CAREER
AVENUES

Aim for
excellence in
Engineering

P E T R O L O G Y

1

G G

Index

Introduction and Origin of the Earth

- ***Important point:*** The Earth has evolved (changed) throughout its history, and will continue to evolve.
- The Earth is about 4.6 billion years old, human beings have been around for only the past 2 million years.
    - Thus, mankind has been witness to only 0.043% of Earth history.
    - The first multi-celled organisms appeared about 700 million years ago. Thus, organisms have only been witness to about 15% of Earth's history.

Thus, for us to have an understanding of the earth upon which we live, we must look at processes and structures that occur today, and interpret what must have happened in the past. One of the major difficulties we have is with the time scale. 1 million years is a relatively short period of time. But one thing we have to remember when studying the Earth is that things that seem like they take a long time to us, may take only a short time to Earth.

Examples:

- A river deposits about 1mm of sediment (mud) each year. How thick is the mud after 100 years? **--** 10 cm hardly noticeable over your lifetime.
- What if the river keeps depositing that same 1 mm/yr for 10 million years? Answer 10,000 meters (6.2 miles). Things can change drastically!

Why Study the Earth?

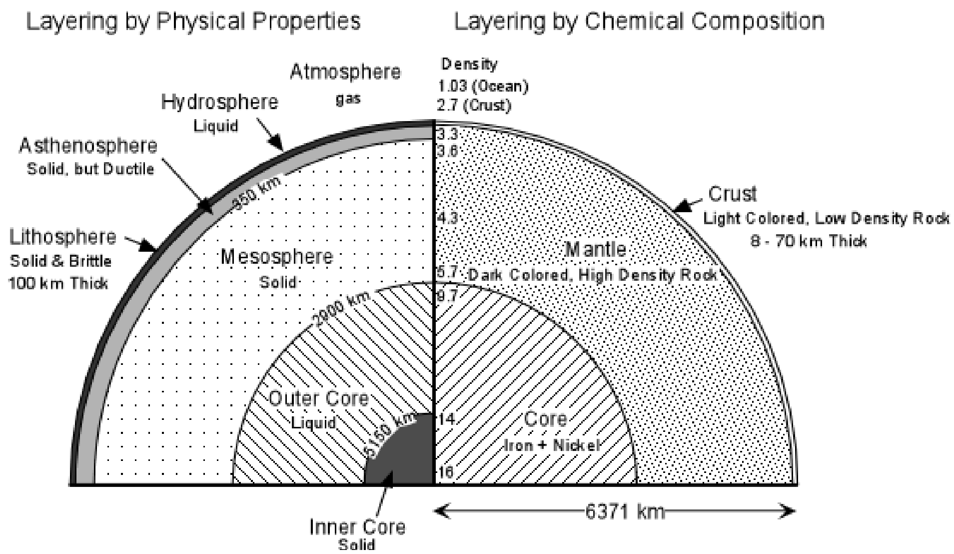
- We're part of it. Dust to Dust. Humans have the capability to make rapid changes. All construction from houses to roads to dams are effected by the Earth, and thus require some geologic knowledge. All life depends on the Earth for food and nourishment. The Earth is there everyday of our lives.
- Energy and Mineral resources that we depend on for our lifestyle come from the Earth. At present no other source is available.
- Geologic Hazards **--** Earthquakes, volcanic eruptions, hurricanes, landslides, could affect us at any time. A better understanding of the Earth is necessary to prepare for these eventualities.
- Curiosity**--** We have a better understanding of things happening around us. Science in general.

How did the Earth originate?

- We start at the beginning of the Universe, when, about 13.6 billion years ago, the Big Bang created the universe from a point source.
- During this process, light elements, like H, He, Li, B, and Be formed. From this point in time, the universe began to expand and has been expanding ever since.
- Concentrations of gas and dust within the universe eventually became galaxies consisting of millions of stars.
- Within the larger stars, nuclear fusion processes eventually created heavier elements, like C, Si, Ca, Mg, K, and Fe.
- Stars eventually collapse and explode during an event called a supernova. During a supernova, heavier elements, from Fe to U, are formed.
- Throughout galaxies clusters of gas attracted by gravity start to rotate and accrete to form stars and solar systems. For our solar system this occurred about 4.6 billion years ago.
- The ball at the center grows dense and hot, eventually nuclear fusion reactions start and a star is born (in our case, the sun).
- Rings of gas and dust orbiting around the sun eventually condenses into small particles. These particles are attracted to one another and larger bodies called planetismals begin to form.
- Planetesimals accumulate into a larger mass. An irregularly-shaped proto-Earth develops.
- The interior heats and becomes soft. Gravity shapes the Earth into a sphere. The interior differentiates into a nickel-iron core, and a stony (silicate) mantle.
- Soon, a small planetoid collides with Earth. Debris forms a ring around the Earth. The debris coalesces and forms the Moon.
- The atmosphere develops from volcanic gases. When the Earth becomes cool enough, moisture condenses and accumulates, and the oceans are born.

The Earth -- What is it?
The Earth has a radius of about 6371 km, although it is about 22 km larger at equator than at poles. Density, (mass/volume), Temperature, and Pressure increase with depth.

Internal Structure of the Earth:



Earth has layered structure. Layering can be viewed in two different ways:

1. Layers of different chemical composition
2. Layers of differing physical properties.

Compositional Layering

- ***Crust*** - variable thickness and composition
    - Continental 10 - 70 km thick - "granitic" (made mostly of Oxygen and Silicon) in composition
    - Oceanic 2 - 10 km thick - "basaltic" (less Silicon than in continental crust, more Magnesium)
- ***Mantle*** - 3488 km thick, made up of a rock called peridotite. Solid but can deform so that it confects (moves in response to temperature differences).
- ***Core*** - 2883 km radius, made up of Iron (Fe) and small amount of Nickel (Ni)

Layers of Differing Physical Properties

- ***Lithosphere*** - about 100 km thick (deeper beneath continents)
- ***Asthenosphere*** - about 250 km thick to depth of 350 km - solid rock, but soft and flows easily.
- ***Mesosphere*** - about 2500 km thick, solid rock, but still capable of flowing.
- ***Outer Core*** - 2250 km thick, Fe and Ni, liquid
- ***Inner core*** - 1230 km radius, Fe and Ni, solid

All of the above is known from observations that have been made from the surface of the Earth, in particular, the way seismic (earthquake waves) pass through the Earth.

The atmosphere is the outermost layer. It has the lowest density and consists mostly of Nitrogen (78%) and Oxygen (21%).

Composition of the Earth
The bulk chemical composition of the Earth is mostly Iron (Fe, 34.6%), Oxygen (O_2, 29.5%), Silicon (Si, 15.2%), and Magnesium (Mg, 12.7%), with other elements making up the other 8%.

These elements are distributed unevenly due to the layering, with Fe being concentrated in the core, Si, O_2, and Mg being concentrated in the mantle, and Si, O_2, and the other elements being concentrated in the thin veneer of the crust.

How do we study the Earth?
In order to understand the Earth, we must use the scientific method. This first involves making observations concerning what it there, what it is made of and what processes are operating. These observations are then used to develop hypotheses or theories to explain what we see. These hypotheses or theories are then tested by making further observations, doing experiments, or doing some kind of modeling, either physically or theoretically.
An idea proposed early in the history of human study of the Earth was the principle of Uniformitarianism.

Principle of Uniformitarianism
Processes that are operating during the present are the same processes that have operated in the past. i.e. the present is the key to the past. If we look at processes that occur today, we can infer that the same processes operated in the past.

Problems:

- Rates **--** rates of processes may change over time for example a river might deposit 1 mm of sediment /yr if we look at it today. but, a storm could produce higher runoff and carry more sediment tomorrow. Another example: the internal heat of the Earth may have been greater in the past than in the present **--** rates of processes that depend on the amount of heat available may have changed through time.
- Observations **--** we may not have observed in human history all possible processes. Examples: Mt. St. Helens, Size of earthquakes.

Perhaps a better way of stating the ***Principle of Uniformitarianism*** is that the laws of nature have not changed through time. Thus, if we understand the physical and chemical laws of nature, these should govern all processes that have taken place in the past, are taking place in the present, and will take place in the future.

Petrology Basics

Here is a summary of useful information that we studied in previous chapters.

Sedimentary rocks

Sedimentary rocks are formed in layers of sediment in lakes and seas. The layers get buried and the weight of the ground above squeezes out water. Salt crystallises out and cements the particles together. Only sedimentary rocks contain fossils. Heat and pressure in other types of rock destroy any traces of fossils. Comparing fossils in sedimentary rock can give information about the ages of the rock. Sedimentary rocks form from pre-existing rock particles - igneous, metamorphic or sedimentary. The Parent rock undergoes **WEATHERING** by chemical and/or physical mechanisms into smaller particles. These particles are **TRANSPORTED** by ice, air or water to a region of lower energy called a sedimentary basin. **DEPOSITION** takes place as a result of a lowering of hydraulic energy, organic biochemical activity or chemical changes (e.g., solubility). Once deposited, the sediments are **LITHIFIED** (turned into rock) through **COMPACTION** (decrease in rock volume due to weight of overlying sediment) and **CEMENTATION** (chemical precipitation in pore spaces between grains which "glues" the rock together. The primary mineralogical and textural characteristics of the rock can be modified as the sediments are buried deeper in the earth's crust and undergo an increase in both temperature and pressure.

Four main sedimentary rocks are:
Sandstone - made from sand particles
Limestone - made from seashells. Mostly calcium carbonate. Lots of fossils
Mudstone or Shale - made from mud (finer grain than sand). Splits easily into layers.
Conglomerates - Look like concrete containing pebbles held together by fine cement.

Metamorphic Rocks

When sedimentary rocks are forced underground they are compressed and heated and their structure and texture changes. As long as they don’t melt they are called metamorphic rocks. Slate is formed from mudstone or clay. Tiny plate-like particles line up in the same direction. Slate can be split into thin sheets. Under more steady heat and pressure, layers of interlocking crystals form. Marble is limestone which has reformed as tiny crystals. Marble is much harder than limestone. Metamorphic rocks are formed where a parent rock, called the protolith, is subjected to changes in pressure, temperature or chemistry (such as addition of fluids). The rock cycle picture at the beginning of this section shows several areas where metamorphism is common.

In subduction zones: as the oceanic plate descends into the mantle, both the sediments and the basalt floor are subjected to high pressure and low to high temperature conditions. Fluids may play an important role chemically change the rocks' composition.

Adjacent igneous intrusions - contact metamorphism, where cooler rocks are altered by contact with a hot igneous intrusion, is another common type of metamorphism.

At spreading centres (mid-ocean ridge): Fluids play an important role in hydrothermal alteration associated with magma emplacement on the sea floor at mid-ocean ridges.

Metamorphic processes are of two types:
Regional metamorphism caused by heat and pressure.
Contact metamorphism caused by heat only when rocks are close to magma or intrusive

Igneous Rocks

Igneous rocks form when molten magma pushed up towards the Earth’s surface. They contain minerals in randomly arranged interlocking crystals. Intrusive igneous (or Plutonic) rocks cool slowly with big crystals. Granite forms underground. It is very hard and decorative. Extrusive Igneous rocks cool quickly with small crystals. Basalt forms on top of the Earth after bursting out of a volcano. It has relatively small crystals because it cooled quickly. Igneous rocks form by direct crystallisation of minerals from a magma melt; we see a surface expression of magmatic activity at sea-floor spreading ridges and other rift zones, volcanic arcs (subduction zones) and hot spots (intraplate volcanism). **Intrusive** (**plutonic**) rocks crystallise at depth, whereas **extrusive** (**volcanic** and **pyroclastic** rocks)

rocks crystallise after the magma reaches the earth's surface. In general, extrusive rocks have a finer grained texture than intrusive rocks. Igneous rocks are often classified according to the percentage of SiO_2.

Metamorphic Rocks

•Metamorphic rocks take their name from the term metamorphism, meaning change of form or shape. The term is used to describe all changes in mineral assemblage and rock texture that take place in rocks in the solid state.

•Metamorphic rocks are thus another derivative or secondary rock (like sedimentary rocks), in that there must be an original rock in order to create a metamorphic rock.

Metamorphic conditions

•Temperatures between 200°C-700°C (1200°F), and pressures between those equivalent to those produced by 2000 m – 40 km of overlying rock are considered metamorphic conditions. Thus, the simple compaction that sediments typically undergo during lithification does not qualify as metamorphic pressure.

• Note: Not all changes in rocks are classified as metamorphism. Temperatures and pressures common at the Earth's surface are considered a weathering environment, while temperatures lower than about 200°C are considered sedimentary conditions.

• The action of fluids is also important in metamorphism, as they speed up chemical reactions by mobilizing ions.

• Heat for metamorphism comes from contact with hot magma bodies, as well as the radioactive decay of elements such as Uranium (U) and Potassium 40 (K). Pressure for metamorphism comes from burial – either by water or other rock layers. (FYI: 1000 bars of pressure [1 kilobar] are equivalent to 2 miles or 3 km of overlying rock)

• Metamorphic rocks reach the surface by several processes, most notably tectonic uplift and erosion of overlying layers.

Types of metamorphism

•Contact metamorphism occurs adjacent to bodies of hot igneous rock that are intruded into cooler rock of the crust. Rock next to the intruded magma becomes heated and metamorphosed, usually in zones of different metamorphic grades as one moves away from the magma. These are typically shallow conditions (0-6 km), so pressure is low.

•Burial metamorphism occurs in zones where sediments are buried deeply in a sedimentary basin. When these sediments reach temperatures above 200°C, they may begin growing new minerals and thus become metamorphic rock.

•Regional metamorphism produces the most common metamorphic rocks. As the name implies, it occurs over wide areas, under high pressures due to deep burial (5-20 km, sometimes more than 30 km). The process involves a considerable amount of mechanical deformation and chemical crystallization. As a result, regionally metamorphosed rocks are usually foliated.

What happens during metamorphism?

• The changes that occur in rocks during metamorphic conditions include reactions to form new minerals from the atoms mobilized by metamorphic conditions, minerals that change form, the addition of new materials and recrystallization. As mentioned above, deformation of new and existing mineral forms also can occur, especially under high pressure conditions.

• New minerals can be formed as atoms are mobilized by heat, pressure and fluid addition. The various building blocks of minerals come into play to be able to recombine in a limited fashion, creating new minerals.

• Minerals can also change form without changing composition. Arrangement of atoms in a mineral might become more compact or rearranged in some other way as the atoms are mobilized. The addition of new materials leads to new minerals forming. Finally, minerals can recrystallize; they become smaller and denser under high pressure conditions.

Does de-metamorphism occur?

• Typically, no. Rocks do not return to their previous state after metamorphism. This is because during metamorphism, ingredients can be lost (commonly the more volatile compounds like water). Also, reactions are often irreversible. In the same way that once a rock crystallizes it cannot be melted again without subjecting it to high temperatures, a rock that has undergone recrystallization cannot go back to its previous state.

• Retrograde metamorphism does occur, but under very specific conditions.

Rock types

• Each metamorphic rock has a parent rock — the original rock before it was altered. Different rocks create different metamorphic offspring.

• Rocks are classified by their metamorphic grade. Low grade rocks have undergone low pressures and/or temperatures; in this case, the original structure of the rock (right down to included fossils) can often be seen. High grade rocks have undergone high pressure and/or temperature, and may lose all trace of their original appearance.

• Shale and mudstone, the most common sedimentary rocks, are altered into a series of rocks depending on the grade of metamorphism — the amount of temperature and pressure applied. The sequence goes from slate (a roofing material) to phyllite, to schist, to gneiss. Each is identified by the grain size of the rock.

• Basalt, the most common type of igneous rock, typically metamorphoses into greenschist (which contains low-grade chlorite, a green mineral), then to amphibolite (containing amphibole), then to granulite.

• Because limestone and sandstone do not contain sheet- or chain-structure minerals, they typically lack foliation. They form marble and quartzite respectively.

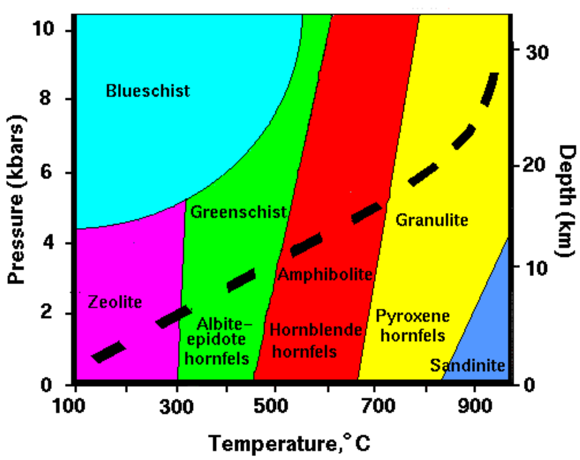
Metamorphic facies

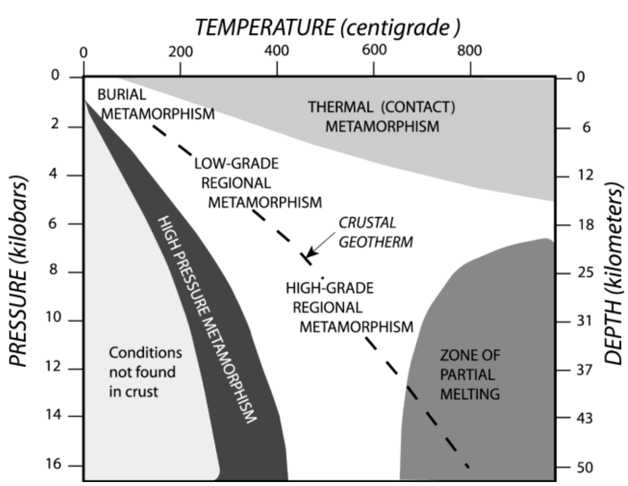
•Metamorphism does not change the chemical composition of rocks, except in terms of the loss or addition of water, carbon dioxide and other volatiles.

•Metamorphism changes primarily the mineral assemblage of a rock, rather than the chemical composition.

•Therefore, the mineral assemblages we find in metamorphic rocks are controlled by the metamorphic conditions — pressure and temperature, combined with rock composition.

•This can be diagrammed as below:





Metamorphism : Types, Rocks and Facies

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^{o}C and pressures below about 300 MPa (MPa stands for Mega Pascals), this is equivalent to about 3,000 atmospheres of pressure.

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

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

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

Metamorphism Definition:
When rocks are subjected to deep burial, tectonic forces such as folding, and high pressures and temperatures, the textures and mineral compositions begin to change. This process, called **metamorphism**, is the solid-state transformation (no melting) of a rock mass into a rock of generally the same chemistry but with different textures and minerals.

Usually the **metamorphic rock** looks quite different from the original rock, called the **parent rock** or **protolith.** Metamorphic rocks often show contorted patterns of folding that indicate they were soft enough to bend (**plastic deformation**). Folding is achieved by the application of great pressure over long periods. The intensity of the metamorphism increases with increasing temperature and/or pressure, and the highest "grade" of metamorphism approaches partial melting of the rock, almost completing the rock cycle.

Types of Metamorphism
There are two major kinds of metamorphism: regional and contact.
Regional metamorphism. Most metamorphic rocks are the result of **regional metamorphism** (also called **dynamothermal metamorphism).** These rocks were typically exposed to tectonic forces and associated high pressures and temperatures. They are usually foliated and deformed and thought to be remnants of ancient mountain ranges. Regional metamorphism is associated with deep burial and large-scale tectonic activity (plate collisions). The principal agents of metamorphism are heat and pressure

Metamorphic grades. The different groups of minerals, or **assemblages**, that crystallize and are stable at the different pressure and temperature ranges during regional metamorphism distinguish distinct **metamorphic grades**, or **faces.** The grades are usually named for the dominant minerals or colors that identify them.

Regional Metamorphic Rock Facies

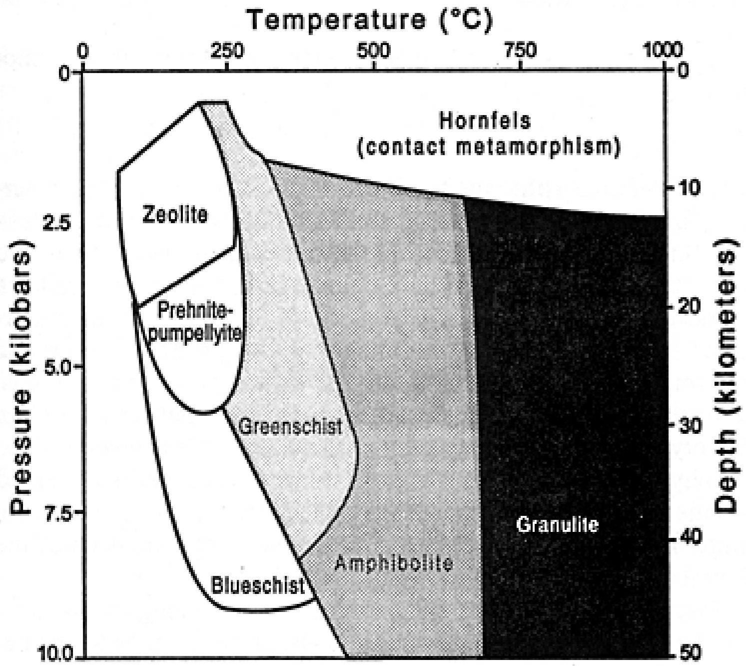
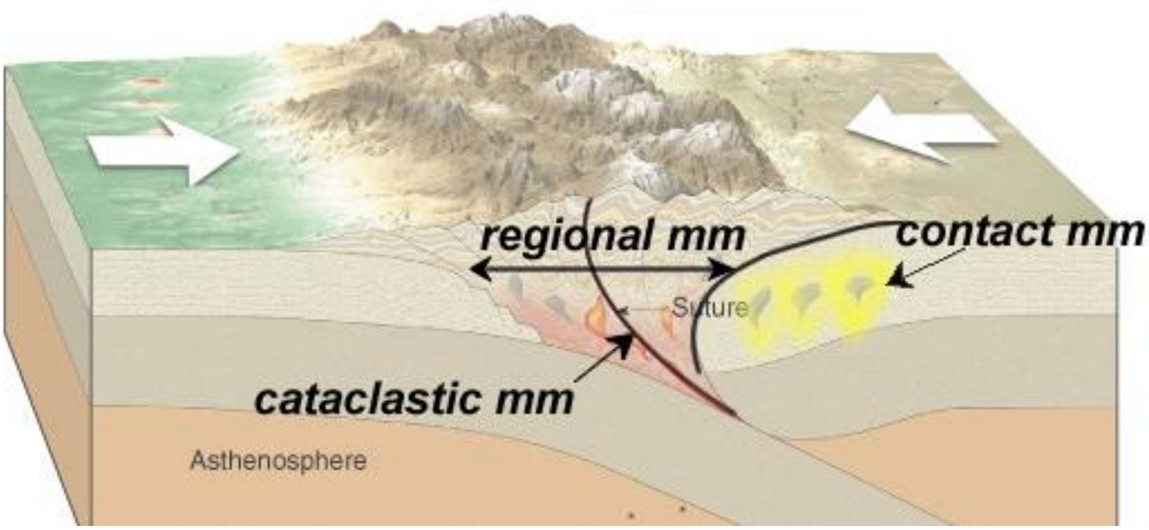


Figure: Regional Metamorphic Rock Facies

In general, proceeding from **low grade** (lower pressure and temperature) to **high grade** (higher pressure and temperature), the following facies are recognized:

- **Zeolite**: low temperature, low pressure
- **Prehnite-pumpellyite**: low temperature, low-medium pressure
- **Greenschist**: low-medium temperature, low-medium pressure
- **Blueschist**: low-medium temperature, high pressure
- **Amphibolite**: medium-high temperature, medium-high pressure
- **Granulite**: high temperature, high pressure

Contact metamorphism. Contact metamorphism (also called thermal metamorphism) is the process by which the country rock that surrounds a hot magma intrusion is metamorphosed by the high heat flow coming from the intrusion. The zone of metamorphism that surrounds the intrusion is called the **halo** (or **aureole**) and rarely extends more than 100 meters into the country rock. Geostatic pressure is usually a minor factor, since contact metamorphism generally takes place less than 10 kilometers from the surface. Contact metamorphism is the metamorphism of rocks surrounding igneous intrusions. Heat is the principal agent of metamorphism.

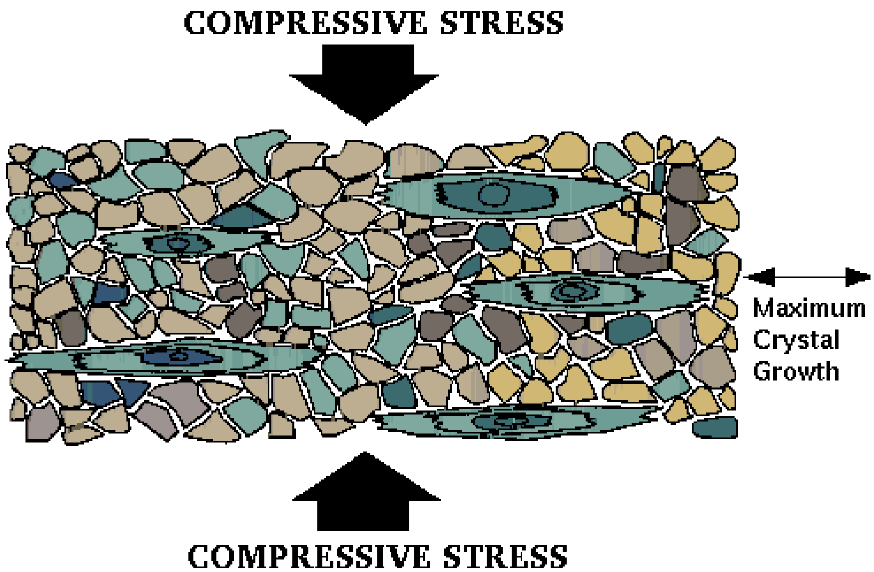


Textures of metamorphic rocks

Like all rocks, metamorphic rocks are classified by their texture and composition.
Definition: Texture refers to the size, shape, orientation and distribution of mineral grains in a rock. In metamorphic rocks texture is determined by the type and grade of metamorphism, and the composition of the original rock, or protolith. There are two basic metamorphic textural categories: foliated and non-foliated.

Metamorphic Rock Types
Metamorphic rocks are classified by texture and by mineral composition.
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.

Foliation
Foliation is a texture that occurs when a rock is put under pressure. As metamorphism proceeds, and the sheet-structure minerals like mica and chlorite start to grow, the minerals are oriented so that the sheets are perpendicular to the direction of maximum stress.
It forms in a variety of ways, but in every case, *the foliation is at right angles to the direction of greatest compression.*



a. Foliation can simply form when objects in the rocks are flattened.
b. Foliation can form when flattening causes platy mineral grains to align, much the way toothpicks would be aligned when swept up by a broom.
c. Solutions often remove large amounts of material from rocks as they are being deformed. The solutions move in the direction of least resistance.
d. Elongate crystals grow in the direction of least resistance.
e. Pockets of molten material may form during high-temperature metamorphism, and these may be flattened. This is one possible way banding in gneiss forms.
f. Shear, like along a fault, also produces foliation. As the shear deformation becomes greater, the foliation becomes stronger and more closely aligned with the fault plane.

Foliated rocks:

These rocks have a planar or flaky fabric. This appearance is caused by the parallel arrangement of platy minerals (mostly micas) and some needle-like minerals (amphibole/hornblende). The development of foliation is dependent on the mineralogy of the rock and the metamorphic process that created it. If a rock is foliated it may have one of the following types of foliation. The name of a foliated rock is based on the type of foliation it exhibits.

1. Slaty foliation (slaty cleavage): Microscopic foliation resulting from the parallel alignment of microscopic clays and micas. Slaty rocks exhibit a closely spaced rock cleavage. Rock fragments are flat, smooth and have a dull luster. Rock name = slate
2. Phyllitic foliation: Microscopic foliation similar to slaty foliation. However surfaces may be bent, and have a slightly shining luster. Rock name = phyllite
3. Schistose foliation: Macroscopic foliation consisting almost exclusively of platy or needle-like crystals, which have a parallel or sub-parallel orientation. Rock name = schist
4. Gneissic foliation: Macroscopic texture consisting of alternating bands of schistose material and granular (non-foliated) layers. Bands are commonly between .5 - 2 cm wide and the granular component typically composes more than 40% of the rock. Rock name = gneiss

Non-foliated rocks:

Non-foliated rocks are massive with no definable fabric. Rocks composed entirely of equidimensional mineral, such as quartz, feldspar, or calcite and rocks metamorphosed by heat under low-pressure conditions are typically not foliated.

Table: Classification of Foliated Metamorphic Rocks

TEXTURE	FOLIATION	COMPOSITION	METAMORPHIC ROCK
Micro-scopic	**Slaty Rock Cleavage** (breaks into smooth, flat fragments and has a dull luster)	microscopic clay minerals and incipient micaceous minerals	**Slate**
	Phyllitic Foliation (breaks into smooth, flat or wavy fragments and has a shiny luster)	microscopic micaceous minerals	**Phyllite**
Macro-scopic	**Schistose Foliation** (composed predominantly of tabular or needle-like minerals. Rock cleavage is fair to good.)	**Variable** Contains one or more of the following minerals: biotite, chlorite, muscovite, talc, garnet hornblende, quartz, feldspar, etc.	**Schist** (Examples: biotite schist, chlorite schist, talc schist, muscovite garnet schist, mica schist, hornblende schist, amphibolite etc.)
			Gneiss (Examples: biotite gneiss, hornblende gneiss, mica gneiss, amphibolite, etc.)
	Gneissic Foliation (contains dark-colored schistose layers or lenses that alternate with non-schistose granular layers of quartz and feldspar.)		

Table. Classification of Non-Foliated Metamorphic Rocks		
TEXTURE	**COMPOSITION**	**ROCK**
Randomly-oriented crystals. May be microscopic.	**Talc and Green Amphibole** (white-green, soapy feel, H<2.5)	**Soapstone**
	Serpentine (shades of green, waxy luster, commonly microscopic)	**Serpentinite**
Original bedding may be visible.	**Variable** (quartz, feldspar, andalusite, mica, etc.)	**Hornfels**
Composed of granular crystals.	**Calcite** (white-to-brown, H < 5.5)	**Marble**
	Quartz (white-to-brown, H > 5.5)	**Quartzite**

Example: Banding in Gneiss

a. Often the banding in gneiss (a metamorphic rock with composition similar to granite) is a relic of original bedding, especially if the original rocks had alternating beds of dissimilar composition.

b. As ferromagnesian minerals form, they accumulate iron and magnesium from their surroundings, which become depleted. The result is a mass of ferromagnesian minerals surrounded by quartz and feldspar.

c. As rocks begin to melt, the granitic components melt first, following Bowen's Reaction Series in reverse. As the melt collects, the remaining rock becomes enriched in ferromagnesian minerals. This is another way to create alternating bands of light and dark minerals.

d. As folding progresses, the sides (or *limbs*) of folds become progressively more thinned out. Alternating bands of segregated and finely-intermingled minerals result.

•Other textures (slaty cleavage, schistosity) occur as pressure increases.

•Mineral assemblages are altered in metamorphic rocks as well. For any given rock composition, each assemblage is characteristic of a given range of temperature and pressure.

•Some minerals are almost exclusive to metamorphic rocks, such as talc, chlorite, and epidote.

Metamorphic Textures Definitions

Texture: Is a term that describes the size, shape and orientation of the grains constituting a rock, as well as the relationship between these grains.

<u>Elements of metamorphic textures:</u>

1- Crystal size:

<0.1 mm v. fine-grained
0.1-1mm fine-grained
1-5 mm medium-grained
5-10mm coarse-grained
> 10 mm v. coarse-grained

2-Shape:

Idioblastic: If the mineral grain is euhedral
Subidioblastic: If the grain is subhedral
Xenoblastic: If the grain is anhedral

3- Macroscopic to mesoscopic textures (general textures):

(i) Slaty

(ii) Schistose: A schist has a lepidoblastic foliation if this foliation is defined by oriented micas, and a nematoblastic foliation if such a foliation is defined by the orientation of prismatic minerals as amphiboles and pyroxenes.

(iii) Gneissic: A complex banded texture made of schistose layers or bands alternating with bands commonly characterized by a granoblastic texture.

(iv) Granoblastic: granular, interlocking equidimensional grains of subequal size; no preferred orientation or cleavage.

(v) Hornfelsic: Fine-grained, granular interlocking grains, possibly of variable shapes and sizes. No preferred orientation.

4- Mineral-mineral relations:

5- Order of crystallization: Crystalloblastic series

6- Relationship between deformation and metamorphism: Through the identification of pre-, syn- and post-tectonic minerals.

Types of metamorphic textures and mineral-mineral relations

Metamorphic textures can be grouped into three main groups:

- **A- Relict textures (palimpsest textures)**: are textures inherited from the original rock type, and which have survived metamorphism.
- **B- Typomorphic textures:** textures characteristic of metamorphism
- **C- Superimposed textures:** textures characteristic of a post- metamorphic event, e.g. alteration, weathering, ... etc.

Other smaller groups as “reaction textures”, “polydeformational textures”, … etc. may also be typomorphic or replacement, but are grouped separately because they have some genetic connotation.

<u>A- Relict Textures</u>

There are several types of relict textures. Relict textures in metamorphic rocks are indicated by applying the prefix "blasto" to the original textural name. Relict textures are best preserved in low-grade rocks. Examples of such textures include:

- porphyritic
- ophitic
- intergranular

- amygdaloidal
- spherulitic
- variolitic
- pisolitic
- oolitic

Please refer to your notes on igneous and sedimentary petrology if you cannot remember any of these terms.

B- Typomorphic textures

Textures characteristic of thermal metamorphism:

When thermal metamorphism is not associated with any deformation, the mineral grains are randomly oriented, resulting in either granoblastic or hornfelsic textures. Please note that the granoblastic texture can also develop in regionally metamorphosed rocks. The following are some of the types of granoblastic textures:

1- Granoblastic polygonal: where the equidimensional grains may have well developed crystal faces resulting in straight grain boundaries, and where triple junctions are common.

2- Granoblastic interlobate: where the grain boundaries are somewhat irregular

3- Granoblastic amoeboid: where all the grains have irregular outlines, and all the minerals are anhedral.

4- Granoblastic decussate: where the interlocking randomly oriented crystals are somewhat elongate, prismatic or subidioblastic. Usually applied to rocks with one or two mineral species only. Triple junctions are common.

5- Nodular: results from the growth of oval - shaped porphyroblasts of such minerals as cordierite or scapolite in association with other randomly oriented minerals as Qz, ..etc.

Textures of dynamic metamorphism:

6- Porphyroclastic: A texture produced by the crushing or fragmentation of large grains, resulting in two distinct grain size distributions of the same mineral: coarser grained porphyroclasts and finer grained fragments.

7- Mortar: similar to porphyroclastic but in which the smaller fragments are further crushed to finer and finer sizes (close to becoming powders), while some porphyroclasts still persist.

8- Protomylonitic: A more advanced stage of cataclasis, where some minerals begin to deform in a ductile manner, giving rise to an incipient foliation or preferred orientation.

9- Orthomylonitic (mylonitic): Where the rocks develop a well - defined foliation. In quartz rich rocks, an orthomylonitic fabric is often indicated by quartz crystals elongated like ribbons or flames (ribbon quartz).

10- Polygonized/ recrystallized/ annealed (ultramylonitic): The most advanced stages of cataclastic metamorphism result in the recrystallization of the highly strained crystals into smaller ones developing a granoblastic polygonal texture. At the same time, a foliation defined by micaceous or prismatic minerals persists.

Crystallization textures:

11- Porphyroblastic: Where coarse - grained metamorphic minerals (porphyroblasts) occur in a matrix of finer grained crystals.

12- Poikiloblastic: Where coarse - grained metamorphic minerals contain numerous inclusions of finer - grained crystals of other minerals. It is of different types:

a- Fish-net or skeletal texture: rapid crystallization

b- Sieve texture

c- Rotational texture: where the inclusions are oriented at an angle that suggests that the poikiloblast may have rotated during its growth, thus indicating syndeformational or syntectonic growth. An alternative interpretation of such texture is the rotation of the foliation during the growth of the poikiloblast, which still makes the growth syndeformational.

d- Snowball: Similar to rotational texture, but where the inclusions define a spiral shaped trail, which may have developed from the "rolling over" of the poikiloblasts.

e- Helicitic: Where the poikiloblasts overgrow the pre-existing foliation. This texture therefore indicates post-tectonic crystallization of the poikiloblasts.

C- Replacement textures (superimposed in part!)

13- Mesh texture: develops in serpentinites, where the needle shaped serpentine minerals occur in aggregates interwoven like a mesh.

14- Hour-glass texture: Also in serpentinites, where the serpentine minerals replace the granular olivine crystals giving rise to hour-glass like appearances.

15- Bastite texture: A third texture that occurs in serpentinites, where Opx crystals were completely replaced by aggregates of serpentine minerals retaining the prismatic shape of the original Opx.

16- Pseudomorphic replacement textures:

(i) single-crystal
(ii) multicrystal
(iii) multi-phase, multi-crystal

D- Reaction textures

17- Epitaxial overgrowth: Epitaxial overgrowth is characterized by optical continuity between the mineral and its overgrowth. Both the mineral and the overgrowth must belong to the same structural group, and may possibly be the same mineral. This type of overgrowth is controlled fully by the the matrix mineral.

18- Topotactic replacement: One mineral overgrows another of a similar structure (e.g. Actinolite rims on glaucophane). Orientation of overgrowing mineral is controlled by that of the overgrown one.

19- Kelyphitic texture (also a replacement texture): A kelyphitic texture is a replacement of one mineral along its rim by an intergrowth of two or more minerals, in a way that the new minerals almost completely surround the mineral being replaced. The term is most commonly used when the replacing minerals form during retrogression. Examples include kelyphitic rims of chlorite + Fe-oxides after garnet.

20- Reaction-rim texture: when one mineral replaces another along its rims, suggesting a reaction between both phases. The contacts between both phases are irregular.

21- Corona texture: several concentric layers of one or more minerals completely encircling an older phase. The layers (which range from one to five in number) represent a sequence of reactions that have taken place (none to completion) to replace the mineral in the core or center of the corona. Coronas form during both prograde or retrograde metamorphism.

22-Atoll texture: where the core of a mineral is dissolved or replaced leaving behind a surviving rim. Such textures usually form due to an original compositional zoning within the mineral with the replaced core.

E- Intergrowth texture

23- Symplectites (also a reaction texture): Are irregular fine-grained mineral intergrowths that form as a result of a certain reaction that did not go to completion. These intergrowths are often recognized by their wormy appearance and often occur along the boundaries of reacting minerals (or ones not in equilibrium).

Examples of commonly intergrown mineral pairs: Qz-Feldspar/ Amph-Spinel/ Plag-Mgt/ Gt-Qz/ Plag-Cpx/ Bt-Qz/ Ep-Qz/ Amph-Plag. Note that a common type of symplectitic intergrowth is the *myrmekitic texture* commonly observed in granites, where wormy quartz occurs in plagioclase crystals in contact with biotite. Symplectitic intergrowths are more common in high temperature rocks.

F- Polydeformational/Polymetamorphic textures

24- Crenulated cleavage/schistosity: Results from the folding of a foliation.

25- S-C fabric: A more advanced stage of crenulation, where one or more minerals are orientated along the crenulated surfaces to define a new foliation (S_2) at an angle to the older one (S_1). This commonly involves some form of "recrystallization".

G- Special textures and features

26- Pressure shadows: are ellipsoidal regions adjacent to a rigid crystal where minerals grow developing textures that differ from those defined by the same minerals in the rest of the sample. Growth in a pressure shadow is therefore influenced by the crystal faces of the rigid mineral which seem to "protect" the minerals in its immediate vicinity from the deformation affecting the same minerals in other parts of the sample. Accordingly, the foliation wraps around the rigid crystal and its shadow.

27- Mica fish: Are lenticular porphyroblasts of mica which commonly develop in a shear stress environment and can be used to indicate the sense of shear.

28- Kink bands (deformational bands): Are bends and twists within some minerals as a result of their deformation. Kink bands develop in pre-tectonic minerals.

29- Zoning: Compositional change of a crystal, often accompanied by a change in some of its optical properties.

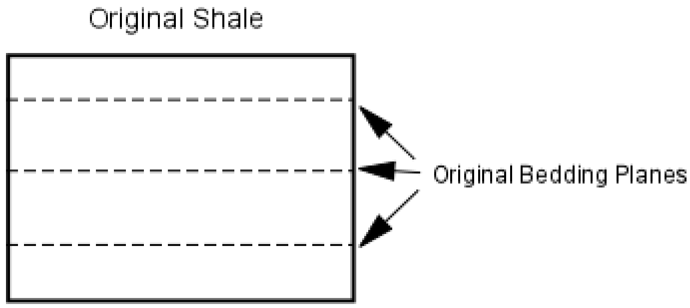
30- Twinning: Some twinning may be induced by deformation.

31- Exsolution texture: results from the incomplete miscibility between two components (end-members) of a solid solution series. A decrease in temperature may result in the separation of these two phases, one in the other commonly along cleavage planes. Common in high grade rocks that cooled slowly.

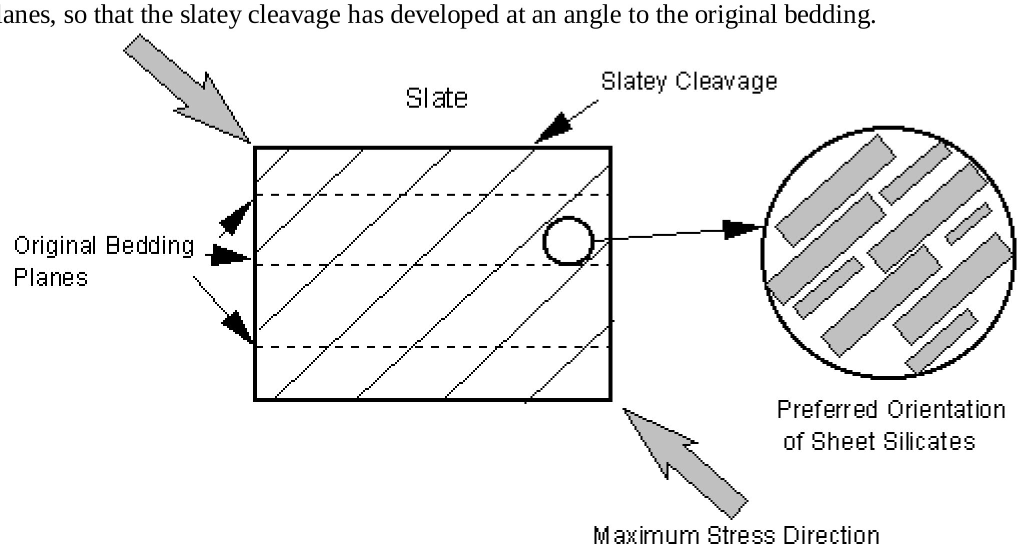
Foliated metamorphic rocks

If a rock is foliated, its name is determined by the type of foliation present and the dominant minerals—for example, a **kyanite schist.** If the minerals are segregated into alternating light-colored and dark-colored layers, the rock is called a **gneiss. Slates** are generally fine-grained, dark-colored, metamorphosed sedimentary rocks that split easily along slaty foliations and were formed under low-grade temperature and pressure conditions. **Phyllites** are slightly more metamorphosed than slates and contain mica crystals that impart a glossy sheen. A **schist** is coarser grained than phyllite or slate and has aligned minerals that can be identified with the naked eye. Some varieties of schist are mica, garnet-mica, biotite, kyanite, and talc schist. A schistose rock composed of the mineral serpentine is called a **serpentinite.**

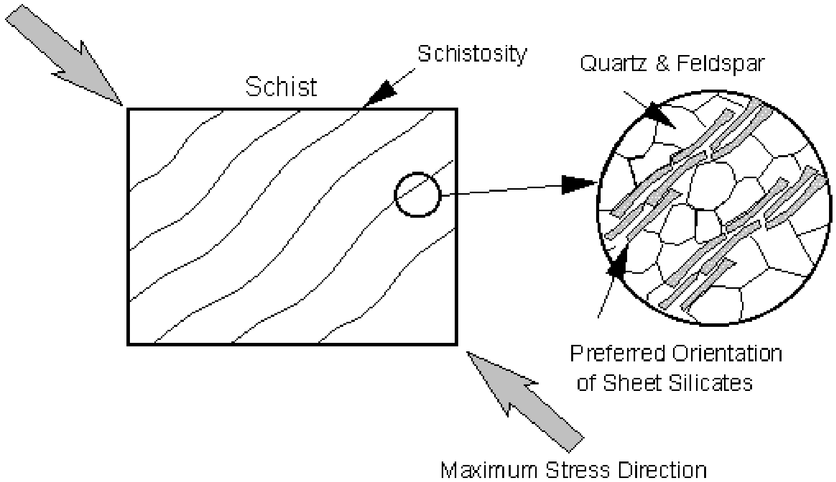
Foliated Metamorphic Rocks Example - metamorphism of a shale, made up initially of clay minerals and quartz all of clay or silt size.



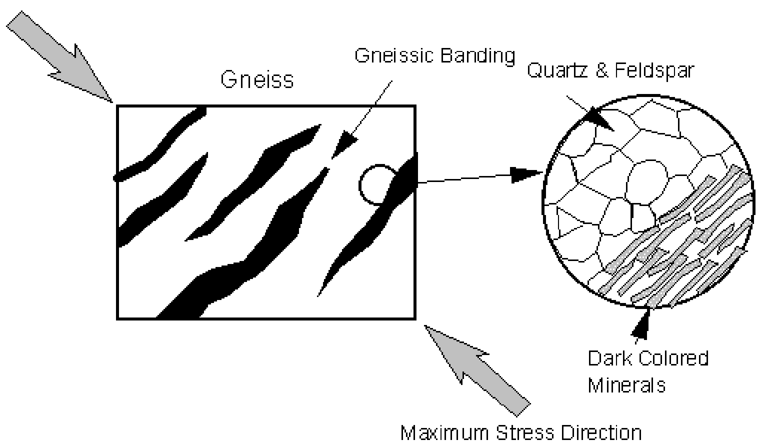
Slate - Slates form at low metamorphic grade by the growth of fine grained chlorite and clay minerals. The preferred orientation of these sheet silicates causes the rock to easily break along the planes parallel to the sheet silicates, causing a ***slatey cleavage.*** Note that in the case shown here, 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.
Migmatites form when temperatures are hot enough to partially melt the rock. The magma is sweated out, or injected, as layers between foliation planes in the rock.
An example of the categories a shale would pass through as temperatures and pressures increase (from low grade to high grade) is as follows: shale/slate/phyllite/mica schist/gneiss/migmatite.

Non-foliated rocks

Nonfoliated metamorphic rocks. If a rock is not foliated, its name is derived from its chemical composition. A quartz-rich rock such a sandstone, for example, is called a **quartzite** when it has been metamorphosed. A metamorphosed limestone is called a **marble.** When rocks (especially shales and basalts) are affected by contact metamorphism, they often develop a texture called **hornfels.** A hornfels rock is characterized by evenly distributed, very fine-grained mica crystals that give it a more massive, equigranular appearance.

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.

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.

Table: Common metamorphic rocks and their protoliths

Metamorphic Rock	Composition: dominant mineral(s)	Protolith
marble	calcite	**limestone**
quartzite	quartz	**quartz sandstone**
serpentinite	serpentine	**ultramafic rock**
amphibolite (hornblende schist)	amphibole (e.g. hornblende)	**basalt** or **gabbro**
greenstone/green schist	chlorite, green amphibole	**mafic rock**

muscovite (garnet) schist	muscovite, garnet	**mudstone** or **shale**
orthogneiss[1]	quartz, feldspar, mica, etc.	**granite** or other igneous rock
paragneiss[2]	quartz, feldspar, mica, etc.	**layered detrital rock** (e.g. shale with interbedded sandstone
[1] Orthogneiss contains thin wavy discontinuous schistose lenses resulting from the alignment of micaceous minerals when an igneous rock is regionally metamorphosed. [2] Paragneiss Metamorphosed layered sedimentary rock. Typically exhibits well-defined schistose and non-schistose layers.		

Hydrothermal Rocks

Hydrothermal essentially means “hot water.” **Hydrothermal rocks** are those rocks whose minerals crystallized from hot water or whose minerals have been altered by hot water passing through them. Thus, these rocks are distinct from metamorphic rocks, which are created by solid-state mineral transformations. In fact, many hydrothermal rocks (such as those that form from hot springs and geysers or crystallize as veins in cracks in other rocks) actually build up in layers, much as sedimentary rocks do.

Veins result when hot water moves through cracks in the bedrock of the crust. The water leaches elements from the rocks it passes through. Various minerals are precipitated on the sides of the crack as the temperatures decrease. The shape and orientation of the minerals depends on the temperature, pressure, and rate of flow. When all the available space in the crack has been filled with mineral deposits, the crack is sealed and the vein is complete.

The water involved in hydrothermal processes is usually either seawater that is moving downward through oceanic crust near midoceanic ridges or meteoric water. **Meteoric water** is water that is derived from the atmosphere as rain or snow and that moves down into the bedrock from the earth's surface. Water trapped in the original sediments during deposition and lithification (**connate water**) can also be included in hydrothermal reactions but is not a major source of hydrothermal fluid. **Magmatic water** derived from magmas is also a minor component.

The water is heated to very high temperatures as it moves deeper into the crust. It eventually rises again, often removing elements from the rocks it passes through and carrying them in solution. As the hot water rises toward the surface, it begins to cool. This temperature drop induces a number of chemical reactions, and hydrothermal minerals are precipitated.

Metasomatism is the process by which hot-water solutions carrying ions from an outside source move through a rock mass via fractures or pore space. Some of the rock mass is usually dissolved away, and the ions introduced by the water are incorporated into the new minerals that precipitate. Unlike metamorphism, metasomatism can significantly change the overall chemistry of the parent rock. Elements commonly added during metasomatism are iron, sodium, potassium, oxygen, and silica. Easily soluble elements, such as calcium and magnesium from limestones, are often dissolved and carried away, creating more room for new chemical reactions.

Metamorphism and Plate Tectonics

Metamorphic rocks result from the forces active during plate tectonic processes. The collision of plates, subduction, and the sliding of plates along transform faults create differential stress, friction, shearing, compressive stress, folding, faulting, and increased heat flow. The tectonic forces deform and break the rock, creating openings, cracks, faults, breccias, and zones of weakness along which magmas can rise. Generally speaking, the greater the tectonic forces, the higher the pressures and temperatures affecting a rock mass and the greater the amount of resulting structural deformation and metamorphism.