general, the grain size of metamorphic rocks tends to increase with increasing grade of metamorphism, as seen in the progression form fine grained shales to coarser (but still fine) grained slates, to coarser grained schists and gneisses.

Texture of Metamorphic Rocks

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.

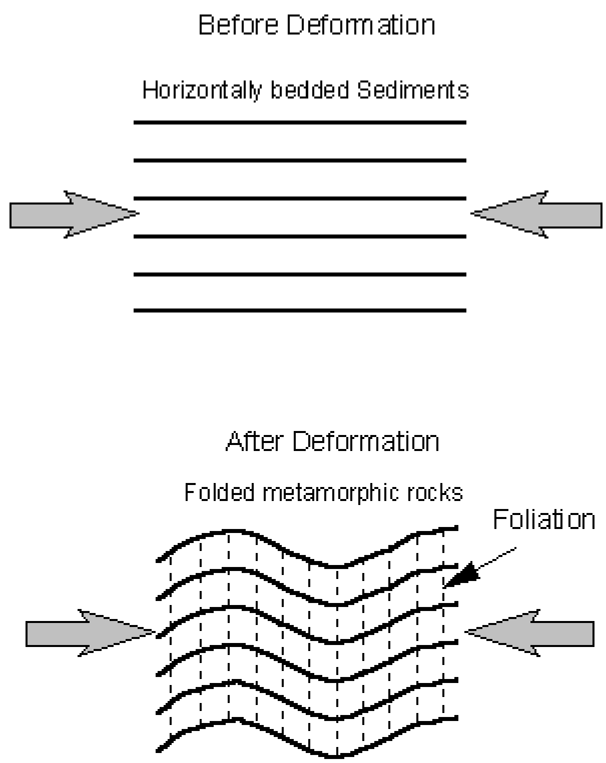
Protolith

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

Metamorphism and Deformation

Most regionally metamorphosed rocks (at least those that eventually get exposed at the Earth's surface) are metamorphosed during deformational events. Since deformation involves the application of differential stress, the textures that develop in metamorphic rocks reflect the mode of deformation, and foliations or slatey cleavage that develop during metamorphism reflect the deformational mode and are part of the deformational structures.

The deformation involved in the formation of fold-thrust mountain belts generally involves compressional stresses. The result of compressional stress acting on rocks that behave in a ductile manner (ductile behavior is favored by higher temperature, higher confining stress [pressure] and low strain rates) is the folding of rocks. Original bedding is folded into a series of anticlines and synclines with fold axes perpendicular to the direction of maximum compressional stress. These folds can vary in their scale from centimeters to several kilometers between hinges. Note that since the axial planes are oriented perpendicular to the maximum compressional stress direction, slatey cleavage or foliation should also develop along these directions. Thus, slatey cleavage or foliation is often seen to be parallel to the axial planes of folds, and is sometimes referred to axial plane cleavage or foliation.

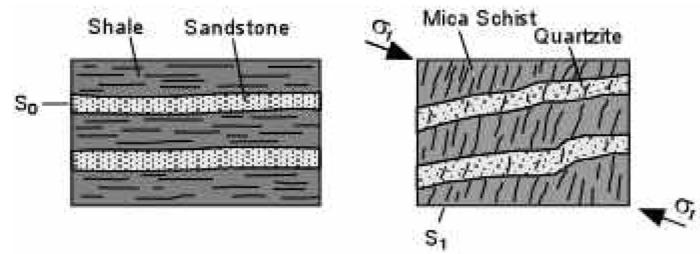


Metamorphic Differentiation

As discussed above, gneisses, and to some extent schists, show compositional banding or layering, usually evident as alternating somewhat discontinuous bands or layers of dark colored ferromagnesian minerals and lighter colored quartzo-feldspathic layers. The development of such compositional layering or banding is referred to as ***metamorphic differentiation.*** Throughout the history of metamorphic petrology, several mechanisms have been proposed to explain metamorphic differentiation.

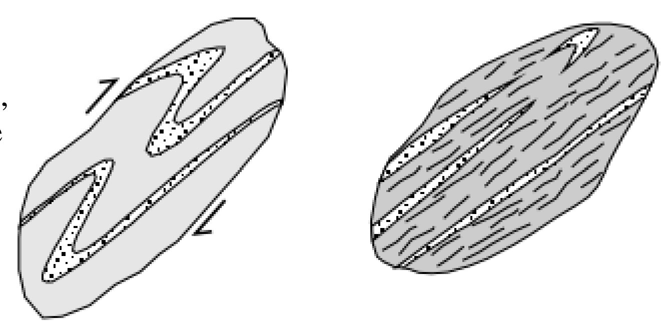
1. **Preservation of Original Compositional Layering.** In some rocks the compositional layering may not represent metamorphic differentiation at all, but instead could simply be the result of original bedding. For example, during the early stages of metamorphism and deformation of interbedded sandstones and shales the compositional layering could be preserved even if the maximum compressional stress direction were at an angle to the original bedding.

In such a case, a foliation might develop in the shale layers due to the recrystallization of clay minerals or the crystallization of other sheet silicates with a preferred orientation controlled by the maximum stress direction.



Here, it would be easy to determine that the compositional layers represented original bedding because the foliation would cut across the compositional layering.

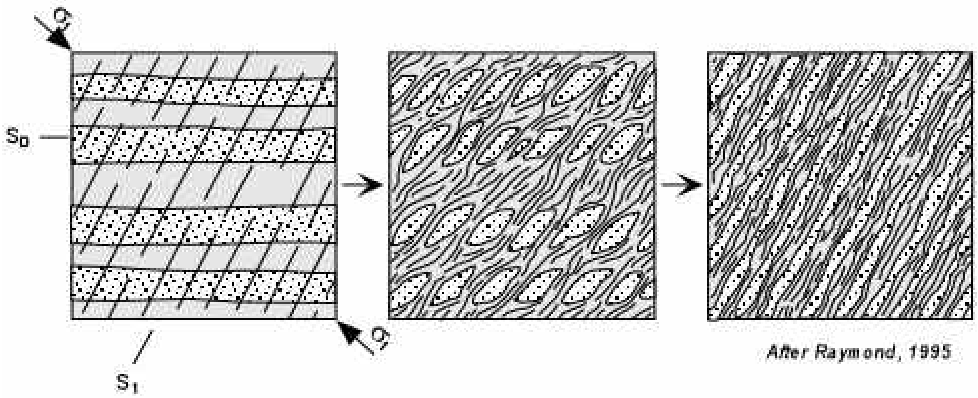
In highly deformed rocks that have undergone both folding and shearing, it may be more difficult to determine that the compositional layering represents original bedding. As shearing stretches the bedding, individual folded beds may be stretched out and broken to that the original folds are not easily seen.



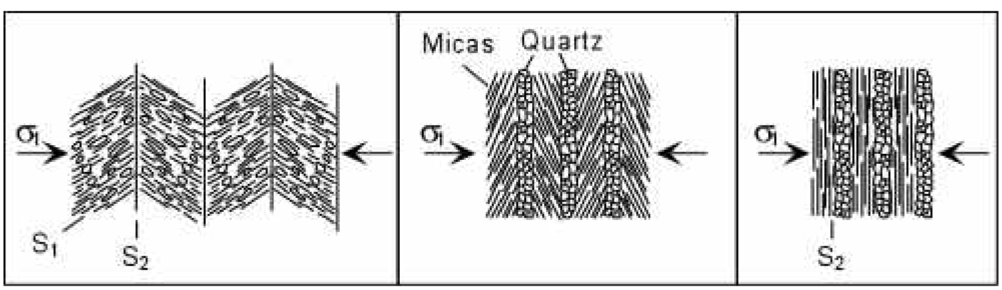
Similarly, if the rock had been injected by dikes or sills prior to metamorphism, these contrasting compositional bands, not necessarily parallel to the original bedding, could be preserved in the metamorphic rock.

2. **Transposition of Original Bedding.** Original compositional layering a rock could also become transposed to a new orientation during metamorphism. The diagram below shows how this could occur. In the initial stages a new foliation begins to develop in the rock as a result of compressional stress at some angle to the original bedding. As the minerals that form this foliation grow, they begin to break up the original beds into

small pods. As the pods are compressed and extended, partly by recrystallization, they could eventually intersect again to form new compositional bands parallel to the new foliation.

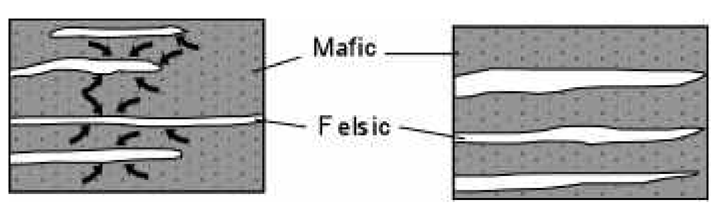


3. **Solution and Re-precipitation.** In fine grained metamorphic rocks small scale folds, called kink bands, often develop in the rock as the result of application of compressional stress. A new foliation begins to develop along the axial planes of the folds. Quartz and feldspar may dissolve as a result of pressure solution and be reprecipitated at the hinges of the folds where the pressure is lower. As the new foliation begins to align itself perpendicular to σ_1, the end result would be alternating bands of micas or sheet silicates and quartz or feldspar, with layering parallel to the new foliation.



4. **Preferential Nucleation.** Fluids present during metamorphism have the ability to dissolve minerals and transport ions from one place in the rock to another.

Thus felsic minerals could be dissolved from one part of the rock and preferentially nucleate and grow in another part of the rock to produce discontinuous



layers of alternating mafic and
felsic compositions.

Migmatization. As discussed previously, migmatites are small pods and lenses that occur in high grade metamorphic terranes that may represent melts of the surrounding metamorphic rocks. Injection of the these melts into pods and layers in the rock could also produce the discontinuous banding often seen in high grade metamorphic rocks. The process would be similar to that described in 4, above, except that it would involve partially melting the original rock to produce a felsic melt, which would then migrate and crystallize in pods and layers in the metamorphic rock. Further deformation of the rock could then stretch and fold such layers so that they may no longer by recognizable as migmatites.

(COMPILED BY GDC HANDWARA)