	Parent Rock	After Thermal Metamorphism		After Dynamothermal Metamorphism *
Sedimentary Rocks	Mudstones, Shales Graywacke	Greenstone (Hornfels)	OR	Slate > Phyllite > Schist > Gneiss
	Quartz Sandstone Arkose, Chert	Quartzite	OR	Quartzite
	Limestone Dolostone	Marble	OR	Marble
	Conglomerate Breccia	Metaconglomerate	OR	Stretched Pebble Metaconglomerate
Igneous Rocks	Felsic & Intermediate Igneous Rocks	Felsic & Intermediate Igneous Rocks are usually stable under these conditions	OR	Gneiss
	Mafic Igneous Rocks	Greenstone	OR	Schist > Gneiss

In term of field occurrence, this refers to the environment of formation of metamorphic rocks. It shows the way a particular metamorphic rock has been formed such as in contact, regional and dynamic metamorphism. Since it is often difficult to distinguish a marble formed as a result of contact metamorphism from that formed by regional metamorphism; field occurrence of such marble is necessary to guide a geologist on its formational history.

❖ TEXTURE AND STRUCTURE

Texture or fabric of metamorphic rocks derived in the field and in the laboratory by such methods as megascopic, microscopic and petrofabric analyses constitute comprehensive records of intensity and deformation involved in metamorphism. Based on texture, metamorphic rocsk are grouped into two (2) major categories;

(a) Foliated metamorphic rocks
(b) Non-foliated metamorphic rocks

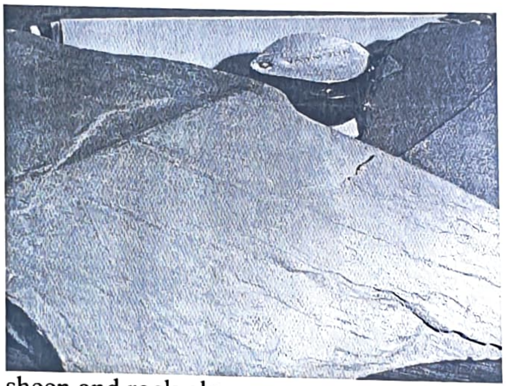
Foliated Metamorphic Rocks

These are rocks that possess planar fabric or foliation caused by the preferred orientation (alignment) of minerals formed under differential stress. They have significant amount of sheet silicate (platy minerals) and are classified by composition, grain size and foliation types. Example of rock here include slate, phyllite, schoist, granulite (some), migmatite etc.

Slate: this is a fine-grained rock with well develop platy cleavage. The cleavage results from incipient parallel growth of micaceous minerals due to low-grade regional metamorphism of fine-grained clastic sediments such as mud, shale, silt or tuff. Individual minerals are too fine to be identified in hand specimen except via chemical analysis. The matrix minerals is typically chloritic, illitic and kaolinitic.

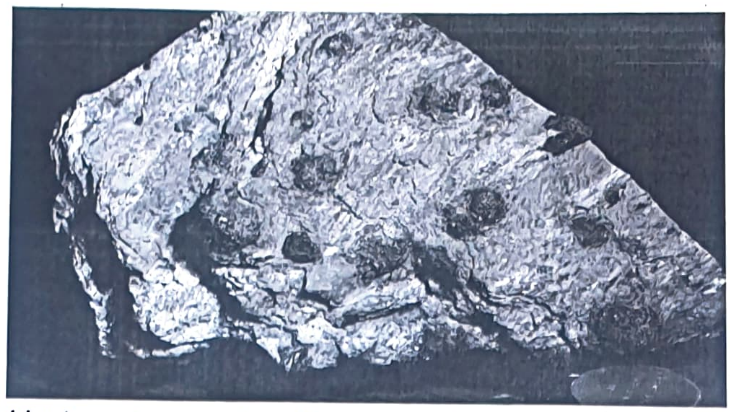
Slate

Phyllite: it is a very fine-grained schistose rock resulting from more advanced low-grade regional metamorphism (increase in metamorphic conditions) than that involved in the formation of slate. The surface schistosity has a peculiar lustrous silky sheen due to development of new mica and chlorite. Quartz and albite are often present. In term of grain size, phyllite is larger than that of slates but finer than in schists. They often possess greenish to reddish colourations. Phyllites fall into three (3) mineralogical categories; sericite phyllites, chlorite phyllite, and sericite-chorite phyllite.



Phyllites with glossy sheen and rock cleavage

Schist: these are foliated rocks of medium to coarse crystalline texture. Unlike phyllites, most of the mineral constituents of schist are easily identified without the aid of microscope. Foliation is caused by the parallel or nearly parallel alignment/orientation of micaceous minerals. The most common minerals in schists are quartz, feldspar, and micas and hornblende. If one of these constituents makes up to 50% or more of the rock, the rock is called mica, quartz or hornblende schist respectively. But if none make up to 50%, the name of the two most abundant cknstituents are used e.g garnetiferrous mica schist. Sometimes you can have a grain size ranging from fine-medium through coarse grains.



Schist (garnet muscovite schist), muscovite crystals are visible and silvery, garnets occur as large dark porphyroblasts.

Gneisses: these are medium to coarse graines irregularly banded rocks. The fabric of gneisses are formed by alternating concentrations of mica rich (dark) layers and quartzo-feldspathic (light) layers, variation in grain size and concentration of pink and white feldspars inlayers. Gneisses have poorer schistosity compared to schist because of the predominance of quartz and feldspar. Schists are simply distinguished from gneisses by the way they break; Schists break into slabs (1 -10mm) or into pencil-like columns, whereas gneisses break into much thicker slabs or even across the layering. The grade of metamorphism in gneiss is higher than in schist; hence gneisses are high-grade metamorphic rocks. Like schists, gneisses occur in great variety and are named in various ways.

Gneiss with obvious layering

Common terms such as granite-gneiss refers to the composition of pre-metamorphic rocks. Conglomerate gneiss and quartzitic gneiss indicate percentage whereas augen gneiss display conspicous structure. Quartzo-feldspathic gneiss include a group of metamorphic rocks in which quartz and feldspar chiefly k-feldspar are dorminant. These quartzo-feldspathic gneisses are formed by metamorphism of siliceous rocks such as granite, granodiorite and also arenaceous sedimentary rocks such as arkoses.

Gneiss derived from igneous origin is termed orthogneiss while those derived from sedimentary protolith is referred to as paragneiss.

Migmatite: these are complex small scale matrix of granite and other rocks. Migmatites may consist of several varieties of complexly interlayered more or less schistose or gneissic rocks. They generally form bands or layers of light and dark coloured materials. Gradational contacts between light and dark coloured layers are common. Compared with non-migmatized rocks, dark bands are darker and light bands lighter and contain small amount of mafic minerals. Migmatites are the highest grade metamorphism above which you enter into anatexis (partial melting), then magma generation. Two broad types of migmatites are known;

(a) **Agmatite:** is a type of migmatite characterized by the dissection of the gneissic or schistose rocks by quartzo-feldspathic dykes and pegmatites. The occurrence of agmatite is a strong indication that partial melting or anatexis occurred in a migmatite terrain.
(b) **Lit-Par-Lit Gneiss:** this consist of alternating light and dark coloured bands. The dark bands usually containing hornblende and biotite may be subordinate to the light coloured bands which contain mostly feldspar and quartz. In most cases, these bands are parallel to each other but occasionally they are contorted and folded. Lit-par-lit gneiss is synonymous with banded gneiss and indicates that there was injection of granitic materials into the rock to form migmatite. Common within the Nigerian Basement complex.

Migmatite when partial melting begins

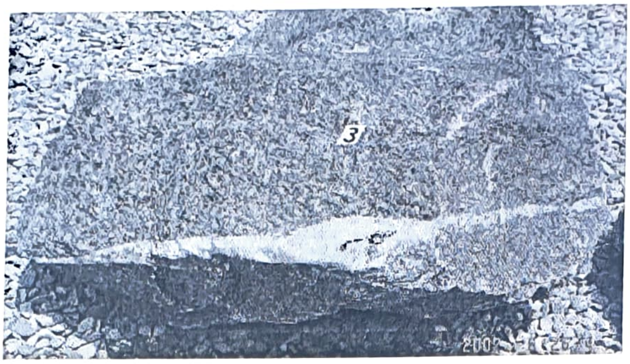
Non-Foliated Metamorphic Rocks

These are metamorphic rocks that have no evident planar fabric or foliation, recrystallized and/or neocrystallized under conditions where there was no differential stress and are composed of equant minerals only. They are classified mainly by the minerals present or the chemical composition of the protolith. Examples of rocks under this category are;

Hornfelses: fine grained non-foliated, dense, usually dark rocks formed near contact of Igneous intrusions. Hornfelses break into splintery fragments that have translucent edge-like horn.

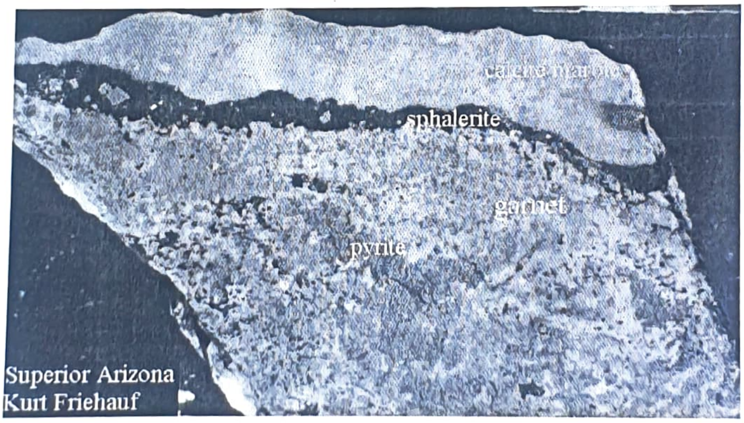
Hornfels (metamorphosed basalt)

Granofels: medium-coarse grained, ganoblastic rock without or with only indistinct foliation or lineation. Generally coarser than a hornfels and largely lacks the texture of a gneiss.



Granofel

Skarns: they are coarse-grained calc-silicate rock commonly consisting of grossularite/andradite, garnet, diopside and epidote. Tactite is synonymous to skarns.

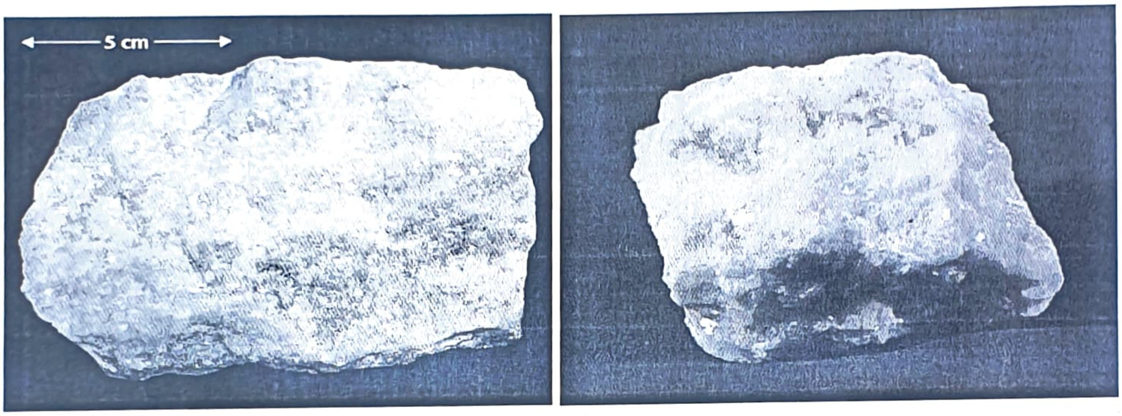


Skarns

Serpentinites: these are rocks fromed by hydration/alteration of ferromagnesian minerals such as olivine and pyroxene in peridotite and consists almost entirely serpentine group of minerals. Chlorite, talc, tremolite or carbonates may occur as accessory minerals. Serpentinites are generally green to dark green in colour but when weathered turnes orange brown.

Serpentinite

Marble: marble is a metamorphic rock consisting primarily of recrystallized and interlocking grains of calcite or dolomite. Few percentage diopside, tremolite, garnet or other minerals may be present. Marble possesses granoblastic texture.

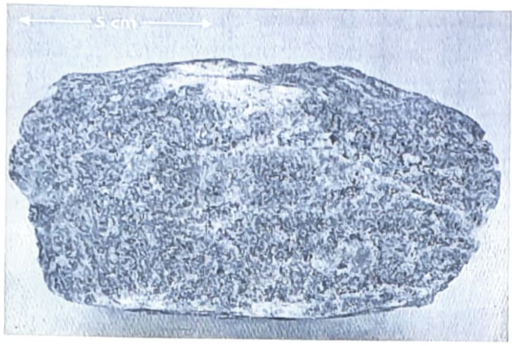


Marble

Eclogites: they are extremely high pressure metamorphic rock, medium grained, green to darkgreen rock dominated by green pyroxene (omphacite i.e Sodium – and Aluminium-rich diopside) and a pyrope-rich garnet (less red garnet).

Quartzite/Mte

Quartzite/Metaquartzite: metamorphic rock consisting primarily ~~mainly~~ of recrystallized and interlocking grain of quartz. Either massive, foliated. Few percentage of mica or other minerals may be present.



Quartzite

OTHERS

Granulites: they are an even-textured, medium to coarse grained rocks consisting of minerals mainly quartz and feldspar with some pyroxene (omphacite), garnet or mica occurring in lesser amount. Granulite has a granoblastic texture. It is poorer in mica than gneiss, but has a rough/weak gneissic layering defined by lighter and darker layers and may consist of flat lenses of quartz and/or feldspar. It results from very high grade regional metamorphism. Specific mineral assemblages include hypersthene, biotite, ilmenite/magnetite, plagioclase (An_{30-65}) etc , depending on the original rock or protolith. Granulites are sometimes considered as foliated metamorphic rock.

Amphibolites: these are medium to coarse grained hornblende-plagioclase metamorphic rocks which may be foliated or lineated due to preferred orientation of the hornblende. They are equivalent to basalts or gabbros. They may be orthoamphibolite if the parent rock is igneous in origin or paraamphibolite if the protolith is of sedimenatry origin. Amphibolites are also mostly considered as part of non-foliated metamorphic rocks.

Amphibolite

Mylonites: a hard, fine grained metamorphic rock with a streak or weakly foliated texture formed by intense shearing. Less deformed, larger grains may survive as relicts embedded in a sheared groundmass. Mylonites form in shear zones in folded mountain belts along transform fault plate boundaries.

❖ MINERALOGICAL COMPOSITION

This gives an idea of the parent (Protolith) rock that gives rise to the metamorphic rock hence, different compositional parent rocks will metamorphosed to give different rocks of varying composition and as such, the metamorphic rocks could be classified on this basis. For example, if the metamorphic rock is made up of mainly quartz, thus the parent rock from which it was formed is likely to be sandstone or highly quartz-rich granite.

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 biotitegarnet schist. A gneiss containing hornblende, pyroxene, quartz, and feldspar would be called hornblende-pyroxene gneiss. A schist containing porphyroblasts of K-feldspar would be called K-feldspar porphyroblastic schist. So also, if the metamorphic rock is made up of mainly quartz, thus the parent rock from which it was formed is likely to be sandstone or highly quartz-rich granite. By virtue of this last statement, mineralogical composition could give insight to the original protolith.

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 coloured 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 SiO2. 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.

❖ 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:

1. **Pellitic Metamorphic Rocks:** These rocks are derivatives of aluminous sedimentary rocks like shales and mudrocks. They are rich in clay minerals and have relatively high alumna (Al_2O_3) and potash, which usually give rise to the generation of rock dominant in mica. Owing to the abundant mica and other clay mineral contents, meta-pellite commonly show good schistocity, resulting in the formation of mica-schist, high aluminous minerals such as andalusite, kyanite and sillimanite, cordierite are common in such rocks. Almandine, garnet and staurolite also occur.

2. **Quartzo-feldspathic Metamorphic Rocks:** rocks of this group are usually derived from either quartzo-sedimenatry rocks or felsic igneous rocks. They are characterized by low MgO (magnesium oxide), iron oxide (FeO) and high silica content.
3. **Calcareous Metamorphic Rocks:** these are formed from rocks that are originally composed of pure or ordinary pure calcium carbonate in the form of either aragonite or calcite. Metamorphic recrystallization will change the original rock to calcite or aragonite depending on the prevailing conditions. Aragonites are usually formed at higher depth of sediment burial and relatively high temperature whereas calcite is formed at shallow depth of sediment burial and relatively low temperature. If the original rock contains other minerals other than calcium carbonate in of impurities such as MgO and SiO_2, their metamorphism usually produce such minerals as Tremolite (amphibole). Diopside (pyroxene). Wollastonite (amphibole and contact metamorphic rock..), and other cal-silicate minerals. If the original rock contain abundant allumina, plagioclase, epidote and hornblende will be produced. The rock type so formed will be mineralogically similar to the metamorphic rock derived from mafic igneous rocks.
4. **Basic or Mafic Metamorphic Rocks:** These are rocks that are derived from basic igneous rocks containing about 50% silica. They are rich in MgO, CaO, FeO, Al_2O_3. They commonly produce such minerals as chlorite, epidote, and actinolite at low temperature and hornblende at higher temperature from amphibolite. At still high temperature, clino and ortho-pyroxene and plagioclase rocks are formed.
5. **Ultramafic Metamorphic Rocks:** these are rock of about 40 - 45% silica and they occur in many metamorphic terrain and they are derivative of peridotite and characterized by absence of feldspar and abundance of Mg. Minerals such as talc, brucite, tremolite, magnesite, antigonite, serpentine characterized such rock.
6. **Ferriginous and Manganiferous Rocks:** 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. While Rocks that are characterized by the presence of Mn-rich minerals are termed manganiferrous rocks. They are characterized by such minerals as Stilpnomelane and spessartine.

METAMORPHIC GRADE

Metamorphism grade refers to the degree of metamorphic intensity that takes place during the process of metamorphism. Metamorphic grade could be progressive (prograde metamorphism) or retrogressive (retrograde metamorphism). The former, been with increasing in metamorphic factors/conditions while the latter represents a decrease in metamorphic factors.

Based on the increasing metamorphic conditions (prograde metamorphism), they are low, intermediate and high grade metamorphisms. The metamorphic grade of a rock is determined by identifying its **index minerals**, which are silicate minerals that form only under specific metamorphic condition. Other metamorphic minerals can be formed under varied conditions.

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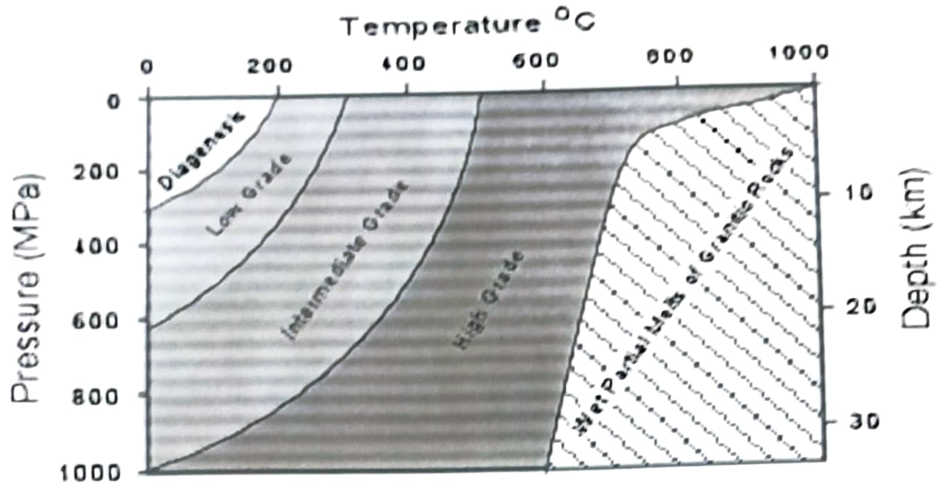
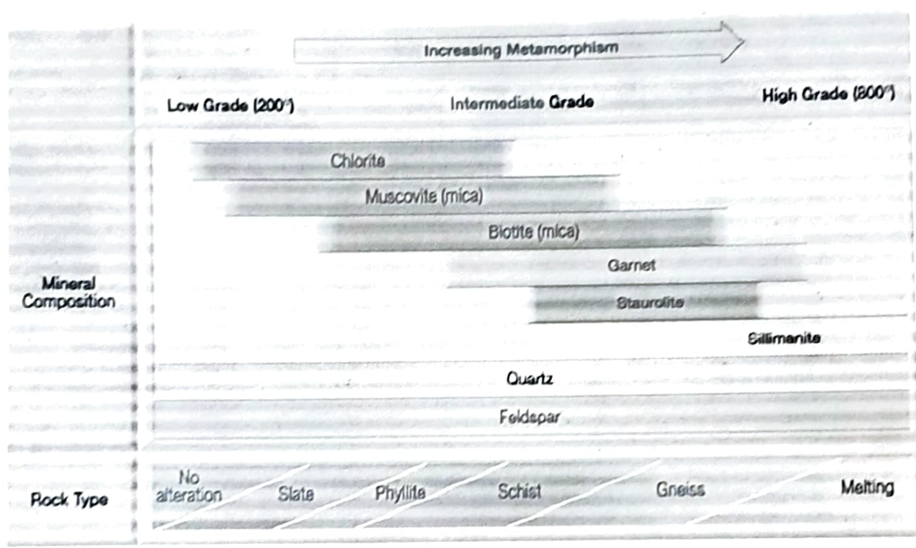
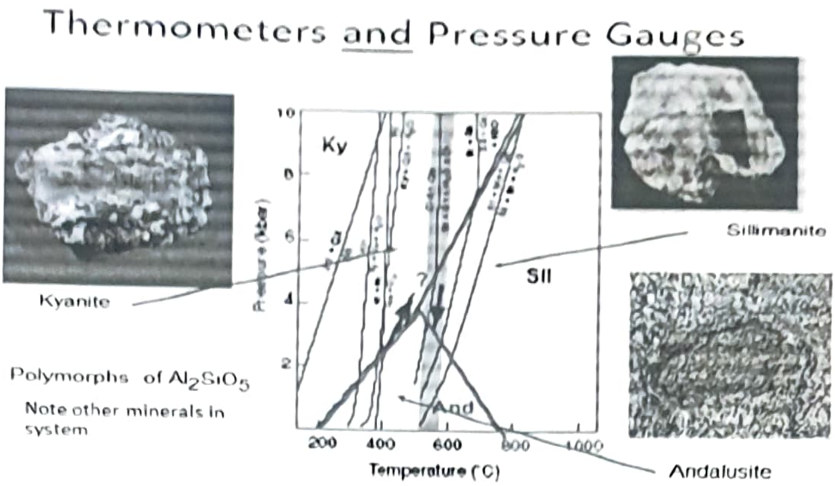




Index Minerals in metamorphic rocks

Note Quartz and Feldspar are not index minerals: Why?



METAMORPHIC FACIES

Metamorphic rocks that forms under the same conditions of temperature and pressure (depth of burial) are said to belong to a metamorphic facies. Thus, metamorphic facies can be described as an assemblage of minerals or mineral paragenesis denoting metamorphism that takes place under the same conditions of temperature and pressure. This implies that metamorphic facies is a group of metamorphic rocks characterized by similar mineral paragenesis (mineral assemblage) as a reflection of the formation of these rocks under similar conditions of temperature and pressure.

It is important to note that most metamorphism does not involve a change in the elemental composition of the original rock. As a result, the kind of metamorphic rocks contained within a particular metamorphic facies depends on the composition of the original rock.

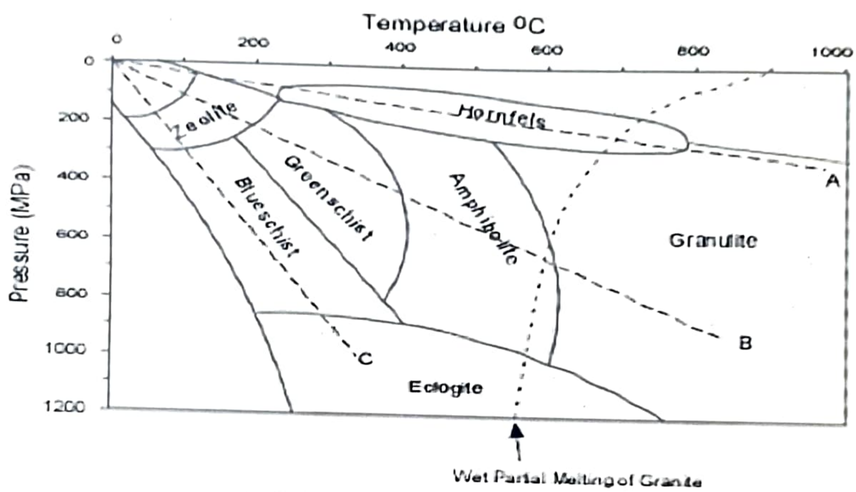
In general, metamorphic rocks do not drastically change chemical composition during metamorphism, except in the special case where metasomatism is involved (such as in the production of skarns, as discussed above). The changes in mineral assemblages are due to changes in the temperature and pressure 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.

Metamorphic Facies

Depth\Temp	300C	400C	500 C	600 C	700 C	800 C
5 km	*Zeolite*	*Contact Metamorphism* - Andalusite forms				
10 km - 3 kb		***Greenschist***	***Amphibolite***		***Granulite***	
15 km	***Blueschist***	Chlorite, Biotite form	Garnet, Staurolite,		Sillimanite forms Muscovite breaks	
20 km - 6 kb		•*Slate*	Kyanite form		down to K-feldspar	
25 km		•*Greenstone*	•*Schist*		Partial Melting	
30 km - 9 kb		•*Quartzite* •*Marble*	•*Amphibolite* •*Quartzite*		•*Gneiss*	
35 km			•*Marble* •*Gneiss*			
40 km - 12 kb	Not Found		*Eclogite* (Mantle)			

- Metamorphic rocks reveal temperature and pressure conditions in the earth.

Metamorphic Facies



A = High Geothermal Gradient (contact metamorphism), Low P, High T

B = Normal Geothermal Gradient (regional metamorphism), High P, High T

C = Low Geothermal Gradient (subduction), High P, Low T

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.

Below are the typical minerals in rocks that are derived from sediments (pelitic rocks). That is, these will be found in slate, schist and gneiss. The minerals shown in parentheses are "optional" and don't always appear, but they can be essential for identifying a facies.

- Zeolite facies (Low T - Low P): illite/phengite + chlorite + quartz (kaolinite, paragonite)
- Prehnite-pumpellyite facies (Mod - High T - Low P): phengite + chlorite + quartz (pyrophyllite, paragonite, alkali feldspar, stilpnomelane, lawsonite)
- Greenschist facies (Mod to High T - Mod P): muscovite + chlorite + quartz (biotite, alkali feldspar, chloritoid, paragonite, albite, spessartine)
- Amphibolite facies (Mod to High T - Mod P): muscovite + biotite + quartz (garnet, staurolite, kyanite, sillimanite, andalusite, cordierite, chlorite, plagioclase, alkali feldspar)
- Granulite facies (Mod to High T - Mod P): alkali feldspar + plagioclase + sillimanite + quartz (biotite, garnet, kyanite, cordierite, orthopyroxene, spinel, corundum, sapphirine)
- Blueschist facies (Low T - High P): phengite + chlorite + quartz (albite, jadeite, lawsonite, garnet, chloritoid, paragonite)
- Eclogite facies (Mod - High T - High P): phengite + garnet + quartz

Mafic rocks (basalt, gabbro, diorite, tonalite etc.) yield a different set of minerals at the same P/T conditions, as follows:

- Zeolite facies: zeolite + chlorite + albite + quartz (prehnite, analcime, pumpellyite)
- Prehnite-pumpellyite facies: prehnite + pumpellyite + chlorite + albite + quartz (actinolite, stilpnomelane, lawsonite)
- Greenschist facies: chlorite + epidote + albite (actinolite, biotite)
- Amphibolite facies: plagioclase + hornblende (epidote, garnet, orthoamphibole, cummingtonite)
- Granulite facies: orthopyroxene + plagioclase (clinopyroxene, hornblende, garnet)
- Blueschist facies: glaucophane/crossite + lawsonite/epidote (pumpellyite, chlorite, garnet, albite, aragonite, phengite, chloritoid, paragonite)
- Eclogite facies: omphacite + garnet + rutile

Ultramafic rocks (pyroxenite, peridotite etc.) have their own version of these facies:

- Zeolite facies: lizardite/chrysotile + brucite + magnetite (chlorite, carbonate)
- Prehnite-pumpellyite facies: lizardite/chrysotile + brucite + magnetite (antigorite, chlorite, carbonate, talc, diopside)
- Greenschist facies: antigorite + diopside + magnetite (chlorite, brucite, olivine, talc, carbonate)
- Amphibolite facies: olivine + tremolite (antigorite, talc, anthopyllite, cummingtonite, enstatite)
- Granulite facies: olivine + diopside + enstatite (spinel, plagioclase)
- Blueschist facies: antigorite + olivine + magnetite (chlorite, brucite, talc, diopside)
- Eclogite facies: olivine

CHANGES ACCOMPANYING METAMORPHISM

The major changes that accompany the process of metamorphism are two:

- Textural changes
- Mineralogical changes

Textural changes

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. However, emphasis shall be 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.

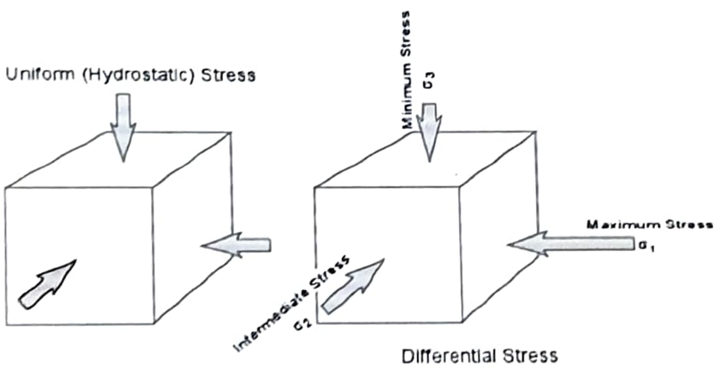
Foliation

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).*

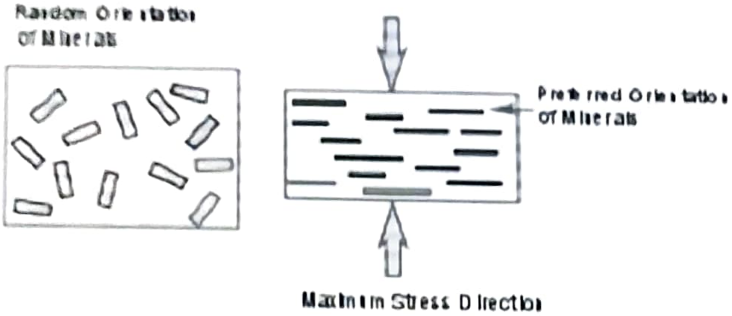
***Differences* between hydrostatic and differential stresses**

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 force acting equally from all directions. It is a type of *stress, called hydrostatic stress or uniform stress or geostatic pressure or confining pressure.*
- *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 1, the minimum principal stress is called 3, and the intermediate principal stress direction is called 2. Note that extensional stress would act along the direction of minimum principal stress.

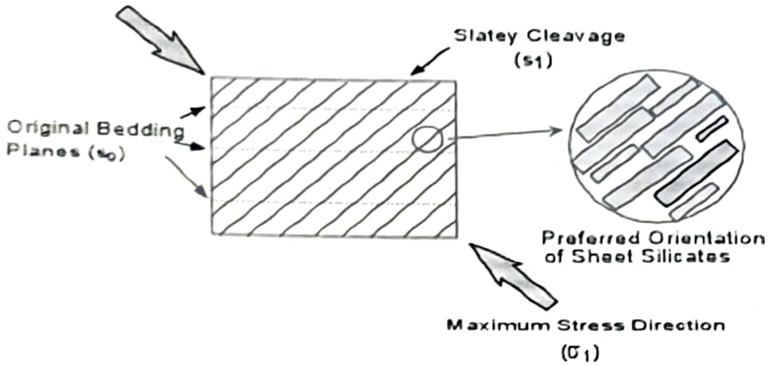


- If differential stress is present during metamorphism, it can have a profound effect on the texture of the rock.
- Rounded grains can become flattened in the direction of maximum compressional stress.
- Minerals that crystallize or grow in the differential stress field may develop a preferred orientation. 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

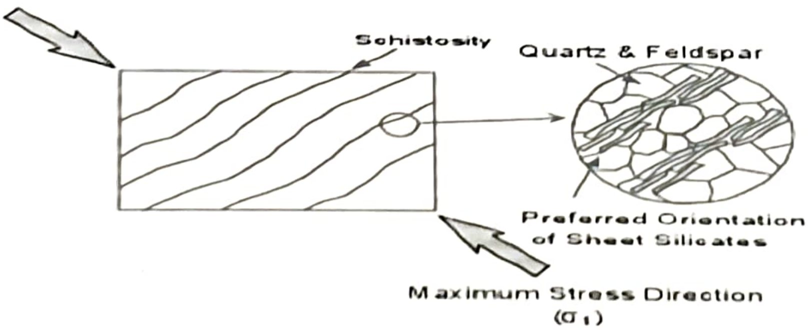


Example - metamorphism of a shale (made up initially of clay minerals and quartz)

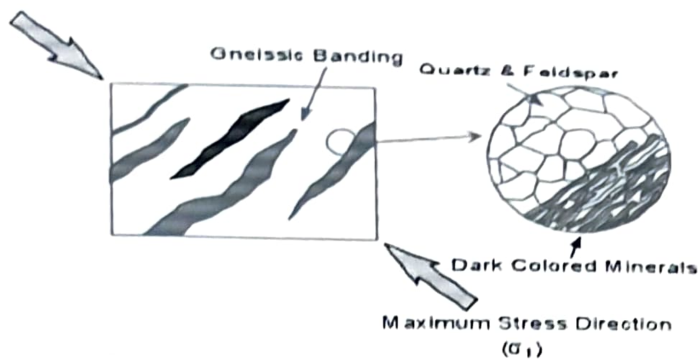
- *Slate: Slates form from shale at low metamorphic grade by the growth of fine grained chlorite and* clay minerals. The preferred orientation of these sheet silicates causes the rock to easily break planes parallel to the sheet silicates, causing a *slaty cleavage.*



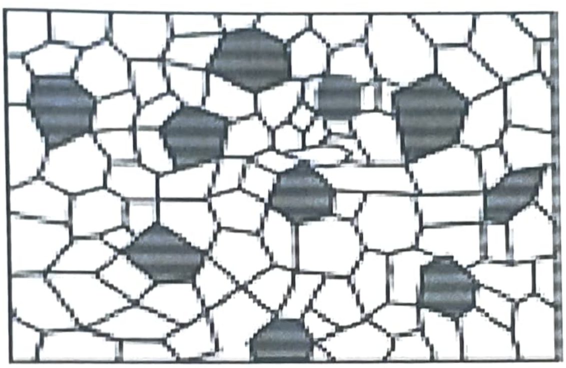
- *Schist - The size of the mineral grains* tends to enlarge with increasing grade of metamorphism. Eventually the rock develops a near planar foliation caused by the preferred orientation of sheet silicates (mainly biotite and muscovite). Quartz and feldspar grains however show no preferred orientation.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



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



Granulite texture

METAMORPHIC DIFFERENTIATION

- Metamorphic differentiation refers to the separation of originally homogeneous rock into bands of contrasting mineralogy during high grade metamorphism.
- It is a collective term for the various processes by which minerals or mineral assemblages are locally segregated from an initially uniform parent rock during metamorphism e.g. Garnet porphyroblast in fine grained mica schist
- The term 'metamorphic differentiation' was first used by Stillwell (1918), but the first detailed description was given by Turner (1941) when he described compositionally layered schists formed from originally massive, unbedded greywacke from Otago.

- Explanations for metamorphic differentiation presented in the literature are mainly based on models involving the passive concentration of more dense, less soluble mineral phases by the solution and selective removal of more soluble phases. This occurs in response to metamorphic processes, closely associated with shearing stress during deformation (Sander, 1930; Eskola, 1932; Ramberg, 1952; Bennington, 1965; Talbot and Hobbs, 1968; Spry, 1969; Gray, 1977).

- Layering found in mylonites was considered by Schmidt (1932) to be the result of different mechanical behaviour of various minerals. Amphibole and mica, being more ductile, adjust by gliding and recrystallization and are smeared out into intensely sheared layers. More brittle minerals, such as feldspar and quartz, are rotated and segregate into layers between the shears.

- Ghaly (1969) described some Lewisian rocks from NW Scotland which showed a gradation from hornblende-feldspar schist to striped and banded schist and gneisses, through to hornblendic and felsic lenses and pods. He proposed that they had been formed by a process of metamorphic differentiation involving solution, recrystallization, and mechanical differentiation acting simultaneously or separately. Deformation was an essential prerequisite for its operation.

- Talbot and Hobbs (1968) and Gray (1977) described differentiation associated with discrete crenulation cleavages.

- Gray produced analytical data which showed that all the cleavage zones studied had a consistent decrease in SiO_2, and increases in Al_2O_3 and K_2O with respect to the host rock.

- He concluded that the differentiated nature, microfabrics, and microtextural relations of discrete crenulation cleavages suggested that they were 'solution planes'.

METASOMATISM AND METASOMATIC ROCKS

The term metasomatism was introduced by Naumann (1826). *Metasomatism, metasomatic process and metasomatose are sometime synonyms although some authors use metasomatose as a name* for specific varieties of metasomatism (e.g. Na-metasomatose, Mg-metasomatose, etc.).

Metasomatism is defined as follows:

- Metasomatism: *is a special type of hydrothermal metamorphism or metamorphic process by which the chemical composition of a rock or rock portion is altered in a pervasive manner and which involves the introduction and/or removal of chemical components as a result of the interaction of the rock with aqueous fluids (solutions). During metasomatism the rock remains in a solid state.*
- A good example is when Dunite containing olivine reacts with water to give serpentine and brucite (reaction shown below). Another good example of metasomatism is