MOUNTAIN TOP UNIVERSITY

E-Courseware

COLLEGE OF BASIC AND APPLIED SCIENCES

Mountain Top University
Kilometre 12, Lagos-Ibadan Expressway, MFM Prayer City, Ogun State.
EMAIL: support@mtu.edu.ng
Website: www.mtu.edu.ng.
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COURSE GUIDE

COURSE TITLE: General Petrology

COURSE CODE: GLY 204

LECTURER(S): Adeoye James A. (Ph.D.)

COURSE OBJECTIVES

GENERAL INTORDUCTION AND COURSE OBJECTIVES

Introduction to Geology deals with earth history, landforms, introductory aspect of minerals and rocks. It is a foundational course which is taken along with option in physics, mathematics, chemistry and biology to prepare student for advance geosciences courses.

COURSE CONTENTS

Lecture One: History of the Earth and Universe

Lecture Two: Minerals: Classification, Properties and Description.

Lecture Three: Magma and Rocks: Classification, Properties and Description.

LECTURE ONE

HISTORY OF THE EARTH AND UNIVERSE

1.0 Introduction

This topic addresses the Big Bang theory, Galaxy, Solar system, Planet, layers of the earth and its composition. The earth system which includes Atmosphere, Hydrosphere, Biosphere and Geosphere will be discussed. The structure of the earth in terms of its compositional and mechanical layering such as Core, Mantle and Crust are introduced to form the bedrock for building other geological knowledge.

Objectives

At the end of this lecture, students should be able to:

1. describe the earth history;
2. explain what the earth structures and composition ; and
3. cope with other field of geology courses that will be introduced subsequently

Pre-Test

1. Write a short note on how the earth was formed.
2. Describe the earth structure and its compositions.
3. What is a solar system?

CONTENT

1.1 Big Bang Theory

A Belgian priest named Georges Lemaître first suggested the big bang theory in the 1920s when he theorized that the universe began from a single primordial atom. Matter as we know did not exist at the time of the Big Bang, only pure energy does. Within one second, the four fundamental forces which include gravity, electromagnetic force, strong and weak nuclear forces.

1.2 Galaxy

The universe is made up of many galaxies which are made up of many stars. The universe began with the protons and neutrons fusing to form the nuclei of hydrogen and helium atoms after about 300,000 years later when the temperatures were cool enough. In about 200 million years later, with expansion still occurring, stars and galaxies began forming from leftover matter (hydrogen and helium). Nuclear fusion in stars has reduced the original composition of 100% H and He to 98% and whenever a dying star explodes, the heavier elements created by fusion are blown into space to be recycled by newly forming stars. Then the overall composition of the galaxies gradually kept changing to the heavier elements. Our solar system is located in the Milky Way Galaxy, an Interstellar Cloud, known as Giant Molecular Clouds. The Milky Way is part of a cluster of about 30 other galaxies. Our galaxy contains at least 100 billion stars, of which the sun is one. Astronomers have a variety of evidence that the sun formed from a cloud of gas and dust almost 5 billion years ago.

1.3 Earth

The central bulge in the Milky Way galaxy is at the center and contains mostly blue stars, gas and dust. Our solar system is located in one of the spiral arms around the center bulge. The Earth is the third planet from the sun among eight planets in the solar system. Earth is an oblate spheroid, wider at the equator than at the poles. The Earth's axis is an imaginary line that runs through the center of the earth from the North Pole to the South Pole, and is "tilted" with relation to this imaginary line 23.5^0. One rotation about the Earth's axis takes 24 hours. This is called a day. Rotation about the Earth's occurs from west to east. (Counter clockwise)

The earth has a system that keeps it running. The systems are atmosphere, hydrosphere, biosphere and geosphere. The geosphere compositionally consists of the core, mantle and crust.

Core composed of iron and some nickel. It is divided into the solid inner core and the liquid outer core with 3,700°C - 7,000°C temperature.

Mantle is the most voluminous and contains solid rock, parts of which flow slowly, generally upward or downward depending on whether it is hotter or colder than adjacent mantle with 1,000°C to 3,700°C.

Crust compose of oxygen, silicon, and aluminum. It is thin but dense oceanic crust and thick but less dense continental crust with 0°C to 1,000°C temperature.

Bibliography

- Physical Geology Fifteenth Edition by Plummer C. C., Carlson, D. H. and Hammersley L.
- The Solar System 7th Edition by Seed Backman

LECTURE TWO

MINERALS: CLASSIFICATION, PROPERTIES AND DESCRIPTION

1.0 Introduction

This subject is very important for every would-be geoscientist because minerals forms the basic constituents of the earth materials. Minerals will be geologically define from the general use or abuse by a non-geoscientist. Its classification base on elemental composition and origin, properties that differentiate them from others, and as well as their types will be discussed in this lesson.

Objectives

At the end of this lecture, students should be able to:

1. geologically define minerals;
2. describe the properties of minerals;
3. classify minerals in to their respective groups; and
4. identify basic rock forming minerals

Pre-Test

1. What is a mineral?
2. List and explain five mineral and their general properties.
3. List minerals in their order of increasing hardness.
4. What are Gem stones?
5. Mention two most abundant elements in minerals

CONTENT

1.1 Minerals

A mineral is a homogeneous, naturally occurring, inorganic, crystalline solid that has a specific chemical composition. Naturally occurring suggest that a mineral must form through natural geologic processes, inorganic means they are not composed of the complex hydrocarbon molecules that are the basis of life-forms such as humans and plants, specific chemical composition indicate that they have a chemical formula, and crystalline structure reveals atoms that make up the mineral are arranged in an orderly, repeating, three-dimensional pattern.

1.2 Mineral Compositions

Minerals are composed of atoms of elements bonded together in an orderly crystalline structure. Atoms are the smallest, electrically neutral assemblies of energy and matter that we know exist in the universe that consist of a central nucleus surrounded by a cloud of electrons. The nucleus contains positively charged protons and neutral particles called neutrons. An element is defined by the number of protons in its nucleus or its atomic number. About 98.5% of crustal mineral mass is from eight (8) elements namely, Oxygen 46.6%, Silicon 27.7%, Aluminum 8.1%, Iron 5.0%, Calcium 3.6%, Sodium 2.8%, Potassium 2.6%, Magnesium 2.1% and others 1.5 %. Minerals are usually compounds such as quartz (SiO_2), Pyrite (FeS_2) Olivine etc. $(Mg,Fe)_2(SIO_4)$ or a naturally occurring element e.g. gold (Au), Copper (Cu), Diamond (C) etc. Minerals also possess a characteristic crystal structure and therefore exclude non-crystalline minerals such as glass.

1.3 Properties of Minerals

The properties of mineral depend on their chemical composition and crystal structure which can be diagnose through physical or chemical means. Some minerals could be characterize by taste, others by magnetic properties but their physical properties are the most relevant and they include external shape, crystal habit, cleavage, lustre, colour, hardness, streak, and specific gravity.

i. Crystal Habit

This is a description of a mineral's consistent shape. Common descriptive term of habit includes Flakes - thin plates (typical of mica minerals), Needle-like - thin, long crystals, Tabular – Flattened but not flaky, Prismatic - elongate-but not needle-like, Fibrous - typical of e.g. asbestos minerals.

ii. Color

This is commonly the most striking feature of a mineral, but can be misleading. For example, quartz (SiO_2) is ideally colourless and transparent but we have varieties of it. Color may be diagnostic for a few minerals, but in general, a given mineral can have a range of colors.

Various colors of quartz, SiO_2. Milky quartz, bluish quartz, amethyst, rose quartz, citrine quartz and smoky quartz.

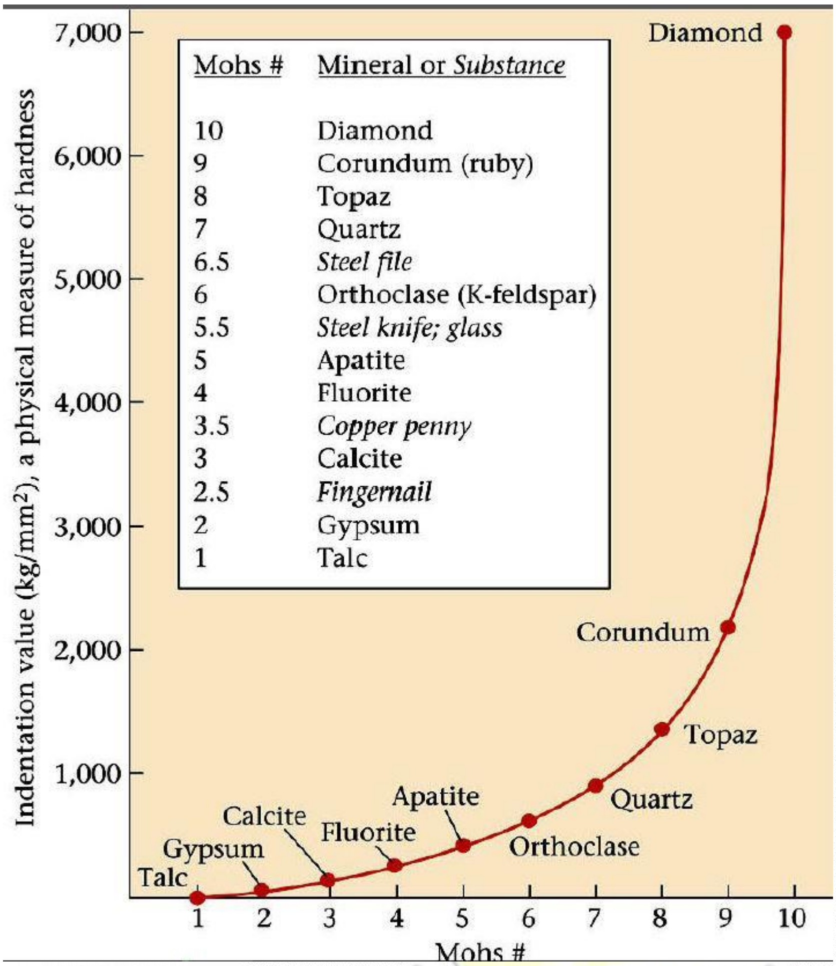
iii. Streak

The color of the pulverized powder of a mineral may be different from individual crystals. Pyrite (FeS_2) has a metallic lustre and is brassy yellow in colour. Hematite (Fe_2O_3) can have various colors, but its streak is always red-brown. Streak is more consistent than color and is found by scraping a mineral against a porcelain plate

iv. Hardness

This is a relative resistant of minerals to scratching. A relative scale of hardness of mineral is presented on the Moh's Scale. This is divided into 10 steps and the minerals of the scale will scratch all minerals below it. The softest mineral has hardness scale of 1 while the hardest minerals is on scale 10.

Moh's Scale of Relative Hardness		
Number in Scale	**Mineral Name**	**Hardness of some Objects**
10	Diamond	
9	Corundum	
8	Topaz	
7	Quartz	
6	K-feldspar	
		Pocket Knife; glass
5	Apatite	
4	Fluorite	
		Copper coin
3	Calcite	
		Finger nail
2	Gypsum	
1	Talc	



v. Specific Gravity

This is the weight of a substance divided by the weight of an equal volume of water. It derived from the density of the substance and water. Density is the mass per unit volume. It is measured in gm/cm^3. Gold (Au)-19.3, Galena (PbS)- 7.6, Pyrite (FeS_2)- 5.2, Olivine $(Mg,Fe)_2(SiO_4)$ 3.2 – 4.4, Quartz (SiO_2) – 2.6, Halite (NaCl) – 2.2

vi. Fracture and Cleavage

•**Cleavage:** The tendency of a mineral to break along a preferred direct or plane of weakness in the crystal lattice.

•**Fracture:** The mineral breaks in no consistent manner

–Equal bond strength in all directions

•**Conchoidal Fracture:** The tendency for a mineral to break along irregular scoop-shaped fractures that are not related to weaknesses in the crystal structure

vii. Lustre

This is the quality and intensity of light reflected from a mineral. There are two very important groups of minerals that exhibit lustre- metallic and non-metallic minerals. Metallic lustre-adamantine-is highly sparkling.

viii. Tenacity

This is the resistance that a mineral offers in breaking, crushing, bending or tearing i.e its cohesiveness. These are commonly termed brittle, malleable, ductile, flexible, and elastic.

ix. Other properties

These other properties are useful in relevant cases. e.g. There are other special characteristics that some minerals exhibit that allow us to identify them

–Reacts to Acid [Calcite and Dolomite: CaCO3 & Ca(Mg)CO3]

–Magnetic [Magnetite: Fe_3O_4]

–Salty taste [Halite: NaCl]

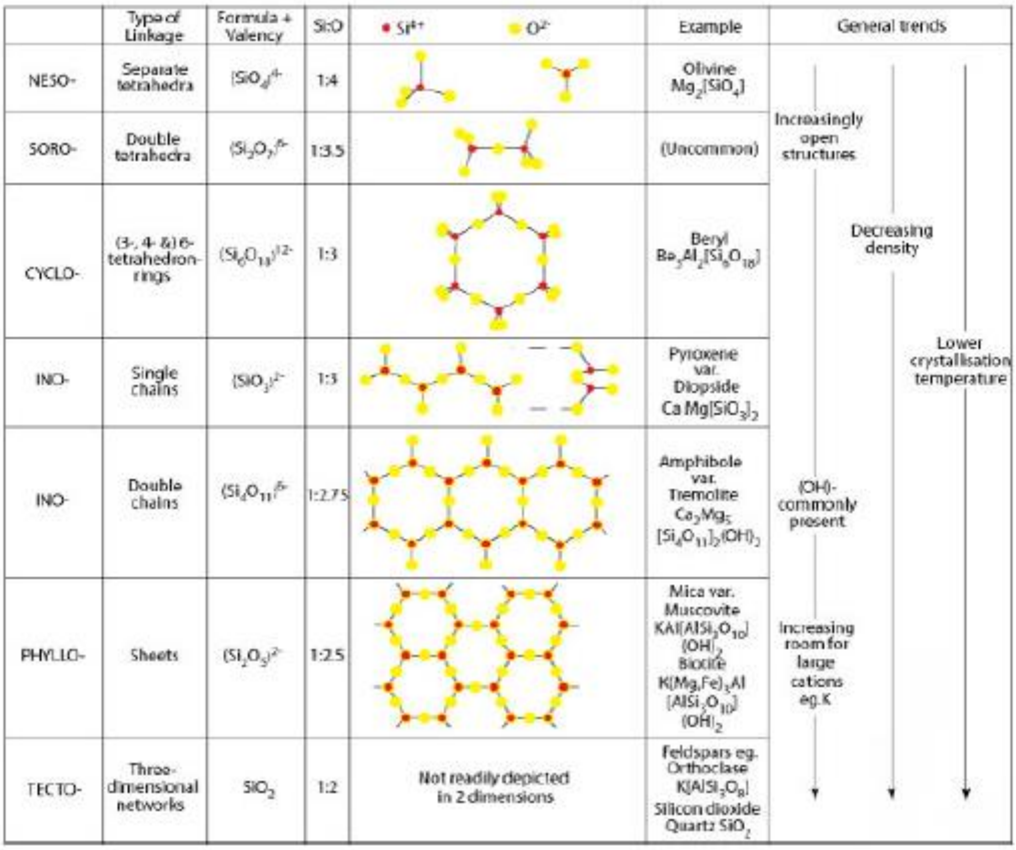
1.4 Classes of Minerals

Minerals are classified by their dominant anion. They are Silicates (SIO_2^{4-}), Oxides (O^{2-}), Sulfides (S^-), Sulfates (SO_4^{2-}), Halides (Cl^- or F^-), Carbonates (CO_3^{2-}), and Native Elements (Cu, Au, C)

a. Silicates (SiO_2^{4-})

The crust is dominated by the elements oxygen and silicon. Oxygen forms O^{2-} anions and compounds that contain O^{2-} are called oxides. Silicon forms Si4+ cations. Silicon and oxygen together form an extremely strong complex ion: called silicate ion [SiO4]4-. Minerals that contain the silicate ion are silicate minerals and they dominate the crust.

Oxide has an ionic radius of 1.32A^o whereas Si^{4+} is a relatively small cation with an ionic radius of 0.42 A^o. Considering the ions as spheres, 4 large oxygen ions can be packed around one small silicon ion giving a tetrahedral structure.



	Type of Linkage	Formula + Valency	Si:O	• Si^{4+} • O^{2-}	Example	General trends
NESO-	Separate tetrahedra	$(SiO_4)^{4-}$	1:4		Olivine $Mg_2[SiO_4]$	
SORO-	Double tetrahedra	$(Si_2O_7)^{6-}$	1:3.5		(Uncommon)	Increasingly open structures
CYCLO-	(3-, 4- &) 6-tetrahedron-rings	$(Si_6O_{18})^{12-}$	1:3		Beryl $Be_3Al_2[Si_6O_{18}]$	Decreasing density
INO-	Single chains	$(SiO_3)^{2-}$	1:3		Pyroxene var. Diopside $CaMg[SiO_3]_2$	Lower crystallisation temperature
INO-	Double chains	$(Si_4O_{11})^{6-}$	1:2.75		Amphibole var. Tremolite $Ca_2Mg_5[Si_4O_{11}]_2(OH)_2$	(OH)- commonly present
PHYLLO-	Sheets	$(Si_2O_5)^{2-}$	1:2.5		Mica var. Muscovite $KAl[AlSi_3O_{10}](OH)_2$ Biotite $K(Mg,Fe)_3Al[AlSi_3O_{10}](OH)_2$	Increasing room for large cations eg.K
TECTO-	Three-dimensional networks	SiO_2	1:2	Not readily depicted in 2 dimensions	Feldspars eg. Orthoclase $K[AlSi_3O_8]$ Silicon dioxide Quartz SiO_2	

b. Native Elements (Cu, Au, C)

Gold, silver, copper and platinum all occur naturally in the form of native metal elements but most of them are rare! Native non-metallic minerals include the two polymorphs of carbon, diamond and graphite, and the element sulphur. Native sulphur forms soft, yellow, orthorhombic crystals where volcanic gases have been active.

c. Sulphides

The sulphides form an important group of minerals that include the majority of the ore minerals. They (nearly) all have metallic lustre and high densities. Examples of minerals in this group include Galena (PbS), Sphalerite (also known as zinc blende) (ZnS), Pyrite (FeS_2) It is sometimes referred to as 'fools gold". It is the most widespread sulphide mineral and occurs as an accessory mineral in many rock types. Chalcopyrite (CuFeS2

d. Oxides

Examples are Corundum (Al_2O_3), Hematite (Fe_2O_3), Ilmenite ($FeTiO_3$), Magnetite (Fe_3O_4), Chromite ($FeCr_2O_4$)

e. Chlorides and fluorides

Halite (NaCI) Fluorite (CaF_2)

f. Carbonates

Calcite (CaCO3), Aragonite, Dolomite $CaMg(CO_3)_2$ Magnesite ($MgCO_3$)), Siderite ($FeCO_3$)

g. Sulphates

Gypsum Gypsum (CaSO4.2H20) forms monoclinic crystals which are usually tabular on (010). Swallowtail twins are common, as illustrated in Fig. 2.2a. It has a perfect (010) cleavage and defines H = 2.. G —2.3. Gypsum is colourless, white or grey; it can be transparent. Crystalline gypsum is also known as selenite. Satin spar is a fibrous variety; alabaster is a fine-grained massive variety. Gypsum is a widely distributed mineral in sedimentary rocks and is formed by the evaporation of seawater, usually together with halite — rock salt The attractive aggregates known as "desert roses" are composed of gypsum. Gypsum also occurs together with many ore minerals in veins.

Barytes (BaSO4) usually forms colourless or white tabular orthorhombic crystals with perfect (001) cleavage. It has a notably high density for a non-metallic mineral (G = 4.5) and H = 3- Barytes occurs together with a variety of ore minerals in veins.

h. Phosphates

Apatite Apatite (Cas(PO4),(F,C1,0H)) is a hexagonal mineral which commonly forms long prismatic crystals. It is usually greenish in colour. It has hardness = 5 and can just be scratched with a knife. G —3.18. Apatite is a very widely distributed accessory mineral but also occurs in large deposits, sometimes in pegmatites where it can form large green hexagons.

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- Minerals and Rocks by J. Richard Wilson 1st Edition © 2010 Richard Wilson & Ventus Publishing& bookboon.com

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LECTURE THREE

ROCK: ORIGIN, CLASSIFICATION AND PROPERTIES

1.0 Introduction

The rock subject comes up after mineralogy class because rocks in the earth's crust and mantle are made up of mineral assemblages with chemical compounds, elements, molecular bonds which are formed from ordered atomic structures. Therefore, the origin, classification, and properties of rocks will be introduced in this lesson.

Objectives

At the end of this lecture, students should be able to:

1. define and describe a rock;
2. explain the origin of different rocks; and
3. classify rocks base on their origin and composition.

Pre-Test

1. What is a rock?
2. Mention the three types of rock.
3. Describe process of rock formation.
4. Which of the rock is the most abundant and why?

CONTENT

1.1 Rock

A rock is naturally formed, consolidated material usually composed of grains of one or more minerals. Rocks are grouped into three types based on their mode of formation. They are Igneous, Sedimentary and Metamorphic rock. James Hutton (1727–1797), the eminent 18th century gentleman farmer and founder of modern geosciences, authored the concept of the rock cycle, which depicts the inter-relationships between igneous, sedimentary, and metamorphic rocks.

1.2 Magma

Magma is a molten rock. Heat that contributes to the generation of magma comes from the very hot earth's core (where temperatures are estimated to be greater than 5,000 ^{o}C). It is conducted toward the earth's surface either through convection or by hot mantle plumes. A magma consists mostly of liquid rock matter, but may contain also crystals of various minerals, and may contain a gas phase that may be dissolved in the liquid or may be present as a separate gas phase. Magma can cool to form an igneous rock either on the surface of the Earth - in which case it produces a volcanic or extrusive igneous rock, or beneath the surface of the Earth, - in which case it produces a plutonic or intrusive igneous rock.

Characteristics of Magma

Types of Magma

Types of magma are determined by chemical composition of the magma.

1. Basaltic magma -- SiO_2 45-55 wt%, high in Fe, Mg, Ca, low in K, Na
2. Andesitic magma -- SiO_2 55-65 wt%, intermediate in Fe, Mg, Ca, Na, K
3. Rhyolitic magma -- SiO_2 65-75%, low in Fe, Mg, Ca, high in K, Na

Gases in Magmas

At depth in the Earth nearly all magmas contain gas dissolved in the liquid, but the gas forms a separate vapor phase when pressure is decreased as magma rises toward the surface. This is similar to carbonated beverages which are bottled at high pressure. The high pressure keeps the gas in solution in the liquid, but when pressure is decreased, like when you open the can or bottle, the gas comes out of solution and forms a separate gas phase that you see as bubbles. Gas gives magmas their explosive character, because volume of gas expands as pressure is reduced. The composition of the gases in magma are: Mostly H_2O (water vapor) with some CO_2 (carbon dioxide), Minor amounts of Sulfur, Chlorine, and Fluorine gases
The amount of gas in a magma is also related to the chemical composition of the magma. Rhyolitic magmas usually have higher dissolved gas contents than basaltic magmas.

Temperature of Magmas

Temperature of magmas is difficult to measure (due to the danger involved), but laboratory measurement and limited field observation indicate that the eruption temperature of various magmas is as follows:

Basaltic magma - 1000 to 1200^oC

Andesitic magma - 800 to 1000^oC

Rhyolitic magma - 650 to 800^oC.

Viscosity of Magmas

Viscosity is the resistance to flow (opposite of fluidity). Viscosity depends on primarily on the composition of the magma, and temperature.

Higher SiO_2 (silica) content magmas have higher viscosity than lower SiO_2 content magmas (viscosity increases with increasing SiO_2 concentration in the magma).

Lower temperature magmas have higher viscosity than higher temperature magmas (viscosity decreases with increasing temperature of the magma).

Thus, basaltic magmas tend to be fairly fluid (low viscosity), but their viscosity is still 10,000 to 100,0000 times more viscous than water. Rhyolitic magmas tend to have even higher viscosity, ranging between 1 million and 100 million times more viscous than water. (Note that solids, even though they appear solid have a viscosity, but it is very high, measured as trillions time the viscosity of water). Viscosity is an important property in determining the eruptive behavior of magmas.

Viscosity of Magmas

Viscosity is the resistance to flow (opposite of fluidity). Fluidity or viscosity of magma depends on the percentage of its silica content and temperature. Silica rich is acidic magma while silica poor is basic magma. The acidic magma are more viscous, do not spreads but piles up at one place while basic magma poor in silica are less viscous, moves faster and occupies larger area. Lower temperature magmas have higher viscosity than higher temperature magmas (viscosity decreases with increasing temperature of the magma).

Thus, basaltic magmas tend to be fairly fluid (low viscosity), but their viscosity is still 10,000 to 100,0000 times more viscous than water. Rhyolitic magmas tend to have even higher viscosity, ranging between 1 million and 100 million times more viscous than water. (Note that solids, even though they appear solid have a viscosity, but it is very high, measured as trillions time the viscosity of water). Viscosity is an important property in determining the eruptive behavior of magmas.

Formation of Magma

Magma forms through decompression and flux melting. Decompression melting principles is based on the fact that the melting point of a mineral generally increases with increasing pressure and pressure increases with depth in the Earth's crust, just as temperature does. So for magma to form, decompression melting needs to takes place when a body of hot mantle rock moves upward and where the pressure is reduced. Decompression melting is an important process at divergent plate boundaries, where mantle material is rising and melting beneath mid-oceanic ridges. The magma flows beneath the earth surface to form an intrusive igneous rock or above the earth surface (where it is called lava) by a volcanic eruption to form an extrusive igneous rock. Flux melting – this occurs when enough water is present under high pressure, a dramatic change occurs in the melting process. Water sealed in under high pressure helps break the silicon-oxygen bonds in minerals, causing the crystals to liquefy. A rock's melting temperature is significantly lowered by water under high pressure. Flux melting is an important process at convergent plate boundaries, where subduction carries water down into the mantle.

Volcanic Eruptions

In general, magmas that are generated deep within the Earth begin to rise because they are less dense than the surrounding solid rocks. As they rise they may encounter a depth or pressure where the dissolved gas no longer can be held in solution in the magma, and the gas begins to form a separate phase (i.e. it makes bubbles just like in a bottle of carbonated beverage when the pressure is reduced). When a gas bubble forms, it will also continue to grow in size as pressure is reduced and more of the gas comes out of solution. In other words, the gas bubbles begin to expand.

If the liquid part of the magma has a low viscosity, then the gas can expand relatively easily. When the magma reaches the surface, the gas bubble will simply burst, the gas will easily expand to atmospheric pressure, and a non-explosive eruption will occur, usually as a lava flow (Lava is the name we give to a magma on the surface of the Earth).

If the liquid part of the magma has a high viscosity, then the gas will not be able to expand easily. Thus, pressure will build inside the gas bubble(s). When the magma reaches the surface, the gas bubbles will have a high pressure inside, which will cause them to burst explosively on reaching atmospheric pressure. This will cause an explosive volcanic eruption.

Explosive Eruptions

Explosive eruptions are favored by high gas content and high viscosity (andesitic to rhyolitic magmas). Explosive bursting of bubbles will fragment the magma into clots of liquid that will cool as they fall through the air. These solid particles become pyroclasts (meaning - hot fragments) and tephra or volcanic ash, which refer to sand- sized or smaller fragments.

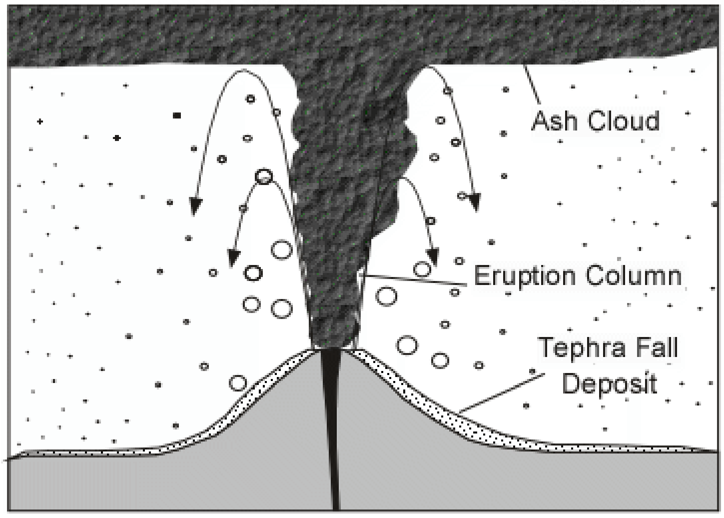
Tephra and Pyroclastic Rocks		
Average Particle Size (mm)	Unconsolidated Material (Tephra)	Pyroclastic Rock
>64	Bombs or Blocks	Agglomerate
2 - 64	Lapilli	Lapilli Tuff
<2	Ash	Ash Tuff

Blocks are angular fragments that were solid when ejected.

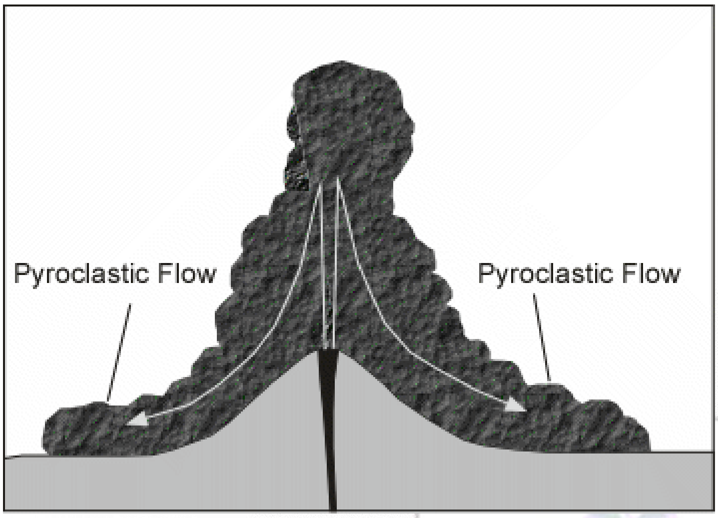
Bombs have an aerodynamic shape indicating they were liquid when ejected.

Bombs and lapilli that consist mostly of gas bubbles (vesicles) result in a low density highly vesicular rock fragment called pumice.

Clouds of gas and tephra that rise above a volcano produce an eruption column that can rise up to 45 km into the atmosphere. Eventually the tephra in the eruption column will be picked up by the wind, carried for some distance, and then fall back to the surface as a tephra fall or ash fall.



If the eruption column collapses a pyroclastic flow will occur, wherein gas and tephra rush down the flanks of the volcano at high speed. This is the most dangerous type of volcanic eruption. The deposits that are produced are called ignimbrites if they contain pumice or pyroclastic flow deposits if they contain non-vesicular blocks.



Non-explosive Eruptions

Non explosive eruptions are favoured by low gas content and low viscosity magmas (basaltic to andesitic magmas).

If the viscosity is low, non-explosive eruptions usually begin with fire fountains due to release of dissolved gases.

Lava flows are produced on the surface, and these run like liquids down slope, along the lowest areas they can find.

Lava flows produced by eruptions under water are called pillow lavas.

If the viscosity is high, but the gas content is low, then the lava will pile up over the vent to produce a lava dome or volcanic dome.

Volcanism

Volcanism occurs when magma makes its way to the Earth's surface. Whether eruptions are violently explosive or relatively "quiet" is largely determined by two factors: (1) the amount of gas in the lava or magma and (2) the ease or difficulty with which the gas can escape to the atmosphere. The viscosity, or resistance to flow, of a lava determines how easily the gas escapes. The more viscous the lava and the greater the volume of gas trying to escape, the more violent the eruption. These influence the shape and height of a volcano.

Lava is a mixture of molten silicate rock, crystals, and gas. Volcanoes are landforms formed by the extrusion of lava or the ejection of rock fragments from a vent. Volcanoes come in many shapes and sizes, and eruptions can vary widely in their duration, violence, and the type of material erupted. Eruptions dominated by lava flows are called effusive eruptions and are typically less dangerous than explosive eruptions.

Benefit of Volcanic

The dangers associated with volcanoes provide a compelling reason to study them, there are many other reasons. Volcanoes provide geologists with information on processes occurring within the mantle. Volcanic eruptions can affect the Earth's climate. Volcanoes can also be beneficial.

i. **Creation of New Land**

The overall effects of volcanism have been favorable to humans in creating new land e.g in Hawaii. Lava flowing into the sea and solidifying adds real estate to the island of Hawaii. Kilauea volcano has been erupting since 1983, producing out an average of 325,000 cubic meters of lava a day and this is the equivalent to 40,000 truckloads of material. In twenty years, 2.5 billion cubic meters of lava were produced. This is enough to build a highway that circles the world over five times. Were it not for volcanic activity, Hawaii would not exist. When lava flows into the sea and solidifies, more land is added to the islands. Hawaii is, quite literally, growing. In addition to gaining more land, Hawaii benefits in other ways from its volcanoes. Weathered volcanic ash and lava produce excellent, fertile soils (think pineapples and papayas). Moreover, Hawaii's periodically erupting volcanoes (which are relatively safe to watch) are great spectacles that attract both tourists and scientists, benefiting the island's economy.

ii. Geothermal Energy

Underground heat energy generated by volcanic or igneous activity is harnessed for human needs. Steam or superheated water trapped in layers of hot volcanic rock is tapped by drilling and then piped out of the ground to power turbines that generate electricity. The United States is the biggest producer of geothermal power, followed by the Philippines, Indonesia, Mexico, and Italy. Naturally heated geothermal fluids can also be tapped for space or domestic water heating or industrial use, as in paper manufacturing.

iii. Effect on Climate

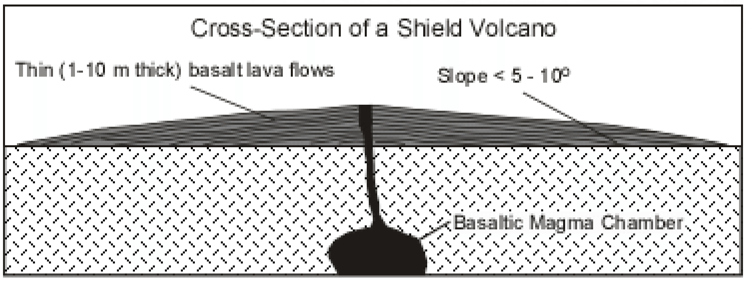
The atmosphere was created by degassing magma during the time following Earth's formation. Even now, gases and dust given off by major volcanic eruptions can profoundly alter worldwide climate. Occasionally, a volcano will spew large amounts of fine volcanic dust and gas into the high atmosphere. Winds can keep fine particles suspended over the Earth for years. The 1991 eruption of Mount Pinatubo in the Philippines produced noticeably more colorful sunsets worldwide. More significantly, it reduced solar radiation that penetrates the atmosphere. Measurements indicated that the worldwide average temperature dropped approximately one degree Celsius for a couple of years. While this may not seem like much, it was enough to temporarily offset the global warming trend of the past 100 years.

The 1815 eruption of Tambora in Indonesia was the largest single eruption in a millennium—40 cubic kilometers of material were blasted out of a volcanic island, leaving a 6-kilometerwide depression. The following year, 1816, became known as "the year without summer." In New England, snow in June was widespread, and frosts throughout the summer ruined crops. Parts of Europe suffered famine because of the cold weather effects on agriculture. Measurements indicated that the worldwide average

Volcanic Landforms

Shield Volcanoes

A shield volcano is characterized by gentle upper slopes (about 5^o) and somewhat steeper lower slopes (about 10^o). Shield volcanoes are composed almost entirely of thin lava flows built up over a central vent.



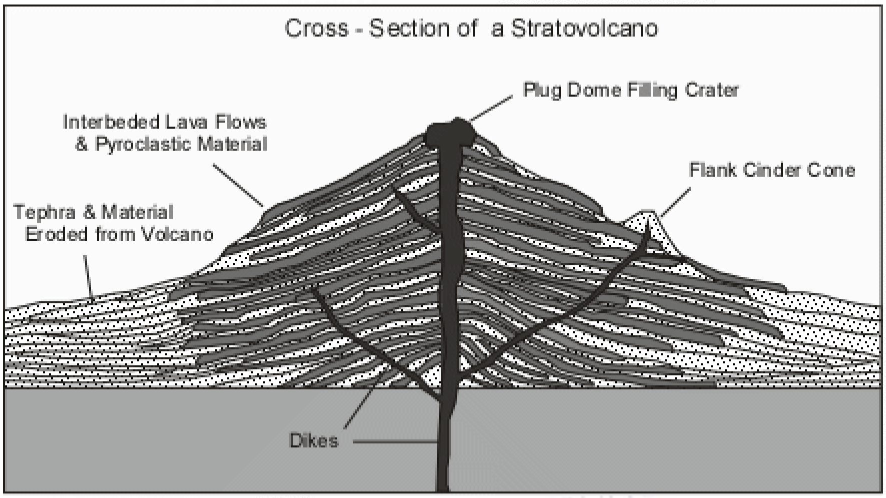
Most shields are formed by low viscosity basaltic magma that flows easily down slope away form a summit vent.

The low viscosity of the magma allows the lava to travel down slope on a gentle slope, but as it cools and its viscosity increases, its thickness builds up on the lower slopes giving a somewhat steeper lower slope.

Most shield volcanoes have a roughly circular or oval shape in map view.

Very little pyroclastic material is found within a shield volcano, except near the eruptive vents, where small amounts of pyroclastic material accumulate as a result of fire fountaining events.

Stratovolcanoes (also called **Composite Volcanoes**)

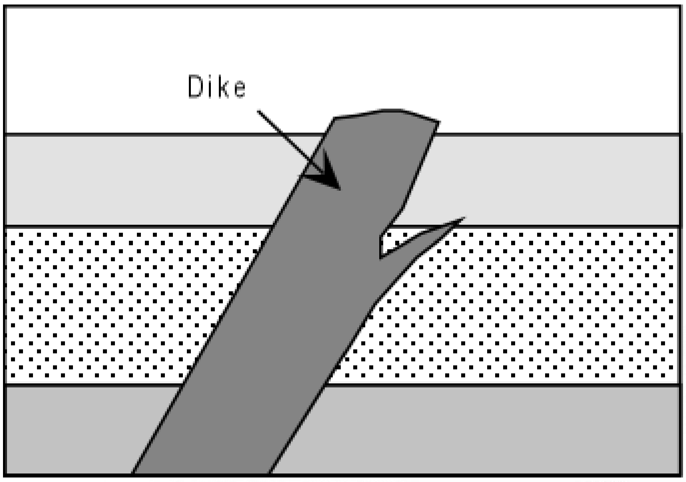


Plutonic (Intrusive) Igneous Rocks

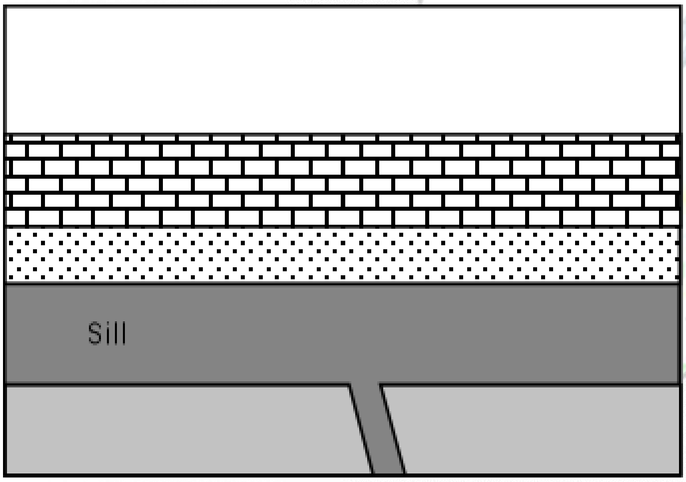
Hypabyssal Intrusions

Intrusions that intrude rocks at shallow levels of the crust are termed hypabyssal intrusions. Shallow generally refers to depths less than about 1 km. Hypabyssal intrusions always show sharp contact relations with the rocks that they intrude. Several types are found:

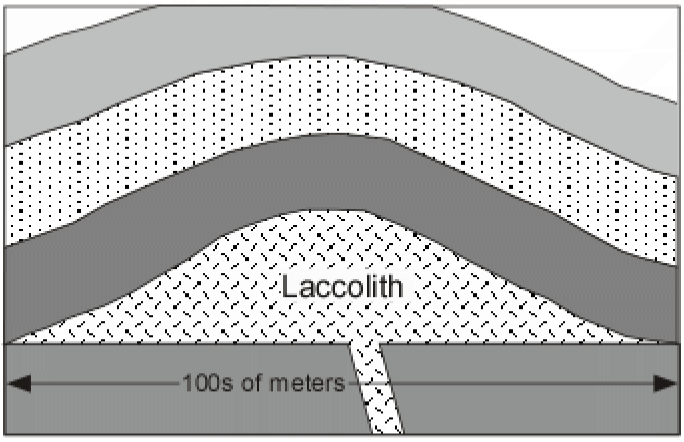
- **Dikes** are small (<20 m wide) shallow intrusions that show a discordant relationship to the rocks in which they intrude. Discordant means that they cut across preexisting structures. They may occur as isolated bodies or may occur as swarms of dikes emanating from a large intrusive body at depth.



• **Sills** are also small (<50 m thick) shallow intrusions that show a concordant relationship with the rocks that they intrude. Sills usually are fed by dikes, but these may not be exposed in the field.



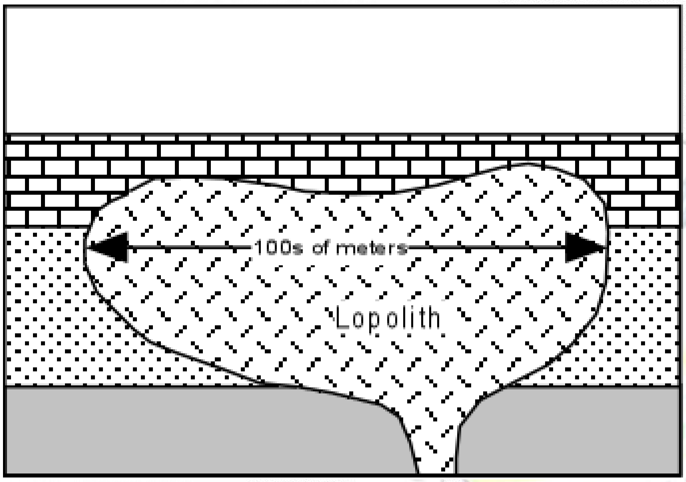
• **Laccoliths** are somewhat large intrusions that result in uplift and folding of the preexisting rocks above the intrusion. They are also concordant types of intrusions.



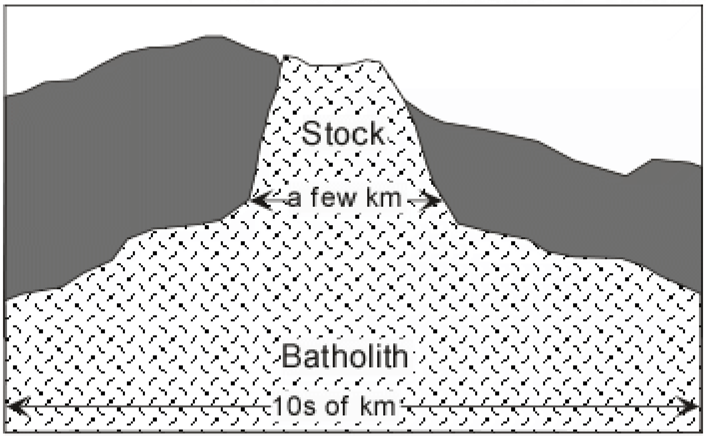
Plutons

Plutons are generally much larger intrusive bodies that have intruded much deeper in the crust. Although they may show sharp contacts with the surrounding rocks into which they intruded, at deeper levels in the crust the contacts are often gradational.

- Lopoliths are relatively small plutons that usually show a concave downward upper surface. This shape may have resulted from the reduction in volume that occurs when magmas crystallize, with the weight of the overlying rocks causing collapse of into the space once occupied by the magma when it had a larger volume as a liquid.



- **Batholiths** are very large intrusive bodies, usually so large that there bottoms are rarely exposed. Sometimes they are composed of several smaller intrusions.
- **Stocks** are smaller bodies that are likely fed from deeper level batholiths. Stocks may have been feeders for volcanic eruptions, but because large amounts of erosion are required to expose a stock or batholith, the associated volcanic rocks are rarely exposed.

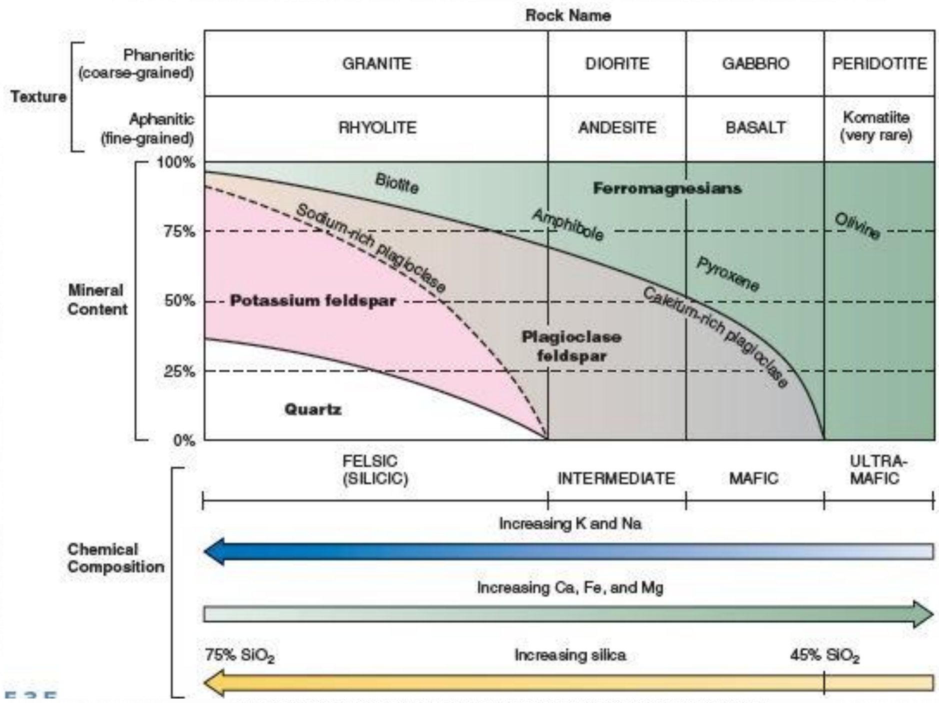


Volcanic (Extrusive) Igneous Rocks

1.3 Igneous Rock

This rock forms from molten magma. They can be classified by their mode of formation, texture, chemical and mineral composition.

1.3.1 Igneous Rock classification



Classification chart for the most common igneous rocks (Adopted from Plummer and others, 2016)

i. Mode of Formation

There are two types of igneous rock depending on where the magma solidify. They are extrusive or volcanic and intrusive or plutonic igneous rocks. The extrusive (volcanic) igneous rocks form when molten rock erupts from Earth's interior through a volcano or fissure and cools rapidly at the surface in form of lava and hence it does not have any specific shape. It could also be pyroclastic flow where the eruption is very violent and send the lava or volcano materials into the airspace. They always have fine textures because of the rapid cooling that gives no time for crystal settings. The examples of such rocks are rhyolite, andesite and basalt.

The intrusive (plutonic) igneous rocks are crystalline products of magma that has intruded into the crust and solidifies slowly beneath the surface. They are always coarse grained because their crystals are well set under the slow cooling process. Examples of this type of rocks are granite, diorite and gabbro.

ii. Chemical Composition

There are four categories of igneous rocks base on their chemical composition. They are felsic, intermediary, mafic and ultramafic.

a. **Felsic Rocks**

   This is a silica-rich igneous rocks with a relatively high content of potassium and sodium (the fel comes from feldspar, which crystallizes from the potassium, sodium, aluminum, and silicon oxides while si is for silica). They tend to be dominated by the light-colored minerals quartz, potassium feldspar, and plagioclase feldspar, with only small amounts of the dark ferromagnesian minerals, e.g. granite and rhyolite They have silica content of 65% or more (by weight) are considered to be silica-rich and remaining 25 % to 35 % of these rocks are mostly aluminum oxide (Al_2O_3) and oxides of sodium (Na_2O) and potassium (K_2O). They usually contains only very small amounts of the oxides of calcium (CaO), magnesium (MgO), and iron (FeO and Fe_2O_3).

b. **Intermediate Rocks**

   They have silica content between 55 % and 65 % with significant amounts (30 – 50 %) of dark ferromagnesian minerals like pyroxene and amphibole as well as light-colored plagioclase feldspar and small amounts of quartz. Example is diorite, the coarse-grained and andesite, the fine-grained rock. They are typically medium-gray or greenish-gray in color.

c. **Mafic Rocks**

   Their silica content range between 45 % and 55 % by weight (silica-poor) and compose more of the oxides of aluminum, calcium, magnesium, and iron. Rocks in this group are called mafic which comes from magnesium and ferrum, the Latin word for iron. Mafic rocks are made up predominantly of gray plagioclase feldspar and the ferromagnesian minerals pyroxene and olivine and tend to be dark in color. Examples are gabbro- the coarse-grained, intrusive rock and basalt- dark, fine-grained, extrusive rock.

d. Ultramafic Rocks

These rocks contain less than 45% silica and rich in iron, magnesium, and calcium. They typically composed almost entirely of the ferromagnesian minerals olivine and pyroxene with no feldspars and quartz. Komatiite, the volcanic ultramafic rock, is very rare, Peridotite, the coarse-grained intrusive rock, compose of olivine and pyroxene are the examples of most abundant ultramafic rock.

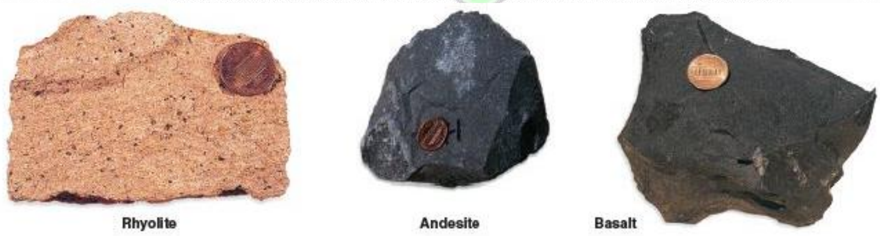
iii. Textural Composition

The rate of cooling and viscosity are the two critical factors that determine grain sizes during the solidification of igneous rocks.

a. Crystalline Textures

Aphanitic (a , "not"; phaner, "visible") Texture:- Rocks are typically fine-grained, i.e their crystals are too small to see easily with the naked eye examples are the extrusive rocks.

The grains, if they are crystals, are small because magma cools rapidly at the Earth's surface, so they have less time to form. Some intrusive rocks are also fine-grained; these occur as smaller bodies that apparently solidified near the surface upon intrusion into relatively cold country rock (probably within a couple kilometers of the Earth's surface).



Phaneritic (from phaner, meaning visible) Texture are those rocks in which their crystals are large enough to be seen easily with the naked eye. They are coarse-grained. The crystals of plutonic rocks are commonly interlocked in a mosaic pattern.

Pegmatite is an extremely coarse-grained (crystals ranging in size from a few centimeters to several meters in length) igneous rock.

Porphyritic texture - are larger crystals (Phenocrysts) that are enclosed in a groundmass of finer-grained crystals or glass. Some porphyritic rocks have a phaneritic groundmass. The larger phenocrysts enclosed in the groundmass are much bigger, usually 2 or more centimeters across. These rocks are considered to be intrusive. Porphyritic granite is an example.

b. Glassy Textures

With extremely rapid or almost instantaneous cooling, individual atoms in the lava are "frozen" in place, forming glass rather than crystals. Obsidian, which is a dark volcanic glass, is one of the few rocks that is not composed of minerals. Because obsidian breaks with a conchoidal fracture, it can be broken in such a way as to produce very sharp edges. The manufacture of obsidian tools dates back to the Stone Age. Today, some surgeons use obsidian for scalpel blades as the cutting edge can be many times sharper than steel surgical scalpels.

c. Textures due to Trapped Gas

A magma deep underground is under high pressure, generally high enough to keep all its gases in a dissolved state. On eruption, the pressure is suddenly released and the gases come out of solution. When a lava solidifies while gas is bubbling through it, holes are trapped in the rock, creating a distinctive vesicular texture. Vesicles are cavities in extrusive rock resulting from gas bubbles that were in lava, and the texture is called vesicular. Vesicular basalt is quite common.

Scoria, a highly vesicular basalt, actually contains more gas space than rock. In more viscous lavas, where the gas cannot escape as easily, the lava is churned into a froth (like the head in a glass of beer). When cooled quickly, it forms pumice, a frothy glass with so much void space that it floats in water.

Powdered pumice is used as an abrasive because it can scratch metal or glass. For example, powdered pumice is used in the production of pencil erasers. You may also have a piece of pumice in your shower that you use to buff the bottom of your feet.

d. Fragmental Texture

When pyroclastic material (ash, pumice, or crystalline rock fragments) accumulates and is cemented or otherwise consolidated, the new rock is called tuff, or volcanic breccia, depending on the size of the fragments.

A tuff is a rock composed of fine grained pyroclastic particles (dust and ash).

A volcanic breccia is a rock that includes larger pieces of volcanic rock.

1.4 Sedimentary Rock

These are secondary rocks formed from the loose fragments or detrital or clastic sediments produced by weathering of older rocks, transported, deposited and undergoes lithification (compaction and/or cementation of sediments). Sediments comprise of rock pieces, mineral grains that precipitates out of water, shell fragments and other loose materials. The four main process that leads to the sedimentary rock formation includes weathering of rocks, transportation, deposition and lithification.

1.4.1 Weathering

The term weathering refers to the processes that change the physical and chemical character of rock at or near the surface. Weathering can be grouped into mechanical (Physical) and chemical processes.

a. Mechanical weathering (physical disintegration) includes several processes that break rock into smaller pieces. The change in the rock is physical; there is little or no chemical change. Rocks can be physically weathered by jointing i.e. formation of cracks in rocks. Joints are form in rocks due to, stretching, or cooling (contraction).

Examples of mechanical weathering

Frost wedging where water fills cracks, freezes, expands, and forces cracks to open causing them to grow. This can lift large blocks.

Root wedging is the same as frost wedging except that roots pry open the cracks.

Salt wedging occurs when evaporating water flows through rocks. The salt crystals pry open the cracks.

b. Chemical weathering is the decomposition of rock from exposure to water and atmospheric gases (principally carbon dioxide, oxygen, and water vapor). As rock is decomposed by these agents, new chemical compounds form. Chemical weathering is typically strongest in warm wet climates.

Types of Chemical weathering:

Dissolution- primarily affects carbonates and salts when a chemical reaction breaks down minerals into new compounds.

E.g. $CaCO_3$ (Calcite) + H_2CO_3 (carbonic acid) = Ca^{2+} (aq) + $2HCO^{-3}$ (bicarbonate)

Hydrolysis- Water acts to 'loosen' chemical bonds to break down minerals. Works faster in slightly acidic water. E.g. H_2O (acidic) ==> H^+ + OH^-,

H^+ + $KAlSi_3O_8$ (K-feldspar) ==> $Al_2Si_2O_5(OH)_4$ (Kaolinite) + K+ (aq) Kaolinite is a clay mineral

Oxidation- This happens when an element loses an electron and commonly when it bonds with oxygen. E.g. $4Fe^{2+}$ + $3O_2$ ==> $2(Fe^3+)2O_3$ (iron lost an electron and went up in charge)

Hydration- When absorption of water into some minerals (mainly clays) causes them to expand

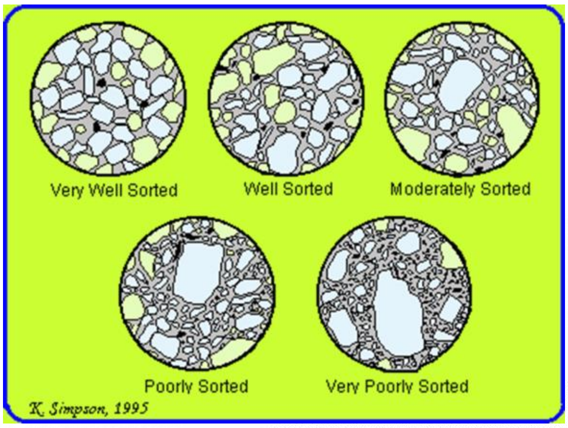
1.4.2 Types of Sedimentary rock

There four types of sedimentary rock. They are Clastic (Detritals), Biochemical, Organic and Chemical.

a. **Siliciclastic Sedimentary Rocks-** These are cemented fragments of pre-existing rocks. They are eroded or transported from weathering site commonly by currents of wind, water, and moving ice (glaciers) to a new locations (downhill or downstream) and deposited, buried and lithified. Clastic rocks are categorized into i. Rudaceous rocks- made up of rounded or sub-rounded pebbles and cobbles e.g. conglomerate; ii. Arenaceous rocks- made up of mainly sand e.g. Sandstone. These rocks are either accumulated by wind action or deposited under water action or marine or Lake Environment; and iii. Argillaceous rocks which are made up of clay size sediments e.g. Shale, mudstones, siltstones. Clastic sedimentary rocks can further be classified base on size, composition, angularity and sphericity, sorting and type of cement. They are largely controlled by mode of transportation, parent rocks and distance of deposition environment to source. **Grain size** are Boulder (>256mm), Cobble (64-256 mm), Pebble (4-64 mm), Granule (2-4mm), Gravel (>256 - 2 mm), Sand 2- 0.062 mm, Silt (0.062-0.004 mm), Clay (<0.004 mm).

Sphericity is the degree of roundness. It helps in knowing the distance of transportation

Sorting of the sediments also suggest the mode of deposition and transportation.



b. **Biochemical Sedimentary Rocks-** This is a sedimentary rock that organisms play a major role in their formation. Many organism have shells of $CaCO_3$ (calcite or polymorph aragonite). Others have shells of silica. When the organism dies, its soft part rots away or turns to organic matters while their shells accumulate to form a biochemical sediments. The shell or skeleton can break into small fragments during transportation and forms calcium-rich sediment at their depositional environments. The common example of such carbonate rocks is limestone. There are many varieties of limestone of biochemical origin such as reef limestone that are dominated by coral reefs, fossiliferous limestones consists shells and shell fragments, Oolites or Oolitic limestones contains small spheres of calcite, chalk that consists of microscopic shells of plankton called forminifera etc.

c. Organic Sedimentary Rocks- They consist of carbon-rich plant remains. The common examples are coal and lignite. It is formed from the remains of plants that grew in swamps or forest. The plant remains became buried and, after being subjected to elevated temperatures and pressures, were converted to the black combustible rock which consist of > 50% carbon.

d. Chemical Sedimentary Rocks- They form as result of precipitation of minerals from aqueous solutions. There are three main types of chemical sediments; Evaporites, Travertines and dolomite/chert. Evaporites formed from evaporation of salt water in a no outlet lake system and a warm climate. Examples of evaporates are gypsum ($CaSO_4.2H_2O$), halite

(NaCl), sylvite (KCl) etc. Travertine is a chemical variety of limestone which forms by direct precipitation from water without organisms being involved. Water, especially acidic water, can dissolve calcite in limestone. The carbonate material is, however, commonly precipitated again, often in limestone caves where salagmites and salactites are formed. This is common around hot spring. Dolomites and chert forms due to the chemical replacement mechanism. Dolomite ($CaMg(CO_3)_2$) forms as a result of reaction between calcite and Mg-bearing groundwater. Chert is an extremely fine-grained (cryptocrystalline) variety of quartz. Black chert called flint. Most plankton have shells composed of carbonate, but some have shells composed of SiO_2. This silica is distributed throughout biochemical limestone are deposited on the sea floor, becomes dissolved by percolating water and may be deposited elsewhere. Deposition may occur along bedding planes, form nodules or take place in an irregular fashion. Reddish chert is called jasper.

1.4.3 Sedimentary Structures

Sedimentary structures are features found within sedimentary rock that help indicate how they formed. These structures are good indicators of paleoenvironments since they usually form during or shortly after deposition of the sediment but before lithification. Sedimentary deposits are formed through material or sediments transportation except in few cases where processes such as biological build up produces coals, reef, and evaporite precipitation. The interaction of sediments with the transporting medium and organisms at the deposition sites gives rise to sedimentary structures. These features are preserved in the rock and consequently provide a record of the process responsible for their formation. Sedimentary structures can be classified into three: physical, chemical and biogenic.

a. **Physical sedimentary structures-** These are the most visible structures most common in clastic rocks. Examples are Beddings if large scale or stratifications if small scale (planar, trough, cross, herring bone), hummocky cross stratification, graded bed, lamination, scour marks, mud crack, flaser bedding, lenticular bedding, etc. These structures are formed from diverse depositional environments.

b. **Chemical sedimentary structures** – Theses are formed as a result of reactions that occur after deposition and can be referred to as diagenetic structures. Examples are stratification, nodules, concretions, deformation and stylolites.

c. **Biogenic sedimentary structures -** They are simply structures that originated through the activities of organisms. They include the following: (1) bioturbation structures (burrows, tracks, trails, root penetration structures), (2) biostratification structures (algal stromatolites, graded bed ding of biogenic origin), (3) bioerosion structures (borings, scrapings, bitings), and (4) excrement (coprolites, such as fecal pellets or fecal castings).

1.5 Metamorphic Rocks

Metamorphic rocks are igneous, sedimentary, or other metamorphic rocks that have been changed by heat, pressure, and chemical reactions with fluids and gases. The textures and composition of the original rock (Protolith) are changed during metamorphism. The effects of metamorphism can form new crystalline structures in rocks, cause the formation of new minerals, and produce the coarsening of texture and layering of minerals. Metamorphic petrology is the study of the solid-state chemical changes that take place in minerals and rock. Abundant evidence now exists to indicate that the mineral assemblages of the common sedimentary and volcanic rocks, when buried and subjected to high temperatures and pressures, become thermodynamically unstable, resulting in the production of new minerals and new textures. James Hutton, a Scottish doctor became fascinated by metamorphic rocks and published a book, Theory of the Earth (1795), and outlined many fundamentals of geology that are still used today. He is referred to as the father of geology. Charles Lyell – first proposed the word metamorphism in his book, Principles of Geology (1833).

Metamorphic Systems

In many cases the bulk chemical composition of the rocks involved remains the same, such that the resultant change are in mineralogy and texture. This is referred to as **Isochemical** metamorphism, and the metamorphic system in this case has remained closed. However, if there is loss or gain, the bulk chemistry varies and this may cause changes in mineralogy, texture and chemistry. This process is referred to as **Allochemical** metamorphism and in this case the metamorphic system is said to be open, allowing exchange of material.

Metamorphism

Metamorphism (a word from Latin and Greek that means literally “changing of form”) refers to changes to rocks that take place in Earth’s interior. Metamorphism doesn’t include weathering, diagenesis, and melting. It is a solid-state process. The transformations of rocks occur in the solid state (meaning the rock does not melt) as result of heat and pressure which may give new textures, new mineral assemblages, or both. The new rock is a metamorphic rock can also be formed as a result of squashing or shearing. Metamorphic rocks can be identified through their textures (grains are interlocked and grew in place), types of minerals (certain minerals only grow under metamorphic temperatures and pressures called a metamorphic mineral assemblage, or metamorphic facies) and foliation (the alignment of platy minerals or alternating layers of light (felsic) and dark (mafic) minerals).

1.5.1 Agents of Metamorphism

a. Heat

Increased temperature (T) agitates the atoms in a crystal lattice and eventually causes that lattice or the chemical bonds to break down and reform to a structure that is stable at the higher temperature (T). This is Prograde metamorphism i.e. it occurs at increasing temperature (T) and or pressure (P). As the new lattice cools, it is able and has time to change back to a structure stable at a lower temperature (T). This is Retrograde metamorphism. The same applies for changing pressure regimes (environment).

Heat sources for metamorphisms are:

- The increase of temperature with increasing depth (thermal gradient) within the earth. Below 30 m temperature increases at approximately 30oC per km depth
- Heat production due to earth's movements particularly those of very large size.
- Heat coming from large bodies of intrusive magma. Probably the most important of the three sources.

b. Pressure

High pressures cause minerals with 'open' lattices to collapse, forming more dense crystals. Most metamorphic rocks form at 40 - 100 km depth where pressures are 10,000 - 30,000 times greater than the surface of the Earth. Pressure can be divided into two types:

- **Hydraulic Pressure**

This is also referred to as hydrostatic stress, or uniform stress. This is purely a function of depth within the earth i.e. at deeper levels the overlying load increases and in consequence the pressure increases. Hydrostatic pressure (P) tends to produce minerals with more compact atomic structures i.e. of greater densities. Hydrostatic pressure (P) is equal in all directions.

- **Shear Stress**

Shear stress is directed pressure that is greatest in a single direction unlike hydraulic pressure. It is associated with large scale movements within the crust and upper mantle. It causes changes in the form and orientation of minerals and promotes mechanical breakdown. It is also referred to as differential stress i.e. when forces are not equal in all directions, minerals may deform and change shape.

c. Hydrothermal Fluids – More than just water, hydrothermal fluids are solutions that chemically react with minerals. The fluids include hot water, steam, and supercritical fluid. Hydrothermal fluids are chemically-active in that they are able to dissolve certain minerals, so they are solutions, and not just water.

Supercritical Fluid is a substance that forms under high temps and pressures that has properties of both gas and liquid. Supercritical fluids permeate rocks like a gas and react with minerals like a fluid.

Where does this fluid come from?

1. groundwater that percolates downward.
2. water and volatiles released from magma
3. water is released during some metamorphic reactions

$KAl_3Si_3O_{10}(OH)_2 + SiO_2 ===> KAlSi_3O_8 + Al_2SiO_5 + H_2O$

Muscovite Quartz K-Feldspar Sillamanite Water

Hydrothermal fluids speed metamorphic reactions because fluids allow for easy transport of ions and fluids are consumed in some reactions

Metasomatism – The process by which a rock's chemical composition changes due to reactions with hydrothermal fluids. This commonly results in the formation of veins, mineral filled cracks.

d. Time

Metamorphic change is a slow process because metamorphism involves changing the rock while it is solid. During metamorphism, several processes are at work. Recrystallization causes changes in minerals size and shape. Chemical reactions occur between the minerals to form new sets of minerals that are more stable at the pressure and temperature of the environment, and new minerals form as a result of polymorphic phase transformations (recall that polymorphs are compounds with the same chemical formula, but different crystal structures.

1.5.2 Types of Metamorphism

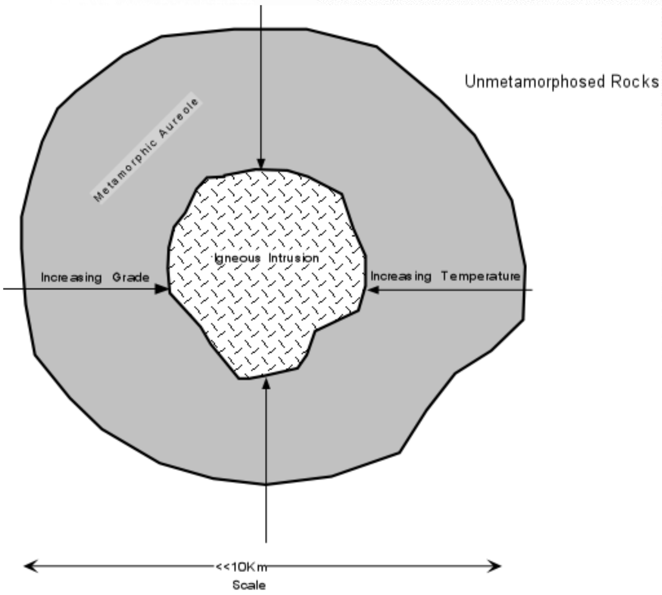
There are four main types of metamorphism, namely dynamic or dislocation metamorphism, contact metamorphism, burial metamorphism and regional metamorphism. A brief summary of their pressure and temperature regime occurrence is summarized here below:

a. Dynamic or Dislocation Metamorphism

This occurs in areas of intense local deformation e.g. in faults and thrust zones. It is essentially a destructive process but some new mineral growth may occur. Temperature and Pressure are usually low but the fault movements that cause rocks to slide past one another produces frictional heating. Dynamic metamorphism is not very common and is restricted to a narrow zone along which the sliding occurred. The rock that is produced is called a mylonite.

b. Contact Metamorphism

This is high Temperature low Pressure metamorphism which occurs near intrusive igneous bodies. The zone of metamorphism around an intrusion is referred to as metamorphic aureole. Metamorphic effects are obviously greatest nearest to the intrusion.

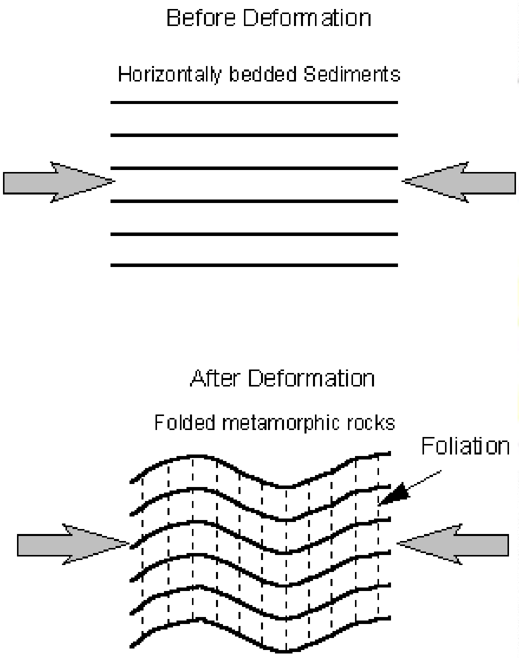


c. Burial Metamorphism

These are changes simply due to Temperature and Pressure increases resulting from depth of burial or overburden stress.

d. Regional Metamorphism

This is a very large-scale phenomenon that occurs at depth owing to the regional thermal gradient. The effects cover very large areas. It is due to combination of temperature, hydrostatic and directed stress and to fluids such that intensity of effects varies laterally as well as vertically. There is no simple relationship to depth or to proximity of igneous bodies. At its highest levels partial melting of rocks occurs and granitic melts are produced.

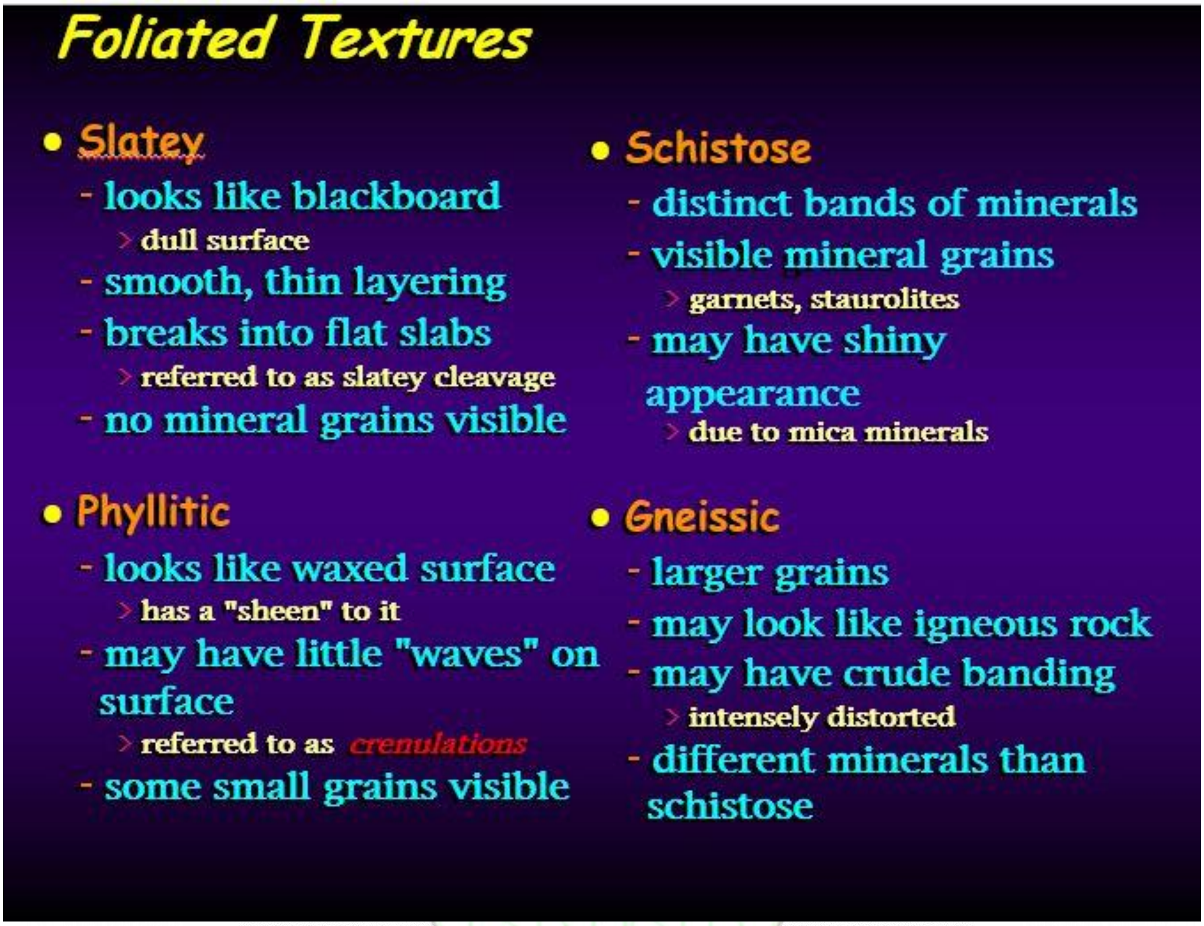


1.5.3 Types of Metamorphic Rocks

Metamorphic rocks are grouped into foliated and non-foliated categories.

a. Foliated Metamorphic Rocks

Foliation is the repetition of planar surfaces or layers in a metamorphic rock. The layers can be paper-thin or meters thick. This happens because when rocks are subjected to differential stress, platy minerals align or alternating light and dark layers form, giving the rock a planar fabric, called foliation. Examples of such rock are slate, phyllite, flattened clast Conglomerate, schist, gneiss, and migmatite.



b. Non-Foliated Metamorphic Rocks

These are metamorphic rocks that have recrystallized and/or neocrystallized but do not typically have a foliation (usually because grains are not sufficiently elongated). They are distinguished based on composition, but may be foliated if subjected to significant differential stress. Examples of such rocks are hornfels, amphibolite, amphibo quartzite, and marble.

1.5.4 Metamorphic Grade

Metamorphic grade is a general term for describing the relative temperature and pressure conditions under which metamorphic rocks form. As the temperature and/or pressure increases on a body of rock we say that the rock undergoes prograde metamorphism or that the grade of metamorphism increases.

Prograde Metamorphism – this is the transformation of lower grade metamorphic rocks to higher grade ones due to an increase in temperature and pressure. Prograde reactions liberate H_2O and CO_2 from the metamorphic body.

a. Low-grade are rocks that form under low temperatures (200 - 320^o C). Low grade metamorphic rocks are characterized by an abundance of hydrous minerals (minerals that contain water, H2O, in their crystal structure). Examples of hydrous minerals that occur in low grade metamorphic rocks are Clay Minerals, Serpentine, Chlorite etc

b. High-grade metamorphism takes place at temperatures greater than 600^{o}C and relatively high pressure. As grade of metamorphism increases, hydrous minerals become less hydrous, by losing H_2O and non-hydrous minerals become more common. Examples of less hydrous minerals and non-hydrous minerals that characterize high grade metamorphic rocks are Muscovite - hydrous mineral that eventually disappears at the highest grade of metamorphism, Biotite - a hydrous mineral that is stable to very high grades of metamorphism, Pyroxene and Garnet - a non-hydrous mineral.

c. Intermediate-grade are rocks that form under temperatures (320 - 600^o C)

Retrograde Metamorphism – This is the transformation of higher grade metamorphic rocks to lower grade ones e.g., amphibolite into greenschist generally due to decreasing temperature. As temperature and pressure fall due to erosion of overlying rock or tectonic uplift, one might expect metamorphism to follow a reverse path and eventually return the rocks to their original un-metamorphosed state. Such a process is referred to as retrograde metamorphism. If retrograde metamorphism were common, we would not commonly see metamorphic rocks at the surface of the Earth. Since we do see metamorphic rocks exposed at the Earth's surface retrograde metamorphism does not appear to be common. The reasons for this include:

- chemical reactions take place more slowly as temperature is decreased
- during prograde metamorphism, fluids such as H_2O and CO_2 are driven off, and these fluids are necessary to form the hydrous minerals that are stable at the Earth's surface.
- chemical reactions take place more rapidly in the presence of fluids, but if the fluids are driven off during prograde metamorphism, they will not be available to speed up reactions during retrograde metamorphism.

a. Metamorphic facies – These are groups of metamorphic minerals that form under similar temperature and pressure conditions.

Metamorphic Compositions

•Occasionally, for simplicity, geologists will simply refer to the composition of a metamorphic rock

i. Mafic (or Basic) Metamorphic Rock – lots of mafic minerals
ii. Calcareous Metamorphic Rock – Calcite-bearing protoliths (limestone)
iii. Quartzo-Feldspathic (i.e. felsic) Metamorphic Rocks – form from protoliths that contain a lot of feldspar and quartz (e.g. granite, diorite)

•Occasionally geologists will simply refer to metamorphic rocks by their protolith

–Metasedimentary rock (Metaconglomerates)

–Metaigneous rock

–Pelitic Metamorphic Rock (Sedimentary protolith)

Metamorphic Rocks	Special Metamorphic Minerals	Common Metamorphic Minerals
Amphibolite	Actinolite	*Quartz*
Blueschist	*Chlorite*	*Orthoclase*
Eclogite	*Corundum*	*Plagioclase*
Gneiss	*Epidote*	*Amphibole*
Granulite	*Garnet*	*Pyroxene*
Greenschist	*Graphite*	*Biotite*
Greenstone	*Kyanite*	*Muscovite*
Hornfels	Serpentinite	Chlorite
Marble - Limestone	*Sillimanite*	
Marble - Dolomite	*Staurolite*	
Migmatite	Talc	
Phyllite		
Quartzite		
Schist		
Serpentinite		
Slate		
Soapstone		

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