UNIT 13

TYPES OF METAMORPHISM

Structure

13.1 INTRODUCTION

You have read about agents, processes and products of metamorphism in the previous unit. You have read that metamorphism is the process that brings about changes in the mineralogical and/or structural and/or chemical constituents in a rock (dominantly solid). Metamorphism in rocks is caused by factors, i.e. changes in temperature (T), pressure (P), shearing stress, and chemically active fluids or gases. You also learnt about the chemical reactions during metamorphism and metamorphic minerals.

Now in this unit you will study about types, grades and zones of metamorphism. You will also be introduced to the concept of metamorphic facies.

Expected Learning Outcomes

After reading this unit you should be able to:

- discuss the types of metamorphism;
- explain grades of metamorphism;
- describe zones of metamorphism;
- learn about concept of metamorphic facies; and
- classify metamorphic facies on the basis of pressure/ temperature (P/T) gradient.

13.2 TYPES OF METAMORPHISM

Let us discuss types of metamorphism.

Geologists deal with various types of metamorphic rocks resulted due to various processes of metamorphism. One way or system of classifying types of metamorphism is to use the following terms:

Thermal metamorphism: In this the changes take place mainly due to heat.

Dynamic metamorphism: The changes taking place in a rock involve deformation and recrystallisation.

Dynamothermal metamorphism: It is the combination of temperature and stresses.

We will discuss here the traditional classification scheme of types of metamorphism. Broadly we can differentiate metamorphism into regional and local extent on the basis of geological setting as:

- **Regional metamorphism** consists of geologic processes which act over widespread areas occupying long linear belts and cause metamorphic changes in vast expanses of rock.
- **Local metamorphism** is a type of metamorphism that is caused due to the localized effects of metamorphism in a small region. Metamorphism may be directly attributed to a localised cause, such as a magmatic intrusion, faulting or a meteorite impact.

In Table 13.1 you can learn about the types of metamorphism falling under the above two categories.

Table 13.1: Different types of metamorphism categorised according to their extent.

Regional Extent	Local Extent
Regional Metamorphism (Orogenic)	Contact (Igneous) Metamorphism
Ocean-floor Metamorphism	Cataclastic Metamorphism
Subduction Metamorphism	Impact Metamorphism
Collision Metamorphism	Hydrothermal Metamorphism
Burial Metamorphism	Lightening Metamorphism
	Combustion Metamorphism

Now we will discuss about few types of metamorphism listed above one by one.

13.2.1 Regional Metamorphism

Miyashiro (1973) suggested the use of the term **orogenic metamorphism** over the commonly used term **regional metamorphism** or **dynamothermal metamorphism**. Orogenic metamorphism is the most significant type of metamorphism affecting the rocks. The effects of such type of metamorphism are observed over large, regional scale dimensions like the mountain belts. This involves changes in temperature, pressure and deviatoric stress (deformation and recrystallisation). This type of metamorphism is caused by mountain building or orogenic processes and is characteristic of orogenic belts where recrystallisation is accompanied by deformation. You have read about mountain building in Block 4 of BGYCT-131 course. Regional metamorphism is associated with large-scale tectonic processes, such as ocean-floor spreading, crustal thickening related to collision of plate, subduction and deep basin subsidence. Rocks undergoing orogenic metamorphism exhibit a penetrative fabric both in the hand specimen and at the microscopic level with preferred orientation of grains in phyllites, schists and gneisses. The extent of orogenic metamorphism in terms of area extends over large belts, thousands of kilometres long or hundreds of kilometres wide and appears to be a long-lasting process of millions or tens of millions of years.

Miyashiro (1973) introduced **ocean-floor metamorphism** for transformations occurring in the vicinity of the mid-oceanic ridges. You have read about mid-oceanic ridges in Block 4 of BGYCT-131 course. The metamorphic rocks cover large areas of the ocean floor by lateral sea-floor spreading. Most of these rocks are non-schistose, and of basic to ultrabasic composition (peridotites, basalts). Although, the temperature gradient is much higher (up to several 100°C/km), ocean-floor metamorphism shows similarity to continental burial metamorphism. Extensive veining and metasomatism, produced by convection of large amounts of heated sea water, is another characteristic feature of ocean-floor metamorphism (Fig. 13.1). Water within the crust is forced to rise in the area close to the source of volcanic heat, which results in further drawing in more water. This eventually creates a convective system where cold seawater is drawn into the crust, heated to 200 °C to 300 °C as it passes through the crust, and then released again onto the seafloor near the ridge. This convective circulation leads to chemical interaction between rocks and sea water which marks the resemblance of ocean-floor metamorphism to hydrothermal metamorphism.

Orogenic metamorphism can be characterised under two different kinds of regional scale transformations such as subduction zone metamorphism and collision zone metamorphism. **Subduction zone metamorphism** is related to an early high-pressure and low-temperature type metamorphism. You have read in Block 4 of BGYCT-131 course that oceanic lithosphere is forced down into the hot mantle at the subduction zones. As the slab subducts deeper and deeper into the mantle, the high pressure is developed. The lithostatic pressure increases due to the increasing force of collision between tectonic plates. Subduction zone metamorphism takes place under the very high-pressure but relatively low-temperature conditions (Fig. 13.2). Indus suture zone in Ladakh Himalaya is a good example of subduction zone metamorphism.

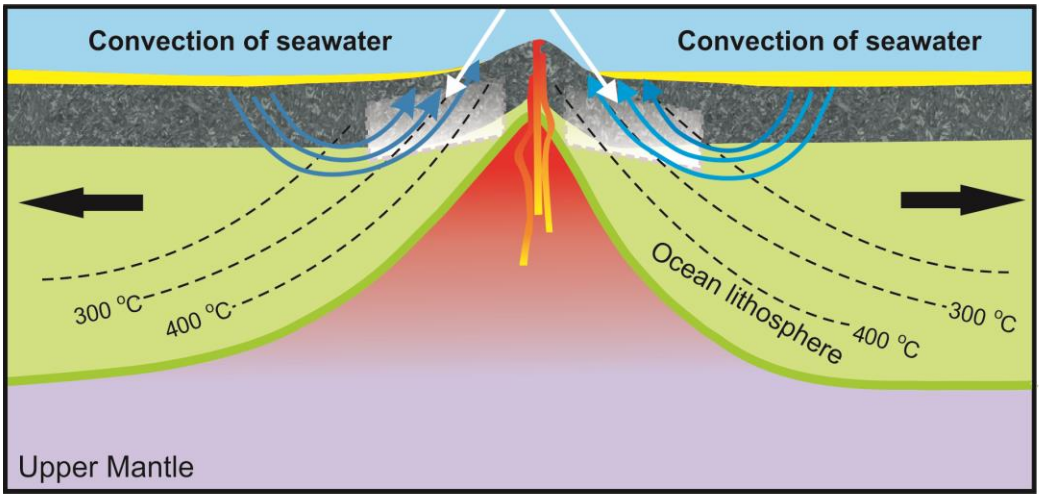


Fig. 13.1: Cartoon showing ocean-floor metamorphism of ocean crustal rock on either side of a spreading ridge.

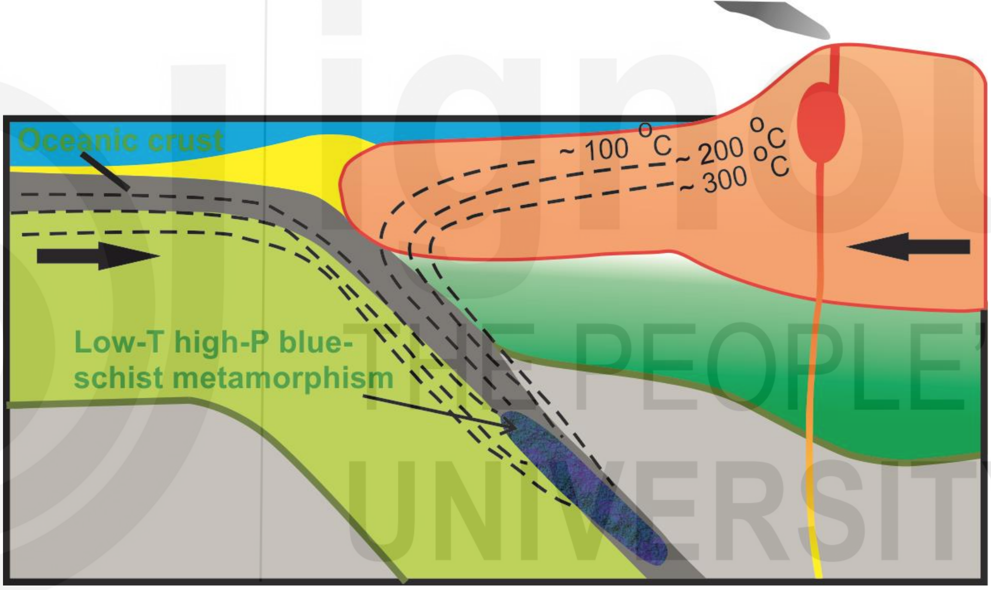


Fig. 13.2: Subduction zone (regional) metamorphism of oceanic crust at a subduction zone occurs at high pressure but relatively low temperatures.

Collision zone metamorphism also includes metamorphism of continental crust along convergent tectonic margins (where plates collide). The collisional forces cause rocks to be folded, broken, squeezed and stacked on each other. The deeper rocks are within the stack suffer high grade of metamorphism due to high pressures and temperatures.

Both these types of orogenic metamorphism (subduction and collision zone) are related to major intervals of a Wilson cycle of orogeny, in which a number of distinct episodes of crystallisation and deformation are included. Regional metamorphism is witnessed by the increase in grain size and significant changes in texture of the rock with increasing metamorphism, as shown in Figure 13.3. Individual deformation phases have definite characteristics such as, attitude and direction of schistosity, folding, and lineations. Field observations can help delineate several phases of deformation, which can be put into a time sequence. You shall read in detail about texture in the next unit. The relationships between structural features and mineral growth can be unravelled by observing textures in thin section microscopy, which further helps in establishing the time relations of deformation and metamorphism.

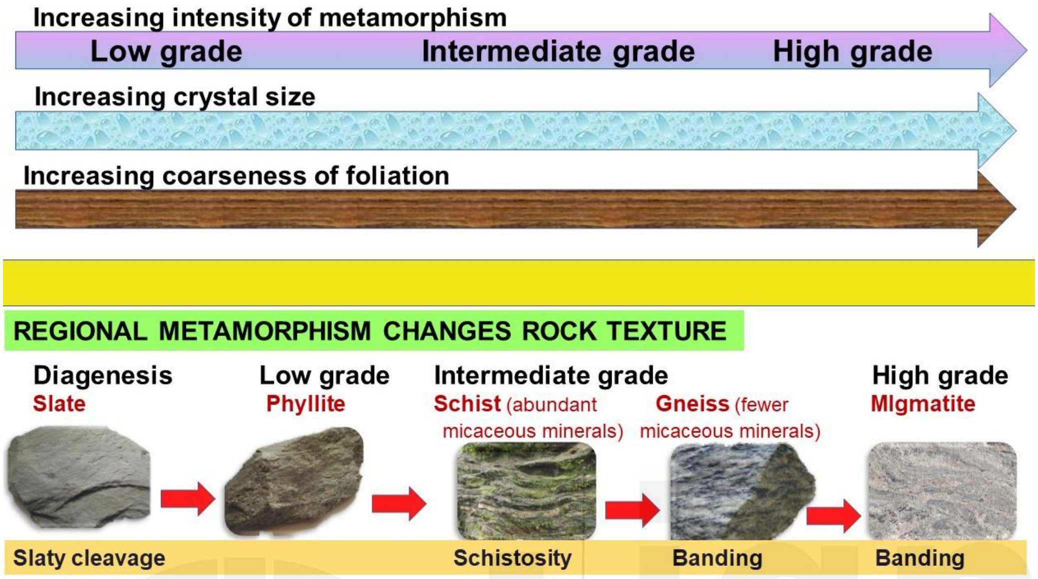


Fig. 13.3: Relation between intensity of metamorphism, crystal size, coarseness of foliation and changes in rock texture in regional metamorphism.

13.2.2 Burial Metamorphism

Burial metamorphism occurs at bottom of thick sedimentary rock piles. It begins typically at the depths of 6 to 10 km, where temperature ranges between 100^{o}C and 200^{o}C depending on the geothermal gradient. The process of burial metamorphism in which, interlayered volcanic rocks or magmatic intrusion in a geosyncline and sediments are affected by low temperature regional metamorphism, was given by Coombs (1959). When the sediments are buried deeply, due to the increasing temperature and pressure the new minerals begin to recrystallise and grow (Fig. 13.4). Rocks affected by burial metamorphism do not show foliated appearance. The burial metamorphism takes place at relatively low temperatures (up to ~300 °C) and pressures (100s of m depth) as metamorphic processes progress. The characteristic feature~~s~~ of the resultant rocks are that the original fabrics are largely preserved, which leads to lack of schistosity as discussed above. The newly-formed mineral assemblage is closely associated with the remnant minerals grains from the original rock, as mineralogical changes are usually incomplete. There is intense similarity between deep-seated diagenesis and burial metamorphism which cannot be distinguished. Burial metamorphism can be well observed in rocks of southern New Zealand and Chile.

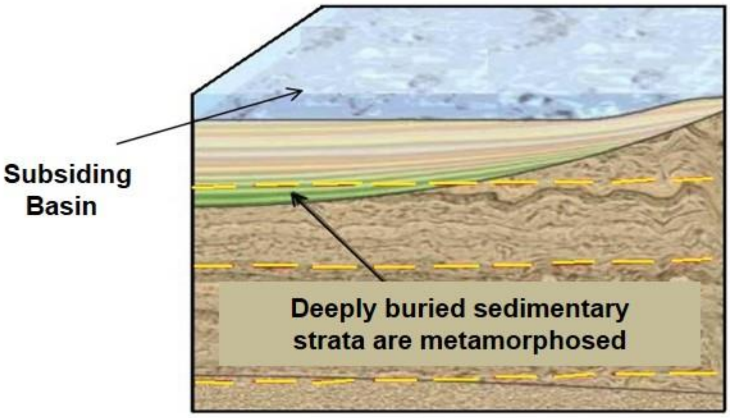


Fig. 13.4: Deeply buried sediments undergo burial metamorphism due to grow the heat and pressure.

13.2.3 Contact Metamorphism

You have read about regional and burial metamorphism. Now let us read about the contact metamorphism.

Contact metamorphism is a type of metamorphism of local extent. The intruding magma bodies are emplaced in diverse environments from crustal to upper mantle depths, in both continental and oceanic settings. Magma bodies are intruded into the country rocks (surrounding rocks) causing baking effect in them. Contact metamorphism is essentially caused by the influx of heat from an igneous intrusion undergoing cooling. Gases and fluids are released by the crystallising magma. The rocks affected by contact metamorphism are the **country rocks**. **Contact aureole** is the zone in which the effect of contact metamorphism is seen. Thus, the contact aureole is the result of baking on the surrounding country rocks by an igneous intrusion. The range of the width of metamorphic aureole surrounding an igneous body varies from several meters to a few kilometres. It may be only 2 cm wide adjacent to a small dike or it may be 2 km wide at the contact with a large, slow-cooling granite pluton. Figure 13.5 shows the intrusion of magma within the limestone country rock resulting in the formation of marble in the contact aureole. A common contact metamorphic rock is hornfels (German for "hard rock"). Contact metamorphism is also known as **thermal metamorphism**.

Please recall that you have read about contact metamorphism and contact metasomatism in Block 4 of BGYCT-133 course.

The most obvious effects of contact metamorphism are where sedimentary rocks, specially shales and limestones are in contact with larger igneous bodies while in some aureoles local deformation related to emplacement of the igneous mass can be observed. Rocks exhibiting contact metamorphism are fine-grained and lack schistosity, for example, marble, quartzite, hornfels.

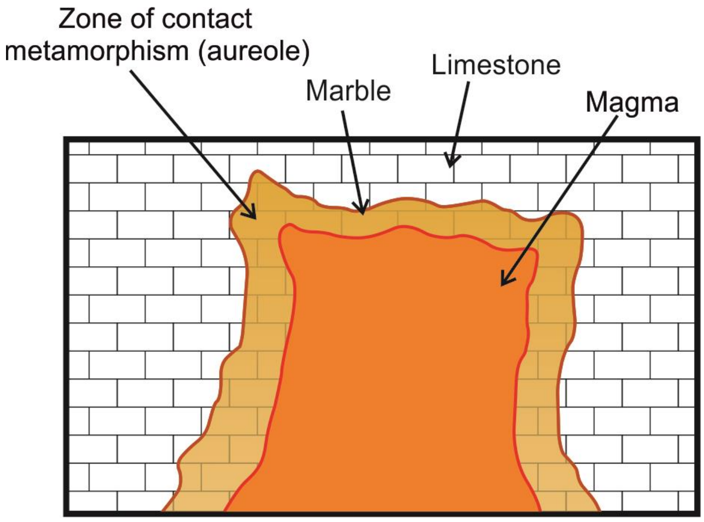


Fig. 13.5: Magma intruding in the limestone country rock and zone of contact metamorphism (aureole).

13.2.4 Cataclastic metamorphism

Cataclastic metamorphism occurs due to mechanical deformation, like that along a fault zone. This results in the generation of heat by friction such as along a fault zone and the rocks undergo shearing along with grain size reduction and tend to be mechanically deformed (Fig. 13.6). Cataclastic metamorphism is restricted to a narrow zone along which the shearing occurred. It was observed that cataclastic metamorphism is favoured by high strain rates under high shear stress at relatively low temperatures; therefore, the process involves pure mechanical forces causing crushing and granulation of the rock fabric in the vicinity of faults and overthrusts. Rocks formed as a result of cataclastic is are non-foliated and are known as fault breccias and fault gauge. **Mylonites** are developed as a consequence of ductile deformation at ambient metamorphic conditions, while pseudotachylites likely form at brittle ductile transition where shear heating generates sufficient heat to melt the rocks. A pseudotachylite is a rock whose aphanitic groundmass is similar to black basaltic glass (tachylite). Terms such as **dislocation** or **dynamic metamorphism**, initially coined to represent regional metamorphism, are now sometimes used as synonyms for cataclastic metamorphism.

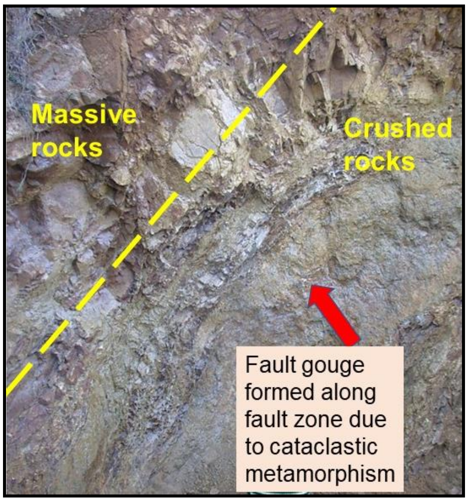


Fig. 13.6: Rocks are pulverised along the fault zone. Yellow dashed line marks the fault.

13.2.5 Impact Metamorphism

Impact metamorphism occurs and changes in rocks and minerals are observed resulting from the high velocity impact of a meteorite or bolide and shock waves are developed. On its impact the energy represented by the meteorite’s mass and velocity is transformed into heat and shock waves pass through the impacted country rock. This is also known as shock metamorphism. It lasts for a very short duration of a few microseconds which results in melting and vaporization of the rocks under impact. Presence of **shocked quartz** and newly formed coesite and stishovite as well as minute diamonds and brecciated and partly melted rock produced by impact known as **suevite** define the mineralogical characteristics (Fig. 13.7). The point of impact is marked by typical pressures and temperatures of the order of several 100 GPa or more and tens of thousands of degrees. Impact metamorphism can also produce glass known as **tektite**. It is gravel-size glass grains ejected during an impact event.

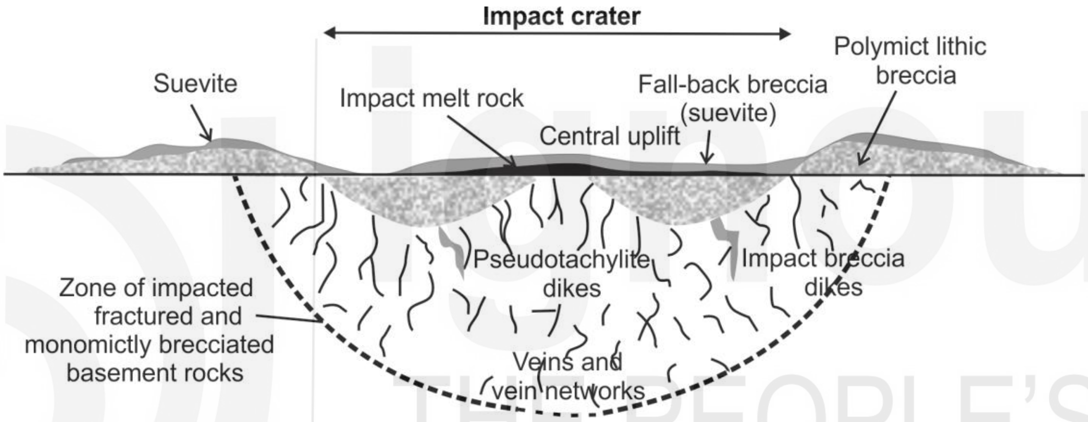


Fig. 13.7: Diagram showing the geology of a meteorite impact crater and associated impact metamorphic effects and products. (Source: Frey and Butcher, 1994)

13.2.6 Hydrothermal Metamorphism

You have read about hydrothermal mineralisation in Block 4 of BGYCT-133 course. Now let us discuss hydrothermal metamorphism.

Hydrothermal metamorphism is a type of metamorphism in which hot ascending water-rich fluids play a significant role and percolate into and react with the host rock. The term coined by Coombs (1961) is of great academic interest as the active geothermal fields help in the study of recent state of metamorphism. This process is related to ore genesis, rock alteration and geothermal energy where hot solutions or gases percolated through fractures, causing mineralogical and chemical changes in the surrounding rocks. Hydrothermal metamorphism is typically of local extent in that it may be related to a specific setting, e.g. when an igneous intrusion mobilises H_2O in the surrounding rocks. **Hydrothermal solution** is underground hot water-rich fluid capable of transporting metals in solution. In contrast to the usual study of metamorphism where temperature, pressure and fluid composition is carried out indirectly by the study of mineral assemblages, here we can directly measure these parameters in boreholes. Active geothermal areas which serve as excellent examples of hydrothermal metamorphism are known from California, Iceland, New Zealand (Fig. 13.8) and Japan.

Fig. 13.8: Active geothermal area in Roturva, New Zealand. They are excellent examples of hydrothermal metamorphism. (Photo credit: Dr. S.D. Shukla)

13.2.7 Lightning and Combustion Metamorphism

The spontaneous combustion of organic matter, coal, oil and gas at or near the Earth's surface at extreme temperatures of 1000-1500°C, causes **combustion metamorphism**. With increasing temperature burnt rocks, clinkers and slag or paralava are produced, which may crop out over a large area where combusted organic-bearing strata are dipping gently, whereas the contact aureoles are generally only a few meters thick. **Lightning metamorphism** is of local extent due to a strike of lightning. The resulting entirely glassy rock is known as **fulgurite**.

So, you have learnt the types of metamorphism. Before discussing the grade and zone of metamorphism, spend a few minutes to perform an exercise to check your progress.

SAQ 1

a) List the types of metamorphism of local extent.

b) What is burial metamorphism?

c) What is contact aureole?

d) What is pseudotachylite?

e) List the products of impact metamorphism.

f) Define hydrothermal solution.

13.3 GRADE OF METAMORPHISM

In the previous section we had discussed about the different types of metamorphism.

Let us now read about the grades of metamorphism.

Now you are familiar with the concept that different regions on the Earth's crust experience different magnitudes of temperature, stress or pressure. Therefore, all the metamorphic processes do not take place under the same physical conditions. As a consequence, the rock may undergo different extents or grades of metamorphism, depending on the recrystallisation and new mineral formation under a particular set of conditions. The term 'metamorphic grade' was introduced by Tilley (1924) to indicate the relative intensity of metamorphism or, in other words the peak temperature of recrystallisation. Geologists use the term metamorphic grade in a formal way to indicate the intensity of metamorphism or in other words the magnitude or the degree of metamorphic change. Terms like very-low grade',' low grade', 'medium grade',' high grade' and 'very- high grade' metamorphism are conveniently used in this regard. The boundaries between each segment are characterised by a drastic change in mineral composition or mineral assemblage appropriate for the bulk composition of the rock.

Metamorphic grade refers to the temperature and/ or pressure under which a rock was metamorphosed. In the previous unit you had learnt that metamorphic minerals in a rock form under specific conditions, they are used to identify the temperature and pressure of the metamorphic conditions.

The metamorphic grades have been used to indicate the relative intensity of metamorphism, as related to either increasing temperature or increasing pressure conditions of metamorphism or often both (Fig. 13.9) as discussed below:

- **Low-grade metamorphism** takes place at temperatures between 200°C to 320°C, and at relatively low pressure. Low grade metamorphic rocks are characterised by an abundance of hydrous minerals (minerals that contain H_2O, in their crystal structure). Examples of hydrous minerals that occur in low grade metamorphic rocks are clay, mica minerals and chlorite. The metamorphic rocks like slate and phyllite result from low grade metamorphism.
- **High-grade metamorphism** takes place at temperatures greater than 320°C and relatively high pressure. As grade of metamorphism increases, hydrous minerals become less hydrous, by losing H_2O and non-hydrous minerals become more common. Let us look at the examples of less hydrous minerals and non-hydrous minerals that characterise high grade metamorphic rocks. Muscovite is a hydrous mineral that eventually disappears at the highest grade of metamorphism. Biotite is a hydrous mineral that is stable even at very high grades of metamorphism. Pyroxene is a non-hydrous mineral. Garnet is a non-hydrous mineral. Metamorphic rocks like schist and gneiss result from high grade metamorphism.

Depending on whether accompanied by increasing or decreasing temperature two types of metamorphism can be distinguished:

- **Prograde (= progressive) metamorphism** is a metamorphism giving rise to the minerals which are typical of a higher grade, i.e. formed at higher temperature than the former phase assemblage. Metamorphism that occurs while temperature and pressure progressively increase is called prograde metamorphism.

- **Retrograde (= retrogressive) metamorphism** is a grade of metamorphism that gives rise to the minerals which are typical of a lower grade (i.e. lower temperature) than the former phase assemblage. It takes place as temperature and pressure fall due to erosion of overlying rock or due to tectonic uplift. In such cases we might expect metamorphism to a follow a reverse path and eventually return the rocks to lower metamorphic grade.

The different grades of metamorphism yield different metamorphic mineral assemblages. As the grade increases, recrystallisation and neocrystallisation tend to produce coarser grains and new mineral assemblages that are stable at higher temperatures and pressures.

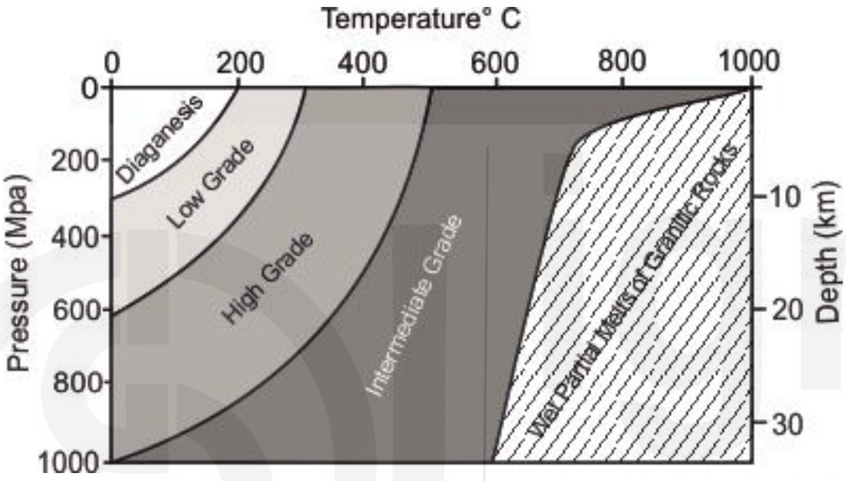


Fig. 13.9: The grade of metamorphism increases with depth. Temperature and pressure increase as we move deeper into the Earth.

13.4 ZONES OF METAMORPHISM

You have learnt about the types and grades of metamorphism in the previous sections. Now let us learn about the zones of metamorphism.

George Barrow in 1912 and C.E. Tilley in 1925, mapped regional metamorphic rocks in Scotland and made one of the first systematic studies of the variation in rock types and mineral assemblages with progressive metamorphism. In their classic work they suggested that an area could be subdivided into a series of **metamorphic zones**, each based on the appearance of a new mineral in the metamorphosed pelitic rocks, as the metamorphic grade increased. You have read about the index minerals in Unit 12 of this course. The metamorphic zones are marked on the basis of the first appearance of **index mineral** that was thought to be dependent on its temperature of formation and burial depth.

The sequence of index minerals with increasing metamorphic grade is as follows:

Chlorite→ Biotite→ Almandine Garnet→ Staurolite→ Kyanite→ Sillimanite (Fig. 13.10 and Table 13.2)

The mineral zones are defined on the basis of systematic distribution of individual mineral(s) occurring in distinct regional zones. A line on a map joining points of the first appearance of a certain index mineral gives the low-grade limit, after which the zone is named. A similar line indicates the high-grade limit of a particular zone, which is defined by the appearance of another higher-grade index mineral. In Tilley's definition two adjacent mineral zones are separated by a line known as a **mineral zone boundary or an isograd**, for example, the biotite zone is the zone occurring between the biotite and almandine-garnet mineral zone boundaries. An index mineral may and in many cases does persist in the higher grades than the zone which it characterises, but sometimes it is also restricted to a single mineral zone. These zonal sequences after Barrow are called **Barrovian zones** which are found in many other areas and are characteristic for the medium-pressure metapelites.

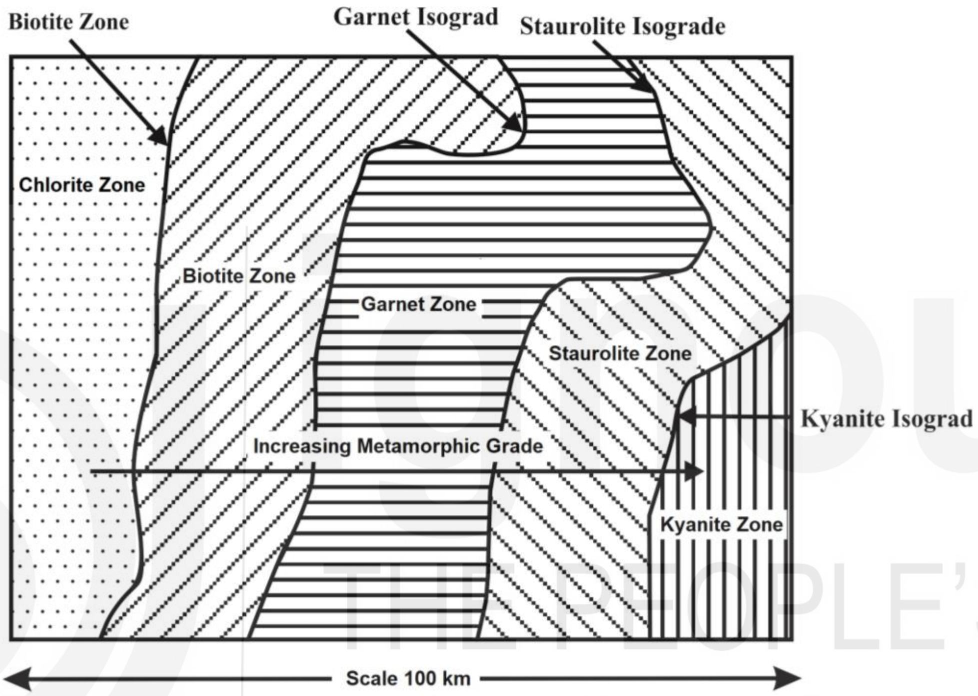
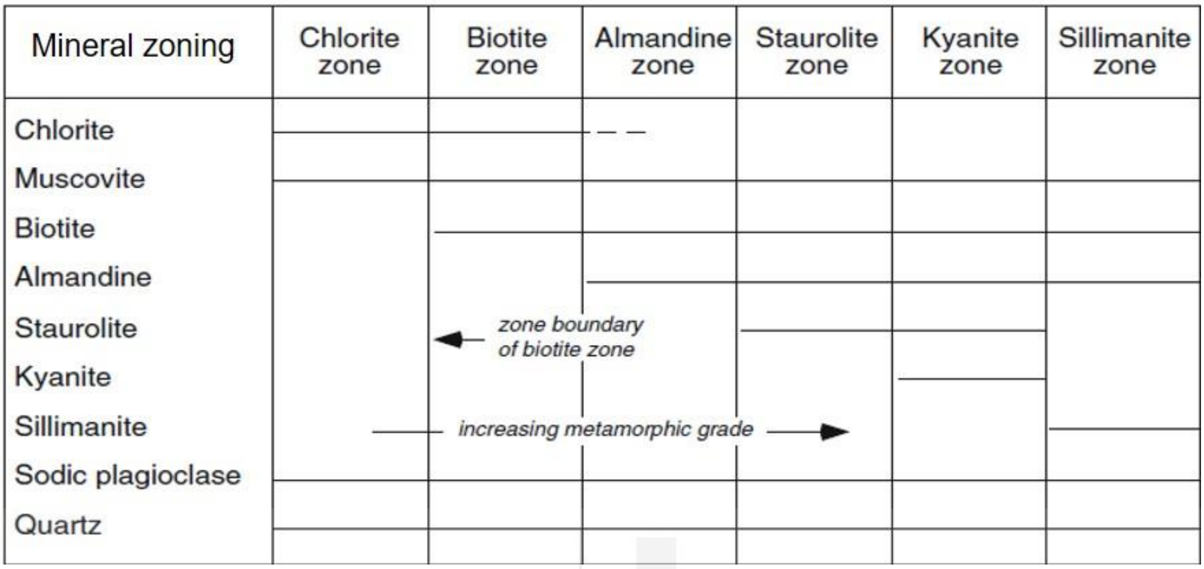


Fig. 13.10: Mineral zones showing increasing grades of metamorphism.

The sequence of zones recognised by George Barrow, and the rocks and typical metamorphic mineral assemblage in each, are:

- **Chlorite zone**: Pelitic rocks are slates or phyllites and typically contain chlorite, muscovite, quartz, and albite.
- **Biotite zone**: Slates give way to phyllites and schists, with biotite, chlorite, muscovite, quartz, and albite.
- **Garnet zone**: Schists with conspicuous red almandine garnet, usually with biotite, chlorite, muscovite, quartz, and albite or oligoclase.
- **Staurolite zone**: Schists with staurolite, biotite, muscovite, quartz, garnet, and plagioclase. Some chlorite may persist.
- **Kyanite zone***:* Schists with kyanite, biotite, muscovite, quartz, plagioclase, and usually garnet and staurolite.
- **Sillimanite zone**: Schists and gneisses with sillimanite, biotite, muscovite, quartz, plagioclase, garnet, and perhaps staurolite. Some kyanite may also be present.

Table 13.2: Distribution of some metamorphic minerals in pelitic rocks from Barrovian zones of the Scottish Highlands. (Source: Bucher and Frey, 1994)



13.5 CONCEPT OF METAMORPHIC FACIES

You have learnt about types, grades and zones of metamorphism. Now let us study the concept of metamorphic facies.

The concept of metamorphic facies was first introduced by P. Eskola (1915), who defined it as: “A **metamorphic facies** includes rocks which may be supposed to have been metamorphosed under identical conditions. As belonging to certain facies, we regard rocks which, if having an identical chemical composition, are composed of the same minerals”. Later, Turner, Fyfe and Verhoogen (1958) modified this scheme and recognised 11 metamorphic facies and defined the metamorphic facies as:

“**Metamorphic facies** is a set of metamorphic mineral assemblages, repeatedly associated in space and time, such that there is a constant and therefore predictable relation between mineral composition and chemical composition.”

The mineralogical assemblages of both contact and regional metamorphic facies, including the set of minerals formed in a rock developed under a particular range of P and T. (Fig. 13.11). The metamorphic facies can be classified into three categories on the basis of pressure/temperature gradient:

- **Facies of low pressure**
- **Facies of medium to high pressure**
- **Facies of very high pressure**

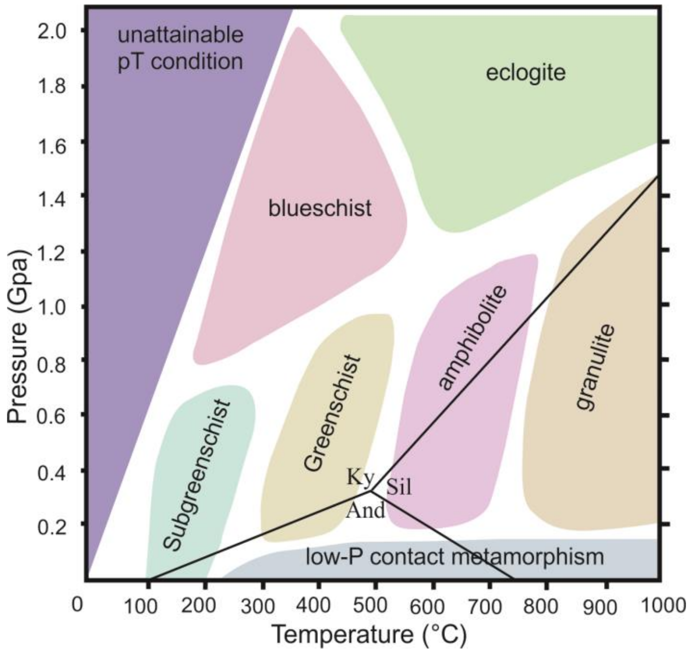


Fig. 13.11: Pressure-Temperature fields of metamorphic facies. (Source**:** Bucher and Frey, 1994)

13.5.1 Facies of Low Pressure

The facies falling under low pressure are mentioned in Table 13.3.

Table 13.3: Facies of low pressure and temperature range.

S. No.	Facies	Temperature Range
1.	Albite-Epidote Hornfels	400-500/550°C
2.	Hornblende-Hornfels	500/550-700°C
3.	Pyroxene-Hornfels	650-850°C
4.	Sanidinite	>850°C; P<500 bars

1. **Albite-Epidote-Hornfels Facies** is facies at low pressure and relatively low temperatures of about 300°C to 400°C in the outer margins of contact aureoles. Pressure ranges from 100 bars to 3000 bars. Characteristic minerals include quartz, muscovite, biotite, chlorite, andalusite, actinolite, calcite, dolomite, albite, and epidote.

2. **Hornblende-Hornfels Facies** occur in contact aureoles and may pass outward with decreasing metamorphic grade into Albite-Epidote-Hornfels facies. Hornblende-plagioclase defines the typical assemblage of basic hornfels. Pressure ranges up to 3kbar. The occurrence of muscovite+ biotite+ quartz with andalusite+ cordierite differentiates it from the amphibolite facies of regional metamorphism.

3. **Pyroxene-Hornfels Facies** develop in the inner aureoles of contact metamorphism. Pressure ranges up to 3kbar. Presence of Fe-cordierite and absence or rarity of andalusite/sillimanite indicates that the P was quite low.

4. **Sanidinite Facies** is restricted to xenoliths in the basic lavas and dykes. The facies are characterised by the minerals such as: mullite, cordierite, tridymite, spinel, sanidine, anorthite, diopside, periclase and forsterite. The beginning of sanidinite facies suggests a temperature of >800°c whereas, the field occurrence indicate that P must have been <500 bars.

13.5.2 Facies of Medium to High Pressure

The facies medium to high pressure are mentioned in Table 13.4.

Table 13.4: Facies of medium to high pressure and temperature range.

S.No.	Facies	Temperature Range
1.	Zeolite	200-400°C
2.	Prehnite-Pumpellyite	350-450°C
3.	Greenschist	400-500/550°C
4.	Amphibolite	500/550-700°C
5.	Granulite	700-800°C

1. **Zeolite Facies** is the lowest grade regional metamorphic facies with temperature and pressure range 200-400°C and 4 to 8 kbar respectively. The characteristic minerals which define this facies are: analcime, heulandite, laumontite, prehnite, pumpellyite, lawsonite and albite.
2. **Prehnite-Pumpellyite Facies** is transitional to the greenschist facies at higher T and to the zeolite facies at lower T and P conditions. Typical minerals in this facies are quartz, albite, prehnite, pumpellyite, chlorite, stilpnomelane, muscovite, and actinolite. This facies is well developed in greywacke-type sediments.
3. **Greenschist Facies**: This is one of the major facies of low-grade regional metamorphism which derives its name from the very common green-coloured schists that dominate many metamorphic terrains and some high-strain zones. These are associated with geosynclinals sediments. The greenschist facies conditions range from 400-500/550°C and pressures of 4 to 8 kbar. The greenschist facies is characterised by chlorite, chloritoid, stilpnomelane, pyrophyllite in the presence of muscovite and calcite are diagnostic minerals of this facies. Greenschist facies can be further subdivided into the following zones:
    - Chlorite Zone
    - Biotite Zone
    - Almandine Zone
4. **Amphibolite Facies:** The name is given due to the occurrence of hornblende-plagioclase mineral assemblage in the metabasic rocks ~~of~~ that have undergone regional metamorphism. It is widely distributed in the Precambrian terrains and in the eroded parts of the orogenic belts. The temperature range of this facies is from 540°C to 675°C. The pressure is always greater than 4kbar. The diagnostic mineral assemblage of the basic rocks is hornblende-plagioclase and the pelitic schists are characterised by biotite, muscovite, almandine garnet, staurolite, kyanite and sillimanite in different sets of combinations. Three zones have been recognised within the amphibolite facies:
    - Staurolite Zone
    - Kyanite Zone
    - Sillimanite Zone

5. **Granulite Facies** was defined on the basis of ideal assemblages in which mica and amphiboles are not stable. They are best represented by exposures in the Archaean crystalline complexes like the Southern Granulite Terrain of the Indian shield. Hypersthene is the most diagnostic mineral in both pelitic and mafic compositions of this facies. Rocks of granulite facies are marked by pleochroic hypersthene, pyrope-almandine rich garnets, microperthitic K-feldspars, antiperthitic plagioclase and granoblastic-mosaic or granulitic texture. Granulite facies rocks represent the highest temperature of metamorphism, lying in the range of 700/750°C to 800/850°C. Pressure ranges vary from 3 to 13 kbar

13.5.3 Facies of Very High Pressure

The facies medium to high pressure are mentioned in Table 13.5.

Table 13.5: Facies of very high pressure and temperature range.

S.No.	Facies	Temperature Range
1.	Glaucophane-Lawsonite (Blueschist)	200-400°C
2.	Eclogite	>700°C

1. **Glaucophane-Lawsonite Schist Facies (Blueschist Facies)** are low-temperature and very high-pressure rocks. Most of these rocks are found located in current or former active subduction complexes such as the Circum-Pacific belt, the Franciscan metamorphic complex, San Francisco, and the Indus-Tsangpo suture zone in the Himalaya, where these rocks are found associated with eclogites. The temperature and pressure ranges for this facies are around 200°- 400°C and 6 to 8 kb respectively.
2. **Eclogite Facies** are characterised by the critical mineral pair Omphacite+ Garnet (pyrope) in the rocks of gabbroic or basaltic composition under high pressure and temperature. Eclogite facies are difficult to be mapped as they occur only as lenses or small bodies as xenoliths in metamorphic complexes of different grades. The temperature ranges from 800-1000°C with pressure >15 kb.

So, you have learnt the grade and zones metamorphic rocks and concept of metamorphic facies. Before discussing further spend a few minutes to perform an exercise to check your progress.

SAQ 2

a) Define the grade of metamorphism.

b) Differentiate between the prograde and retrograde metamorphism.

c) What is the basis of metamorphic zone?

d) What is the mineral zone boundary?

e) What is metamorphic facies?

f) List the three zones of greenschist facies.

13.6 SUMMARY

In this unit you have read about types, grade and zones of metamorphism and the concept of metamorphic facies. Let us summarise:

- Broadly the metamorphism can be categorized into the regional or local extent. Regional metamorphism consists of geologic processes which act over widespread areas and cause metamorphic changes in vast expanses of rock such as ocean-floor metamorphism, subduction metamorphism, collision metamorphism and burial metamorphism.
- Local metamorphism is a type of metamorphism that is caused due to the localized effects of metamorphism in a small-scale region. Metamorphism may be directly attributed to a localised cause such as a magmatic intrusion, faulting or meteorite impact.
- Local metamorphism includes contact (igneous) metamorphism, cataclastic metamorphism, impact metamorphism, hydrothermal metamorphism, lightening and combustion metamorphism.
- Metamorphic grade refers to the temperature and/ or pressure under which a rock was metamorphosed. Low-grade metamorphism takes place at temperatures between 200ºC to 320ºC, and at relatively low pressure. High-grade metamorphism takes place at temperatures greater than 320ºC and relatively high pressure.
- The mineral zones are defined on the basis of systematic distribution of individual mineral(s) occurring in distinct regional zones. The sequence of index minerals with increasing metamorphic grade has been distinguished as follows:

  Chlorite→ Biotite→ Almandine Garnet→ Staurolite→ Kyanite→ Sillimanite
- Metamorphic facies is a set of metamorphic mineral assemblages, repeatedly associated in space and time, such that there is a constant and therefore predictable relation between mineral composition and chemical composition.
- The metamorphic facies can be divided into three categories on the basis of pressure/ temperature gradient: (1) Facies of low pressure; (2) Facies of medium to high pressure; and (3) Facies of very high pressure.

13.7 ACTIVITY

- Make a list of Indian occurrences of metamorphic rocks.
- Make a list of gem stones that are metamorphic minerals.

13.8 TERMINAL QUESTIONS

1. Discuss in detail about the regional metamorphism.
2. When the contact metamorphism does take place?
3. Explain the grade of metamorphism. Draw a neat well labelled diagram.
4. Describe the metamorphic facies on the basis of pressure/temperature (P/T) gradient.

13.9 REFERENCES

- Bucher K. and Frey M. (1994) Petrogenesis of metamorphic rocks. Springer, Berlin, 318 p.
- Coombs D.S. (1961) Some recent work on the lower grades of metamorphism. Australian Journal of Science 24: 203-215p.
- Coombs D.S., Ellis A.J., Fyfe W.S. and Taylor A.M. (1959) The zeolite facies, with comments on the interpretation of hydrothermal syntheses. Geochim. Cosmochim. Acta, 17, 53-107p.
- Ernst, W. G. (1976) Petrologic phase equilibria. San Francisco, W. H. Freeman, 333p.
- Eskola, P. (1915) On the relations between the chemical and mineralogical composition in the metamorphic rocks of the Orijarvi region. Comm. geol. Finlande Bull., 44, 1-107 (in Finnish), 109-145 (in English).
- Bucher, K, and Frey, M. (1994) Petrogenesis of metamorphic rocks. 6th edition. Berlin, Heidelburg: Springer-Verlag.
- Fyfe W.S., Turner F.S. and Verhoogen J. (1958) Metamorphic reactions and metamorphic facies. Mem. Geol. Soc. Amer., 73, 259 p.
- George Barrow, (1912) The Geology of the Districts of Braemar, Ballater, and Glen Clova. By, F.G.S., E. H. Cunningham Craig, B.A., F.G.S.; with contributions by L. W. Hinxman, B.A., F.R.S.E. 8vo; pp. vi, 138, with 7 plates. Edinburgh, 6d. Geological Magazine, 9(11), 520-521. doi:10.1017/S0016756800115912.
- Tilley, C. E., (1925) Metamorphie Zones in the Southern Highlands of Scotland, Q.J.G.S., vol. lxxxi. 100p.
- Miyashiro, A. (1973) Metamorphism and metamorphic belts. Allen & Unwin, London, 492p.
- Tilley, C. E. (1924) Contact-metamorphism in the Comrie area of the Perthshire Highlands. Quarterly Journal of the Geological Society of London, 80, 22–71p.

13.10 FURTHER/SUGGESTED READINGS

- Mukherjee, P.K. (2000) A Text Book of Geology. The World Press, Kolkata, 638p.
- Tyrell, G. W. (1973) The principles of Petrology. John Wiley & Sons, 349p.
- Bucher, K, and Frey, M. 1994. Petrogenesis of metamorphic rocks. 6th edition. (Berlin, Heidelburg: Springer-Verlag.)

13.11 ANSWERS

Self Assessment Questions

1 a) Contact metamorphism, cataclastic metamorphism, impact metamorphism, hydrothermal metamorphism, lightening metamorphism and combustion metamorphism.

b) Burial metamorphism occurs at bottom of thick sedimentary rock piles. It begins typically at the depths of 6 to 10 km, where temperature ranges between 100ºC and 200ºC depending on the geothermal gradient.

c) Contact aureole is the zone in which the effect of contact metamorphism is seen.

d) A pseudotachylite is a rock whose aphanitic groundmass is similar to black basaltic glass (tachylite).

e) Shocked quartz, coesite, stishovite, minute diamonds, suevite and tektite.

f) Hydrothermal solution is underground hot water-rich fluid capable of transporting metals in solution.

2 a) Metamorphic grade refers to the temperature and/ or pressure under which a rock was metamorphosed.

b) Prograde metamorphism gives rise to the minerals which are typical of a higher grade. Whereas retrograde metamorphism is a grade of metamorphism that gives rise to the minerals which are typical of a lower grade.

c) Metamorphic zone is based on the appearance of a new mineral in the metamorphosed pelitic rocks, as metamorphic grade increases.

d) Two adjacent mineral zones are separated by a line known as a mineral zone boundary.

e) Metamorphic facies is a set of metamorphic mineral assemblages, repeatedly associated in space and time, such that there is a constant and therefore predictable relation between mineral composition and chemical composition.

f) Chlorite Zone, Biotite Zone, Almandine Zone.

Terminal Questions

1. Please refer to subsection 13.2.1. Discuss ocean-floor metamorphism, subduction zone metamorphism and collision zone metamorphism.
2. Please refer to subsection 13.2.3.
3. Please refer to section 13.3.
4. Please refer to section 13.5.