

Block

4**METAMORPHIC PETROLOGY**

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Acknowledgement: Ms. Savita Sharma for assistance in preparation of CRC and some of the figures.
August, 2020

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ISBN:

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Printed and published on behalf of Indira Gandhi National Open University, New Delhi by the Registrar, MPDD, IGNOU. Printed by :

BGYCT-135: PETROLOGY

Block 1 Igneous Petrology- I

Unit 1 Introduction to Petrology

Unit 2 Textures and Structures of Igneous Rocks

Unit 3 Classification of Igneous Rocks

Block 2 Igneous Petrology- II

Unit 4 Concept of Magma

Unit 5 Crystallisation of Magma

Unit 6 Felsic and Intermediate Rocks

Unit 7 Mafic and Ultramafic Rocks

Block 3 Sedimentary Petrology

Unit 8 Formation of Sedimentary Rocks

Unit 9 Textures of Sedimentary Rocks

Unit 10 Sedimentary Structures

Unit 11 Classification of Sedimentary Rocks

Block 4 Metamorphic Petrology

Unit 12 Metamorphism

Unit 13 Types of Metamorphism

Unit 14 Textures and Structures of Metamorphic Rocks

Unit 15 Classification of Metamorphic Rocks

BLOCK 4: METAMORPHIC PETROLOGY

Metamorphic petrology deals with the investigations of the mineralogical, microstructural, textural and chemical changes in metamorphic rocks. Metamorphic rocks are derived from pre-existing igneous, sedimentary or metamorphic rocks as they undergo mineralogical, chemical and/or structural changes. These rocks are also an important part of Earth. Rock cycle has been changing the face of the Earth for millions of years. Metamorphic rocks are an important part of that change. Metamorphic rocks are part of the process that creates new rocks and helps the rock cycle to go on. Metamorphic rocks are quite useful to mankind. They are used in making buildings, roads, insulation, jewellery, powders, etc. Metamorphic rocks can be different shapes, sizes, and colours. Do you know that the lightning striking the sand can transform it into a metamorphic rock called fulgurite? Scientists learn and unravel mysteries about Earth's plates and their movements by studying metamorphic rocks. The location, appearance and mineral assemblage of these rocks provide clues and facts about changes above and below Earth's surface such as subduction, accretion, trench advance or retreat and collisional orogenesis.

In **Block 4 Metamorphic Petrology** we will discuss about the factors, processes and products of metamorphism; types, factors, zones and grades of metamorphism. We will also discuss about the structures, factors affecting textures and types of textures found in metamorphic rocks. Megascopic and petrographic details of some common metamorphic rocks have also been discussed.

In **Unit 12 Metamorphism** you will get acquainted with the process and products of metamorphism, low and high limits of temperature and pressure in metamorphism. The unit also discusses about factors affecting and the chemical reactions leading to metamorphism with suitable examples.

In **Unit 13 Types of Metamorphism** we will familiarise with the types of metamorphism, metamorphic facies, zones and grade of metamorphism.

In **Unit 14 Textures and Structures of Metamorphic Rocks** we will learn about textures and structures found in metamorphic rocks and factors affecting textures of metamorphic rocks.

Unit 15 Classification of Metamorphic Rocks discusses the classification of metamorphic rocks. We would also read the megascopic and petrographic characters of common metamorphic rocks.

Expected Learning Outcomes

After studying this block, you should be able to:

- describe the processes of metamorphism;
- identify products of metamorphism;
- discuss the factors affecting metamorphism;
- explain types, zones and grades of metamorphism;
- familiarise with the basic concept of facies of metamorphic rocks;
- describe the textures and structures of metamorphic rock;

- classify the metamorphic rocks; and
- discuss megascopic and petrographic characters of common metamorphic rocks.

After studying this block, you will be able to get familiar with the concept of the processes that form metamorphic rock and explain some of the common metamorphic rocks.

In order to evaluate your learning while reading the self-learning material of this block, we have provided self-assessment exercises under the caption “**Self Assessment Questions (SAQ)**” at a few places and at the end “**Terminal Questions**” in all units of the block, which invariably end with answers to the questions, set in these exercises. You should attempt the exercises yourself and not be tempted to look up the answers given under the caption “Answers” beforehand. It should be noted that the check your progress is provided as study tools to help you keep on the right track as you read the units. You have been provided with the links of **audio and video materials** related to this course. They are blended with the self-learning material. You are instructed to watch/listen these audio video programmes and **answer the questions** given after “terminal question”.

We advise that as you read the units, jot down important points in the space provided in the margins of each page. In fact, broad margins in the booklet are provided for you to write your notes on. Make your notes as you work through the materials. This will help you prepare for the term end examination (TEE) and also in assimilating the content.

Your feedback pertaining to this block will help us undertake maintenance and timely revision of the block. Send your feedback to us to the address given below or e-mail to

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We hope that you would enjoy reading the self-learning material.

Wishing you success and all the best in this endeavour!!



UNIT 12

METAMORPHISM |

Structure

12.1	Introduction	12.6	Metamorphic Processes
	Expected Learning Outcomes		Pressure and Temperature Conditions in Crust and Mantle
12.2	Basic Concepts		Heat Flow and Geotherms
12.3	Factors Affecting Metamorphism		Chemical Reactions Leading to Metamorphism
	Temperature	12.7	Products of Metamorphism
	Geothermal Gradient		Metamorphic Minerals
	Load Pressure (P_{load})		Index Minerals in Metamorphic Rocks
	Fluid Pressure (P_{fluid})		Why do we Study Metamorphic Rocks?
	Shear Stress	12.8	Summary
12.4	Limits of Metamorphism	12.9	Activity
	Low-Temperature Limit	12.10	Terminal Questions
	High-Temperature Limit	12.11	References
	Low-Pressure Limit	12.12	Further/Suggested Readings
	High-Pressure Limit	12.13	Answers
12.5	Protolith		

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.

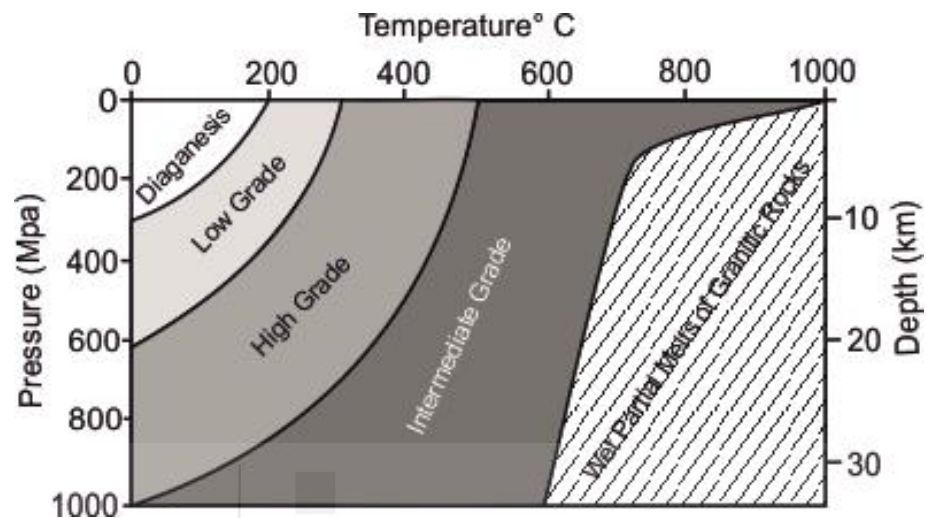


Fig. 12.1: The grade of metamorphism increases as the temperature and pressure increase with depth.

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 20° C to 30°C 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 (ΔT) with the vertical thickness (Δz). **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^2); 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 $\mu\text{cal cm}^{-2}\text{s}^{-1}$, equivalent to $4.2 \mu\text{Js}^{-1}\text{cm}^{-2}$ or $0.042 \text{ Js}^{-1}\text{m}^{-2}$. 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 $1^\circ\text{C}/30\text{m}$. Geothermal gradients can go as high as up to $50^\circ\text{C}/\text{Km}$ 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.

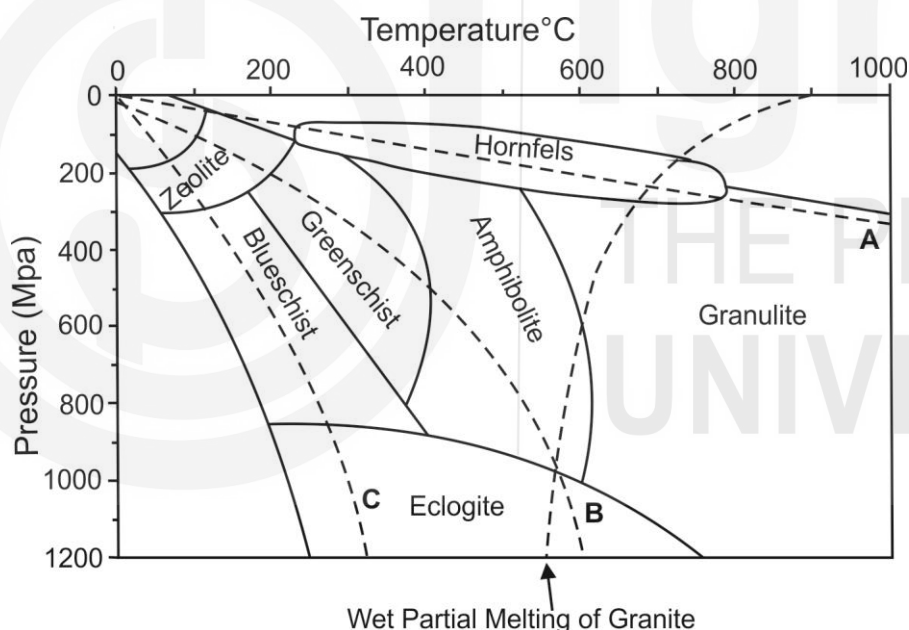


Fig. 12.2: Graph depicting the relationship of geothermal gradient with the metamorphic facies. 'A'- High geothermal gradient (contact metamorphism), Low P, High T; 'B'-Normal geothermal gradient (regional metamorphism), High P, High T; 'C'-Low geothermal gradient (subduction), High P, Low T.

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.

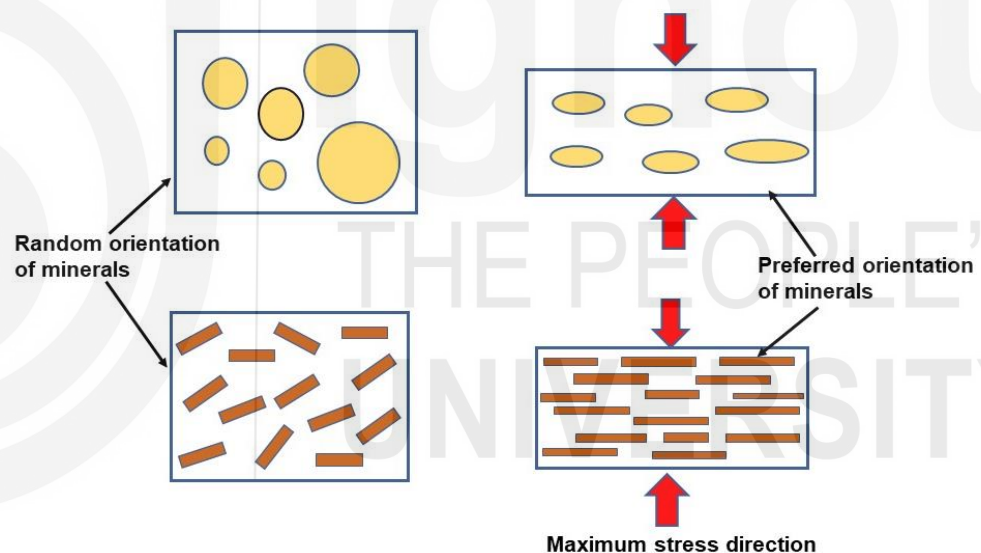


Fig. 12.3: Flattening and orientation due to pressure or stress.

12.3.4 Fluid Pressure (P_{fluid})

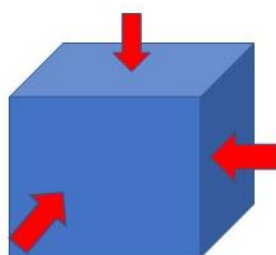
You have read that the Earth's crust has water in its composition. The meteoric water, groundwater or seawater that comes in contact with intruding magma usually contains rich combination of metallic cations, dissolved compounds, some ions and volatiles (H_2O , CO_2 and SO_2). Such chemically enhanced 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 $P_{\text{H}_2\text{O}}$ (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 ($P_{\text{fluid}} = P_{\text{load}}$), 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

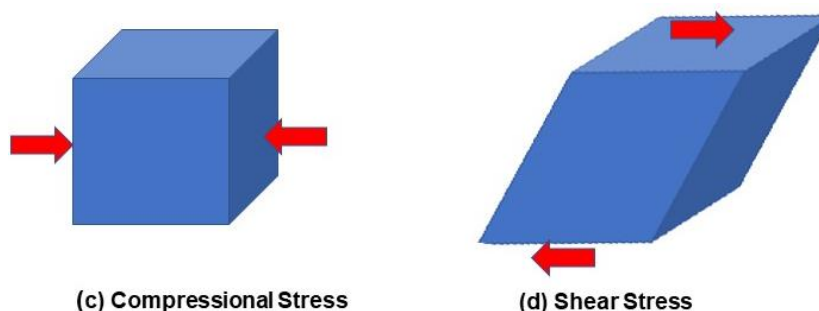


Fig. 12.4: Diagrams showing types of stress: a) Confining stress; b) Tensional stress; c) Compressional stress; and d) Shear stress.

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 of 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.

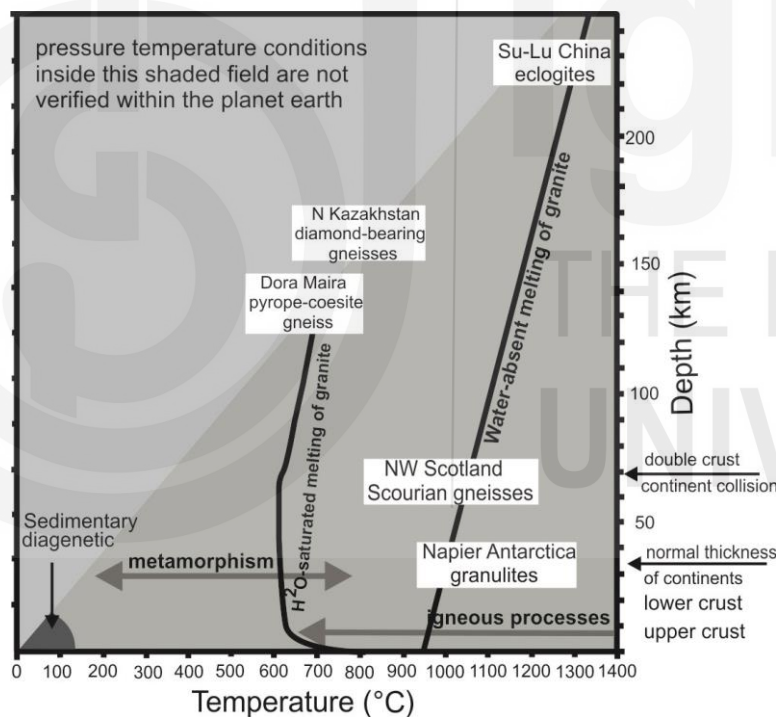


Fig. 12.5: The pressure temperature ranges of metamorphic processes. (Source: Bucher & Grapes, 2011). The P–T gradients of four typical geodynamic settings are shown. The boundary between diagenesis and metamorphism is gradational. Note that the metamorphic field has no upper P–T limit on this diagram, 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; Sajeew 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 $T > 150\text{-}200^\circ\text{C}$	
Upper temperature limit	High pressure limit
In crustal rocks; $750\text{-}850^\circ\text{C}$ (max. recorded $T \sim 1, 150^\circ\text{C}$)	Presently, some rocks collected at the Earth surface are known to have once formed at 100-200km depth, $\approx 3\text{-}6\text{GPa}$
In many regional scale metamorphic areas T does not exceed $\sim 650\text{-}700^\circ\text{C}$	

SAQ 1

- Define metamorphism.
- List the sources of thermal energy responsible for metamorphism.
- Name two elements producing heat due to radioactive decay.
- Higher geothermal gradient is found in _____.
- Mention the low-and high-temperature limits during metamorphism?
- 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 (H₂O) and carbon dioxide (CO₂). 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, CaCO₃). 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 H₂O 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.

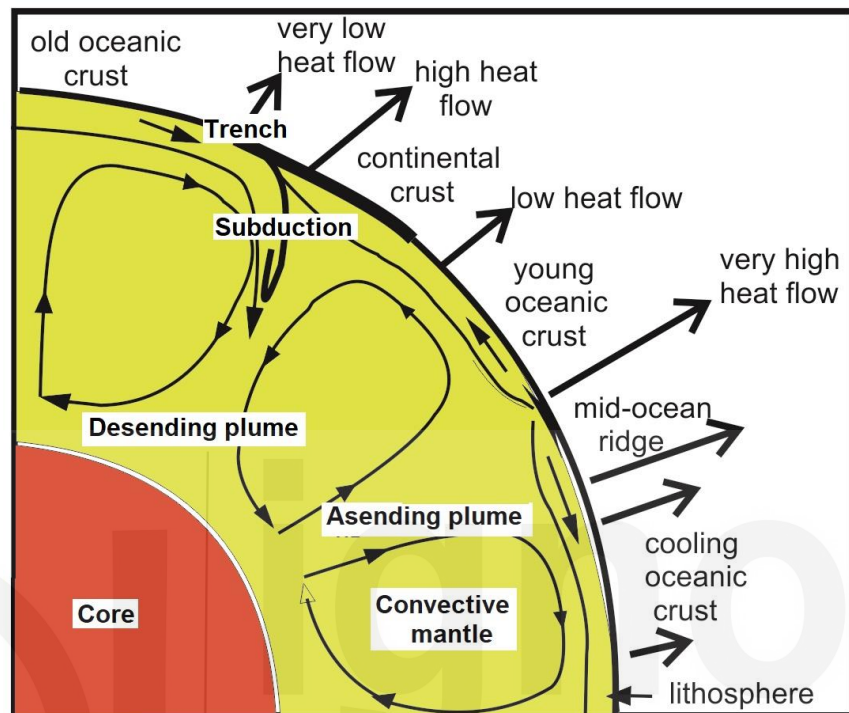


Fig. 12.6: Heat transfer between hot interior and cold surface of the Earth by conduction. (Source: Bucher and M. Frey, 1994)

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. Exchange Reactions

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. Polymorphic Reactions

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 H₂O 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 H₂O. Prograde metamorphism ensures the removal of H₂O from the hydrated phases. The removal of the hydrates is facilitated by the increasing temperature during the prograde metamorphism.

Example:



7. Decarbonation Reactions

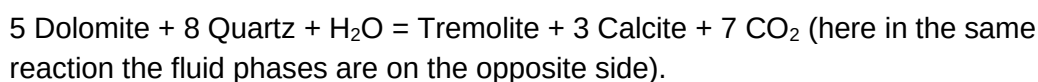
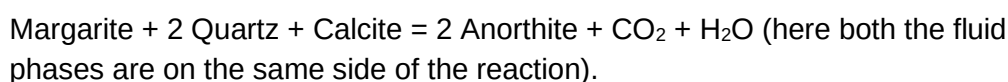
During the metamorphism of the calcareous rocks and other CO₂ bearing rocks carbon dioxide is released. CO₂ is released by the decomposition of carbonate minerals (dolomite, calcite etc.). However, the existence of pure CO₂ is highly questionable, therefore, CO₂ occurs either with H₂O or with some other volatiles.



8. Mixed Volatile Reactions

Two fluid phases viz. CO₂ and H₂O 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:



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: $2\text{Fe}_3\text{O}_4 + \frac{1}{2} \text{O}_2 = 3 \text{Fe}_2\text{O}_3$

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** ($\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$) 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** ($\text{Mg}(\text{OH})_2$) 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 minerals 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** ($\text{MgCaSi}_2\text{O}_6$) 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** ($\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$) 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: $\text{Ca}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$. 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

- Define protolith.
- List types of protolith.
- What are endothermic and exothermic reactions?
- List the processes involved in solid-solid reactions.
- Define geobarometer and geothermometer.
- 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.

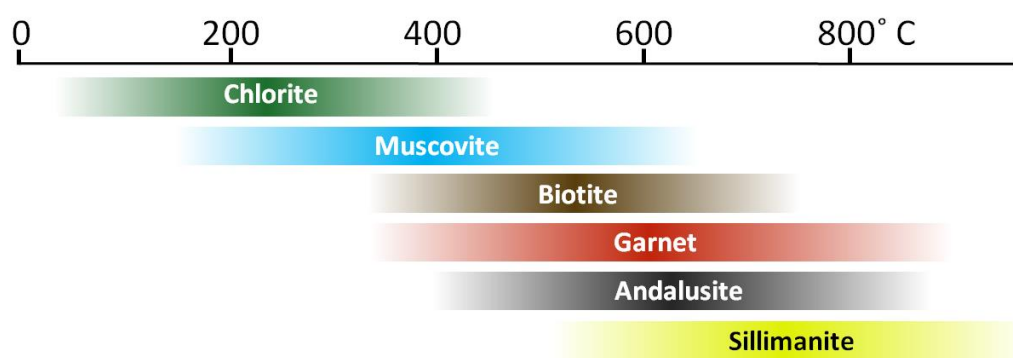


Fig. 12.6: Metamorphic index minerals and approximate temperature ranges. (Source : <https://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/07/image027.png>)

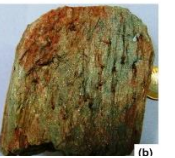
12.7.3 Why do we Study Metamorphic Rocks?

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 as 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°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

- 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.
 - 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.
 - Uranium (U), thorium (Th), potassium (K)
 - Subduction zones
 - Low-temperature limit of metamorphism is around 150-200°C. High-temperature limits of metamorphism have been reported between 750-850°C in crustal rocks.
 - Pore pressure is the pressure exerted by the fluids between the grains in a porous rock.
- Protolith refers to the original or parent rock, prior to metamorphism.
 - Quartzo-feldspathic, pelitic, calcareous, basic/ultrabasic and ferruginous.
 - 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.
 - 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.
 - 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.
 - Please refer to subsection 12.7.1.

Terminal Questions

- 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.



TYPES OF METAMORPHISM |

Structure

13.1	Introduction	13.4	Zones of Metamorphism
	Expected Learning Outcomes	13.5	Concept of Metamorphic Facies
13.2	Types of Metamorphism		Facies of Low Pressure
	Regional Metamorphism		Facies of Medium to High Pressure
	Burial Metamorphism		Facies of Very High Pressure
	Contact Metamorphism	13.6	Summary
	Cataclastic Metamorphism	13.7	Activity
	Impact Metamorphism	13.8	Terminal Questions
	Hydrothermal Metamorphism	13.9	References
	Lightning and Combustion Metamorphism	13.10	Further/Suggested Readings
13.3	Grade of Metamorphism	13.11	Answers

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.

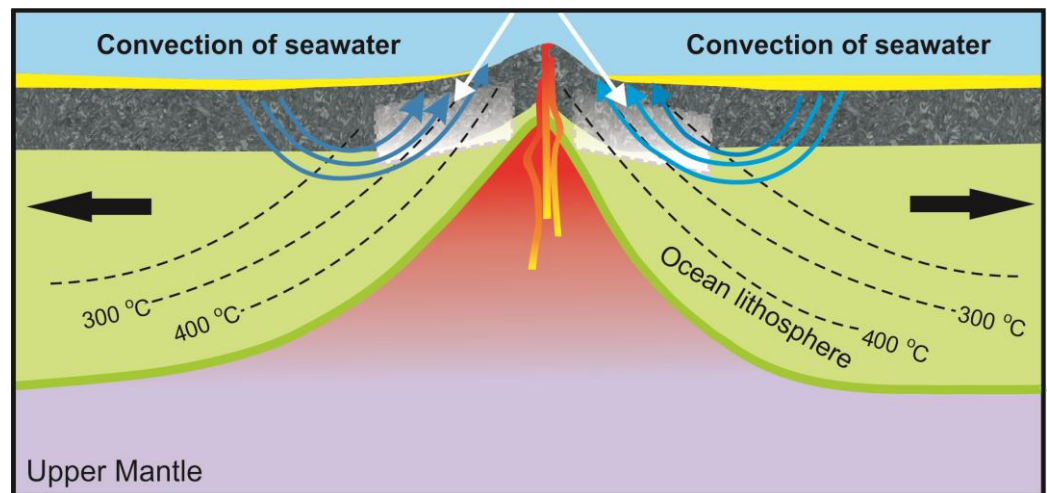


Fig. 13.1: Cartoon showing ocean-floor metamorphism of ocean crustal rock on either side of a spreading ridge.

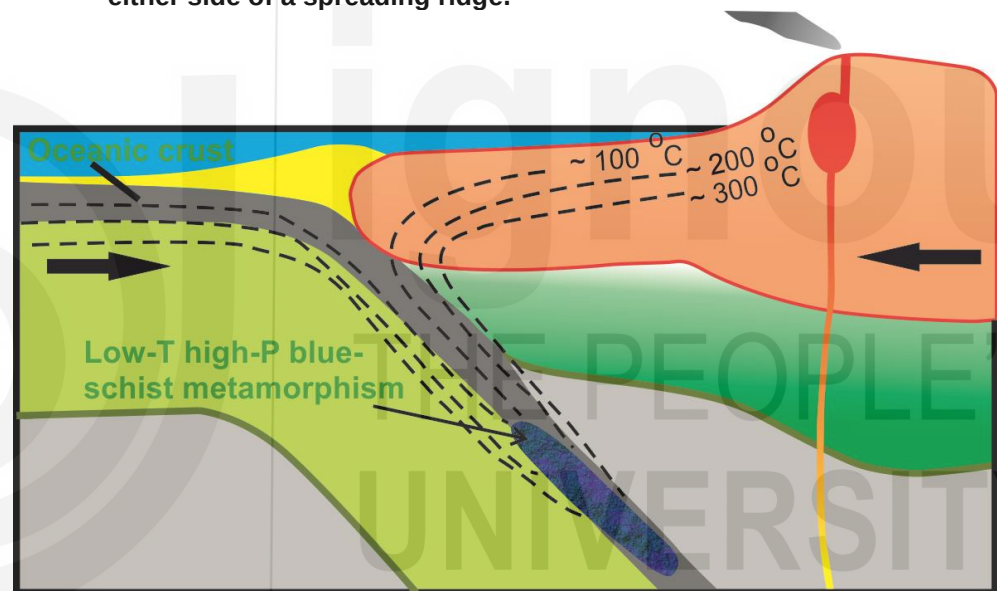


Fig. 13.2: Subduction zone (regional) metamorphism of oceanic crust at a subduction zone occurs at high pressure but relatively low temperatures.

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.

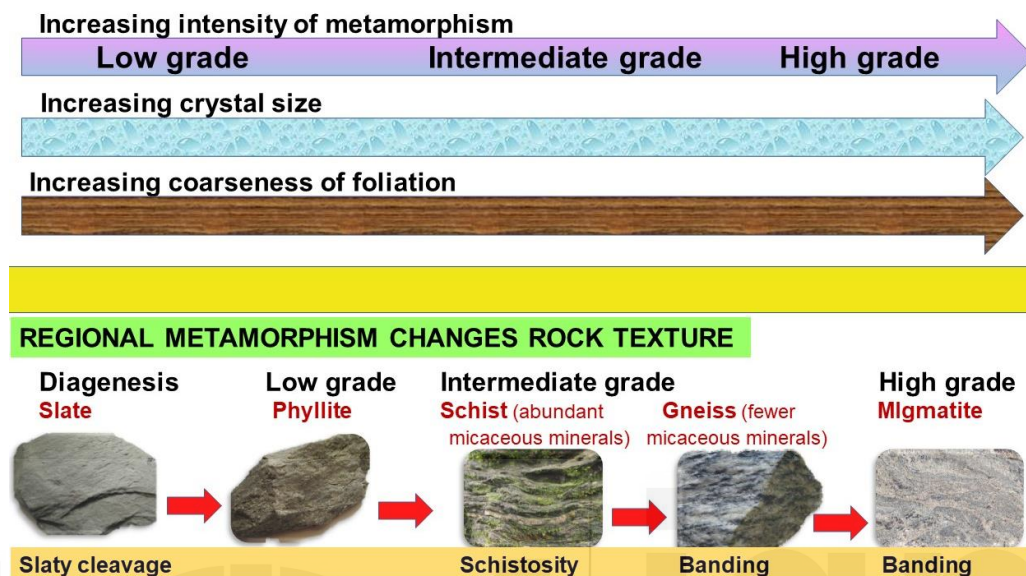


Fig. 13.3: Relation between intensity of metamorphism, crystal size, coarseness of foliation and changes in rock texture in regional metamorphism.

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°C and 200°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 features 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.

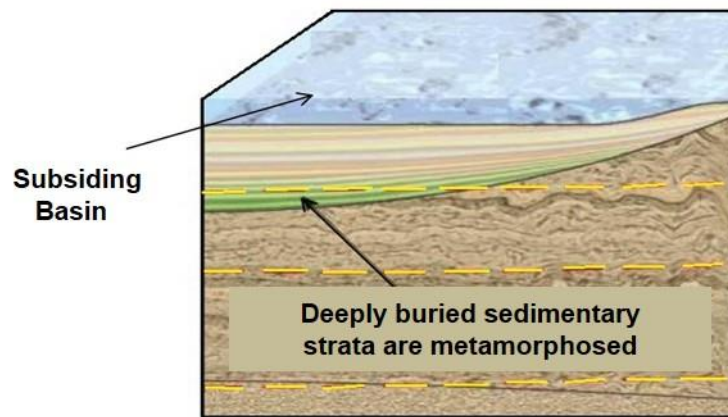


Fig. 13.4: Deeply buried sediments undergo burial metamorphism due to grow the heat and pressure.

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.

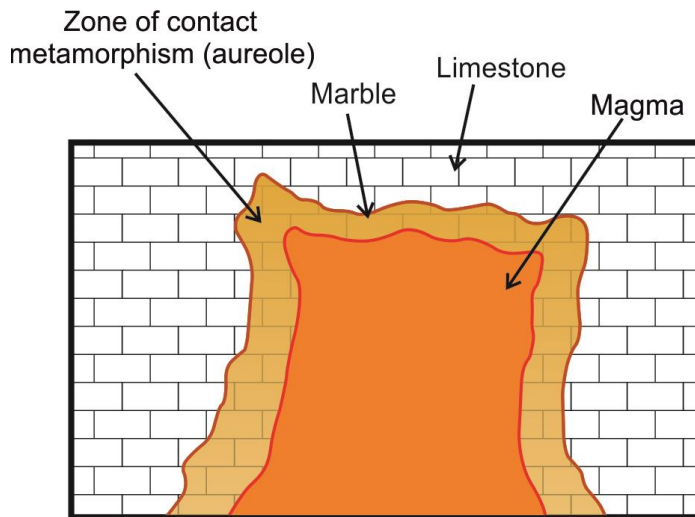


Fig. 13.5: Magma intruding in the limestone country rock and zone of contact metamorphism (aureole).

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 are non-foliated and are known as fault breccias and fault gouge. **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.

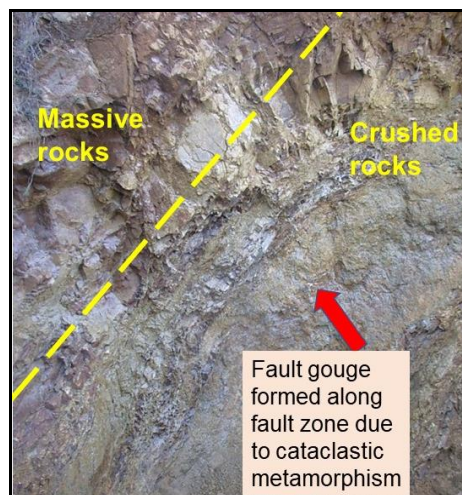


Fig. 13.6: Rocks are pulverised along the fault zone. Yellow dashed line marks the fault.

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.

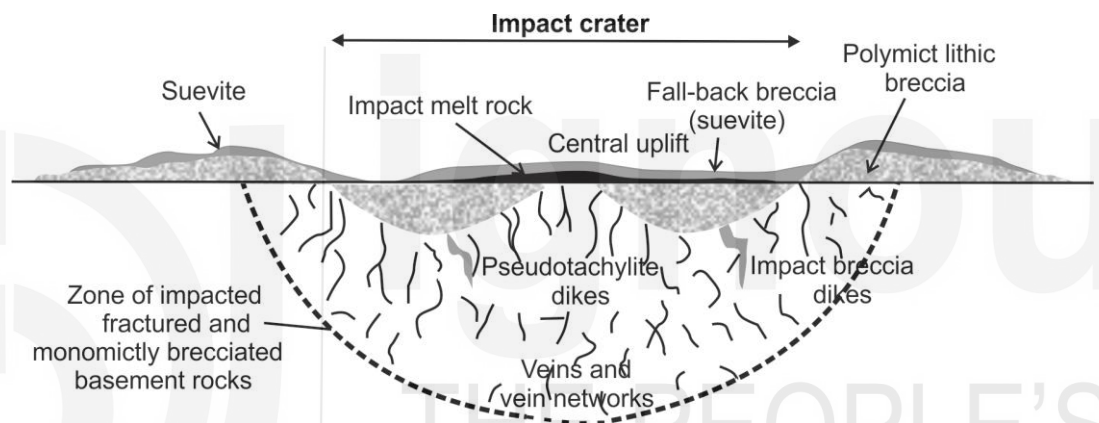


Fig. 13.7: Diagram showing the geology of a meteorite impact crater and associated impact metamorphic effects and products. (Source: Frey and Butcher, 1994)

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 Roturua, 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

- List the types of metamorphism of local extent.
- What is burial metamorphism?
- What is contact aureole?
- What is pseudotachylite?
- List the products of impact metamorphism.
- 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 H₂O, 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 H₂O 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 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.

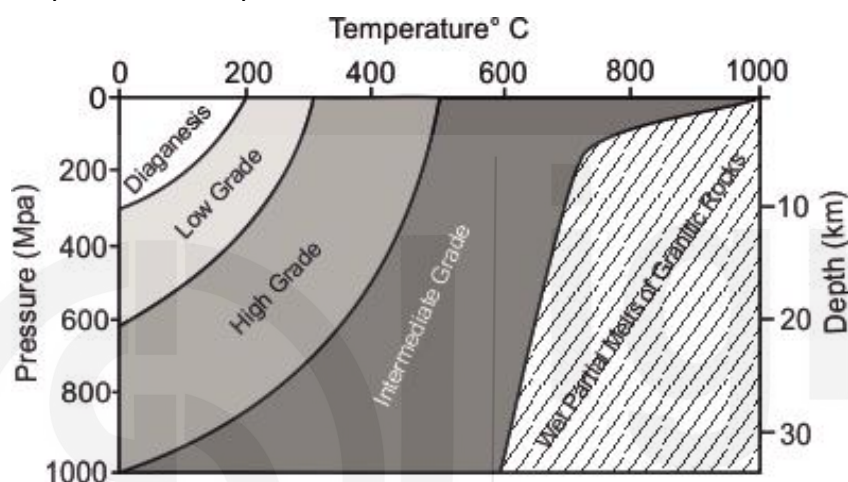


Fig. 13.9: The grade of metamorphism increases with depth. Temperature and pressure increase as we move deeper into the Earth.

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.

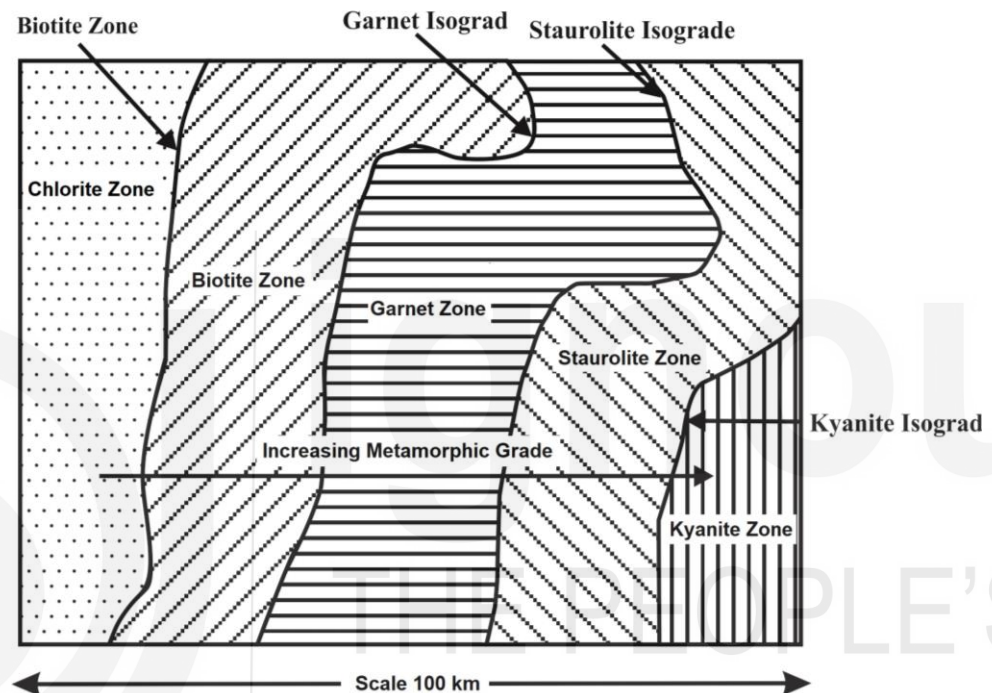


Fig. 13.10: Mineral zones showing increasing grades of metamorphism.

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)

Mineral zoning	Chlorite zone	Biotite zone	Almandine zone	Staurolite zone	Kyanite zone	Sillimanite zone
Chlorite			---			
Muscovite						
Biotite						
Almandine						
Staurolite						
Kyanite						
Sillimanite						
Sodic plagioclase						
Quartz						

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**

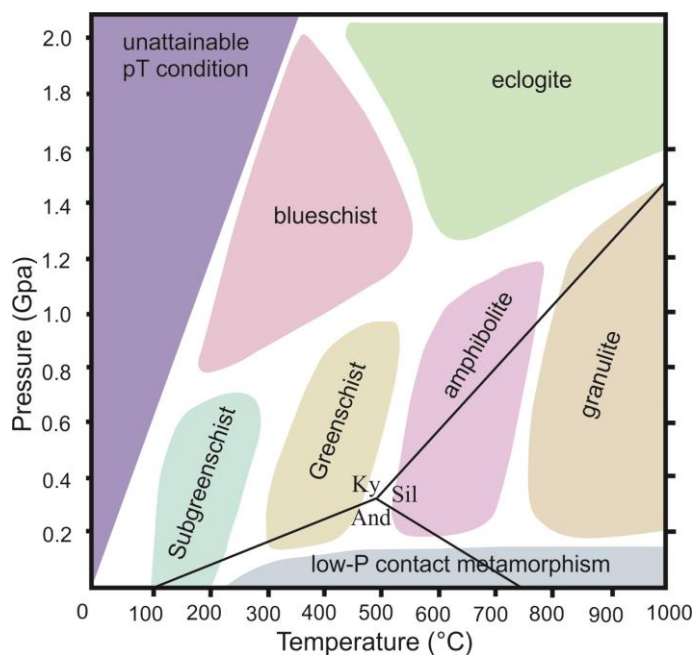


Fig. 13.11: Pressure-Temperature fields of metamorphic facies. (Source: Bucher and Frey, 1994)

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

- 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.
- 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.
- 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.
- 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 geosynclinal 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 200°C to 320°C, and at relatively low pressure. High-grade metamorphism takes place at temperatures greater than 320°C 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.

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13.10 FURTHER/SUGGESTED READINGS

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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 100°C and 200°C 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.



Texture and Structure of Metamorphic Rocks

Structure

- | | |
|--|--------------------------------------|
| 14.1 Introduction | 14.5 Structures in Metamorphic Rocks |
| Expected Learning Outcomes | Foliation and Lineation |
| 14.2 Factors Affecting Textures | Slaty Cleavage |
| 14.3 How Do Metamorphic Textures Form? | Schistose Structure /Texture |
| 14.4 Textures in Metamorphic Rocks | Gneissose Structure/Texture |
| Palimpsest Textures | Cataclastic Structure |
| Typomorphic Textures | Pseudotachylite |
| Reaction Textures | 14.6 Summary |
| Intergrowth Textures | 14.7 Activity |
| | 14.8 Terminal Questions |
| | 14.9 References |
| | 14.10 Further/Suggested Readings |
| | 14.11 Answers |

14.1 INTRODUCTION

You have learnt about factors affecting metamorphism, products and processes of metamorphism in Unit 12 and types, grades, zones of metamorphism and metamorphic facies in Unit 13. Now in this unit we will learn about textures and structures found in metamorphic rocks. Metamorphic rocks are generally associated with lots of frameworks which may range from microscopic scale to the very large scale such as tens of kilometres.

These constructions within the rocks may be induced structurally or mineralogically. The induction of such structures depends on kinematic as well

as thermodynamic adjustments in the protolith rocks or the rocks undergoing metamorphism. These structures and textures provide important clues to the crustal dynamics and evolution.

While studying the textures and structures of igneous and sedimentary rocks you have been introduced to the terms such as texture and structure in Unit 2 and Units 9 and 10 of this course. Let us recall, 'texture' is used to describe the size, shape, and arrangement of grains within a rock. Mostly igneous and many sedimentary rocks consist of mineral grains that have a random orientation. However, metamorphic rocks contain platy minerals and/or elongated minerals such as micas and amphiboles, which display some kind of preferred orientation in which the mineral grains exhibit a parallel to subparallel alignment. Structures in metamorphic rocks are a product of unbalanced directive forces and various interrelated textures are present in the rock unit. The term structure includes features on a large scale or on outcrop scale or on the hand specimen scale, or even at a regional scale. On the contrary the term **texture** is used for features at small scale, viz. from microscopic to hand specimen scale. Mutual agreement and arrangement of minerals in the rock unit, their shape, size and growth are the responsible factors for the development of a certain texture. Metamorphic rocks are rich in different type of structures and textures which are simply modifications brought about in the fabric and mineralogy of the metamorphic rocks with the changing physicochemical conditions. You have read about these physicochemical conditions while discussing factors of metamorphism in Unit 12.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ acquaint with the factors affecting metamorphic textures;
- ❖ discuss palimpsest, typomorphic, reaction and intergrowth textures in metamorphic rocks; and
- ❖ explain the structures, viz. foliation and lineation, slaty cleavage, schistose and gneissose structures in metamorphic rocks.

14.2 FACTORS AFFECTING TEXTURES IN METAMORPHIC ROCKS

Before studying the textures in metamorphic rocks, let us examine the factors controlling the metamorphic mineral content, textures and structures. They depend on the following factors:

1. Composition of the parent rock
2. Temperature during metamorphism
3. Pressure during metamorphism
4. Effects of tectonic forces
5. Effects of chemically active fluids.
6. Time

Let us discuss about them briefly.

1. **Composition of the parent rock** is very significantly reflected in the resulting metamorphic rock as usually no new elements (other than water) are added to parent rock/protolith. The mineral makeup of the parent rock also largely determines the degree to which each metamorphic factor/agent brings about change. For example, when the magma forces its way into surrounding rock, high temperatures and hot fluids may alter the host rock. If the host rock is composed of minerals that are comparatively not reactive, such as quartz grains in sandstone, then the alterations or changes that may occur will be confined to a narrow zone next to the pluton. However, when the host rock is a limestone, which is highly reactive, the zone of metamorphism may extend to a larger distance from the intrusion. Most metamorphic rocks have the same overall chemical composition as their protolith/ parent rock. However, it is possible that the loss or acquisition of volatiles such as water (H₂O) and carbon dioxide (CO₂) may take place. Therefore, when we try to find out or ascertain the parent material from which metamorphic rocks were derived, the most important clue comes from the chemical composition of the parent rock.
2. **Temperature during metamorphism** is controlled primarily by the outward flow of heat from Earth's deep interior, as we have discussed in the previous unit while discussing factors affecting metamorphism. It is important for you to understand that all the minerals are stable over finite temperature range. The new minerals formed are stable under different temperature conditions. But if temperature gets high enough, melting will occur and this would lead to the formation of an igneous rock.
3. **Pressure during metamorphism** typically increases 1 kilobar per 3.3 km of burial within the crust. The pressure is generally proportional to the depth of burial within the Earth. We have discussed that the confining pressure is the pressure applied equally in all directions. The minerals formed under high-pressure have a more compact structure that results in a higher density.
4. **Tectonic forces** often lead to forces that are not equally distributed in all directions, known as **differential stress**. The compressive stress causes flattening perpendicular to the stress and the shearing stress causes flattening through sliding parallel to the stress. The planar rock texture of aligned minerals produced by differential stress is known as foliation which increases with pressure and time.
5. **Chemically active fluids** have a catalysing role to play during metamorphism. The rising temperature causes water to be released from unstable minerals. The hot water (as vapour) being very reactive is most important and acts as rapid transport agent for mobile ions.
6. **Time** is an extremely important factor controlling metamorphism. The formation of metamorphic minerals and textures may take thousands to millions of years. The longer time period allows newly formed stable minerals to grow larger and the development of more clearly defined foliation. It involves processes like recrystallisation, phase change, metamorphic reaction, pressure solution and plastic deformation. These processes sometimes occur alone and sometimes together.

14.3 HOW DO METAMORPHIC TEXTURES FORM?

The formation of metamorphic minerals and textures takes place slowly; it may take thousands to millions of years. The most common processes are:

- **Recrystallisation** changes the shape and size of grains without changing the identity of the minerals constituting the grains. For example, during recrystallisation of limestone and formation of marble, a tightly fitted mosaic of large crystals of calcite may replace a cluster of small and rounded grains of calcite cement together.
- **Phase change** transforms one mineral into another mineral with the same composition but with a different crystal structure. For example, the transformation of quartz into a denser mineral called coesite represents a phase change. Both the minerals have the same formulae (SiO_2) but different crystal structures. Phase change involves a rearrangement of atoms.
- **Metamorphic reaction** or **neocrystallisation** (from the Greek *neos*, for new) which results in the growth of new mineral crystals that differ from those of the protolith. During neocrystallisation, chemical reactions digest minerals of the protolith to produce new minerals of the metamorphic rock. For this process to take place, atoms migrate (diffuse) through solid crystals that is a very slow process, and/or dissolve and reprecipitate at grain boundaries.
- **Pressure solution** takes place when a wet rock is squeezed more strongly in one direction producing ions that migrate through the water to precipitate elsewhere. Precipitation may take place on faces where the grains are squeezed together less strongly. Thus, pressure solution causes grains to become shorter in one direction and elongated in another.
- **Plastic deformation** takes place when a rock is squeezed or sheared at elevated temperatures and pressures. Under such conditions minerals behave like soft plastic and change shape without breaking. Such deformation can take place together with the metamorphic reactions.

14.4 TEXTURES IN METAMORPHIC ROCKS

Now let us learn about the textures found in metamorphic rocks. Metamorphic textures demonstrate a great diversity in the size, shape, orientation and spatial arrangement of crystals which results from variable P-T (pressure and temperature) conditions during the metamorphism. Metamorphic textures could be categorised into four groups:

1. Palimpsest Texture
2. Typomorphic Texture
3. Reaction Textures
4. Corona Texture
5. Intergrowth Texture

14.4.1 Palimpsest Texture

The primary texture of the original rock is sometimes found to exist which is known as palimpsest texture. We use the term 'blastic' or 'blast' as suffix to represent the resembling metamorphic equivalents of igneous textures. Palimpsest texture is also known as **relict texture** because it is the texture which has survived metamorphism and shows the inheritance of protolith rock textures even after the metamorphism. Low-grade metamorphic rocks show good preservation of relict textures and are formed in such a way that deformation gets limited to let the preservation happen. Examples of palimpsest (relict) texture includes: blasto-ophitic, blastoporphyritic, blasto-intergranular texture, and others.

You have read about all these textures in Unit 2 of this course where textures found in igneous rocks have been addressed. We will discuss them as relict textures in metamorphic rocks.

1. **Blasto-ophitic texture:** Plagioclase laths are seen suspended in a pyroxene matrix (sometimes olivine). Plagioclase laths may be seen fully surrounded in the matrix (ophitic) or they may be partially surrounded (sub-ophitic). This type of texture at a microscopic level if found intact even after deformation in a metamorphic rock is said to be a relict texture (Fig. 14.1).



Fig. 14.1: Photomicrograph showing plagioclase laths, as inclusion within big augite crystal indicative of blasto-ophitic texture, under XP. Note few plagioclase laths on the margin are partially enclosed. (Field of View = 2mm; Source: www.alexstrekeisen.it)

2. **Blasto-intergranular texture:** The igneous relict textures in metamorphic rocks that show occupancy of interstices formed between plagioclase crystals by ferromagnesium minerals (such as pyroxene, olivine etc.) The interstices are generally formed between two large crystals and are angular (Fig. 14.2).
3. **Blasto-porphyritic texture:** Larger grains or crystals are surrounded by the fine-grained matrix or glassy groundmass (Fig. 14.3). They are more common in extrusive igneous rocks but may occur in medium- to coarse-grained igneous rocks. Their presence in a metamorphic rock is considered to be of a relict of the texture existing in the parent rock.

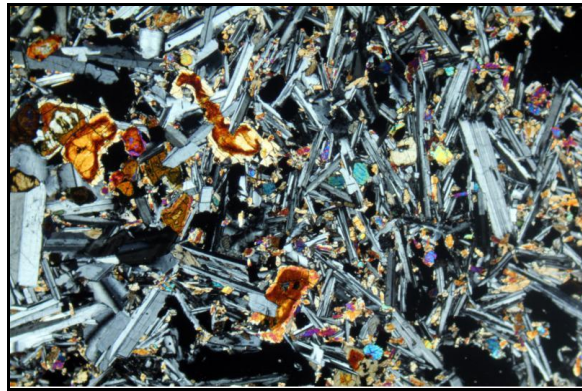


Fig. 14.2: Photomicrograph showing coarse-grained blasto-intergranular texture in a metamorphic rock under XP. Angular interstices between the plagioclase laths are occupied by pyroxene mineral (orange brown). This is indicative of basalt as a protolith. (Source: www.alexstrekeisen.it)

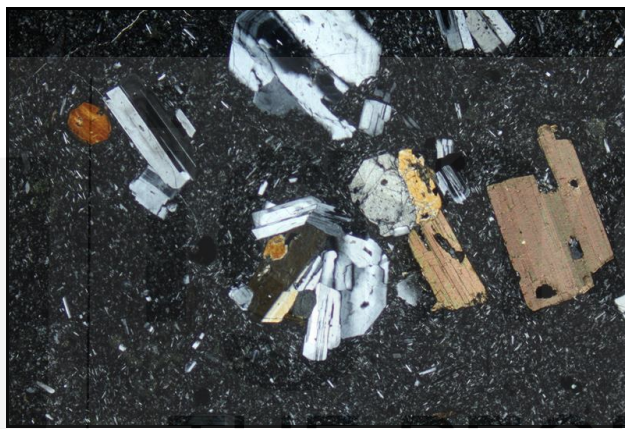


Fig. 14.3: Photomicrograph showing larger crystals of plagioclase, biotite and clinopyroxene clustered and surrounded by fine grained groundmass depicting blasto-porphyritic texture. (Source: www.alexstrekeisen.it)

4. **Blasto-cumulate texture:** Early formed crystals with high density settle down giving rise to cumulate texture. This texture survives metamorphism and is preserved as relict texture in metamorphic rocks.

14.4.2 Typomorphic Texture

These textures are characteristic and are developed in metamorphic rocks either by the dynamic forces or by the effect of thermal action or crystallisation.

A) Textures Based on Dynamic Forces

Textures based on the dynamic forces can be categorised into:

- Porphyroclastic texture
 - Mylonitic texture
- 1) **Porphyroclastic Texture:** Due to deformation in the metamorphic rock, the softer minerals get crushed and form groundmass while the resistant minerals get fragmented and appear to be larger than the surrounding minerals. Two distinct grain size distributions of the same mineral, viz. coarser grained porphyroclasts and finer grained fragments are produced. The larger grain is known as the porphyroclast and resulting texture is called as porphyroclastic texture (Fig. 14.4).

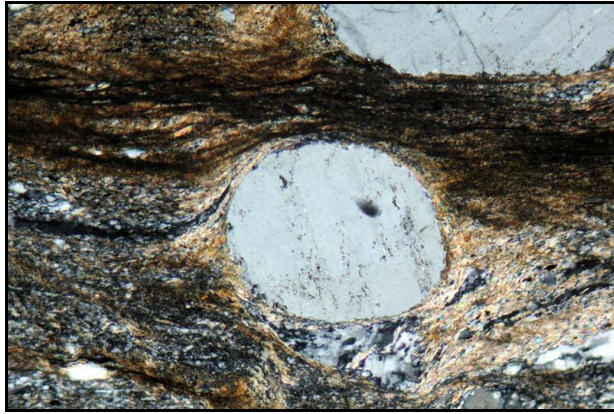


Fig. 14.4: Photomicrograph of porphyroblast grain consisting of quartz (rounded grain) surrounded by softer minerals in groundmass exhibiting porphyroclastic texture under XP. (Field of View = 2mm; Source: www.alexstrekeisen.it)

2) **Mylonitic Texture:** The development of foliation planes or oriented minerals in the metamorphic rocks is such that it forms the platy minerals or quartz (ribbon quartz) to orient in a particular direction (Fig. 14.5). Ductile deformation due to cataclastic metamorphism is thought to be the prime cause for such a textural development in metamorphic rocks. Based on the development of foliation mylonitic texture may categorised as:

- **Protomylonitic:** When development of foliation mylonitic texture is incipient or preserves initiation of mylonitisation;
- **Orthomylonitic:** When the rocks develop a well - defined foliation. Quartz grains get oriented in a ribbon-like fashion;
- **Ultramylonitic:** It is most advanced stage of cataclastic metamorphism and results in the recrystallisation of the highly strained crystals into smaller ones to develop a granoblastic polygonal texture.

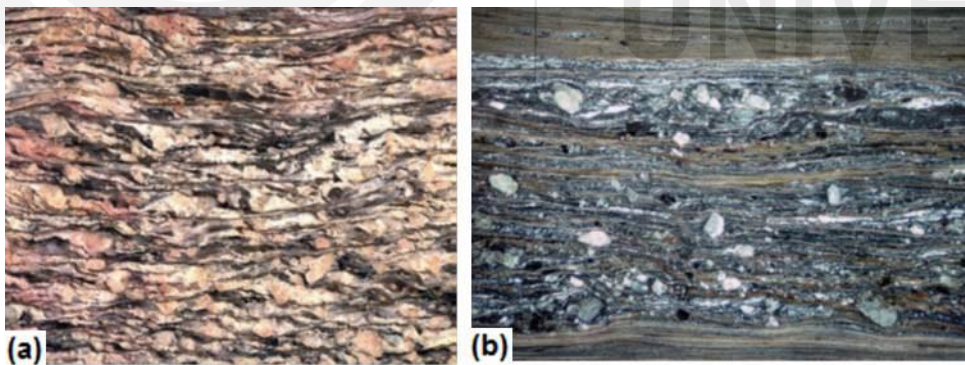


Fig. 14.5: a) Mylonite on an outcrop scale. (Source: www.alexstrekeisen.it); b) Photomicrograph of mylonite between two ultramylonite bands under XP. (Field of view = 5mm; Source: Wiersma et al., 2009)

B) Textures Based on Thermal Effect

We have discussed the typomorphic texture produced due to the dynamic effect. Now we shall discuss typomorphic textures based on thermal effect. When thermal metamorphism is not associated with any deformation, the mineral grains show a randomly oriented texture, unarranged and scrambled giving rise to either granoblastic or hornfelsic textures. However, the

development of granoblastic texture may occur in regionally metamorphosed rocks too. Textures based on thermal effect can be:

- Nodular texture
- Granoblastic texture

1) **Nodular Texture:** When the growth of oval-shaped porphyroblasts of minerals such as cordierite or scapolite takes place in association with randomly distributed quartz and other minerals, then the texture so developed is called as nodular texture in the metamorphic rocks (Fig. 14.6).

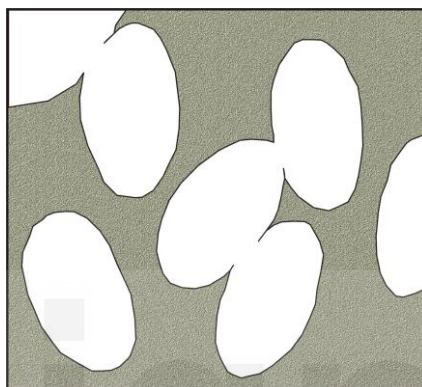


Fig. 14.6: Nodular texture: diagrammatic representation in a thermally metamorphosed rock. (Source: Spry, 1969)

2) **Granoblastic Texture:** This is a characteristic texture developed in a non-foliated metamorphic rock such as marble or quartzite. The grains are equigranular to nearly equigranular and form a welded mosaic of recrystallised mineral grains. The development of porphyroblastic grains is not seen.

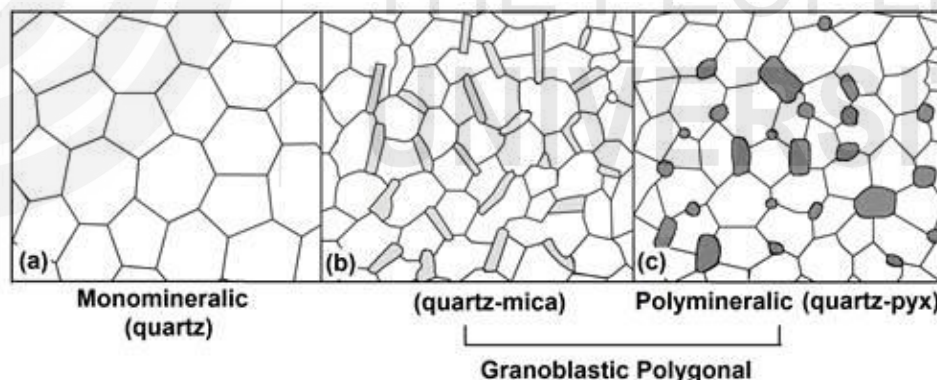


Fig. 14.7: Diagrammatic representation showing different possible polygonal granoblastic textures in a non-foliated metamorphic rock: a) Monomineralic quartz in quartzite; b) and c) Polymineralic quartz-mica and quartz-pyroxene. (Source: Spry, 1969)

The granoblastic texture may vary from equidimensional grains having straight grain boundaries and well-developed crystal faces, as in polygonal granoblastic texture (Fig. 14.7) to irregular grain boundaries (as in interlobate granoblastic texture). There may also be a situation where along with the grain irregularity the minerals are anhedral too (as in amoeboid granoblastic texture). When mineral grains are interlocked, randomly oriented and prismatic or elongated in habit with common triple junctions then such a granoblastic texture is called a **decussate granoblastic texture** (Fig. 14.8).

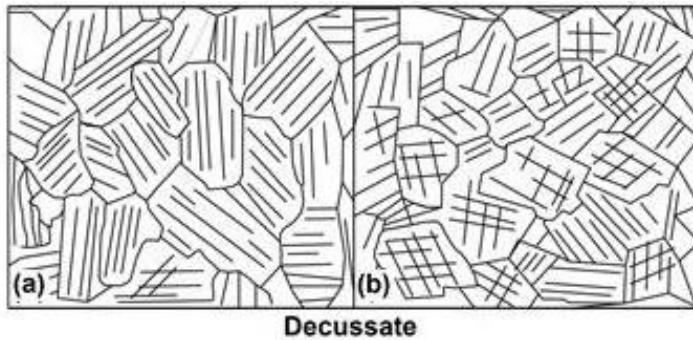


Fig. 14.8: a) and b) Diagrammatic representations show decussate granoblastic texture in non-foliated metamorphic rock. (Source: Spry, 1969)

C) Crystallisation Textures

Apart from textures based on dynamic and thermal effect, crystallisation textures also fall in the typomorphic type of metamorphic textures in which coarse-grained metamorphic textures develop. Some of the crystallisation textures are:

- Porphyroblastic texture
- Poikiloblastic texture

1) **Porphyroblastic texture:** When coarse-grained minerals are seen to occur in a fine-grained ground mass or are surrounded by fine-grained minerals then such a texture is called as **porphyroblastic texture** and the large mineral grain is called a **porphyroblast**. The metamorphic minerals like garnet and staurolite tend to recrystallise and form large, individual crystals while other minerals such as mica and biotite tend to form masses composed of small interlocked grains. Rock will typically contain large crystals of one mineral embedded in a matrix of small crystals of the other, e.g. large garnets are often found embedded in a mass of fine-grained muscovite or biotite (Fig. 14.9). Porphyroblastic texture in metamorphic rocks is quite similar in appearance to the porphyritic texture found in igneous rock.

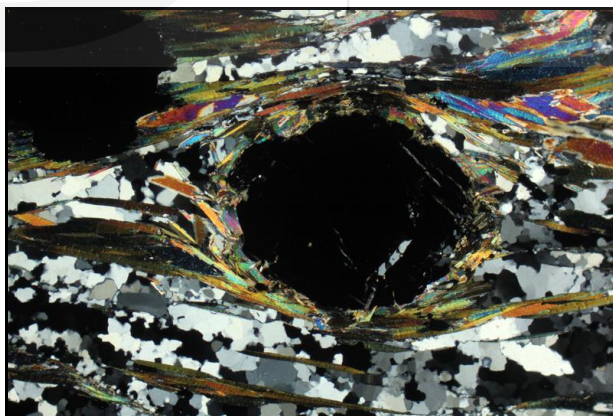


Fig. 14.9: Photomicrograph showing porphyroblastic texture with garnet as a porphyroblast under XP. (Field of view = 2mm; Source: www.alexstrekeisen.it)

2) **Poikiloblastic texture:** This type of texture is marked with the addition of several fine-grained inclusions within the porphyroblast grain. The orientation of the mineral grains occurring as inclusions may be random, helictic or spiral or seem to be rotated (Fig. 14.10).

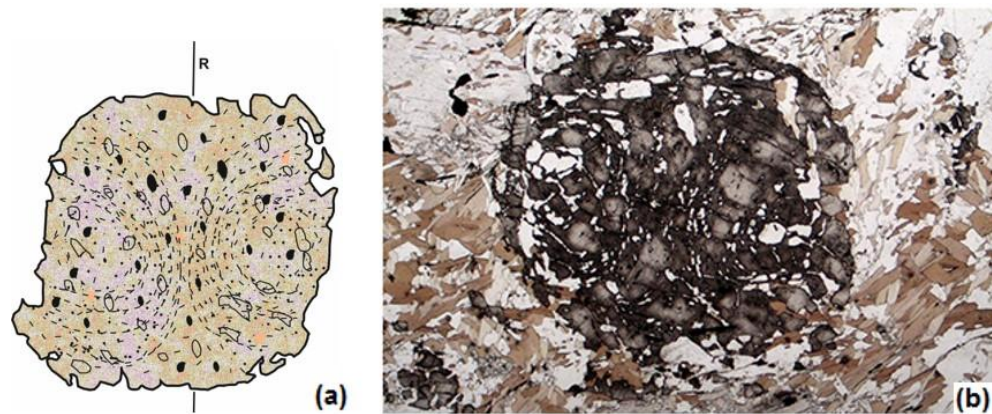


Fig. 14.10: Poikiloblastic texture showing inclusions with helictic orientation within the porphyroblast, 'R' = Rotation axis. (Source: Bard, 1980)

14.4.3 Reaction Texture

You have learnt about palimpsest (relict) and typomorphic textures in the previous sections. Now let us study the reaction texture.

When a new mineral formation takes place either by the replacement of older mineral or by the reaction between two phases or sequential reactions; the formation of new minerals take place in the form of concentric rings around a pre-existing grain. This texture is known as reaction texture. Some of the important reaction textures are:

- Reaction-Rim texture
 - Kelyphitic texture
- 1) **Reaction-Rim texture:** When replacement of an older phase (mineral) takes place along the rim of the mineral then a new mineral is formed. The rim becomes irregular and forms a contact between the two mineral phases indicating some reaction taking place between both the phases (Fig. 14.11).
 - 2) **Kelyphitic texture:** In this texture also, replacement takes place but by the intergrowth of two or more minerals. The resultant texture is such that the new minerals completely encircle the replaced mineral (Fig. 14.12). This type of texture generally develops in retrogressive metamorphic rock. It is also called as a **replacement texture**.

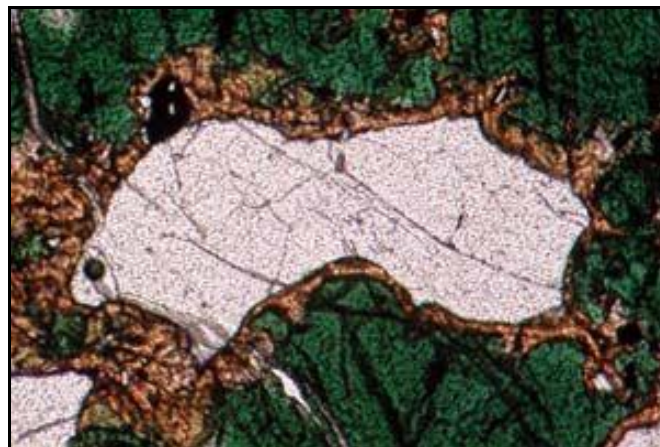


Fig. 14.11: Reaction- Rim of garnet between plagioclase and hornblende. (Source: www.academic.brooklyn.cuny.edu)

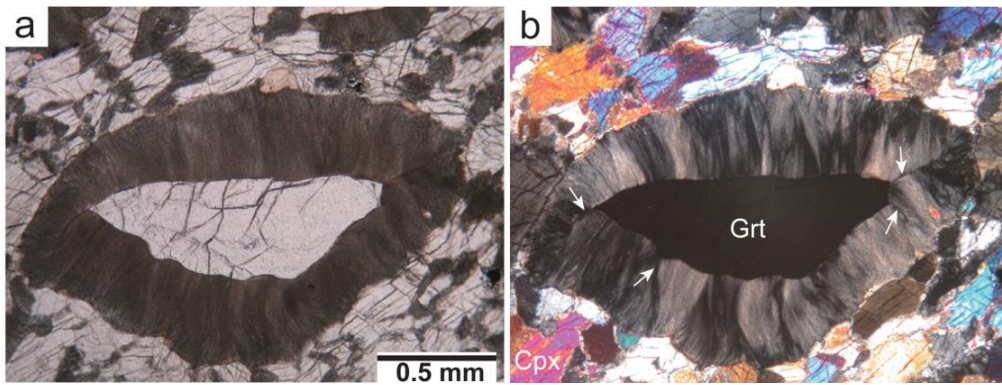


Fig. 14.12: Kelyphitic texture showing garnet-clinopyroxenite; a) PPL; and b) XP.
(Source: Obata, 2007)

14.4.4 Corona Texture

This type of texture may develop in both prograde and retrograde phase of metamorphism. One or more minerals form a complete rim around the older phase present in the centre or core of the texture such that the geometry resembles a corona (Fig. 14.13). The rim layers formed may range from one to five in numbers depending upon the number of reactions that have taken place.

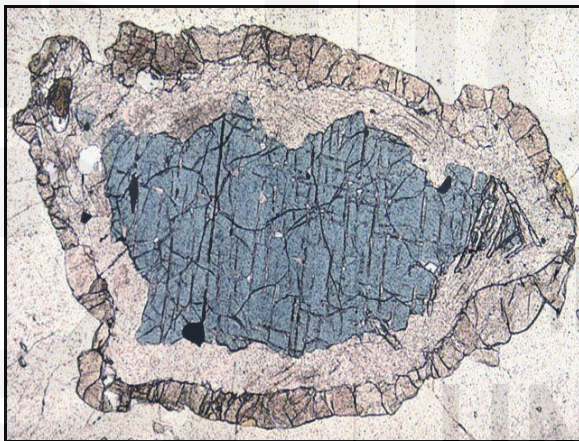


Fig. 14.13: Photomicrograph showing orthopyroxene in the outer rim – sillimanite (middle layer) corona on sapphirine (blue). (Source: Sandiford, 1985)

14.4.5 Intergrowth Texture

Symplectite texture is represented by worm-like appearance of minerals formed along the boundary of the older minerals which are reacting. Fig. 14.14 shows symplectite intergrowth of orthopyroxene– garnet–cordierite. It is also called a reaction textures in which fine-grained mineral intergrow irregularly due to some reaction taking place at the rim of the previously formed mineral.

Myrmekitic texture is one such example wherein vermicular, or wormy quartz intergrows plagioclase (Fig. 14.15). This type of texture is commonly seen in high-temperature metamorphic rocks.

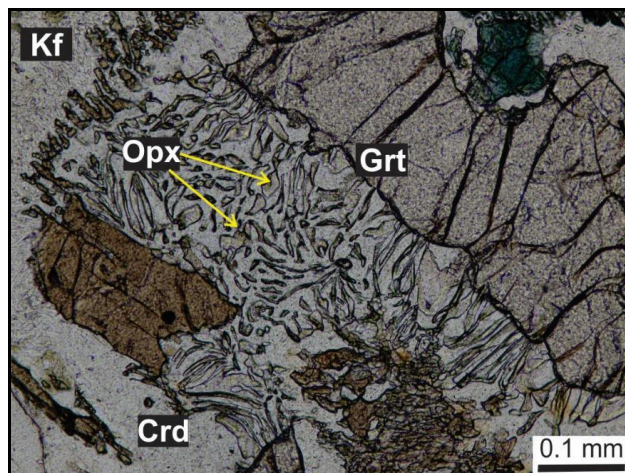


Fig. 14.14: Photomicrograph showing symplectite intergrowth of orthopyroxene (Opx) – garnet (Grt) – cordierite (Crd) under XP. (Source: Prakash et al. 2017)

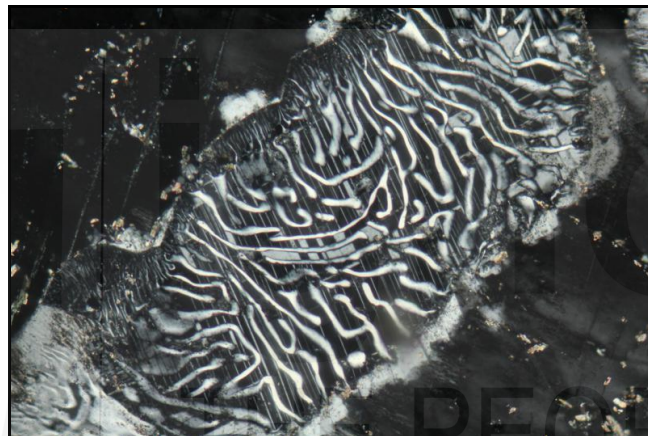


Fig. 14.15: Photomicrograph showing myrmekite texture in plagioclase. Note wormy quartz in plagioclase. (Field of view = 2mm; Source: www.alexstrekeisen.it)

So, you have learnt about the textures found in metamorphic rocks. Before discussing about the structures in metamorphic rocks, please spend few minutes to perform an exercise to check your progress.

SAQ 1

- What is recrystallisation?
- What are the denser polymorphs of quartz?
- What is pressure solution?
- Why is palimpsest texture known as relict texture?
- What is porphyroblastic texture?
- What is kelyphitic texture?

14.5 STRUCTURES IN METAMORPHIC ROCKS

We have discussed the textures found in metamorphic rocks in the above section. Let us now study structures commonly found in the metamorphic rocks. Some of the common structures related to the metamorphic rocks are:

14.5.1 Foliation and Lineation

Foliation indicates a texture displayed by metamorphic rocks in which mineral grains exhibit a preferred, directional orientation. The alignment of platy minerals or alternating layers of light (felsic) and dark (mafic) minerals is seen in foliated metamorphic rocks. The layering within metamorphic rocks is called foliation. It is derived from the Latin word *folia*, meaning "leaves". Penetrative surfaces which are nearly or fully parallel defining the planar fabric elements are called **foliation** and the penetrative sets comprising of parallel or nearly parallel lines forming a linear fabric element are termed **lineation** (Fig. 14.16). The term penetrative structures occur virtually all over the rock body even at the microscopic level. However, structures penetrative in one domain may not be penetrative in other domain/s.

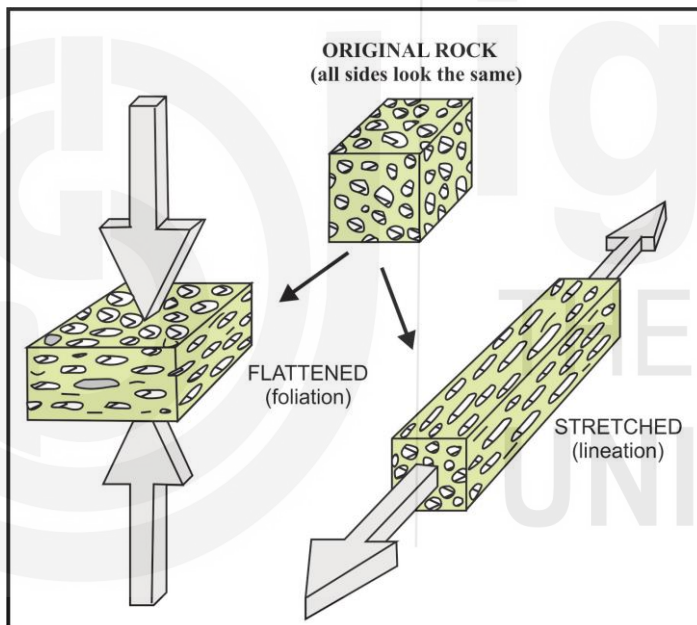


Fig. 14.16: Representation of the processes involved and type of morphology developed in foliation and lineation. (Source: www.usgs.gov)

Foliation is a planar feature whereas lineation is a linear feature. Foliations could be seen on all sides of the rocks as lines and lineations are viewed as circular to irregular specks or dots on at least one surface of the rock. The development of planar and linear features takes place in a plane perpendicular to the maximum principal stress applied on parallelly arranged flaky minerals (mica, chlorite) as evident from the foliations. Cleavage is the tendency of a rock to break along surfaces of a specific orientation. All cleavages are foliations, and the two terms are often used to describe the same structure. Foliation is a more general term than cleavage because it includes planar geometric features that might not result in a cleavage.

Foliations and lineations could be morphologically classified (Twiss and Moore, 2007) as given in Table 14.1 and 14.2. Foliations are distinguished by

differences in preferred orientation of mineral grains in structure or in composition. Foliations defined by a spacing of 10 μm or more are known as spaced foliations. Continuous foliations exhibit finer structure or in other words are closely spaced. **Spaced foliations** are categorised into three categories: compositional, disjunctive, and crenulation foliations. **Compositional foliations** are marked by layers, or laminae, of different mineralogical composition. **Disjunctive foliations** are characterised by thin cleavage domains or seams, marked by concentrations of oxides and/ or strongly aligned platy minerals. **Crenulation foliations** are formed by harmonic wrinkles or chevron folds that develop in a pre-existing foliation. **Continuous foliations** are defined either by domains with spacing less than 10 μm and they are divisible by grain size into **fine** and **coarse** continuous foliations. Slate and schists have fine and coarse continuous foliation respectively. Some of the most common rock types showing foliation are the phyllites, schists and gneisses. Feldspars commonly show lineation and foliation in granites.

Table 14.1: Morphological classification scheme for foliation.

Foliation and Cleavage	Spaced	Compositional
		Disjunctive
		Crenulation
	Continuous	Fine
		Coarse

Lineation may be structural or mineralogical. **Structural lineation** is marked by the selective preference of orientation of linear structures in the rock whereas the **mineral lineation** is formed by alignment of minerals parallelly (Fig. 14.17). The mineral orientation is seen associated either with elongated (amphiboles) mineral grains, acicular (sillimanite) **mineral grains** or elongate **polycrystalline** aggregates. Structural lineation can be categorised as: **discrete** and **constructed**. Discrete lineations are formed by the orientation of discrete objects such as ooids, pebbles and fossils. Constructed lineations are formed from planar features such as intersection of two foliations, crenulation hinge lines, boudin lines, structural slickenlines, and mullions. You have read about this in Block 3 of BGYCT-131 course.

Table 14.2: Morphological classification scheme for lineation.

Lineations	Structural	Discrete
		Constructed
	Mineral	Polycrystalline
		Mineral grain

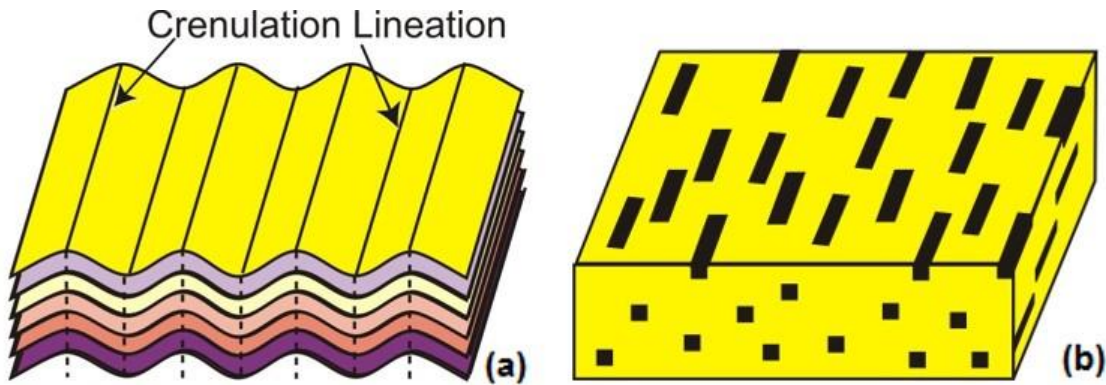


Fig. 14.17: a) Crenulation lineation; and b) Mineral lineation.

14.5.2 Slaty Cleavage

Slaty structure has a strong parallelism in the foliation of fine-grained clay minerals and platy minerals such as micas impart a strong slaty cleavage. Parallel alignment or layering of fine-grained platy minerals (Fig. 14.18) in a certain direction falling perpendicular to the stress maximum gives a plane parallel to bedding called as slaty cleavage. This kind of planar feature develops in fine-grained rocks such as slate and phyllite. Here when the protolith undergoes metamorphism then clay minerals get converted to chlorite. The other platy minerals could be micaceous type. Such a structure (texture) forms under low-grade metamorphic conditions that wane off with increasing grade in metamorphism. The slaty cleavage develops when compression causes clay flakes to reorient and regrow into an orientation perpendicular to the direction of compression. The plane so formed is a foliation plane of weakness along which the rock splits very easily into thin plates or layers (Fig. 14.19). This cleavage allows it to split into thin sheets that make excellent roofing shingles.

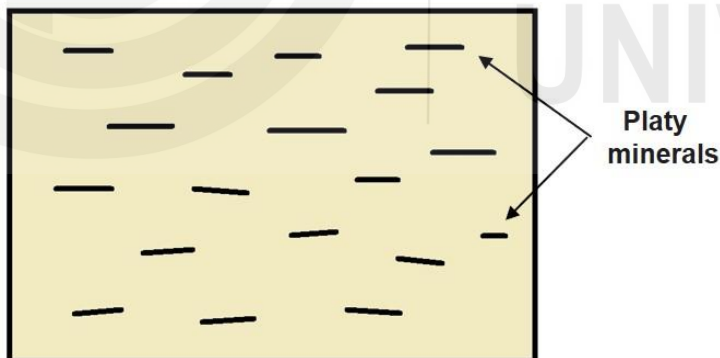


Fig. 14.18: Development of slaty cleavage in a sedimentary protolith. Note the alignment of platy minerals.

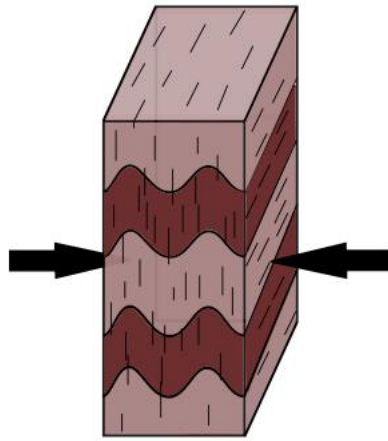


Fig. 14.19: Schematic representation of continuous foliation indicating formation of slaty cleavage.

14.5.3 Schistose Structure /Texture

Schistose structure or schistosity is strongly foliated texture produced by the growth of minerals. Schist has a foliation or mineral alignment of medium to coarse-grained minerals. Schistosity is defined by the preferred orientation of large mica flakes. This texture is found in mica schist, chlorite schist and hornblende schist.

Schistosity is the layering developed due to the parallel arrangement of micaceous minerals or platy minerals developed as the result of metamorphism under directed pressure in low to medium grade coarse-grained metamorphic rocks. Grain size increases and the grains could be easily identified even with the unaided eye (Fig. 14.20). The structure so developed is again a planar feature forming a foliation plane. The mineral content and the grain size in schistosity are different from that in the slaty cleavage. In schistose structure chlorite breaks to form minerals such as feldspar, mica and quartz etc. The newly developed minerals align themselves in such a manner that their longer axis is oriented parallel to the directed maximum stress (Fig. 14.21). The rocks having such a texture are called as **schists**. The other minerals, viz. kyanite, sillimanite, staurolite etc. are also part of the foliation plane. Along the foliation plane, the rock having schistosity is weak and could be cleaved with some difficulty.



Fig. 14.20: Rock cutting polished surface showing schistosity or schistose structure. (Source : https://flexiblelearning.auckland.ac.nz/rocks_minerals/rocks/schist.html)

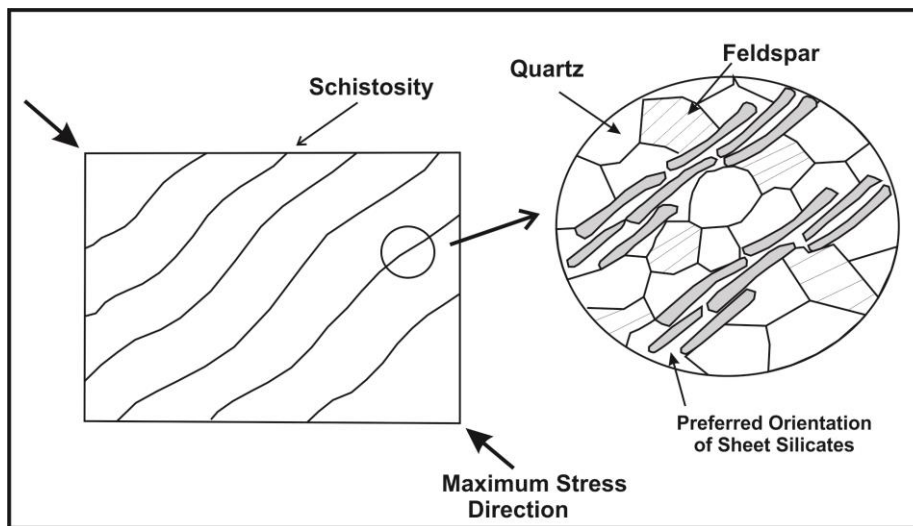


Fig. 14.21: Schistosity development and stress direction forcing minerals to align perpendicular to the latter forming foliation plane.

14.5.4 Gneissose Structure/Texture

Gneissose structure shows discontinuous banding of light-coloured medium to coarse-grained minerals such as quartz and feldspar and dark-coloured minerals such as pyroxene and hornblende with granulose texture. Thus, the light and dark bands of different compositions are arranged alternately. These bands are produced by the segregation of minerals. This compositional layering or gneissic banding gives the gneiss a characteristic striped appearance. The banded structure is formed due to metamorphic differentiation and alteration of schistose rocks when the latter is exposed to very high grade of regional metamorphism. The bands so formed are of two types - the dark bands and the light bands, and the arrangement is such that they appear to alternate (Fig. 14.22). The lighter bands are composed of felsic minerals and the dark bands comprise of mafic minerals (Fig. 14.23). The difference between the aforementioned bands may just not be limited to colour and mineralogy but also in the texture of the bands. Such megascopic display is exclusive of the rocks known as gneiss. The fabric of gneisses is comparably weaker than the schistosity and continues to get weaker with the lessening of mica content in the rock (Fig. 14.24). Once the partial melting starts the process of migmatization commences with eventually the unmelted parts comprising the darker layers and the melted parts comprise the light-coloured layers.



Fig. 14.22: Gneissose banding in hand specimen.

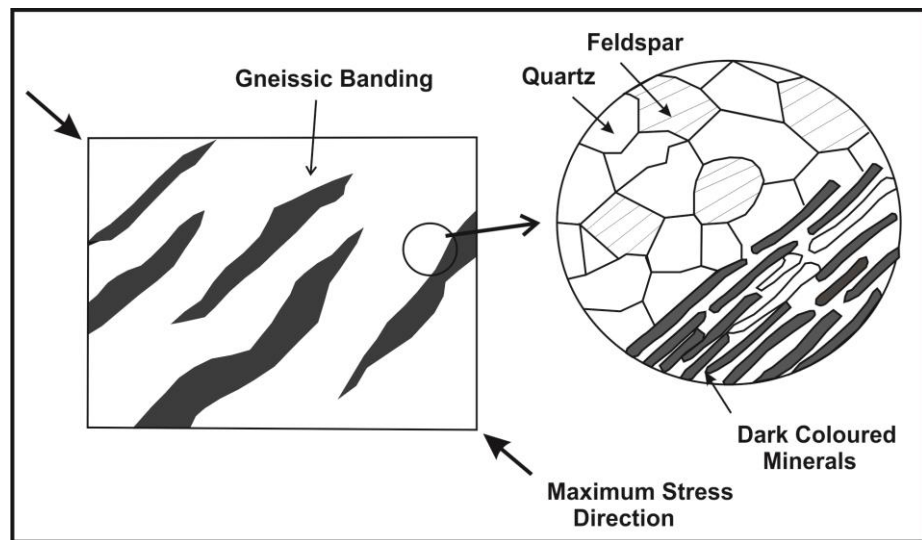


Fig. 14.23: Stress alignment and processes leading to the formation of bands in gneiss. Note that the bands in gneiss are discontinuous.

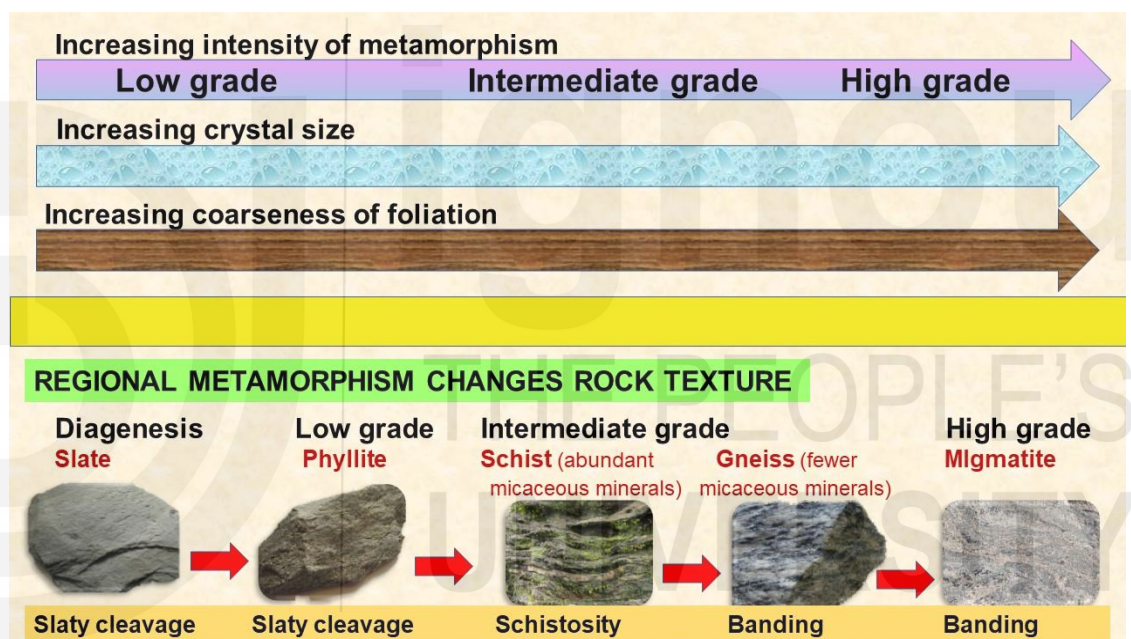


Fig: 14.24: Foliated rocks are classified by metamorphic grade, grain size, type of foliation and banding. As the intensity of metamorphism increases crystal size and coarseness of foliation increases.

14.5.5 Cataclastic Structure

The cataclastic structure is a tectonically developed structure. The stress plays its role in the absence of high temperature and fragments the rock due to intense shearing. They are produced against the directed pressure acting along a fault zone where two rock units after faulting slide past each other. The softer minerals in the rock due to shearing get powdered while the resistant minerals, which overcome the crushing force to some extent, get shattered and crushed forming crushed breccias (Fig. 14.25). The pulverisation of minerals is essentially due to the sliding action but no crystallisation of new minerals occurs. The resultant texture due to such a stand out of minerals finds similarity with the porphyritic texture and is thus called as the **porphyroclastic** or **pseudoporphyrific** structure. When the shear stress is high enough along with

the reasonably raised temperatures the mylonitic structure develops (Fig. 14.26).

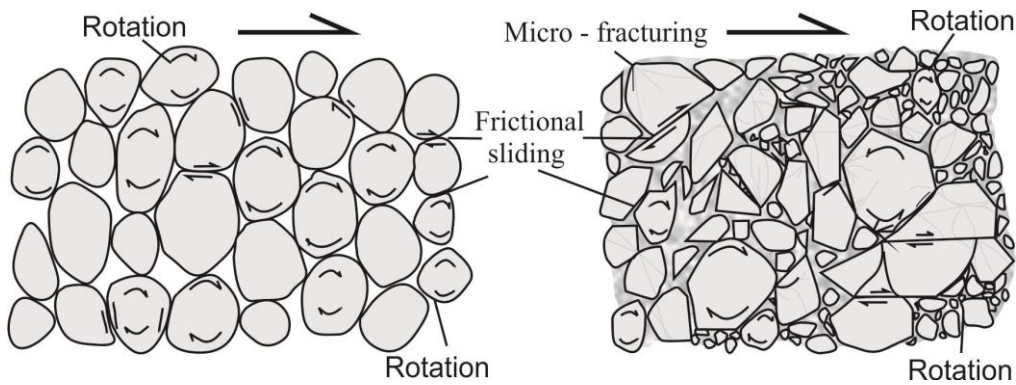


Fig. 14.25: Diagrammatic representation of processes involved in cataclastic metamorphism: a) Granular flow-rock fabric pre-deformation; b) Post-deformed whole rock showing cataclastic structure. (Source: Haakon Fossen, 2010)



Fig. 14.26: Microstructure of a mylonite texture. (Source: Lapworth, 1899)

14.5.7 Pseudotachylite

A dark coloured, very fine-grained rock developed due to devitrification of glass and occurring as veins is called as pseudotachylite (Fig. 14.27). The name has a prefix of pseudo- so as to indicate its resemblance to the basaltic glass (tachylite). The complete devitrification of glass is in response to frictional melting that takes place as a consequence of either seismic faulting (due to rapid movement of fault) or impacting (melt produced due to heat emanation by shock) or during landslides (melt produced due to heating as a consequence of large blocks moving during landslides).



Fig. 14.27: Injection vein of pseudotachylite. (Source: <http://www.lpl.arizona.edu/~rlorenz/pseud.html>)

Pseudotachylites formed in seismic faulting may occur as injected vein type (vein injection in walls) or fault vein type (along the fault surfaces) or they may occur as pseudotachylite breccia (matrix in tectonic breccias). Pseudotachylites are taken as palaeoseismic (earthquake) indicators.

Learners, you have now learnt the details of structures found in the metamorphic rocks. Before going to the next section, please spend a few minutes to perform an exercise to check your progress.

SAQ 2

- What is slaty cleavage?
- Define schistosity.
- Define gneissose structure.
- Mention a cataclastic structure.
- What is pseudotachylite?
- What is mineral lineation?

14.12 SUMMARY

Let us summarise what we have learnt in this unit:

- Structure includes features on large scale or outcrop scale or hand specimen scale or they may be at a regional scale also. On the contrary the term texture is used for features at small scale, i.e. from the microscopic to the hand specimen scale.
- The factors controlling the metamorphic mineral content, textures and structures depend on: (1) composition of the parent rock; (2) temperature; (3) pressure; (4) effects of tectonic forces and chemically active fluids; and (5) time.
- The most common processes responsible for formation of textures are: recrystallisation, phase change, metamorphic reaction or neocrystallisation, pressure solution and plastic deformation.

- Metamorphic textures could be categorised into: (1) palimpsest textures; (2) typomorphic textures; (3) reaction textures; (4) corona texture; and (5) intergrowth textures.
- Palimpsest texture is also known as relict texture because it is the texture which is inherited from the protolith rock textures that is preserved even after the metamorphism.
- Typomorphic textures are developed in metamorphic rocks either by the dynamic forces or by the effect of thermal action or by crystallisation.
- The development of reaction texture takes place either by the replacement of the older mineral or by the reaction between the two phases. Corona texture develops in both the prograde and retrograde phase of metamorphism.
- Foliation is a planar feature whereas lineation is a linear feature. The development of planar and linear features takes place in a plane perpendicular to maximum principal stress applied on parallelly arranged flaky minerals (mica, chlorite).
- The slaty cleavage develops when compression causes clay flakes to reorient and regrow into an orientation perpendicular to the direction of compression.
- Schistosity is the layering developed due to the parallel arrangement of micaceous minerals or platy minerals developed as the result of metamorphism in low to medium grade coarse-grained metamorphic rocks.
- Gneissose structure shows discontinuous banding of light-coloured medium to coarse-grained minerals.
- The cataclastic structure is a tectonically developed structure. Dark coloured, very fine-grained rock developed due to devitrification of glass and occurring as veins within the sheared country rocks are called pseudotachylite.

14.12 ACTIVITY

- Make a list of textures and structures you have studied and draw their sketches.
- Try to look for the structures that you studied in the slabs used in the kitchen and on the floors.

14.13 TERMINAL QUESTIONS

1. Discuss the factors affecting textures in the metamorphic rocks.
2. Describe palimpsest textures present in the metamorphic rocks.
3. Describe typomorphic textures found in the metamorphic rocks.
4. What is foliation and lineation? Discuss their morphological classification.

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14.15 FURTHER/SUGGESTED READINGS

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14.16 ANSWERS

Self Assessment Question

- 1
 - a) Recrystallisation changes the shape and size of grains without changing the identity of the minerals constituting the grains.
 - b) Coesite, stishovite.
 - c) Pressure solution, takes place when a wet rock is squeezed more strongly in one direction producing ions that migrate through the water to precipitate elsewhere.
 - d) Palimpsest texture is also known as relict texture because it is the texture which has survived metamorphism and shows the inheritance of protolith rock textures even after the metamorphism.
 - e) When coarse-grained minerals are seen to occur in a fine-grained ground mass or are surrounded by fine-grained minerals then such a texture is called as porphyroblastic texture and the large mineral grain is called a porphyroblast.
 - f) In this texture also, replacement takes place but by the intergrowth of two or more minerals.
- 2
 - a) Parallel alignment or layering of fine-grained platy minerals (Fig. 14.16) in a certain direction perpendicular to the stress maximum defined by parallel alignment of micas and/or kaolinite is called as slaty cleavage.
 - b) Schistosity is the layering developed due to the parallel arrangement of micaceous minerals or platy minerals developed as the result of metamorphism under directed stresses in low to medium grade coarse-grained metamorphic rocks.
 - c) Gneissose structure shows discontinuous banding of alternating bands of light-coloured medium to coarse-grained minerals such as quartz and feldspar and the bands comprising dark-coloured minerals.
 - d) Porphyroclastic or pseudoporphyratic structure.
 - e) A dark coloured, very fine-grained rock developed due to devitrification of glass and occurring as veins is called as pseudotachylite.
 - f) Mineral lineation is formed by parallel alignment of minerals.

Terminal Questions

1. Please refer to section 14.1.
2. Please refer to subsection 14.4.1.
3. Please refer to subsection 14.4.2.
4. Please refer to subsection 14.5.1, Tables 14.1 and 14.2.



CLASSIFICATION OF METAMORPHIC ROCKS

Structure

- | | |
|--|---------------------------------|
| 15.1 Introduction | 15.3 Common Metamorphic Rocks |
| Expected Learning Outcomes | Slate |
| 15.2 Classification of Metamorphic Rocks | Phyllite |
| Parent Rock | Schist |
| Structure and Texture | Gneiss |
| Mineralogical Composition | Marble |
| Types of Metamorphism | Quartzite |
| Grade of Metamorphism | 15.4 Summary |
| | 15.5 Terminal Questions |
| | 15.6 References |
| | 15.7 Further/Suggested Readings |
| | 15.8 Answers |

15.1 INTRODUCTION

You have learnt about factors, processes and products of metamorphism in Unit 12; types, grades, zones and facies of metamorphism in Unit 13; textures and structures of metamorphic rocks in Unit 14. Now in this unit we shall discuss the classification of metamorphic rocks. Metamorphic rocks can be classified on the basis of texture, structure, parent rock, grade and mineralogical composition or most importantly facies.

Expected Learning Outcomes

After reading this unit you should be able to:

- ❖ list the basis of classification of metamorphic rocks;
- ❖ discuss the classification of metamorphic rock based on parent rock, structure and texture, mineralogical composition, types and grade of metamorphism;
- ❖ differentiate between the foliated and non-foliated metamorphic rocks;
- ❖ describe the megascopic and petrographic characters of foliated rocks such as slate, phyllite, schist and gneiss; and
- ❖ explain the megascopic and petrographic characters of non-foliated rocks such as marble and quartzite.

15.2 CLASSIFICATION OF METAMORPHIC ROCKS

Metamorphic rocks can be classified on the basis of parent rock, texture, structure, mineralogical composition, metamorphic processes, grade and facies. Classification of metamorphic rocks have been summarised in Table 15.1.

15.2.1 Parent Rock

In the previous units the importance of temperature and pressure in determining the mineral assemblage in the metamorphic rocks has been emphasised. Try to recall!

In Unit 12 you have read that the composition of parent rock also plays an important role in determining the minerals formed during metamorphism. For example, it is not possible to form quartzite (composition silica oxide) from pure limestone (composition calcite). The metamorphic rocks can be classified on the basis of diverse origin of parent rock, viz. igneous, sedimentary or metamorphic.

- **Metamorphic rock of sedimentary origin:** These are the rocks metamorphosed from rocks of sedimentary origin and are also known as **parametamorphic** or **metasedimentary rocks**. For example, pelitic shale is metamorphosed to form slate; psammatic sandstone to quartzite; calcareous limestone to marble. Pelite is a term applied to metamorphic rocks derived from a fine-grained (<1/16 mm) largely clay bearing sedimentary protolith or parent rock. Psammite is a term applied to metamorphic rocks derived from an arenaceous (quartz-dominated) sedimentary protolith.
- **Metamorphic rock of igneous origin:** They are the rocks metamorphosed from rocks of igneous origin and are also known as orthometamorphic or metaigneous rocks. The parent igneous rock can be basic or acidic in nature. For example, dolerite, a basic igneous rock undergoes metamorphism to form amphibolite. Let us consider example of granite. It is acidic igneous rock that undergoes metamorphism to form granite gneiss.

- **Metamorphic rock of metamorphic origin:** The metamorphic rocks can also originate from a pre-existing metamorphic rock.

15.2.2 Structure and Texture

You have read in Unit 14 that metamorphic textures are studied under two categories based on the presence or absence of foliations viz. foliated and non-foliated. The term foliation refers to the texture caused by the parallel alignment of mineral grains. In textural classification, the rocks are classified on the basis of their physical appearance in hand specimen or outcrop, i.e. rocks may display slaty cleavage, schistosity or gneissosity. Therefore, the rock names slate, schist or gneiss are widely used. Rocks constituted of very sheet-like, tabular mineral grains that split into thin and even slabs are said to display slaty cleavage or foliation. The rocks which contain mineral grains that are large enough to be recognised in hand specimen, are well foliated and cleave into thin flakes are characterise schistose rocks. The large mineral grains in schistose rocks are called **porphyroblasts**. Gneissic rocks are generally coarse-grained that comprise alternating light and dark coloured bands of minerals arranged parallel to each other and may also show lenticular texture. Non-foliated rocks do not display foliation, and their massive and granular appearance resembles sedimentary rocks. Metamorphic rocks in which there is no visible orientation of mineral crystals have a non-foliated texture. For example, marble and quartzite are massive, medium to coarse grained and display granular texture with minerals visible to unaided eye.

We have discussed commonly found structures in metamorphic rocks in Unit 14. The metamorphic rocks have been classified on the basis of structures as follows:

- The phyllitic structure is characteristic of phyllite.
- The slaty structure is distinctive of slate.
- Schistose structure characterises schist displaying a preferred alignment of platy minerals, for example in mica schist, chlorite schist and hornblende schist.
- Gneissose structure is exclusively shown by the banded metamorphic rocks like gneisses, e.g. granitic gneiss.
- Granulose texture is characteristic of massive metamorphic rocks that exhibit welded interlocking mosaic of crystals, e.g. quartzite and marble.
- Migmatitic texture is observed in the metamorphic rocks like migmatite that displays alternating light and dark coloured bands, e.g., migmatite.

15.2.3 Mineralogical Composition

The metamorphic rocks can also be classified on the basis of mineralogical composition or facies. You have read about facies in Unit 13. Each facies comprise of a stable mineral assemblage depending on the combination of temperature, pressure and original composition. This classification depends on the ability of identifying critical or index minerals in a rock using microscope or other laboratory methods. The name of the rock is modified by the name of an index mineral placed as a prefix to the group name, e.g. garnet schist. The

name of the index mineral indicates specific conditions of metamorphism and metamorphic rocks are classified according to mineral composition.

15.2.4 Types of Metamorphism

The metamorphic rocks can be classified on the basis of the types of metamorphism. You have learnt about types of metamorphism in Unit 13 in detail. Types of metamorphism have been categorised into the regional extent and local extent. The types of metamorphism such as regional (orogenic), ocean-floor, burial, subduction and collision metamorphism fall under regional extent. Whereas contact (igneous), cataclastic, hydrothermal, impact (shock), lightening and combustion metamorphism are of local extent.

Table 15.1: Summary of classification of metamorphic rocks with different protoliths and their resultant metamorphic rocks and related textures.

Parent Rock	Texture	Rock Name	Type	Grade	Remarks
Mudstone	foliated	slate	regional	lower	Breaks into plates, slaty cleavage
Mudstone	foliated	phyllite	regional	moderate	More shiny and crenulated than slate
Mudstone	foliated	schist	regional	moderately high	Different schists recognised on the basis of mineral content
Mudstone	foliated	gneiss	regional	high	Well-developed light and dark colour banding
Granite	foliated	gneiss	regional	high	Well-developed light and dark colour banding
Quartz sandstone	non-foliated	quartzite	contact	low-high	Sugary texture composed of interlocking quartz grains, relatively hard, won't fizz with acid
Limestone	non-foliated	marble	contact	low-high	Sugary texture composed of interlocking calcite grains, relatively hard, fizzes with acid
Basalt	non-foliated	metabasalt	contact	low	Greenish colour due to chlorite

15.2.5 Grades of Metamorphism

Grade of metamorphism is also used in classifying metamorphic rocks. You have learnt about grades in Unit 13 in detail. Grade of metamorphism has been categorized into low- and high grade. Low-grade metamorphism takes place at temperatures between about 200°C to 320°C, and relatively low pressure. Whereas, the high-grade metamorphism takes place at temperatures higher

than 320°C and relatively high pressure. As grade of metamorphism increases, hydrous minerals become less hydrous, by losing H₂O and non-hydrous minerals become more common.

There also exists agreement in naming a rock, for example, if a rock is monomineralic, it may be named after the dominant mineral such as- quartzite dominated by quartz. But most rocks contain 3 or more minerals, in that case the minerals are listed (with a hyphen between them) and placed in order of increasing modal amount before the group name, e.g. garnet-chlorite-hornblende schist, hornblende being in the maximum amount and garnet being the minimum. Some geologists also use the prefixes such as para- or ortho- which are used respectively for sedimentary and igneous protoliths (parent rock), for e.g. - para-gneiss and ortho-gneiss. If the original protolith is still recognizable the prefix meta- is added to the name of the rock, e.g. metabasalt, metagranite, etc.

Learners you have learned about the different classification schemes of metamorphic rocks in this section. Before discussing about the common metamorphic rocks, let us spend few minutes to perform an exercise to check your progress.

SAQ 1

- What is granulose texture?
- List the types of metamorphism of regional extent.
- Quartz sandstone is metamorphosed to _____.
- Limestone is metamorphosed to _____.
- High grade metamorphism takes place at temperatures greater than _____.

15.3 COMMON METAMORPHIC ROCKS

In this section the megascopic and microscopic characters of common metamorphic rocks will be discussed. This will also help you in identification of metamorphic rocks in hand specimen and under the microscope. On the basis of structure and mineralogy, the metamorphic rocks can be divided into foliated and non-foliated rocks.

- Foliated Metamorphic Rocks** have suffered a good amount of directed pressure during their genesis. The development of foliation surfaces or foliation planes takes place due to the pressure. The development of foliation planes takes place as the result of alignment of platy minerals. This eventually leads to the formation of weak planes and the rock becomes easily cleavable along these foliation surfaces. The sequence of foliated metamorphic rocks in accordance with their grade is: slate, phyllite, and gneiss.
- Non-Foliated Metamorphic Rocks** do not suffer any shear stress due to their formation near the surface. The development of foliation planes or surfaces does not take place in non-foliated rocks. Marble and quartzite are the types of metamorphic rocks which suffer a high stress but still don't

develop foliated texture because of the absence of flaky/platy minerals in the rock. The absence of foliation surfaces and schistosity in the rock makes the rock hard and compact.

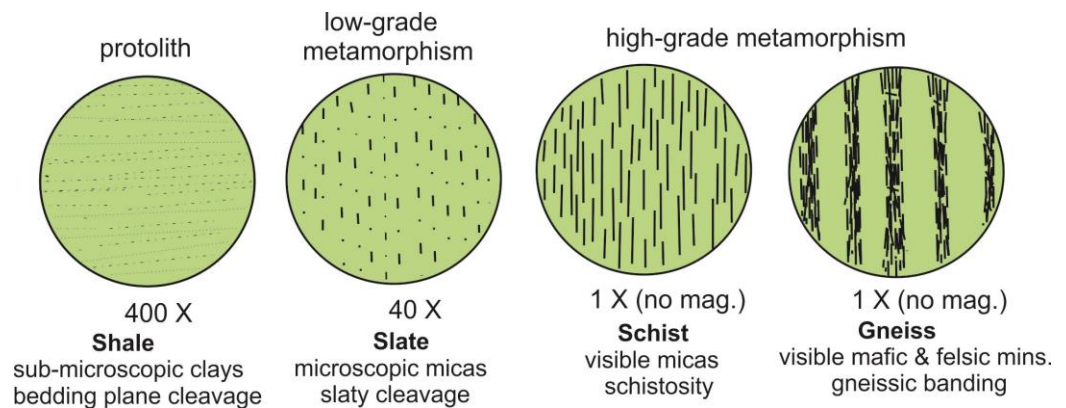


Fig. 15.1: Development of foliation planes with increase in grade in metamorphism resulting in different types of foliated metamorphic rocks.

Now we will discuss megascopic and petrographic characters of foliated rocks such as slate, phyllite, schist and gneiss.

15.3.1 Slate

Slate generally displays close resemblance to shale. Slate is a fine-grained foliated metamorphic rock formed by low-grade regional metamorphism of shale or mudstone. Aluminum rich minerals in shale are metamorphosed to micaceous minerals in slate. The parallel alignment of these flaky/ platy minerals gives rise to foliation in slate which causes the slate to break along these foliation planes easily. Slate exhibits slaty cleavage or excellent rock cleavage, i.e. tendency to break into thin and flat slabs or sheets (Fig. 15.2).

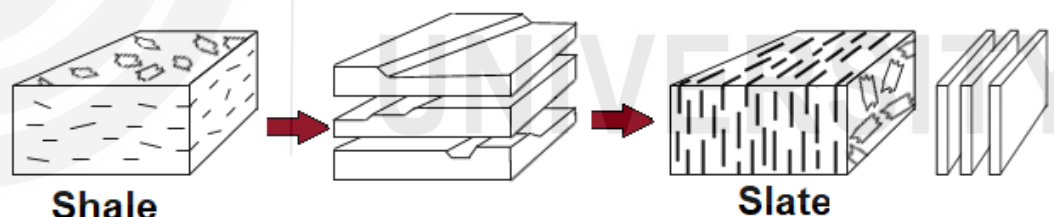


Fig. 15.2: Metamorphism of shale protolith to slate and evolution of shale fissility to foliation in slate.

- a) **Megascopic characters:** In hand specimen foliation can be seen at the millimeter scale with fine grains and variable colours with shades of black, grey (Fig. 15.4a) and green etc. While in thin section the textural association could be identified with new mica growing in a direction perpendicular to the direction of stress. Slate is most often formed by the low-grade metamorphism of shale, mudstone, or siltstone. Slate's colour depends on its mineral constituents. Often black (carbonaceous/graphitic) slate contains organic material; red slate gets its colour from iron oxide; and green slate usually contains chlorite. The original shale bedding (relict bedding) is sometimes preserved as colour contrasts in a slate. In most cases the slate's fracture cleavage lies at some angle to the original bedding plane. Slate displays perfect slaty cleavage with smooth surface and breaks easily along the planes parallel to the sheet silicates, causing a slaty cleavage. Essential

minerals are biotite, chlorite, muscovite and accessory minerals are apatite, graphite, magnetite, tourmaline or zircon.

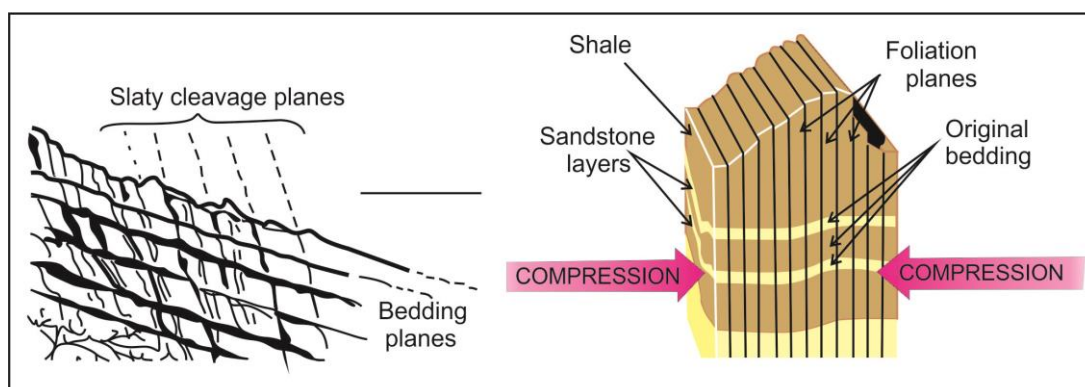


Fig. 15.3: Relation between foliation and bedding plane.

- b) **Petrographic characters:** At microscopic level the fine texture of the rock doesn't let the identification of micas easy (Fig. 15.4b). Texturally, slate is very fine-grained, well foliated with parallel foliation or layering of fine-grained platy minerals such as chlorite. Crenulation cleavage may be present. The slate is formed due to metamorphism of mudstone/ siltstone / shale.

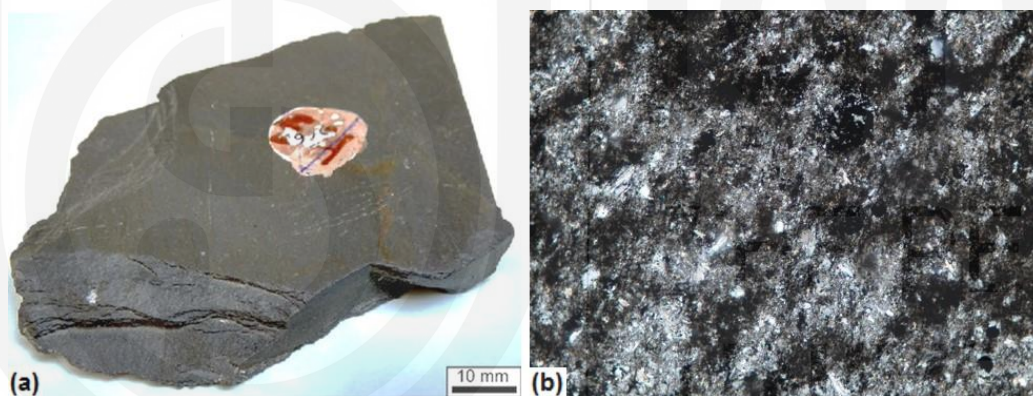


Fig. 15.4: a) Hand specimen of slate; and b) Photomicrograph of indiscernible mica crystals in slate (XP image, 10x).

15.3.2 Phyllite

You have read about the slate. Now let us read about the phyllite.

Phyllite is a fine-grained foliated metamorphic rock formed by the metamorphism of slate. The foliation is caused by preferred orientation of very fine-grained mica. It represents a gradation in the degree of metamorphism between slate and schist. Its constituent platy minerals are larger than those in slate but not yet large enough to be readily identifiable with the unaided eye. Although phyllite appears similar to a slate, it can be easily distinguished from slate by its glossy lustre and its wavy surface. Phyllite usually exhibits rock cleavage and is composed mainly of very fine crystals of either muscovite or chlorite, or both.

The condition of formation of phyllite requires the P-T conditions similar to the low-grade metamorphism of regional type. Phyllite is characterised by silky sheen due to the presence of fine-grained mica minerals that is called the

phyllitic luster commonly observed at the cleavage surfaces. The fissile property of the protolith doesn't fade off and is retained in phyllite.

- a) **Megascopic characters:** In hand specimen phyllite resembles slate since it is fine grained, hard with foliations of millimeter scale (Fig. 15.5a). Phyllite displays less compaction with tints of grey and phyllitic lustre. Phyllite is variable in colour with shades of grey with sheen. It is fine to medium grained, hard but less compact. Phyllite is foliated on mm scale with well-developed foliations. Surface of the phyllite is typically lustrous and sometimes wrinkled. Presence of mica (biotite and muscovite) flakes give rise to a satin luster to phyllite and it displays phyllitic structure. Essential minerals are muscovite, biotite, quartz and plagioclase. Sericitic mica, graphite and chlorite are accessory phases. Phyllite is a low grade (higher than the slate) metamorphic rock. Shale or mudstone is protoliths of phyllite.
- b) **Petrographic characters:** The textural characters of phyllite are similar to the slate but the most perceptive character is the prominence of foliation planes due to mica growth (Fig. 15.5b). Phyllite is fine to medium grained (0.1-1.00 mm particle size), foliated (mm scale) and quite commonly wrinkled or wavy. The foliations are well-developed. Flaky minerals are aligned perpendicular to c axis giving rise to lineation. Essential mineral are muscovite, biotite, quartz and plagioclase. Accessory minerals are sericitic mica, graphite and chlorite.

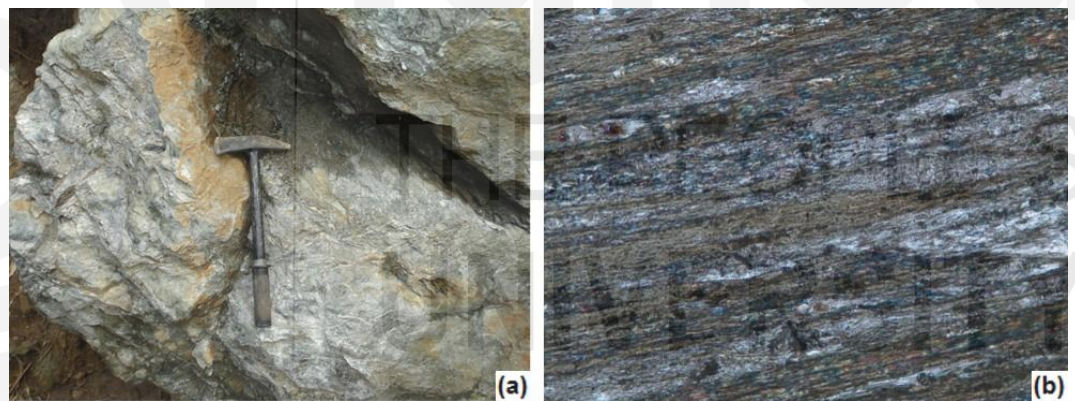


Fig. 15.5: a) Silvery phyllite with phyllitic shine due to the presence of white mica; and b) Discernible mica crystals in Phyllite under XP, (magnification 10x).

15.3.3 Schist

Schist is a strongly foliated medium grained metamorphic rock in general. It is formed on the continental side of a convergent plate boundary by the metamorphism of rocks at higher metamorphic grade than slate. Schist is a medium to coarse-grained metamorphic rock possessing foliation known as schistosity. Schist is composed of flaky/platy mineral grains that are large enough to be discerned with naked eye. The alignment of these flaky/platy minerals leads to the formation of foliation surfaces. The foliation surfaces so formed are quite distinct and coarse due to higher degree of crystallisation in micaceous minerals. Apart from describing texture, the term schist describes rocks having a wide variety of chemical compositions. In order to indicate the variation in composition, mineral names are prefixed to the rock name 'schist'.

For example, schists composed primarily of muscovite and biotite is called mica schist. Many metamorphic rocks comprise some common accessory minerals like garnet and staurolite which occur as porphyroblasts. In that case the rock is called garnet-mica schist, hornblende-schist, and staurolite-mica schist depending on the dominance of minerals occurring as porphyroblasts.

- a) **Megascopic characters:** Hand specimen identification could be done with the help of prominent schistosity planes which range from millimeter to centimeter scale. The rock has suffered high directional stress and has thus become hard and compact and the growth of mineral grains make it somewhat coarse-grained rock (Fig. 15.6a). Schist is fine to medium grained and often crystals can be seen by unaided eyes. Quartz and feldspar grains show no preferred orientation. Schist is smooth and rough in touch. The flaky minerals in schist form roughly parallel layers. The rock breaks easily when hammered due to the presence of mica. It displays schistose structure. Essential minerals are mica, quartz, and plagioclase. Quartz, feldspars, kyanite, chlorite, garnet, staurolite and sillimanite may be present as accessory minerals. Schist is intermediate/medium metamorphic grade between phyllite and gneiss.
- b) **Petrographic characters:** Microscopically the schist can be identified by the continuous foliation planes and coarse texture (Fig. 15.6b). The foliation is in the form of banding in which flakes of micaceous minerals could be seen oriented in a particular direction. Parallel orientation of mica flakes give rise to schistose structure. Essential minerals are muscovite, quartz and plagioclase. Porphyroblasts of garnet are common. Quartz, feldspars, kyanite, chlorite, garnet, staurolite and sillimanite are accessory minerals.

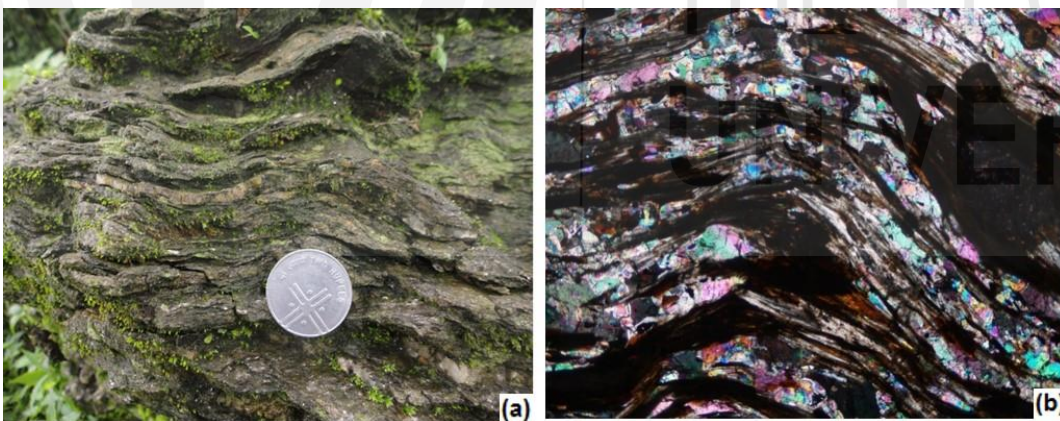


Fig.15.6: a) Biotite Schist showing folded schistosity; and b) Schistose bandings showing fold in schist (XPL image, 2x).

15.3.4 Gneiss

Gneiss is a compositionally layered metamorphic rock; typically composed of alternating dark-coloured and light-coloured layers with variable thickness. Gneiss is a medium to coarse grained rock that shows much similarity with schist rocks as they both show light and dark coloured bands of felsic and mafic minerals respectively. Most of the gneisses are felsic in composition and are derived from high grade metamorphism of granite or often from shale. During high-grade metamorphism the light and dark components separate, giving

gneisses their characteristic banded or layered appearance. Gneisses can also comprise primarily of dark minerals. For example, an amphibole-rich rock that exhibits a gneissic texture is called amphibolite. Gneiss is formed by regional metamorphism from a variety of protoliths. These banded gneisses often exhibit evidence of deformation, including folds and sometimes faults.

- a) **Megascopic characters:** Gneisses are metamorphic rocks in which granular and elongated (as opposed to flaky/platy) minerals predominate. It is characterised by alternate light and dark coloured bands comprising minerals of respective colours which is responsible for the compositional and/or structural variation. The banding is not continuous unlike schist. Foliation is distinct but the rock does not cleave along the foliation planes like slate and schist. Colour is variable with alternate dark and light bands. Gneiss exhibits gneissose structure. Quartz, feldspars, mica and amphiboles with alternate light and dark coloured bands give rise to the gneissic bands in the rock. Light and dark bands of felsic (such as feldspar and quartz) and mafic minerals (biotite, pyroxene, amphibole, garnet etc) characterise gneiss.
- b) **Petrographic characters:** In thin section petrography of the gneiss is differentiated from the schist by the foliated bands which are discontinuous and wane off in gneisses. This is due to the inactivity of slip planes with increase of temperature. Also, the grains are relatively bigger in size than schist due to static recrystallisation. Quartz, feldspars, mica and amphibole grains alternate as light and dark coloured bands giving the rock a gneissic banding. Light band comprise felsic minerals such as feldspar and quartz while the dark bands comprise mafic minerals such as biotite, pyroxene, and amphibole.

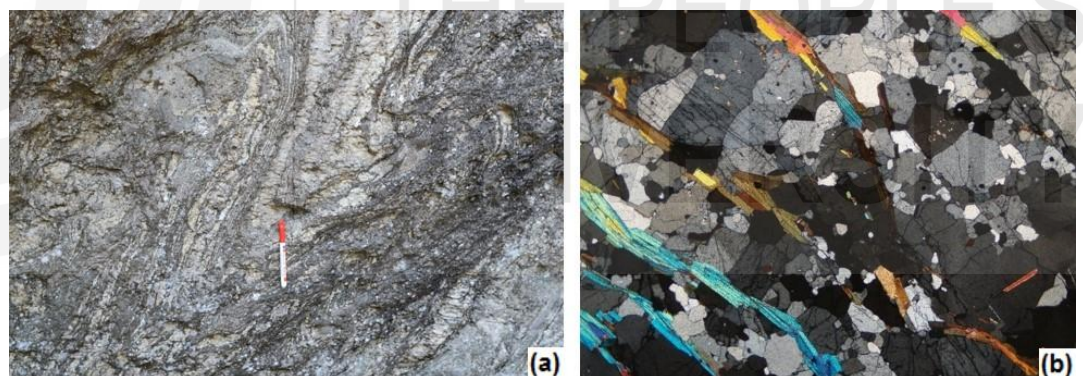


Fig. 15.7: a) Folded gneiss; and b) Coarse grains with discontinuous foliation bandings in gneiss (XPL image, 2x).

15.3.5 Marble

Marble is a non-foliated, high temperature and pressure, thermal and regionally metamorphosed rock generally formed by metamorphism of limestone or dolostone. Marble comprising dolomite (18 mole% of Mg + limestone) is called a dolomarmarble. Pure marble is white and composed essentially of the mineral calcite. During the formation of marble, calcite comprising the protolith recrystallises so the fossil shells, pore spaces and distinction between grains and cement disappears. On metamorphism the calcite crystals are reconstituted in a denser and equigranular form of calcite crystals (Fig. 15.8) rendering the rock compact even though the calcite has a hardness of only 3 on

the Moh's hardness scale. Marble usually forms in convergent tectonic setting or due to the heating of limestone or dolomite by the ascending magma. Unlike quartzite, marble could be scratched with a metal blade. Marble is easy to cut and shape because of its low hardness. White marble is particularly prized as a stone from which monuments and statues are made developed, such as the Taj Mahal in India. Unfortunately, marble's composition of calcium carbonate causes it to weather when exposed to acid rain. Marble formed from limestone interbedded with shale appears banded and exhibits visible foliation. On their deformation, these banded marbles develop highly contorted mica-rich folds that give the rock a rather artistic design. These decorative marbles have been used as a building stone ever since human civilisation.

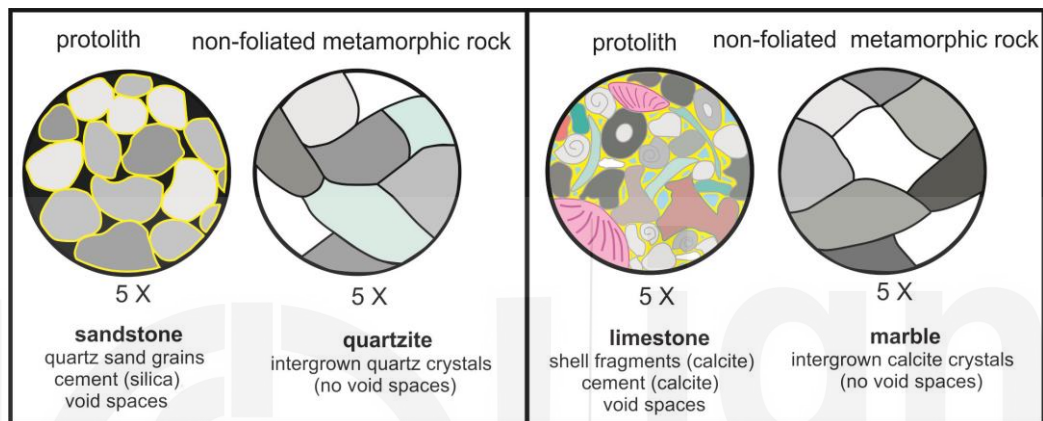


Fig. 15.8: Protolith and grain differentiation between quartzite and marble.

(Source: <https://bostoncollege.instructure.com/courses/1325378/pages/v11b-metamorphic-rocks>)

- a) **Megascopic characters:** Marble is medium to coarse grained, crystalline, equigranular, hard and compact. Marble displays granular and saccharoidal (sugary) texture. It typically consists of fairly uniform mass of interlocking calcite crystals. The marble can be of pink, grey, green, or even black colour which is due to the impurities inherited from parent rock or protolith. Pure marble is white, whereas, marble with traces of iron is reddish or pink. As primarily the marble is composed of calcium carbonate it reacts with dilute acid.

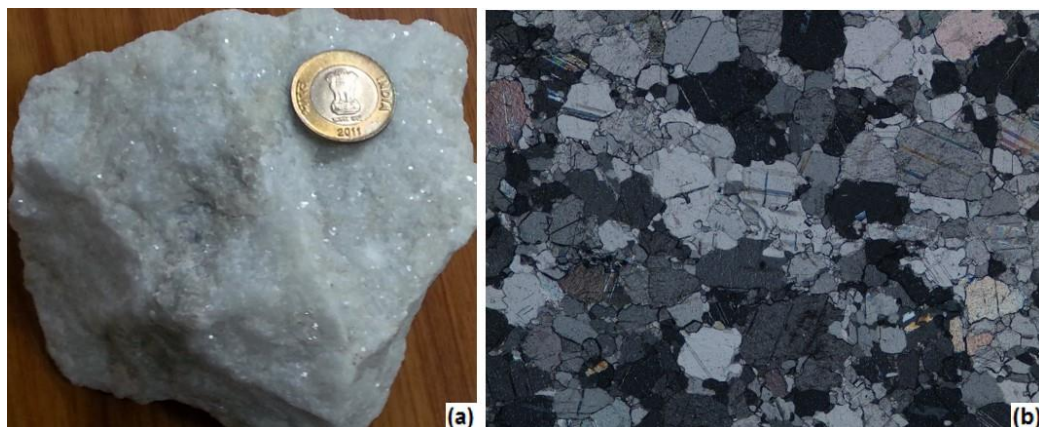


Fig. 15.9: a) Hand specimen of Marble; and b) Coarse grains with sugary texture in marble (XPL image, 4x).

- b) **Petrographic characters:** Marble is medium to coarse grained and displays crystalline, granular and sugary texture with interlocking grains. Three sets of calcitic rhombohedral cleavage are present in marble at microscopic level. This cleavage pattern becomes more prominent when there is presence of dolomite in marble. Though, marble is very much confused with quartzite still mineralogical composition and compactness of marble makes the distinction easy. Its mineral composition is dominantly calcite or dolomite. Clay minerals, micas, quartz, pyrite, iron oxide, and graphite may also be present.

15.3.6 Quartzite

Quartzite is a non-foliated hard metamorphic rock. It is formed by the metamorphism of pure quartz sandstone. Alteration of quartz rich (>90% quartz) sandstone takes place due to the pressure, heat and chemical activity during the metamorphism. During metamorphism, the pre-existing quartz grains recrystallise, giving rise to the new larger grains. Under moderate- to high-grade metamorphism, the quartz grains in sandstone fuse together and make the rock denser, equigranular and hard. In the process, the distinction between cement and grains as also open pore spaces disappear and grains become interlocking. The recrystallisation is often so complete that when broken, quartzite will split through or across the quartz grains rather than along their curved boundaries. It is formed along the convergent plate boundaries and along the orogens. Quartzite is a common metamorphic rock as its protolith sandstone too is common.

- a) **Megascopic characters:** Pure quartzite is white, but iron oxide may produce reddish or pinkish stains due to presence of ferrous mineral. It is sometimes green also (fuchsite quartzite). Quartzite looks glassier than sandstone and does not have the grainy, sandpaper like surface characteristics of sandstone. It is medium grained, equigranular comprising interlocking grains of quartz giving a sugary appearance. It is hard and compact and shows granulose texture and structure. Unlike marble, quartzite cannot be scratched with a metal blade due to the predominance of quartz which gives the rock hardness corresponding to 7 on Moh's hardness scale. Quartzite is dominantly composed of quartz but some mineral impurities such as hematite may be present. Minerals like micas, feldspars, garnets and some amphiboles may also be present.



Fig. 15.10: Quartzite samples from IGNOU Headquarters: a) Quartzose quartzite; and b) Ferruginous quartzite.

- b) **Petrographic characters:** Quartzite in thin section is medium grained, equigranular, with interlocking grains of quartz with appreciable compactness. It shows granular, sugary texture. Apart from quartz other minerals if present are considered to be impurities (hematite etc.). Other mineral like hematite, mica, feldspar, garnet and some amphibole may be present.

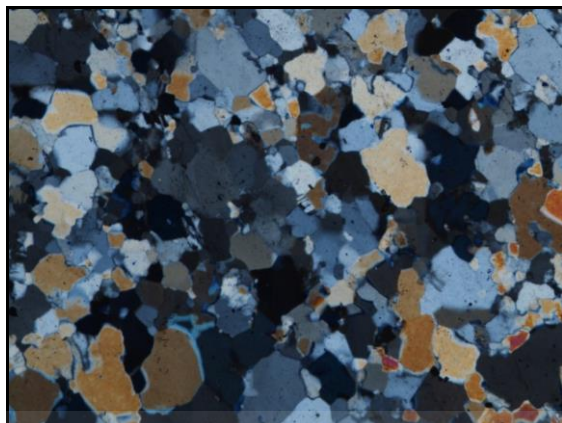


Fig. 15.11: Coarse grains with sugary texture in marble (XPL image, 4x).

Table 15.2: Characteristics of some of the common metamorphic rocks.

Non-foliated			
Parent Rock	Metamorphic Rock	Dominant Minerals	Distinguishing Characteristics
Limestone, Dolomite	Marble Dolomitic marble	Calcite or dolomite	Coarse, interlocking grains with rhombohedral cleavage, effervesces to drop of acid
Quartz sandstone	Quartzite	Quartz	Interlocking grains of granular quartz, hard, scratches glass
Shale, Basalt	Hornfels	Fine-grained mica	Fine-grained dark rock, may have some coarser minerals present, usually scratches glass
Foliated			
Parent Rock	Metamorphic rock	Dominant minerals	Characteristics
Shale	Slate	Clay minerals, micas	Fine grained, splits easily, slaty cleavage
Shale	Phyllite	Micas	Fine-grained rock with silky lustre, usually splits along wavy surfaces

Learners, you have learnt about the common metamorphic rocks in this section. Before progressing further, let us spend a few minutes to perform an exercise to check your progress.

SAQ 2

- Differentiate between foliated and non-foliated metamorphic rocks.
- Mention two examples each of foliated and non-foliated rocks.
- Gneiss exhibits _____ structure.
- Marble displays granular and _____ texture.

15.4 SUMMARY

Let us summarise what we have learnt in this unit:

- Metamorphic rocks can be classified on the basis of parent rock, texture, structure, mineralogical composition, metamorphic processes and grade.
- Metamorphic rock can be of sedimentary, igneous or metamorphic origin.
- Metamorphic rocks have been classified as phyllitic structure, slaty structure, schistose structure, gneissose structure, granulose texture and migmatitic texture.
- The metamorphic rocks can also be classified on the basis of mineralogical composition or facies.
- Types of metamorphism has been categorised into regional extent and local extent. The types of metamorphism such as regional (orogenic), ocean-floor, burial, subduction and collision metamorphism fall under regional extent. Whereas contact (igneous), cataclastic, hydrothermal, impact (shock), lightening and combustion metamorphism are of local extent.
- Grade of metamorphism has been categorized into low- and high grade.
- On the basis of structure and mineralogy, the metamorphic rocks can be divided into foliated and non-foliated rocks.
- The foliated metamorphic rocks in accordance with their grade are: slate, phyllite, and gneiss.
- Marble and quartzite are non-foliated rocks having granular and equidimensional texture.

15.5 TERMINAL QUESTIONS

1. How are metamorphic rocks classified on the basis of parent rock?
2. Discuss the megascopic and petrographic characters of slate.
3. Describe the megascopic and petrographic characters of schist.
4. Explain the megascopic and petrographic characters of quartzite.

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15.8 FURTHER/SUGGESTED READINGS

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15.9 ANSWERS

Self Assessment Questions

- 1 a) Granulose texture is found in massive metamorphic rocks exhibiting welded interlocking mosaic of crystals, e.g. quartzite and marble.
b) The types of metamorphism such as regional (orogenic), ocean-floor, burial, subduction and collision metamorphism fall under regional extent.
c) Quartzite
d) Marble
e) 320°C
- 2 a) Foliated metamorphic rocks have suffered a good amount of directed pressure during their genesis. The development of foliation surfaces or foliation planes takes place due to the pressure. Whereas non-foliated metamorphic rocks do not suffer any shear stresses due to their formation near the surface. The development of foliation planes or surfaces does not take place in non-foliated rocks.
b) Foliated-schist and gneiss; non-foliated-marble and quartzite
c) Gneissose
d) Saccharoidal

Terminal Questions

1. Please refer to subsection 15.2.1.

2. Please refer to subsection 15.3.1.
3. Please refer to subsection 15.3.3.
4. Please refer to subsection 15.3.6.



GLOSSARY

- Apparent fibers** : Cross sections of serpentine plates that look fibrous in thin section.
- Augen structure** : It refers to a larger, stronger crystals (like feldspar, quartz, garnet) embedded in a metamorphic matrix and sheared into an asymmetrical eye-shaped crystal.
- Aureole** : A zone of contact metamorphism that surrounds an intrusion.
- Background alteration** : Alteration has pervasively affected the entire rock and is not primarily bound to veins or foliation planes
- Banded structure** : Term used for prominent layering or banding in veins or nodules. These types of structures are formed due to successive deposition or replacement of pre-existing rocks such as granite gneiss.
- Banded vein** : Vein with rhythmic layering parallel to the vein walls.
- Bastite** : Serpentine texture after chain and layer silicates preserving important textures of the protolith (e.g., plastic deformation) and pre-serpentine alteration assemblages.
- Black smokers** : The mineral laden water emerging from the seafloor through hydrothermal vents. It is named after the dark-colored precipitates produced when the hot vent water meets cold seawater.
- Burial metamorphism** : It occurs when rocks are deeply buried, at depths of more than 2000 meters. Burial metamorphism commonly occurs in sedimentary basins, where rocks are buried deeply by overlying sediments.
- Cataclasite** : A type of breccia that forms in a brittle way within fault zones.
- Chrysotile** : White asbestiform serpentine, usually in veins with magnetite.
- Composite vein** : Compositionally zoned vein containing different mineral assemblages that may or may not represent different generations.

Confining pressure	: It has equal pressure on all sides and is responsible for causing chemical reactions to occur just like heat.
Contact metamorphism	: It occurs in rock exposed to high temperature and low pressure when hot magma intrudes into or lava flows over pre-existing country rocks.
Cross-fiber vein	: Asbestiform or pseudofibrous vein in which the fibers (or apparent fibers) are oriented perpendicular to the vein walls.
Directed stress	: An unequal balance of forces on a rock in one or more directions. It is also called differential or tectonic stress. These stresses are generated by the movement of lithospheric plates.
Fibrous	: Single crystals resembling organic fibers or crystalline aggregates that look like they are composed of fibers.
Foliation	: This term describes minerals lined up in planes. Minerals most notably the mica group, are mostly thin and planar.
Geothermal gradient	: The average change in temperature that is experienced as material moves into the Earth. Near the surface, this rate is about 25°C/km.
Glaucophane	: This mineral has a distinctive blue color, is an index mineral found in blueschist facies, associated with converging plate boundary.
Gneissic banding	: Metamorphic foliation in which visible silicate minerals separate into dark and light bands or lineation. These grains tend to be coarse and often folded.
Gondite	: Metamorphic rock comprising spessartine variety of garnet.
Hornfels	: Non-foliated rock which is identified by its dense, fine grained, hard, blocky or splintery texture composed of several silicate minerals.
Hydrothermal metamorphism	: Metamorphism which occurs with hot fluids going within rocks, altering and changing the rocks.
Index minerals	: They form at certain temperatures and pressures to identify metamorphic grade and provide important

clues to a rock's protolith and metamorphic conditions.

- Khondalite** : Khondalite is quartz–manganese-rich garnet–rhodonite schist. It may also contain sillimanite and graphite. It is found in the Eastern Ghats between Vijayawada and Cuttack in India.
- Metamorphic facies** : Group of minerals called facies assemblages. They provide information about the metamorphic processes that have affected the rocks and are useful in interpreting the history of a metamorphic rock.
- Metamorphic texture** : This term is used for the description of the shape and orientation of mineral grains in a metamorphic rock.
- Migmatite** : Since gneisses form at the highest temperatures and pressures, some partial melting may occur. This partially melted rock is a transition between metamorphic and igneous rocks. Migmatites appear as dark and light banded gneiss.
- Mylonites** : Metamorphic rocks created by dynamic recrystallisation, generally resulting in a reduction of grain size.
- Non-foliated** : This type of texture does not exhibit lineation, foliation, or other alignments of mineral grains. Non-foliated metamorphic rocks are typically composed of just one mineral, and usually show the effects of metamorphism with recrystallisation in which crystals grow together but have no preferred direction.
- Phase diagram** : Chart that show the stability of different phases of a substance at different conditions.
- Regional metamorphism** : It occurs when parent rock is subjected to increase temperature and pressure over a large area.
- Subduction zone metamorphism** : It is a type of regional metamorphism that occurs when a slab of oceanic crust is subducted under the continental crust.

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