UNIT-III PETROLOGY

PETROLOGY : The branch of geology dealing with the origin, occurrence, structure, and history of rocks.

3.1. IGNEOUS PETROLOGY

- Igneous rocks constitute one of the three rock families.
- Continental and oceanic crust are made of igneous rock.
- Intrusive igneous activity, the cooling of magma within Earth, forms most common igneous rocks.

Why study igneous rocks?

Molten rocks – magma

- The majority of rocks we see on the surface are solid
- Only at active volcanoes are we lucky enough to see rocks in their molten state
- Understanding how rocks melt is important

Why do rocks melt?

- In theory if you get rocks hot enough, just like ice, they will melt (>800°C)
- But as usual with geology it isn't that simple
- Minerals melt at different temparatures
- Pressure & water also complicate things.

Earth's Internal Heat

Earth's temperature increases with depth. This geothermal gradient is about 2.5°C per km near the surface but varies from area to area. The geothermal gradient decreases markedly at greater depths and is thought to be only 1°C per km in the mantle.

oceans-continents-Earth's Internal Heat

- Most of Earth's internal heat derives from radioactive decay of uranium, thorium and potassium 40. Rock is a poor heat conductor, so it takes relatively little radioactive decay to build up significant heat.
- The temperature at the base of the crust is 800-1200°C whereas at the mantle outer core boundary it is 3500-5000°C . Earth's center is estimated to be very near that of the Sun's surface, 6500°C .

Effects of pressure

- Most lavas erupt at 1000°C & temps in the mantle are higher than this
- As P increases so does melting temp
- The reverse of this is decompression melting

Effects of water

- H_2O (or water vapour) will lower the melting temp.
- Works the same way that salt does on ice.
- Effect of water increases with pressure.

Properties of Magma and Lava

• All igneous rocks derive either directly or indirectly from magma. Lava is magma that has reached Earth's surface.
• Plutonic (intrusive) igneous rocks form as magma cools and crystallizes within Earth.
• Volcanic (extrusive) igneous rocks form by cooling and crystallization of lava or by consolidation of pyroclastic material, such as volcanic ash, ejected from volcanoes.

Properties of magma
• It is not possible to study magma directly (can get very close in places like Hawaii)
• However, studying lavas can tell us a lot
• Magmas have a range of compositions
• Characterized by high temperatures
• Have the ability to flow

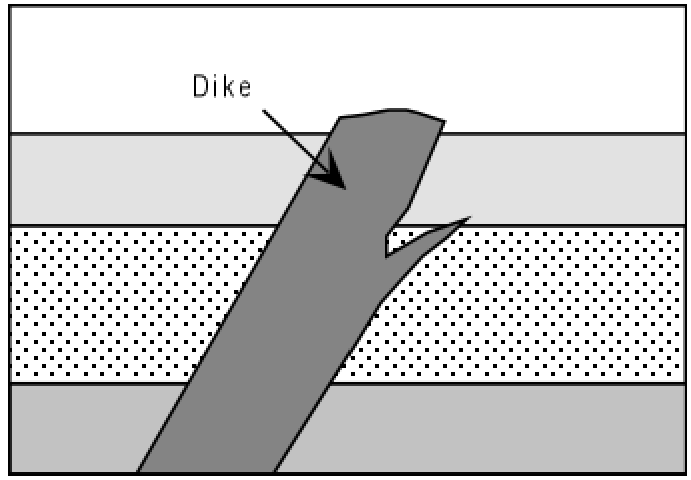
Magma Composition
• Silicate minerals are by far the most abundant minerals in the crust and silica is the most abundant constituent of magma.
• The bulk chemical composition of magma is dominated by the most abundant minerals
Si - Al - Fe - Ca - Mg - Na - K - H – O
• These major elements occur as oxides (SiO2)
• SiO2 = ~45 to 75% of rocks
• Water and CO2 make up 0.2 - 3 %
• Minor and trace elements make up the remainder

Cooling rates
• Intrusive (plutonic) rocks cool slowly while extrusive (volcanic) rocks cool quickly
• The cooling rate determines whether or not crystals form
• So cooling and crystallization determine the texture of the rock

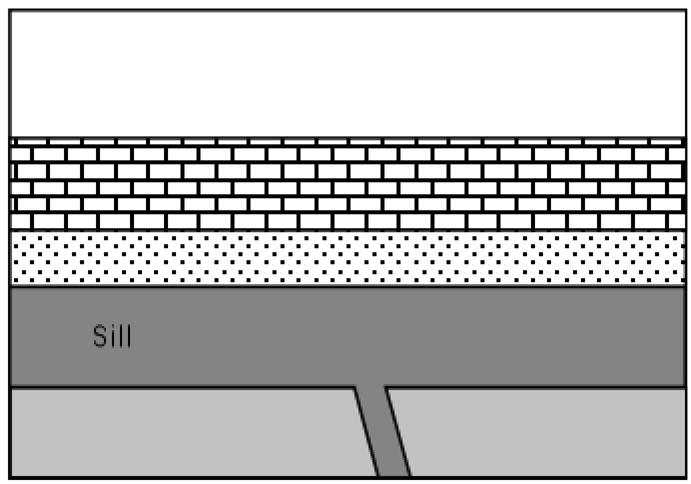
Texture
• Texture refers to the size, shape and arrangement of minerals' grains and is an important characteristic of igneous rocks. Grain size records cooling history.
• An ***aphanitic*** texture consists of an aggregate of very small mineral grains, too small to be seen clearly with the naked eye. Aphanitic textures record rapid cooling at or very near Earth's surface and are characteristic of extrusive (volcanic) igneous rocks.

3.1.1.Plutonic And Hypabyssal Intrusion Igneous Rock-structures

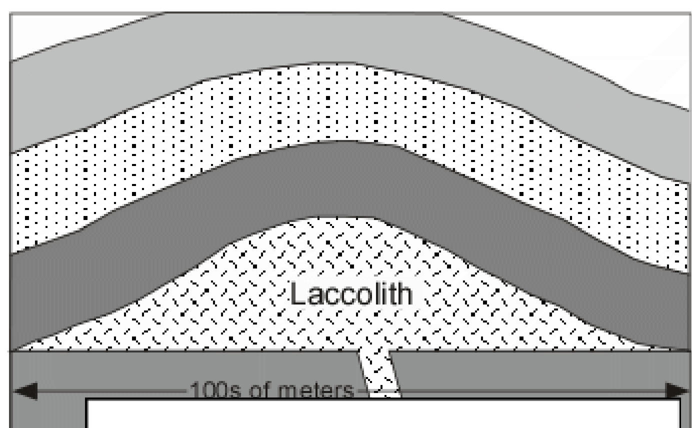
•Intrusions that intrude rocks at shallow levels of the crust are termed hypabyssal intrusions. Shallow generally refers to depths less than about 1 km. Hypabyssal intrusions always show sharp contact relations with the rocks that they intrude. Several types are found:



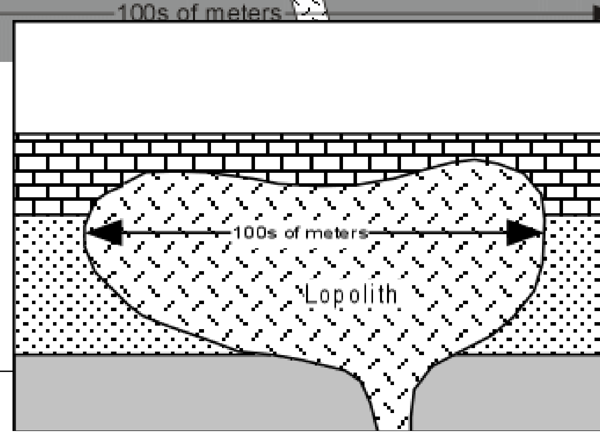
•Dikes are small (<20 m wide) shallow intrusions that show a discordant relationship to the rocks in which they intrude. Discordant means that they cut across preexisting structures. They may occur as isolated bodies or may occur as swarms of dikes emanating from a large intrusive body at depth.



•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.

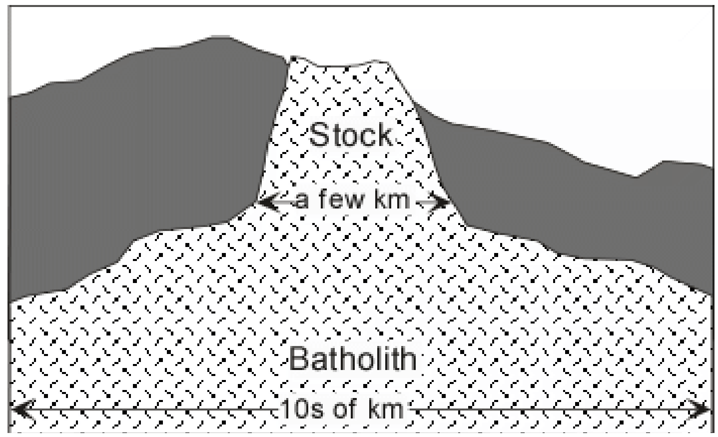


•**Plutons** are generally much larger intrusive bodies that have intruded much deeper in the crust.

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.

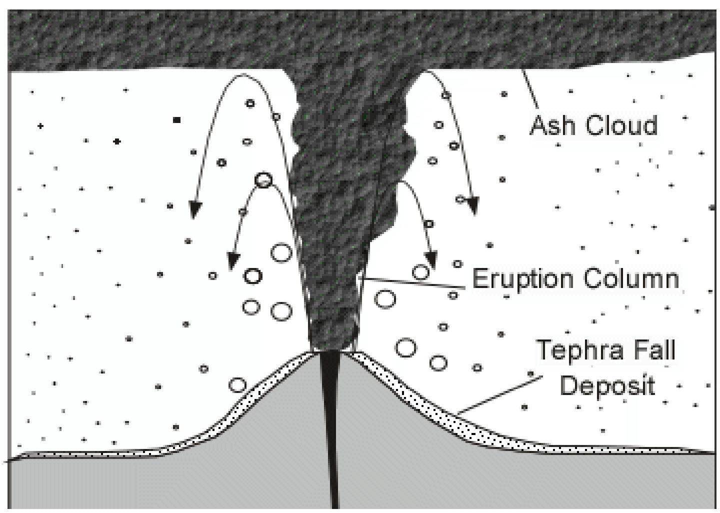
•**Batholiths** are very large intrusive bodies, usually so large that there bottoms are rarely exposed. Sometimes they are composed of several smaller intrusions.



•**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.

3.1.2. Volcanic (Extrusive) Igneous Rocks

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.

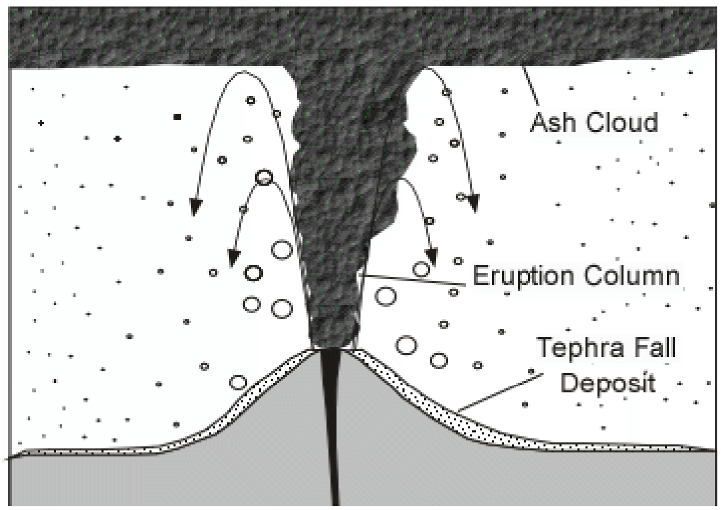
Tephra and Pyroclastic Rocks

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

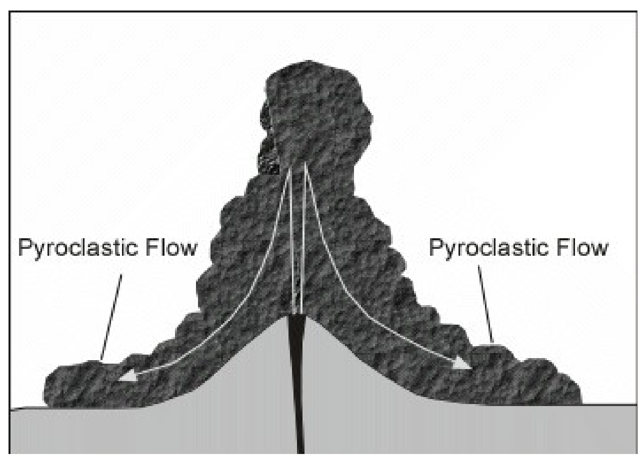
•Blocks are angular fragments that were solid when ejected.

•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

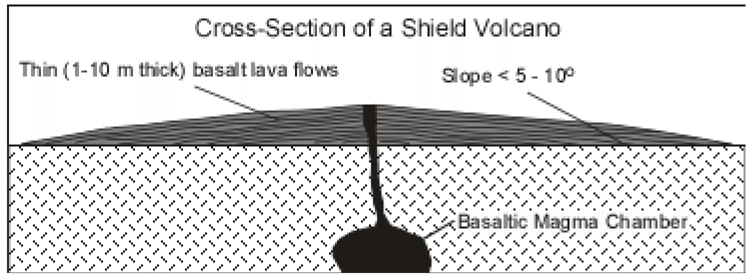
Non explosive eruptions are favored by low gas content and low viscosity magmas (basaltic to andesitic magmas).

•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.

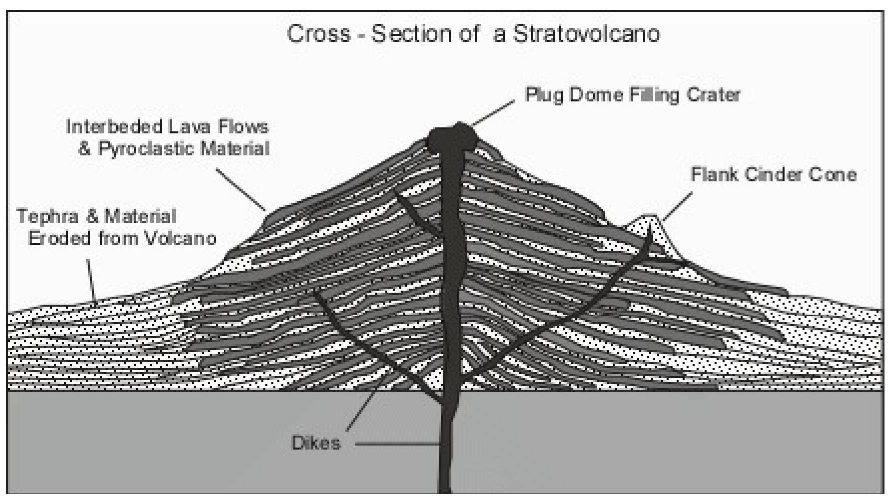
•Lava flows produced by eruptions under water are called pillow lavas.
•If the viscosity is high, but the gas content is low, then the lava will pile up over the vent to produce a lava dome or volcanic dome.

Volcanic Landforms
Shield Volcanoes



•A shield volcano is characterized by gentle upper slopes (about 5o) and somewhat steeper lower slopes (about 10o).
•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.

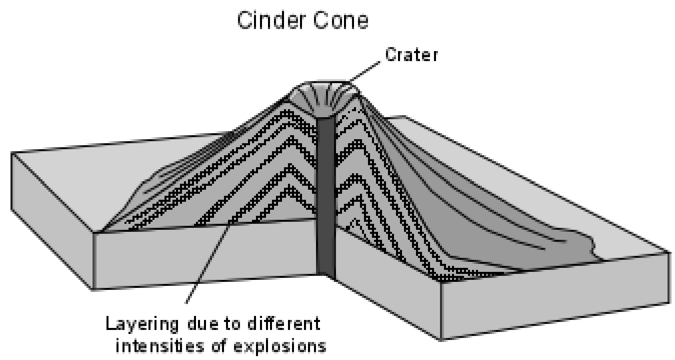
Stratovolcanoes (also called Composite Volcanoes)



•Have steeper slopes than shields, with slopes of 6 - 10o low on the flanks to 30o near the summit.
•Steep slope near the summit result from thick, short viscous lava flows that don't travel far from the vent.
•The gentler slopes near the base are due to accumulations of material eroded from the volcano and to the accumulation of pyroclastic material.
•Stratovolcanoes show inter-layering of lava flows and pyroclastic material, which is why they are sometimes called composite volcanoes. Pyroclastic material can make up over 50% of the volume of a stratovolcano.
•Lavas and pyroclastics are usually andesitic to rhyolitic in composition.
•Due to the higher viscosity of magmas erupted from these volcanoes, they are usually more explosive than shield volcanoes.
•Stratovolcanoes sometimes have a crater at the summit, that is formed by explosive ejection of material from a central vent. Sometimes the craters have been filled in by lava flows or lava domes, sometimes they are filled with glacial ice, and less commonly they are filled with water.

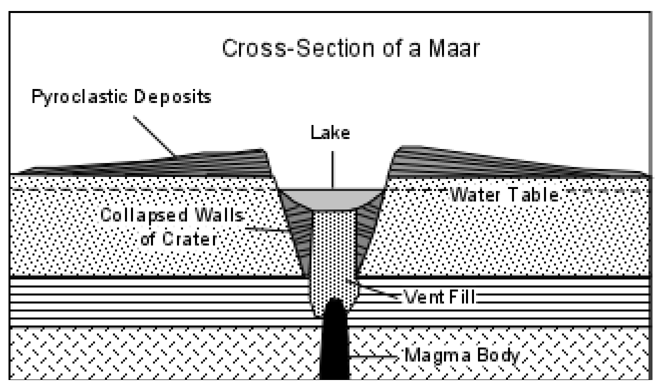
•Long periods of repose (times of inactivity) lasting for hundreds to thousands of years, make this type of volcano particularly dangerous, since many times they have shown no historic activity, and people are reluctant to heed warnings about possible eruptions.

Tephra Cones (also called Cinder Cones)



•Tephra cones are small volume cones consisting predominantly of tephra that result from strombolian eruptions. They usually consist of basaltic to andesitic material.
•They are actually fall deposits that are built surrounding the eruptive vent.
•Slopes of the cones are controlled by the angle of repose (angle of stable slope for loose unconsolidated material) and are usually between about 25 and 35o.
•They show an internal layered structure due to varying intensities of the explosions that deposit different sizes of pyroclastics.
•On young cones, a depression at the top of the cone, called a crater, is evident, and represents the area above the vent from which material was explosively ejected. Craters are usually eroded away on older cones.
•If lava flows are emitted from tephra cones, they are usually emitted from vents on the flank or near the base of the cone during the later stages of eruption.
•Cinder and tephra cones usually occur around summit vents and flank vents of stratovolcanoes.
•An excellent example of cinder cone is Parícutin Volcano in Mexico. This volcano was born in a farmers corn field in 1943 and erupted for the next 9 years. Lava flows erupted from the base of the cone eventually covered two towns.
•Cinder cones often occur in groups, where tens to hundreds of cones are found in one area

Maars

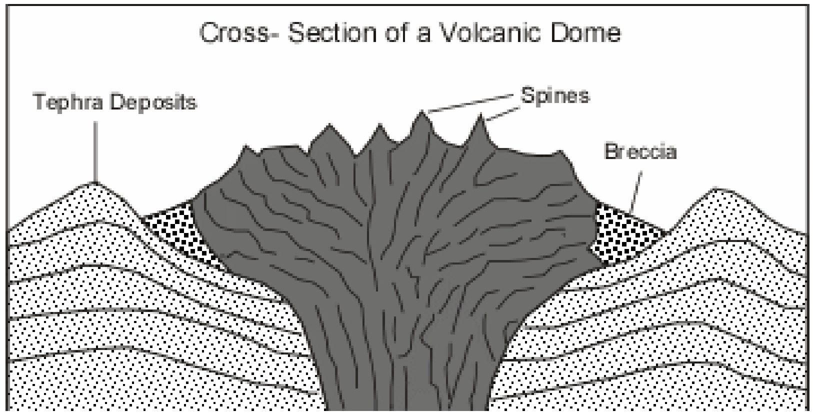


•Maars result from phreatic or phreatomagmatic activity, wherein magma heats up water in the groundwater system, pressure builds as the water to turns to steam, and then the water and preexisting rock (and some new magma if the eruption is phreatomagmatic) are blasted out of the ground to form a tephra cone with gentle slopes.

Parts of the crater walls eventually collapse back into the crater, the vent is filled with loose material, and, if the crater still is deeper than the water table, the crater fills with water to form a lake, the lake level coinciding with the water table.

Lava Domes (also called Volcanic Domes)

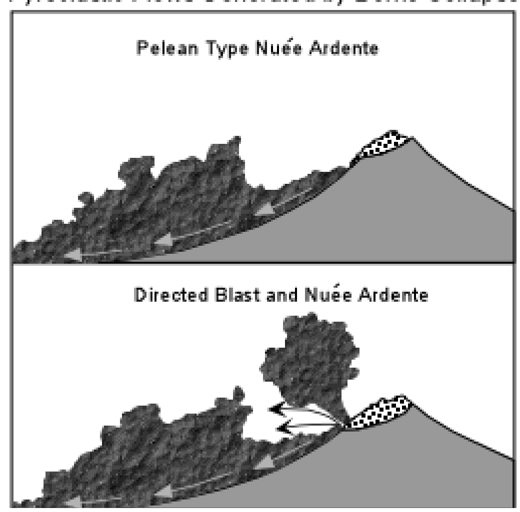
•Volcanic Domes result from the extrusion of highly viscous, gas poor andesitic and rhyolitic lava. Since the viscosity is so high, the lava does not flow away from the vent, but instead piles up over the vent.



•Blocks of nearly solid lava break off the outer surface of the dome and roll done its flanks to form a breccia around the margins of domes.

•The surface of volcanic domes are generally very rough, with numerous spines that have been pushed up by the magma from below.

Pyroclastic Flows Generated by Dome Collapse



•Most dome eruptions are preceded by explosive eruptions of more gas rich magma, producing a tephra cone into which the dome is extruded.

•Volcanic domes can be extremely dangerous. because they form unstable slopes that may collapse to expose gas-rich viscous magma to atmospheric pressure. This can result in lateral blasts or Pelean type pyroclastic flow (nuee ardent) eruptions.

Craters and Calderas

•Craters are circular depressions, usually less than 1 km in diameter, that form as a result of explosions that emit gases and tephra.

•Calderas are much larger depressions, circular to elliptical in shape, with diameters ranging from 1 km to 50 km. Calderas form as a result of collapse of a volcanic structure. The collapse results from evacuation of the underlying magma chamber.

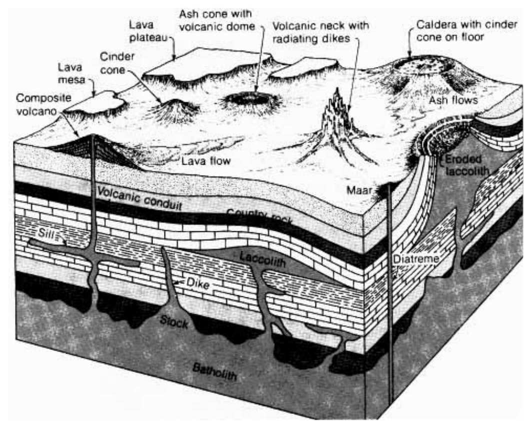
•In shield volcanoes, like in Hawaii, the evacuation of the magma chamber is a slow drawn out processes, wherein magma is withdrawn to erupt on from the rift zones on the flanks.

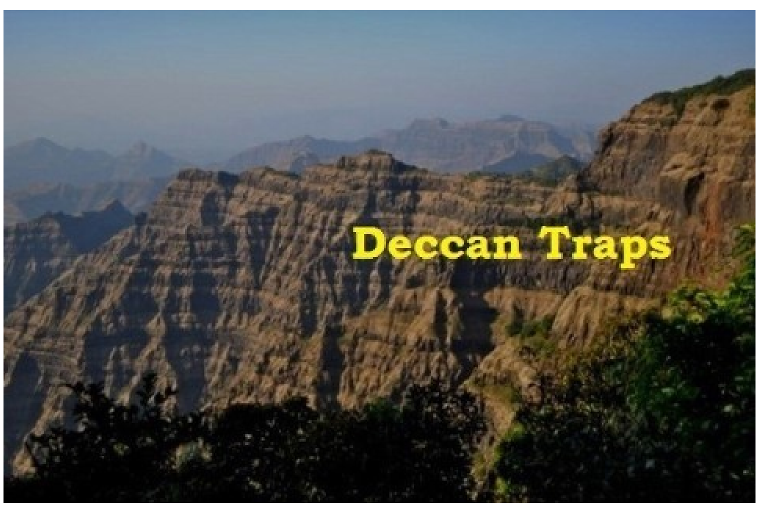
•In stratovolcanoes the collapse and formation of a caldera results from rapid evacuation of the underlying magma chamber by voluminous explosive eruptions that form extensive fall deposits and pyroclastic flows.

•Calderas are often enclosed depressions that collect rain water and snow melt, and thus lakes often form within a caldera.

Plateau Basalts or Flood Basalts

•Plateau or Flood basalts are extremely large volume outpourings of low viscosity basaltic magma from fissure vents. The basalts spread huge areas of relatively low slope and build up plateaus.





•In India the Deccan traps is best example for basaltic flow.

•Historic example occurred in Iceland in 1783, where the Laki basalt erupted from a 32 km long fissure and covered an area of 588 km2 with 12 km3 of lava. As a result of this eruption, homes were destroyed, livestock were killed, and crops were destroyed, resulting in a famine that killed 9336 people.

•In Oregon and Washington of the northwestern U.S., the Columbia River Basalts represent a series of lava flows all erupted within about 1 million years 12 million years ago. One of the basalt flows, the Roza flow, was erupted over a period of a few weeks traveled about 300 km and has a volume of about 1500 km3.

Cooling rates

• Intrusive (plutonic) rocks cool slowly while extrusive (volcanic) rocks cool quickly
• The cooling rate determines whether or not crystals form
• So cooling and crystallization determine the texture of the rock

Texture

• Texture refers to the size, shape and arrangement of minerals' grains and is an important characteristic of igneous rocks. Grain size records cooling history.

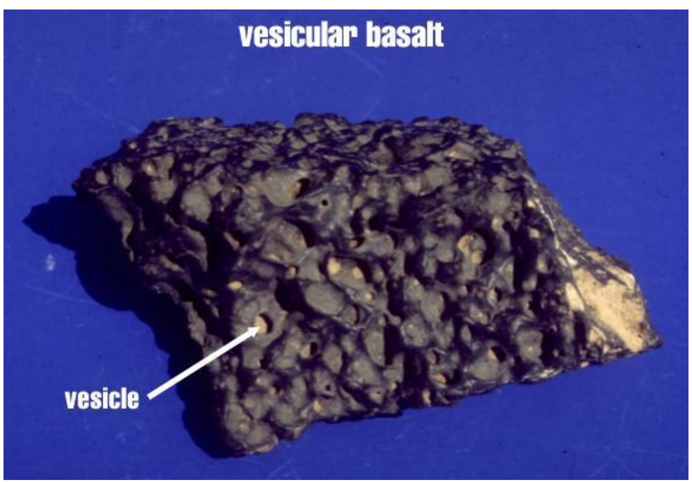
• An ***aphanitic*** texture consists of an aggregate of very small mineral grains, too small to be seen clearly with the naked eye. Aphanitic textures record rapid cooling at or very near Earth's surface and are characteristic of extrusive (volcanic) igneous rocks.

3.1.3. VOLCANIC AND PLUTONIC ROCK TEXTURES

Volcanic rock textures:

Quench or smooth

• Very rapid cooling of lava produces a "glassy texture". The lava cools so quickly that atoms do not have time to arrange in an ordered three-dimensional network typical of minerals. The result is natural glass, or obsidian



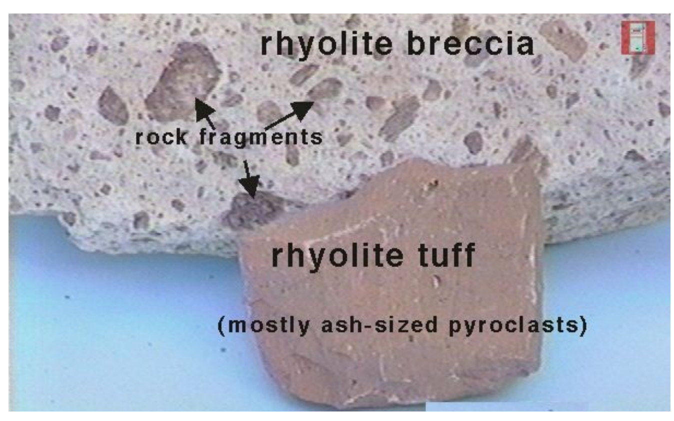
Vesicular

• Gases trapped in cooling lava can result in numerous small cavities, vesicles, in the solidified rock.

Pyroclastic

• Igneous rocks formed of mineral and rock fragments ejected from volcanoes by explosive eruptions have pyroclastic (fragmental) textures. The ejected ash and other debris eventually settles to the surface where it is consolidated to form a pyroclastic igneous rock.

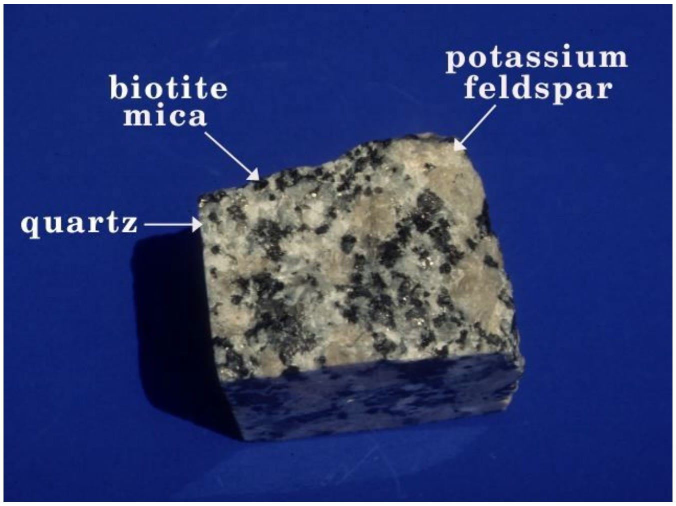
• Much of this material consists of angular pieces of volcanic glass measuring up to 2mm



Plutonic textures:

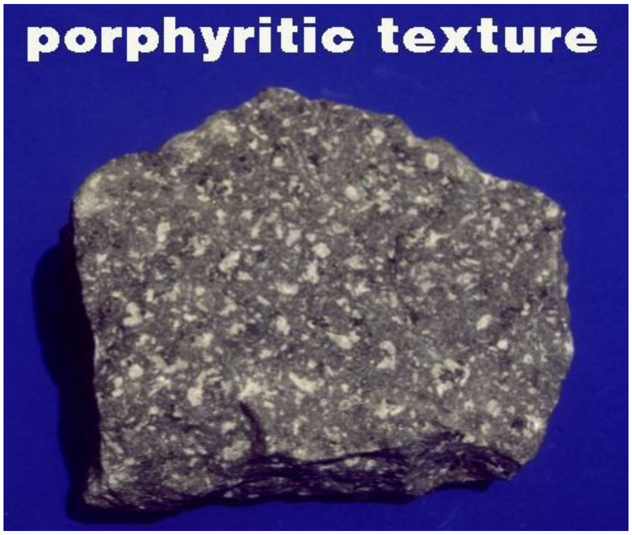
Phaneritic

• A ***phaneritic*** (coarse grained) texture consists of an aggregate of large(several mm in size) mineral grains, easily visible without magnification. Phaneritic textures record slow cooling within Earth and are characteristic of intrusive (plutonic) igneous rocks.



Porphyritic

• Igneous rocks comprised of minerals of two or more markedly different grain sizes have a porphyritic texture. The coarser grains are called phenocrysts and the smaller grains groundmass. Porphyritic textures result from changes in cooling rate and include both aphanitic porphyrys and phaneritic porphyrys.



Another aspect of texture, particularly in medium to coarse grained rocks is referred to as fabric. ***Fabric*** refers to the mutual relationship between the grains. Three types of fabric are commonly referred to:

1. If most of the grains are ***euhedral*** - that is they are bounded by well-formed crystal faces. The fabric is said to be ***idomorphic granular***.

2. If most of the grains are ***subhedral*** - that is they bounded by only a few well-formed crystal faces, the fabric is said to be ***hypidiomorphic granular***.

If most of the grains are ***anhedral*** - that is they are generally not bounded by crystal faces, the fabric is said to be ***allotriomorphic granular***.

If the grains have particularly descriptive shapes, then it is essential to describe the individual grains. Some common grain shapes are:

- *Tabular* - a term used to describe grains with rectangular tablet shapes.

- *Equant* - a term used to describe grains that have all of their boundaries of approximately equal length.
- *Fibrous* - a term used to describe grains that occur as long fibers.
- *Acicular* - a term used to describe grains that occur as long, slender crystals.
- *Prismatic* - a term used to describe grains that show an abundance of prism faces.

Other terms may apply to certain situations and should be noted if found in a rock.

- *Vesicular* - if the rock contains numerous holes that were once occupied by a gas phase, then this term is added to the textural description of the rock.
- *Glomeroporphyritic* - if phenocrysts are found to occur as clusters of crystals, then the rock should be described as glomeroporphyritic instead of porphyritic.
- *Amygdular* - if vesicles have been filled with material (usually calcite, chalcedonay, or quartz, then the term amygdular should be added to the textural description of the rock. An amygdule is defined as a refilled vesicle.
- *Pumiceous* - if vesicles are so abundant that they make up over 50% of the rock and the rock has a density less than 1 (i.e. it would float in water), then the rock is pumiceous.
- *Scoraceous*- if vesicles are so abundant that they make up over 50% of the rock and the rock has a density greater than 1, then the rock is said to be scoraceous.
- *Graphic* - a texture consisting of intergrowths of quartz and alkali feldspar wherein the orientation of the quartz grains resembles cuneiform writing. This texture is most commonly observed in pegmatites.
- *Spherulitic* - a texture commonly found in glassy rhyolites wherein spherical intergrowths of radiating quartz and feldspar replace glass as a result of devitrification.
- *Obicular* - a texture usually restricted to coarser grained rocks that consists of concentrically banded spheres wherein the bands consist of alternating light colored and dark colored minerals.

3.1.4. Mineral composition of Igneous Rocks

- Common igneous rocks are composed of one or more of six minerals
- Quartz, feldspar, mica, amphibole, pyroxene and olivine
- Quartz and feldspar are light coloured minerals
- Amphibole, pyroxene and olivine are dark ferromagnesian minerals
- Rocks dominated by qtz + fspar are ***felsic***
- Rocks dominated by ferromagnesian minerals are ***mafic***

Classifying Igneous Rocks

• Most igneous rocks can be classified on the basis of texture and composition.
• Compositional equivalents

Vesicular	**Pumice Scoria**			
Basalt	Aphanitic	Rhyolite	Andesite	
Gabbro	Phaneritic	Granite	Diorite	Peridotite
Mafic	**Colour Textures**	Felsic	Intermediate	**Ultramafic**
Glassy	Obsidian			

Igneous Rock Classification Chart

Composition of Igneous Rocks

• Magma composition controls the composition of the igneous rocks formed by cooling and crystallization.

• Due to crystal settling, assimilation, magma mixing and sequential mineral crystallization, a parent magma can yield igneous rocks of a variety of compositions.

• **Ultramafic igneous rocks** contain <45% Si and are composed of ferromagnesian (Fe- & Mg-rich) silicate minerals. These rocks are commonly dark colored because the minerals that comprise them, olivine, pyroxene, and Ca-plagioclase, are black to olive green. The ultramafic rock peridotite is composed almost entirely of olivine. Peridotite makes up the upper mantle, but like most ultramafic rocks, it is rare at the surface.

Mafic (45-52% silica) igneous rocks are dark colored because they are largely composed of Ca-plagioclase and pyroxene. Basalt is fine-grained, whereas gabbro is coarse-grained. Basalt is the most common extrusive (volcanic) igneous rock. The lower part of oceanic crust is comprised of gabbro.

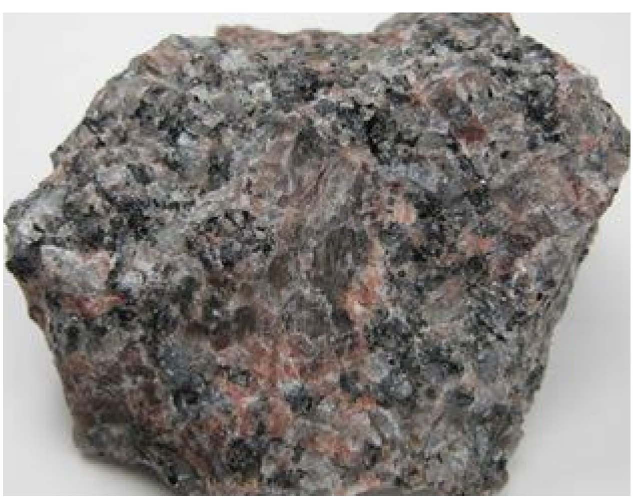
Intermediate (53-65% silica) igneous rocks contain nearly equal amounts of dark colored ferromagnesian silicate minerals such as amphibole and biotite and light colored plagioclase feldspar. Andesite is fine-grained, whereas diorite is coarse-grained. Andesite is formed of lava erupted from volcanic island arcs. Diorite is fairly common in continental crust.

Pegmatite

Diorite

Basalt

Gabbro



Granite

Andesite

3.2.SEDIMENTARY PETROLOGY

Sedimentary Rocks and their processes

Sedimentary Rocks (Soft rock)

Sedimentary rocks are composed of sediment, all solid particles derived by mechanical and chemical weathering as well as minerals precipitated from solution by chemical or biochemical processes.

Introduction

• Chemical and biochemical sediments respectively consist of minerals precipitated from solution by the inorganic chemical processes or the activities of organisms.

• Detrital sediments are solid particles derived by weathering. Particle size is particularly important for classifying this type of sediment.

Why Study Sedimentary Rocks?

• Sediments and sedimentary rocks are the most commonly encountered Earth materials. They cover 75% of the continents and nearly all of the ocean floor except at ocean ridges.
• Features preserved in sedimentary rocks record the environmental conditions at the time the sediment was originally deposited.Therefore sedimentary rocks are especially important for deciphering Earth history.
• Much of our knowledge of the evolution of life on Earth derives from fossils preserved in sedimentary rocks.
• Some sediments and sedimentary rocks are resources in their own right, or contain resources.

What are sediments?

• Sediments are particulate matter derived from physical or chemical weathering of the earths crust which are subsequently transported by wind, water or ice.

Talus

• large rock fragments
• weathering of rocks in mountainous regions

Sediment transport & deposition

• Sediment is transported by wind, water and ice. Ice is a solid and so can carry sediment particles of any size, but wind transports only sand and smaller particles.
The most prolific transport agent is running water. The larger the particle size, the more vigorous the current required for transport.
• Whether transported by water, wind, or ice, sediment eventually accumulates in a geographic area known as a depositional environment.
• Abrasion during transport reduces particle size and smoothes sharp corners, a process known as rounding.
• Transport & depositional processes influence sorting, which refers to the variety of particle sizes present in a sediment or sedimentary rock. Sorting and rounding provide information that can help decipher the history of a sedimentary deposit.

Important factors of depositional environments

• Type of transporting agent (water, wind, ice)
• Flow characteristics of depositing fluid (velocity or variation in velocity)
• Size, shape, and depth of body of water, and circulation of water
• Geochemical parameters (T, P, O content, and pH)
• Types and abundances of organisms present
• Types and composition of sediments entering environment

Sediment Transport & Deposition

Sediments are deposited in a variety of continental, marine, and transitional environments. Physical, chemical, and biological processes operating in the depositional environment impart distinctive characteristics to the accumulating sediment.

Terminology

• Lithification, which involves compaction and cementation, converts sediments to sedimentary rocks.
• Compaction, driven by the weight of sediment overlying a deeper layer, reduces the volume of a deposit as particles pack more closely and pore space is reduced.
• Cementation binds one particle to another by chemical precipitation of minerals in sediment pore space. Common cements include quartz, calcite, and hematite.
• Lithification of gravel, sand, and mud requires both compaction and cementation, but compaction alone is sufficient to lithify mud.

3.2.1.TYPES OF SEDIMENTARY ROCKS

Clastic sedimentary rocks such as **breccia**, **conglomerate**, **sandstone**, **siltstone**, and **shale** are formed from mechanical weathering debris.

Chemical sedimentary rocks, such as **rock salt**, **iron ore**, **chert**, **flint**, some **dolomites**, and some **limestones**, form when dissolved materials precipitate from solution.

Organic sedimentary rocks such as **coal**, some **dolomites**, and some **limestones**, form from the accumulation of plant or animal debris.

• Clastic sedimentary rocks are formed from the mechanical break up of other rocks and are classified based on the particle size, e.g. sandstone. Closer to the source the grains will tend to be larger and more angular

• Chemical sedimentary rocks are formed from the precipitation of minerals from solution, e.g. limestone formed from the calcium carbonate or halite formed from the drying up of an inland sea.
• Biogenic sedimentary rocks are produced directly from biological activity, e.g., coal, chalk and chert.

Clastic or Detrital rocks

Detrital sedimentary rocks are formed of solid particles such as sand & gravel derived by weathering. These rocks are classified by the size of their constituent particles

Sediment Name & Size	Description	Rock Name
gravel (>2 mm)	Rounded gravel	Conglomerate
	Angular gravel	Breccias
sand (1/16-2 mm)	mostly quartz	Qtz sandstone
	>25% feldspar	Arkose
silt (1/16-1/256 mm)	mostly silt	Siltstone
clay (<1/256 mm)	mostly clay	*Claystone

* fissile claystone is called shale

Chemical sedimentary rocks

Chemical sedimentary rocks are formed of ions taken into solution by chemical weathering of parent material. Many have crystalline texture of interlocking mineral grains. These rocks are classified based on their mineral composition.

Texture	Compostion	Rock Name
varies	calcite ($CaCO3$)	*limestone
varies	dolomite [$CaMg (CO3)2$]	**dolostone
crystalline	gypsum ($CaSo4 . 2H2O$)	rock gypsum
crystalline	halite ($NaCl$)	rock salt

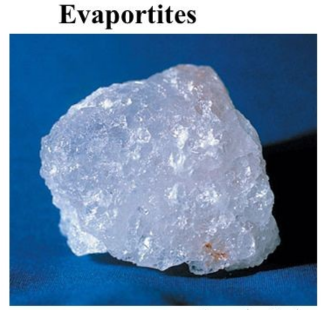
** most limestone is biochemical*

*** dolostone is chemically altered limestone*

Rock Gypsum

Limestone

Evaportites



Rock Salt

Evaporites are chemical sedimentary rocks formed by precipitation of minerals from evaporating water. Rock salt and rock gypsum are most common and are important resources

Biochemical sedimentary rocks

Biochemical sedimentary rocks are formed of ions taken into solution by chemical weathering of parent material, as are chemical sedimentary rocks. Organisms aid in the precipitation of biochemical sedimentary rocks

Texture	Composition	Rock Name
*clastic	calcite ($CaCO3$) shells, etc.	limestone
crystalline	altered microscopic shells of qtz	chert
	carbon from altered plant remains	coal

* composed of individual particles or grains, fragments of shells or similar grains in the case of biochemical limestone

Limestone derived from bio-chemical processes is much more common than that formed by inorganic processes. Limestone composed of skeletal fragments of marine invertebrates is quite common. Both coquina and fossiliferous limestone contain abundant skeletal material. Coquina, however, contains much pore space, but pores of fossiliferous limestone are filled with cement and mud.

Chert is composed of quartz and is found as nodules in limestone, or in distinct layers where it is composed of the microscopic shells of tiny marine organisms. Coal consists of the compressed, altered remains of land plants that occupied swamps and bogs.

3.2.2. SEDIMENTARY FACIES FORMATION

Sedimentary facies are bodies of sediment or sedimentary rock containing distinct chemical, physical, and biological attributes imparted by their environments of deposition.

• In marine coastal areas for example, several facies accumulate simultaneously on various areas of the seafloor. Each area is characterized by a distinct set of environmental conditions which influences sediment type.

• The stacking arrangement of sedimentary rocks records the lateral relationships between facies/environments at the time of sediment deposition.

• In coastal areas, the stacking of sediment layers deposited in laterally adjacent environments results from movement of the shoreline with relative changes in sea level.

Marine transgression

As shorelines move, depositional environments and the sediments accumulating in them follow. A landward shift in the shoreline gives rise to a marine transgression (relative rise in sea level). As facies shift landward with the shoreline, nearshore sediments come to overlie old land surfaces, and offshore sediments are stacked atop those of the nearshore. Transgressions produce a distinctive vertical arrangement of facies, with offshore deposits atop the stack.

Sedimentary Structures

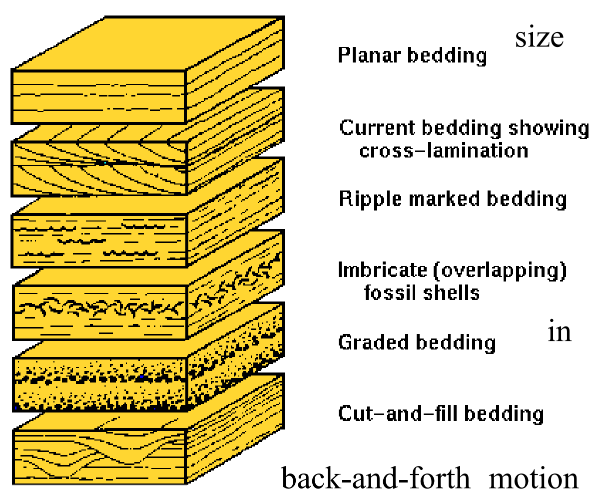
Sedimentary structures are features formed in sediment by physical or biological processes at the time of, or shortly after deposition. Strata or beds are layers that differ in color, texture, and composition from rock layers above and below. Crossbedding refers to inclined layers within a given bed. Formed by wind or water, this feature slopes downward in the direction of flow.

The 3 types of bedding

• Parallel, cross-bedding and graded bedding

Graded bedding

Graded bedding refers to an upward decrease in grain size within an individual bed. It is often found in the deposits of turbidity currents, high density submarine flows. As turbidity currents slow, larger particles are deposited first and progressively smaller ones deposited as flow continues to weaken.

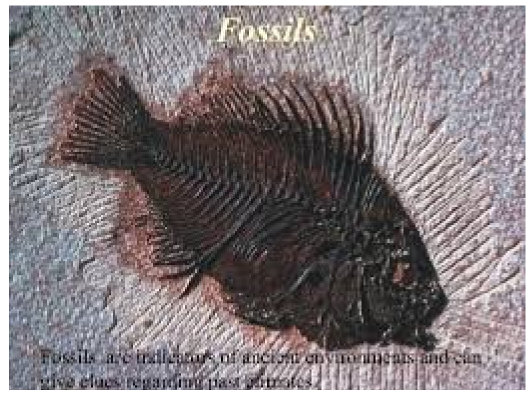


Ripple marks, small ridges separated by intervening troughs, form on sand deposits and are often preserved in the rock that forms from these deposits. Current ripple marks have asymmetric cross-sections and record flow in one direction as in streams. Wave-formed ripple marks have symmetric cross-sections generated by the back-and-forth motion of waves.

Mud cracks are shrinkage cracks that form polygonal patterns of intersecting fractures. They form when clay-rich sediment dries. Mud cracks are preserved in sedimentary rocks and indicate that the depositional environment was one where periodic drying occurred, such as on a river floodplain, a lake shore, or tidal flat.

Fossils

Fossils are the remains or traces of ancient organisms. They provide insight for prehistoric life, but also are useful for reconstructing depositional environments.



The morphology of an ancient organism or its life habits reveal important information about the environment in which the organism lived. For example, heavy-shelled clams lived in shallowwater, turbulent conditions, whereas clams from quite low-energy settings have thin, fragile shells. Filter-feeding organisms like corals require clear seawater because suspended sediment clogs their feeding organs.

Depositional Environments

• Continental:
• Fluvial: Alluvial Fan, Braided Stream, Meandering Stream
• Desert
• Glacial
• Deltaic: delta plain, delta front, prodelta
• Marginal marine:
• Beach
• Lagoon
• Tidal Flat
• Neritic: Continental shelf, organic reef
• Marine:
• Oceanic: Continental slope

Resources in Sedimentary rocks

• Sand and gravel for building and road construction.
• Limestone for manufacture of cement.
• Gypsum for manufacture of wallboard.
• Phosphate-bearing sedimentary rock for fertilizer.
• Quartz sand for manufacture of glass.

• Carnotite, a uranium-bearing mineral mined to fuel nuclear reactors, is found associated with plant remains in sandstones formed in ancient stream channels.
• Uranium – Canada is the worlds largest producer. Derived from sedimentary rocks. Uraninite is easily oxidized and dissolved in groundwater but equally easily reduced and precipitated in the presence of organic matter.
• Hematite & magnetite, iron ore minerals, are found in chemical sedimentary rocks known as BIFs
• Bauxite – major source of Al
• Placer deposits - gold, tin and diamonds
• Fossil fuels – coal, oil and natural gas

3.3. METAMORPHIC ROCKS & PROCESSES

Lava flow (above) bakes mud layer (below) into a brick red shale during the process of CONTACT metamorphism

Metamorphic rocks and processes

- Metamorphism comes from the Greek words"Meta" - change"Morphe" – form.
- Metamorphic rocks form by solid-state (no melting) transformation of preexisting rock by processes that take place beneath Earth's surface.
- Chemical, mineralogical and structural adjustments of solid rocks to physical and chemical changes at depths below the region of sedimentation

Why Study Metamorphic Rocks?

- Studies of metamorphic rocks provide insights into the physical and chemical changes that take place deep within Earth. The presence of index minerals in metamorphic rocks allows geologists to asses sthe temperatures and pressures the parent rock encountered.

- Knowledge of metamorphic processes and rocks is valuable, because metamorphic minerals and rocks have economic value. For example, slate and marble are building materials, garnets are used as gemstones and abrasives, talc is used in cosmetics, paints, and lubricants, and asbestos is used for insulation and fireproofing.

- Metamorphic rocks are some of the oldest on Earth, are widely exposed in the core areas, known as shields, of continents, and make up a large portion of the roots of mountain ranges.

Limits of metamorphism

- Metamorphism is a response to the Earths geothermal gradient (~30°C/km)
- At ~5km the temperature is ~150°C this is the point at which diagenesis ends and metamorphism begins.
- 5 km is also the point at which pressure is high enough for recrystallisation and new mineral growth (1500 times atmosphere). The upper limit is about 800°C

3.3.1. AGENTS OF METAMORPHISM

There are three main sources of chemically active fluids:

- pore waters of sedimentary rocks,
- fluids from cooling magma,
- water from dehydration of water-bearing minerals like gypsum ($CaSO_4 \cdot 2H_2O$)

Pore fluids

- As well as transporting material pore fluidsa ct as a reservoir
- As pressure and temperature increase material is transferred from the fluid to the minerals and vice versa
- In this way fluids serve to catalyse the reactions
- Metamorphism will drive fluids out of hydrous minerals forming veins

• An example of metamorphism by fluid activity is seawater moving through the hot basalt of the oceanic crust.

Olivine in the basalt is transformed to the mineral serpentine.
$$2Mg2SiO4 + 2H2O \longrightarrow Mg3Si5O5(OH)4 + MgO$$

Pressure
Lithostatic pressure results from the weight of overlying rocks, is applied equally in all directions, and increases with depth of burial.

The minerals of parent rocks subjected to increasing lithostatic pressure recrystallize as smaller and denser minerals. The pressure increase with depth in the ocean is similar to lithostatic pressure.

Directed pressure: Most metamorphic rocks form under conditions of differential stress. **Differential pressure** refers to the conditions where pressure is greater in one direction than in another. It is associated with deformation and mountain building and produces distinctive metamorphic textures and features. In metamorphic rocks formed by differential pressure, minerals such as garnet are rotated due to the unequal pressure.

Temperature
• Heat increases the rate of the chemical reactions that yield new minerals as parent rocks are metamorphosed.
• The heat may come from magma intrusion or deep burial via subduction at convergent boundaries.
• In country rock surrounding a magma body, heat's effect decreases with distance from the magma body.

Time
• The chemical reactions involved in metamorphism are relatively slow
• The longer the metamorphic event lasts the larger the grain size
• It is thought that coarse grained metamorphic rocks took millions of years to form
• But temperature, pressure and fluid content are more important

Causes of metamorphism
The processes that cause metamorphism are

• Mechanical deformation
• Chemical recrystallisation

Mechanical processes include grinding, crushing & fracturing.
Chemical recrystallisation includes changes in composition, growth of new minerals, recrystallisation and changes in pore fluid compositions. Metamorphism involves both chemical and mechanical changes but in varying proportions.

3.3.2. TYPES OF METAMORPHISM

There are basically three types of metamorphism

• Contact metamorphism (heat)

• Dynamic metamorphism (pressure)

• Regional metamorphism (heat & pressure)

Contact Metamorphism

Contact metamorphism occurs when heat or release of chemically active fluids from a magma or lava body alter the adjacent country rock.

• Two types of contact metamorphism are recognized:

• Alteration due to baking of country rock

• Alteration due to hot chemically active solutions, known as hydrothermal alteration.

• Hydrothermal alteration, In the final stages of cooling, magma releases large volumes of hot, mineral-charged solutions into the surrounding country rock, which causes hydrothermal alteration.

• Concentric zones of alteration surrounding a magma body comprise an aureole. The zone closest to the intrusion contains higher temperature metamorphic minerals whereas more distant zones contain lower temperature minerals. The size, temperature, and magma composition of an intrusion as well as the mineralogy of the country rock controls the width of the metamorphic aureole.

The boundary between an igneous intrusion and the surrounding metamorphic aureole can be sharp or transitional.

Dynamic Metamorphism

Dynamic metamorphism occurs along fault zones where rocks have been altered by high differential pressure. Rocks formed by dynamic metamorphism are restricted to narrow zones adjacent to faults and are known as mylonites. Mylonites are commonly hard, dense, fine-grained, and contain thin laminations. Such rocks are found along the famous San Andreas Fault of California.

Regional Metamorphism

• Regional metamorphism occurs over broad areas, is cause by high pressure and temperature, and deformation in deeper portions of the crust. It is most obvious along convergent plate boundaries

• This is the most common form of metamorphism.

• As crustal thickening progresses material at the bottom of the pile is subjected to increased temperature and pressure.

• If the burial is slow then heat and pressure build equally.

• If the burial is fast the the poor conductivity of rocks means that pressure builds quicker than temperature.

• Geologists recognize low, medium, and high grade regional metamorphism based on index minerals that form at specific pressure-temperature conditions.

• Beginning with a clay-rich parent rock such as shale and tracking its subjection to ever more intense pressure and heat illustrates the sequence of index minerals formed by low- to high-grade regional metamorphism. For example, chlorite forms under low-grade conditions, staurolite and kyanite under intermediate-grade, and sillimanite under high-grade conditions.

Index minerals

Index minerals were identified that could define metamorphic grade

• We know that the chemical composition of metamorphosed rocks does not change
• Metamorphism is isochemical
• Elements are redistributed but not lost
• Consequently any changes are the result of temperature and pressure
• This has led to the concept of metamorphic facies

Each facies represents a characteristic range of temperature and pressure
High P
Low T
High T
Low P

Metamorphism & Natural Resources

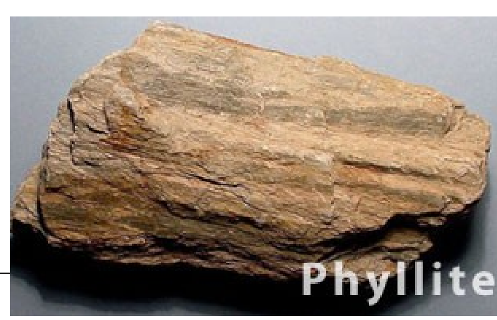
• Metamorphic minerals and rocks provide many valuable resources, marble and slate the two most widely used.

• Economically valuable metamorphic minerals include: talc to talcum powder, graphite for pencils and dry lubricant, garnet and corundum for abrasive and gemstones, kyanite for hightemperature porcelain.
• Asbestos has had broad use as insulation and fireproofing.

3.3.3. TYPESS OF METAMORPHIC ROCKS AND THEIR TEXTURES

(Terminology:-Foliation: layering or banded appearance produced by exposure to heat and directed pressure
Protolith: parent rock)

Foliated: Slate
• Parallel orientation of grains
• Low grade metamorphic, slaty texture
• Protolith: shale/mudstone



Foliated: Phyllite

• Very fine grained mica
• Barely macroscopic
• Crenulated parallelism, sheen

Foliated: Chlorite Schist
• Mid-grade metamorphic rock
• Schistose texture

Foliated: Muscovite Schist

Foliated: Garnet Schist

Foliated: Gneiss
• High grade metamorphic
• Gneissic banding: 1mm to cm's scale
• Protolith: Shale, mudstone, igneous rock

Non-Foliated and Foliated: Amphibolite

• Coarse grained, high grade
• Protolith: Mafic and Ultramafic igneous rocks

Non-Foliated: Marble
• **$CaCO_3$**
• **Metamorphosed limestone!**
• **Beware of colours**

Non-Foliated: Quartzite
• Metamorphism of sandstone
Protolith: Sansstone

Non-foliated: Hornfels

Protolith: anything

Heat sources: magma chambers, dikes, sills

High Pressure Metamorphic Rocks:

Blueschist and Greenschist
Eclogites: Subductions zones!

Blueschist

Greenschist

Anthracite
• Protolith: Bituminous coal
• Conchoidal fractures

Anthracite