PREFACE

In a bid to standardize higher education in the country, the University Grants Commission (UGC) has introduced Choice Based Credit System (CBCS) based on five types of courses viz. *core, generic, discipline specific elective, ability and skill enhancement* for graduate students of all programmes at Honours level. This brings in the semester pattern which finds efficacy in sync with credit system, credit transfer, comprehensive continuous assessments and a graded pattern of evaluation. The objective is to offer learners ample flexibility to choose from a wide gamut of courses, as also to provide them lateral mobility between various educational institutions in the country where they can carry their acquired credits. I am happy to note that the university has been recently accredited by National Assessment and Accreditation Council of India (NAAC) with grade “A”.

UGC (Open and Distance Learning Programmes and Online Programmes) Regulations, 2020 have mandated compliance with CBCS for U.G. programmes for all the HEIs in this mode. Welcoming this paradigm shift in higher education, Netaji Subhas Open University (NSOU) has resolved to adopt CBCS from the academic session 2021-22 at the Under Graduate Degree Programme level. The present syllabus, framed in the spirit of syllabi recommended by UGC, lays due stress on all aspects envisaged in the curricular framework of the apex body on higher education. It will be imparted to learners over the six semesters of the Programme.

Self Learning Material (SLMs) are the mainstay of Student Support Services (SSS) of an Open University. From a logistic point of view, NSOU has embarked upon CBCS presently with SLMs in English / Bengali. Eventually, the English version SLMs will be translated into Bengali too, for the benefit of learners. As always, all of our teaching faculties contributed in this process. In addition to this we have also requisioned the services of best academics in each domain in preparation of the new SLMs. I am sure they will be of commendable academic support. We look forward to proactive feedback from all stakeholders who will participate in the teaching-learning based on these study materials. It has been a very challenging task well executed, and I congratulate all concerned in the preparation of these SLMs.

I wish the venture a grand success.

Professor (Dr.) Subha Sankar Sarkar
Vice-Chancellor

NETAJI SUBHAS OPEN UNIVERSITY
Under Graduate Degree Programme
Subject : Honours in Geography (HGR)
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Course : Geotectonics and Geomorphology
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First Print : November, 2021

Printed in accordance with the regulations of the Distance Education Bureau
of the University Grants Commission.

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Unit 1 ❑ Earth's Tectonic And Structural Evolution With Reference To Geological Time Scale

Structure

1.0 Ovjectives

- The learners will learn about the tectonic and structural evolution of the earth
- To learn about the different Era’s
- To learn about the geological Time Scale

1.1 Introduction

The geologic time scale (GTS) is an arbitrary chronological arrangement or sequence of geologic events that relates geological strata to time. The Geologic Time Scale (GTS) is used as a measure of the relative or absolute duration or age of any part of geologic time and is used by geologists, paleontologists, and other Earth scientists to describe the timing and relationships of events that have occurred during Earth’s history. GTS is an internationally developed and agreed scheme of subdividing the passage of time since the origin of Earth. The original structure of GTS was developed during the late nineteenth to early twentieth century. The geological time scale is currently maintained by the International Commission on Stratigraphy (ICS), which is part of the International Union of Geological Sciences (IUGS). The time scale is continuously being updated as we learn more about the timing and nature of past geological events. Today, the geologic time scale is hierarchically divided (from largest to smallest) into Eons, Eras, Periods, Epochs, and Ages. The corresponding rocks that represent these subdivisions are referred to as Eonothems, Erathems, Systems, Series, and Stages. Geologic Time Scale divisions mark major events which highlight changes in climate, geography, atmosphere, and life.

1.2 Dating Techniques

Geologists often need to know the age of ancient rocks and fossils of the living organism that they find. There are two types of age determination methods—1) Relative dating and 2) Absolute dating.

• Relative Dating

Geologists in the late 18th and early 19th century studied rock layers and the fossils in them to determine relative age. William Smith was one of the most important scientists who helped to develop knowledge 01 the succession of different fossils by studying their distribution through the sequence of sedimentary rocks in southern England. 'Relative age' means the age of one object compared to the age of another, not the exact age of an object. This method can only be used when the rock layers are in their original sequence. Most common relative dating techniques are stratigraphy and bio-stratigraphy which are only used to know which of the object is older or younger. So, the relative dating is less advanced technique as compared to the absolute dating.

• Absolute Dating

The absolute dating is the technique which tells about the exact age of the artifact or the site using different modern methods. The absolute dating is also known as the numerical dating as it comes up with the exact numerical age of the item. Modern geologists use a variety of techniques to establish absolute age, including radiometric dating, tree rings, ice cores, and annual sedimentary deposits. Radiometric dating is the most useful of these techniques—it is the only technique that can establish the age of objects older than a few thousand years. Unlike relative dating, which relies on sequencing of rock layers (i.e. younger vs. older), absolute dating can produce an actual age in years. The table below shows characteristics of some common radiometric dating methods.

Table 1.1 : Different dating Method

Dating method	Material dated	Age range dated
Carbon-14 to nitrogen-l4 (radiocarbon)	Organic remains, archaeological artifacts	Up to 70,000 years ago
Luminescence	Tephra, loess, lake sediments	Up to 100,000 years ago
Fission track	Tephra	10,000 to 400 million years ago
Potassium-40 to argon-40	Volcanic rocks	20,000 to 4.5 billion years ago
Uranium-238 to lead-206	Volcanic rocks	I million to 4.5 billion years ago

• Isotopic Dating Methods

Absolute age can be determined by using radiometric dating. It was only in the early part of the 20th century, when isotopic dating methods were first applied, that it became possible to discover the absolute ages of the rocks containing fossils.

Isotopic dating of rocks, or the minerals in them, is based on the decaying rates of certain unstable **isotopes** of elements. Decaying rates of elements have been constant over geological time. It is also based on the premise that when the atoms of an element decay within a mineral or a rock, they stay there and don’t escape to the surrounding rock, water, or air.

Elements are defined by the number of protons and neutrons in the atomic nucleus. The mass of a neutron is almost identical to that of a proton. When an element’s atoms have **different numbers of neutrons** they are said to be isotopes of that element. Some isotopes are unstable and break down into other isotopes through a process called radioactive decay. Radioactive decay is characterized by beta decay, where a neutron changes into a proton by giving off an electron, and alpha decay, when isotopes give off 2 protons and 2 neutrons in the form of an alpha particle and changes into a new product. The original isotope is called the parent and the new isotope product is called the daughter. Radioactive isotopes can be found in the rock record because radioactive isotopes are incorporated into the crystals of igneous rock as it cools.

• Half-Life of elements

Half-life is the time required for half of the parent material to change or decay. Half-lives can be calculated from measurements on the change in mass of a nuclide and the time it takes to occur. If an isotope has a half-life of 4000 years, then after 4000 years ½ of the parent isotope remains. After another 4000 years, ½ of ½ or ¼ of the original amount of parent isotope remains. In another 4000 years (12,000 years total), ½ more of the remaining amount decays, so after 3 half-lives, there only remains 1/8 (½ of ½ of ½) of the original parent isotope. So, if the half-life and the proportion of parent isotope to daughter isotope are known, then the absolute age of the rock is determined by simple calculation. This method is called radiometric dating.

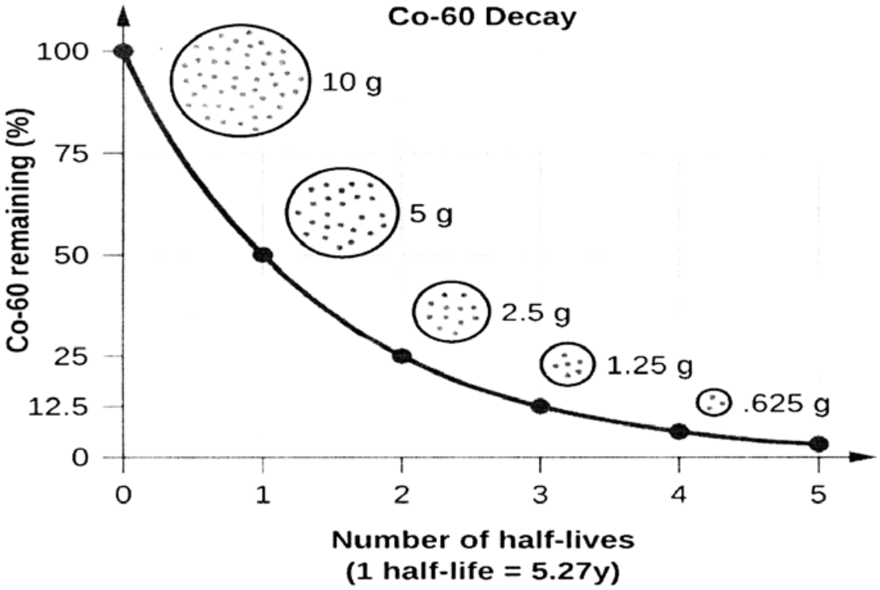


Fig 1.1: Radioactive decay and half-life

1. Potassium-Argon Dating

Potassium-Argon dating is the only viable technique for dating very old archaeological materials. Geologists have used this method to date rocks as much as 4 billion years old. This method is widely used for numerical age measurement of rocks, especially igneous rocks, which are formed by cooling of magmas after emplacement or after eruption as lava flows. Since potassium is a constituent of many common minerals and occurs with a tiny fraction of radioactive potassium-40, it finds wide application in the dating of mineral deposits. One of the isotope pairs widely used in geology is the decay of ^{40}K to ^{40}Ar (potassium-40 to argon-40). ^{40}K is a radioactive isotope of potassium that is present in very small amounts in all minerals that have potassium in them. It has a half-life of 1.3 billion years, meaning that over a period of 1.3 BY one-half of the ^{40}K atoms in a mineral or rock will decay to ^{40}Ar, and over the next 1.3 BY one-half of the remaining atoms will decay, and so on. By comparing the proportion of K-40 to Ar-40, and knowing the decay rate of K-40, the date that the rock formed can be determined.

2. Uranium-lead Dating

Of all the isotopic dating methods in use today, the uranium-lead method is the oldest and the most reliable. Uranium (U) comes in two common isotopes with atomic weights of 235 and 238 (^{235}U and ^{238}U), Both are unstable and radioactive. So. this method uses the radioactive decay of uranium isotopes (^{238}U, ^{235}U, ^{232}Th) into stable isotopes of lead (Pb) (^{206}Pb) ^{207}Pb, and ^{208}Pb, respectively). ^{238}U decays to ^{206}Pb (half-life = 4510 Ma) by a process of eight alpha-decay steps and six beta-decay steps. ^{235}U decays to ^{207}Pb (half-life = 713 Ma) by a similar series of stages that involves seven alpha-decay steps and four beta-decay steps. These differing rates of decay help make uranium-lead dating one of the most reliable methods of radiometric dating because they provide two different decay clocks. This provides a built-in cross-check to more accurately determine the age of the sample. **Uranium-lead** is one of the oldest and most refined of the radiometric dating schemes. It can be used over an age range of about 1 million years to over 4.5 billion years.

3. Radiocarbon Dating

Radiocarbon dating is a common method used to date anything that was once alive (including plants) and up to 70,000 years old. All living things take in carbon from the environment in the form of carbon-I 2 and carbon-l 4. When an organism dies, carbon intake stops and the carbon-I 4 begins to decay at a known rate. Scientists can determine how much C-14 remains in an organism by measuring radiation emitted by the C-14 isotopes. Carbon dating can be used on wood, plants, humans, and even old paper made out of papyrus. The half-life ofC-14 is 5,730 years. Because of this, it should not be used with material older than ~70,000 years or 12 half-lives.

However, it has also some limitations. Substances must have obtained C-14 from the atmosphere. For this reason, aquatic samples cannot be effectively C-14 dated.

1.3 DIvision Of Time In GTS

In the geological time scale, the largest defined unit of time is the eon, which is further divided successively into eras, periods, epochs, and stages. The period is the basic unit of geological time in which a single type of rock system is formed. Two or more periods comprise a geological Era. Two or more Eras form an Eon, the largest division of geologic time. Some periods are divided into epochs.

• The Eons

An eon, the largest division of the geologic time scale, spans hundreds to thousands of millions of years. Geological time has been divided into four eons: **Hadean, Archean, Proterozoic, and Phanerozoic**. The first three of these represent almost 90% of Earth's history. The last one, the Phanerozoic (meaning "visible life"), is the time that we are most familiar with because Phanerozoic rocks are the most common on Earth, and they contain evidence of the life forms that we are all somewhat familiar with.

Fig 1.2 : The Eons of Earth's history

• The Eras

The term Phanerozoic means visible life, which refers to the fact that fossils are usually quite evident in sedimentary rocks deposited during the Phanerozoic. The Phanerozoic—the past 540 Ma of Earth's history—is divided into three eras: the Paleozoic (early life), the Mesozoic (middle life), and the Cenozoic (new life), and each of these is divided into a number of periods. Most of the organisms that we share Earth with evolved at various times during the Phanerozoic.

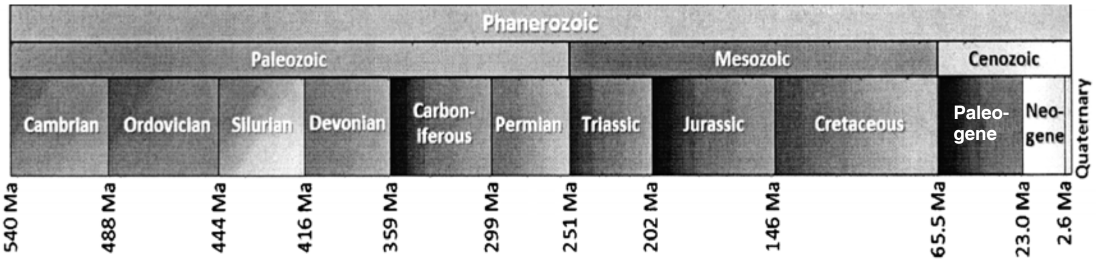


Fig 1.3 : The Eras (middle row) and Periods (bottom row) of the Phanerozoic

• The Periods

Period is one of several subdivisions of geologic time enabling cross-referencing of rocks and geologic events from place to place.The Cenozoic which represents the past 65.5 million years ago to present is divided into three periods: the Paleogene (65.5 to 23.03 million years ago), Neogene (23.03 to 2.6 million years ago) and the Quaternary (2.6 million years ago to present). Paleogene and Neogene are relatively new terms that now replace the deprecated term, Tertiary.

• The Epochs

An **Epoch** is a subdivision of the geologic timescale that is longer than an age and shorter than a period. The Paleogene is subdivided into three epochs: the Paleocene (65.5 to 55.8 million years ago), the Eocene (55.8 to 33.9 million years ago), and the Oligocene (33.9 to 23.03 million years ago). The Neogene is subdivided into two epochs: the Miocene (23.03 to 5.332 million years ago) and Pliocene (5.332 to 2.588 million years ago). Most of the boundaries between the periods and epochs of the geological time scale have been fixed on the basis of significant changes in the fossil record.

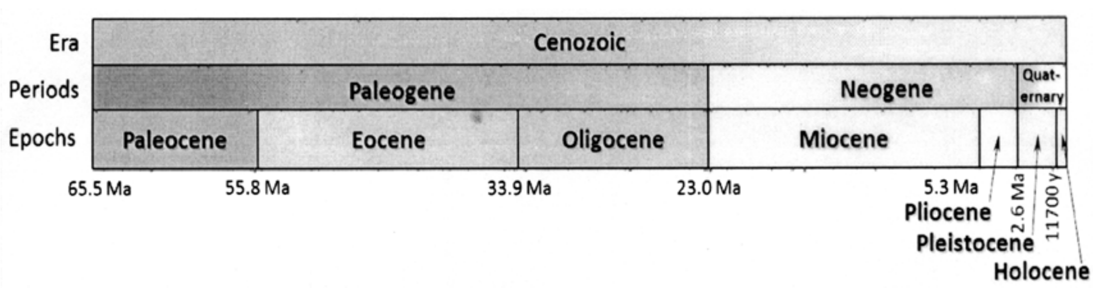


Fig 1.4 : The periods (middle row) and epochs (bottom row) of the Conozoic

Table 1.2 : of GTS with years.

Years Ago	Supereon	Eon	Era	Period	Years Ago
Present		PRECAMBRIAN	Cenozoic	Quaternary	*1.8 mil.*
				Tertiary	*65 mil.*
65 mil.			Mesozoic	Cretaceous	*145 mil.*
				Jurassic	*200 mil.*
				Triassic	*245 mil.*
245 mil.			Paleozoic	Permian	*290 mil.*
				Carbonferous	*360 mil.*
				Devonian	*410 mil.*
				Silurian	*440 mil.*
				Ordovician	*505 mil.*
				Cambrian	
544 mil.					
544 mil.	PRECAMBRIAN	Proterozoic			
2.5 bil.		Archean			
3.8 bil.		Hadean			
4.6 bil. *Origin of Earth*					

1.4 HISTORY OF GTS

- Nicholas Steno (1638-1686) was the first to lay down the principles underlying geologic time scales in the late seventeenth century. Steno in 1669 described two basic geologic principles. The first stated that sedimentary rocks are laid down in a horizontal manner, and the second stated that younger rock units were deposited on top of older rock units. Steno's principles were simple, but applying them to real rocks proved complex.

  During the eighteenth century, geologists came to realize that the Sequences of strata were often eroded, distorted, tilted, or even inverted after deposition.

Besides, strata laid down at the same time in different areas could have entirely different appearances.

- Another related concept was introduced by James Hutton (1726-1797) in 1795, and later emphasized by Charles Lyell (1797-1875) in the early 1800s. This was the idea that natural geologic processes were uniform in frequency and magnitude throughout time, an idea known as the “principle of uniformitarianism”.
- The first serious attempts to formulate a geologic time scale that could be applied anywhere on Earth were made in the late I 8th century. Geologists of that time divided the rocks of Earth’s crust into four types: Primary, Secondary, Tertiary, and Quaternary. Each type of rock, according to the theory, formed during a specific period in Earth history. Most geologists at this time believed the Earth was much older than 6,000 years. They also believed that the Primitive rocks were covered by an average of at least two miles of Secondary and Tertiary strata, which showed slow deposition during successive periods of calm and catastrophe
- The ‘identification of strata by the fossils’ was developed in the early 19th century by Georges Cuvier, Jean d’Omalius d’Halloy, and Alexandre Brongniart. Next major contribution to the geologic. time scale was by WiIIiam Smith (1769-1839), a British surveyor and amateur geologist. In 1815 Smith produced a geologic map of England in which he successfully demonstrated the validity of the principle of faunal succession. This principle simply stated that fossils are found in rocks in a very definite order. This principle led others that followed to use fossils to define increments within a relative time scale
- The early time scales were only relative because 19th century geologists did not know the ages of the rocks. That information was not available until the development of isotopic datingtechniques early in the 20th century. The first geologic time scale that included absolute dates was published in 1913 by the British geologist Arthur Holmes. In 1977, the Global Commission on Stratigraphy (now the International Commission) started an effort to define global references (Global Boundary Stratotype Section and Points) for geologic periods and faunal stages. The tables of geologic periods presented here are in accordance with the dates and nomenclature proposed by the International Commission on Stratigraphy.

1.5 Geological And Biological Events Of GTS

Four main time spans generally mark the Geologic Time Scale. The first, Precambrian Time, is not an actual era on the scale because of the lack of diversity of life, but the other three are defined eras:

1.5.1 Precambrian Supereon

Precambrian time covers the vast bulk of the Earth's history, starting with the planet's creation about 4.5 billion years ago and ending with the emergence of complex, multi-celled life-forms almost four billion years later. The end of this time span saw the rise of a few more complex animals in the oceans, such as jellyfish. There was still no life on land, and the atmosphere was just beginning to accumulate the oxygen needed for higher-order animals to survive.

Several rock types yield information on the range of environments that may have existed during Precambrian time. Evolution of the atmosphere is recorded by banded-iron formations (BIFs), paleosols (buried soil horizons), and red beds, whereas tillites (sedimentary rocks formed by the lithification of glacial till) provide clues to the climatic patterns that occurred during Precambrian glaciations. Precambrian includes approximately 90 percent of geologic time. It extends from 4.6 billion years ago to the beginning of the Cambrian Period (about 570 Ma). It includes 3 eons namely :

- **Hadean Eon (4.6 - 3.8 bya) :** The Hadean Eon isn't formally recognized, but it essentially marks the era before there were any rocks. During the Hadean period the Late Heavy Bombardment occurred (approximately 3800 to 4100 Ma) during which a large number of impact craters are believed to have formed on the Moon as well as other planets including earth.
- **Archean Eon (3.8-2.5 bya) :** The Archean Eon began about 3.8 billion years ago with the formation of Earth's crust and extended to the start of the Proterozoic Eon 2.5 billion years ago. During this time, the Earth's crust cooled enough that rocks and continental plates began to form. Archean rocks are often heavily metamorphized deep-water sediments, such as graywackes, mudstones, volcanic sediments, and banded iron formations. Carbonate rocks are rare, indicating that the oceans were more acidic due to dissolved carbon dioxide. Archean greenstone-granite belts contain many economic mineral deposits, including gold and silver.

- Proterozoic Eon (2.5-0.57 bya) : The period of Earth's history that began 2.5 billion years ago and ended 542.0 million years ago is known as the Proterozoic, which is subdivided into three eras: the Paleoproterozoic (2.5 to \.6 billion years ago), Mesoproterozoic (\.6 to 1 billion years ago), and Neoproterozoic (1 billion to 542.0 million years ago) The geologic record of the Proterozoic is much better than that for the preceding Archean. Many of the most exciting events in the history of the Earth and of life occurred during the Proterozoic - stable continents first appeared and began to accrete, a long process taking about a billion years. The first traces of life appear nearly 3.5 billion years ago, in the early Archean. However clearly identifiable fossils of stromatolites, layered mounds produced by the growth of microbal mats, become common in the rock record of this eon.

Table 1.3 : Brief tabular outline of historical evolution.

Era	Period	MYBP	Epoch	MYBP	Milestone in Biology	Major Geological events
Cenozoic	**Quaternary**	3	**Holocene** **Pleistocene**	0.4 3	Age of Humans	Wisconsin Ice 7000 BP: Cycles of glaciations
	Tertiary	65	**Pliocene** **Miocene** **Oligoccne** **Eocene** **Palcocene**	5 25 38 55 65	**Hominidae** 5 MYBP Radiation of Mammalia & Aves; Dominance of Teleosts	N & S Americajoin; Continents assuming modern positions
Mesozoic	**Cretaceous**	135			Massive extinctions Origin of **Angiosperms**, colonial insects	**K/T Boundary event;** N America & Eurasia separate; S America & Africa separate
	Jurassic	215			Age of Dinosaurs; Origin of Aves Origin of Teleost fishes	**Breakup of Pangaea** as Gondwanaland (S) & **Laurasia** (N)
	Triassic	250			**Gvmnosperms** dominant; Origin of *Therapsida Origin of Dinosaurs	**Continents adrift**
Paleozoic	**Permian**	290			**"Great Dying"**: >95% of marine invertebrates extinct	**Pangaea** supercontinent & **Tethys Sea**
	Carboniferous [Pennsylvanian / Mississippian]	360			Forests of tree ferns; Age of Arnphibia; Origin of **Amniota**	Origins of coal fields

Era	Period	MYBP	Epochs	MYBP	Milestone in Biology	Major Geological events
	Devonian	405			Abundant terrestrial life: bryophytes, club mosses, Insecta Age of Fishes; Origin of Amphibia	**Pangaea coalescing**
	Silurian	435			Invasion of Land by Arthropoda & Trachaeophyta Origin of **Gnathostomata** *Ostracodermi dominant; Origin of *Placodermi	
	Ordovician	505			Invertebrates dominate seas; Trilobites dominant	
	Cambrian	570			**Origin of** Vertebrata **"Cambrian explosion"**: Invertebrate phyla & algae abundant	
Proterozoic [Sinian]	**Vendian** **Sturtian**	610 800 3800			Origin of Chordata *(Pikaia)* Origins of Life	
Archaeozoic [Hadean]		4560			—	Oldest rocks

Source : www.geosociety.org

1.5.2 Phanerozoic Eon

The Phanerozoic Eon covers roughly 545 million years and is typically subdivided into three eras. These eras are: A) Paleozoic Era: 542 to 251 million years ago; B) Mesozoic Era: 251 to 65 million years ago and C) Cenozoic Era: 65 million years ago to present.

1.5.2.1 Phanerozoic Era

The Paleozoic spanned from roughly 542 Ma to roughly 251 Ma, and is subdivided into six geologic periods; from oldest to youngest they are: the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian.

• Cambrian Period

The Paleozoic Era began with a metaphorical explosion of life called The Cambrian explosion', which saw single-celled bacteria evolve into an abundance of diverse organisms. The emergence of all the animal phyla that exist today can trace their origins back to the 40 million-year span that was the Cambrian explosion. The period gets its name from Cambria, the Roman name for Wales, where Adam Sedgwick, one of the pioneers of geology, studied rock strata. In the early Cambrian, Earth was generally cold but was gradually warming.

Rocks of Cambrian age are distributed in the Great Basin of the western United States, parts of the northeastern United States, Wales, Scandinavia and the Baltic region, Siberia, and China, among other places.

P-T extinction

The end of the **Paleozoic Era** (251 million years ago) was more like an 'implosion of life,' as much as 96% of all life on Earth went extinct during the event known as the **P-T extinction** (Permian- Triassic extinction). Although the cause is not entirely understood, the P-T extinction almost turned Earth into a lifeless planet.

• Ordovician Period

Ordovician Period, in geologic time, the second period of the Paleozoic Era. It began 485.4 million years ago, following the Cambrian Period, and ended 443.8 million years ago, when the Silurian Period began. The **Ordovician** period started at a major extinction event called the Cambrian-Ordovician extinction events some time about 488.3 ± 1.7 Ma. During the Ordovician most of the world's landmasses came together to create the supercontinent of Gondwana, which included the continents of Africa, South America, Antarctica, and Australia. Gondwana drifted south throughout the period, finally settling on the South Pole. For the most part the Earth's climate was warm and wet, with sea levels rising as much as 600 meters above those of today. Ordovician rocks have the distinction of occurring at the highest elevation on Earth-the top of Mount Everest.

• Silurian Period

The Silurian is a major division of the geologic timescale that started about 443.7 ± 1.5 Ma. During the Silurian, Gondwana continued a slow southward drift to high southern latitudes. The climate was much warmer during this Period. This caused the glaciers to melt and the seas to rise. Cratons and continent fragments drifted together near the equator, starting the formation of a second supercontinent known as Euramerica. The vast ocean of Panthalassa covered most of the northern hemisphere. During the Silurian, continental elevations were generally much lower than in the present day, and global sea level was much higher.

• Devonian Period

The Devonian Period occurred from 416 million to 358 million years ago. It is often known as the “Age. of Fishes,” although significant events also happened in the evolution of plants, the first insects and other animals. During this period, the world’s land was collected into two supercontinents, Gondwana and Euramerica (or Laurussia). The period was a time of great tectonic activity, as Laurasia and Gondwanaland drew closer together. The continent Euramerica was created in the early Devonian by the collision of Laurentia and Baltica, which rotated into the natural dry zone along the Tropic of Capricorn. There is limited evidence of ice caps, and the climate is thought to have been warm and equitable. Near the end of the Devonian, a mass extinction event occurred. Glaciation and the lowering of the global sea level may have triggered this crisis, since the evidence suggests warm water marine species were most affected.

• Carboniferous Period

The Carboniferous extends from about 359.2 ± 2.5 Ma, to about 299.0 ± 0.8 Ma. In the United States, the Carboniferous is divided into two epochs. The Mississipian Epoch is the older one third and the Pennsylvanian Epoch is the more recent two-thirds. A global drop in sea level at the end of the Devonian reversed early in the Carboniferous; this created the widespread epicontinental seas and carbonate deposition of the Mississippian.

Table 1.4 : Geologic milestones in GTS

Years Ago	**Event** (Some Important Dates in the History of the Earth)
4,600,000,000	Origin of the Earth
3,900,000,000	Oldest Dated Crustal Rocks
3,800,000,000	Oldest Evidence for Life
2,000,000,000	First Oxygen Atmosphere/Ozone Layer Forms
900,000,000	Oldest Metazoan Fossils
510,000,000	Oldest Fossil Fish
458,000,000	First Land Plants
375,000,000	That important first step: Amphibians Evolve
245,000,000	Huge Mass Extinction at End of Permian Period / Close of the Paleozoic Era
200,000,000	First Mammals
160,000,000	First Birds
145,000,000	Atlantic Ocean first opens
130,000,000	Angiosperms (Flowering Plants) on the Scene
65,000,000	Adaptive Radiation of Mammals, Dinosaurs Go Extinct, Close of the Mesozoic Era/Beginning of the Cenozoic Era
3,400,000	New discoveries of Australopithecus afarensis (Lucy) fossils from Ethiopia
2,000,000	Pleistocene Ice Age begins
600,000	Age of Homo erectus fossils from Ethiopia
125,000	Oldest rocks in the Bahamas
100,000	Homo sapiens appears in the fossil record
15,000	Last ice sheet retreats from northern United States
7,000	Grahams Harbor, San Salvador, Bahamas floods due to rising sea level after ice sheets are reduced to modern day volume
506	Columbus lands in New World
?	You were born

Source: Ritger, S.D. and R.H. Cummins. 1991. Using student-created metapho

The large land masses of Euramerica and Gondwana continued to move toward one another and collide during this Period resulting into land uplifted into mountains. So the Carboniferous period was called a time of ‘active mountain-building’. Geologically, the Late Carboniferous collision of Laurasia into Gondwana produced the Appalachian Mountain belt of eastern North America and the Hercynian Mountains in the United Kingdom. A further collision of Siberia and eastern Europe created the Ural Mountains of Russia.

The Carboniferous Period is famous for its vast swamp forests. Vegetation included giant club mosses, tree ferns, great horsetails, and towering trees with strap-shaped leaves. Over millions of years, the organic deposits of this plant debris formed the world’s first extensive coal deposits.

- **Permian Period**

The Permian extends from about 299.0 ± 0.8 Ma to 251.0 ± 0.4 Ma. The Permian period ended in the largest mass extinction ever known in the Earth. By the early Permian, the two great continents of the Paleozoic, Gondwana and Laurussia had collided to form the supercontinent Pangaea. During the Permian, all the Earth’s major land masses except portions of East Asia were collected into a single supercontinent known as Pangaea. Two important groups of animals dominated the Permian landscape: Synapsids (reptiles) and Sauropsids (mammal-like reptiles). During the early Permian period, large portions of southern Pangea were covered by glaciers, but by the beginning of the Triassic period temperature was gradually increasing with the reappearance of vast rain forests at or near the equator. The Permian Period ended with the greatest mass extinction event in Earth’s history. In a blink of Geologic Time - in as little as 100,000 years - the majority of living species on the planet were wiped out of existence.

1.5.2.2 Mesozoic Era

The Mesozoic Era lasted almost 180 million years from approximately 250 to 65 million years ago. This era includes 3 well known periods called the Triassic, Jurassic, andCretaceous periods. During the Mesozoic, or “Middle Life” Era, life diversified rapidly and giant reptiles, dinosaurs and other monstrous animals wandered the Earth.

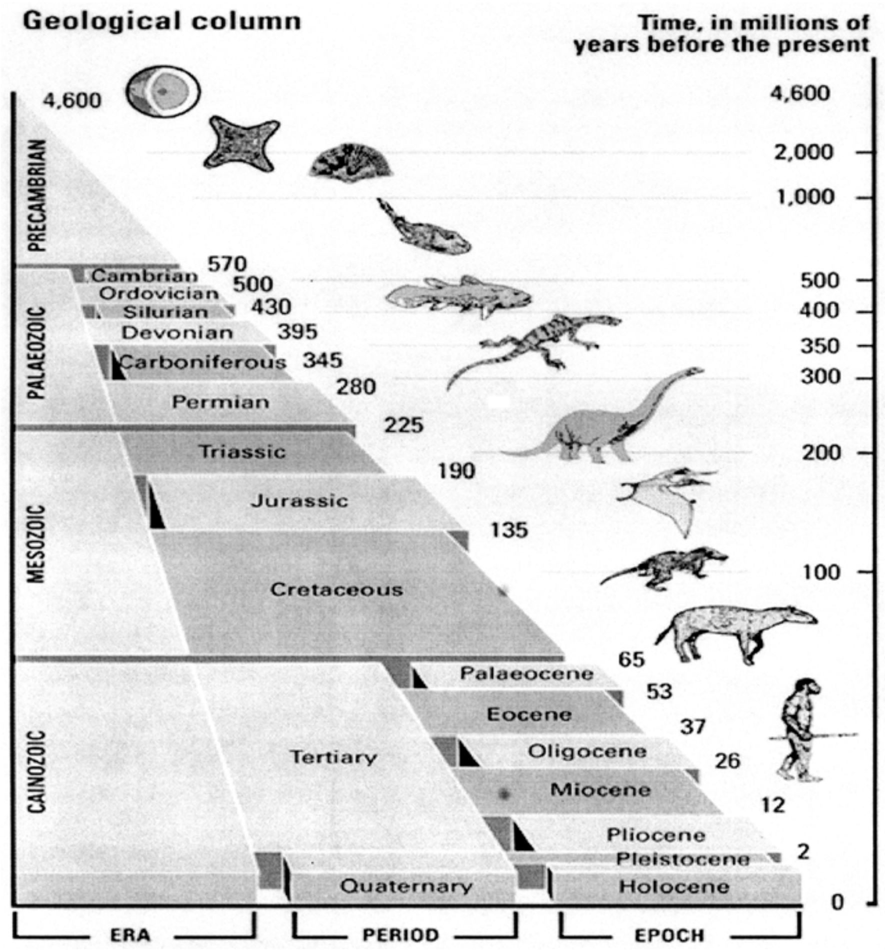


Fig 1.5: Major geological column in relation to appearance of animals

Source: geologyearthscience.com

• Triassic Period

The **Triassic** period extends from about 251 ± 0.4 to 199.6 ± 0.6 Ma. During this period, almost all the Earth's land mass was concentrated into a single supercontinent centered more or less on the equator, called Pangaea. Terrestrial climates were predominately warm and dry with very hot summers and cold winters resulting into highly seasonal monsoon climate prevailed nearer to the coastal regions. In the early Triassic, it appeared that the Therapsids or the genus, *Lystrosaurus* (one of the survived animals in the Permian Extinction) would dominate the new era. However, by the mid-Triassic, most of the Therapsids had become extinct and the more reptilian Archosaurs were clearly dominant. During the late Triassic Period, the relative importance of land animals grew. Reptiles increased in diversity and number, and the first dinosaurs appeared.

- **Jurassic Period**

The Jurassic period extends from about 199.6 ± 0.6 Ma to 145.4 ± 4.0 Ma. The Jurassic was a time of significant global change in continental configurations, oceanographic patterns, and biological systems. During the Jurassic Period, the supercontinent Pangaea split apart. The northern half, known as Laurentia/Lauresia, was splitting into North America and Eurasia. The Gulf of Mexico opened in the new rift between North America and what is now Mexico's Yucatan Peninsula. The southern half, Gondwana, was drifting into an eastern portion forming into present day Antarctica, Madagascar, India and Australia, and a western portion forming into present day Africa and South America. Climates were warm, with no evidence of glaciations.

Reptiles were the dominant animal life forms during the Jurassic Period. Some of the largest animals ever to live were dinosaurs of the Jurassic Period. Sauropods, the "lizard hipped" dinosaurs (Herbivorous) were common followed by Carnosaurus means "meat-eating dinosaur' .The earliest known bird, *Archaeopteryx,* took to the skies in the late Jurassic, most likely evolved from an early coelurosaurian dinosaur. Early mammals also were present, though they were still fairly insignificant.

- **Cretaceous Period**

The Cretaceous period extends from about 145.5 ± 4.0 Ma to about 65.5 ± 0.3 Ma. During the Cretaceous Pangaea completed its breakup into present day continents, although their positions were substantially different at the time. However, by the end of this period, Laurasia had separated into North America and Eurasia and Gondwana had separated into South America, Africa, Antarctica, and Africa. Madagascar and the Indian subcontinent were still connected and would separate after the Cretaceous period.

The Cretaceous period marks the end ofthe age of Dinosaurs with what is known as the Great Extinction. However, this period gives us some of the most beloved dinosaurs of modem days, like the Triceratops and, of course, the Tyrannosaurusrex, king of the dinosaurs. Flowering plants (angiosperms) began to appear for the first time. This in turn contributed to an increase In insect populations.

The extinction occurred at the end of the Cretaceous Period, about 65.5 million years ago. The end-Cretaceous extinction is best known of the "Big Five" because it was the end of all dinosaurs except birds (the *non-avian dinosaurs).* It also created opportunities for mammals. The real cause of extinction is not identified yet. However, there is evidence of plant decay which would have contributed to the extinction, as all dinosaurs, whether directly or indirectly, depended on plant life. This could have been caused by large asteroid collisions or volcanic eruptions or both.

1.5.2.3 Cenozoic Era

The Cenozoic Era is the most recent of the three major Eras. The Cenozoic spans only about 65 million years, from the end of the Cretaceous Period to the present. The Cenozoic is sometimes called the Age of Mammals, because the largest land animals have been mammals during that time. The Cenozoic era is divided into three periods, and seven systems:

Table 1.4 : Divisions of Cenozoic Era

Paleogene (65-23 Ma)	
1. Paleocene	(65.5 Ma - 55.8 Ma)
2. Eocene	(55.8 Ma - 33.9 Ma)
3. Oligocene	(33.9 Ma - 23.03 Ma)
Neogene (23-2.5 Ma)	
2. Miocene	(23.03 Ma - 5.33 Ma)
3. Pliocene	(5.332 Ma - 2.588 Ma)
Quaternary (2.5 Ma-present)	
4. Pleistocene	(2.588 Ma - 12,000 years)
5. Holocene	(12,000 years - present

- **Paleogene period**

The **Paleogene** period is a unit of geologic time that began 65.5 ± 0.3 and ended 23.03 ± 0.05 Ma. This period consists of the Paleocene, Eocene, and Oligocene Epochs.

i) Paleocene Epoch

The Paleocene Epoch lasted from 65.5 ± 0.3 Ma to 55.8 ± 0.2 Ma. This Epoch opens and closes with major events in Earth's history. The Paleocene epoch immediately followed the mass extinction event at the end of the Cretaceous, known as the K-T boundary (Cretaceous - Tertiary), which marks the demise of the dinosaurs including about 80% of animals.

During this epoch, North America, Greenland, and Europe were joined together in a supercontinent called Laurasia in the Northern Hemisphere. North America was connected to Asia by a land bridge and beginning to break away from Greenland. In the Southern Hemisphere, Gondwana, another supercontinent that had previously begun breaking apart, continued to do so through this epoch intoSouth America, Africa, India, Australia, and Antarctica. Africa was heading north towards Europe, slowly closing the Tethys Ocean, and India began its migration to Asia that would lead to a tectonic collision and the formation of the Himalayas.

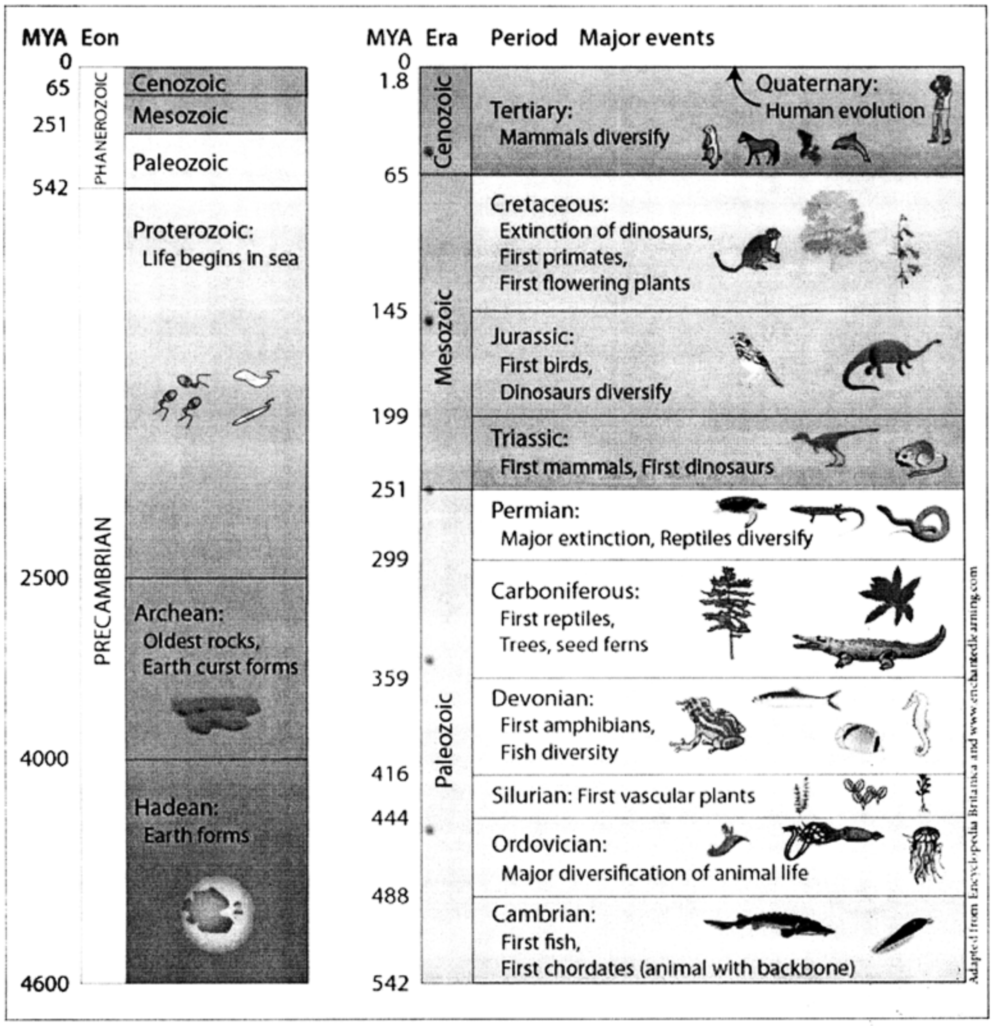
Climate during this epoch was cooler and dryer than the previous period. However, it rapidly warmed up. The end of the Paleocene (55.5/54.8 Ma) was marked by a sudden global change known as ‘the Paleocene-Eocene Thermal Maximum’, which upset oceanic and atmospheric circulation and led to the extinction of numerous deep-sea benthic foraminifera and on land, a major turnover in mammals.

The Paleocene is usually broken into early, middle, and late sub-epochs which correspond to the following faunal stages, from youngest to oldest:

ii) Eocene Epoch

The Eocene epoch commenced 10 million years after the extinction of the dinosaurs, 65 million years ago, and continued for another 22 million years, up to 34 million years ago. During the Eocene (55.8 ± 0.2 - 33.9 ± 0.1 Ma), the continents continued to drift toward their present positions. By the beginning of the Eocene, Gondwana had almost split apart, but Australia, Antarctica and South America remained joined. The northern supercontinent of Laurasia began to break up, as Europe, Greenland and North America drifted apart. The Rocky Mountains in western North America were formed during this time as well. In Europe, the Tethys Sea finally vanished, while the uplift of the Alps isolated its final remnant, the Mediterranean. India continued its journey away from Africa and began its collision with Asia, folding the Himalayas into existence.

Marking the start of the Eocene, the planet heated up in one of the most rapid (in geologic terms) and extreme global warming events recorded in geologic history, called the Paleocene-Eocene Thermal Maximum. This was an episode of rapid and intense warming (up to 7°C at high latitudes) that lasted less than 100,000 years. At the beginning of the Eocene, the high temperature and warm moist environment created luxurious growth of forests spreading throughout the earth from pole to pole. This epoch was a great time for the evolution of mammals. Rhinoceroses, three-toed horses, and early relatives of pigs, camels, and hippopotamuses first appear.



Source : earthwww.com.

Fig 1.6 Major Biological milestones in GTS

iii) Oligocene Epoch

It extends from about 34 million to 23 million years before the present. During the Oligocene, the continents continued to drift toward their present positions. Antarctica continued to become more isolated, and finally developed a permanent ice cap. Mountain building in western North America continued. Alps started to rise in Europe as the African plate continued to push north into the Eurasian plate. Angiosperms (flowering plants) continued their expansion throughout the world; tropical and sub- tropical forests were replaced by temperate deciduous woodlands. Major changes during the Oligocene included a. There were two major trends in mammalian evolution during the Oligocene epoch. First the global expansion of grasslands and a regression of tropical broad leaf forests to the equatorial belt resulting into *opening of a new ecological* niche for grazing mammals. Consequently, on land, mammals such as horses, deer, camel, elephants began to dominate, except in Australia .. This period also marked the start of a generalized cooling, with glaciers forming in Antarctica for the first time during the Cenozoic. The cooling trend was also responsible for the reduced diversity in marine plankton, the foundation of the food chain. Gradual cooling formed ice sheets in the higher latitudes. The increase in ice sheets led to a fall in sea level.

• Neogene Period

The Neogene Period encompasses the interval between 23 million and 2.6 million years ago and includes the Miocene (23 million to 5.3 million years ago) and the Pliocene (5.3 million to 2.6 million years ago) epochs. The Neogene covers about 20 million years. During this period, mammals and birds continued to evolve into roughly modern forms, while other groups of life remained relatively unchanged. Early hominids, the ancestors of humans, appeared in Africa.

i) Pliocene Epoch

The Pliocene extends from 5.332 million to 2.588 million years before present. Moving continents during the Pliocene Epoch made a lot of mountain ranges. Himalayas in Asia, Rocky and Appalachian Mountains in North America and the Alps in Europe were formed during the Pliocene. During this Epoch, North America and South America were joined together for the first time at the Isthmus of Panama. During the Pliocene epoch, the earth continued its cooling trend from previous epochs, still, average global temperatures were 2-3 QC higher than today. In North America, rhinoceroses became extinct. Camels, some of large size, were abundant and diverse, as were horses. The first recognizable *hominins,* the australopithecines, appeared in the Pliocene. However, near the end of the Pliocene, about 2.58 Ma, the current ice age began.

ii) Miocene Epoch

The Miocene extends from about 23.03 to 5.332 Ma. By the Miocene Epoch, North America and Europe were basically in the position they are today. Africa had moved north to collide with Europeand form the Alps mountain range. Similarly, to the east, India collided with Asia and created the Himalayan Mountains. Two major ecosystems first appeared during the Miocene: kelp forests (shallow underwater ecosystems with algae communities) and grasslands. In Eurasia and North America, the spread of grasslands forced an evolutionary change in herbivorous mammals. Mammal diversity reached its peak during the Miocene. The earth went from the Oligocene through the Miocene and into the Pliocene, with the climate slowly cooling towards a series of ice ages.

• Quaternary Period

The quaternary period began 2.6 million years ago and extends into the present. The Quaternary Period is divided into two epochs: the Pleistocene (2.588 million years ago to 11.7 thousand years ago) and the Holocene (11.7 thousand years ago to today). The Quaternary period saw a large number of climatic oscillations on a scale that was probably greater than at any other time in the last 60 My. Glaciers advance from the Poles and then retreat, carving and molding the land with each pulse. Sea levels falland rise with each period of freezing and thawing.

i) Pleistocene Epoch

The Pleistocene, the first epoch of the Quaternary Period, is the geological epoch which lasted from about 2,588,000 to 11,700 years ago, spanning the world’s recent period of repeated glaciations. It is characterized by lower sea levels than the present epoch and colder temperatures. The end of the Pleistocene corresponds with the end of the last glacial period. During much of the Pleistocene, Europe, North America, and Siberia were covered by extensive ice sheets and glaciers. The Pleistocene was an important time because it was when the human genus first evolved. Many of the animals common today were also common in the Pleistocene. Deer, big cats, apes, elephants, and bears could all be found in a Pleistocene landscape. Europe and Asia had significant populations of African fauna.

ii) Holocene Epoch

The Holocene Epoch began 12,000 to 1 1,500 years ago at the close of the Paleol ithic Ice Age and continues through today. Ice melt caused world sea levels to rise about 35 meters in the early part of the Holocene. Even though the human species was well developed before this epoch, it is still often called the "Age of Man" because of the huge impact humans have had on Earth during this time. The beginning of the Holocene Epoch is marked by the end of the Paleolithic Ice Age, when the Earth started to warm again and glaciers melted into the oceans. Animal and plant life have not evolved much during the relatively short Holocene, but there have been major shifts in the distributions of plants and animals.

1.6 Significance Of GTS

The geological time scale (GTS) is a system of chronological dating that relates geological strata with time. Geological strata are referred to the sequence of soil or sediments or rocks which is relative to the space where the fossils of the dead organisms are found. It describes some significant events like:

i) The geological time scale provides information about the list of rock layers by age.

ii) Stratigraphical age of the rock layers can be determined simply by relative dating methods.

iii) GTS gives an idea and evidence of evolution both biological and geological

iv) STS articulates information about type of plants and also focuses when plants first appeared.

v) The GTS is a system of chronological dating that relates with time. Geological strata are referred to the sequence of soil or sediments relative to the space where the fossils of the dead organisms are found.

GLOSSARY

1. **Absolute age:** The age of an object as established by some precise dating method, such as radiometric dating
2. **Absolute dating:** A means of estimating the age of rocks with some degree of accuracy using measurements of radioactive isotopes.
3. **14C method:** A method for determining the age in years of organic matter by calculating the amount of radioactive carbon still remaining, as compared to the stable isotope, 12e.
4. **Cenozoic:** The third and current (most recent) geologic era of the Phanerozoic Eon, this began 65.5 million years ago.
5. **Daughter element:** The element or isotope which is produced by radioactive decay.
6. **Eon:** The largest division of geologic time in the geological timescale, embracing several Eras (for example, the Phanerozoic, 540 m.y. ago to present);
7. **Epoch:** A division of the geologic time shorter than a period.
8. **Era:** A division of the geologic time shorter than an eon, and measuring major stages in the evolution of life - e.g. Paleozoic, Mesozoic, Cenozoic.
9. **Fossil:** Petrified remains of the plants and animals. A fossil may be a bone, shell, leaf impression, footprint, insect in amber, etc.
10. **Hadean:** The oldest eon in the history of the Earth, extending from the origin of the Earth about 4.5 billion years ago to around 3.8 billion years ago.
11. **Half-life:** The amount of time it takes for half the atoms of a radioactive isotope to decay.
12. **Holocene epoch:** The most recent geologic epoch of the Quaternary Period extending from the end of the Pleistocene (I 1,000 years ago) to the present.
13. **Geological time scale:** A system of chronologic measurement relating stratigraphy to time that is used by geologists, paleontologists and other earth scientists to describe the timing of events that have occurred during the history of the Earth.
14. **Isotope:** Atoms of a given element that have the same atomic mass. Most elements have more than one isotope. Most radioactive elements used for dating have one radioactive isotope and at least one stable isotope.
15. **Mesozoic:** The second era of the Phanerozoic eon, lasting from 251 to 65.5 million ago, and characterised by the dominance of reptiles both on land and seas.

16. **Paleozoic:** The earliestera of the Phanerozoic eon, but also the longest, lasting from 542 to 251 million years ago.
17. **Phanerozoic:** The most recent of the four eons of geologic time. Characterized by complex multicellular life.
18. **Proterozoic:** The name means the era of "first (animal) life". This was the third eon in Earth history, during which eukaryote life and an oxygen atmosphere appeared.
19. **Radioactivity:** The spontaneous decay of the nucleus of an element resulting into the change in the number of protons in the nucleus and therefore creates an atom of a new element.
20. **Stratigraphy:** The succession and age relation of layered rocks.

1.7 Summary

This unit allows the learners to know about the earth's tectonic evolution and the different eras through which evolution has taken place.

1.8 Questions

A. Short Type (within 200 words)

1. Define Geologic Time Scale.
2. What is isotope?
3. Order the units of time from greatest to least.
4. When was the first great explosion of life recorded in the fossil record?
5. Explain the differences between relative and absolute dating.
6. What are the four eras of the earth? Mention with age.
7. What is period in geologic time scale?
8. Describe the major geological events under carboniferous period.
9. Can scientists use the same principles they use to study Earth's history.
10. What are the different eras of geologic time?
11. What is Holocene epoch?
12. Describe major tectonic events under Permian period.
13. How does an eon differ from an era?
14. Explain major geological events of Jurassic Period.

15. What is halflife of isotope?
16. Describe how the time scale was created.
17. Explain the relationships among eons, eras, epochs, and periods of the geologic time scale.
18. What is 14C method of dating?
19. Explain different periods of Cenozoic era?
20. Explain different periods of Mesozoic era?
21. What is P-T extinction?
22. Explain the characteristics of Eocene Epoch.

B. Long Type (within 600 words)

23. Describe in brief the tectonic and structural evolution of Paleozoic Era.
24. Describe in brief the tectonic and biological evolution of Mesozoic Era.
25. Describe in brief the biological and structural evolution of Cenozoic Era.
26. How did scientists account for fossils and other geological evidence as they developed the geologic time scale?
27. Explain characteristics of different eons under Precambrian supereon.
28. Describe in brief the tectonic and biological evolution of different epoch under Paleogene Period.

Unit 2 ❑ Earth's Interior With Special Reference To Seismology

Structure

2.2 Objectives

- To learn about the Earthi interior
- To know about the theories of Isostasy

2.1 Earthquake And Seismology

2.1.1 Introduction

There are certain sudden movements on the earth's crust which abruptly change its features and the chief among them is the earthquake. An earthquake is an oscillation or vibration of the surface of the earth caused by a sudden disturbance of the equilibrium of the rocks at or beneath the earth's crust. In other words, an earthquake the result of a sudden release of stored energy in the earth's crust that creates 1 seismic waves or shocks. There may be foreshocks and aftershocks. which are the energy released before and after the main quake. The place of origin of the earthquake below the ground is called the *focus* or *hypocenter.* The point on the surface which is vertically above the focus is the *epicenter.* Earthquake waves first come to that point, and therefore, shocking effects are maximum on that point or areas.

Seismology is the study of earthquakes and seismic waves that move through and around the earth. Or, in other words, Seismology may be called as scientific discipline that is concerned with the study of earthquakes and of the propagation of seismic waves within the Earth. In the late 19th and early 20th centuries national and regional scientific societies devoted to the advancement of seismology were created in Japan, Europe, and North America. The International Association of Seismology (IAS) was first organized in 1901, but was dissolved after World War I. Seismology was one of the original six Sections of the International Union of Geodesy and Geophysics (IUGG) when it was created again after the World War I in 1919.

2.1.2 Seismic Wave

When the earthquake occurs, the vibration called seismic waves spread out in all directions from the focus. Three main types of waves are propagated during earthquakes.

These are as follows :

- **Primary Wave :** These are called longitudinal or compressional or simply *'P'* waves. P wave makes the particles vibrate in the direction of their movements. The average speed is within 5 to 14 km/sec. P waves travel with the fastest speed through the interior layers & arrive first at the surface.
- **Secondary Wave :** These are called transverse or shear waves, or simply'S' waves. Their rate of movement is less than that of the longitudinal waves. The average speed is within 5 to 8 km/sec. They are unable to pass through liquid layers in the interior. The vibration caused by S waves is at right angles to the direction of their movements.

- **Surface Wave :** Surface Waves are those waves which travel over the surface of the earth. They are the long waves and their speed is the lowest among three. But they are the most terrible and are responsible for most of the destruction associated with an earthquake. Surface waves are of two types:

  (1) the Rayleigh wave or L wave: an elliptical motion decreasing with depth (similar to ocean waves).

  (2) the Love wave: a lateral motion (sideways shaking).

Why can't S-waves travel through liquids?

S-waves are shear waves, which move particles perpendicular to their direction of propagation. They can propagate through solid rocks because these rocks have enough shear strength. The shear strength is one of the forces that hold the rock together, preventing it from falling into pieces. Liquid materials lack this type of shear strength because atomic attractions are low compare to solids which means rigidity is low. S-waves need a medium that is rigid enough for them to propagate. This is why S-waves cannot propagate through liquids.

a) L-waves : They travel near the earth's surface and within a depth of 30-32 kilometers from the surface. These are also called Rayleigh waves named for John William Strutt, Lord Rayleigh, who mathematically predicted the existence of this kind of wave in 1885. A Rayleigh wave rolls along the ground just like a wave rolls across a lake or an ocean. Because it rolls, it moves the ground up and down and side-to-side in the same direction that the wave is moving. They generally move at a slower rate than Love waves.

b) Love waves : Love waves make the ground vibrate at right angles to the direction of Waves, named after A.E.H. Love, a British mathematician who worked out the mathematical model for this kind of wave in 1911.They are a variety of S-waves where the particles of an elastic medium vibrate transversely to the direction of wave propagation, with no vertical components. They Involve shear motion in a horizontal plane. However, Love waves are most destructive kind of seismic wave.

Table 2.1 Difference between S Waves and P Waves.

P waves	S waves
1. First wave to hit seismographs, i.e., P-waves travel at the greatest speed.	1. Second waves to hit seismographs, i.e, S-waves travel following the P waves.
2. They are compression waves	2. They are shear waves
3. Can move through solids and liquids	3. Can only move through solids.
4. Shake the medium in the direction in which they are propagating	4. Shake the medium in the direction perpendicular to which they are moving
5. The P waves from an earthquake arrive first. but because of their small amplitudes don't do as much damage as the S waves and surface waves which follow.	5. S waves travel typically 60% of the speed of P waves. They are typically more damaging than the P waves because they are several times higher in amplitude.

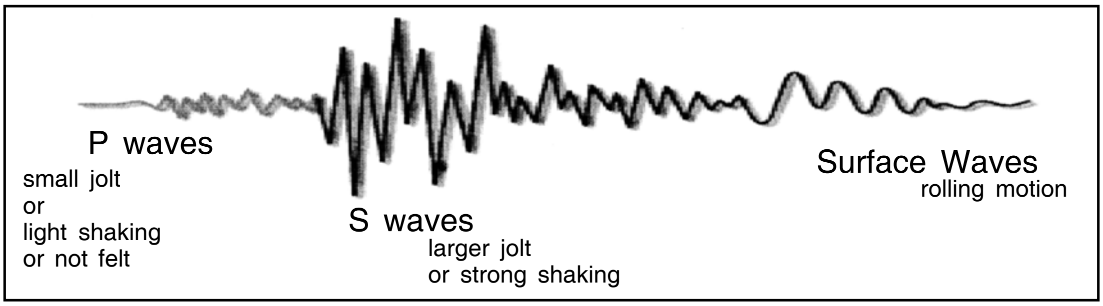


Fig. 2.1 : Propagation of P, S and Surface Wave

2.1.3 Causes Of Earthquake

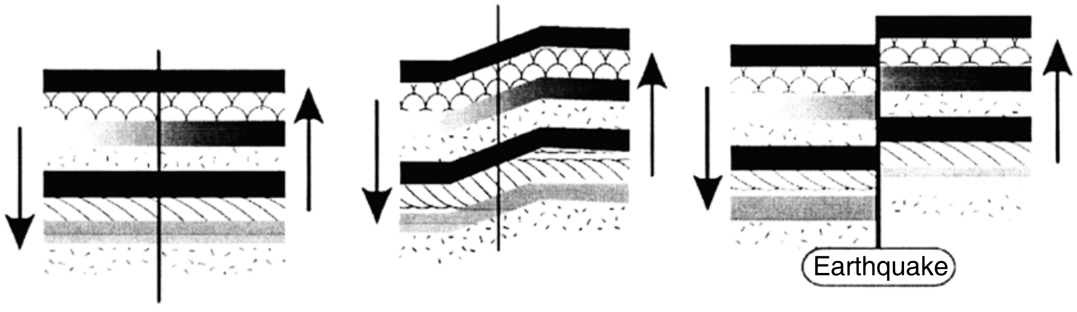
Earthquakes are a result of many factors. These are as follows:

1. Elastic Rebound Theory

Geologist Henry Fielding Reid introduced first (1906) the concept of 'Elastic Rebound' mechanism for the occurrence of earthquakes. According to him earthquake should have involved an "elastic rebound" or previously stored elastic stress. This may be explained by the following example. If a stretched rubber band is broken or cut elastic energy stored in the rubber band during the stretching will suddenly be released. Similarly. the crust of the earth can gradually store elastic stress that is released suddenly during an earthquake.

So, the **elastic rebound theory** is an explanation for how energy is spread during earthquakes. As rocks on opposite sides or a fault are subjected to force and shin, they accumulate energy and slowly deform until their internal strength is exceeded. /\t that time, a sudden movement occurs along the fault, releasing the accumulated energy. and the rocks snap back to their original undeformed shape. If the stress is large enough, rocks undergo deformation, i.e. a change of shape and/or volume. The amount of deformation experienced by a rock is called strain. The behavior of a rock in response to stress can be elastic, brittle or ductile. A rock behaves in an elastic manner when it recovers its original shape after the stress is removed. When the stress exceeds a value called the rock strength, the rock experiences a permanent deformation. Fault or fold is the good example in this regard. Deformation with breaking of rock (i.e. fault), or without breaking (i.e. fold) may gradually occur in the earth crust because of the temperature/pressure changes.

As a result, most of the earthquakes are produced by the brittle deformation of rocks. They are confined to the cold rigid lithosphere, mostly the crust, where rocks behave in a brittle manner. Rocks of the asthenosphere under conditions of high temperature and high pressure display a ductile behavior.



Rocks on each side of the fault are forced to move, but rocks at the fault are "locked" together.

Because rocks are locked together, they bend. storing energy like a coiled spring.

Rocks suddenly "let go". springing back, causing an earthquake.

Fig 2.2 : Elastic Rebound Theory

2.1.4 Earthquake Shadow Zone

Seismic waves recorded at increasing distances from an earthquake indicate that seismic velocities gradually increase with depth in the mantle. However, at arc distances of between about 105° and 140° no P waves are recorded. Furthermore, no S waves are recorded beyond about 105° and 140° no P waves are recorded. Furthermore, no S waves are record beyond about 105°. This is called Shadow zone. The shadow zone results from S waves being stopped entirely by the liquid core and P waves being bent (refracted) by the liquid core. Or in other sense, from the lack of S waves and a great slowing of the P wave velocity (by about 40%) it was deduced that the outer core is made of liquid.

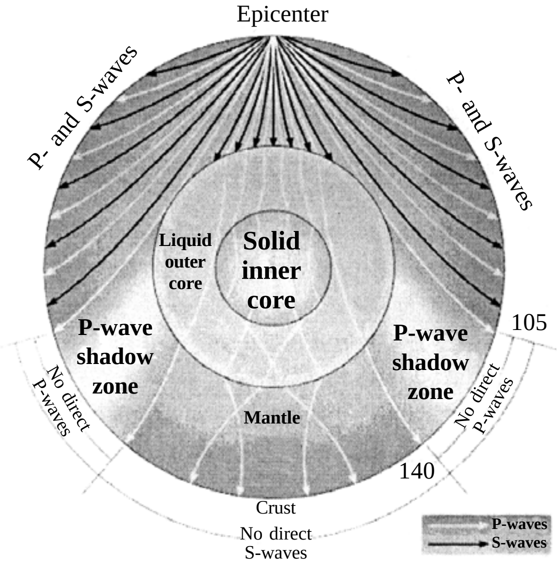


Fig 2.3 : Path of Earthquake waves

2.2 Earth's Interior Study With Reference To Seismology

Our knowledge of the interior structure ofthe earth is certainly based upon some indirect evidences, as it is not possible for man to study the interior of the earth directly. The maximum depth of mines where man have gone for direct observation is petroleum digging of no more than 12 km .This depth is obviously negligible in comparison to the radius of the earth (6371 Km). So, man has to depend upon some indirect evidences like study of the earthquake waves, study of the ancient rocks etc for detailing of the interior information of the earth.

2.2.2 Layers Of The Earth

The shape of the earth is like a sphere. It has three different layers or zones - crust, mantle and core. The outer layer of the earth is the *crust* or the lithosphere which is hard and composed of rocks and minerals. The innermost part is known as the core, composed of heavy metals and in-between there is a transitional layer known as mantle. Before going to discuss in details of different layers, we may introduce the concept of seismic discontinuity, properties of these actually mark the layers of interior.

2.2.3 Seismic Discontinuities

When seismic waves pass between geologic layers with contrasting seismic velocities, reflections, refraction (bending), and the production of new wave phases often result. This type of sudden jumps in seismic velocities across a boundary is known as seismic discontinuities. Different well known discontinuities are listed below: When an earthquake occurs the seismic waves (P and S-waves) spread out in all directions through the Earth’s interior. ... Sudden jumps in seismic velocities accross a boundary are known as seismic discontinuities.

a) **Conrad Discontinuity :** The transition zone between the upper and lower part of the lithosphere, is called as Conrad discontinuity. The name comes from the Austrian geophysicist Vector Conrad (1876 - 19(2). According to geologists the upper crust in the continental region consists of felsic rock such as granite and the lower one consists of more magnesium rich malic rocks such as basalt. So, Conrad discontinuity should correspond to a sharply defined contact between the chemically distinct layers of SIAL and SIMA. In passing through the Conrad discontinuity the velocity of longitudinal seismic waves increases abruptly from approximately 6 to 6.5km/sec.

b) **Mohorovicic Seismic Discontinuity :** This seismic discontinuity is now known as the Moho. It is the boundary between the crust and the mantle. The name came after the Croatian seismologist Andrija Mohorovicic’ (1857-1936) who discovered it. The depth to the Moho beneath the continents averages around 35 km but ranges from around 20 km to 70 km. The Moho beneath the oceans is usually about 7 km below the seafloor.

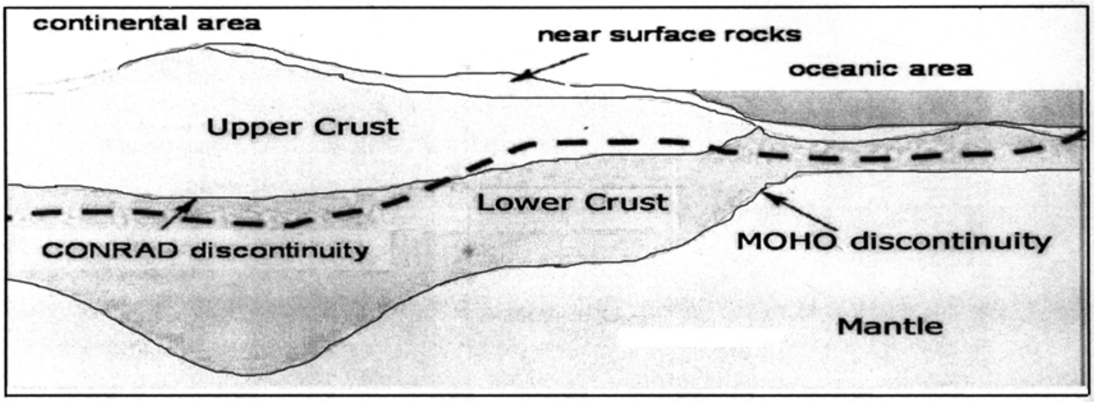


Fig 2.4 : Mohorovicic discontinuity

c) **Gutenberg Seismic Discontinuity/Core-Mantle Boundary :** Geophysicists Beno Gutenberg (1889-1960) established an accurate boundary line — or discontinuity — that separates and divides the lower mantle from the outer core. According to him this discontinuity occurs at a depth of about 2,900 km below the surface. At that depth there is an abrupt change in the seismic waves that travel through Earth. In addition, at this depth, P waves decrease in velocity while S waves disappear completely. This distinct change marks the boundary between two sections of Earth's interior, known as the lower mantle (which is considered solid) and the underlying outer core (believed to be molten). Shear waves could not penetrate this molten layer and P waves would be severely slowed and refracted (bent).

d) **Repetti discontinuity :** The discontinuity between the upper mantle and the lower mantle is known as Repetti Discontinuity. The portion of the mantle which is just below the lithosphere and asthenosphere. but above the core is called as Mesosphere. This discontinuity is locate at effrt a depth of 700 km with a density 4.3 gm/cc. Here a dense olivine layer begins to transform into 'spinels' giving rise to geological faults.

e) **Lehman Seismic Discontinuity/Inner Core-Outer Core Boundary :** The discontinuity between the upper core and the lower core is called as Lehmann Discontinuity, named after Danish seismologist Inge Lehmann (1888 -1993). Sudden increase in P-wave velocities at a depth of 5150 km is observed because of changing state of a molten outer core to a sol id inner core.

Lehmann Discontinuity

In between Lighter Outer Crust and Denser Inner Crust there lies an area called as Lehmann Discontinuity. It is formed due to sudden change in the density between the two layers. The Danish seismologist Inge Lehmann (1888 199.1) deduced this **discontinuity** in 1936 marked by an abrupt increase of P-wave and S-wave velocities at the depth of 220J:30 krn., It appears beneath cant incnts, but not usually beneath oceans. Here, the p, and S-Wave velocities have an abrupt **increase** by 3-4%.

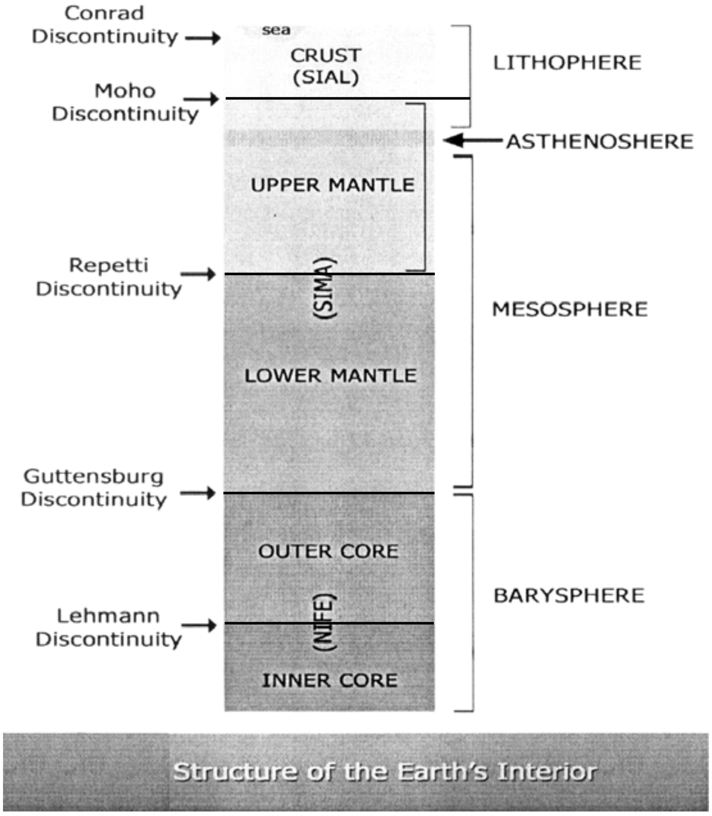


Fig 2.5 Location of discontinuity

2.2.4 The Crust

This is the upper most and thinnest layer of the earth. It forms the continents and the ocean beds and its thickness varies from 16 to 40 km. In the continental areas its thickness varies from 30 to 50 km and in the oceanic areas between 10 to 12 km.

It constitutes less than I percent of earth’s volume and 0.4 percent of its mass. Average density of crust is only 2.85 i.e. 2.85 times heavier than water.

- Conrad Discontinuity: Transition zone between SIAL and SIMA.
- Mohorovicic Discontinuity: Transition zone between the Crust and Mantle.
- Repiti Discontinuity: Transition zone between Outer mantle and Inner mantle.
- Gutenberg Discontinuity: Transition zone between Mantle and Core.
- Lehman Discontinuity: Transition zone between Outer core and Inner core.

Crust is composed of various kinds of rocks and minerals. In its upper most part we find sedimentary layer, though it is not continuous over entire surface of the earth. In the continental areas there is a layer of granitic masses just below the sedimentary cover while in the oceanic areas there is hardly sedimentary rock and mostly composed of basaltic masses.

Crust is subdivided into two sub-layers. The upper layer is known as *Sial* and composed of mostly lighter rocks. It contains silica (Si) and aluminum (AI), that’s why it is known as *Sial.* The lower layer is generally heavier and composed of rocks with Silica (Si) and Magnesium (Ma) and known as *Sima.* Generally speaking, the continents are made up of *Sial* and oceans are made up of *Sima. Sial* and *Sima* is divided by a discontinuity known as *Conrad discontinuity.*

The temperature of the crust increases with depth. reaching values typically in the range from about 500°C to 1.000°C at the boundary with the underlying mantle.

The crust and tectonic plates are not the same. Plates are thicker than the crust and consist of the crust plus the shallow mantle just beneath it.

2.2.5 The Mantle

The intermediate layer between the Crust and the Core is the Mantle. It occupies 83 percent of earth’s volume and 69 percent of its mass. It is separated from crust by the *Mohorovic discontinuity* or *Moho,* according to the name of the scientist *A Mohorovic.* The mantle extends from Moho to 2900 km. It is a solid layer and is sub-divided into three layers - an upper mantle from Moho to 370 km, an intermediate mantle from 370 to 720 km and a lower mantle from 720 km to 2900 km.

The mantle is composed of dense and rigid rocks which has predominance of minerals of magnesium and iron content. The upper part of mantle (70-700 km) is known as *Asthenosphere* which is characterized by plastic flow and is the source region of most of the earth internal energy. Here convectional current is the dominant mode of heat transfer which causes the plate movement. The density varies from 3 to 3.5 in the upper mantle to about 4.5 to 5.5 in the lower mantle. The temperature increases with depth from 870 deg to 2200 deg C.

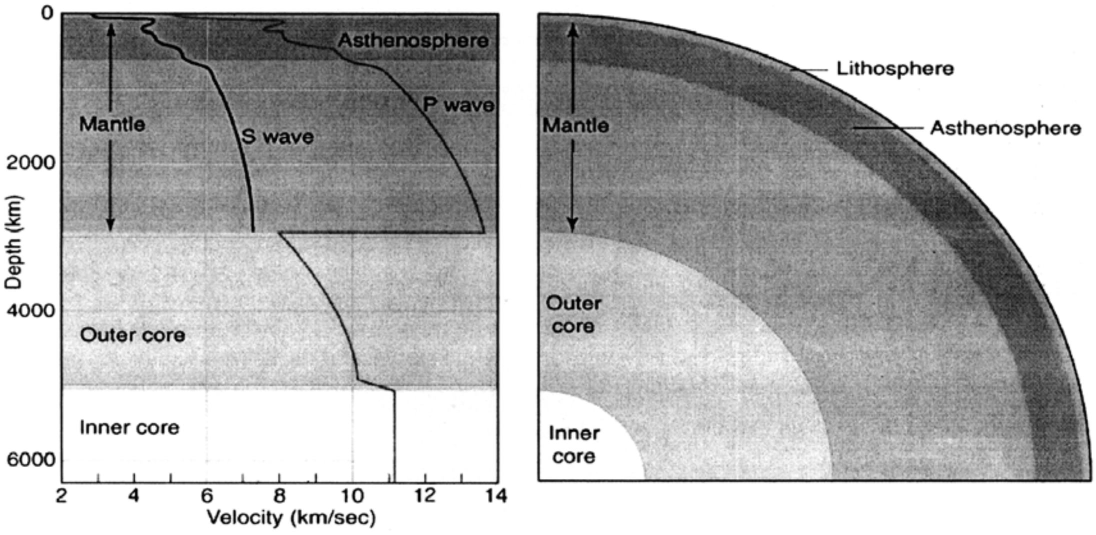


Fig 2.6 : Velocity of P & S waves

2.2.6 The Core

The inner most layer i.e. the core occupies 17 percent of earth's volume and 34 percent of its mass. The core-mantle boundary is defined by *Weichart-Gutenberg* discontinuity at 2900 km.The outer core extends from 2900 to 5144 km and inner core from 5144 to 6371 km i.e. centre of the earth.

The outer core is considered to be a state of homogeneous liquid which is composed of mostly nickel and chromium while inner core is solid and is believed to contain metallic nickel and iron and therefore it is known as *nife* (ni + fe). So the density increases from 5.1 in the core-mantle boundary to about 13.1 in the centre of the earth. The temperature also gradually increases. The temperature of the outer core ranges from 4400 QC in the outer regions to 6100 QC near the inner core.

Table 2.3 : Comparative study among different layers

	Thickness (km)	Density (g/cm^3)		Types of rock found
		Top	Bottom	
	30	2.2		Silicic rocks
			2.9	Andesite, basalt at base
Upper mantle	720	3.4		Peridotite, eclogite, olivine, spinel, garnet, pyroxene
			4.4	Perovskite, oxides
Lower mantle	2,171	4.4		Magnesium and silicon oxides
			5.6	
Outer core	2,259	9.9		Iron + oxygen, sulfur, nickel alloy
			12.2	
inner core	1,221	12.8		Iron + oxygen sulfur, nickel alloy
			13.1	
Total thickness	6,404			

Source: Anderson, Don L. (1989) : Theory of the Earth, Boston, Blackwell Publications.

Low velocity zone

A zone within the asthenosphere in the upper mantle that is defined on seismic criteria. It varies in depth between 50 and 250 km and represents part of the mantle that may be about 5% liquid. It transmits S-waves but both S- and P-wave velocities are reduced.

2.3 Isostasy : Models of Airy and Pratt

Isostasy is a fundamental concept in the geology where the lighter crust is floating on the denser underlying mantle. The term 'lisostasy' is derived from Greek words 'iso' and 'stasis' meaning "equal standing". However, the term 'isostasy' was first coined in geology in 1899 by the American geologist Clarence Dutton. According to him, the concept of isostasy tries to explain how different topographic heights can exists on the Earth's surface and why. Isostasy occurs when the buoyancy force pushing the lithosphere up equals the gravitational force pulling it down. So, geologists think that the Earth's lithosphere floats on a plastic like upper part of the mantle, the asthenosphere. The effects of isostasy were first noticed near large mountain ranges. This principle can also be described as isostatic equilibrium. Isostatic equilibrium is an ideal state where the crust and mantle would settle into in absence of disturbing forces. However, in reality the waxing and waning of ice sheets; erosion, sedimentation, and extrusive volcanism are examples of processes that disturb this Isostatic equilibrium. In the case of Earth movement, Isostatic equilibrium is associated with the balancing of forces due to different weights of landmasses in relatively close proximity. As for example, if a mountain range is rising and the sea bed is falling then it may be balanced as the weight of material removed by erosion from the mountain is deposited onto the seabed. Isostatic observations are important tools to study the Earth's geology, composition, structure and dynamics.

2.3.1 Concept Of Isostasy

The idea of isostasy was first put forwarded by Leonardo Da Yinci in fifteenth century, wherein he had explained the balancing condition between the rises of mountain with the removal of materials. The development of isostasy further grew in eighteenth century, when the French scientist, Pierre Bouguer, who had attempted to determine the Earth's mean density by measuring the deflection of the plumb-line (vertical direction) by the mass of a nearby mountain. In 1735 Pierre Bouguer during his expedition of the Andes, noticed that towering volcanic peak of Chimborazo was not attracting the plumb line as it should have done. He thus explained the reason, that the gravitational attraction of the Andes is much smaller than that to be expected from the mass represented by these mountains. Besides, he estimated that the ratio of density of crust to the mean density of the Earth for Chimborazo mountain in Ecuador is quite higher than the Quito mountain in Peru. This erroneous result indicated that the deflection of the vertical caused by the mountain was too small for its estimated mass.

In the first half of the nineteenth century (1806-1843), the English geodesist George Everest (1859) carried out triangulation surveys in India. He took 160 km apart two stations - Kalianpur and Kaliana in the Himalayan base in India. He observed that the distance measured by triangulation between Kalianpur on the lndo-Ganges plain and Kaliana in the foothills of the Himalayas differed substantially. The difference of latitude between two stations as determined, on the one hand by astronomical methods and on the other by measurement (triangulation), was found to differ appreciably. Difference between two results amounted to 5.23 seconds is as given below—

1. Result obtained through triangulation method = 5°23' 42.294"
2. Result obtained through astronomical method =5°23’37.058"
3. Difference =5.236"

According to him that discrepancy must have caused by errors in geodetic measurements.

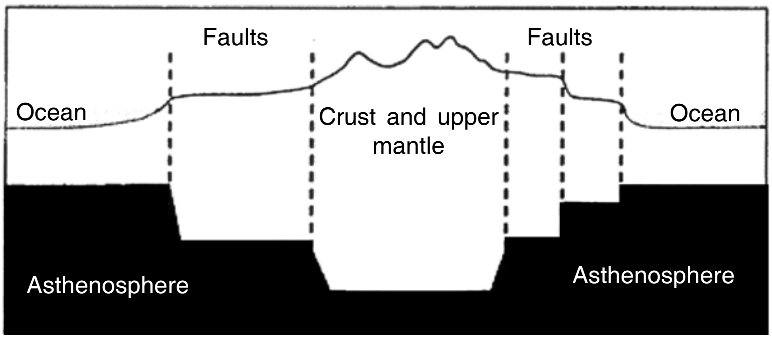


Fig. 2.7 General Concept of Isostasy

The interpretation of this discrepancy was brought the fact that the enormous mass as well as huge attritional forces of the Himalaya were responsible. Latter on, an attempt was made by Pratt (1855) to estimate the amount of this attraction. He assumed that the mountain mass as a whole have an average density which is approximately 2.7 and his calculation sowed that the mountain should cause a much larger deflection of the vertical than they actually did.

1. Gravitational deflection at Kaliana=27.853"
2. Gravitational deflection at kalianpur=II.968"
3. Difference=15.885"

Thus, the difference of 15.885" was in fact more than 3 times the observed deflection of 5.236" during the survey by Everest. Pratt's calculation pointed out another fact that the Himalaya was not exerting the attraction according to its enormous mass and the attraction of the mountain range on the plumb-line was So, scientists tried to believe that local excess of attraction, due to major relieffeatures, was compensated for by some deficiency of density below the surface.

2.3.2 Airy's Concept of Isostasy

Sir George Biddell Airy (1801-1892) opined that the inner part of the mountain cannot be hollow, rather the excess weight of the mountains are compensated by the lighter materials below. The crust of relatively lighter material (SIAL) is floating in the substratum of denser material (SIMA). As for example, Himalayan Mountains are floating in th.e denser magma with maximum portion sunk in the magma in the same way as a boat floats in water. According to Airy "the great mass of the Himalayas was not only a surface phenomenon - the lighter rocks of which they are composed do not merely rest on the level surface of denser material beneath, but, as a boat in water, sink into the denser material." For example, an iceberg floats in water in such a way that for everyone part to be above water level, nine parts of the iceberg remain below water level. If we assume the average density of the crust and the substratum to be 2.67 and 3.0 respectively, for everyone part of the crust to remain above the substratum, nine parts of the crust must be in the substratum. In other word, the law of floatation demands that the ratio of free board to draught is 1 to 9. At the same way, it is said that roughly 9 km height of the Himalaya must have a root in the substratum, which is 9 times more in length in substratum than the height of the Himalaya.

Fig. 2.8 : Sir George Biddell Airy (1801-1892)

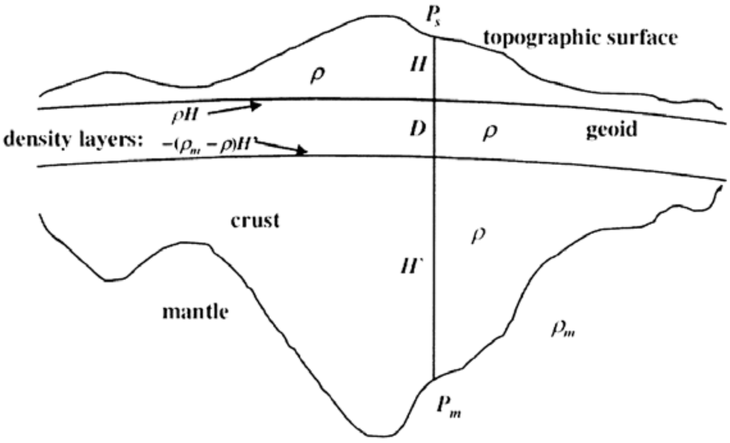


Fig. 2.9 : Isostatic compensation of topography by Airy model

Based on this observation, Airy postulated that ‘if the land column above the substratum is larger, its greater part would be submerged in the substratum, and if

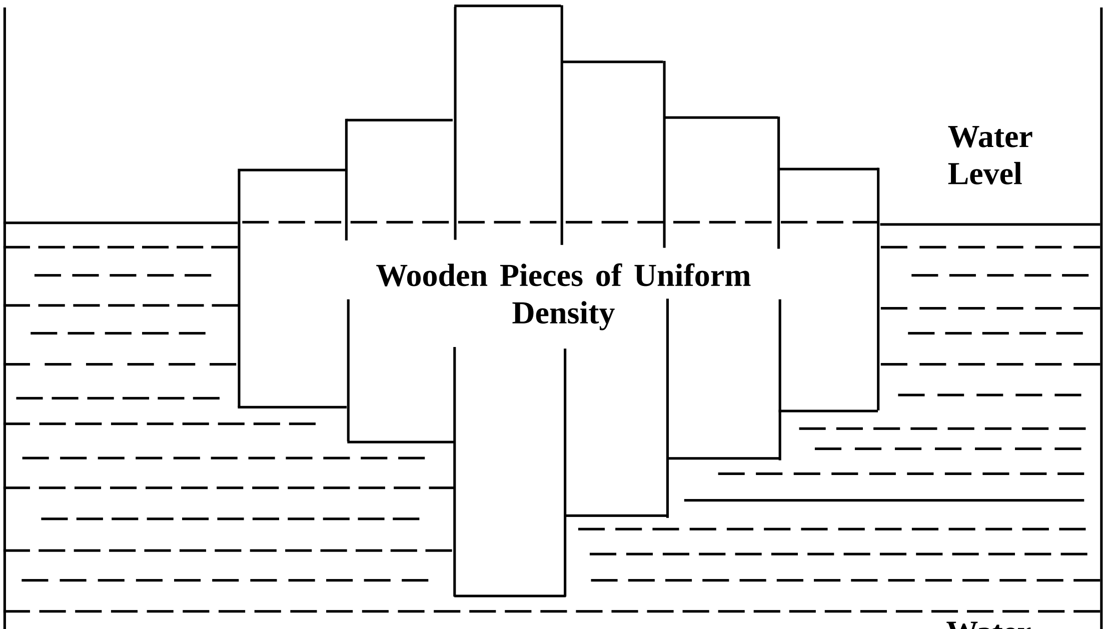


Fig 2.10 : Airy’s Experiment (Wooden piece have greater height, larger part of that wooden piece get submerged into the water and the other side the piece have lesser height, smaller part of that piece get submerged into the water).

the land column is lower, its smaller part would be submerged in the substratum'. According to Airy the density of different columns of the land (plains, plateaus, mountains, etc.) remains the same. Hence, he proposed the idea of 'uniform density with varying thicknesses'. It means that the continents are made of rocks having uniform density, but their thickness or length varies from place to place. In order to prove this concept Airy took several pieces of iron of varying lengths and put them into a basin with full of mercury. These pieces of iron' sunk up to varying depths depending on their lengths. Same things happen if we take some wooden pieces of varying length and put them into a basin with full of water.

- **Criticism of Airy's hypothesis**

Though the concept of Airy commands great respect among the scientific community, but, it also suffer from certain defects and faults.

1. Airy claimed that every upstanding part must have a root below in according to its heights. Thus, the height of the Himalaya is 8,848 m on the land part then its root would be equivalent to 8,848 × 9=79,632m (according to free board to draught ratio as I to 9). But, the root is not 'possible to be at such a great depth, because the root material will automatically melt due to higher temperature found at that depth. In fact, interior temperature increases with increasing depth at the rate of 1°C per 32m.
2. According to Airy the density of different columns of the land (e.g. mountains, plateaux, plains etc.) remains the same. In other words, density does not change with depth, that is, 'uniform density with varying thickness.' This means that the continents are made of rocks having uniform density but their thickness or length varies from place to place. But, in reality, it is absolutely wrong. Continents are made up of both igneous rocks of higher density as well as sedimentary rocks of lower density materials.
3. Airy suggested that blocks of the I ithosphere had a constant density of 2.7 g/cm^3 and floated in the asthenosphere of density 3.3 g/cm^3. But it is not true in practical. The average density of oceanic crust is 3.0 g/cm^3, while continental crust has an average of 2.7 g/cm^3. Besides, About 60% of Earth's surface is currently occupied by oceanic crust.

4. Airy’s model was based on the assumption of thin crust, but somewhere crust extends up to 70 -100 km. besides, this model was not in accord with the contraction theory of the earth.

2.3.3 Pratt’s Concept Of Isostasy

John Henry Pratt (1809-1871), a mathematician, proposed his hypothesis on isostasy balance in 1855, stating that the mountain ranges having low density masses extend higher level than other masses of greater density. According to his concept, there is a level of compensation, above which density varies from one column to another, but, there is no change in density below this level. So, according to Pratt, there is a difference in the density of rocks in the crust and at the heights of the crustal blocks/ columns are determined by their densities. As such, blocks made up of lighter material are at higher elevation than those consisting of denser material. Thus, the rocks constituting the elevated masses and depressed areas exert equal pressure at the level of compensation. So, the central theme of his theory may be expressed as **“uniform depth with varying density”**. Equal surface area must underlie equal mass along the line of compensation.

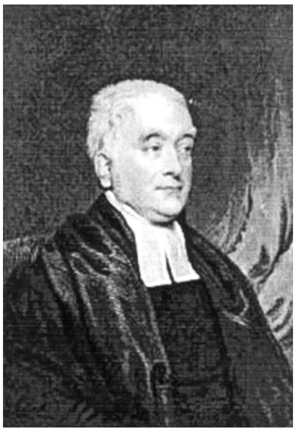


Fig. 2.11 : John Henry Pratt (1809-1871)

J.H. Pratt’s role is commendable i~connection with isostasy in India. During the survey of the Indo-Gangetic plain, carried out by Sir George Everest, the Surveyor-General of India, in 1855, the difference in latitude between Kalianpur and Kaliana (5.236 seconds of arc, corresponding to a distance on the ground of 168 m.) was determined astronomically as well as by direct triangulation on the ground. A few years later Archdeacon Pratt explained the causes of this difference. Pratt found that the density of each higher part is less than a lower part. In other word, the density of mountain is lower than the plateau, similarly, the density of plateau is less than the plain and density of plain is less than the ocean floor and so on. It means that there is an inverse relationship between density and height of the relief.

Pratt started studying the rocks of the Himalaya and its neighboring plains, when he was studying the difference of gravitational deflection of 5.236 during the geodetic survey of Kaliana and kalianpur. According to Pratt density only varies in the lithosphere, not in the pyrosphere and barysphere. Thus, Pratt's concept is related to the "law of compensation" not in the "law of floatation". According to him different relief features are standing only because of the fact that their respective mass is equal along the line of compensation because of their varying densities.

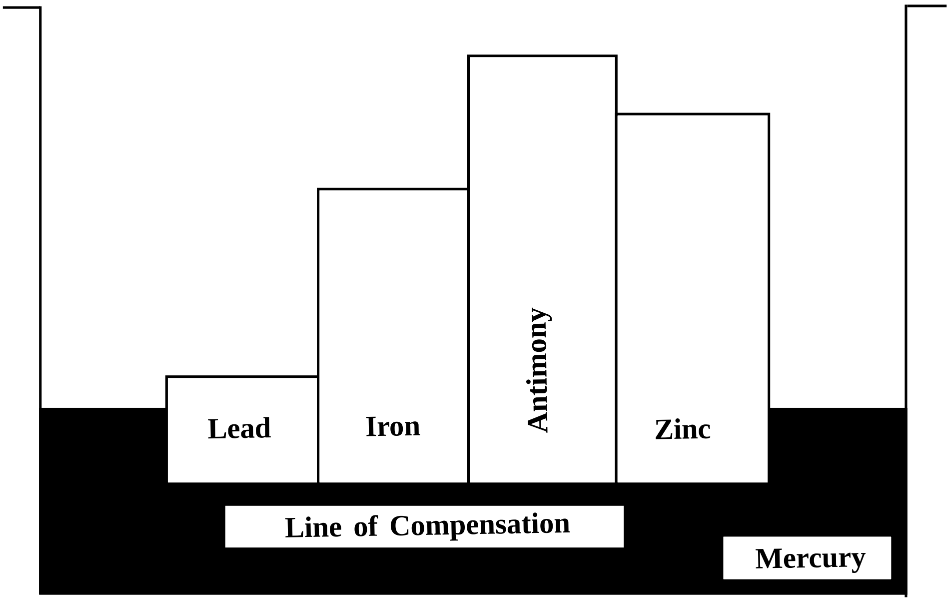


Fig 2.12 : Airy Model (Various columns of lead, iron, antimony and zinc with different densities are put in a basin filled with mercury. There is variation in the height of columns with varying densities above the level of mercury, but inside the mercury they are in a line of uniform depth).

- **Criticism**

1. Pratt does not believe in law of floatation, but, if we look minutely the concept of Pratt, than we can see that there is a glimpse of law offloatation indirectly.
2. Pratt does not believe in the concept of "root formation" but very close perusal of his concept on isostasy, does indicate the glimpse of such idea indirectly.
3. Even though Pratt does '}it support the root concept directly, but indirectly he seems to be In agreement with the concept of mountains having roots in the denser medium i.e. sima.
4. Level of compensation at about 100 km depth in the lithosphere is not supported by most of the geologist.

2.3.4 Other Theories

- **Theory of Hayford and Bowie**

Two American geodesists J.F. Hayford (1868-1925) and W. Bowie (1872-1940) have propounded their concepts of isostasy (1924) almost similar to the concept of Pratt. According to them there is a plane where there is complete compensation of the crustal parts. Densities vary with elevations of columns of crustal parts above this plane of compensation. According to them, the crust is composed of lighter material under the mountains than under the tloor of the oceans. Therefore, there is inverse relationship between the height of columns of the crust and their respecti ve densities. There is such a zone below the plane of compensation where density is uniform in lateral direction. The level of compensation is supposedly located at the depth of about 100 km. However, it is true that the views expressed by Hayford and Bowie were in close agreement with those of Pratt. Hayford and Bowie were able to prove that the anomalies in gravity relate directly to topographic features.

- **Concept of Heiskanen**

Finnish scientist W. A. Heiskanen (1895-1971) had an attempt to compromise between the Airy and Pratt models. This hypothesis says that approximately two-thirds of the topography is compensated by the root formation (the Airy model) and one-third by Earth's crust above the boundary between the crust and the b substratum (the Pratt model).

2.3.5 Global Isostatic Adjustment

From the above discussion it is clear that, there is no complete isostatic adjustment over the globe or there is no single theory ofisostasy to explain isostatic balance of the surface configurations. One of the reason is that our earth is still behaving unstable and thus geological forces (endogenetic forces) coming from within the earth very often disturb such isostatic adjustment. According to an estimate Himalayan mountain are still rising at the rate of 0.5 cm per years under the process of isostatic recovery. The isostatic adjustment in these areas could not be achieved till now.

Endogenetic forces and their tectonic effects are the causes of imbalance on the surface but nature always tries to make an isostatic adjustment with itself. Similarly, sometimes climatic changes occur at such an extensive global scale that there is accumulation of thick ice sheets on the land surface and thus increased burden causes isostatic disturbance. Besides, exogenetic forces are trying to eliminate the differences on the surface of the earth and in this process they are peeling off, transporting down to far tlung places, and depositing them. In this process, isostatic balance is maintained by the underneath tlowage of material by subsidence at the place of depojition and upliftment at the peeling of place in their proportion to the denudation. Thus, the process of redistribution of materials ultimately restores the disturbed isostatic condition to complete isostatic balance.

2.4 Summary

This unit deals with the study of the sudden movements on the earth’s the layering of the earth’s interior and the concept of Isostasy.

2.5 Glossary

1. **Asthenosphere:** The layer below the lithosphere that is marked by low seismic-wave velocities and high seismic-wave attenuation.
2. **Body wave:** A seismic wave that can travel through the interior of the earth. P-waves and S-waves are body waves.
3. **Core:** The center of Earth, an area constituting about 16% of the planet’s volume and 32% of its mass. Made primarily of iron and another, lighter element possibly sui fur.

4. **Crust:** The uppermost division of the solid Earth, representing less than I % of its volume and varying in depth from 3 mi. to 37 mi. (5-60 km). Below the crust is the mantle.
5. **Earthquake:** The sudden release of stored elastic energy caused by the sudden fracture and movement of rocks along a fault.
6. **Epicenter:** The point on the earth's surface directly above the focus *(hypocentrei* of an earthquake.
7. **Foreshock:** An earthquake that is smaller than. and precedes. a "mainshock". Forcshccks tend to occur in the same area as the main shock.
8. **Gutenberg discontinuity:** Discontinuity in seismic velocity that marks the boundary between the core and the mantle: named after seismologist Bene Gutenberg.
9. **Island arc:** Chain of islands above a subduction zone.
10. **Lithosphcrc:** The outer, rigid shell of the Earth above the Asthenosphere. It contains the crust. continents. and plates.
11. **Love wave:** A major type of surface wave having a horizontal motion that is shear or transverse to the direction of propagation (travel). It is named after A.E.II. Love, the English mathematician who discovered it.
12. **Low-velocity zone:** Any layer in the Earth in which seismic wave velocities are lower than in the layers above and below.
13. **Magnitude:** Magnitude is a measure of the amount of energy released during an earthquake. It may be expressed using the Richter scale.
14. **Mantle:** The main bulk of the Earth, between the crust and the core, ranging from depths of about 40 to 3470 km. It is composed of dense silicate rocks and divided into a number of concentric shells. Under Eastern Canada, it can be found at around 40 km depth.
15. **Moho:** The boundary between the crust and the mantle in the earth. This is a depth where seismic waves change velocity and there is also a change in chemical composition.
16. **Outer core:** Outer liquid shell of the Earth's core, probably iron with some oxygen: inner radius. 1221 km, outer radius, 3480 km.

17. **P wave:** Also called primary, longitudinal, push, pressure, dilatational, compressional, or push-pull wave. P waves are the fastest body waves and arrive at stations before the S waves, or secondary waves.
18. **Rayleigh wave:** A type of surface wave having a retrograde elliptical motion at the Earth's surface. These are the slowest. but often the largest and most destructive, of the wave types caused by an earthquake.
19. **Richter Scale:** Magnitude is measured on the basis of ground motion recorded by an instrument and applying standard correction for the epicentral distance from recording station. It is linearly related to the logarithm of amount of energy released by an earthquake and expressed in Richter Scale.
20. **Ring of Fire:** 40,000-km-long region that surrounds the Pacific Ocean known for its 452 volcanoes and 90% of the worlds earthquakes. Also called the Circum-Pacific belt, this zone of earthquakes includes 81% of the worlds largest earthquakes.
21. **S wave:** Also called shear, secondary, rotational, tangential, distortional, transverse, or shake wave. These waves carry energy through the Earth in very complex patterns of transverse (crosswise) waves. These waves move more slowly than P waves, but in an earthquake they are usually bigger.
22. **Seismic wave:** Seismic waves are vibrations generated by sudden movements of rock. After earthquakes occur, the seismic waves propagate from the hypocentre to the surface of the Earth.
23. **Seismograph:** A very sensitive instrument used to record and measure earthquakes.
24. **Seismologist:** A scientist who studies earthquakes, seismic sources, and wave propagation through the Earth.
25. **Seismology:** The study of earthquakes, seis
26. mic sources, and wave propagation through the Earth.
27. **Shadow zone:** The area on the Earth's surface protected from seismic wave arrivals.
28. **Surface waves:** Waves that move over the surface of the Earth. Rayleigh and Love waves are surface waves.
29. **Geodesy:** Geodesy is the science of accurately measuring and understanding the Earth's geometric shape, orientation in space, and gravity field.

30. **Gravity Anomaly:** Gravity anomalies are the differences between the observed acceleration of Earth's gravity and the values predicted from some model of how the gravity would be predicted to appear.

31. **Gravity:** Gravity is the force by which a planet or other body draws objects toward its center. The force of gravity keeps all of the planets in orbit around the sun.

32. **Isostasy:** The vertical readjustment of the surface of the earth due to the addition or removal of weight. Commonly associated with the advance and retreat of glacial ice.

33. **Isostatic Adjustment:** The movement of the solid part of the earth until it is in balance; also called Isostatic compensation. The prime example of Isostatic adjustment is the continents "floating" on the denser parts of the crust.

34. **Isostatic Equilibrium:** The shifting of the rock beneath the Earth's crust in response to theshifting in the weight above the Earth's crust.

2.6 Questions

A. Short Type (within 200 words)

1. How the composition and structure of Earth' layers are different as you go deeper into Earth?
2. What are the key elements of the structure of the earth?
3. What are the 4 major layers of the Earth and the predominant elements in each layer?
4. What are the categories when Earth is divided according to its chemical composition?
5. What are body waves? Explain in brief.
6. Explain the direct sources of information about the interior of the earth.
7. Why do earthquake waves develop shadow zone?
8. Briefly explain the indirect sources of information of the interior of the earth other than those of seismic activity.
9. What are the effects of propagation of earthquake waves on the rock mass through which they travel?
10. What is **Rayleigh wave**?
11. What are the differences between the inner core and the outer core?

12. Why is the outer core liquid, while the inner core is solid?
13. Which is denser-continental crust or oceanic crust? and why?
14. What information do earthquakes give you about Earth's interior?
15. How do waves behave differently in Earth's interior?
16. What is **Lehman Seismic Discontinuity**?
17. Which layer of the earth's interior has the lowest density and why?
18. What is Mohorovicic discontinuity?
19. What is Gutenberg Seismic Discontinuity?
20. What can earthquakes tell us about the interior of the earth?
21. What is the difference between the epicenter and the focus of an earthquake.
22. What are seismic waves and what is the difference between a P-wave, an S-wave?
23. For each increase of magnitude by a factor of I, how much more energy is released?
24. Which of the scales is more accurate measure of the energy released by large earthquakes and why?
25. What is the difference between the Richter's scale and the Mercalli Scale?
26. How does ground shaking during an earthquake depend on such things as distance from the epicenter and type of bedrock?
27. What are the causes of tsunami waves?
28. What are P-wave and S-wave shadow zones and what do they tell us about the interior of the earth?
29. What is the significance of the P-wave shadow zone? How does it arise?
30. What is the significance of the S-wave shadow zone? How does it arise?
31. What is Low Velocity Zone?
32. Explain the effects of earthquakes.
33. What is Isostasy and how does it pertain to Earth's mountains?
34. What is the concept of Isostasy?
35. How does Isostasy affect the earth's crust?

36. How would you tell if an area is in isostatic equilibrium?
37. What is meant by isostasy?
38. Explain the concept of isostasy according to Airy.
39. Explain the concept of isostasy according to Pratt..
40. What do you mean by Heiskanen isostasy Model?
41. What is the concept of Hayford and Bowie regarding Isostasy
42. What do you mean by Global Isostatic Adj ustment?
43. How much of a mountain is b~ow the surface?
44. Where different topographic heights are accommodated by changes in crustal thickness, in which the crust has a constant density?
45. Identify the major Criticism of Airy's hypothesis:
46. What do you mean by Isostatic Compensation.

B. Long Type (within 600 words)

1. Explain the elastic rebound theory on the cause earthquakes with diagram.
2. What is the global distribution of earthquakes? What can we learn from patterns in this distribution?
3. Compare mantle with Core on the basis of temperature, pressure and geological composition
4. Describe mineralogical and seismological characteristics of mantle.
5. Compare among P wave, S wave and L wave generated by earthquakes.
6. Describe the tectonic causes of earthquakes.
7. Describe major earthquake belts and explain causes of such distributions
8. Explain different seismic discontinuities in the earth's interior.
9. Explain the isostasy concepts of Airy and Pratt
10. Distinguish between Pratt and Airy concept of isostasy
11. Describe the concept of theory ofisostasy historically.
12. Explain the isostatic adjustment by various experiments. Explain the views of Airy in this regard.

Unit 3 ❑ Plate Tectonics : Processes At Constructive, Conservative, Destructive Margins And Hotspots; Resulting Landforms

Structure

3.0 Objective

- To learn about the Plalte Tectonic Theory and the various boundaries.

3.1 Introduction

Plate Tectonic Theory is a comprehensive theory explaining the structure of the earth's crust and many associated phenomena viz. mountain building, folding and faulting, continental drift, vulcanicity, seismic events (earthquakes) etc. resulting

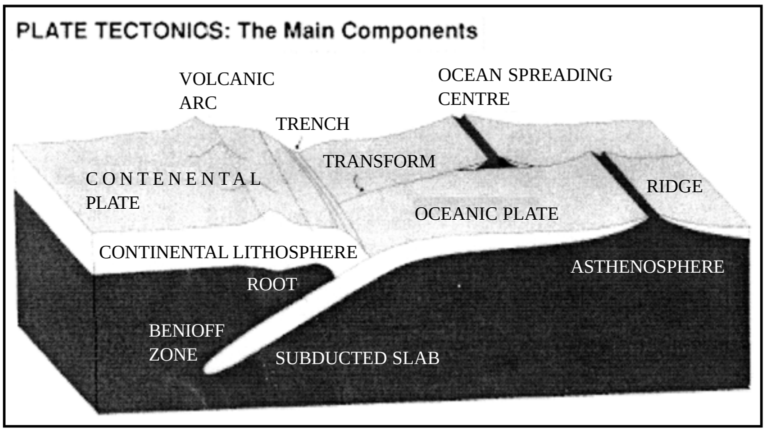


Fig. 3.1 : Model of plate tectonics

from the interaction of rigid lithospheric plates which move slowly over the underlying mantle. The rigid lithospheric solid landmass having a thickness of about 100 km composed of Earth's crust and some portion of upper mantle are technically called 'Plates'. The term 'plate' was first used by Canadian Geologist John Tuzo Wilson in 1965. The whole mechanism of the evolution, nature and motion and resultant reactions of plates is called' Plate Tectonics'.

- **History of the Concept**

The concept of plate tectonics was formulated in the 1960s. But the theory of plate tectonics was not created from scratch by a genius' mind. Like every scientific theory, it results from centuries of observations and compilation of many scientists' works like continental drift theory by Wegner (1912), seafloor spreading theory by Harry Hess (1960), convection current theory by Arthur Holmes (1944) and theory of Paleomagnetism (1956). According to them the Earth's lithosphere is composed of seven major plates and many minor plates. The seven major plates are the African plate. Antarctic plate, Eurasian plate, Indo-Australian plate, North American plate, Pacific plate and South American plate.

Dan Peter McKenzie and Robert Ladislav Parker discussed in detail the mechanism of plate motions on the basis of Euler's Geometrical Theorem in 1967. Prof. Harry Hess (1960) elaborated the mechanism of Plate movement on the basis of the evidences of sea floor spreading. WJ. Morgan and Le Pichon elaborated the various aspects of plate tectonics in 1968. However, the theory of plate tectonics developed by geoscientists during early 1960s is often described as a most revolutionary concept in the history of Earth's science. It is now widely accepted that most complex geological riddles, past and present, are solved conveniently by the concept of plate tectonics.

Major Plates

Pacific Plate, North American Plate, Eurasian, African Plate, Antarctic Plate Australian Plate, South American Plate

Minor Plates

Carribbean Plate, Cocos Plate, Caroline Plate, Juan de Fuca Plate, Juan Fernandez micro Plate, Iranian Plate, South sandwich Plate, Myanmar Plate, Anatolian Plate, Nazca Plate, Nubian Plate, Philippines Plate, Okhotsk Plate, Scotian Plate, Eastern micro Plate, Somalian Plate, Arabian Plate, Solomon Plate, Fiji Plate, Bismarck Plate.

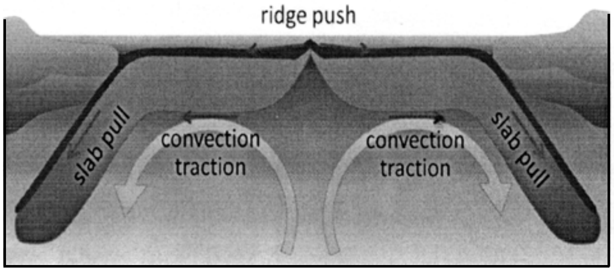
3.2 Mechanism Of Plate Tectonics

The driving force behind plate tectonics is the ‘convection current’ in the mantle where heat from the Earth’s interior causes currents of hot rising magma and cooler sinking magma to flow, moving the plates of the crust along with them. Actually, convection currents beneath the asthenosphere move the crustal plates in differerit directions. The source of heat driving the convection currents is radioactivity deep in the Earth’s mantle. Hot material near the Earth’s core rises and colder mantle rock sinks. Two plates moving together under the impact of thermal convective currents collide against each other and the plate boundary having relatively denser material is sub-ducted under the other plate boundary of relatively lighter materials. This subduction zone is also called Benioff Zone. The subduction of plate boundaries causes lateral compressive force which ultimately squeezes and folds the sediments and material of the margins at the plates and thus mountains are formed. Three types offorces are responsible for moving of the plates.

1. **Slab Pull:** This force occurs as a subducting plate sinks into the hot mantle beneath it. The process of a tectonic plate descending into the mantle is termed subduction. Slab pull occurs when an **oceanic** plate subducts into the underlying mantle. The subducting plate, usually basalt, is denser than the material it is subducting into, purely due to its difference in temperature. As the plate sinks into the mantle, it acts to pull the rest of the plate behind it. This force is considered by some to be the primary force driving plate motion at collision zones. However, there are some plates, where there is little or no subduction occurring such as the Antarctic Plate.

2. **Ridge Push:** Gravitational force that causes a plate to move away from the crest of an ocean ridge is called ridge push force. Ridge pu~ is induced by the pressure gradient at the ridge crest due to its higher elevation with respect to the surrounding oceanic lithosphere. Actually, newly-formed plates at oceanic ridges are warm, and so have a higher elevation at the oceanic ridge than the colder, more dense plate material further away. So, gravity causes the higher plate at the ridge to push away the lithosphere that lies further from the ridge. Ridge push is still considered to be

of significance, especially where there is little or no slab pull acting on the plate (e.g. *the Antarctic Plate).*



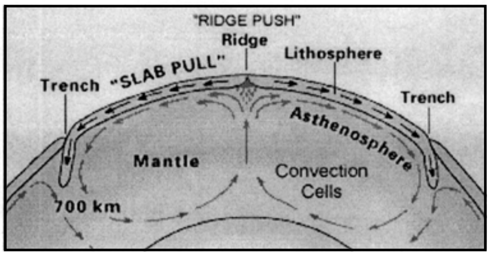


Fig. 3.2(a) : Ridge push effects **3.2(b) : convectional current**

3. Mantle Convection: Mantle convection is the slow creeping motion of Earth's solid silicate mantle caused by convection currents carrying heat from the interior.Heat in the interior is generated from the radioactive decay of elements which creates molten rock called magma in the asthenosphere. Convection currents transfer heat from one place to another by mass motion of molten rock. The heat transfer function of convection currents drives the plates. Molten rock rises up from the bottom after becoming hotter and less dense from the heat of the earth's core. As the rock loses heat into the earth's crust, it becomes relatively cooler and more dense, sinking back down to the core and completes the path as convective cell. The mantle's convective motions break the lithosphere into plates and move them around the surface of the planet. These plates may move away from, move by, or collide with each other.

Rates of Plate Movement

Plates move at rates of about a few centimeters per year. Rate of plate movement is estimated based on radiometric dating of ocean crust. By determining the age of a crustal sample, and knowing its distance from the MOR at which it formed, scientists estimate the rate of new ocean floor as well as movement of the plates. Today, measurement of plate motion is done by satellite imageries. Results from this methods are more accurate. Sometimes, the rate of plate movement is determined by the bands of normal and reverse magnetic fields that parallel the mid-oceanic ridge. However, the rates are of considerable variation. For example, while the Arctic Ridge has the slowest rate (less than 2.5 cm/yr), the East Pacific

Rise in the South Pacific has the fastest rate (more than 15 cm/yr). An interesting fact is that the movement of Indian plate from south to equator was one of the fastest plate movements in history.

3.3 Plate Tectonic Activities

There are three kinds of plate tectonic boundaries: divergent, convergent, and transform plate boundaries.

1. Divergent Boundary

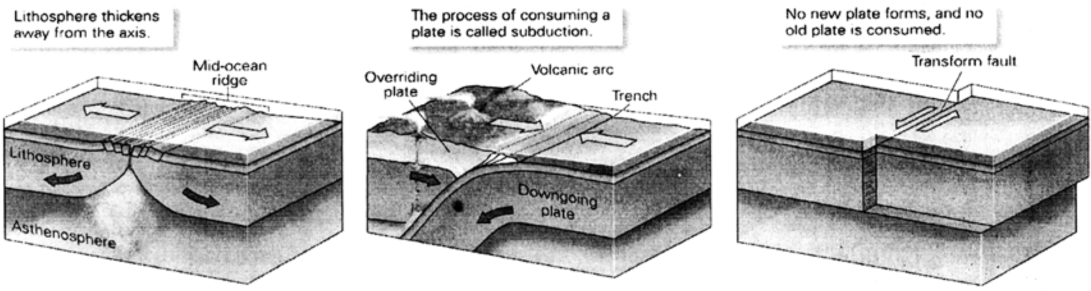
A divergent plate boundary occurs when two tectonic plates move away from each other. Divergent plate boundary is also called as constructive plate boundaries, spreading boundary, or accreting plate boundary. Along these boundaries, basaltic lava eject through long fissures from below. These basalt lavas are cooled and solidified and are added to the trailing margins of the divergent plates and thus new oceanic crust is continuously formed.

i) Divergent Plate Boundary - Oceanic

When a divergent boundary occurs beneath oceanic lithosphere, the rising convection current below lifts the lithosphere, producing a mid-ocean ridge. Effects that are found at a divergent boundary between oceanic plates include: a submarine mountain range such as the Mid-Atlantic Ridge; volcanic activity in the form of fissure eruptions; shallow earthquake activity; creation of new seafloor and a widening ocean basin.

ii) Divergent Plate Boundary - Continental

When a divergent boundary occurs beneath a thick continental plate, the pull-apart is not vigorous enough to create a clean, single break through the thick plate material. Here the thick continental plate is arched upwards from the convection current's lift, pulled thin by extensional forces, and fractured into a rift- shaped structure. As the two plates pull apart, normal faults develop on both sides of the rift, and the central blocks slide downwards. Earthquakes occur as a result of this fracturing and movement. The East Africa Rift Valley is a classic example of this type of plate boundary.



Lithosphere thickens away from the axis.

The process of consuming a plate is called subduction.

No new plate forms, and no old plate is consumed.

(a) At a divergent boundary, two plates move away from the axis of a mid-ocean ridge. New oceanic lithosphere forms.

(b) At a convergent boundary, two plates move toward each other; the downgoing plate sinks beneath the overriding plate.

(c) At a transform boundary, two plates slide past each other on a vertical fault surface.

Fig. 3.3 : Different types of plate Movements

2. Convergent Plate Boundary

Convergent plate boundary' is those Jtere two plates collide against each other. They are also known as 'consuming plate boundaries' or 'destructive plate boundaries'. Here the leading edge of one plate having relatively lighter material overrides the other plate and the overridden plate boundary of relative denser material is sub ducted or thrust into the upper mantle and thus a part of the crust in lost in the mental. This is why convergent plate margins are called destructive margins. There are three types of convergent boundaries.

i) Oceanic/Oceanic Convergent Boundary

When a convergent boundary occurs between two oceanic plates, one of those plates which are older and denser will subduct beneath the other. The subducting plate is, therefore, heated as it is forced deeper into the mantle, and at a depth of about 150 km the plate begins to melt resulting into the creation of magma. Magma chambers that reach the surface break through to form a volcanic eruption cone. In the early stages of this type of boundary, the cones will be deep beneath the ocean surface but later grow to be higher than sea level. This produces volcanic island chain. Sometimes, this boundary includes a seafloor trench marking the earthquake-rattled subduction zone. An example of an oceanic/oceanic convergent boundary is that between the Pacific and Mariana plates, which includes the Mariana Islands arc and a subduction zone encompassing the Mariana Trench, the deepest part of the World Ocean.

Japan, the Aleutian Islands, and the Eastern Caribbean islands of Martinique, St. Lucia, and St. Vincent and the Grenadines are examples of islands formed through this type of plate boundary. Other features of an oceanic/oceanic convergent boundary are the forearc basin between the trench and the island arc and the backarc basin on the opposite side of the arc. Powerful earthquakes shake a wide area on both sides of the boundary.

ii) Continent/Continent Convergent Plate Boundary

In this type of convergent boundary, a powerful collision occurs between two continental plates. Since neither plate is stronger than the other, they crumple and are pushed up. In general, they prevent subduction since both of the plates have a density much lower than the mantle. Although, there may be a small amount of subduction where or the heavier lithosphere below the continental crust might break free from the crust and subduct.

However, due to such collision, fragments of crust or continent marginal sediments might be caught in the collision zone between the continents, forming a highly deformed melange of rock. The intense compression can also cause extensive folding and faulting of rocks up to hundreds of kilometers into the plate interior.

The classic example of a continental/continental convergent boundary is the rumpled overlap where the Indian Plate drives into the Eurasian Plate, a tectonic collision that has thrown up the greatest mountains in the world - the Himalayas - as well as the vast, high Tibetan Plateau to the west. The process is believed to have started more than 50 million years ago and this is continuing. The Alps also grew in similar fashion via the collision of the African and Eurasian plates.

iii) Continent/Ocean Convergent Plate Boundary

When a continental plate meets an oceanic plate, the thinner, denser, and more flexible oceanic plate sinks beneath the thicker, more rigid continental plate. This is called subduction. Subduction causes deep ocean trenches to form. The rocks pulled down under the continent begin to melt. As a result volcanic arc develops on the continental side of the boundary. Other important effect between an oceanic and continental plate collision includes shallow earthquake activity along the continent margin. Ocean trench develops immediately off shore of the continent and a I ine of volcanic eruptions develops at the cost of destruction of oceanic lithosphere.

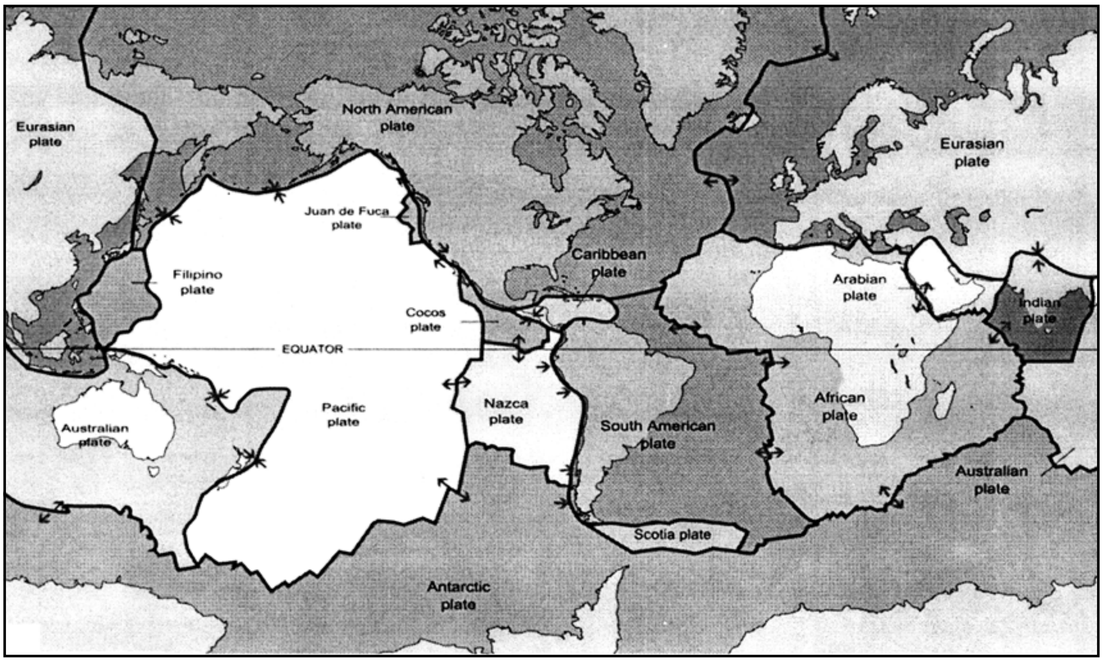
The western coastline of the United States is a classic example of convergent plate boundary where the Juan de Fuca oceanic plate is subducting beneath the North

American continental plate. The Andes Mountain Range of western South America is another example of a convergent boundary where the *Nazca Plate* is subducting beneath the South American plate.

3. Transform Plate Boundary

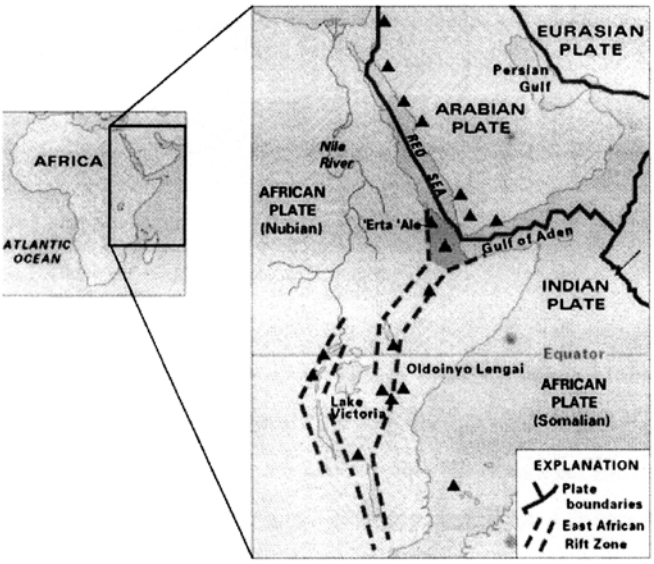
Two plates sliding past each other in a horizontal direction forms a transform plate boundary. This boundary is also known as conservative plate boundaries. Lithosphere is neither produced nor destroyed as the plates slide horizontally past each other. This is the only type of plate boundary which does not produce volcanoes or mountains. The fracture zone that forms a transform plate boundary is known as a transform fault. Most transform faults are found in the ocean basin and connect offsets in the mid-ocean ridges. Transform boundaries and the resulting faults produce many earthquakes because edges of tectonic plates are jagged rather than smooth. As the plates grind past each other, the jagged edges strike each other, as a result a lot of stress builds up at the fault line. This stress is released in quick bursts in the form of an earthquake when the plates suddenly slip into new positions.

These structures are so-called strike-slip faults. The San Andreas Fault in western US, the North Anatolian Fault in Turkey, the Dolores-Guayaquil Mega fault in the



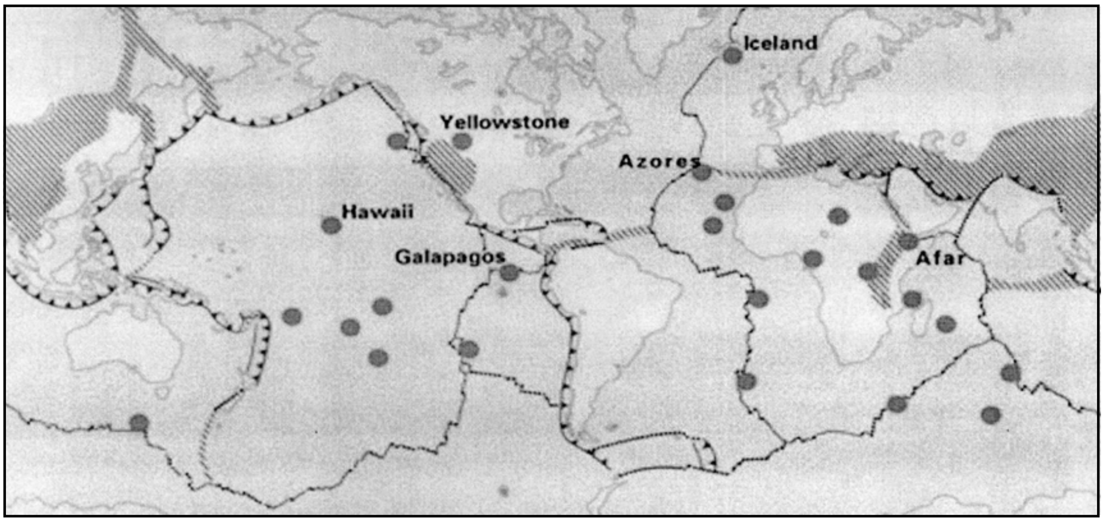
3.4 : World major crustal plates

northern Andes are some examples of huge strike-slip faults transecting continental crust. The best-studied strike-slip fault is the San Andreas Fault in California. It is located at the boundary between the Pacific plate (moving northwest) and North American plates (moving southeast) and runs roughly 1,300 km through Northern and Southern California. This fault connects the Ejiilt Pacific rise in the South and the Explorer ridge in the north. Both are divergent boundaries. Along this fault, the Pacific Plate has been grinding horizontally past the North American Plate for ten million years at an average rate of about 5 cm/yr.



3.5 The well-known Transform Boundaries of Africa

A volcanic "hotspot" is an area in the mantle from which heat rises as a thermal plume from deep in the Earth. Many hot spots are located in the middle of a lithospheric plate. High heat and lower pressure of this region facilitates melting of the rock. This melt, called magma, rises through cracks and erupts to form volcanoes. Often the hot spot creates a chain of volcanoes. The best example of a hot spot volcanic chain is the Hawaiian Islands. Hotspots of the lithosphere are, therefore, unique feature because it does not occur at the boundaries of Earth's tectonic plates, where other volcanism occurs. The mantle plumes that form hots pots are thought to be relatively stationary, while tectonic plates are not. Scientists believe that there are about 40 to 50 hot spots around the world. Most hotspots, also known as "mantle plumes," occur beneath oceanic plates; Yellowstone, however, is a good example of a hotspot beneath a continental part of a plate.



—— Plate boundary ▲▲ Subduction Zone ● Prominent hotspot ▨ Plate boundary zones in which demormation is defuse and boundaries are not well defined Source: USGC (pubs.usgs.gip)

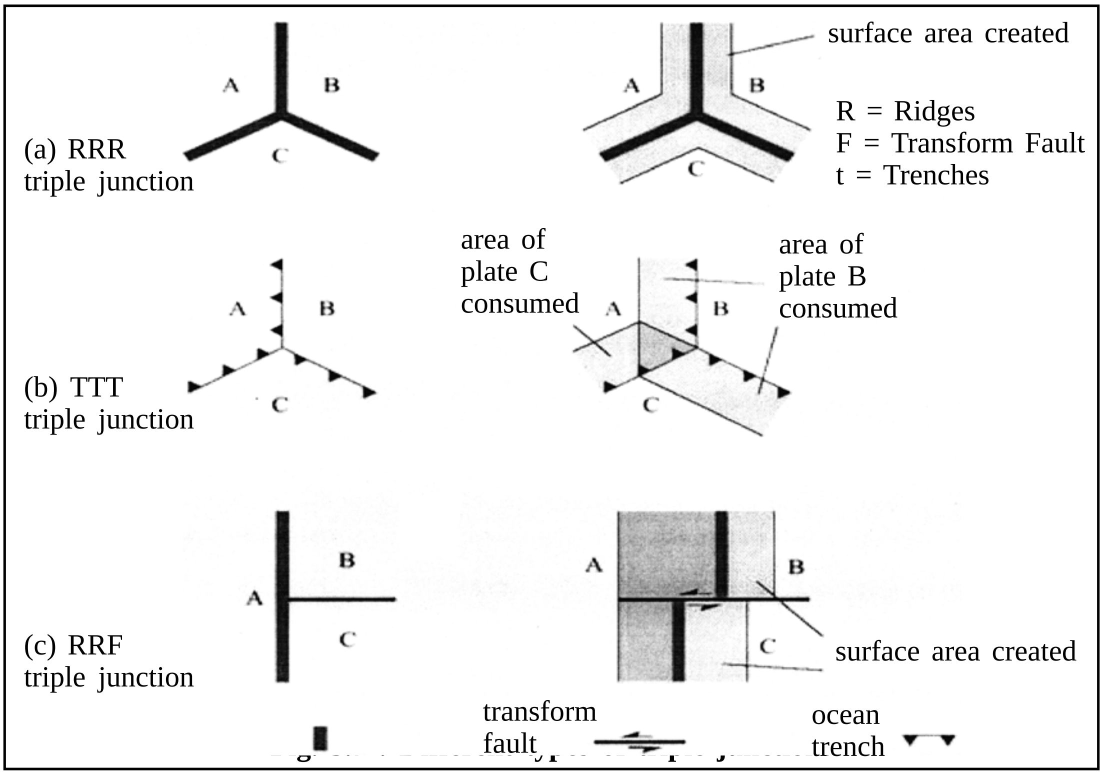
Fig 3.6 Hotspot region of the world

3.4 Triple Junction

The point where three lithospheric plates meet is known as Triple Junction. It has been suggested that mantle plumes are responsible for the upward doming of the crust at these locations, producing a three- way radial fracture. There are roughly 50 plates on Earth with about 100 triple junctions among them. An example is the Red Sea, Gulf Aden and East African Rift Valley. For convenience, geologists use the notation R (ridge), T (trench) and F (fault) to define triple junctions. For example, a triple junction known as an RRR could exist when all jBree plates are moving apart. But most triple junctions combine two trenches or two faults — in that case, they are known as RFF, TFF, TIF, and RTI. A triple junction involving three ridges (RRR triple junction) is always stable, while a triple junction between three trenches (TIT) is almost *unstable.* A triple junction between two ridges and a transform fault (RRF) can only exist for a short instant in geological time, and decays immediately to two FFR stable plate junctions. They are important as they provide a tool to calculate kinematic evolution of plate boundaries and their motion cause significant reworking of Iithospheric material.

However, in nature, the seven types of stable triple junctions are identified. These include:

- **RRR:** These are located in the South Atlantic, the Indian Ocean, and west of the Galapagos Islands in the Pacific.
- **TTT:** This type of triple junction is found in central Japan. One of the best example is the the’ Boso Triple Junction’ where the Okhotsk, Pacific and Phillippine Sea plates meet.
- **TTF: Only** one of these types of triple junctions is identified off the coast of Chile.
- **TTR:** This type of triple junction is located on Moresby Island, western North America.
- **FFR, FFT:** The triple junction type is found at the San Andreas Fault and the Mendocino Transform Fault in the Western U.S.
- **RTF:** This type of triple junction is found at the southern end of the Gulf of California.



3.5 Merits And Demerits Of Plate Tectonic Theory

- **Merits**

1. The theory of plate tectonics was advanced in the 1960s and 1970s to establish new information about the earth's ancient history as well as real mechanism behind the drifting of the continents as proposed by Wegener.
2. Plate tectonics focuses fundamental concept of geosciences which integrates many branches into a single proposal and suggests some basic assumptions based on geology and paleontology.
3. Plate tectonics defines the movements and features of the Earth's surface now and in the past. However, the greatest worth of Plate tectonics theory is to focus the location of earth's most devastating geological events like earthquake and volcanism.
4. Plate tectonic theory is the unifying theory of geology and geo physics. It establishes a framework into which all large-scale geological phenomena, like earthquakes, volcanoes, and the existence of ocean basins and continents are explained with reliability.
5. This theory first explains the age distribution of oceanic crust as well as magnetic information in rocks in the oceans.

- **Demerits**

A number of objections have been raised to the theory of plate-tectonics. Some of them are as follows:

1. There are weak evidences of thermal convection in the mantle, which is mainly considered as the driving force for plate motion.
2. As the volume of the earth is static, then rate of creation of new plate and destruction of plate would be the same. But, in reality divergent plate boundary is quite larger than the convergent plate boundary.
3. The pushing down of solid lithosphere into the mantle to a depth as much as 700 km following convectional current is difficult to imagine. It is also not answerable that how a ridge over the rising limb of a mantle convection cell would be carried down on the descending limb of the same cell.

4. The plate tectonic theory is unable to give the explanation of all the mountain building process in the earth. There are certain mountain ranges, such as the Eastern highlands of Australia, Drekenburg mountain of South Africa and Sierra-Dalmar of Brazil which are not related to plate tectonics.
5. No adequate explanation exists for why only the Pacific plate sub-ducted and destroyed and other oceanic floor is being extended. The length of spreading zone (ocean ridges) is far higher than the subduction zone (ocean trench). The rate of construction is more than the rate of destruction.
6. The finding of Precambrian and Cambrian rocks near the crest of the Mid-Atlantic ridge contradicts the theory of plate-tectonics. According to the plate tectonic theory the rocks of the sea- floor cannot be more than five or ten million years old.

Despite all these criticisms and limitations, plate tectonic theory is a revolutionary and comprehensive attempt which scientifically explains the present distribution and arrangement of the continents and ocean basin. It also provides as satisfactory explanation of the distribution of volcanoes and earthquakes. It has also confirmed the theory of Continental Drift and theory of sea floor spreading.

3.6 Summary

Plate tectonic theory in a unifying theory of geology and geophysics. The age distribution of oceanic crust as well as magnetic information in locks is well explained. This unit well explains the boundaries of the crust.

3.7 Glossary

1. **Asthenosphere:** the soft, flexible upper layer ofthe mantle, on which the tectonic plates move
2. **Convection currents:** m0'jrment within hot fluids, when the heat source is on the bottom, such as in a boiling pot of soup on the stove. Convection currents happen because the hotter material is less dense and rises; when it reaches the surface, it cools

and becomes less dense, so it sinks. This rising and sinking creates a circular motion within the fluid.

3. **Convergent plate boundaries:** where two tectonic plates move toward each other.
4. **Crustal plate:** A rigid layer of the Earth's crust that is believed to drift slowly.
5. **Destructive plate margin:** Tectonic plate margin where two plates are converging and oceanic plate is subducted - there could be violent earthquakes and explosive volcanoes.
6. **Divergent plate boundaries:** where two tectonic plates move away from each other.
7. **Hot spots:** Where the Earth's crust is thin so magma is able to break through the surface, forming volcanoes
8. **Paleomagnetism:** An area of historical geology devoted to studying the direction and intensity of magnetic fields in the past, as discerned from the residual magnetization of rocks.
9. **Plate:** One of the huge sections which make up the Earth's crust. The plates are continuously moving.
10. **Plate boundary:** The place where two or more plates in the Earth's crust meet.
11. **Plate margins:** Boundaries between plates.
12. **Plate tectonics:** The theory that the Earth's crust and upper mantle (the lithosphere) is broken into a number of more or less rigid, but constantly moving, segments or plates.
13. **Seafloor spreading:** The process by which new oceanic crust forms when magma rises up and solidifies at the mid-ocean ridges. The newer crust pushes the older crust out to each side, which is why the age of the sea floor increases with distance away from the mid-ocean ridges.
14. **Seismicity:** The frequency and distribution of earthquakes in a certain area, recorded by seismographs
15. **Subduction zone:** A dipping planar zone descending away from a trench and defined by high seismicity, interpreted as the shear zone between a sinking oceanic plate and an overriding plate.
16. **Subduction:** Movement of the edge of one tectonic plate under another. Subduction takes place at convergent plate boundaries.

17. **Transform plate boundary:** where two tectonic plates slip past each other, moving in opposite directions.
18. **Triple junctions:** At most three plates can come together at a point; this is called a triple junction.

3.8 Questions

A. Short Type (within 200 words)

1. What is lithospheric plate?
2. What is plate tectonics?
3. Explain the mechanism of plate movement.
4. Discuss the activities at plate margins.
5. Describe the distribution of earthquakes and volcanoes with the help of plate boundaries.
6. Describe the plate motions along the Himalayan Mountains.
7. Provide two kinds of evidence that support the theory of plate tectonics
8. How does the San Andreas Fault relate with the plate tectonics?
9. What is the driving force behind the movement of litho spheric plates on the Earth's surface? About how fast do the plates move?
10. What type of Plate Boundary is causing the Pacific Ocean to shrink?
11. What are the characteristics of a Subduction Zone?
12. How does the movement of plates cause earthquakes?
13. Name the types of tectonic plates that are colliding at African rift valley. What feature is being formed and why?
14. Name at least three types of evidence that a hotspot lies below Yellowstone National Park.
15. How many major tectonic plates have scientists identified?
16. What is a volcanic hotspot?
17. How does volcanic hotspot relate with the plate tectonics?
18. How do volcanoes help to identify the locations of plates boundaries?

19. What happens to magma at divergent boundaries?
20. Name three areas where plate boundaries may be located.
21. Where are most divergent boundaries located and why?
22. What happens when two plates made of continentallithosphere collide?
23. What happens when two plates made of oceanic lithosphere collide?
24. How are transform boundaries different from other types of boundaries?
25. What is an example of a convergent boundary at South America?
26. What is an example of a divergent boundary in the mid-Atlantic?
27. What three mechanisms of Earth's convecting system work together to cause plate motions?
28. Explain how mantle convection moves lithospheric plates.
29. Describe the three types of plate boundaries and whether they are prone to earthquakes and volcanoes.

B. Long Type (within 600 words)

30. What are the three types of plate boundaries and what type of geologic activity is found at each?
31. How does the theory of plate tectonics explain the locations of volcanoes, earthquakes, and mountain belts on Earth?
32. Discuss the geological activities at different plate margins with diagrams.
33. What force(s) drives plate tectonics? What are the different types of plate boundaries and what geological features do they create?
34. Describe how plate tectonics processes lead to changes in Earth's surface features.
35. Explain in brief the geological activities of the hotspot areas.

Unit 4 ❑ Folds And Faults—Origin And Types

Structure

4.0 Objectives

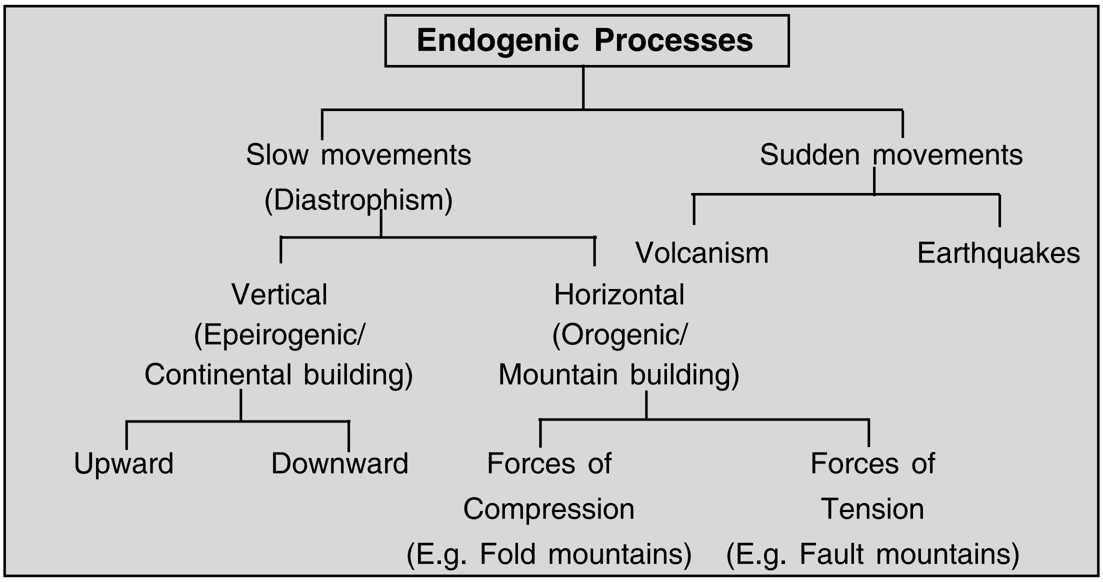
- The learners will learn about the movements within the earth
- The folding and faulting within the earth

4.1 Earth Movements

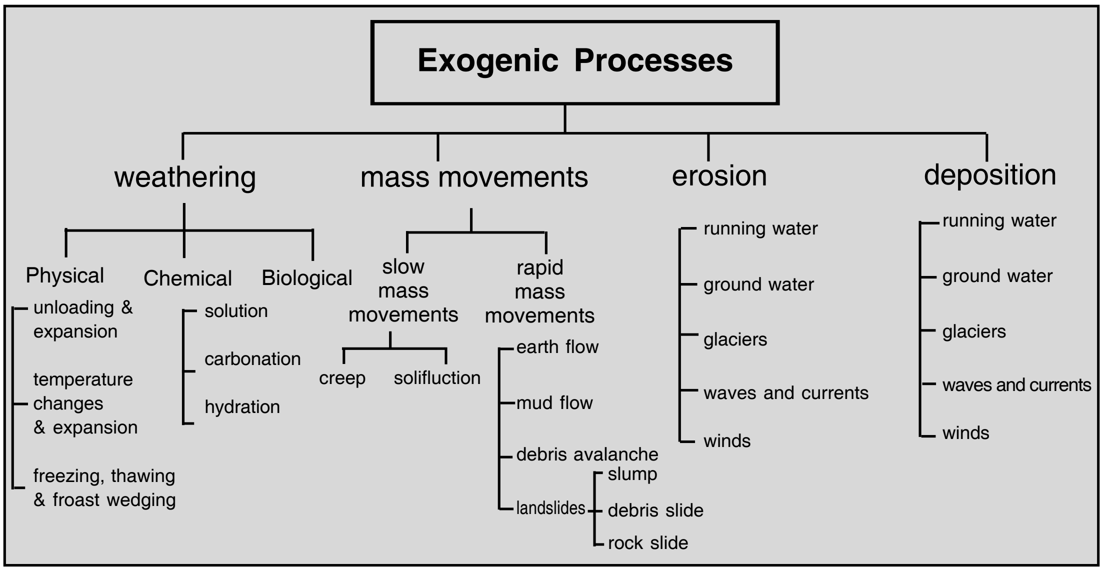
The crust of the earth is not stable everywhere. It is always changing. There are certain forces and movements which are always active in shaping the eath's crust. The forces which lead to change the surface are generally termed as diastrophism or earth movements. There are two types of forces working on the earth's crust, i.e. i) Endogenic Forces and ii) Exogenic Forces.

Earth Movements

i) **Endogenic Forces :** Endogenic forces originate within the earth itself. They are related to the heat of the interior and the problems of isostasy. They are also known internal processes. Accordingly they are of two types—a) slow forces and b) sudden forces. Slow forces bring about subsidence and elevation. The sudden forces include within their scope the earth quake and the volcanic eruptions. Due to these sudden effects considerable changes take place in the crust of the earth i.e. all of a sudden the areas are elevated or submerged. The energy of Endogenic forces is mostly generated by radioactivity of the interior minerals along with rotational, tidal friction and primordial heat from the origin of the earth. This energy due to geothermal gradients and heat flow from within induces diastrophism and volcanism in the Iithosphere. All processes that move, elevate or build up portions of the earth's crust come under diastrophism. They include : a) **Orogenic processes** involving mountain building through severe folding and affecting long and narrow belts of the earth's crust; b) **Epeirogenic processes** involving uplift or warping of large parts of the earth's crust.



ii) **Exogenic forces :** Exogenic forces are connected with the atmosphere and consequently are external / to the earth. The forces which derive their strength from the earth's exterior or originate within the earth's atmosphere are callejr as exogenic forces or external forces. The action of exogenic forces results in wearing down and hence they are considered as land wearing forces. Weathering, mass wasting, erosion, and deposition are the main exogenic processes. All the exogenic processes are covered under a general term- denudation, which means strip off or uncover. The elements of nature capable of doing these exogenic processes are termed as geomorphic agents The common agents are the wind, water, waves etc. An agent is a mobile medium (like running water, moving ice, winds, waves etc) which removes, transport and deposits earth materials. Gravity and gradients are the two things which make these agents mobile. The gravitational force acts upon all earth materials having sloping surface and tends to produce movement of matter in the down-slope direction. This creates stress and induces deformation to the particles.



4.2 EpeIrogenic Movement

The word 'epeirogeny' was coined by G. K. Gilbert in 1890 from the Greek word *epeiros* (which means mainland) and *genesis* (which means birth). However, later on, the trem is expressed as 'upheavals' or 'depressions' of land. The movement is caused by a set of forces acting along an Earth radius, such as those contributing to isostasy and faulting in the lithosphere. Eperiogenic movement is strictly vertical movement of continent and it acts along the radius of the earth. So it is also known as radial movements of the earth.

- **The Features of Epeirogenic Movements**

(a) The most characteristicfeature of the epeirogenic movement is that there is no crumpling ofthe rock-beds. The beds remain near~ horizontal.

(b) These earth movements affect areas of wide areal distribution.

(c) The periods of epeirogenic movements are quite large.

(d) These movements are reversible In nature. The same area may undergo upheaval followed by subsidence and vice versa.

(e) They affect the thickness of the sedimentary series, being formed, at the time of their operation.

(f) Epeirogenic or continent forming movements act along the radius of the earth; therefore, they are also called radial movements. Their direction may be towards (subsidence) or away (uplift) from the center. The results of such movements may be clearly defined in the relief.

- **Examples**

i) **Uplift Examples of Relief :** Raised beaches, elevated wave-cut terraces, sea caves and fossiliferous beds above sea level are evidences of uplift. Several places which were on the sea some centuries ago are now a few kms inland. For example, Coringa near the mouth of the Godavari, Kaveripattinam in the Kaveri delta and Korkai on the coast of Thirunelveli, were all flourishing sea ports about 1,000 to 2,000 years ago. The Cantabrian Coast of Spain on the Bay of Biscay has raised beaches reaching over 275 m above the water in some places, caused by an uplift of the land.

ii) **Subsidence Examples of Relief :** Submerged forests and valleys as well as buildings are evidences of subsidence. In 1819, a part of the Rann of Kachchh in Gujrat was submerged as a result of an earthquake. The Andamans and Nicobars have been isolated from the Arakan coast by submergence of the intervening land. A large part of the Gulf of Mannar and Palk Strait is very shallow and has been submerged in geologically recent times.

4.3 Orogenic Movement

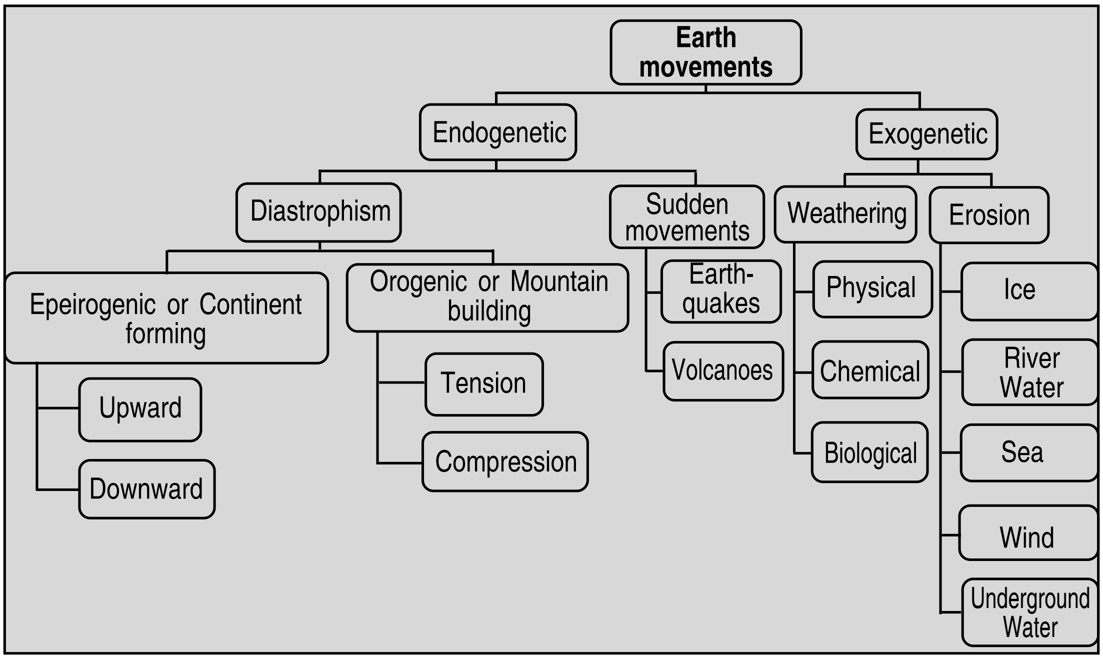
Orogenic movement is horizontal movements of plates or it is also known as the mountain forming movements which acts tangentially to the earth surface. Due to this process, the crust is severely deformed into folds. In true sense, Orogeny creates compression force which acts towards a point from two or more directions resulting into mountain building process where crust is severely deformed into several types of folds. The word Orogeny has been derived from the Greek word ‘Oros’ meaning mountain. The term was first introduced by the American geologist G.K. Gilbert in

1890 to describe the process of mountain building as distinguished from epeirogeny. An orogen or orogenic belt develops when a continental plate crumples and is pushed upwards to form one or more mountain ranges; this involves many geological processes collectively called orogenesis.

The processes of orogeny can take tens of millions of years and build mountains from plains or from the seabed. The topographic hjight of orogenic mountains is related to the principle of isostasy, that is, a balance of the downward gravitational force upon an up thrust mountain range (composed of light, continental crust material) and the buoyant upward forces exerted by the dense underlying mantle.

An orogenic event may be studied: (a) as a tectonic structural event, (b) as a geographical event, and (c) as a chronological event. So, Orogenic events cause distinctive structural phenomena related to tectonic activity. It affects rocks and crust in particular regions, and it happens within a specific period.

Orogeny is usually accompanied by folding and faulting of strata, development of angular unconformities and the deposition of clastic sediments in areas adjacent to the orogenic belt. Orogenies may result from subduction, and the under thrusting of continents by oceanic plates, continental collisions, the overriding of oceanic ridges by continents.



4.4 Folding

4.4.1 Definition And Characteristics

Folds are expressed in the wave like bending of the layers of rocks without their discontinuity. This bending or crumpling of rocks into folds is conditioned by the property of solid bodies to undergo plastic deformations. Folds are, therefore, developed in the country-rocks whenever the region is subjected to severe pressure or stress. So folds are the wave like secondary curvature induced on a planner surface. The resulting form is made up of a series of alternate crests and troughs. However, folds are of various size and form and rarely occur as isolated feature. The consecutive crests and troughs may be hundreds of kilometers apart for an exceptionally large fold, while the smallest folds may have several crests and troughs within a span of a few centimeters only.

4.4.2 Anatomy Of A Fold

In any fold there can be distinguished geometrical elements with the help of which its morphology can be described. The main geometrical elements offolds are limbs, axis, hinge, angle offold, axial plane etc.

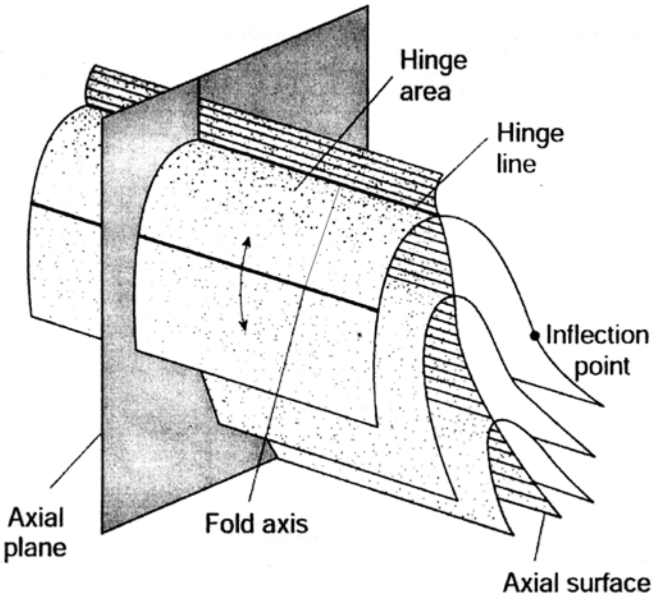


Fig 4.1: Anatomy of a Fold

i) *Limbs* are lateral parts of a fold, where the layers are inclined in one direction. Any two successive limbs together constitute one individual unit of fold. It is also known as flank.

ii) *Hinge* is the line running through the points of maximum curvature of any of the beds forming fold. The area adjacent to the maximum curvature of a fold is known as hinge area.

iii) *Core* of fold isthe inner part of the fold adjoining the hinge of fold.

iv) *Profile/Axial plane* is an imaginary plane which divides the folds into two. equal halves as symmetrically as possible. The axial plane may be vertical, horizontal, inclined or even a curved surface.

v) *Fold axis* is the line of intersection ofthe axial plane with the horizontal surface.

vi) *Angle of a fold* is the angle formed by the imaginary continuation offold limbs till their intersection. It may vary between 0° and 90°.

vii) *Plunge* of the fold is the angle the fold axis makes with the horizontal. Most of the folds have plunges and therefore known as plunging folds.

viii) *Height* of the fold is the vertical distance between the hinges of the adjacent anticline and syncline. It is also known as the amplitude ofa fold.

ix) *Width* of a fold is the distance between the axi al lines of two adjacent anticlines or synclines.

4.4.3 Causes Of Folding

Folding may be either due to tectonic causes or due to non-tectonic causes. The tectonic folding may be due to anyone or more of the following mechanisms.

(a) Folding due to Tangential Compression : Lateral Compression is believed to be the main cause for throwing the rocks of the crust into different types of folds. In general, this primary force is believed to act at right angles to the trend of folds under the influence of the tangential stresses, folding may develop in any of the three ways: flexural folding, flowage folding and shear folding.

(i) **Flexural Folding :** It is that process of folding in which the competent or stronger rocks are thrown into folds due to their sliding against each other under the influence of lateral compression. In flexural folding, the amount of slip depends on a number of factors such as: thickness 0 fthe layers, nature of the contact, distance from the hinge point and type of the rocks involved.

(ii) **Flowage Folding :** During the compression, the viscous or plastic mass like rock such as clays, shales, gypsum and rock salt etc get buckled up and deformed at varying rates suffering unequal distortion. In such cases the thickness of the resulting fold does not remain uniform.

(iii) **Shear Folding :** Folding, sometimes, is attributed to shearing stresses rather than simple compression. In such a process, initially, numerous closely spaced fractures develop in the rock. In the second stage, different amounts of displacement occur and finally, the rocks take up folded due to shearing stresses.

(b) Folding due to Intrusions : Magma intrusion from beneath has been found to be the cause of up arching of the overlying strata. In this region, highly viscous magma may be forced up and, as a result, the overlying sedimentary host rocks are bodily lifted up to provide space for the rising magma.

(c) **Folding due to Differential Compression :** During the stage of compaction in a basin of sedimentary formation, strata results in warping or folding of different types. Such folds are, however, totally dependent on the load from above and are attributed to superficial causes. These are, therefore, non-tectonic folds.

4.4.4 Classification Of Fold

The forms of folds are highly varied. Their classification is based on a number of different features.

- **ACCORDING TO THE CURVATURE AND SHAPE :**

Folds may be divided into the following types based on curvature or shape of the fold.

i) **Antiform :** An Antiform is a fold which is generally convex upwards. So, here the limbs commonly slope away from the axial plane.

ii) **Synform :** Synforrn is a fold which is generally concave upwards. The limbs, in a Synforrn commonly slope towards the axial plane.

DOME AND BASIN

The Antiform which has more or less equal length and width and dips in all direction away from a central region is known as *dome*. On the other hand, when it dips from all directions towards a central region is known as *basin*. However, beds folded in the form of domes or basins commonly exhibit circular or elliptical outcrops on a level surface. So, *domes* are like circular anticlines with the oldest strata exposed in the middle while basins are like round synclines, with the youngest strata exposed in the core.

ANTICLINE AND SVNCLINE

Anticline and Syncline are the most common form of Antiform and Synform respectively. In an anticline younger beds are found upwards and therefore, the older rocks constitute tie core. On the other hand in case of syncline younger beds are found towards the core or the centre of curvature of the fold. Anticlines and Synclines always occur in succession in any folded region.

iii) **Anticlinorium :** A large anticline with a number of secondary folds of smaller size developed on it is known as Anticlinorium. It is formed when the horizontal cornpressive tangential forces do not work regularly.

iv) **Synclinorium :** A large Syncline with a number of secondary folds of both syncline or anticline of smaller size developed on it is known as Synclinorium.

v) **Box fold :** The fold which has large flat area at the crest or trough and therefore, looks like a box is known as box fold.

• ACCORDING TO THE LIMB DIRECTION OR DIP DIRECTION

According to the dip direction folds are said to be symmetrical, asymmetrical, rnonoclinal, overturned, isoclinal etc type.

i) **Symmetrical :** A fold is said to be symmetrical when its axial plane is vertical and as a consequence either of the limbs has the same amount of dip.

ii) **Asymmetrical :** If the axial plane of a fold is inclined and as a result limbs have unequal dip the fold is known as asymmetrical.

Distinction between Symmetrical & Asymmetrical fold

Symmetrical fold	Asymmetrical fold
1. When two limbs of a fold are almost of equal length, the shape of the fold assumes symmetrical one.	1. When two limbs of a fold are mot equal in length, shape & size it appears asymmetrical.
2. Axial plane is vertical	2. Axial plane is inclined
3. Limbs have same amount of dip	3. Limbs have unequal amount of dip

iii) **Isoclinal :** If, in any fold, the limbs have the same amount of dip towards the same direction, as a consequence limbs are parallel to each other; the fold is described as isoclinal. In this case axial plane may be vertical or inclined and therefore they are termed as vertical isoclinal and inclined isoclinal respectively. However, in all isoclinal cases, the inter limb angle varies between 0° and 10°.

iv) **Over or Overturned :** If the axial plane is inclined to a considerable amount and as a result one limb seems to be turned under another the fold is described as over or overturned fold. Here both the limbs dip towards the same direction.

v) **Recumbent :** When a fold is very much overturned so that its axial plane is horizontal or very nearly so (0° to 10°) it is known as recumbent fold.

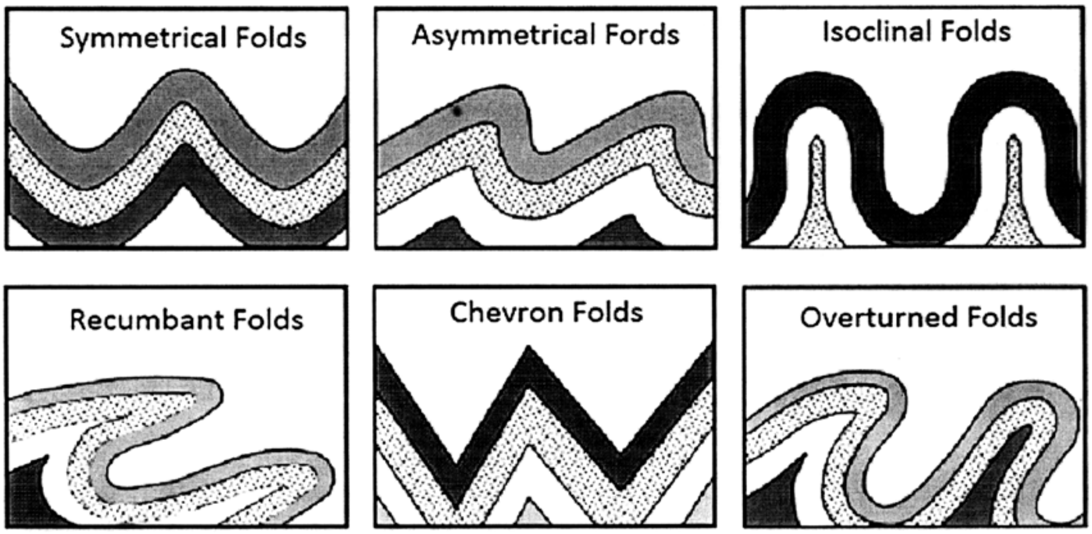


Fig 4.2 Different types of fold

vi) **Over thrust fold :** In extreme cases, fracture may occur in the fold due to excessive pressure and as a result, the upper limb of the recumbent fold slides forward over the lower one along the thrust plane. This type of fold is known as over thrust fold.

vii) **Nappe :** The over riding portion of the thrust that has moved a long distance (generally a mile or more) at low angle is called nappe. After long erosion, portions of a nappe may become isolated remnants called klippe.

- **ACCORDING TO THE INTERLIMB ANGLE**

Folds may be classified into gentle, open, closed or tight category based on interlimb angle.

i) **Gentle :** If the inter limb angle ofa fold varies between 120° and 180°, the fold is known as gentle type.

ii) **Open :** Open fold is one in which inter limb angle may vary between 90° and 120°.

iii) **Closed :** If the interlimb angle of a fold is greater than 30° but less than 90° the fold is said to be closed one.

iv) **Tight :** If the inter limb angle of a fold is less than 30°, it is described as tight fold.

- **OTHER CATEGORY**

Formation of some folds depend on different factors like nature of rocks, duration of the compressive forces, elasticity of rocks etc. the main varieties of such folds are as follows :

i) **Monocline :** The fold in which beds are relatively tlat but appears to have been locally to exhibit higher dips is known as monocline fold. It is sometimes described as half a fold. It is form by vertical movement and generally found fault below monocline.

ii) **Plunge :** In most cases the axes of simple folds are commonly horizontal. if the axis of the fold is no longer remain horizontal and slopes towards some direction, the fold is called *plunging or plunge fold*. However, the angle between the axis of the fold and the horizontal is known as the *plunge*. In anticline, plunge is directed towards nose and in syncline it is directed away from nose.

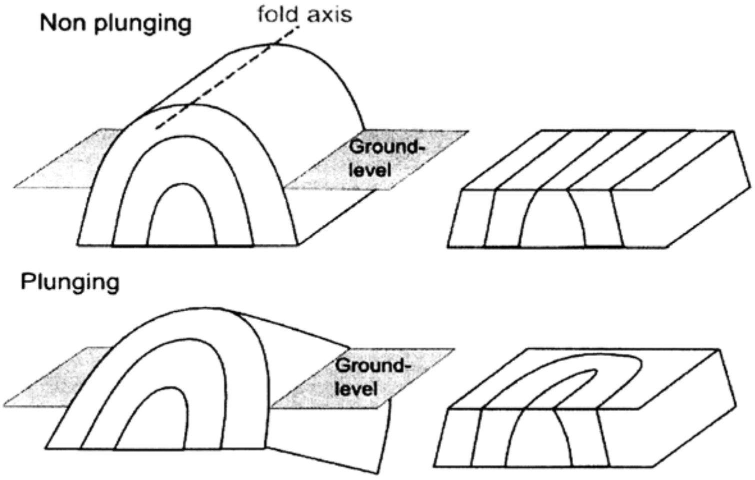


Fig 4.3 Plunging and Non-plunging fold

iii) **Fan :** If, in any fold, both the limbs are overturned and therefore looks like a fan, is described as a *fan* fold. It may be anticlinal fan fold or synclinal fan fold. In this case the limbs of anticlines dip towards each other and the limbs of synclines dip away from each other.

iv) **Chevron :** A chevron fold is one in which the crest or hinges are sharp angular and limbs are of equal length and straight. Well developed, these folds develop repeated set of v-shaped beds. They develop in response to regional or local compressive stress. Inter-limb angles are generally 60 degrees or less.

v) **Drag :** A drag fold is a minor fdfd formed either subsidiary to a main fold or along the side of a fault where the vertical displacement has made tlexures and puckers in the rocks on either side. They are generally asymmetrical in nature.

vi) **Doubly plunging :** Folds do often plunge along two opposite directions and are then described as doubly plunging folds.

4.4.5 Influence Of Folds On Landform

i) **Ridge-Valley Topography :** In the initial stage anticlines and synclines have come into existence with little erosional modification and the anticlines form mountain crests and syncline forms valley or troughs. Therefore, in a vast folded area, anticlines and synclines show up as long linear parallel anticlinal ridges and synclinal valleys. This is known ridge and valley topography. Trellis drainage pattern generally develop in this area where consequent streams flow along the valley and subsequent streams join into the valley at almost right angles.

ii) **Inversion topography :** In folded areas, the crest of the mountains or anticlinal ridge is a weak zone as the area shows maximum curvature. As a result, erosion opens up the anticline and rivers are developed. Further erosion of the anticlines by the rivers decreases its height and the eroded materials may deposit into the nearby synclinal valleys. Thus the synclinal structure of the mountain remains high, forming mountains while the anticlinal structure eroded by the river, forms a valley. This type of landform is known as inversion of relief.

iii) **Hogback and Cuesta topography :** *Hogbacks* are the resistant remnant of eroded and folded layers of, rocks. It has linear sharp ridge on steep dipping sedimentary rocks, the opposite slope of which may be symmetrical in shape. They generally develop when dip angle of rock layers exceed 45°. Here dip anglel and erosional slope is more or less equal. While *Cuesta* is an asymmetrical ridge with long gentle slope (1° - 20°) corresponding to the dip of a resistant bed and a steep slope on the cut edges of the beds. This type of land form generally develops in an open fold areas.

iv) **Homoclinal ridge and Valley topography :** Homoclinal ridge and valley are the most striking landforms encountered in areas of folded structure. Homoclinal ridges develop upon the dipping beds on the flanks ofanticlines and synclines while Homoclinal valley may develop when a belt of weak rocks lie between resistant beds.

v) **Zigzag ridge topography :** If the axis of a fold does not remain horizontal for long distances the fold tapers to an apex where the limbs meet, typically in a V-shape. Such features are called *plunging anticlines* and *plunging synciines.* Sometimes, the ridges formed due to dissection of folds will not run parallel but converge in the direction of pitch of an anticlinal fold, and in the opposite direction in a syncline. This gives rise to a pattern of converging and diverging or zigzag ridges.

4.5 Faulting

A fault is a fracture in the earth's crust along which movement has taken place and where the rock strata on the two sides therefore do not match. When the earth's crust bends folding occurs, but when it cracks, faulting happens. So, in contrast with joints, faults are well defined cracks along which the rock masses on either side have suffered relative displacement. This displacement may occur in any direction and its magnitude may vary between wide limits. Faulting may be caused by tensional force or compressional force. Usually earth movements generate tensional forces that tend to pull the crust apart and faults are developed.

4.5.1 Anatomy Of Fault

Like a fold a fault has different elements and definition of these elements is summarized below.

i) **Strike :** The direction of the line along which an inclined bed of a fault intersects a horizontal plane is known as the strike of the bed.

ii) **Dip :** Dip of the fault is the angle between a horizontal surface and the plane of the fault. It is measured in a vertical plane lying at right angles to the strike of the fault. It ranges in between 0° and 90°.

iii) **Hade :** Hade is the angle which the fault plane makes with the vertical plane. It is commonly I determined by the subtraction of dip from 90°.

iv) **Fault plane :** Fault plane is the plane along which the displacement takes place. The total displacement due to a fault is described as its net slip.

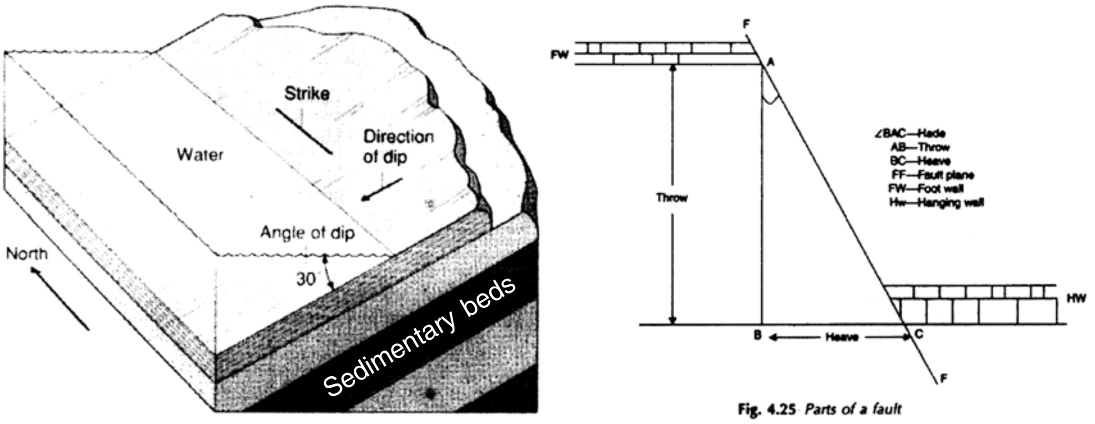


Fig. 4.25 Parts of a fault

Fig 4.4 : Anatomy of a Fault

v) **Hanging wall and foot wall :** In case of an inclined the two blocks are laying on both side of fault plane, and generally one of the di.!tocated blocks appears to rest on the other. The former is called the hanging wall and the later the foot wall. In simply, the part above the fault plane is known as the hanging Plane and the one below it is the foot wall.

vi) **Up thrown & down thrown side :** In any fault one of the dislocated blocks appears to have been shifted downwards in comparison with the other. The former, therefore, is known as the down thrown side while the later up thrown side.

vii) **Throw & heave :** The throw of a fault is the vertical component of the apparent displacement of a bed measured along the direction of dip of the fault. Similarly the horizontal component of the apparent displacement is known as heave or gape.

4.5.2 Causes Of Faulting

Faults are generally caused under the influence of stresses acting upon the rocks of the crust of the earth from within. Any rock on or below the crust may withstand all the operating stresses up to a limit, which depends upon its cohesive strength and internal friction. But, when that limit is crossed by the operating stresses, the rock yields by fracturing or breaking along certain directions. After the development of these fractures, the blocks created along the fractures suffer sudden (or gradual) displacement along these fractures. The displacement may take place essentially along the fracture surface or in different directions and for different distances depending upon the magnitude of the operating stresses thus giving rise to different types of faults.

So, both Tensional tectonic forces and shearing tectonic forces are responsible for faulting. Tensional tectonic forces pull in opposite directions in a way that stretches and thins the impacted part of the crust. Rocks, however, generally are stressed and broken rather than bending or stretching plastically, when subjected to tensional forces. Broken discrete blocks, called fault blocks, are then separated from each other by normal faults. In order to accommodate the extension of the crust, one crustal fault block slides downward along the normal fault relative to the adjacent fault block. The direction of motion along a normal fault is opposite to that along a reverse or thrust fault. Anderson (1905, 1951) showed that the three major classes of faults (reverse, normal, and strike-slip) result from the three principal classes of inequality that may exist between the principal stresses.

4.5.3 Cassification Of Faults

There are two main basis of classification of faults—Genetic and Geometrical. Sometimes faults are also classified on the basis of dip of the fault plane and the direction of relative movement of the rocks on its two sides. However, here all the classifications are discussed briefly.

• GENETIC CLASSIFICATION

i) **Normal fault :** A normal fau1t is one in which the hanging wall has apparently moved down with respect to the footwall. They are caused exclusively by the tensional forces and in these faults, the maximum stress is vertical. So they are called vertical fault or gravity fault or tensional fault. The fault plane is usually inclined at an angle between 45° and 90°. However, due to the incluned nature of the fault plane and downward displacement ofa part of the strata, normal faults cause an extension in the crust wherever they occur.

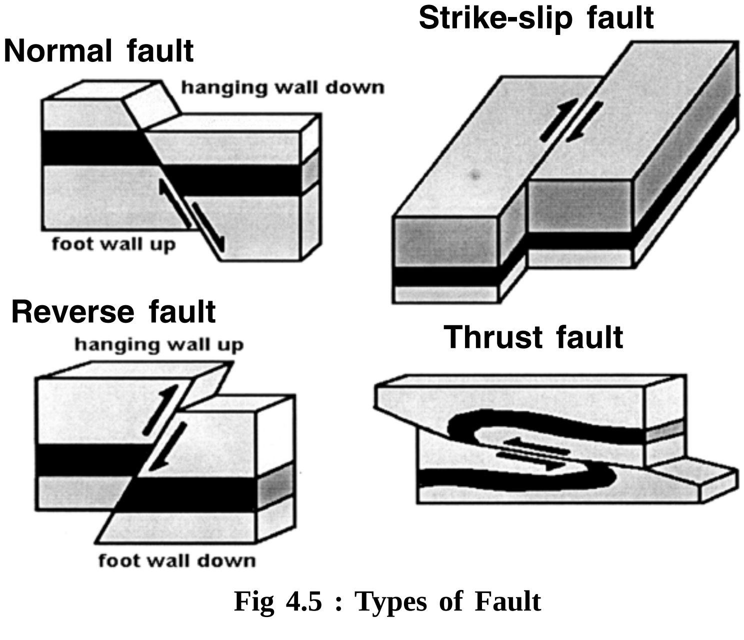


Fig 4.5 : Types of Fault

ii) **Reverse fault :** A reverse fault is one in which the hanging wall moves relatively over the footwall. They are regarded as a shear deformation under the conditions of compression ofthe earth's crust and the maximum stress is horizontal. In reverse faults, the fault plane is generally inclined between horizontal and 45 degrees although reverse faults with steeply inclined fault surface have been also encountered.

Distinction between Symmetrical and Asymmetrical fold

Normal fault	Reverse fault
1. A normal fault is one in which the hanging wall has apparently moved down with respect to the footwall.	1. A reverse fault is one in which the hanging wall moves relatively over the footwall.
2. Normal faults are caused by tensional force.	2. Reverse faults are caused by compressional forces.
3. Normal faults generally cause extension of surface area.	3. Reverse faults result shortening of the surface area.
4. In normal fault vertical stress is maximum while horizontal stress is minimum.	4. In reverse fault vertical stress is minimum while horizontal stress is maximum.
5. The fault plane is usually inclined at an angle between 45° and 90°.	5. The fault plane is usually inclined at an angle between 40° and 0°.
6. A normal fault has a steep, straight fault scarp. With passing time there develops a prominent fault line scarp.	6. Reverse fault also produces steep scarp but this will not stay for long and therefore there was no prominent fault line scarp.
7. Normal faults are known as gravity fault or tensional fault.	7. Reverse faults are known as thrust fault or Compressional fault.

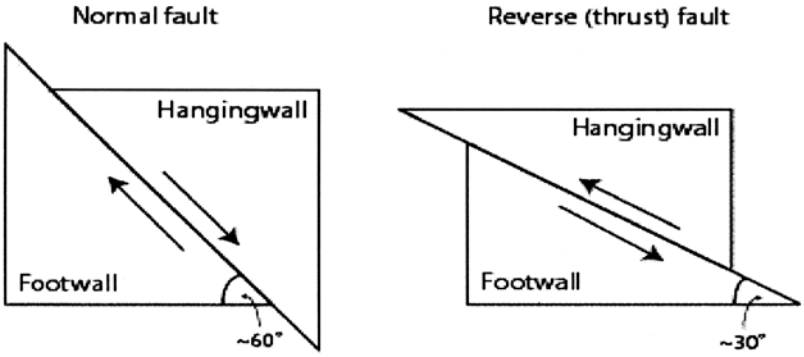


Fig 4.6 : Anatomy of Normal and Reverse fault

iii) **Thrust fault :** Fault in which the hanging wall has moved up in relation to the foot wall and fault plane dipping an angle of less than 45° is known as thrust fault or low angle reverse fault. Over thrusts are those in which the initial dip is 10° or less and the net slip is measurable in terms of kilometers. While, in case of under thrusts the dip is also 10° or less and the foot wall side moved and pushed itself underneath the hanging wall.

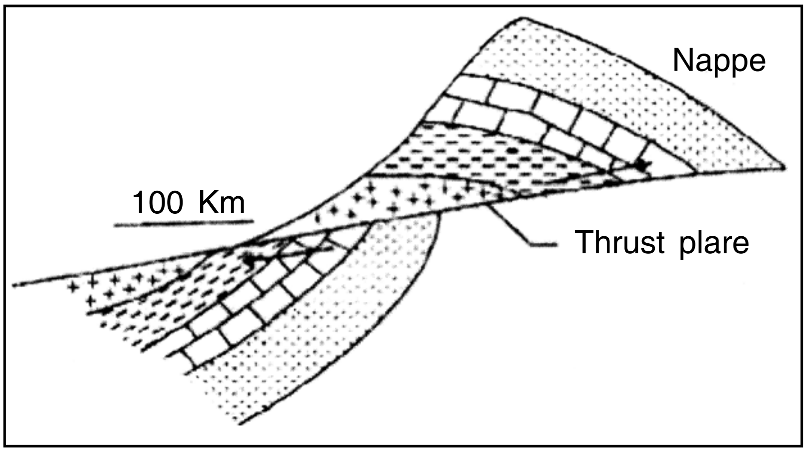


Fig 4.7 : Thurst fault

iv) **Nappe :** Due to continuedjsorizontal movements and compressive force a large solid rock may move a long distance, preferably a mile or more at low angle over the underlying rocks either by over thrusting or recumbent folding. Such broken portion is known as nappe. Several examples of nappes are traceable in the vast fold mountains like Alps or Himalayas.

- **GEOMETRIC CLASSIFICATION**

i) **Strike slip fault :** The fault where displacement remains essentially parallel to the strike of the fault is described as the strike slip fault. So vertical displacement is almost nil. They are formed when there is strong horizontal movement along the fault plane. These are also known as transcurrent, transform or tear faults. In case of tear fault the strike of the fault is transverse to the strike of the country rock but the displacement is along the strike of the fault plane. When the displacement occurs to the left on the far side of the fault, the fault is known as left-lateral or sinistral faults while the displacement takes place to the right on the far side of the fault the fault is known as right-lateral or dextral fault.

ii) **Dip slip fault :** Dip slip fault is a normal or reverse fault on which the only component of movement lies in a plane normal to the strike of the fault surface. Here vertical displacement is only found and there is no horizontal displacement.

iii) **Diagonal slip fault :** A vertical or inclined fault where displacement occurs in any direction other than the direction of dip and strike of the fault plane is described commonly as a diagonal or oblique slip fault. Here both vertical and horizontal displacement occurs together.

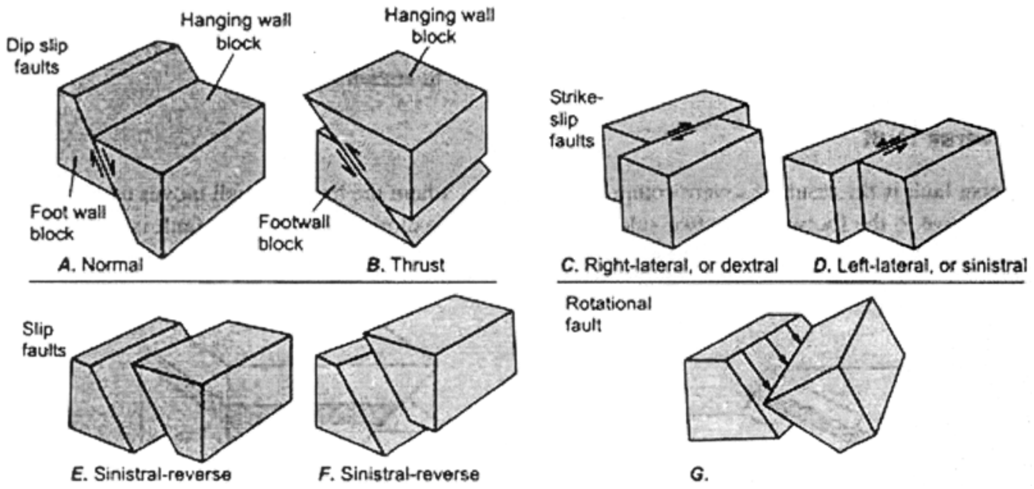


Fig 4.8 : Types of fault

• BASED ON THE DIRECTION OF RELATIVE MOVEMENT OF THE ROCKS ON ITS TWO SIDES.

i) **Strike fault :** A vertical or inclined fault that strikes parallel to the strike of the country beds (not parallel to the strike of the fault plane) is known as strike fault. the dip of the strata involved. Here fault line & strike of the country rocks are parallel to each other.

ii) **Dip fault :** Dip fault is a vertical or inclined fault that strikes parallel with the dip of the strata involved (not parallel to the dip of the fault plane). Here strike of the fault plane & strike of the country rocks lie at right angle.

iii) **Bedding fault :** A bedding fault is oriented essentially parallel to the bedding planes of the country rocks. it is, therefore, a special case of strike fault.

iv) **Diagonal fault :** The fault that strikes in any inclined direction with respect to the strike of the country rock is known as diagonal fault.

- **OTHER FAULTS**

i) **Parallel fault :** When there lie a series of fault having the same dip & strike parallel fault may develop. It may be vertical or inclined.

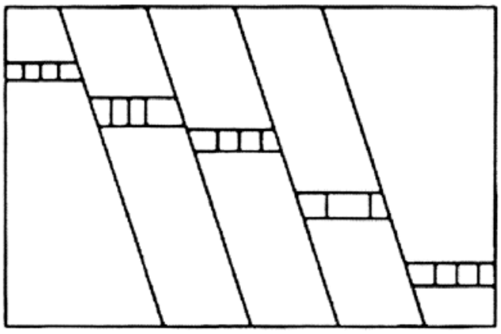


Fig 4.9 : Parallel Fault

ii) **Step fault :** If the successive blocks of parallel fault are downthrown more & more towards a particular direction, it looks like the steps in a staircase and sesulting structure is known as step fault.

iii) **Peripheral fault :** Curved faults of more or less circular or arc like outcrop on a level surface are described commonly as peripheral fault.

iv) **Radial fault :** When a number of faults radiate in different direction from a particular point, the structure is known as radial faults.

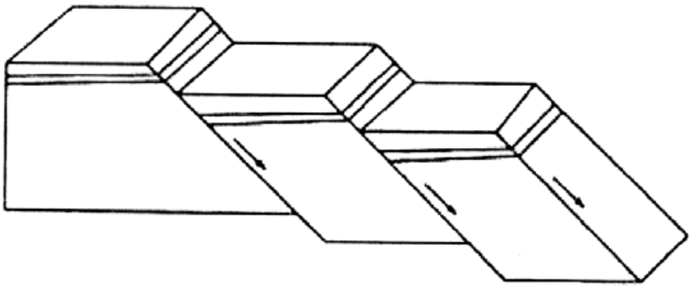


Fig 4.9 : Step fault

v) **Hinge faults :** Hinge faults are produced by rotational movement between two fault blocks where the displacement increases from zero to a maximum alone the strike.

vi) **Pivot fault :** In a pivot fault one block appears to have rotated about a point on the fault plane such that for part of its length the fault is normal with decreasing throw.

TRANSFORM FAULT

A large scale strike slip fault between or within crustal plates with displacement wholly or mostly in the horizontal plane is known as transform fault. They are largely found on the ocean floor. They cut across and offset the rift zones of mid oceanic ridges, throughout the world. The most important surface expression of transform faults are San Andreas fault, California fault, Alpine fault, Philippines fault etc.

4.5.5 Influence Of Fault On Landform

i) **Block Mountain and Horst :** Block Mountain or Horst is the common features in a faulted region. Block Mountain may be formed by the up throwing of a block on one side of pair of parallel fault. Thus the up thrown block stands like a mountain and is known as Block Mountain. They are generally bounded by a fault scarp on one side & gentle slope on the other side. The mountain ranges of the Great Basin of the USA belong to this category. The Western Ghats in India, Sierra Nevada in USA etc are the characteristic example of Block Mountains.

When the blocks are thrown up in between fault planes, these are known as *Horsts*. These horsts have scarp like slopes. In this case the central block is not only up thrown but the side blocks are also relatively down thrown so that the whole mass appears like a dome. The Black Forest Mountain in Germany, the Vosges in France, the Satpuras & Vindhyans in India etc are the common examples of Horsts.

ii) **Rift Valley or Grabben :** A narrow block dropped down between two normal faults is a Rift valley. They are usually long & narrow. Tensional forces are generally responsible for the formation of such valley. A rift valley is known as Graben in German language. The Grate lakes of Africa, Dead Sea of Israel, the red Sea, the Rhine valley in Germany, the Normada & the Tapi valley in India are considered to be the examples of rift valleys.

iii) **Ramp valley :** Sometimes a rift valley may result from the forcing down of a central block along reverse fault. Such depressed valley between two reverse fault is known as Ramp valley. Some stretches of the Brahmaputra valley is considered to be the example of Ramp valley.

iv) **Fault scarp and fault line scarp :** The steep topographic slope caused by faulting is known as fault I scarp. Normal fault gives rise to scarp which is rather steep and straight slope while reverse fault generally results fault scarp with oVjihanging cliff.

As erosion proceeds, the cliff or scarp gradually disappears and irregularities of relief may rise along the line of the fault due to forces of erosion, leaving the actual fault line buried beneath sediments. This is known as fault line scarp. Fault line scarp generally develops in the second or third cycle of erosion. So the fundamental difference between a fault scarp and fault line scarp is that the former is produced by movement of the fault, whereas the latter is produced by differential resistance to erosion on either side of the fault line. There may develop two different types offault line scarp, such as:

a) **Resequent fault line scarp :** When the soft rocks constitute the down thrown side of a fault scarp it continues to lower the ground and the new scarp facing in the same direction as in the original fault scarp. This is known as Resequent fault line scarp.

b) **Obsequent fault line scarp :** When the hard rocks constitute the down thrown side and soft rocks the up thrown side of a fault scarp, the long continued erosion will produce reverse condition i.e. up thrown side will now become down thrown. Such a fault line scarp facing the opposite way to the original fault scarp is known as Obsequent fault line scarp.

v) **Composite fault scarp :** According to cotton In 1917, composite fault scarp may develop in a faulted region where the scarp height is due partly to differential erosion and partly to fault movement. A typical example of such fault scarp is found in the northern portion of East Humboldt Mountain in USA.

vi) **Waterfall, spring and lakes :** Sometimes fault develops in the river course as a result of earth's movement and with palsing time fault line scarp produces rapids or waterfall. Sometimes such faults may block river flow and develop lake. Sometimes, under ground water may come out along the fault plane and/ault scarp spring develop.

4.6 Summary

The crust is not stable everywhere. There are various Endogenic and Exogenic forces that are operating with the earth's crust and hence folding and faulting taking place.

4.7 Glossary

1. **Amplitude :** Half the height of the structure measured from crest to trough
2. **Arc length :** The distance between two hinges of the same orientation measured over the folded surface
3. **Axial surface :** The surface containing the hinge lines from consecutive folded surfaces
4. **Crest :** The topographically highest point of a fold, which need not coincide with the fold hinge
5. **Cross section :** A vertical plane through a fold
6. **Culmination :** High point of the hinge line in a noncylindrical fold
7. **Cylindrical fold :** Fold in which a straight hinge line parallels the fold axis; in other words, the folded surface wraps partway around a cylinder
8. **Depression :** Low point of the hinge line in a noncylindrical fold
9. **Fold axis :** Fold generator in cylindrical folds
10. **Hinge :** The region of greatest curvature in a fold
11. **Hinge line :** The line of greatest curvature
12. **Limb :** Less curved portion of a fold
13. **Non-cylindrical fold :** Fold with a curved hinge line
14. **Profile plane :** The surface perpendicular to the hinge line
15. **Trough :** The topographically lowest point of a fold, which need not coincide with the fold hinge
16. **Dip slip :** Offset parallel to dip (up or down)
17. **Faults :** Deep cracks caused by movement of rock during earthquakes. Different rock types are often seen on each side of a fault.
18. **Folds :** Bending of rock layers caused by compression of rocks, usually as part of

mountain-building when tectonic plates collide.

19. **Footwall :** Block of rock below fault plane
20. **Grabens :** Down-dropped fault blocks.
21. **Hanging Wall :** Block of rock above fault plane
22. **Horsts :** Uplifted fault blocks.
23. **Joints :** Fractures in the rock which have opened up perpendicular to the walls (or faces), generally without any shearing of one side past the other
24. **Low-angle fault :** Dip 10-30 deg.
25. **Normal Faults :** Dip-slip fault in which hanging wall moves down relative to footwall
26. **Oblique slip :** Offset oblique to fault dip.
27. **Reverse Faults :** High-angle, dip-slip fault in which hanging wall moves up relative to footwall
28. **Steep fault :** High angle dip (60° - 80°)
29. **Strike slip :** Offset parallel to fault strike
30. **Strike Slip Faults :** Hanging wall and footwall offset along strike of fault plane (neither up or down)
31. **Strike slip :** Left or right lateral
32. **Thrust :** Often low angle - offset up dip
33. **Thrust Faults :** Low-angle, dip slip fault in which hanging wall moves up.

4.8 Questions

A. Short Type (within 200 words)

1. What is faulting?
2. How are Fold Mountains formed?
3. Discuss four main features of faulting
4. Explain three types of faults.
5. What are limbs? Explain it with the help of a diagram.
6. The orientation ofa plane in space is expressed by its attitude; a term consisting of two components, strike and dip. Define strike and dip.

7. Why do normal faults tend to be steeper than reverse faults?
8. How could dome-and-basin patterns form?
9. How does nappe form?
10. How does transform fault develop?
11. Which forces cause faulting and folding?
12. How Block Mountains are formed?
13. Explain the anatomy of the fold.
14. What is drag fold?
15. Distinguish between resequent fault line scarp and obsequent fault line scarp.
16. Distinguish between fault scarp and fault line scarp.
17. What do you mean by low angle and high angle fault?
18. How parallel fault is developed?
19. How does chevron fold form?
20. Distinguish between normal and reverse fault.
21. Explain major differences between fold and fault.
22. What is the difference between a strike-slip fault and a dip-slip fault? Use a simple diagram showing each.
23. What is the difference between symmetrical and asymmetrical fold.
24. Distinguish between thrust fault and reverse fault.
25. Distinguish between recumbent and overturned folds.
26. Draw and label a diagram depicting the different parts of a fault.
27. Define strike and dip of a fault.
28. Draw a cross-section of a fold labeling axial plane and limbs.

B. Long Type (within 600 words)

29. What is a fault and what are the different types?
30. How are the different types offaults classified?
31. Define fold. Descri be different parts of a fold with diagram.
32. How fault is formed? Describe anatomy of a fault.
33. Classify fold based on axial plane and describe each with diagram.

34. Describe causes offolding and faulting.

35. Describe different landforms produced by folding.

36. Describe different topographic expressions developed by faulting.

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Unit 5 ❑ Degradational Processes : Weathering, Mass Wasting and Resultant Landforms

Structure

5.0 Objectives

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5.1 Introduction

Weathering is the breakdown and alteration of rocks at Earth's surface through physical and chemical reactions with the atmosphere and the hydrosphere. Joints and fractures facilitate weathering because they permit water and gases in the atmosphere to attack a rock body at considerable depth. They also greatly increase the surface area on which chemical reactions can occur. The major products of weathering are spheroidal rock forms, a blanket of regolith, and dissolved ions. Soil is the upper part of the regolith—a mixture of clay minerals, weathered rock particles, and organic matter. Climate and rock type greatly influence the type and rate of weathering.

Erosion is the physical removal and transportation of weathered material by water, wind, ice, or gravity. Weathering is the physical disintegration or chemical alteration of rocks at or near the Earth's surface. Weathering process occurs at or near the Earth's surface and produce changes to the landscape that influences surface and subsurface topography and landform development. Weathering is the breakdown and alteration of rocks at Earth's surface through physical and chemical reactions with the atmosphere and the hydrosphere.

By definition, weathering is different from erosion. Weathering involves only the breakdown of rock, whereas erosion involves the removal of debris produced by the breakdown. In reality, however, weathering and erosion are intimately involved with one another. Weathering disintegrates solid rock and produces loose debris. Erosion by running water, wind, and ice removes the debris and exposes fresh rock, which is then weathered, and the cycle continues. The results of weathering are seen everywhere, from the debris along hill slopes to decomposed monuments of antiquity. In weathering, rocks adjust and are altered to forms more stable at low pressure, low and fluctuating temperatures, and the chemical environment with abundant water that prevails at Earth's surface. Thus, metamorphic rocks and igneous intrusions are generally most susceptible to weathering.

5.2 Types of weathering

Weathering, involves a multitude of physical, chemical, and biological processes, but three main types of weathering are recognized:

(A) **Physical weathering:** Physical weathering is the mechanical fragmentation of rocks from stress acting on them. Physical (or mechanical) weathering breaks the rock mass into small particles. It is strictly a physical process involving no change in chemical composition. It is strictly a physical process involving no change in chemical composition. Ice wedging may be the most important type. Examples: exfoliation, frost wedging, salt wedging, temperature changes, and abrasion.

(B) **Chemical weathering:** Chemical weathering involves chemical reactions with minerals that progressively decompose the solid rock. Chemical weathering alters the rock by chemical reactions between elements in the atmosphere and those in the rocks. Most geologists believe that chemical weathering is most important in terms of total amount of rock breakdown.

The major types of chemical weathering are dissolution, carbonation, hydration, acid hydrolysis, and oxidation.In most places, however, the two processes work together, each facilitating the other, so that the final product results from a combination of the two processes.

(C) **Biological weathering** is the disintegration or decay of rocks and minerals caused by chemical or physical agents of organisms. Examples: organic activity from lichen and algae, rock disintegration by plant or root growth, burrowing and tunnelling organisms, and acid secretion.

Joints and fractures facilitate weathering because they permit water and gases in the atmosphere to attack a rock body at considerable depth. They also greatly increase the surface area on which chemical reactions can occur.The major products of weathering are spheroidal rock forms, a blanket of regolith, and dissolved ions. Soil is the upper part of the regolith—a mixture of clay minerals, weathered rock particles, and organic matter.Climate and rock type greatly influence the type and rate of weathering.

5.3 Controlling factors of Weathering

A. Different types of Mechanical Weathering:

1. **Block disintegration** due to temperature change have great impact upon many rocks. Due to differential heating and repetition of expansion and contraction of outer rock layers due to diurnal range of temperature in the hot desert areas causes tension and stress which introduce parallel joints in the rocks. The rocks then are disintegrated along the joints and broken big blocks are dislodged from main rock mass and often fall down slope due to gravity.

2. **Exfoliation due to unloading** is a mechanical weathering process whereby the rocks which are buried under thick covers of overlying rocks are disintegrated, when they are exposed to the surface due to removal of superincumbent load, consequently the pressure in the rock is released along parallel alignments near the surface of the bedrock and layers or slabs of the rock along these alignments break off from the bedrock and move downhill by gravity. Often this phenomenon is called Sheeting (R. H. Jahns, 1943). Cambering process refers to fracturing of brittle sandstone beds along

vertical joints due to expansion caused by unloading of super incumbent load and consequent release of confining pressure (G. W. Bain, 1931 and C. D. Olier, 1969). Process of Spalling refers to the development of platy rock fragments, irregular shaped in the rocks due to unloading of super incumbent load.

3. **Exfoliation due to temperature and wind** also called Onion Weathering refers to peeling off concentric shells of rocks due to combined actions of heat and wind in hot arid and semi-arid region. It is common in crystalline rocks where the outer shell of rocks become loose due to alternate expansion and contraction due to high temperature during day and low temperature during night respectively and these loosened shells are removed by strong winds.
4. **Frost wedging** is a mechanical weathering process caused by the freeze-thaw action of water that is trapped between cracks in the rock. This process gradually weakens, cracks, and breaks the rock through repetitive freeze-thaw weathering cycles. When water freezes, it expands and applies pressure to the surrounding rock forcing the rock to accommodate the expansion of the ice.
5. **Granular Disintegration** due to temperature changes is often not the dominant form of weathering, but instead temperature changes tend to accelerate other forms of weathering already occurring. This process is more common in desert climates because they experience extreme fluctuations in daily temperature changes. This gradual expansion and contraction of mineral grains weakens the rock causing it to break apart into smaller fragments or to fracture. Warmer temperatures may cause some minerals to expand, and cooler temperatures cause them to contract. Daily (diurnal) and seasonal temperature changes affect certain minerals and facilitates the mechanical weathering of bedrock.
6. **Salt wedging** is most common in drier climates, such as deserts. Salt wedging occurs when salts crystallize out of solution as water evaporates. As the salt crystals grow, they apply pressure to the surrounding rock weakening it, until it eventually cracks and breaks down, enabling the salt crystal to continue growing.

7. **Abrasion** occurs when rocks collide against each other while they are transported by water, glacial ice, wind, or gravitational force. During abrasion, rocks may also weather the bedrock surface they are coming into contact with as well as breaking into smaller particles and eventually individual grains.

B. Different types of Chemical Weathering

1. **Carbonation** is a process by which carbon dioxide and rainwater or moisture in the surrounding environment chemically reacts to produce carbonic acid, a weak acid that reacts with carbonate minerals in the rock. The reaction creates new compounds which tend to be softer and weaker than the original parent rock material. Carbonation dominates the weathering of calcareous rocks (limestone and dolomites) where the main mineral is calcite or calcium carbonate (CaCO3). Calcite reacts with carbonic acid to form calcium hydrogen carbonate (Ca (HCO3)2) that, unlike calcite, is readily dissolved in water. This is why some limestone is so prone to solution. The reversible reactions between carbon dioxide, water, and calcium carbonate are complex. In essence, the process may be written:

   $CaCO_3 + H_2O + CO_2 + Ca^{2+} \Leftrightarrow 2HCO_3^-$

   This formula summarizes a sequence of events starting with dissolved carbon dioxide (from the air) reacting speedily with water to produce carbonic acid, which is always in an ionic state:

   $CO_2 + H_2O\ H^+ \Leftrightarrow HCO_3$

   Carbonate ions from the dissolved limestone react at once with the hydrogen ions to produce bicarbonate ions:

   $CO_3^{2-} + H^+ \Leftrightarrow HCO_3^{2-}$

2. **Hydrolysis** is a chemical reaction between H+ and OH- ions in water and the minerals in the rock. The H+ ions in the water react with the minerals to produce weak acids. An example of hydrolysis: Anhydrite (CaSO4) can absorb two water molecules to become gypsum (CaSO4·2H2O).

   Carbonic acid forms when rainwater combines with carbon dioxide in the atmosphere or the soil by the reaction:

$H_2O + CO_2 = H_2CO_3$

(water) (carbon dioxide) (carbonic acid)

This acid may then react with calcite to form calcium and bicarbonate ions in solution. This reaction may be expressed as follows :

$CaCO_3 + H_2CO_3 = Ca^{2+} + 2HCO_3^-$

(calcite) (carbonic acid) (calcium bicarbonate)

Some silicate minerals may also dissolve, although not as readily as calcite. For example, pyroxene will slowly dissolve when it is in contact with acidic waters according to the following reaction :

$MgSiO_3 + H_2O + 2H_2CO_3 = Mg^{2+} + 2HCO_3^- + H_4SiO_4$

(pyroxene) (water) (carbonic acid) (ions) (silicic acid)

3. **Hydration** is a process where mineral structure in the rock forms a weak bond with H20 which causes the mineral grains to expand, creating stress which causes the disintegration of the rock. Hydration often produces a new mineral compound that is larger than the original compound. The increased size expanse the rock and can lead to decay. Hydration can also lead to color changes in the weathered rock surface.

4. **Oxidation** occurs when oxygen and water react with iron-rich minerals and weaken the structure of the mineral. During oxidation the minerals in the rock will change colours, taking on a ‘rusty’, reddish- orange appearance. In this reaction, the iron in silicate minerals unites with oxygen to form the mineral hematite (Fe2O3). Hematite is deep red, and if it is dispersed in sandstone or shale, it imparts a red colour to the entire rock. Limonite [FeO(OH)] is another common weathering product. It is formed by oxidation combined with a reaction with water.

   $2Fe_2SiO_4 + 2H_2O + O_2 = 2Fe_2O_3 + 2H_4SiO_4$

   (ilivine) (water) (oxygen) (hematite) (silicic acid)

5. **Solution** most commonly occurs on rocks containing carbonates such as limestone, but may also affect rocks with large amount of halite, or rock salt Solution occurs when minerals in rock dissolve directly into water. The most soluble natural minerals are chlorides of the alkali metals: rock salt or halite (NaCl) and potash salt (KCl). These are found only in very arid climates.

Gypsum ($CaSO4.2H2O$) is also fairly soluble, as is limestone. Quartz has a very low solubility. The solubility of many minerals depends upon the number of free hydrogen ions in the water, which may be measured as the pH value

6. **Biochemical Weathering: Chelation:**This is the removal of metal ions, and in particular ions of aluminium, iron, and manganese, from solids by binding with such organic acids as fulvic and humic acid to form soluble **organic matter–metal complexes**. The chelating agents are in part the decomposition products of plants and in part secretions from plant roots. Chelation encourages chemical weathering and the transfer of metals in the soil or rock.

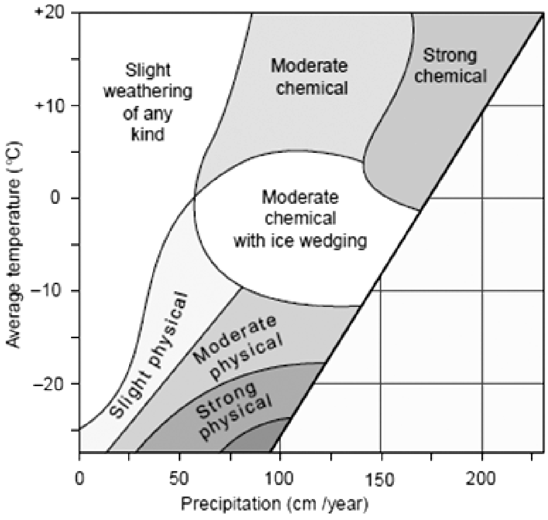
C. Biological Weathering

1. Secretion of acids -Some organisms, such as snails, barnacles, or limpets, attach themselves to rocks and secrete acid, acids that chemically dissolve the rock surface.
2. Burrowing and tunnelling organisms - Some animals may burrow or tunnel into rocks or cracks in rocks and cause the rock to break down and disintegrate. Small animals, worms, and other insects, often contribute to this form of biological weathering.
3. Rock disintegration by plant growth - The most common form of biological weathering is when plant roots penetrate into cracks and crevices of rocks and cause the rock to split or break into smaller particles through mechanical weathering. The presence of organisms growing, expanding, or moving across the surface of the rock also exerts a small amount of abrasion and pressure that gradually cause the mechanical weathering of the rock as the organisms extract various minerals.
4. Organic activity from lichen and algae and decaying Plants -The decaying of plant materials can also produce acidic compounds which dissolve the exposed rock. This bio-chemical weathering process leaches minerals from the rock causing it to weaken and breakdown.

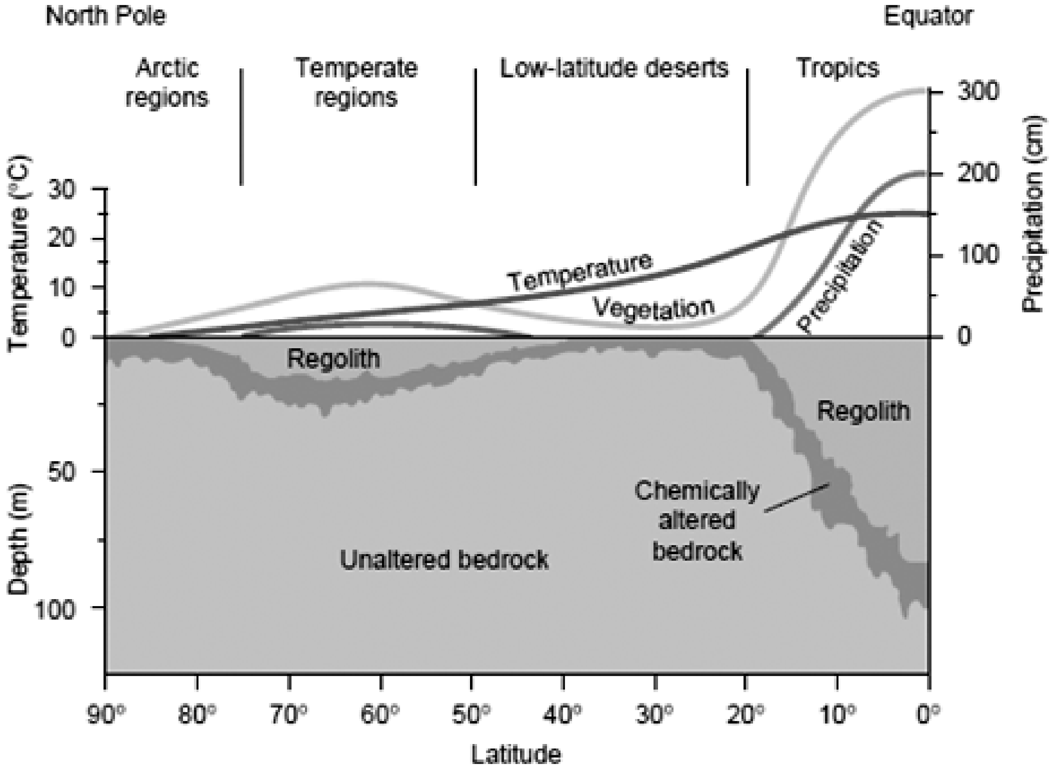
5.4 Climate and Weathering

Climate can also produce differential weathering responses for the same rock type. For example, limestone weathers more quickly in wet climates than dry climates Climate is the single most important factor influencing weathering. It determines not only the type and rate of weathering, but also the characteristics of regolith and weathered rock surfaces. Intense chemical weathering occurs in hot, humid regions and develops a thick regolith. Chemical weathering is minimal in deserts and Polar Regions. Climate is of major importance in weathering because rainfall, temperature, and seasonal changes all directly affect the style and rates of weathering. The influence climate has on weathering is apparent in the striking contrasts of the soil in the tropics, deserts, and polar regions In physical weathering, perhaps the most important temperature changes are the ones that produce continual cycles of freezing and thawing that result in repeated expansion of water ice in the rock and soil, and thus mechanical fragmentation. The rate of chemical reactions (and biological activity) also tends to increase as temperature increases. Commonly, a 10°C increase in temperature doubles reaction rates.

The relative importance of various types of weatheringdepends on temperature and rainfall. This diagram shows that strong chemical weathering occurs where both temperature and precipitation are high. Physical weathering is strongest where the mean annual temperature is between –10° and 10°C and precipitation is between 25 and 100 cm. Weathering is at a minimum where annual precipitation is below 25 cm.



Climate controls the type and extent of weathering because of the combined effects of precipitation, temperature, and vegetation. Weathering is most pronounced in the tropics, where precipitation, temperature, and vegetation reach a maximum. Conversely, a minimum of weathering is found in deserts and Polar Regions, where these factors are minimal.



5.5 Differential weathering / Rates of weathering

The differences in rates of weathering due to different types of rocks, textures, or other characteristics are referred to as differential weathering. Some rocks are harder than other rocks, and will weather slower than softer rocks. Weathering rates will not only vary depending on the type of weathering process, whether it is mechanical, chemical, or biological, but they will also vary depending on the rock material that is being weathered.

The rate at which weathering processes decompose and break down a solid rock body depends on three main factors:

(1) Susceptibility of the constituent minerals to weathering,

(2) Climate, and

(3) The amount of surface exposed to the atmosphere.

A consideration of the rate at which weathering proceeds, is a good way to review its controlling factors. Rates of weathering can be calculated by measuring the amount of decay on rock surfaces of known age. Tombstones, ancient buildings, and monuments, for example, provide datable rock surfaces for estimating rates of weathering. These studies show that in some climates, several centimetres of rock can be decomposed in a few decades, whereas the same rock remains unaltered in other climates.

5.6 Weathering of Major rock types

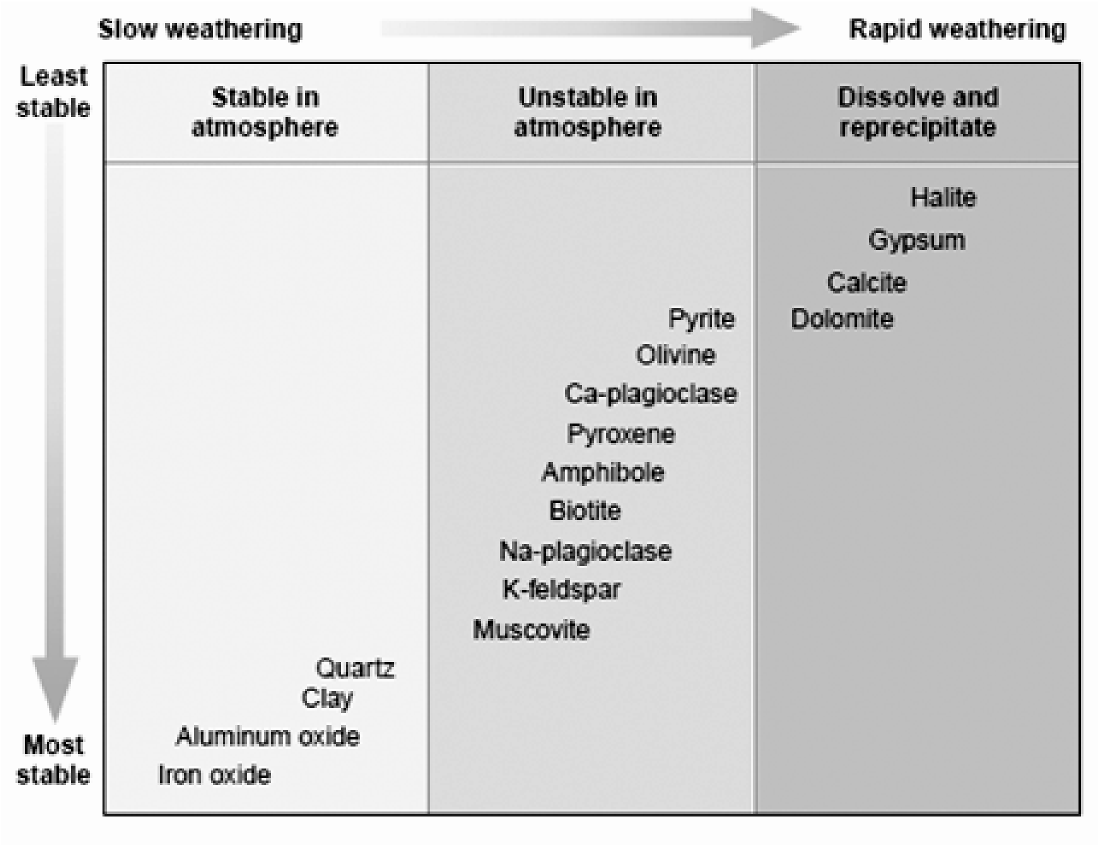
The weathering of rocks is influenced by a number of variables, such as the mineral composition, the texture of the rock, and the climate in which weathering occurs. Differential weathering is a result of differences in the rates of weathering. Weathering is influenced by so many factors that it is difficult to make a meaningful generalization concerning the weathering of specific rock types. Limestone, for example, may weather and erode into a soil-covered valley in a humid climate, whereas the same formation forms a cliff in an arid climate. Similarly, well-cemented quartz sandstone may be extremely resistant to weathering, whereas sandstone with high clay content is likely to be soft and weak and weather rapidly.

Table : Weathering Reactions For Common Minerals

Original Mineral	General Formula	Weathering Reactions	Dissolved Ions	Residual Minerals
Gypsum	$CaSO_4 \bullet 2H_2O$	Dissolution by water	Ca, SO_4	
Halite	NaCl	Dissolution by water	Na, Cl	
Olivine	$(Mg.Fe)_2SiO_4$	Oxidation		Fe oxides
		Dissolution by acid	Mg, Fe	
Pyroxene	Ca(Mg, Fe)Si2O6	Oxidation		Fe oxides
		Dissolution by acid	Mg, Fe, Ca	
Amphiboles	$NaCa(Mg, Fe)_5AlSi_7O_{22}(OH)_2$	Oxidation	Fe oxides	
		Partial solution by acid	Na, Ca, Mg	Clay
Plagioclase	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$	Partial solution by acid	Na, Ca	Clay

K-feldspar	$KAlSi_3O_8$	Partial solution by acid	K	Clay
Muscovite	$KAl_3Si_3O_{10}(OH)_2$	Partial solution by acid	K	Clay
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	Oxidation	Fe oxides	
		Partial solution by acid	K.Mg	Clay
Quartz	SiO_2	Resists dissolution		
Calcite	$CaCO_3$	Dissolution by acid	Ca	
Dolomite	$CaMg(CO_3)_2$	Dissolution by acid	Mg, Ca	
Pyrite	FeS_2	Oxidation	SO_4	Fe oxides

Relative susceptibility to weathering varies widely among common minerals found at Earth’s surface. Minerals at the top of the diagram react to form minerals near the bottom that are stable at low temperatures and pressures and in the presence of abundant water and oxygen. The ultimate weathering products of many rocks are clays, quartz, and oxides of aluminium and iron.



5.7 Products of weathering

The major products of weathering are:

(1) rock bodies modified intospherical shapes;

(2) a blanket of loose, decayed rock debris, known asregolith, of which soil is an important part; and

(3) ions in solution.

5.8 Topography related to Differential Weathering and Erosion

If resistant rocksare found in the center of a syncline, they will eventually createa topographic high regardless of the structural downfold. Weakrocks, even when forming an anticline, are too easily attacked byweathering and erosion to exist in the landscape as a topographichigh for very long. Variation in rock resistance to weatheringcanyon base, ancient resistant metamorphic rocks have produceda steep-walled inner gorge. The topographic effects of differentialweathering and erosion tend to be more prominent and obviousin landscapes of arid and semiarid climates. In these dry environments,chemical weathering is minimal, so slopes and varyingrock units are not generally covered under a significant mantle ofsoil or weathered rocks. In addition, vegetation typically does notmask the topography in arid regions as it does in humid regions.Another example of differential weathering and erosioncan be seen in the Appalachian Ridge and Valley region of the eastern United States. The rock structure hereexerts a strong and often highly visible influence on theappearance of landforms and landscapes. Given sufficienttime, rocks that are resistant to weathering and erosiontend to stand higher than less resistant rocks. Resistant rocks stand out in the topography as cliffs, ridges, ormountains, while weaker rocks undergo greater weatheringand erosion to create gentler slopes, valleys, andsubdued hills.An outstanding example of how differential weatheringand erosion can expose rock structure and enhanceits expression in the landscape is the scenery at Arizona’sGrand Canyon. In the arid climate ofthat region, limestone is resistant, as are sandstones andconglomerates, but shale is relatively weak. Strong andresistant rocks are necessary to maintain steep or verticalcliffs. Thus, the stair-stepped walls of the Grand Canyonhave cliffs composed of limestone, sandstone, or conglomerate,separated by gentler slopes of shale. At the consists of sandstone, conglomerate, shale and limestone foldedinto anticlines and synclines. These folds have been erodedso that the edges of steeply dipping rock layers are exposed asprominent ridges. In this humid climate region, forested ridgescomposed of resistant sandstones and conglomerates stand up to700 meters (2000 ft) above agricultural lowlands that have beenexcavated by weathering and erosion out of weaker shales andsoluble limestones.

5.9 Degradational Processes : Mass Wasting

INTRODUCTION

Mass wasting is the downslope translation of weathered and bedrock materials under the influence of gravity. Tectonics, local geology, and weathering intensity all contribute to the generation of materials susceptible for movement. These hillslope processes deliver material to a stream that ultimately carries the eroded debris to the sea. There have been many classification schemes utilized to describe these processes, some more complex than others. In general terms, useful classification is based on the process involved and the knowledge that processes can, and often do, change during a single event. Thus, a useful process-based classification includes a range of processes and responses.

Styles of mass wasting includes falls, slides, flows, and creep where the primary differences between these are fluid content, size and amount of material in transport, and rate. Falls occur in areas where steep outcrops, hills, or mountains contain bedrock formations that are fractured and dip in a favorable attitude to promote slope failure by falling blocks. Once a block is released, it can break into smaller pieces as it bounces to the bottom of the slope. It can also become fluidized by either air or water and end up as a debris flow. The slope at the base of a rock fall area typically is mantled by a pile of debris referred to as talus. In semi-arid terrains, weathered rock, soil, and other surficial deposits built up through time are often released during heavy rainfall (or triggered by seismic shaking) and begin to move as a mass. Downslope, fluid content increases and the debris becomes a flow and often is channelized in stream channels. Particles in transport vary (by source area) and range from boulders and rock to flows having the properties of wet cement. In mountain terrains, alluvial fan deposits present at the base of the slopes record several episodes of flows. The morphology of the fans are similar to a delta from a major river where each flow event proceeds down the steepest channel. The fan aggrades through time and shifts to flow through other channels as the surface of the fan changes through time.

Mass wasting is the downhill movement of rock and soil material due to gravity. The term "landslide" is often used as a synonym for mass wasting, but mass wasting is a much more broad term referring to all movement downslope. Technically, **landslide** is a general term for faster mass wasting where the regolithmoves. Unconsolidated fragments of rock located on top of the bedrock are called **regolith**. This loose material along with overlying soils are often what typically moves during a mass wasting event, but bedrock can move (rock topples) or a more liquid-driven movement can occur in mudflows. Movement by mass wasting can range from slow to rapid where it can be dangerous, such as during debris flows. Areas with steep topography and rapid rainfall, such as the California coast, Rocky Mountain Region, and Pacific Northwest, are particularly susceptible to hazardous mass wasting events. This chapter discusses the fundamental mechanisms driving mass wasting processes, types of mass wasting, examples and lessons learned from famous mass wasting events, how mass wasting can be predicted, and how people can be protected from this potential hazard.

Slope Strength

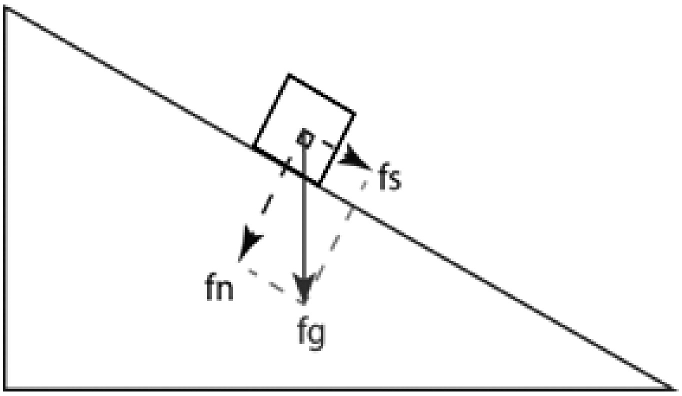


Fig :Forces on a block on an inclined plane (fg = force of gravity; fn = normal force; fs = shear force).

Mass wasting occurs when a slope is too steep to remain stable with existing materials and conditions. Slope stability is ultimately determined by two principal factors: the angle of the slope and the strength of the underlying material. In the figure, a block of rock situated on a slope is being pulled down toward the Earth's center by the force of gravity (fg). The force of gravity is, for the most part, constant on the Earth's surface (small variations exist that depend on the local elevation and the density of the underlying rock). The gravitational force acting on a slope can be divided into two components: one pushing the block down the slope (the **shear force** or **driving force**, fs), and the other pushing into the slope (the **normal force** or**resisting force**, fn), producing friction. The relationship between shear force and normal force is called**shear strength**. For the block to move, the shear force has to be greater than the normal force; that is, the driving force has to be greater than the resisting force (friction). When the normal force is greater than the shear force, then the block does NOT move downslope. However, if the slope becomes steeper or if the earth material is weakened, causing the shear force to exceed the normal force, then downslope movement can occur.

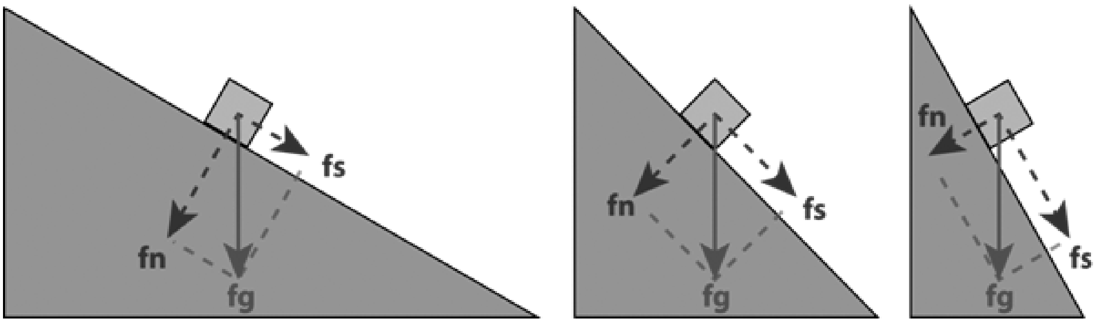


Fig : Change in force vectors as the slope angle increases.

As slope increases, the force of gravity (fg) stays the same and the normal force decreases while the shear force proportionately increases.

In the above figure, the force vectors change as the slope angle increases. The gravitational force doesn't change, but the shear force increases while the normal force decreases. The steepest angle at which rock and soil material is stable (and will NOT move downslope) is called the **angle of repose** and is measured from horizontal. When a slope is at the angle of repose, the shear force is in equilibrium with the normal force. If the slope becomes just slightly steeper, the shear force exceeds the normal force, and the material starts to move downhill. The angle of repose varies for all materials and slopes depending on many factors such as grain size, grain composition, and water content. The figure below shows the angle of repose for sand that is poured into a pile on a flat surface. The sand grains cascade down the sides of the pile until coming to rest at the angle of repose. At that angle, the base and height of the pile continue to increase but the angle of the sides remains the same.

Fig :Angle of repose in a pile of sand.

The shear strength of a slope also depends on the water content of the material. Water can significantly change the shear strength of a particular slope. Water is located in **porespaces**, which are empty air spaces in sediments or rocks between the grains. For example, assume a dry sand pile has an angle of repose of 30 degrees. If water is added to the sand, the angle of repose will increase, possibly to 60 degrees or even 90 degrees, such as a sand castle being built at a beach. But if too much water is added to the pore spaces of the sand castle, then the water decreases the shear strength, lowers the angle of repose, and the sand castle collapses.

Another factor influencing shear strength, are planes of weakness in sedimentary rocks. Bedding planes can act as significant planes of weakness when they are parallel to the slope and less so if they are perpendicular to the slope. At locations A and B, the bedding is nearly perpendicular to the slope and the bedding is relatively stable. At location D, the bedding is nearly parallel to the slope and the bedding is quite unstable. At location C the bedding is nearly horizontal and the stability is intermediate between the other two extremes. Additionally, if clay minerals form along bedding planes they can absorb water and become slick. When a bedding plane of shale (clay and silt) becomes saturated, it can lower the shear strength of the rock mass and cause a landslide such as at the GrosVentre Slide discussed below.

Factors That Control Slope Stability

Mass wasting happens because tectonic processes have created uplift. Erosion, driven by gravity, is the inevitable response to that uplift, and various types of erosion, including mass wasting, have created slopes in the uplifted regions. Slope stability is ultimately determined by two factors: the angle of the slope and the strength of the materials on it.

In Figure below a block of rock situated on a rock slope is being pulled toward Earth's centre (vertically down) by gravity. We can split the vertical gravitational force into two components relative to the slope: one pushing the block down the slope (the **shear force**), and the other pushing into the slope (the **normal force**). The

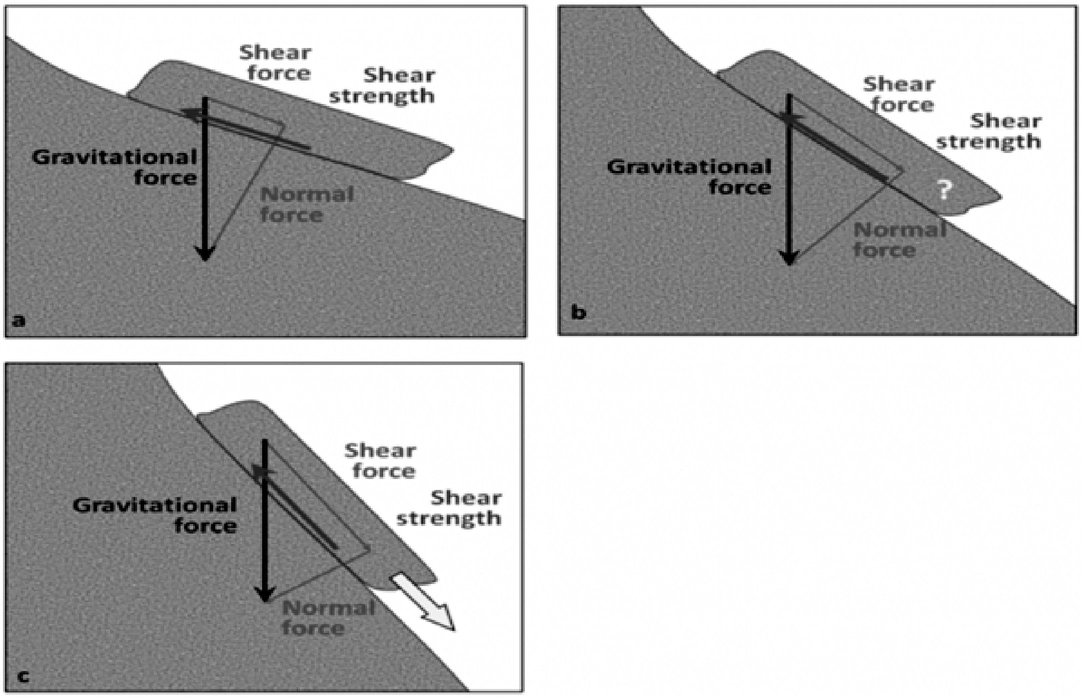


Fig : Differences in the shear and normal components of the gravitational force on slopes with differing steepness are noticed. The gravitational force is the same in all three cases.

In (a) the shear force is substantially less than the shear strength, so the block should be stable.

In (b) the shear force and shear strength are about equal, so the block may or may not move. In (c) the shear force is substantially greater than the shear strength, so the block is very likely to move. [SE]

shear force, which wants to push the block down the slope, has to overcome the strength of the connection between the block and the slope, which may be quite weak if the block has split away from the main body of rock, or may be very strong if the block is still a part of the rock. This is the **shear strength**, and in Figure a, it greater than the shear force, so the block should not move. In Figure b the slope is steeper and the shear force is approximately equal to the shear strength. The block may or may not move under these circumstances. In Figure c, the slope is steeper still, so the shear force is considerably greater than the shear strength, and the block will very likely move.

Fractures, metamorphic foliation, or bedding can significantly reduce the strength of a body of rock, and in the context of mass wasting, this is most critical if the planes of weakness are parallel to the slope and least critical if they are perpendicular to the slope. This is illustrated in Figure 15.3. At locations A and B the bedding is nearly perpendicular to the slope and the situation is relatively stable. At location D the bedding is nearly parallel to the slope and the situation is quite unstable. At location C the bedding is nearly horizontal and the stability is intermediate between the other two extremes.

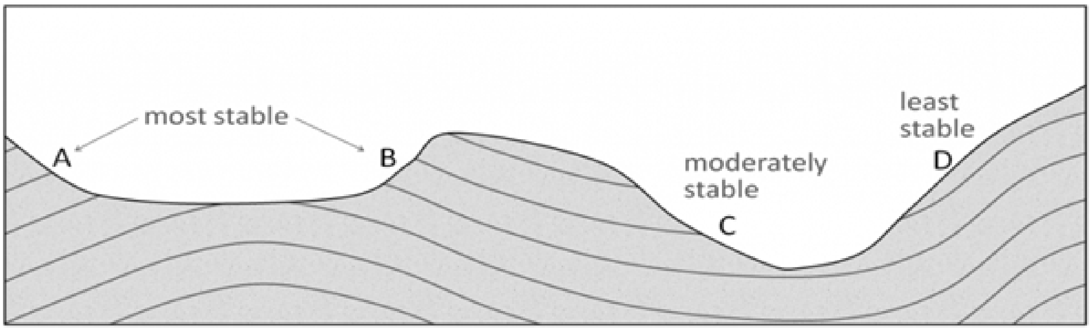


Fig :Relative stability of slopes as a function of the orientation of weaknesses (in this case bedding planes) relative to the slope orientations. [SE]

Internal variations in the composition and structure of rocks can significantly affect their strength. Schist, for example, may have layers that are rich in sheet silicates (mica or chlorite) and these will tend to be weaker than other layers. Some minerals tend to be more susceptible to weathering than others, and the weathered products are commonly quite weak (e.g., the clay formed from feldspar).

TYPES OF MASS WASTING:

Mass wasting events are classified based on the type of movement and type of material. Since there are several ways to classify mass wasting events, the USGS Figure and the table below show terms used in this classification. In addition, mass wasting types often share common morphological features observed on the surface such as the head scarp (commonly seen as crescent shapes on a cliff face), hummocky (uneven) surface, accumulations of talus (loose rocky material falling from above), and toe of slope covering existing surface material**.**

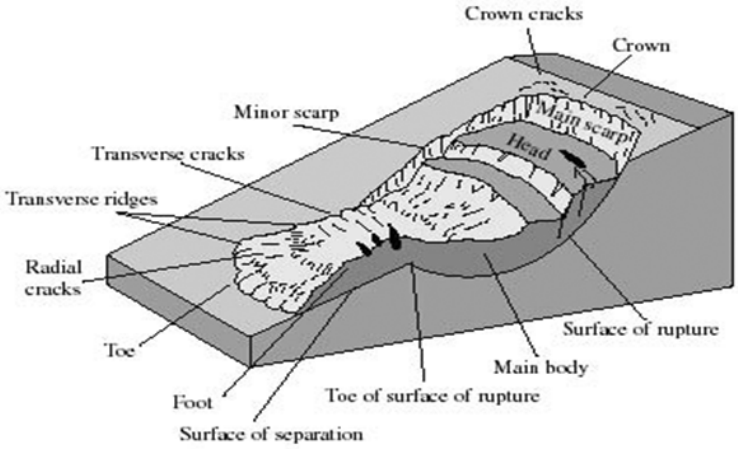


Fig :Common terms for landslides.

The types of mass wasting are summarized in Table below:

Type of Movement	**Primary Material Type and Common Name of Slide**		
	Bedrock	**Soil Types**	
		Mostly Coarse-Grained	**Mostly Fine-Grained**
Falls	Rock Fall	—	—
Rock Avalanche	Rock Avalanche	—	—
Rotational Slide (Slump)	—	Rotational Debris Slide (Slump)	Rotational Earth Slide (Slump)
Translational Slide	Translational Rock Slide	Translational Debris Slide	Translational Earth Slide
Flows	—	Debris Flow	Earth flow
Soil Creep	—	Creep	Creep

The three criteria used to describe slope failures are:

- The type of material that failed (typically either bedrock or unconsolidated sediment)
- The mechanism of the failure (how the material moved)
- The rate at which it moved

The type of motion is the most important characteristic of a slope failure, and there are three different types of motion:

- If the material drops through the air, vertically or nearly vertically, it's known as a **fall.**
- If the material moves as a mass along a sloping surface (without internal motion within the mass), it's a **slide.**
- If the material has internal motion, like a fluid, it's a **flow**.

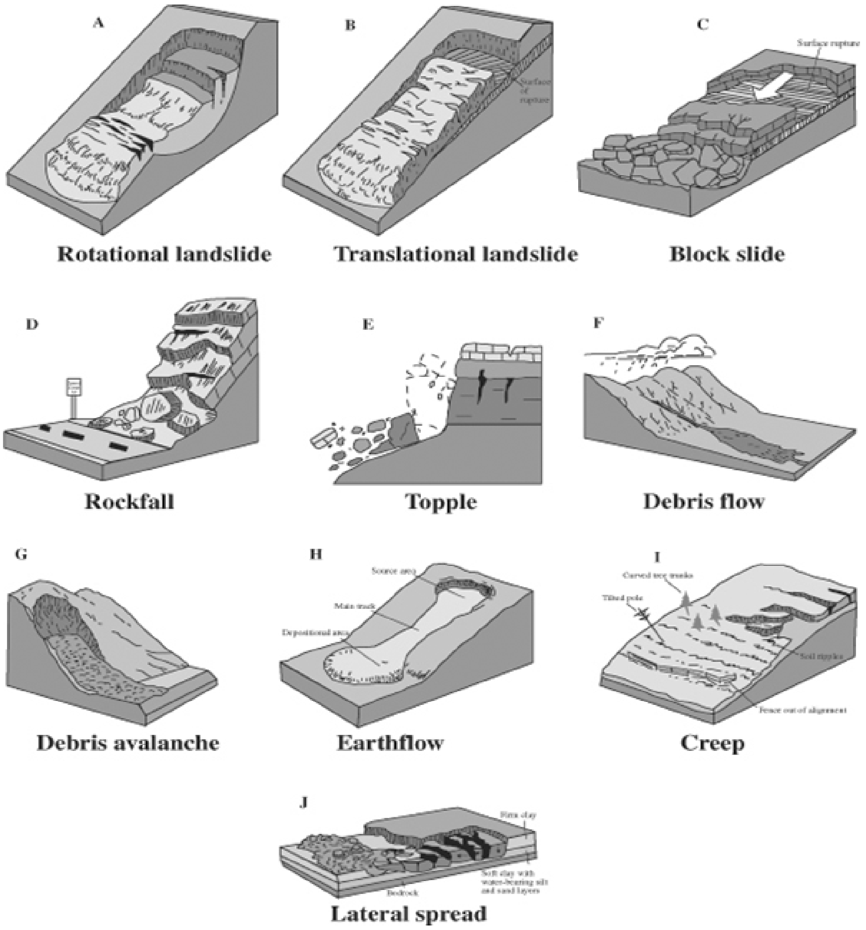
Many slope failures involve two of these types of motion, some involve all three, and in many cases, it's not easy to tell how the material moved.

Classification of slope failures based on type of material and type of motion [SE]:

Failure Type	**Type of Material**	**Type of Motion**	**Rate of Motion**
Rock fall	Rock fragments	Vertical or near-vertical fall (plus bouncing in many cases)	Very fast (>10s m/s)
Rock slide	A large rock body	Motion as a unit along a planar surface (translational sliding)	Typically very slow (mm/y to cm/y), but some can be faster
Rock avalanche	A large rock body that slides and then breaks into small fragments	Flow (at high speeds, the mass of rock fragments is suspended on a cushion of air)	Very fast (>10s m/s)
Creep or solifluction	Soil or other over-burden; in some cases, mixed with ice	Flow (although sliding motion may also occur)	Very slow (mm/y to cm/y)

Slump	Thick deposits (m to 10s of m) of unconsolidated sediment	Motion as a unit along a curved surface (rotational sliding)	Slow (cm/y to m/y)
Mudflow	Loose sediment with a significant component of silt and clay	Flow (a mixture of sediment and water moves down a channel)	Moderate to fast (cm/s to m/s)
Debris flow	Sand, gravel, and larger fragments typically faster)	Flow (similar to a mudflow, but	Fast (m/s)

Mass wasting: Movement Type and Primary Earth Material.



Rotational landslide
Translational landslide
Block slide
Rockfall
Topple
Debris flow
Debris avalanche
Earthflow
Creep
Lateral spread

Rock Fall

Falls are abrupt movements of rock that detach from steep slopes or cliffs. Separation occurs along existing natural breaks such as fractures or bedding planes, and movement occurs as free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of water.

Rock fragments can break off relatively easily from steep bedrock slopes, most commonly due to frost-wedging in areas where there are many freeze-thaw cycles per year. If you've ever hiked along a steep mountain trail on a cool morning, you might have heard the occasional fall of rock fragments onto a **talus slope**. This happens because the water between cracks freezes and expands overnight, and then when that same water thaws in the morning sun, the fragments that had been pushed beyond their limit by the ice fall to the slope below.

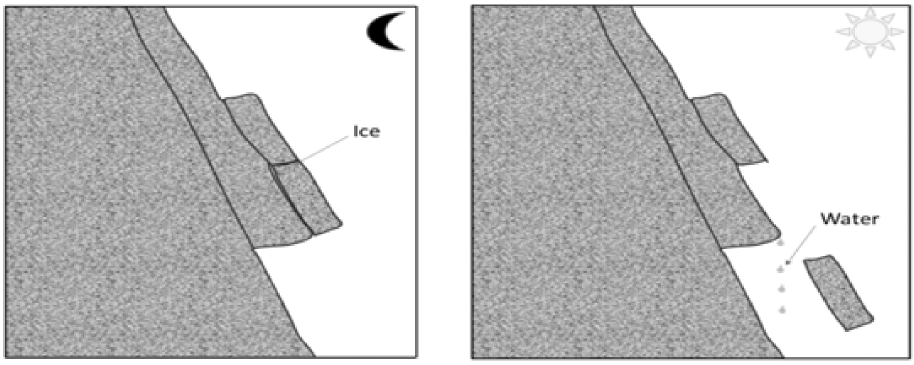


Fig :The contribution of freeze-thaw to rock fall [SE]

Rock Slide

A rock slide is the sliding motion of rock along a sloping surface. In most cases, the movement is parallel to a fracture, bedding, or metamorphic foliation plane, and it can range from very slow to moderately fast. The word **sackung** describes the very slow motion of a block of rock (mm/y to cm/y) on a slope.

Rotational slides show movement along a curved rupture surface with a commonly slow movement rate.

Translational slides are movements along a plane of distinct weakness between the overlying slide material and more stable underlying material, and are often rapid. Slides can be further subdivided into rock slide, debris slide, or earth slides depending on the type of the material involved. The largest and fastest slides are called **sturzstroms**, or long-run-out landslides.

A good example is the Downie Slide north of Revelstoke, B.C., which is shown in Figure 15.9. In this case, a massive body of rock is very slowly sliding down a steep slope along a plane of weakness that is approximately parallel to the slope.

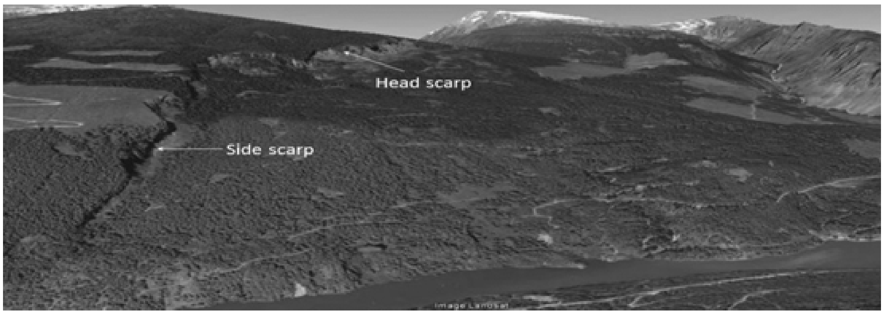


Plate : The Downie Slide, a sackung, on the shore of the Revelstoke Reservoir (above the Revelstoke Dam). The head scarp is visible at the top and a side-scarp along the left side. [from Google Earth]

Rock Avalanche

If a rock slides and then starts moving quickly (m/s), the rock is likely to break into many small pieces, and at that point it turns into a **rock avalanche**, in which the large and small fragments of rock move in a fluid manner supported by a cushion of air within and beneath the moving mass. The 1965 Hope Slide was a rock avalanche, as was the famous 1903 Frank Slide in southwestern Alberta. The 2010 slide at Mt. Meager (west of Lillooet) was also a rock avalanche, and rivals the Hope Slide as the largest slope failure in Canada during historical times+ .

Plate : The 2010 Mt. Meager rock avalanche, showing where the slide originated (arrow, 4 km upstream). It then raced down a steep narrow valley and out into the wider valley in the foreground. [Mika McKinnon photo, http://www.geomika.com/blog/2011/01/05/the-trouble-with-landslides/ Used with permission.]

Creep or Solifluction

Soil creep is the imperceptibly slow downward movement of material caused by shear stress sufficient to produce permanent deformation in unconsolidated material. The very slow — mm/y to cm/y — movement of soil or other unconsolidated material on a slope is known as creep. **Creep** which normally only affects the upper several centimetres of loose material, is typically a type of very slow flow, but in some cases, sliding may take place also. Creep can be facilitated by freezing and thawing because, as shown in Figure , particles are lifted perpendicular to the surface by the growth of ice crystals within the soil, and then let down vertically by gravity when the ice melts. The same effect can be produced by frequent wetting and drying of the soil. A type of soil creep is **solifluction**, which is slow movement of soil lobes on low-angle slopes due to repeated freezing and thawing of soil in high-latitude (Arctic) cold locations. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges.In cold environments, **solifluction** is a more intense form of freeze-thaw-triggered creep. Creep is most noticeable on moderate-to-steep slopes where trees, fence posts, or grave markers are consistently leaning in a downhill direction.

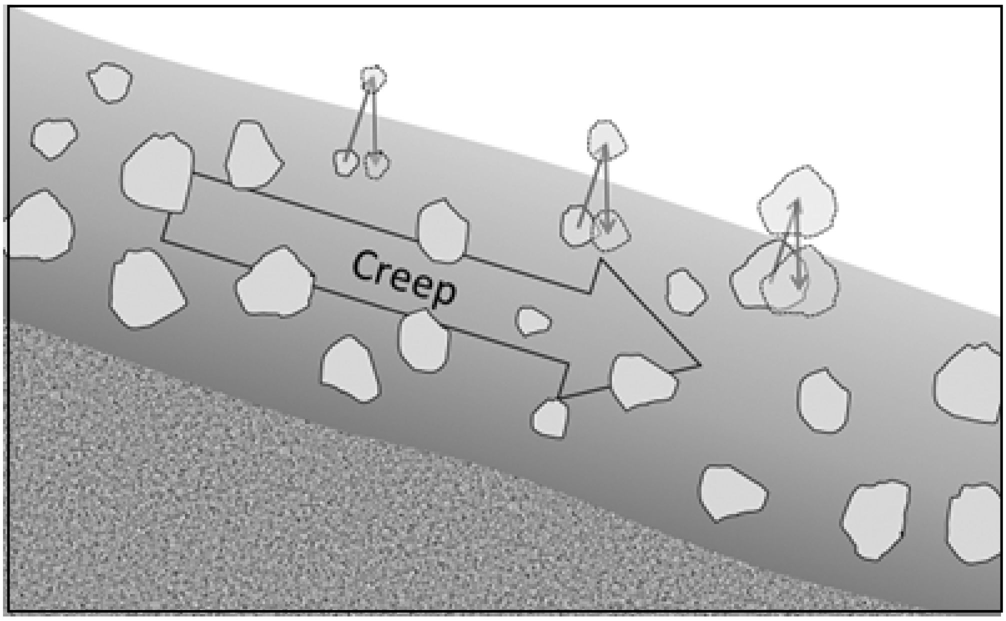


Fig : A depiction of the contribution of freeze-thaw to creep. The blue arrows represent uplift caused by freezing in the wet soil underneath, while the red arrows represent depression by gravity during thawing. The uplift is perpendicular to the slope, while the drop is vertical. [SE]

Slump

Slump is a type of slide (movement as a mass) that takes place within thick unconsolidated deposits (typically thicker than 10 m). Slumps involve movement along one or more curved failure surfaces, with downward motion near the top and outward motion toward the bottom. They are typically caused by an excess of water within these materials on a steep slope.

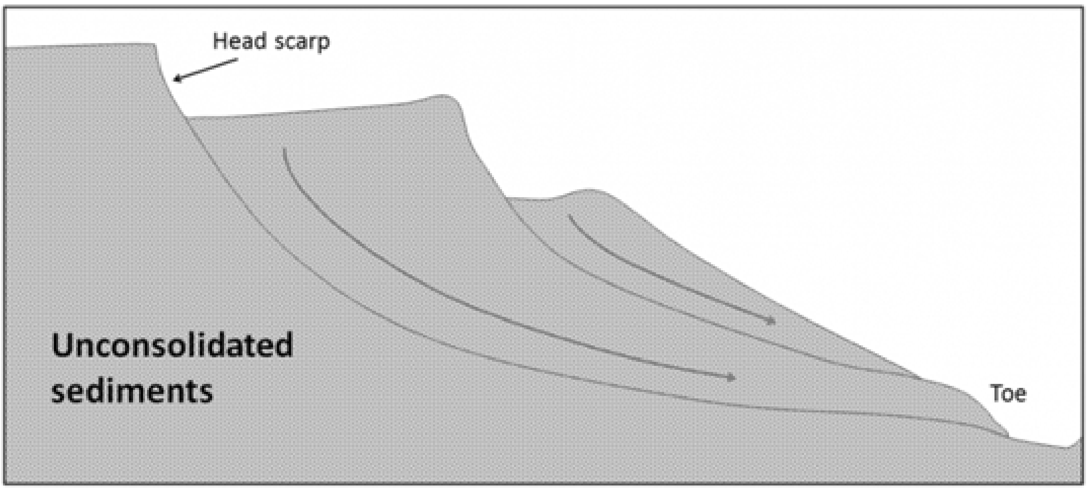


Fig : A depiction of the motion of unconsolidated sediments in an area of slumping [SE]

Mudflows and Debris Flows

When a mass of sediment becomes completely saturated with water, the mass loses strength, to the extent that the grains are pushed apart, and it will flow, even on a gentle slope. This can happen during rapid spring snowmelt or heavy rains, and is also relatively common during volcanic eruptions because of the rapid melting of snow and ice. (A mudflow or debris flow on a volcano or during a volcanic eruption is a *lahar*.) If the material involved is primarily sand-sized or smaller, it is known as a mudflow, such as the one shown in Figure.

Flows are mass wasting events in which the material is mixing internally, sometimes with abundant water, and moving at rapid speeds with long runouts at the slope base. Flows are commonly separated into **debris flow** (coarse material) and **earthflow** (fine material) depending on the type of material involved and the amount of water.

Preventing and Delaying Mass Wasting

As already noted, we cannot prevent mass wasting in the long term as it is a natural and ongoing process; however, in many situations there are actions that we can take to reduce or mitigate its damaging effects on people and infrastructure. Where we can neither delay nor mitigate mass wasting, we should consider moving out of the way.

It is comforting to think that we can prevent some effects of mass wasting by mechanical means, such as the rock bolts in the road cut, or the drill holes used to drain water out of a slope, or the building of physical barriers, such as retaining walls. What we have to remember is that the works of humans are limited compared to the works of nature. Delaying mass wasting is a worthy endeavour, of course, because during the time that the measures are still effective they can save lives and reduce damage to property and infrastructure. The other side of the coin is that we must be careful to avoid activities that could make mass wasting more likely. One of the most common anthropogenic causes of mass wasting is road construction, and this applies both to remote gravel roads built for forestry and mining and large urban and regional highways. Road construction is a potential problem for two reasons.

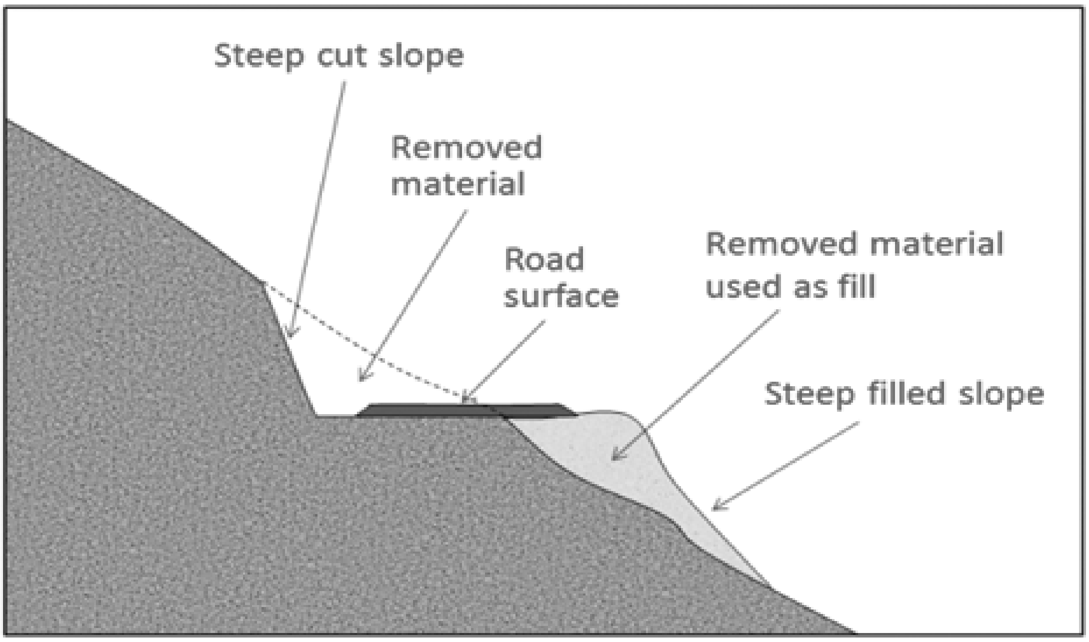


Fig :An example of a road constructed by cutting into a steep slope and the use of the cut material as fill. [SE]

First, creating a flat road surface on a slope inevitably involves creating a cut bank that is steeper than the original slope. This might also involve creating a filled bank that is both steeper and weaker than the original slope. Second, roadways typically cut across natural drainage features, and unless great care is taken to reroute the runoff water and prevent it from forming concentrated flows, oversaturating fill of materials can result.

Apart from water issues, engineers building roads and other infrastructure on bedrock slopes have to be acutely aware of the geology, and especially of any weaknesses or discontinuities in the rock related to bedding, fracturing, or foliation. It is widely believed that construction of buildings on the tops of steep slopes can contribute to the instability of the slope. A more likely contributor to instability of the slope around a building is the effect that it and the changes made to the surrounding area have on drainage.

5.11 Summary

The unit deals with the different types of weathering and the processes involved in mass wasting. It is important because it produces unconsolidated material from which soil is formed.

5.12 Questions

Long question

1. What is denudation? Give a brief description about the various types of weathering with examples.
2. Define weathering and mass wasting. Describe the impact of mass wasting on landforms.
3. What are the process of chemical weathering? Discuss the importance of chemical weathering in the humid tropics?
4. Are different weathering processes basically dependent in climate? Support your answer with suitable examples.

Short question

1. Distinguish between solifluction and soil creeping.
2. Distinguish between graular disintegration and exfoliation.
3. Distinguish between slump and slide.
4. Distinguish between hydrolysis and hydration.

Unit 6 ❑ Processes of Entrainment, Transportation and Deposition by different Geomorphic agents. Role of Humans in Land Development

Structure

6.0 Objective

- To learn about the processes of entrainment and transportation.
- To study about the role of humans in land development.

6.1 Introduction

Landforms evolve over a long period of cyclic and geologic time, inheriting the imprints of past process rates and/or process domains. The principles and methods of evaluating the signature of environmental change are highlighted here. The process-form relationships provide the building blocks also for the optimum utilization of the land resources of the earth, and quantitative assessment of the stability of geomorphic systems and the quality of environment.

6.2 Processes of entrainment

In physical geography, **entrainment** is the process by which surface sediment is incorporated into a fluid flow (such as air, water or ice) as part of the operation of erosion.For example,process of entrainment occurring at subfreezing temperatures. Entrainment mechanisms and emphasize that recent evidence from both physics and glaciology implies an active role for liquid water-dependent processes in subfreezing ice. Entrainment of rock fragments beneath cold glaciers can probably occur by creep (Sugden and John, 1976), but the high viscosity of ice makes this mechanism a difficult one for fine grained Particles Cold-based glaciers can actively entrain basal material. This provides a general mechanism for formation of dirty basal layers, and may in some cases be an important geomorphic process. Subfreezing entrainment is likely facilitated by interfacial water films, which also allow sliding and abrasion by cold glaciers. This process initiates the bursts of motion experienced by any particle and the size of the largest particle a stream can entrain under any given set of hydraulic conditions is thus called competence. It is very difficult to determine however for several reasons:

1. Particles are entrained by a combination of fluvial forces
2. Flow velocity is neither constant nor easily measured, and,
3. Sediment of the same size may be packed together differently. One method used to represent the flow conditions in competence relationships, is measuring the critical shear stress. It is proportional to the depth-slope product and can be expressed by the Du Boys equation for boundary shear: $\tau c = \gamma * R * S$

   where τc = critical shear stress

   γ = specific weight of the water

   R = hydraulic radius

   S = slope

Bank erosion is the process of entrainment that determine the type and magnitude of erosion that occurs on the channel floor. Fluvial entrainment promotes bank erosion in two ways:

- Corrasion—shear stress generated by water flow–operates on all surfaces, and
- Cantilevers—differential Corrasion produces overhangs which collapse.

6.3 Processes of Transportation

Transportation is the movement of material across the Earth's surface by water, wind, ice or gravity. It includes the physical processes of traction (dragging), suspension (being carried) and saltation (bouncing) and the chemical process of solution.During transportation, water preferentially carries away small particles in the process called washing. Wind does the same in the process called winnowing. The material not carried away may be left behind as a lag deposit or a pavement.Transportation and weathering are the two phases of erosion. Mass wasting is usually considered separately from transportation. Rivers transport material in four ways:

Solution—minerals are dissolved in the water and carried along in solution. This typically occurs in areas where the underlying bedrock is limestone.

Suspension—fine light material is carried along in the water.

Saltation—small pebbles and stones are bounced along the river bed.

Traction—large boulders and rocks are rolled along the river bed.

PROCESSES OF DEPOSITION

Deposition is the processes where material being transported by a river is deposited. Deposition occurs when a river loses energy. This can be when a river enters a shallow area (this could be when it floods and comes into contact with the flood plain) or towards its mouth where it meets another body of water.Rivers flood on a regular basis. The area over which they flood is known as the floodplain and this often coincides with regions where meanders form. Meanders support the formation of flood plains through lateral erosion.When rivers flood the velocity of water slows. As the result of this the river's capacity to transport material is reduced and deposition occurs. This deposition leaves a layer of sediment across the whole floodplain. After a series of floods, layers of sediment forms along the flood plain.Larger material and the majority of deposition occur next to the river channel. This is the result of increased friction (with the flood plain) causing the velocity of the river to slow and therefore rapidly reduce its ability to transport material. This leaves a ridge of higher material next to the river channel on both banks of the river known as a levee.

If entrainment of sediment represents a threshold of erosion, a similar threshold must exist when sediment in transport is deposited. A long episode in which less sediment leaves the bed than is returned, results in a distinct period of aggradation.

While a long episode in which more sediment leaves the bed than is returned results in a distinct period of degradation. Fluvial deposition is important to geomorphology in several ways.

1. *On a long-term basis,* continued deposition results in landforms that reflect distinct periods of geomorphic history–glacial chronologies.
2. *On a short-term basis,* deposition creates bottom forms such as dunes, bars, and riffle-pool sequences that are closely interrelated with channel pattern and the character and distribution of flow within the channel–ecological reconstructions.
3. Finally, *short-term and long-term mechanics of deposition* have implications beyond the boundaries of geomorphology–gold mining and contaminant plume migration.

6.4 Role of Humans in Land Development

The physical environment of humankindis virtually in no part exemptfrom some kind of human influence, usually cascading through the system and actingback on human society itself. Therefore, it is a logical research objective to analyse the problems resulting from the above interactions in the most comprehensiveapproach possible. Now the individual disciplines of earth sciences, specializedon different spheres of the global environment, should devote more attention toresearch of that kind.

Role of humans in land developmentstudieslandforms, their changes and impacts on other spheres of the global environment:

- Firstly, today the human agent is equal in importance to other factors in the shapingof the Earth's landforms. Although the intensity of its influence dependson the energy released by human society, which is insignificant compared tothe endogenic forces of the Earth (tectonic movements, volcanic activity, earthquakes),it is not only commeasurable to the energy which drives most of theexogenic processes but even surpasses the effectiveness of some of them.
- Secondly, geomorphologists have to study this problem since the geomorphicimpact of humans is growing exponentially. Exponential popula-

tion increaseinvolved higher demands and the energy made available to meet the demandsresulted in large-scale reworking of surface materials–at an even more rapidlygrowing rate.

- Thirdly, human impact on the Earth's surface does not only influence other naturalsystems but have a reaction on itself as well to an ever-increasing degree. Therightful judgement that humans are the inhabitants (or sometimes victims) of anenvironment created (or modified) by themselves is also true for the geomorphicaction of humans.

The subject of anthropogenic geomorphology is thedescription of the wide and ever-widening range of surface landforms, extremelydiverse in origin and in purpose, created by the operation of human society. By nowhuman action has established itself as one of the geomorphic agents. It is found that anthropogenic geomorphologycan also be interpreted more narrowly and widely but certainly in amore complex way.

In a narrower sense, although all human constructions (buildings, industrialplants) modify the appearance of the landscape, they are not regarded as subjectsof geomorphological investigation. Such artificial constructions contrastwith their environs in size or other properties and undoubtedly influence them.

In a broader sense, the artificially created landforms have manifold influences on theenvironment (e.g. alterations in meso- and microclimate, biota, etc.). In addition,they may also modify natural processes. New geomorphic processes maybe initiated or active processes may be intensified or weakened or even inhibited.As a consequence, new landforms may be generated–not directly by humanactivities but they would have not formed or not formed in the manner theydid without previous human interference. Human geomorphic action may inducecascading environmental changes, whose study obviously lies within the scopeof anthropogenic geomorphology. The investigation of the impacts also coversthe geomorphic processes induced by the objects which were excluded fromanthropogenic geomorphological research above.

The inevitable complexity of anthropogenic geomorphology derives from thecharacter of natural systems and human activities. Humans interfere with thesesystems, including geomorphological ones; from outside and thus necessarilydisturb the natural order (dynamic equilibrium) of the processes, which hasevolved over timespans of various lengths. Man-made landforms are alien to thelandscape and through establishing new geomorphological conditions, humansdrastically upset the equilibrium. With the appearance of such landforms–ifthey are not used anymore and not maintained by humans–tendencies towards anew equilibrium begin to show. For the society it means uncertainty or occasionallyeven a threat. On the one hand, it is not easy to predict either thedirection of transformation or the nature of the new equilibrium. Both may bedeleterious not only for society but also for other natural systems. On the otherhand, in the first period of the relaxation time necessary to reach a new equilibrium,changes are rather rapid and may even lead to disastrous consequences.

An obvious aspect is to classify role of human in land development*according to the characterof the human activity*. Here another general principle of dynamic geomorphologyis applied. Since landforms are usually produced by interplay of differentprocesses, it is not always easy to distinguish the contribution of the individualprocesses in the resulting landscape. The following fields where the role of human activities has been identified are as follows:

- ***Mining***—The processes involved and the resulting landforms are usually called montanogenic.
- ***Industrial*** **impact** is reflected in industrogenic landforms.
- ***Settlement*** **(urban)** expansion exerts a major influence on the landscape over ever increasing areas. The impacts are called urbanogenic.
- Traffic also has rather characteristic impacts on the surface.
- As the first civilizations developed, highly advanced farming relied on rivers; ***water management*** (river channelization, drainage) occupies a special position in anthropogenic geomorphology.
- ***Agriculture*** is another social activity causing changes on the surface. Agrogenic impacts also include transformation due to forestry.
- Although ***warfare*** is not a productive activity it has long-established surface impacts.
- In contrast, the impacts of ***tourism and sports*** activities are rather new fields of study in anthropogenic geomorphology.

6.5 Summary

Entrainment is the process by which surface sediment is incorporated into a fluid flow. These hrechanisues are dealt in the unit along with the processes of transportation. The role of humans in Land development is also highlighted.

6.6 Questions

Long question

1. What is sediment entrainment?
2. What factors contribute in the transportation of sediments?
3. What are the three ways that sediments can be transported?

Unit 7 ❑ Development of River network and Landforms on Uniclinal and Folded structures

Structure

7.0 Objective
7.1 Introduction
7.2 Inversion of Relief
7.3 Uniclinal/Homoclinal/Monoclinal Structure
7.4 Summary
7.5 Model Questions

7.0 Objective

- To help the learners to learn about the river network and landforms

7.1 Introduction

FOLDED STRUCTURE

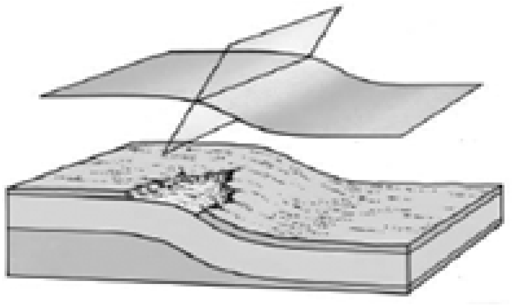
Folds are warps in rock strata during ductile deformation. They are three dimensional structures ranging in size from microscopic crinkles to large domes and basins that are hundreds of kilometers across. Most folds develop by horizontal compression at convergent plate boundaries where the crust is shortened and thickened. Broad, open folds form in the stable interiors of continents, where the rocks are only mildly warped. Almost every exposure of sedimentary rock shows some evidence that the strata have been deformed. In some areas, the rocks are slightly tilted; in others the strata are folded like wrinkles in a rug. Small flexures are abundant in sedimentary rocks and can be seen in mountainsides and road cuts and even in hand specimens. These warps in the strata are called **folds** and are a manifestation of ductile deformation in response to horizontal compression. This kind of deformation is also called contraction. Large folds cover thousands of square kilometers, and they can best be recognized from aerial or space photographs or from geologic mapping. Like faults, folds form slowly over millions of years, as rock layers gradually yield to differential stress and bend. Folds are of great economic importance because they commonly form traps for oil and gas and may control localization of ore deposits. Consequently, it is of more than academic interest to understand folds.

Fold Nomenclature. Three general types of folds are illustrated in the Figure below. They are:

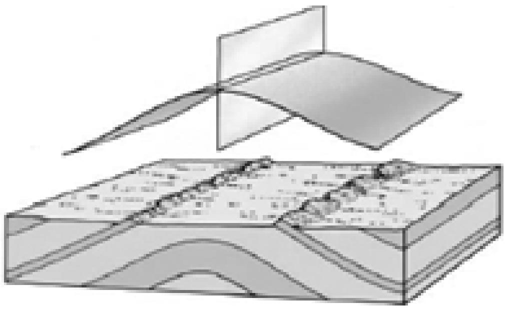
An **anticline,** in its simplest form, is up arched strata, with the two **limbs** (sides) of the fold dipping away from the crest. Rocks in an eroded anticline are progressively *older* toward the interior of the fold.

Synclines, in their simplest form, are down folds, or troughs, with the limbs dipping toward the centre. Rocks in an eroded syncline are progressively *younger* toward the centre of the fold.

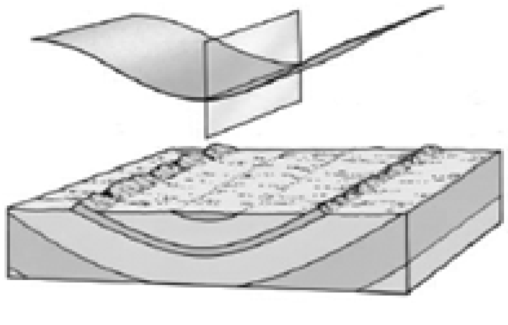
Monoclines are folds that have only one limb; horizontal or gently dipping beds are modified by simple step like bends.



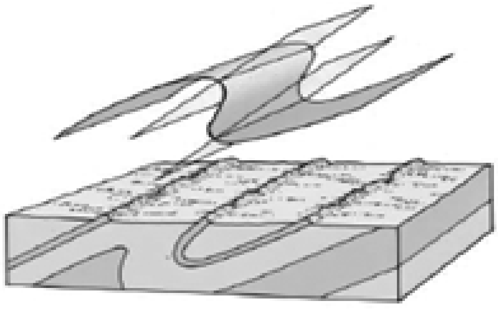
Monoclines



Anticline

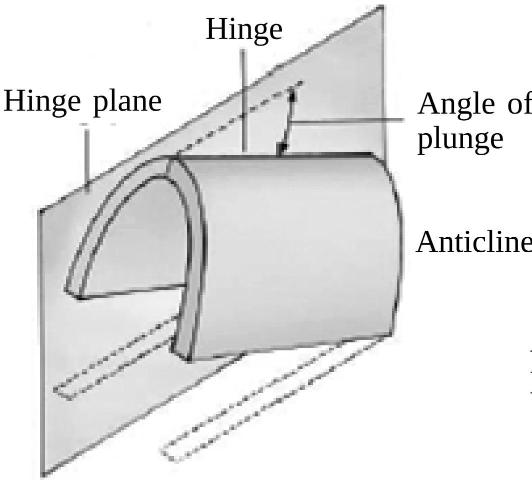


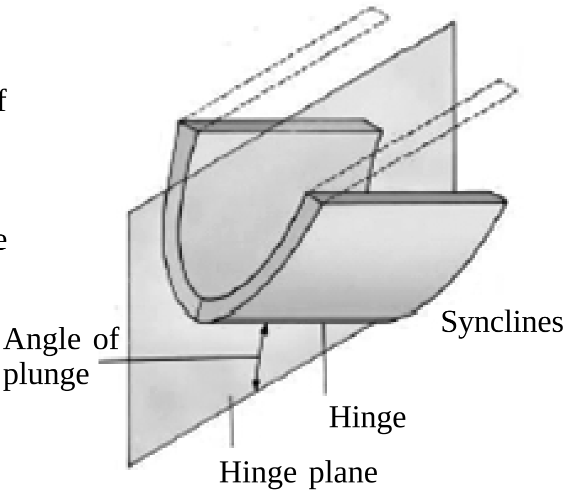
Synclines



Overturned
anticline and syncline

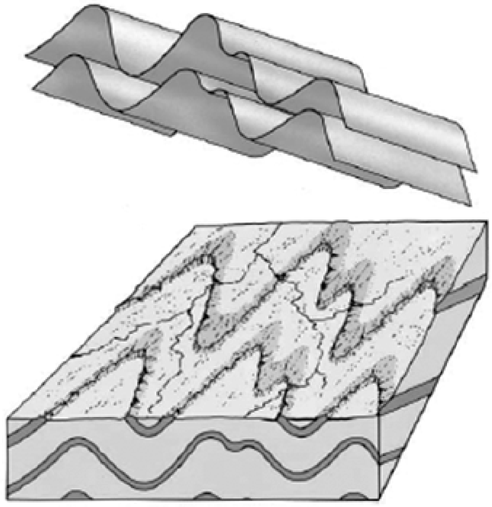
For purposes of description and analysis, it is useful to divide a simple fold into two more-or-less equal parts by an imaginary plane known as the **hinge plane.** The hinge marks the region of maximum curvature in the fold.The line formed by the intersection of the hinge plane and a bedding plane is the **hinge line,** and the downward inclination of the hinge line is called the **plunge**.





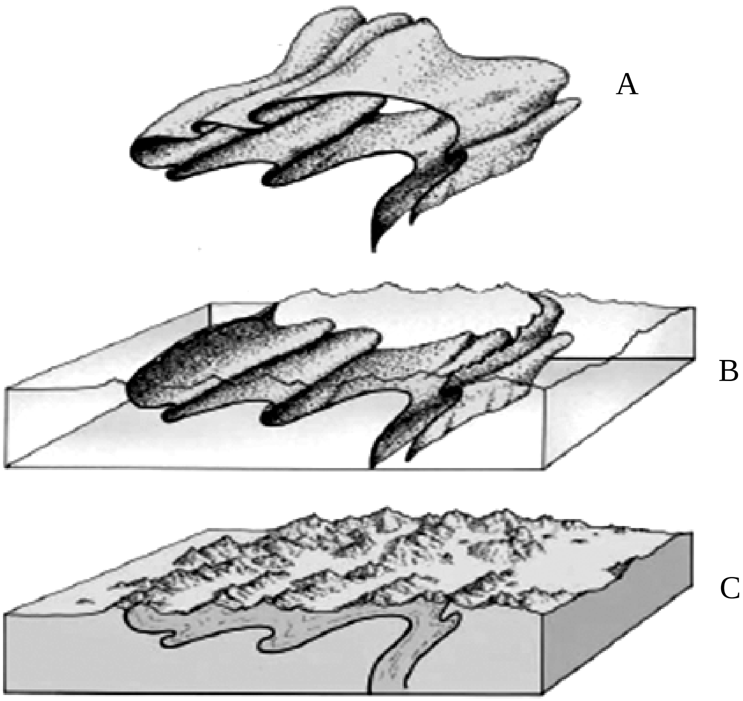
A **plunging fold,** therefore, is a fold in which the hinge line is inclined. In most folds, the hinge plane is not vertical but is inclined, and the fold is overturned and one limb is steeper than the other direction the hinge plane is rotated from vertical indicates the direction the rocks were displaced. In other words, movement is toward the steep limb.

Fold Belts: Where contraction is intense (typically in **orogenic belts** at convergent plate boundaries), the rock layers are deformed into a series of tight folds in a



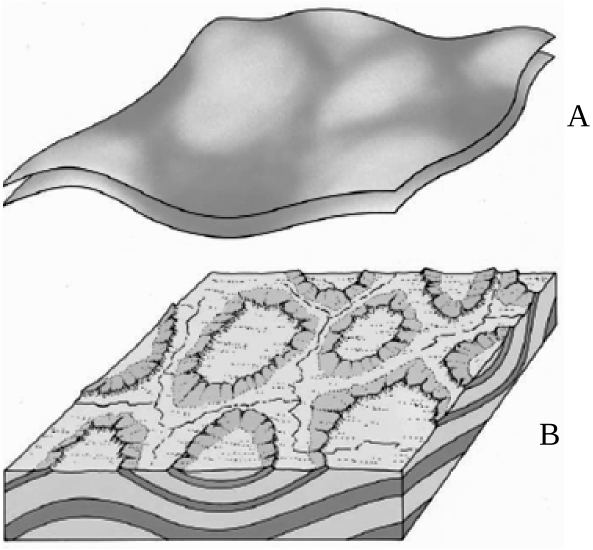
long linear belt. The internal geometry of many fold belts is not exceedingly complex. In many ways, the folds resemble the wrinkles in a rug. However, complexity in the outcrop patterns of fold belts results from erosion, so folds may be difficult to recognize on aerial photographs without some experience in geologic observation and interpretation.

The diagrams above illustrate a fold belt with plunging folds and its surface expression after the upper part has been removed by erosion. The outcrop of the eroded plunging anticlines and synclines forms a characteristic zigzag pattern. The nose of an anticline forms a V that points in the direction of plunge and the oldest rocks are in the centre of the fold. The nose of a syncline forms a V that opens in the direction of plunge, and the youngest rocks are in the center of the fold. Together, the outcrop pattern, the strike and dip of the beds, and the relative ages of the rocks in the center of the fold make it possible to determine the structure's subsurface configuration. Thrust faults commonly form in association with these contractional folds. Intense deformation in the cores of some mountain ranges produces complex folds. Some folds are refolded. Such structures commonly exceed 100 km across and can extend through a large part of a mountain belt.



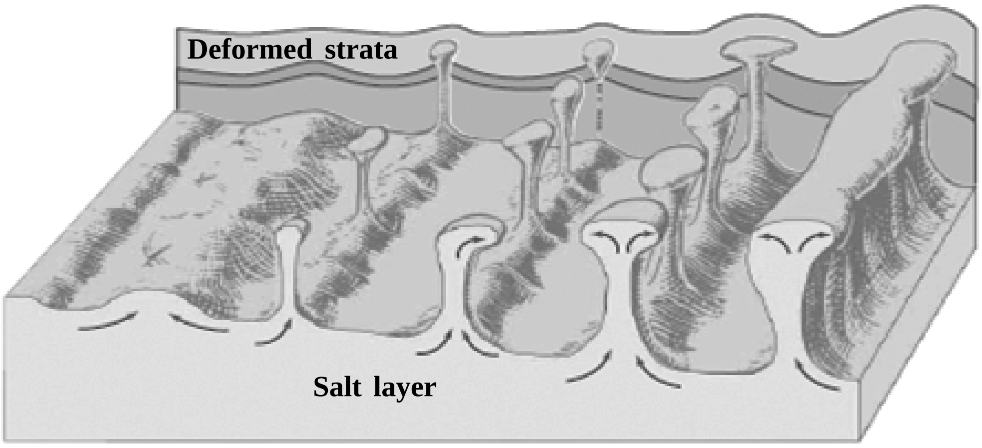
The Figure above illustrates the geometry and surface expression of a large complex fold. Figure A is a perspective drawing of a single bed in a typical complex fold. This **overturned fold** is a huge anticlinal structure with numerous minor anticlines and synclines forming indentations on the larger fold; Figure B shows the fold after it has been subjected to considerable erosion, which has removed most of the upper limb. Note the cross section of the structure on the mountain front and the outcrop pattern compared with that in Figure A. The topographic expression of complex folds is variable. They usually are expressed in a series of mountains as shown in Figure C. Complex folds are common in the Swiss Alps , but they were recognized only after more than half a century of detailed geologic studies. They are also common in the roots of Ancient Mountain systems and thus are exposed in many areas of the shields. An excellent example of an orogenic belt is the Zagros Mountains of southern Iran. The fold belt is only a small part of the Alpine Himalaya chain that extends from southern Europe and across southern Asia.

Domes and Basins: In contrast to fold belts at convergent margins, the sedimentary rocks covering much of the continental interiors have been only gently warped into broad **domes** and **basins** many kilometers in diameter. Although these flexures in the sedimentary strata are extremely large, the configuration of the folds is known from geologic mapping and from information gained through drilling. The nature of these flexures and their topographic expression are illustrated in Figures below.



The form of a single bed warped into broad domes and basins is here. If erosion cuts off the tops of the domes, the surface exposure of the layer looks like the one shown in Figure B.The deformed layers in both domes and basins typically have circular or elliptical outcrop patterns. There is a major difference, however. The rocks exposed in the central parts of eroded domes are the oldest rocks, whereas the rocks exposed in the centers of basins are the youngest.The rule of Vs is also a useful tool to interpret the structure of domes and basins. Thus, for domes the Vs point away from the center and for basins they point inward. A classic example of a broad fold in the continental interior is the large dome that forms the Black Hills of South. Resistant rock units form ridges that can be traced completely around the core of the dome, and non-resistant formations make up the intervening valleys. How these broad domes form is still enigmatic. Their circular shapes and distance from convergent margins are puzzling. Many could have formed by multiple periods of deformation. For example, gentle east-west contraction far from an active convergent margin, followed by north-south contraction related to a different plate margin, could produce a series of broad domes and intervening basins.

Diapirs: Some domes and basins also could form by vertical adjustments caused by density differences in the crust or upper mantle. Many small domes, are associated with buoyant rise of material that is less dense than the overlying rock. For example, in thick sequences of sedimentary rocks, beds of salt may deform and rise as a **diapir,** a streamlined body shaped somewhat like an inverted teardrop. Plugs of salt may rise and pierce overlying sedimentary strata to form salt domes. The deformed sedimentary beds are faulted and typically dip away from the center of the structure. The



white mass in the lower right part of the figure below is a salt dome that has reached the surface to flow like a glacier. The movement of salt has modified the seafloor south of the Mississippi delta on a grand scale, with subsidence basins and domes pockmarking the seafloor.

Topographic Expression of Folded Strata: Processes and forms of eroded structural folds

A. Anticlinal Ridge: structural anticline mirrored in surface form of a ridge or hill:

(1) "Unbreached" anticline: resistant folded layers un-dissected along axial plane of fold

(2) "Breached" anticline: folded layers along axial plane of fold are incised by erosion and down-cutting streams.

B. Anticlinal Valley: Breached anticline- structural anticline eroded in form of topographic valley along axis of fold

(1) Result of easily eroded lithologies along axial plane of fold.

(2) Topographic Inversion- sense of structural relief opposite of that of topographic relief. e.g. Anticlinal Valleys, Synclinal Ridges

C. Synclinal Valley: sense of structural relief = sense of topographic relief

D. Synclinal Ridge: topographic ridge formed along axis of syncline

E. Non-plunging Fold Patterns

(1) Parallel sets of hogbacks oriented symmetrical about fold axis

(a) Anticlines: oldest strata exposed along axis

(b) Synclines: youngest strata exposed along axis

(2) Scarp face and dip slope relations apply as above

F. Plunging Folds and "Zig-Zag" Mountains: Plunging Folds result in alternating V or Zig-Zag shaped topography

(a) Plunging Anticlines: Homoclinal ridges converge to apex in direction of plunge and "V" of pattern points down plunge

(b) Plunging Synclines: Homoclinal ridges diverge in direction of plunge, converge in "up plunge" direction and "V" of pattern points up plunge.

Trellis drainage patterns typically develop where sedimentary rocks have been folded and then eroded to varying degrees depending on their strength. The Rocky Mountains of B.C. and Alberta are a good example of this, and many of the drainage systems within the Rockies have trellis patterns. Trellis drainage patterns look similar to their namesake, the common garden trellis. Trellis drainage develops in folded topography like that found in the Appalachian Mountains of North America. Down-turned folds called synclines form valleys in which resides the main channel of the stream. Short tributary streams enter the main channel at sharp angles as they run down sides of parallel ridges called anticlines. Tributaries join the main stream at nearly right angles.

7.2 Inversion of Relief

Inversion of relief in folded structure is a unique phenomenon which causes reverse sequence of topographic features. Inversion of relief occurs in the folded structure having sym-metrical folds having alternate sequence of anti-clines and synclines and simple formation (fig.). With the initiation of fluvial erosion under the process of cycle of erosion after the folding of sedimentary rocks longitudinal master consequent streams (strike streams) and tributary consequent streams following slope direction are originated in the synclines and dip slopes of the anticlines respec-tively. The master consequent flows in the syncline from higher slope towards lesser gradient. The streams originating on the flanks of the anticlines (dip slopes) join the master consequents as tributary streams. These tributaries are called as transverse consequents or lateral consequents which develop their valleys through headward erosion of the anti-clines. With time, the crests of anticlines are breached and subsequent streams develop along the axes of anticlines. These subsequent streams continue to deepen their valleys due to maximum vertical erosion of anticlinal crests because of maxi-mum tension on crests with the result synclinal master consequent streams are eliminated and anti-clinal streams become master streams. This process results in the formation of valleys in the place of anticlines and ridges in the place of synclines. Thus, the previous topographic feature of original anticlines and synclines are reversed by the formation of synclinal ridges (in place of original anticlines) and anticlinal valleys (in the place of original anticlines) due to prolonged denudation and the process of inversion of relief is completed.

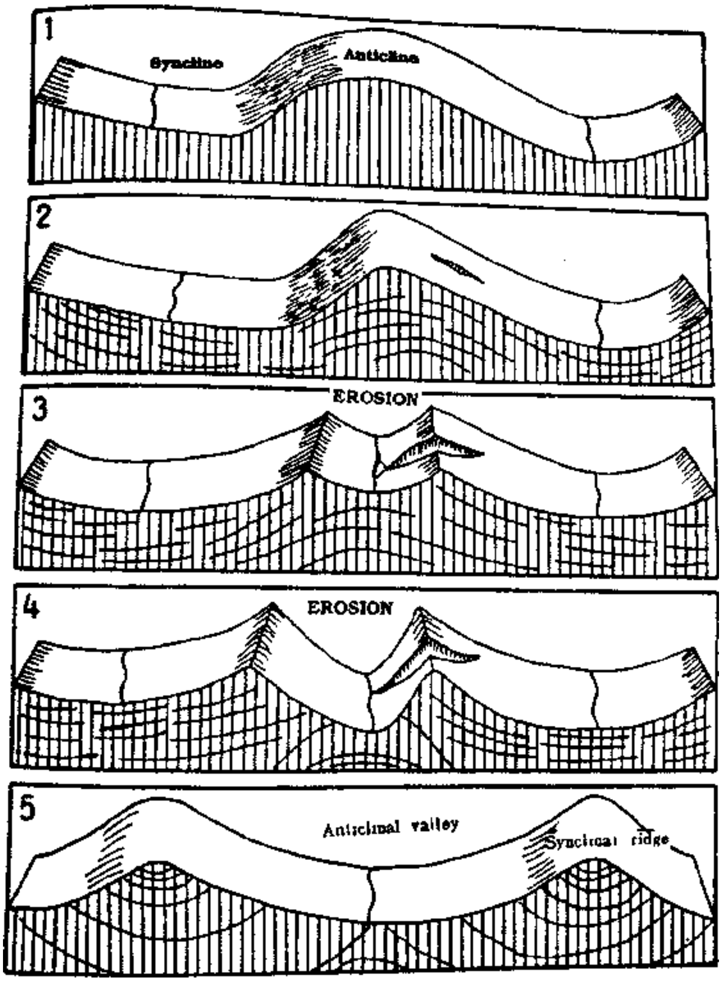


Fig. : Inversion of Relief

7.3 Uniclinal/Homoclinal/Monoclinal Structure

In structural geology, a uniclinal / monoclinal / homoclinal structure (from old Greek: homo = same, cline = inclination), is a geological structure in which the layers of a sequence of rock strata, either sedimentary or igneous, dip uniformly in a single direction having the same general inclination in terms of direction and angle. A homocline can be associated with either one limb of a fold, the edges of a dome, the coast-ward tilted strata underlying a coastal plain, slice of thrust fault, or a tilted fault block. When the uniclinal strata consists of alternating layers of rock that vary hardness and resistance to erosion, their erosion produces either cuestas, homoclinal ridges, or hogbacks depending on the angle of dip of the strata. On a topographic map, the landforms associated with homoclines exhibit nearly parallel elevation contour lines that show a steady change in elevation in a given direction. In the subsurface, they characterize by parallel structural contour lines. Unicline and Uniclinal are obsolete and currently uncommon terms that are defined and have been used by geologists and geomorphologists in an inconsistent and contradictory manner.

Topographic Expression of Tilted Strata

a. Homoclinal Structure: Homo = same, Cline = inclination; homoclinal structure = uniformly tilted beds

(1) Differential Erosion Processes: Strike and dip of homocline provide preferred directions of weakness, and hence preferred directions of stream orientation

(a) Selective Headward Erosion: cuts "strike valleys" along non-resistant rock layers

(b) Resistant Strata: "strike ridges" standing above valleys

(c) Net Result: Topography of parallel ridges (resistant strata) and valleys (non-resistant strata)

(2) Homoclinal Ridges: erosionally - resistant "strike ridges" in tilted rock terrain

a. Asymmetric Cross-Sectional Ridge Profile

i) Scarp Face: more steeply inclined "bed" face

ii) Dip Slope: topographic slope formed along dip-plane or bedding plane of resistant unit (scarp faces > steepness than dip slopes)

b. Cuestas: homoclinal ridges formed in gently tilted homoclinal sections <25-30° dip

c. Hogbacks: homoclinal ridges formed in more steeply tilted homoclinal sections >30-40° dip *d. Homoclinal Stream Shifting:* as initial streams begin cutting rock on newly formed homoclinal surface, down-cut the more easily eroded layers (e.g. shale) along strike.

(1) Vertical Limit of Downcutting: underlying resistant bed

(2) Dip-slope forces streams to "shift" laterally down dip laterally carving the more easily eroded strata

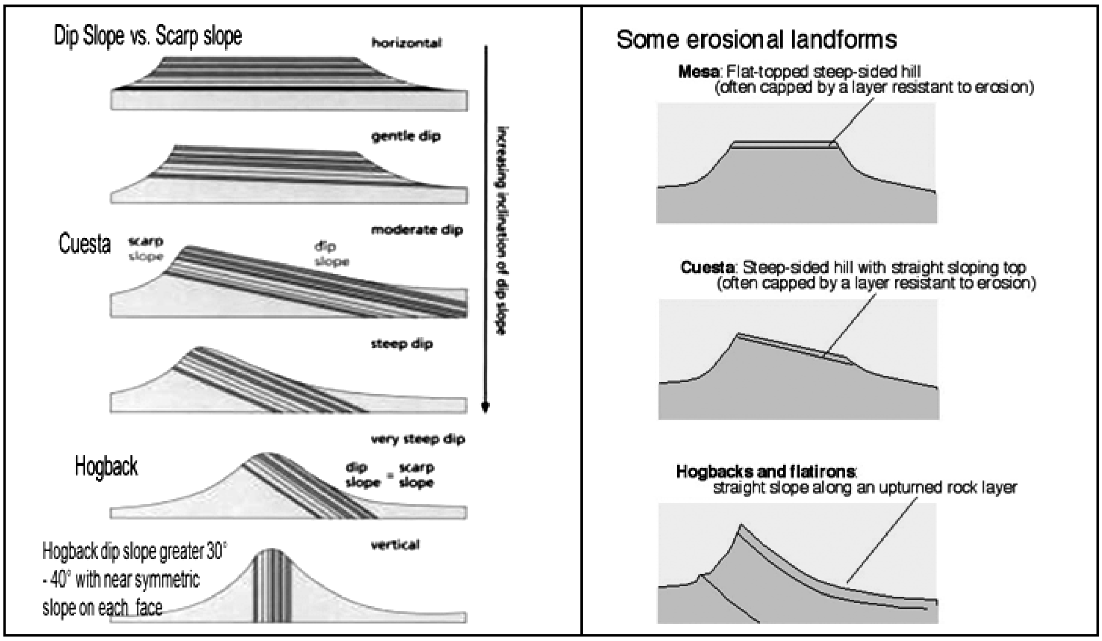
e. Erosional Retreat of Homoclinal Ridge:

(1) Scarp-face Retreat: because scarp faces are higher angle than dip slopes, the scarp face is more energetically eroded over time. Scarp face retreats laterally in down-dip direction.

(2) Homoclinal Shifting: homoclinal valleys migrate laterally in down-dip direction, and vertically along dip slope

(3) V-shaped Notches (a) where streams incise homoclinal ridges perpendicular to strike, via headward erosion, V-shaped notches are cut through the scarp face. (b) Law of V's: In the case of a v-shaped notch, the apex of the "V" points down dip in the direction of dip.

Thus, monoclinal structures are those in which the strata dip in one direction, but displays local steepening and flattening of dip along "monoclinal flexures". The major drainage patterns that develop in these structures are:



a. Consequent: stream patterns formed synchronously as beds are tilted, and drainage flows in direction of dip. Stream courses are “consequence” of initial slope of surface.

b. Subsequent: stream pattern developed in accordance to erosional resistance of folded or tilted strata. Form “subsequent” to structural deformation

c. Antecedent: streams maintain stream course (pattern) that was established prior to structural deformation (unaltered by deformation patterns) for e.g. Susquehana River cutting through Valley and Ridge near Harrisburg.

7.4 Summary

This unit gives the leasuers a vivid picture of the folded structure innession of relief and the landforms formed therby.

7.5 Questions

Long question

1. Discuss the different types of landforms developed in folded topography. Illustrate your answer with suitable sketches.
2. Discuss the different types of landforms developed in Uniclinal structure. Illustrate your answer with suitable sketches.
3. Describe the development of landforms in a terrain of folded structure.

Short question

1. Discuss any two typical landforms present in an area of uniclinal structure.
2. Discuss any two typical landforms presend in an area of folded structure.
3. Distinguish between a hogback and a cuesta.

Unit 8 ❑ Landforms on Igneous Rocks with Special Reference to Granite and Basalt

Structure

8.0 Objectives

- The learners will learn about the various landforms formed on igneous rocks.

8.1 Introduction

Landforms resulting from igneous processes may be related to eruptions of extrusive igneous rock material or emplacements of intrusive igneous rock.In broader sense, igneous rocks are of two types i.e. **Intrusive and Extrusive**.

A. Intrusive Igneous rocks crystallize below Earth's surface, and the slow cooling that occurs there allows large crystals to form. As the Intrusive Igneous rocks are made of magma that cools and solidifies, as a result they are coarse grained. Intrusive rocks are in the different forms according to the shape and size of the intrusive body and its relation to the other formation into which it intrudes. Typical intrusive formations are batholith (very large igneous intrusion), stocks, laccoliths (Igneous intrusion with depressed central region), sills (horizontal layer which runs parallel to rocks) and dikes (vertical layer of solidified magma between two rocks).

Intrusive Igneous rocks that form at depth within the crust are termed **plutonic** (or abyssal) rocks and are usually coarse-grained. Intrusive igneous rocks that form near the surface are termed hypabassal rocks and they are usually medium-grained. **Hypabyssal** rocks are less common than plutonic or volcanic rocks and often form dikes, sills, laccoliths, loppoliths, or phacoliths .Examples of intrusive igneous rocks are diorite, gabbro, granite, pegmatite, and periodite.

B. Extrusive Igneous Rocks erupt onto the surface, where they cool quickly to form small crystals. Some cool so quickly that they form an amorphous glass. These rocks include andesite, basalt, pumic, rhyolite, and tuff. Hence such rocks are smooth, crystalline and fine-grained. Basalt is a common extrusive igneous rock and forms lava flows, lava sheets and lava plateaus. Some kinds of basalt solidify to form long polygonal column. The Giant causeway in Antrim, Northern Ireland is an example. Deccan plateau of India is also basaltic plateau.

Magma is stored below the surface in reservoirs called magma chambers. It creates and follows paths called conduits to the surface. This network is often referred to as the volcano's plumbing system. These networks can cover vast areas.When magma cools and solidifies in these spaces, Intrusive or plutonic igneous rocks are formed deep beneath the Earth's surface. Intrusive features like stocks, laccoliths, sills, and dikes are formed. If the conduits are emptied after an eruption, they can collapse in the formation of a caldera, or remain as lava tubes and caves.The mass of cooling magma is called a **pluton**, and the rock around is known as **country rock**. Slow cooling over thousands to millions of years allows large visible crystals to form. Common **igneous rock types** include granite, gabbro, and diorite. Large plutons can form along convergent **tectonic plate boundaries.**

8.2 Landforms on Granite

Granite is a common **acidic plutonic igneous rock** whose major mineralogical components include quartz, alkali feldspar (K–, Na–feldspar), plagioclase (Na–Ca–feldspar) and mica. The petrological definition of granite refers to rocks in which quartz accounts for 20-60 % and plagioclase 10-65 % of the sum quartz?+?alkali feldspar?+?plagioclase. Outcrops of granitic rocks represent around 15 % of the continental area. They are particularly common in the tectonically stable shield areas (cratons) of the continental lithospheric plates and in recent orogenic areas affected by uplift and erosional un-roofing. Granite is one of the most common rocks found on earth and is associated with landforms vastly different from those found in karsts regions and different climatic zones tend to produce different granite landforms due to their distinct climate regimes.

Formation of Granite: Granite, one of the intrusive igneous rocks was formed from the solidification of granitic magma. When granitic magma is viscous and moves slowly, it seldom travels far enough to reach the surface but solidifies underground to form granitic plutonic structures such as batholiths (that form core of mountains). Since the rock is usually relatively more resistant to weathering and erosion than the surrounding rocks, it will be exposed after denudation (erosion). As it is formed underground under high pressure and heat, it is prone to the weathering process of pressure release.

Chemical composition of granite: made up of 25-35% quartz, >50% feldspar, and other minor minerals such as mica. Feldspar and biotite are chemical unstable and are susceptible to hydrolysis, therefore, although rock is resistant to mechanical weathering due to its physical strength, it is prone to chemical weathering and will be weathered easily in humid climate. When feldspar reacts with water, KOH and alumino-silica acid is produced. The former is carbonated and removed in solution while the latter is broken down into clay minerals (kaolinite) and silicic acid (removed in solution). Therefore, granular disintegration will occur when feldspar is reduced to kaolinite clay while unaltered quartz remains as sand particles, forming a mass of Gruss (A loose accumulation of fragmental products formed from the weathering of granite). At a more advanced stage of weathering, the regolith will crumble in residual debris. Embedded within the residual debris are unweathered and rounded corestones due to selective weathering along joints to produce blocks and their subsequent weathering by spheroidal weathering.

Rock texture of granite: Granite is characterised by large crystals that make it phaneritic, which is due to the slow solidification of granitic magma that takes place deep within the crust due the high temperature and pressure that that causes it to cool slowly. Therefore, there is ample time for crystallisation to take place and the large crystals that form leads to the development of large minerals.

Rock Structure of granite: Granite is high in secondary permeability since it possesses numerous joints, including shrinkage joints and sheet joints, which encourages selective weathering along these lines of weaknesses. Where these joints intersect at right angles, block disintegration will result, followed by spheroidal weathering and the formation of corestones.

8.3 Granitic Rocks and Associated Landforms

Weathering and erosion in arid regions underlain by granitic bedrock produce unique characteristic landforms. Spheroidal weathering is a form of chemical weathering in which concentric shells of decayed rock (ranging from a few millimetres to a couple meters) are successively loosened and separated from a block of rock. In the subsurface, groundwater penetrates along fractures and causes the chemical breakdown of rock along surfaces. Sharp corners at the intersection of fractures tend to break down first. In this manner, blocks of granitic bedrock (or other rocks that do not have layers or bedding) tend to become rounder as weathering proceeds. In humid regions, spheroidal weathering of granite typically occurs in the subsurface. In contrast, in arid regions the rate of chemical weathering is slow relative to the rate of surface erosion. As a result, in granitic terrains knob-shaped outcrops and spheroidal blocks accumulate on the surface. In the Mojave region, granite typically breaks down to form fairly uniform quartz- and feldspar-rich, coarse-sandy sediment compared to other rock types. In addition, many of the major pediment areas in the Mojave National Preserve have granitic bedrock. This is probably directly related to the more-or-less uninform weathering and erosion characteristics of large, homogeneous granitic intrusions.

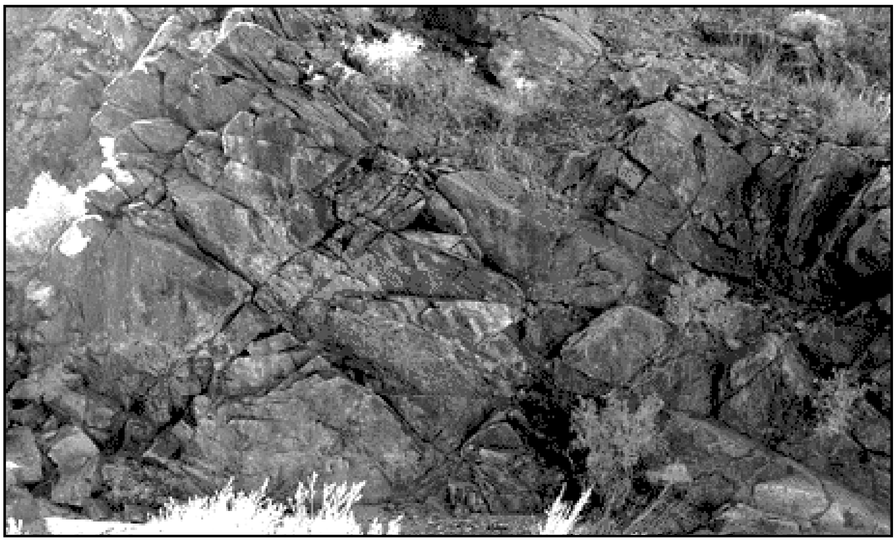


Plate 8.1: Fractured granite bedrock is exposed along Globe Wash in the Providence Mountains.

Plate 8.2: The characteristic rounded boulders and knob-shaped outcrops throughout the Granite Mountains formed as a result of spheroidal weathering and erosion of fractured granite.

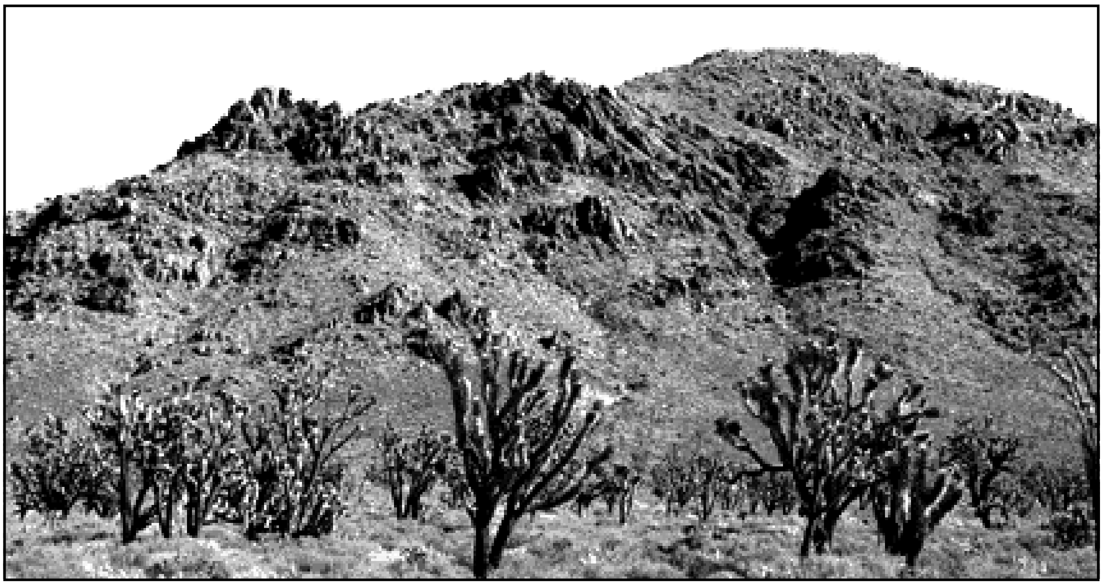


Plate 8.3: Large granitic intrusions of Cretaceous age are the bedrock of Kessler Peak in the southern Ivanpah Mountains. A Joshua-tree forest blankets a pediment surface in the foreground. This view is along Cima Road east of the Teutonia Mine area.

Landform Development in the Humid Tropics: Due to the high temperatures and high precipitation through the year, chemical weathering far exceeds the rate of transportation processes such as rain wash, creep and fluvial action. Therefore, deep regolith layers known as saprolite builds up over millions of years, completely masking the solid rock underneath over wide areas.

Landform development in the seasonally humid tropics: In this area, regolith is less thick than in the humid tropics as during seasonal drought, rainfall amount is reduced and the rate of chemical weathering, and thus regolith formation, is retarded. A higher degree of surface run-off and erosion occurs during the wet season, leading to removal of the regolith layer, as at the end of the dry season, there are less dense vegetation and more exposed earth where rainwash process is more effective. the rate of regolith formation by chemical weathering therefore lags behind that of regolith removal by erosion processes. When surface erosion outpace weathering, regolith layers will decrease in thickness or be removed altogether. Basal surface of weathering will also be revealed(whole or part) at the land surface and contributes to landform development. Landforms include Tors, and Inselbergs.

Tors: Tors aresmall hills or heaps of boulders, 4 to 20m high, rising abruptly from the surrounding gentle ground surface, which are abundant in places like Zimbabwe and Uganda. Linton(1955) suggests they are formed when subterranean chemical weathering widened the joints in between the blocks of granite in the tropics, and water would have attack the edges of the blocks, widening the joints and forming ever-shrinking corestones. As the amount of weathered material built up, transportation processes would have removed it, eventually exposing corestones as an upstanding mass of boulders.

Inselbergs: Inselbergs aresteep-sided, isolated hills that rise abruptly above the surrounding plains and show much variety in scale and morphology. It includes ruware, bornhardts, blocky inselbergs and castle koppies. Formed by etch planation (theory). Inselbergs are very durable landforms, as they comprise mainly of unjointed rock cores, and are virtually indestructible.

Bornhardt: Bornhardts aremost common form of inselberg that are characterised by great height exceeding 300m and possess nearly vertical or even overhanging sides. The rounded summit and thick rock sheets are determined by massive sheet jointed in the rock produced by pressure release. These rock sheets may curve down sharply at the dome margin to form major vertical joints and they normally range between 0.5 to 1.5m in thickness although sheets as thick as 10m have been observed. However, some evidence suggests that sheeting may be a superficial phenomenon, with 4-5 layers enclosing a solid and unjointed core of great durability.

Blocky inselbergs: Blocky Inselbergsresemble large scale tors which may exceed 300m in height that develop when rectangular jointed is dominant, which guided weathering.

Ruware: Ruwares are whale-back dome which possesses smooth convex surfaces that are low and dome-shaped. They are incipient (initial stage) inselbergs formed in the early stage of development and may grow in height to become a Bornhardt.

Castle Koppies: Castle Koppies arelow, irregular hills formed when inselbergs are subjected to prolonged sub-aerial weathering and collapse.

Etchplains and the Etchplanation theory: Land surfaces which have been subjected to one or more phases of deep weathering, followed by partial or complete removal of regolith cover. Theory that suggests that inselbergs standing in isolation above etchplains are product of downwearing processes, due to climatic change. During pluvial periods, weathering is concentrated where joints are numerous and closely spaced, which is followed by an interpluvial period when rate of erathering is reduced, causing vegetation to degenerate, and allows more effective surface wash to strip the unprotected regolith. Since the basal surface of weathering is undulating due to the different rates of weathering of granite(result of presence of irregularly-spaced joints in the rock), this active removal or regolith will expose the smooth and elongated ruware for up to 15m or more in height. When a number of pluvial and interpluvial periods alternate, the ruware will become progressively higher with each cycle of weathering and stripping, as the rate of weathering of the expose ruware lags behind that of the plains, due to the fact that bare rock inselbergs shed rainwater rapidly and dry out in the tropical sun is therefore resistant to chemical weathering. Simultaneously, areas marginal to the domes receive increments of water, and thus, the weathering process is accentuated in the etchplains. This result in a more undulating basal surface of weathering that gives rise to taller inselbegs after the regolih is stripped off during the next interpluvial period.

8.4 Landforms on Basalt

Basalt is an extrusive igneous rock that is very dark in colour. It is the most common type of rock in the Earth’s crust and it makes up most of the ocean floor. It is made of many dark coloured minerals such as pyroxene and olivine. Basalt also contains some light coloured minerals such as feldspar and quartz, but the amounts are small. Basalt is a very common dark-colored volcanic rock composed of calcic plagioclase (usually labradorite), clinopyroxene(augite) and iron ore (titaniferous magnetite). Basalt may also contain olivine, quartz, hornblende, nepheline, orthopyroxene, etc. Basalt is a volcanic equivalent of gabbro. Basalt is usually black or dark gray and relatively featureless. It is composed of mineral grains which are mostly indistinguishable to the naked eye. Basalt may also contain volcanic glass. Basalt may contain phenocrysts (larger crystals within fine-grained groundmass) and vesicules (holes that were filled by volcanic gases). Black colour is given to basalt by pyroxene and magnetite. Both of them contain iron and this is the reason why they are black. So this is iron again which is responsible for the coloration of basalt. Plagioclase, volumetrically usually the most important constituent, is mostly pale gray in colour. Basalt is a major rock type that occurs in virtually every tectonic setting. Basalt is clearly the most common volcanic rock on Earth and basaltic rocks (including gabbro, diabaseand their metamorphosed equivalents) are the most common rocks in the crust[2]. Basalt is also common on the Moon and other rocky planets of the Solar System.

Basalt is the original constituent of the crust from which almost all other rock types have evolved. Basalt forms when mantle rocks (peridotite) start to melt. Rocks melt incongruently. It basically means that melt that forms has a different composition from the source rocks. Of course, it can only happen if rocks melt only partially, but this is exactly what happens in the upper mantle. It melts partially to yield basaltic magma which is less dense and rises upward to form new oceanic crust in mid-ocean ridges or volcanoes and intrusives (dikes, sills) in many other tectonic regimes. Basalt is the source rock of other more evolved volcanic rocks like dacite, rhyolite, etc.

Typically, you can’t see most of the mineral crystals without using a microscope because quick cooling prevents large crystals from forming. Basalt forms when lava reaches the Earth’s surface at a volcano or mid ocean ridge. The lava is between 1100 to 1250° C when it gets to the surface. It cools quickly, within a few days or a couple weeks, forming solid rock. Very thick lava flows may take many years to become completely solid.

Subaerial basalt forms lava flows or pyroclastic fields and cones. Two main types of basaltic lava flows are **Aa lava** and **Pahoehoe lava**.Aa lava has rough rubbly irregular crust while Pahoehoe is smooth. Lava crust of Aa type is broken into pieces while Pahoehoe retains its continuity. Both lava flow types are massive beneath the crust and this massive interior may be columnar. Columns are separated from each other by narrow cracks which form because cooling basaltic magma contracts. Cracks start to form at the surface and propagate deeper as lava cools. Submarine basalt usually forms pillows. Pillow basalt forms as a result of very rapid cooling. Outer part of forming pillow cools very quickly in contact with cold seawater while the interior still fills with molten lava.

Basalt mostly forms lava flows because it is among the least viscous magma types and therefore does not generate explosive volcanic eruptions, but sometimes pyroclastic material is formed when magma contains more volcanic gases. Basaltic rocks can be thrown out of volcanic vents as lapilli (singular: lapillus) and volcanic bombs. Basaltic volcanoes are fed by dikes (planar intrusive rock bodies when solidified that cut through other rocks) and sills (similar to dike but generally parallel to pre-existing bedding planes).

Plateau or Flood basalts are extremely large volume outpourings of low viscosity basaltic magma from fissure vents. The basalts spread huge areas of relatively low slope and build up plateaus. The only historic example occurred in Iceland in 1783, where the Laki basalt erupted from a 32 km long fissure and covered an area of 588 km2 with 12 km3 of lava. As a result of this eruption, homes were destroyed, livestock were killed, and crops were destroyed, resulting in a famine that killed 9336 people.

A **Shield Volcano** is characterized by gentle upper slopes (about 5^o) and somewhat steeper lower slopes (about 10^o).Shield volcanoes are composed almost entirely of relatively thin lava flows built up over a central vent. Most shields were formed by low viscosity basaltic magma that flows easily down slope away from the summit vent. The low viscosity of the magma allows the lava to travel down slope on a gentle slope, but as it cools and its viscosity increases, its thickness builds up on the lower slopes giving a somewhat steeper lower slope.Most shield volcanoes have a roughly circular or oval shape in map view.Very little pyroclastic material is found within a shield volcano, except near the eruptive vents, where small amounts of pyroclastic material accumulate as a result of fire fountaining events. Shield volcanoes thus form by relatively non-explosive eruptions of low viscosity basaltic magma.

Basalt columns are caused by the rapid cooling of lava, about 90% of which is made of a kind of volcanic rock called basalt. As the rock cools, it contracts and cracks on the surface—those cracks then penetrate the ground and create long, geometric columns. This phenomenon is called columnar jointing.

Fig 8.4: Basaltic lava flows of Kilauea volcano in Hawai'i.

Fig 8.5: Aa lava in the foreground. La Palma, Canary Islands.

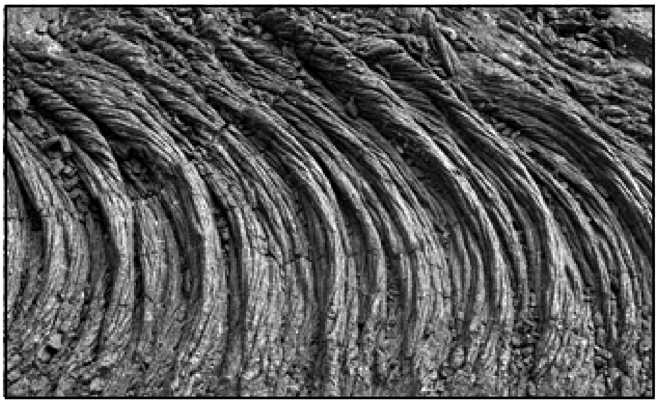


Fig 8.6: Pahoehoe lava (ropy lava). La Palma, Canary Islands.

Fig 8.7: Basalt columns. Giant's Causeway, Northern Ireland.

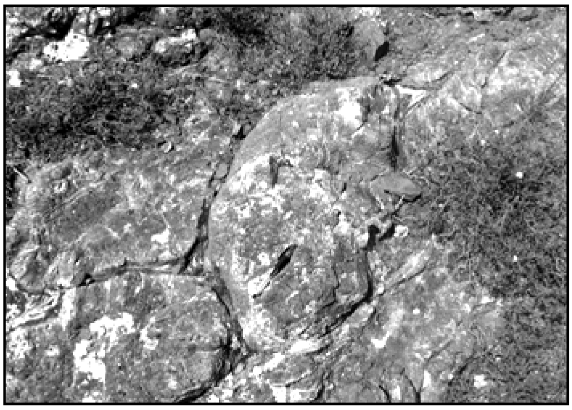


Fig 8.8: Pillow lava near Fasoula, Troodos ophiolite, Cyprus. Pillow lava is very common on Earth, but difficult to find because almost all of it is on the ocean floor. Examples can be found on land usually where former ocean floor is tectonically squeezed between two blocks of continental crust.

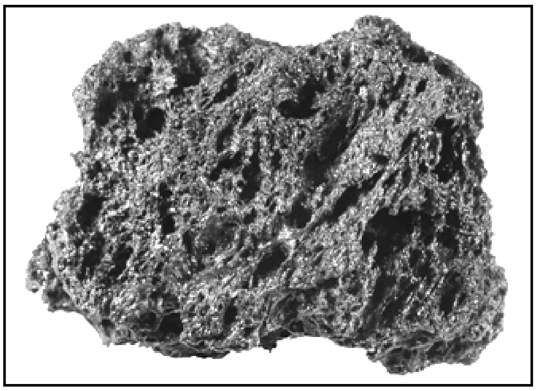


Fig 8.9: Scoriaceous lapillus from Etna, Italy. Despite being 5 cm in width it weighs only 15 grams because it is filled with gas bubbles (vesicules). Similar rock type with a felsic composition is pumice.

Fig 8.10: Sometimes dikes are so close to each other that the whole outcrop is composed of them. These sheeted dikes in Cyprus once fed volcanoes on the ocean floor.

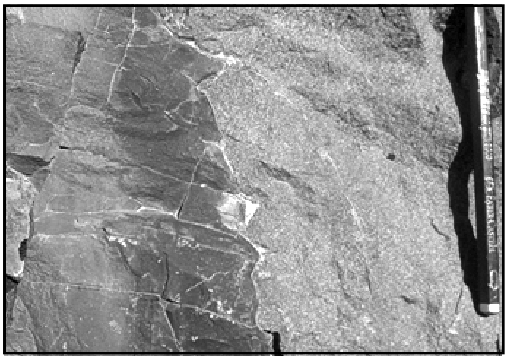


Fig 8.11: Dikes are composed of basalt and diabase. Diabase is nothing more than coarse-grained basalt. Here is a contact between basalt (on the left) and diabase in Cyprus. The basaltic dike is fine-grained because it is younger and was chilled (it lost heat rapidly to the diabase dike on the right).

Fig 8.12: Columns in basalt are perpendicular to the cooling front. In this case it is evident that basalt formed a tube (filled lava tunnel). Such conduits are common phenomena in volcanic islands and provide a way for the volcano to enlarge itself because magma can flow great distances inside such thermally insulated tubes before solidifying. Tenerife, Canary Islands.

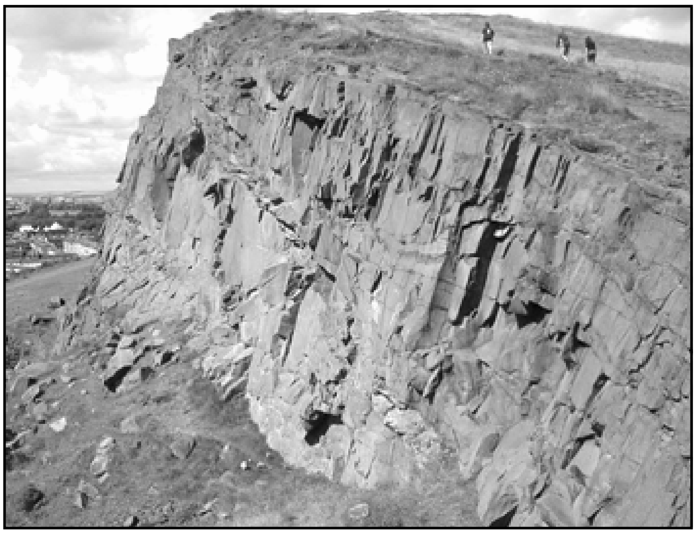


Fig 8.13: Dikes and sills are often visible on the ground and may become notable landforms. Salisbury Crags in Edinburgh is basaltic sill.

Metamorphism and weathering: Basalt is largely composed of minerals with little resistance to weathering. Hence, basalt as a whole also tends to disintegrate faster than granite and other felsic rock types. Magnetite is one of the most resistant common minerals in basalt and forms the bulk of heavy mineral sands. Other minerals disintegrate and release their components to water as ions or form clay minerals. Iron and aluminum are among the least mobile ions and therefore tend to form laterite deposits enriched in these elements.Basalt metamorphoses to a number of different rock types, depending on pressure, temperature, and the nature of volatile compounds that react with minerals in basalt. Most common metamorphic rocks with basaltic protolith are chlorite schist, amphibolite, blueschist, and eclogite.

Fig 8.14: Black sand forms in volcanic islands when quartz and biogenic grains are not available. Here is a basaltic cliff and black sand on La Palma, Canary Islands.

8.5 Differences Between Basalt and Granite

Basalt is an igneous, volcanic rock that forms commonly in oceanic crust and parts of continental crust. It forms from lava flows which extrude onto the surface and cool. Its principle minerals include pyroxene, feldspar, and olivine. It is common both on Earth and other planetary bodies. Granite is an igneous plutonic rock which is very common in continental crust. It forms from subterranean magma chambers that cool and harden beneath the surface and then become exhumed and exposed at the surface. Basalt and granite are similar in the they are both igneous, silicate rocks and common on Earth. They also have numerous differences. Basalt is extrusive, mafic, and common throughout the Solar System whereas granite is intrusive, felsic, and common only on Earth.

Although there are some similarities between basalt and granite, there are also significant differences between these two rock types.

- Basalt is volcanic, or extrusive, forming at the surface, while granite is plutonic, or intrusive, forming beneath the surface.
- Basalt is mafic while granite is felsic
- Basalt is common on both Earth and other Solar System bodies such as the Moon and Mars while granite is only common on Earth and rare elsewhere in the Solar System
- Basalt can form in a few days to months, whereas granite plutons can take millions of years to cool and harden.
- Basalt is more common in oceanic crust while granite is more common in continental crust.

Feature	**Basalt**	**Granite**
Surface Location	Extrusive	Intrusive
Composition	Mafic	Felsic
Distribution	Common on most silicate terrestrial planetary bodies	Only common on Earth
Formation time	Days to months	Millions of years
Associated Crust	Oceanic and continental crust	Usually continental crust

8.6 Summary

This unit deals with the landforms on igneous rocks and the various formation on granitic and basaltic landforms.

8.7 Questions

Long question

1. Discuss the formation of landforms on basaltic lithology.
2. Discuss the formation of landforms on granitic lithology.
3. Describe the landforms produced in a granitic region under humid tropical climate.

Unit 9 ❑ Karst Landforms : Surface and Sub-surface

Structure

9.0 Objectives
9.1 Introduction
9.2 Karst Topography
9.3 Karst Landforms
9.4 Depositional Landforms
9.5 Summary
9.6 Questions

9.0 Objectives

- To study about the Karst topography
- To study the Karst landforms and the depositional landforms

9.1 Introduction

The term ***karst*** describes a distinctive topography that indicates dissolution (also called chemical solution) of underlying soluble rocks by surface water or ground water. Although commonly associated with carbonate rocks (limestone and dolomite) other highly soluble rocks such as evaporates (gypsum and rock salt) can be sculpted into karst terrain.Understanding caves and karst is important because ten percent of the Earth's surface is occupied by karst landscape and as much as a quarter of the world's population depends upon water supplied from karst areas. Though most abundant in humid regions where carbonate rock is present, karst terrain occurs in temperate, tropical, alpine and polar environments. Karst features range in scale from microscopic (chemical precipitates) to entire drainage systems and ecosystems which cover hundreds of square miles, and broad karst plateaus.

Although karst processes sculpt beautiful landscapes, karst systems are very vulnerable to ground water pollution due to the relatively rapid rate of water flow and the lack of a natural filtration system.

Limestone is an organically formed sedimentary rock consisting primarily of calcium carbonate in the form of the mineral calcite. Rainwater dissolves the limestone by the following reaction: Calcite + Carbonic acid = Calcium ions dissolved in ground water + Bicarbonate ions dissolved in ground water.In its pure state, limestone is made up of calcite or calcium carbonate but where magnesium is also present it is termed as dolomite. Limestone is soluble in rainwater.

9.2 Karst Topography

The degree of development of karst landforms varies greatly from region to region. Large drainage systems in karst areas are likely to have both fluvial (surface) and karst (underground) drainage components. As stated in the introduction, the term karst describes a distinctive topography that indicates dissolution of underlying rocks by surface water or ground water.Water falls as rain or snow and soaks into the soil. The water becomes weakly acidic because it reacts chemically with carbon dioxide that occurs naturally in the atmosphere and the soil. Rainwater seeps downward through the soil and through fractures in the rock responding to the force of gravity. The carbonic acid in the moving ground water dissolves the bedrock along the surfaces of joints, fractures and bedding planes, eventually forming cave passages and caverns.

Karst topography is named after the typical topography developed in limestone rocks of Karst region in the Balkans adjacent to the Adriatic Sea. Karst topography includes typical landforms in any limestone or dolomitic region, produced by the action of groundwater through the processes of solution and deposition.

Conditions for the Formation of Karst Topography

The following conditions are required for a limestone to develop into karst topography:

1. A region with a large stretch of water-soluble rocks such as limestone at the surface or sub-surface level
2. Limestones should not be porous.
3. Complex patterns of joints in limestones are noticedand these rocks should be dense, thinly bedded and well jointed.
4. A perennial source of water and a low water table to allow the formation of conspicuous features.
5. Moderate to abundant rainfall to cause the solvent action of water i.e. solution of rocks

6. Thick strata of limestone (20 feet or more)
7. Karst topography does not develop in deserts.

Erosional Processes:

Solution

Main reaction: $CaCO_3 + H_2O + CO_2 \Rightarrow Ca^{+2} + 2HCO_3^-$

calcite + water + carbon dioxide ⇒ calcium ion + carbonic acid

Factors controlling the solution rate are

- Amount of dissolved CO_2
  - partial pressure of CO_2 in air
    - increase $CO_2 \Rightarrow$ increase quantity of CO_2 absorbed by water
    - CO_2 higher in caves than open air
    - CO_2 may be quite high in soil
  - temperature: cooler water can dissolve more CO_2 than warmer water at a given CO_2
  - biological processes: decaying humus is important source of CO_2
- Concentration Ca in solution
  - mixing of unlike water masses, regardless of original saturation, results in under saturated solution
  - under saturation promotes more solution
  - may explain formation of caves just below water table where vadose & phreatic water mix
- Climate
  - temperature, precipitation, biological activity
  - runoff generation is most important aspect of climate

Resisting Framework

Lithology: ideal conditions require limestone that is:

- fairly pure
  - over 60% calcite for some karst
  - over 90% calcite for fully developed karst
- very thick
- mechanically strong
- massively jointed

Structure: porosity and permeability

- porosity: percentage of pore spaces in a given volume of rock or soil
    - primary porosity - intergranular voids; affected by:
        - grain size distribution
        - particle shape
        - degree of packing
    - secondary porosity: voids due to joints, faults, fractures or bedding planes
        - promotes circulation by increasing permeability
    - porosity important only if rocks are also permeable
- permeability: ease with which rock or soil transmits water

Mechanism of erosion in Karst region

- In Karst regions, rocks are permeable, thinly bedded and highly jointed and cracked.
- Thus there is the general absence of surface drainage as the surface water has gone underground
- After vertically going down to some depth, the water under the ground flows horizontally through the bedding planes, joints or through the materials themselves.
- Rocks are eroded due to this downward and horizontal movement of water.
- It is through the chemical process of solution and precipitation deposition by surface water and groundwater, varieties of landforms are developed in rocks like limestones or dolomites rich in calcium carbonate.

9.3 Karst Landforms

The Karst landforms are results of the ground water erosion.Water that occupies pores, cavities, cracks and other spaces in the crustal rocks in known as ground or underground water. The main source of underground water is precipitation and melt-water which infiltrates in the rocks.Slow moving ground water can dissolve huge quantities of soluble rock and carry it away in solution. It dissolves limestone, rock salt, ad gypsum. In some areas, it is the dominant agent of erosion and produces karst topography, which is characterized by sinkholes, solution valleys, and disappearing streams.The work of ground water is however more significant in the regions of karst topography.Approximately 15% of the Earth's land area has developed karst topography with outsatanding examples found in Bosina, Crotia, southern China, Puerto Rico, Yucatan of Mexico, Florida, Australia, Mehalaya, Siberia.

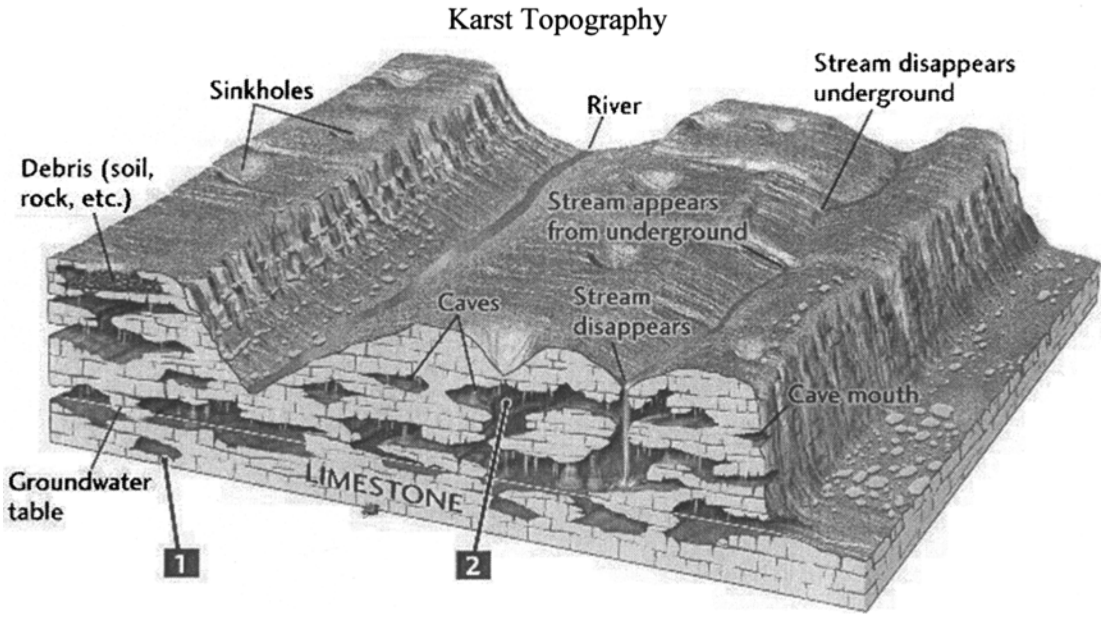


Fig. 9.1: Karst Landforms

Erosional Landforms

Sinkhole: Small to medium-sized round to sub-rounded shallow depressions called swallow holes form on the surface of limestones through solution where rainwater sinks into the limestone at a point of weakness. Sinkholes are a common feature in limestone/karst areas.A sinkhole is an opening more or less circular at the top and funnel-shaped towards the bottom. There is a great variation in sizes of Sinkholes with areas from a few sq. m to a hectare and with depth from a less than half a metre to thirty metres or more. These holes grow in size through continuous solvent action. They are also referred to as solution sinks

Caves and Caverns:A natural cavity, chamber which leads beneath the surface of the earth generally in a horizontal or obliquely inclined direction. It may be in the form of a passage or a gallery. Most caves are formed in limestone rock, because it is easily dissolved by carbonation. Rainwater dissolves atmosphere carbon dioxide and forms a weak acid. It then percolates through the fractures and bedding plane, slowly dissolving and enlarging the opening plane, slowly dissolving and enlarging the openings. As cave grows larger, they become unstable and tend to collapse.

Blind Valley: It is a type of valley in karst topography. It may be occupied by a stream which disappeared underground as the valley lower end as it approaches and enclosing rock well. Consequently, the valley looks like a dark valley.

Tower Karst : Tower karst are steep, cone-shaped hills, In tropical areas, where dissolution is at a maximum because of the abundance of water from heavy rainfall, a particular type of karst topography known as tower karst develops. (e.g South China, Sumatra and Yucatan Peninsula)

Uvalas: They are long, narrow to wide trenches, also referred to as Valley sinks. Several sinkholes and Dolines may merge together as a result of subsidence to form a large depression called an Uvala.Through solution and collapse, Dolines may coalesce and form Uvalas or valley sinks which are depressions up to several kilometers in diameters.

Lapies/ Karren: These are grooved, fluted and ridge-like features in an open limestone field. These ridges or lapies form due to differential solution activity along parallel to sub-parallel joints. Eventually, the lapie field may transform into smooth limestone pavements.

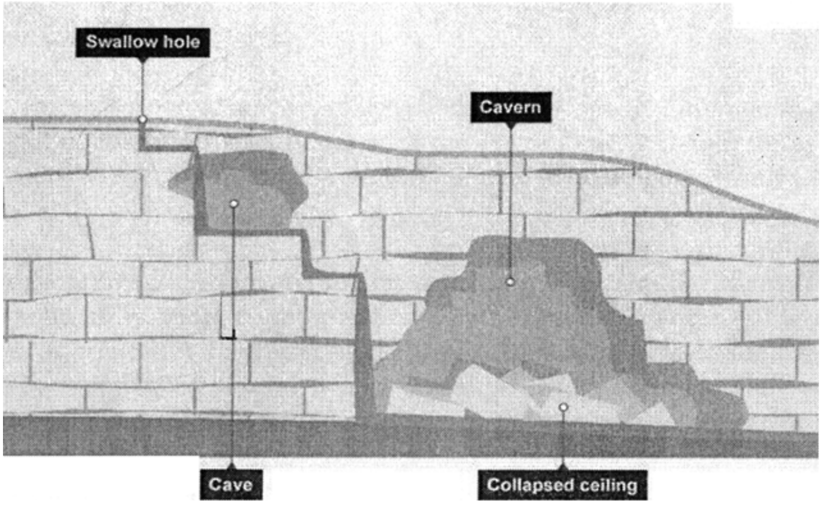


Fig 9.2: Caves and Caverns

Limestone Pavements: A limestone pavement is a natural karst landform consisting of a flat, incised surface of exposed limestone that resembles an artificial pavement. These are formed by the solvent action of underground water in the limestones, causing progressive widening and enlargement of joints and cracks in the trenches. The enlarged joints are called grikes and the isolated, rectangular blocks are termed as clints.

Caves: Cave formation is prominent in areas where there are alternating beds of rocks (sandstone, shale, quartzite) with limestone or dolomite in between or in areas where limestones are dense, massive and occurring as thick beds.Water percolates down either through the materials or through cracks and joints and moves horizontally along bedding planes.Gradually, the limestone dissolves along these bedding planes resulting in the creation of long and narrow gaps called caves.

Doline: They are also referred to as Collapse sinks. They are less common than sinkholes. They might start as solution forms first, and if the bottom of a sinkhole forms the roof of a void or cave underground, it might collapse leaving a large hole opening into a cave or a void below.

Polje : It is large depression in a karst region with steep sides and flat floor. It is drained by surface water sources. It is termed as open polje, but if drained by means of shallow holes, it is closed Polje. A polije is a very large, flat-floored depression in the karst region.They are often formed by merging of several uvalas or partly due to faulting.They are commonly found in subtropical and tropical latitudes.Some of these may also appear in the temperate region. They may also be found in boreal regions, though very rarely.During the rainy season, parts of the floor which are at or near the water table may become temporary lakes.Drier areas are fertile. Usually covered with thick sediments, they are used extensively for agricultural purposes

Natural Bridge: These are erosional feature in karst topography. They are formed either due to the collapse of roofs of caves or due to disappearance of surface streams.

Ponor: A ponor is a natural surface opening in the karst regions. They are found directly underneath the sinkholes. A ponor is kind of a portal where a surface stream or lake flows either partially or completely underground into a karst groundwater system.

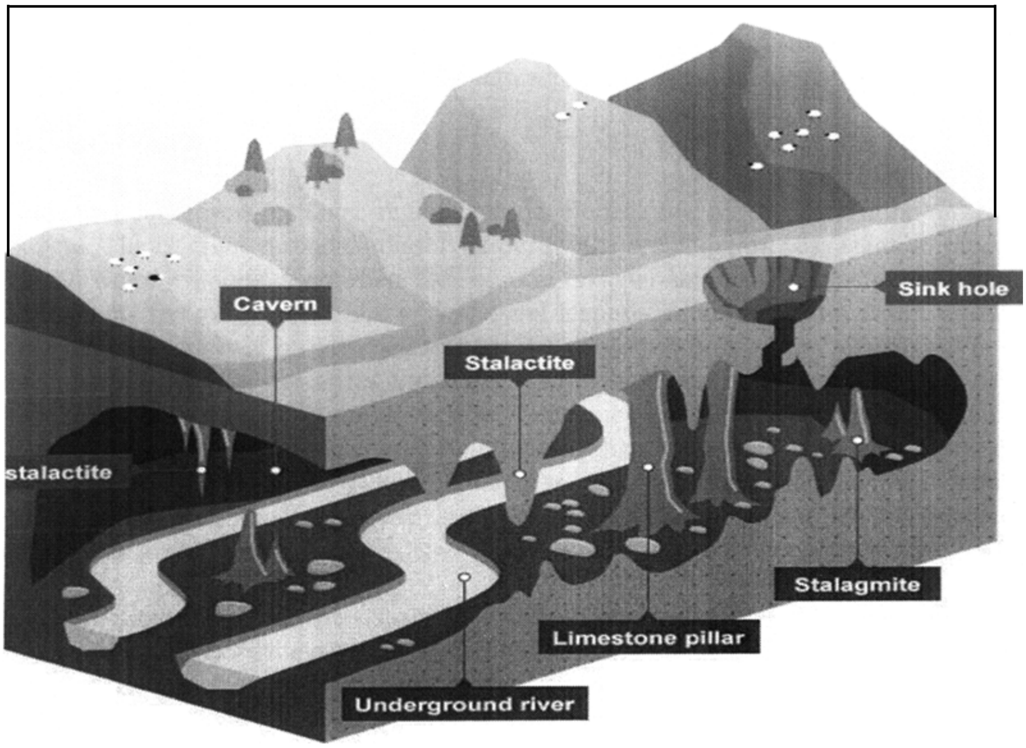


Fig 9.3: Stalactite, Stalagmite and Limestone Pillars

9.4 Depositional Landforms

Depositional landforms in karst region are developed due to the deposition of calcium carbonate. The calcium carbonate dissolved during the erosional process starts to precipitate when the water evaporates or when the solution is super-saturated.Stalactites, Stalagmites and Pillars are the most spectacular underground features, found in the limestone caves.The mineral matter dissolved by groundwater can be deposited in a variety of ways. The most spectacular deposits are stalactites and stalagmites, which are found in caves. Less obvious are the deposits is permeable rocks such as sandstones are the deposits in permeable rock such as sandstones and conglomerates. Here groundwater commonly deposits mineral matter as cement between grains.The mineral matter dissolved by ground water can be deposited in a variety of ways.The deposits are known as *"Dripstones"*. Some of the depositional landforms are given below:

Stalactites: Stalactites are the sharp, slender, downward-growing icicles of different diameters that hang from the cave roofs. Stalactites have a variety of forms. Their bases are normally broad which taper towards the free ends. The water carries calcium in solution and when this lime-charged water evaporates, it leaves behind the solidified crystalline calcium carbonate.

Stalagmites: Stalagmites form due to dripping water from the surface or through the thin pipe, of the stalactite, immediately below it. Moisture dripping from the roof trickles down the stalactite and drops to the floor where stalagmites are formed due to deposition of calcium. Stalagmites may take the shape of a column, a disc, with either a smooth, rounded bulging end or a miniature crater-like depression.

Pillars: Over a long period, the stalactite is eventually merged with the stalagmite. Thus, the pillars or columns of different diameters are formed.

9.5 Summary

The Karst landforms varies greatly from region to region, developed in limestone regrous. The depositional landforms are spectacular and are formed due to deposition of calcium carbonate.

9.6 Questions

Long question

1. Discuss the characteristics of landforms developed in the region of limestone.
2. Discuss the landforms produced in a karst region.

Short question

1. Explain the formation of the different types of dolines.
2. Distinguish between Uvala and Polije.

Unit 10 ❑ Glacial and Fluvio-glacial Processes and Landforms

Structure

10.0 Objectives

- The learners will learn about the various glacial erosional and depositional
- To learn about the fluvio-glacial processes

10.1 Introduction

GLACIAL PROCESSES AND LANDFORMS

Glaciers are thick masses of flowing/moving ice. Theyoriginate on land from the compaction and re-crystallization of snow, thus are generated in areas favoured by a climate in which seasonal snow accumulation is greater than seasonal meltinginPolar Regions and high altitude/mountainous regions. Glaciers shape the land through processes of erosion, transportation and deposition, creating distinct landforms.

Snowfield is a region that displays a net annual accumulation ofsnow

Snowline is an imaginary line defining the limits of snow accumulation in a snowfield above which continuous, positive snow cover

10.2 Classification of Glaciers

Glaciers may be classified as per the following bases—

A. Based on morphology and relationship with topography

- **Confined glaciers:** niche, cirque, and valley glaciers
- **Transitional:** ice field/transection glacier, piedmont and outlet glaciers
- **Unconfined glacier:** ice sheet and ice cap
- **Floating glaciers:**
  - **Ice shelf:** large unconfined floating glacier
  - **Tidewater glacier:** valley or outlet glacier terminating in the ocean

B. Based on thermal regime

- warm-based or temperate (bed is at pressure-melting temperature)
- cold-based or "polar" (glacier is frozen to the bed; no basal meltwater)

C. Based on Activity (related to mass balance)

- active (advancing or at equilibrium)
- undernourished (retreating)
- dead (no longer flowing)

Different aspects of a Glaciers

Glacier mass balance is the accounting of input and output or accumulation and ablation i.e. glacial budget

- **Zones of accumulation:** Sources are precipitation, wind deposition, avalanche and condensation (rime); surface of the (alpine) glacier is concave upward.
- **Equilibrium line** generally called snowline.
- **Zone of wastage/ablation:** melting (from below and above), sublimation, calving; surface of the glacier(alpine)is convex upward.

Types of Glacial Flow:

1. **Creep** (ductile/plastic deformation) occurs at depths > 60m
2. **Brittle deformation** (typically occurs at depths < 60 m)
3. **Basal sliding** (requires basal water)
4. **Regelation slip** (subglacial meting and refreezing)
5. **Subglacial flow** (deformable bed)

Rate of creep

- ○ Glen's flow law (Flow rate = kT^3): strain rate is proportional to the cube of shear stress and increased with rising Temperature (K is the constant related to temperature and T is shear stress).
- ○ Shear stress (T) = pghsinΘ (where p is the density of ice, g is gravity and Θ is the slope of the ice surface).

Internal flow variations:

It is due to internal stress caused by internal variation in flow and transport directions—

- Longitudinal (compressive and extensive)
- Lateral (converging and diverging)
- Extending flow causes ice to flow toward the bed compressive flow causes ice to flow towards the surface.

10.3 Glacial Erosional Processes

- **Abrasion**: As the glacier moves downhill, rocks that have been frozen into the base and sides of the glacier scrape the rock beneath. The rocks scrape the bedrock like sandpaper, leaving scratches called **striations** behind.
- **Plucking/quarrying**: Rocks become frozen into the bottom and sides of the glacier. As the glacier moves downhill it '**plucks**' the rocks frozen into the glacier from the ground.
- **Rafting**: It is a process of sediment transport of large blocks.
- **Subglacial meltwater erosion**

Rates of erosion will vary considerably but where:

- temperatures fluctuate around freezing point,
- where rocks are more **jointed** and **faulted** providing weaknesses,
- where slopes are slightly steeper leading to more rapid glacier movement (very steep slopes can lead to extended flow, a thinning of the ice and reduced erosive power,
- two or more glaciers meet and combine to give an increased depth of ice,
- ice moves by **rotational flow** in corrie glaciers leading to over-deepening of the hollow.

10.4 Glacial Erosional Landform Features

Large-scale features of erosion by glaciers are :

Glacial Troughs and Associated Landforms

Troughs/U-shaped valleys (alpine and continental) and related features: A **U-shaped valley** has a flat floor and steep sides. Interlocking spurs eroded by the river are called truncated spurs. Hanging valleys are left by old tributaries. A ribbon lake may form in the river.In mountain environments, valley glaciers severely modify former river valleys to produce very deep, steep-sided, flat-floored U-shaped valleys or glacial troughs.

Variations in rock resistance or locations where glaciers merge give rise to over-deepening of the valley floor and the formation of long, narrow **ribbon lakes.**

Where over-deepening occurs along the coasts, **deep sea fjords** may form as sea-levels rise and flood the former glaciated valley.

Along the sides of the glacial troughs are **truncated spurs,** rocky outcrops which form the ends of former interlocking spurs that have been eroded by the valley glacier.

Tributary river valleys contain only **small valley glaciers** and due to the small amount of erosive power that they have, these valleys remain at a higher level and form **hanging valleys**, often with dramatic waterfalls where tributary streams re-join the main valley.

In the glacial troughs post-glaciation, small **misfit streams** occupy the now enlarged valleys.

Cirques (alpine): Cirques or a corrie is an armchair-shaped hollow found on the side of a mountain. This is where a glacier forms. In France corries are called cirques and in Wales they are called cwms.

How does a corrie form?

- Snow collects in a sheltered hollow on the side of a mountain. This is usually on North-facing slopes in the northern hemisphere. The snow doesn’t melt in the summer because it is high up, sheltered and cold.
- Every winter, more snow collects in the hollow. This becomes compacted and the air is squeezed out leaving ice.
- The back wall of the corrie gets steeper due to freeze-thaw weathering and plucking.

- The base of the corrie becomes deeper due to abrasion.
- As the glacier gets heavier it moves downhill. The glacier moves out of the hollow in a circular motion called rotational slip.
- Due to less erosion at the front of the glacier a corrie lip is formed.
- After the glacier has melted a lake forms in the hollow. This is called a corrie lake or tarn.

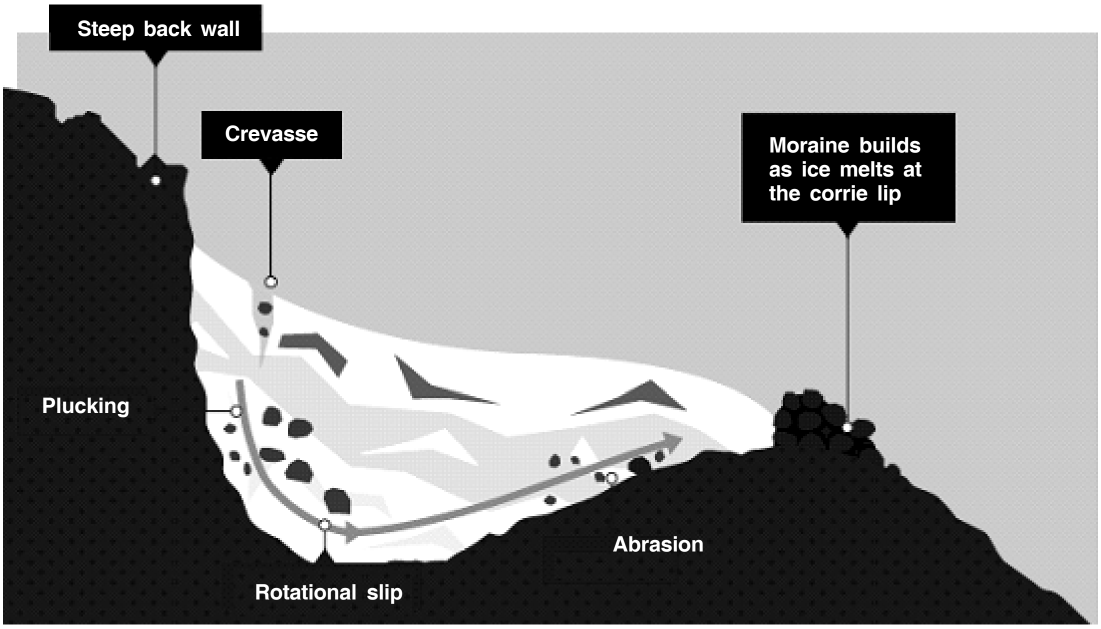


Fig 10.1: Cirque and associated erosional features.

Arêtes—this is a narrow ridge of land that is created when two corries erode back towards each other

- **Pyramidal peak—**if three or more corries erode back towards each other, at the top of a mountain a pointed peak or Horn (alpine)is left behind

Other features of erosion

When a glacier moves downhill it erodes everything in its path through abrasion and plucking. Glaciers usually follow the easiest route down a mountain, which is often an old river valley.

Interlocking spursare created by a river are eroded at the ends by the glacier to create truncated spurs. After the glacier has melted it leaves a U-shaped glacial trough. Sometimes the glacial trough fills with water, called a ribbon lake. Old tributaries, which would have once fed into the valley are left suspended and are known as hanging valleys.

Intermediate features:

- rochemoutonnee (asymmetrical)
- whalebacks (symmetrical)
- flybergs

Small scale features of erosion (good directional indicators)

Ice is capable of transporting huge quantities of rock. Some rocks fall on to the surface of the ice from the valley sides and are transported as supraglacial debris.Some material finds its way into the ice via crevasses to be transported as englacial debris.Where there is basal sliding, debris may also be picked up below the ice and be transported as subglacial debris.Glaciers that move relatively quickly and that transport large amounts of debris at the base, are capable of powerful physical erosion which can drastically alter the pre-glacial landscape.Chemical erosion, because of the low temperatures is relatively ineffectual.Weathering, in the form of frost-shattering (freeze-thaw) aids the erosion processes by providing a ready supply of broken rock debris.If this debris is incorporated into the sides and base of the ice, abrasion becomes active, sandpapering the rock surfaces to produce smooth, gently sloping landforms.

- **Striations, scratches or grooves** are found everyone on bare rock surfaces and are useful to indicate direction of glacier movement.
- **Plucking** is a process that is now regarded as only a minor erosion process as only a small quantity of already fractured rock is capable of being removed by ice which freezes to the rock surface and then moves forward, pulling out the loose blocks. Plucking produces jagged slopes to landforms.
- **Roche moutonnees** are large rock obstructions that have been smoothed by abrasion on the upstream side (stoss) but have irregular, jagged surfaces on the downstream side (lee) where plucking has occurred.

- As glaciers move across the landscape, they come across large rock obstructions such as volcanic plugs or particularly resistant rocks. These outstanding **crags** remain after glaciation and may protect a tail of softer material which slopes gently away from the crag on the leeward side. Edinburgh Castle stands on one of these crag-and-tail landforms.
- **chattermarks,crescent gouges**, etc.

Characteristic glacial products

- rock flour and erratics

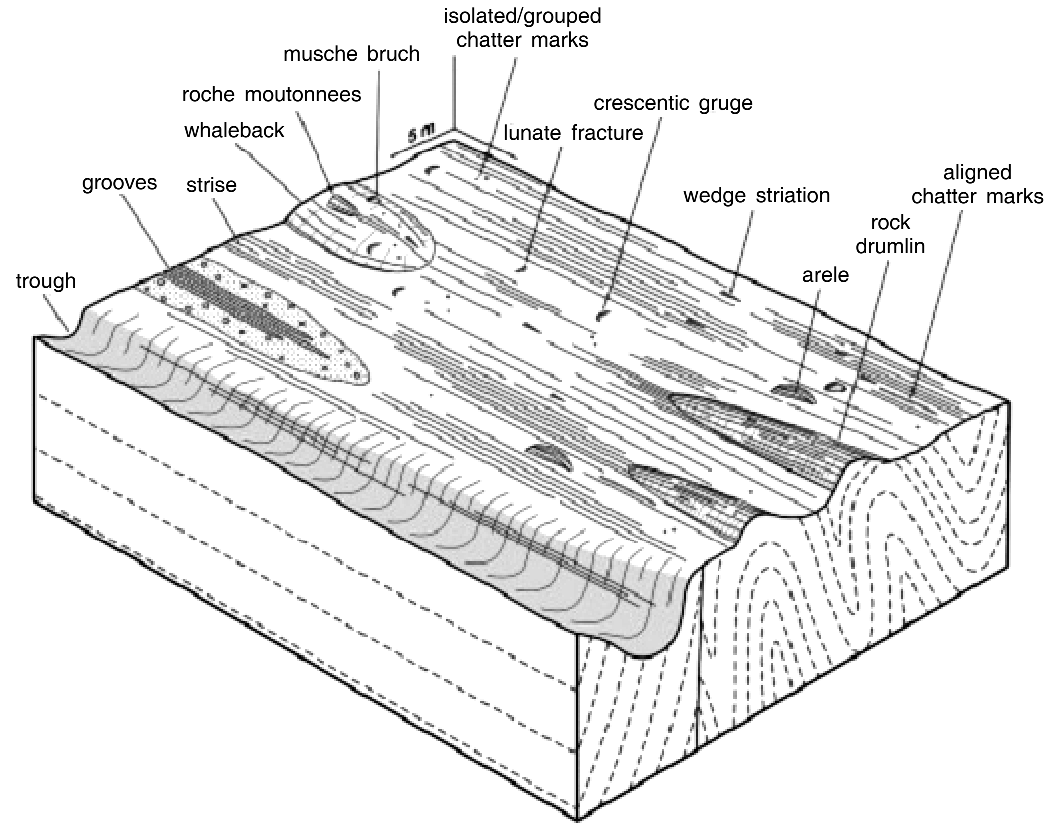


Fig. 10.2: Small Scale Glacial Erosional Features.

10.5 Glacial Transportational Landforms

Glaciers move very slowly. As they move, they transport material from one place to another:

- As freeze-thaw weathering occurs along the edge of the glacier pieces of rock, which break off larger rocks, fall onto the glacier and are transported.
- Rocks plucked from the bottom and sides of the glacier are moved downhill with the ice.
- Bulldozing is when rocks and debris, found in front of the glacier, are pushed downhill by the sheer force of the moving ice.
- Rotational slip is the circular movement of the ice in the corrie.

10.6 Glacial Deposition

Environments and Processes

1. **Glacial** - formed by the ice

- Subglacial release (shearing and/or melting)
- Ablation
- dumping
- pushing (glaciotectonic)
- mass-wasting

2. **Glaciao - fluvial** - deposited by braided glacial meltwater

3. **Glacial marine/lacustrine** - sediment carried by meltwater and deposited in a marine or lake environment

4. **Aeolian** - windblown and deposited sediment (e.g. loess)

10.7 Glacial Depositional Landforms

Glacial Deposits -The name given to all material deposited by a glacier is called **glacial till** or **boulder clay**. A ***moraine*** is a glacially formed accumulation of unconsolidated debris. Moraines often take the form of a belt of low hills composed of till. It is deposited directly from glacial ice. Deposited material creates a range of interesting features such as:

Subglacial Deposits:

- **Ground moraine**: Ground moraine is nothing but a blanket of lodgement and ablation till. It is till deposited beneath a steadily retreating glacier that was lodged beneath the glacier and generally found behind the terminal moraine.

Wetland areas are often created in ground moraine which is a convenient way of identifying them from a topographic map.

- **Erratics:** These are rocks that have been deposited by the glacier. They are usually made of a rock type that would not be found in that area. This suggests that erratics can be carried a long way from an area of different geology.
- **Drumlins**: These are formed both by erosion and deposition. Glaciers can move moraine around in unusual ways which produce interesting features. Drumlins are mounds of deposited moraine. They have a steep side and a sloping side. They can be small or large. They are sometimes described as having **'basket of eggs'** topography because of the unusual landscape they create.

○ Composition: till and/or glacio-fluvial sediments

○ Shaped like and inverted spoon; steep side faces up-ice

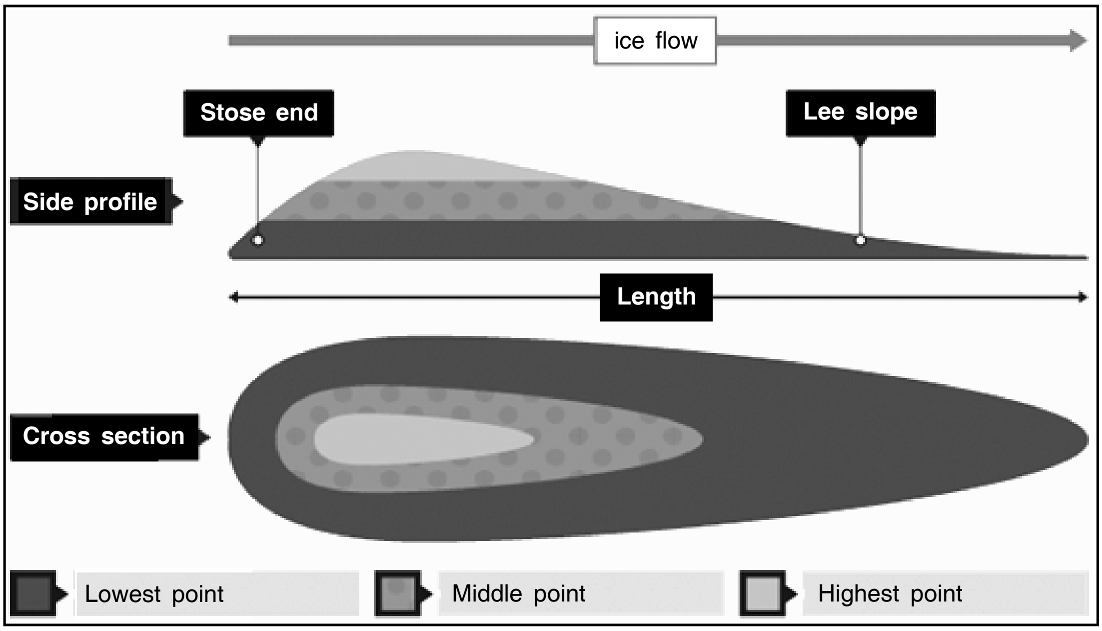


Fig 10.3: Cross Section along the Moraine

Marginal Moraines

- Form: ridge parallel (lateral) or perpendicular (end) to flow
- Process: dumping during a still stand, push during minor or major re-advance

Types of Moraine:

- **End moraines(terminal and recessional):** Those forming at the leading edge of the glacier***end moraine*** can be found. A ***terminal moraine*** is an end moraine that marks the furthest advance of the ice sheet. A ***recessional moraine*** and end moraine deposited when the ice sheet pauses during retreat.
- **Lateral (alpine) or interlobate (continental):***Often, uplands will cause an ice sheet to separate into lobes.* ***Interlobate moraines*** form between lobes of the ice sheet.
- **Lateral moraine -** material deposited along both sides of the glacier. This moraine is usually made up of weathered material that has fallen from the valley sides above the glacier.
- **Push moraine:** If there is a major re-advance of the glacier or ice sheet, the end moraines are bulldozed forward to create push moraines.
- **Medial moraine -** material deposited in the middle of the glacier. This is caused by the lateral moraines of two glaciers when they meet.
- **Recessional moraine:** When there are long pauses in the deglaciation process, a series of recessional moraines, often smaller than terminal moraines, may form to mark the various stages of glacial retreat.

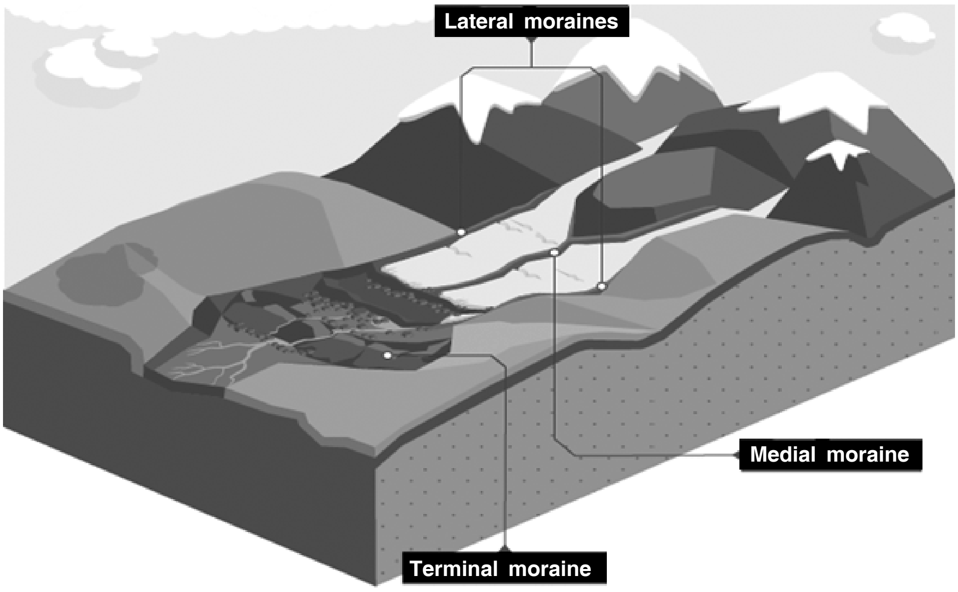


Fig 10.4: Types of Moraine

10.8 Fluvio-glacial processes and Landforms

Cold environments are subject to temperature fluctuations that can convert water to ice, and back again. When (melt)water is in its liquid state it can transform glacial environments through both erosional and depositional processes. Collectively these are known as 'fluvioglacial processes'.Fluvioglacial landscapes are areas that are the result of the actions of glacial meltwater. The processes of fluvial erosion create a distinctive landscape with features unique to this environment. The landscapes can be categorised into contemporary and relic landscapes.Contemporary fluvioglacial landscapes are found in areas where glaciers currently exist: on the fringes of polar areas and in the many alpine environments, such as the Himalayas, the Rockies, South Island New Zealand, Iceland and the Andes.

Erosional processes: There are four main types of erosion -

Hydraulic Action—the sheer force of the water erodes the bed and banks of the meltwater channel. The meltwater will force air into fissures in the bed and banks of the channel resulting in pressure cavitation, causing material to be loosened. This material will then be carried away by the stream in times of high discharge to be deposited in an outwash plain.

Abrasion—stones in transport within the water are thrown at the bed and the banks of the meltwater channel, eroding them. Where the bed and banks of channels are formed from soft rock or sediment, this process will occur rapidly. This process can over-deepen and widen the meltwater channel.

Corrosion—where weak acids within the water react with the rocks, bed and banks of the channel. This erosional process will only take place when the rock type is affected by acids, such as limestone.

Attrition—rock fragments in transport are thrown into one another during channel turbulence. This will reduce the size and smooth the shape of material. Material will change from angular glacial material to rounder, smoother material; evidence of fluvial erosion and subsequent deposition.

Depositional processes: Deposition occurs when glacial ablation periodically reduces so meltwater streams have a smaller discharge. It also takes place with increasing distance from the ice front as meltwater load increases while energy input is dispersed. When discharge decreases, so does velocity and the stream's energy is also reduced. Lower energy results in the meltwater stream depositing its load. Fluvial deposition is sorted, with the larger, heavier materials being deposited first and smaller materials further away, and fine materials at the furthest extent.

Erosional landforms:

Meltwater Deposits: As the glacier melts, the water carries fine material which is eventually deposited. All of the material moved by the glacial melt water is called glacial drift or glacial till. Glacial outwashes the sand and gravel deposited by the running melt water leaving the glacier. The material is sorted. The heavier particles of sand and gravel are deposited in the glaciated valley. The lighter, finer particles such as clay are deposited further away from the glacier and are deposited in the outwash plain.

Meltwater channels: These form where the meltwater from a glacier follows a pre-existing river channel. The large volume of water released from the glacier has high levels of energy together with considerable load in the form of rock fragments released from the ice mass which results in rapid erosion taking place. The channels are over deepened, particularly by abrasion, to form meltwater channels. These may also take the form of glacial overflow channels.

Moulin: A moulin is an erosional feature (rather than a landform) which occurs on the surface of a glacier. Meltwater erodes by abrasion through the ice creating this feature, which is a circular inlet down which meltwater enters the body of the glacier via deeply eroded vertical shafts. They are responsible for considerable quantities of meltwater flowing within the body of the glacier and contribute to many depositional fluvioglacial landforms.

Depositional landforms:

Outwash plains: These are formed in front of a glacier and are where material is deposited over a wide area, carried out from the glacier by meltwater. Discharge occurs from both the melting snout of the glacier and the emergence of meltwater streams from within the body of the glacier. The finest sediments are carried further away from the glacier. Coarser materials are deposited nearer to the snout of the glacier as the meltwater drops these first as its energy declines.It forms ahead of the terminal moraine as melt water from the snout of a glacier deposits stratified drift.

The outwash plain is a relatively flat surface that may be pock marked with depressions called kettles. If numerous kettles are present the surface is called a pitted outwash plain.

Eskers: an esker is formed when there is a sub-glacial meltwater channel flowing within the body of the glacier and sediment is deposited within this channel. After the ice age when the glacier melts, a ridge of sediment is left behind representing where the previous meltwater tunnel deposits descended to the valley floor as the surrounding ice melted. It looks like a winding ridge that follows the general route of the glacier and consists of coarse sand and gravel and visually, may be likened to a medial moraine.

Kames: These are accumulations of partially-sorted material found at the front of a melting or stationary glacier. These mounds build up in height as a glacier melts and meltwater streams carry material from within and under the glacier to be deposited immediately in front of the glacier into meltwater lakes. The lakes are often formed from dammed meltwater ponding up between the retreating glacier snout and terminal or recessional moraines. The deposition occurs as the meltwater flow loses energy upon emergence from the ice mass. The process continues and material is repeatedly deposited on top of the growing kame and may form a kame delta.

Kame terraces are formed in a similar way but rather than in front of the glacier they are generated along the sides of the glacier. Meltwater streams flow along the convergence of the glacier’s lateral edge and the valley side. They deposit material on the bed of their temporary channels which, when the glacier retreats fully, collapses to leave a ridge of partially sorted and rounded material to slump along the valley side.

Kettle holes: Kettle holes are formed when large blocks of ice calve from the main glacier onto an outwash plain. As the glacier retreats the block of ice is left stranded. The ice then gets surrounded and possibly buried by subsequent meltwater deposits and outwash. Eventually, when the temperature increases and the ice block melts it leaves a large depression in the ground that the ice occupied. These are known as kettle holes. Where the depressions subsequently fill with rainwater, they are known as kettle lakes.

Varves: Varves are successive layers of fine sediments deposited by meltwater streams into glacial lakes. During the summer months when discharge is higher, more sediments flow into the lake and deposits accumulate more rapidly. Coarse material in particular, such as sand and silt, flows into the lake during the summer melt and is deposited on the lake bed. During the winter where there is little or no discharge in meltwater streams, finer material and organic matter within the lake will sink to the bottom. This gives a distinct series of layers to the sediment.

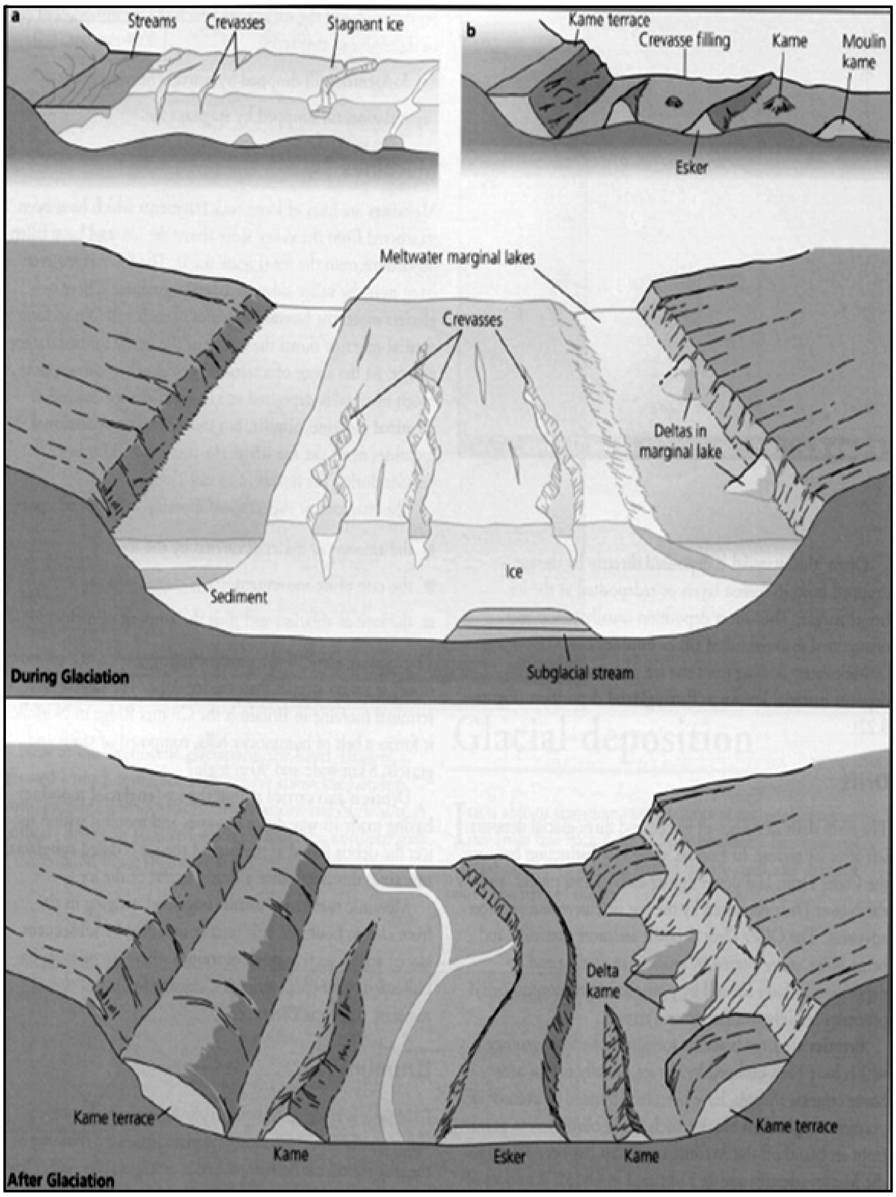


Fig 10.5: Fluvio-Glacial Landforms.

10.9 Summary

This unit deals with the Glacial and fluvio-glacial processes and landforms. The classification of glaciers are based on morphology. Glacial erosional processes such as abrasion, rafting, plucking are predominant in high latitudes.

The transportational landforms are a result of freeze-thaw wealhering, rotational slip and buldozing. The stectacular glacial depositional landforms such as erratics, drumlins, marginal moraines, end moraines, etc. are found in the galcial regious. The fluvio-glacial processes act in areas that are the result of the actions of glacial melt water.

10.10 Questions

Long question

1. Explain the various landforms produced by glacial erosion.
2. Explain the various landforms produced by glacial deposition.
3. Explain the various landforms produced by glacio-fluvial deposition.
4. Discuss the erosional features in a glaciated mountainous region.

Short question

1. Describe different types of moraine.
2. Explain the formation of cirques and glacial steps.
3. Describe the different types of moraine.
4. Explain the formation of kame terraces and eskers.
5. How does an esker form?
6. What do you mean by glacial terrace?
7. How do glacial troughs and hanging valleys develop?

Unit 11 ❑ Aeolian and Fluvio-Aeolian processes and Landforms

Structure

11.0 Objectives

11.1 Introduction

11.2 Forces involved in Aeolian geomorphic process

11.3 Factors affecting wind crosion

11.4 Erosional processes

11.5 Aeolian erosional and Depositional landforms

11.6 Fluvio-aeolian Landforms

11.7 Summary

11.8 Questions

11.0 Objectives

- To learn about the aeolian processes and landforms.
- To learn about the fluvio-aeolian landforms.

11.1 Introduction

The word ‘aeolian’ is considered to be derived from the Greek word ‘aeolus’ meaningGreek god of the wind as well as ‘aeolians’ a Greek tribe.Thus the term aeolian refers to a geomorphic process that is created by moving air known as the wind. It produces varieties of landforms by erosion and deposition. Wind is an important geomorphic agent in arid environments and in other smaller areas where fine sediments are exposed to wind where surface cover is lacking, e.g., beaches, floodplains, deserts, soil disturbed by agriculture. Otherwise wind is not an important geomorphic agent due to its low density relative to rock: 1/2000 as opposed to 1/1.6 for water/rock. Given the buoyant force of water, little energy is required to keep sediment suspended, whereas in air only the finest sediments (dust) remain in suspension.It cannot develop any landscapes by itself but it requires some materials as tools (particles of sand, silt etc.).

Aeolian processes, involving erosion, transportation, and deposition of sediment by the wind, occur in a variety of environments, including the coastal zone, and cold and hotsemiarid and arid regions, along the borders of rivers andlakes, as well as over agricultural fields in many climates.Aeolian processes are responsible for the production of avariety of erosional landforms that range in scale from individual rocks (ventifacts)to larger and more complex landforms namely,yardangs, inverted relief, and defination basins. Inaddition, the wind is responsible for the emission and/ormobilization of dust (mineral aerosols of silt and clay size) and the transport of this material to distant marine and terrestrial areas, where it contributes significantly to soil formation and the nutrient status of a variety of ecosystems. Major depositional landforms comprise deposits of loess (silt)and areas of sand dunes (sand seas and dunefields).

11.2 Forces involved in Aeolian Geomorphic Process

Driving forces

- variations in atmospheric pressure
- wind blows down the pressure gradient
- erosion and subsequent deposition doesnot necessarily help wear landscape down; gravity is not a driving factor

Resisting forces

- friction
- vegetation, micro- and macro-topography
- particle size
- cohesion and aggregation
- presence of crusts

11.3 Factors affecting wind erosion

1. Wind Velocity

- $E = V^3 rho$, where E is erosivity, V is velocity and rho is air density.
- Thus the erosivity of wind is an exponential function of wind velocity, *i.e*. if the wind velocity doubles, the wind is 8X more erodible or, if it triples, the wind is 27 times more erodible,that is why we observe massive wind erosion (dust) with a significant increase in wind speed.

2. Surface Cover

- An extremely important factor since there is no wind erosion on a vegetated surface.

- Wind velocity decreases exponentially near the ground and is theoretically zero on a natural (i.e. rough) surface; thus erosivity (V^3 is dramatically reduced).
- On a windy day, put your nose next to the ground and you will discover there is no wind; small birds and insects take advantage of this on windy days.
- The zone of little or no wind is called the laminar sublayer (or the boundary layer), the rougher the surface (e.g. taller the vegetation) the deeper the layer of laminar air flow (i.e. no turbulence to entrain and suspend sediment).
- There is no wind in the interior of a closed forest.

3. Grain Size

- Threshold erosional velocity is related to the square root of particle size.
- Thus when the threshold velocities for various particle size plot as a straight line when the particle size axis is on a square root scale.
- The threshold velocities are slightly lower for sand when impact among grains (saltation and creep) is taken into account.
- The fluid threshold velocities (wind shear) plot as two straight lines that slope down to converge at a minimum threshold velocity for coarse silt and fine sand (i.e. these are the most easily eroded grains)with smaller particle sizes grains tend to cohere when wet and resist erosion.
- Larger grains resist erosion by virtue of their greater size (mass).

11.4 Erosional processes

A. Deflation: process of wind removing particles from the surface (entrainment)

- Lift: results from combination of wind velocity and turbulence. Threshold (critical) velocity is the function of particle size, cohesion. Turbulence changes in wind speed and direction. as turbulence increases, susceptibility of particles to lift increases.

- Bombardment: collision of moving particles with stationary ones or with solid surfaces. Abrasion is the collision with solid surfaces

- Drag: results from difference in force exerted on windward versus leeward side of particles, or difference in force exerted on top versus bottom of particles. It initiates sliding and rolling; doesn’t lift particles off ground.

B. Abrasion (sand blasting)

Impact of entrained sand grains against rock surfaces and other grains are—

Yardangs—wind abraded ridges oriented with the prevailing winds and separated by abraded chutes that conduct windblown sand

Ventifacts—are stones faceted (planed) by abrasion, with changing direction of dominant winds, different facets merge along sharp ridges to transform rounded stones to angular Ventifacts.

EROSION		TRANSPORTATION	DEPOSITION	
METHODS	FEATURES	METHODS	CAUSES	NATURE OF DEPOSITS
Deflation	Desert Pavement of lag deposits			
Corrasion or Abrasion	Cave rocks, Mushroom Table & Pedestal rock Yardang Ventifacts	Saltation Suspension Rolling or Traction	Loss of velocity, settling of heavy particles, rain	Dunes Loess Ripples
Impact or Attrition				

WIND EROSION TRANSPORTATION AND DEPOSITION

Transportational process

- *Suspension*
  - held in air for extended time periods due to velocity and turbulence
  - particles smaller than ~ 0.1 mm; very fine sand, silt, clay
- *Saltation*
  - fine to medium sand; 0.1 to 0.5 mm
  - particles too large to stay in suspension for extended periods
  - hopping or bouncing motion
    - saltating grains may bounce and become airborn again; more likely on hard, non-sandy surfaces

    - bombardment sets new grains in motion; increase in number of grains moved increases exponentially
    - presence of saltating grains decreases near-surface wind velocity
    - bombardment may allow entrainment below threshold velocity
    - Creep: sliding or rolling
  - particles larger than ~0.5 mm
  - ~95% dune sand transportation occurs by saltation.
- *Creep (Traction)*
  - movement of coarse sand and pebbles (up to 6x larger than saltating grains) as they slide and roll impacting one another and transferring momentum
  - usually does not occur with velocities less than 4.5 m/sec

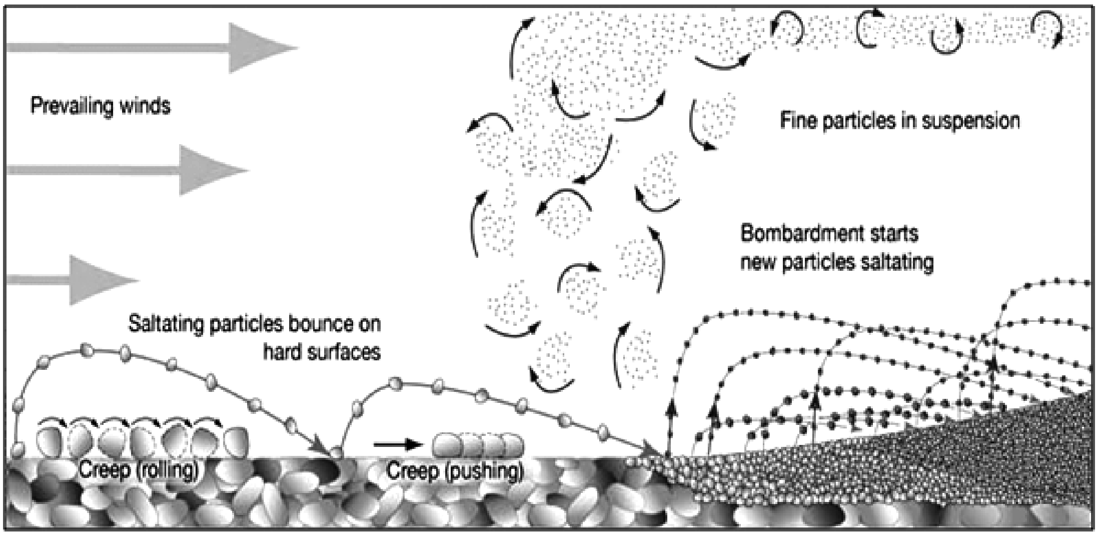


Fig 11.1: Aeolian transportation

Depositional Process

Any obstruction to wind results in deposition. Deposition is caused due to reduction in velocity, increased load, Rain and function of particle size.

Sorting of Deposits:

- The finest fraction is removed from the aeolian landscape as dust and accumulates elsewhere as loess.

- Saltating grains out distance the traction load, leaving a lag of creeping and non-transported grains.
- With exponential increase in sand transport with wind velocity, energy is quickly diverted from erosion to transport dissipating much of the wind energy.
- Thus wind velocity increases over barren rock surfaces, where sediment transports and the friction among saltating grains and with the stationary sand is not a factor.
- Sand is transported until friction over a rough surface (sand or vegetation) or an obstruction causes a decrease in wind velocity and deposition.
- Thereforeaeolian landscapes are characterized by a mosaic of 1) windswept and sandblasted surfaces, 2) stony lag deposits, 3) sand sheets or dune fields, and 4) loess sheets.
- Unlike other geomorphic processes wind does not result in the lowering of the landscape (denudation) towards an ultimate base level, rather sediment is usually just moved within a closed system in the direction of prevailing winds, unless it gets exported (e.g. transferred into a river).

11.5 Aeolian Erosional and Depositional Landforms

Aeolian Landforms are formed by the erosion and deposition of windblown sediments. The sediments are generally sourced from deserts, glacial deposits, rivers, or coastal shorelines. Aeolian sediments are often composed of well- rounded, sand- to silt-sized particles that are weathered by wind abrasion during transport. Sediments are deposited when the velocity of the wind falls and there is not enough energy available to entertain and transport the sediments. Sands will begin to accumulate wherever they are deposited and often continue to move along the ground.

Erosional Landforms

Ventifacts: Ventifactsare formed by abrasion effect. These faceted rocks are Stones with flat surfaces, commonly distinguished by two or more flat faces meeting at sharp ridges, generally well-polished.shaped by abrasionThe windward face of the rock is flattened and smoothened. If it has one smooth surface then it is known as EINKANTER and if three, then DREIKANTERS.

Fig 11.2: Ventifacts

Yardangs: Yardangsis anelongatedstreamlined ridges oriented parallel to wind direction**.** This remnant rock feature sculpted by abrasive action. It is composed of cohesive silts and clays, sandstone, or limestone. It is seen in regions with strong uni-directional winds. ManyYardangs were formed during dry, windy periods of Pleistocene.

Fig 11.3: Yardangs

Zeugen: Zeugen isa table-shaped area of rock found in arid and semi-arid areas formed when more resistant rock is reduced at a slower rate than softer rocks around it under the effects of wind erosion.

The main difference between a zeugen and an yardang are -

- The yardang is smaller than a zeugen.
- Yardangs are formed on vertical strata while zeugen on horizontal strata.
- Yardangs are formed by deflation while zeugen by abrasion.
- Yardangs are formed on vertical hard/soft layers of rock, while zeugen (this is its plural form) are formed on horizontal bands of hard/soft rocks giving it a more mushroom-like shape. The Great Sphinx of Giza has been sculpted in a yardang.

Desert Pavements or Lag Deposits: Theseareformed by aeolian or fluvial processes, wherelarger stones set in or on a matrix of finer material. They are formed when wind carries finer, more lightweight particles such as sand away. Large particles are left behind and protected from further erosion – desert pavements. They are also called as desert armor and the areas covered with large sized rocks are called Hamadas.

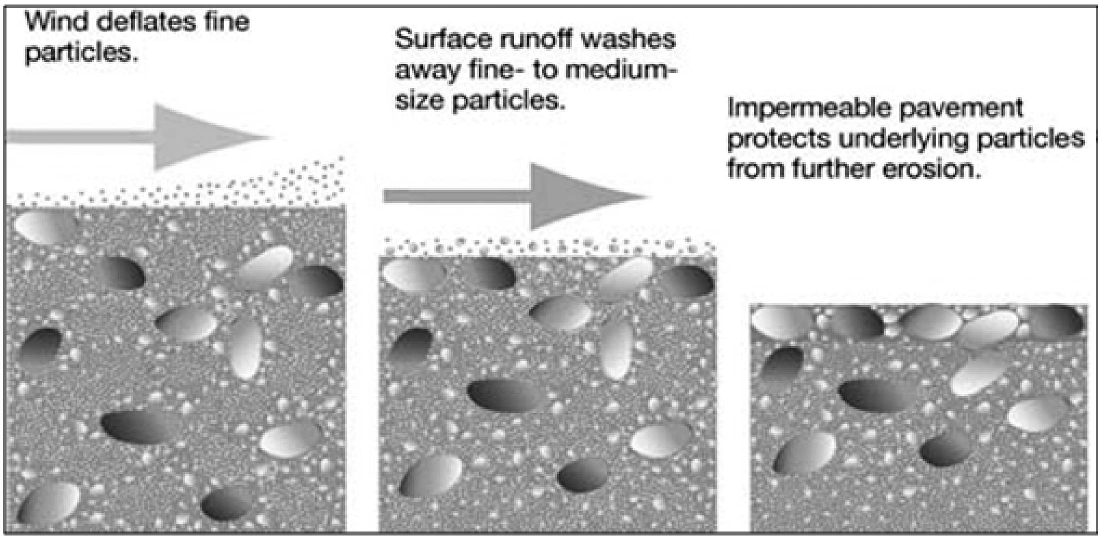


Fig 11.4: Desert Pavement

Mushroom Table and Pedestal Rocks: They areisolated rocks from which the base has been partially cut by the undercutting of the wind.

Deflation Basinsor deflation hollows or blow outs: These are depressions formed from barren unconsolidated material. They are formed by eddy air currents. It measures from few centimetres to several kilometres across, with a depth up to 10m.

Oasis: In geography, an oasis (plural: oases) is an isolated area of vegetation in a desert, typically surrounding a spring or similar water source. Oases also provide habitat for animals and even humans if the area is big enough. The location of oases has been of critical importance for trade and transportation routes in desert areas.

Depositional Landforms

Ergs (sand seas): Theseare "sand seas" with vast sand sheets.They cover 1/4 - 1/3 of the area of true deserts. The largest sandy deserts overlie poorly consolidated sandy bedrock. Rub'al Khali in Saudi Arabia is world'slargest sand sea. Nebraska Sand Hills is largest in western hemisphere.

Dune fields: smaller than ergs but contain significant number of dunes (e.g. coastal areas)

Sand sheets: These are very subdued dunes and low relief. They also contain undulating sandy hills in sub-humid environments (*e.g.* large parts of the Great Sand Hills of Saskatchewan and the Sand Hills of Nebraska).

Sand Shadow: These are accumulations of sand on either side of a fixed obstacle (e.g. shrub or tuft of grass).

Sand Drift: Accumulation of sands are called Sand Drifts.In the lee of a gap between obstacles or in the still air at the base of an escarpment, are known as Sand Drifts.

Loess: Most of the dust carried by dust storms is in the form of silt-size particles. Deposits of this windblown silt are known as loess. Loess is a homogeneous, typically non-stratified, porous, friable, slightly coherent, often calcareous, fine-grained, silty, pale yellow or buff, windblown (aeolian) sediment. It generally occurs as a widespread blanket deposit that covers areas of hundreds of square kilometers and tens of meters thick. Loess deposits are unusually fertile. They are also used for building construction. The thickest known deposit of loess, 335 meters, is on the Loess Plateau in China. Loess tends to develop into highly rich soils. Loess deposits are geologically unstable by nature, and will erode very readily.

Takyrs: Takyrs are flat smooth clayey deserts, ranging in size from a few sq.m to several sq. kms. They develop as separate basins. A takyr is usually formed in a shallow depressed area with a heavy clay soil, which is submerged by water after seasonal rains. After the water evaporates, a dried crust with fissures forms on the surface. Wind is a major geological agent. It changes the landscapes of arid and semi-arid regions with new landforms. It is a highly dynamic system forming unstable landforms. Wind created landforms are subjected to wind action again and again. Understanding of their movements and deposition is a basic requirement in earth sciences.

Wind ripples: These are small sand ridges oriented perpendicular to prevailing winds.They are small sand waves with a wavelength of about 1 m, i.e. the typical path length of saltating grains. They are ephemeral and mobile, i.e. move, disappear and reform during wind storms. Ripples are commonly found on the windward slopes of sand dunes.

Fig 11.5: Wind Ripples.

Dune: Dunes areclassic aeolian landforms. They are either stable or advancing landform of windblown sand. It originates as a mound of free sand from a sandy surficial deposit (e.g. beach, weathering sandstone) or from a blowout. As the mound grows it develops the dune asymmetry characterized by a gentle windward slope and a leeward slip face at the angle of repose for sand. Some dunes with longitudinal shape have a ripple but several others of magnitude difference in size, and thus dunes are much less mobile and more persistent. Dunes migrate downwind as sand saltates up the windward face (*i.e.* ripples migrate), accumulates where the wind dies just over the crest, and then flows (mass wasting) over the slip face. The dunes are of various types. They are as follows:

1. Barchan Dune:

- classic desert dune
- crescentic in plan view, horns (cusps) project downwind and thus the head faces into the wind and the slip face is concave downwind
- isolated, freely migrate across desert plains maintaining their form

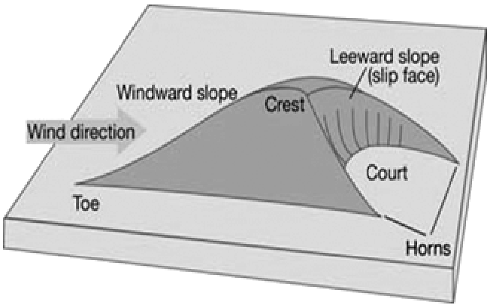


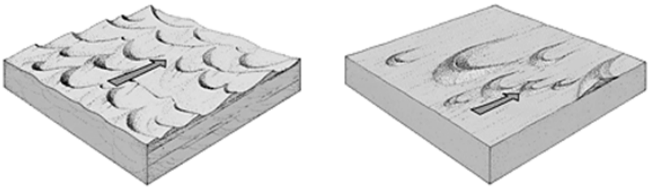
Fig 11.6: Barchan Dune

2. Parabolic Dune:

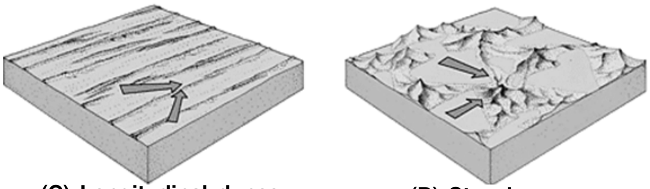
- Associated with vegetation, so form in sub-humid and semiarid environments (rather than arid) where vegetation is nearby (e.g. beaches, grasslands).
- originate as a blowout, dune forms as the head of the dune at the downwind edge of the blowout develops the dune asymmetry and advances beyond the horns
- stability of the sides and horns used to be attributed to vegetation but recent research (including P. David and S. Wolfe in Saskatchewan) suggest that water is a more important factor, so the stability of parts of a parabolic dune and the presence of vegetation are both related to water
- Eventually deflation lowers the blowout to the water table or to an underlying stratum lacking sand (*e.g.* bedrock or stony clay till) and the dune becomes impoverished.

3. Transverse Dune:

- linear, cuspate and forms perpendicular to the wind, with large sand supply and low winds
- with stronger winds they evolve into barchans
- usually occur on beaches, floodplain alluvium or erodible sandy bedrock rather than in dry deserts



(A) Transverse dunes (B) Barchan dunes



(C) Longitudinal dunes (D) Star dunes

Fig 11.7: Types of Dunes

4. *Longitudinal or Seif Dune:*

o large (kms in length, ~ one km wide) linear forms parallel to the strong persistent winds

o formed in dry subtropical deserts with irregular sand supply

o separated by lag gravel

o whaleback: a ridge of coarse sand left in the path of a migrating longitudinal dune

5. *Star Dune*:

o Large pyramidal or star shaped dunes with three or more sinuous radiating ridges from central peak sand.

o It has three or more slip faces and does not grow along the ground but does grow vertically.

11.6 Fluvio–Aeolian Landforms

The interaction between fluvial and aeolian processes can significantly influence landforms. When rivers and sand dunes meet, the interaction of sediment transport between the two systems can lead to change in either one or both systems.There are six prominent fluvial-aeolian interactions. (1) Fluvial flow extends into the aeolian system until it is dammed by aeolian landforms; (2) interdune areas (overbank interdunes) upstream of aeolian dams, and alongside channels are flooded; (3) water erodes dunes alongside channels and interdunes; (4) flood waters deposit sediment in interdune areas; (5) fluvially derived groundwater floods interdunes (interdune playas); (6) wind erodes fluvial sediment and redeposits it in the aeolian system. Some of the distinctive fluvio-aeolian landform features are as follows:

Rill: In hill slope geomorphology, a rill is a narrow and shallow channel cut into soil by the erosive action of flowing water.

Gully: A gully is a landform created by running water. Gullies resemble large ditches or small valleys, but are metres to tens of metres in depth and width.

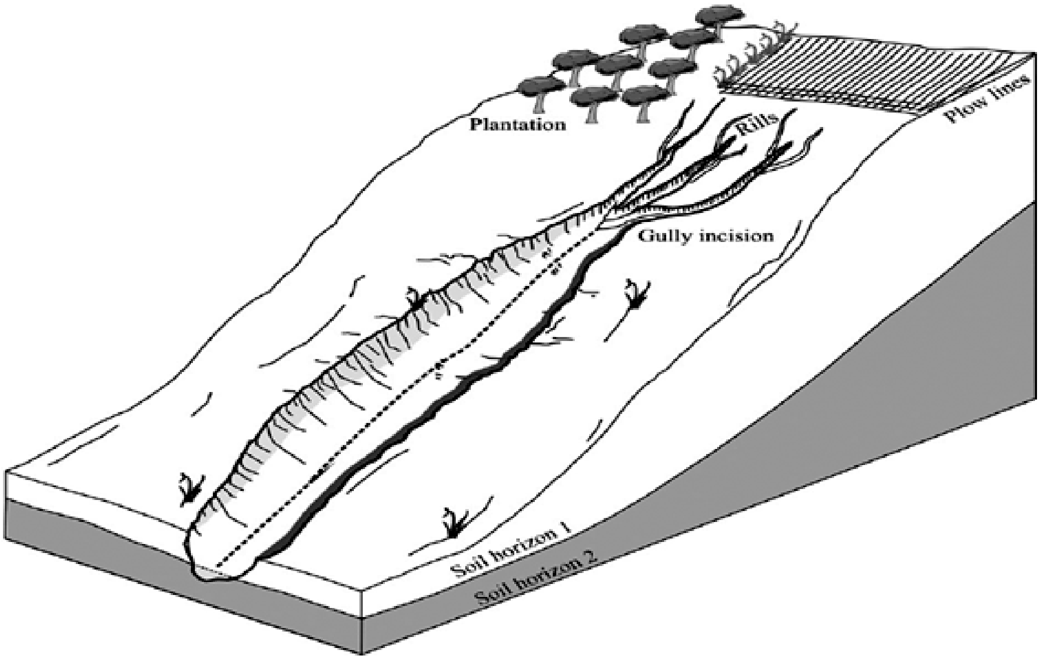


Fig 11.8: Gully Incision.

Ravine: A ravine is a landform narrower than a canyon and is often the product of stream cutting erosion. Ravines are typically classified as larger in scale than gullies, although smaller than valleys.

Badland Topography: In arid regions occasional rainstorms produce numerous rills and channels which extensively erode weak sedimentary formations.Ravines and gullies are developed by linear fluvial erosion leading to the formation of badland topography.Badland, area cut and eroded by many deep, tortuous gullies with intervening saw-toothed divides. The gullies extend from main rivers back to tablelands about 150 m (500 feet) and higher. The gully bottoms increase in gradient from almost flat near the main rivers to nearly vertical at the edges of the tablelands. Because the rocks are not uniform in character, differences in erosion result in stair-step profiles. The joining and separating of the gullies cause many isolated irregular spires, small flat-topped buttes, or mesas, and produce a landscape of jagged, fluted, and seemingly inaccessible hills.Badlands develop in arid to semiarid areas where the bedrock is poorly cemented and rainfall generally occurs as cloudbursts. The dry, granular surface material and light vegetation is swept from the slopes during showers, leaving the gullies bare.The term badland was first applied to a part of southwestern South Dakota, which French-Canadian trappers called the mauvaisesterres pour traverser (the “bad lands to cross”); later it was applied to other areas with similarly eroded topography. Example: Chambal Ravines.

Bolsons: The intermontane basins in dry regions are generally known as bolsons.Bolson, (from Spanish bolsón, “large purse”), a semiarid, flat-floored desert valley or depression, usually centred on a playa or salt pan and entirely surrounded by hills or mountains. It is a type of basin characteristic of basin-and-range terrain.

Playas: Three unique landforms viz. pediments, bajadas and playas are typically found in bolsons.Small streams flow into bolsons, where water is accumulated. These temporary lakes are called playas.After the evaporation of water, salt-covered playas are called salinas.

Pediments: In form and function there is no difference between a pediment and an alluvial fan; however, pediment is an erosional landform while a fan is a constructional one.

A true pediment is a rock cut surface at the foot of mountains.

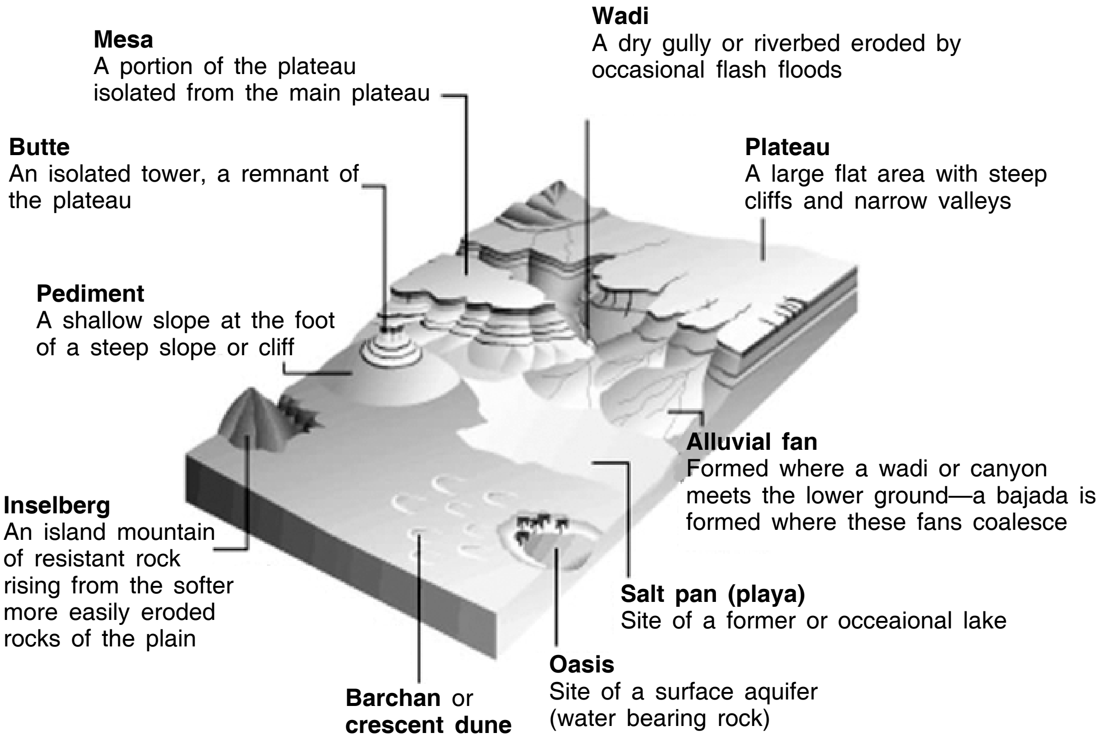


Fig 11.9: Fluvio – Aeolian Landforms

Bajada: A Bajada, (Spanish: “slope”,) also spelled Bahada is a broad slope of debris spread along the lower slopes of mountains by descending streams, usually found in arid or semiarid climates. A bajada is often formed by the coalescing of several alluvial fans. Such coalescent fans are often mistaken for erosional landforms known as pediments. The repeated shifting of a debouching stream from one side of a fan to the other spreads the sediment widely and almost uniformly. As the sediment eventually grows together, the slope may extend outward from the mountain front to a distance of several kilometres. A bajada is usually composed of gravelly alluvium and may even have large boulders interbedded in it. The slope is usually less than 7°. In humid climates, landforms of this nature are usually referred to as piedmonts. Thus, they are moderately sloping depositional plains located between pediments and playa.Several alluvial fans coalesce to form a bajada.

11.7 Summary

This unit deals with the different forces that are involved in aeolian geomosphic process. These processes occur in a variety of environments and are responsible for a variety of landforms. The interaction between fluvial and aeolian processes also influence landforms. Distinctive fluvio-aeolian features include rill, gully, ravive, badland topography, playas, bajada etc.

11.8 Questions

Long question

1. Explain the various landforms produced by Aeolian erosion.
2. Analyze the evolution of landforms produced by the processes of Aeolian deposition.
3. Explain the various landforms produced by fluvio-aeolian erosion.
4. Give an account of the landforms developed by the depositional action of wind in hot deserts with suitable sketches.

Short question

1. Explain the formation of zuegen and yardang.
2. Explain the formation of Inselberg.
3. Describe different types of dunes.
4. Distinguish between Corrosion and Corrasion.
5. Explain the formation of parabolic dunes and seifs.
6. What are the difference between a pediment and a bajada?

Unit 12 ❑ Models on Landscape Evolution : Views of Davis, Penck, King and Hack

Structure

12.0 Objective

- To learn about the various models of lands cape evolution.

12.1 Introduction

The larger task of endogenetic forces is to create irregularities on the surface of the earth by volcanism, mountain building, etc. As soon as these end forms are exposed the various processes of weathering start working on them. Soon these are weathered, and in due course of time, the weathered products are transported by various agents. The whole period, during which erosion processes erode the new surface to sea level, is one cycle and since erosion plays an important role in it, it is called the cycle of erosion.

The significance of the cycle concept is that it explains the sequential development of landforms in a temporal framework. Three views on the cycle of erosion are most important. These are of Davis, Penck and King. These views relate to the sequential development of landforms in an orderly fashion during which the slope also evolves in a variety of ways. Thus, these cycles, while describing the development of landforms, also give information about the evolution of slopes.

12.2 W.M. Davis: The Geographical Cycle

The first model of landscape evolution to gain widespread acceptance within the discipline was remarkably influential and persistent but no longer dominates research thinking like it did, but still used as a teaching tool and residual influence reflected in the way geomorphologists cling to cyclical models. W.M. Davis was geography professor at Harvard University. He wrote about his model from 1880-1938. Like his contemporaries in natural science he was strongly influenced by Charles Darwin (On the Origin of the Species) and Charles Lyell (Principles of Geology), although used evolution as a notion of history (inevitable progress or change over time) rather than a process and took a deterministic rather than probabilistic view of evolution like Darwin.

Thus Davis aspired to a deductive, theoretical, genetic model of landscape evolution. The concepts of structure, process and time were his theoretical framework:

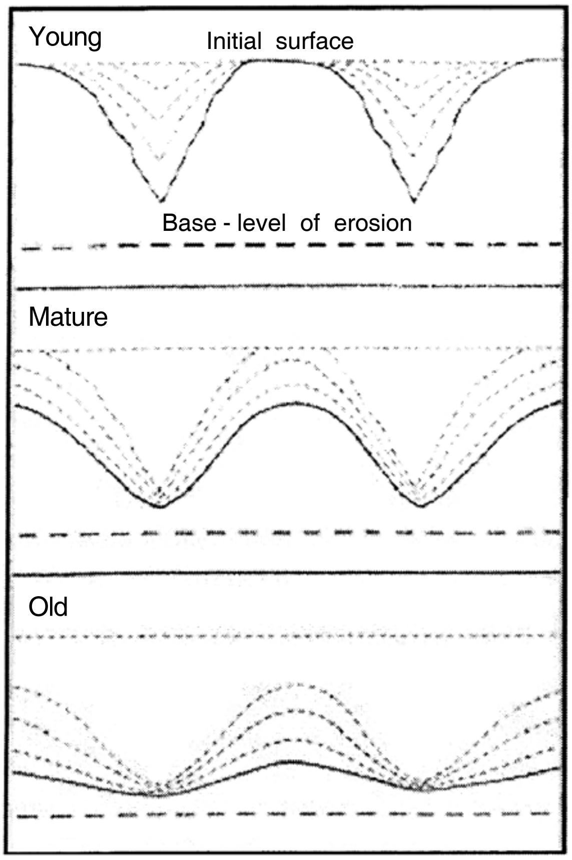


Fig 12.1: Stages of valley Development.

- Structure was regional and considered as an initial condition (beyond the scope of his model).
- Process was the sum of weathering and transport rather than specific processes or mechanisms, although since his cycle was based on the assumption of a normal climate, *i.e.* humid temperate fluvial processes were predominant.

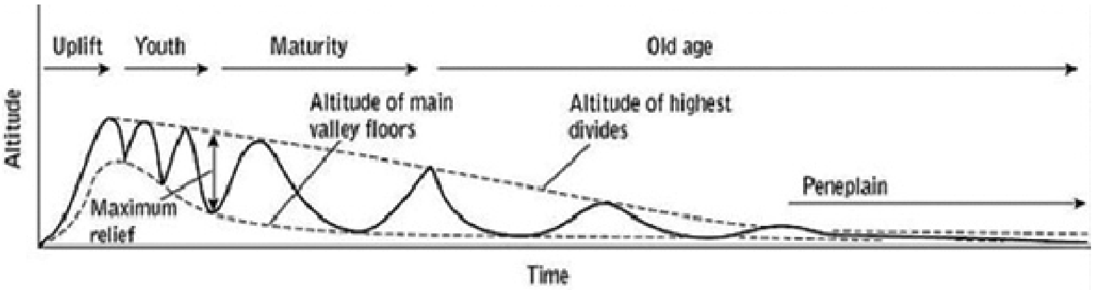


Fig 12.2: The geographic cycle of Davis.

- Time was the central theme, but time in the sense of landscape development relative to the completion of the entire geographical cycle, *i.e.*, extent of landscape development or stage.

Davis assumes that each landscape has definite life history. As soon as a landmass emerged,erosional agents start their works on it andfinally take it to ultimate featureless surface.Newly uplifted landmass been called initial surface upon which erosion starts.For the purposes of demonstrating his cycle concept in the mostsimple and persuasive away, Davis imagined as an initial form a mass of land uplifted from beneath the sea by earth movements.

The Stage of Youth

Davis assumed that the up lift the land took place very rapidly, sothat the processes of denudation were able to act almost from the starton what was in effect, a stable mass.If the climate were sufficientlyrainy, as would normally be thecase in humid temperate lands, a system of rivers would quicklydevelop on the emerged land surface,this would comprise a numberof consequent streams whose directions of flow and velocities (andthus erosional capabilities) would be determined by the gradients ofthe initial surface. From the stage of infancy, these streams would cut rapidly downwards, and would in duecourse from deep valleys. On these stops, weathering and slumpi***ng*** would operate, but at quite a slow rate compared with the speed of river for a long period the valley profiles would be approximatelyV-shaped except in areas of complex geologicalstructure where stepped profiles would be developed.Throughout this stage, parts of the initial land – surface would bepreserved on the watershed between the consequent streams, Ininfancy the extent of this initial surface would be considerable butwould be gradually diminished later in the youthful stage as the valleyside slopes experienced retreat and as tributary streams began toextend their valleys in to the interfluve areas by headword erosion.

The Stage of Maturity:

By the onset of this stage the deepening of the v- shaped valleyscharacteristic of youth would have been slowed down considerably. Through the formation of their valleys the various streams wouldthroughout youth have lowered their channels nearer and nearer to what Davis termed “the base – level of erosion” (which is normallythe level of sea into which the eventually flow, and below which cannoterode. In the process the longitudinal gradients of the streamswould have become ever gentler, stream velocities would havebeen reduced,and the streams would possess less and less energy touse in moving their loads and attacking their beds, In fact, Davis suggested that, early in the stage of maturity, streams would attain acondition of grade of equilibrium, in which the entire energy of thestream is consumed in the movement of water and its load.The gentle meanders of the youthful streams responsible for theinter – locking spur supposedly typical of youthful valleys, wouldbecome wider and more pronounced, and at many points the valley – side slopes would be undercut and driven back, By the end of themature stage, slope angles in general would have been considerably

reduced by the process of divide wasting and smoothly curving slopeprofiles with no major breaks, wouldDominate the landscape, An important result of divide wasting duringmaturity would be the reduction of relief, or in other words a decreasein the vertical height separating interfluve summits and valley floors.

The Stage of Old Age:

By this stage the processes of landscape evolution would havebecome extremely slow in operation. This running down of the cyclewould have resulted from the gradual reduction of river gradients andan associated decline of stream energy and the continued lowering inangle of valley – side slope so that creep and wash would become lessand less active and mantle of slope detritus, impending mechanicalweathering, would be extensive By comparison with youth andmaturity the stage of old age would therefore be extremely protracted. River would continue to broaden their valleys by meandering soproducing near – level valley floors over which during times offlooding alluvium would be deposited to give broad flood plains. Bythe end of old stage the relief would assume the form of a very gentle undulatingplain,termed, by Davis a “ peneplain “ standing only alittle above the base level of erosion. Above the peneplain a fewisolated hills, as yet unconsummated by divide wasting, wouldremain. Such residuals were referred to by Davis as “monadnocks”.

Evaluation

Since the time of Davis, some geomorphologists have agreed thatthe peneplain should be regarded as purely theoretical landforms, onthe ground that the conditions of stable base level needed for thecompletion of a full cycle of erosion cannot have persisted for asufficiently long period of time. There is certainly much evidence toshow that gentle earth – movements, involving both elevation anddepression, are taking place today, and during the organic periods of the past crystal instability must have been greater. Another argument is that, when a landmass is under – going erosion, itwill tend to experience continuousuplift, simple because the unloadingwill initiate compensatory isostatic movements, As a result riverswill always be incising their valleys, and attainment of the peneplainstage will be postponed indefinitely, It is true that in an area perfectly preserved surfaces of peneplanation do not exist at or nearpresent sea level.

Interruptions to the Cycle of Erosion:

Based on the concept of geomorphology " complexity ofgeomorphic evolution is more common that simplicity ", it can besaid that multicyclic evolution of landscapes is more common that theyhave superimposed upon it youth – full features as a result of theinterruptions of cycle (like climatic change and sea level fluctuationsand rejuvenation)

Rejuvenation—Dynamic rejuvenation may be caused byepeirogenic uplift of a landmass with accompanying tilting andwarping. Such movements may be rather localized and associatedwith neighbouring organic movements, or they may be, as thought bysome, would wide in nature. Localized down tilting, warping orfaulting of a drainage basin will result in streams which now havetransporting power in excess of that required for transport of theirloads.

12.3 Walter Penck : Relating Landforms to Crustal Movements

The best known manifestation of Penck's model is the retreating slope profile, where evolution of the profile is controlled by rate of output (river erosion) at the base and rate of uplift of the land. He was able to deduce various slope profiles for different combinations of river erosion, uplift and rock resistance, by assuming that stronger rock requires steeper slopes for the same rate of denudation. He also modelled stream longitudinal profile as controlled by uplift, rock type and stream discharge. Another expression of his model was three categories of landform assemblage according to tectonic history (versus normal climate):

- great folding from lateral forces (orogenic)
- dome formation without folding (epeirogenic)
- stable regions

Penck also envisaged three landscapes resulting from slow, intermediate and rapid rates of uplift. Morphologically, they were similar to Davis' old, mature and young stages, but whereas Davis ascribed morphology to age (time-dependent), Penck's model was largely time-independent based on tectonic history.

Evaluation of Penck's model is hindered by its hurried writing, posthumous publication and confused representation in English, including misrepresentation by Davis who was defending his own ideas. Although there were important flaws and contradictions in Penck's work, and it was poorly translated or misrepresented especially by adherents to the Davisian school, it was the one comprehensive alternative to the cycle of erosion and thus was a focus for contrary ideas, such as emphasis on process rate (both endogenic and exogenic) and greater attention to slope retreat.

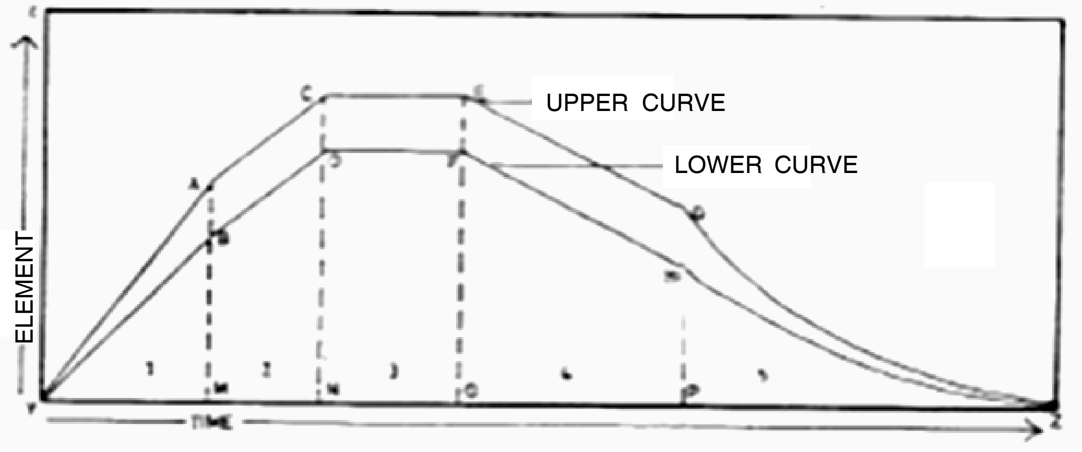


Fig 12.3: Penck's Model of Landform Development

Upliftment and Erosion:

Penck believes that upliftment takes place through different rate. He says that erosional activities and their agents will not wait for the final upliftment. As soon as any landmass comes above the sea level, the agents of erosion start their work and both these incident takes place together, but after some time upliftment will finish and degradation will continue until the land mass come to the ultimate base level or near to that when degradation is not possible. Penck says that from beginning to end. The rate of upliftment is not the same. In the beginning it is quick, then it becomes normal and at last with decreasing rate. So to express these three rates of upliftment Penck has three German terminologies.

Aufsteitgendeentwikelung:- This is the first stage of upliftment in which within a short period the rate of upliftment becomes very high.

Gleichforigecntwiekclung this is the middle one stage between the above two.

Abstsigendecntwickelung:- in this stage it becomes very slow and in decreasing order.

In this graph, it is quite clear that are two curves upper and lower. Here upper curves represent absolute height and that of lower Curve river valley. AB, CD EF and GH show the relief of different Stages. He has divided the whole process into five categories:

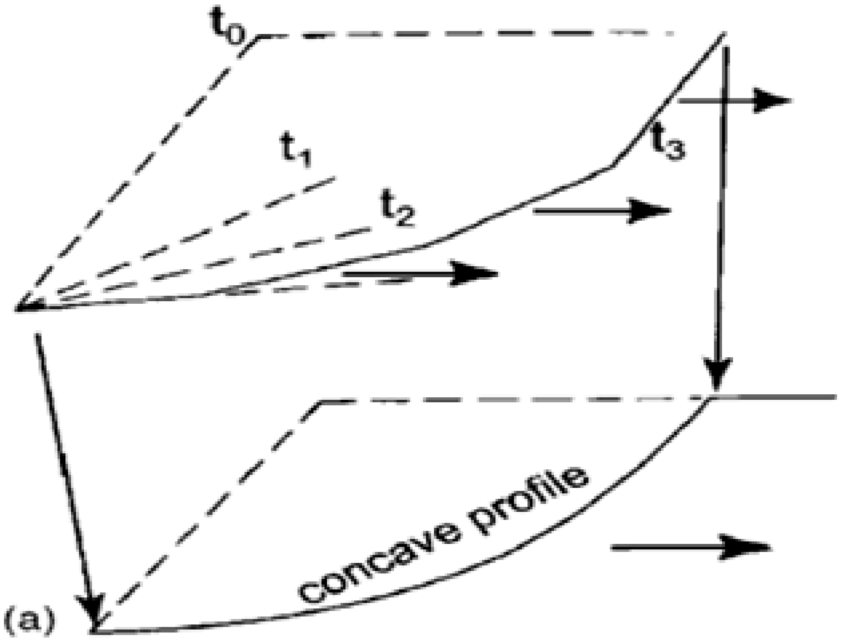


Fig 8.4: Graph of Penckian Cycle.

Fig : The Penck model. (a) Diagram showing slope replacement (upper profile) caused by successive retreat of an infinite number of inclined valley bottoms leading to a smooth concave profile (lower concave profile). Penck envisioned an initially steep linear cliff (t0), being replaced by progressively more gentle slope segments (t1 – t3).

First case– There is an increase in the height of landmass above the sea level. Upper curve is rising more than the lower curved which means the rate of upliftment is more than the rate degradation and this is why the relief is increasing Though the valley is being Eroded but interfluve summits or divided summits are not affected by this degradation.

Second case–It is quite clear from the graph – as – upper curve AC and lower curve BD.

Third case – In this case neither relief is increasing or decreasing nor erosional curve show increase or decrease. So both has same intensity that means all the new rise is cut down by the degradation agents and thus they are Parallel but constant it is shown on the graph by upper curve CE and lower curve DF.

Fourth case – After the third case the uplift in the landmass is finished and now in this case down cutting and side cutting is prominent. So due to this reason both curve show the same rate of degradation in terms of absolute height and absolute valley bottom. So both curves show parallel ongoing trend. It is shown in the graph by EG (upper curve) and FH (lower curve).

Fifth case – In this case the downcutting decreased and the lateral cutting is still in operation which results the lowering of upper curve rapidly than the lower curve. Thus both curves come closer to one another. This means again there is no relief left that uplifted landmass and this is called endrumpf with a small elevation, also called featureless low land reached at the ultimate base level.

Slope Replacement Theory of Penck

Penck recognized concavo-convex hillslopes similar to what Davis was observing in eastern North America. However, the Penckian model for their origin was altogether different. Penck is the father of slope replacement as a mechanism for hillslopes evolution. Whereas Davis's hillslopes are transport limited and always covered with a creeping regolith mantle, Penck's hillslopes are predominantly weathering limited with little to no regolith cover, except, implicitly at their base where regolith transported downslope is allowed to accumulate. Originally steep and straight slope profiles weather parallel to them except for a small, step-like flattening at the base of the slope, the 'haldenhang', which is presumably controlled by the angle of repose of the hillslope debris. Retreat of the 'haldenhang' results in an even lower-gradient basal slope called the 'abflachungshang'. The process continues with successive 'abflachungshang' retreating, each leaving a basal slope of lower angle than itself. The integrated result is a concave-up slope that has replaced the original steep, straight slope. Penck went on to propose mechanisms of how the upper part of the concave profile would flatten to produce an upper slope convexity using arguments similar to those used by Gilbert (1909).

12.4 Model of Lan scape Evolution by L.C. King

Lester Charles King (1907–1989) was an English geologist and geomorphologist known for his theories on scarp retreat. King's ideas are contained in his 2 books:-

1) Morphology of the Earth (published in 1960) and

2) Canons of Landscape Evolution (1953).

King received his training from C.A Cotton in Davisian morphology,T.J.D Fair for the ideas of slope and Alex L. Du Toit for ideas on tectonics. Kings ideas are influenced by his observations in southern Africa. His ideas included some components from the model of Davis and Penck. He rejected some of these and introduced some completely new ideas.He rejected the relationship between uplift and slope formed by Penck.He accepted the idea of structure- process and slope given by Davis but he changed the sequence in which process was placed first. Process for King meant the semi-arid environment.The semi-arid environment was suggested by king because in these type different types of river mass wasting and weathering process are important in addition to the work of river. His ideas represent a combination of Process, structure,crustal movement and mass wasting.

Kings idea can be understood in terms of 3 components: 1) Slope element 2)Development of Hill slope 3)Epigene cycle of erosion

Slope elements:

King used four slope elements which were initially proposed by 'Wood'. Each element is semi-independent. Any one of the elements can be completely absent on a given slope. This is particularly true for free face.

1) Waxing slope: It is a convex segment at the crest of the slope. It is covered by weathered material. Transportation on the surface is dominated by soil creep.
2) Free face: It is similar to cliff proposed by Penck.It is bedrock out creep which retreats parallel to itself under the influence of weathering processes and uniform removal of material. However areas which do not have enough large relative relief, free face may not develop.
3) Debris slope: Its development is dependent upon free face. If free face is there, debris slope will be there and vice-versa.
4) Waning slope: It has a gentle concave profile. There may be bedrock or transported material covering eroded bed rock surface, when the eroded transported debris cover such a surface it is known as pediment.

Parallel retreat:

Each of the upper parts of the slope retreats by the same amount and maintain the same angle. Therefore, the convexity, free face and debris slope all retain the same length. The concavity extends in length and becomes slightly gentler in angle. This is called pediment This type of evolution is called a parallel retreat.

Pediplanation:

He envisaged the parallel retreat of a single free face slope unit, leaving a broad, concave pediments sloping at an angle of 6-7 degree or less at its base. Gradually over time, pediments coalesce to form pediplains and this mode of landscape development, is therefore called pediplanation.

Development of Hill slopes:

- King rejected the climatic basis of landscape development and suggested that all landscapes are basically similar.
- He featured semi-arid climate as normal climate because acc.to him high proportion of earth surface have this type of climate and it has been dominant climate throughout the geological history of the earth.
- He accepted the division of tectonics movements by penck i.e. orogeny, epeirogeny and cymatogeny.
- Pedimentation was proposed as a basic process in hill slope development by king.
- Parallel retreat of slope results in emergence and expansion of a pediment which have a concave form.
- At an advanced stage of development these pediment on both sides of land mass join together.On this type of surface there are isolated erosional remnants. These are the Inselbergs, Bornhardt and Monadnocks.

Inselberg, Bornhardt and Monadnocks:

He theorized that once pediment surfaces have been formed, they persist with little change until the next phase of surface uplift promotes a new cycle of river incision and

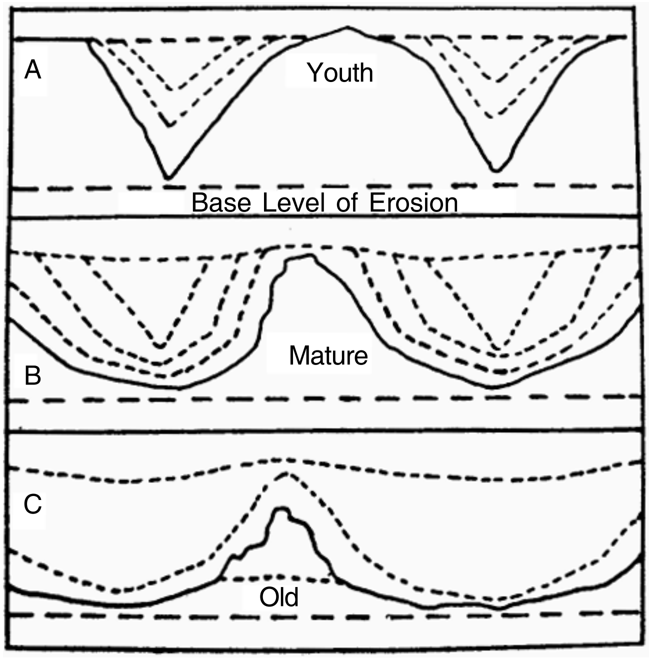


Fig: 8.8 Pediplanation cycle according to L.C. King.

escarpment retreat, which consumes existing pediplains and creates new ones. Like Davis, King envisioned impulsive uplift and long response times of landscape adjustment. He never accepted the Davisian concave-convex slope; he favouredPenck's view of concave hill slopes and slope replacement. On the basis of Penck's model he conclude that the landscape assumes the form of a series of nested, retreated escarpments.

Epigene Cycle of Erosion

- The term epigene refers to the surface. Therefore the epigene cycle of erosion is related to water and wind, in addition to weathering and mass wasting. It doesn't include glacial, marine, volcanic and karst processes.
- King accepted the concept of stages (i.e. at continental scale, there are massive erosional surfaces forming large staircase) and rejected the concept of crustal movements for creating of slope for cycle.
- The initiation of landscape depends upon the mode of development of hill sides.
- There are 2 different modes of development of hill sides:-

1. (a) Valley formation through stream incision.
   (b) Formation of valley sides due to tectonic forces.
2. Gentle lifting towards the sea. Acc. ording to him development of landscape depends upon mode of stream incision.

Development of landscape by stream incision—

- In this case valley sides are very steep because of uplift. The longitudinal profile of the river is broken by the development of knick points. The breaks in rivers beds form knick points.
- The river tries to remove or erode these knick points which recede in the upstream direction.
- River incision become important and youthful v-shaped valleys are formed. At this stage there can 2 variations. 1) A surface can be developed into a highly dissected plateau, for e.g. the Appalachian plateau around Pittsburgh. 2) The type of structure in a surface can provide different types of drainage pattern.

Land development on tectonic forms

- His ideas on this aspect are based on his observation in coastal South Africa particularly Drakensberg mountains. The monoclinal warping results in continental scarps. These scarps are at right angle to the drainage lines.

- The drainage line is the major agent for the removal of material created through the progress of a particular cycle. The erosional processes results in the retreat of these continental scarp. The removal of the material results in the parallel retreat of the scarps. Between two scarps is a cyclic landscape surface. Different epigene cycles produce different cyclic surfaces.
- At the base of each scarp there is a knick points. The knick point and scarp retreat at the same time. Two types of scarp can develop :- 1) Uniform wall like erosional scarp. 2) A scarp marked by dissection. The dissected part is generally located at upper elevation.
- In such cases the land is broken into a no. of hill slope segments. This is similar to the youthful stage after the youthful stage is over the slope experience parallel retreat.Due to this the areas of inter-fluvial divide are reduced or eroded.

Evaluation of King's concept

Lester C King's model of landscape evolution is similar to Davis' in that uplift is episodic and rapid in comparison with rates of denudation, and that the overall morphology of a landscape at any point in time is diagnostic of its evolutionary stages of development. King emphasized the role of erosion alone in the formation of pediment whereas Davis has emphasized both erosion and deposition in the formation of pediplains. His model is very comprehensive. His ideas of Cymatogeny are basically outside the scope of geomorphology. It is more related to plate tectonics and geo-physics.

12.5 John T. Hack: a Time-independent Model

John T. Hack is the champion of time-independent model where landscape variability due to age is not modelled, but rather considered a source of variability in landscape from related to contemporary process. This approach assumes a dynamic equilibrium between contemporary surficial processes and the surface upon which they are acting. Hack chose dynamic equilibrium as his conceptual and methodological framework. He derived this perspective directly from G.K. Gilbert who worked in the western US, where the dramatic semiarid landscape seems youthful and dynamic. Hack applied dynamic equilibrium to reinterpretation of the Appalachian Mountains, the landscape that lead Davis to think in terms of change over time.

The ***goal*** of the theory of Hack is to explain the landscapes of any region of the earth's surface on the basis of present denudational processes operating therein and to demonstrate lithological adjustment to landforms (for which he presented examples from the Shenandoah Valley of the Appalachians, USA).

The ***reference system*** of Hackian model is that 'geomorphic system is an **open system** which always tends towards steady state while his model may be stated as ***'the shape of the landforms reflects the balance between the resistance of the underlying materials to erosion and the erosive energy of the active processes.'***

The **basic premise of** Hackian model of landscape development is that***'the landscape and the processes that form it are part of an open system which is in steady of balance'* (Hack, 1960).**

Hack further conceived the following reference systems on the basis of his basic assumptions—

(i) 'There is balance between denudational processes and rock resistance'.

(ii) 'There is uniform rate of down wasting in all components of landscapes.'

(iii) 'Differences and characteristics of form are explicable in terms of spatial relations in which geologic patterns are primary consideration' (Hack, 1960).

(iv) The processes (denudational) which operate today have carved out the landscapes of the earth's surface.

(v) 'There is lithologic adjustment to landforms'.

Though J.T. Hack did not construct evolutionary model of landscape development directly but he did opine ***'that evolution is also a fact of nature and that the inheritance of form is always a possibility' (Hack, 1960).*** Though he did not build a model of progressive changes in landforms through time with changing environmental conditions but he opined that 'landforms do experience changes with changing equilibrium conditions but these changes are not like Davisian evolutionary changes.

Hack postulated the concept of variations in landscapes in relation to varying conditions of balance between rates of upliftment and erosion viz.-

(i) The rate of upliftment is balanced with the rate of erosion. If there is rapid rate of upliftment and erosion, there are produced high reliefs. This condition is maintained so long as the higher rate of upliftment and erosion remains constant.

(ii) So long as the rate of upliftment increases, the relief also increases so that rate of erosion matches the increasing rate of upliftment.

(iii) When the rate of upliftment becomes zero i.e. when upliftment stops, then relief also declines, though ridge and ravine topography is still maintained.

Hack has opined that if the diastrophic movement is gradual and if it is balanced by the denudational processes (i.e. rates of upliftment and erosion are equal) then landscape, while changing from one form to the other, remains in equilibrium condition. On the other hand, if there is rapid rate of diastrophic movement, then relict landforms are preserved until new equilibrium condition is not attained. Hack also developed a ***'continuous down wasting model'*** which though envisages tendency for dynamic equilibrium but it is not necessary that the dynamic equilibrium is in steady state. He himself admitted that 'though there is possibility for steady state but it is not possible in reality.'

He further opined, 'that evolutionary models can be conceived on the basis of base level of erosion. In this context he considered three conditions of base level viz.

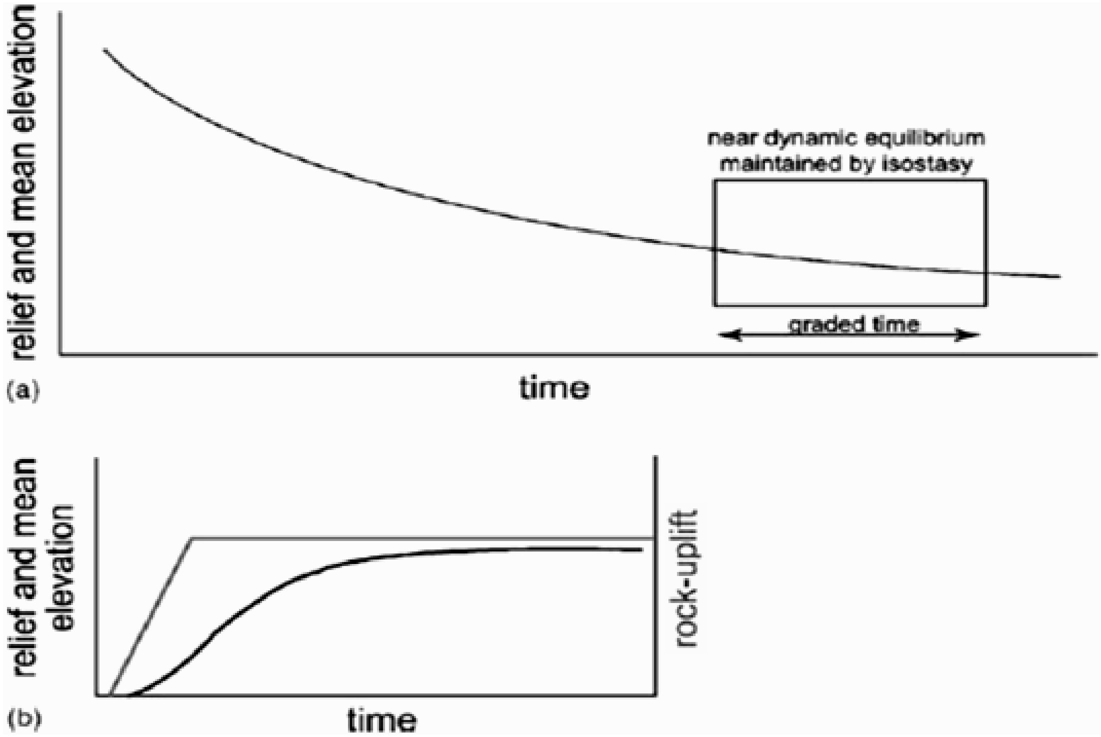
(i) stable base level,

(ii) positive (rise) change in base level and

(iii) Negative (fall) change in base level.

The basic features of dynamic equilibrium as applied to spatial relations within a drainage basin by Hack:

- all elements of the topography are mutually adjusted so that they are down wasting at the same rate.
- forms and processes are in a steady state of balance.
- differences and characteristics of form are explainable in terms of spatial relations in which geologic patterns are the primary consideration rather than a theoretical evolutionary development.
- Opposing forces (inputs and outputs) are in a state of balance where their effects cancel out to produce a steady state.



Attainment of a near time-invariant relief and mean elevation of a dynamic equilibrium landscape (a) attained over graded time during a protracted period of decay (cyclic time) and (b) attained as a flux steady-state between the input of rocks by tectonic processes and output by erosion.

Hack also maintained that his model is not comprehensive, that time can also be invoked to explain landscape features, but it does apply to the entire range of spatial scales of interest to geomorphologists. Under dynamic equilibrium, landscapes evolve without obvious change, unless there is a change in energy inputs (climatic change, tectonism) or surface resistance. Examples of the latter include the denudation of surface materials to expose harder or softer materials, or the accumulation of coarse materials in valley bottoms. The consequent adjustment to these changes represents disequilibrium but does not conflict with the time-independent perspective. Hack argued like Penck that rates of uplift and erosion are linked, although he related erosion plus relief to uplift and rock resistance and had a thin database to support this relationship.

Evaluation of dynamic equilibrium:

- The past usually is poorly or only partly known, thus a model based on current conditions has a definite advantage.

- Mutual relationship with process geomorphology
- Time-independent is an end-member of the distribution of systems and system models; these are fairly easily identified (*e.g.* and under fit stream is time-dependent relative to valley form but time-independent with respect to channel form)
- However, it is not usually this easy to resolve the complex forms that represent both time-independent and time-dependent behaviour; attention to spatial and temporal scale help, for example time-independent behaviour is more likely at more local scales, and the influence of past processes is proportional to their intensity and inversely proportional to time elapsed since the event
- Dynamic equilibrium implies characteristic forms as opposed to relaxation forms
- Situations where form is not maintained include uplift exceeding rates of erosion or increasing relief controlled by difference in rock resistance (*e.g.*, inversion of topography)
- When small segments of landscape evolution are sampled it becomes difficult or impossible to distinguish between dynamic equilibrium (trending mean), steady state (constant mean) and dynamic metastable equilibrium (two scales of oscillations). Hack referred to both steady state and dynamic equilibrium; however a trending mean is much more likely in geomorphic systems.
- Dynamic equilibrium is more of a conceptual framework than a fully tested corroborated model, which will require much more extensive data bases. However, it is a very useful framework in that the reduced role of time is replaced with an expansion of spatial variability and the integration of parts of landscapes. In this respect it is tied to a systems approach and the notion that systems move toward equilibrium at a rate proportional to their distance from it. Thus those far from equilibrium change quickly (time-independent) and thus near equilibrium change slowly (time-dependent). This systems perspective unites both the time-dependent and time-independent viewpoints.

12.6 Summary

The models of lands cape evolution are dealt in this unit. The significance of the various models explans the sequential development of landforms. Three views of cycle of erosion are very important.

12.7 Questions

Long question

1. Give a critical account of Davis's normal cycle of erosionwith sketches.
2. Discuss the time independent model of Hack.
3. Explain critically the cycle of erosion concept as envisaged by King.
4. Explain critically the cycle of erosion concept as envisaged by Penck.
5. Explain the geomorphic ideas of J.T. Hack and point out how it is different from thecyclic concept of landform evolution.

Short question

1. Discuss the concept of parallel retreat by Penck.
2. Briefly describe the concept of peniplain by Davis.
3. Briefly describe the concept of pediplain by L.C. King.
4. Distinguish between peneplain and pediplain.
5. Describe the four components of slope according to the model of L.C. King.
6. What is meant by 'interruption' of normal cycle of erosion?