WEATHERING

Before we discuss the other types of rocks (Sedimentary and Metamorphic) we need to have an understanding of the processes that cause the breakdown of rocks, either to form new minerals that are stable on the surface of the Earth, or to break the rocks down into smaller particles . This process is called ***weathering***, and is also the first step in a process that we call ***erosion***.

Geologists recognize two categories of weathering processes

1. ***Physical Weathering*** - disintegration of rocks and minerals by a physical or mechanical process.

2. ***Chemical Weathering***

Although we separate these processes, as we will see, both work together to break down rocks and minerals to smaller fragments or to minerals more stable near the Earth's surface.

Physical Weathering

Physical weathering takes place by a variety of processes. Among them are:

- Development of ***Joints*** - Joints are regularly spaced fractures or cracks in rocks that show no offset across the fracture (fractures that show an offset are called faults).

    - Joints form as a result of expansion due to cooling or relief of pressure as overlying rocks are removed by erosion.

    - Joints form free space in rock by which other agents of chemical or physical weathering can enter.

- Crystal Growth - As water percolates through fractures and pore spaces it may contain ions that precipitate to form crystals. As these crystals grow they may exert an outward force that can expand or weaken rocks.

- Heat - Although daily heating and cooling of rocks do not seem to have an effect, sudden exposure to high temperature, such as in a forest or grass fire may cause expansion and eventual breakage of rock. Campfire example.

- Plant and Animal Activities -
    - Plant roots can extend into fractures and grow, causing expansion of the fracture. Growth of plants can break rock - look at the sidewalks of New Orleans for example.

    - Animals burrowing or moving through cracks can break rock.

- ***Frost Wedging*** - Upon freezing, there is an increase in the volume of the water (that's why we use antifreeze in auto engines or why the pipes break in New Orleans during the rare freeze). As the water freezes it expands and exerts a force on its surroundings. Frost wedging is more prevalent at high altitudes where there may be many freeze-thaw cycles.

Chemical Weathering

Since many rocks and minerals are formed under conditions present deep within the Earth, when they arrive near the surface as a result of uplift and erosion, they encounter conditions very different from those under which they originally formed. Among the conditions present near the Earth's surface that are different from those deep within the Earth are:

- Lower Temperature (Near the surface T = 0-50^{o}C)
- Lower Pressure (Near the surface P = 1 to several hundred atmospheres)
- Higher free water (there is a lot of liquid water near the surface, compared with deep in the Earth)
- Higher free oxygen (although O_2 tied up bonded into silicate and oxide minerals - at the surface there is much more free oxygen, particularly in the atmosphere).

Because of these differing conditions, minerals in rocks react with their new environment to produce new minerals that are stable under conditions near the surface. Minerals that are stable under P, T, H_2O, and O_2 conditions near the surface are, in order of most stable to least stable:

- Iron oxides, Aluminum oxides - such as hematite Fe_2O_3, and gibbsite $Al(OH)_3$.
- Quartz*
- Clay Minerals
- Muscovite*
- Alkali Feldspar*
- Biotite*
- Amphiboles*
- Pyroxenes*
- Ca-rich plagioclase*
- Olivine*

Note the minerals with *. These are igneous minerals that crystallize from a liquid. Note the minerals that occur low on this list are the minerals that crystallize at high temperature from magma. The higher the temperature of crystallization, the less stable are these minerals at the low temperature found near the Earth's surface (see Bowen's reaction series in the igneous rocks chapter).

The main agent responsible for chemical weathering reactions is water and weak acids formed in water.

- An acid is solution that has abundant free H^+ ions.
- The most common weak acid that occurs in surface waters is carbonic acid.
- Carbonic acid is produced in rainwater by reaction of the water with carbon dioxide (CO_2) gas in the atmosphere.

$$\underset{\text{water}}{H_2O} + \underset{\text{carbon dioxide}}{CO_2} \longrightarrow \underset{\text{carbonic acid}}{H_2CO_3} \longrightarrow \underset{\text{hydrogen ion}}{H^+} + \underset{\text{bicarbonate ion}}{HCO_3^-}$$

H^+ is a small ion and can easily enter crystal structures, releasing other ions into the water.

Types of Chemical Weathering Reactions

- ***Hydrolysis*** - H^+ or OH^- replaces an ion in the mineral. Example:

$$\underset{\text{Orthoclase}}{4KAlSi_3O_8} + \underset{\text{Hydrogen ion}}{4H^+} + \underset{\text{water}}{2H_2O} \longrightarrow \underset{\text{Potassium ion}}{4K^+} + \underset{\text{Kaolinite (clay mineral)}}{Al_4Si_4O_{10}(OH)_8} + \underset{\text{quartz}}{8\ SiO_2}$$

- ***Leaching*** - ions are removed by dissolution into water. In the example above we say that the K^+ ion was leached.
- ***Oxidation*** - Since free oxygen (O_2) is more common near the Earth's surface, it may react with minerals to change the oxidation state of an ion. This is more common in Fe (iron) bearing minerals, since Fe can have several oxidation states, Fe, Fe^{+2}, Fe^{+3}. Deep in the Earth the most common oxidation state of Fe is Fe^{+2}.

$$\underset{\text{Pyroxene}}{3Fe^{+2}SiO_3} + \underset{\text{Oxygen}}{1/2O_2} \longrightarrow \underset{\text{Magnetite}}{Fe_3O_4} + \underset{\text{Quartz}}{3SiO_2}$$

- ***Dehydration -*** removal of H_2O or OH^- ion from a mineral.

$$\underset{\text{Goethite}}{2FeO \cdot OH} \longrightarrow \underset{\text{Hematite}}{Fe_2O_3} + \underset{\text{water}}{H_2O}$$

- ***Complete Dissolution***

$$\underset{\text{Calcite}}{CaCO_3} + \underset{\text{Carbonic Acid}}{H_2CO_3} \longrightarrow \underset{\text{Calcium ion}}{Ca^{2+}} + \underset{\text{Bicarbonate ion}}{2(HCO_3)^-}$$

Weathering of Common Rocks

Rock	Primary Minerals	Residual Minerals*	Leached Ions
Granite	Feldspars	Clay Minerals	Na^+, K^+
	Micas	Clay Minerals	K^+
	Quartz	Quartz	---
	Fe-Mg Minerals	Clay Minerals + Hematite + Goethite	Mg^{+2}
Basalt	Feldspars	Clay Minerals	Na^+, Ca^{+2}
	Fe-Mg Minerals	Clay Minerals	Mg^{+2}
	Magnetite	Hematite, Goethite	---
Limestone	Calcite	None	Ca^{+2}, CO_3^{-2}

*Residual Minerals = Minerals stable at the Earth's surface and left in the rock after weathering.

Weathering Rinds, Exfoliation, and Spheroidal Weathering

When rock weathers, it usually does so by working inward from a surface that is exposed to the weathering process. This may result in:

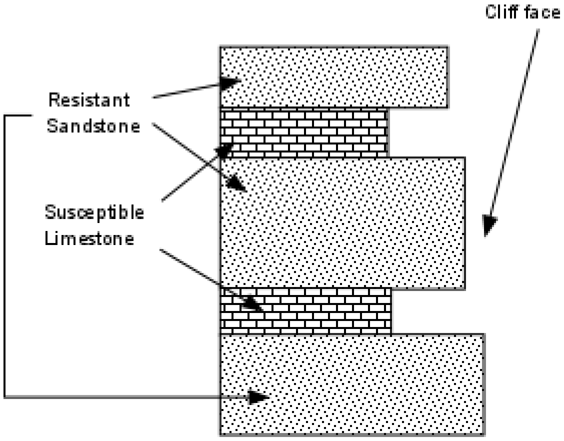
- ***Weathering Rinds*** - a rock may show an outer weathered zone and an inner unweathered zone in the initial stages of weathering. The outer zone is known as a weathering rind. As weathering continues the thickness of the weathering rind increases, and thus can sometimes be used as an indicator of the amount of time the rock has been exposed to the weathering process. (See figure B6.2, on page 161 in your text)

- ***Exfoliation*** - Concentrated shells of weathering may form on the outside of a rock and may become separated from the rock. These thin shells of weathered rock are separated by stresses that result from changes in volume of the minerals that occur as a result of the formation of new minerals. (See figure 6.10 in your text).

- ***Spheroidal Weathering***
  3-dimensional network, the rock will be broken into cube like pieces separated by the fractures. Water can penetrate more easily along these fractures, and each of the cube-like pieces will begin to weather inward. The rate of weathering will be greatest along the corners of each cube, followed by the edges, and finally the faces of the cubes. As a result the cube will weather into a spherical shape, with unweathered rock in the center and weathered rock toward the outside. Such progression of weathering is referred to as spheroidal weathering (See figures 6.11 & 6.12 in your text).

Factors that Influence Weathering

- Rock Type and Structure-
    - Different rocks are composed of different minerals, and each mineral has a different susceptibility to weathering. For example a sandstone consisting only of quartz is already composed of a mineral that is very stable on the Earth's surface, and will not weather at all in comparison to limestone, composed entirely of calcite, which will eventually dissolve completely in a wet climate.
    - Bedding planes, joints, and fractures, all provide pathways for the entry of water. A rock with lots of these features will weather more rapidly than a massive rock containing no bedding planes, joints, or fractures.
    - If there are large contrasts in the susceptibility to weathering within a large body of rock, the more susceptible parts of the rock will weather faster than the more resistant portions of the rock. This will result in ***differential weathering.***

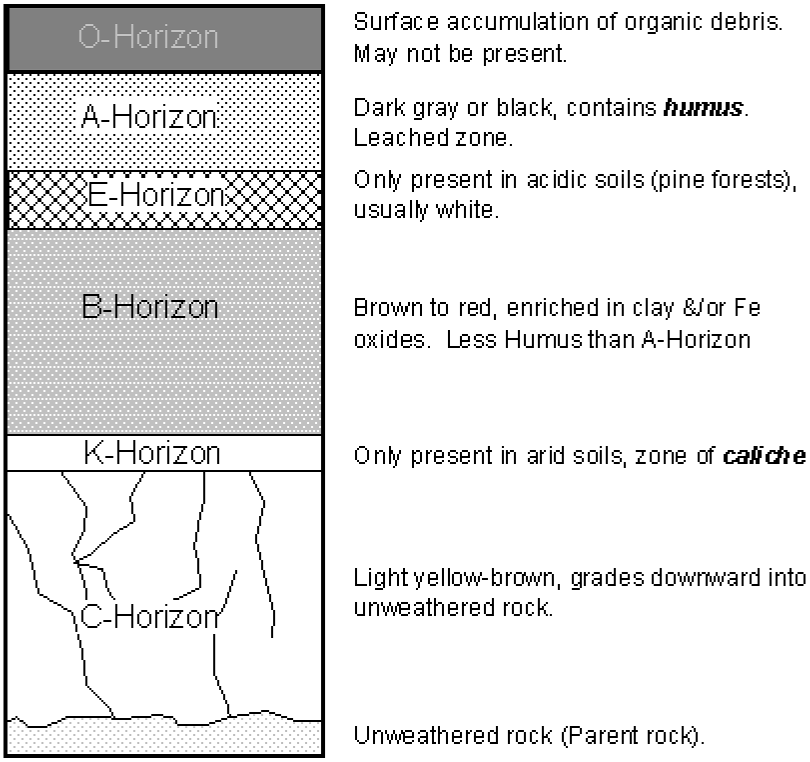


- Slope - On steep slopes weathering products may be quickly washed away by rains. On gentle slopes the weathering products accumulate. On gentle slopes water may stay in contact with rock for longer periods of time, and thus result in higher weathering rates.
- Climate- High amounts of water and higher temperatures generally cause chemical reactions to run faster. Thus warm humid climates generally have more highly weathered rock, and rates of weathering are higher than in cold dry climates. Example: limestones in a dry desert climate are very resistant to weathering, but limestones in a tropical climate weather very rapidly.
- Animals- burrowing organisms like rodents, earthworms, & ants, bring material to the surface were it can be exposed to the agents of weathering.
- Time - since a rate is how fast something occurs in a given amount of time, time is a crucial factor in weathering. Depending on the factors above, rates of weathering can vary between rapid and extremely slow, thus the time it takes for weathering to occur and the volume of rock affected in a given time will depend on slope, climate, and animals.

Soils

Soils are an important natural resource. They represent the interface between the lithosphere and the biosphere - as soils provide nutrients for plants. Soils consist of weathered rock plus organic material that comes from decaying plants and animals. The same factors that control weathering control soil formation with the exception, that soils also requires the input of organic material as some form of Carbon.

When a soil develops on a rock, a soil profile develops as shown below. These different layers are not the same as beds formed by sedimentation, instead each of the horizons forms and grows in place by weathering and the addition of organic material from decaying plants and plant roots.



Although you will not be expected to know all of the soil terminology discussed on pages 162 through 164 in your text, the following terms are important.

- ***Caliche*** - Calcium Carbonate (Calcite) that forms in arid soils in the K-horizon by chemical precipitation of calcite. The Ca and Carbonate ions are dissolved from the upper soil horizons and precipitated at the K-horizon. In arid climates the amount of water passing through the soil horizons is not enough to completely dissolve this caliche, and as result the thickness of the layer may increase with time.

- ***Laterites*** - In humid tropical climates intense weathering involving leaching occurs, leaving behind a soil rich in Fe and Al oxides, and giving the soil a deep red color. This extremely leached soil is called a laterite.

- ***Paleosols*** - If a soil is buried rapidly, for example by a volcanic eruption, the soil may be preserved in the geologic record as an ancient soil called a paleosol.

Soil Erosion

In most climates it takes between 80 and 400 years to form about one centimeter of topsoil (an organic and nutrient rich soil suitable for agriculture). Thus soil that is eroded by poor farming practices is essentially lost and cannot be replaced in a reasonable amount of time. This could become a critical factor in controlling world population.

Wind as a Geologic Agent

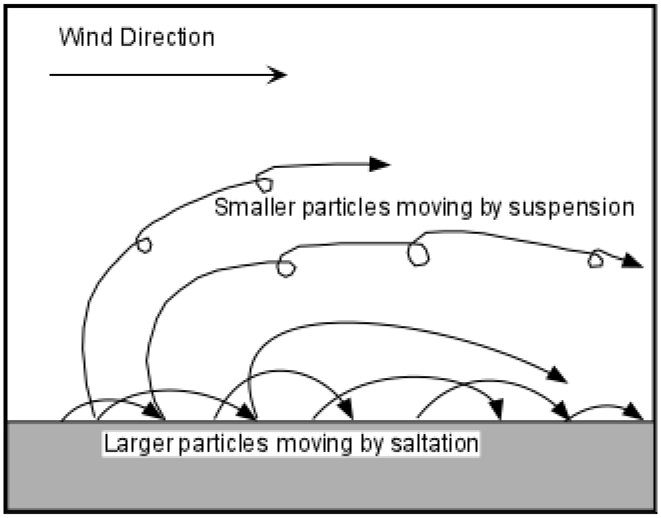
Wind is common in arid desert regions because:

1. Air near the surface is heated and rises, cooler air comes in to replace hot rising air and this movement of air results in winds.
2. Arid regions have little or no soil moisture to hold rock and mineral fragments.

Wind has the ability to transport, erode, and deposit sediment. In this lecture we will discuss each of these aspects of the wind.

Sediment Transportation by Wind

Wind transports sediment near the surface by saltation. Just as in the bed load of streams, saltation refers to short jumps of grains dislodged from the surface and jumping a short distance. As the grains fall back to the surface they may dislodge other grains that then get carried by wind until they collide with ground to dislodge other particles. Smaller particles can become suspended in the wind and may travel for longer distances.



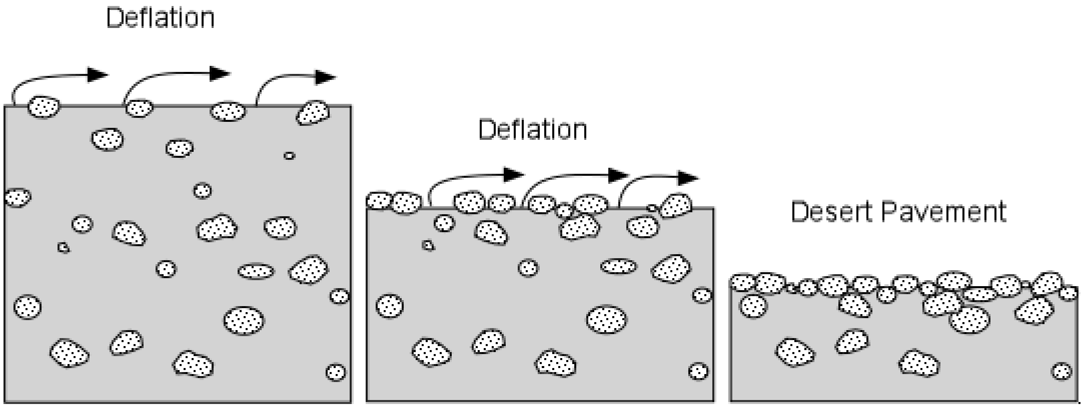
Sand Ripples - Occur as a result of larger grains accumulating as smaller grains are transported away. Ripples form in lines perpendicular to wind direction.

Wind blown dust - Sand sized particles generally do not travel very far in the wind, but smaller sized fragments can be suspended in the wind for much larger distances.

Wind Erosion

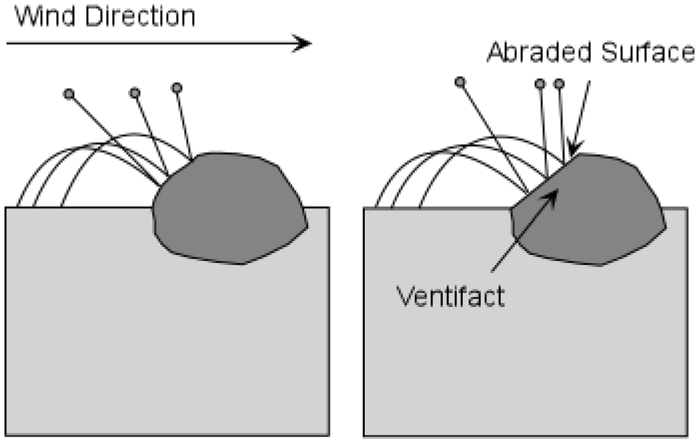
Wind can be effective agent of erosion anywhere that it is strong enough to act. Wind can erode by ***deflation*** and ***abrasion***.

- ***Deflation*** is the lowering of the land surface due to removal of fine-grained particles by the wind. Deflation concentrates the coarser grained particles at the surface, eventually resulting in a surface composed only of the coarser grained fragments that cannot be transported by the wind. Such a surface is called ***desert pavement***.



- ***Ventifacts*** are any bedrock surface or stone that has been abraded or shaped by wind-blown sediment in a process similar to sand blasting.

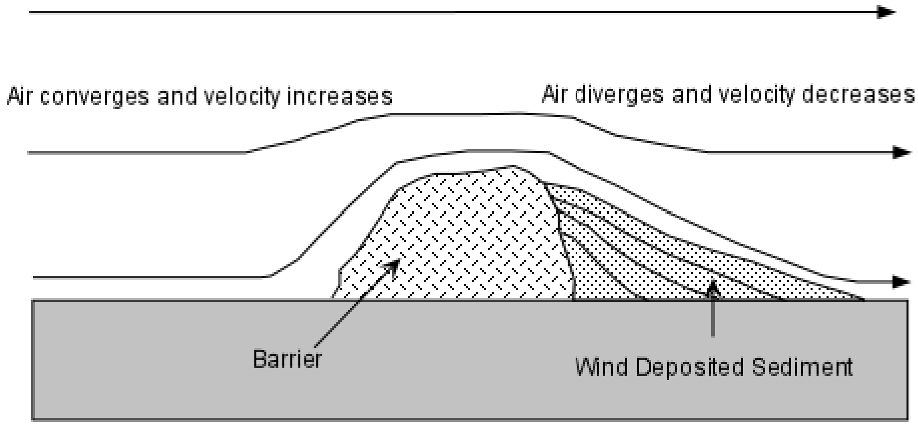
- ***Yardangs*** are streamlined wind-eroded ridges commonly found in deserts.



Wind Deposits

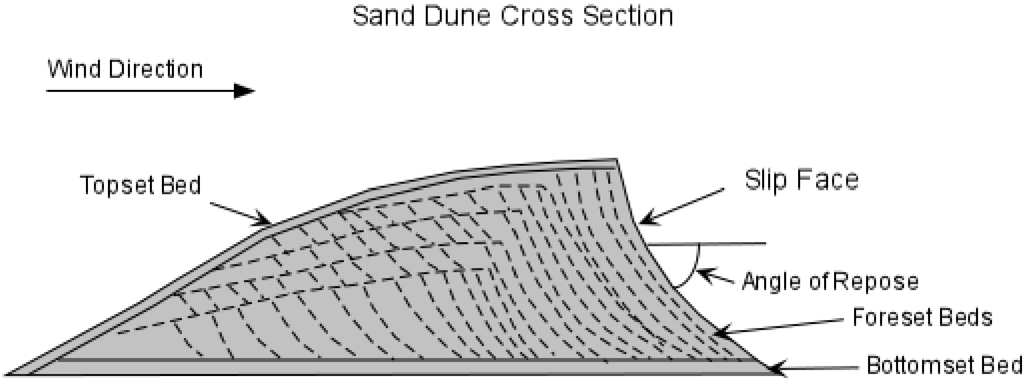
Wind can deposit sediment when its velocity decreases to the point where the particles can no longer be transported. This can happen when topographic barriers slow the wind velocity on the downwind side of the barrier. As the air moves over the top of the barrier, streamlines converge and the velocity increases.

After passing over the barrier, the streamlines diverge and the velocity decreases. As the velocity decreases, some of the sediment in suspension can no longer be held in suspension, and thus drops out to form a deposit.

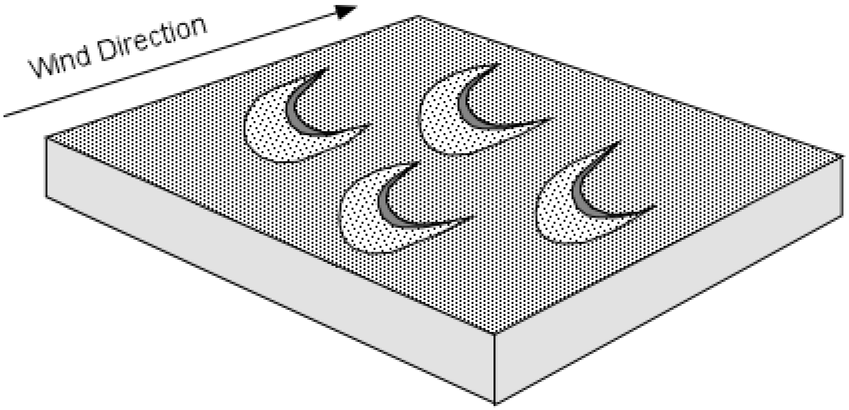


Topographic barriers can be such things as rocks, vegetation, and human made structures that protrude above the land surface.

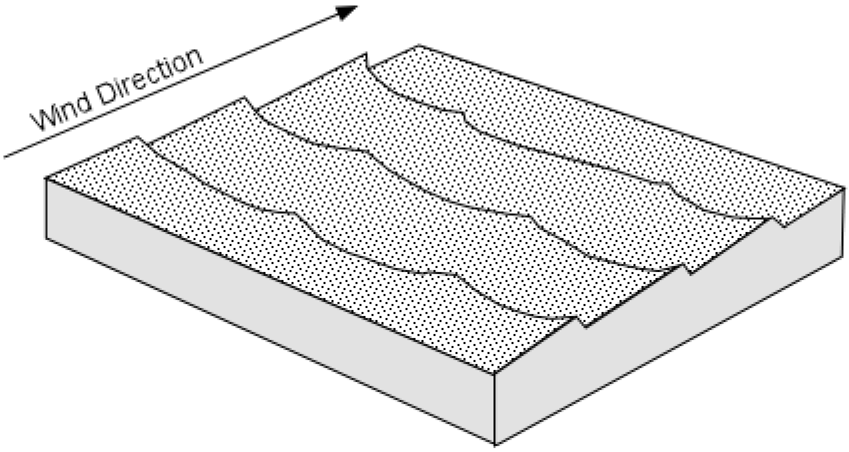
- ***Sand Dunes* -** Sand dunes form when there is (1) a ready supply of sand, (2) a steady wind, and (3) some kind of obstacle such as vegetation, rocks, or fences, to trap some of the sand. Sand dunes form when moving air slows down on the downwind side of an obstacle. The sand grains drop out and form a mound that becomes a dune.
  - Sand dunes are asymmetrical mounds with a gentle slope in the upwind direction and steep slope called a ***slip face*** on the downwind side. Dunes migrate by erosion of sand by wind (saltation) on the gentle upwind slope, and deposition and sliding on the slip face, and thus are cross-bedded deposits.



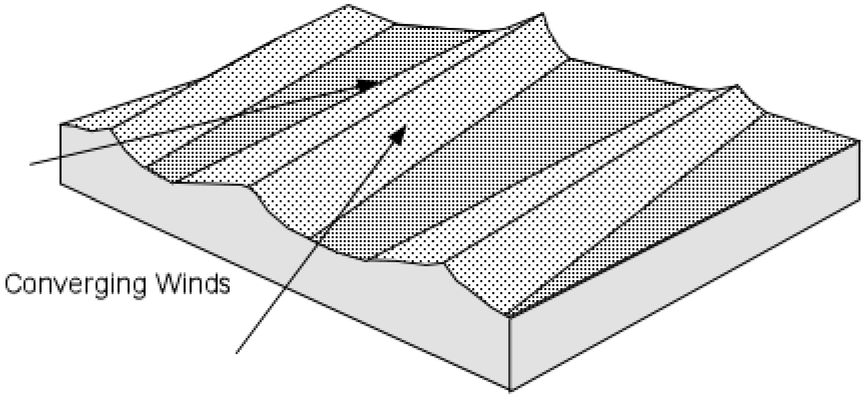
  - Dunes may cover large areas and reach heights up to 500m.
  - Types of sand dunes (Note: most of this material will be covered on slides in lecture):
    - ***Barchan Dunes*** - are crescent-shaped dunes with the points of the crescents pointing in the downwind direction, and a curved slip face on the downwind side of the dune. They form in areas where there is a hard ground surface, a moderate supply of sand, and a constant wind direction.



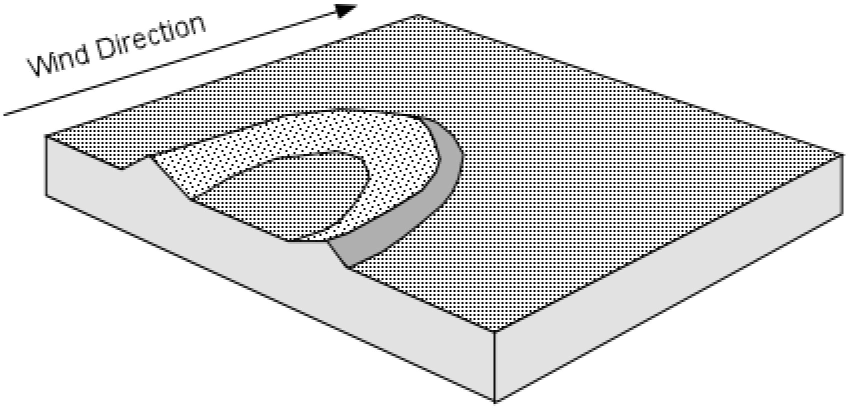
    - ***Transverse dunes*** - are large fields of dunes that resemble sand ripples on a large scale. They consist of ridges of sand with a steep face in the downwind side, and form in areas where there is abundant supply of sand and a constant wind direction. Barchan dunes merge into transverse dunes if the supply of sand increases.



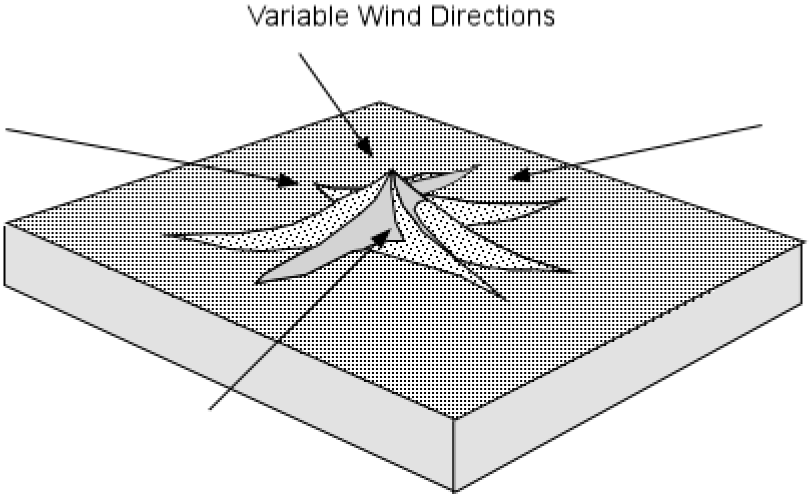
- ***Linear Dunes*** - are long straight dunes that form in areas with a limited sand supply and converging wind directions.



- ***Parabolic*** (also called ***blowout***) ***Dunes*** - are "U" shaped dunes with an open end facing upwind. They are usually stabilized by vegetation, and occur where there is abundant vegetation, a constant wind direction, and an abundant sand supply. They are common in coastal areas.



- ***Star Dunes*** - are dunes with several arms and variable slip face directions that form in areas where there is abundant sand and variable wind directions.



- Wind Blown Dust - Dust consists of silt and clay sized particles that are often packed together with smooth surface. Such packed dust is difficult to remove by wind erosion alone, unless the surface is very dry or is disturbed. When dust it is disturbed, dust storms may develop, and dust may be transported by the wind over large distances. Most soil contains some silt and clay particles deposited by the wind.

  A large deposits of wind deposited dust is called ***loess***. Much loess was derived from debris left by glacial erosion.

- Dust in Ocean Sediments and Glacial Ice. - Dust can be transported by the wind and by glacial ice onto the surface of the oceans. As a result, much of the fine grained continent-derived sediment that reaches the abyssal plains of the oceans was originally transported by winds or icebergs.

- Volcanic Ash - During explosive volcanic eruptions, large quantities of dust-sized tephra can be ejected into the atmosphere. If ejected high enough, such ash can become suspended in the wind and carried for long distances. Eventually it will settle out to become wind-deposited sediment.

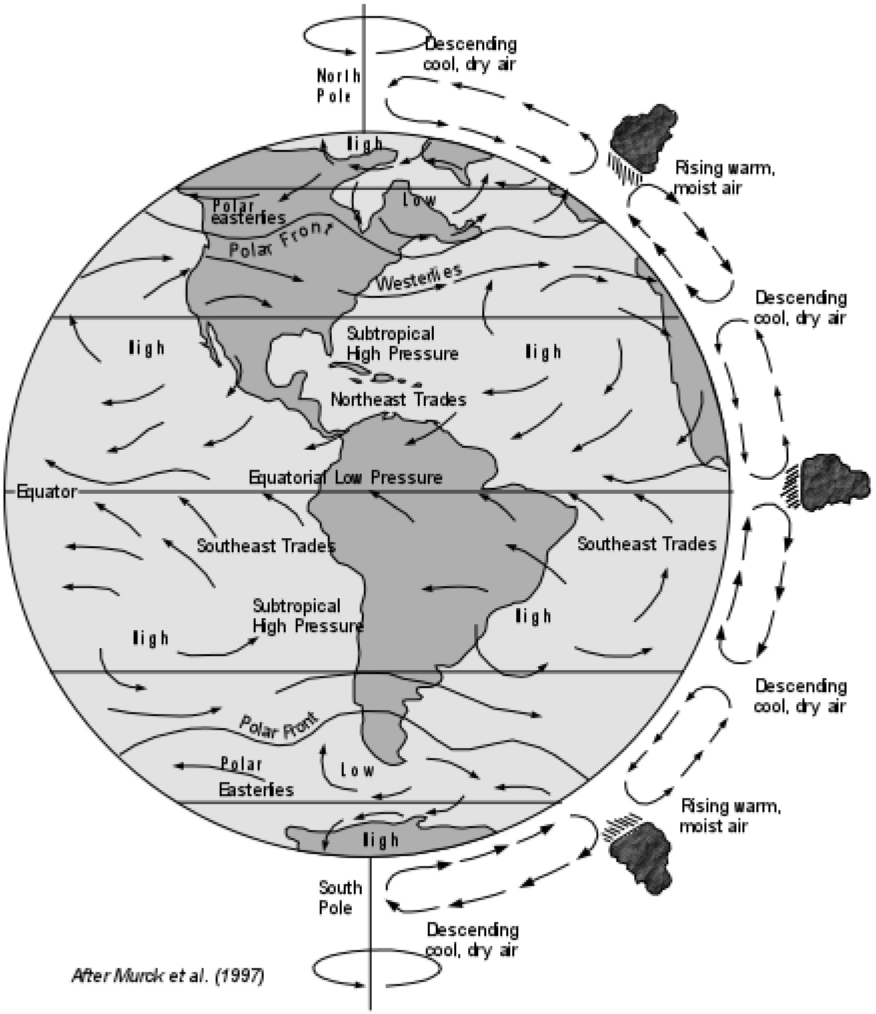
Deserts

Deserts are areas where rainfall is less than 250 mm (10 in.)/year, or where evaporation exceeds precipitation. Thus, deserts are areas that we think of as arid.

Origin of Deserts

Deserts originate by several different mechanisms that result in several different types of deserts.

- ***Subtropical Deserts*** - the general atmospheric circulation brings dry, subtropical air into mid-latitudes. Examples: Sahara of Northern Africa, Kalhari of Southern Africa, and the Great Australian Desert.



After Murck et al. (1997)

- ***Continental Deserts*** - Areas in the continental interiors, far from source of moisture where hot summers and cold winters prevail. Examples: Gobi, Takla Makan

- ***Rainshadow Deserts*** - Areas where mountainous regions cause air to rise and condense, dropping its moisture as it passes over the mountains. Examples: Deserts east of the Sierra Nevada Mountains, California & Nevada, East of the Cascades of Oregon and Washington, and East of the Andes Mountains in South America.

- ***Coastal Deserts*** - Areas where cold upwelling seawater cools the air and decreases its ability to hold moisture. Examples : Atacama Desert of coastal Peru, Namib Desert of coastal South Africa.
- ***Polar Deserts*** - Cold polar regions where cold dry air prevails and moisture available remains frozen throughout the entire year. Examples: Northern Greenland, and ice-free areas of Antarctica.

We will concentrate on the first four types of deserts, the one's which occur in hot arid climates.

Surface Processes in Deserts

The same geologic processes operate in deserts as in other more humid climates. The difference is the intensity to which the processes act.

- Weathering and Mass Wasting

    - Deserts have little soil because moisture is so low and the rate of chemical weathering is slow.

    - Little plant life because of lack of soils and water. Plants tend to hold soil and fine-grained rock fragments in place.

    - The desert surface is dominated by mechanical weathering processes. If we compare the surface features of deserts with those in humid regions, we find that:

        - deserts are dominated by rock falls, rock slides, and the accumulation of coarse grained material, and generally have steeper slopes.

        - humid regions have soil and fine-grained regolith covering slopes, with creep being the dominant mass-wasting process, resulting in curved gentle slopes.

- Streams and Fluvial Landforms (Note: these features will be shown as slides in class)

  Surface waters are rare in deserts. Streams that do flow in deserts usually originate at higher elevations and supply enough water for the stream to pass through the desert region. Streams in deserts tend to be intermittent, that is they flow only during rains. For this reason, flash floods and braided streams are common.

    - Alluvial Fans and Bajadas - An alluvial fan forms where a mountain stream enters a broad flat valley and deposits sediment as its velocity decreases on entering the flatter valley (see chapter 9). When a linear mountain range has several closely spaced valleys, the alluvial fans may coalesce to form a gentle undulated slope on the sides of the bounding lowlands. Such coalesced alluvial fans are known as ***Bajadas***.

    - ***Pediments*** - A pediment is broad bedrock surface with a gentle slope away from highlands. With distance away from the highlands the pediment passes beneath a thin cover of alluvial sediment derived from erosion of the pediment. The highlands remain as residual hills as the pediment matures.

    - ***Playa Lakes*** - Standing bodies of water like lakes are rare in desert regions because rainfall and input from streams occurs only intermittently. Lakes that do form during the rare periods of rainfall, quickly evaporate, leaving a dry lake bed behind. Playa Lakes (also called dry lakes) are formed in basins of internal drainage. The lake beds often consist of salts (evaporites) that were carried in by streams and precipitated during evaporation. These precipitated salts give the dry lake bed a white color resembling a beach (playa means beach in Spanish).

    - ***Inselbergs*** - The word inselberg means island mountain in German. Inselbergs are steep sided hills that rise above a surrounding relatively flat plain. They appear to form because the rock making up the inselberg is more resistant to erosion than the rocks that once made up the surrounding plain. Once an inselberg forms, it sheds water due to its steep slopes, and its steep slopes tend to not develop soil. The surrounding less resistant rock collects this water and is subjected to more rapid rates of chemical weathering. Thus as the surrounding plain is reduced by stream erosion and weathering faster than the more resistant rock. Inselbergs are common in desert regions, although they can also occur in other areas where differential erosion takes place.

Desertification

Desertification occurs as a result of climatic changes, such as changing positions of the continents, or changes in ocean and air circulation patterns. Human impacts, such as overgrazing, draining of land, and lowering of the groundwater table, can also contribute to desertification. As vegetation dies out, the soil is more easily eroded and may be lost so that other vegetation becomes destabilized. Since soil can hold moisture, if the soil erodes, the area may become arid, and the desert expands.

GEOLOGICAL ACTION OF GLACIER

Glaciers constitute much of the Earth that makes up the cryosphere, the part of the Earth that remains below the freezing point of water. Most glacial ice today is found in the polar regions, above the Arctic and Antarctic Circles. While glaciers are of relatively minor importance today, evidence exists that the Earth's climate has undergone fluctuations in the past, and that the amount of the Earth's surface covered by glaciers has been much larger in the past than in the present. In fact, much of the topography in the northern part of North America, as well as in the high mountain regions of the west, owe their form to erosional and depositional processes of glaciers. The latest glaciation ended only 10,000 years ago.

Definition of a glacier

A glacier is a permanent (on a human time scale, because nothing on the Earth is really permanent) body of ice, consisting largely of recrystallized snow, that shows evidence of downslope or outward movement due to the pull of gravity.

Types of Glaciers

- ***Mountain Glaciers*** - Relatively small glaciers which occur at higher elevations in mountainous regions.
    - Smallest of these occupy hollows or bowl-shaped depressions on sides of mountains (***cirque glaciers***).
    - As cirque glaciers grow larger they may spread into valleys and flow down the valleys as ***valley glaciers***. Paths these valley glaciers take are controlled by existing topography.
    - If a valley glacier extends down to sea level, it may carve a narrow valley into the coastline. These are called ***fjord glaciers***, and the narrow valleys they carve and later become filled with seawater after the ice has melted are ***fjords***.
    - If a valley glacier extends down a valley and then covers a gentle slope beyond the mountain range, it is called a ***piedmont glacier***.
    - If all of the valleys in a mountain range become filled with glaciers, and the glaciers cover then entire mountain range, they are called ***ice caps***.

- ***Ice Sheets***: (Continental glaciers): are the largest types of glaciers on Earth. They cover large areas of the land surface, including mountain areas. Modern ice sheets cover Greenland and Antarctica. These two ice sheets comprise about 95% of all glacial ice currently on Earth. They have an estimated volume of about 24 million km^3. If melted, they contain enough water to raise sea level about 66m (216 ft.). This would cause serious problems for coastal cities (L.A., NY, Washington DC, New Orleans, Miami, SF etc). The Greenland ice sheet is in some places over 3000 m (9800 ft) thick and the weight of ice has depressed much of the crust of Greenland below sea level. Antarctica is covered by two large ice sheets that meet in the central part along the Transantarctic Mountains. These are the only truly polar ice sheet on earth (North Pole lies in an ocean covered by thin layer of ice.

- ***Ice Shelves***: Ice shelves are sheets of ice floating on water and attached to land. They usually occupy coastal embayments, may extend hundreds of km from land and reach thicknesses of 1000 m.

Glaciers can also be classified by their internal temperature.

- Temperate glaciers - Ice in a temperate glacier is at a temperature near its melting point.
- Polar glaciers - Ice in a polar glacier always maintains a temperature well below its melting point.

The Formation of Glacial Ice

Glaciers can only form at latitudes or elevations above the ***snowline***, which is the elevation above which snow can form and remain present year round. The snowline, at present, lies at sea level in polar latitudes and rises up to 6000 m in tropical areas. Glaciers form in these areas if the snow becomes compacted, forcing out the air between the snowflakes. As compaction occurs, the weight of the overlying snow causes the snow to recrystallize and increase its grain-size, until it increases its density and becomes a solid block of ice.

Changes in Glacier Size

A glacier can change its size by ***Accumulation***, which occurs by addition of snowfall, compaction and recrystallization, and ***Ablation***, the loss of mass resulting from melting, usually at lower altitude, where temperatures may rise above freezing point in summer. Thus, depending on the balance between accumulation and ablation during a full season, the glacier can grow or shrink.

Movement of Glaciers

Glaciers move to lower elevations under the force of gravity by two different processes:

- Internal Flow - called creep, results from deformation of the ice crystal structure - the crystals slide over each other like deck of cards. This type of movement is the only type that occurs in polar glaciers, but it also occurs in temperate glaciers. The upper portions of glaciers are brittle, when the lower portion deforms by internal flow, the upper portions may fracture to form large cracks called **crevasses**. Crevasses occur where the lower portion of a glacier flows over sudden change in topography (see figure 16.12 on page 420of your text).
- Basal sliding - meltwater at base of glacier reduces friction by lubricating the surface and allowing the glacier to slide across its bed. Polar glaciers are usually frozen to their bed and are thus too cold for this mechanism to occur.

The velocity of glacial ice changes throughout the glacier. The velocity is low next to the base of the glacier and where it is contact with valley walls. The velocity increases toward the center and upper parts of the glacier.

Glaciation

Glaciation: is the modification of the land surface by the action of glaciers. Glaciations have occurred so recently in N. America and Europe, that weathering, mass wasting, and stream erosion have not had time to alter the landscape. Thus, evidence of glacial erosion and deposition are still present. Since glaciers move, they can pick up and transport rocks and thus erode. Since they transport material and can melt, they can also deposit material. Glaciated landscapes are the result of both glacial erosion and glacial deposition.

Glacial Erosion (note: most of this material will be presented as slides in class)

- Small scale erosional features
    - Glacial striations - long parallel scratches and grooves that are produced at the bottom of temperate glaciers by rocks embedded in the ice scraping against the rock underlying the glacier (see figure 16.17 in your text).
    - Glacial polish - rock that has a smooth surface produced as a result of fined grained material embedded in the glacier acting like sandpaper on the underlying surface.
- Landforms produced by mountain glaciers
    - ***Cirques*** - bowl shaped depressions that occur at the heads of mountain glaciers that result form a combination of frost wedging, glacial plucking, and abrasion. Sometimes small lakes, called ***tarns*** occur in the bottom of cirque.
    - ***Glacial Valleys*** - Valleys that once contained glacial ice become eroded into a "U" shape in cross section. Stream erosion, on the other hand, produces valleys that are "V" shaped in cross section (see figure 16.20 in your text).
    - ***Arêtes*** - If two adjacent valleys are filled with glacial ice, the ridges between the valleys can be carved into a sharp knife-edge ridge, called an arête.
    - ***Horns*** - Where three or more cirques are carved out of a mountain, they can produce a sharp peak called a horn (see figure 16.19 in your text).
    - ***Hanging Valleys*** - When a glacier occupying a smaller tributary valley meets the larger valley, the tributary glacier usually does not have the ability to erode its base to the floor of the main valley. Thus, when the glacial ice melts the floor of the tributary valley hangs above the floor of the main valley and is called a hanging valley. Waterfalls generally occur where the hanging valley meets the main valley.
    - ***Fjords*** - Fjords are narrow inlets along the seacoast that were once occupied by a valley glacier, called a fjord glacier.
- Landforms produced by Ice Caps and Ice Sheets
    - Abrasional features - The same small-scale abrasional features such as striations and glacial polish can occur beneath ice caps and ice sheets, particularly in temperate environments.

  - Streamlined forms - The land surface beneath a moving continental ice sheet can be molded into smooth elongated forms called ***drumlins*** (see figure 16.22 in your text).

Glacial Deposits

Since glaciers are solid they can transport all sizes of sediment, from huge house-sized boulders to fine-grained clay sized material. The glacier can carry this material on its surface or embedded within it. Thus, sediment transportation in a glacier is very much different than that in a stream. Thus, sediments deposited directly from melting of a glacial can range from very poorly sorted to better sorted, depending on how much water transport takes place after the ice melts. All sediment deposited as a result of glacial erosion is called ***Glacial Drift***.

- Ice Laid Deposits

  - ***Till*** - nonsorted glacial drift deposited directly from ice. Till consists of a random mixture of different sized fragments of angular rocks in a matrix of fine grained, sand- to clay-sized fragments that were produced by abrasion within the glacier. This fine-grained material is often called rock flour because it is really ground up rock. A till that has undergone diagenesis and has turned into a rock is called a ***tillite.***

  - ***Erratics*** - a glacially deposited rock or fragment that now rests on a surface made of different rock. Erratics are often found many kilometers from their source, and by mapping the distribution pattern of erratics geologists can often determine the flow directions of the ice that carried them to their present locations.

  - ***Moraines*** - are deposits of till that have a form different from the underlying bedrock. Depending on where it formed in relation to the glacier moraines can be:
    - ***Ground Moraines*** - these are deposited beneath the glacier and result in a hummocky topography with lots of enclosed small basins.

    - ***End Moraines and Terminal Moraines*** are deposited at the low elevation end of a glacier as the ice retreats due to ablation (melting) (see figure 16.22 in your text).

    - ***Lateral Moraines*** are deposits of till that were deposited along the sides of mountain glaciers.

    - ***Medial Moraines*** - When two valley glaciers meet to form a larger glacier, the rock debris along the sides of both glaciers merge to form a medial moraine (see figures 16.10 and 16.16 in your text). These black streaks in an active glacier, as well as the deposits left behind after the ice melts are called medial moraines.

  - ***Glacial Marine drift*** - Glaciers that reach the oceans or even lakes, may calve off into large icebergs which then float on the water surface until they melt. Upon melting, the rock debris that they contain becomes immediately deposited on the sea floor or lakebed as an unsorted chaotic deposit. Sometimes single large rock fragments fall out on the floor of the water body, and these are called ***dropstones***.

- Stratified Drift - Glacial drift can be picked up and moved by meltwater streams which can then deposit that material as stratified drift.
    - ***Outwash Plains*** - Streams running off the end of a melting glacier are usually choked with sediment and form braided streams, which deposit poorly sorted stratified sediment in an outwash plain. These deposits are often referred to as outwash.
    - ***Outwash Terraces*** - If the outwash streams cut down into their outwash deposits, the banks from river terraces called outwash terraces.
    - ***Kettle Lakes*** - If depressions form underneath a glacier and remain after the glacier is melted then water filling these depressions become small lakes where fine-grained sediment is deposited. The state of Minnesota is called the land of a thousand lakes, most of which are kettle lakes.
    - ***Kames*** and ***Kame Terraces***. Streams and lakes forming on top of stagnant ice may deposit stratified sediment on top of the glacier. When the glacier melts these deposits are set down on the ground surface. The former lake deposits become kames, and the former stream deposits become kame terraces (see figure 16.25 in your text).
    - ***Eskers*** - Eskers are long sinuous ridges of sediment deposited by streams than ran under or within a glacier. The sediment deposited by these streams becomes an esker after the ice has melted.

Glacial Ages

The last glaciation ended about 10,000 years ago. But the period between 10,000 years ago and 3 my ago (Pleistocene epoch) was a time of many glacial and interglacial ages. During this period sea level fluctuated because:

- during glaciations the continental land masses were depressed by weight of ice.
- during glacial periods much sea water was tied up in glaciers so sea level was lower.
- during interglacial periods sea level was higher due to melting of the ice.
- during interglacial periods land that were covered with ice during a glaciation are uplifted due to removal of the weight of the ice.

Based on evidence from glacial deposits and glacial erosion features geologists have been able to document at least 4 glaciations during the Pleistocene. But recent studies of deep-sea sediments and dating of these deposits suggest that there were at least 30 glaciations that occurred during the Pleistocene. This evidence comes from studies of fossils found in deep-sea sediment cores, and what they tell us about ocean surface temperatures in the past. The results come from studies of the isotopes of oxygen.

- Oxygen has two major isotopes, ^{18}O, which is considered heavy, and ^{16}O, which is considered light. Both of these isotopes are stable and non-radiogenic, so their ratio is constant through time.

- Because ^{16}O is lighter, it is preferentially evaporated with sea water from the oceans, and thus gets concentrated in the water that eventually falls on the continents as rain or snow. Because of this, ^{18}O gets concentrated in ocean water.

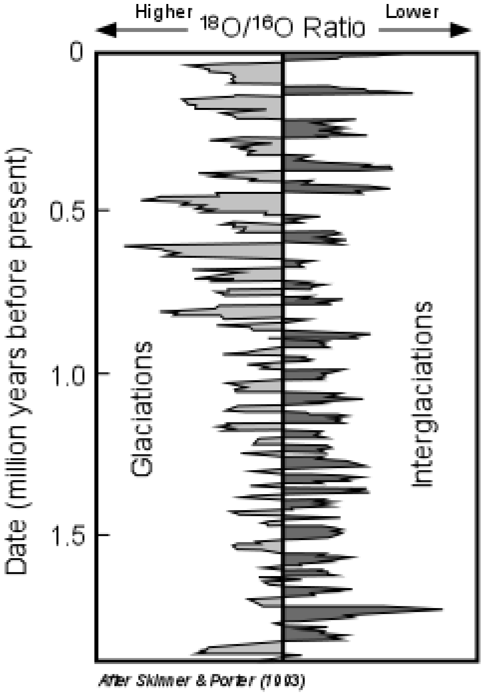
- During constant climatic conditions the ^{16}O lost to evaporation returns to the oceans by rain and streams, so that the ratio of ^{18}O to ^{16}O (^{18}O / ^{16}O) is constant.

- But, during a glaciation, some of the ^{16}O gets tied up in glacial ice and does not return to the oceans. Thus during glaciations the ^{18}O / ^{16}O ratio of sea water increases.

- During an interglaciation, on the other hand, the ^{16}O that was tied up in glacial ice returns to the oceans causing a decrease in the ^{18}O / ^{16}O ratio of seawater.

Thus, we expect that during glaciations the ^{18}O / ^{16}O ratio in seawater will be high, and during interglaciations the ^{18}O / ^{16}O ratio in seawater will be low.

Since organisms that live in the oceans extract Oxygen from seawater to form their carbonate (CO_3^{-2}) shells, measuring the ^{18}O / ^{16}O ratio in the shells of dead organisms gives a record of past ocean temperatures. The record for the past two million years is shown here and in figure 16.30 on page 434 of your text. This suggests about 30 glaciations separated by interglaciations during the past 2 million years.



After Skinner & Porter (1003)

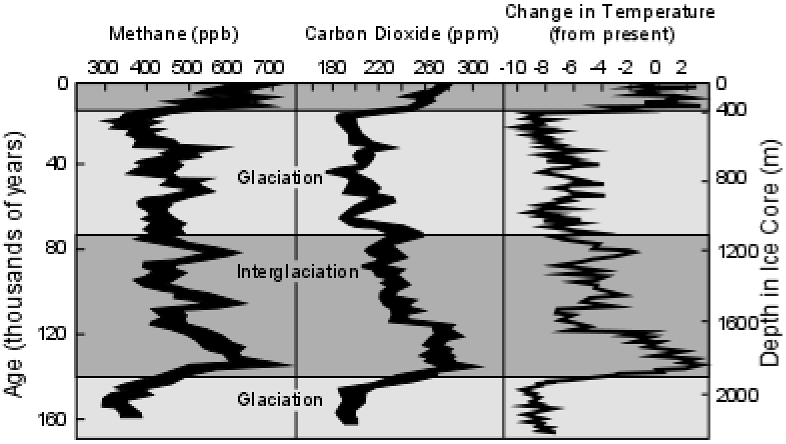
During the last 1 million years it appears that each glacial - interglacial cycle has lasted about 100,000 years, but earlier cycles were about 40,000 years long.

Other periods of glaciation are known from the geologic record, mainly from preserved glacial striations and tillites (consolidated till). The earliest recognized glaciation occurred about 2.3 billion years ago, but at least 50 other glaciations are recognized to have occurred during the Paleozoic era.

Causes of Glacial Ages

In order to understand what causes these cycles of glacial - interglacial episodes we need a much better understanding of what causes global climate changes. Because human history is so short compared to the time scales on which global climate change occurs, we do not completely understand the causes. However, we can suggest a few reasons why climates fluctuate.

- Long term variations in climate (tens of millions of years) on a single continent are likely caused by drifting continents. If a continent drifts toward the equator, the climate will become warmer. If the continent drifts toward the poles, glaciations can occur on that continent.
- Short-term variations in climate are likely controlled by the amount of solar radiation reaching the Earth. Among these are astronomical factors and atmospheric factors.
  - Astronomical Factors -
    - Variation in the eccentricity of the Earth's orbit around the sun has periods of about 400,0000 years and 100,000 years.
    - Variation in the tilt of the Earth's axis has a period of about 41,000 years.
    - Variation in the way the Earth wobbles on its axis, called precession, has a period of about 23,000 years.
    - The combined effects of these astronomical variations results in periodicities similar to those observed for glacial - interglacial cycles.
  - Atmospheric Factors- the composition of the Earth's atmosphere can be gleaned from air bubbles trapped in ice in the polar ice sheets. Studying drill core samples of such glacial ice and their contained air bubbles reveals the following:
    - During past glaciations, the amount of CO_2 and methane, both greenhouse gasses that tend to cause global warming, were lower than during interglacial episodes.



After Skinner & Porter (1993)

    - During past glaciations, the amount of dust in the atmosphere was higher than during interglacial periods, thus more heat was likely reflected from the Earth's atmosphere back into space.
    - The problem in unraveling what this means comes from not being able to understand if low greenhouse gas concentration and high dust content in the atmosphere caused the ice ages or if these conditions were caused by the ice ages.

- Changes in Oceanic Circulation - small changes in ocean circulation can amplify small changes in temperature variation produced by astronomical factors.

- Other factors
    - The energy output from the sun may fluctuate.

    - Large explosive volcanic eruptions can add significant quantities of dust to the atmosphere reflecting solar radiation and resulting in global cooling.

2.9. WORK OF STREAMS

The term *"stream"* includes the channelized flow of any size, from the smallest brook to a very large river like Ganga. Although the term *"river"* and *"stream"* are used synonymously, the term *" river"* is preferably used to denote a main stream into which several tributaries flow.

The geological work of streams is to *"erode"* the valleys, *"transport"* the material thus eroded, and *"deposit"* the same in the lower reaches at favourable sites.

2.9.1. Stream Erosion

The streams cause erosion in four ways : (*i*) chemical action, (*ii*) hydraulic action, (*iii*) abrasion, and (*iv*) attrition.

Chemical Action. It includes the solvent and chemical action of water on country rocks. The chemical decay works along joints and cracks and thus helps in breaking the bedrocks.

Hydraulic Action. The swiftly flowing water hammers the uneven faces of jointed rocks exposed along its channel and removes the jointed blocks. This process of erosion is called *"hydraulic action"*. At the bottom of waterfalls, the channels are eroded at an enormously rapid rate by the hydraulic action.

Abrasion. The flowing water uses rock fragments such as pebbles, gravels, and sands as a tool for scratching and grinding the sides and floor of the valley. This process of erosion is called *"abrasion"*.

Attrition. It is the breaking of the transported materials themselves due to mutual collision. The attrition causes the rock fragments to become more rounded and smaller in size.

In addition to the above, the streams acquire their load by many other means. Much of the material carried by a stream is contributed by underground water, overland flow and mass wasting.

2.9.2. Stream Transportation

The amount of solid material transported by a stream is called its *"load"*. The streams transport it in three ways : (*i*) in solution (dissolved load), (*ii*) in suspension (suspended load), and (*iii*) along the bottom (bed load).

Dissolved Load. The dissolved load is brought to the stream by groundwater. Some amount of it is also acquired directly from soluble rocks which occur along the stream's course.

Suspended Load. Suspended load forms the major portion of the load carried by streams. Usually only smaller particles such as clay and silt travel in suspension, but during floods much larger particles are carried this way.

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Bed Load. The forward force of moving water acts more directly on the larger grains at the bottom, pushing, rolling and sliding them along. The particles moved in this way constitute the *"bed load"* of a stream. Locally the medium size material may travel partly by rolling as bed load and partly in suspension. This process of intermittent jumping is called *"saltation"*. In saltation, the heavy particles are lifted occasionally for a few seconds by a swift eddy.

The velocity of a stream is affected by a number of factors, including gradient, channel size and shape, load, and discharge. The increase of velocity increases the transporting power of a river as much as the 6th power of the velocity.

$$\text{Transporting Power} \propto V^6$$

It means that during floods the transporting power of a stream suddenly rises very much and it becomes capable of moving big boulders which would otherwise remain quite immovable.

2.9.3. Deposition

The loose rock materials transported by a stream downstream, are deposited where the velocity of flowing water is reduced. The sorting of the material takes place automatically as the large and heavier particles settle quickly while the smaller and lighter ones continue their journey further ahead. The material which a stream deposits as sediment is called *"alluvium"* or *"alluvial deposits"*.

2.10. FEATURES OF STREAM EROSION

Pot Holes. *"Pot holes"* are the circular and deep holes, cut into solid rocks by sand grains and pebbles, swirling in fast eddies. They are commonly found on the channel floor.

Waterfalls. The falling of stream water from a height is called a *"waterfall"*. Waterfalls occur at places where the stream profile makes a vertical drop. Such a situation is usually found where gently inclined, erosion resistant beds overlie the nonresistant beds. The softer rock is eroded fast while the harder one offers resistance and forms a ledge at a height, from which the stream's water falls down deep into the gorge (*Fig.* 2.5). When the water falls over the ledge, it erodes the less

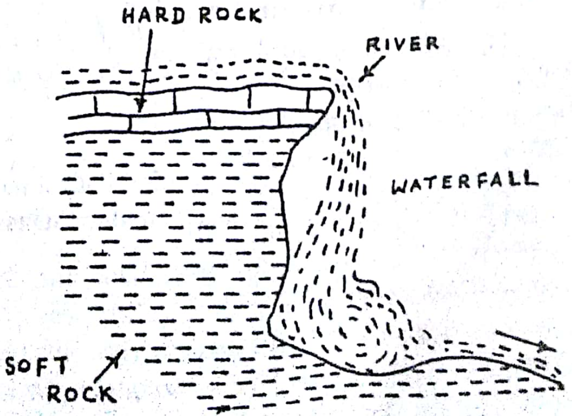

Fig. 2.5. Water fall.

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resistant beds of the cliff. Due to this undercutting a portion of the upper resistant bed breaks off and the waterfall retains its vertical cliff while it gradually moves upstream. Niagara Falls (U.S.A.) have retreated approximately 11 kilometers upstream since its formation.

Gorges. Narrow and deep river valleys which develop in hard rocks are called "*gorges*".

Meanders. The symmetrical S-shaped loops found in the course of a river, are called "*meanders*". Meanders develop in mature rivers. Mature rivers are those which have cut down to an approximately graded profile. In such rivers side cutting becomes very prominent which results in the development of meanders. The meanders grow due to deposition of sediment along the slipoff side and erosion at the undercut side (*Fig.* 2.6).

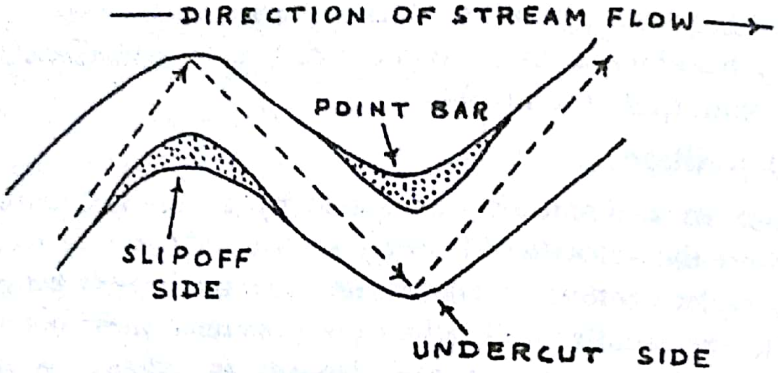

Fig. 2.6. Meanders.

Meanders continually change their position. They move both downstream and to the side (*Fig.* 2.7). The sideways movement occurs because at bends the swiftest currents shift toward the outside bank causing erosion at the outside of the curve and deposition on inside of the curve. In this way a stream migrates sideways and slightly downstream by eroding its outer bank and depositing a sand bar at the inner bank.

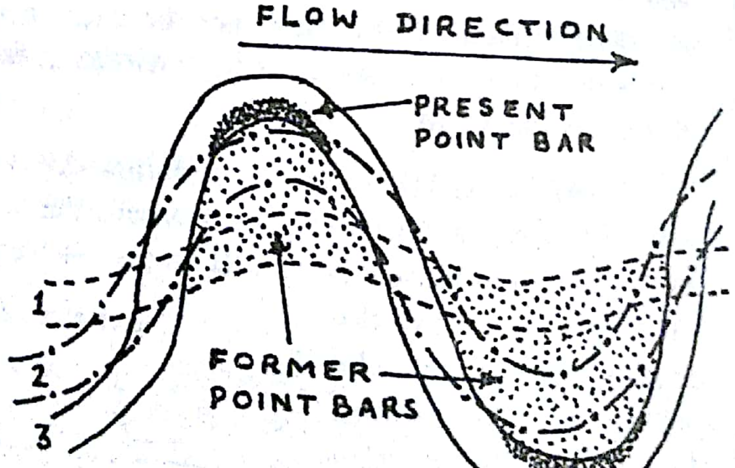

Fig. 2.7. Lateral movement of meanders. 1, 2 and 3 are three stages in the meander movement.

Oxbow Lake. The meanders grow by eroding its outer bank and depositing sediments at the inner bank. During this process the sharpness of the river bends increases progressively and the neck of meander becomes narrow and narrow. Finally a stage comes when the river cuts through the neck and starts flowing straight leaving behind its roundabout course. Such left out old meanders which remain filled with stagnant water, are called "*oxbow lakes:* (*Fig.* 2.8).

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Entrenched Meanders. On many occasions, the land is uplifted. The uplifting of a mature stream would cause it to give up lateral erosion and revert to downcutting. Rivers of this type are said to be *"rejuvenated"* (*Fig.* 2.9). When a meandering river is rejuvenated, it starts downcutting again. As a result the meandering channel is deepened and the old meanders get entrenched into the bedrock. Such meanders are called *"entrenched meanders"*.

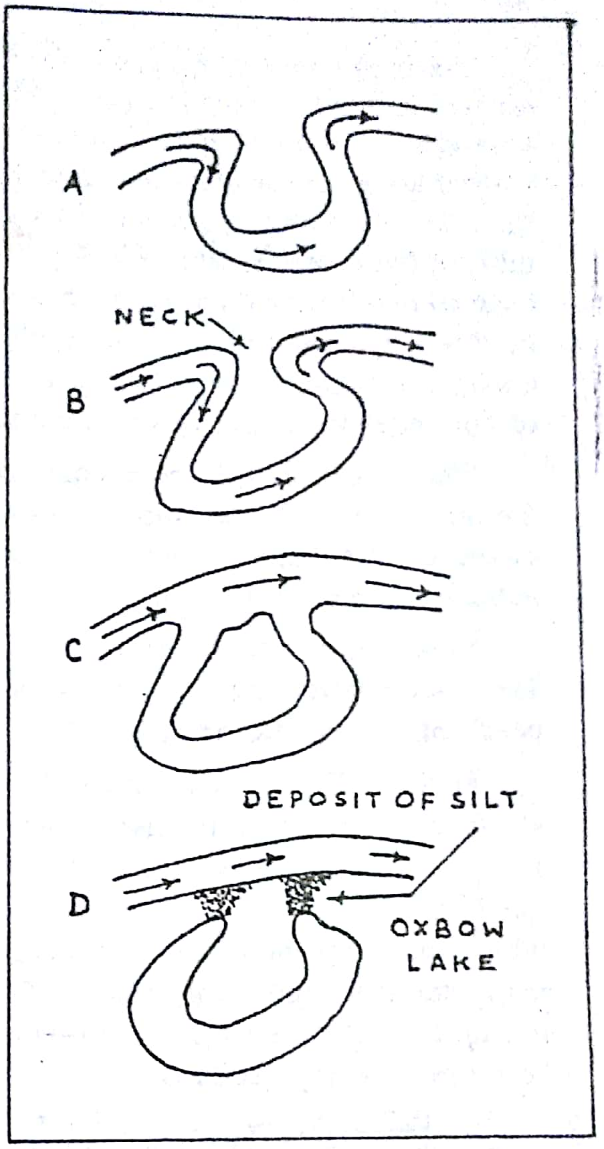

Fig. 2.8. Formation of an oxbow lake.

2.11. DEPOSITIONAL LANDFORMS

Alluvial Fans. The alluvial material which flows down from mountains, accumulates at foot hills where the stream enters a plain. The deposition occurs due to abrupt change in the gradient of river valley. Such deposits spread out in the shape of flat fans and are called *"alluvial fans"*. Usually the coarse material is dropped near the base of the slope while finer material is carried further out on the plain. Alluvial fans from many adjacent streams along a mountain may merge to form a long wedge of sediment called *"alluvial aprons"*.

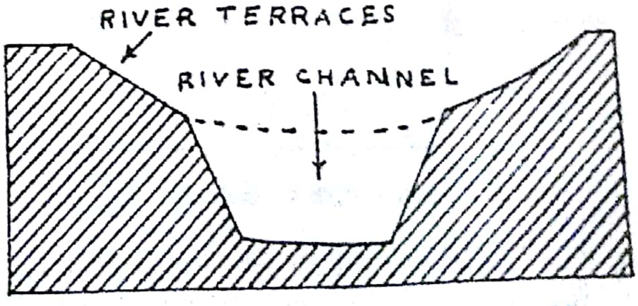

Fig. 2.9. River valley showing rejuvenation.

Flood Plains. During floods a river overflows its bank and submerges the adjacent lowlying areas where deposition of alluvial material takes place. A wide belt of alluvial plain formed in this way on either side of a stream, is called *"flood plain"*. Its name is appropriate, because the flood plain gets submerged only when a river overflows its bank at flood stages (*Fig.* 2.10).

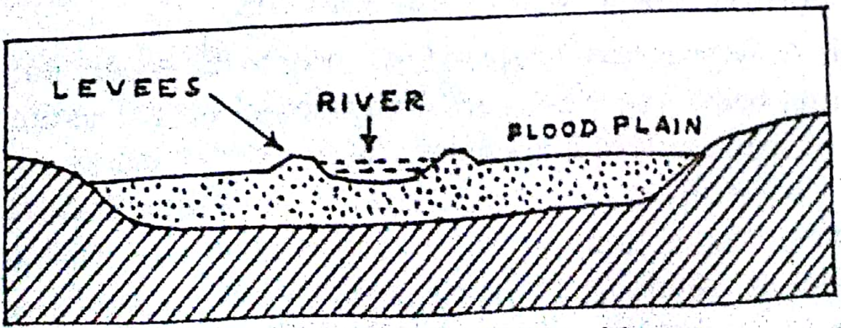

Fig. 2.10. Flood plain and Natural levees.

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Natural Levees. *"Natural levees"* are the low ridges which are formed on both sides of a river channel by the accumulation of sediment. They tend to confine the flow of river water into its channel between flood stages. The natural levees occur in rivers which have broad flood plains. During floods the river overflows its bank and its velocity decreases rapidly. As a result most of the coarse sediment is deposited along the area bordering the river channel and finer sediments are deposited more widely over the flood plain. In this way, successive floods build up ridges on both sides of a river channel, which are called *"natural levees"* (*Fig. 2.10*). The natural levees of the lower Mississippi river rise 6 meters above the valley floor.

The area behind the levees are poorly drained as water can not flow up the leevees to join the river. The marshes thus formed, are called *"back swamps"*. A tribulary stream often has to flow parallel to the main stream untill it can breach the levee. Such streams are called : *"yazoo tributaries"*.

Point Bars. In meandering rivers, sediment deposits occur as point bars. The *"point bars"* are the crescent shaped deposits which occur at inside bends of a river channel (*Fig. 2.6*).

Deltas. *"Deltas"* are deposits built at the mouths of streams. The deltas are usually triangular in shape with their apex pointed upstream. When a stream enters an ocean or lake, the currents of the flowing water dissipate quickly. This results in the deposition of the series of sedimentary layers which make up the delta. The material of most deltas is well sorted and many deltas are uniformly graded. The structure of a delta deposit is shown in *Fig. 2.11*. It consists of three sets of beds : (*i*) bottomset beds, (*ii*) foreset beds, and (*iii*) top-set beds.

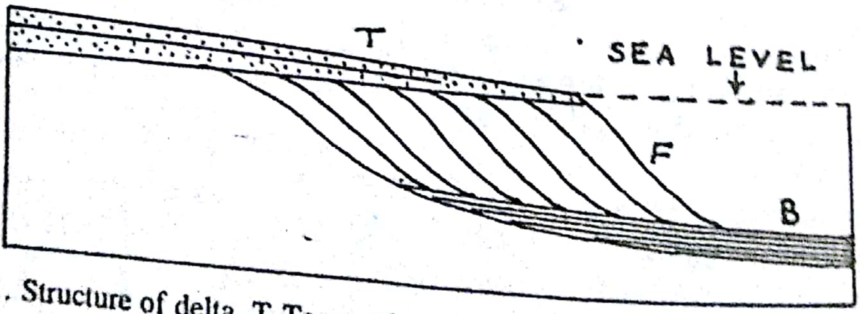

Fig. 2.11. Structure of delta. T-Top set beds, F-Fore set beds, B-Bottom set beds.

(*i*) *Bottomset Beds.* The thin horizontal beds which overlie the ocean bottom, are called *"bottomset beds"*. They are mainly composed of fine grained sediment, such as silts and clays.

(*ii*) *Foreset Beds.* Foreset beds begin to form prior to the accumulation of bottomset beds. These beds are composed of coarse sediment which is dropped almost immediately when a river enters a lake or ocean. The foreset beds appear similar to crossbedding and their angle of slope varies from 12° to 32° depending on the grain size of the material.

(*iii*) *Topset Beds.* Foreset beds are covered by thin nearly horizontal topset beds. These beds occupy the upper surface of the delta. They are composed of a mixture of coarse and fine materials.

Major rivers, such as the Ganga, form large deltas thousands of square kilometers in area. On large deltas the main channel of river divides to form several smaller branches, called *"distributaries"*. They discharge water in various paths to the sea.

2.12. BASE LEVEL AND GRADED STREAMS

Longitudinal Profile. Plot of the relative elevation of a stream bed from headwaters to mouth is called its *"longitudinal profile"*. The longitudinal profile of a stream is generally concave upward which is in accordance with the steady downstream decrease in slope.

Base Level. The level which controls the depth of stream erosion is called a *"base level"*. As base level is the lower limit of the longitudinal profile, streams can not cut below this level. There are two types of base level : (*i*) ultimate base level, and (*ii*) local base level. The *"ultimate base level"* represents the lowest level to which a stream can erode its valley. It is therefore the level at which the mouth of a stream enters a lake or the ocean. Resistant rockbeds, waterfalls, lakes or artificial dams which lie along a river course form *"local base levels"*. They act as limiting levels for the stretches that exist immediately upstream. Thus local base levels are temporary obstructions to downcutting encountered by a stream.

Any change in base level causes a stream to change its characterstics. Lowering of base level increases the stream's gradient. As a result the velocities increase and downcutting is accelerated. The erosion first starts from near the mouth and then works upstream untill the stream profile is adjusted along its full length. Thus the bedrock channel is deepened and parts of the old valley floor are left as a terrace along the walls of the new valley. Such steps-like features are called *"river terraces"* (*Fig. 2.9 and 2.12*).

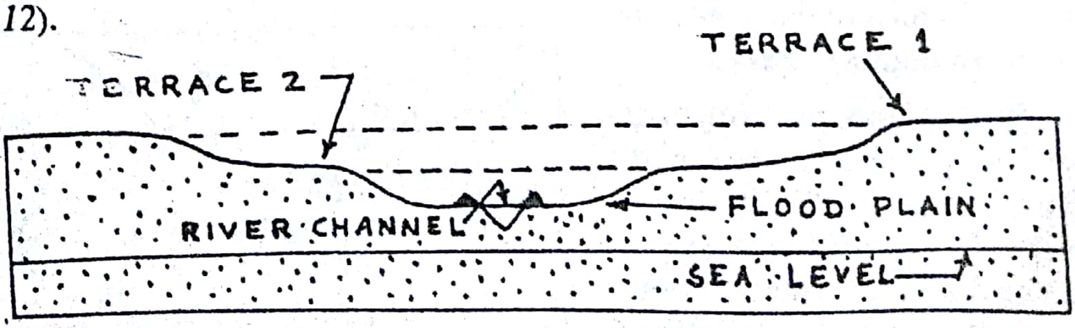

Fig. 2.12. River terraces.

A rise in base level reduces the stream's sediment transporting capacity. As a result the stream deposits sediment thereby building up its channel. Sometimes the capacity of a loaded stream is lowered to such an extent that heavy aggradation takes place. Now the single river channel can no longer

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Coarse sand	Between 2.0–0.6 mm
Medium sand	Between 0.6–0.2 mm
Fine sand	Between 0.2–0.06 mm
Silt	Between 0.06–0.002 mm
Clay	Less than 0.002 mm

2.8. WORK OF WIND

The air currents in motion is called *"wind"*. The wind is an important agent of erosion, transport and deposition. Its work is particularly seen in arid regions.

2.8.1. Wind Erosion

Although wind erosion is not restricted to arid and semiarid regions, it does its most effective work in these areas. Wind does erosion in three ways : (*i*) deflation, (*ii*) abrasion, and (*iii*) attrition.

(*i*) **Deflation.** Lifting and removal of loose material by wind is called *"deflation"*. By this process the land surface is gradually lowered. In many desert areas deflation produces hollows or basins with their bottoms at water table. Such basins containing some water are called *"oases"*.

(*ii*) **Abrasion.** During dust stroms the wind carries minute grains of sand in suspension. They dash and collide against the exposed rock masses and cause erosion. This process in which sand grains are used as tools for eroding rocks, is called *"abrasion"*.

(*iii*) **Attrition.** The particles that travel with wind, collide against one another. These mutual collisions lead to their further break down and the process is called *"attrition"*.

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2.8.2. Erosional Features

The important features of wind erosion are polishing of rock faces and formation of ventifacts and pedestal rocks.

Ventifacts. Wind armed with sand abrades rocks near the ground surface. This effect is called *"sand blasting"*. When pebbles and boulders are subjected to sand blasting they develop flat sides and sharp edges. If these stones contain coarse crystals of unequal hardness, they become pitted. Such stones which are polished, pitted and contain sharp edges are called *"ventifacts"*. These stones are faceted by erosion of their windward side.

Pedestal Rocks. Pedestal rocks are the undercut vertical columns of rocks which have wider tops and narrower bases. When wind blows, the sand particles being heavy travel near the surface and cause undercutting of rock faces (*Fig. 2.2*).

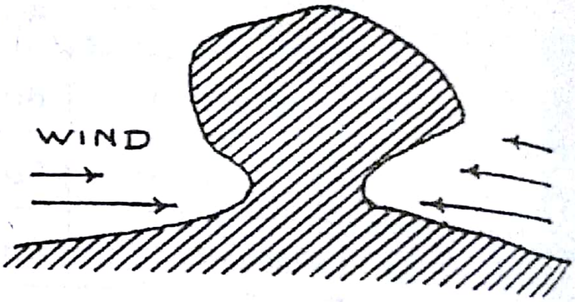

Fig. 2.2. Pedestal rock.

2.8.3. Wind Transport

Turbulent wind can easily sweep small dust particles and carry them to great distances in suspension. Sands, however, are transported in a series of jumps or these merely roll along the ground. The process by which sand particles travel in a series of jumps is called *"saltation"*. The greater part of the sand grains are transported very near the ground surface and they are seldom lifted more than a meter above the ground.

2.8.4 Wind Deposits

The wind deposits are commonly called the *"eolian deposits"*. The rock particles in the eolian deposits are generally well rounded and are sorted according to their size and weight. Wind deposits are of two types : (*i*) accumulations of sand, called *"sand dunes"*, and (*ii*) deposits of silt, called *"loess"*

Sand Dunes. The wind generally deposits sand in mounds. These mounds are called *"sand dunes"*. The sand travelling as bed load in wind accumulates wherever it meets any obstruction, such as a boulder or a bush. As the accumulation of sand grows, it traps even more sand. In this manner

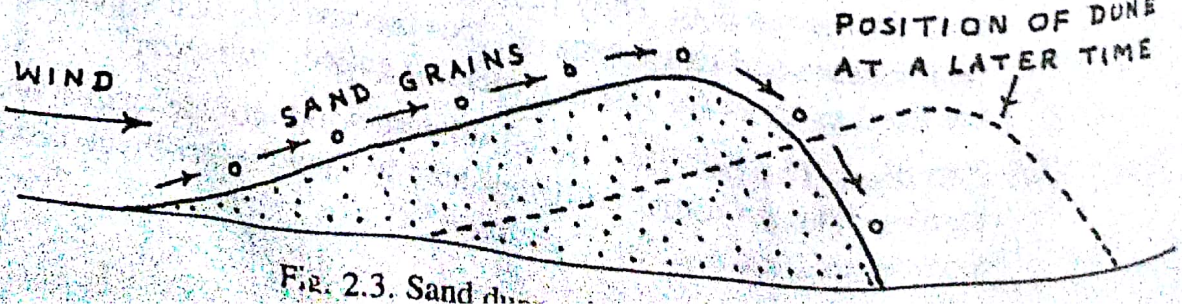

Fig. 2.3. Sand du

dunes are created. Sand dunes have a gentle slope (5° to 15°) on the windward side and a steeper slope (20° to 30°) on the lee side. The height of sand dunes depends on the wind speed and the size of sand grains. Dune heights of 30 meters are not uncommon. The sand dunes migrate slowly in the direction of wind movement (*Fig. 2.3*). In some cases they move as much as 20 meters per year. The migrating sand dunes may advance and cover farm land, rail roads, highways and other valuable property. Their movement may be checked by planting vegetation. The sand dunes are of four types : (*i*) transverse dunes, (*ii*) barchans, (*iii*) longitudinal dunes, and (*iv*) complex dunes.

(*i*) **Transverse Dunes.** Transverse dunes have their longer axis at right angles to the direction of wind. They are formed in areas with strong winds where more sand is available.

(*ii*) **Barchans.** "*Barchans*" are crescent shaped dunes the convex side of which faces the wind direction. The horns or wings of the crescent point in the direction of wind flow (*Fig. 2.4*). Barchans are formed where wind is nearly unidirectional. They occur in groups in areas of greatest sand supply. The height of large dunes does not exceed 30 meters and their point to point length is generally 300 meters.

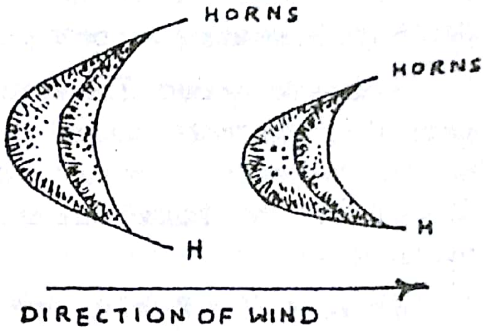

Fig. 2.4. Barchans

(*iii*) **Longitudinal Dunes.** The dunes which are elongated in the wind direction, are called *"longitudinal dunes"*. These dunes usually develop in strong winds in areas where small amount of sand is available. The longitudinal dunes may reach heights of 100 meters and may extend for about 90 kilometers. In the Arab countries these dunes are called *"seifs"* because they appear similar to an Arab sword.

(*iv*) **Complex Dunes.** In areas where the direction of wind varies, *"complex dunes"* are formed. They are of irregular shape.

Loess. The suspended load transported by wind consists mainly of silt and dust particles. When it settles, it forms a blanket deposit of silt, known as *"loess"*. These deposits are typically nonstratified and have a grayish yellow colour. Loess is composed of many minerals including quartz, felspar, hornblende and calcite. These materials are derived by wind from deserts or from flood plains of rivers. Deposits of loess are very fertile. Loess deposits in some parts of China approach a thickness of 300 meters or more.

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GEOLOGICAL ACTION OF WIND

Wind-action is conspicuous in semi-arid and arid regions, but it is particularly strong in deserts. Aeolian topography is created by the geological faction of wind, which can conveniently be divided into the following three stages :

(*a*) Erosion, (*b*) Transportation, (*c*) Deposition.

(*a*) **Erosion.** The wind accompolishes erosion by three means :

(*i*) Deflation. (*ii*) Abrasion. (*iii*) Attrition.

(*i*) **Deflation.** Deflation is the process of removal of loose soil or rock-particles, along the course of the blowing wind. This process operates well in dry regions with little or no rainfall.

(*ii*) **Abrasion.** Abrasion is the sand blast action of wind with sand against the rocks. The loose particles that are blown away by

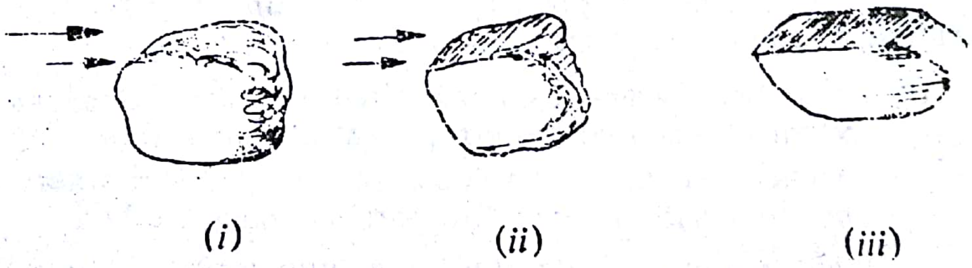

(*i*) (*ii*) (*iii*)

Fig. 15·1. Showing stages of development of ventifacts due to wind-abrasion.

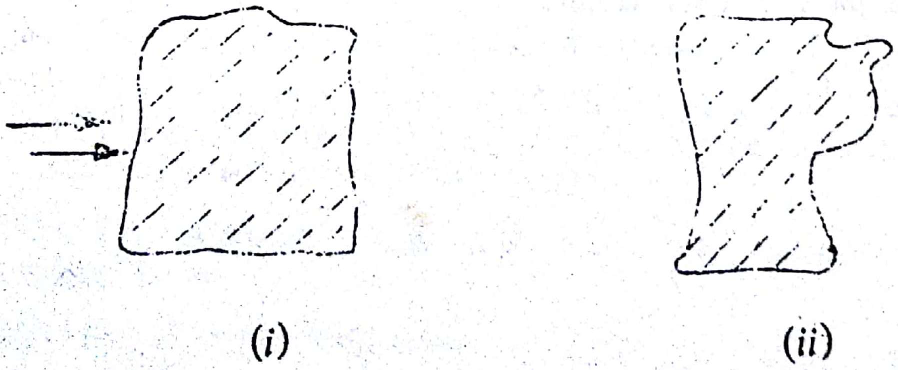

(*i*) (*ii*)

Fig. 15·2. Formation of pedestal rock due to wind-abrasion the wind serve as tools of destruction and when they move on some rock-surface they bring about a scraping of the surface.

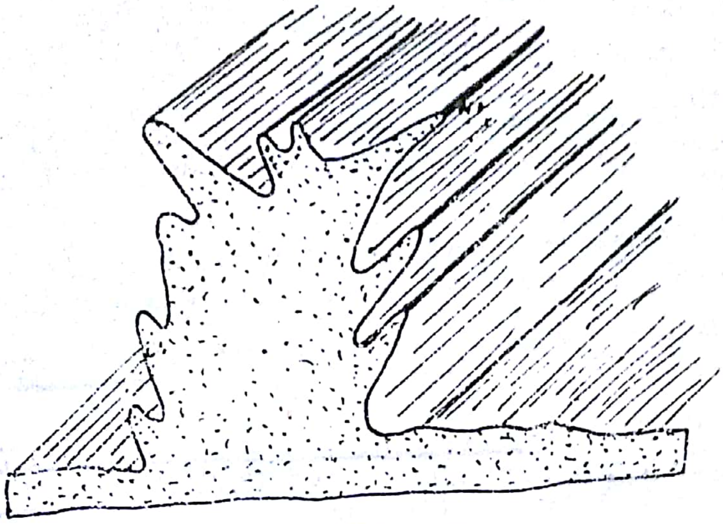


Fig. 15·3. Yardang.

(*iii*) **Attrition.** Attrition is the grinding action. While on transit wind born particles often collide with one another. Such mutual collision brings about a further grinding of the particles.

Important Erosional Features and Associated Landforms

(*i*) **Hamada.** Due to deflation, when the loose particles are swept away, only the hard mantle is left behind which is known as *Hamada.*

(*ii*) **Yardang.** A grooved or furrowed topographic form produced by wind abrasion, which is elongated in the direction of prevailing winds and is usually strongly under cut, is known as Yardang.

(*iii*) **Pedestal rock.** A wide rock-cap standing on a slender rock column, produced because of the wind-abrasion, is known as a pedestal rock.

(*iv*) **Ventifacts.** These are pebbles faceted by the abrasive effects of wind-blown sand. Ventifacts with one smooth surface is called *Einkanters* and with three smooth faces as *Dreikanter* ; when only two abraded faces are left, it is called *zweikanter.*

(*v*) **Mushrom-table.** It is a tabular mass of more resistant rock resting on under-cut pillars of softer material. They are very often elongated in the direction of the prevailing wind and are also known as '*Zeugen*'.

(*vi*) **Honey-comb structure.** Rocks consisting of hard and soft parts get differential abrasion and the resulting feature is known as honey-comb structure.

(*vii*) **Blow-outs.** These are broad-shallow caves in hills, broad-shallow depression in deserts.

(*viii*) **Desert pavement.** It is made up of a layer of residual pebbles and cobbles strewn upon the surface while intervening finer particles have been removed as a result of deflation.

(*xi*) **Millet-seed sands.** These are rounded desert sand grains, resulted through the process of attrition and have resemblance with millet seed grains.

(*b*) **Transportation.** Wind-transportation is totally dependent on wind-velocity. There are three methods of wind-transportation :

(*i*) **Traction.** Where particles are removed through rolling and creeping.

(*ii*) **Saltation.** Here the particles, which are too heavy to remain in suspension and lighter to be transported in traction, are transported through a series of bounces.

(*iii*) **Suspension.** Very light particles like dust and cloud, smoke etc. move with the wind quickly but settle very slowly, remain in suspension in the air.

(*c*) **Deposition.** Wind-formed deposits are called aeolian deposits. Wind is an excellent agent for sorting of materials according to their size, shape or weight. Pebbles and boulders cannot be carried away and are left back to form *lag deposits*. The clayey and silty fractions are deposited as *loess*, which does not show any stratification. Wind deposits take two general forms as :

(*i*) Sheets, (*ii*) Piles.

'*Sheet deposits*' are the dust deposits laid down on large area. '*Piles deposits*' include the various types of dunes which accumulate from sand and silt carried in saltation.

Depositional Features :

(*i*) **Sand hill.** Mounds of sand whose surface is irregular is called sand hill.

(*ii*) **Sand dune.** When the mound is in the form of a round hillock or a ridge with a crest, it is called a sand dune. In structure a dune has a gentle slope towards the wind-ward side and a steep-face towards the lee-side. The shape of a dune is controlled by

(*a*) amount of sand supply,

(*a*) wind-velocity,

(*c*) constancy of wind direction, and

(*d*) amount and distribution of vegetative cover.

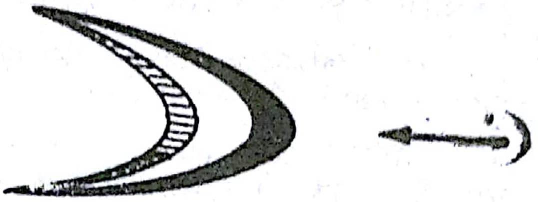
Geomorphic Features Produced Due to Wind-Action

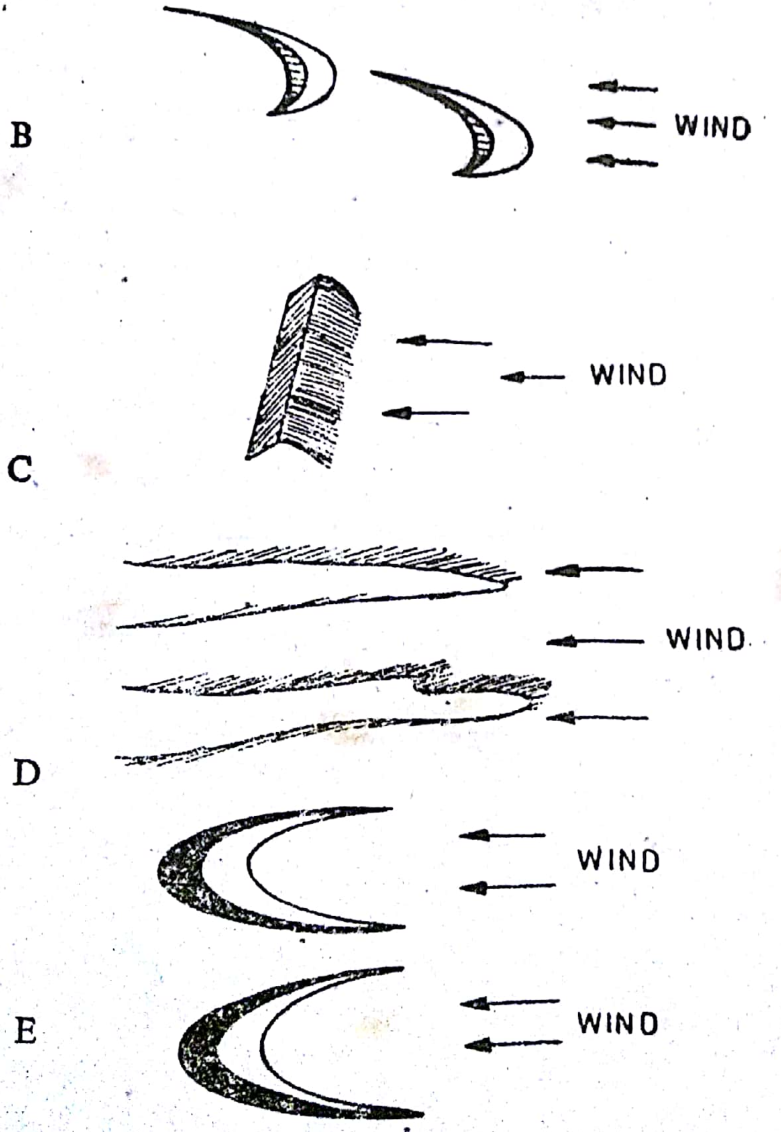
Types of Sand-Dune

(*i*) Barchan. Barchan are the crescentic shaped dunes with the points or wings directed downwind.

(*ii*) Seif. It is similar to barchan except one wing is missing, caused by an occasional shift in wind direction.

(*iii*) Transverse dune. Elongated dunes form at right angles to the prevailing wind.





(A) These are, just the barchans, (B) One wing of barchan is missing here. (C) Transverse dunes. (D) Logitudinal dunes. (E) Parabolic dune.

(*iv*) **Fore dune.** Ridge-like deposits of wind borne sand formed along the coast of sea or lakes.

(*v*) **Longitudinal dune.** Elongated ridges of sand found to lie parallel to the direction of blowing wind.

(*vi*) **Parabolic dune.** These are of parabolic shape, their horns point towards the direction opposite to that of the blowing-wind.

(*vii*) **Whale back dune.** It is a very large longitudinal dune with flat tops, on which barchans or seifs may occur.

The space between the dunes is called '*Gassis*' and the water which is available in shallow wells and support vegetation in desert areas, form what is known as '*Oasis*'.

Optical Mineralogy :-

* A fundamental principle of optical mineralogy is that most minerals - even dark coloured minerals and others that appear opaque in handspecimens - transmit light if we slice them thinly enough.

→ Minerals with metallic lustre and a few others are termed Opaque minerals. They don't transmit light even if they are thin section thickness.

→ Non-opaque minerals are those that transmit light.

→ Non-opaque minerals are further divided into those that are Isotropic (having the same properties in all directions) and those that are Anisotropic (having different optical properties in different directions).

→ Anisotropic minerals are further divided according to whether they are an uniaxial or a biaxial and according to whether they have a positive or negative optic signe.

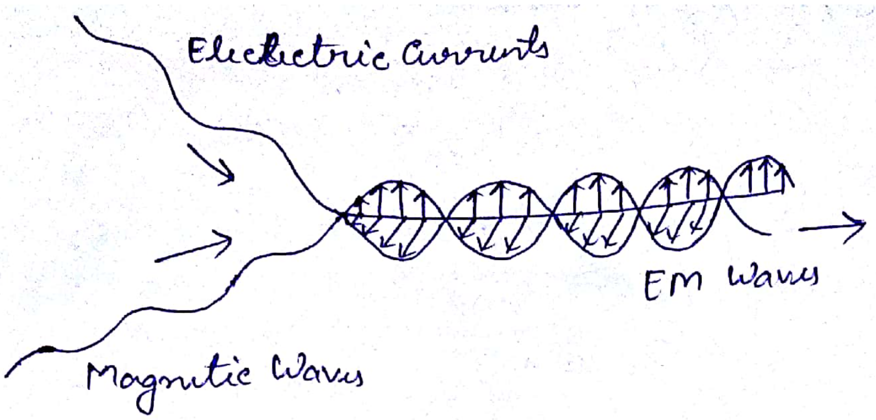
* Light is one form of electromagnetic radiations.

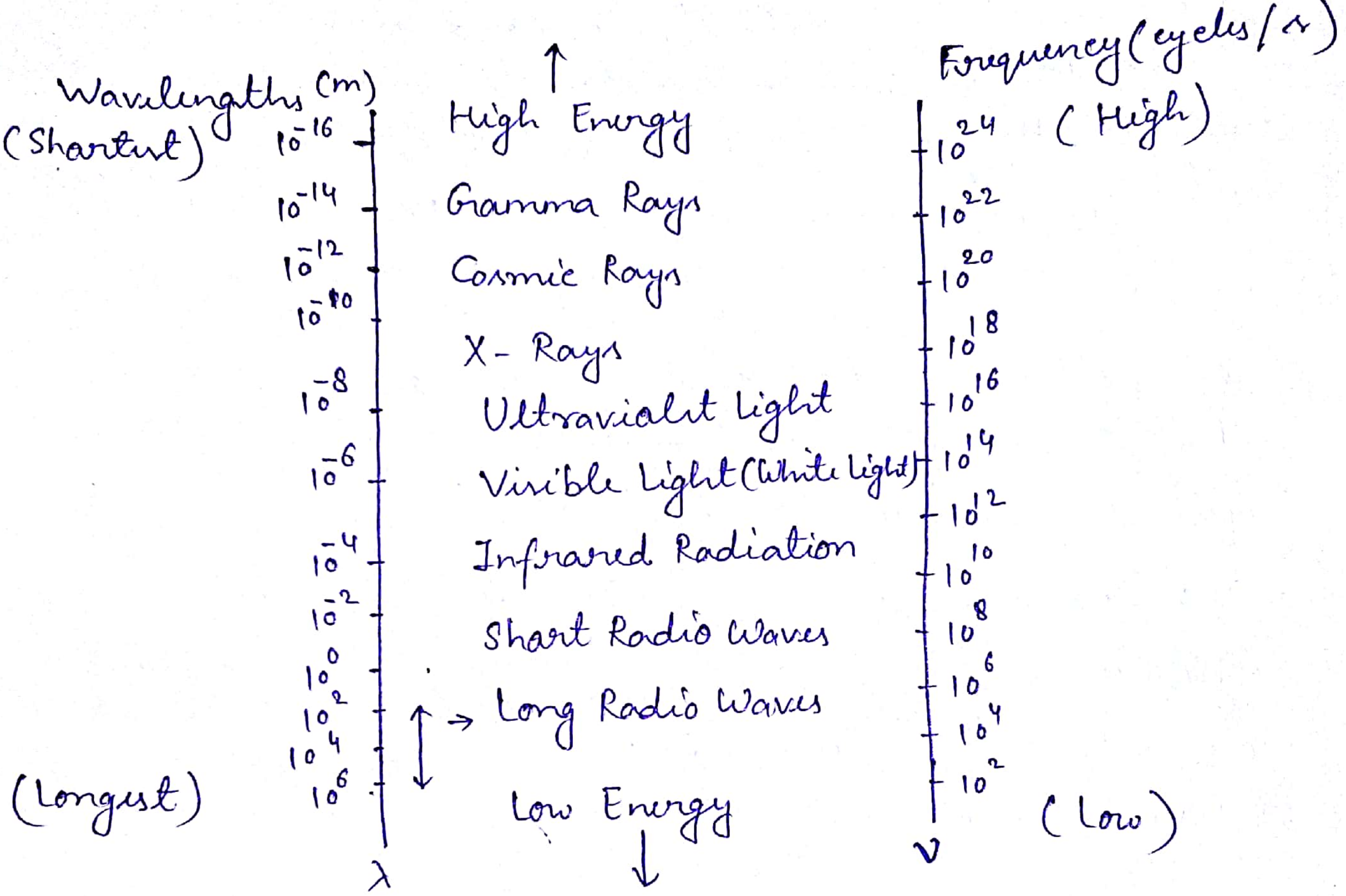
eg - Radio waves, ultraviolet light, and X-rays are other forms of electromagnetic radiation.

→ Light waves, like all electromagnetic radiation ~~state~~ are characterized by a particular wavelength λ, a frequency ν, and a polarization state. The velocity V, of the wave is the product of λ and ν.

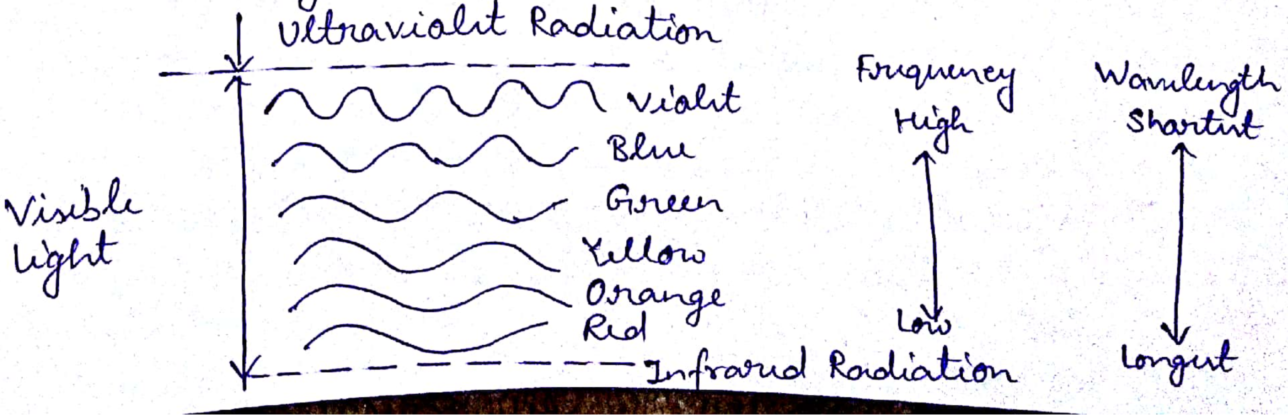
$$\boxed{V = \lambda \nu}$$

In vaccum the velocity of light = 3×10^8 m/s





* White light is polychromatic (many coloured), containing a range or spectrum of wavelengths. Polychromatic light can be separated into different wavelengths in many ways. When one wavelength is isolated, the light is monochromatic (single coloured).



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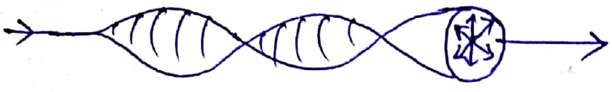
* Polarized Light! –

→ When the vibration motion of a light wave is perpendicular or nearly perpendicular to the direction it is propogating. These types of light are called polarized light.

→ In normal, unpolarized beams of light, waves vibrate in many directions.

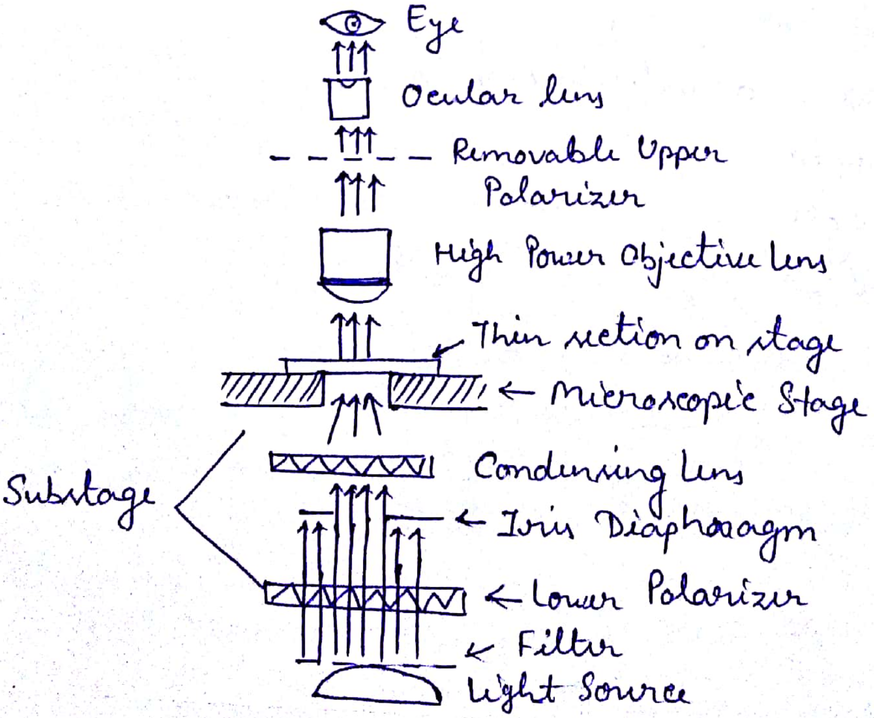


Unpolarized Light

Polarized Light

→ Light is a plane polarized light which are polarized in different ways. Reflection from a shiny surface can partially or completely polarize light because light vibrating in planes parallel to the reflecting surface is especially well reflected, while the light vibrating in other direction is absorbed.

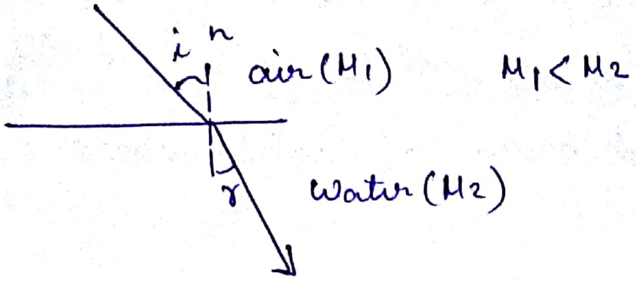
→ Polarizing microscope or petrological microscope is used to determine the properties (optical) of minerals and also in petrogenesis of rocks.

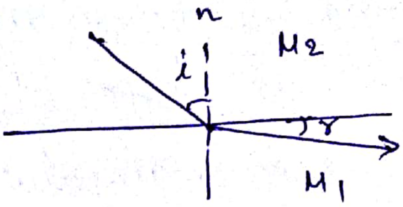


Orthoscopic Illumination

* The thickness of a thin section plate is taken 0.10 - 0.15 mm.

Snell's Law: (Light Refraction)





$$\boxed{\frac{\text{Sin}\,i}{\text{Si}\,r} = \frac{\mu_2}{\mu} \approx \mu}$$

* Petrological microscope and they include:

1)- In Plane Polarized Light (PPL)

- a)- Form - i)- Euhedral
  - ii)- Subhedral
  - iii)- Anhedral
- b)- Colour and Pleochroism
- c)- Relief, whether positive or negative through Becke-line method.
- d)- Cleavage and Fracture
- e)- Inclusion

2)- Under Crossed Nicols: (XPL)

- a)- Isotropism / Anisotropism
- b)- Birefringence and interference colour
- c)- Type of extinction
- d)- Extinction angle
- e)- Twinning and zoning
- f)- Alteration
- g)- Association

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Relief and Becke Lines :-

Relief : the term describes the contrast between the mineral and its surroundings (in this case, liquid).

→ Relief depends upon the refractive index of the two or more body.

→ Grains with low relief are barely visible, while those with high relief stand out clearly.

Low Relief

Medium Relief

High Relief.

→ As the difference in indices increases, relief becomes more noticeable.

→ Minerals with high refractive indices show high (+ve) relief because their index of refraction is greater than that of the epoxy. They also tend to show structural flaws such as scratches, cracks, or pits or more than those with low refractive indices.

→ Some minerals (fluorite,) with very ~~low relief or~~ very low refractive indices also show high relief (-ve relief) because their index of refraction is lower than that of the epoxy.

→ A few minerals (such as calcite) display variable relief ~~for most purposes~~ with stage rotation; variable relief is a useful diagnostic property.

→ If $n_{mineral} > n_{liq}$ (where n = refractive indices), the light rays are refracted and converge after passing through the grains.

→ If $n_{mineral} < n_{liq}$, light rays are refracted and diverge

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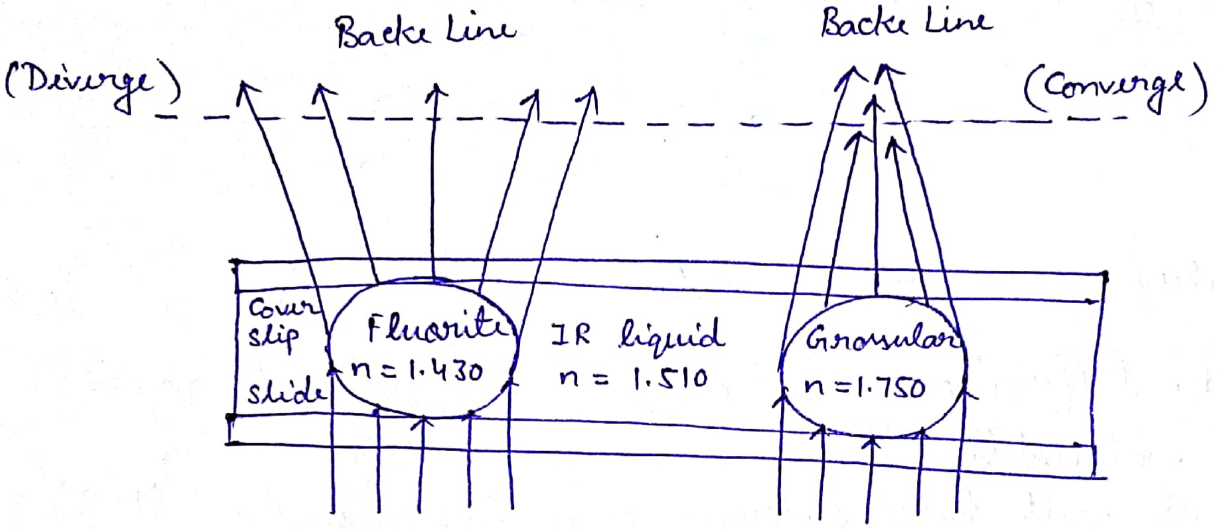
after passing through the grains.

* **Becke Line:** If we slowly lower the microscope stage, shifting the focus to a point above the mineral, a bright narrow band of light called Becke Line appears at the interface and moves toward the material with higher refractive index.



$n_{fluorite} < n_{liq} < n_{granular}$

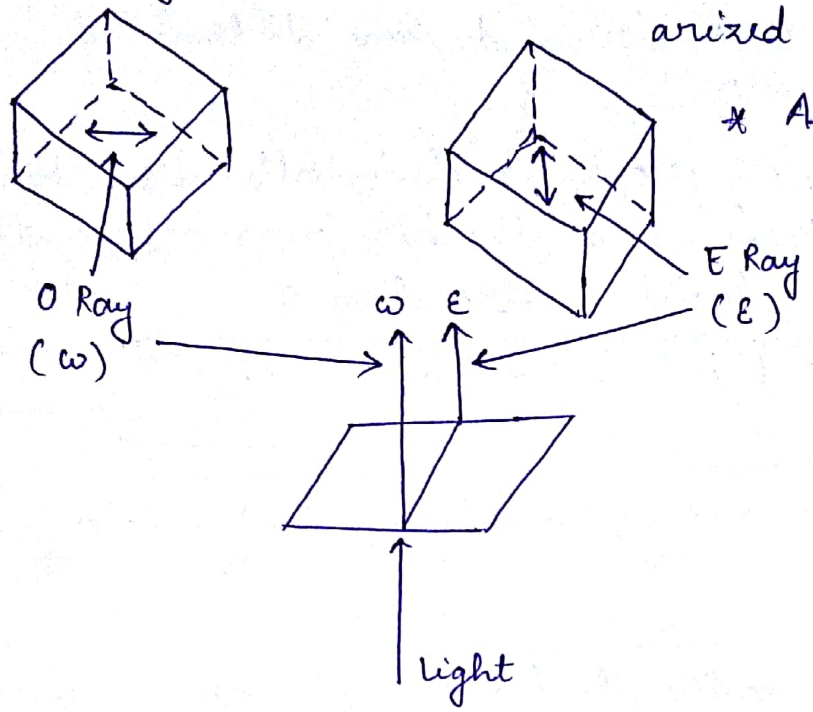
Double Refraction :-

→ Upon entering an anisatropic crystals, light is normally split into two palarized rays, each traveling through the crystal along a slightly diffrent path with a slightly different velocity and refractive index.

→ For uniaxial minerals, we call the two rays the Ordinary ray (O ray), symbolized by 'ω' and the extraordinary ray (E-ray), symbolized by 'E'.

* The O ray travels a path predicted by Snell's Law, while E ray does not.
* The directions of the O-ray and E-ray vibrations depend on the direction the light is traveling through the crystal structure, but vibration directions of the two

rays are always perpendicular to ~~ea~~ each other. We call the splitting of light beam into two perpendicularly polarized rays <u>Double Refraction</u>



* All anisotropic ~~show~~ minerals shows double refraction.

* If the light encounters an isotropic mineral on the stage, it slows as it passes through the mineral but is still E-W polarized when it emerges.

* Calcite is one of the few common minerals that exhibit double refraction easily seen without a microscope, but even minerals that exhibit subtler double refraction can be tested using polarizing filters.

* All isotropic substances, does not exhibit double refraction.

* As the two rays pass through an ~~is~~ anisotropic crystal they travel at different velocities unless they are travelling parallel to an optic axis. We call the two rays the <u>Slow Ray</u> and the <u>Fast Ray</u>. Because the rays travel at different velocities, their refractive indices must be different.

$\boxed{\text{* Bi}^{n}\text{fringes } \delta' = n_{slow} - n_{fast}}$ It varies depending on the direction light is traveling through the crystal and ranges from zero to some maximum value (δ) determined by crystal structure

* Retardation : when the slow ray emerges from an anisatropic crystal, the fast ray has already emerged and travelled some distance. This distance is the retardation Δ.

→ Retardation is proportional to both the thickness (t) of the crystal and to the birefringence in the direction the light is traveling δ'.

$$\boxed{\Delta = t \times \delta' = t \times (n_{slow} - n_{fast})}$$

* The birefringence and retardation of isatropic crystals are always zero.

* Most anisatropic minerals have birefringence between 0.01 and 0.20. Interference colours are a function of birefringence.

Crystal Between Crossed Polars :-

* When we are viewing an isatropic crystal using XPL. It will remain dark through 360° of stage rotation. This is because the light emerging from the mineral retains the polarization it had on enterring and will always be EW polarized. It can't pass through the upper polarizer, oriented at 90° to the lower polarizer. The effect is the same as if no mineral were on the stage.

* When we are viewing an anisatropic crystal with XPL., light is split into two rays unless we are looking down an optic axis. The two rays, after emerging from the crystal, travel on to the upper polarizer where they are resolved into one ray with NS polarization. Because the vibrations of both the rays are normally not perpendicular to the upper polarizer, components of the both pass through the upper polarizer, components of both

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pass through the upper polarizer and combine to produce the light reaching our eye.
As we rotate the microscope stage, the relative intensity of the two rays emerging from the crystal vary.
Every 90° the intensity of one is zero and other is vibrating perpendicular to the upper polarizer.

* If we used a monochromatic light (one wavelength) source in our microscope and looked at an anisotropic crystal under XPL, it would go from light to complete darkness as we rotate the stage.

Extinction would be occurred every 90° and maximum brightness would be at 45° to the extinction position.

Interference Colour :

* Interference colour is the colour exhibit by a section of an anisotropic mineral under XPL. The interference colour is produced by interference between the two rays produced as light passes through an anisotropic mineral, the fast ray and the slow ray.
Interference between two rays produces colour different from the incident source light by constructive interference since the phase of the fast ray is shifted relative to the slow ray.

→ Interference colours depend on the retardation of different wavelengths, which is in turn depends on the orientation, birefringence and thickness of a crystal.

→ Interference colours change intensity and hue as we rotate the stage, they disappear every 90° when mineral goes extinct.

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→ Very low order interference colours, corresponding to a retardation of < 200nm, are gray and white.

→ The interference colour of a mineral with very low birefringence then, changes from white (or gray) to black every 90° as we rotate the microscope stage.

→ For minerals with slightly greater birefringence, yellow, orange or red interference colour will appear when we rotate the stage. These colours, corresponding to retardation 200 nm to 550 nm, are called first Order colours.

→ As retardation increases further, colour repeat every 550nm. They go from violet to red (Second Order) and then from violet to red (Third Order). They become more pastel (washed out) in appearance as order increases.

→ Fourth Order Colours are often so weak that they appear "pearl" white and may occasionally be confused with first order white.

Interference Colour Orders	Birefringence	Retardation	Examples
1)- Ist Order Colour	Very low-low	Low	~~White~~ Leucite, Nepheline, Apatite, Beryl, Qz, feldspar.
2)- IInd Order Colour	Medium	Medium	Kyanite, OPX, Andalusite
3)- IIIrd Order Colour	High	High	Tourmaline, Sillimanite, Amp.
4)- IVth Order Colour	Very High	Very High	Titanite (Sphene) Calcite, Dolomite, Rutile.

~~Ist Order: Gray to white~~
~~IInd Order: Yellow, Orange, Red~~
~~IIIrd Order:~~

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Very Low Order! Gray and White <200nm (Δ)

Ist Order! White, Yellow, Orange, Red. (200-550nm =Δ)

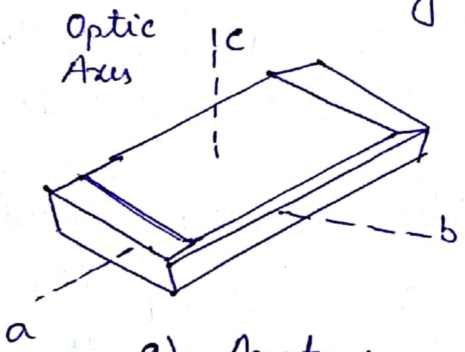
IInd Order! Violet, Blue, Green, Yellow, Orange, Red
(~550 - ~1100nm=Δ)

IIIrd Order! Violet, Blue, Green, Yellow, Orange, Red
(But washed out) (~1100 - ~1650nm=Δ)

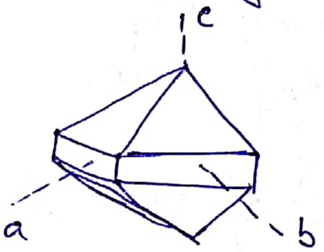
Uniaxial and Biaxial Minerals !-

- For uniaxial minerals; we need two indices of refraction (ε and ω).
- For biaxial mineral, we need three indices of refraction (α, β, and γ).

→ Optic Axes! are directions that light can travel through a crystal without being split into two rays.



a) - Anatase
(uniaxial-)

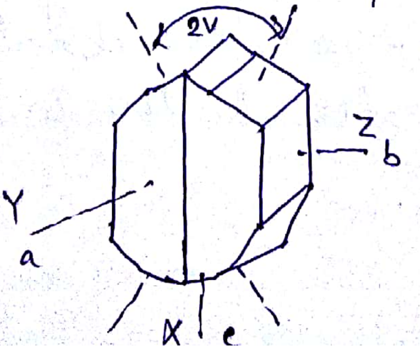


b) - Xenotime
(uniaxial +)

→ If ω < ε, the mineral is uniaxial (+)

→ If ω > ε, the mineral is uniaxial (-)

- Most minerals are biaxial, having two optic axes. Light passing through a biaxial crystal experiences double refraction unless it travels parallel to an optic axis.



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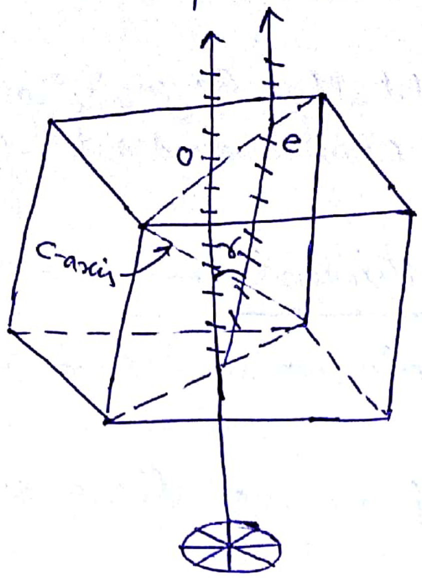
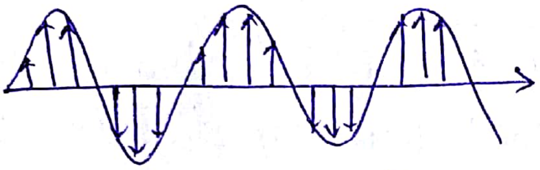
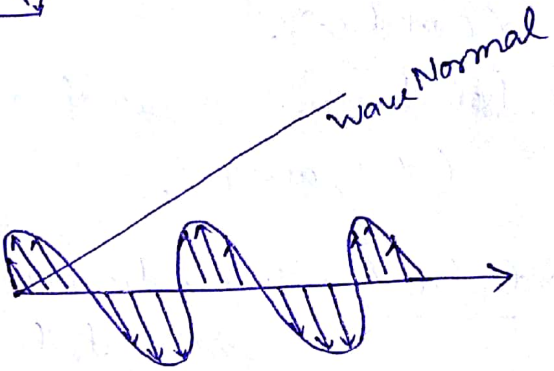
* The absolute birefringence of uniaxial minerals is defined as $|\omega - \varepsilon|$ (the absolute value of the difference between the extreme refractive indices).





Ordinary Ray
(O Ray or ω Ray)



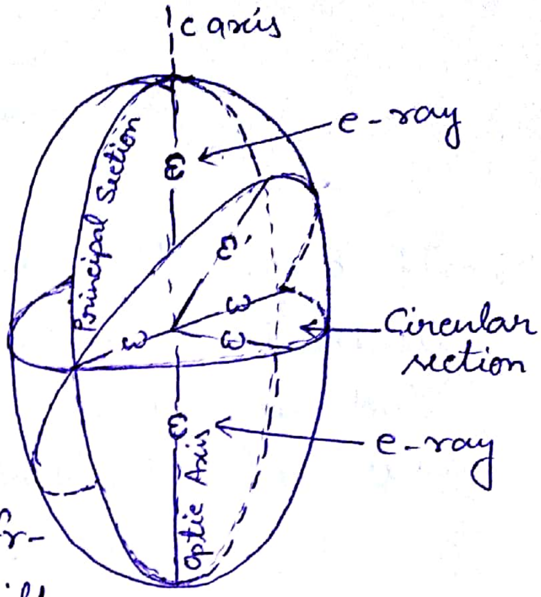
Extraordinary Ray
(E Ray or ε ray)

→ Wave Normal: A line drawn that is perpendicular to the vibration direction of the e-ray is called wave normal. It turns out the wave normal direction does obey Snell's Law. eg- Calcite

* Uniaxial Indicatrix:

→ The uniaxial indicatrix is constructed by first orienting a crystal with its c-axis vertical. Since c-axis is also the optic axis in uniaxial crystals, light traveling along the c-axis will vibrate perpendicular to the c-axis and parallel to the ω-refractive index direction.

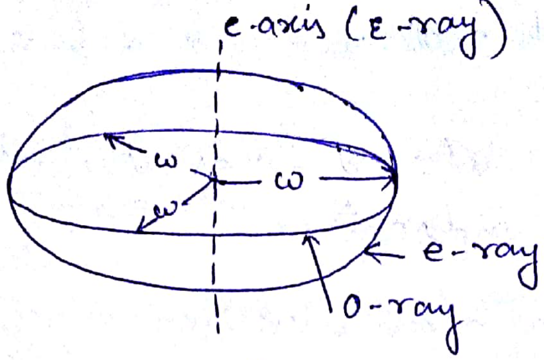
→ If vectors are drawn with ~~li~~ lengths proportional to the refractive index for light vibrating in the direction, such vectors would define a circle with radius ω.
This circle is referred to as the <u>circular section</u> of the uniaxial indicatrix.



→ Light vibrating along directions perpendicular to the c-axis or optic axis is broken into two rays that vibrate perpendicular to ~~the c-axis~~ each other. One of these rays, the e-ray vibrates parallel to the ε refractive index. Thus a vector with length proportional to the ε refractive index will be larger than or smaller than the vectors drawn perpendicular to the optic axis and will define one axis of an ellipse. Such an ellipse with ε direction as one of its axes and ω direction as its other axis is called the <u>Principal Section</u> of the uniaxial indicatrix. Light vibrating parallel to any direction associated with a refractive index intermediate between ε and ω will have vector lengths intermediate between those of ε and ω and are referred to as ε' direction. Thus, uniaxial indicatrix is seen to be ellipsoid of revolution. There are an infinite number of principal sections that would cut the indicatrix vertically.

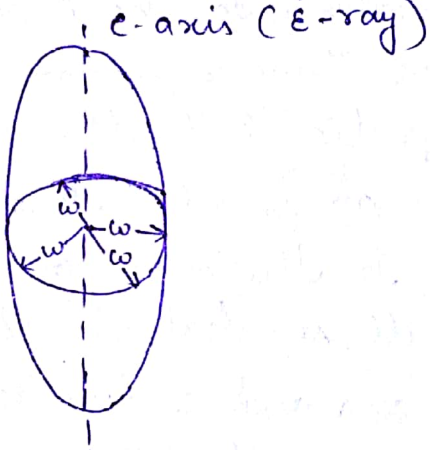
* <u>Optic Sign for Uniaxial Minerals</u> :– (<u>Uniaxial Indicatrix</u>)

i)- If $\omega > \varepsilon$ the optic sign is (-ve) and the uniaxial indicatrix would take the form of an oblate spheroid, Such an indicatrix is elongated in the direction of the stroke of a (−) minus sign.



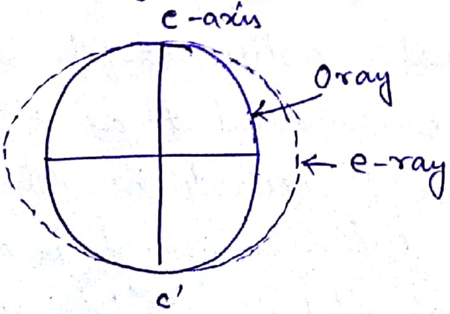
−ve Sign

ii) - If ε > ω the optic sign is positive and the uniaxial indicatrix would take the form of a prolate spheroid. Such an indicatrix is elongated in the direction of the vertical stroke of a (+) plus sign.

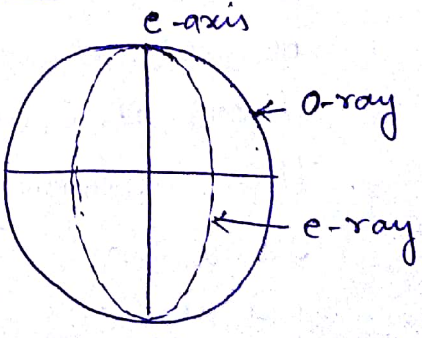


+ve Sign

Ray Velocity Surfaces of Uniaxial Crystal



O ray velocity < e-ray velocity
(Negative Crystal)



O ray velocity > e-ray
(Positive Crystal)

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Application of Uniaxial Indicatrix:-

* The uniaxial indicatrix provides a useful tool for thinking about the vibration directions of light as it passes through a uniaxial crystal.

Uniaxial Minerals:

Tetragonal, ~~Hexg~~ Hexagonal crystal system

* Biaxial Minerals:-

→ Orthorhombic, Monoclinic, Triclinic crystal system of minerals are biaxial mineral.

→ Biaxial crystals have 2 optic axes, and this distinguishes biaxial crystals from uniaxial crystals.

→ Biaxial refractive indices are as fallows:

i)- The smallest refractive index : α or X

ii)- The intermediate refractive index : β or Y

iii)- The largest refractive index : γ or Z.

→ All biaxial have optical symmetry equivalent to 2/m 2/m 2/m. But, in each of the crystal systems, the optical directions have different carrespondence to the crystallographic directions.

e.g.- a)- In ~~orthorhombic~~ monoclinic crystals, one of the X(α), Y(β), or Z(γ) directions or indices is parallel to the b- crystallographic axis, and other two do not coincide with crystallographic directions.

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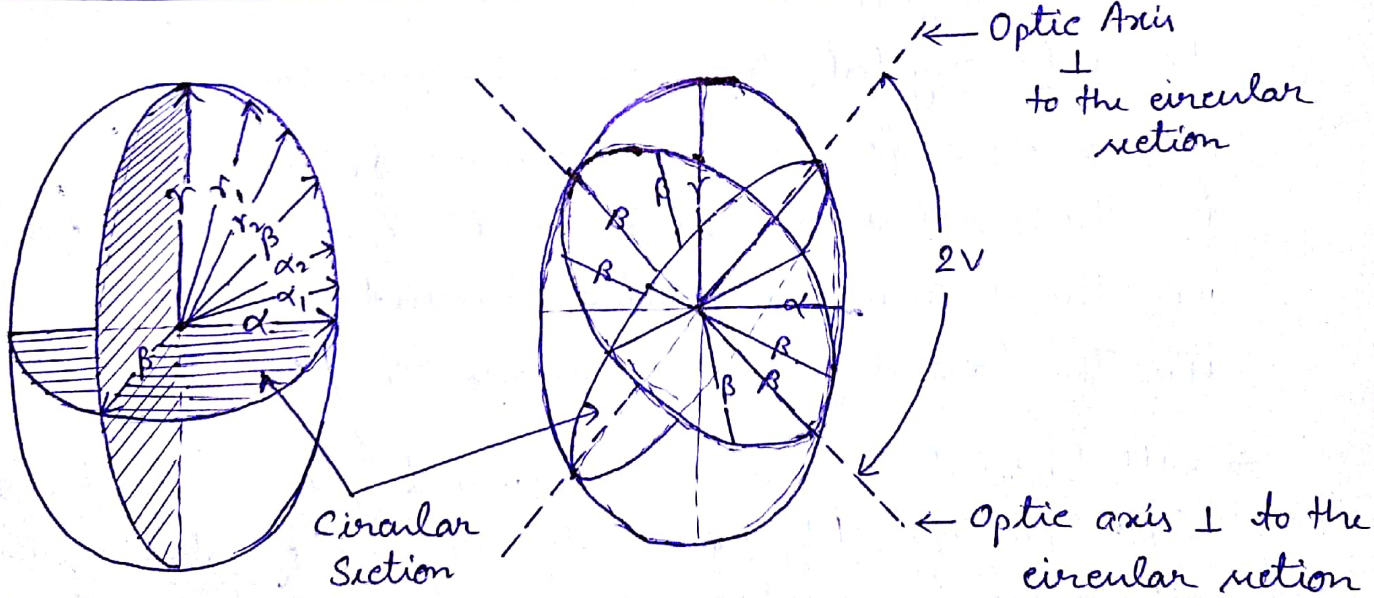
b) - ~~In monoclinic crystals, one of the X(α), Y(β), Z(γ)~~ orthorhombic
~~directions or indices is parallel~~

b) - In orthorhombic crystals, the optical directions correspond to the crystallographic axes i.e the X direction and its corresponding refractive index α can be either a, b or c crystallographic axes, the Y direction and β can be parallel to either a, b or c and the Z direction or γ can be parallel to either a, b or c.

c)- In triclinic crystals none of the optical directions or indices coincide with crystallographic directions, although in some rare case of the indices migh coincide with one of the crystallographic directions.

Biaxial Indicatrix and Optic Sign!



2V is the acute angle between the optic axes.

Just like in uniaxial minerals, if one is looking down one of the optic axes, the light travelling along optic axes will be vibrating in the β direction and thus the mineral would be extinct for all rotation positions.

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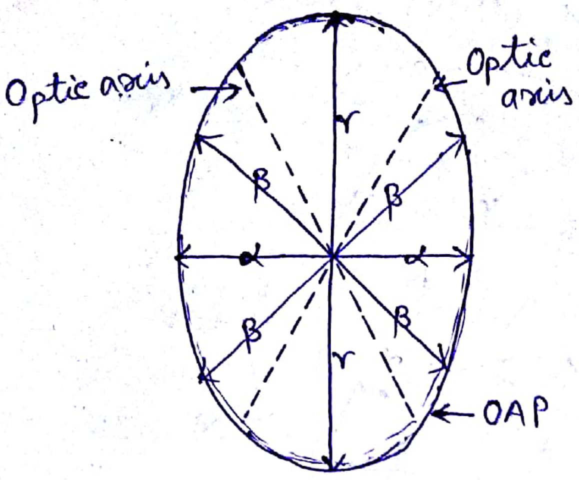
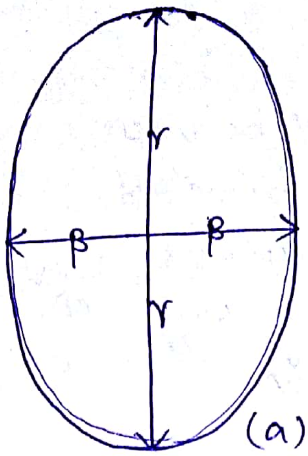
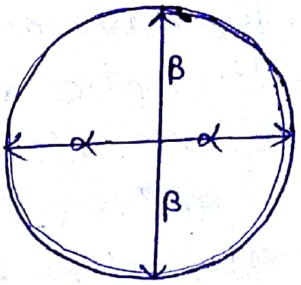
→ The three principal planes of biaxial indicatrix are:





(a)



(b)

The plane containing the α and γ directions also contains the optic axes which are perpendicular to the β directions. The plane is called the Optic Axial Plane (OAP).

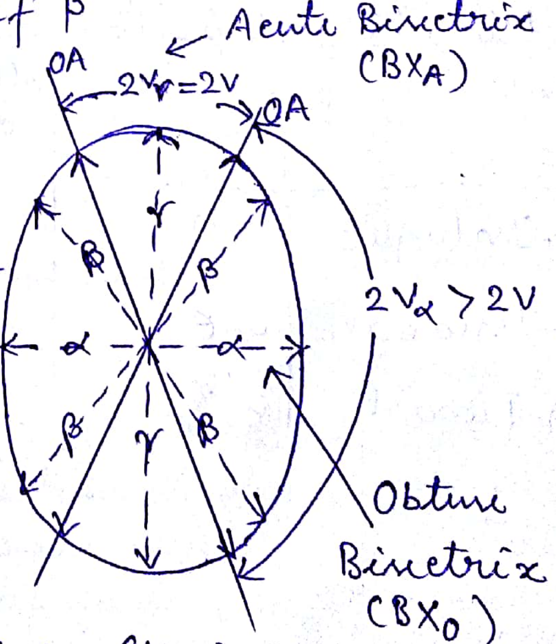
The other two principal planes contain the γ and β directions and the α and β directions respectively.

Optic ~~Sing~~ Sign of Biaxial Mineral :-

* The optic sign of biaxial minerals depends on whether the β refractive index is closer to that of α or to γ.

i) - Biaxial Positive:

→ A mineral is biaxial positive if β is closer to α than γ.



(+ve)

→ The acute angle 2V between optic axes is bisected by γ refractive index direction. Thus we say that γ is the Acute Bisectrix (CBX$_A$) because it bisects this angle.

→ In the case of biaxial positive mineral, $2V_\gamma$ is the acute bisectrix while $2V_\alpha$ bisects the obtuse angle between the optic axes (called Obtuse Bisectrix (CBXO)).

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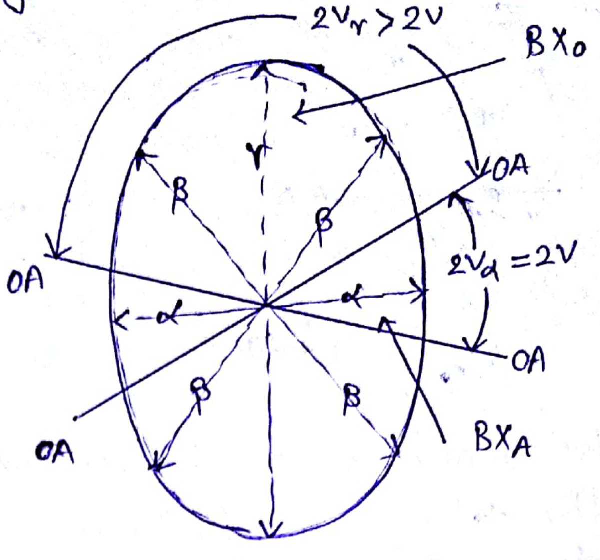
ii)- Biaxial Negative

→ A mineral is biaxial negative if β is closer to γ than α.

→ The acute angle 2V between the optic axes is bisected by α refractive index direction. Thus we say that α is the BX_A. While γ is BX_O.



(-ve)

$$2V_\alpha + 2V_\gamma = 180°$$

If 2V = 90° the mineral has no optic sign.

If 2V = 0° the mineral is uniaxial.

Indices of Refraction and Birefringence for light passing through isotropic and anisotropic minerals :-

Minerals	Principal Indices of Refraction	Index of Refraction for light travelling parallel to an Optic axis	Indices of Refraction in a Random direction	Birefringence in a Random direction	Maximum possible Birefringence
i)-Isotropic	n	n	n	0	0
ii)- Uniaxial	ω, ε	ω	ω, ε'	$\delta' = \lvert\omega - \varepsilon'\rvert$	$\delta = \lvert\omega - \varepsilon\rvert$
iii)- Biaxial	α, β, γ	β	α', γ'	$\delta' = \gamma' - \alpha'$	$\delta = \gamma - \alpha$

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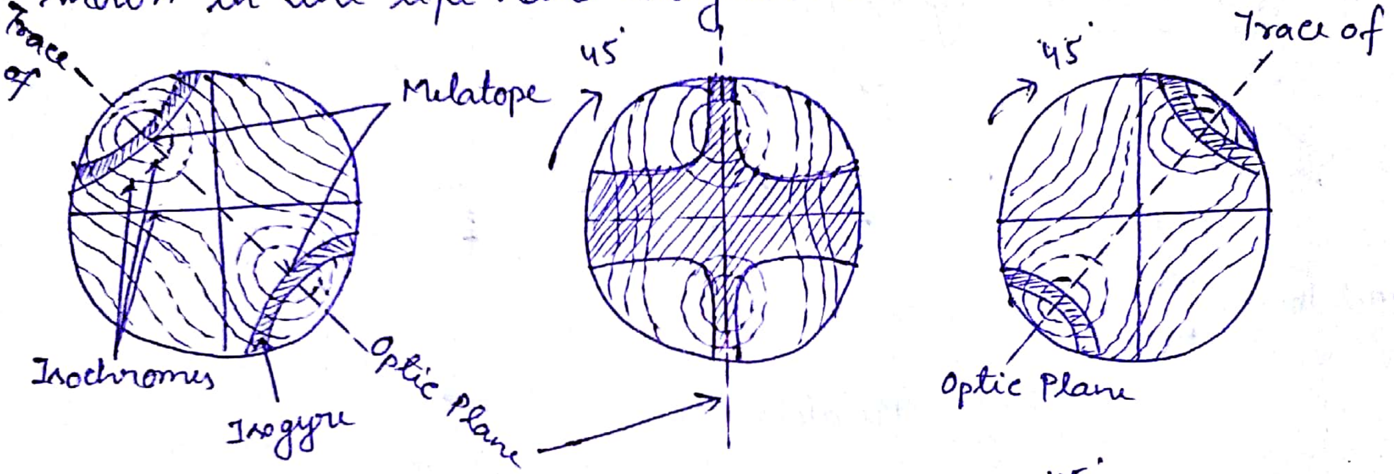
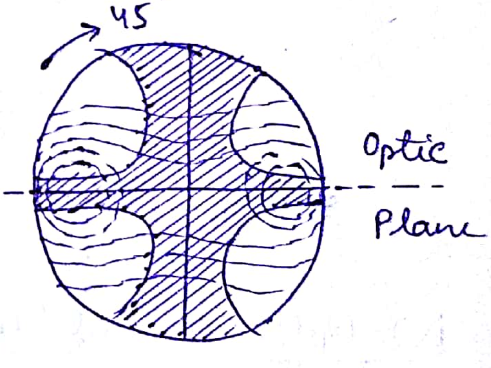
Biaxial Interferenge Figures :- (Using Quartz Wedge) Bertrand Lens

* Four primary type of biaxial interference are seen. Only two of these are commonly used.

i)- Acute Bisectrix Figures (BX_A)

Looking down acute bisectrix (the γ- direction ⊥ to the stage if the crystal is optically +ve or the α direction ⊥ to the stage if the crystal is -ve), at 45° off extinction in conoscope mode, one would see the interference figure shown in the left hand diagram below:





→ The dark isogyre mark the positions where light vibrating parallel to the polarizer has passed through of the crystal.

→ At the point of maximum curvature of isogyre are the two melatopes that mark the positions where rays that travelled along the optic axis emerge from the field of view.

** The distance between the two melatopes is proportional to the angle 2V between the optic axes.

→ Also seen are isochromes which show increasing interference colour in all directions away from the melatopes. The number of isochromes and maximum order of the interference colours seen will increase with increasing thickness and absolute birefringence of the crystal.

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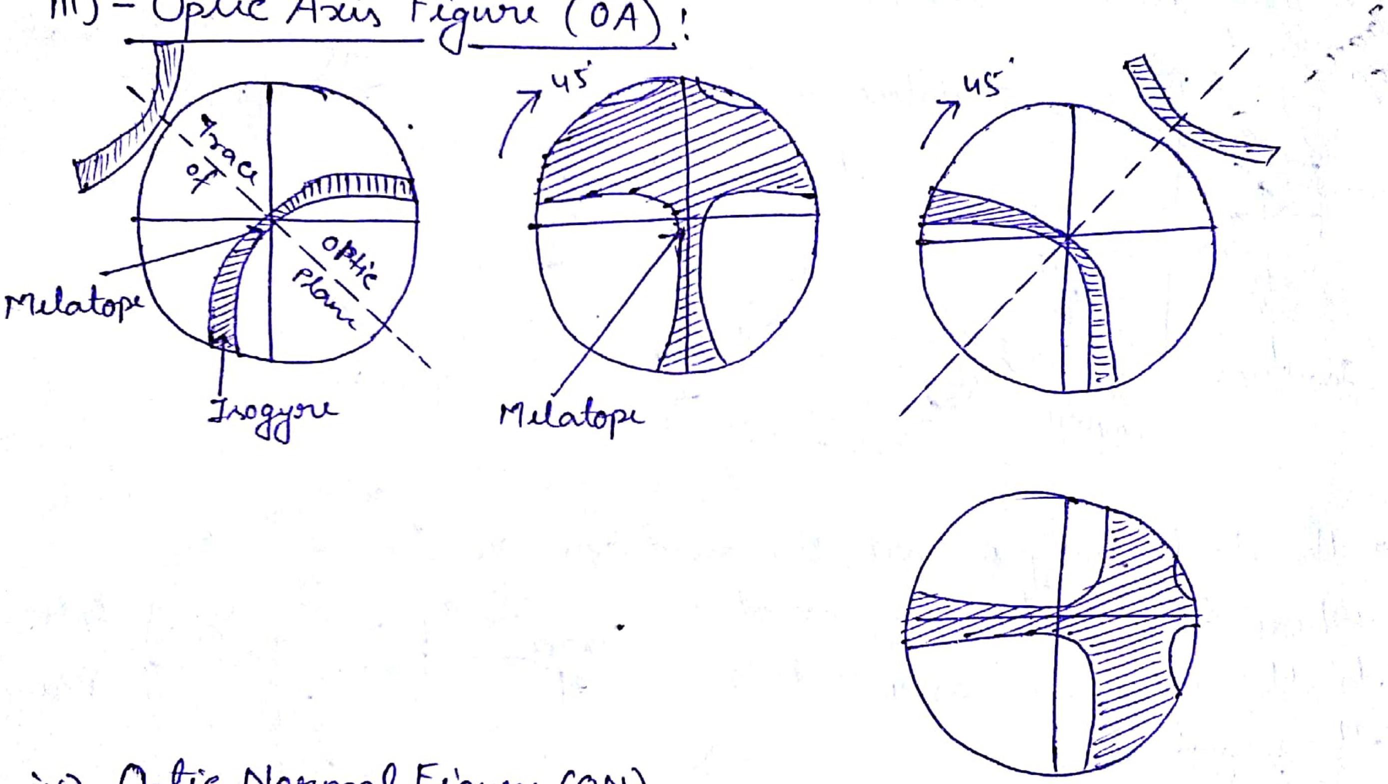
→ Shown in the figure is the trace of the optic axial plane which includes the two optic axes.

ii) - Obtuse Bisectrix Figure (BX_O)

BX_O figure will be similar to the BX_A, except the melatopes will be outside of the field of view of the time during a 360° rotation. Still, every 90° the broad cross will form as the OAP becomes parallel to one of the cross-hairs.

iii) - Optic Axis Figure (OA):



iv) - Optic Normal Figure (ON)

If the principal β direction of the indicatrix is oriented perpendicular to the stage, such that the crystal's previliged directions are α and γ, then changing to conoscope mode will produce an optic normal figure, also called flash figure.

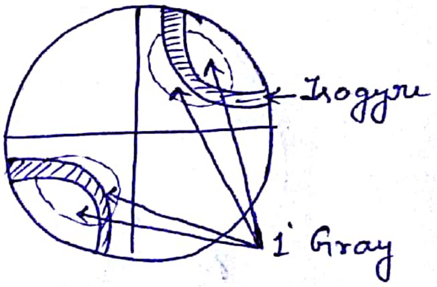
Determination of Optic Sign :-

* Biaxial interference figures are most useful for the determination of optic sign and estimation of the 2V angle, both of which are useful diagnostic properties of biaxial minerals.

i) - Acute Bisectrix Figure :- (BX_A) (Using Mica Plate)

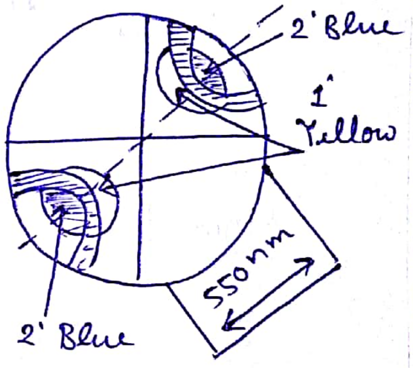
→ To determine the optic sign of a biaxial mineral from a BX_A figure, position the isogyres so that the melatopes are in the NE and SW quadrants.

→ There should be an area near the melatopes that shows a 1' gray interference colour.



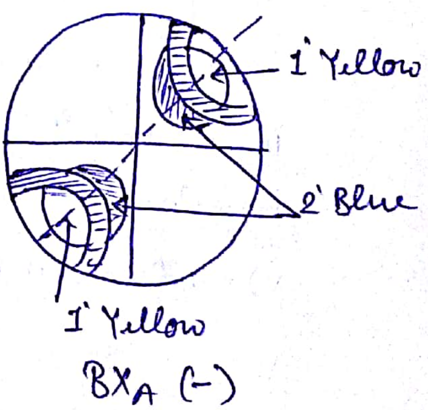
→ Observe this area as you insert the 550nm or 1' red compensator.

→ If the 1' gray area in region between the two isogyres turns yellow, the mineral is biaxial positive.



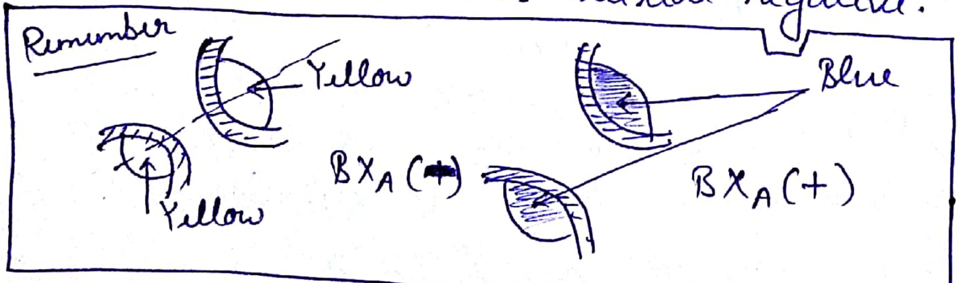
BX_A (+)

→ If the 1' gray area inside of both isogyres turns yellow the mineral is biaxial negative. i.e. 1' gray area in region between the two isogyres turns blue the mineral is biaxial negative.



BX_A (−)

Remember



ii) - Centered Optic Axis Figure :- (OA) (Using Mica Plate)

* Optic axis figures probably provide the easiest method for determination of optic sign because grains with an orientation that would produce an OA figure are perhaps the easiest to find.

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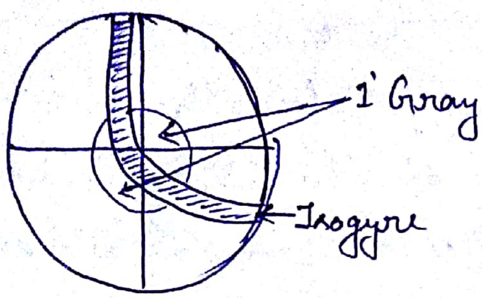
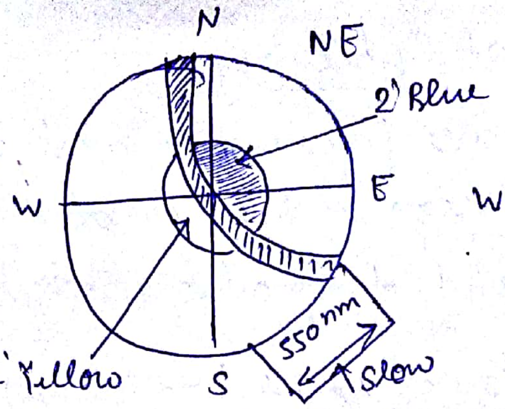
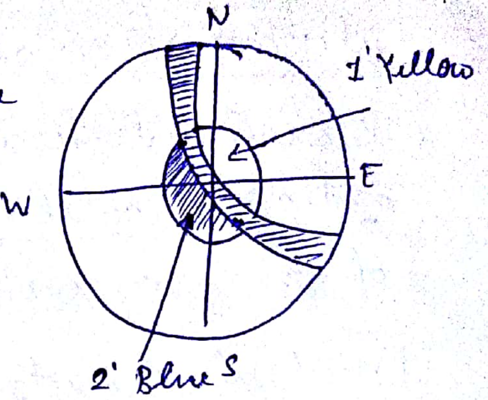


↑
Using Mica Plate

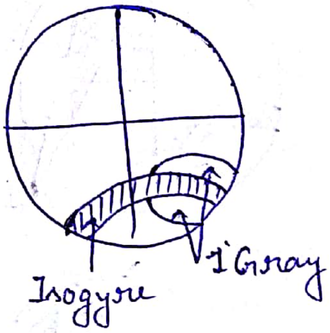


OA (+)

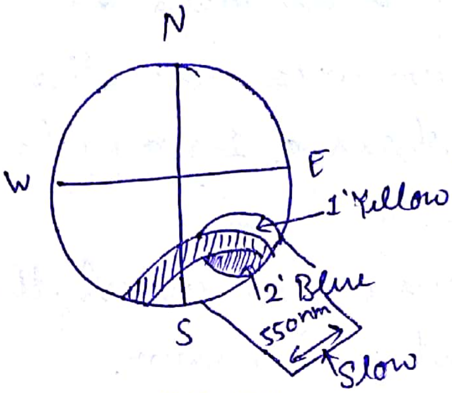


OA (−)

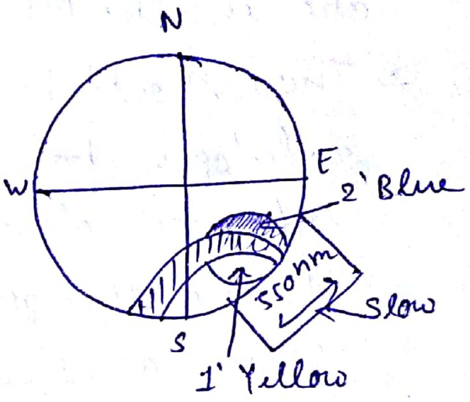
iii) - Off-Centered Figures !- (OC)



↑
Using Mica Plate



OC (+)



OC (−)

How to Locate different types of Biaxial Interference Figures !-

Types of Interference Figure	Level of Interference Colours
i)-Optic Normal Figure (ON)	Maximum
ii)-Obtuse Bisectrics Figure (BX_o)	Relatively High
iii)- Acute Bisectrix Figure (BX_A)	Relatively Low
iv)- Optic Axis Figure (OA)	None
v)- Off centered OA (OC)	Very Low

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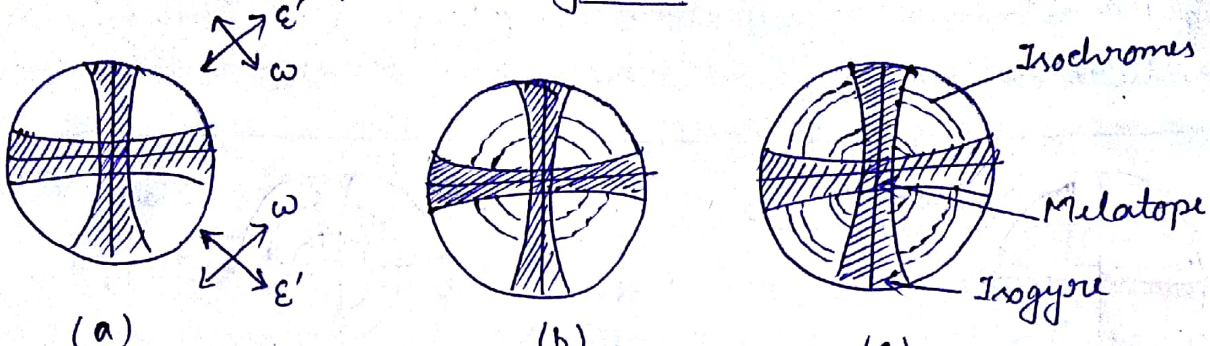
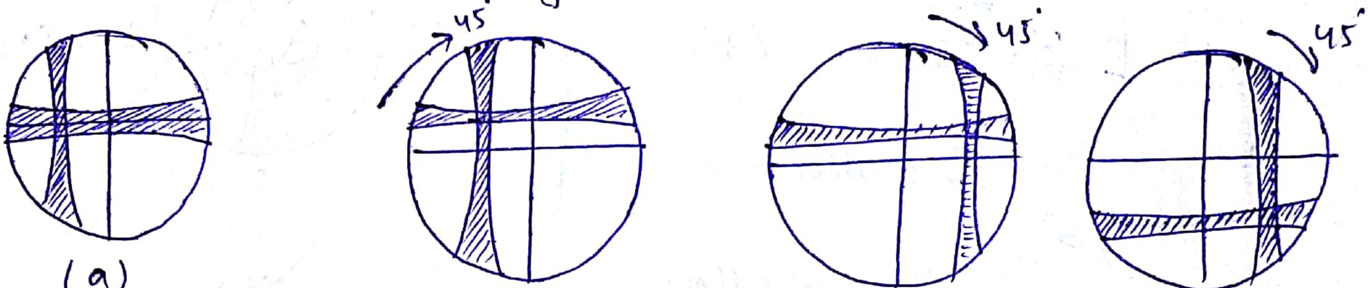
Uniaxial Interference Figure:-



(a) (b) (c)

Centered Uniaxial Interference Figure



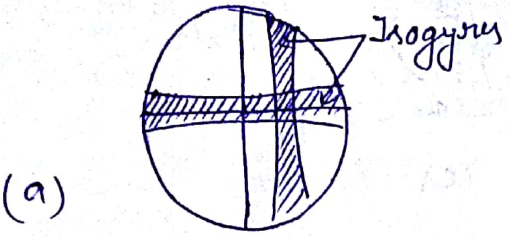
(a) (b) (e) (g)

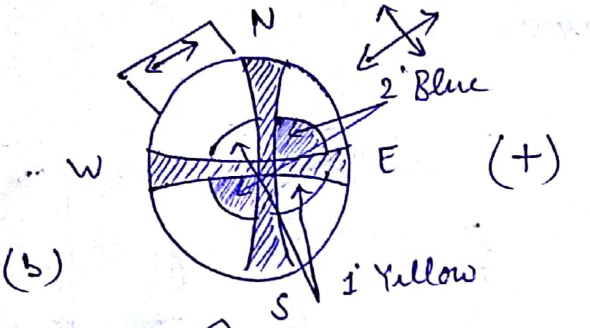
Off-centered Uniaxial Interference Figure

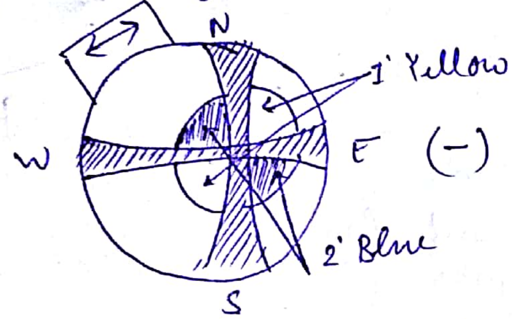
Optic Sign of a Uniaxial Minerals:-

* To determine the optic sign of a uniaxial mineral, it is necessary to know whether ω > ε or ε > ω. We do this by examing an optic axis figure and using an accessary plate with known orientation of the fast and slow rays. Standard accessary plates have their slow direction oriented SW-NE at 45° to both polarizer. The plate is inserted, and we observe interference colour changes or isochrome (colour ring) movement in the SW and NE quadrants of the interference figure.

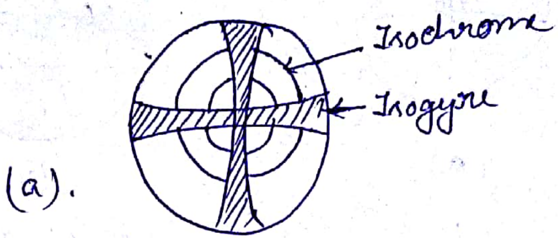
Off-centred Figure
(Low Birefringence)

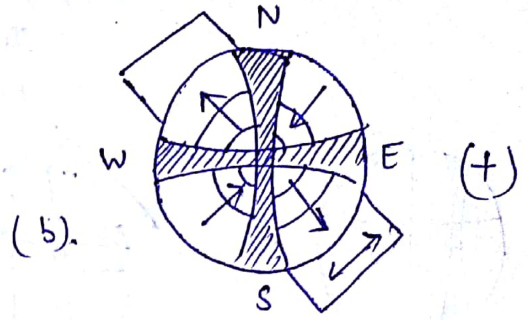


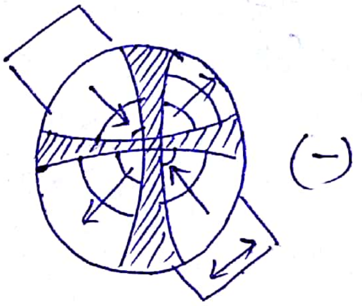




Slightly Off-centred Figure
(High Birefringence)







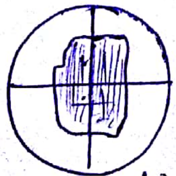
↑
Using Mica Plate

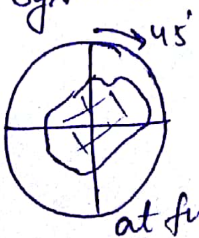
Extinction Angle :—

→ Extinction angle is the property that involves ~~dt~~ determining the angle between the crystallographic ~~ax~~ direction as exhibited by a crystal face or cleavage and one of the principal vibration direction.

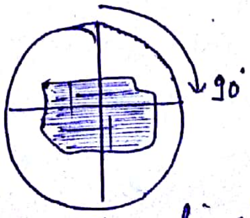
a)- **Parallel Extinction:** Minerals with cleavages that exhibit parallel extinction go extinct when their cleavages or direction of elongation are parallel to the upper or lower polarizer.

eg- Monoclinic System


at extinction



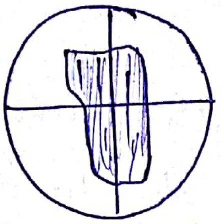
at full Illumination



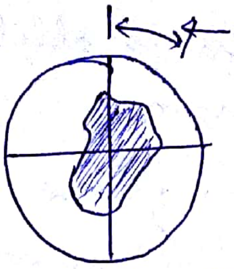
at extinction

b) - Inclined Extinction ! Minerals go extinct when their cleavages or directions of elongation are at angle to the upper and lower polarizer.

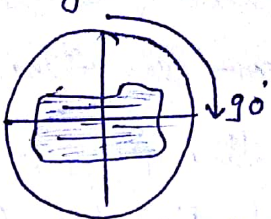
eg - Many monoclinic and all triclinic systems mineral.



at partial extinction



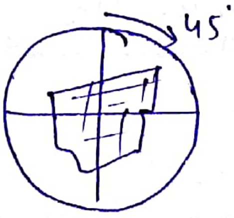
at extinction



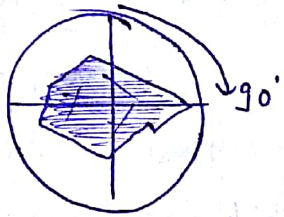
at partial extinction

c) - Symmetrical Extinction ! they go extinct at angles symmetrical with respect to cleavages or crystal faces. Because an extinction angle depends on grain orientation, determining an extinction angle for minerals in thin sections requires measurements on a number of different grains, or on one grain in the correct orientation.

at extinction



at full Illumination



at extinction

eg - Orthorhombic Systems.

Sign of Elongation :-

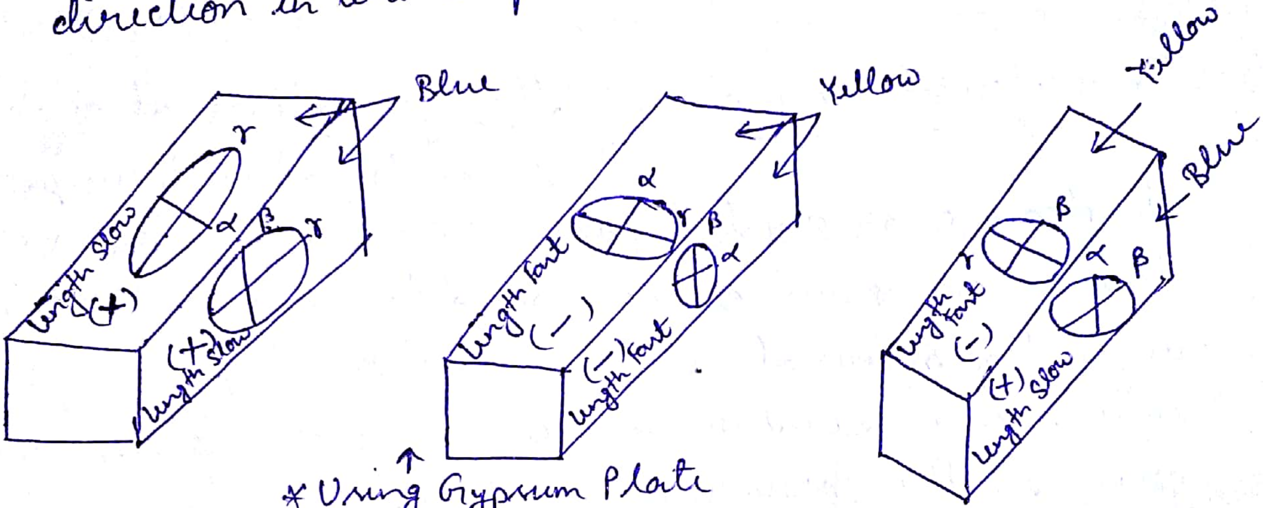
* For minerals that commonly show an elongated habit, the sign of elongation could be an important property.

→ Sign of elongation is determined by positioning the grain so that its elongation direction is parallel to the slow direction of the compensator.

→ Before ~~int~~ inserting the compensatar find an area near the edge of the grain that shows a 1' gray interference colour.

→ If the gray area turn blue then the mineral's slow direction (γ- direction) is parallel to the slow direction of ~~com~~ in the compensatar.

→ If the gray area turns yellow, then the mineral is fast direction (α- direction) is parallel to the slow direction in the compensatar.



↑
* Using Gypsum Plate

Accessory Plates (Compensatar) :—

i) - Quartz Wedge
ii) - Gypsum Plate
iii) - Mica Plate

These plates are made in such a way that the fast vibration direction (X or α - direction) of each is parallel to their length.

i) - **Quartz Wedge**: is very thin wedge shaped plate of quartz in which the fast vibration direction is parallel to its length.

When the quartz wedge is moved forward in the microscope slot, the first order, second order, third order etc interference colours are produced successively.

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ii) - Gypsum Plate! is made by cutting a gypsum crystal to such a thickness that is produces a first order red interference colour between XPL. Gypsum plate has fast vibration direction along its length.

→ This plate is also called "sensitive tint plate" because with a slight increase in double refraction, it gives a blue colour and with a corresponding decrease, its colour changes to yellow.

iii) - Mica Plate! The mica plate is also called "Quartz wave plate". This plate consists of a thin cleavage flake of muscovite which produces a path difference of quartz of a wave length of yellow light.

Pleochroism!

* Pleochroism is the property where the mineral shows a different absorption colour associated with different vibration directions.

→ In uniaxial minerals the two main vibration directions could have different absorption colours, and any intermediate direction would show an intermediate colour.

→ In biaxial crystals, three different absorption colours are possible, one associated with each of the principal indices. Intermediate directions will give intermediate colours.

→ Uniaxial ~~pleo~~chroism is called Dichroism. eg - Tourmaline

→ Biaxial chroism is called pleochroism.

→ The pleochroic formula is usually given in terms of three principal refractive indices, for example a biaxial mineral could have the pleochroic formula!

X (α) = red, β (Y) = pink, Z (γ) = clear

→ Uniaxial minerals may have pleochroic formula
ω = colour 1, ε = Colour 2.
If optic axis is perpendicular to the stage, only one colour will be observed.

Vickers Hardness!

Minerals	Mean Value	Range	Remarks
1)- Molybdenite	17	16-19	⊥ to cleavage
2)- Molybdenite	23	21-28	∥ to cleavage
3)- Covellite	72	69-78	
4)- Galena	76	71-84	
5)- Pyrolusite	76	76	⊥ to fibres
6)- Stibnite	77	42-109	
7)- Chalcocite	84	68-98	
8)- Bornite	103	97-105	
9)- Chalcopyrite	194	186-219	
10)- Pyrrhotite	248	230-259	Anisotropic section
11)- Pyrrhotite	303	280-318	Isotropic section
12)- Tetrahedrite	51	328-367	
13)- Wolframite	73	357-394	
14)- Ilmenite	536	519-553	
15)- Ilmenite	68	659-703	
16)- Goethite	556 80	525-620 772-824	Microcrystalline Coarsely crystalline
17)- Magnetite	560	530-599	
18)- Psilomelane	572	503-627	
19)- Pyrite	1165	1027-1240	
20)- Chromite	1206	1115-1210	

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CRYSTAL

Crystals are Solid geometric figures which are bounded by well defined more or less plane surfaces called 'faces'.

CRYSTALLOGRAPHY :

Crystallography is a branch of mineralogy which deals with the study of crystals and the laws that govern their growth, external shape and internal structure

HISTORY OF CRYSTALLOGRAPHY

In 1669 Nicholaus Steno has proposed Interfacial angle.

In 1780 Caronged has invented Goniometer to measure the Interfacial angle.

Steno's Law

In 1782, steno's Law was proposed by Rome del' Isle.

steno's Law states that " The angle betn two identical faces of a Say mineral are always Same. The shape & size may vary.

Iso-Morphism (W.H Walasfon in 1809)

A mineral having Same atomic str & different chemical compn are called Iso-morphism.

Ex: plagioclase feldspar of triclinic system.

Polymorphism

In 1821 Eithard Mitscherlich give an Idea about polymorphism.

A mineral having diff atomic structure & Same chemical compn are called polymorphism.

Ex: Andalusite, kyanite, Sillimanite, Quartz, Diamond

Elements of symmetry -:

Every crystal possesses a certain symmetry the geometric locus about which a group of repeating operation act is known as a symmetry element.

(i) Center of symmetry -: repetation is with respect to a point. A crystal is said to posses a center of symmetry if it equi-distance from the center.

(ii) Plane of symmetry -: with respect to a line. It is an immaginary plane which passes through the center and divided in to two parts such that part is mirror image of another.

e.g → In cube there are 9 planes of symmetry. Tetragonal prisim 5 planes.

(iii) Axis of symmetry -: It is an imaginary line through the crystal about which if the crystal is rotated, It gives the observere exactly the same view more than once in a single roation if the same view is repealed 2, 3, 4 ... times

crystallographic axis -: these are the line present with in the crystal where solid angle can be refered (a, b, c)

a = always runs from front to back

b - " " " left to right

c - " " " top to bottom.

ZONE

(i) a group of faces are arranged in such manner that thee're intersection edges are

Form :- It

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parallel to each other. such faces constitute a 'zone'.

(ii) The imaginary axis to which the faces are parallel to each other called 'zone axis'.

UNIT CELL

→ Faces of a crystal bear a definite relation to the internal structural pattern of atoms. The structural pattern consists of units, in each unit there is a group of atoms linked in a fixed spatial relationship to one another. It is called unit cell.

→ All the physical, chemical, optical characters are found in it.

INTERFACIAL ANGLE

→ In the crystal, the angle between adjacent faces is called 'interfacial angle'. Because crystal faces have a direct relationship to the internal structure, it follows that the faces have a definite relationship to each other. The relationship is expressed by law of the constancy of interfacial angles, which states that interfacial angle betn corresponding faces are constant for all crystals of a given material.

→ It is measured by goniometer.

Different type of form associated with form

(1) Pinacoid - It is a open form, consisting of two faces which cuts one axis and remain parallel to the other two axis.

(2) Pedion - It is represents by one face only.

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(3) Prisim -: It is also an open form consis of four faces. vertical faces ||al to c axis.

(4) Pyramids -: It is a closed form having eight faces each face of which cuts the vertical axis and cuts one or more horizontal axes of equal or in-equal distance.

(5) Domes -: It is a open form intermided betn prisim and a pyramid. whose faces cuts the vertical axis and one of the horizontal axes. These are also known as 'horizontal prisim'.

Crystal Systems

On the basic of axes there are 6 types of crysta system.

(1) Isometric or cubic system.

a, b, c

orthogonal axis = $a \perp b \perp c$

$a = b = c$, $\alpha = \alpha = \alpha$

In this system three axis which are equal length and mutually perpendiculare and interchangable. Two axis are horizontal and one is vertical.

(2) Tetragonal system.

a_1, a_2, a_3

orthogonal axis $a_1 \perp a_2 \perp a_3$

$a_1 = a_2 \neq a_3$

In this system three mutually ⊥ar axes. Two horizontal axis are equal and the vertical axis is longer or shorter than the other two.

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Form -: It is repre

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(3) Hexagonal system -:

$a \wedge b = \gamma$, $b \wedge c = \alpha$, $a \wedge c = \beta$

$a_1 \wedge a_2 \wedge a_3 = 120$, $a_1 = a_2 = a_3$

$a_1 \wedge c = a_2 \wedge c = a_3 \wedge c = 90°$

There are four axis, three of this equal length and lie at angle 120° to each other. These horizontal axes are equal in length. The four axis is vertical and may be shorter or longer in length than that of the horizontal ones.

(4) Orthorhombic system

$a \neq b \neq c$ and $a \wedge b \wedge c = 90°$

(brachy axis)

It consists of three axes of unequal length and are mutually perpendicular.

(Macro axias)

(5) Monoclinic system -:

$a \neq b \neq c$, $a \wedge c \neq 90°$, $b \wedge c = 90°$

In this system there are three unequal crystallographic axes. The 'a' and 'c' are inclined to each other at an oblique angle and the 'b' axis is perpendicular to the plane of the two.

(6) Triclinic system -:

$a \neq b \neq c$, $a \wedge b \wedge c \neq 90°$

There are three unequal axes all intersecting at oblique angles.

Axial Ratio

The 'unit length' of crystallographic axes length of the unit cell edges. The ratio between the lengths of the axes of the crys

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Isometric or cubic system -:

(1) Axial relation ship

→ 3 crystallographic axes.

→ All are equal length and mutually interchangble

→ $a_1 = a_2 = a_3$, $a_1 \wedge a_2 \wedge a_3 = 90°$

(2) symmetry element

→ plane of symmetry - 9 < 3 axial, 6 diagonal

→ Axies of symmety - 3^{IV} 6^{II} 4^{III} = 13

→ centere of symmety - present.

→ It is called Holohedral class / Hexoctal class or Galena type

(3) Forms

There are seven basic form in the class.

(i) Cube

→ six square faces. It is a closed form.

→ Make angle 90° to each other

→ Each face cuts a-axis at unit distane and runs parallel ~~to~~ othere two axes.

→ General symbol = (100)

(ii) octahedron

→ Eigtht equilateral triangulare faces.

→ Each face intersect the three crystallographic axes at equal length.

→ General symbol - (111)

(iii) Dodecahedron

→ 12 rhomb shaped faces.

→ Each intersects the two crystallographic equally and is parallel to the third.

→ General symbol (110)

(iv) Tetra hexa hedron.

(i) 24 no. of faces.

→ Each face is an isosceles triangle

→ Each face intersects one axis at unity, the second axis at some multiple of unity and is parallel to the third.

hko
hok
hll

→ General symbol (hko)

(v) Trisoctahedron.

→ 24 no. of faces.

→ Each face cut two axes equal distance and cuts the 3rd at greater distance.

→ General symbol (hhl)

(vi) Trapezohedron

→ 24. no. of faces.

→ Each face cuts two axis at equal distance and third at the smaller distance.

→ general symbol (hll)

(vii) hexaoctahedron

→ It has 48 no. of faces.

→ Each face cuts all the axes at un-equal len

→ General symbol (hkl)

Common mineral in this system.

Galena (PbS), Magnetite - FeO Fe_2O_3 - Fe_3O_4

Chromite - $FeOCr_2O_3$, Garnet, Fluorspar, Leac

→ Isometric system has max^m symmetry.

→ It is the normal class of the cubic system

→ this system also called galena type.

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