A Study on Metamorphism: its Kinds, Effects and Grades

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Abstract

Metamorphism is defined as the mineralogical, chemical and structural adjustments in solid rocks to physical and chemical conditions which have been imposed due to changes in pressure and temperature or both. Metamorphism occurs below the surface zones of weathering and cementation. Conditions of metamorphism differ from the conditions under which the rocks in question were originally formed. Metamorphism produced as a result of the progressive increase in temperature and pressure, i.e. by burial of a rock within the earth, is termed prograde metamorphism and in general terms is characterized by dehydration reactions, which release water. With increasing depth of burial the pressure and temperature of the material increases along the follwong gradients:

- *P gradient 3.5 kbar/10 km*
- *T gradient 20-30°C/km*

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Introduction

Metamorphism is the change of minerals or geologic texture (distinct arrangement of minerals) in pre-existing rocks protoliths , without the protolith melting into liquid magma (a solid-state change). The change occurs primarily due to heat, pressure, and the introduction of chemically active fluids. The chemical components and crystal structures of the minerals making up the rock may change even though the rock remains a solid. Changes at or just beneath Earth's surface due to weathering or diagenesis are not classified as metamorphism.The surrounding conditions that play important role in this regard are temperature, pressure and chemically active fluids. When there is a change in any one or more of these parameters around the rock there must take place a corresponding change in the nature of the rock also. What kind of change will take place in the rock?

This will depend on the nature of rock under question and the extent of change in the temperature-pressure-chemical environment set of conditions. The changed rock is called the metamorphic rock and it will be stable under the new set of conditions till there is a further change in those conditions.

Factors of Metamorphism:

Metamorphic changes in the rocks are primarily the result of three main factors that are also sometimes called as agents of metamorphism:

1. Temperature
2. Pressure and

3. Chemical Environment.

These agents may act individually or collectively. The metamorphic changes are most pronounced when these factors operate collectively and in a big way.

1. Temperature:

Rocks are made up of minerals that are normally stable at temperatures below 200°C. However, when the temperature around these rocks changes due to one reason or the other, the mineral composition of the rocks undergoes some changes in order to adjust to the new temperature conditions.

Two common sources of heat for such a metamorphism to take place are the internal heat (increase in temperature with depth: thermal gradient:) and the magmatic heat (rise in temperature around magmatic intrusions). The internal heat becomes operative when rocks formed at surface (e.g. sedimentary and volcanic rocks) are pushed downwards due to some geological process (folding, faulting etc.) where they have to withstand much higher temperature.Similarly, when a magmatic intrusion like a sill or a dyke invades the country rock from below, the host rocks around the margins of intrusion suffer sudden and enormous changes in their temperature. They are also metamorphosed in order to be stable under the new conditions.It is believed that most metamorphic changes induced by the heat factor take place between 300°-850°C. Above 850°C, some components of rock may actually start melting and hence rocks formed from their resolidification shall be included in the category of igneous rocks.

2. Pressure:

Many metamorphic changes are induced solely due to the pressure factor whereas in great majority of cases pressure is the dominant factor and is assisted considerably by the heat factor. Any given rock at some depth below the surface is subject to pressure from two sources- first, load of the overlying burden and second, crustal movements during the convergence of the tectonic plates.

The first type of pressure acts generally in a vertical direction and the process of change in the structure of the rock are often referred as load metamorphism. The pressure from orogenic activity is generally lateral or horizontal and is commonly termed as directed pressure. Rocks situated near the plate boundaries or within the geosynclinal belts are especially prone to directed pressure and often show severest degree of metamorphic changes.

3. Chemical Environment:

Presence or absence of chemically active fluids within the body of the rocks (the pore fluids) or around them plays very important role in the process of all types of metamorphism. With the rise in temperature, the pore fluids undergo expansion and become very active in disturbing or even breaking the original crystal boundaries of the involved minerals.New minerals are created that are stable in the changed conditions. This process is called recrystallisation that takes place essentially in a solid state. Sometimes fluids present around the rocks also come in contact with them at elevated temperatures and react with the minerals within the rocks producing many changes in their composition and structure.This type of change is termed metasomatism. Among such chemically active pore fluids and external fluids may be mentioned water, carbon dioxide, hydrofluoric acid, bromine and fluorine. Water in the form of steam is considered the single most important agent. The water may be present in the minerals as water of crystallisation or simply as pore fluid or it may be supplied externally by magmatic bodies.

Kinds of Metamorphism:

Three major kinds of metamorphism differentiated on the basis of factor most dominant in causing it are:

A. Thermal metamorphism,

B. Dynamic metamorphism and

C. Dynamothermal metamorphism.

A. Thermal Metamorphism:

It is a general term including a variety of metamorphic processes in which the heat factor has played an important role. The pressure and chemically active fluids, though operating are attributed assisting roles.

Contact Metamorphism is a common type of thermal metamorphism observed in rocks existing close to the magmatic intrusions, injections and lava flows. In this case, the heat from magmatic source travels through the body of the surrounding rocks that undergo structural and mineralogical changes depending upon their original composition and intensity of the heating effects. Other things being the same, the effect is most intense in the immediate neighbourhood of the magmatic source and decreases with distance from the contact points.Pyrometamorphism is another type of thermal metamorphism in which case a part of country rock may actually get entrapped within a magmatic body. The effects result due to intense localized heating (short of melting). It is illustrated by changes in a block of sedimentary rock that has incidentally fallen in a body of flowing lava. The block may be so much heated up that its original minerals are forced to recrystallise and rearrange themselves in accordance with the conditions imposed by the acute rise in temperature.Plutonic Metamorphism is a process of metamorphism that takes place due to equally important role of imposed loads (due to burial at great depths) and very high temperatures that become natural at those great depths. Such changes take place in rocks that are pushed down during crustal movements to positions where high temperature and high pressure become almost a permanent feature.

In all types of thermal metamorphism the change is generally in the direction of mineralogical reconstitution. These processes may induce changes varying from simple baking effect (optalic metamorphism) to complete or nearly complete recrystallisation of almost all of the original minerals.

B. Dynamic Metamorphism:

It is also called clastic metamorphism, mechanical metamorphism or dislocation metamorphism and is brought about by conditions in which pressure factor plays a dominant role. Sometimes the pressure is of the type of hydrostatic type such as load of the overlying rocks. The process is then called load metamorphism. In the dynamic metamorphism, there is no or very little formation of new minerals (compare with the thermal metamorphism). These are the original textures and structures of the rocks that are partially or totally obliterated. New textures and structures are imposed on the effected rocks.

C. Dynamothermal Metamorphism:

This is also referred as REGIONAL METAMORPHISM and may be considered as the most important as well as prevalent type of metamorphic processes. This involves development of large-scale changes in the structural and chemical constitution of the pre-existing rocks under the combined action of pressure, temperature and fluids.

Such conditions were available during the mountain building activity repeatedly in the history of the Earth. The latest plate-tectonics theories also postulate convincingly development of conditions leading to the large-scale regional metamorphic effects at the margins of converging tectonic plates.

Metamorphic rocks formed through regional metamorphism occur in the form of extensive mountain belts and also as the core portions of many old eroded mountain systems throughout the world. They bear evidence of formation of new minerals as well as imposition of new textures and structures on an extensive scale.

Metasomatism:

It may be broadly defined as a "metamorphic process involving essentially formation of new minerals by the mechanism of chemical replacement of pre-existing minerals under the influence of chemically active fluids."The metasomatic replacement of minerals takes place at atomic level and in solid state.

The chemically active fluids may be provided:

(i) From within the rock, such as pore fluids, in which case the end result of metasomatic change would be a mere replacement of the atoms, the total chemical composition of the rock remaining the same. This is sometimes referred as mineral metasomatism.

(ii) From outside the rock, such as from magmatic emanations or ground water sources in which case many new minerals may be formed in the rock by the interaction of the atoms of the invading fluids with those of the rock. The net result would be a definite change in the bulk chemical composition of the rock as a whole. This is, therefore, sometimes referred as rock metasomatism.

The process of metasomatism is sometimes further distinguished into:

i. Hydrothermal – when the fluids are in the form of solutions;

ii. Pneumatolytic – when the fluids are in the form of gases or vapours;

iii. Additive – when the net result of the process is addition of a new constituent; and

iv. Expulsive – when some component gets removed from the original composition of the rock.

A common fact observed in the case of metasomatism is that the total volume of the rock remains by and large unchanged after the process is completed. Further, the changes can take place over a wide range of temperature and pressure and like other metamorphic processes are completed essentially in solid state.

Metasomatism is quite common in silicate and carbonate rocks.

Effects of Metamorphism:

A variety of changes may be caused in pre-existing rocks subjected to metamorphic processes.

This depends primarily on following two major factors:

(i) The type of rock involved in the process;

(ii) The kind of metamorphic process operating on those rocks.

Generally speaking, the metamorphic process may result in one or more of the following main categories of effects on the involved rocks:

(i) Recrystallisation,

(ii) Rock flowage,

(iii) Granulation and

(iv) Metasomatic replacement.

(i) Recrystallisation:

All the changes in the direction of mineralogical reconstitution and textural pattern of rocks during the process of metamorphism are collectively expressed by the term recrystallisation. This process involves simultaneous growth of new crystals from the existing ones by atomic restructuring due to rise in temperature with or without concurrent rise in pressure but facilitated by pore fluids in most cases.

The change takes place essentially in a solid state. This effect is most notable in the rocks adjoining the magmatic intrusions or those coming in contact with lava flows.

In such cases following conditions control the extent of recrystallisation:

(a) The size of the igneous intrusion or the lava flow which serves as the source of heat.

(b) The initial temperature of the magma or lava and also its rate of cooling; the higher the initial temperature, the greater is the effect; again, the slower the rate of cooling, greater is degree of recrystallisation.

(c) The nature of magma or lava – magmatic melts rich in chemically active fluids will induce a greater degree of recrystallisation as compared with those which are poor or free from these fluids.

(d) The nature of rock – it is the single most important factor in that the same rock under different conditions may suffer different set of changes during the process of recrystallisation. Chemical composition and original texture define the susceptibility of a rock to recrystallisation.

(ii) Rock Flowage:

By rock flowage is understood actual movement and reorientation of the mineral constituents of rock under the influence of loads acting during the metamorphic processes. The term should not be taken to give the impression that rocks change their physical state (from solid to liquid) and start flowing when subjected to pressure.Rock flowage is simply the slippage of the grains or crystals essentially in solid state making them orient themselves in such a way as not to offer any further resistance to the applied forces. This may result in flattening of mineral constituents, their gliding over one another and development of peculiar structures like rock cleavage and foliation. Rock flowage is believed to be a common process at greater depths, near the roofs and walls of magmatic boundaries and also along margins of tectonic plates.

(iii) Granulation:

Sometimes under the influence of dominant stress rocks develop granulation which signifies the birth of very fine fractures within the body of rock involving even the individual minerals. The pressure being of confining type, the mineral fragments bound by these fractures retain their solidarity in the natural state.

But as soon as the rock is removed from its original place, and a little pressure applied, it crumbles into fragments, e.g. in schists. Granulation is favoured by hard and insoluble character of the constituent minerals as well as by higher confining pressures.

(iv) Metasomatic Replacement:

Metasomatism is essentially a process of simultaneous replacement at atomic level by which minerals of a rock are changed into other minerals by addition or subtraction of atoms under the influence of chemically active fluids from the surrounding environment.

Silicate and carbonate rocks are easily altered by metasomatic changes. The process may involve exchange of, addition to or expulsion of metallic or non-metallic compounds from an original rock. Thus it may be alkali metasomatism, sulphur metasomatism and so on.

When the attacking fluids are in vaporous state, the process is distinguished as pneumatolytic metasomatism or simply as pneumatolysis. Vapours of water, boron, fluorine and many alkali metals emanating from magmatic bodies take active part in changing the mineralogical composition of rocks surrounding these bodies.

Thus a granite rock attacked successfully by water vapours in combination with boron and fluorine gases may suffer a mineralogical change whereby original felspars (e.g. $KaAlSi_3O_8$) may get partially or completely changed into a new mineral tourmaline (borosilicate of aluminium). The original granite rock is thus changed metasomatically into a tourmaline-granite (when the replacement is only partial, i.e. some felspar is still left unchanged) or into a schorl rock (when all the felspar of granite is changed into tourmaline).

Similarly, when a granite rock is attacked by steam and fluorine vapours only, felspars are altered to lithium mica and the new rock is called Greisen. This metasomatic change is sometimes termed as Greisening. Kaolinisation is another such process where felspars are converted to kaolin under the influence of steam vapours. Dolomitization is a metasomatic conversion of limestone into dolomite {$CaMg(CO_3)_2$} in the presence of Mg++ rich solutions.

Metamorphic Grades, Zones and Facies:

Metamorphic Grades:

The approximate extent or degree – qualitatively speaking – to which an original rock has been changed due to metamorphism is expressed by the term metamorphic grade. Three terms are used to express the grades – low grade, medium grade and high grade. These grades are indicated by the presence of a set of minerals that are called the index minerals. These minerals are stable only within the temperature-pressure range considered characteristic of that particular grade.

Main features of these three grades are broadly summarized as follows:

(a) Low Grade:

It prevails within a temperature range of 200°-400° C and a large pressure range. Important index minerals are – laumonite, prehnite, and lawsonite.

(b) Medium Grade:

This grade prevails up to a temperature range of 650°C and is indicated by the index minerals like staurolite and cordierite. Pressure variations play an important role in determining the stability of various minerals formed in this grade.

(c) High-Grade:

It is believed to begin at temperatures around 580°C under pressure of 3.5 kb and continues up to temperature of 800°C and above. A typical example indicative of high-grade metamorphism is provided by the breakdown of muscovite mica in the presence of quartz and plagioclase. Hypersthene is a typical index mineral of high-grade metamorphism and granulites are the common resulting metamorphic rocks.

Isograd:

It is defined as a line on a geological map of metamorphic rocks joining the points of same grade of metamorphism as indicated by the presence of same type of index minerals. This concept has been found very convenient in tracing the progress of metamorphism in the given region. In practice, an assemblage of index minerals rather an individual mineral is used for drawing isograds.

Another term isoreaction grade is sometimes used when similar reactions as indicated by mineral assemblages at different places in a metamorphosed area are clearly understood.

Metamorphic Zones:

The grade of metamorphism generally increases with depth for the simple reason that both temperature and pressure factors become strong and stronger at deeper levels within the crust of the earth. This fact has given birth to the concept of Metamorphic Zones that signify the range of metamorphic effects at different depths below the surface. In other words, zones indicate depth-wise extension of particular grades of metamorphism in a general way.

The three metamorphic zones are:

(i) Epizone,

(ii) Mesozone and

(iii) Ketazone.

(i) The Epizone:

It is the near surface zone and is characterised by a low temperature (generally less than 300°C) and strong shear stress. Rocks in this zone are, therefore, metamorphosed chiefly under the influence of dynamic metamorphism. The common rocks resulting in this zone are Slates and Mica Schists.

(ii) The Mesozone:

It is the middle zone in which the temperature factor becomes rather moderate (300°-500°C) and the pressure factor is of both the types: shear as well as hydrostatic type. Dynamothermal metamorphism is the typical process of this zone and high-grade schists like biotite-garnet schists are chief rocks formed.

(iii) The Ketazone:

It is the high temperature and great depth type metamorphic zone where hydrostatic stresses are quite dominant. Plutonic metamorphism is the representative kind and rocks formed in this zone include great variety of Gneisses.

Conclusion:-

It is essential that all the minerals in an assemblage must be thoroughly identified before a metamorphic rock is placed into a proper facies. Thus, presence of pyrope, garnet and omphacite is essential for placing a rock into Eclogite facies.

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