UNIT 12

METAMORPHISM

Structure

12.1 INTRODUCTION

You have been introduced to the term metamorphism and metamorphic rocks have been introduced while discussing Rock cycle in Unit 1 of this course, i.e. Petrology of this course. Recall! you had learnt that the earlier metamorphic rocks originate when a pre-existing rock/ protolith (which can be igneous, sedimentary, or metamorphic) undergoes a solid-state change when subjected to high temperature and high pressure in the presence of fluids that typically comprise H_2O and CO_2 and some other ions. In fact, the metamorphic reactions are controlled by a combination of temperature, pressure and fluid composition that are known as factors of metamorphism. Such conditions are found deep within the Earth. Every metamorphic rock has a parent/protolith or a precursor rock. Metamorphism refers to changes in parent rock or protolith in the solid state without involvement of melting. We can view the process of metamorphism as somewhat similar to cooking that involves placing the mixed ingredients at a higher temperature (and/or pressure). The food is cooked due to the changes occurring largely in solid state. Metamorphic rocks are characterised mainly by the changes in mineralogy, structure and texture. Changes in chemical composition may also take place.

This unit addresses the factors affecting, processes and products of metamorphism.

Expected Learning Outcomes

After reading this unit you should be able to:

- define metamorphism;
- know the factors affecting metamorphism;
- explain low-and high temperature and low-and high pressure of metamorphism;
- describe types of protolith;
- discuss metamorphic processes in relation to temperature and pressure;
- learn about metamorphic reactions; and
- get acquainted with products of metamorphism.

12.2 BASIC CONCEPTS

The word "**metamorphism**" comes from the Greek words (*Meta* means ‘change’, *Morph* means ‘form’) therefore metamorphism refers to ‘change of form’.

Charles Lyell, a British geoscientist introduced the term metamorphism in reference to mineralogical and structural changes in the outcrops of deeply eroded mountains. **Metamorphism** is the process that brings about changes in the mineralogical and/or structural and/or chemical constituents in a rock (dominantly in solid state). Metamorphism is regarded as a thermal phenomenon in which heat is the most important source of energy causing mineralogical and textural reconstruction. Metamorphism at highest grades coexists with partial melting and may involve changes in bulk chemical composition of the rock. The term **metasomatism** is applied, if change in bulk composition is the dominant metamorphic process. You have read about metasomatism is discussed in block 4 of BGYCT-133 course.

The IUGS (International Union of Geological Sciences) Subcommission on the systematics of metamorphic rocks gives the following definition-
metamorphism is understood as a transformation or recrystallisation of a rock in the solid state caused by increased temperature and pressure at

considerable depths in the Earth. The definition allows no appreciable change in bulk composition, but excludes surface alteration by leaching and mechanical disaggregation. The type of metamorphism depends on the relative values of temperature, confining pressure, pressure or chemical activity or fugacity of water, deformation or directed pressure and their variation with time.

We shall discuss the 'new conditions' or factors or agents, to which the parent rock is subjected during the process of metamorphism in the following section. During the process of metamorphism, the mineral and rock deposits undergo changes and continue to adapt till equilibrium with the new environmental conditions is reached. Metamorphism cannot be attributed only to the dynamics taking place within the Earth or below the surface of Earth at tens of kilometres. Metamorphism may occur very close to the surface of the Earth. The process though for most of its part does not involve complete melting of the rock, but partial melting or generation of the anatectic melt at the highest grades of metamorphism is well known. The process during which the complete melting of rock occurs is considered to be of igneous rather than metamorphic nature.

Now let us discuss the factors of metamorphism.

12.3 FACTORS AFFECTING METAMORPHISM

Let us learn that the metamorphism in rocks is caused by changes in temperature (T), pressure (P), shearing stress, and chemically active fluids or gases that leave the system but may be trapped as fluid inclusions in metamorphic minerals formed at considerable depths in the Earth's crust. You have read earlier that the rocks undergoing metamorphism may be igneous, sedimentary or pre-existing metamorphosed rocks which do not undergo any chemical changes except loss of fluids.

12.3.1 Temperature

Temperature is the most common cause or the driving factor in the process of metamorphism. It provides the heat energy required by the chemical reactions that results in the recrystallisation of existing minerals and/or the formation of new minerals or neomineralisation. Thermal energy responsible for metamorphism comes from the following sources:

- Heat generated within the deep interior of the Earth and is left over from accretion more than 4.5 billion years ago,
- Heat released by decay of radioactive elements,
- Frictional heat generated along faults or shear zones which is local and restricted to near-surface regions of the Earth, and
- Latent heat of crystallisation from igneous intrusions and magma.

Rocks undergoing regional metamorphism in the deeper regions of the lithosphere are deformed and the mechanical energy involved in thrusting is also transformed into some thermal energy. The mode of heat transport from high to low-temperature area is by conduction because rocks are mostly solid during metamorphism. Continuously the heat is transferred from the Earth's interior to the surface due to heat production by radioactive decay of uranium (U), thorium (Th), potassium (K). The grade of metamorphism increases as the temperature due to geothermal gradient and pressure on a body of rock increase with depth (Fig. 12.1). Metamorphic grade is a general term for describing the relative temperature and pressure conditions under which metamorphic rocks form. You will read about geothermal gradient in the next section.

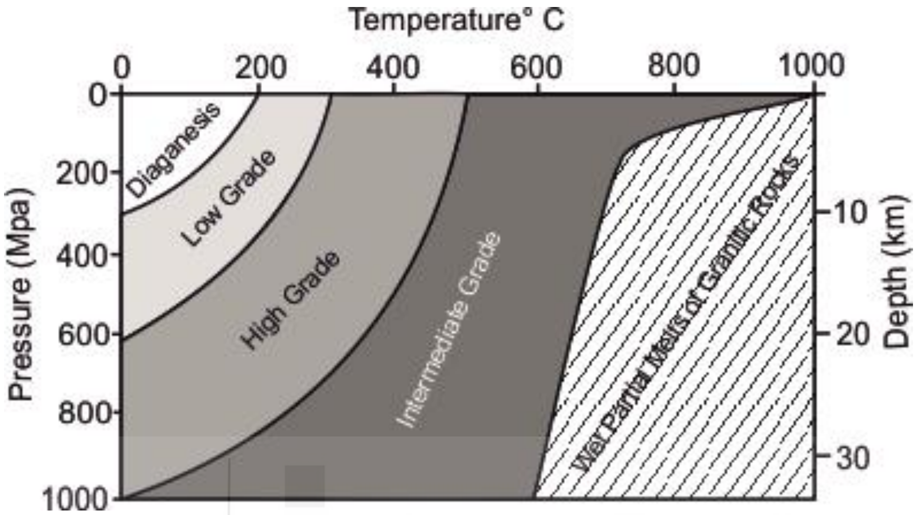


Fig. 12.1: The grade of metamorphism increases as the temperature and pressure increase with depth.

Heat may also be transported by the igneous intrusions from the mantle to the shallower layers of the crust. Whenever magma forms, it rises toward the surface due to buoyancy and intrudes the country rocks. Its baking effect on the cool country rocks produces contact metamorphism. You have read about contact metamorphism in Block 4 of BGYCT-133 course.

12.3.2 Geothermal Gradient

You have read about geothermal gradient in BGYCT-131 course. **Geothermal gradient** is the rate of increase of temperature in the Earth with depth. Temperature increases at the rate of 20º C to 30ºC per kilometre downwards in the Earth's crust. The rocks formed at Earth's surface are transported to greater depths experience a gradual increase in temperature (Fig. 12.1). Thus, in a rock buried to a depth of about 8 kilometres where temperatures are about 200˚C the clay minerals will tend to become unstable. They will begin to recrystallise into new minerals, such as chlorite (it is mica like mineral formed by the metamorphism of iron and magnesium rich silicate minerals) and muscovite, which are stable in this environment. At 10 to 40 km depth (range of the typical middle to lower continental crust) the continental geotherm is significantly lower than the oceanic crust. Geothermal gradient or geotherm is given as the increase or change of T (∆T) with the vertical thickness (∆z). **Heat flow** is the movement of heat (energy) from the interior of the Earth to the surface. The heat flow (q), measured as W/mK = Watts per meter Kelvin, is proportional to the thermal gradient:

$$q \propto (\Delta T/\Delta z)$$

$$\text{or } q = k(\Delta T/\Delta z)$$

where k is the proportionality constant, known as the conductivity of rock, (k is the amount of heat conducted per second through an area of 1 m^2s); z is the depth measured downward from the surface.

This equation can be used to calculate heat flow for any part of the Earth's crust in which both thermal gradient and thermal conductivity of the rocks can be measured.

Heat flow is measured in Watt per square meter (W/m^2), although it is better to use heat flow units (HFU), where 1 HFU is defined as $\mu cal\ cm^{-2}s^{-1}$, equivalent to 4.2 $\mu Js^{-1}\ cm^{-2}$ or 0.042 Js^1m^2. It has been calculated that the heat flow from the Earth's interior is 30 milli watts per square meter. However, heat flow measurements at the surface of the Earth vary between about 30 and 120 mW/m^2. Thus, the geothermal gradient for stable continental zones is of the order of 1°C/30m. Geothermal gradients can go as high as up to 50°C/Km in some areas, whereas in subduction zones the geotherms are low, which indicates that the rate of burial is high. Higher geothermal gradients may be caused by igneous intrusions, plumes/hotspots, crustal extension, lithospheric mantle delamination, etc. Figure 12.2 shows the relationship of geothermal gradient with the metamorphic facies. You can see that as the depth increases the metamorphic facies of higher temperature and pressure develop.

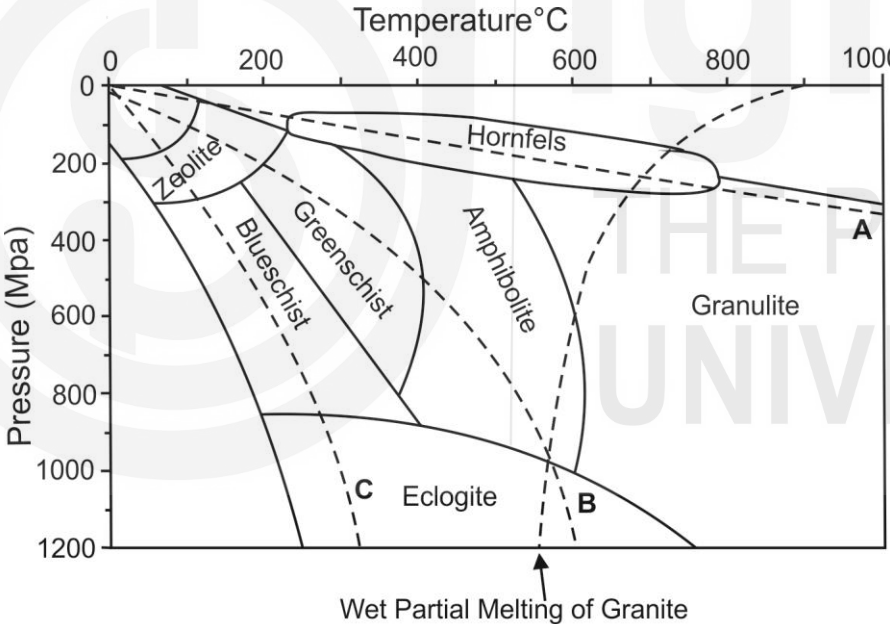


Fig. 12.2: Graph depicting the relationship of geothermal gradient with the metamorphic facies. 'A'- High geothermal gradient (contact metamorphism), Low P, High T; 'B'-Normal geothermal gradient (regional metamorphism), High P, High T; 'C'-Low geothermal gradient (subduction), High P, Low T.

12.3.3 Load Pressure (P_{load})

You have read in the above section that temperature plays a significant role in the processes of metamorphism. Similarly, the pressure or stress applied to the rock also induces metamorphism and changes rock's chemical composition, mineralogy and texture. The identification of the resultant metamorphic rock depends not only on the temperature, chemical composition of the parent rock and chemically active fluids but also on the pressure at which the metamorphism took place. The change of pressure in rocks is analogous to the change in positions along the vertical space coordinate (z) which means from the surface of the Earth to the center of the Earth (it is assumed that pressure surfaces are parallel to the surface of the Earth). Therefore, the pressure on a volume of rock at certain depth (h) is a function of acceleration due to gravity (g) and the average density (ρ) of the overlying material. The prevailing pressure is called the **load pressure** (P_{load}) or **lithostatic pressure** (P_{litho}) or total pressure (P_{total} or P_{solid}), which is equivalent to the pressure on a given volume of rock or the load of the overlying rock or lithostratigraphic column. The load pressure is responsible for development of denser and anhydrous minerals (anhydrous mineral contains no water in chemical combination) at great depths.

Load pressure, also called lithostatic pressure, is general force applied equally in all directions. For example, a swimmer under water experiences a force applied equally in all directions. Pressure increases with depth due to the weight of overlying rocks and is called **confining pressure**. It acts on rock simultaneously and equally in all dimensions and increases with depth like temperature, as the thickness of the overlying rocks increases. Thus, we can conclude that the metamorphic rocks from the deeper levels of the Earth are denser than those formed at shallower depths of the crust.

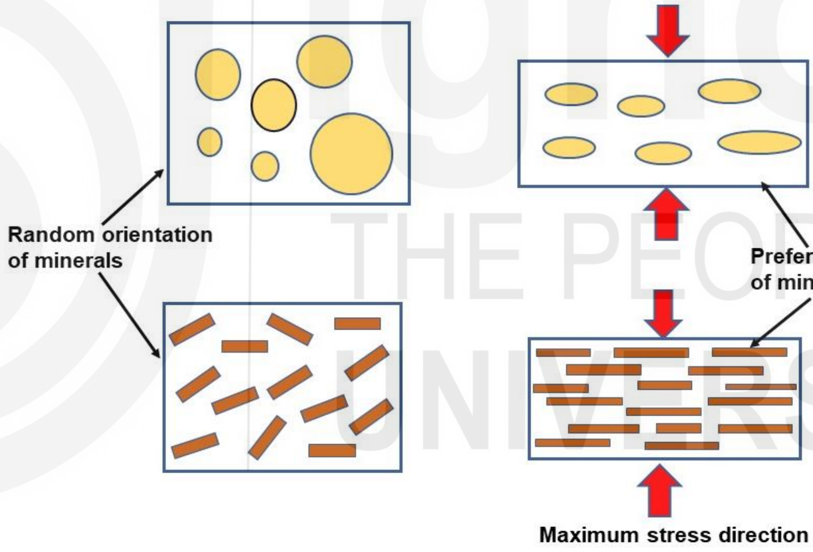


Fig. 12.3: Flattening and orientation due to pressure or stress.

12.3.4 Fluid Pressure (P_{fluid})

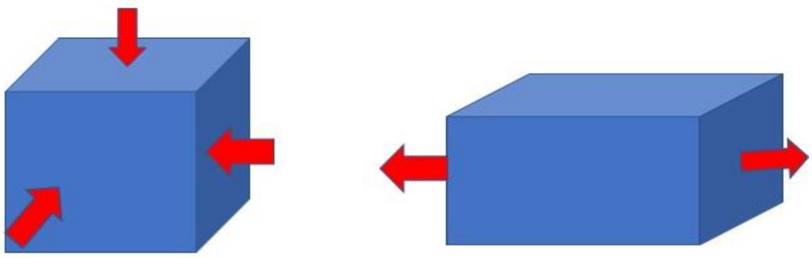
You have read that the Earth's crust has water in its composition. The meteoric water, groundwater or seawater that comes in contact with intruding magma usually contains rich combination of metallic cations, dissolved compounds, some ions and volatiles (H_2O, CO_2 and SO_2). Such chemically enhanced waters play an active role during metamorphism. The addition of water (and the gases & ions) accelerates chemical reactions within different minerals due to ability of volatiles to dissolve ions forming new minerals. The geothermal gradient suggests that T and P_{load} increases simultaneously with an increase in depth. Huge volumes of aqueous fluids are liberated by compaction in a sedimentary sequence along continental margins and in the subduction zones. Most of the water present in the pore spaces and hydrous minerals, viz. kaolinite, illite, montmorillonite is released by sediments during compaction.

You have learnt in Block 2 of BGYCT-133 course that minerals like clays, micas and amphiboles contain water in their crystalline structures. The elevated temperatures and pressures can cause the dehydration of these minerals. In sedimentary rocks, a large amount of water can be stored in the pores of the rock. The released fluids are chemically active and often act as a catalyst, reactant, or product during metamorphism. A few percent of structurally bound water is driven out of the rocks with increasing temperature. With increasing depth of burial and temperature, there must be more or less continuous breakdown of hydrous minerals over the entire range of metamorphic conditions (clay minerals→ chlorites→ micas→ amphiboles). Presence of a free fluid phase helps define fluid pressure (P_{fluid}) or P_{H2O} (in case of pure water) which plays an important role in controlling stability fields of the hydrated phases such as micas and amphiboles and carbonate phases when the fluid is CO_2. Considering the consistency of mineral assemblages present in the metamorphic facies and the ordered sequence of index minerals, it is generally agreed that water pressure and load pressure are approximately equal ($P_{fluid} = P_{load}$), in all the metamorphic terrains of the world, except in granulite facies metamorphism.

12.3.5 Shear Stress

A solid rock, at depth, under a load pressure (P_{load}), is said to be in hydrostatic equilibrium, i.e. it is subjected to equal forces in all directions. This stress caused by external force is thus, isotropic (equal in all the directions) and is represented by a sphere having rock-system in the center (Fig. 12.4). But if the force is exerted in a particular direction, for example when plate tectonics comes into play, in case of converging lithospheric plate, the stress remains no longer isotropic. This anisotropic stress system is now represented by a triaxial stress ellipsoid with the maximum stress σ_1, minimum stress σ_3 and intermediate stress σ_2. This **shearing stress** or better known as **deviatoric stress** is maximum in planes situated at 45˚ to the principal stress σ_1 or to the minimum stress σ_3. The P_{stress} plays an important role:

1) Metamorphic reactions are accelerated due to speeding up of ionic diffusion which would be otherwise too slow to be effective.
2) The shearing stress increases the total area of the grain surface, causes flow in a mineral aggregate, and renews the surface contacts between the grains.
3) The temperature ranges of stability of some minerals are extended owing to high shearing stress.
4) It also decreases the melting point and increases the solubility of minerals.



(a) Confining Stress (b) Tensional Stress

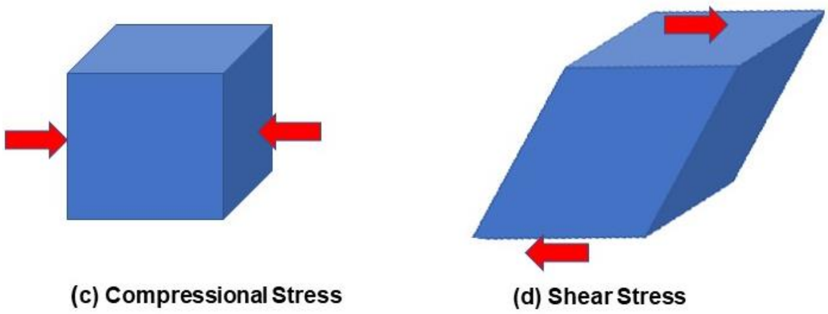


Fig. 12.4: Diagrams showing types of stress: a) Confining stress; b) Tensional stress; c) Compressional stress; and d) Shear stress.

12.4 LIMITS OF METAMORPHISM

As per the definition given by the IUGS, it can be said that the limits of metamorphism are governed by two important physical variables, viz. temperature and pressure. We have discussed them in the previous section. Metamorphism doesn't include weathering, diagenesis, and melting. Metamorphism occurs at temperatures and pressures higher than 150°C and 300 MPa (MPa stands for Mega Pascals equivalent to about 3,000 atmospheres of pressure). Here we will discuss the low- and high-temperature and low- and high-pressure limits of metamorphism.

You have read about diagenesis in Unit 8 Formation of Sedimentary Rocks, in this course. It refers to changes that occur during the formation sedimentary rocks. Diagenetic processes occur at temperatures below 150°C and pressures below about 300 MPa.

12.4.1 Low-Temperature Limit

The precise limits of metamorphism within the Earth's crust cannot be defined sharply, as there is no sharp distinction between the zone of high-grade metamorphism and magma formation by rock melting as well as that between diagenesis and low-grade metamorphism. These limits are indicated by lower and upper temperature limits. The material under investigation plays an important role in setting the temperatures at which the transformations begin. For example, transformation of evaporites, vitreous material and organic material, begin to take place at comparatively lower temperatures than transformation of most carbonate and silicate rocks.

In most of the rocks, phase transformations begin shortly after sedimentation and continue with increasing burial, making it arbitrary whether such transformations are diagenetic or metamorphic. The demarcation between diagenesis and the beginning of metamorphism is not very well defined. In silicate rocks, the low-temperature limit of metamorphism is around 150 ± 50 °C. The beginning of metamorphism is marked by the first appearance of the following minerals:

- Prehnite
- Pumpellyite
- Fe-Mg-carpholite
- Paragonite

- Stilpnomelane
- Lawsonite
- Glaucophane

However, it should be noted that these minerals may also be found as detrital grains in unmetamorphosed sediments and the distinction can be made by thin section analysis.

12.4.2 High-Temperature Limit

You have learnt about the low-temperature limit of metamorphism. In reference to the above-mentioned definition of metamorphism, beginning of melting is a part of metamorphism at the highest grades as long as the rocks continue in the solid state. At higher temperatures, melting of rocks will be initiated, and these temperatures of melting will define the high-temperature limit of metamorphism. The factors on which these melting temperatures are strongly dependent are:

- Rock composition,
- Pressure, and
- Amount of water present.

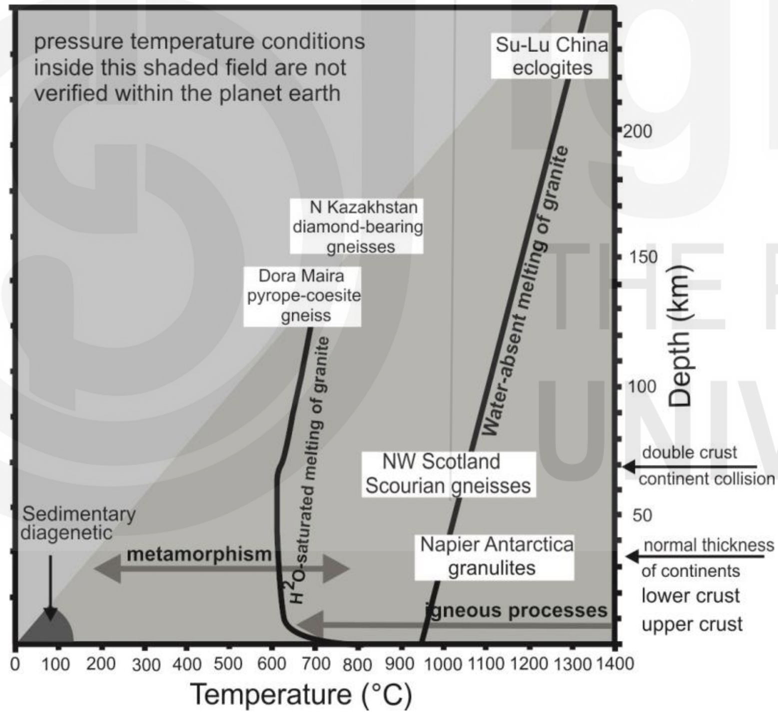


Fig. 12.5: The pressure temperature ranges of metamorphic processes. (Source: Bucher & Grapes, 2011). **The P–T gradients of four typical geodynamic settings are shown. The boundary between diagenesis and metamorphism is gradational. Note that the metamorphic field has no upper P–T limit on this diagram, and that there is a large overlap for metamorphic and magmatic conditions.**

For example, in the Figure 12.5 we can see the granitic rocks begin to melt at a temperature of 660°C whereas, basaltic rocks need higher temperatures of about 800°C (at 500 MPa and in presence of an aqueous fluid), but if water is absent, these temperatures are increased. In absence of water, the melting temperatures of granitic and basaltic rocks is raised to 1000°C and >1120°C respectively. The highest temperatures of crustal metamorphic rocks, determined by indirect methods of thermobarometry, were reported to be 1000-1150°C (Lamb et al. 1986; Harley and Motoyoshi 2000; Sajeev and Osanai 2004). Napier Complex (Antarctica), Scourian gneiss (Scotland), and the Highland Complex (Sri Lanka) are examples of such magnesian- and aluminous-rich gneisses, termed Ultra high temperature (UHT) metamorphic rocks. Another category of rocks termed as granulites are found in the lower continental crust of geologically active areas. Their melting temperatures are reported to be about 750-850°C and mark the typical upper limit of crustal metamorphism. At temperatures above 1500°C, a given volume of rock in solid state, in the convecting mantle undergoes processes such as recrystallisation and various phase transformations.

12.4.3 Low-Pressure Limit

The load pressure is directly dependent on the depth and can be applied in three different ways:

- The pressure exerted by the fluids between the grains in a porous rock is known as the **pore pressure**. The increase in the rate and ease of ion exchange depends on the presence of water which acts as a catalyst and speeds up reactions.
- The pressure exerted by the weight of the overlying rocks is the **load pressure** which brings minerals into contact with each other over long periods of time.
- The high pressure exerted over relatively short periods of time causes the rock to undergo folding and faulting is known as **shear stress** or **directed** pressure.

Though the lower pressure limits of metamorphism are undefined, metamorphism in **contact aureoles** may occur at near surface pressures of a few bars, if a magma rises towards the surface. You have read about contact aureole in Block 4 of BGYCT-133 course.

In all cases, the higher the pressure, the greater is the degree of metamorphism. Reactions that depend on pressure only are less common than temperature dependent reactions.

12.4.4 High-Pressure Limit

You have read about low-pressure limit in previous section. Now let us read about high-pressure limit.

For a very long time, we believed that the highest limit of pressure in metamorphic crustal rocks corresponded to the lithostatic pressure at the base of a normal continental crust of a thickness of 30-40 km, which does not exceed 10 kbar. But as better calibrations were available, in some metamorphic mafic rocks the mineral assemblages often recorded pressures of 15-20 kbar (Table 12.1). These metamorphic mafic rocks of high density and consequently formed at high pressure were said to be equivalents of basalts, and were called **eclogites** (Fig. 12.2 and 12.5).

Table 12.1: Tabulated temperature and pressure conditions for the lower and the upper limits.

Temperature	Pressure
Lower temperature limit	**Low pressure limit**
0°C for processes in near surface environments, rock-water reactions	0.1 MPa at contact with lava flows at the surface
Conventionally, the term metamorphism implies T>150-200°C	
Upper temperature limit	**High pressure limit**
In crustal rocks; 750-850°C (max. recorded T~1, 150°C	Presently, some rocks collected at the Earth surface are known to have once formed at 100-200km depth, =3-6GPa
In many regional scale metamorphic areas T does not exceed ~650-700°C	

SAQ 1

a) Define metamorphism.

b) List the sources of thermal energy responsible for metamorphism.

c) Name two elements producing heat due to radioactive decay.

d) Higher geothermal gradient is found in _______________.

e) Mention the low-and high-temperature limits during metamorphism?

f) What is pore pressure?

12.5 PROTOLITH

In the previous section the term 'protolith' has been referred to many times. Protolith refers to the original or parental rock, prior to metamorphism. The original textures are often preserved in the low-grade metamorphic rocks which allow us to determine the likely protolith. But, as the grade of metamorphism increases, original textures exhibited by the parent rocks are replaced or overprinted with metamorphic textures and other clues. In such cases the mineralogy or the bulk chemical composition of the rocks are used to determine the protolith.

Let us discuss different types of protoliths or parent rocks.

- **Quartzo-feldspathic**: The granitic rocks and arkosic sandstones composed dominantly of quartz and feldspar fall under this category. These minerals are stable over a wide range of temperatures and pressures. Thus, the metamorphic rocks that contain mostly quartz and feldspars with only minor amounts of aluminous minerals are likely to have a quartzo-feldspathic parent.

- **Pelitic**: These metamorphic rocks are derivatives of aluminous sedimentary rocks like shales and mudrocks. They have high concentrations of alumina as they are recognised by an abundance of aluminous minerals, like clay minerals, micas, kyanite, sillimanite, andalusite, and garnet.
- **Calcareous**: Calcareous rocks are rich in calcium. Apart from calcium the carbonate rocks contain other minerals resulting due to metamorphism of associated siliceous detrital minerals that were present in the rock. Low grade metamorphosed calcareous rocks are identified by the abundance of carbonate minerals like calcite and dolomite. With increasing grade of metamorphism calcite and dolomite 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 are found.
- **Basic/Ultrabasic**: 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.
- **Ferruginous**: The rocks rich in Fe with little Mg are known as ferruginous. These rocks could be derivatives of Fe-rich cherts or ironstones. They are characterised by an abundance of Fe-rich minerals like Fe-rich serpentine, Fe-rich talc, ferroactinolite, hematite, and magnetite at low grades, and ferrosilite, fayalite and almandine garnet at higher grades.

Most metamorphic rocks have the same overall chemical composition as the parent rock from which they formed, except for the possible loss or acquisition of volatiles such as water (H_2O) and carbon dioxide (CO_2). Thus, the chemical composition of parent rock provides important clue to establish the parent material from which metamorphic rocks were derived. High in the Alps in southern part of Europe the large exposures of the metamorphic rock marble are found. Marble and the common sedimentary rock limestone have the same mineral composition (calcite, $CaCO_3$). Therefore, it seems reasonable to conclude that limestone is the parent rock of marble. The degree to which each metamorphic agent will cause change is largely governed by the mineral makeup of the parent rock. For example, when magma forces its way into surrounding rock, high temperatures and hot magmatic fluids may alter the host rock. The original chemical composition of a parent rock or protolith greatly affects the mineralogy of its metamorphic product.

12.6 METAMORPHIC PROCESSES

You have read about the agents of metamorphism, limits of metamorphism and types of protolith. Now we will read about the metamorphic processes and products. Metamorphism is an isochemical process which brings changes in both modal composition as well as the mineral composition constituting the rock. It is well established that the factors controlling the chemical reactions occurring also control the processes leading to mineral and metamorphic rock formation.

These metamorphic processes are a cause of following sub processes within the mantle and crust of the Earth.

- mechanical disequilibrium,
- transient chemical change, and
- thermal alteration

The disequilibrium state is brought about by the dynamic processes operating within the Earth which are of geological background. It is evident that the metamorphic processes as a whole are a result of disequilibrium and changes brought in factors which control the reactions and transportation in the rocks. Once an equilibrium state or steady state is achieved the metamorphic processes terminates. However, a rock always attempts reaching the equilibrium conditions and termination of the metamorphic processes. This results in a stable assemblage wiping out older assemblage either partially or completely. If the reaction goes to completion then the old assemblage will be completely obliterated and if the reaction doesn't reach completion then the old assemblage will be only partially wiped out.

Metamorphic processes are studied as:

1. Chemical reactions occurring between two or more minerals, between minerals and gases and between fluids and liquids (where H_2O plays a prime role).
2. Thermodynamic processes such as exchange and transportation of heat and substances between two domains acting as two different systems.

Apart from the above factors or parameters one more important variable is time because metamorphism may or may not be a continuous process and hence it occurs in different episodes.

12.6.1 Pressure and Temperature Conditions in Crust and Mantle

When the rock is subjected to stresses, it results in transfer of some property to compensate the effect of the applied force. Similarly, any change in temperature conditions leads to heat flow from a high temperature rock unit to a low temperature rock unit. This heat flowage continues until both the rock units reach the same temperature. The direction of the heat flow is from high heat source to low heat sink such that the heat vector is perpendicular to the temperature isotherms.

12.6.2 Heat Flow and Geotherms

After reading about the heat flow in the crust and mantle, let us read about the heat flow and its relation with the geotherms. Heat flow at the surface is a combined effect of the following:

- Conductive heat transferred from the interior of the Earth (Fig. 12.6);
- Radioactive elements decay;
- Mantle convection.

The net heat flow may remain zero, if the heat flowing out is equal to the heat flowing in to the crustal volume. This is known as **steady-state geotherm**. It may also be possible that the heat flowing into the crustal volume is more than that of the heat leaving the crustal volume. In such a case the extra heat reserved in the crustal volume would be used either to facilitate **endothermic**

reactions taking place within the rock or to raise the temperature of the rock unit. However, if the heat flow tends to be more than the heat flown into the crustal volume, it results in the heat loss from the rock system. In such a condition the rock cools but the **exothermic reactions** try to compensate this cooling by producing some extra heat.

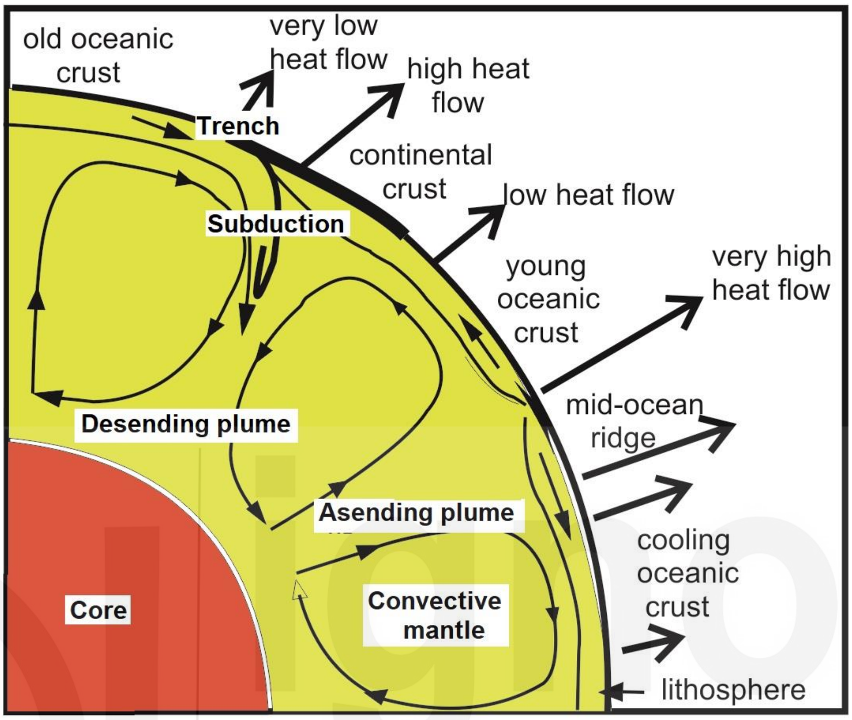


Fig. 12.6: Heat transfer between hot interior and cold surface of the Earth by conduction. (Source: Bucher and M. Frey, 1994)

The metamorphic rocks originate when the pre-existing rocks are subjected to high heat, high pressure, hot, mineral-rich fluids or, more commonly from the combination of these factors. Such conditions are found deep within the Earth. We have discussed about these 'new conditions' or agents to which the parent rock is subjected during the process of metamorphism. During this process, mineral and rock deposits change and adapt until equilibrium with the new environmental conditions is reached.

12.6.3 Chemical Reactions Leading to Metamorphism

Let us study the following type of chemical reactions that actually bring up alteration or modification in the mineral composition of the metamorphic rocks:

1. **Solid-Solid Reactions**

These reactions involve the solid phases of the reactants. All the solid-solid reactions are potential candidates in quantifying pressure and temperature conditions i.e. they are good geobarometers and geothermometers. Solid-solid reactions can take place by the following processes:

1. the diffusion (transfer) of ions from one mineral to another
2. the reorganisation of a crystal structure
3. removal of water from a hydrous mineral
4. the addition (or subtraction) of ions through an active fluid

Hydrous minerals contain $(OH)^-$ ions, anhydrous minerals are water-free and dehydration reactions expels off water from hydrous minerals to make them more stable anhydrous minerals at greater temperature and pressure.

Geobarometers are minerals or group of minerals whose existence, coexistence, or element distribution, is stable between known pressure limits at given temperatures. **Geothermometers** are natural mineral systems used to estimate the temperatures that produce an equilibrated mineral assemblage in a metamorphic rock through element partitioning between minerals.

This is because of the fact that all such reactions involve no dependency of equilibrium conditions on the fluid phase composition. However, you should not understand that there is no existence of any fluid phase in such a metamorphic reaction. The solid-solid reactions are of following types:

i. **Net – Transfer Reactions**: As the name suggests transfer of components from the reactant phases to product phases takes place which may involve both anhydrous and volatile phase components. They are also called as coupled reactions. They are of two types:

ii. **Terminal Reactions**: Complete disappearance of a phase takes place after a certain limit of pressure – temperature condition is reached.
Example : Jadeite + Quartz = Albite (anhydrous phase)

iii. **Non-Terminal Reactions**: In this type of net – transfer reaction the mineral assemblages either appear or disappear.
Example: Diopside + Al_2SiO_5 = Grossular + Pyrope

2. **<u>Exchange Reactions</u>**

When exchange of components takes place only between certain anhydrous or volatile conserving mineral phases only then such a reaction is called an exchange solid-solid metamorphic reaction.

Examples:

- Forsterite + Ferrosilite = Fayalite + Enstatite (anhydrous phase)
  Here Fe-Mg exchange takes place between olivine and orthopyroxene.
- Pyrope + Annite = Almandine + Phlogopite (volatile conserving phase)

3. **<u>Polymorphic Reactions</u>**

In such solid – solid reactions transition in phase takes place in which the mineral chemistry remains the same but the mineralogical phase transits to another polymorph.

Examples:

- $CaCO_3$ Calcite = Aragonite
- C Graphite = Diamond

It involves the transformation of mineral into a second mineral having the same chemistry but with a different crystal structure. Aluminosilicates are good example in metamorphic geology, viz. sillimanite, kyanite, and andalusite. Polymorphic minerals tend to have very different characteristics even though their formula is the same

4. **Solvus Reactions**

This type of the reaction takes place either in limited solid solution (at a temperature below the critical temperature where a solvus is defined) or in phases with complete solid solution (at high temperature). In this type of reaction exsolution of a new phase along some slip plane takes place from the prior phase. These types of reactions are very useful in geospeedometry (assessing the rate of metamorphism) and geothermometry.

Examples :

Calcite – Dolomite

Plagioclase – K-feldspar

5. **Reactions Involving Volatiles**

Appearance or disappearance of phases makes such reactions considerably of net-transfer type.

6. **Dehydration Reactions**

These reactions involve H_2O in metamorphic reactions. It is the most common scenario which makes such type of metamorphic reactions most common among all other types of reactions. These reactions show the presence of higher temperature products which usually lack H_2O. Prograde metamorphism ensures the removal of H_2O from the hydrated phases. The removal of the hydrates is facilitated by the increasing temperature during the prograde metamorphism.

Example:

Muscovite + Quartz = Sillimanite + K-feldspar + H_2O

7. **Decarbonation Reactions**

During the metamorphism of the calcareous rocks and other CO_2 bearing rocks carbon dioxide is released. CO_2 is released by the decomposition of carbonate minerals (dolomite, calcite etc.). However, the existence of pure CO_2 is highly questionable, therefore, CO_2 occurs either with H_2O or with some other volatiles.

Example: $CaCO_3 + SiO_2 = CaSiO_3 + CO_2$

8. **Mixed Volatile Reactions**

Two fluid phases viz. CO_2 and H_2O are involved and the reaction takes place in two ways such that in this case both the fluid phases are either on one side (either reactant or product side) or the fluid phases are on the opposite sides in the same reaction.

Example:

Margarite + 2 Quartz + Calcite = 2 Anorthite + CO_2 + H_2O (here both the fluid phases are on the same side of the reaction).

5 Dolomite + 8 Quartz + H_2O = Tremolite + 3 Calcite + 7 CO_2 (here in the same reaction the fluid phases are on the opposite side).

9. **Oxidation – Reduction Reactions**

Change in the oxidation state one or more elements takes place during this type of metamorphic reaction. Unlike other metamorphic reactions redox reactions may not involve volatile components in the reaction and also the redox reactions may be formulated in ionic form too.

Example: $2Fe_3O_4 + ½ O_2 = 3 Fe_2O_3$

12.7 PRODUCTS OF METAMORPHISM

You will read about metamorphic minerals and metamorphic rocks considered as products of metamorphism.

12.7.1 Metamorphic Minerals

Metamorphic rocks yield many attractive minerals, such as garnet, corundum (varieties of which include sapphire and ruby), and kyanite. **Metamorphic minerals** form in place within the solid rock due to changes in temperatures and pressures. The mineral assemblages that occur in metamorphic rocks depend on four factors:

- Bulk chemical composition of the original rock,
- Pressure conditions during metamorphism,
- Temperature conditions during metamorphism, and
- Composition of fluid phase present during metamorphism

When the rock is subjected to higher pressure and temperature then the mineral assemblage developed represents stable chemical equilibrium. If the conditions prevail for a long time then the equilibrium can be achieved. Since metamorphism usually involves long periods of geologic time, most metamorphic rocks represent an equilibrium mineral assemblage.

Metamorphic rocks tend to be dominated by minerals such as feldspar, quartz, muscovite, biotite, amphibole, and calcite/dolomite. However, a few minerals are found exclusively or mainly in metamorphic rocks. Some of the important metamorphic minerals are actinolite, almandine (garnet), andalusite, anthophyllite, aragonite, brucite, chlorite, chloritoid, cordierite, corundum, diopside, enstatite, epidote, fayalite, forsterite, glaucophane, grossular (garnet), hematite, heulandite, hypersthene, ilmenite, jadeite, kyanite, lawsonite, magnetite, periclase, prehnite, pumpellyite, serpentine, sillimanite, sphene, staurolite, talc, tremolite, wollastonite.

The details of some common metamorphic minerals listed above are given below:

- **Actinolite** is hydrous Ca-Mg-Fe sheet-silicate mineral also called as green amphibole,
- **Almandine** ($Fe_3Al_2(SiO_4)_3$) is a nesosilicate also known as almandite, is a species of mineral belonging to garnet group. Almandine occurs in metamorphic rocks like mica schists, associated with minerals such as kyanite, staurolite and andalusite.

- **Andalusite** (Al_2SiO_5) is an aluminium nesosilicate mineral. It is trimorphic with kyanite and sillimanite, being the lower pressure mid temperature polymorph respectively. Andalusite converts to sillimanite at higher temperatures and pressures.
- **Anthophyllite** is an amphibole mineral and magnesium iron inosilicate hydroxide. It is the product of metamorphism of magnesium-rich rocks, especially ultrabasic igneous rocks and impure dolomitic shales.
- **Aragonite**, widespread mineral, the stable form of calcium carbonate ($CaCO_3$) at high pressures.
- **Brucite** ($Mg(OH)_2$) is the mineral form of magnesium hydroxide. It is a common alteration product of periclase in marble and low-temperature hydrothermal vein mineral in metamorphosed limestones and chlorite schists.
- **Chlorite** is a hydrous Fe-Mg-Al sheet-silicate mineral~~s~~ and typically form green, flaky microscopic crystals. Chlorite is found in low grade metamorphic rocks.
- Chloritoid is found in phyllites, schists and marbles. It results from low to medium grade regional metamorphism as well as in hydrothermal environments.
- **Cordierite** is a magnesium iron aluminium cyclosilicate and typically occurs in contact or regional metamorphism of pelitic rocks.
- **Diopside** ($MgCaSi_2O_6$) is a monoclinic pyroxene mineral and is found in a variety of metamorphic rocks, such as in contact metamorphosed skarns developed from high silica dolomites.
- **Enstatite** is the magnesium endmember of the pyroxene silicate mineral series enstatite ($MgSiO_3$)-ferrosilite ($FeSiO_3$). This magnesium rich member is common rock-forming mineral found in igneous and metamorphic rocks.
- **Epidote** is typically pistachio green in colour. It is a common mineral in greenschist and amphibolite facies metabasites.
- **Glaucophane** is a sodic amphibole that characterises the subduction-related blue-schist facies.
- **Grossular** ($Ca_3Al_2(SiO_4)_3$) is a calcium-aluminum species of the garnet group of minerals. It is found in contact metamorphosed limestones.
- **Hornblende** is hydrous Ca-Mg-Fe-Al sheet-silicate mineral, common constituent of metabasites of the amphibolite and granulite facies.
- **Periclase** is a magnesium mineral that occurs naturally in contact metamorphic rocks and is a major component of most basic refractory bricks.
- **Prehnite** is hydrous Ca-Mg silicate and a low-temperature sheet silicate that is a common constituent of zeolite and prehnite-pumpellyite facies metabasites.

- **Sillimanite,** kyanite and andalusite are polymorphs of Al_2SiO_5, each occurring under different temperature-pressure regimes and are therefore rarely found together in the same rock. It develops in alumina-rich pelites under different conditions of temperature and pressure. It is an index mineral indicating high temperature but variable pressure.
- **Staurolite** is a mineral that is commonly found in schist and gneiss. It forms when shale is strongly altered by regional metamorphism. It is often found in association with almandine garnet, muscovite, and kyanite-minerals that form under similar temperature and pressure conditions.
- **Talc** is hydrous Mg-silicate mineral that results from the metamorphism of magnesian minerals such as serpentine, pyroxene, amphibole, and olivine, in the presence of carbon dioxide and water.
- **Tremolite** is a member of the amphibole group of silicate minerals with composition: $Ca_2Si_8O_{22}(OH)_2$. It forms by metamorphism of sediments rich in dolomite and quartz.
- **Wollastonite** is a calcium inosilicate mineral and forms when impure limestone or dolostone is subjected to high temperature and pressure sometimes occurs in skarns or contact metamorphic rocks.
- **Zeolites** are a group of minerals that typically form in cavities within volcanic rocks, due to very low-grade metamorphism.

SAQ 2

a) Define protolith.

b) List types of protolith.

c) What are endothermic and exothermic reactions?

d) List the processes involved in solid-solid reactions.

e) Define geobarometer and geothermometer.

f) List any ten metamorphic minerals.

12.7.2 Index Minerals in Metamorphic Rocks

Index minerals in metamorphic rocks indicate grade of metamorphism, i.e. extent to which original rock was metamorphosed. Figure 12.6 shows some common minerals in metamorphic rocks. They are arranged in order of the temperature ranges within which they tend to be stable. The stability range of each mineral is still small enough that the minerals can be used as markers for those metamorphic conditions. Index minerals make good markers of specific ranges of metamorphic conditions.

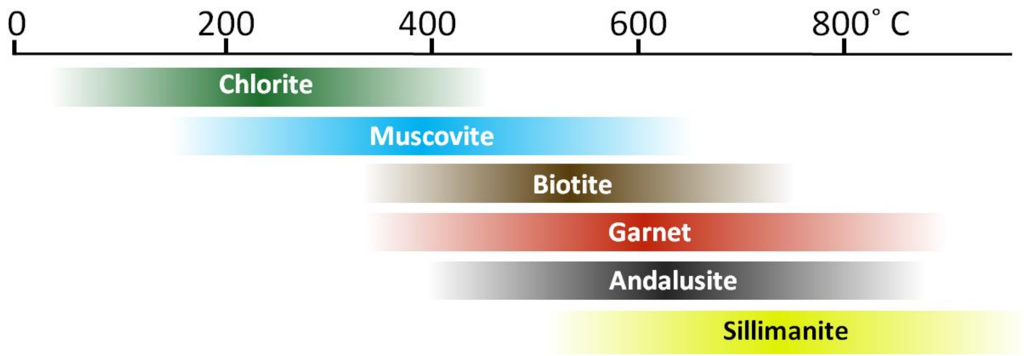


Fig. 12.6: Metamorphic index minerals and approximate temperature ranges. (Source : https://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/07/image027.png**)**

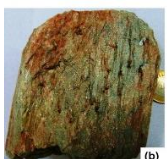
12.7.3 Why do we Study Metamorphic Rocks?

Let us read why do we study metamorphic rocks?

Metamorphic rocks provide insights into the physical and chemical changes that take place deep within Earth. The index minerals present in metamorphic rocks allows geologists to assess the temperatures and pressures that the parent rock encountered. The metamorphic minerals and rocks have economic value thus the knowledge of metamorphic processes and rocks is very significant. Metamorphic rocks such as slate and marble, are also used are building materials; talc is used in cosmetics, paints, and lubricants; garnets are used as gemstones and abrasives; graphite is used as insulator, refractory and lubricant; and asbestos is used for insulation and fireproofing. Metamorphic rocks are some of the oldest rocks present on Earth. They are widely exposed in the core areas, known as shields of continents, and make up a large portion of the roots of mountain ranges.

Let us list the common metamorphic rocks that are products of metamorphism as given in Table 12.2. We will discuss about these rocks in detail in Unit 15 of this course.

Table 12.2: Foliated and non-foliated metamorphic rocks.

Texture		Characteristics	Protolith	Metamorphic rock name	
Increasing	FOLIATED	Very fine-grained rock tends to split in parallel fractions (slaty cleavage)	Shale	Slate	
		Fine grained rock with grains only visible as satin lustre. Similar to slate with satin lustre and may have wrinkled cleavage	Shale	Phyllite	
		Contain shiny muscovite (light) or biotite (dark) micas, other minerals quartz, talc, garnet and amphibole may be seen. Has schistose pattern of foliation.	Shale or igneous rocks	Schist	

		Contain alternating bands of light and dark minerals (usually biotite and amphibole) known as gneissic banding	Shale or igneous rocks	Gneiss	
NON-FOLIATED		Equigranular grains of quartz which has hardness 7	Sandstone or Siltstone	Quartzite	
		Equigranular grains of calcite having hardness 4, reacts freely with dilute HCl	Limestone	Marble	

12.8 SUMMARY

In this unit we have read about the factors affecting metamorphism, processes and products of metamorphism. Let us summarise what we have learnt:

- Metamorphism is the process that brings about changes in the mineralogical and/or structural and/or chemical constituents in a rock (dominantly solid). Metamorphism is regarded as a thermal phenomenon in which heat is the most important source of energy causing mineralogical and textural reconstruction.
- Metamorphism in rocks is caused by changes in temperature (T), pressure (P), shearing stress, and chemically active fluids or gases that leave the system but may be trapped as fluid inclusions in metamorphic minerals formed at considerable depths in the Earth's crust.
- The source of thermal energy responsible for metamorphism comes from the heat generated within the deep interior of the Earth, decay of radioactive elements, frictional heat generated along faults or shear zones and latent heat of crystallization from igneous intrusions and magma.
- Metamorphism occurs at temperatures and pressures higher than 150^{o}C and 300 MPa (Mega Pascals equivalent to about 3,000 atmospheres of pressure).
- Protolith refers to the original or parent rock prior to metamorphism. Types of protoliths or parent rocks can be quartzo-feldspathic, pelitic, calcareous, basic/ultrabasic and ferruginous.
- The chemical reactions responsible for alteration or modification in the mineral composition of the metamorphic rocks are solid-solid reactions, exchange reactions, polymorphic reactions, solvus reactions, reactions involving volatiles, dehydration reactions, decarbonation reactions, mixed volatile reactions and oxidation – reduction reactions.
- Metamorphic minerals form within the solid rock due to changes in temperatures and pressures. The development of mineral assemblage depends on four factors: (1) bulk chemical composition of the original rock; (2) pressure conditions during the metamorphism; (3) temperature conditions during the metamorphism; and (3) composition of fluid phase present during the metamorphism.

- Index minerals in metamorphic rocks indicate grade of metamorphism, i.e. extent to which original rock was metamorphosed.
- The metamorphic minerals and rocks have economic value. Metamorphic rocks provide insights into the physical and chemical changes that take place deep within Earth.

12.9 ACTIVITY

- Observe the marble slabs in flooring and try to study. Note down the variations and also take photographs.
- Make a list of metamorphic minerals used as gemstones and write their chemical composition. Download their photographs and make a collage.

12.10 TERMINAL QUESTIONS

1. Discuss in brief, the factors affecting metamorphism.
2. Explain the low- and high-pressure limits of metamorphism.
3. Describe any five metamorphic reactions.
4. Discuss index minerals in metamorphic rocks.
5. Discuss the significance of studying metamorphic rocks.

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12.12 FURTHER/SUGGESTED READINGS

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12.13 ANSWERS

Self Assessment Questions

1 a) Metamorphism is the process that brings about changes in the mineralogical and/or structural and/or chemical constituents in a rock (dominantly solid). Metamorphism is regarded as a thermal phenomenon in which heat is the most important source of energy causing mineralogical and textural reconstruction.

b) Heat generated within the deep interior of the Earth and is left over from accretion more than 4.5 billion years ago; heat released by decay of radioactive elements; frictional heat generated along faults or shear zones which is local and restricted to near-surface regions of the Earth; and latent heat of crystallisation from igneous intrusions and magma.

c) Uranium (U), thorium (Th), potassium (K)

d) Subduction zones

e) Low-temperature limit of metamorphism is around 150-200°C. High-temperature limits of metamorphism have been reported between 750-850^{o}C in crustal rocks.

f) Pore pressure is the pressure exerted by the fluids between the grains in a porous rock.

2 a) Protolith refers to the original or parent rock, prior to metamorphism.

b) Quartzo-feldspathic, pelitic, calcareous, basic/ultrabasic and ferruginous.

c) If the heat flowing into the crustal volume is more than that of the heat leaving the crustal volume in that case the extra heat reserved in the crustal volume is used to facilitate endothermic reactions. If the heat flow tends to be more than the heat flow into the crustal volume it results in the heat loss from the rock system giving rise to the exothermic reactions.

d) Diffusion of ions from one mineral to another; reorganization of a crystal structure; removal of water from a hydrous mineral; and addition (or subtraction) of ions through an active fluid.

e) Geobarometer are minerals or group of minerals whose existence, coexistence, or element distribution, is stable between known pressure limits at given temperatures. Geothermometers are natural mineral systems used to estimate the temperatures that produce an equilibrated mineral assemblage in a metamorphic rock through element partitioning between minerals.

f) Please refer to subsection 12.7.1.

Terminal Questions

1. Please refer to the section 12.3. Discuss temperature, geothermal gradient, load pressure, fluid pressure and shear stress.

2. Please refer to the subsections 12.4.3 and 12.4.4.
3. Please refer to the subsection 12.6.3.
4. Please refer to the subsection 12.7.2.
5. Please refer to the subsection 12.7.3.