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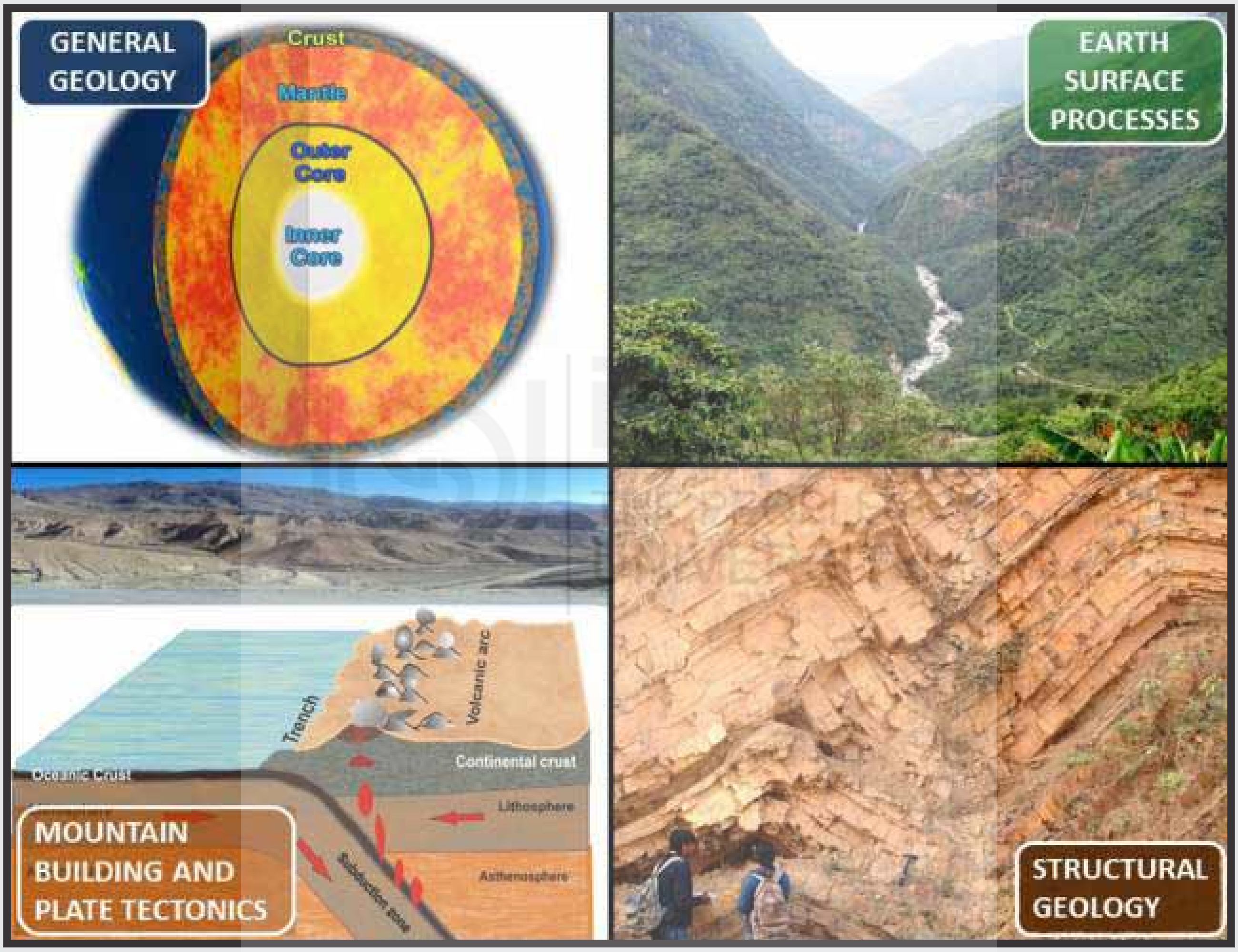
BGYCT – 131
PHYSICAL AND STRUCTURAL GEOLOGY



Mountain Building and Plate Tectonics 4

“शिक्षा मानव को बन्धनों से मुक्त करती है और आज के युग में तो यह लोकतंत्र की भावना का आधार भी है। जन्म तथा अन्य कारणों से उत्पन्न जाति एवं वर्गगत विषमताओं को दूर करते हुए मनुष्य को इन सबसे ऊपर उठाती है।”

– इन्दिरा गांधी

“Education is a liberating force, and in our age it is also a democratising force, cutting across the barriers of caste and class, smoothing out inequalities imposed by birth and other circumstances.”

- Indira Gandhi

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BGYCT-131
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Block

4

MOUNTAIN BUILDING AND PLATE TECTONICS

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BGYCT-131: PHYSICAL AND STRUCTURAL GEOLOGY

List of audio / video materials related to this course

1. Earth System Science and Society -Part 1
   Link: https://www.youtube.com/watch?v=dVbjNn0ZHRg

2. Earth System Science and Society- Part 2
   Link : https://www.youtube.com/watch?v=0GMPIOrCdcE

3. Geoinformatics: An Introduction
   Link: https://youtu.be/vu7f5aFoox0

4. Applications of Geoinformatics
   Link: https://youtu.be/tfSDp2TO-Eg

5. Weathering, its types and Significance
   Link: https://www.youtube.com/watch?v=gBYijIPPVgc

6. Soil: Product of Weathering
   Link: https://www.youtube.com/watch?v=y-SENU4Abv8

7. Landslides: Its types and causes
   Link: https://youtu.be/cI73TU0hjQk

8. Landslides: Mitigation measures
   Link: https://www.youtu.be/BcUVeL43x7c

9. Deccan Volcanism-an Inside Story
   Link: https://www.youtube.com/watch?v=1a3glcg0oGs

10. Himalaya-an Overview
    Link: https://www.youtube.com/watch?v=vK5Cglisa1Y

11. Evolution of Himalaya
    Link: https://www.youtube.com/watch?v=gVGZKqrjVZY

Development of audio/video programmes is a continuous process. For recent materials pertaining to the course you may visit Youtube page of the School of Sciences, IGNOU.

Alternatively, you can visit eGyankosh website of IGNOU.
Link : http://egyankosh.ac.in/handle/123456789/36575

BLOCK 4: MOUNTAIN BUILDING AND PLATE TECTONICS

Mountains are the easily recognisable common features of the Earth. They have always been a source of inspiration to mankind. Man has always strived to overpower the mystic and mystery of mountains. The magnificent and majestic mountains observed world over are Fold Mountains, e.g. the Himalaya, Alps, Andes, Rocky Mountains. In fact, it was the inquisitiveness for the origin of Fold Mountains that gave birth to a dominant idea that the same forces that folded the rocks also formed the mountains. Over the past two centuries many theories of mountain building and orogeny have been proposed. The geosynclinal theory gained popularity, though it had many limitations. Developed from the 1950s through the 1970s, plate tectonics is the modern version of continental drift, a hypothesis first proposed by Alfred Wegener. Sea floor spreading hypothesis was very influential in setting the stage for the emerging plate tectonics theory. Orogeny or the process of mountain building occurs when two tectonic plates collide – either forcing material upwards to form mountain belts such as the Himalayas or the Alps or causing one plate to be subducted below the other, resulting in volcanic mountain chains such as the Andes. Plate tectonics is the subject matter of discussion in Earth sciences that attracts a good deal of interest and is very often featured in popular science programmes on TV and radio. This block comprises three units, wherein you will be acquainted to the basic concepts of mountain building, orogeny theories of mountain building with special emphasis to plate tectonics.

Unit 14 introduces the fundamentals of mountains, their importance and mountain building. This unit elaborates on the classification based on their location, age of orogeny and mode of origin. In addition, the unit also discusses evidences of orogenic processes.

Unit 15 deals with the theory of continental drift, its supporting evidences and historical development. This unit also elaborates on the forces responsible for drifting of continents and explains it with supporting evidences in favour of sea floor spreading. This unit also summarises historical perspectives on the theories related to mountain building.

In **Unit 16,** we will learn about the principles of plate tectonics and types of lithospheric plates and plate boundaries. We will identify and discuss the driving forces for plate motion. Finally, this would help us to integrate plate tectonics with continental drift, sea floor spreading and mountain building. We will also try to learn the evolution of Himalaya in the light of plate tectonics theory.

Expected Learning Outcomes

After studying this block, you should be able to:

- provide elementary idea of mountain building and classify mountains;
- discuss the concept and evidence of orogenic processes.
- enumerate the theory and evidences of continental drift;
- explain the hypothesis and evidences for sea floor spreading;
- summarise historical perspectives on the theories of mountain building;
- elaborate the principles of plate tectonics;
- illustrate types of lithospheric plates, plate boundary and plate margin;
- evaluate the causes or driving forces for plate motion;
- discuss evolution of Himalaya in the lifht of plate tectonics theory; and
- integrate the theory of plate tectonics with continental drift, sea floor spreading and mountain building.

We hope that after studying this block you will acquire basic knowledge of mountain building processes, orogeny, continental drift, seafloor spreading and plate tectonics.

Wishing you success in this endeavour!!

UNIT 14

MOUNTAIN BUILDING AND OROGENIC PROCESSES

Structure

14.1 INTRODUCTION

While witnessing the beauty of rivers, seas, oceans, hills and mountains, we may often think that these landforms are there since the birth of our planet Earth. The frequent occurrences of disasters like earthquakes and volcanoes force us to think that Earth was not the same as it is now. Let us recognise that the Earth is undergoing constant changes and is being remodelled by various geological processes, which can be exogenic and/or endogenic. The changes-small or large, continuous or sporadic, or gradual or catastrophic are one of the most exciting things in geology because in many cases they are observable. Some of these changes may take thousands or millions of years like mountain building processes. In this unit, we will introduce the various processes of mountain building.

Expected Learning Outcomes

After studying this unit, you should be able to:

- ❖ classify mountains;
- ❖ list forms of mountains and their importance;
- ❖ describe mountain building processes; and
- ❖ discuss evidences of orogenic processes.

14.2 CLASSIFICATION OF MOUNTAINS

We all have seen mountains or hills. Some of us might be having our houses in mountainous terrain. **Mountain** is a large terrain feature that rises abruptly from the surrounding levels. When there is a group of closely spaced mountains or parallel ridges we call it a mountain range. You might be aware that the mountain is often the source of major river systems influencing the regional and global climatic conditions of the world. Let us consider some examples of Indian rivers like Ganga, Yamuna, Indus, Brahmaputra, Kaveri (Cauvery), Mahanadi, etc. which have their origin in hills and mountains. The Himalaya for example forms a barrier and protect the Indian subcontinent from cold winds originating from Central Asia. They even block the movement of South West Monsoon that ascends and cause rainfall on the southern slopes of the Himalaya. Mountains are embodiment of incredible beauty and tranquillity that make them important tourist destinations. They are the storehouse of natural resources and also provide suitable sites for generation of hydro-electricity. The fertile plains formed in the lower valleys are the result of the sediments brought from the flowing rivers that take birth in the high altitude mountain regions.

Let us address the following questions while studying the mountains:

- geological structures associated with mountains
- age and origin of rocks of the mountains
- the processes involved in the mountain building activity.

Out of all the questions highlighted above, the last one is more critical to understand. Geologists are trying to understand the formation of mountains.

Mountains are the second order relief features on the Earth's surface. They rise as a single prominent feature or in a group as a chain. They cover around one-fifth of the land surface which are distinct centres of biodiversity. Usually, they have steep slopes and rounded to sharp peaks. Let us differentiate a mountain from a hill. It is important to note that elevation and areal extent of the spread of higher relief over an area is used to distinguish them. Generally, if the height of a landmass exceeds 600 meters, it is called a **mountain** and if it is less than 600 meters and localised, it is termed **hill**.

Let us learn different related terms used for the different forms of mountains present on the Earth surface.

- **Mountain range** exists in a linear system of mountains and hills having several ridges, peaks, summits and valleys. All the hills and mountains are of same age; however, there may be some physical and structural variations in each hill and mountain of the range, e.g. Karakoram Range or Ladakh Range.
- **Mountain chain** is represented by chain of parallel, long and narrow mountains of different age, occasionally separated by a plateau.
- **Mountain system** consists of mountain ranges of same age but they are separated by valleys.
- **Mountain group** comprises assemblage of several unsystematic patterns of different mountain systems.

- **Cordillera** is represented by several mountain ranges, mountain chains, systems and groups. It is not only characterised with the presence of mountains but also other features such as intervening valleys, plateaus, intermontane basins, etc. The Western Cordillera of USA is a classical example.

In the following sections we will classify mountains based on their location, age of orogeny and mode of origin.

14.2.1 On the Basis of Location

On the basis of location we can classify mountains in the following two types:

- **Continental mountains**: They are found on the continental regions. Examples of continental mountains are the Himalaya, Aravalli, Satpura, Western and Eastern Ghats of India; Kunlun, Tien Shan, Altai mountains of Asia; Rockies, Appalachians of North America; Alpine mountain chains of Europe; the Urals of Russia.

- **Oceanic mountains**: They are found on continental shelves, ocean floors and mid oceanic ridge systems. Mid Atlantic Ridge is a good example. You will read more examples of the oceanic mountains in Unit 16 Concepts of Plate Tectonics of this course.

14.2.2 On the Basis of Period of Origin

Mountains can also be classified based on the geological period of origin. Let us discuss them.

- **Precambrian mountains**: Some of the mountains were formed during Precambrian between 3800 and 550 million years ago. These mountains have been subjected to upheaval, denudation and metamorphism. The still noticeable remnants appear as 'residual mountains'. Some of the examples are Anamalai and Nilgiri mountains in India and Laurentian mountains in Canada.

- **Caledonian mountains**: They came into existence between approximately 430 and 380 million years ago, e.g. Aravallis and Mahadeo of India, Appalachians of North America are the consequence of the Caledonian orogeny.

- **Hercynian mountains**: They came into existence between approximately 350 and 250 million years ago, e.g. Caucasus mountains in Europe, Altai, Tien Shan mountains of Asia and Ural Mountains in Russia are the outcome of Hercynian orogeny.

- **Tertairy or Alpine mountain** system was formed from around 65 million years ago to present day, e.g. the Rockies in North America, the Alpine mountains of Europe, the Atlas mountains of north-western Africa and the Himalaya of the Indian subcontinent were the result of the Alpine orogeny. They are the loftiest mountains with rugged terrain. In India, most recently formed mountains are the Himalaya.

14.2.3 On the Basis of Mode of Origin

We are concerned with the classification of mountains based on the mode of origin as it is geologically important. According to the mode of origin, mountains are classified into following five types:

- Volcanic mountains
- Erosional mountains
- Fold mountains
- Rift valley and block mountains
- Residual or relict mountains

A) **Volcanic Mountains**

They are also known as mountains of accumulation, because of the piling of volcanic material that had deposited around the zone of volcanic eruption. We know that due to high temperature deep inside the Earth, rock materials are in the form of molten magma. When the magma is ejected to the Earth's surface as volcanic eruption, it erupts as lava, ash, tuffaceous material and volcanic gases (Fig. 14.1). Volcanic mountains are formed when the magma from beneath the Earth makes its way to the surface and forms a cone. Tuff comprises porous rock of volcanic ash consisting small particles less then 2 mm. The deposited material around the vent increases in height paving the way for the formation of a mountain (Fig. 14.2). Some of the classical examples of volcanic mountains are Deccan volenics in India, Fuji Yama in Japan, Vesuvius in Italy, and Mauna Loa and Mauna Kea in Hawai.

- Watch this video to know more about Deccan Volcanics.
  Link : https://www.youtube.com/watch?V-1a3glcgoGs

Fig. 14.1: Volcanic ejecta, ash and tuffaceous material in the volcanic mountain. (Photo credit : Dr. Meenal Mishra)

Volcanic mountains formed under the ocean rise to the sea surface and appear as oceanic islands. The Aleutian Islands of Alaska is a classical example.

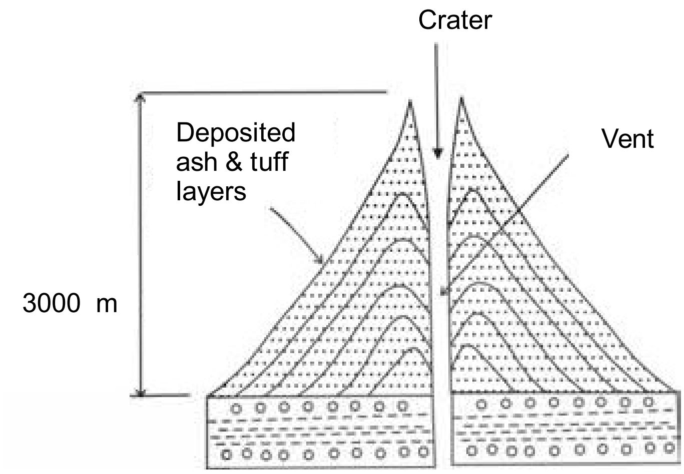


Fig. 14.2: Deposition of ash and tuff layers around the volcanic vent.

B) **Erosional Mountains**

They are considered to be the remnants of the final phase in the history of mountain formation. These mountains are formed when the old mountains formed by magmatic intrusion(s) get eroded to the present day elevations by the action of external forces and also due to the **isostatic** readjustment. They are also called as **Dome Mountains** as they are formed due to upwarping of the exposed surface (Fig. 14.3). Dome Mountains are originated when a large amount of magma pushes up from below the Earth's crust but actually does not reach the surface to erupt; rather it cools and hardens below the surface and takes shape of a dome (Fig. 14.4). Thus, domed mountains are also known as **Upwarped Mountains**. We can compare the Dome Mountains as blisters on the Earth's surface, in view of the fact that the intruded magma causes upwarping and eventually gets exposed as the overlying material is eroded. They are also known as **Erosional Mountains**. Since the dome

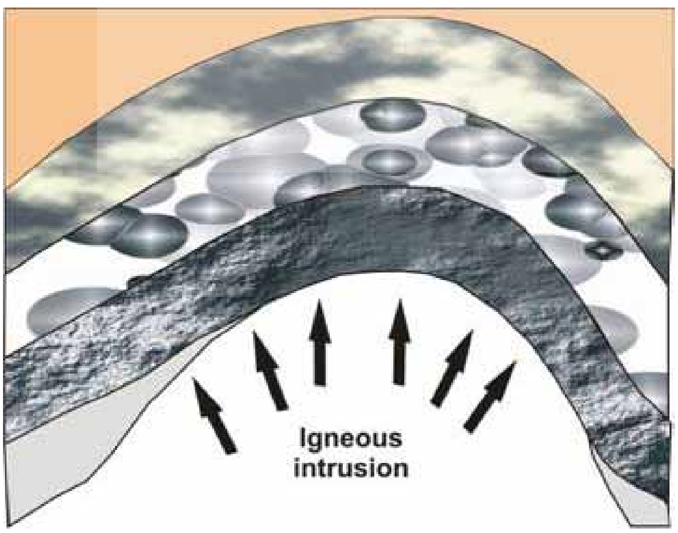


Fig. 14.3: Diagram showing the formation of a dome mountain.

is higher than its surroundings, erosion works from the top creating a circular mountain range. Classical examples of erosional or dome or upwarped mountains are Mount Abu in Rajasthan (India) and Cincinati Dome in USA.

Fig. 14.4: A view of a dome mountain from the Pir Panjal Range, Kashmir.
(Photo credit: Sainandini Mishra)

C) **Fold Mountains**

They are the most common type of mountains found on the Earth surface covering a vast area and stretching thousands of kilometres as shown in Fig. 14.5. Fold Mountains mainly consist of uplifted folded sedimentary rocks. Horizontal compressional forces, acting on the huge pile of deposited sedimentary rocks in the oceanic basin for millions of years, causes folding of rocks (Fig. 14.6). As the time passes, due to the Earth movements the rocks are uplifted to a considerable height and results in the formations of Fold Mountains. The collision of **continental plates** cause uplifting and folding of crust and result in the formation of mountains. Since the mountains are folded in nature, they are also known as **diastrophic mountains**. The Himalayas of India as shown in Fig. 14.7a and Alps in Europe (Fig. 14.7b) are the good examples of Fold Mountains. Let us list some of the common features of fold mountains:

- They occur in linear belt with roughly parallel ridges.

- They are structurally folded and are made up of thick sedimentary successions which are mostly deposited in the shallow marine environment.

- Tectonic activity that leads to faulting, thrusting and igneous activity combined with metamorphism can be seen in fold mountains.

Fig. 14.5: Map showing distribution of the Fold Mountains. (map not to scale)
(Source: www.mapofimages.com/world-mountain-maps)

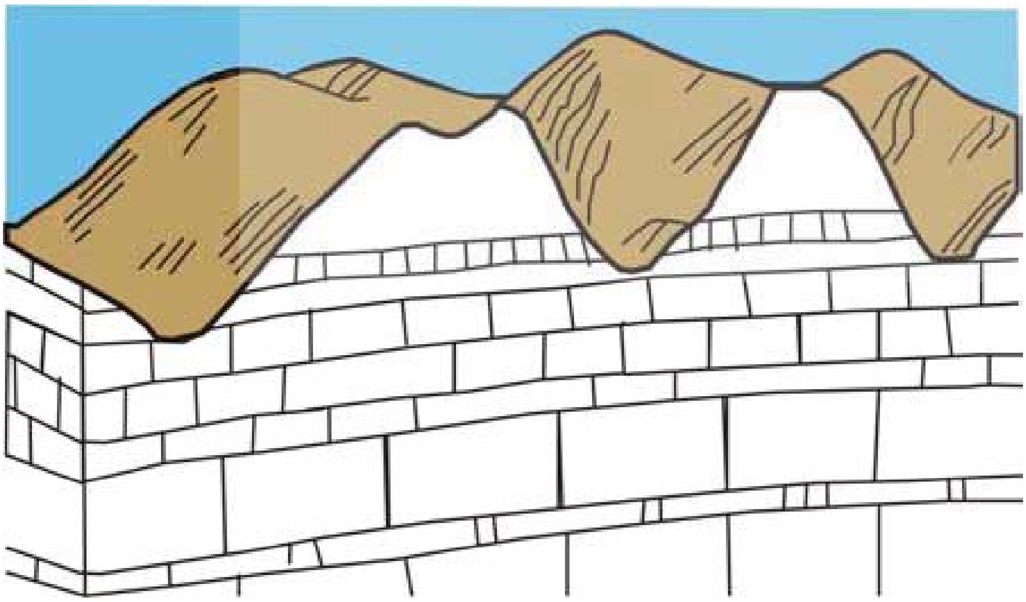


Fig. 14.6: Sketch of Fold Mountains.

Fig. 14.7a: A panoramic view of the Himalaya, near Nainital, Uttarakhand - a classical example of fold mountains. (Photo credit: Ishani Srivastava)

Fig. 14.7b: Panoramic view of Alps, Switzerland- an example of fold mountains. (Photo credit: Dr. S.D. Shukla)

Fold Mountains can be classified on the basis of their ages:

i) **Young Fold Mountains:** They are the highest and most rugged mountains. They have been formed between a time period of 25 to 10 million years ago. They are characterised by a complex folding and faulting system. Erosion and weathering on these mountains are caused by running water, ice, winds, etc. They contain the world's highest mountain peak such as Mt. Everest (8848 m) of the Himalaya. The Alps and Andes are also some of the examples of the young fold mountains.

ii) **Old Fold Mountains:** These are very ancient mountains of more than 200 millions years old. Many of them exist as relict mountains as they were subjected to denudation and weathering. The presence of irregular form of peaks, monadnocks, plateaus and sculptured domes are some of the characteristic features of these mountains. The Appalachians in

North America and Urals in Russia are the good examples of old fold mountains.

D) **Rift Valley and Block Mountains**

Mountains associated with the rift valley system are called rift valley or fault-block or block mountains. Before knowing about these mountains, let us learn what is a rift valley? **Rift valley** is a linear shaped, narrow depression or fault on the Earth's surface, developed by the extensional forces of the Earth's crust. The uplifted blocks of the rift valley are called **Block Mountains** or **horsts** and the intervening dropped blocks are called **graben** as shown in Fig. 14.8. When a piece of a land engulfed between two almost parallel faults is raised to certain height in comparison to its surrounding area, results in a Block Mountain. Thus, Block Mountains (or Fault-block mountains) are formed when faults or cracks in the Earth's crust force the intervening blocks upwards or downwards. Fault-block Mountains usually have a steep front side and a sloping back side. The classical example is Narmada rift valley, Central Asia (Fig. 14.9).

E) **Residual or Relict Mountains**

They are the products of weathering and erosion. The different agents of erosion like winds, glaciers, river, and oceans active on the Earth surface, erode the old mountains and plateaus at some or other time by leveling to a certain height and results in the formation of Residual or Relict Mountains.

They are formed by differential erosion because of differing erodability of rocks in the region. The weathering and erosion is a continuous process, as such it takes thousands of years to erode the soft rocks into sand and the left over hard rocks remain standing in a considerably reduced height. Certain resistant areas called **monadnock** may withstand the lowering by geological agents. Certain plateaus such as Deccan Plateau in Peninsular India are dissected by the flowing rivers, eroding and leveling them more than that of the relict or residual mountains. Few examples of residual mountains include the Anamalai, the Nilgiris, the Aravallis and the Rajmahal traps in India.

We have read about different terms associated with mountains and their classifications. In the next section, we shall discuss about mountain building processes.

Before proceeding further, let us have short break to check your progress.

SAQ 1

a) Define a mountain and write its importance.

b) What are the characteristics of a cordillera?

c) Classify the mountains based on this origin.

d) List some examples of Fold Mountains.

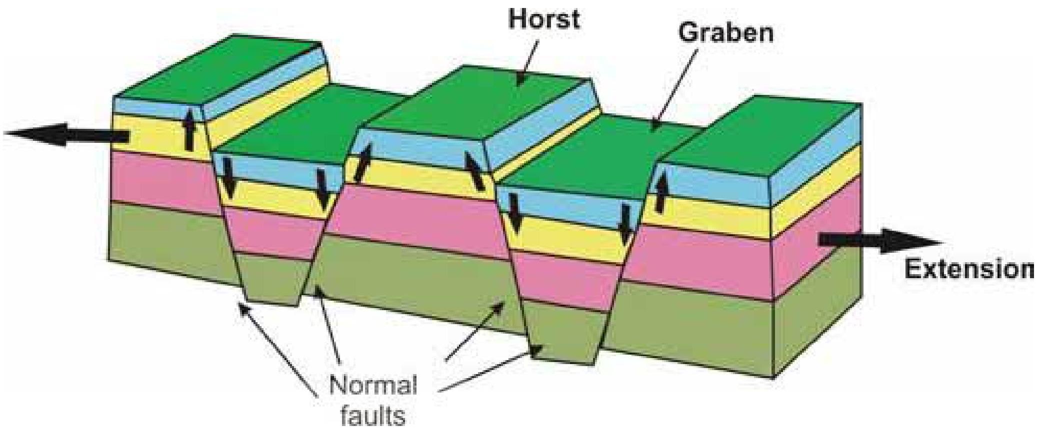


Fig. 14.8: Diagram showing the formation of horst and graben in a rift valley as a result of normal faulting.

Fig. 14.9: A view of the river Narmada flowing in a rift valley, Jabalpur, Madhya Pradesh. (Photo credit: Dr. Nishi Rani)

14.3 MOUNTAIN BUILDING

Mountains are formed by slow but gigantic movements and deformation in the Earth's crust. The process of mountain building is generally explained based on the mode of formation, in view of the fact that Fold Mountains occur as largest and most complex mountain systems of the world. As noticed by the Geologists, Fold Mountains are formed due to compression, squeezing, folding and upliftment of the thick pile of sediments deposited in the ocean basins. However, the precise mechanism which would have caused them has long been debated. Although many theories have been advocated to account for the process, the aspects of mountain building have long puzzled geologists. The mountain building process is also called the **orogenic process**.

We know that Mt. Everest is the highest peak on Earth at 8848m above the mean sea level. The rock at the top of the peak is a marine limestone, deposited on the sea floor about 450 million years ago! This is an amazing fact!! You might question – how did that rock deposited in the ocean basin now found at the highest peak on Earth? Its answer lies in the mountain

Fig. 14.10: Photograph showing residual or relict mountains from near Pallam, Tamil Nadu.

building or orogenic processes. There are complex systems involved in the mountain building process. In early 20th century, much before the plate tectonics theory advocated **geosynclinal theory** helped us in understanding the major mountain building processes. However, geosynclinal theory has now been replaced by theory of plate tectonics.

Let us study about geosynclinal theory in brief.

14.3.1 Geosynclinal Theory

Geosynclinal theory was proposed by James Hall in 1850s and later modified by J.D. Dana during 1870s. Geosynclinal theory is now an obsolete concept, which originally was built on the characteristic features and the process involved in the formation of Folded Mountains. It talked in relation to the existence of the synclines as long linear troughs and opined that the subsidence of crust took place under the weight of the deposited sediments. **Geosyncline** is a term still occasionally used for a subsiding linear trough caused by the accumulation of sedimentary rock strata deposited in a basin. The deposited sedimentary rock strata with associated volcanism and plutonism undergo compression, deformation and upliftment to form a mountain range. It had explained orogeny in following five stages:

a) **Geosynclinal stage**: When a large linear trough undergoes gradual subsidence due to the weight of larger amount of deposited sediments, the geosynclinal stage is developed. Due to isostatic adjustments the layer below the deposited sediments in the continental shelves becomes synclinal as shown in Fig. 14.11a.

b) **Lithogenesis stage**: In this stage, the deposited sediments get compacted and cemented due to the downward pressure developed by the weight of larger amounts of sediments deposited and results in the formation of solid rocks (Fig. 14.11b).

c) **Tectogenesis**: In this stage, Earth's crustal rocks are deformed due to high presure of deposited sediments, geothemal gradients and tectonic activity resulting in the formation of geological structures shown in Fig. 14.11c.

d) **Orogenesis stage**: This stage results in the formation of long linear mountain chains due to folding, faulting and thrusting developed by the compressional forces within the sediments of a geosyncline. This is followed by generation of magma, its upward movement and intrusion in the overlying sediments. As shown in Fig. 14.11c, the complex mountain chain finally results in formation of sedimentary and metamorphic rocks which are folded and faulted in nature.

e) **Glyptogenesis stage**: In the post orogenic phase, the erosion removes the material from the top and sculptures the surface forms. Consequently, the batholith spread underneath the Earth is exposed due to the upward isostatic adjustments developed within the mountain (Fig. 14.11d).

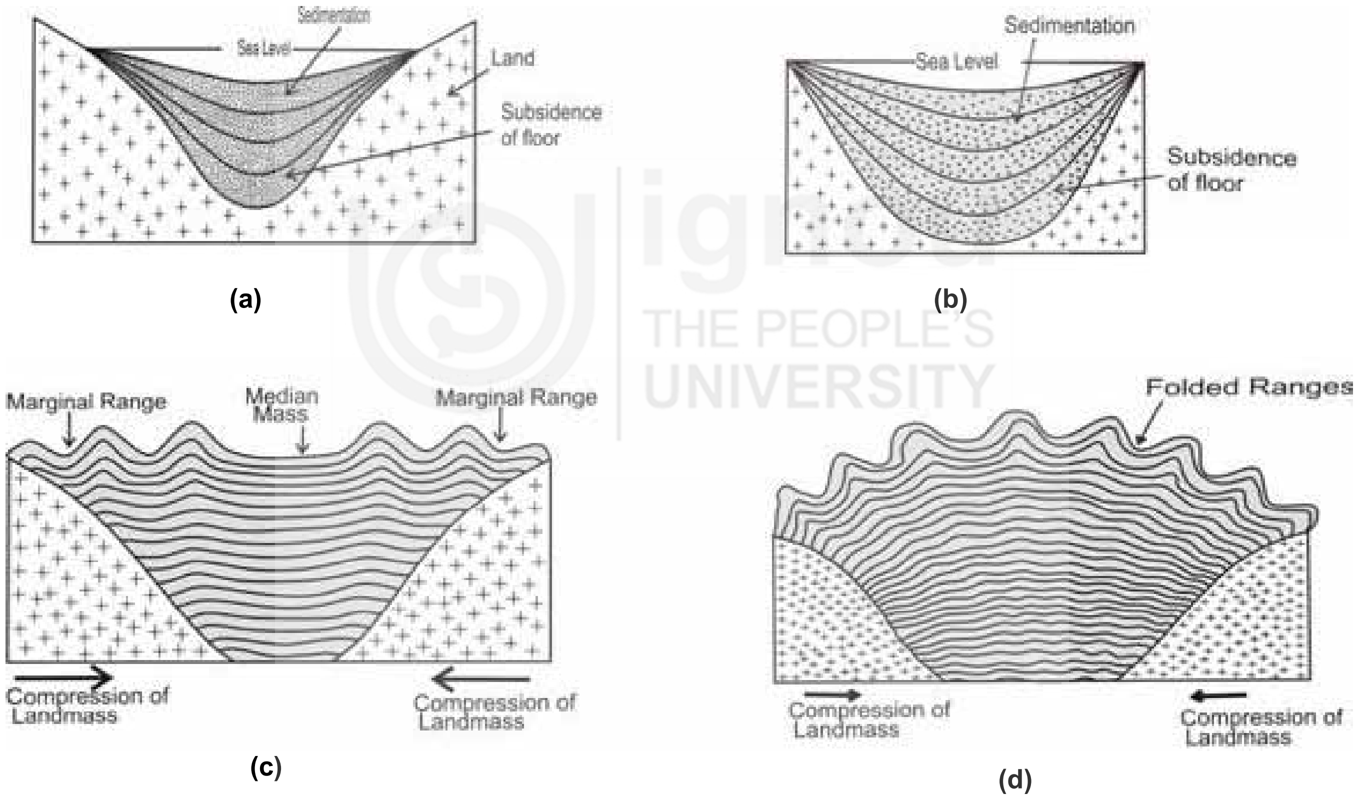


Fig. 14.11: Stages in geosynclinal theory: a) Geosynclinal; b) Lithogenesis; c) Tectogenesis and Orogenesis; and d) Glyptogenesis stages.
(Redrawn from Singh, 2012)

Even though the geosynclinal theory could provide basic steps for explaining the theory of mountain building processes and the underlying cause of orogenesis, it was unable to explain the reasons for subsidence in the geosynclines. Why did sediments accumulate relatively undisturbed for millions of years and suddenly go through a period of deformation? Such unanswered questions drove geologists to continue to search answers for mountain building. Plate tectonics theory provides answer to many of the questions pertaining to mountain building.

We will now go through the concept of plate tectonics in the following subsection.

14.3.2 Plate Tectonics Theory

According to this, mountains form when large segments of Earth's lithosphere called **plates** are displaced horizontally. Fold Mountains form as the result of compression when two continental plates collide with each other. This provides explanation for the processes like folding, faulting, thrusting, magmatism, metamorphism and upliftment of thick pile of sediments accumulated along continental margins. We would discuss in detail about plate tectonics in Unit 16 Concept of Plate Tectonics of this course. Let us now familiarise ourselves with the evidences of orogenic processes.

14.4 EVIDENCES OF OROGENIC PROCESS

Orogeny relates to mountain building and **epeiorogeny** is the formation of continents and oceanic basins. Both the processes involve tectonic deformation of Earth's crust. Orogeny is the term which encompasses the complex tectonics processes in Mountain belts where the outer layers experience thrusting, folding and faulting, metamorphism and plutonic activity operate in the deeper and inner layers of the earth. Thus, orogeny, the process of mountain building, provides a record for the study of geographical, tectonics, structural event, chronological events occurred in the geological past.

You have read that after the orogeny has taken place, it takes millions of years for the mountains to get eroded. The remnants of the earlier mountains may provide useful clues to unravel the orogenic processes. The characteristic features helpful in identifying the rock types are metamorphism, volcanism, magmatic intrusion and sedimentary deposits. The orogeny in the geological history can be known by studying the **petrotectonics assemblage** of rocks, e.g. ophiolites, ophiolitic mélange, stratigraphy and associated geological structures such as folds and thrust faults.

Ophiolites are pieces of oceanic plate that have been thrusted (obducted) onto the edge of continental plates. They are an assemblage of mafic to ultramafic lavas and hypabyssal rocks found in association with sedimentary rocks like greywackes (hard compact sandstone with high quartz and feldspar and) radiolanan cherts. Ultramafic rock consist of ailica percentage less than 45 while Mgo s more then 18% to and Feo is high. Radiolarian chertis silica rich sedimentary rock consisting of microfossils. **Ophiolitic mélange** is the term used for dismembered ophiolite displaying block-in-matrix fabric, i.e. big blocks of rocks (belonging to ophiolitic assemblage) of mappable size lying in fine grained matrix (Fig. 14.12). Ophiolitic mélange shows lateral stratal disruption.

Let us discuss the details of rock types which provide us the evidences for the orogenic processes.

Igneous rocks: The major types of igneous rocks formed during orogeny are plutonic and volcanic rocks. The formation of batholith is an indication of past orogeny. Although predominant plutonic rocks are granite and granodiorite however, the rocks of mafic and intermediate composition are also present. Ultramafic rocks constitute an important part of petrotectonic assemblage, i.e. ophiolite and ophiolitic mélange attractive rocks consist of silica percentage less than 45 while MgO is more than 18% and FeO is high.

Metamorphic rocks: In general, regional metamorphism is extensively widespread during orogeny. Nearly all types of metamorphic rocks are formed throughout the orogenic process but predominant rock types formed in larger volumes at high temperature conditions are schist and gneiss. The mountains that are originated on the seaward side during orogeny of large mountain belts are dominated by high-pressure and low-temperature metamorphic rocks.

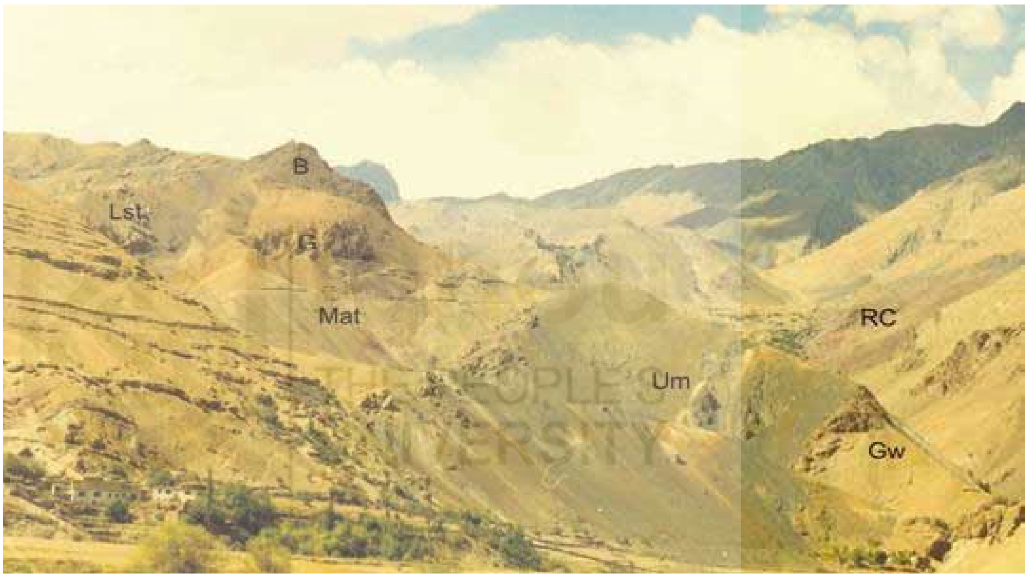


Fig. 14.12: Ophiolitic mélange from the Ladakh Himalaya, Shergol with dismemberd blocks of ultramafics (Um), basalt (B), gabbro (G), limestone (Lst), radiolarian chert (RC), greywacke (Gw), metamorphic rocks lying in fine grained matrix (Mat).

Sedimentary rocks: These rocks are formed by uplifting and erosion of mountains provide a record of orogeny. Due to the process of weathering and erosion, sediments are deposited within or on the margins of orogenic regions forming the sedimentary rocks. All types of sedimentary rocks are formed but most abundant are the varieties of sandstones i.e. greywackes and arkoses. If greywackes are predominant during orogeny, it indicates the active volcanic arc during that time. In the later stages of orogeny, if the volcanic arc shifts to some other place, continuous uplift and erosion take place exposing the igneous and metamorphic rocks. The sediments eroded from these mountains will form arkose (a type of sandstones) rich in quartz and feldspar minerals. The groups of sedimentary rocks that are formed due to the precipitation of sea water are limestone and chert/ radiolarian chert, which are also typical of orogenic regions.

Epeiorogeny is the gentle uplift or subsidence of the broad areas of cratonic part of the continents but with little igneous activity, faulting occures, metamorphism, or intense deformation. In contrast to orogeny, epierogeny occurs on the crust in a non-linear fashion covering vast areas. Epeirogenic regions are characterised by domes, arches, and basins.

Epeirogeny results in the development of disconformities in a regional scale and the deposits formed from the events of marine regression.

Now we know that the processes associated with orogeny are the horizontal plate movements and with epierogeny are the vertical plate movements.

Marine regression is a geological process occuring when area of submerged seafllor are exposed above sea level.

We shall read about theories of mountain building and concept of plate tectonics in the next two units.

Let us check your progress.

SAQ 2

a) List the different stages in geosynclinal theory.

b) Differentiate between orogeny and epeirogeny.

c) List the sedimentary which are evidences of orogenic processes.

14.5 ACTIVITY

1. Now you are familiar with the Fold Mountains having studied about them in this unit. Name the mountain ranges marked with numbers from 1-7 on the map in Fig. 14.13.

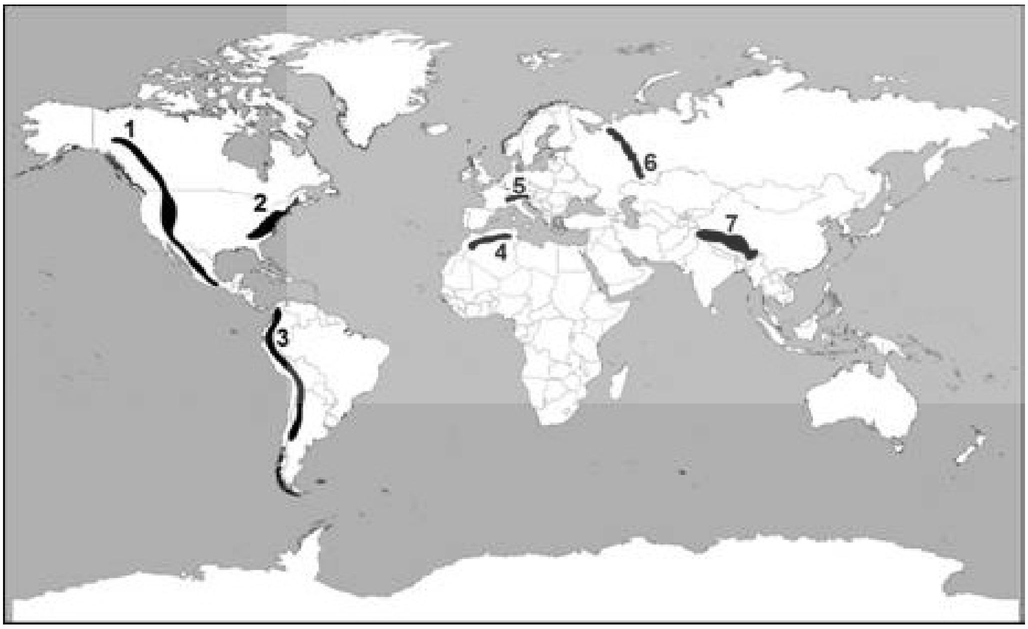


Fig. 14.13: Map of world showing major mountain ranges.

Now open the world atlas to check the correct answer.

2. List the mountains cited as examples in this unit. Take a world map and try to locate them.

14.6 SUMMARY

Let us summarise what we have learnt in this unit:

- Mountains, are the areas of incredible beauty, which are isolated or interlinked and elevated masses considerably above the average altitude of their surroundings.
- Mountains also form the vital source for major river systems and influence the regional and global climatic conditions of the world. Apart from that they are storehouse of natural resources, potential regions for generation of hydro-electricity, source of water and promote tourist and hotel industries.
- Mountains are represented by numerous forms such as mountain ridge, mountain range, mountain chain, mountain system, mountain group and cordillera.
- Mountains are classified into volcanic mountains, erosional mountains, fold/diastrophic mountains, fault-block mountains and residual/relict mountains based on their mode of origin.
- Mountain building process involves complex building mechanism which can be elucidated by geosynclinal theory. However, geosynclinal theory is no longer considered as a valid theory because of several drawbacks and it is now replaced by plate tectonics which have provided explanations to the mountain building processes.
- Geosynclinal theory advocated five stages of mountain building process, viz., geosynclinal, lithogenesis, tectogenesis, orogenesis, and glyptogenesis stages.
- Orogeny is the process of formation of mountains and epeirogeny is the process of development of continents and oceans.
- Different rock types or petrotectonics assemblage, ophiolitic and ophiolitic mélange and associated geological structures preserved in the mountains provide useful clues for unraveling the orogenies in geological history.

14.7 TERMINAL QUESTIONS

1. Distinguish between a hill and a mountain? Explain the different forms of mountains.
2. Explain the types of mountains based on mode of origin with suitable diagrams and examples.
3. What are geosynclines? Describe the process of mountain formation from geosynclines.
4. Discuss the rock types associated with orogeny and provide an evidence of orogenies.
5. Write a brief account on how epeirogeny differs from orogeny.

14.8 REFERENCES

- Singh, S. (2012) Physical Geography. Prayag Pustak Bhawan, India.
- www.mapofimages.com/world-mountain-maps. (accessed on 20th December, 2015.

14.9 FURTHER/SUGGESTED READINGS

- Singh, S. (2012) Physical Geography, Prayag Pustak Bhawan, India.
- Lal, D.S. (2011) Physical Geography, Sharda Pustak Bhawan, India.

14.10 ANSWERS

Self-Assessment Questions

1. a) Mountain is a large terrain feature that rises abruptly from surrounding levels. Mountains are the storehouse of natural resources, generation of hydro-electricity, source of water, form fertile plains act as climatic divide and promote tourist and hotel industries.

   b) Cordillera is represented by several mountain groups, ridges, ranges, mountain chains and mountain systems. It is not only characterised with the presence of mountains but also other features such as intervening valleys, plateaus, intermontane basins, etc. It showcases the orogenic belt at a continental scale, e.g. Western Cordillera of USA.

   c) Volcanic Mountains, Erosional Mountains, Fold Mountains, Rift valley and Block mountains, Residual/Relict Mountains.

   d) Appalachians and Rockies in North America; Andes in South America; Alps in Europe and Himalayas in India.

2. a) The five stages in geosynclinal theory are: (1) Geosynclinal; (2) Lithogenesis; (3) Tectogenesis; (4) Orogenesis and (5) Glyptogenesis stages.

   b) Orogeny relates to mountain building whereas epeiorogeny is the formation of continents and oceanic basins. Epeiorogeny involves the uplift of broad areas of Earth crust as opposed to orogeny with the narrow uplift of folded mountains.

   c) Greywackes and arkoses (sandstones), shale, limestone and chert.

Terminal Questions

1. Please refer to section 14.2 and elaborate the following points. If the height of a landmass exceeds 600 meters, it is called mountain and if it is less than 600 meters, it is termed hill. Different forms of the mountains

present on the Earth surface: mountain ridge, mountain range, mountain chain, mountain system, mountain group, cordillera.

2. Please refer to sub-section 14.2.3 and elaborate the following points, give suitable diagram and examples. According to mode of origin, the mountains are classified into five following types: Volcanic mountains, Erosional Mountains, Fold Mountains, Rift valley and Block Mountains, Residual/Relict Mountains.

3. Please refer to sub-section 14.3.1 and elaborate with suitable diagram five stages as listed according to geosynclinal theory: Geosynclinal, Lithogenesis, Tectogenesis, Orogenesis, and Glyptogenesis stages.

4. Please refer to section 14.4.

5. Please refer to section 14.4.

UNIT 15

THEORIES OF MOUNTAIN BUILDING

Structure

15.1 INTRODUCTION

Whenever we talk of mountains, our mind visualises highlands which are majestic and magnificent. The very thought of mountains conjures up beautiful images of places like the Himalaya, Nilgiri, Aravalli, Satpura, Alps, etc, which have always inspired the mankind but at the same time, our mind questions how these wonderful features formed on Earth! The process of formation of mountains is commonly known as **mountain building**. Several hypotheses have been proposed from time to time to explain the phenomenon. We will discuss those in latter part of this unit.

You may also wonder to know that many mountains found on the continents are made up of ocean sediments. This indicates ocean's role in mountain building. Therefore, we need to understand the oceans and continents also before discussing the theories of mountain building. In this unit, we will also discuss the historical and gradual development of the hypotheses and theories related to drifting of continents, spreading of ocean floor, etc. and their role in developing modern theory of plate tectonics.

Expected Learning Outcomes

After reading this unit, you should be able to:

- ❖ provide elementary idea of mountain building;
- ❖ discuss the continental drift hypothesis and its historical development;
- ❖ list the evidences of continental drift;
- ❖ enumerate the forces responsible for drifting of continents;
- ❖ explain the hypothesis of sea floor spreading;
- ❖ list the evidences for sea floor spreading; and
- ❖ summarise historical perspectives on the theories related to mountain building.

15.2 CONTINENTAL DRIFT HYPOTHESIS

We have been introduced to the term mountain building in Unit 14 Mountain Building and Orogenic Processes. Although many ideas were proposed from time to time but the concepts of mountain building gained momentum with the emergence of the concept of continental drift, sea floor spreading and convection current theories. Let us discuss about them now.

Ever since it was realised that the coastlines on both sides of the Atlantic Ocean juxtapose together like a jig-saw fit (Fig. 15.1 and 15.2), it gave birth to the theory of **continental drift**. This theory was first initiated in 1910 by F.B. Taylor, an American physicist. It states that the continents are not stationary but they have moved in the geological past. But pioneer of the theory of continental drift is Alfred Lothar Wegener, a 32 years old German meteorologist and geophysicist who first suggested this theory in 1912. Wegener accredited his new idea in his book 'Die Entstenung der Kontinente und Ozeane (The origin of continent and ocean) of which four editions appeared during 1915 to 1928.

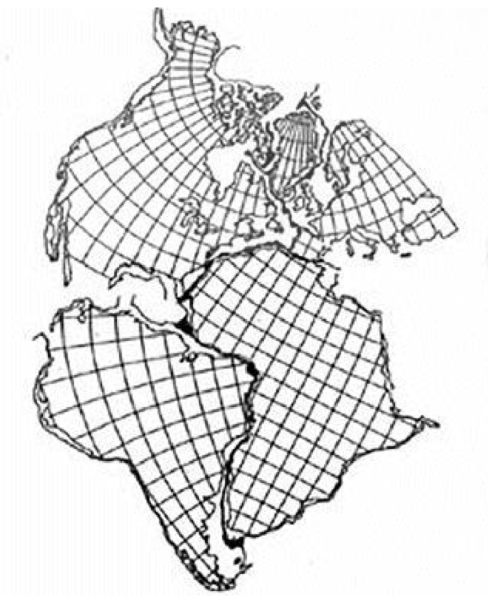


Fig. 15.1: Jigsaw fit of the coastlines of Atlantic Ocean. (Source: http://www.age-of the-sage.org/plate_tectonics/continental_drift.html)

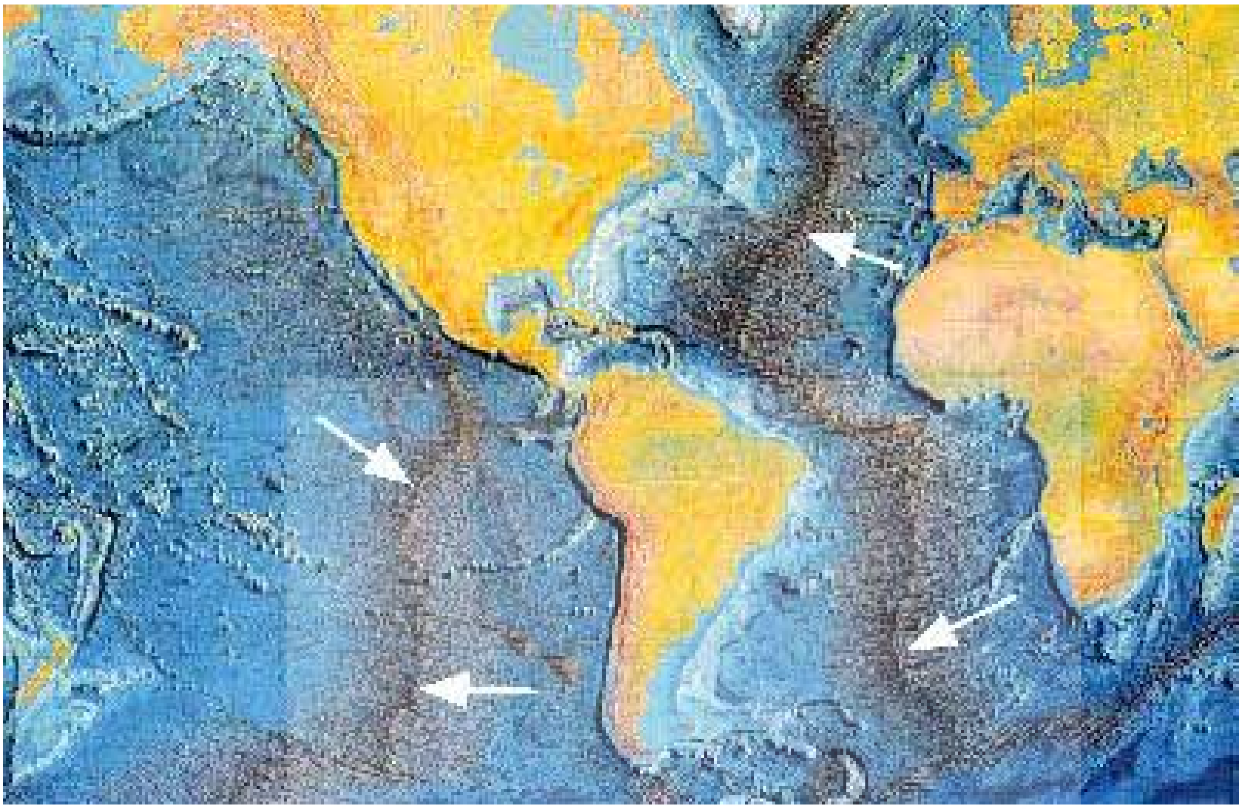


Fig. 15.2: Present day coastlines of Atlantic Ocean. The continents are depicted by shades of yellow while oceanic areas by shades of green. You can notice presence of a ridge in the middle part of the ocean. (Source : www.usgs.gov)

Wegener recognised and termed the assemblage of all continents as a supercontinent and named it as **Pangaea** (meaning "all lands" in Greek) as in Fig. 15.3a and oceanic part as **Panthalassa** (meaning 'all oceans' in Greek). Pangaea got fragmented into many smaller continents which drifted across to form present day distribution patterns (Fig. 15.3a and b). Wegener's theory was based on evidences from geological data, continuity of older structures, stratigraphic formations, fossil fauna and flora across the present continental shorelines. He was basically a meteorologist, who brought to notice of the world the presence of widespread **glaciation** in Permo-Carboniferous times (period in geological time scale around 225 million years ago). Glaciation is the process by which the earth is covered by glaciers or ice sheets. This glaciation had affected most of the southern continents while northern Europe and Greenland had experienced tropical conditions. The present day southern continents were centred on the pole and the northern continents around equator (Fig. 15.3a). Wegener also suggested that the continental drift occurred in response to the centripetal force experienced by the high standing continents because of the Earth's rotation. Centripetal force is a force which acts on a body moving in a circular path and is directed towards the centre around which the body is moving.

225 Million years ago

(a)

200 Million years ago

(b)

Present Day

(c)

Fig. 15.3: Stages of evolution of different continents from: a) Supercontinent Pangaea; b) Pangaea began to break up about 200 million years ago; and c) Eventually fragmenting into the continents as we know them today. (*Source* : www.usgs.gov.)

Though Wegener's theory was based on data which were drawn from several disciplines but it had certain limitations. A weakness in Wegener's theory was that it could not satisfactorily answer the most fundamental question raised by his critics, i.e. what kind of forces could be strong enough to move such large masses of solid rock over such great distances?

Undaunted by rejection, Wegener devoted the rest of his life in pursuing additional evidences to defend his theory. He froze to death in 1930 during an expedition crossing the Greenland ice cap but the controversy he spawned raged on.

In 1937, Alexander Du Toit, Professor of Geology at Johannesburg University and one of Wegener's staunchest supporters, proposed that Pangaea (Fig.15.3a) first broke into two large continental landmasses, **Laurasia** (comprising of North America, Greenland, Europe and parts of Asia) in the northern hemisphere and **Gondwanaland** (consisting of South America, Antarctica, Africa, Madagascar, India and Australia) in the southern hemisphere (Fig. 15.3b). Laurasia and Gondwanaland then continued to break apart into continents that exist today (Fig. 15.3c). The term 'Laurasia' was developed from a combination of Laurentia (a region of Canada) and Asia, while Gondwanaland (meaning land of Gonds) after an ancient tribe in Madhya Pradesh. The two supercontinents Laurasia and Gondwanaland were separated by an ocean named 'Palaeo-Tethys' after the Greek goddess of the sea 'Tethys'.

15.2.1 Evidences of Continental Drift

We have read about historical development of theory of continental drift. This was based on number of supporting evidences.

Let us discuss some of them.

- **Geometrical reconstruction**: If you paste the world map on the cardboard and cut it into pieces, the geometrical shape of the continents and try to bring together the adjacent continents, you would find that the pieces fit together like zig-saw (Fig 15.4). This shows that the continents may have been once together and later on fragmented and drifted apart. Wegner noticed the remarkable similarity between the coastlines on opposite sides of Atlantic Ocean (Fig. 15.1 and 15.2).

- **Geological evidences**: Geologically, the coastlines of the landmass on both sides of the Atlantic Ocean are found to be identical in terms of lithology and stratigraphy, fossil content, geologic structures and style of tectonic deformation. For example, Wegner found the evidence of 2.2 billion year old igneous rocks in Brazil that closely resembled similarly aged rocks in Africa. Similar evidences can be found in mountain belts that terminate at one coastline and reappear on landmasses across the ocean.

- **Palaeoclimatic evidences**: Wegener strongly felt that palaeoclimatic (*palaeo*=ancient, *climate*=climate) data would support the idea of mobile continents. The evidences of glaciations of Carboniferous times (200 million years ago) are found equally on the South America, southern Africa, Madagascar, Falkland, peninsular India, Australia and Antarctica, suggesting they were once locked up landmasses, during Carboniferous period as shown in Fig. 15.3.

- **Palaeontological evidences**: Fossils of land plants like **Glossopteris** and **Gangamopteris** were found in rocks 225 million years ago, widespread in places over Africa, Australia, India, which are now widely separated. Remember!! that seeds of these extinct plant species cannot survive in the saline water of ocean; hence, it is obvious the plants grew and became extinct at the time when all these continents were part of Gondwanaland.

- **Sea floor spreading**: Expansion in the floor area of the ocean is called sea floor spreading. The studies of sea floor spreading phenomenon have confirmed that the continents were once united as a supercontinent Pangaea which later got fragmented and drifted. The sea floor between these drifted continental blocks has spread during last 200 million years. We will study more about sea floor spreading in Section 15.3.

- **Palaeomagnetic evidences**: Palaeomagnetic evidences are based on study of the Earth's magnetic field through the geological time. Let us learn about it by citing an example. We know that a typical ocean also has an underwater range of mountains, which is generally known as Mid-Oceanic Ridge (MOR). You can notice the presence of MOR in the ocean floor in Fig. 15.2. The MOR has been active in geological past and is still active. It pours out lava (called basalt-rock rich in iron and magnesium minerals) under the sea. The magnetic mineral in newly formed lava would preserve magnetic record of Earth's polarity of that time, when it was being solidified from magma. The crystallization of magnetic minerals like magnetite (Fe_3O_4) is affected by magnetic forces. If the lava contains such minerals then the magnetic records of that particular time, such as north and south magnetic poles and magnetic force lines will be preserved in such magnetic minerals. This will remain preserved until it gets demagnetised by temperatures beyond certain critical limit called **Curie temperature**. Palaeomagnetic records are studied with the help of an instrument called magnetometer. If a ship with a **magnetometer** moves over the ocean, many strips of **normal and reversed polarity** are observed in the oceanic floors. The records of these strips of normal and reversed polarity are found to be symmetrical as mirror image along the MOR., Two Englishmen- Drummond H. Matthews and Frederick J. Vine in 1963 proposed that the new oceanic crust acted like a magnetic tape recorder insofar as magnetic anomaly strips parallel to the ridge. These strips of basalt had been magnetised alternately in normal and reversed order, reflecting the changes in polarity of the Earth's magnetic field.

  More and more such palaeomagnetic studies on the Earth have suggested that the magnetic north and south poles have wandered from place to place and even reversed their positions in its history. It has been observed that the magnetic pole-positions of the present globe were different during the geologic past and by joining these poles, a curve is obtained, which is known as **polar wandering curve**. The records of the polar wandering and polar reversals when analysed over different continents, suggested that the landmasses were once together and latter drifted to present positions.

15.2.2 Forces Responsible for Drifting of Continents

We have read about various evidences that provide testimony to the theory of continental drift. Now let us acquaint ourselves with different ideas put forth by various people about the forces responsible for drifting of the continents.

- **Wegener's concept**: According to Alfred Wegener, the continents are dominantly formed of lighter material **'SiAl'**, comprising of silicon (Si) and aluminum (Al) which float over relatively denser rock material '**SiMa**'- comprising of silicon (Si) and magnesium (Mg). You have learnt about Sial and SiMa in Unit 1 and Unit 4 of this course. The drifting of the continents (SiAl), is attributed to the gravitational pull of the Sun and Moon or forces which cause tides in the ocean. The concept was rejected because the tidal forces are too small for providing forces responsible for continental drift.

- **Holmes's Convection Current concept**: In 1928, Arthur Holmes invoked the mechanism of thermal convection in the mantle as the driving force of continental drift. According to him, convection currents were generated due to radioactive heating in the interior of the Earth. The concept could not gain importance because the radioactive heating is too low to cause movements of continents. Though both Wegener and Holmes' ideas of forces responsible for drifting continents are rejected but they laid the foundation from which modern ideas developed.

- **Plate Tectonic theory**: Although Wegener's theory of continental drift had many evidences in its support but it could not explain properly the forces responsible for the drifting of the continents. Plate tectonic theory considers the role of convection currents in the drifting of the continents but not in the same way as Holmes had suggested. The processes involved in the plate tectonics will be discussed in detail in Unit 16. We would briefly discuss in this unit the theory of plate tectonics and how it is able to explain the drifting mechanism of the continents

15.3 HYPOTHESIS OF SEA FLOOR SPREADING

We have talked about sea floor spreading while discussing about evidences of continental drift. Now let us go through its historical developments.

The term **sea floor spreading** was proposed in 1961 by Naval Reserve Rear Admiral Robert S. Dietz, a scientist with the U.S. Coast and Geodetic Survey and Professor Harry H. Hess of Princeton University in 1962 in their endeavor to explain the phenomenon of continental drift. Hess' research ultimately resulted in a ground-breaking hypothesis now better known as sea floor spreading. It is considered as one of the most important contributions in the evolution of plate tectonics theory.

Hess explained the principle of ocean floor spreading with the example of Atlantic Ocean. According to him, the drift between the North America and Europe continents would have been accomplished by the gradual growth of Atlantic Ocean (Fig.15.1 and 15.2). As the ocean gradually grows wider the continental margins move apart; or in other words, continents drift. He calculated that South America and Africa had both moved 2500 km apart during an interval of 250 million years from the mid-Atlantic ridge at the rate of 10 mm/year.

The growth of the ocean floor requires formation of new crustal material for which it is believed that volcanic activity was continuously going on under sea along a ridge in middle portion of the ocean. As already mentioned earlier, these are called Mid-Oceanic Ridges (MORs), where lava is continuously pouring out from deeper portion of the Earth adding up new crustal material on both flanks.

15.3.1 Evidence of Sea Floor Spreading

The data generated from Joint Oceanographic Institutions Deep Earth Sampling (JOIDES) project in 1969 (Fig. 15.4), the Deep Sea Drilling Project (DSDP), and International Phase of Ocean Drilling (IPOD) project in 1976 provided testing ground for sea floor spreading. These generated the evidences in favour of sea floor spreading hypothesis. Let us read about the evidences in favour of sea floor spreading.

Fig. 15.4: JOIDES Resolution is the deep-sea drilling ship of the 1990s, which carries more than 9,000 m of drill pipe, is capable of precise positioning and deeper drilling. (Source: http://pubs.usgs.gov/gip/dynamic/glomar.html)

1. **Age of rocks**: Samples obtained from the direct drilling of the ocean floor were dated isotopically and it was found that the youngest rocks are observed along MOR while the older rocks occur in the marginal part of the ocean, towards the continent. It indicates that age of the rocks gradually increases towards continent in a symmetrical pattern on both flanks of the MOR (Fig. 15.5).

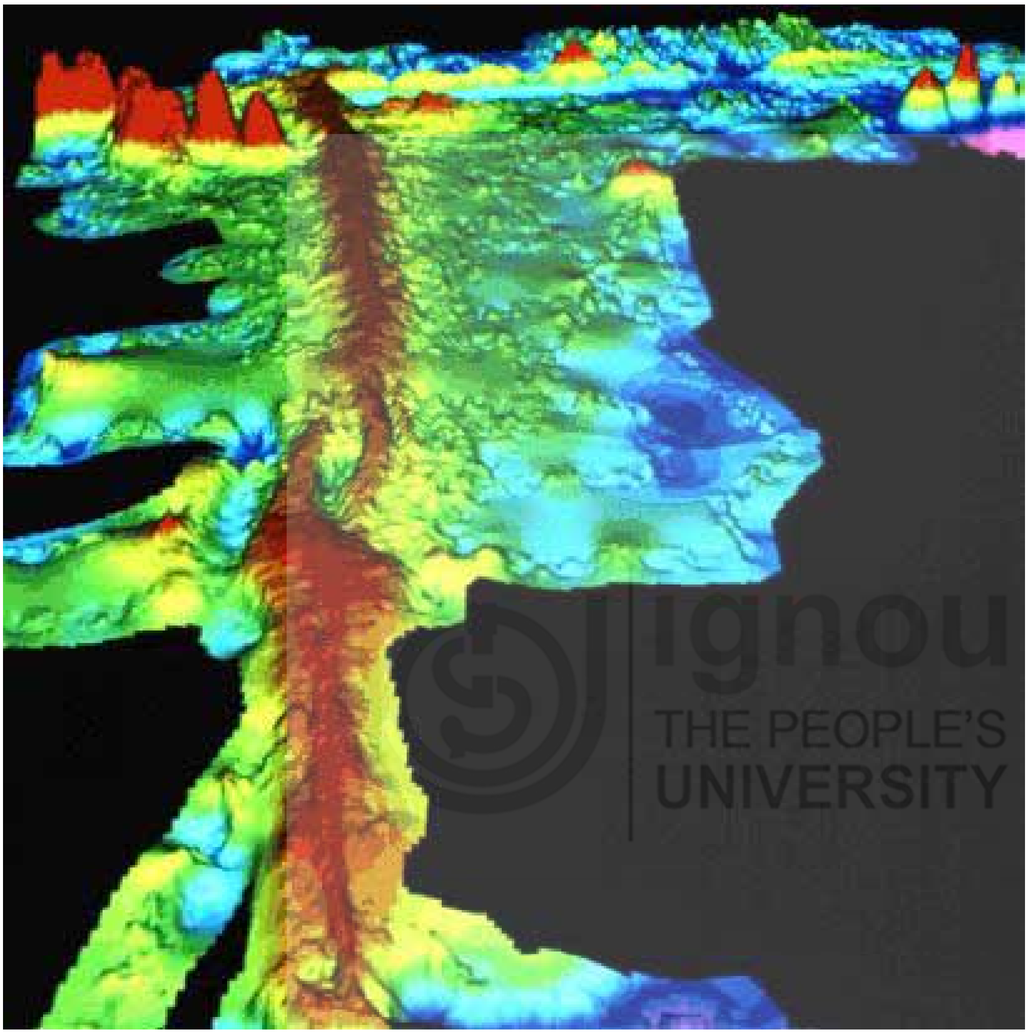


Fig. 15.5: Computer-generated detailed topographic map of a segment of the Mid-Oceanic Ridge, a small part of the East Pacific Rise. "Warm" colours (yellow to red) indicate the ridge rising above the seafloor, and the "cool" colours (green to blue) represent lower elevations. (Source: http://pubs.usgs.gov/gip/dynamic/topomap.html)

2. **Anomalous high values of heat**: The active volcanic islands are associated with the crest of Mid Atlantic ridge. Frequent occurrence of earthquakes and lack of sediments at ridge crests explain sea floor spreading. The anomalous high values of heat reflect the emplacement of hot mantle-derived material in the vicinity of the crest of Mid Oceanic Ridge.

3. **Drilling and dredging**: Direct observations, drilling and dredging have provided evidences for sea floor spreading. No material more than about 180 million years in age had ever been recorded from deep ocean floor.

4. **Magnetic anomalies**: Palaeomagnetic survey and **magnetic anomalies** recorded in the rocks of ocean floor provide an evidence for sea floor spreading. Magnetic Anomaly is a local variation in the Earth's magnetic field resulting from variations in the chemistry or magnetism of the rocks. Mapping of variation over an area is valuable in detecting structures obscured by overlying material.

5. **Looking for alternate phenomenon**: Although Hess' idea of sea floor spreading appears to be genuine even with the modern data, if we consider that sea is expanding and nothing of the continent or ocean is being destroyed or consumed, the Earth's area would have expanded to a great extent! Since the Earth is not increasing in surface area by any significant amount, there must be some other phenomenon that maintains the constant surface area of the Earth. Which is that phenomenon?

We will try to find answer for this question later in this unit when we study about plate tectonic theory but before that let us try to know what actually causes sea floor to expand or spread.

SAQ 1

a) What are Pangaea and Panthalassa?

b) List the evidences in favour of continental drift theory.

c) Enumerate evidences of sea floor spreading.

15.3.2 Driving Mechanism of Sea Floor Spreading

We have learnt about evidences of seafloor spreading.

Now let us look at the mechanisms responsible for sea floor spreading. **Arthur Holmes** proposed that the chief driving mechanism for the sea floor spreading could be the convection currents generated within the interior of the Earth. He considered that there is continuous heat generation in the interior of the Earth due to presence of radioactive elements due to which the convection currents rise above in a circulatory motion. Let us understand this with an example. This phenomenon is just like heating process in liquids. If we put few crystals of potassium permanganate in a beaker containing water and heat the beaker from below, we will notice the convection currents rising up and down following a circulatory motion (Fig. 15.6). Thus, if pieces of objects (such as segments of Earth's crust) are floating they will attain a divergent motion and distance between them may increase. The places, where two convection currents are moving in opposite directions the ocean floor above expands and new MOR lava emerges and spreads over the ocean floor. His idea could not get acceptance because heat produced by radioactive minerals is not enough to cause such motion. However, later the idea of convection current helped in development of plate tectonic concept.

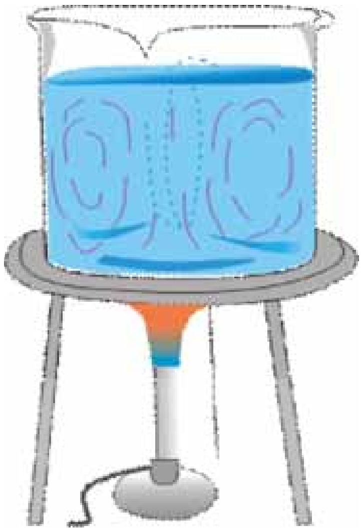


Fig. 15.6: Schematic showing convection currents motion.

According to the plate tectonic concept the convection currents are generated in a circulatory motion which ascend from deep mantle and come to the upper mantle and move to some distances following the periphery and finally descend back to the deep mantle. These convection currents have tremendous power to move or drag the **lithospheric plate** to some distance over the **asthenosphere**. You will learn more about lithospheric plate and asthenosphere under concepts of plate tectonics later in this unit. At the places where such convection currents have their motion in opposite directions, the lithospheric blocks called 'plates' move in opposite directions (Fig. 15.7). The opposite movements of the plates cause development of a fracture at the MOR, which is filled up immediately by upwelling of lava due to submarine volcanism. This lava forms the newest crust. Since the convection currents are continuously in motion, the new crust is continuously being added on the sea floor causing sea floor spreading. The convection currents are generated not through radioactive minerals as proposed by Holmes but due to the internal heat of the mantle, while the lithosphere is relatively cool.

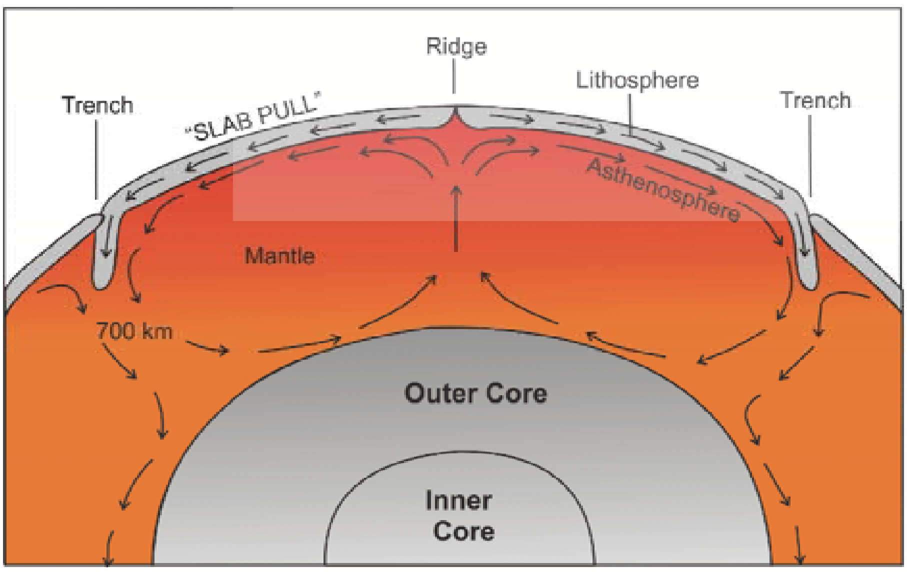


Fig. 15.7: Cells of convection currents in the interior of the Earth.
(Source: www.indiana.edu/~g105lab/1425chap13.htm)

15.4 THEORIES OF MOUNTAIN BUILDING

Several hypotheses have been put forward to explain the causes of mountain building. Some of these theories are totally outdated now but they are being mentioned here to provide a historical resume of thought process which eventually terminated in the modern theory of plate tectonics. They are listed below:

1. Contraction Hypothesis
2. Expansion Hypothesis
3. Continental Drift Hypothesis
4. Oscillation and Undation Hypothesis
5. Convection Current Hypothesis
6. Plate Tectonics Theory

15.4.1 Contraction Hypothesis

The idea of contraction hypothesis was given by Warision in nineteenth century. This was later developed by Jeffreys in 1929, on the basis of the thermal history of the Earth. He proposed that the inner portion of the mantle below 700 km was neither cooling nor changing in volume and the outermost layer about 100 km had already cooled to reach equilibrium and this too was not changing in volume. Thus cooling and contraction were confined to the layers at the depth between 100 km and 700 km. Since the inner radius of this layer was fixed, this zone could contract only by stretching and thinning. This zone was thus in tension but its contraction and thinning resulted in compression in the outermost layer above 100 km. Jeffreys called the surface at about 100 km depth where the change from extension to compression occurred, as '**level of no strain'**. According to Jefferys mountains were built by this contraction and stretching in the outermost layer of the earth. The theory could not gain popularity because certain phenomena like metamorphism seen in the mountains could not be explained.

15.4.2 Expansion Hypothesis

Jolly proposed in 1925 that Earth is expanding because of radioactive heating. Carey in 1958 postulated that since oceanic area is expanding, the globe as a whole is also expanding. Palaeomagnetic and palaeoclimatic studies was the resonance to his thought that the original diameter of the Earth was less than half of its present size and surface area was less than a quarter. Thus, worldwide expansion breaks the Earth's crust into blocks. These blocks tend to rotate sinistrally (anticlockwise) in the southern and dextrally (clockwise) in the northern hemisphere because of shearing forces created between polar and equatorial regions due to adjustment of angular momentum. According to Jolly, these forces are responsible for mountain building. Many Earth scientists like Egyed in 1957, Tuzo J. Wilson in 1961, A. J. Eardley in 1962 also admitted that Earth is slowly expanding.

Now the questions which remain to be answered are; has the expansion actually occurred and has the ocean water remained constant in volume?

15.4.3 Continental Drift Hypothesis

Wegener believed that the Earth comprises three layer system; the outer layer as '**SiAl**', intermediate layer as '**SiMa**' and innermost layer as '**Nife**'. **SiAl** comprises lighter masses of continents, which float over ocean floor SiMa. According to him Pangaea was disrupted and the broken land mass or continents drifted away from each other. He also postulated that the mountains were formed because crumpling occurred due to resistance offered by SiMa. The observations like shortening across mountains, the approximate parallelism of the coast line of Atlantic oceans and other southern continents support his ideas.

The greatest weakness of this hypothesis is that it never revealed satisfactorily about the forces, which are required to move or drift the continents. Relationship of deep earthquakes to mountain building also could not be explained.

15.4.4 Oscillation and Undation Hypothesis

Haarman in 1930 postulated that the disequilibrium in the layered Earth's crust is due to the vertical movements, which were generated due to influence of an undefined cosmic factor. This resulted in the formation of 'geotumours' separated by 'geodepressions' caused by the flow of sub-crustal sialic matter forming the depressions to the rising tumours. When the cosmic influence moved in relation to Earth, the tumours also moved. This resulted in oscillating action of emergence and submergence. In the second phase, the sediments in depressions were lifted up, and consequently glided down the slopes of the new tumours. Later, the folded and structurally accumulated rocks were lifted up and in the third phase they became mountain chains. On the basis of Haarman's theory, Van Betmmelen in 1932 and 1935 suggested 'Theory of Undation' according to which the mountain chains were formed by sub-crustal gliding.

The main objection to the theory is that the basis of cosmic influence is not known and also the gliding tectonic is not able to explain the structural features of all mountains on Earth.

15.4.5 Convection Current Hypothesis

The theory of convection current has been given by Holmes in 1930 and several other tectonic geologists. This theory is based on the **heat flow** in the mantle. Heat flow is the production of the temperature gradient and the thermal conductivity of the mantle. Menard's study in 1960 and 1961 has revealed a zone of abnormally high heat flow along East Pacific Rise and low heat flow in the east of the East Pacific Rise. Menard believes that the descending convection current causes a certain amount of compression in the trench regions. Such heat flow anomalies is also supported by the geoscientists like Dietz in 1961, Wilson in 1963 and Hess in 1962 proposed that the ocean floor descends into the marginal trenches under the influence of convection current in the mantle. The convection current theory thus by and large assumes that the mountains are formed by such compression. This theory could explain the pattern of distribution of continents and oceans. It could also account for the features of active island arcs (such as Japan, Philippines). Currents are necessary to carry off heat generated within the Earth by radioactive elements. Despite these supporting evidences, the main objection for the theory was that it assumes the old idea of the permanency of the continental blocks. However, it must be admitted that convection current theory as proposed by Holmes was a precursor to plate tectonic movement which recognises the role of convection currents as the main force behind plate movement.

15.4.6 Plate Tectonics Theory

The plate tectonic theory came into light in 1970s through the combined efforts of many scientists of different countries working together or independently. It is considered a comprehensive theory which is able to explain many complexities of continental drift, volcanism, folding, faulting orogeny, etc. This theory assumes that the globe is made up of rigid masses called '**plate**' consisting of lithosphere which floats and moves along the convection current over the asthenosphere.

The main difference between the continental drift theory and the plate tectonics is that the former postulates the movement within the lithosphere itself, i.e. between continents and oceans while the later talks of the total movement of the lithosphere over the asthenosphere. A plate theory comprises the total lithosphere.

The convection current may causes three types of plate movements, namely -

- convergent – when two plates move towards each other.
- divergent – when two plates move away from each other
- strike-slip – when two plates neither move away nor towards each other but they slide past each other. This type of motion occurs along large strike-slip faults in the ocean. These faults are called **transform faults.**

According to this theory convergent motion of plates and their collision is responsible for mountain building. We will read in detail about the concept of plate tectonics in Unit 16 Plate Tectonics but before that let us learn about the mountain building periods here.

15.5 MOUNTAIN BUILDING PERIODS

Study of different mountains of the world reveals that some mountains, like Aravalli, are very old and now they are decaying while some others like Himalaya, are young and still rising. With the advent of theory of Plate Tectonics we are now aware that there were many more mountains since the Earth was formed in its geological past. Thus, Earth has witnessed the process of mountain building at different times. This mountain building takes place in impulses called **orogenic phases**. An **orogenic period** comprises several orogenic phases. **Orogenic Belt** consists of one or several related mountain systems which have been deformed in an orogenic period.

We have read in Unit 14 about classification of mountains based on orogenic periods. In the history of the Earth, many major orogenic periods have been recorded. Some of these are:

- **Precambrian orogeny** (before 550 million years ago) comprising several orogenic periods dating from 3800 to 550 million years ago for example Rodinian orogeny at 1100 ma;
- **Caledonian mountains** came into existence between approximately 430 and 380 million years ago, e.g. Aravallis and Mahadeo hills of India, Appalachians of North America are the consequence of Caledonian orogeny;
- **Hercynian orogeny** (Between 350 and 250 million years ago). It is also called as **Variscan Orogeny** in Europe; and
- **Tertiary or Alpine or Himalayan orogeny** (Palaeocene i.e. 65 million years ago to present day)

SAQ 2

a) Convection currents have tremendous power to move or drag the .... to some horizontal distance over the asthenosphere.

b) Expansion Hypothesis proposed that Earth is expanding because of ....

c) The theory of convection current is based on the .... in the mantle.

d) 3 types of plate boundaries are convergent, divergent and.................... ....

15.6 SUMMARY

In this unit we have learnt about various hypotheses and theories related to mountain building. Let us summarise what we have learnt in this unit:

- Mountain building includes the geological processes related to plate tectonics, deformation, shortening of crust, folding, faulting, volcanic activity, igneous intrusion and metamorphism. The process of mountain building is also known as orogenesis.
- Alfred Wegener recognised the assemblage of all continents as a supercontinent during Carboniferous period (~ 220 million years ago) and named it as 'Pangaea' and remaining oceanic part as 'Panthalassa'. All present day continents are broken into fragments from Pangaea and have moved away from each other. The theory describing movement of the continents is referred to as continental drift theory.

- There are many evidences for continental drift. They are based on geometrical reconstruction, geological, paleoclimatic, paleontological, sea floor spreading and palaeomagnetic evidences.
- Harry Hess proposed the hypothesis of sea floor spreading, according to which the floor of the ocean is continuously expanding.
- Evidences for hypothesis of sea floor spreading are based on age of rocks, anomalous high heat values, direct observations, drilling and dredging and magnetic anomalies.
- Convection current hypothesis given by Arthur Holmes presumes movement of the continents and sea floor spreading due to convection current cycle generated out of radioactive heating in the interior of the earth
- The hypothesis of continental drift, sea floor spreading and convection current cycles are factual but the processes or mechanisms proposed by their propounders of these theories are not tenable in the light of present day knowledge.
- Plate tectonics theory developed during 1970s is able to explain many observed phenomena on earth such as drifting of continents, spreading of ocean floors, convection current cycles, mountain building, etc.
- The mountain building hypotheses include contraction hypothesis, expansion hypothesis, continental drift hypothesis, oscillation and undation hypothesis and convection current hypothesis. However mountain building process is best explained by plate tectonics theory.
- Four major orogenic periods have been recorded in the history of the Earth. These are Precambrian orogeny, Celedonian orogeny, Hercynian orogeny and Tertiary or Alpine or Himalayan orogeny.

15.7 ACTIVITY

Take a map of the world and try to cut out the continents from it. Arrange the cut pieces again in their relative position. Try to fit the adjacent continents and check what do you notice.

Hint : You will observe that they have good fitting for a single supercontinent (called Pangaea).

15.8 TERMINAL QUESTIONS

1. Discuss the theory of continental drift? Give the evidences in support of continental drift.
2. Explain the forces responsible for drifting of continents as given by Wegener and Arthur Holmes.
3. Explain sea floor spreading and discuss the different concepts of driving mechanism for sea floor spreading.

4. Give a brief account of how the theories for the causes of mountain building evolved with time.

15.9 REFERENCES

- De Sitter, L.U. (1956) Structural Geology, McGraw-Hill Book Company.
- http://indiana.edu/~g105lab/1425chap13.htm
- http://pubs.usgs.gov/gip/dynamic/topomap.html
- http://pubs.usgs.gov/gip/dynamic/glomar.html
- http://www.age-of-the-sage.org/plate_tectonics/continental_drift.html

(Websites accessed between 25th November 2014 and 4th December 2015).

15.10 FURTHER/SUGGESTED READINGS

- http://pubs.usgs.gov/publications/text/dynamic.html.
- Kearey, P. and Vine, F.J. (2009) Global Tectonics, 3rd Edition, Blackwell Science Ltd.

15.11 ANSWERS

Self-Assessment Questions

1. a) The assemblage of continents i.e. supercontinent as 'Pangaea' (meaning "all lands" in Greek) and remaining oceanic part as 'Panthalassa' (meaning 'all oceans' in Greek).

   b) Geometrical reconstruction, geological evidences, paleoclimatic, paleontological, seafloor spreading and palaeomagnetic evidences.

   c) Please refer to subsection 15.3.1 and discuss in brief about age of rocks, magnetic anomalies, drilling and dredging and anomalous high values of heat.

2. a) Lithospheric plates

   b) Radioactive heating

   c) Heat flow

   d) Strike-slip/ Transform fault

Terminal Questions

1. Please refer to section 15.2 and subsection 15.2.1.
2. Please refer to subsection 15.2.2.
3. Your answer must cover salient aspects from section 15.3 and subsection 15.3.2.
4. Please refer to section 15.4. Your answer should include contraction hypothesis, expansion hypothesis, continental drift hypothesis, oscillation and undation hypothesis, convection current hypothesis and plate tectonics theory.

UNIT 16

PLATE TECTONICS THEORY

Structure

16.1 INTRODUCTION

In the previous unit, we were introduced to the term 'plate tectonics'. Tectonics comes from the Greek word *tekton*, meaning 'builder'. You might have heard this term while discussing natural disasters like earthquakes, tsunami or volcanic activity in television and radio programmes. This is because plate tectonics is considered to be a comprehensive theory which is able to explain many complexities of continental drift, volcanism, folding, faulting, orogeny that have transformed the landscape features we see across the globe today.

Plate tectonics also known as **global tectonics** is considered to be fundamental concept in Earth sciences. It became popular in the decade of sixties of the 20th century. In the early 1970s, the emergence of the **theory of plate tectonics** started a revolution in Earth sciences. This is a landmark in studies related to Earth and is considered as one of the three most coveted developments in science. Plate tectonics has proven to be as important to the Earth sciences as the discovery of the structure of atom was to physics and chemistry and the theory of evolution or deciphering of the DNA structure was to the life sciences. It became possible to explain diverse phenomenon like earthquakes and the spreading of sea floor in a plausible manner with plate tectonics concept. Sea floor spreading hypothesis was very influential in setting the stage for the emerging plate tectonics theory. We have read about continental drift in Unit 15 Theories of Mountain Building. Plate tectonics theory may be considered as the modern version of continental drift theory proposed by Alfred Wegener.

Let us learn more about the theory of plate tectonics in this unit.

Expected Learning Outcomes

After reading this unit, you should be able to:

❖ discuss the basic considerations of plate tectonics;

❖ describe the types and nature of lithospheric plates with present day examples;

❖ explain different types of plate boundary and associated features;

❖ evaluate reasons for the phenomena like earthquakes, volcanoes, continental drift, sea floor spreading and mountain building; and

❖ elucidate the evolution of Himalaya.

16.2 BASIC CONSIDERATIONS OF PLATE TECTONICS

Now let us read about the basic consideration of plate tectonics theory.

The quest for scientific explanation of certain observations such as why earthquakes and volcanic eruptions occur in very specific areas around the world, and how and why great mountain ranges like the Alps and Himalaya formed? In this context let us recall we have already read about 'Ring of Fire' encircling the Pacific Ocean in Unit 4 Earthquakes and Volcanoes of this Course. The gradual developments in studies carried out by Alfred Wegener (on Continental drift), Harry Hess (on Sea floor spreading) and Arthur Holmes (on Convection Currents) paved way for understanding of Earth's internal processes. However as there were some shortcomings in their hypotheses which have been modified logically with the development of plate tectonics theory

Let us acquaint ourselves with the basic considerations of plate tectonics theory in order to realise them better.

- 'Sea floor spreading' occurs and new oceanic crust is continuously generated at irregular line source that is along the active **Mid Oceanic Ridges (MORs)**. MORs are under water oceanic ridge systems.

- The phenomenon of convection current circulation is active in the interior of the Earth. Let us recall that we have learnt about this in section 15.8 of the previous Unit 15. However, the source of heat for rising of convection currents is not the thermal gradient heat flow and the radioactivity as suggested by Holmes. The currents circulating in the mantle are in fact formed at the boundary of mantle and outer core; where the temperature is very high.

- The theory accepts that continental drift has occurred in the geological past and is still in the process. The basic idea in this concept is that the present position of continent and sea is not a permanent feature of the Earth's surface but they undergo continuous change.

- The Earth is of constant surface area, and if not, the changes occur at insignificant rates.

- We have read about three broad divisions of the Earth namely, crust, mantle and core in Block 1 of this course. Plate tectonics however gives importance to the segment of the Earth called 'lithosphere', which comprises crust and part of upper mantle. 'Plates' are rigid segments of lithosphere, movement of which over 'asthenosphere' are responsible for many tectonic features present on the globe.

Let us learn more about lithosphere, asthenosphere and lithospheric plates in the next section.

16.3 LITHOSPHERIC PLATES

We have been acquainted with the terms like lithosphere and asthenosphere in Unit 3 Structure and Composition of Earth. Let us recall these terms in relation to plate tectonics concept.

- **Lithosphere**: It is the segment of Earth which comprises Earth's crust and part of upper mantle lying above **asthenosphere** (Fig.16.1). Lithosphere is colder and more resistant outer shell of the Earth. The continents, oceans and mountains lie on the upper part of lithosphere that is the crust. The lower boundary of lithosphere is demarcated by asthenosphere, about which we will discuss little later in this section.

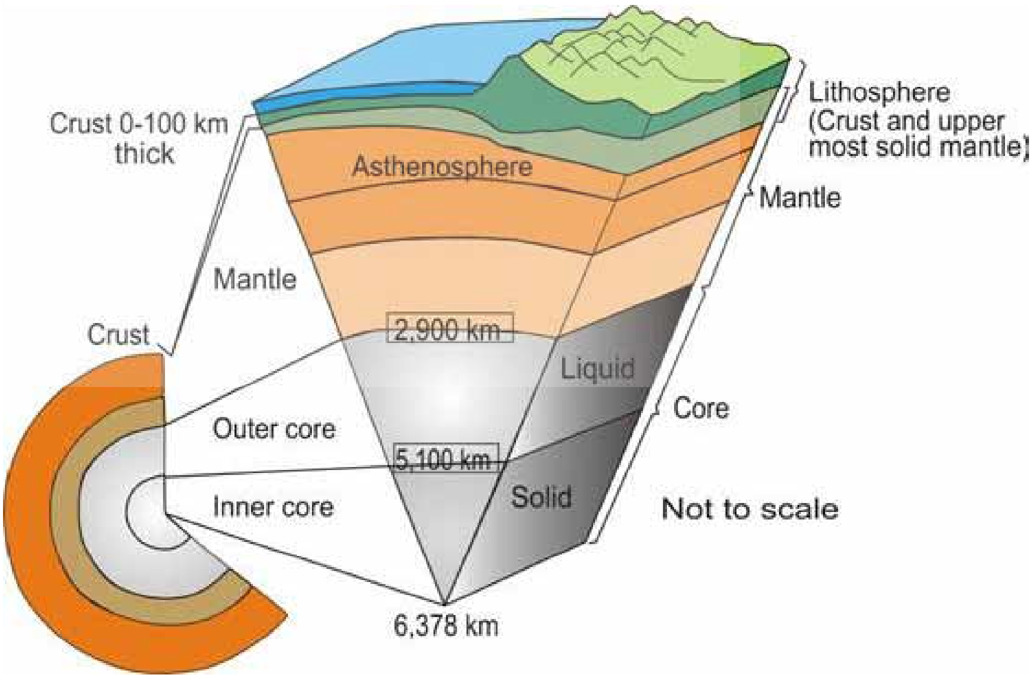


Fig. 16.1: Internal structure of the Earth showing lithosphere and asthenosphere. (Source: https://igs.indiana.edu/Geothermal)

- **Lithospheric Plates**: Earth is constituted of many different segments of lithosphere known as lithospheric plates. These lithospheric plates are also known as **tectonic plates** or simply **plates**. Let us comprehend this with the analogy of a soccer ball. We can compare the tectonic plates with the leather pieces joined together in a soccer ball. The boundary limits of these plates are however, demarcated by the scientists based on observed features on the Earth and tectonic activities (not by ocean or continent).

- **Thickness of the Lithospheric Plates**: We have read that temperature and pressure increases as we go deeper inside the Earth. The delicate balance of temperature and pressure in the interior of the Earth is responsible for different physical states of the rocks such as solid, quasi-solid or liquid state. It has been observed that temperature around 1400^{o}C causes melting of lithospheric plates at depth and the zone of asthenosphere starts from here. The lower limit of lithospheric plate lies at an average depth of 100 km. It should also be remembered that the thickness of lithosphere above the astheonsphere is not uniform but varies at different locations. It is generally lesser in the oceanic part of the Earth and greater below the mountains or continents where the thickness may go up to 300 km (Fig. 16.1).

- **Types of Lithospheric plates**: By now we are aware that lithospheric plates comprise of the crust and the upper part of mantle. The crust comprises tremendous highs and lows because it is having high mountains and deep oceans as well. It becomes obvious that the lithospheric plates consist of continents and oceans.

  The lithospheric plates are of following three types:

  Oceanic plate is entirely made up of the oceanic part of the crust. The oceanic crust is constituted of **SiMa**. The Pacific Plate is an example of oceanic plate.

  Continental plate is made up of the continental part of the crust. The continental crust is constituted of SiAl at upper and **SiMa** at the lower part.

  Continent - Oceanic plate consists of the plate containing both continental as well as oceanic parts of the crust. The continental part contains both SiAl and SiMa while the oceanic part is only constituted of sima. Most of the major plates of the world (few exceptions like Pacific plate) are continent-oceanic plates.

- **Asthenosphere**: The word *astheno* comes from the Greek combination of ‘a’ (meaning without) and *stheno* (meaning strength). It is the layer or shell of the Earth, which starts just below the lithosphere at around 100 km depth and may extend upto 350 km (Fig. 16.1). This zone is in semi-viscous state and is also known as Low Velocity Zone (LVZ) because **seismic waves** acquire a low velocity in this zone. Seismic waves are the vibration produced by an earthquake. Asthenosphere is ductile part of the Earth just below the lithosphere, and is about 180 km thick and consists of partially molten rock. The lithospheric plates float and move horizontally over the asthenosphere. The base of the asthenosphere is defined by the deepest known earthquakes (approximately 700 km).

16.4 IDENTIFYING PLATES OF THE EARTH

We have read in the previous section that the plates are considered as rigid segments of lithosphere therefore we do not expect much tectonic activities within a plate. However, we cannot expect the same for the boundaries or the marginal parts of the lithospheric plates. The plate boundaries are marked by frequent and abundant tectonic activities because of its interaction with the neighbouring plates. This implies that the high tectonic activity area on the Earth might be in the vicinity of plate boundaries. Before we actually identify and demarcate the limits of different plates on globe, let us have a look over some observed facts related to tectonic activities found over the globe.

16.4.1 Observed Facts about Tectonic Activities

The linear ridges found in the middle of all oceans of the world are called Mid Oceanic Ridges (MOR) (Fig. 16.2). Quiet type volcanic eruptions are going on continuously along the MOR.

- Numerous shallow focused earthquake epicenters have been recorded along these mid oceanic ridges (Fig.16.3).
- Age of the ocean floor rocks are symmetrically distributed along the MOR. The youngest rocks are found near the MOR while the oldest rocks occur on the flanks of the ocean towards continent side (Fig.16.4).
- Nowhere in the present day the age of the oceanic floor has been found to be greater than 280 million years, on the contrary, continental rocks are found to be greater than 4000 million years (Fig. 16.4).
- The Pacific Ocean is surrounded by active volcanoes. They are so widely distributed that the peripheral part of Pacific Ocean is often called as 'ring of fire' (Fig.16.5). Most of the deep focus earthquakes are found along this ring of fire.
- Volcanic islands in the Pacific Ocean are not randomly distributed but they show their alignment along a curved line or arc. Group of these islands is therefore often called as 'island arc'. The island arc and the deep sea trenches in the Pacific Ocean are found side by side in parallelism (Fig. 16.6). The island arc occurs towards the continent side in the ocean relative to the trenches.

The above mentioned and many other facts related to earthquake occurrences, volcanic activities, deep oceanic trenches, occurrence and alignment of oceanic islands, mountain ranges, palaeomagnetism, polar wandering histories, palaeoclimatic conditions and fossil contents, etc. observed by the Earth scientists have helped them to demarcate the limits of different plates of the present day world. Palaeomagnetism is the study of the record of the Earth's magnetic field in rocks, sediments, or archaeological materials. We have read that polar wandering is the migration of the magnetic poles of the Earth through geological time. Seven major plates and many other minor plates have been identified so far. Let us learn more about them in the following section.

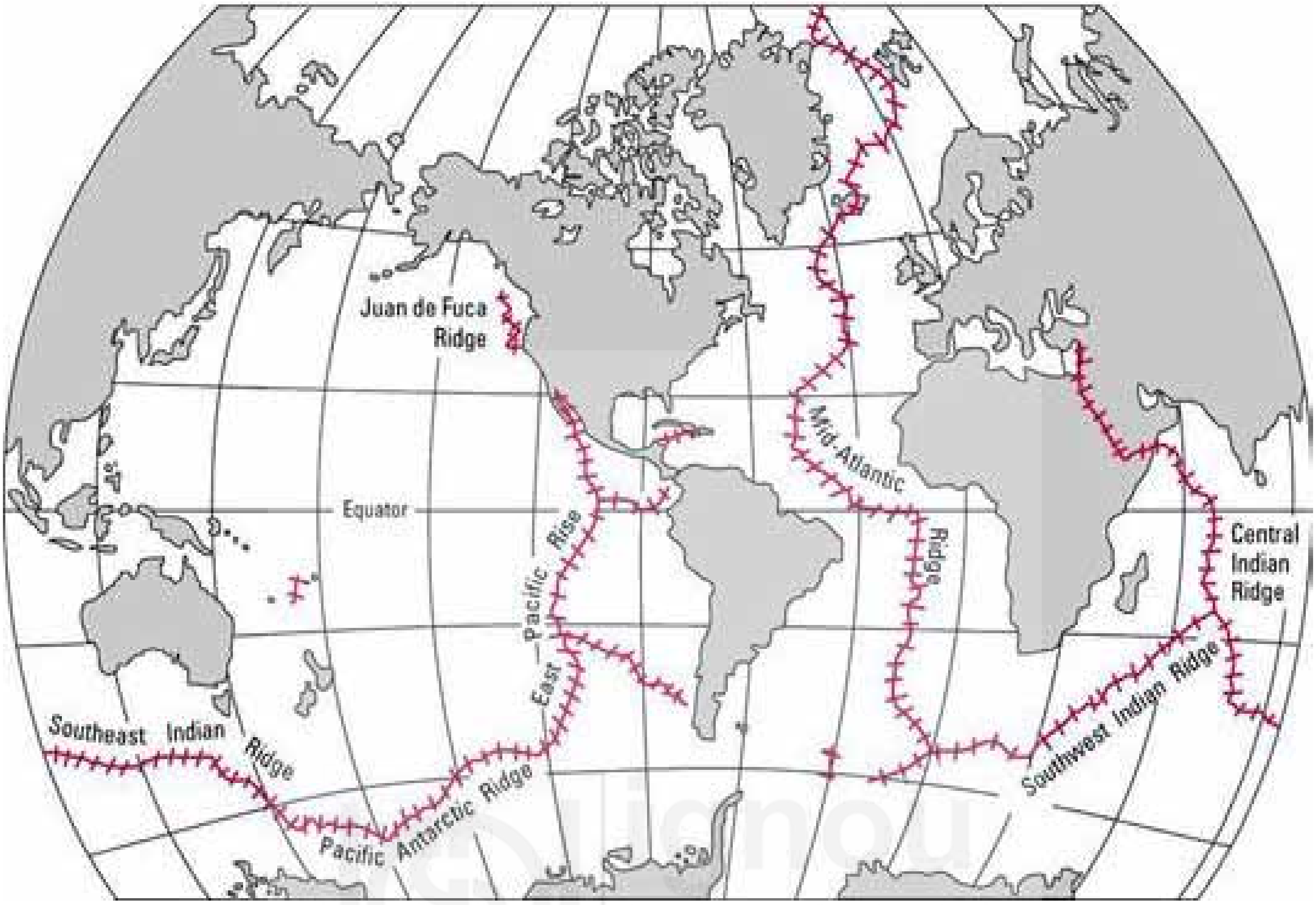


Fig. 16.2: The mid-ocean ridge (shown in red) are linear underwater mountains or highlands found on the ocean floors. (Source: www.eoEarth.org/view/article/164696)

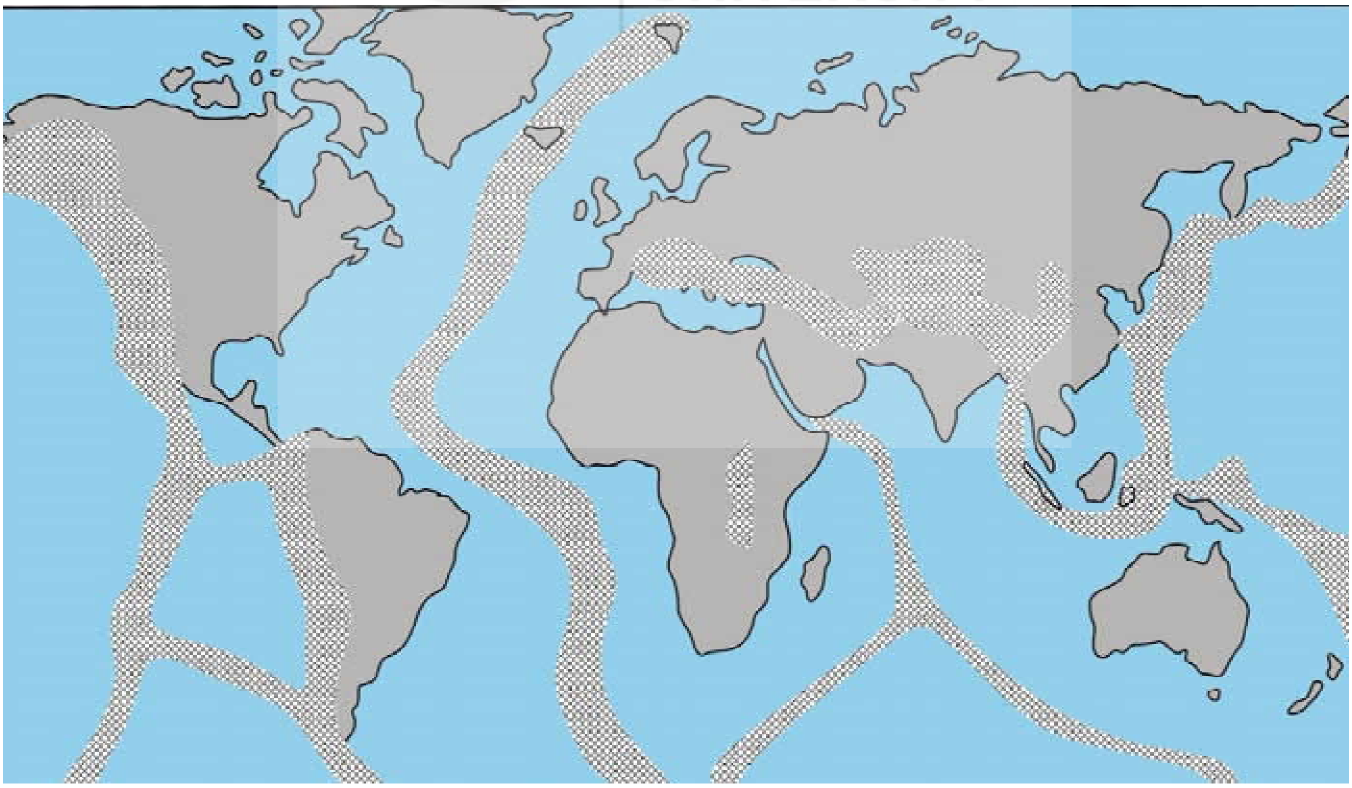


Fig. 16.3: Shaded areas show epicentres of shallow and intermediate earthquakes. Notice that majority of them occur along the mid-oceanic ridges.

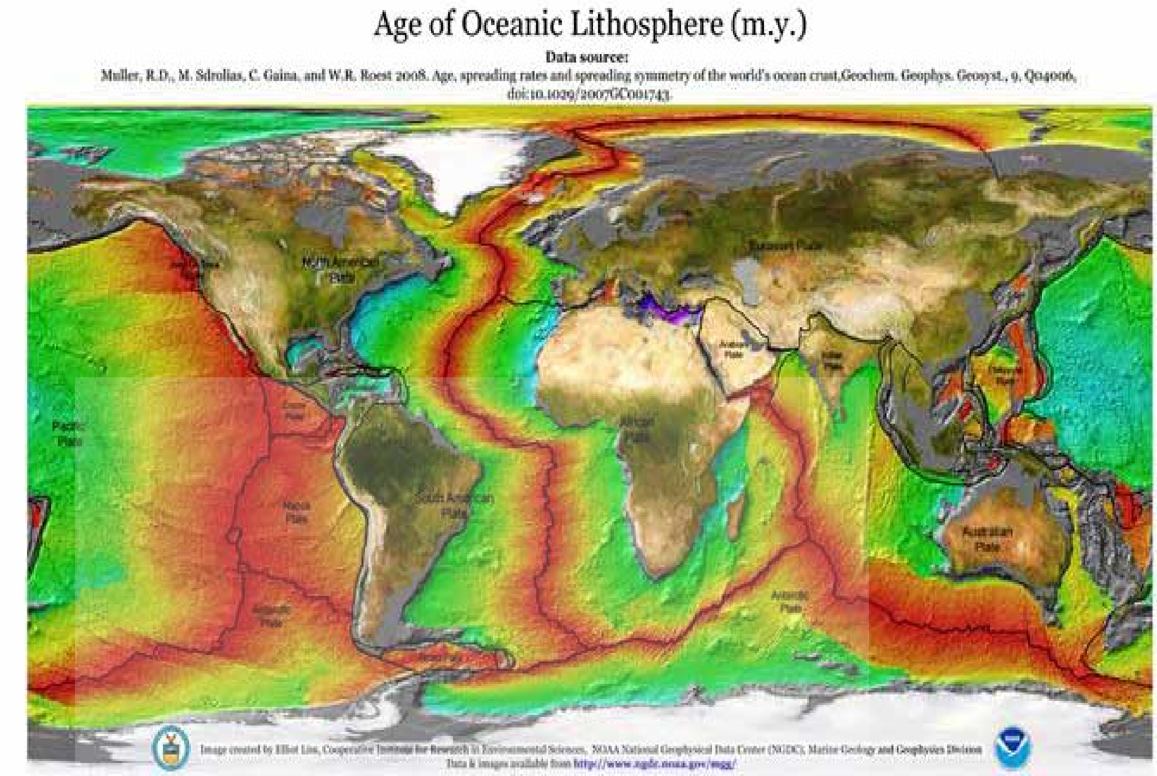


Fig. 16.4: Age of the oceanic floor. Notice that youngest ocean floor occurs along mid-oceanic ridges and older rocks occurs symmetrically both sides of the ridges towards flanks. (Source: https://upload.wikimedia.org/wikipedia/commons/e/e7/2008_age_of_oceans_plates.jpg)

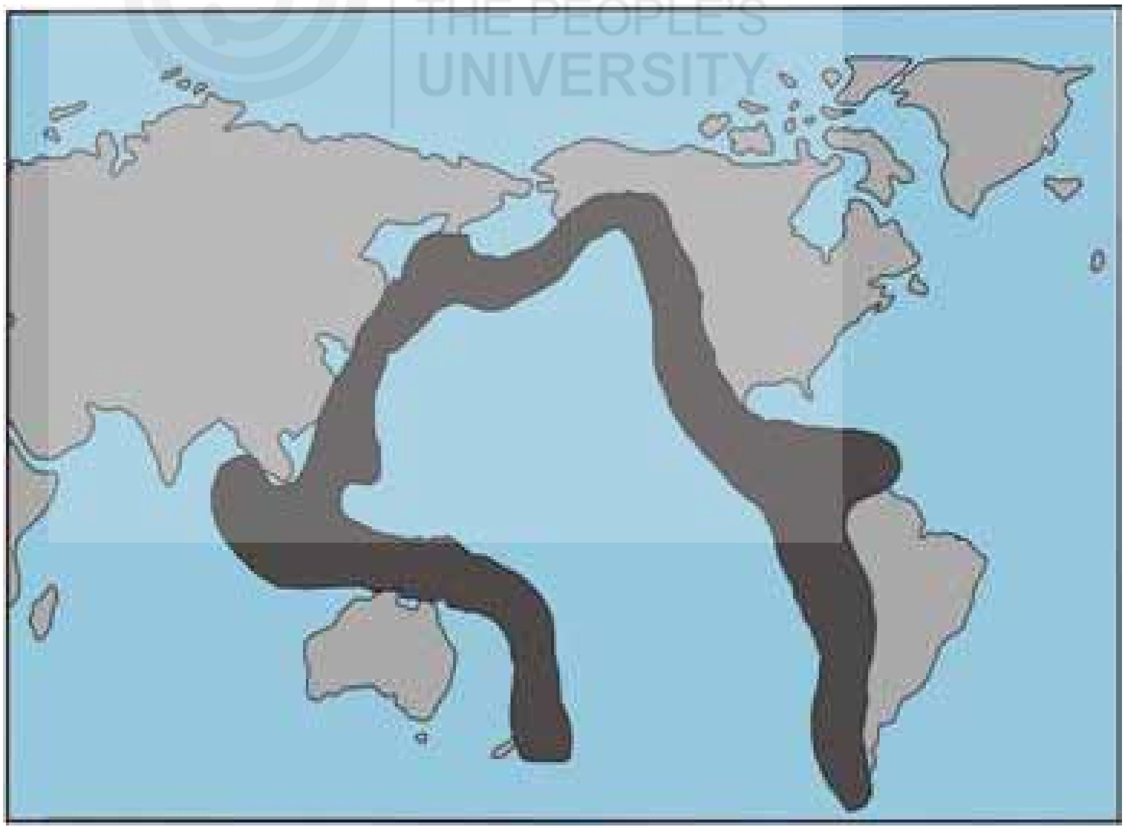


Fig. 16.5: 'Ring of Fire' (shaded area) occuring around the Pacific Ocean. The name is given so because of abundant active volcanoes present in this zone. The volcanic islands are found along arcuate lines. Notice that deep sea trenches also occur parallel to the island arcs and the ring of fire.

16.4.2 Major Plates of the World

In the current configuration, there are **seven major plates** in the world. These major plates exceed 10^7 km^2 in area (Fig.16.6).

1. Eurasian Plate
2. North American Plate
3. South American Plate
4. African Plate
5. Indo-Australian Plate
6. Pacific Plate
7. Antarctica Plate

Besides the seven major plates, there are twenty minor sized plates as well. Some of them are-Nazca plate, Scotia plate, Philippines plate, Caribbean plate, Cocos plate, Juan de Fuca plate, Arabian plate, etc.

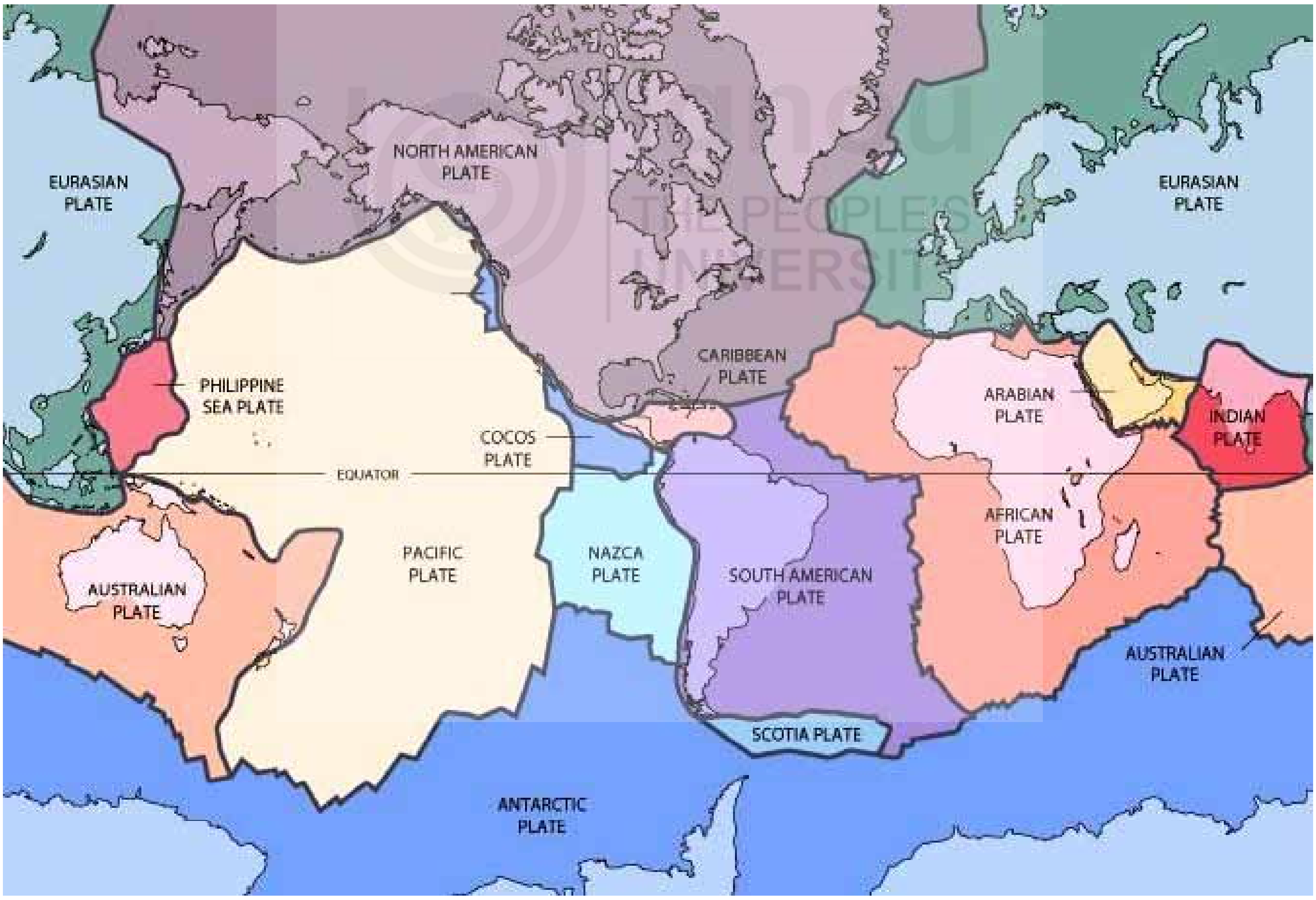


Fig. 16.6: Major tectonic plates of the world. (Source: http://indiana.edu/~g105lab/1425chap13.htm)

Let us have a look at Fig. 16.6 and try to examine the plates shown in the figure whether they are continental, oceanic or continent-oceanic type by comparing with plate boundaries and boundaries of ocean and/or continents. Now we shall read more about the plate boundaries and plate margins.

16.4.3 Plate Boundary and Plate Margin

Let us now discuss about some fascinating aspects of plate tectonics concept.

We shall distinguish between plate boundary and plate margin.

Plate boundary is the surface trace of the zone of motion between two plates. The two plate margins meet at a common plate boundary. **Plate margin** is marginal part of a particular plate.

Let us read about three basic types of plate margins or plate boundaries, based on types of their mutual interactions:

- **Divergent type**: Where two plates move away or diverge from each other. This type of plate boundary is also known as 'constructive' or 'accreting' plate boundary.
- **Convergent type**: Where two plates move towards each other or converge. This type of plate boundary is also known as '**destructive**' or '**consuming**' plate boundary.
- **Transform fault type**: Where two plates neither converge nor diverge but slide past each other. This type of plate boundary is also known as '**Conservative**' plate boundary.

These three types of plate margins are discussed in the next section at points 5, 6, 7 and 8.

16.5 PRINCIPLES OF PLATE TECTONICS

Let us now learn about the working principles of plate tectonics.

1. The lithospheric plates float over asthenosphere and move horizontally because of convection currents in the mantle. The convection currents originate from the boundary of mantle and core (Fig16.7) which move in cyclic motion in clockwise or anticlockwise direction.
2. The two plates move towards each other if the two nearby convection current cycles converge to a common direction. Where the convection currents have their movements in opposite directions, the plates floating over them also have a divergent motion relative to each other (Fig 16.7).
3. Mid Oceanic Ridges (MORs) are formed along the divergent plate boundary (Fig. 16.8). New magma rises up along the MOR to fill the gap between the two diverging plates and forms new ocean floor on both flanks of the MOR. This submarine volcanism is continuously going on along MOR. Plate tectonics assumes that the new lava once solidifies becomes part of the plate by adding up new crust in both the plates. Thus, new crust is formed at divergent plate boundary and hence the divergent plate boundaries are also called as constructive plate boundary or accreting plate boundary.

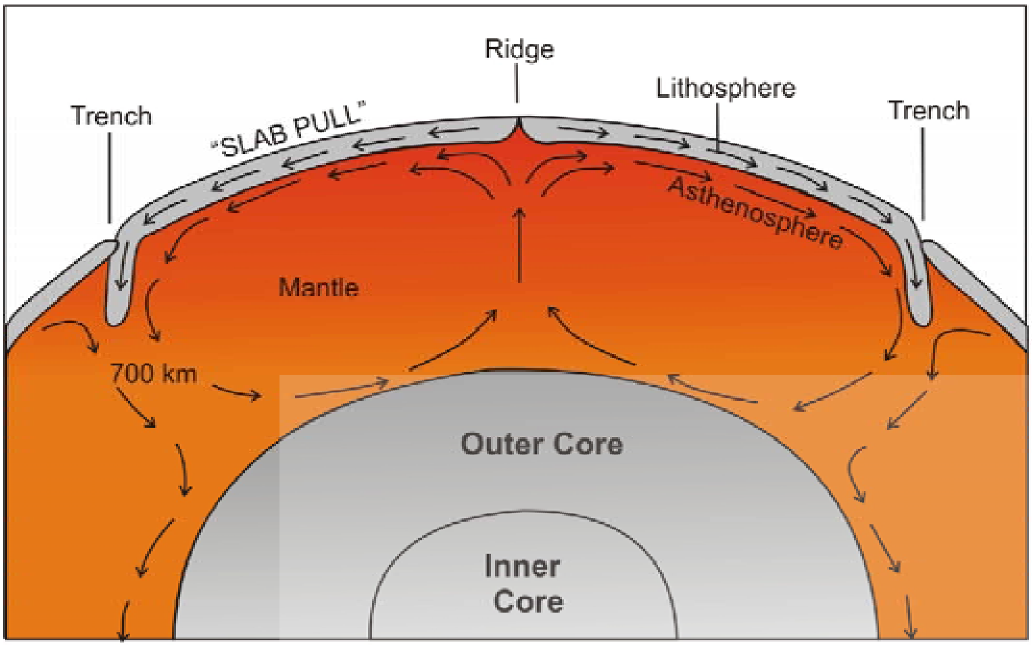


Fig. 16.7: Cells of convection currents in the interior of the Earth.
(Source: www.indiana.edu/~g105lab/1425chap13.htm)

4. Deep oceanic trenches are formed near the convergent plate boundary (Fig. 16.8 and 16.9). When the two oceanic plates move towards each other, one of them (with higher density) goes below the other. This phenomenon has been termed as **subduction**, and the downgoing plate is generally referred as **subducting plat**e while the other as **overriding plate**. The zone along which subduction occurs is known as **subduction zone** or **Benioff zone** (named after the scientist Benioff who discovered it).

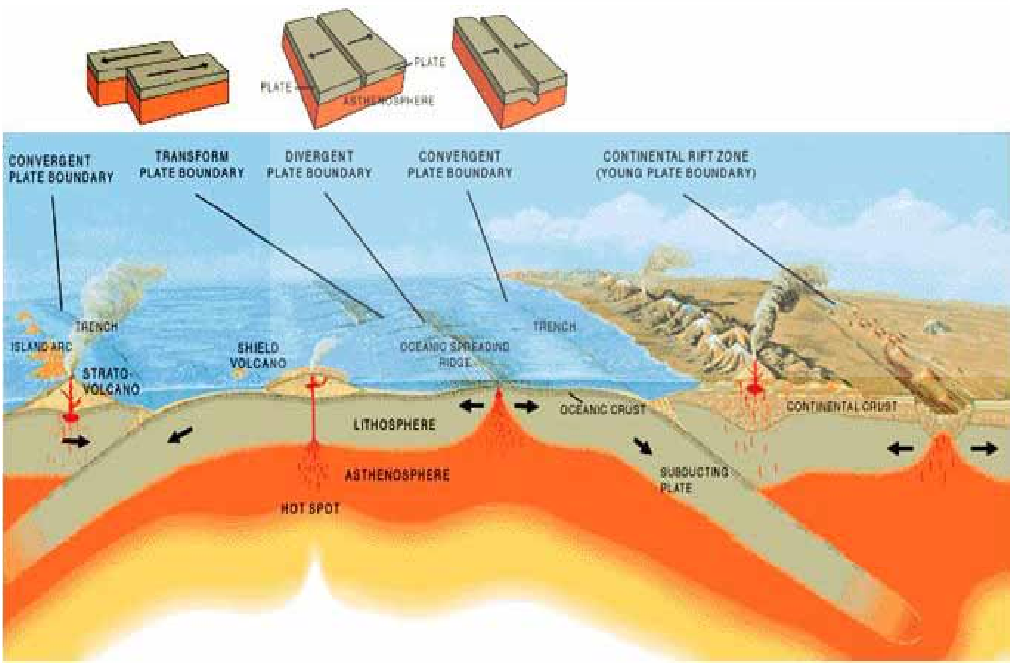
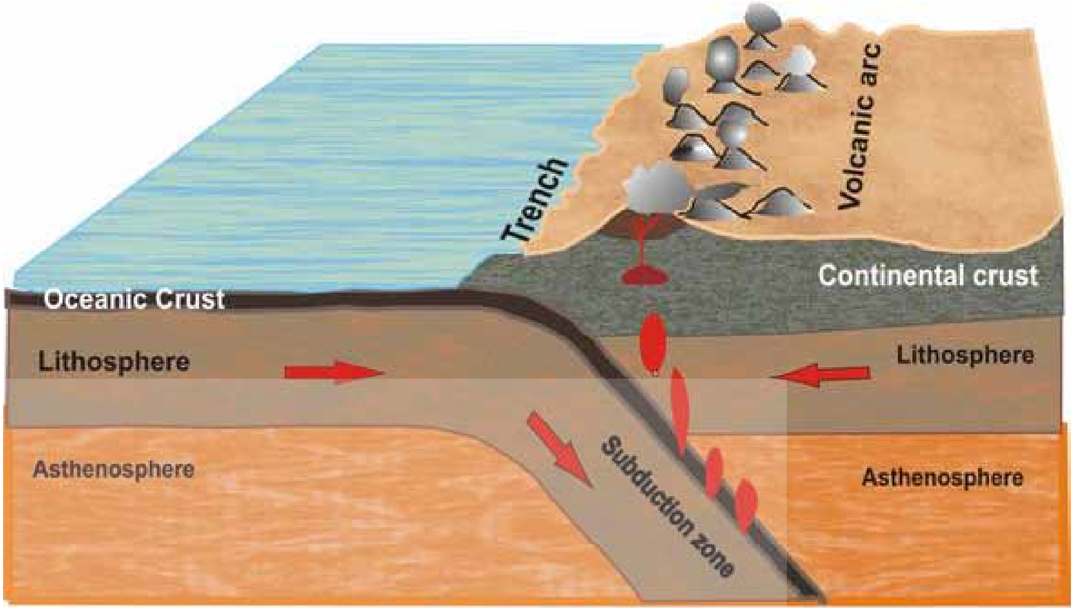


Fig. 16.8: Plates move apart from a divergent boundary and get converge along a convergent boundary according to plate tectonics theory. Mid Oceanic Ridges are displaced by transform faults at transform fault boundary.
(Source: http://indiana.edu/~g105lab/1425chap13.htm)



Oceanic-continental convergence

Fig. 16.9: Subduction zone or Benioff zone, which are only found near trenches.

5. Continuous convergence of oceanic plates causes subducting plate go deeper and deeper into the mantle where it ultimately melts due to high temperature (Fig. 16.8 and Fig. 16.9). Thus at convergent plate boundaries the crust is consumed or destroyed by melting. The convergent plate boundary is therefore often called as **consuming or destructive plate boundary**. Melting causes increase in volume of the rock material and hence the density of the new melt (or regenerated magma) is lighter than surrounding rocks. Due to buoyancy this magma rises upwards and sometimes it even reaches to the surface of the overriding plate forming volcanic islands in the ocean. We have already read in the previous section that a group of such volcanic islands is termed **island arc**.

6. In cases where convergence is between two continental plates; these plates do not undergo subduction instead they collide, deform, get folded and rise upwards to form mountains. Plate tectonics considers that continental part of the plate is made up of lightest material (sial) which cannot subduct (in denser sima) and hence it always float at top parts of the Earth. In case of convergence between continental and continent-oceanic plates, the oceanic part may subduct but not the continental part.

7. According to plate tectonics principles, the new crust are continuously being created at divergent margin and destroyed at consuming plate boundaries. Hence, the sum total of Earth's surface area is maintained as it is neither increasing nor decreasing significantly.

8. Since Earth is a spherical body, movements of the plates are adjusted by many strike- slip faults in order to maintain the spherical geometry of

the Earth. These faults are known as **transform faults** which cross cut the Mid Oceanic Ridges (MORs) (Fig. 16.8 and 16.10). It disrupts the divergent plate boundary (MORs) at many places but here no crust is being created or destroyed. Therefore, the transform fault boundary is also known as **conservative plate boundary**.

9. You have read that volcanic rock are generated at the plate boundaries, e.g. subduction zones and along the Mid Ridges. Volcanism also occurs within the plate interior. This phenomenon is known as **Intraplate Volcanism**. These intraplate regions with voluminous volcanism are called as **Hotspots.** Most hotspots are underlain by large plume of anomalously hot mantle. These mantle plumes are generated in the lower mantle and rise slowly throught the mantle by convection currents. Deccan Volcanism in India (covering many states) is the result of intraplate volcanism during Cretaceous period when Indian Plate came over the Reunion Hotspot.

- Watch this video to know about Deccan Volcanism, mantle plume and hotspot:
  Deccan Volcanism-an Inside Story
  Link : https://www.youtube.com/watch?v=1a3glcg0oGs

Fig. 16.10: Transform faults displacing mid-oceanic ridges.
(Source: http://pubs.usgs.gov/gip/dynamic/understanding.html#anchor3617237)

We have read about principles of plate tectonics and different types of plate boundaries. Let us now discuss about the features associated with these plate boundaries.

16.6 FEATURES ASSOCIATED WITH DIFFERENT PLATE BOUNDARIES

Some of the characteristic features that are generally observed along the different types of plate boundaries are summarised in the Table 16.1 with present day examples.

Table 16.1: Features observed along different types of plate boundaries

Type of Plate Boundary	Nature of Plate Boundary		
	Oceanic - Oceanic	**Oceanic - Continental**	**Continental - Continental**
Divergent	Mid Oceanic Ridge, shallow focus earthquakes, narrow belt of submarine lava on ridge flanks. Example: Mid Atlantic Ridge (Figs. 16.2, 16.3, 16.4)	-	Rift valley, shallow earthquake, wide zone of volcanoes. Example: Great African Rift.
Convergent	Oceanic trench, volcanoes and volcanic islands arcs; shallow, intermediate and deep earthquakes. Example: Mariana trench, Islands of Japan and Philippines in Pacific Ocean (Fig.16.5).	Ocean trench and mountain range in close association; shallow, intermediate and deep earthquakes, wide belt of volcanoes. Example: Peru-Chile Trench, Andes Mountains (Fig.16.5)	Younger mountain ranges, shallow and intermediate earthquakes, no volcanoes. Example: Himalaya, Alps mountains
Transform Fault	Fracture/ Fault zone of ridge and valleys at Mid Oceanic Ridge, shallow earthquakes, Narrow belt only between offset ridges, No volcanoes (Fig. 16.10)	Transform faults offsetting MOR, shallow earthquakes, broad zone, no volcanoes. Example: San Andreas Fault	-

SAQ 1

a) Define plate.

b) Distinguish between oceanic and continental plate.

c) List the seven major plates on the Earth.

d) Differentiate between divergent and convergent plate boundaries

e) How conservative boundaries are different from divergent and convergent plate boundaries.

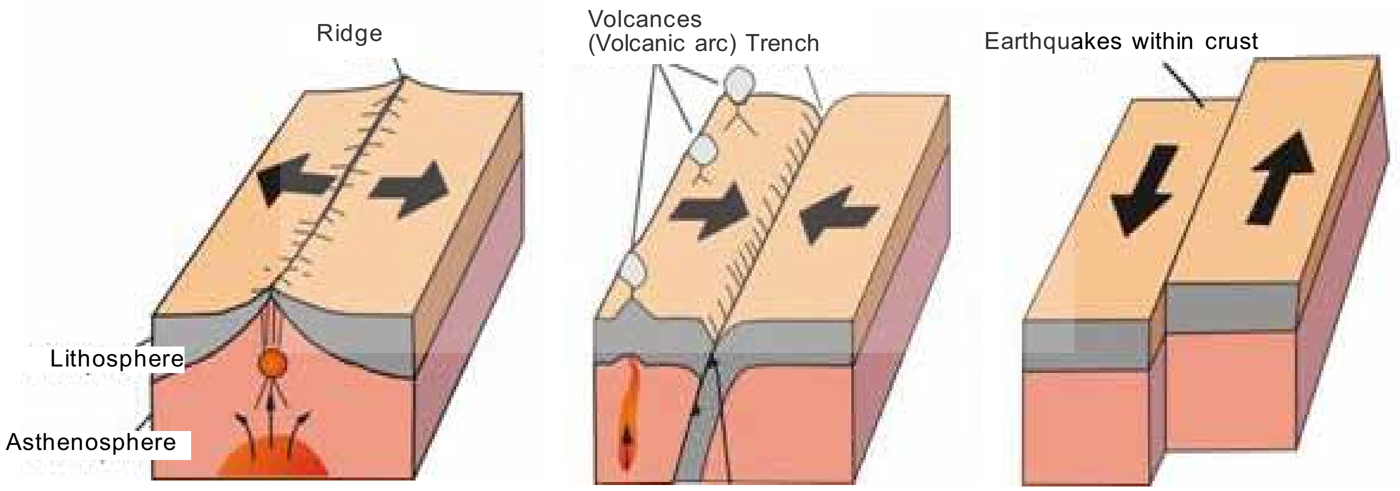
16.7 PLATE TECTONICS EXPLANATIONS FOR IMPORTANT PHENOMENA

We have read about earthquake and volcanoes in Unit 4 Earthquake and Volcanoes and about sea floor spreading, continental drift and mountain building in the previous Units 14 and 15. Let us now review the various phenomena such as earthquakes, volcanic activities, sea floor spreading, continental drift and mountain building with the help of Plate Tectonics Theory.

16.7.1 Earthquakes

Now we know that the plates are continuously moving however, we cannot see this movement because they are too slow to be noticed in life span of a human being. The movement is of the order of growth rate of your nails; say 2.5 cm/ year to 15 cm/year or so. The existing stable rocks on the globe naturally oppose this movement which results in the accumulation of stresses in the rocks. With time, these accumulated stresses exceed the strength of the rocks and the rocks get ruptured. Thus, the stored strain energy is suddenly released due to which, we experience the earthquake tremors. This theory of earthquake generation is known as **Elastic Rebound Theory** because this is just like sudden release of energy from elastic rubber bands, which suddenly breaks on continued stretching and releases the stored energy.

Focus of an earthquake is the actual place of rupture which is generally located at deeper level in the Earth. The convergent plate boundaries are highly prone to earthquakes because of opposed motion of the two plates. The deep focus earthquakes (>300 km depth) are generally found near the Benioff zone where the plates subduct to this depth (Fig. 16.11b). Therefore large number of earthquakes comes every year in the peripheral parts of the Pacific Ocean (Fig.16.12) where subduction zones occur. Shallow and intermediate focus earthquakes are common along the Mid Oceanic Ridges at divergent plate boundaries (Fig. 16.11a, 16.3 and 16.12). Earthquakes along transform fault boundary are shallow and have their focus within the crust (Fig. 16.11c).



(a) (b) (c)

Fig. 16.11: Earthquakes along different plate boundaries: a) Shallow and intermediate focus at divergent plate boundary; b) Deep focus earthqukes at convergent plate boundary; and c) Shallow focus earthqukes at transform Fault plate boundary.
(Source: http://age-of-the-sage.org/tectonic_plates/boundaries_boundary_types.html)

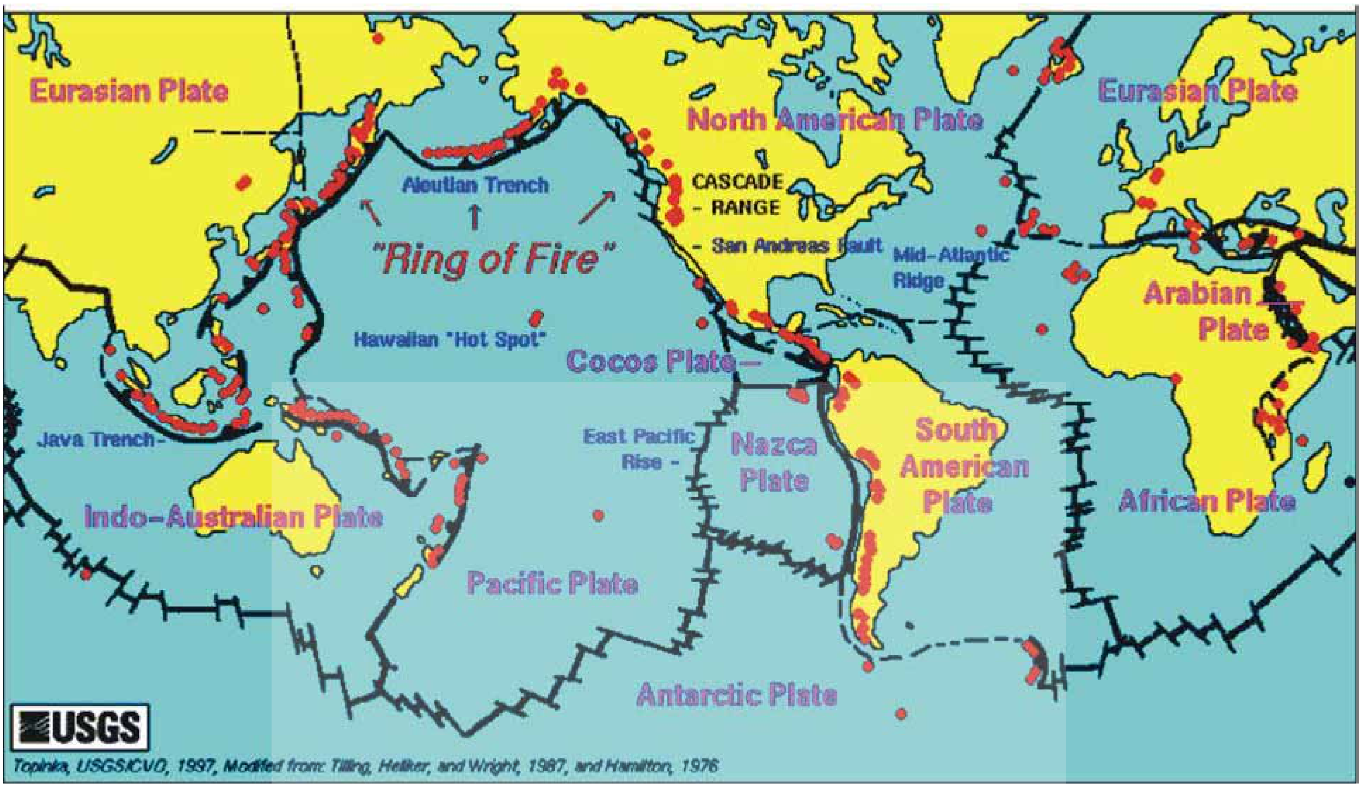


Fig. 16.12: Map showing the relationship between the earthquakes, volcanoes and the plate boundaries. Also indicated on the map is the Ring of Fire.
(**Source:** www.geology.isu.edu)

16.7.2 Volcanoes

While reading the concepts and principles of Plate Tectonics you may have realised by now that there are two types of plate boundaries along which volcanic activities may occur. These are the divergent plate boundary and the convergent plate boundary. At divergent plate boundary where two plates move away from each other, are the Mid-Oceanic Ridges (Fig. 16.8, 16.11a). Here volcanic activities always go on underwater quietly without much explosion. This is because the magma finds easy route between two opposite moving plates and no significant resistance is offered from the overlying crust.

The source of magma (magma chamber) at convergent plate boundary lies at greater depth compared to the divergent plate margins because here they are generated by the melting of the downgoing (subducting) plate (Fig.16.8 and 16.9). This magma has to travel greater distance upwards to come up on the surface after overcoming the resistance of the overlying rocks. Only those magmas are able to outpour at surface which have developed enough forces to come up on the surface. Therefore volcanoes of the island arcs near the convergent plate margins are full of explosive activities. You may note that these volcanoes occur on the overriding plates only at small distance from the deep oceanic trenches or the convergent plate boundary (Fig.16.8 and 16.9). Fig. 16.12 depicts the map of active volcanoes on the Earth along with the present day plate boundaries. The association of volcanic activities and plate margins can be easily noticed in Fig. 16.12.

16.7.3 Continental Drift and Sea Floor Spreading

Now let us learn about the explanations of Plate Tectonics theory for continental drift and sea floor spreading. According to plate tectonic theory, the phenomenon of continental drift was proposed by Wegener. The theory says that continents drift away from the divergent plate margins usually located at Mid Oceanic Ridges located at places where two convection current cycles move upwards and diverge when they reach up to asthenosphere (Fig. 16.7 and 16.8). As a result, the lithospheric plates floating above these currents also diverge which makes the continental portion of the lithospheric plate to drift away. New magma generated from magma chamber occurring at depth rises up to fill the gap developed by divergent motion of the plate at Mid Oceanic Ridge (MOR). Thus, new lava is added up in the ocean floor to form new crust in both the diverging plates. One of the basic assumptions of the plate tectonic theory is that the new lava after its solidification is not a separate entity but it becomes a part of the any of the two plates over which it solidifies. You will recall that because of this, the boundary is also called as constructive or accreting plate boundary. The newly formed oceanic crust is added to expand the ocean floor or in other words, the ocean floor spreading occurs. This process occurs in such a way that the youngest crust is always along the MOR and oldest ocean floor on the flanks of the ocean towards the continent (Fig 16.4). The newly formed oceanic crust forces to move the entire plate including the continental part associated with the plate, symmetrically away from the spreading centre, that is, Mid-Oceanic Ridge. As a result continents too drift away from MOR or continental drift occurs. The Atlantic Ocean presents a typical example of such continental drift as shown in Fig. 16.4.

16.7.4 Mountain Building

The processes of mountain building operate at convergent plate margins where two lithospheric plates are located over two converging downwards convection current cycles in mantle. Because of convergence, one plate goes down or subducts below the other and finally melts up due to high temperature at depth and get destroyed or consumed. We should note that only the oceanic part of the lithospheric plate can subduct not the continental part because continents are made of lighter density masses. When the oceanic part of the plate is completely subducted, the continental parts of the plates collide against each other due to continued convergence. It is important for us to note that the continental part or sialic crust can never go down to subduct because it is less dense. Recall that you have read about sialic crust in Unit 3. The continental or sialic part of the crust is just like the cream floating over milk which cannot be immerse into denser milk. Buoyancy does not allow continental crust to subduct. This collision of the plates causes upward movement of the continental material or sediments and thus the mountains are formed. Compressional forces cause folding of the sediments therefore; these mountains are also called as Fold Mountains. The continued convergence of plate causes rise of mountains higher and higher as in the case of Himalaya which is still rising. In nutshell, we may summarise that according to the plate tectonic theory, 'the mountains are formed due to collision of continental plates at convergent plate boundary'.

Let us now comprehend in the light of plate tectonics concept the story of formation of the Himalaya which resulted due to the collision of Indian plate with Eurasian plate.

16.8 CASE STUDY: EVOLUTION OF HIMALAYA

- Watch these two videos to know about Himalaya and its evolution
  1. Himalaya-an Overview
     Link : https://www.youtube.com/watch?V=VK5Cglisa1Y
  2. Evolution of Himalaya
     Link : https://www.youtube.com/watch?V=g VGZKqrjVZY

Himalaya is one of those mountains of the world, which are still in the process of growing. In order to describe the evolution of Himalaya scientists begin the story from about 250 million years ago (Permian period) when all the continents were united as a single supercontinent 'Pangaea' (Fig. 16.13a) and all the oceans as Panthalassa.

- Initially, Pangaea fragmented into two major landmasses called Laurasia -comprised of North America, Europe, Asia, Greenland, etc.) and Gondwanaland- comprised rest of the continental world including Africa, South America, Antarctica, Australia, India, etc. Around 200 million years ago (Triassic period), Laurasia started moving towards north while Gondwanaland towards south. The new ocean created between these two major landmasses was named as Tethys Ocean (Fig.16.13b).
- Further fragmentation of Gondwanaland occurred around 145 million years ago (during Jurassic period) and Indian landmass (now onwards called as Indian plate) started moving northwards, as a result a new ocean called 'Indian ocean' was created (Fig.16.13c). The newly created Indian Plate was a continent-oceanic type.
- Continued movement of Indian plate allowed Indian Ocean to expand at the cost of Tethys Ocean. The northward movement of Indian plate caused convergence between Indian Plate and north lying Eurasian Plate (Fig. 16.13d). As a result, the oceanic part started subducting below the Eurasian plate. Fig. 16.13d presents the land and ocean configuration at about 65 million years ago (during Cretaceous period), where you can see that area of Tethys Ocean has decreased while that of the Indian Ocean increased.
- Gradually, all the oceanic crust of Indian plate got subducted and consumed. The Tethys Ocean lost its existence (Fig.16.13e) and the sediment pile of Tethys Ocean started crumpling or folding due to

compression. You have realised that continental or sialic material cannot subduct so; they started rising upwards and formed the Himalayan Mountain. Today, the Himalaya represents an example of mountain which is formed by continent-continent collision (Fig.16.14) Since Indian Plate is still moving towards north, the Himalayas are still rising.

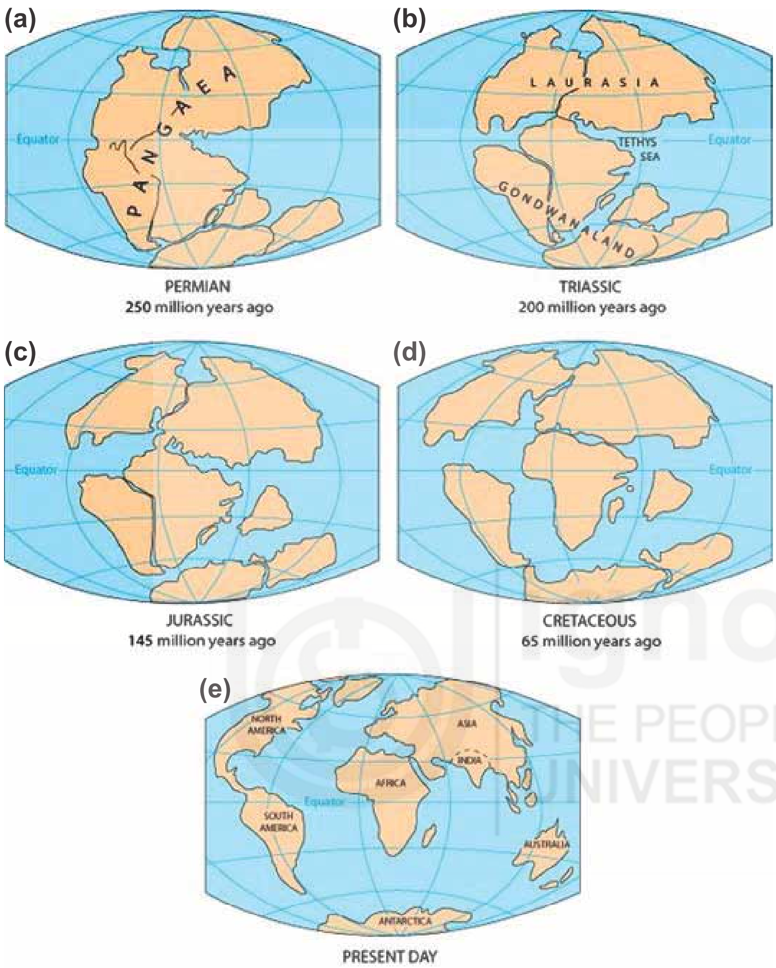


Fig. 16.13: Stages of Evolution of Himalaya from Permian period onwards. (Source: http://i.livescience.com/images/i/000/047/334/i02/Pangaea.jpg?1365037770)

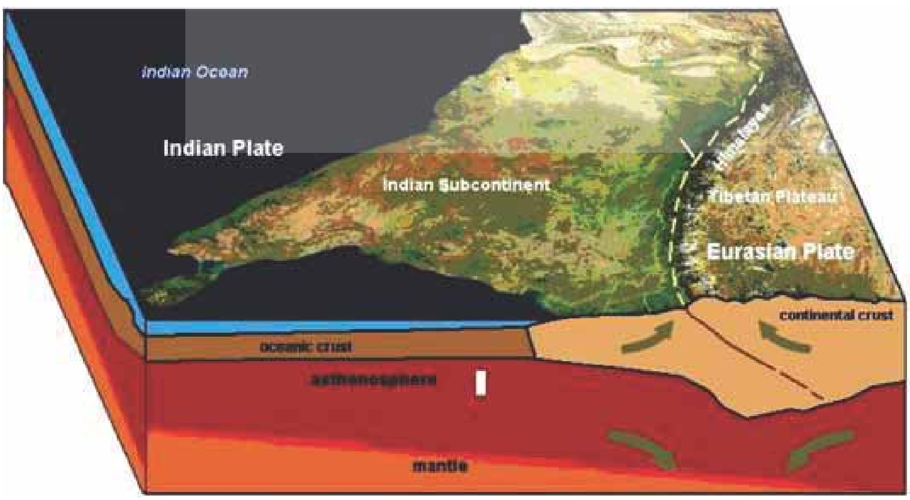


Fig.16.14: Formation of the Himalayas.
(Source: www.geologycafe.com/images/boundary_India.jpg)

We have now recognised that though the Earth is a dynamic planet and the plate tectonics processes are operational on the Earth. We have knowledge of these processes but we have no control over them. The more we know about plate tectonics, the better we can appreciate the grandeur and beauty of the land upon which we live, as well as the occasional violent displays of the Earth's awesome power. We can be aware of the zones prone to earthquakes and volcanic activity and take measures to minimise loss through preparedness.

SAQ 2

a) Why are deep focus earthquakes common in Japan?

b) Where is 'ring of fire' located and why?

c) How would you integrate the plate tectonics explanations for continental drift and sea floor spreading?

d) According to plate tectonic theory what conditions are essentially required for mountain building?

16.9 SUMMARY

Let us summarise what we have learnt in this unit:

- Lithosphere is the segment of the Earth which comprises Earth's crust and a part of upper mantle lying above asthenosphere. Plate Tectonic theory assumes that Earth's lithosphere is divided into numerous plates that move and interact with one another. Seven plates namely, Pacific, Eurasian, Indo-Australian, North American and South American African and Antarctic plates are the major plates of the Earth besides 20 other minor plates.
- The plate boundary is the surface trace of the zone of motion between two plates and plate margin is marginal part of a particular plate.
- There are three types of plates: oceanic, continental and continental-oceanic plate.
- The three types of plate boundaries are divergent type (found along Mid-Oceanic Ridges), convergent type (found along Deep Oceanic trenches) and transform fault type (found across the Mid Oceanic Ridges).
- The plate tectonic theory says that during convergence of the plates, a part or whole of the oceanic plate 'subducts" or goes below the other plate and get consumed. This way a balance in the ocean floor spreading and ocean floor shrinking is maintained and the surface area of the Earth remains almost same.
- Plate tectonic theory postulates that the mountains are formed by the collision of two continental plates which converge towards each other. The theory of plate tectonics is by and large most accepted theory of mountain building.
- This process of mountain building is still going on in case of Himalaya due to collision of Indian plate with Eurasian plate.

16.10 ACTIVITY

1. Observe the physical features of the world using the world atlas and try to locate different mountains on a world map.
2. Try to locate different Oceanic trenches and Submarine ridges or the Mid Oceanic Ridges.
3. Match these geotectonic features with the plate boundaries shown in Fig. 16.6.

16.11 TERMINAL QUESTIONS

1. Discuss the basic considerations of plate tectonics theory.
2. Explain the activities that occur along divergent plate margins.
3. Elucidate the activities that occur along convergent plate margins. Give examples of convergent type of plate boundaries.
4. Elaborate the formation of the Himalaya.

16.12 REFERENCES

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- https://igs.indiana.edu/Geothermal.
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16.13 FURTHER/SUGGESTED READINGS

- http://pubs.usgs.gov/publications/text/dynamic.html.
- Kearey, P. and Vine, F.J. (2009) Global Tectonics, 3rd Edition, Blackwell Science Ltd.

16.14 ANSWERS

Self-Assessment Questions

1. a) A plate is considered as a rigid segment of lithosphere, assumed to move horizontally over the asthenosphere. Lithospheric plates are about 100km thick and comprise crust and the upper part of mantle.

   b) Oceanic plate comprises entirely of oceanic crust constituted of SiMa. The Oceanic plates grow at Mid-Oceanic Ridges and consumed near Deep Oceanic trenches in a subduction zone.

   c) Continental plate is comprised of continental crust which is constituted of sial at upper level and SiMa at lower level. The continental part of the plate is responsible for mountain building.

   Eurasian Plate, North American Plate, South American Plate, African Plate, Indo-Australian Plate, Pacific Plate and Antarctica Plate.

   d) Divergent type plate boundary, also called as constructive or accreting plate boundary, is the common boundary between two such plates which move in opposite direction or diverge. Similarly, convergent type plate boundary also called as destructive or consuming plate boundary is that boundary where the two adjacent plates move towards each other or converge. Divergent plate boundary is found along Mid-Oceanic Ridge while convergent plate boundaries near deep oceanic trenches and island arcs.

   e) Transform fault type where two plates neither converge nor diverge but slide past each other.

2. a) Japan is close to active subduction zone between Pacific plate and Eurasian Plate. Deep focus earthquake originate most commonly in subduction zone. Lithospheric plates go deeper in the subduction zone.

   b) 'Ring of fire' is zone of active volcanoes surrounding the Pacific Ocean.

   These active volcanoes are formed due to rising of that magma which generates due to melting of down going or subducting plate.

   c) Hint: See section 16.7.3

   d) Hint: (a) The two plates must be convergent plates, (b) The two plates must have continental lithosphere, (c) There should be enough convergence so that continent-continent collision actually occurs.

Terminal Questions

1. Your answer should include all the points mentioned in section 16.2.
2. Please refer to sections 16.5 and 16.6. Your answer should include point No. 2, 3 and 7 in section 16.5 and the points mentioned about divergent plate boundary in section 16.6, Table 6.1(first row).
3. Please refer to sections 16.5 and 16.6. Your answer should include point No. 4, 5, 6 and 7 in section 16.5 and points mentioned about convergent plate boundary in section 16.6, Table 6.1 (second row).
4. Your answer should include the content given in section 16.8.

NOTE

NOTE

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