More Practice, More Perfect

Lectures in Petrology

Edit.,

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Preface

Egypt is endowed with vast and various tonnages of mineral resources and commercial deposits (e.g. coal, iron ores, phosphorites, marble, Mn ores….etc). The ideal exploitation of such deposits can be achieved by making integration between the mining engineering and the geological sciences, in particular that concern with the study of minerals and rocks.

Minerals and rocks are considered the main constituents of the mineable and non-mineable ores including metallic and non-metallic mineral deposits (e.g. iron ores, sulphide deposits, glauconites, barite….etc) as well as ornamental and building stones (e.g. limestone, shale, granite, marble…..etc). The science of mining engineering, on the other hand, concerns with different disciplines among which preparation, beneficiation, and metallurgy of the commercial minerals and rocks. To be a good mining engineer, you must be aware all aspects related to minerals and rocks such as: a) the different mineral and rock-forming processes; b) the types and classification of minerals and rocks; c) the mineable and non-mineable minerals and rocks; d) the economic and strategic values of minerals and rocks. The current work let you browse and go through four excited disciplines of geology namely, mineralogy, igneous rocks, metamorphic rock, and sedimentary rocks. This is to know the complete identity of different and various commodities you will be seen in the mining areas, and to learn how you can employ what you know about geological information to solve several problems probably appear before, during and after mining.

My best regards,

Dr. Mahmoud Sabry Abdel-Hakeem, 2022

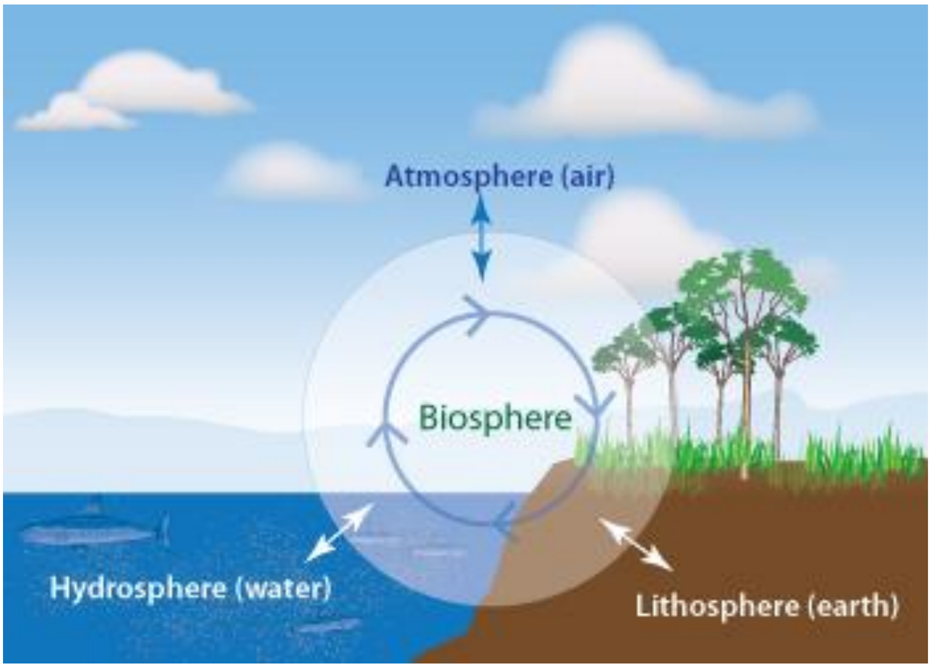
Contents

Lecture#1: Rocks- Definition, Types, and Cycle

1. Rock Definition:

Our planet is enveloped by four main sphere types:

- **Atmosphere** surrounds Earth from all direction and extends vertically up to 10km from sea level. It protects our planet from the harmful sun radiation (e.g. UV).
- **Hydrosphere** represents about 75% of the total area of the earth surface and includes all water bodies that we see (oceans, rivers, lacustrine, lakes….etc).
- **Biosphere** comprises all zones where the different life forms occur.
- **Lithosphere** indicates the solid envelop of the continental and oceanic crusts and consists mainly of different rock types. This sphere includes three different rock types: igneous, metamorphic and sedimentary rocks, with varied thickness between **10km-60km**.



The term rock refers to solid, inorganic/or organic, heterogeneous material consisting of two or more mineral associations and resulting from natural geological processes, which take place on the earth surface or at deep horizons from the surface.

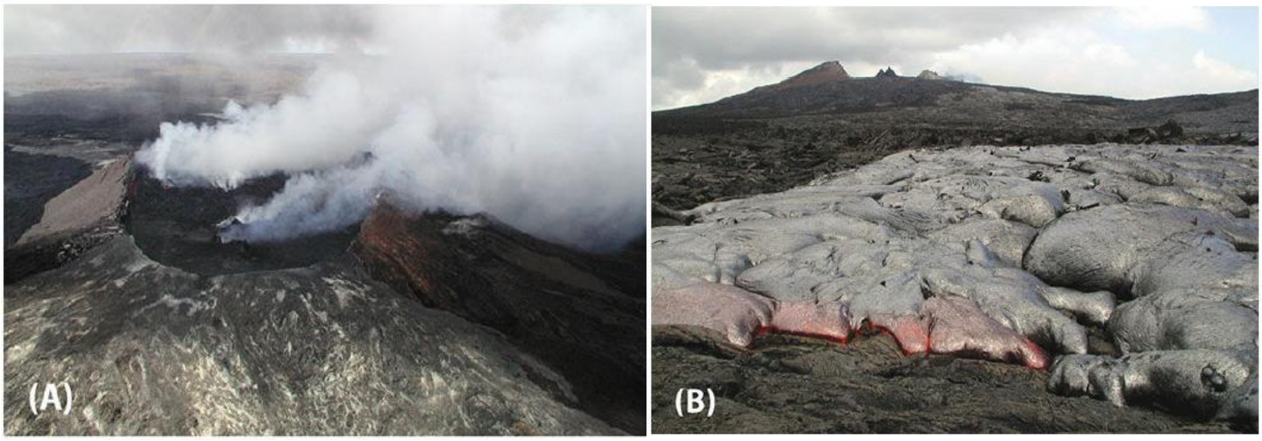
2. Rock types and rock cycle

2.1. Rock types

Rocks are classified, depending on the mechanism of formation, into **igneous**, **metamorphic** and **sedimentary** rocks.

Igneous rocks:

Igneous rocks observed here and there are created by partial melting of the upper mantle rocks, resulting in hot molten phase called magma consisting of diverse and plentiful chemical elements from which the mantle rocks formed. The resultant magma is characterized by lower density than the surrounding country rocks, and hence it tends to ascend toward the upper levels of the earth's crust. The emplacement of magma on the earth surface, **called lava here**, is in the form of volcanic eruptions, and the solidified materials are called volcanic rocks (e.g**. basalt, rhyolite, and andesite**). While the trapped magma in the deep crust levels solidifies to for plutonic rocks (e.g. **granite, diorite, and gabbro**). The latter can be exposed on the earth surface by erosion and tectonic uplifting (such as some of the Red Sea Mountains).



Volcanic eruptions release toxic gases (A) and huge flowing of pillow basaltic lava (B).

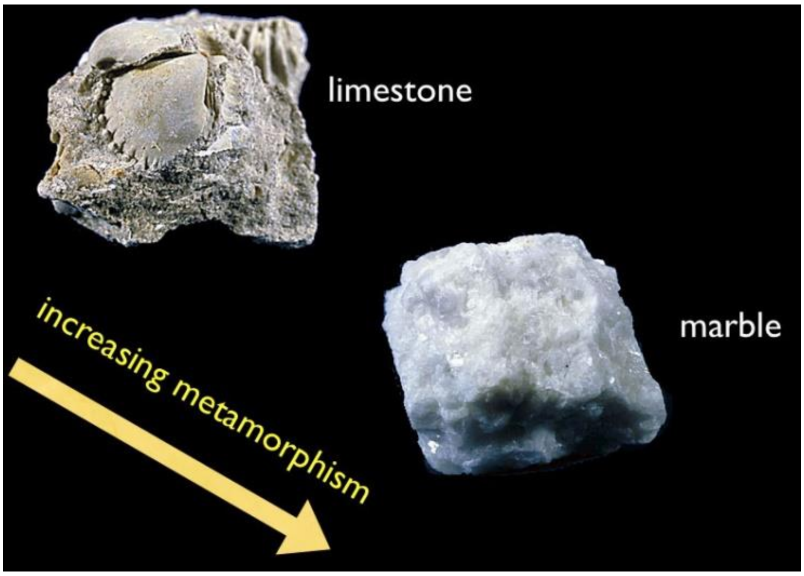
Granite Mountains exposed on the earth surface along the Red Sea Coast

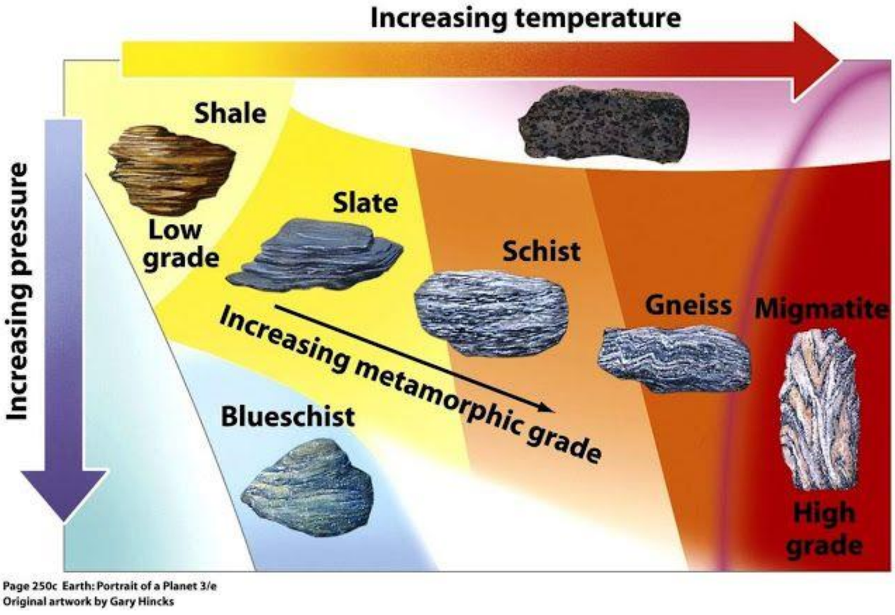
Metamorphic rocks:

When rocks, whether of igneous or sedimentary origin, find themselves in new environments where pressures and temperatures are different from where they formed, minerals change to equilibrate with their new environment, and a new rock is formed. Rocks that are formed in response to changes in environmental factors, such as pressure, temperature, or fluid composition, are described as **metamorphic rocks**.

For example,

- **Marble** is metamorphosed from limestone due to temperature changes.
- **Schist** and Gneiss are metamorphosed from shale and politic rocks due to changes in temperature and pressure conditions.

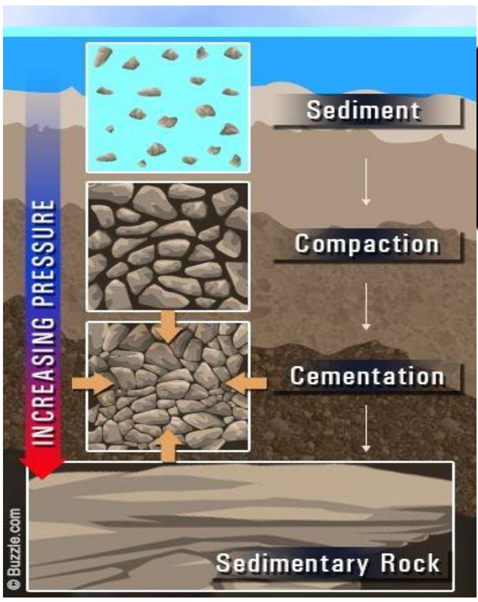


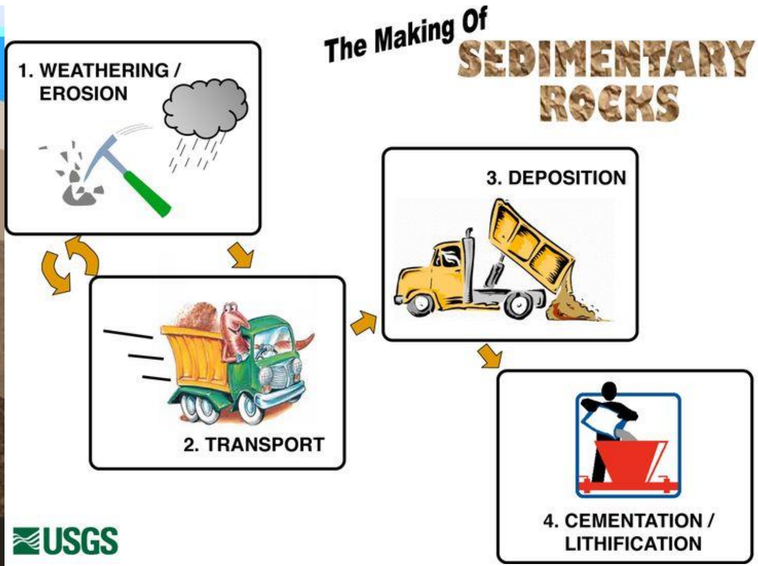


Sedimentary rocks:

Sedimentary rocks are defined as consolidated geological materials driven from erosion, weathering and transportation of pre-existing rocks. A sedimentary rock forms if this sediment finds a basin in which to accumulate. The largest sedimentary basin on the earth surface is ocean where different sedimentary rocks formed and exposed on the land as high mountains (e.g. Gabal Drunka at Assiut, Gabal Duwi at Red Sea). Depending on the formation mechanism, sedimentary rocks can be grouped into:

1. **Clastic sedimentary rocks**, consisting of rock fragments, quartz, feldspar, clay minerals, calcite and iron oxides (e.g. sandstone, siltstone, shale, conglomerate, and breccias)
2. **Bioclastic sedimentary rocks**, consisting of rock fragments, fossil debris, bone fragments, scales, teeth, quartz, feldspar, clay minerals, iron oxide, calcite, and gypsum (e.g. fossiliferous limestone, phosphorite, and fossiliferous shale)
3. **Organic sedimentary rocks**, resulting from sedimentation and accumulation of plant debris, which undergo alteration under the effect of temperature and pressure (e.g. Coal).
4. **Chemical sedimentary rocks**, resulting from the direct precipitation from seawater (e.g. limestone, gypsum, rock salt, and travertine).





What are the difference between sedimentary rocks and basement rocks???

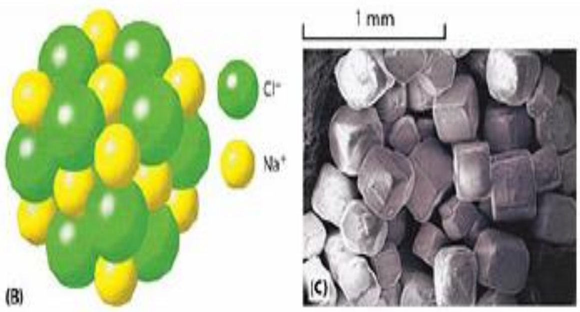
In fact, there are several differences between sedimentary rocks and basement rocks:

- ► **Mode of occurrence**: Sedimentary rocks form on the earth surface, while the basement rocks can form on the surface, at shallow/or great depths.
- ► ***Bedding and layering***: The majority of sedimentary rocks are well-known for their bedding/layering due to changes in mineral composition and grain size during deposition. This is rare for the basement rocks.
- ► **Porosity and permeability**: Sedimentary rocks are characterized by higher degree of porosity and permeability compared to the basement rocks due to the occurrence of vast numbers of intergranular pores between sediment particles.

What is the difference between rocks and minerals?????

- The first difference is what ***so-called homogeneity***. Rocks consist of different mineral associations, while each mineral has unique chemical composition. For more clarification, consider granite rock constitutes quartz, feldspar, mica, and hornblende. Each part of the hand specimen will have a different chemical composition in relative to others. On contrast, each small piece of halite mineral will have the same chemical composition as NaCl.

Hand specimen of granite rock, each part can show different chemical composition in relative to the neighbouring parts.

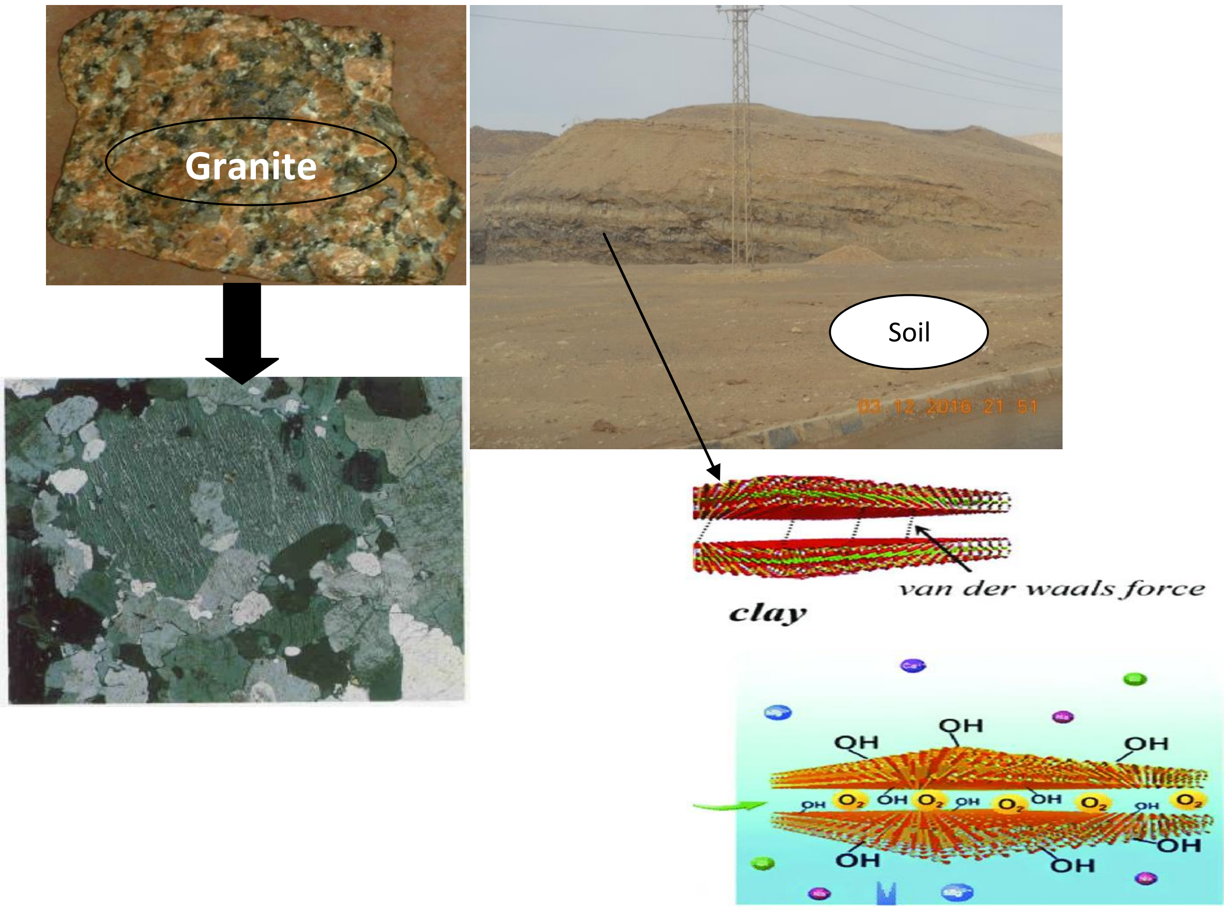


Halite cubes, each micro-area is composed of Na ions connected to Cl.

- Rocks don't have specific crystallographic growth directions, thus it is unexpected to find rock type crystallizes in cubic or tetragonal systems or even rock sample shows cleavage directions.
- Rocks don't have distinguishable lustre or streak.

What is the difference between rocks and soil?????

- Rocks are harder, and in many cases, much harder, than the soils thatblanket the Earth surface. It is the strength of rocks that allow high mountain ranges to stand tall or quarry walls or road cuts to stand at steep angles.
- Rock strength is determined by the way the individual mineral grains are intergrown with one another and the strength of the individual minerals. So, we find that the strength of granite is higher than shale. Granite is composed of quartz, feldspar, mica, and hornblende, which are intergrown with each other without crystallographic orientation. So, there are no weakness planes. On the other side, shale mainly comprises clay minerals occurring as layered sheets connecting to each other by van der Waals force.



2.2. Rock Cycle

- The rock cycle is the process that describes the gradual transformation between the three main types of rocks: **sedimentary, metamorphic, and igneous**. It is occurring continuously in nature through geologic time.
- The rock cycle occurs due to **plate tectonic activity and erosion processes**.
- Steps of rock cycle:

1. Igneous rocks formation

Magma, the molten rock present deep inside the earth, solidifies due to cooling and crystallizes to form a type of rock called igneous rocks. Cooling of igneous rocks can occur slowly beneath the surface of the earth or rapidly at its surface.

2. Weathering

Igneous, sedimentary, and metamorphic rocks present on the surface of the earth are constantly being broken down by wind and water over a long time.

3. Transportation

Carrying away of broken rocks by rain, streams, rivers, and oceans to a distant place from their origin.

4. Deposition

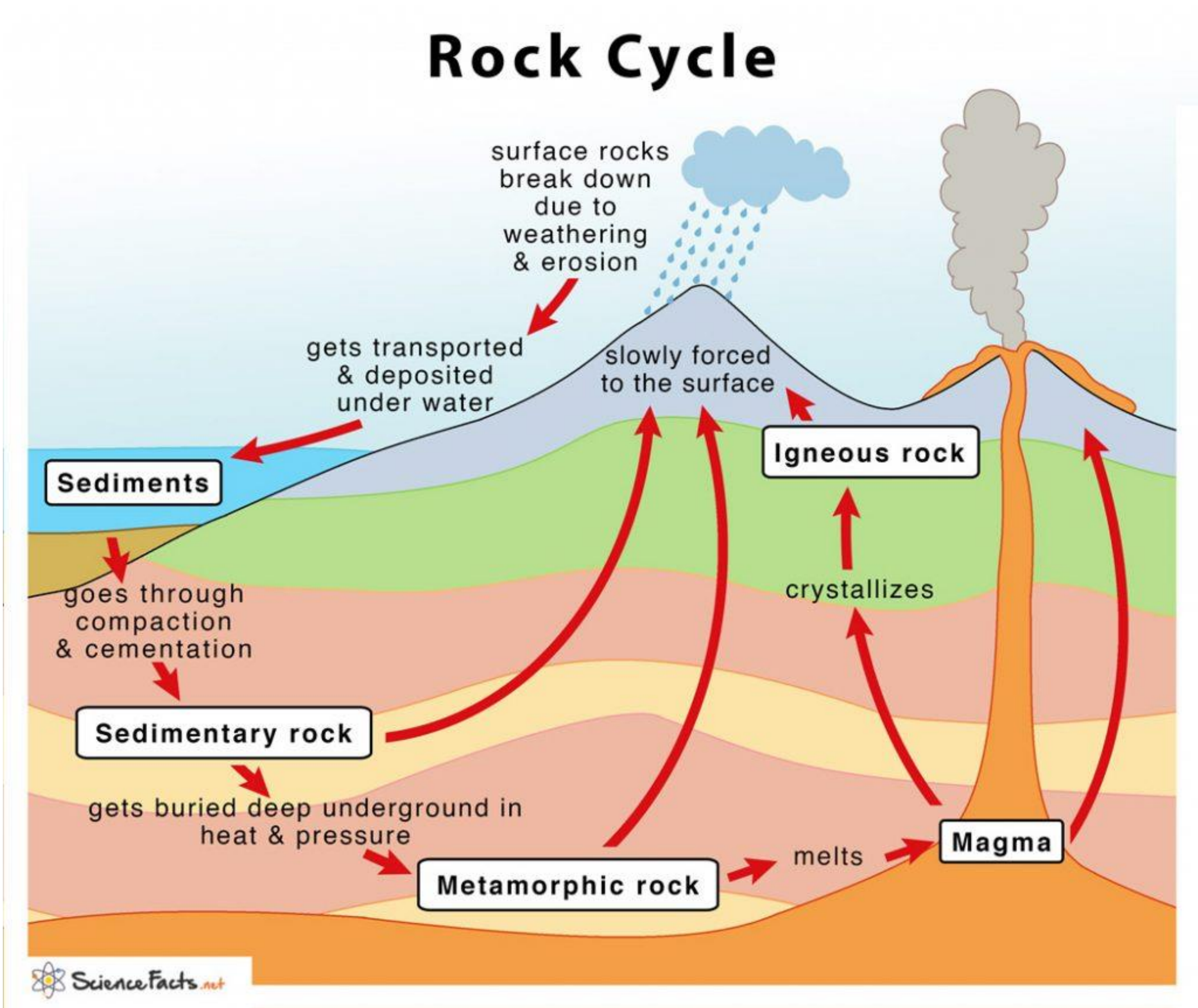
During the carriage of rocks by rivers, the rock particles (mixed with soil) sink and become a layer of sediment. Often the sediments build up and form small accumulations, which over time and pressure turn into sedimentary rock.

5. Sedimentary rocks formation

Due to weathering and erosional activities, the igneous rocks are broken down to form sediments in the form of gravel, sand, silt, and clay, which gets mixed and pressed together for extended periods to form sedimentary rocks.

6. Metamorphic rocks formation

Over a very long period of time, sedimentary and igneous rocks end up being buried deep underground the soil, usually because of the movement of tectonic plates. Deep below the surface, these rocks are exposed to high heat and pressure, which change them into a different type of rock called metamorphic rock.



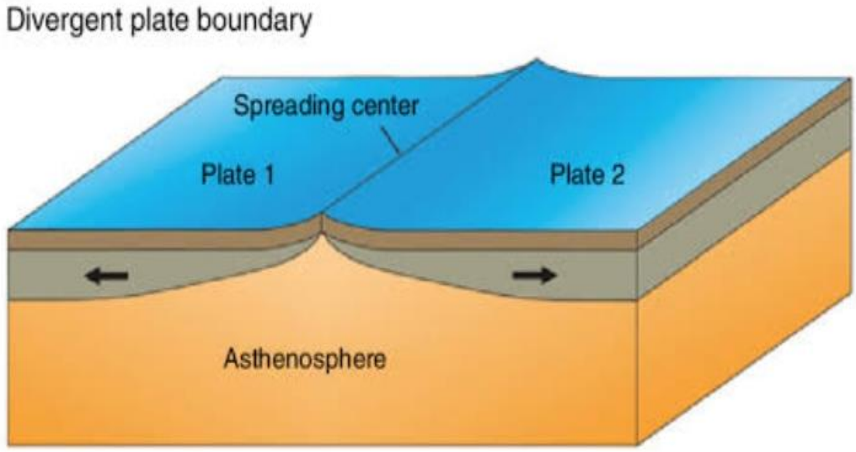
3. Plate Tectonics and Rock Factories

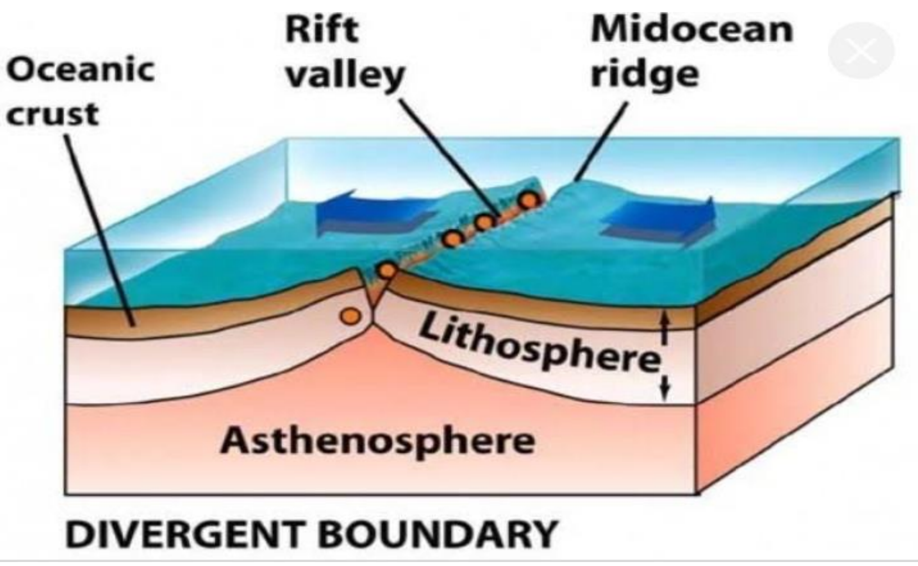
Plate tectonic is a theory states that the solid outer shell of the earth is divided into rigid plates "lithosphere" floating over asthensphere "350 km viscous and ductile region of the upper mantle.

Most rocks are formed at specific plate tectonic locations, which we can think of as **rock factories** – the places where rocks are made in response to plate tectonic-related processes

Divergent plate boundaries.

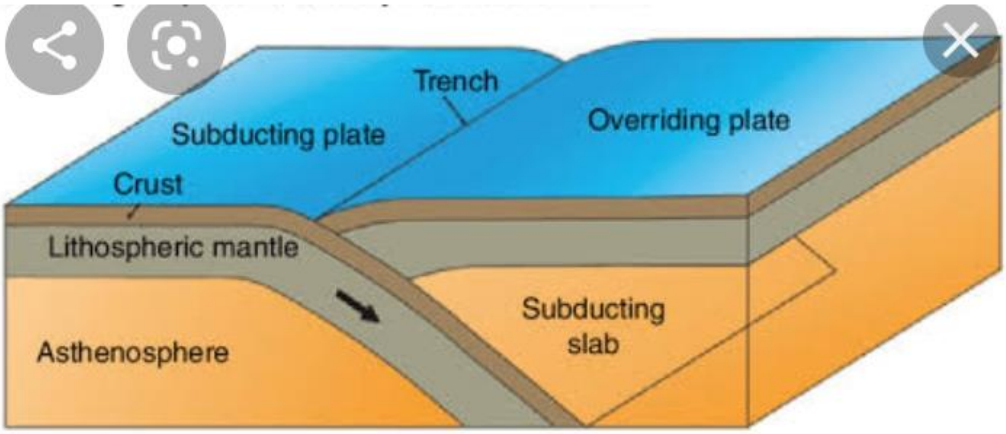
Divergent plate boundaries can occur within continental plates, with formation of rift valleys. These valleys are considered sedimentary basins for different clastic sedimentary rocks such as **sandstones**. The deposition here occur in rivers and lakes formed along rifts, but not in sea/ocean. On the other hand, the molten mantle can find its way to emplace on the earth surface along fissures paralleling the rifts, results in large flat basaltic lava flows called **flood basalts**.





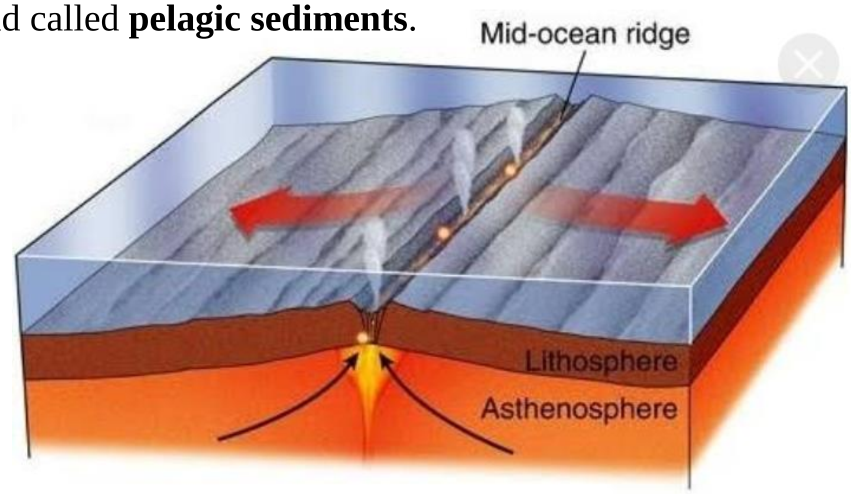
Convergent plate boundaries.

These boundaries are present when continental plate moves toward oceanic plate. The latter is of high density than the latter. So, the oceanic slab is subducted beneath the continental slab and move downward. The increased pressure and temperature cause melting of the subducted basaltic material in the form of magma, which emplaced again on the continental crust as **andesitic volcano** or trapped beneath the surface to form **granitic rocks**.



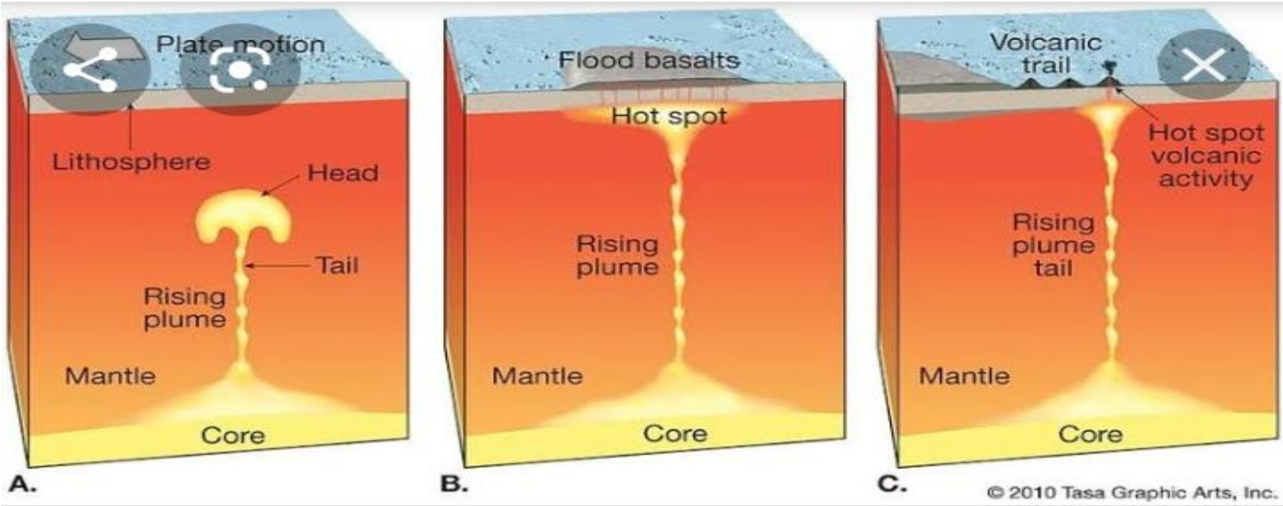
Mid-Ocean Ridge

Mid-ocean rides form when oceanic plates are moved apart. The divergence makes room for magma to rise along fractures to form steeply dipping sheet-like bodies of igneous rock known as dikes and to erupt on the ocean floor along the rift valleys located on the crest of the oceanic ridges. The igneous rocks here include mainly basalt. Because it erupts beneath water, its surface cools rapidly and commonly develops meter-sized blobs of lava known as **pillows**. The main sediments here are silica-rich mud called **pelagic sediments**.



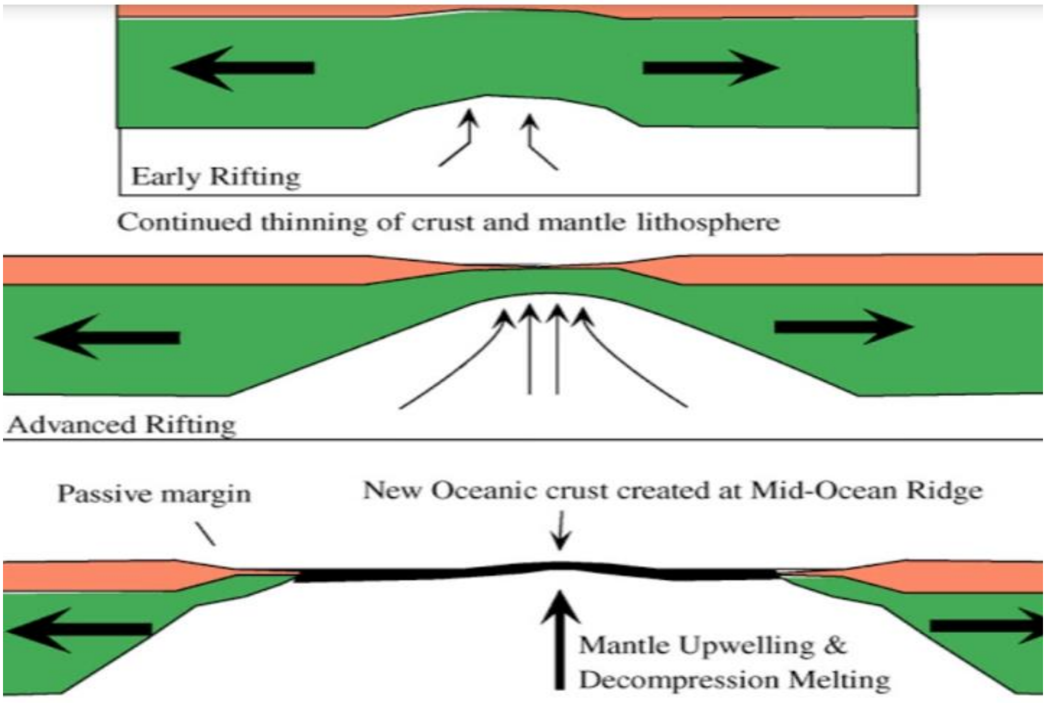
Mantle plumes and hot spots.

Mantle plumes are hot rock currents rising from the mantle due to their lower density than the surrounding rocks. They are subjected to partial melting at the uppermost part of mantle, resulting in hot spots represented by volcanoes on both oceanic crust "basalt" and continental crust "granites".



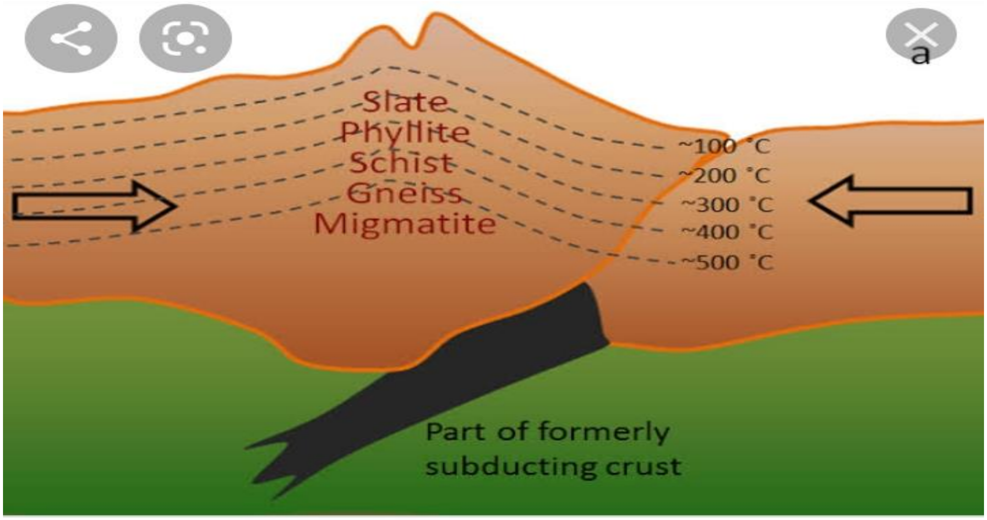
Passive continental margins.

When continents rift apart to form an ocean, passive margins form; that is, the edge of the continent simply abuts the new ocean floor that was formed along the rift. A sequence of sedimentary rocks including sandstone, shale, and limestone is deposited.



Subduction zones

Subduction zones occur when oceanic crust is subducted beneath continental crust. The subducted materials are subjected to an increase in pressure and temperature, leading **metamorphic rocks** to form.

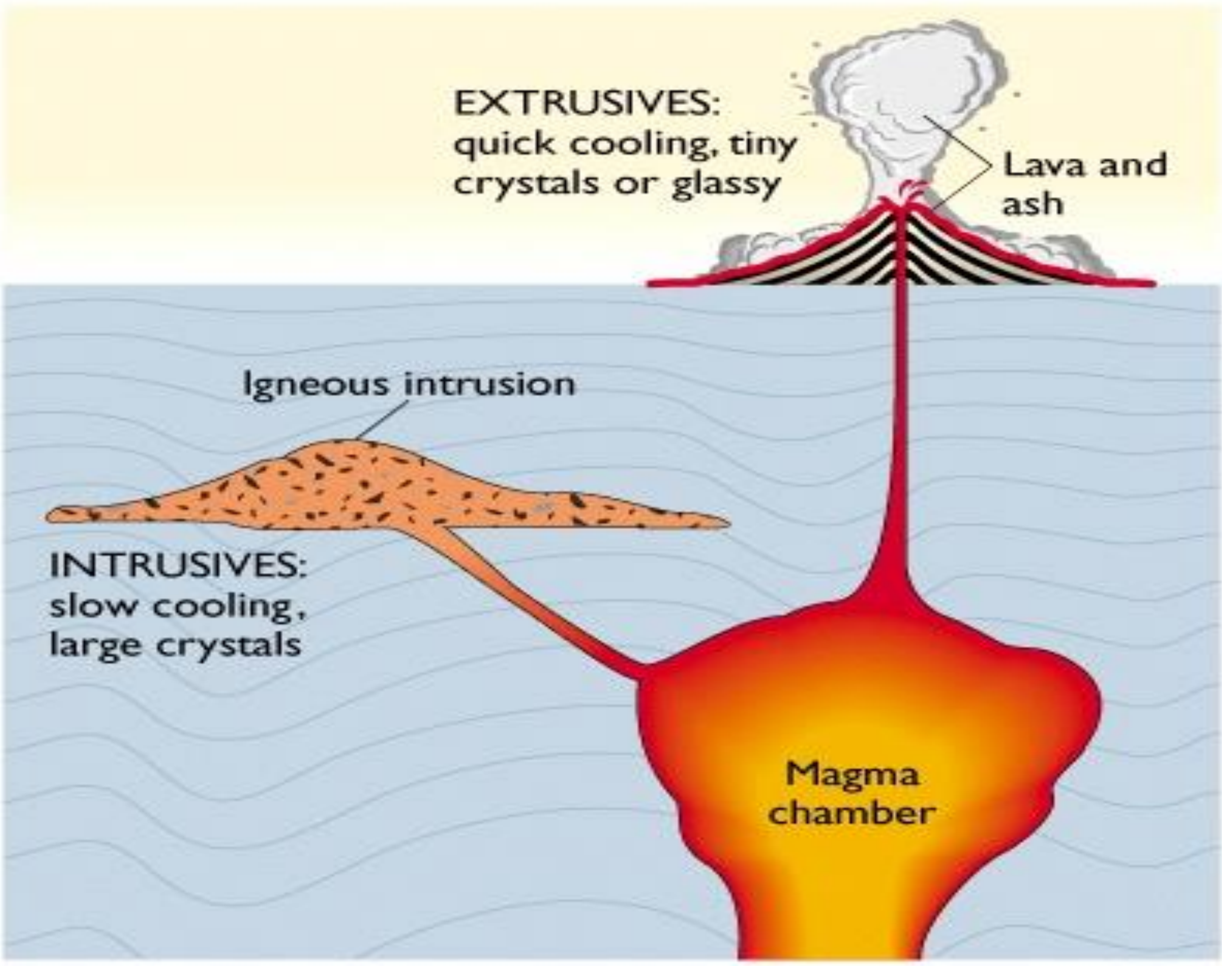


Lecture#2

IGNEOUS ROCKS: Definitions and Magma Crystallization

1. Definition of Igneous Rocks

Igneous rocks are solid, heterogeneous, crystalline materials formed by slow/or rapid cooling of magma/or lava at depths or on the earth surface. There are many different igneous rock types such as granite, rhyolite, gabbro, basalt, diorite, and andesite.



2. Magma and Lava

Magma is the parent material of all rock types that we know. It can be defined as a hot molten rock material formed at the uppermost part of mantle.

Lava is a hot molten rock material originally formed at depths in magma chamber and then emplaced on the earth surface during volcanic eruptions.

3. Partial Melting and Magma Generation

The great variety of magmas and lavas that solidify to produce igneous rocks in Earth's crust are initially formed by a **process called anatexis, which refers to the partial melting of a source rock**. Anatexis produces: (1) a liquid melt fraction enriched in lower temperature constituents, and (2) a residual rock component enriched in higher temperature, refractory elements.

There are two Types of Partial Melting:

1. Equilibrium Melting occurs in a closed system where chemicals are neither added nor removed from the plutonic environment. Equilibrium melting requires that the melt remains in contact with the residual rock throughout the melting process. **As a result, the overall composition of the system remains the same while the composition of melts and solids evolves as follows:**

- ► The melt becomes enriched in low melting temperature constituents. This is most pronounced with small degrees of partial melting **(< 10%)** because the lowest temperature constituents preferentially enter the melt first.
- ► Increased degrees of partial melting (e.g., > 30%) dilute the enrichment of low temperature constituents in the melt; the melt becomes progressively less enriched in low melting temperature elements as higher temperature constituents enter the melt.
- ► The solid refractory residue is enriched in high melting temperature constituents.
- ► With continued partial melting, the solid residue becomes progressively more enriched in the refractory constituents.

2. Fractional /or Disequilibrium Melting implies that solids and melt separate into isolated fractions that do not continue to react together during the melting process.

Because melts are separated from the refractory crystals, liquids and crystals do not remain in equilibrium. Fractional melting produces a melt that is more evolved than the parent source rock from which it was derived. For example, in fractional melting of rocks containing plagioclase and olivine, the early melts are highly enriched in low melting temperature constituents – such as sodium plagioclase and iron olivine – leaving behind a more refractory residual solid enriched in calcium plagioclase and magnesium olivine. Each succeeding melt will be less enriched in low melting temperature constituents than the initial melts. As a general rule, small degrees of partial melting of undepleted (previously unmelted) source rocks produce melts that are highly enriched in low temperature constituents. Larger degrees of melting of previously depleted source rocks produce melts that are significantly less enriched in low temperature constituents. **Fractional melting is especially important in the generation of basalt by the partial melting of mantle peridotite.**

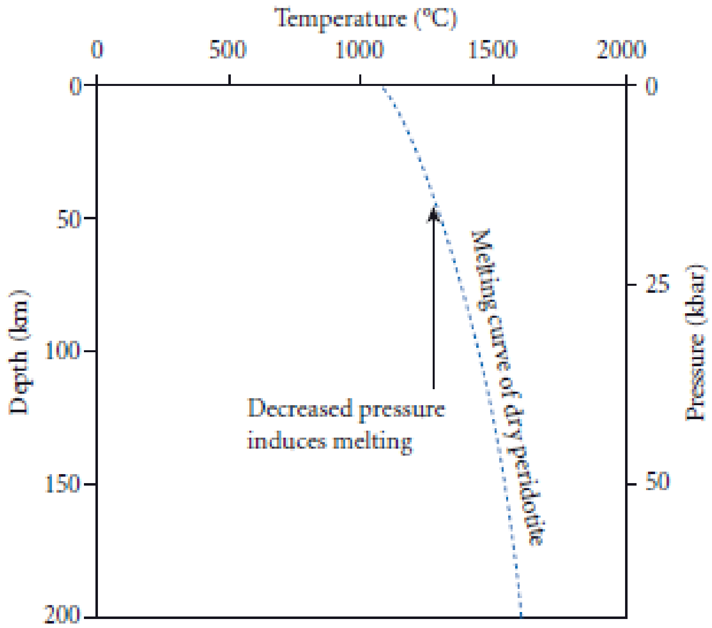
Causes behind Partial Melting

1. Increasing Temperature

Increasing temperature is the most obvious cause for partial melting. Temperature increases with depth within Earth and can be represented by a sloping line called the **geothermal gradient.** The geothermal gradient isn't uniform vertically or laterally within Earth. Earth's average geothermal gradient is 25 ° C/km for the upper 10 km. The geothermal gradient also varies based upon rock age and tectonic setting, ranging from 5–10 ° C/km in old continental lithosphere to 30–50 ° C/km at hotspots, ocean spreading ridges and volcanic arcs. Elevated geothermal gradient sites constitute locations within Earth where mantle peridotite may melt as a result of increasing temperature. These higher temperature regions may be related to hotspots, magmatic intrusions or, less commonly, to localized frictional heating or high concentrations of radioactive elements.

2. Decreasing Pressure

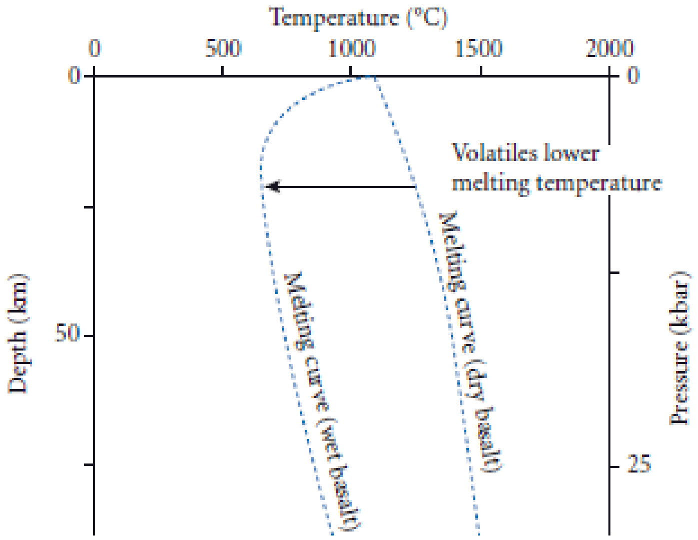
Decompression melting results from a decrease in pressure. Pressure is related to rock depth whereby 10 km depth corresponds approximately to 3.3 kbars. In volatile - poor systems, for example those with low water vapor contents, melting temperatures are proportional to pressure (**water acts as flux agent**). The higher the pressure, the higher the melting temperature. Conversely, as pressure decreases, melting temperature decreases. As a result of lithosphere thinning in extensional environments, the underlying mantle rises upward, effectively decreasing the lithostatic stress. This decompression reduces rock melting temperatures. Decompression melting of mantle peridotite is the primary means by which basaltic magmas are generated at ocean spreading ridges and continental rifts. **Decompression also plays an important role in hotspot regions where warm rocks become less dense, rise and undergo decompression melting.**



Melting temperature of peridotite decreases with decompression.

3. Volatile-Induced Melting

Elevated volatile content under pressure, particularly P H_2O , may significantly lower melting temperatures. In addition to H_2O, other volatiles include compounds such as CO, CO_2 , OH, SO_2 , H_2S, NH_3 , HCl and HF, as well as the elements H, F, Cl, S, He and Ar. Volatiles act as a flux. A **flux** is an agent that reduces the melting temperature of a substance. Water vapor dissolved in magma under pressure tends to weaken Si–O bonds in silicate minerals. As silica bonds are progressively weakened, progressively lower temperatures are necessary to melt solid rock.



Role of water in lowering the melting rock temperature

4. Magma Crystallization and Igneous Rocks Generation

Magma crystallizes to form different rock types starting from Fe&Mg-rich rocks (e.g. basalt and gabbro) to Si & alkali-rich rocks (e.g. granites and rhyolites). Magma crystallization means that the hot molten material is converted into the solid phase "crystals". This scenario is accomplished through physical processes known as ***fractional crystallization*** or ***magmatic differentiation***.

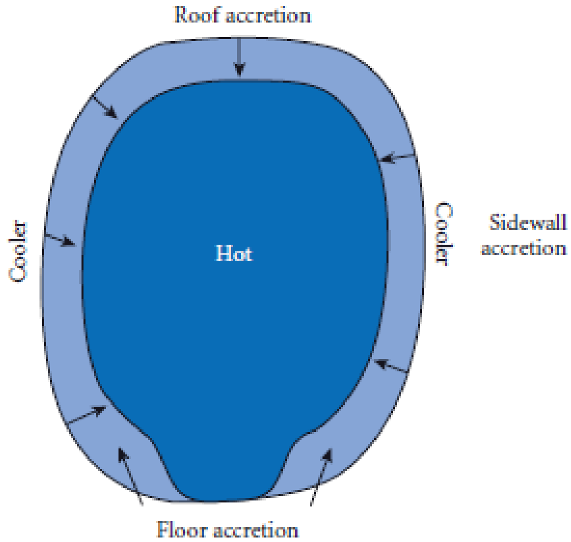
Fractional Crystallization

It involves the effective separation of crystals and melt from an originally homogeneous magma. Models for fractional crystallization involve four mechanisms:

1. *Marginal accretion*

The interior of a magma chamber is well insulated, retains heat and cools relatively slowly. The periphery of the magma chamber in contact with surrounding, cool country rock loses heat by conduction, resulting in relatively rapid crystallization. In addition, crystals in the wall rocks provide nucleation sites for crystal growth.

Crystallization along the walls of the magma chamber in which crystals preferentially form and adhere to the edges results in **marginal accretion.**

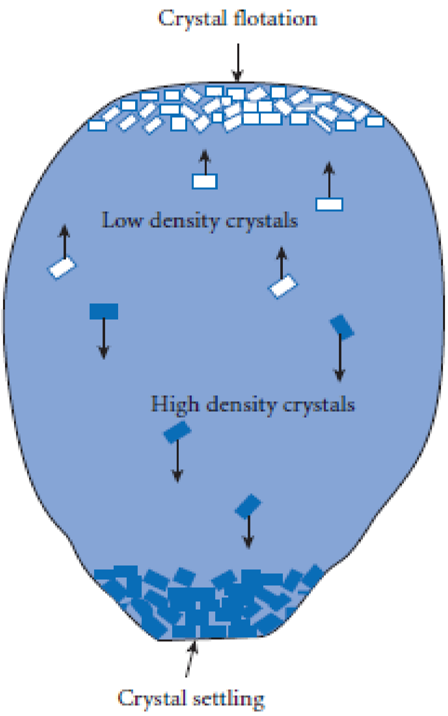


Model for marginal accretion

2. ***Gravitational separation***

Gravitational separation includes fractionation processes that occur when crystals develop with significantly different densities than the surrounding magma. Gravitational separation includes crystal settling and crystal flotation processes. **Crystal settling** occurs when higher density, ferromagnesian crystals settle to the base of a magma chamber relative to the lower density liquid magma. Crystal settling may result in discrete layers of crystal mush such that banded or layered cumulus crystals may precipitate via magmatic "sedimentation" on the pluton floor. **Crystal flotation** can occur if early formed crystals, such as plagioclase, are less dense than the magma. As a result crystals may float towards the roof of a magma chamber, effectively segregating them from the remaining melt.

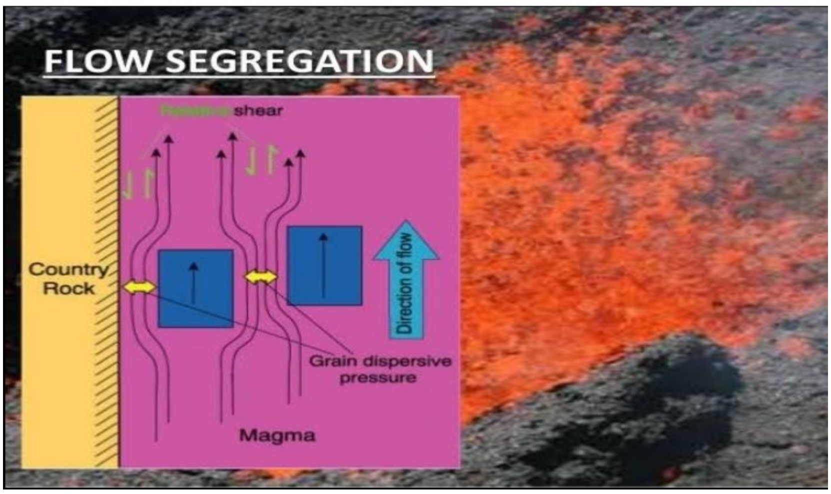
Both crystal settling and crystal flotation imply that individual crystals migrate through a low viscosity magma that has a different density than the crystals. However, in most cases, the differences in density between crystals and magma are vanishingly small and the viscosity of most magmas impedes crystal migration. However, gravitational migration may be possible for large clusters of early formed crystals with higher settling or flotation velocities in very high temperature, low viscosity magma. Crystal migration is far less likely to occur in lower temperature, higher viscosity magmas.



Model for Gravitational settling and crystals migration

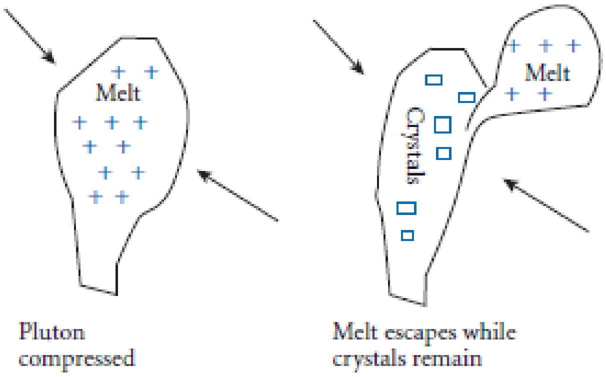
3. *Convective flow*

Convective flow segregation occurs whereby liquids and crystals are segregated due to factors such as velocity, density or temperature. Variations in convective flow velocity within low viscosity magma can result in the sorting of crystals and liquids. The largest or densest crystals will accumulate in regions of high velocity while smaller or lower density crystals accumulate in flow paths of lower velocity.



4. Filter pressing.

The separation of crystals from liquid can occur during the later stages of magma chamber cooling. In this case, cooling can be accompanied by deformation whereby crystals are compacted and rotated while liquids experience expulsion. This variation on crystal – liquid fractionation involves a set of processes under the umbrella of **filter pressing.**



Model for filter pressing

Lecture#3

IGNEOUS ROCKS: Mode of Occurrence& Classification

1. Mode of Occurrence

Depending on the mode of occurrence, igneous rocks can be divided into three main types:

A-Extrusive /or Volcanic Igneous Rocks

Extrusive igneous rocks are formed once the partially melted peridotite "magma" is emplaced/or extruded on the Earth's surface through volcanoes as hot erupted lava, which subjected to rapid cooling as a result of the abrupt decrease in temperature. These rock types are fine-grained and can be called as volcanic rocks (e.g. basalt, rhyolite, dacite, and andesite). The grain fineness of volcanic rocks is ascribed to rapid cooling rate, which don't provide sufficient time for the crystal nuclei to grow as well-developed crystals. So, the result will be volcanic glass or semi-crystalline volcanic rock containing some well-developed crystals surrounded by fine-grained ground, if the rock partly crystallized at depths and then erupted on the Earth's surface.

Note that the chemical composition of the erupted lavas is the same as the deep-seated magmas. So, the resultant volcanic rocks are equivalents for the rock types that crystallize at depth beneath the Earth's surface. For example:

- Rhyolite, Dacite → **Surface equivalent to** → Granite
- Basalt → **Surface equivalent to** → Gabbro
- Andesite → **Surface equivalent to** → Diorite
- Trachyte → **Surface equivalent to** → Syenite

B-Plutonic Igneous Rocks

These rocks are crystallized at deeper parts of the Earth's crust, either close to or far from the magma chamber where peridotite rocks are partly melted. The resultant magma here is undergone a gradual decrease in temperature "slow cooling rate" due to the contact with the refractory country mantle rocks. The slow cooling rate enables the continuous growth of the crystal nuclei, thereby resulting in well-developed, coarse-grained mineral crystals tightly locked with each other to form the final product of the plutonic crystallization, plutonic igneous rocks (e.g. Granite; Gabbro; Diorite; Syenite). Due to the post-genetic tectonic uplifting along with erosion and weathering processes, we can see these plutonic rocks on the Earth's surface (e.g. Granite and Diorite Mountains at the Red Sea Coast.

Gold-hosted Granites at Sukari Mine, Eastern Desert.

C-Intrusive Igneous Rocks

Intrusive igneous rocks include both volcanic and plutonic varieties, which intrude into the surrounding country rocks. For example, we can basalt intruded into granites.

Black-colored basaltic dike is intruded into light-colored granite

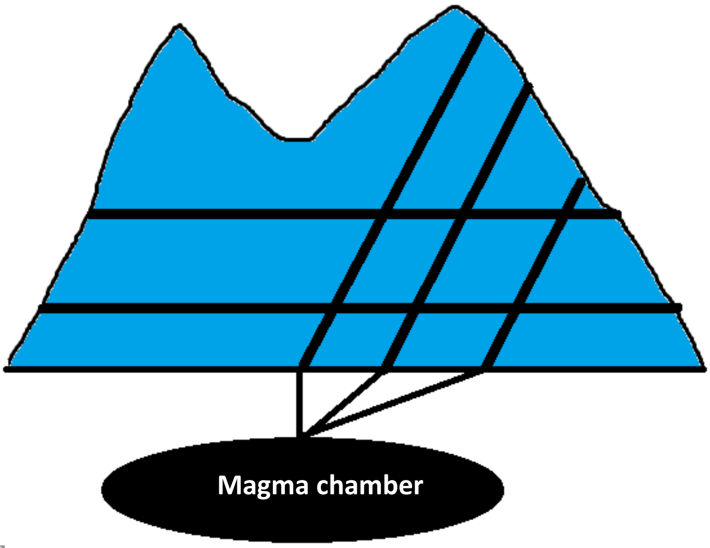
The intrusive igneous rocks occur as:

1. **<u>Shallow intrusive igneous bodies</u>** are reported in various forms such as sills, dikes, and laccoliths.
   - **<u>Shallow intrusive sills:</u>**

Sills are sheet-like, concordant igneous intrusions formed by multiple injections of magma along a plane (e.g. bedding, foliations) of weakness parallel to the layering in the country rocks. <u>Sills commonly form in low viscosity magmas</u>.

- **<u>Shallow intrusive dikes:</u>**

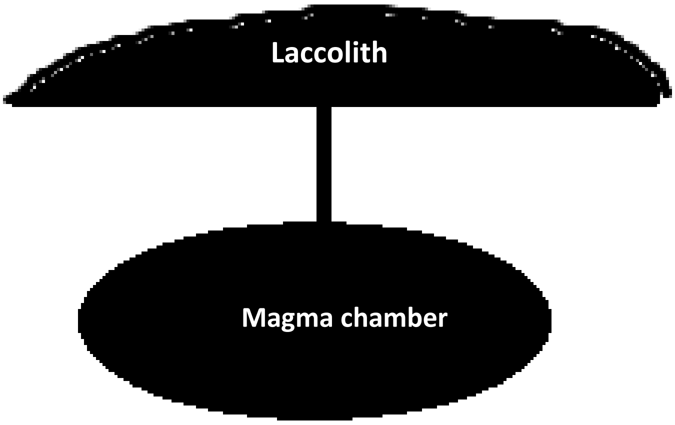
Dikes are sheet-like, discordant igneous intrusions formed by multiple injections of magma. Because dike rocks are typically more resistant to weathering and erosion than surrounding country rock, dike exposures commonly form topographically elevated ridges.



Concordant sills and discordant dikes in limestone

- <u>**Shallow intrusive laccoliths:**</u>

Laccolith is a blister - like concordant pluton characterized by a flat floor and domed roof. Laccoliths are similar to sills in that the magma is injected parallel to the country rock layering. Laccoliths may begin as flat – topped sill structures. The intrusion of additional magma produces sufficient force to bulge the sill roof upward creating a convex structure.



2. **Plutonic intrusive igneous bodies** are reported in various forms such as lapoliths, batholiths, and stocks.

- **<u>Plutonic intrusive Lapoliths</u>**

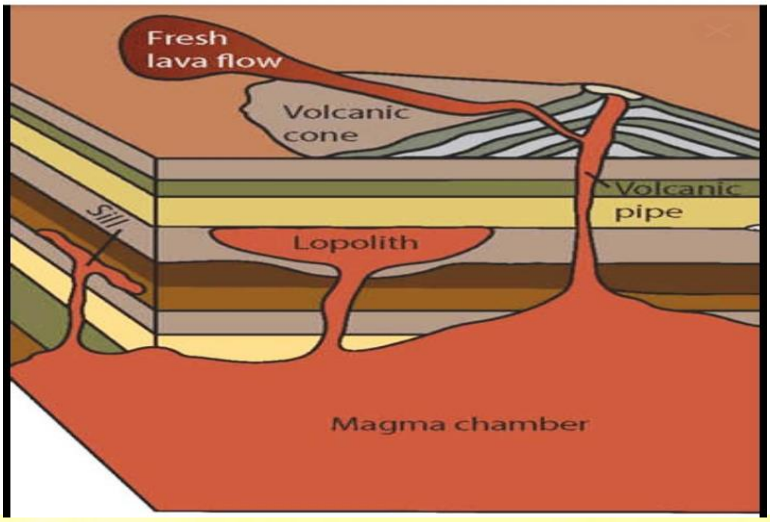
Lopoliths are dish - shaped to funnel – shaped concordant plutons such as Bushveld Complex.

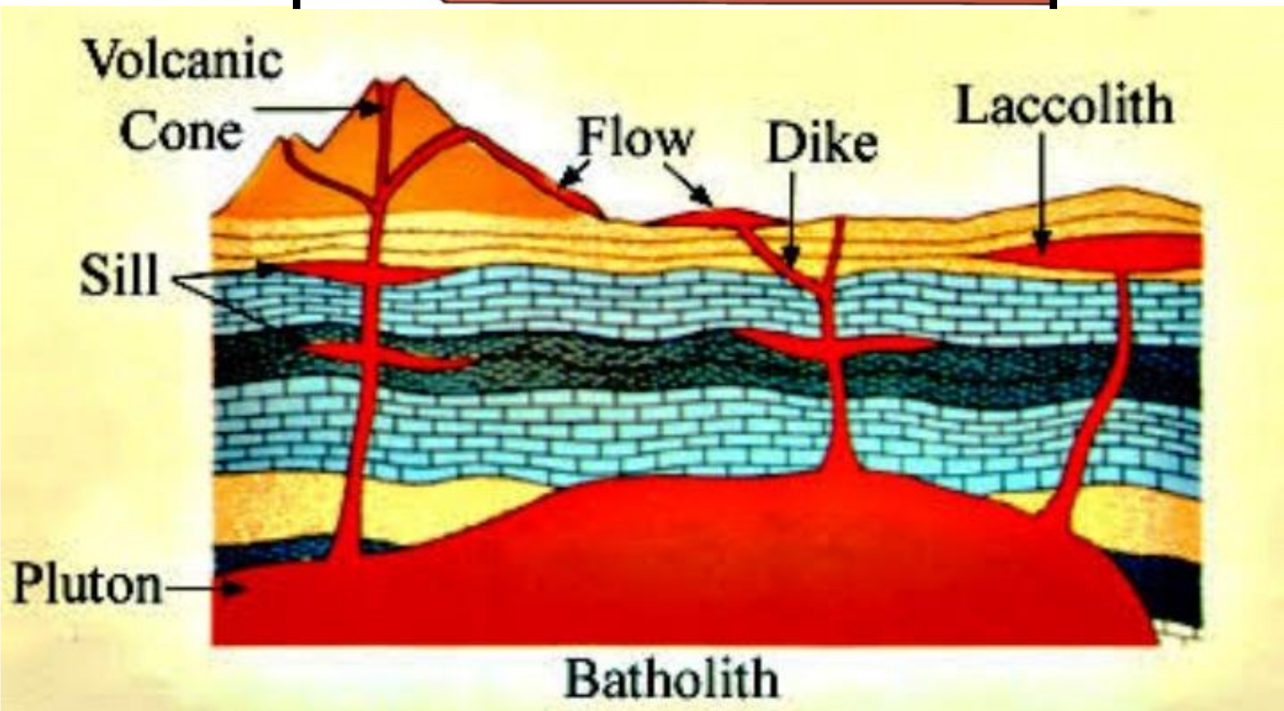
- **<u>Plutonic intrusive Batholiths</u>**

Batholiths are defined as plutons of more or less irregular shape with surface exposures $\geq$100 km ^{2}.

- **<u>Plutonic intrusive Stocks</u>**

Stocks are plutons with surface exposures < 100 km^2.





2. Classification of Igneous Rocks

- Igneous rocks are classified according to composition and texture.
- Composition is determined by magma chemistry.
- Texture refers to the size, shape, arrangement and degree of crystallinity of a rock's constituents.
- Together, these two sets of rock characteristics provide a means to classify rocks and to determine environmental conditions of rock formation.

2.1. Chemical Classification of Igneous Rocks

- Nearly all magmas are silicate magma contain anywhere from 40% to over 75% silica (SiO2). As silica is generally the dominant chemical component, magma and igneous rocks are classified as **ultrabasic** , **basic** , **intermediate** and **acidic** based upon percent SiO2.

Rock group	Weight percent silica (SiO_2)
Ultrabasic	<45%
Basic	45–52%
Intermediate	52–66%
Acidic (silicic)	>66%

- Magma chemistry determines the relative percentage of dark-colored or light-colored minerals. Dark-colored minerals are generally enriched in the elements iron and magnesium and are referred to as ferromagnesian or **mafic** minerals. Light-colored **felsic** minerals are depleted in ferromagnesian elements and are generally enriched in elements such as silicon, oxygen, potassium and sodium.

Classification	Description
Ultramafic	Dark or greenish rocks rich in olivine; may also contain pyroxene or amphibole
Mafic	Dark-colored rocks containing pyroxene, amphibole ± olivine ± biotite
Intermediate	Grayish to salt and pepper-colored rocks rich in plagioclase, amphibole ± biotite ± quartz
Felsic	Light-colored or red rocks rich in potassium feldspar, quartz ± biotite or muscovite

Ultramafic	Mafic	Intermediate	Felsic		Crystalline textures
Peridotite	Gabbro	Diorite	Granodiorite	Granite	Coarse grains (phaneritic)
Komatiite (not shown)	Basalt	Andesite	Dacite	Rhyolite	Fine grains (aphanitic)

2.2. Textural Classification of Igneous Rocks

- ► Igneous rocks can also be classified depending on their texture "size, shape, arrangement, and crystallinity of mineral constituents".
- ► Igneous textures can be broadly categorized depending on crystallinity into ***crystalline and non-crystalline textures***.
- ► **For crystalline textures**, given appropriate time, temperature and pressure conditions, silica tetrahedron structures within cooling magma link together to produce crystals.
- ► In some instances, extremely rapid cooling or the sudden loss of gas may result in solidification without the development of crystals, creating a glassy solid or **non-crystalline texture**.
- ► The degree of crystallization can be classified into **holocrystalline**, **hypocrystalline** and **holohyaline** textures; these terms, simply stated, mean wholly crystalline, partially crystalline/partially glass and wholly glassy textures, respectively.

Crystalline Igneous Textures

According to crystal shape, the following classifications are considered:

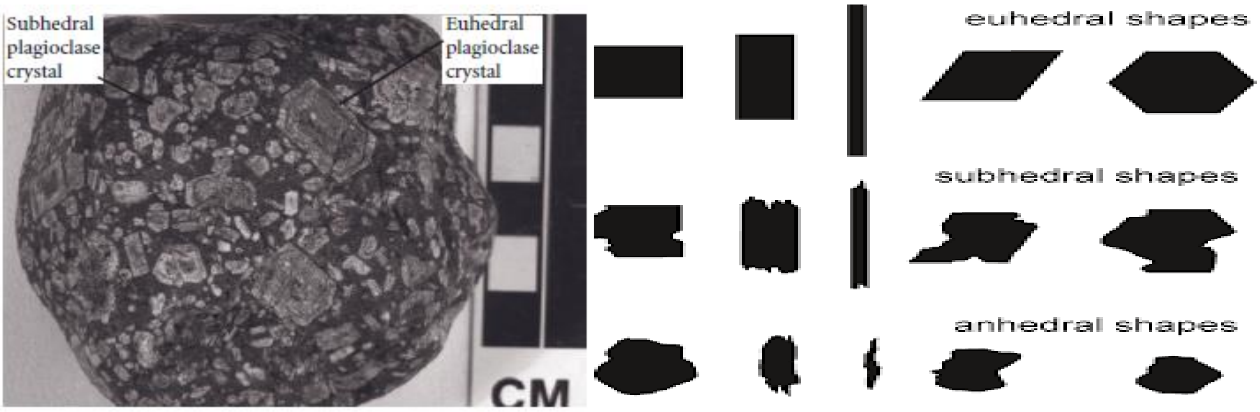
- **Euhedral crystals** contain complete crystal faces that are not impinged upon by other crystals. Euhedral crystals typically develop as early mineral phases in the crystallization of magma. Under such conditions the crystals have abundant free space for growth, enhancing the likelihood that perfectly formed crystal face develop.
- **Subhedral crystal** faces contain partially complete crystal forms in which at least one of the crystal faces is impinged upon by adjacent rock material. In subhedral textures, crystal growth may **be aborted due to**:

• Contact against previously formed minerals.

• Nucleation on pre-existing surfaces such as early formed crystals or the margins of the magma chamber.

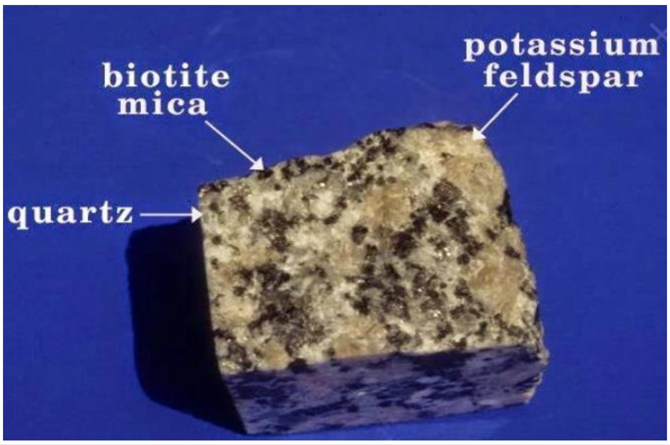
• Resorption in which pre - existing euhedral crystals are partially remelted.

- **Anhedral crystals** lack any observable crystal faces. As crystallization progresses in magma, the space available for the development of euhedral and subhedral crystals diminishes. As a result, anhedral crystal forms are determined by the shape of the existing space. **The remaining voids between existing crystal forms are referred to as interstitial space**.

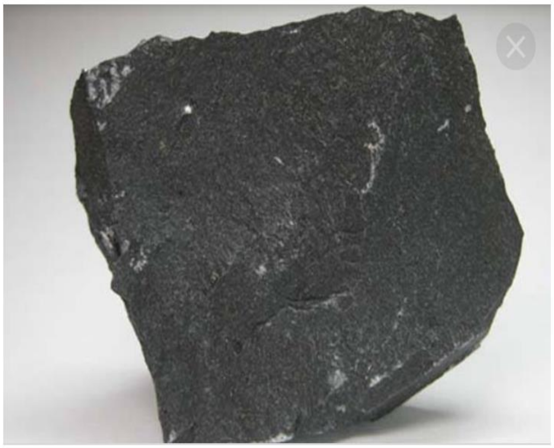


__**According to crystal size, rock textures can be classified as:**__

- **Phaneritic textures** distinguish the coarse-grained igneous rocks whose minerals are all crystallized in large sizes, allowing the identification by the nicked eye. So, these texture types are confined to the plutonic igneous rocks.



- **Aphanitic** textures contain too small crystals to be identified by nicked eye, but the microscopic investigation is needed here. So, these texture types are related to the fine-grained igneous rocks.



- Rocks with **porphyritic textures** consist of two distinctly different size crystals. Large crystals are referred to as phenocrysts ; finer grained material constitutes the groundmass. In **porphyritic-phaneritic** textures, all crystals are visible to the eye, but the phenocrysts are distinctly larger than the groundmass crystals. In rocks with **porphyritic-aphanitic** textures, the larger phenocrysts are embedded in an aphanitic groundmass composed largely of microcrystalline, cryptocrystalline or glassy material.

Non-Crystalline Igneous Textures

Glassy, vesicular and pyroclastic are examples of non - crystalline igneous textures.

- **Glassy textures** develop in lava that solidifies without experiencing significant crystallization (e.g. Obsidian, consisting of glassy amorphous material).

- **Vesicular textures** contain spherical to ellipsoidal void spaces called vesicles, which are analogous to holes in a household sponge. Vesicular textures develop due to exsolution and entrapment of gas bubbles in lava as it cools and solidifies.

- Volcanic eruptions eject broken rock particles of varying sizes, known as **pyroclasts** (which means fiery fragment). Pyroclasts may be ejected into the atmosphere as airborne **tephra** or transported along Earth' s surface as pyroclastic flows. Following accumulation, these particles are cemented or welded together to produce volcanic rocks with fragmental or **pyroclastic textures.**

Lecture#4

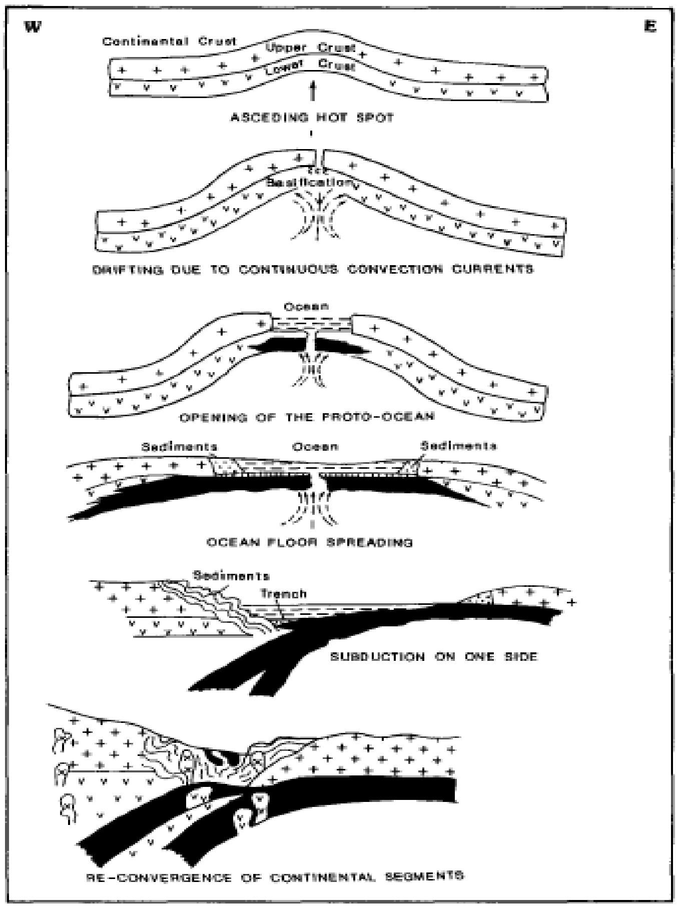
Examples of some Igneous Rocks

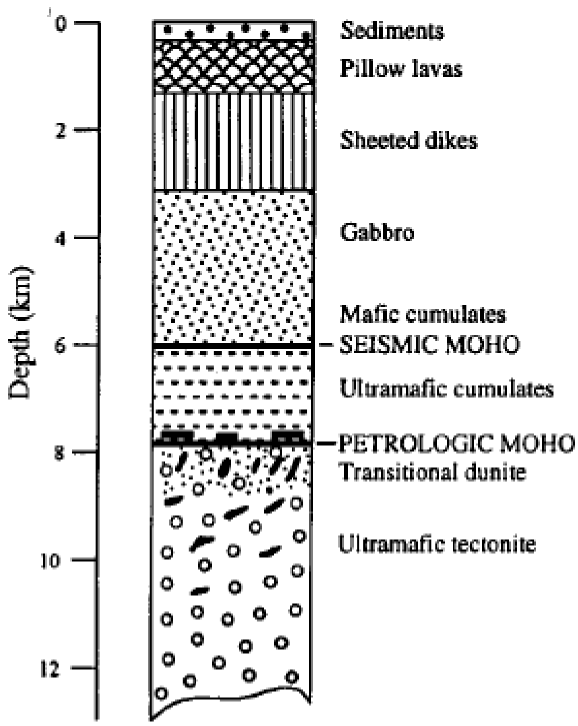
Here we will discuss different types of igneous rocks including ultra-mafic, mafic, intermediate, and felsic varieties in terms of mode of occurrence, mineralogy and texture.

Ultramafic Rocks

1-Mode of Occurrence:

Ultramafic rocks crystallize from magma enriched in MgO "more than 18% MgO" and depleted in Ca, Na, and K. These rocks are cooled at deep parts of the Earth's crust and can be emplaced on the Earth's surface either as ultramafic lavas such as komatiite or as mafic-ultramafic association stripped from the subducted oceanic crust and called ophiolite sequence.





2-Mineralogy:

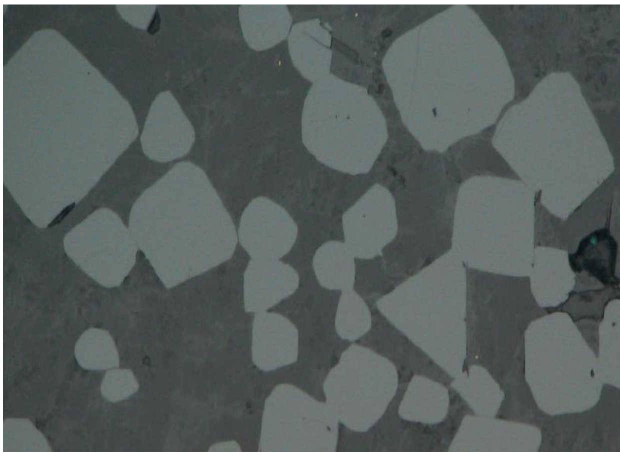
The ultramafic rocks may be composed of one of more ferromagnesian minerals (olivine; pyroxene; hornblende). Note that Ca or alkali feldspars are rare in such rock types due to the early crystallization before reaching plagioclase saturation. For example:

Olivinite---------olivine.
Pyroxenite-------pyroxene.
Peridotite---------Olivine+ Pyroxene.
Dunite-----------Olivine+Pyroxene, the percent of olivine here is higher than peridotite.
Hornblende Peridotite--------Olivine+Pyroxene+Hornblende.

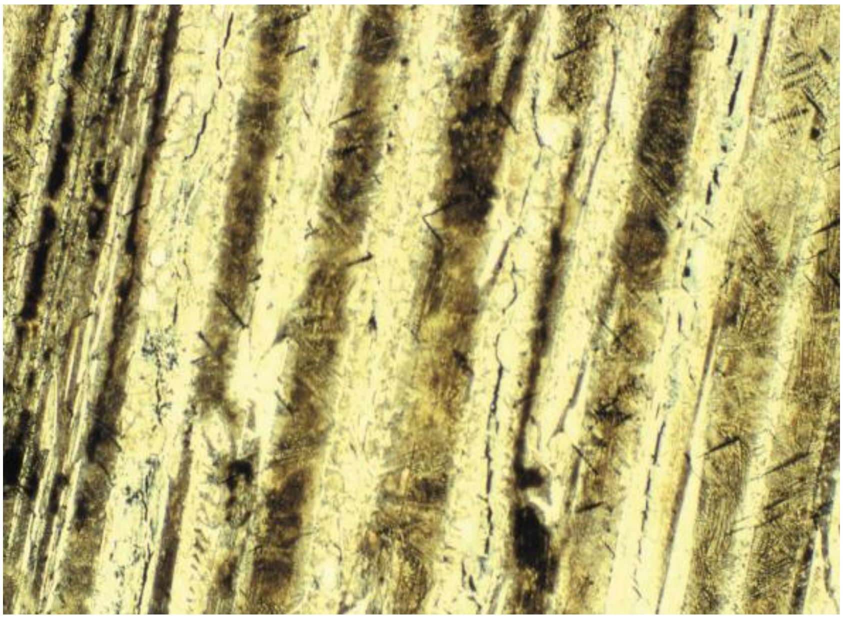
3-Texture and Alteration:

The ultramafic rocks are characterized by cumulus and spinifex textures. The cumulus texture is restricted to the plutonic ultramafic rocks and consists of euhedral-to-subhedral crystals of chromite surrounded by olivine. This texture is resulted from the gravitation separation of chromite and olivine from the parent melt and settling them on the magma chamber floor at the early stages of magmatic crystallization.

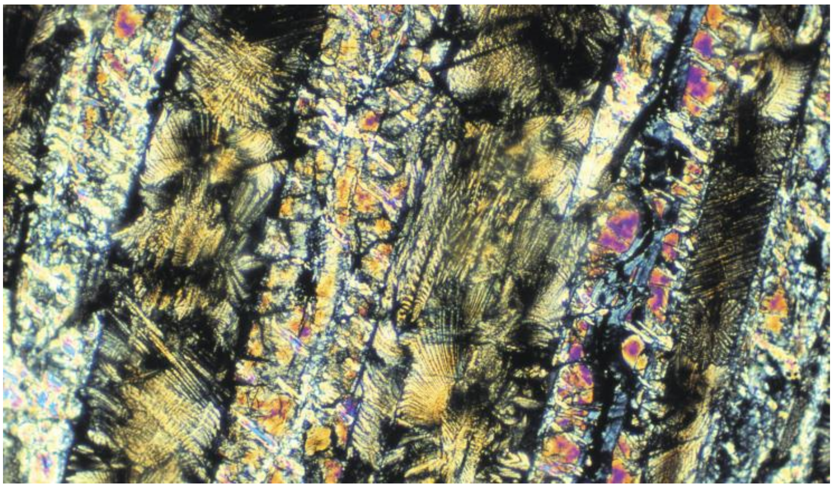
On the other hand, spinifex texture is a characteristic feature of the ultramafic volcanic rocks. On rapid cooling rate, olivine begins to crystallize as elongated platy crystals along with dendritic chromite.



Cumulus texture consisting of euhedral-subhedral chromite crystals "light in color" surrounded by olivine "dark in color".



Spinifex texture consisting of elongated olivine crystals "light in color" with interstitial dendritic chromite "dark in color".



Spinifex texture consisting of elongated olivine crystals "high interference colors" with interstitial dendritic pyroxene "yellow in color".

Regarding alteration,

Ultramafic rocks, whatever their origin, are very prone to hydrothermal alteration. Magnesian olivine and orthopyroxenes react readily with hot aqueous fluids to form serpentine minerals.

Ultramafic rock in which most of the olivine has been altered to serpentine is called a *serpentinit* . Low grade metamorphism of ultramafic c rocks may result in serpentine or talc rocks.

Fayalite+water--------- magnetite+ aqueous silica+hydrogen

$3Fe_2SiO_4+2H_2O$--------$2Fe_3O_4+ SiO_2$ "aqu."+H

Forsterite+aqueous silica+water--------serpentine

$3Mg_2SiO_4+SiO_4+H_2O$-------$2Mg_3Si_2O_5 (OH)_4$.

Serpintinization process

Mafic Rocks

1-Mode of Occurrence:

Mafic rocks are either fine to medium-grained rocks in the form for extrusive and intrusive igneous bodies (e.g. pillow basalt and basaltic dikes in ophiolite sequence) or coarse-grained intrusive igneous bodies (e.g. intrusive gabbro rocks).

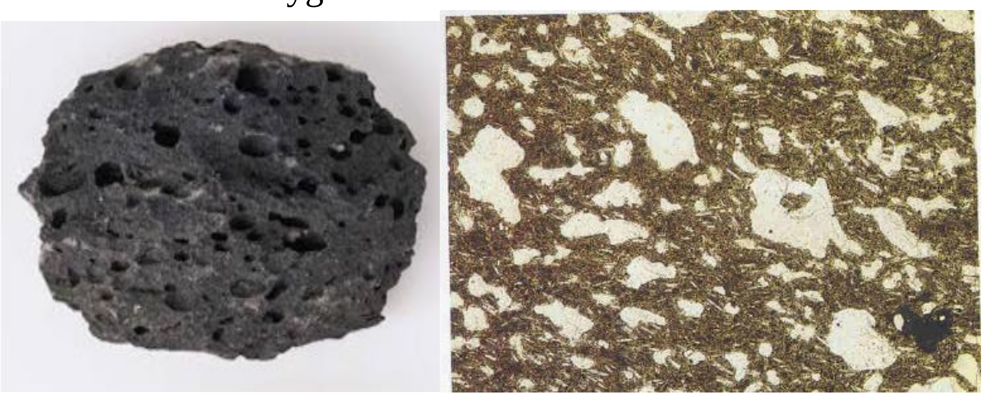
2-Mineralogy:

Mafic rocks crystallize from magma containing 45-52% SiO_2 and MgO less than 15%. This is reflected by the occurrence of specific ferromagnesian minerals including pyroxene and hornblende with lesser amount of olivine. Ferromagnesian minerals are associated with Ca-Na plagioclase mineral series. Quartz cannot be found here due to the consumption of all silica during the crystallization of Fe-Mg minerals and plagioclase. So, these rock types can be classified as silica-unsaturated rocks.

3-Textures:

Vesicular and amygdaloidal Texture in basalt

This refers to porous morphology of the hand specimens caused by degassing of the basaltic lava. The empty voids can be filled with foreign minerals (e.g. calcite, quartz, chlorite) precipitated from the post-genetic invaded fluids. In this case, the vascular texture is called amygdaloidal texture.

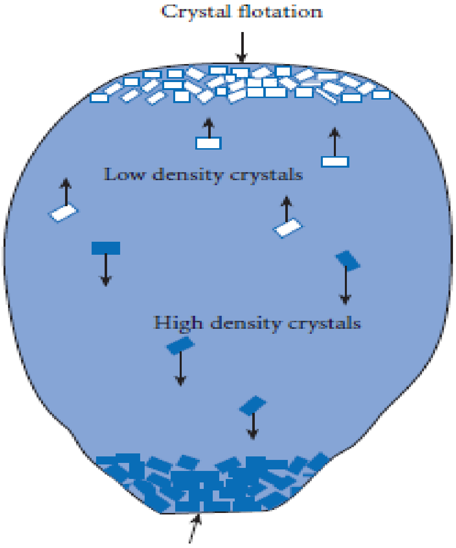


Vesicular texture in basalt.

Amygdaloidal texture in basalt.

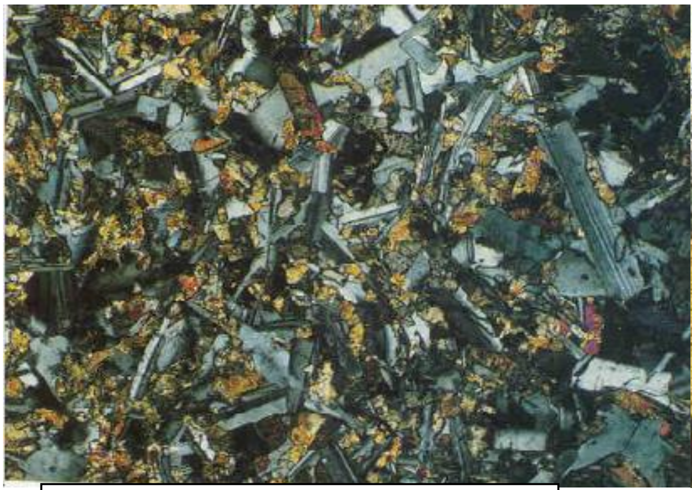
Igneous Layering in Gabbro

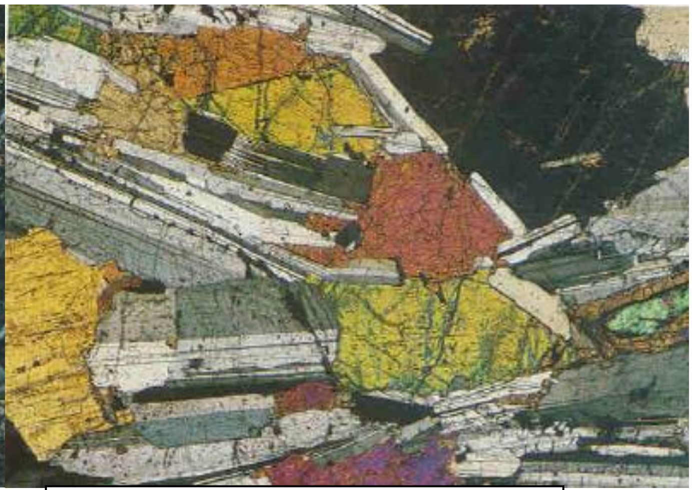
Many gabbro plutons exhibit igneous **layering**. Layering means the upward repetition of planar or shallow trough - shaped layers (centimeters to meters thick) that differ in relative mineral proportions to an extent that is obvious in the field. To form such layers in a plutonic rock requires some kind of crystal - sorting process to have operated during crystallization and deposition. Usually the ferromagnesian minerals have accumulated preferentially at the base of each layer in Fig. 4.7 b whereas felsic minerals are concentrated at the top. Plutonic rocks that are products of such mineral – selective processes – enriched in specific minerals relative to the melt composition – are called **cumulates**.



Intergranular Texture

The spaces between plagioclase crystals are occupied by one or more grains of pyroxene, olivine, and iron oxides. The intergranular texture indicates the simultaneous crystallization of plagioclase and ferromagnesian minerals.



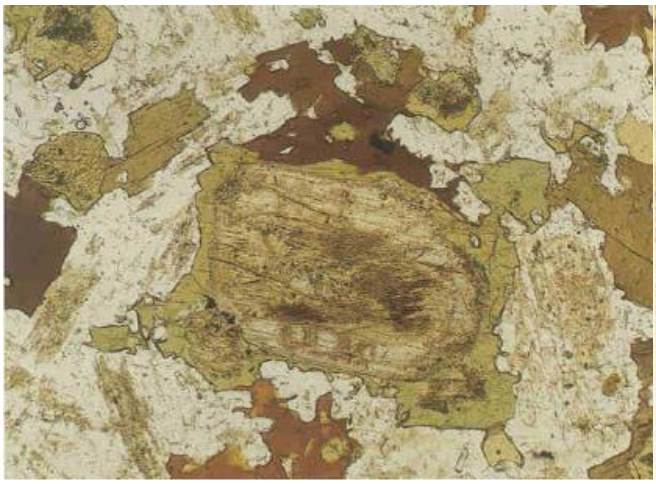


Intergranular texture in basalt.

Intergranular texture in gabbro.

Corona Texture

A crystal of one mineral is surrounded by a rim of another mineral. For example, it can be found olivine crystal is surrounded by rim of pyroxene, hornblende is mantled by biotite, or pyroxene is mantled by rime of hornblende. This rim is presumed to result from the incomplete reaction between the mineral core and the surrounding magma. So, it is expected that the outer rim is crystallized later than the inner core.



Pyroxene is mantled by green rim of hornblende.	Olivine is mantled by brown fibrous rim of pyroxene.

Intermediate Rocks

1-Mode of Occurrence:

Intermediate rocks are either fine to medium-grained rocks in the form of extrusive and intrusive igneous bodies (e.g. andesite) or coarse-grained intrusive igneous bodies (e.g. diorite).

Andesites are (after basalts) the second most abundant volcanic rock type on the Earth. Less evolved andesites may sometimes be difficult to distinguish from basalts in thin section. Andesite lava differs from basalt in its flowing velocity due to the increased viscosity resulting from the high $SiO2$ content in relative to basalt and the occurrence of phenocrysts, which add to the lava flowing resistance.

2-Mineralogy:

The intermediate rocks consist mainly of plagioclase along with hornblende with lesser extent of biotite and pyroxene. The silica content varies between 52%-66%, which completely employed for the crystallization of ferromagnesian minerals "hornblende, biotite, and pyroxene). So, these rock types can be classified as silica-unsaturated rocks. The occurrence of quartz is rarely expected here.

3-Texture:

Porphyritic texture

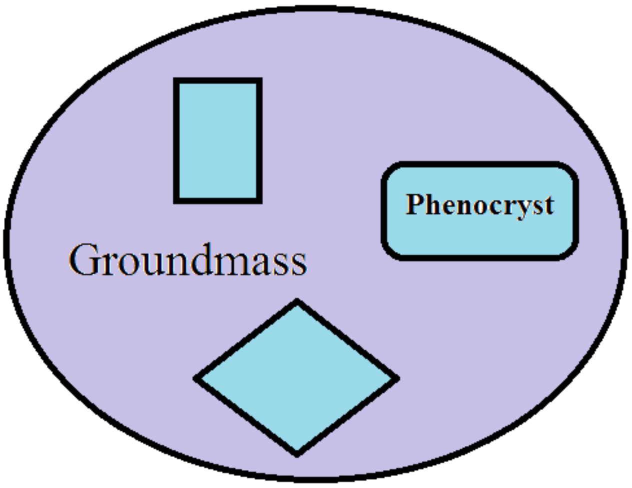
The volcanic intermediate rocks are commonly characterized by porphyritic texture, in which phenocrysts of plagioclase or ferromagnesian mineral are floated in groundmass. The phenocrysts indicate the crystallization under plutonic conditions where the cooling rate is slow, while the groundmass reflects the incomplete crystallization under volcanic conditions where the cooling rate is fast.

Granitic texture

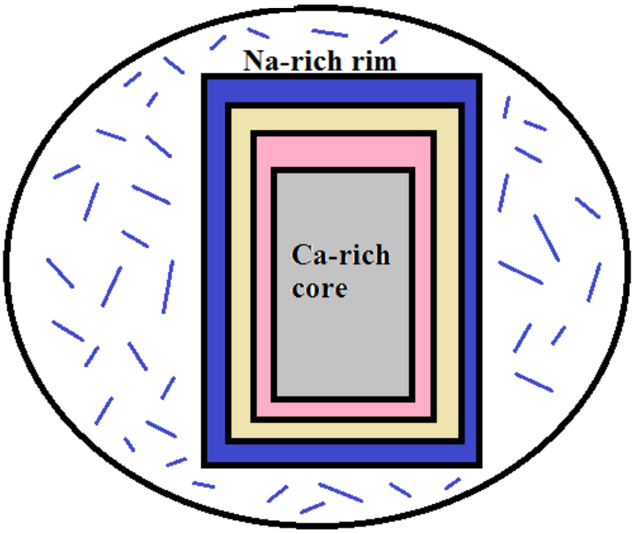
The plutonic intermediate rocks are characterized by equigranualr granitic texture, in which all mineral components are nearby equal in size, and the majority of mineral crystals, exception for plagioclase, are anhedral.

Zoning texture

Sometimes, plagioclase reveals zoning, in which the core is rich in Ca and the outer rim is rich in Na. The gradual decrease in Ca content from the zoning core to rim is ascribed to the reaction between Ca-rich core with the surrounding magma where appropriate amounts of Na partly replace Ca in the crystal structure of Ca-plagioclase, resulting in zones of varying proportion of Na and Ca.



Porphyritic texture



Zoning in plagioclase

Felsic Rocks

1-Mode of Occurrence:

Felsic rocks are either fine to medium-grained rocks in the form of extrusive and intrusive igneous bodies (e.g. dacite and rhyolite) or coarse-grained intrusive igneous bodies (e.g. granites).

The higher level of SiO_2 present in dacite and rhyolite melts, together with their lower temperatures of eruption, increases the viscosity of such melts relative to that of andesite, especially when crystallization has progressed to an advanced degree prior to eruption. Because of these factors, dacite lavas erupt as thick domes constructed directly over the vent rather than more laterally extensive lavas typical of andesite.

Granitic rocks are the most abundant igneous rocks on the Earth's continental crust. They occur as batholiths, stocks, Lapoliths, and ring intrusions. The exposed part on the Earth's surface does not exceed 2 km in vertical extent, and varies between less than $10 km^2$ to more than $1000 km^2$ in surface outcrops.

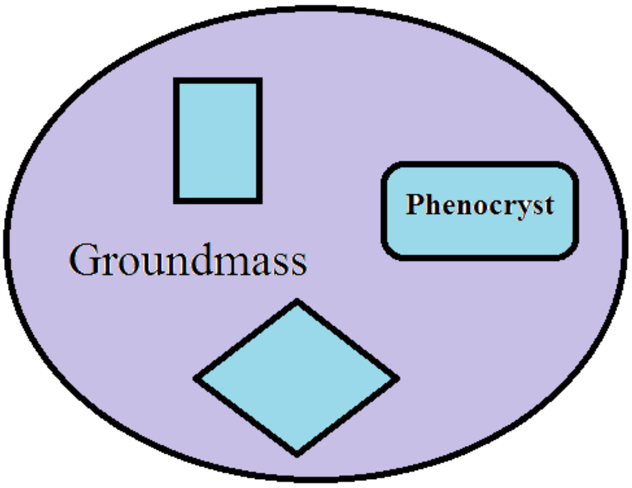
2-Mineralogy:

Due to their high silica content ">66% SiO_2", felsic rocks consist mainly of quartz along with Na-feldspar, k-feldspar, hornblende, biotite, and muscovite. These rocks can be described as silica-saturated rocks.

3-Texture:

Porphyritic texture

The volcanic felsic rocks can reveal porphyritic texture like andesite, in which phenocrysts of plagioclase or ferromagnesian mineral are floated in groundmass. The phenocrysts indicate the crystallization under plutonic conditions where the cooling rate is slow, while the groundmass reflects the incomplete crystallization under volcanic conditions where the cooling rate is fast.



Porphyritic texture

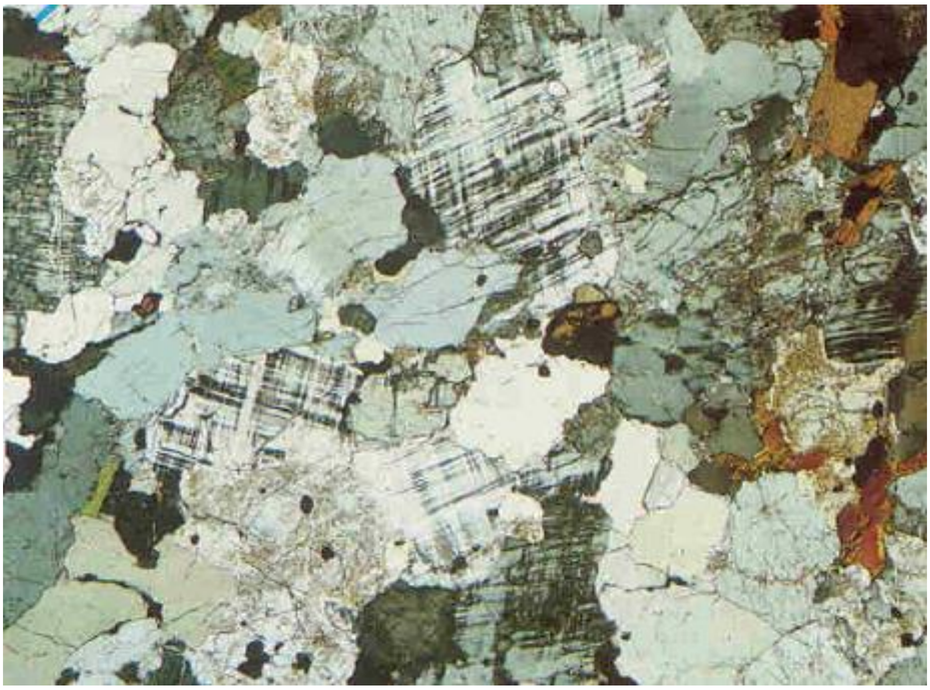
Spherultic texture

Spherulites are spheroidal bodies in a rock; they are composed of an aggregate of fibrous crystals of one or more minerals "quartz and K-feldspar" radiation from a nucleus. This textural pattern indicates the simultaneous crystallization of quartz and K-feldspar.

Spherultic texture

Granitic texture

The plutonic intermediate rocks are characterized by equigranualr granitic texture, in which all mineral components are nearby equal in size, and the majority of mineral crystals, exception for plagioclase, are anhedral.



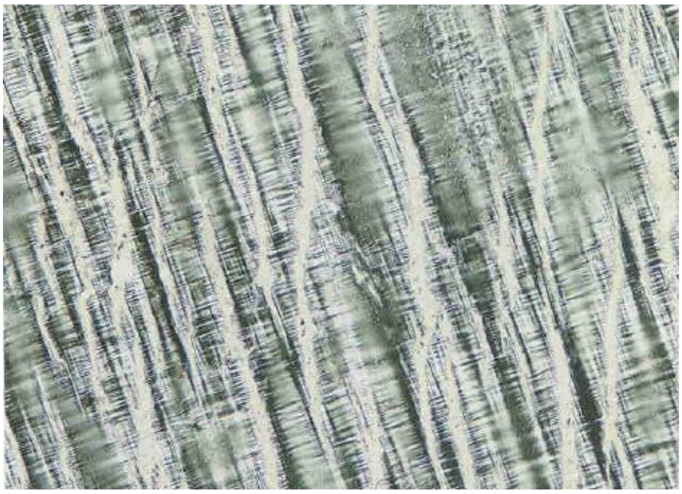
Granitic texture

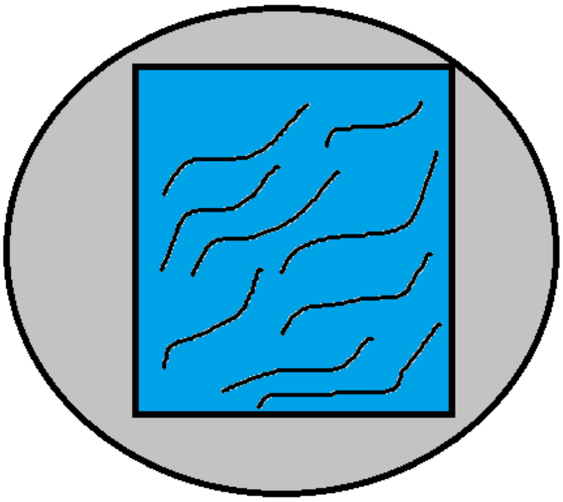
Perthitic texture

Perthite is composed of host crystal of microcline "K-feldspar" containing exsolved lamellae of albite "Na-feldspar". This simultaneous intergrowth is a result of breakdown of the homogeneous solid solution between microcline and albite once temperature decreases. Under high temperature conditions, Na-feldspar and K-feldspar are well-mixed as one liquid phase. The initial cooling leads to semi-stable crystalline structure in which Na and K freely replace each other. On increasing temperature decline, Na and K-feldspar are separated as individual phases. The dominant phase represents the host crystal, while the minor phase is the exsolved bodies.

Anti-perthitic texture

The same mechanism of perthite, with replacing the host crystal by albite.

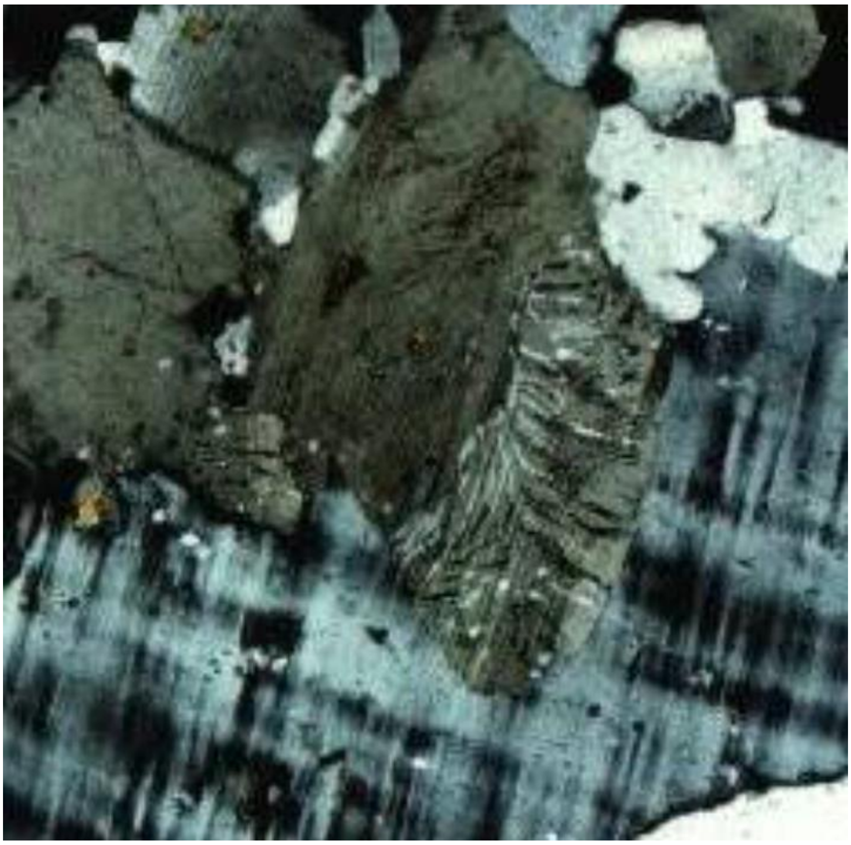




Perthite texture

Myrmekitic texture

This texture type stems from the interaction between plagioclase and K-feldspar, causing release of worm-like shaped forms of silica. The reason behind silica release is that the content of silica in plagioclase is less than that of K-feldspar, so an excess of silica is liberated once plagioclase replaces K-feldspar



Myrmekitic texture

Lecture#5

Metamorphism: Definition, Types, and Grades

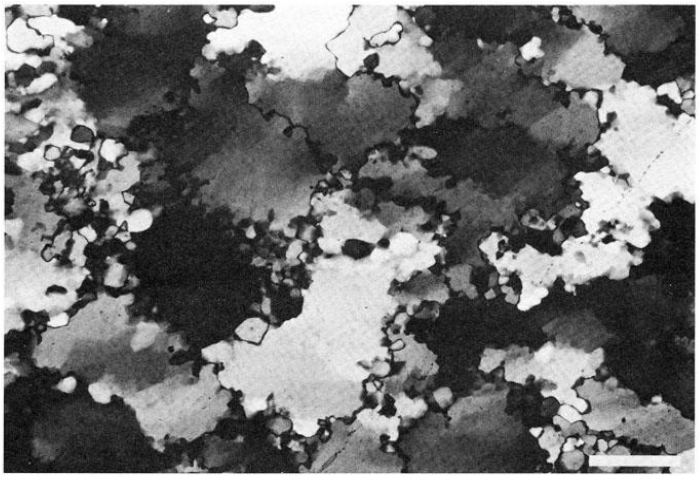
What is the meaning of metamorphism?

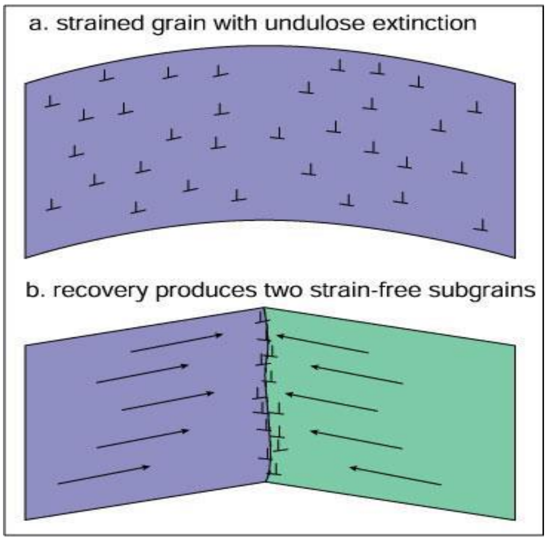
The term metamorphism refers to a combination of physical and chemical changes that can occur in a given rock as a response to the impoed changes in the ambient pressure and/or temperature conditions. Metamorphism occurs usually at temperatures and pressure higher than 200 °C and 300 MPa.

Physical changes may involve simple recrystallization of existing minerals, which may occur under lithostatic load or under directed pressure. These physical changes play an important role in determining the texture of the resulting rock.

Examples for the deformational recrystallization:

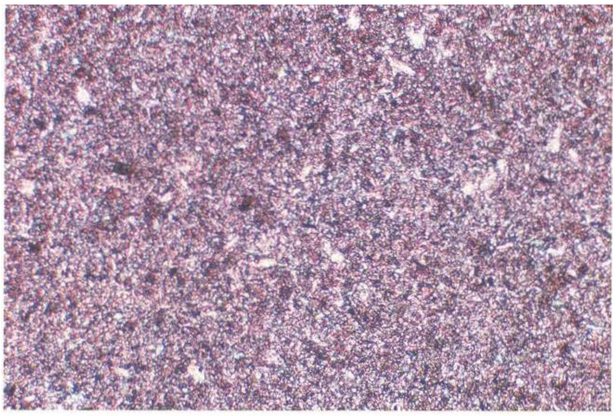
As quartz grains present in granites are subjected to an increase in the surrounding lithostatic pressure, plastic deformation occurs through the entire crystal lattice. This leads to sliding along the crystallographic planes and dislocations(vacancies) are formed in the crystal lattice of quartz. The present disslocations move inside the crystal lattice and form, during the recovery process, subgrain domains that are characterized by undulose extinction.





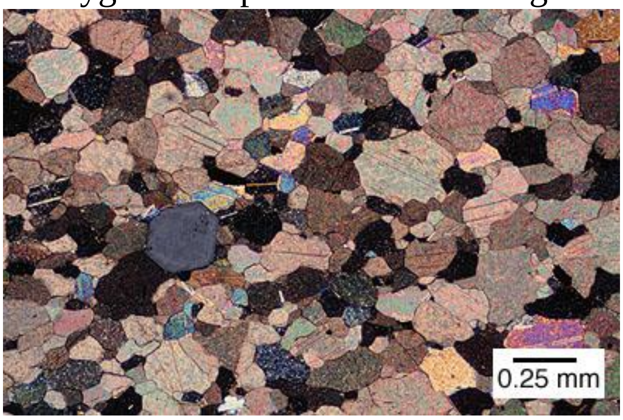
Examples for the temperature-induced recrystallization:

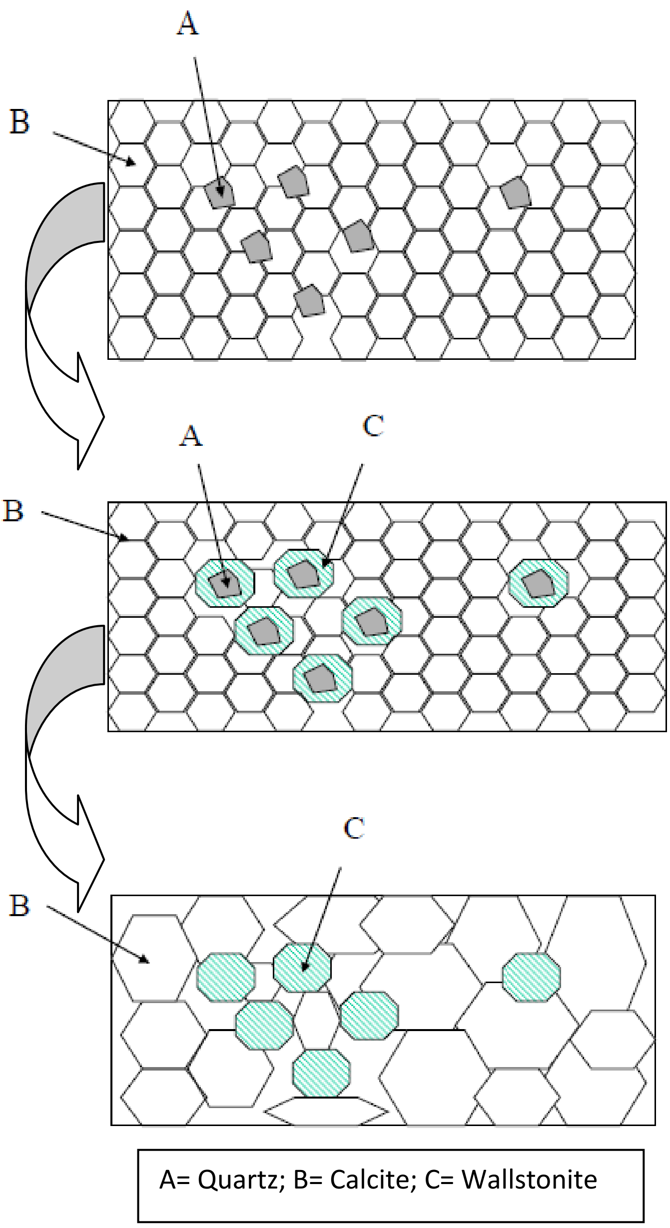
Once limestones are heated by igneous intrusions, the fine-grained calcite crystals "micrite" grow further to form polygonal shape crystals. Under adequate temperature (e.g. 800 ^{o}C), calcite crystals react with quartzgrains to form a new mineral phase, called wallostinite. The latter can cause a complete consumption of quartz.



Fine-grained carbonate matrix

Polygonal shape calcite on heating





When the increased temperature promotes a partial melting, the metamorphic conditions are converted into igneous conditions

<u>Chemical changes</u> occur when new minerals form, because atoms must be exchanged between reacting minerals(e.g. Wallstonite). In contrast, fluids passing through a rock may bring in new elements that replace former elements and change the bulk composition of the rock, a process known as **metasomatism (e.g. serpentinization, talc, silisification, and chloritization)**.

$$2Mg_3Si_4O_5(OH)_4 + 3CO_2 \text{ -----} Mg_3Si_4O_{10}(OH)_2 + 3MgCO_3 + 3H_2O$$

Serpentine **Talc** **Magnesite**

<u>Factors Controlling Metamorphism</u>

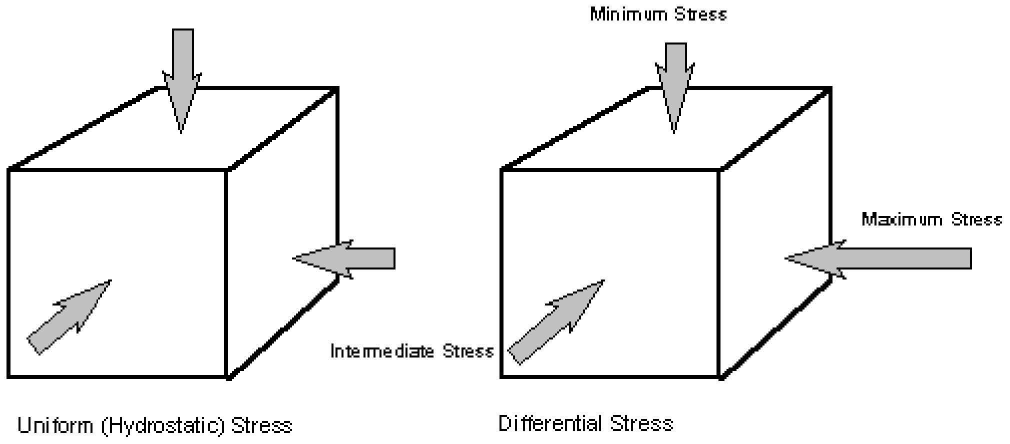
Metamorphism occurs because some minerals are stable only under certain conditions of pressure and temperature. When pressure and temperature change, chemical reactions occur to cause the minerals in the rock to change to an assemblage that is stable at the new pressure and temperature conditions. But, the process is complicated by such things as how the pressure is applied, the time over which the rock is subjected to the higher pressure and temperature, and whether or not there is a fluid phase present during metamorphism.

<u>-Temperature</u>

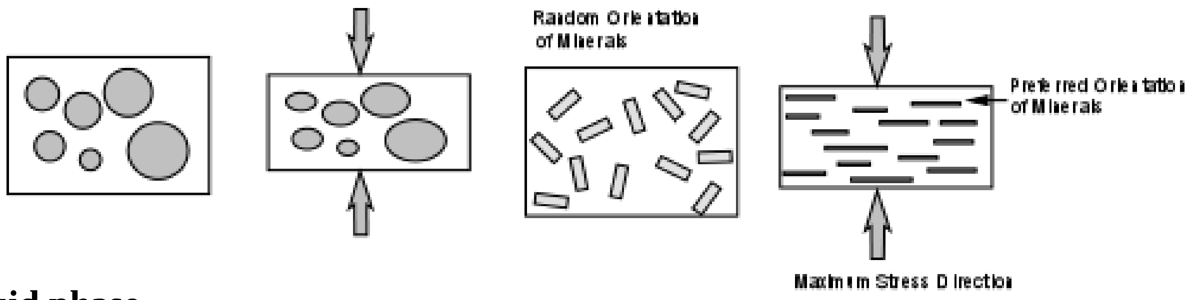
- Temperature increases with depth in the Earth along the Geothermal Gradient, thus higher temperature can occur by burial of rock.
- Temperature can also increase due to igneous intrusion.

<u>-Pressure</u>

- Pressure increases with depth of burial, thus, both pressure and temperature will vary with depth in the Earth. Pressure is defined as a force acting equally from all directions. It is a type of stress, called hydrostatic stress, or uniform stress. If the stress is not equal from all directions, then the stress is called a differential stress.



- ► If differential stress is present during metamorphism, it can have a profound effect on the texture of the rock.



-Fluid phase

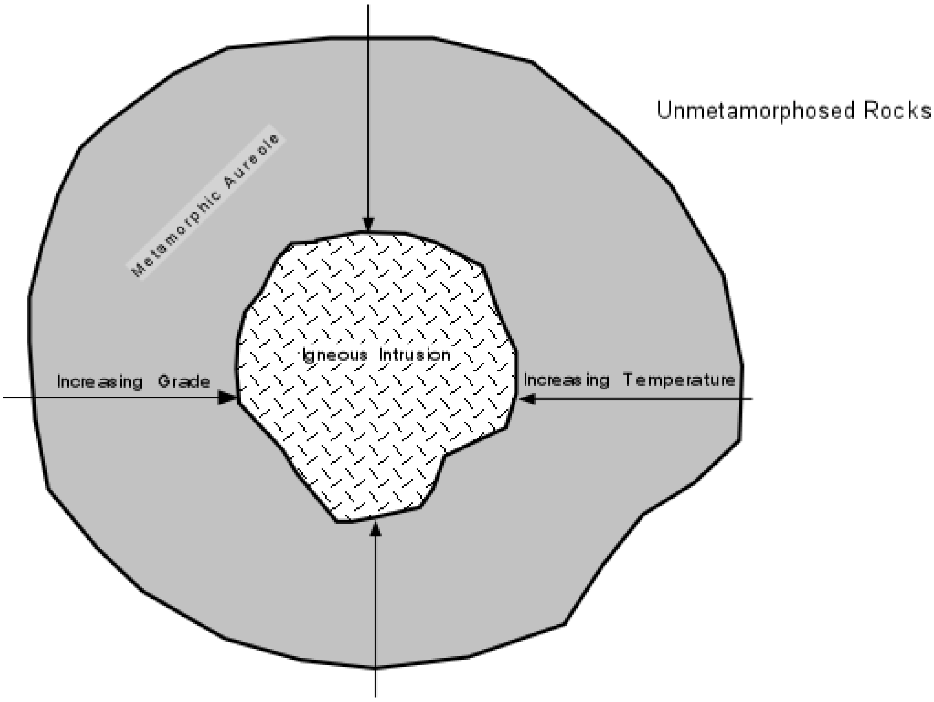
- ► Any existing open space between mineral grains in a rock can potentially contain a fluid. This fluid is mostly H2O, but contains dissolved mineral matter.
- ► The fluid phase is important because chemical reactions that involve one solid mineral changing into another solid mineral can be greatly speeded up by having dissolved ions transported by the fluid

Types of Metamorphism

Metamorphism can be divided into three main types depending on the imposed conditions of temperature and/or pressure:

1-Contact metamorphism/or thermal metamorphism:

It occurs adjacent to igneous intrusions and results from high temperatures associated with the igneous intrusion. Since only a small area surrounding the intrusion is heated by the magma, metamorphism is restricted to a zone surrounding the intrusion, called *a metamorphic aureole*. Outside of the contact aureole, the rocks are unmetamorphosed. The grade of metamorphism increases in all directions toward the intrusion. Because temperature differences between the surrounding rock and the intruded magma are larger at shallow levels in the crust, contact metamorphism is usually referred to as high temperature, low pressure metamorphism. The rock produced is often a fine-grained rock that shows no foliation, called a hornfels. Examples on hornfels include marble and pelitic rocks.



2-Dynamic metamorphism/or Deformational metamorphism:

This type of metamorphism is due to mechanical deformation, like when two bodies of rock slide past one another along a fault zone. Friction-induced heat is not high enough for minerals to grow in their crystal sizes. So, the dynamic metamorphism is dominated by a reduction in grain size and deformational recrystallization (e.g. subgrain domain of quartz). The metamorphic rocks that have undergone dynamic metamorphism are called mylonites, occurring within fault and shear zones.

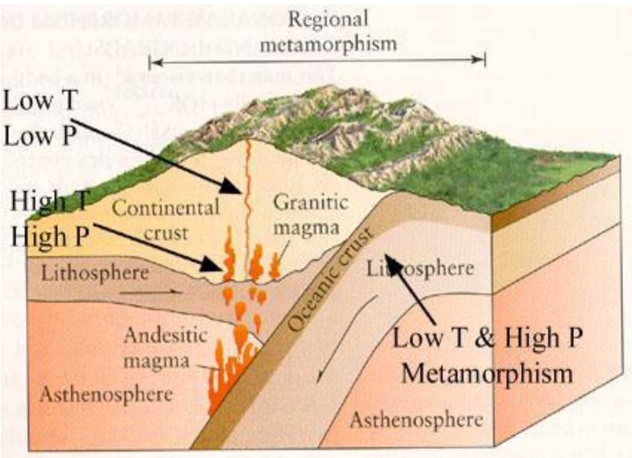
Mylonitization of pre-existing metamorphic rock

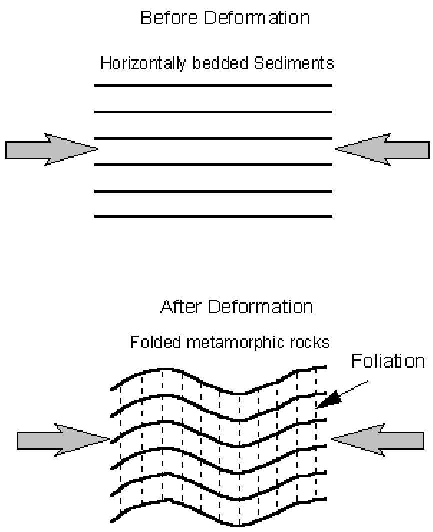
3-Regional metamorphism:

This type of metamorphism occurs over large areas that were subjected to high degrees of deformation along with high temperature conditions. Thus, it usually results in forming metamorphic rocks that are strongly foliated and lineated, such as slates, schists, and gniesses.

The differential stress usually results from tectonic forces that produce a compression of the rocks, such as when two continental masses collide with one another. Thus, regionally metamorphosed rocks occur in the cores of mountain ranges or in eroded mountain ranges. Compressive stresses result in folding of the rock, as shown here, and results in thickening of the crust which tends to push rocks down to deeper levels where they are subjected to higher temperatures and pressures.

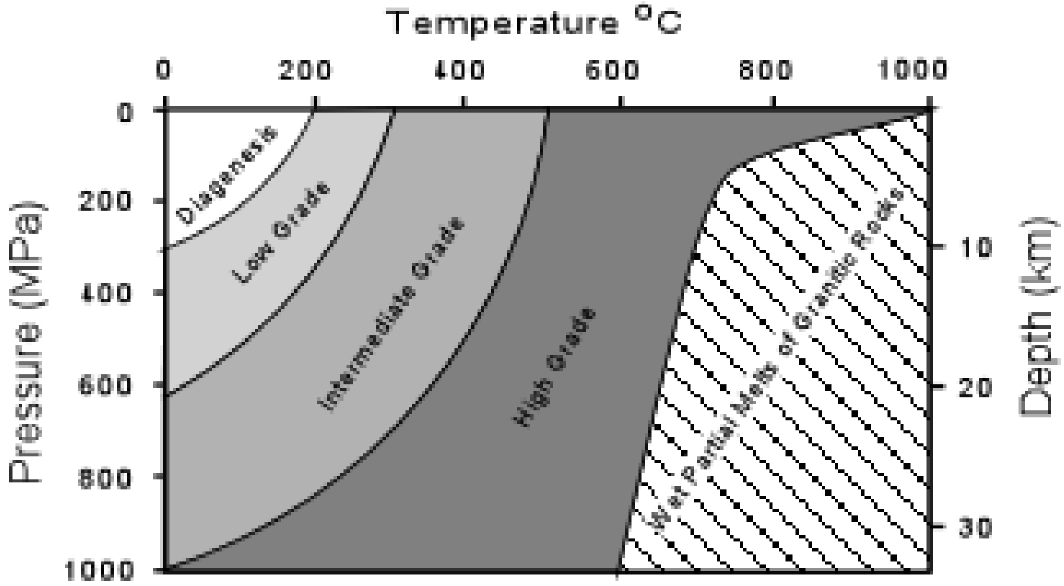
Depending on the above facts, the regionally metamorphosed rocks are characterized by oriented minerals in preferred directions that are perpendicular to the direction of the imposed stress.





Grades of Metamorphism & Index minerals

- 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. ***Metamorphic grade*** is a general term for describing the relative temperature and pressure conditions under which metamorphic rocks form.
- Low-grade metamorphism takes place at temperatures between about 200 to 320°C, and relatively low pressure. Low grade metamorphic rocks are characterized by an abundance of ***hydrous minerals*** (minerals that contain water, H_2O, in their crystal structure, e.g. clay minerals, serpentine and chlorite).
- High-grade metamorphism takes place at temperatures greater than 320oC 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, which characterize high grade metamorphic rocks, include biotite, muscovite, garnet, kyanite, and staurolite.



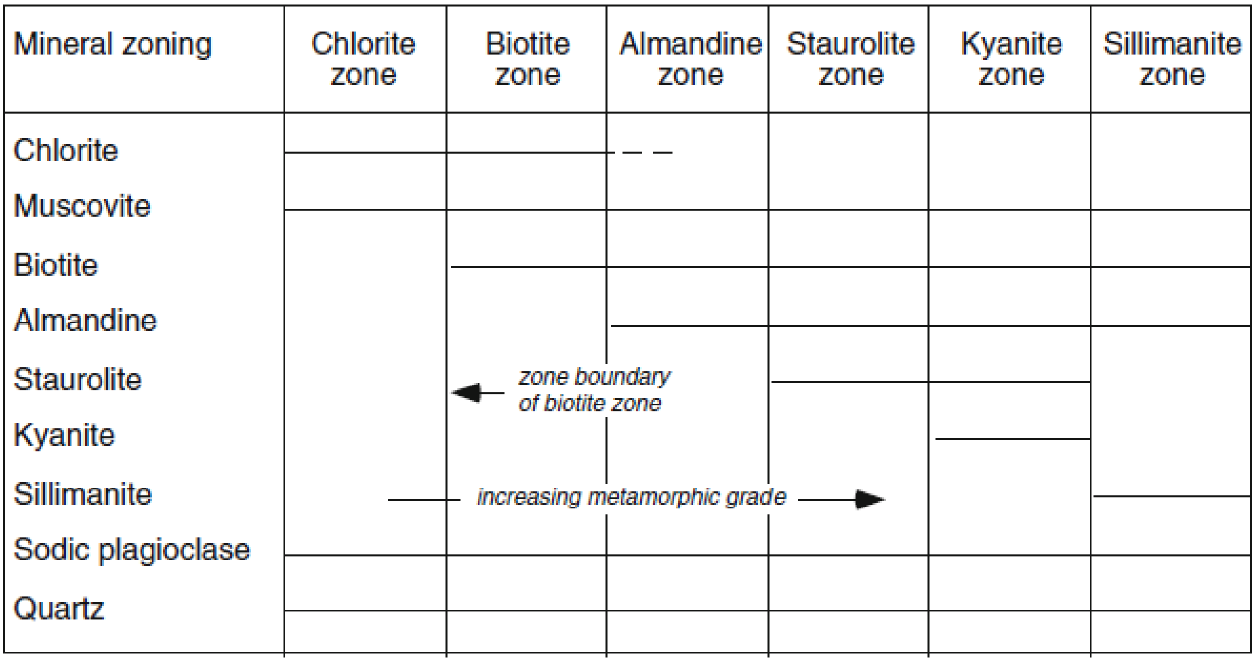
Index Metamorphic Minerals

- Index metamorphic minerals are a specific mineral group that forms only under certain metamorphic conditions of temperature and pressure; therefore, they are called index minerals.
- We can order the index minerals in relative to the direction along which the metamorphic grade increases gradually, as follows:

Chlorite-------Biotite------Garnet-------Staurolite---------Kyanite---------Siliminite

The metamorphic grade increases (an increase in P/T conditions).

- Each index mineral has a characteristic zone starting from the first appearance of a specific index mineral and the first appearance of the following mineral.



Lecture#6

Metamorphic Textures & Metamorphism of Specific Rocks

Textures Classification of Metamorphic Rocks

- Textures of metamorphic rocks can be classified, depending on their origin, into three types:

1-Relict textures, which are inherited from the parent rocks. They are indicated by applying the prefix "blasto" to the original textural name, for example, blasto-porphyritic texture.

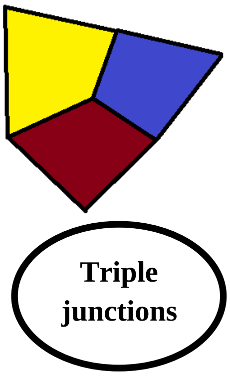
2-Typomorphic textures, which results from the response of rocks to the new imposed metamorphic conditions, as such example, gneissosity and schistosity corresponding to gneiss and schist, respectively.

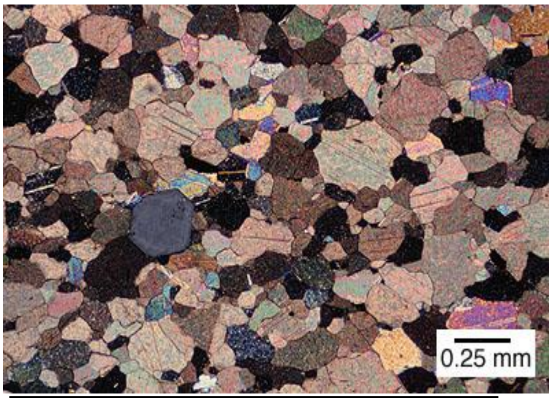
3-Superimposed textures, which characterize a post-metamorphic event like hydrothermal alteration or chemical weathering.

- ***According to orientation of mineral grains***, the metamorphic textures can be divided into:

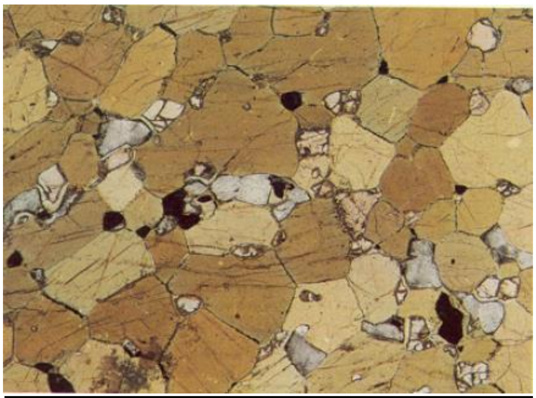
1-Granoblastic texture

A granoblastic texture is an equigranualr texture in which crystals adopt a polygonal morphology with grain triple junctions. This texture type lacks a preferred orientation of its mineral constituents, so it is considered as an indication from the contact metamorphism. Examples include marble, consisting mainly of calcite, and granulite, comprising mainly hornblende.





Granoblastic texture of marble



Granoblastic texture of granulite

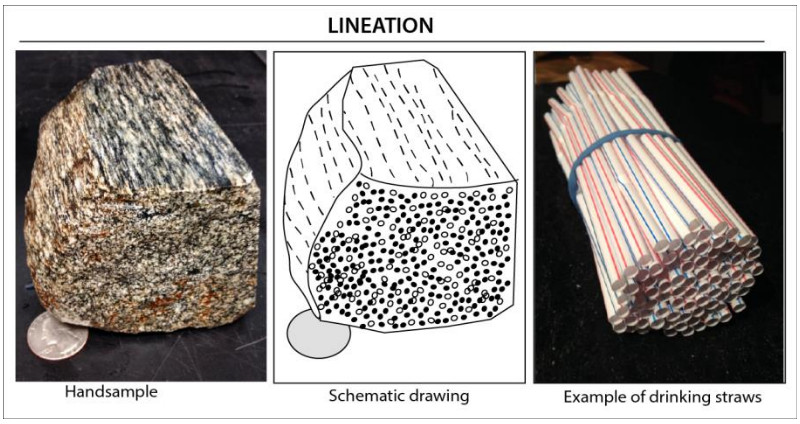
2-Decussate texture

A decussate texture is a metamorphic rock texture comprising of equigranular, interlocking, randonly orientated platy, tabular, prismatic or elongate minerals, *without triple junctions.*

Decussate texture consists of randomly distributed mica plates.

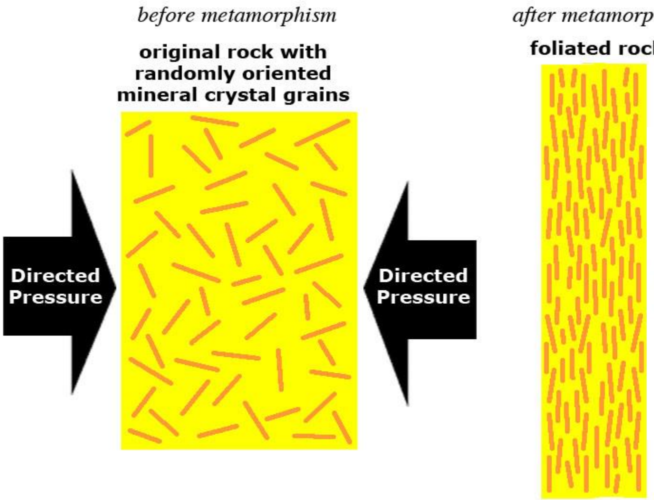
3-Lineation texture

Lineation is a term used to describe the growth of elongated minerals (e.g. hornblende, pyroxene, tuormaline, and quartz) along one crystallographic plane, which is perpendicular to the imposed hydrostatic stress (e.g. hornblende schist).



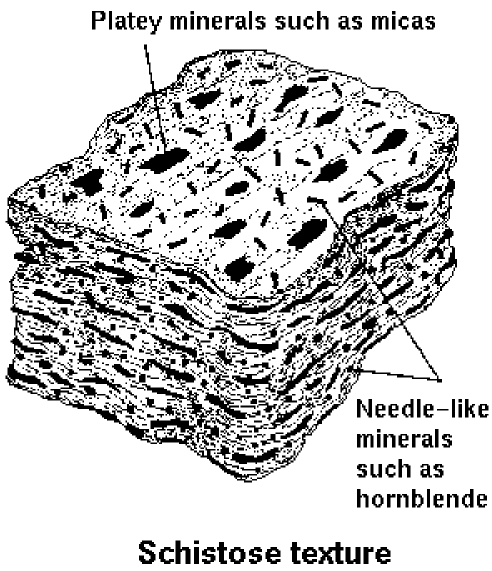
4-Foliation texture

Foliation is a sheet-like, parallel arrangement of platy minerals that grow in two crystallographic directions, which are perpendicular to the imposed hydrostatic stress (e.g. micas, chlorite, and talc). examples of foliated metamorphic rocks involve mica schist, chlorite schist, and biotite gneiss.



5-Schistosity

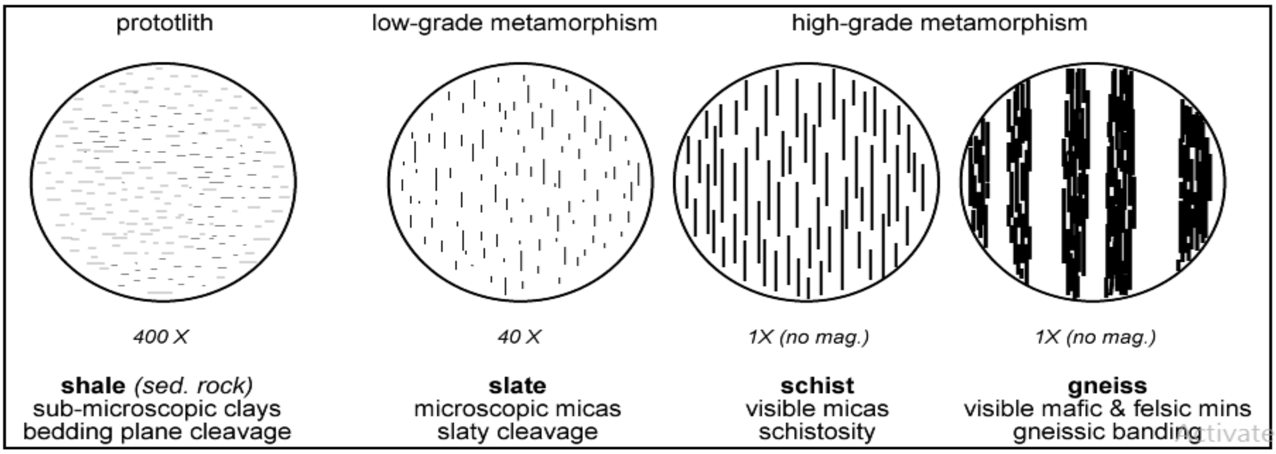
Schistosity is a mode of foliation and/or lineation in a relatively high-grade metamorphic rock. It consists of dark laminae of platy and/or elongated minerals alternating with light laminae of quartz. Note that, rocks can be broken along foliation planes.



Mica Schist (note foliation planes)

6-Gneissosity

Gneissosity is a coarse-gained foliation that is found as alternating dark bands of platy minerals and light bands of quartz and feldspar. unlike schistosity, gneissosity is a crystalline texture without weak planes. It is an indication for the high-grade metamorphism.



Hornblende Gneiss (note banding)

Biotite Gneiss (note banding)

7-Nematoblastic texture

8-Lepidoblastic texture

Metamorphism of Specific Rock Types