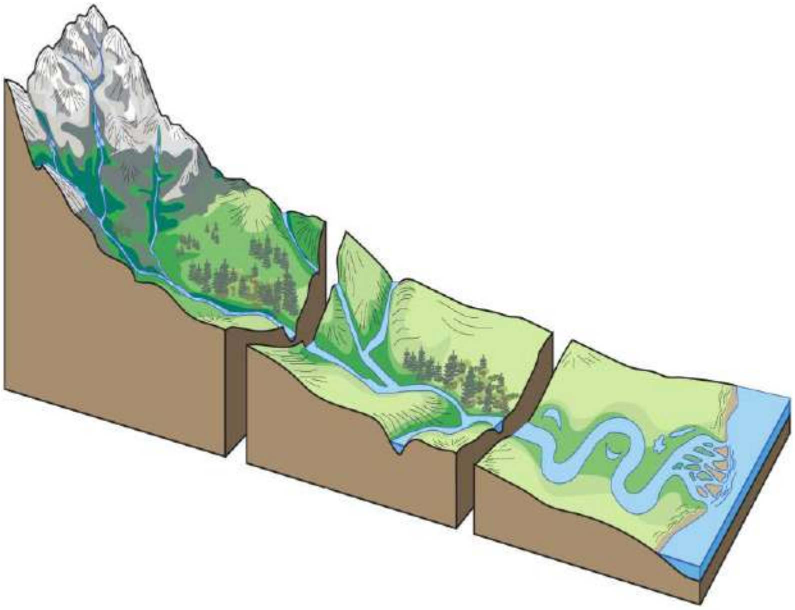
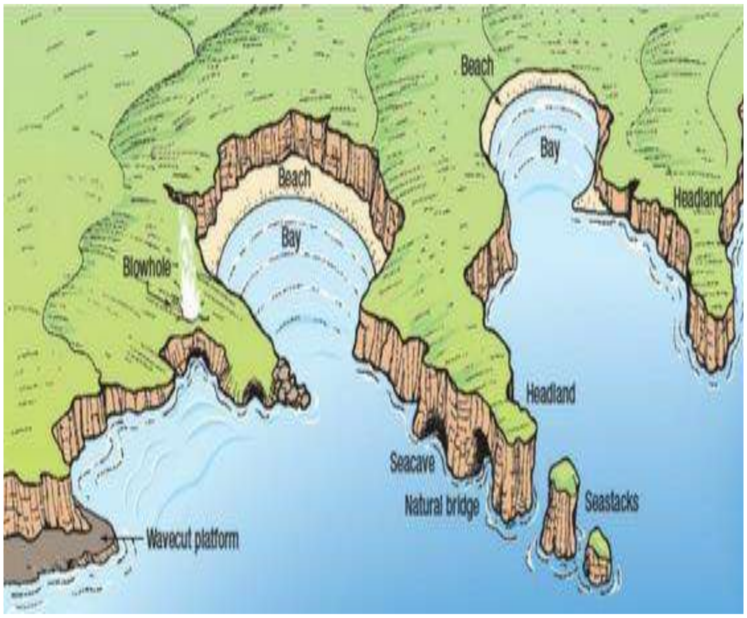
ARNATAKA STATE OPEN UNIVERSITY

Mukthagangothri, Mysuru – 570006

M.Sc. GEOGRAPHY

FIRST SEMESTER





Course Code: MGDSC- 1.1

Geomorphology

Credit Page

Program Name:	M.Sc. Geography	Semester:	I	Block No:	1 - 4
Course Name:	Geomorphology	Credits:	4	Units No:	1 - 16

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Block – 1

Block Introduction

As we know that Geography studies about the earth and its features. To understand the various aspect of the earth, knowledge of Geomorphology is most essential. It is the science which gives a systematic description and analysis about landforms. From ancient time there was a speculation about the origin of the earth. In Ancient, Classical and Modern period, several scholars have postulated various views regarding the origin of the earth, landforms development and others. Doctrine of Uniformitarianism of James Hutton has given new dimension in the field of Geomorphology.

In the very first unit we will discuss the meaning of Geomorphology and various definitions given by several scholars. To understand the various Geomorphologic events, it is very essential to know the basic concepts of Thornbury. This enlightens us about the earth and its phenomenon. After this we have to know the internal structure of the earth. It is required for a geographer to understand the forces affecting the landforms. To explore the interior and its structure, we have to rely mostly on indirect sources. By understanding several evidences, the earth's interior has been classified into different types.

After discussing the structure of the earth, we have understand the movement of continents and oceans. Several theories have been postulated by several scholars. Tetra Hedral hypothesis of Lothian Green, Continental drift theory of Alfred Wegner and the recent theory about Plate tectonics are studied in detail in third unit. Several concepts like Sea-floor spreading, drifting of continents, Paleomagnetism and others have been discussed.

In the fourth unit, the concept of Isostasy has been discussed. It is essential to understand the balance of the layers of the earth by students of Geomorphology. The views of several scholars like Sir George Airy, Archdeacon Pratt, Hayford and Bowie and others have been explained in detail in this unit.

Unit – 1

Basic Concepts of Geomorphology: Thornbury

Structure

1.0. Objectives

In this unit, you are going to study the meaning of Geomorphology and various definitions given by several scholars. The fundamental concepts of Thornburry is discussed in this unit.

After studying this unit, you will come to know the basic concepts of Geomorphology-

- Understanding the meaning of Geomorphology
- Identifying the list of 10 basic concepts of Geomorphology.
- Understanding the various processes operating over the surface.
- Relating the geological structure and its role in the evolution of landforms
- Discussing the topographical features in Pleistocene period.

1.1. Introduction

Our earth is composed of four essential components like Lithosphere, Atmosphere, Hydrosphere, and Biosphere. The lithosphere is the solid outer part of the earth. It is composed of rocks and minerals. The Atmosphere is the gaseous sphere encircling the earth. The hydrosphere is the liquid (water) part of the earth, and Biosphere is a sphere of living beings. All three layers are interrelated to each other.

The science which studies the whole earth or with one or more parts of it is known as Earth Science. Our expanding knowledge has made several branches in Earth Science. The principle earth sciences are – Geology, Geophysics, Hydrology, Meteorology, and Geomorphology. Some scholars do not agree that Geography is an Earth Science and is considered Social Science. But many scholars agree that Geography studies the relations of the physical environment of plants and animals on the earth to their location, growth, and their activities. Geography has been classified into two main branches- Physical Geography and Human Geography.

Geomorphology is a branch of Physical Geography. The term 'Geomorphology' is derived from two Greek words – '*geo*' meaning *'Earth'*, *'morphe'* meaning form, and *'logos'* meaning study. Thus, Geomorphology is a systematic and organized description and analysis of land forms. Geomorphology has a long history of development. The story began when man first attempted to formulate questions concerning landform features. Why were mountains, valleys, deserts, and vast oceans located? where they are now? What were the processes responsible for their evolution? The answers were elusive. From ancient times the subject has been studied in different ways. Hellenic Philosophers, Herodotus, Aristotle, Strabo, Avicenna, Leonardo-da-vinci, Nicolaus Steno, Buffaan, Targioni-Tozetti, Geotthard, Desmarest, De Saussure, M.U.Lomonosov, James Hutton, John Playfair, Charles Lyell, Louis Agassiz, Jean-de-Charpentian, James Geikie, Sir Andrew Ramsey, George Greewood, Jukes, Peschel, Richthofen, Arthur Penck, Major J.W.Powell, G.K.Gilbert, C.E.Dutton, W.M.Davis, etc., are the great scholars of different time who studied various aspects of Geomorphology.

1.2. Definitions of Geomorphology

a) According to **Worcester,** 'Geomorphology is the science of landforms. It is the science that explains the surface of the lithosphere, describes its origin, and interprets its history.

b) **Von Engeln** states that 'Geomorphology also studies the shape of the entire earth and disposition of its larger units along with the landforms.'

c) **Strahler** states that 'Geomorphology is an analysis of the origin and evolution of Earth's features.'

d) **Bloom** defines Geomorphology as the systematic description and analysis of landscapes and the processes that change them.

e) According to **Sparks,** 'Geomorphology is the study of the evolution of landforms, especially landforms produced by the process of erosion..'

f) **Thornbury** – ' It is the science of landforms including the submarine topography'.

g) **Machatschek** ' It is the study of the Physical processes fashioning the form of the solid surface of the earth as well as the resultant landforms'

h) **Ollier** – 'Geomorphology includes the study of both continent-ocean relationships and the origin, evolution, and characteristics of lesser landforms'.

From these entire opinions, one can conclude that Geomorphology is the study of different landforms formed by different processes.

1.3. Basic Concepts of Geomorphology

Before moving to a detailed study about Geomorphology, we shall first try to understand the basic concepts of Geomorphology as outlined in the book 'Principles of Geomorphology' authored by **William.D.Thornburg (1969).** By studying these concepts, it is possible to understand the various aspects of Geomorphology. The ten basic concepts of Geomorphology are:

1) *The same physical processes and that operate today operated throughout geologic time, although not necessarily always with the same intensity as now.*
2) *Geologic structure is a dominant control factor in the evolution of landforms and is reflected in them.*
3) *To a large degree of the Earth's surface possesses relief because the geomorphic processes operate at differential rates.*
4) *Geomorphic processes leave their distinctive imprint upon landforms, and each geomorphic process develops its own characteristic assemblage of landforms.*
5) *As the different eroding agents act upon the Earth's surface, an ordered sequence of landforms is produced.*
6) *Complexity of Geomorphic evolution is more common than its simplicity.*
7) *Little of the Earth's topography is older than tertiary, and most of it is no older than Pleistocene.*
8) *Proper interpretation of present-day landscapes is impossible without a full appreciation of the manifold influence of the geologic and climate changes during the Pleistocene.*
9) *An appreciation of world climates is necessary for a proper understanding of the varying importance of the different geomorphic processes.*
10) *Geomorphology, although concerned primarily with present date landscapes, attains its maximum usefulness by historical extension.*

Let us study each concept of Geomorphology in detail.

Concept - 1:

'The same physical processes and that operate today operated throughout geologic time, although not necessarily always with the same intensity as now.'

It is the most fundamental concept of modern geology. It is also known as the **'Principle of Uniformitarianism.'** It was advocated by Scottish geologist James Hutton in 1785. He also put forward the hypothesis **'present is the key to the past'** in his book **'Theory of the Earth'** published in the year 1795. This concept was further modified and strongly advocated by his friend John Playfair (1748-1819), a Mathematician by profession. He also explained Hutton's view clearly and wrote a book, 'Illustrations of the Huttonian

Theory' in the year 1802. Sir Charles Lyell (1830-1875) fully supported the Principle of Uniformitarianism and gave prominence in his book **'Principle of Geology.'**

Hutton realized that the vast thickness of the older sedimentary rocks is proof of the fact that the process of erosion and deposition has been operational on the surface of Earth for a long period of time. But he applied this principle too rigidly and argued that these geological processes operated throughout the geological time with the same intensity as of now. Even though the geological processes which were operational in the past are even operational in the present, but their intensity is not the same. The intensity of these forces varies and depends on many factors. For Example, Glaciers were most active in the Pleistocene period rather than today. These variations are due to the changes in world climate. In various geological periods, the climate has never been the same and has constantly been changing over time. For Example, the areas which now experience humid climates were once arid deserts or were experiencing hot and dry climates, and those areas which are deserts now were experiencing humid climates in the past. Periods of crustal instability seem to have separated periods of relative crustal stability. But there is no reason to doubt that streams did not cut valleys in the past as they do now. Like that, glaciers, winds, and other forces which operated in different time periods are also operational today. In other words, it is possible for us to understand the mechanism of processes operating in the past with the help of the forces operating today.

Concept - 2:

Geological structure is a dominant control factor in the evolution of landforms and is reflected in them.

In the Geomorphic cycle concept, American Geographer W.M.Davis clearly states that structure, process, and stage are the main controlling factors in the development of landforms. Some Geomorphologists doubt the role of the stage in the evolution of landforms, but no Geologists doubt the significant role of process and structure on the evolution of landforms. Here the term structure is used in the broader sense like folds, faults, unconformities, type of rock, joints, bedding planes, angle, hard rocks, soft rock, the solubility of rock, and others. It also includes the physical and chemical constituents of the rock. The structure also influences stratigraphy like sedimentation, deformation, metamorphism, mineralization, erosion, and others. The rocks under the surface are much older than the landforms developed on them.

Differences in the nature and structure of rocks greatly influence the intensity of weathering and erosion. Hence different processes operate at different intensities in different places. At the same time, climate, the humidity of the soil, forest cover, and others also influence the nature of processes.

A rock may act differently in different climatic conditions. A rock that is affected by one type of process may not be influenced by other processes in different conditions. Example: Sandstone. Sandstone is a porous rock, whereas shale is a non-porous rock. In sandstone regions, most of the rain water percolate into the Earth. Hence surface flow is less. In the regions covered with shale rocks, the surface flow of water is more as it is non-porous and doesn't allow rain water to drain into the Earth. Example: Limestone. Some rocks are insoluble. Example: Granite.

Concept - 3*:*

'To a large degree of the Earth's surface possesses relief because the geomorphic processes operate at differential rates'

As we know that the composition of rocks is not uniform, the physical characteristics of rock-like texture, grain size, composition, and color are not the same. The structure of rocks (hard or soft, permeable or impermeable) also varies from place to place. Hence the processes operating on the Earth act differently on various kinds of rock depending on their lithological factors and structure of rocks. So different kinds of relief features are found over the surface. Hard rocks are eroded slowly compared to soft rocks, which get eroded quickly. Like that, some rocks are soluble (Limestone, Gypsum), and some rocks are insoluble in nature. Due to these factors, different rates of erosion will take place, and various kinds of relief features are formed. Lithology and the structure of rocks are significant in the process of formation of different relief features. At the same time, the local factors like temperature, moisture, height, exposure to the atmosphere, vegetation cover, precipitation, configuration of relief features also influence the differential rate of processes operating at different places and times. So the rate of erosion, weathering, mass-wasting, deposition varies from place to place and time to time.

Concept - 4:

'Geomorphic processes leave their distinctive imprint upon landforms, and each geomorphic process develops its own characteristic assemblage of landforms'.

The surface of the Earth is continuously modified by various processes which are operating over the surface as well as under the surface. The internal or endogenic forces like earthquakes and volcanoes tend to build or uplift the areas which have been reduced by external forces. The exogenic or external forces like weathering, mass wasting, and agents of denudation reduce the uplifted landforms. These two forces operate at different rates at different places and at different times. Hence, we can observe several kind of relief features over the surface. Our ancestors have also recognized the work of these processes. Each geomorphic process, both endogenic and exogenic, creates its own distinctive landforms. For Example, flood plains, alluvial plain and delta are the products of a river, whereas Drumlines and Moraines are the results of Glaciers. Caverns and sinkholes are carved out by the underground water.

Each geomorphic process produces a particular relief feature which makes it possible to classify them to genetic classification. Proper understanding of each process and its landforms provide genetic relationships between these. Each landform created by a particular process has a relationship with other landforms produced by the same geomorphic agent. It means that there is an order or system between landforms created by the same process. A geomorphologist must understand the relationship between these. But we have to remember that landforms are the products of a group of processes. These operations operating under a particular set of climatic conditions are known as morphogenetic system. The evidence of changing climatic conditions can be observed in many landforms of different periods.

Concept - 5:

'As the different eroding agents act upon the Earth's surface, an ordered sequence of landforms is produced'.

Earlier, we believed that landforms were developed in successive stages of development as suggested by W.M.Davis in a geomorphic cycle. He argued that the distinctive characteristics of landforms depend on their development in different stages like youth, maturity, and old age. Finally, we can observe a plain area or low relief, which he termed as ***Peneplain.*** But most geomorphologists believe that landforms have orderly and sequential developments. But they have not completely accepted the stages of youth, maturity, and old age, as suggested by W.M.Davis. This concept is useful at the initial level and found inadequacies in landform evolution and characteristics of landforms in each stage, especially about peneplain.

The processes (Geomorphic Cycles) operating over landscape make a change in landforms. We shall use the term cycle or geomorphic cycle, which is not truly cyclic in nature in landform evolution. The designation of the topography of a certain area as youth, maturity, and old age is not necessarily the same as in another region. The Geology, structure, and climate of these regions will not be the same. The lithology, structure, and climate of these regions will not be the same. The lithology, structure, climate, and diastrophic conditions of two different regions are comparable. It is not necessary that the two areas which are in the same stage have taken in the same time. There is some confusion among several geologists who defined a geomorphic cycle as the period of time required for the reduction of an area to base level rather than the changes which happen over a land mass as it is reduced to base curve.

The partial cycle is an influence drawn from the concept of a completed geomorphic cycle. Due to Earth's dynamic in nature, there is a differential rate of upliftment at several intervals resulted in partial cycles. These cycles also leave pieces of evidence on landscapes. In the tectonically active area, there is very little chance of sequential development of landforms. Continuous upliftment and intervals lead to the landforms in youth or in maturity rather than in a normal cycle.

Concept - 6:

'Complexity of Geomorphic evolution is more common than its simplicity.'

In general, the evolutions of landforms are studied in relation to each process. It is difficult to find that only one process is operating in one region. A particular process may be more powerful than the other processes in one region. Example: Wind is a predominant agent of denudation in arid and semi-arid regions. Whenever there is rainfall, running water will also become an agent of denudation in that region. The evolution of landform is not related to one cycle of erosion, but it is due to several cycles of erosion. We can find residual features of earlier cycles in a particular region where another agent is predominant now. Hence the complexity of geomorphic evolution is due to two reasons. They are (i) the presence of more than one process and (ii) the existence of more than one cycle. Horberg(1952) has classified the landscapes into five major types. They are - (1) Simple landscape, (2) Compound landscape, (3) Monocyclic, (4) Multicyclic, (5) Exhumed or Resurrected landscapes.

(1) Simple landscape: These are formed by a single predominant geomorphic agent/process.

(2) Compound landscape: These are most common in the world. These are formed by the combined work of more than one force. Example: Bimani bad folds near Vishakhapatnam, where the action of rivers, wind, and sea waves are forming different landforms. These landforms are also found in the regions affected by Pleistocene glaciations.

(3) Monocyclic: The landform created by one particular cycle of erosion is called monocyclic landscapes. These are less common compounds compared to multi-cyclic landforms. It is generally found in newly created landforms. Example: Surface of a volcanic cone, the uplifted portion of the ocean floor, lava plain, etc.

(4) Multi-cyclic landscapes: Most of the landforms in the world belong to this type. These are formed by more than one cycle of erosion. Example: Valley within a valley.

River terraces along valley sides above the present floor etc. Monocyclic and multi-cyclic landforms may be either simple or compound in nature. Many landforms in the world were formed in different climatic conditions and are known as polyclimatic landscapes. They exhibit a different type of climate of Pleistocene age.

(5) Exhumed/Resurrected landscapes: These are hidden topographical features. They were buried under igneous or sedimentary cover in the geological past. Due to continuous erosion of the outer cover of these rocks, the underlying rocks were found. They reappear over the surface and are known as Exhumed or Resurrected landforms. Example: Wabash river basin in Northern Indiana of USA flows over a buried periglacial topography.

Concept - 7:

'Little of the Earth's topography is older than tertiary and most of it no older than Pleistocene.'

Most of the Geomorphologists believed that the present landforms are mostly formed in Pleistocene or past Pleistocene period. Thus the landforms are young. Ashley (1931) argues that 90% of the present landforms are formed in the post-tertiary period, and 99% of these belong to the past Miocene period (Less than 10 million years). The folding of the Himalayan Mountains started in the Cretaceous period, but they gained their present height until the Pliocene period, and its associated landforms were formed in the Pleistocene period. It is believed that the structures are old and possibly exhumed, but the landforms over that are young.

The proper interpretation of the present-day landforms can be made with the geological and climatic influences during the Pleistocene period. Glaciations have affected not only North America and Eurasia but also faraway places. The regions which are arid or semi-arid today have had experienced humid climates in the Pleistocene period. The diastrophism which occurred during this period has a huge influence on the topography of the pacific coast.

Few geologists do not accept the fact that present landforms are young. According to them, the landforms are old, and interpretation of these can be made in the context of the long time scale of landscape evolution. It is supported by the concepts like continental drift, plate tectonics, and sea floor spreading. So it is essential to understand geological time scale in the study of the evolution of landforms.

Concept - 8:

'Proper interpretation of present-day landscapes is impossible without a full appreciation of the manifold influence of the geologic and climate changes during the Pleistocene'.

The present-day landforms are mostly influenced by the structure and climatic changes that took place during the Pleistocene period, and these changes have far-reaching effects on different areas of the world, like distant glaciated regions. It is estimated that 10 million square miles of the area have been affected by these climatic changes. The Glacial outwash and windblown materials of the glaciated region were found in non-glaciated regions. There are several shreds of evidence that show that arid and semi-arid regions of the present day have and experienced humid climates during the glacial period. Hundreds of lakes were formed in the USA during this period. These conditions also exist in Asia, South America, and Australia.

The present-day temperate regions have permafrost conditions during Pleistocene time. Due to this, the stream paths have been altered. Several pieces of evidence like widening and down cutting of valleys due to glaciers prove the same. Ohio and Missouri rivers are good examples. The sea-land of the world has also been affected. The sea level has been reduced from 300 to 500 feet. Due to this, new landforms were seen in the coastal area. It has also affected marine organisms like corals. During the interglacial period, a large scale of water has been discharged. Hence the sea level has risen, submerging low land areas in the coastal regions. Due to this retreating of glaciers, hundreds of lakes were formed. The windblown minute particles were deposited at faraway places and formed Loess plain. The great lakes of the USA are also the results of this period.

The diastrophic activity, which was started in the Pliocene (10-20 million years) in many parts of the world, was also continued in the Pleistocene and today also. The diastrophism of the Pleistocene period played a major role in the formation of landforms along the coast of the Pacific Ocean. Deep canyons of the Rocky Mountains are the best examples for which are formed during this period

Concept - 9:

'An appreciation of world climates is necessary to a proper understanding of the varying importance of the different geomorphic processes'.

It is found that climatic factors like temperature and precipitation have an influence on Geomorphic processes directly or indirectly. The type and amount of precipitation, range of temperature, rate of evaporation, the direction and speed of the wind, and other factors have a direct influence over various Geomorphic processes. There are other climatic factors like heavy rainfall, its frequency, frequency of thawing and freezing days, number of maximum rainfall days, the number of days, the slopes exposed to sun, i.e., windward or leeward side of slopes, altitude of mountains in that place,etc. also affect the geomorphic processes. The indirect influence of climate is on the distribution and density of vegetation over the surface.

The basic concepts of Geomorphology have been built in humid temperate regions. We consider that the processes are normal in these regions. We know that there are variations in processes in arid and humid regions. There are several types of arid climate, and we study the normal arid cycle. We have to formulate the basic geomorphic concepts in relation to humid tropical, Arctic, and sub-arctic regions. The processes which are dominant in humid middle latitudes need not be dominant in the lower or higher latitudinal region. Since the climate of these regions is not similar, we have to understand the climate of a region, and then it is possible to understand the geological processes and existing landscapes.

Concept - 10:

'***Geomorphology, although concerned primarily with present-day landscapes attaining its maximum usefulness by historical extension.'***

Geomorphology studies landforms. The present-day landforms were formed in different geological times. Hence a Geomorphologist is to adopt a historical approach to understand these landforms. It is most appropriate to study landforms by using the concept ***'Present is the key to the past'*** of **James Hutton**.

In 1941 Bryann recognized the Historical Nature of Geomorphology, and it is called as Historical approach. It is known as Historical Geology, but modern geologists opposed this view, and they called it Dynamic Geology.

1.4. Let us Sum up

In this unit, we have discussed the meaning of Geomorphology and its various definitions given by different scholars. To understand the various aspects of geomorphology, it is essential to know about the fundamental concepts of Geomorphology. All these concepts will give a deeper and broad picture of the several aspects of geomorphology.

1.5. Key words

Geology: It is the scientific study of Earth. It studies the earth's constitution, structure and history of the development of the Lithosphere.

Geomorphology: It is the systematic study of Landforms.

Structure of rocks: It means the mineral composition of the rock.

James Hutton: Scottish Geologist, who propounded the Principle of Uniformitarianism.

Unconformities: It is a plane of discontinuity that separates two beds.

Stratigraphy: It is the study of strata as a record of geological history.

Metamorphism: Change in the form of rocks.

Peneplain: It represents the landscapes produced at the end of the cycle of fluvial erosion.

1.6. Question for Self Study

1. List out the Fundamental Concepts of Geomorphology.
2. Explain the concept 'the same physical processes and laws that operate today operated throughout the geological time, although not necessarily always with the same intensity as now.'
3. 'Geologic Structure is a dominant control factor in the evolution of landforms and is reflected in them' discuss this concept with illustrations.
4. 'The present is the key to the past,' discuss the significance of this statement in relation to the evolution of landforms.
5. Discuss the influence of Climatic variations and their influence on various geomorphic processes.
6. Write short notes on -
    a) Simple landscapes.
    b) Complex or Compound landscapes
    c) Mono cyclic landforms
    d) Multi cyclic or Poly cyclic landscapes
    e) Resurrected landscapes.

1.7. Further Readings

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UNIT - 2

STRUCTURE OF THE EARTH'S INTERIOR AND LANDFORM DEVELOPMENT

Structure

2.0. Objectives

The main aim of this unit is to provide information related to the invisible interior of the earth. By the end of this unit, you are able to-

- Understand the structure of the interior of the earth and its composition.
- Identify the relationship between the compositions, the density, and temperature in the interior of the earth.
- Recognize the evidences to know the interior and structure of the earth.
- Identify the various layers of the interior of the earth and their characteristics.

2.1. Introduction

A Geographer is mostly concerned with man's activities over the surface. These activities are determined by the physiology of that region. So understanding of physiography of that region is the most important for a Geographer. Hence he has to understand all the forces affecting the landforms. Without understanding the interior of the Earth, it is not possible to understand the forces modifying the physiographic of a region.

2.2. Sources (Evidences) to know the interior of the Earth

Man's direct observation of the composition and properties of the Earth is limited. Investigations by Geo-physicists obtained information about physical properties of the Earth by using various instruments to measure Gravity, Earthquake waves, Earth's magnetism, and others. The sources which provide the information about the interior of the Earth can be classified into two ways – Direct and Indirect sources.

2.2.1. Direct Sources:

Mining areas provide a direct source to know the interior of the Earth. For Example, Gold mines in South Africa at a depth of 3-4 km and Petroleum wells which are at a depth of 4 to 6 km. It is very negligible when we compare it to the radius of the Earth (6371km). Various scientists are working on Deep Ocean drilling projects and Integrated ocean drilling projects, which help us in understanding the Earth's interiors. For Example, Kola drills in the Arctic Ocean are about 12km in depth, and samples collected from these drills have helped scientists a lot in understanding the interior of Earth.

Stones and various exhausts from volcanic eruptions provide direct pieces of evidence to understand the interior of the Earth. During a volcanic eruption, magma that comes out may be used to know the interior of the Earth, but from this source, it is very difficult to know the depth of the source of magma.

2.2.2. Indirect Sources:

We can get information about the interior of the Earth by indirect sources. They are- Density, Temperature, pressure, Meteors, Gravitation, Magnetic field, and Earthquakes.

i) Density: The mass of a substance per unit volume is known as its Density. The average density of Earth is 5.5g/cc. Granite and Basalt rocks are the most common in the upper parts of Earth's interior. Their density is about 2.6g/cc and 3.0g/cc, respectively. As depth increases, the density of the Earth also increases. It is estimated that the density of the Earth in its core is about 8to 12g/cc. The interior of the Earth has a different composition of rocks as compared to its surface. It is believed that the core is composed of metals like Iron and Nickel. Hence scientists argue that the density of Earth varies with several layers of the Earth's interior.

ii) Temperature: Studies from mining activities reveals that the temperature of the interior of the Earth increases as we go deeper and deeper. The average increase in temperature is 1^0C for every 32 meters depth or 1.6^0F for every 100' depth. At this rate of temperature increase, it would be 1200^0 C or 2200^0F at 48km depth. The magma chamber lies at this depth. This rate of increase in temperature is not found at greater depths. It is found that in the upper layers of the interior of Earth, the major source of heat is radioactive minerals like Uranium and Potassium. These are found up to 100km in depth. Below this depth, the occurrence of these radioactive minerals is far less. Hence the temperature at a depth of 400km is about 1500^0C, and at 700km depth, it is 3700^0C. It is estimated that the temperature at the centre of the Earth is around 4000^0C with a variation of +/- 1000^0C at that pressure.

iii) Pressure: In the physical sciences, the perpendicular force per unit area, or the stress at a point within a confined fluid, or the force that a liquid or gas produces when it presses against an area. As we know that the density and temperature increase with the increase in depth, there is a limit to the density of rocks, and it cannot be increased with an increase in pressure. Hence the core must consist of metallic minerals of high density. Through geomagnetism high-density metallic minerals like Iron and Nickel.

iv) Meteors: The materials and structure observed in the meteors are similar to materials found on the Earth. This tells us that processes that had once occurred on Earth might now be taking place on other planets.

v) Gravitation: Gravitational anomalies provide us information about the interior of the Earth. The gravitation is different at different latitudes. It is greater near poles and less at the equator. This is so because of the difference in the distance between the centre and the surface of the Earth. At the equator distance between the centre of Earth and Earth's surface is more compared to that of poles. It is also influenced by other factors. The readings of gravity vary from expected values, and this is called a gravitational anomaly. Geomagnetism also shows that different values of gravity at different places. The distribution of magnetic materials in the Earth's interior also influences these values.

vi) Earthquakes: Earthquake is a sudden and temporary vibration of the earth's surface. The energy released from the beneath travels in the form of earthquake waves. By studying the travel time of earthquake waves, we will get information about the interior of the Earth. There are three types of Earthquake waves, namely- (i) Primary/P-Waves; (ii) Secondary/S-waves; (iii) Surface/L-Waves.

Primary or P waves can pass through in all the mediums like solid, liquid, and gases. These waves are quicker than the secondary waves. They have short wavelengths and high frequency. They are the first strike to the surface of the Earth. The speed of this wave depends on the density and compressibility of the medium.

Secondary or S-waves can move only in solid medium. These waves are capable of changing the shape of the material without changing its volume. Surface Waves are slower compared to primary and secondary waves, but they are most destructive than the others.

Primary and Secondary waves show increasing speed when they are passing from lower to higher density rocks. The study of travel time of earthquake waves with the information of shadow zones, where these two waves are not recorded. By studying the travel time data of the earthquake waves, it is possible to know the interior of the earth.

So by understanding the nature, characteristics, and velocity of these seismic waves, we can find the presence of different density zones inside the earth. The speed of the earthquake waves changes when there is a change in the density of rocks. Three zones or layers are identified based on this.

2.3 Layers of the interior of the earth as noticed by E. Suess

Different scholars have identified several layers in the interior of the earth. According to Austrian E.Suess, he classified the layers of the earth into three layers like –

1. Sial,
2. Sima
3. Nife.

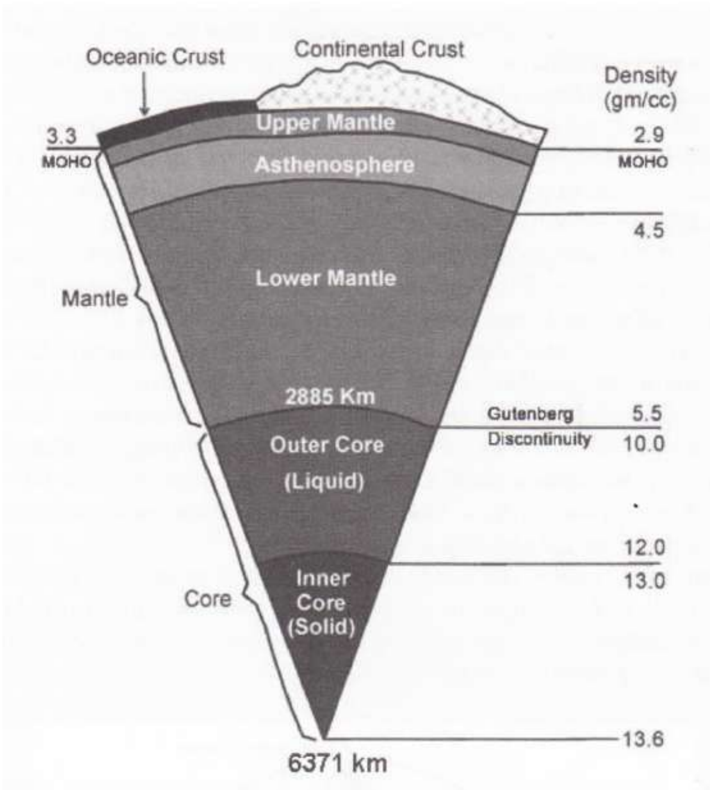

Figure 2.1: Structure of the Earth

2.3.1. Sial:

It is also known as the upper continental crust. It consists of all three types of rocks-Igneous, Sedimentary, and Metamorphic rocks. Suess recognised this layer as Sial or Sali. Silicon (Si) and Aluminium (Al) are the major components found in this layer. Hence it is known as Sial(Si+Al) layer. The specific gravity of this layer is 2.75 to 2.90g/cc. The ***Conard discontinuity*** separates Sial and Sima layers. It also separates the upper crust and lower crust. But this discontinuity is not traceable continuously everywhere because the local transitional character of the region.

2.3.2. Sima:

It is the second layer as identified by Suess. It is located below the Sial layer. It mainly consists of Silicon (Si) and Magnesium (Mg). The specific density varies from 2.9 to 4.75g/cc. He considered this layer is thicker than Sial and its average thickness is between 1000 to 2000 km.

2.3.3. Nife:

It is situated below the Sima layer. It is mostly composed of Nickel (Ni) and Iron (Fe). It consists of metals that have more density (9.71 to 16 g/cc). The presence of iron influences the magnetic property of the Earth's interior.

2.4. Daly's classification

Daly has identified three layers of different densities in the Earth. They are (1) Outer zone; (2) Intermediate zone; (3) Central Zone.

- The outer zone consists of Silicates. Its average density is 3.0g/cc with a thickness of 1600km.
- The intermediate zone is a mixture of Iron and Silicates. Its density varies from 4.5 to 9.0 g/cc.
- Central Zone is made up of Iron and Nickel with an average density of 11.6g/cc. It is solid.

2.5. Harlod Jeffreys Classification

Harlod Jeffreys has classified the Earth's interior into four layers based on the study of seismic waves. They are,

1. Outer layer of Sedimentary rocks.
2. Second layer of granites.
3. Third layer of diorite or thachylyte
4. Fourth layer of dunite or peridotite

2.6. Arthur Holmes Classifications

Arthur Holmes has classified the Earth's interior into two layers. They are,

1. Crust 2. Substratum

2.6.1. Crust: It consists Sial and upper part of the Sima layer. It has a variety of rocks like granite and basalt. The Density of these rocks varies from 2.7 to 3.4 g/cc.

2.6.2. Substratum: Below the crust, This layer is known as substratum. It consists of the lower layer of Sima, where Magnesium is largely found. Silicate is also found in this region.

2.7. Lithosphere, Pyrosphere & Barysphere

Most scientists have classified the Earth's interior into three layers. They are,

2.7.1 Lithosphere: It mostly contains granites. Silica and aluminum are the dominant materials found in the region. The thickness of this layer is about 100km and has an average density of 3.5g/cc.

2.7.2. Pyrosphere: A layer that separates the crust from Pyrosphere is known as ***Mohorovisic Discontinuity or Moho line.*** Pyrosphere lies in between the crust and core of the earth. It extends up to a depth of 2900 km. ***Gutenburg discontinuity*** separates the central core from the Pyrosphere. The average density of this layer is 5.6g/cc. Basalt is the predominant rock of this layer.

2.7.3. Baryosphere: Iron and Nickel are the most dominant materials of this layer. The average density ranges from 8 to 11g/cc. It has a thickness of 3478km. It extends from Gutenberg discontinuity to the core of the Earth(2900 – 6371km).

2.8. Crust, Mantle and Core

In Recent years, by studying the velocity of Earthquake waves, the Earth's interior has been divided into three layers. They are-

(1) Crust

(2) Mantle

(3) Core

2.8.1. Crust:

It is the uppermost layer of the Earth. The thickness of this layer varies from continent to ocean bottoms. Under the oceans, the thickness of this layer varies from 5 to 10kms. Under the landmass, the average thickness of this crust is 35km, and below the mountains, it is about

55 to 70kms. The Mohorocivic discontinuity is its lower boundary. It consists of various type of rocks. Generally, sedimentary rocks are found in the upper part of the layer, and this layer is continuous. Below this layer are the crystalline rocks like Gneisses and Granites. In the lower parts of this layer, one can find Basaltic rocks.

Under the ocean, the thickness of the crust is very thin or even absent. The specific gravity of the upper part of the crust is 2.65g/cc, and the lower portion of the crust is 3.0 g/cc.

2.8.2. Mantle:

Mantle is situated between crust and core. The thickness of this layer is about 2865km and forms 83% of Earth's volume and 68% of the mass. Sea-floor spreading, continental drift, earthquakes, and orogenic activities get energy from this layer. Primary and secondary earthquake waves pass through this layer very fastly as this layer is solid in nature.

The upper part of the mantle consists of Pyrolite. It extends up to 1000km depth. The upper mantle can be further classified into two layers based on the velocity of earthquake waves.

2.8.2.a. Gutenburg layer: It is fromMohorovicic(Moho line) discontinuity to a depth of 410kms. The lithosphere consists of the crust and the upper part of the Gutenberg layer. Under this layer, **Asthenosphere** is located. It is molten and exhibits plasticity. The speed of the earthquake waves reduces in this layer and is hence called the Low-velocity zone.

The velocity of seismic waves increases in the lower part of the upper mantle, which is known as **Golitsyn's layer**. The lower part of the mantle is about 1900 km thick. Here the velocity of seismic waves increases.

2.8.3. Core: It is the deepest layer of the Earth. It extends from 2900 km to the centre of the Earth(6371 km). It constitutes 17% of the volume and 34% of the mass of Earth. In this layer, the secondary earthquake waves suddenly disappear. The upper part of the core is fluid. This layer also reduces the speed of the primary earthquake waves. The temperature (about 5500^0C) and pressure are very high in this layer. The core has been further divided into three layers such as,

2.8.3.a. Outer Core: Outer core is fluid in condition, and it extends from 2900km to 4982km. Secondary earthquake waves will not pass through this region.

2.8.3.b. Middle Core: It is an intermediate layer found between the outer and inner core. The materials in this layer are in the fluid to semi-fluid state. It extends from 4982 km to 5121 km.

2.8.3.c. Inner Core: This layer extends from 5121 km to 6371 kms. We believe that this layer is in solid-state. Here Nickel and Ferrous (NiFe) are predominant. The average density and radius of this layer are 13g/cc and about 1250 km, respectively. It is estimated that the average temperature of the core is about 5500^0 C.

2.9. Let us sum up

Based on the above information, it gives a good explanation about the structure and configuration of the earth's interior. But still, there are many research works carried out in laboratories to know how the rocks react with different temperature and pressure conditions at different depths. In future days we will come to know more information about the interior and structure of the earth.

2.10. Key Words

Density: The mass of a substance per unit volume.

Meteors are also known as shooting stars, are pieces of dust and debris from space that burn up in Earth's atmosphere, where they can create bright streaks across the night sky.

Discontinuity: It is used for a surface at which seismic waves change velocity.

Moho Line: It is a layer that separates the crust from pyrosphere.

Sial: It is a layer of the earth where Silicon and Aluminium are predominating.

Conard Discontinuity: It is a layer that separates Sial and Sima layers.

2.11. Questions for Self Study

1. Explain the evidences to understand the interior structure of the earth.
2. Explain the characteristics of Crust, Mantle, and Core.
3. Describe Sial, Sima, and Nife layers.
4. Explain the various classification made by different scholars regarding the layers of the earth.

2.12. Further Readings

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UNIT – 3

CONTINENTAL DRIFT AND PLATE TECTONIC THEORIES – LAND FORMATION

Structure

3.0. Objectives

This unit gives you a broad picture of the concept of origin and moving of continents. Several scholars propounded their own views regarding this aspect. Continental drift theory sheds light on modern Plate tectonic theory. After studying this unit, you will be able to know-

- The earlier scholars' view about the origin of continents and oceans.
- The proofs given by different scholars about the movement of continents.
- Identify the splitting of continents and drifting of these.
- List out the major and minor plates of the world.
- Identify the various types of plate boundaries.

3.1. Introduction

There are several controversies and arguments regarding the origin of continents and oceans. Lothian Green has postulated Tetrahedral Hypothesis gives a foundation for the displacement of continents. After this, Alfred Wegener and other scholars have postulated their theories regarding the origin of continents and oceans.

3.2. Tetrahedral Hypothesis

His theory (1875) gives a different approach to evaluating the origin of continents and oceans. He assumed that the earth is in a tetrahedral shape and is covered by water in all the side except the apex of the triangle. The apex and the tip are projected out of the water and are believed as continents, and the rest of the surface is covered by oceans.

3.3. Continential Drift Theories

In the olden days, it was believed that all continents and oceans were stable and stationary. But new investigations revealed that the continents are drifting and are not stationary. Several questions were raised in the mind of scientists about Alpine compression, distribution of planets and animals, Upper Carboniferous glaciations, the existence of land bridges, and others. Several scientists advocated many theories regarding the drift and movement of continents and oceans like,

1. Planetesimal hypothesis by Chamberlin.
2. Geosynclinal–orogen theory by Kober.

3. The thermal contraction theory by Jeffreys.
4. The drift theory by Wegener.
5. Drift and Orthodoxy.
6. Radioactivity and the Surface history of the Earth by Joly.
7. The hypothesis of Sliding Continents by Daly.
8. Convection current theory by Holmes.

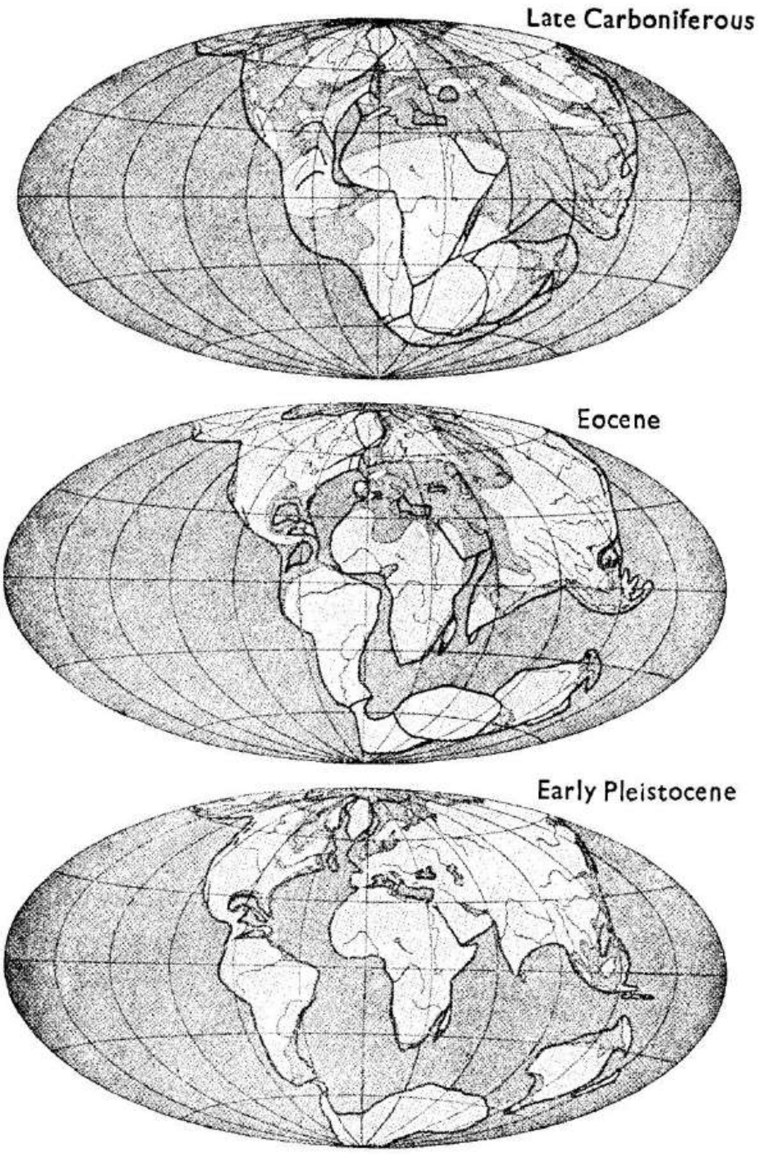
3.4. Theory of Continental drift

Several scientists observed that there is movement of continents. In 1620, Francis Bacon noticed the similarities in the shape of the coastal lines of the Atlantic Ocean of South America and Africa. In 1858 a French scholar Antonio Snider was the first to suggest that the continents are moving. In 1910, F.B.Taylor advocated the hypothesis of horizontal displacement of continents. In 1912, a German meteorologist Alfred Wegner proposed the **'Theory of Continental Drift.'** He stated that all the continents were once joined together to form a single landmass which then drifted apart. He published his views in his book 'The origin of Continents and Ocean' in 1915, but due to First World War, his book was not popularised. In 1924 his book was translated into English, and then his book caught the attention of many scientists. Wegner proved that inter-continental has taken place and even continuing to this day. The main problem he had to explain was the climate change in the geological past. He considered the work of paleo-climatologists, paleontologists, geologists, geophysicists, and others. He initiated a new line of thought regarding the movement of continents. Several geological pieces of evidence show that in the Carboniferous period, rich in natural vegetation and dense forest was found in cool middle latitudes due to the presence of huge coal deposits, whereas cold climate and the presence of glaciers could be found in India, South Africa, South Australia, and Brazil. This shows that landmasses have changed their positions over time.

Wegner collected several pieces of evidences to support his ideas. He suggested that till the Carboniferous period, the present-day continents were one super continent – Pangea, a Greek word meaning 'Entire Earth' (pan-entire; geo-earth). The evidences of glacial deposits (Tillites) show the existence of a single land mass in the Southern Hemisphere. Other proofs like the presence of coal in the most temperate zone, salt, Gypsum, and others during the Carboniferous to Quaternary period supports the existence of a super continent – Pangea.

This super-continent was surrounded by a single water mass, the ocean called 'Panthalassa,' meaning all water. His reconstruction of Pangea was based on matching the continental borders of Africa and South America. The continents of North America, Europe, and Asia constitute the northern part of Pangea, known as Laurasia. The southern part of the super continent was called Gondwana land. These two landmasses were separated by a shallow inland sea called 'Tethys.'

Figure 3.0



Wegner's reconstruction of the distribution of the continents at three periods

New evidences have supported the views of Wegner. Samuel Warren Carry, a Tasmanian Geologist in 1958, has considered a 2000 meter submarine contour between the opposite sides of continents of the Atlantic Ocean (South America and Africa) matched. Alexander du Toit, a South African Geologist, has supported the views of Wegner based on Sedimentology, Palaeontology, and tectonics. According to him, 'Africa and South America have once constituted a single landmass.

According to Snider, the presence of coal in Europe and North America shows that these two landmasses were located in the tropics or near the equator, and if this was so, then South Africa should have been near the South Pole. Wegner assumed that during the Carboniferous period, the South Pole was located on the present-day South African coast. Thus, one can observe that there was not only continental drift but also wandering of poles.

Due to rifting in Pangea, the drifting of continents took place. During the Mesozoic era (230 to 70 million years), the landmasses of southern parts of Pangea started to move. North America began to move away to the west, and finally, Greenland has moved. The gap left in the Atlantic was filled by Sima from below. During the Pleistocene, the poles have reached the present position. Africa was situated across the equator. Later northern part of India, which was earlier buried under the high plateau of Tibet, joined Asia and Australia moved towards the east. The drifting of the continents from the poles is known as **'Polflucht'** (Flight from the poles), and this name was coined by Wegner. According to him, the cause of the movement of continents was the gravitational attraction exerted by bulging near the equator, but he failed to notice that a force million times this gravitational force was required to move the continents.

North and South America's west and its front part clamped with Pacific floor giving rise to great mountains. During the same time, West Indies was formed. The isthmus between South America and Antarctica continents, Southern Antilles was formed. The great oceanic depths represent gapping fissures torn in the Pacific floor, which has not been restored till now. It is believed that different attractions of the moon and sun resulted in the westward movement of continents. Tidal frictions were also responsible for the same. Since tidal force barely affects Earth's rotation, this force alone was not responsible for the movements of continents.

3.4.1. Evidences:

To support his views, Wegner collected several pieces of evidences and proofs from various sources. The most important are;

a) The opposite shores of the Atlantic Ocean have a geographical similarity. According to Wegner, the Atlantic Ocean had a huge rift because of which its sides were rippled. The two sides of this ocean can be easily joined together. The eastern coast of South America can be joined with the western coast of Africa, and the eastern coast of North America can be joined with the western coast of Europe. He called it the jig saw fit of the opposing coasts of the Atlantic Ocean.

b) There is a huge similarity in the nature and type of rocks found on the opposing coasts of the southern Atlantic Ocean, i.e., Brazil and Africa.

c) There is a great resemblance in the geological structure and history of two opposite coasts of the Atlantic Ocean. Example: Appalachian Mountains of North America continue its trend across the North Atlantic Ocean in the old or Hercynian old mountains of South Ireland, Wales, and Central Europe.

d) The same trend has been observed in the Caledonian Mountains of North America are South-west to northeast along the eastern coast into the sea and reappear on the other side of Atlantic Ireland and Scotland in a similar direction.

e) Glacial evidences are found in Brazil, Falkland Islands, South Africa, Peninsular India, and Australia shows that the landmasses were joined together to form Pangea. He pointed out that the south pole was located near Durban along the coast of South Africa.

f) There is a resemblance of Pre-Cambrian rocks of Central Africa, Madagascar, South India, Brazil, and Australia supports that the landmasses had once joined together. In these places, even though the younger rocks are dissimilar, the older rocks are so similar that they support Wegner's views that Pangea really did exist.

g) Paleoclimate evidences show that many ancient climate belts were in different positions from the present-day belts. He believed that continents moved and poles remained stationary.

h) The Banda arc(Indonesia) and deeps are related to New Guinea, which moved towards the west and near to the Equator. New Guinea was regarded as a part of the Australian mass, and it moved toward the west due to push through the Sima to the northeast.

i) Angola (South Africa) and Loanda (Brazil) have a similarity of beds of Cretaceous and Tertiary beds. Folded lands of various places of Brazil have similarities with the beds of the lower Congo region.

j) Close resemblances between the regions of Uruguay and Minas Gerais both in South America to Kaokoveld, a desert in Northern Namibia-Africa.

k) Ranges north of Bahia Blanca correspond to Cape folded ranges.

l) Du Toit, in his paper, found that the mineral provinces of Africa and South America have many similarities and support that these two countries were very near to each other in the recent past. According to him, these two continents were just away by 400 to 800kms.

m) There are certain pieces of evidences that show that the landmasses of the North Atlantic were joined in the past. Similar evidences have even been found in North Greenland and the occurrence of Pre-Cambrian intrusive rocks in Labrador and near Cape Farewell.

n) Another evidence that supports the existence of Pangea is the presence of fossils and fresh water species on the opposite coasts of the Atlantic Ocean.

o) Labrador and newly found lands were separated from Europe during the Quaternary period and moved along the south-west side of Greenland were left behind as a separate block.

p) The Indian part of Gondwana land moved north against the main land of Asian main continent after separating from Africa. Madagascar was left behind. The Himalayas were created when the Indian part of Gondwana land pressed against the Asian mainland.

q) The evidence from the sea floor spreading even show that the landmasses are moving. Example: Greenland is moving towards the west at the rate of 20cm/year.

r) The traces of Glossopieris flora (Late carboniferous glaciations) was found in India, South America, Falkland Islands, Antarctica, and Australia, which provides evidence that Pangea did exist.

s) The small-sized animals (Lemmings) in the northern part of Scandinavia have a tendency to move westward. This proves that in the past, these animals migrated towards the west when the landmasses were joined together.

3.5. Criticism

Wegner has explained his theory on the basis of a number of evidences. Wegner presented his theory as an advocate rather than as a scientist. He gave more importance to the evidences which supported his theory and ignored which were against his theory. But certain evidences were inadequate and criticized by several scholars.

3.5.1. The most important criticism of his theory is that of the forces which were responsible for the drifting of continents towards the west. According to Wegner, the tidal forces of the moon and sun were responsible for the drifting of continents. But if this force was large enough to cause the drift of continents, then it should have stopped the rotation of Earth.

3.5.2. Wegner has stated that the gravitational attraction of the Earth's equatorial bulge was responsible for the movement of landmasses towards the equator or flight from poles. But a force million times of this force is required to make the continents drift.

3.5.3. Wegner failed to give concrete evidence on which type of force was responsible for the drifting of continents.

3.5.4. The jig-saw fit (Atlantic coast) suggested by him is hardly perfect and cannot be expected to be real due to erosion along the geological period.

3.5.5. If Sial was not floating over Sima, then Sima could not offer much resistance to the westward movement of the continents to cause folds and mountain systems (the Rockies and Andes mountain system). Holmes pointed out this; it is possible for the coastal sedimentary deposits to be raised into mountains and ocean floor to bend for trenches.

3.5.6. Wegner has identified those structural and stratigraphical similarities between the two coasts of the Atlantic shows that the two landmasses were joined together. It was unnatural that in the course of drifting, the Sial became thin, and it broke into fragments. It has been seen in the Islands of West Indies and groups of Islands found between South America and Antarctica.

3.5.7 Du Toit, a South African geologist, believed that two existed during the Paleozoic time. Before Alpine-Himalayan orogeny, these two landmasses (Laurasia and Gondwanaland) were separated by the Tethys Sea.

3.5.8 The delta Niger River along the west coast of Africa is a problem in joining of Africa and South American continents. It separates these two continents by about 200km. At least 50 million years are required for the development of this delta.

3.5.9 R.T.Chamberlin noticed that the petrographic analysis of the rocks on either side of the Atlantic shows that the similarity is not found on a greater scale.

3.6. New Evidences:

After 1950, new evidence have supported the movements of continents. The important new evidences are;

(i) Computer Estimates.
(ii) Geological similarities between the southern continents.
(iii) Palaeomagnetic studies.
(iv) Sea-floor spreading.

3.6.1 Computer Estimates: In 1958, S.W.Carey, with his simple experiment, showed that fit of South Atlantic coasts is not accidental. E.C.Bulland, Everelt, and Smith have shown that African and South American coasts can be fitted into each other at a depth of 1000m (500 Fathoms). With the help of the computer, they also identified the similarity between the North Atlantic coasts of Europe and the North America coasts. In the same way, W.P.Sproll and R.S.Dietz in 1969 prepared a computer fit of Australia and Antarctica continents. A.G.Smith and A. Hallam in the 1970s have prepared a computer fit of Africa, South America, Arabia, Australia, and Antarctica along 500-fathom depths. This map resembles the map that Du Toit made in 1937.

3.6.2 Wegner and Du Toit have believed that Africa and South America had joined together. By using radiometric dating, one can observe that the age of rocks in eastern South America and western Africa are the same and they even have the same structure. In 1967, P.M.Hurley and his associates had found the similarity in the geological age of western Africa and eastern Brazil. The age of rocks on the western parts of Africa was about 2000 million years, whereas the age of rocks on the eastern parts was about 550 million years. The age of rocks in Brazil resembles the age of rocks in western Africa. The line dividing these two age provinces has been found in Brazil. Based on this evidence, we can conclude that these two continents were once joined 500 million years ago and they separated by the year 200 to 50 million years ago. (Lower Cretaceous period).

Glacial deposits of the Pre-carboniferous period (350-250 million years) are found in Brazil and western parts of Africa, and this extends from the equator to South Africa. These widely extended deposits are known as **Dwykaseries.** Recent studies show that these deposits were found in South-West Africa, but extensive investigations have resulted in unearthing evidence of these glacial deposits from east to west. Hence huge eroded debris was deposited towards the west. Glacial deposits are called Tillites in the Parana basin of eastern Brazil. It is believed that the source of these glaciers was South-West Africa. Evidence shows that erratic blocks of quartzite and cherts are found in Brazil. These types of rocks are found only in South-West Africa, which supports that these two continents were once joined together.

In the early Jurassic period flood of basalt was found in these two continents. Nearly a million square kilometers of the area were covered by basalt were found in the Parana basin of Brazil. Whereas a large number of dykes and sills are found in the Karoo basin of South Africa. A large scale of basalt was found in the Eastern side of Africa.

There are several evidences that Wegner and Du Toit gave to support their theory. Plant and animal fossils like Glossopteris flora are found in sedimentary rocks of Gondwanaland in South Africa, India, Australia, and South America. Kangaroo and Opossums, which keep their babies in their pouches, are found only in Australia and South America. Animals in Indonesia are completely different from those in Australia, even though they are close to each other. This shows that Australia and South America were once joined and then separated over the course of time.

Fossils of a small reptile, 'Mesosaurus', can be found in Brazil and South Africa. It was highly impossible for a small reptile to cross the Atlantic Ocean. Edwin Colbert and others in 1969 found reptile fossils of the Triassic period in Antarctica. It originally lived in swamps and lakes in several parts of the world, and it cannot cross the oceans to reach freezing Antarctica. This strongly supports the notion that continents did drift. After the Mesozoic era, we can find great resemblance in fauna all over the world.

3.6.3 Paleomagnetism: The strongest evidence in support of continental drift theory was from the paleomagnetic study. Paleomagnetism is the study of Earth's magnetic field and its changes over geological time. The Earth acts as a giant magnet, and its magnetic field is believed to be due to convection currents of molten iron and nickel in its core. Certain rocks like Magnetite (Fe_3O_4), Haematite (Fe_2O_3), etc., record the magnetic field of Earth. During the sedimentation process, grains of magnetic minerals settle with other grains according to the prevailing magnetic field. This magnetic field remained in sediments even when they were transformed into rocks. The magnetism of these old rocks can be measured to determine the strength and direction of the Earth's magnetic field in the past. This is known as **Paleo** or **Remnant** or **Fossil magnetism**. When magma cools, the paramagnetic minerals get magnetized and align themselves in the direction of the Earth's magnetism. Thus, when magma cools, it preserves the Earth's magnetism. This is known as Thermo-Remnant Magnetism (TRM).

In 1965, Creer calculated the positions of the paleomagnetic poles of various geological periods by using paleomagnetic data. He found that South America and Africa were joined in the past across the South Pole during the Palaeozoic era. He found that during the Ordovician period, poles were so widespread that it would not consider the existence of Pangea at that time. From the lower Carboniferous to Jurassic period, the poles came closer together, indicating the existence of Pangea. But in the Cretaceous period, the poles were wide apart, indicating the drift of continents. Thus, various paleomagnetic studies support continental drift theory.

3.6.4 Sea-floor spreading: Hess in 1962 stated that the seafloor of the Atlantic Ocean was spreading. In his hypothesis, he states that the major result of seafloor spreading was the formation of the Atlantic and the Indian oceans. According to him, these oceans were the combined result of rifting and spreading away of sea-floors from submarine ridges. His views were also supported by paleomagnetic studies of the mid-Atlantic Ocean.

Thus, all these evidences strongly support Alfred Wegner's Continental Drift theory and lays a strong foundation for the development of other theories regarding the movement of continents.

3.7. Plate Tectonics:

3.7.1 Introduction: We all know that the Earth is the most dynamic planet in our solar system. The positions of continents and oceans remain the same throughout geological time. The theory of plate tectonics was put forth after Continental Drift Theory by Alfred Wegner. The Plate Tectonic Theory is a more complex and comprehensive section of sea-floor spreading. During the 1960s Theory of Plate tectonics became a major scientific development in Geology, Geophysics, and Geomorphology. This theory is based on continental drift and sea-floor spreading. This theory provides an explanation for a variety of tectonic features like an evolution of fold mountains belts, mid-oceanic ridges, physiography of ocean basins, earthquakes, volcanic activity, movement of continents, formation of new oceans and rocks, the evolution of mountains, etc..

The focal theme of this theory is that the uppermost rigid and cold layer of the Earth's crust- The lithosphere is made of distinctive tectonic plates. **'A Plate is a large rigid slab of rock which moves or slides over the fluid (Plastic) Asthenosphere'.**The process of plate motion and resultant deformation is called plate tectonics. Plate tectonics is a combination of two different words- plate and tectonics. The term 'plate' was first used by J.Tuzo Wilson, a Canadian Geophysicist, in the year 1965, and the term 'tectonics' is of Greek word 'Tectone' meaning the study of movement or activity. D.P.Mackenzie of Cambridge and Parker from America have discussed in detail about the mechanism of plate motions in the year 1967. They postulated a 'Paving stone hypothesis. In 1967, W.J.Morgan of Princeton University and Le Pichon elaborated on the various aspects of plate tectonics. Wilson, Mackenzie, Parker, and Le Pichon have published their findings and laid the foundation for ***'New Global Tectonics'***. After some time, the study of plate tectonics gained momentum. The influence of this theory has done on Geology can be compared to the effect of Darwin's Theory of Evolution on Biology.

3.7.2. Characteristics of Lithosphere: The outer part of the Earth is called Lithosphere. It is consists of three layers;

- Upper crust with an average depth of 25km.
- Lower crust with an average depth of 10km.
- Upper mantle with an average depth of 65km and with a density of about 2.7 to 3.0g/cc.

The average total depth of the Lithosphere is 100km. It is hard and brittle in nature and is mainly made of granite and basalt rocks. It also consists of Silica, Aluminium, Magnesium, Garnic, Olivineand, and Piroxes.

3.7.3. Characteristics of Asthenosphere: It lies below the Lithosphere. The average thickness of the Asthenosphere is about 250km. It mainly consists of the lower mantle, which is a weak and low-velocity zone. The average density of this layer is about 3.4g/cc, and 15% of this is partially liquid. The asthenosphere has many radioactive elements like Uranium, Radium, Thorium, etc... It forms the base for the movement of Lithospheric plates.

The size and shape of these plates vary with their size. Their thickness varies between 100 to 150km. Plates are in constant horizontal motion; their margins are the sites of dynamic activities like – seismic activity, deformation, and magmatism. The plates are of continental dimensions.

3.7.4. Division of plates: Morgan has considered that the mid-oceanic ridges form the boundary between two plates that are moving relative to one another. Not all plate boundaries are well defined. The plate boundaries between North and South America, North America and Eurasia, and Indian and Australian plates are not well defined. Morgan divided the Earth's crust into 20 plates. Le Pichon (1968) has simplified the concept of plate tectonics and divided the Earth into Six major plates and Six smaller plates based on spreading rates calculated from magnetic anomalies.

3.7.5. Types of Plate: There are several views regarding the number of Lithospheric plates. Dietz and Holden have divided the whole Lithosphere into ten plates. W.J.Morgan has classified the Lithosphere into 20 plates. Le Pichon has divided the Lithosphere into six major plates, and they are as follows;

1. The Pacific Plate.
2. The American Plate.
3. The African plate.
4. Eurasian Plate.
5. Australian Plate.
6. The Antarctic Plate.

3.7.6. Six Minor Plates are as follows;

1. Arabian Plate.
2. Philippines Plate.
3. Cocos Plate
4. Caribbean Plate
5. Nasca Plate or East Pacific Plate
6. Scotia Plate.

Most of the plates consist of both continental and oceanic crust. All the plates are in continuous motion and are sliding over the partially fluid Asthenosphere. They also slide with respect to the axis of rotation of Earth. Sometimes these plates crash each other, pull each other apart, or sideswipe each other.

Pacific Plate: It covers most of the Pacific Ocean basin. It is moving in the northwest direction. Its northern and western edges have a converging boundary. It has many boundary segments and triple junctions. The famous and most active transform fault, 'San Andreas fault,' is found under this plate.

American Plate: It covers most of the continental Lithosphere of South and North America and the entire oceanic lithosphere of the Atlantic Ocean. It is moving from east to west in a direction.

The African Plate: It covers the entire African continent and oceanic lithosphere. It occupies the eastern portion of mid-Atlantic Ridge, the North-Western part of the South-Western

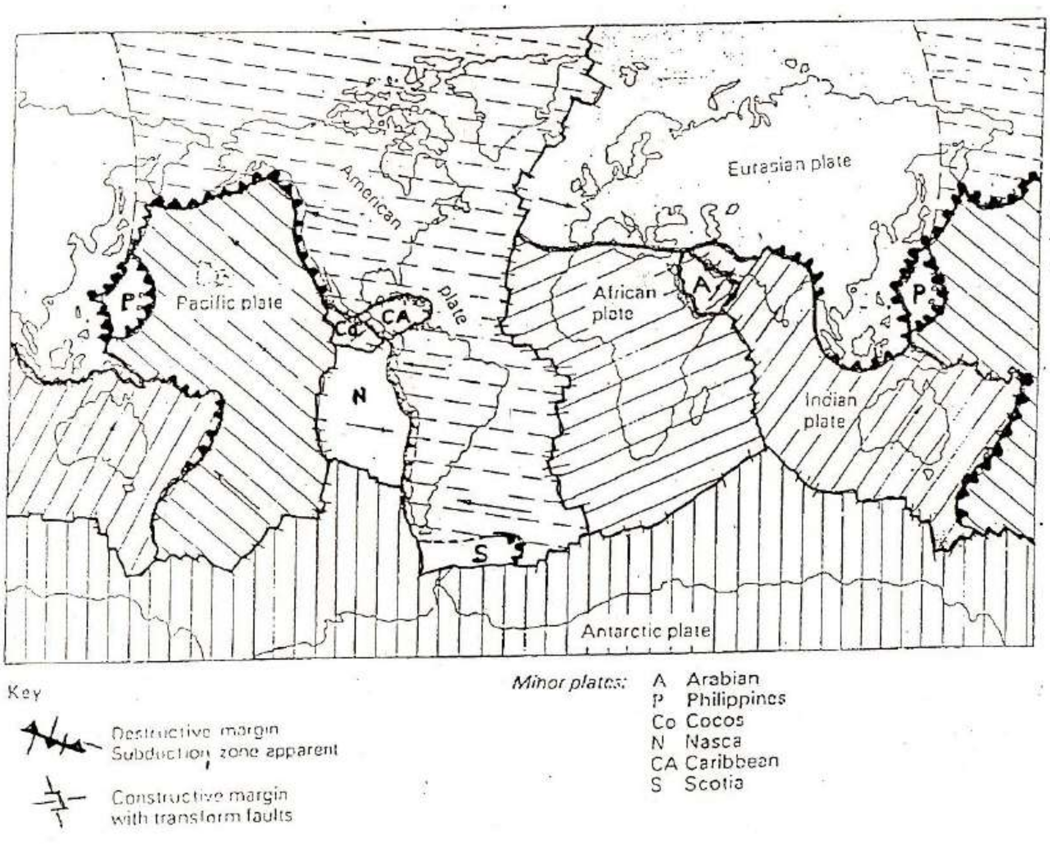
Indian ocean ridge. It is moving from South-West to the North-East direction. It consists of five boundary segments and triple junctions.

Eurasian Plate: It is mostly continental Lithosphere and surrounded by oceanic lithosphere. It is moving from North-East to South-West direction. It has seven boundary segments.

Australian Plate: This is in the form of an elongated rectangle. It is mostly of oceanic lithosphere but also covers Indian and Australian Continental lithosphere. Its movement from southwest to northeast with its five boundary segments and triple junctions are its major features.

Antarctic Plate: It is elliptical in shape and covers the Antarctic continental lithosphere and is surrounded by the Antarctic Ocean lithosphere.

Figure :3.1



Apart from these major plates, there are some minor plates, and they are;

Nasca Plate: It lies towards the South American plate. It has four segments and triple junctions and covers the entire oceanic lithosphere.

Cocos Plate: It lies to the south of Central American countries. It occupies mostly oceanic lithosphere with few triple junctions and boundary segments.

Philippine Plate: It is found in the South-Eastern part of the Eurasian Plate. It consists of two triple junctions and boundary segments.

Caribbean Plate: It lies in the northern part of South America. It consists of two triple junctions and boundary segments.

Arabian Plate: It covers most of Saudi Arabia and adjacent countries. It has four boundary segments and a triple junction.

Scotia Plate: It covers the elongated area of the southern part of South America. It has two boundary segments and triple junctions.

3.8. Triple Junctions and Plate Boundary or Margins:

The meeting point of three plate margins is called **'Triple Junction'.** Each plate margin is the place where two tectonic plates meets together. So plate margin is the marginal part of a particular plate. Two plate margins meet at a common plate boundary. The plate boundaries are associated with various geological events like Earthquakes, Volcanoes, Mid-Oceanic ridges, Oceanic trenches, and others. Most of the active volcanoes of the world are found along plate boundaries.

Plates are moving or floating over the Asthenosphere. Sometimes they crash each other; they pull apart or slide beside one another. Different names are given to plate boundaries depending on how the two plates are moving relative to each other. Depending on the nature of plate boundaries or margins are identified as;

1. Divergent Plate boundary/margin.
2. Convergent plate boundary/margin.
3. Transform plate boundary/margin.

3.8.1. Divergent plate boundary/margin:

When two adjacent plate boundaries move apart in opposite directions, it is called Divergent plate boundary/margin. These are also called Constructive or Accreting plate boundaries. When two plates move away from each other, a fissure develops, making way for hot molten magma to come out and form new oceanic crusts. These plate boundaries do not show uniform spreading. Divergence is most common in mid-oceanic ridges. The Lithospheric plates diverge at the crest of the mid-oceanic ridges.

Continental fracture/crack/rupturing will also take place due to this process. In the beginning stage, very hot mantle rock begins to rise from deep beneath continental plate in fracture, and this causes elevation of continents. This hot mantle rock is known as a mantle plume. Due to the upliftment of the blocks, a rift valley and Graben are formed.

3.8.2. Convergent plate boundary/margin:

This theory assumes that the same amount of material should be destructed in some other place as the same amount of material added along with the spreading centers. This is a must to maintain constancy in the volume of the Earth. This type of distribution takes place where plates converge, and hence this is called Convergent/destructive plate margin. These are also known as leading edges of floating or moving plates. The plates come together or converge in three situations. They are;

- Two plates of oceanic crust moving towards each other. This implies ocean–ocean convergence.
- One plate is having an oceanic crust, and another is the continental crust, and they meet together, i.e., oceanic - continental convergence.
- Two plates of continental crust floating towards each other, i.e., continental – continental convergence.

When ocean–ocean convergence takes place, one plate bends down, and another overrides it. This is known as ***Subduction***. In this subduction zone, ocean trenches are formed.

When plate subduction takes place between the oceanic and continental plates, the oceanic plate goes down, and lighter continental plates override. This causes the formation of Island Arcs at seas. Example: - Japanese Islands.

When the oceanic plate converges with the continental plate, the oceanic plate sinks under the continental plate, and magma rises from the subduction zone (Benioff Zone) forms a volcanic arc within the continental arc. The frontal part of the plate, which does not submerge or sink, is forced to break up into smaller plates, which overrides one another to form a heap like a mountain. This process is known as 'Plate Obduction.'

When continent-continent plates converge, it is known as a continental collision. Here two continental plates move towards each other. In the beginning, between these two continental plates, an oceanic floor existed. When two continental plates move closer to each other, the oceanic floor starts to subduct under one continent. When the ocean basin starts to disappear, the sediments accumulated in the ocean basin have been squeezed into folded mountains like the Himalayas. The zone of collision is known as the 'Suture Zone.' It means that these two plates get stitched together. The collision of the Asiatic and Indian plates, European-African plates, leads to the formation of Himalayan and Alpine mountain chains.

3.8.3. Conservative/Transform/Shear/Parallel Plate boundary or margins:

Here, the crust is either created or destroyed along the margins of the plates, and hence, these are known as conservative plate margins. Two adjacent plates slide along a transform fault or group of parallel faults. San Andreas Fault in California, USA, is the best example for Transform Plate Margins. Transform plate boundaries act as a link between constructive and destructive plate margins by transforming one type of plate motion to other. There are three types of Transform plate boundaries. They are;

i. Ridge – Trench Transform margin.
ii. Ridge – Ridge Transform margin.
iii. Trench – trench Transform margin.

3.9. Causes of Plate Movements:

Plates are like boats floating over semi-liquid Asthenosphere. They move both in the horizontal and vertical directions. It is believed that the main cause for the movement of plates is internal energy. It is also believed that a number of forces also influence the movement of Lithospheric plates. Few examples of these forces are;

i. Radioactivity
ii. Heat flow
iii. Viscosity of the Earth's interior
iv. Seismic Activity
v. Triple junction
vi. Convection currents
vii. Hotspots and Mantle plumes.

The radioactive substances within the earth produce heat on radioactive disintegration, and this heat melts the rocks. Below this, we can find the Asthenosphere. Convectional currents produced due to the movement of rocks liquefied by the heat produced by radioactivity cause the displacement of plates both vertically and horizontally. The intrusion of magma will push the plates away from the mid-ocean ridges. These mid-oceanic ridges are higher than the surrounding ocean floor, and potential energy starts to slip or side towards trenches due to gravitation. So, these two forces ridge push force are responsible for the movement of plates. At the same time, the gravitational force is also responsible for sliding the plate downwards to the trench.

The colder and denser plate compared to the surrounding hotter and lighter mantle makes the denser plate pushed downwards in the mantle. In this process, it loses its negative buoyancy and experiences a slab-resistance force. Scientists also believe that high temperatures can create thermal plumes. It moves vertically from the inner core towards the Asthenosphere, and when it reaches the bottom of the crust, it further increases the temperature and further speeds up convectional currents.

Earthquakes and volcanic activities also provide pieces of evidence of the movement of plates. Most of the active volcanoes and epicenters of earthquakes lie over the plate margins. These plate margins cause endogenetic activities like earthquakes, volcanoes, sea-floor spreading, faulting, marine trenches, and rift valleys. Differential Global Positioning System (DGPS) instrument is used to record the direction of the plate movements. This advanced instrument tells us that minor plates are moving lesser than the major plates. They are moving 0.5 to 16cm per year.

Even today there is a lot of heated debates and research are still going on the forces that influence the movement of plates.

3.10. Significance of Plate Tectonic Theory:

This theory explains a number of mysterious geological phenomena like;

(i) Origin and Distribution of Mountain Ranges.
(ii) Origin and Distribution of Volcanoes and Earthquakes.
(iii) Movement/Drift of Continents.
(iv) Formation of islands arcs, trenches mid-oceanic ridges, rift valleys, sea-floor spreading, etc.

3.11. Critics:

Eventhough there is wide acceptance for this theory, several scholars have raised questions about certain aspects of this theory. A few of these arguments are;

(i) Evidence supporting thermal convection in the lower mantle are not strong, and there are many
problems in it.

(ii) Pushing down-solid plates into the mantle is not adequately explained.

(iii) The presence of pre-Cambrian and Cambrian rocks near the crest of the mid- Atlantic ridges contradicts the theory of plate tectonics.

(iv) The duration for the creation of a new crust is greater than its rate of destruction. This means that in some places, plates move faster and slower in some places. This theory does not give any information regarding this fact.

(v) It is unable to explain why subduction is limited to the pacific coast while spreading is found in all the oceans.

(vi) The juxta fit position of plates and its movements are contradictory.

(vii) The thickness of the plates and the depth of the rift have been questioned.

3.12. Let Us Sum Up

The theory of plate tectonics is based on the continental drift theory by Alfred Wegner. Plate Tectonic theory has been accepted as a fundamental theory explaining and correlating major features of the Earth. It has satisfactorily explained the distribution pattern of earthquakes and volcanoes. This theory has thrown light on the drifting of continents, sea-floor spreading, and other geological events. There is no doubt that this theory is a path-breaking one and has changed one's view on geology and geomorphology.

3.13. Key Words

Pangaea: In the Carboniferous period, there existed a single landmass called 'Pangaea.'

Panthalassa: Pangaea was surrounded by a huge water body called 'Panthalassa.'

Gondwanaland: In the Permian period (225 million years ago), the Pangaea split into two landmasses; one is Laurasia, another one is Gondwanaland.

Magmatism: It is the location of magma within and at the surface of the outer layers of magma that solidifies and forms igneous rocks.

Plate boundary: The location where two plates meet is called a Plate Boundary.

Plate Subduction: It is a process where one Lithospheric plate is pushed below another into the Asthenosphere.

Plate Obduction: It is a process; if one plate does not subduct, it is forced to break up into smaller plate-lets that ride over another to form a mountain-like heap.

Triple Junctions: The meeting point of three plate margins.

Suture Zone: The zone of the plate's collision is known as the Suture zone. Here two plates stitched together.

Thermal Plume: It is generated by gas rising above the heat source. The gas rises because thermal expansion makes warm gas less dense than the surrounding cooler gas.

3.14. Questions for Self study

1. Discuss the main evidence in support of the theory of Continental Drift.
2. Explain the main criticisms of Wegener's theory of Continental Drift.
3. Explain the Continental drift theory of Alfred Wegener.
4. List out the world's major and minor plates.
5. Explain Plate tectonic theory.
6. Explain the types of Plate boundaries.
7. Discuss the causes of Plate movements.
8. Briefly explain the criticisms of Plate tectonic theory.

3.15. Further Readings

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UNIT - 4

ISOSTASY

Structure

4.0. Objectives

This unit gives you a bird eye view regarding the concept of Isostasy, its development and various views of different scholars. After studying this unit, you will able to

- Understand the principle behind the concept of Isostasy
- Examine the development of the concept of Isostasy
- Analyse the logic behind the views of different scholars
- Examine the concept of Isostatic adjustments.

4.1. Introduction

The basic fundamental concept for an earth science student is to understand the balance of earth equi-balance. The term Isostasy is derived from two Greek words, 'iso' meaning equal and 'stasis' meaning still. Isostasy refers to a state of balance, a gravitational equilibrium between the Earth's lithosphere and Asthenosphere. In other words, it is the floatation balance of different blocks of the crust overlying a denser mantle. Based on the densities of underlying rocks, it is a state of gravitational equilibrium between continents, ocean floor, mountains, plateaus, and plains on rotational earth. The term isostasy was first used by an American geologist C.E.Dutton in 1889.

4.2. Principle of Floatation

To understand the logic in the theory of Isostasy, let us take a simple example of a small boat. Here boat floats over water as wood (boat) is less dense than water. When a person sits in the boat, the boat just sinks down a few inches. If a person follows the previous person, the boat sinks a bit further. But when a person gets out of the boat, the boat rises a bit, and when a man gets out, the rises even more. What we can infer from this example is that a substance floating on a fluid material it isn't always stationary but constantly moves both horizontally and vertically. This is based on Archimedes's Principle of Floatation. It states that the upward buoyant force experienced by the body which is either fully or partially immersed in the fluid is equal to the amount of fluid it displaces. Buoyancy is an upward force exerted by a fluid that opposes the weight of a partially or fully immersed object. This buoyant force is the reason for a less dense object to float over a much denser liquid.

Similarly, the earth's crust is floating on a semi-liquid layer called Asthenosphere. It is a fact that the earth's crust is not static and is maintaining a balance between high and low-density layers. The earth's crust has been classified as;

1. Continental crust 2. Oceanic crust.

The upper part of the earth's crust is built of lighter rocks that are floating on the sub-stratum of denser rocks.

4.3. Development of Theory of Isostasy

In 1735, Pierre Bouguer's exploration of the Andes mountains surprised him that the deflection of the plumb line towards the mountain was much less than his estimates. He suspected that the gravitational attraction of Andes mountain is smaller as compared to the mass of these mountains.

Similar deviations were observed by Sir George Everest, Surveyor General of India. He was assigned to survey the Indo-Gangetic Plain. He adopted three methods of surveying like Triangulation, Trigonometrical and Astronomical methods to find out Latitudinal values. He took three points for Triangulation—Kaliana in foothills of Himalayas and Kalianpur in Gangetic plains. The difference found between these places through the Astronomical and Triangulation method was 5.236 seconds of arc, which is equal to 108metres or 550 feet on the ground. This variation is due to the attraction of the Himalayas and Tibetian plateau. In the Astronomical method, the deflection of Plumb bob is found at Kaliana, which was close to the Himalayan mountains. But this error doesn't occur in the triangulation method. After further investigation by Everest, he concluded that the error has occurred due to the Himalayan mountains, which are comprised of denser material that has attracted plumb-bob. It led to the development of two concepts, i.e., the crust which is found under the mountains has less dense rocks, and the crust is floating over a high-density mass. It assumes that the huge mass of mountains that is found above the sea level consists of a less dense subsurface structure. This concept suggests that topography is supported by a deep root.

Isostasy assumes that the existence of a level surface of constant pressure within the mantle is known as ***'Depth of Compensation.'***

4.4. The Concept of Sir George Airy

Sir George Biddell Airy, an English mathematician and astronomer, used his own methods of surveying. He used the principle of floatation by Archimedes. Based on this principle, he advocated his Theory of Isostasy. He assumes that equal density material with uneven thickness and uneven depth of submergence.

To prove his theory, he conducted two experiments. He took few ice cubes and submerged them in the glass container having water. They were of different sizes, and they floated unevenly. But they sank nine times their size above the water level. In his second experiment, he took wooden blocks of different sizes with equal density. He put these blocks in a water container, and the wooden blocks floated. The wooden blocks start to float at different heights. The block, which is higher than the other blocks, has also sunk deeper than the other blocks in the water. These blocks are in a state of hydrostatic balance or equilibrium. In a similar example, the landmasses are composed of a similar density of rocks and sink into sub-stratum in proportion to their height.

Figure:4.0

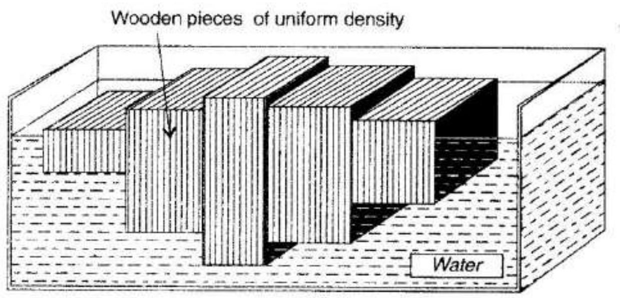


Illustration of the concept of Airey on Isostasy

He assumed that the continents and islands are floating on a denser mass and that excess of matter above the upper surface of the substratum is balanced by deep projections of the lighter material into the substratum. In other words, the sial masses are in hydrostatic equilibrium or balance.

4.5. Views of Airy about the error

1. He suggested that the lighter sial of the Himalayas is floating over the dense material of sima.

So it displaced substratum about nine times of Himalayas found over the surface.

2. This displacement has caused low gravitation in the Himalayan region and less attraction of plumb bob towards the Himalayas has caused an error.
3. The earth's major relief features are balanced by underlying differences of density.
4. All relief features of the earth are in a state of balance between the raised topography and immersed topography in the substratum.
5. The earth's major relief features are balanced by the underlying differences in density.

Demerits:

The views of Airy contain few errors, and the most important of them are as follows;

(i) According to Airy, Himalayas have a root of nine times than the height of mountain but, at that great depth, it would have melted due to high temperature.

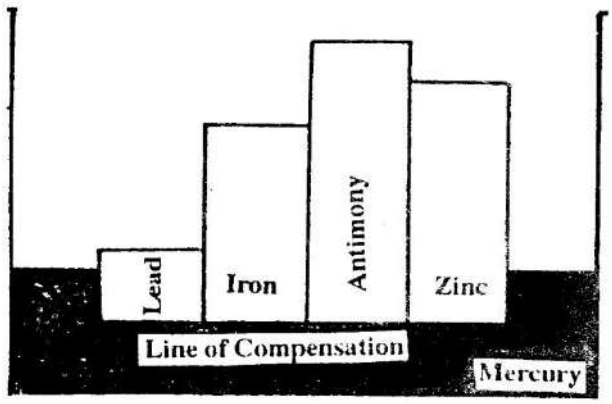
(ii) If the crust is of uniform density, there should be the same types of rocks. Actually, the Earth's crust is consisting of different types of rocks.

4.6. Concept of Archdeacon Pratt

Archdeacon Pratt, while studying the difference of gravitational deflection between Kaliana and Kalianpur, was 5.236 seconds during the geodetic survey. After taking the average density of Himalaya as 2.75, he calculated the gravitational force of Himalaya and came to the conclusion that the difference was 15.885 seconds. He found that the deflection was three times more than the observed deflection of 5.236 seconds. Then he studied the rocks of the Himalayas, the plain and plateau region, where he found that the density of mountains is lesser than the density of plateau and the density of plateau is lower than the plain. Then the density of the plain is lesser than the ocean floor. It means that there is an inverse relationship between height and density. Higher the height, lower the density, and vice-versa.

According to him, the gravitational attraction of the Himalayas was less than the mass of it because the Himalayas are made of rocks that have less density. He believed in the law of compensation. In his opinion, there is a level of compensation above which there is a difference of height of columns due to variation of density. But there is no change in density below this level. He suggested **'uniform depth with varying density.**

Figure-4.1



Uniform depth with varying density

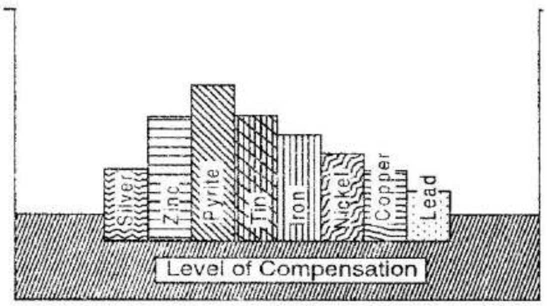
To prove his hypothesis, he took several materials with different densities and with the same weight. Zinc, Iron, Lead, and Platinum were immersed in a container filled with mercury. All the metallic blocks sink at equal depth but float at different heights. The density of mercury is about 13.534g/cc, and the density of other metals is less than mercury (Lead 11.34 g/cc, Iron 7.874 g/cc, Antimony 6.697 g/cc, and Zinc 7.14 g/cc). According to him, different relief features mass is equal along the line of compensation due to their varying densities. The relative density of mountains, plateau, and plains are not the same because a denser block covers lesser volume and a less dense block covers greater volume.

His theory has been criticized. Bowie criticized that Pratt does not believe in the law of floatation. He did not believe directly in root formation.

4.7. Concept of Hayford and Bowie

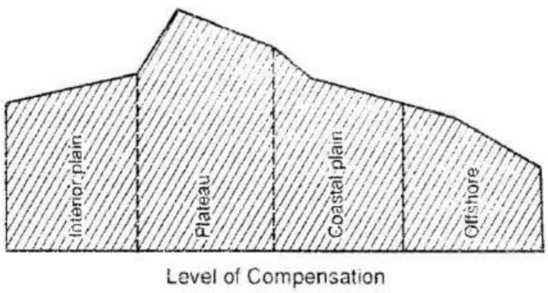
Hayford and Bowie are two American surveyors. They showed the relationship between gravity with isostasy and topography. In their experiment they took eight metallic columns of Silver(Ag 10.49 g/cc), Zinc(Zn 7.14 g/cc), Pyrite($FeS_2$5g/cc), Antimony(Sb 6.68 g/cc), Iron(Fe 7.84 g/cc), Tin(Sn 7.2 to 7.5 g/cc), Copper(Cu 8.8 g/cc) and Lead(Pb 11.34 g/cc) are all submerged in a container.

Figure:4.2



All eight metallic columns were submerged in mercury with the same depth. This equal depth is known as the Isopiestic level or level of compensation. It shows that, with different densities of landforms, their base level remains equal or the same. They are supported by Sima which is denser and heavier than all others. This diagram (4.2) shows that the columns of low density were found higher than the high density of columns. Similarly, low-density regions stand higher than high-density regions. According to Bowie and Hayford, the level of compensation is found at a depth of 100km. The earth's crust consists of varying density material. They found that the raised relief features are balanced by the denser material, and the earth's crust is compensated by its size. The concept of Hayford and Bowie is close to the arguments of Pratt but, Joly has criticized the concept of these and supported the views of Airy.

Figure:4.3



4.8. Vening Meinesz Theory of Isostasy:

Venning's concept is based on the idea of regional isostatic compensation. By careful observation and study on the relationship between topography and gravity anomalies over prominent relief features like deep-sea trenches and Island Arcs in South-East Asia, he concluded that isostatic compensation is not always a local phenomenon. He assumed that an upper elastic layer is overlying on a week layer. The strength of the overlying layer of any relief feature is distributed over a wide horizontal distance than the feature itself. The topography load bends the upper layer downwards into the fluid substratum, which is pushed aside. The fluid in this layer is forced upwards due to the lifting effect(buoyancy).

4.9. Theory of Joly

Joly presented his theory on isostasy in the year 1925. He objected to the view of Hayford and Bowie about the existence of a level of compensation at a depth of about 100km. At this depth, the materials are in a liquid state where the level of compensation is not possible. He also criticized the view that density varies above the level of compensation. According to him, in this situation, geological events will disturb the level of compensation. He identities that below 16km (10 miles) thickness of uniform density, it (density) will not remain the same in this layer. He assumes that the level of compensation is a zonal phenomenon. He believed in the zone of compensation but not in the line of compensation. His views support the concept of Airy.

4.10. Concept of Holmes:

He assumes that the elevated crustal parts are lighter materials with low density. They are deeply rooted because of lighter materials below these. Arthur Holmes and D.L.Holmes have considered 50km depth as isostatic compensation, because at this depth, geological events will not disturb for a longer time. They made an attempt to explain the concept of equal weight along with the level of compensation. They try to explain the idea of equal weight along with the level of equal pressure with an example of a plateau of 4km height plateau of 1km height, plain at sea level, and ocean plain at 5km depth. The weight of all these along the level of equal pressure is almost heaven to each other. They explain the relationships between surface features and crustal structures.

4.11. Isostatic Adjustment

When agents of denudation erode the landforms, the weights of the crust below these landforms were reduced. Eroded materials were deposited at sea-floor and delta, leading to more pressure. Due to this pressure difference in the mantle, there is a sub-crustal flow of sima under high area towards the low-pressure area. Hence high-pressure area sinks, and low pressures region rises. This process is known as isostatic adjustment or re-adjustment. Sometimes this isostatic balance is distributed. During the Pleistocene Ice age, large areas of Europe and North America were covered by a thick layer of ice which leads to more loads (pressure) on the crust. Hence large area was depressed during this period. When the ice sheets were melted, the load will be reduced, and the land started to rise, and it is still continuing. Example: Raised beaches of Finland and Scandinavia show an uplift of 250 meters. This process is continuing in this region.

4.12. Let us sum up

It is clear that the mountains are less dense than plains, and plains are less dense than the sea crust. In other words, the raised features like mountains, plateau, and plains are balanced. The above hypothesis states that the crust is floating and they are not static. They are moving vertically and horizontally like a boat. The crust is in a state of balance. This theory is important in geology which explains the vertical movement of the earth's crust. Due to the dynamism of the earth, the surface is changing. The deformation and tectonic activity are present as a natural phenomenon due to the flotation principle.

4.13. Key Words

Asthenosphere: It is a semi-liquid layer mainly composed of silicon and magnesium. In the upper most zones, the density of this layer is about three g/cc, and in the bottom, it varies from 4 to 5 g/cc.

Equilibrium: A state of balance, especially between forces or influences that are working in opposite ways.

Principle of Flotation: When a body floats in a liquid, the weight of the liquid displaced by its immersed part is equal to the total weight of the body.

Depth of Compensation: A mass above sea level is supported below sea level, and there is a certain depth at which the total weight per unit area is equal all around the Earth.

Plumb bob: A **plumb bob**, or plummet, is a weight, usually with a pointed tip on the bottom, suspended from a string and used as a vertical reference line or **plumb line**.

4.14. Questions for self-study

1. Explain the development of Isostasy as a concept in the field of Earth Science.
2. Discuss the surveying of George Everest and its results.
3. Discuss Pratt's view of Isostasy and on what basis he arrives at a conclusion?
4. Explain Airy's view on Isostasy.
5. Explain Hayford and Bowies Gravitational anomaly in the field of Isostasy.

4.15. Further Readings

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