1 The Dynamic Earth

Introduction :

Away from the bustling noise of crowded cities or man-made activities; the Earth appears like a stable, calm and peaceful planet in tranquillity of nature. It is however a highly dynamic planet similar to all other planets in the Solar system; and is orbiting around the Sun at ~30 km/s. It is also internally dynamic, as evident from the phenomena of plate tectonics operating through geological ages. The Earth on its surface is undergoing many dynamic processes as expressed by the activity of oceans, rivers, glaciers, winds and atmospheric circulation. We can distinguish the Earth's dynamism into: a) the orbital or planetary dynamics; b) the surface dynamics or Earth surface processes; and c) the internal dynamics as part of the evolution of the Earth. This chapter describes the internal dynamics of the Earth. It is therefore, necessary to learn about the internal structure/interior of the Earth in order to understand its expression on the surface by the processes such as plate tectonics.

The Interior of the Earth :

The Earth evolved as a planet from Solar nebula at about 4.56 Ga, and gradually shaped into a spherical body (fig.1.1). With the ongoing cooling, the outermost layer called the crust was formed. The temperature of the universe is of the order of -270 °C, and the Earth's interior is at >4000 °C. Presently the average surface temperature of the Earth is 14°C - 15°C, and the temperature at the core of the Earth is 6000 °C. This results in temperature gradient with the Earth's interior. This temperature gradient of the Earth is however not linear and shows several kinks that are influenced by the compositional layering (fig. 1.2). The heat loss occurs by processes such as conduction, convection and advection. Whereas, the heat generated is mainly in the form of the primordial heat accrued during the formation of the planet. Convection and advection being physical processes, the Earth material in the form of magma is simultaneously undergoing differentiation and mixing to cause depletion of original magma that was available during the early part of planetary evolution. Convection plays a major role in driving the plates, (fig. 1.2, 1.3) while advection gives rise to formation of ocean floor and other events like lava eruption on the surface.

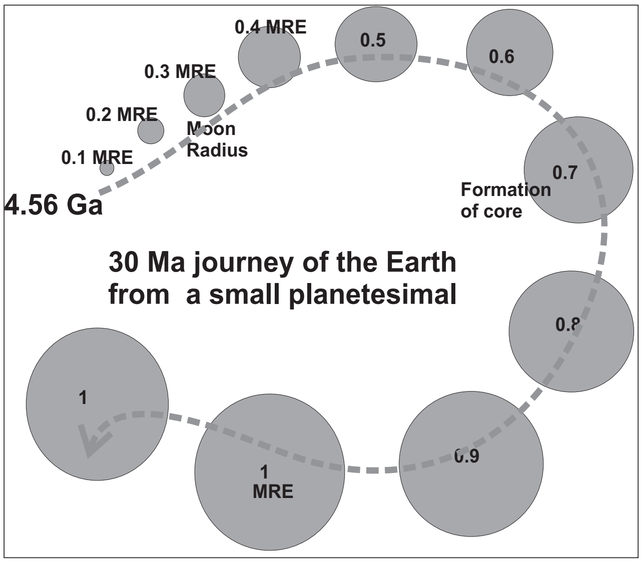


Fig. 1.1 : Evolution of the Earth from a planetismal state

Formation of the Earth from an asteroid like body to a spherically layered Earth system at ~4.53 Ga is one of the most dynamic internal process the Earth has experienced in its early stage of evolution. Note the step-wise differentiation particularly at 0.3 MRE (mean radius of the Earth), initiation of magma oceans at ~0.5 MRE and segregation of the core at 0.7 MRE (fig 1.1). The overall size of the planet is increased because of addition of mass as the Earth cleared its own orbit.

process facilitates layering of the Earth where compositional and temperature stabilities are achieved. These processes were more dynamic during the initial phase of evolution of the Earth. Heavier elements like Fe and Ni sank towards the center of gravity of the Earth forming the inner core.

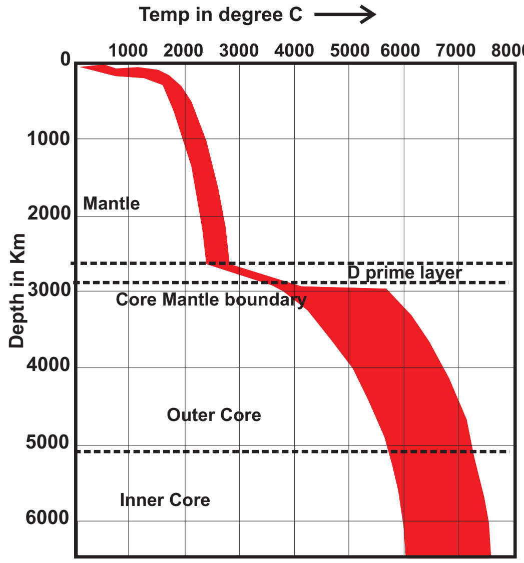


Fig. 1.2 : Internal layering of the Earth

Earth comprises mainly of silicate compounds (minerals) having definite crystal structures and compositions that remain stable at particular pressure (P) and temperature (T) conditions of the molten magma to solid rocks. Molten magma is dynamic and experiences changing Pressure - Temperature (P-T) conditions due to its upward/downward movement (convection and advection). Change in temperature with depth is influenced by the convection current that governs physical movement of the magma.

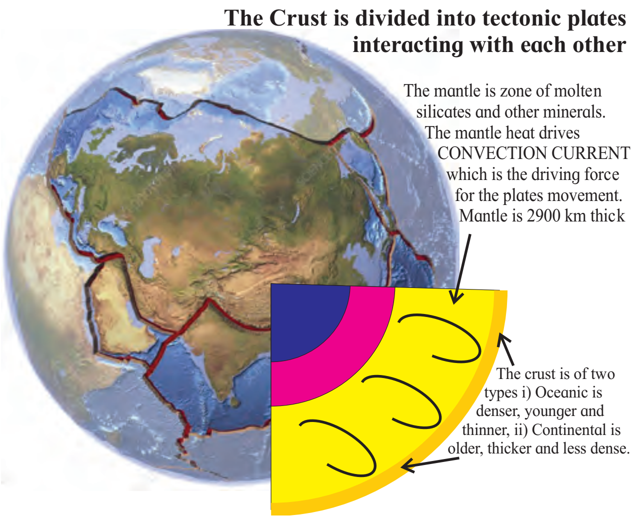


Fig. 1.3 : Convection current governing the surface dynamics of the Earth

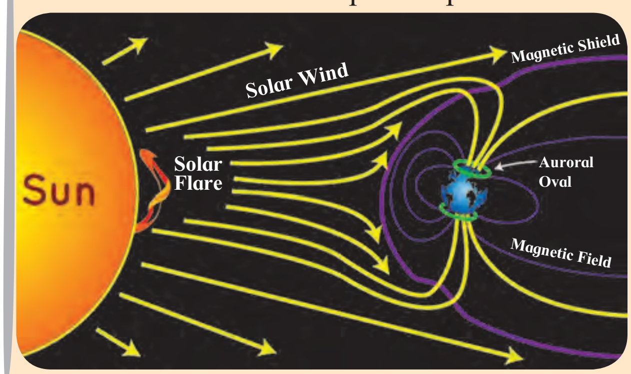
Convection also facilitates differentiation of magma compounds, where heavier melt (compounds) sink deeper into the Earth. This

A) The Core:

Core is divided into inner and outer core as a result of P-T stability conditions of Fe-Ni compounds wherein P increases the melting point of Fe-Ni compounds making the inner core to remain solid. Lowering of the Pressure at about 5100 km results in melting of Fe-Ni matter to produce the liquid outer core. The outer core being liquid, is therefore more dynamic and the convection currents created are supposed to generate the Earth's magnetic field.Information about the core is obtained indirectly from seismology.

Do you know?

The magnetic field generated by the Earth's core, protects it's surface from the solar winds that are high energy electromagnetic radiations, of potentially harmfully charged particles. Without the magnetic field, the Earth would be an inhospitable planet.



Inner Core :

The temperature at the centre of the Earth reaches upto ~ 6,000°C and is largely considered to be the heat left over after the planet's creation (primordial heat), apart from other sources like heat generated by radioactive decay. Inner core is ~1,200 km thick, and is about the same size as the Earth's moon. Due to the tremendous pressure, material in the core does not melt and hence it remains solid.

The Outer Core :

The outer core is ~2,200 km thick. Density of the outer core is about 10 -12 gm/cc. The temperature in the outer core ranges from 2,200°C to 4,900°C. The molten material comprises mostly of iron with little nickel. About 10% of it is made up of other elements, most likely oxygen and sulphur.

Discontinuities are layered boundaries in the interior of the Earth discovered through seismic studies.

Boundary between inner core and outer core is named as Lehmann discontinuity after its discovery by the Danish seismologist Inge Lehmann (fig. 1.4).

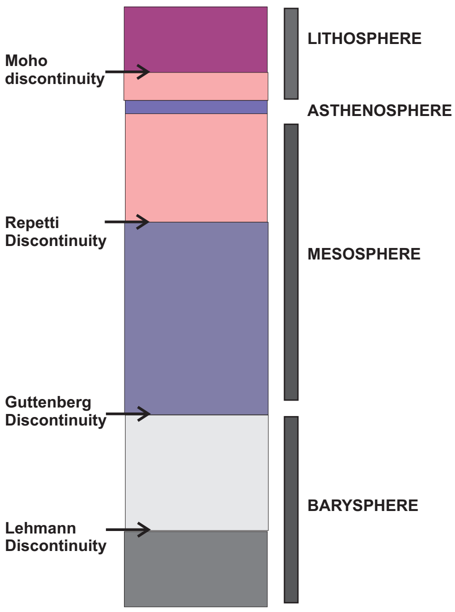


Fig. 1.4 : Discontinuities in the interior of the Earth

B) The Mantle :

Earth's Mantle has a thickness of about 2900 kms. It is the most important layer governing the geodynamic processes of the Earth. Mantle is divided into upper (~640 kms) and lower mantle (~2200 kms).

Lower mantle : It is more viscous than the upper mantle and it convects slowly. It is known to have temperatures as high as 2,200°C. Lower mantle compositionally contains magnesium, silicon and oxygen with small amounts of iron, calcium, and aluminium to forms a typical mineral known as perovskite ($MgSiO_3$).

Upper mantle : The upper mantle consists of two different types of layers, namely lithosphere and the asthenosphere. The rigid lithosphere is composed of a rocky crust that is ~40 kms to 280 km thick and floats on top of the asthenosphere. Asthenosphere is ~180 km thick with temperature as high as ~1,450°C. Asthenosphere is less rigid than the lithosphere and behaves plastically. Lithosphere mainly represents the rock composition known as peridotites, which contains the mineral olivine and pyroxene. Peridotites are heavier than most of the crustal rocks and therefore they tend to sink into the upper mantle.

The Crust :

The Crust is brittle and most fragile outermost layer of the Earth and is the main source of earthquakes. It represents mountains, ocean floor and all the landforms and is part of lithosphere. Crust under the oceans is thin, measuring 5 to 10 km and under land is between 20 and 70 km. It is therefore, divided into two types: oceanic crust and continental crust.

The oceanic crust found beneath the oceans is composed of basalt, while the continental crust is largely made up of granites. However, a large part of the continental crust is eroded and transferred to the ocean basins in the form of sediments which can later be recycled along with the oceanic crust. Rocks as old as 3.8 Ga can be found on the continental crusts; and are the source of information for the geodynamic history of the Earth. Continents are therefore a rich source of knowledge about the evolution of the Earth.

Earliest impressions of the dynamics of the Earth were philosophically routed and several hypothesis were proposed. It was during the early 17th century that the dynamics of the Earth were understood from geological records. As discussed and hypothesized by many philosophers and geologists during the 17th century, continents are floating over the asthenosphere making the continental/ lithospheric plates. The most acceptable explanation of these observations has been offered by the theory of 'Continental Drift'.

The Continental Drift Theory:

Internal dynamics of the Earth is expressed by changes on its surface i.e., the crust. For over a long time, humans were unable to explain the origin of various surface features of the Earth, and it was during early 17th Century when the geological idea of continental drift evolved as a hypothesis and a school of thought. It faced many criticisms due to imagination and limitations to explain the driving forces. This was also due to the state of knowledge of science and technology until the advent of geophysics (particularly seismology and magnetism) during the nineteenth century. However, the continental drift is the basic theory which evolved the concept of plate tectonics, a revolution in geology. It is therefore necessary to learn both these aspects in detail which are pivotal to understand many of different subjects within the scope of Geology.

Do you know?

The theories of continental drift and plate tectonics are evolved over four centuries as accounted in the time line below :

1620 Francis Bacon noted 'conformable instances' along the opposite sides of the mapped Atlantic coastlines.

1858 Antonio Snider-Pellegrini suggested that 'the continents were linked during Carboniferous Period'. He observed that plant fossils in coal-bearing strata of that age were similar in both Europe and North America.

1885 The famous Austrian geologist Edward Seuss identified similarities between plant fossils from South America, India, Australia, Africa and Antarctica to suggest the name 'Gondwana' (after the indigenous homeland of the Gond people of India). He defined it as an ancient supercontinent 'Gondwana Land' surrounded by the ancient ocean named 'Tethys'.

1910 American physicist and glaciologist Frank Bursley Taylor proposed the concept of 'continental drift' to explain the apparent geological continuity of the American Appalachian mountain belt (extending from Alabama to Newfoundland) with the Caledonian Mountains of NW Europe (Scotland and Scandinavia), occurring on two opposite sides of the Atlantic Ocean.

1912 Alfred Wegener, the German meteorologist who spent his entire life to gather evidences re-proposed the theory of continental drift. He compiled a considerable amount of data, and suggested that during the late Permian, all the continents were once assembled into a supercontinent named 'Pangaea', meaning all Earth. Pangaea began to break apart after the beginning of the Mesozoic Era, about 200 Ma ago, and continents then slowly drifted into their current positions.

1937 South African geologist Alexander du Toit supported to the theory by drawing maps illustrating a northern supercontinent called Laurasia (i.e. the assembled land mass of North America, Greenland, Europe and Asia) as explanation for distribution of coal-forming plants, and widely scattered coal deposits in the Northern Hemisphere.

1944 Wegener's theory was also consistently promoted by an eminent British geologist and geomorphologist Arthur Holmes in 1930s and 1940s, through his renowned book 'Principles of Physical Geology'.

1940–1960 The ocean floor topography was discovered through improvements in geophysical surveying after World War II. Harry Hess (captain in the US Navy, later professor at Princeton), proposed 'Seafloor Spreading', a pivotal concept to continental drift and plate tectonics

1961 The American geologists Robert Dietz, Bruce Heezen and Harry Hess proposed that the linear volcanic chains called mid-ocean ridges in the ocean basins are the sites of ocean floor spreading.

1963 Two British geologists, Fred Vine and Drummond Matthews, finally proposed a hypothesis that convincingly explained magnetic reversal stripes onto the ocean floor. They suggested that the new oceanic crust formed in the process of ocean floor spreading acquired its magnetisation in the prevailing global magnetic field. By linking these observations to Hess's sea-floor spreading model, they laid the most convincing foundation and proof for modern plate tectonics.

1965 Canadian Professor J. Tuzo Wilson offered a fundamental reinterpretation of Wegener's continental drift theory and became the first person to use the term 'plates' to describe the division and pattern of relative movement between different regions of the Earth's surface (i.e. plate tectonics).

1960s - Present day. There was an increasingly wide acceptance of the theory of plate tectonics gaining a better understanding of the boundaries and structure of the lithospheric plates, with several modern tools of approach.

Continental Drift Theory :

Alfred Wegener proposed this theory in 1915 published in a book entitled 'The Origin of Continents and Oceans'. He proposed the existence of Supercontinent called Pangaea that began breaking apart about 200 million years ago (fig. 1.5).

Fig. 1.5 : Reconstruction of the supercontinent Pangea

He further gathered various evidences to prove that the Continents were drifted to present positions. The evidences used in support of continental drift hypothesis are shown in (fig. 1.6): A) Fit of the continents, B) Fossil similarities across continents, C) Matching of mountain ranges on different continents, D) Rock types, structural similarities and E) Paleoclimate evidences.

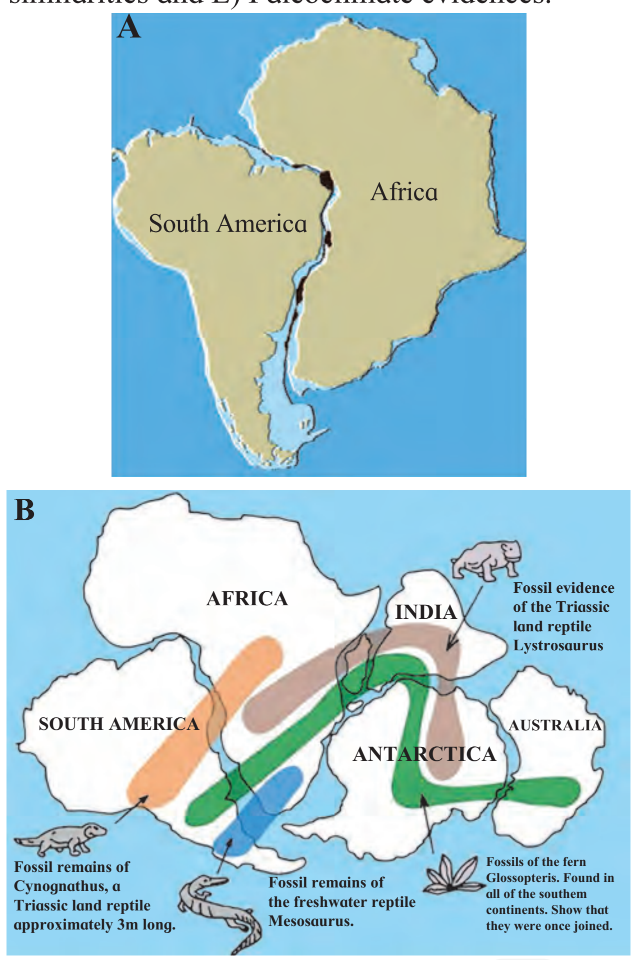


Fig 1.6 : (A-E). Various evidences as foundation to the theory of continental drift

Major objection against the theory of continental drift was its inability to provide a mechanism capable of moving continents across the globe. Wegener drift theory suggests that, continents broke through the ocean crust, much like ice breakers cut through ice was not convincing. The renewed interest in continental drift was supported by the ocean floor magnetic anomalies and the apparent polar wandering. Records from ocean floor also explained the driving mechanism and forces. This encompassed the foundation to another great theory called Plate tectonics.

Plate Tectonics :

During the 1950's and 1960's new technology permitted extensive mapping of the ocean floor which mainly benefited the geoscience community to refine the continental drift with scientific evidences. In 1963, Fred Vine and D. Matthews linked the discovery of magnetic stripes in the ocean crust near ridges to Hess's concept of seafloor spreading. They revealed that the ridges were spreading and creating new crusts (fig. 1.7); and if dated they can find the rate of sea floor spreading. These rates of seafloor spreading are accurate to the drifting of adjoining continents.

FORMATION OF MAGNETIC ANOMALIES AT A MID-OCEAN RIDGE

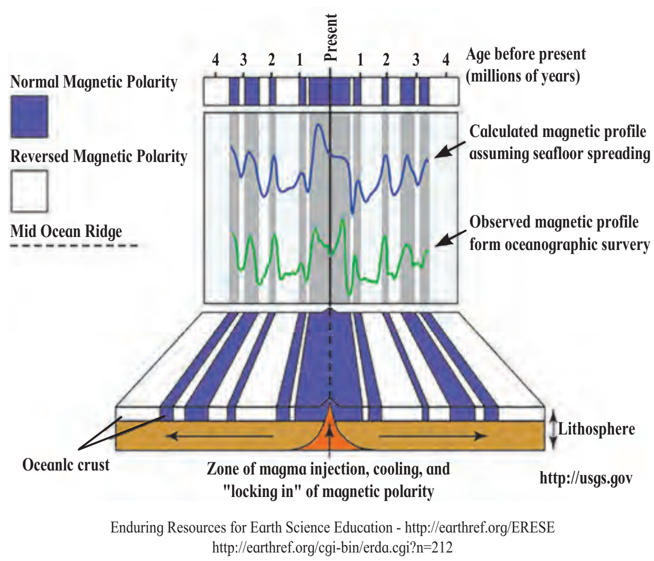


Fig. 1.7 : Symmetry of anomaly pattern with respect to ridge depicting the centre of spreading in opposite direction

Plates are well defined by belts of seismicity e.g. linear pattern of earthquake. Earthquakes are generated as the plates interact. Thus all the plates on the globe are interacting with each other (fig. 1.8)

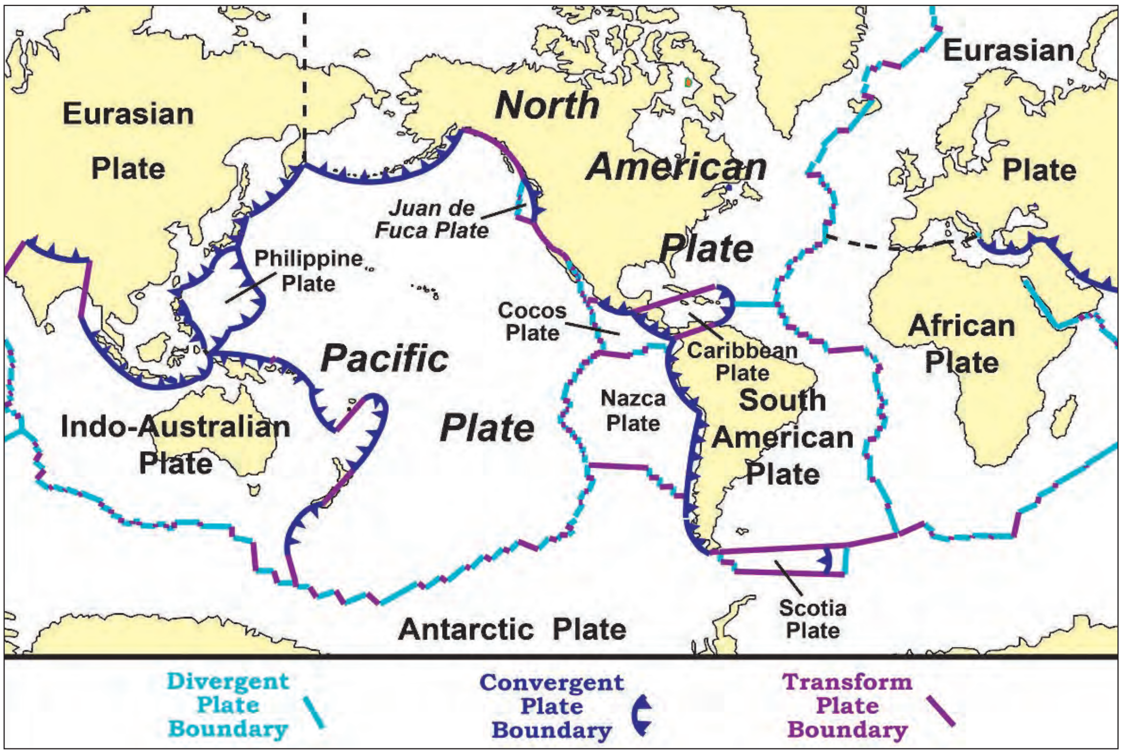


Fig. 1.8 : Major Lithospheric plates on the globe

Plate boundaries :

All major interactions among individual plates occur along their boundaries that are classified into different types : (1) Divergent plate boundaries (also called constructive margins); (2) Convergent plate boundaries (destructive margins) and (3) Transform fault boundaries (conservative margins). Each plate is bounded by a combination of the three types of boundaries and new plate boundaries can be created.

1) Divergent plate boundaries :

These boundaries are located along the oceanic ridges where the ocean floor is spreading and are called as constructive plate margins as they form new plate material (fig. 1.9). Along well-developed divergent plate boundaries, the seafloor is elevated forming the oceanic ridges.

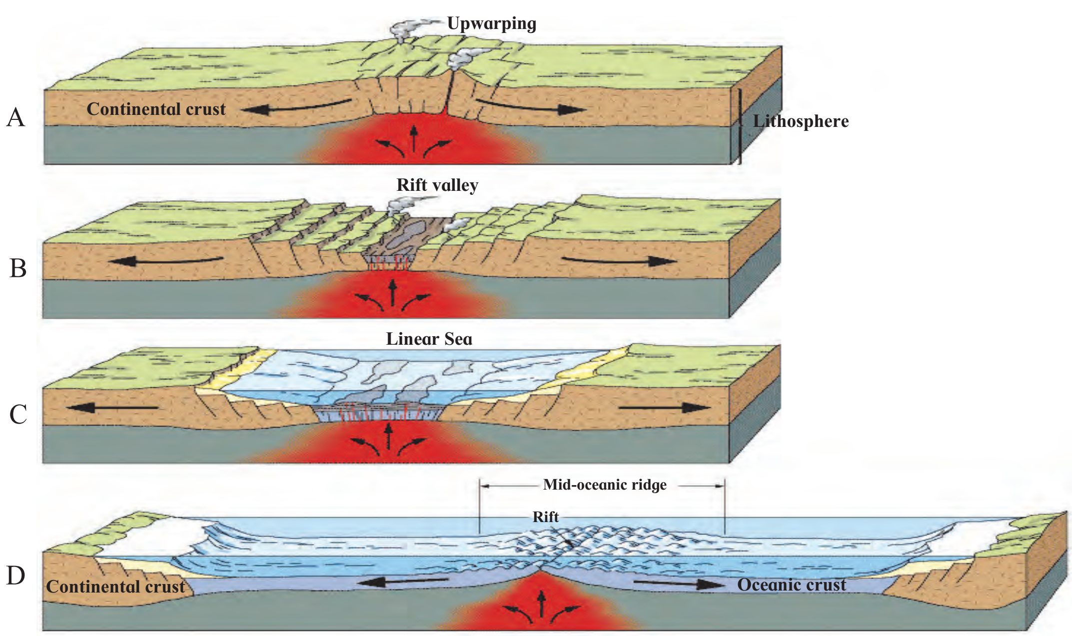


Fig. 1.9 : Development of Midoceanic Ridge in the ocean

Continental rifts are a kind of divergent plate boundaries where the landmass is split into two or more smaller segments. The best example for such a boundary can be seen in East African rifts valleys (fig. 1.10) and the Rhine Valley in northern Europe.

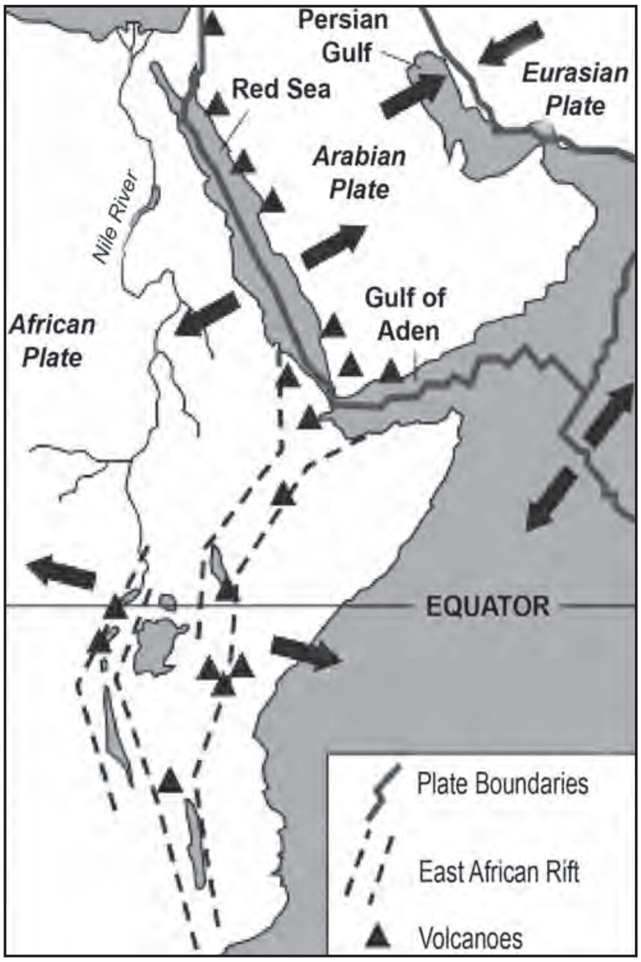


Fig. 1.10 : East African Rift valley as an example of divergent continental margin

2) Convergent plate boundaries :

Older portions of oceanic plates are returned to the mantle along the destructive plate margins. The descending plate forms an ocean trench called subduction zones (fig. 1.11). The plate dips at an average angle of 45° where it descends into the mantle. There are three types of convergent plate boundaries.

A) **Ocean – continent convergence**

B) **Ocean – ocean convergence**

C) **Continent – continent convergence**

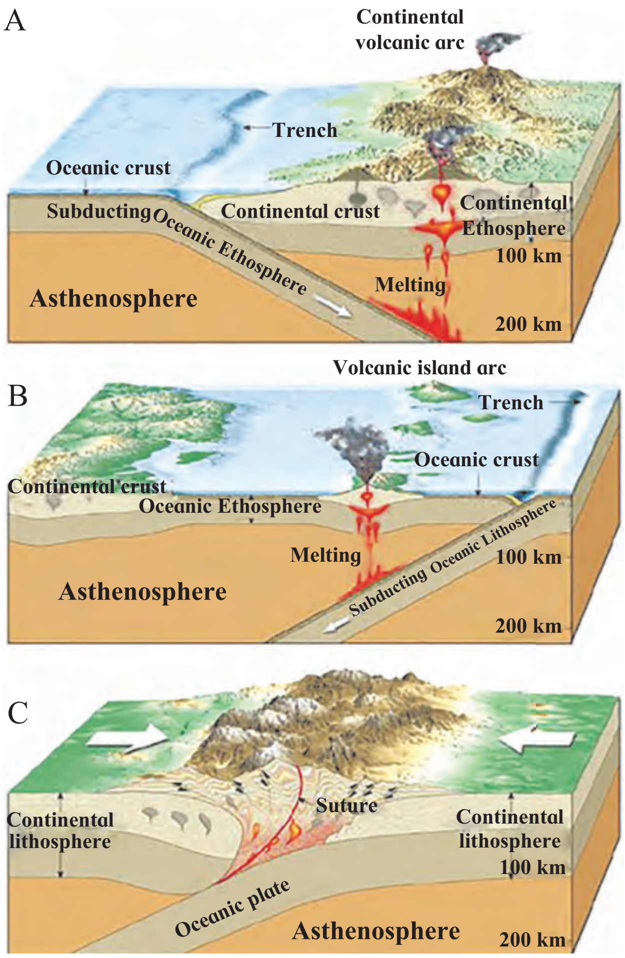


Fig. 1.11 : Types of convergent plate boundaries

3) Transform fault boundaries :

Plates slide past one another without creating/destroying any new lithosphere as transform faults (fig. 1.12). Most of the transform faults join two segments of a mid-ocean ridge as parts of prominent linear breaks in the oceanic crust known as fracture zones. Some interesting examples of Transform fault are the San Andreas fault (USA) (fig. 1.13) and the Alpine fault of New Zealand cutting through continental crust.

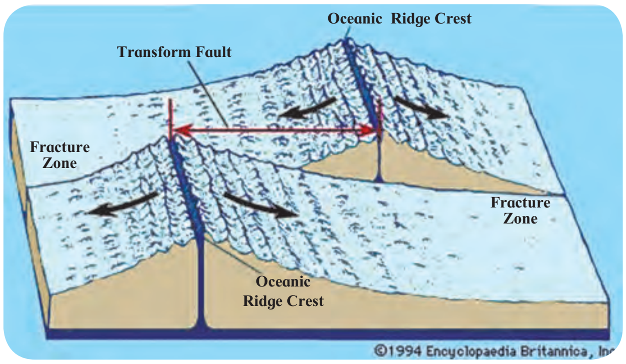


Fig. 1.12 : Concept of transform fault

Fig. 1.13 : San Andreas Transform Faults

Types of Mountains :

Mountains express the dynamics of the interior of the Earth and hence are very significant in understanding plate tectonics. They are positive relief structures or landforms rising above the surrounding land. Mountain building involves a combination of movements and processes such as upliftment, folding, deformation, faulting, metamorphism, igneous activity, erosion and sedimentation. The younger mountains achieve highest elevation as the rate of uplift exceeds the rate of erosion e.g., Mount Everest (8848 m). Different mechanisms of mountain building process evolve into various types of mountains.

There are four main types of mountains: i) fold mountains, ii) fault-block mountains, iii) volcanic mountains, and iv) relict mountain.

Fold Mountains are formed when two plates collide or a compressive force is developed within a plate. Many of the world's great mountain ranges are fold mountains including the Andes, Himalayas, and the Rockies.

Fault-block Mountains are formed along fault lines and either side of the fault are called fault blocks. Some of the fault blocks are pushed up, while others are pushed down resulting in the difference in elevation. Satpuras and Vindhyans are considered as fault-block mountains.

Volcanic Mountains are caused by volcanic activity when magma erupts all the way to the surface of the Earth. The hot magma will cool and harden forming a mountain. Examples of the volcanic mountains include Mount Fuji in Japan and Barren island in the Bay of Bengal, the only active volcano in India.

Relict type of mountains are formed by differential erosion e.g. Sahyadris.

Do you know?

Mountain ranges of India : India is a unique country representing almost all kinds of mountain types of the world. Below is the summary of information on some of the important mountain ranges of India. Students may search a map of India from reliable web resources to locate the mountains listed in the table as an activity.

Mountains	Salient Features
Karakoram Range	A sub range of the Hindu Kush Himalaya, K2, the second highest peak in the world is located here Famous Glaciers : Siachen Glacier, Biafo Glacier.
Ladakh Range	Southeastern extension of the Karakoram Range. from the mouth of the Shyok River in Ladakh to the border with Tibet
Zanskar Range	Boundary line between Ladakh region of Kashmir & remaining two regions of the state i.e. Jammu and Kashmir Highest peak : Kamet. Coldest place in India: Dras (The Gateway to Ladakh) Famous Passes : Shipki, Lipu Lekh (Lipulieke), and Mana Pass

Pirpanjal Range	Separates Jammu Hills to the south from the Kashmir (Kashmir Valley), beyond which lie the Great Himalayas Highest Point : Indrasan. India's longest rail tunnel known as Pir Panjal Railway Tunnel, Banihal road tunnel Famous Passes : Pir Panjal Pass, Banihal Pass, Rohtang pass
Dhauladhar Range (White Range)	Spread in J & K and Himachal, with home to major hill stations like Kullu, Manali & Shimla Highest peak : Hanuman ji Ka Tiba, or 'White Mountain'
Shivalik Range	Southernmost & Outer Himalayas also known as Manak Parbat in ancient times. About 2,400 km long from Indus till Brahmaputra.
Aravali Range	Means 'line of peaks', runs across Gujarat, Rajasthan, Haryana & Delhi, and Mewar hills Highest Peak : Gurushikhar, Mt Abu. Famous passes : Pipli Ghat, Haldi Ghat.
Kaimur Range	Eastern portion of the Vindhya Range in MP, UP & Bihar, Parallel to river Son
Mahadeo Range	Forms the central part of the Satpura Range, located in MP. Highest peak : Dhoopgarh
Ajanta Range	Maharashtra, south of river Tapi, sheltering caves of world famous paintings of Gupta period
Rajmahal Hills	In Jharkhand, made up of basaltic rocks, Point of Ganges bifurcation,
Garo Khasi Jaintia Hills, Mikir Hills	Continuous mountain range in Meghalaya a group of hills located to the south of the Kaziranga National Park (Assam), a part of the Karbi Anglong Plateau
Abor Hills	Hills of Arunachal Pradesh , near the border with China, bordered by Mishmi and Miri Hills
Mishmi Hills	In Arunachal Pradesh with its northern & eastern parts touching China. Situated at the junction of North Eastern Himalaya and Indo-Burma ranges
Patkai Range	Also known as Purvanchal Range, consist of three major hills. The Patkai-Bum, the Garo-Khasi-Jaintia and Lushai Hills situated on India's north-eastern border with Burma
Vindhya Range	A complex, discontinuous chain of mountain ridges, hill ranges, highlands & plateaus running through Madhya Pradesh, Gujarat, Uttar Pradesh and Bihar Highest peak – Sadbhawna Shikhar.
Satpura Range	A range of hills in central India. Passes through Madhya Pradesh, Gujrat, Maharashtra, Chhattisgarh Highest peak : Dhupgarh
Dalma Hills	Located in Jamshedpur, famous for Dalma national park & minerals like iron ore & manganese
Girnar Hills	Gujarat
Harishchandra	At Pune, acts as a water divide between Godavari & Krishna, hills made up of Deccan basaltic lava
Balaghat range	Between MP & Maharashtra, famous for manganese deposits.
Nilgiri Hills	Referred as Blue mountains, a range of mountains in the westernmost part of Tamil Nadu at the junction of Karnataka and Kerala Hills are separated from the Karnataka plateau to the north by the Moyar River and from the Anaimalai Hills & Palni Hills to the south by the Palghat Gap

Palani Hills	Eastward extension of the Western Ghats ranges,adjoin the high Anamalai range on the west, and extend east into the plains of Tamil Nadu
Anamalai Hills	Also known as Elephant Hill. A range of mountains in the Western Ghats in Tamil Nadu and Kerala with highest peak Anamudi
Cardmom Hills	Part of the southern, Western Ghats located in southeast Kerala and southwest Tamil Nadu
Pachamalai Hills	Also known as the Pachais, Eastern Ghats in Tamil Nadu

Summary :

- Surface of the Earth is an expression of the dynamic processes that are occurring in the interior of the Earth.
- The Earth's interior is divided into several compositional and thermal layers interacting with each other by conduction, convection or advection resulting into many dynamic activities such as plate tectonics.
- Plate tectonics is one of the most important phenomenon which explains several important processes occurring on the surface.
- Mountain ranges are the locations where the signatures of the Earth's internal dynamics since geological past are evident and can be studied readily by geologists.

EXERCISE

Q. 1. Choose the correct alternative :

1) The difference between the temperature of Universe and the interior of the Earth is of the order of
   a) 2000° C b) 10000° C
   c) 600° C d) 6000° C
2) The lower boundary of mantle convection is set at about …… Km from the surface of the Earth.
   a) 5000 km b) 2000 km
   c) 2900 km d) 300 km
3) Although the inner core and outer core are of approximately the same composition (Fe-Ni), the inner core remains solid due to
   a) Increase in melting point of the compound due to increase in Pressure.
   b) Decrease in melting point of the compound due to increase in Pressure
   c) Increase in melting point of the compound due to decrease in Pressure
   d) The source of heat is in the outer core.
4) When two plates collide, they are likely to form
   a) Fault-block mountains
   b) Volcanic mountains
   c) Domal mountains
   d) Fold mountains

Q. 2. Very short answer :

1) How do the convection currents maintain the temperature of the mantle?
2) What controls the temperature gradient of the Earth?
3) What is the main driving force for plate motion?
4) Why has the radius of the Earth increased from its very early stage of formation?

Q. 3. Short answer :

1) Write down any two major points describing the difference between Continental crust and Oceanic crust.
2) The Himalaya and Sahayadri are two different types of mountains, justify this sentence.
3) Mention any two most important properties of asthenosphere.
4) Give any two examples of the continental landmasses that broke up as a result of break-up of the supercontinent PANGEA.

Q. 4. Short answer :

1) Give any three evidences that indicate the continents have drifted.
2) Describe how magnetic strips on the ocean floor explain the Plate tectonics.
3) Give an example of the divergent continental margin.
4) Describe how relict type of mountains are formed.

Q. 5. Long answer :

1) Describe what tectonic activity is undergoing at the western margin of South American plate.
2) Describe what are the limitations of Continental drift theory and how the theory of Plate tectonics resolved them.
3) Describe different types of plate boundaries and exemplify then with the Indian-Australian plate.
4) Write a short note on the San Andreas Transform fault of North America.
5) Give an account on the internal layering of the Earth.

Q. 6. Assessing Unseen para :

"To find out whether these changes are due to changes of composition, temperature or other parameters, we turn to density, which is the most useful quantity that can be determined with reasonable precision. Density is deduced by combining information from seismology with knowledge of the mass of the Earth, deduced from its gravitational attraction, and its moment of inertia, determined from the movement, or precession, of its axis of rotation. The resulting density variation with depth inside the Earth is not uniquely determined, but it is known within fairly close limits at most depths, so that next we can ask what material will match the density at any specified depth".

Quoted from : The Inaccessible Earth: An integrated view to its structure and composition By Brown and Musset p.2

1) What does the authors wants to indicate by saying "reasonable precision when determination of the density".
2) How is the density of such a large body like the Earth's is determined?
3) How the composition of the material at great depths in the interior of the Earth is determined?
4) What is the interrelation of density, mass, temperature and pressure?

Q. 7. Unseen para :

"A theory of mantle convection is a dynamical theory of geology, in that it describes the forces that give rise to the motions apparent in the deformation of the Earth's crust and in earthquakes and to the magmatism and metamorphism that has repeatedly affected the crust. Such a dynamical theory is a more fundamental one than plate tectonics, which is a kinematic theory it describes the motions of plates but not the forces that move them. Also plate tectonics does not encompass mantle plumes, which comprise a distinct mode of mantle convection".

Quoted from : Dynamic Earth: Plates, Plumes and Mantle Convection - GEOFFREY F. DAVIES p.4

1) In what way the author emphasizes that the Earth's crust is linked to the mantle?
2) Distinguish between some of the kinematic and dynamic aspects of the Earth.
3) How the author emphasize mantle plume to explain both dynamic and kinematic changes of the Earth.