3

AGE OF THE EARTH

3.1 Introduction

Like the complex and mysterious problems of the origin of the solar system and the earth there is a lot of difference of opinions about the age of the earth and its past gèological history. Various scientists have attempted to calculate the age of the earth on the basis of different scientific basis, experimental researches and logical arguments but their findings, results and conclusions are so varied and contrasting that it becomes very difficult to arrive at convincing conclusion which may be acceptable to the majority of scientific community. In fact, it is quite difficult task to find out the exact time of the origin of the earth and periods of its evolutionary stages. It may be argued that geological processes work so slowly that no one can observe them fully during one's lifetime. This is why Scottish geologist James Hutton opined in 1775 that 'the earth's surface undergoes frequent changes but these changes consume such a long time that it becomes difficult for the man to find out the dates of such changes.' In fact, the dating of the past geological events is 'wild catting' as there is 'no vestige of a begnning, no prospect of an end' (James Hutton). Inspite of the fact that no universally acceptable method could be evolved till now to calculate the age of the earth and its geological events, several methods and concepts have been propounded from time to time and are still being proposed to unravel the mystery of the earth's history. It is, therefore, desirable to discuss some of the prevalent concepts and methods to have some generalized understanding of the chronological sequences of the earth.

3.2 Religious Concept

Serious efforts have been made since time immemorial by the religious priests, philosophers and astrologers to calculate the age of the earth. Old Iranian religious priests calculated the age of the earth as 1200 years while Archbishop Usher of Iceland in 1664 maintained that the earth was created at 9.00 A.M. October 26, 4004 B.C. (presumably Greenwich mean time) but these concepts cannot be accepted because these only make a fun of the age of the earth. According to Indian religious records the age of the earth has been determined as 2 billion (2000 million) years. The following version of Karmakand gives some idea about the age of earth :

'ब्राह्मणे द्वितीय परार्धे श्री स्वेतवाराह कल्पे वैवस्त,
मन्वन्तरे अष्टाविंशतितमे कलियुगे कलि प्रथम चरणे।'

Indian religious experts have calculated the age of the earth on the basis of the interpretation of the above statement as 1,972,949,032 years (about 2.0 billion years). This calculation is based on guess work and deduction but it nearly matches with the calculations based on scientific and mathematical methods but the result (2 billion years) is not closer to commonly accepted age of the earth (4 to 5 billion years).

3.3 On the Basis of Oceanic Salinity

Present-day oceanic waters contain salt content but it is believed that the oceans at the time of their creation would have contained pure water, that is water without salt content. Later on rainwater after passing through continental surfaces removed salt contents

from the land areas due to subaerial erosion and thus terrestrial salt used to reach the oceans through the rivers and thus oceanic water began to become saline. With the passage of time oceanic salinity continued to increase. It has been generally established on the basis of experiments and observations that about 60 per cent of sodium of the oceanic salt is contributed by the rivers. It has also been demonstrated that there is more or less similarity between the oceanic salt and the salt brought down by the rivers. It has been believed on this basis that rivers are the major source of oceanic salinity. Thus, there is gradual increase in the oceanic salinity because of deposition of terrestrial salt by the rivers in the oceans every year. If the total amount of oceanic salt is known and if the annual rate of increase of oceanic salinity is determined, the age of the oceans may be calculated and determined.

$$\text{Thus, the age of the oceans} = \frac{\text{total oceanic salt}}{\text{annual rate of oceanic salinity}}$$

(1) Joly has calculated, on the basis of a series of experiments, the total amount of salt of all the marine waters to be 1.26×10^{22} grams. He has further maintained that about 1.56×10^{14} grams of salt are derived from the land areas and are deposited in the oceans every year. Thus, on the basis of data of oceanic salinity as provided by Joly the age of the oceans can be calculated as follows -

$$\text{age of the oceans} = \frac{1.26 \times 10^{22}}{1.56 \times 10^{14}} = 80{,}000{,}000 \text{ yrs}$$

It appears, on the basis of the aforesaid calculation, that world oceans were created about 80 million years ago, so the earth might have been originated much earlier to the origin of the oceans but question arises, how many years ago? There is no unanimity about the probable answer to this question. Some scientists believe that the oceans were created at least 40 million years after the origin of the earth. If we accept this corollary, then the age of the earth becomes 120 million years but this calculation is totally false because the earth may not be so young. It may be pointed out that 200 million years old rocks of the oceanic crust have already been dated on the basis of the study of palaeomagnetism.

(2) A few scientists have tried to demonstrate correlation between the deposition of salt in the oceans and periods of mountain building at global scale. According to them the amount of salt brought to the oceans by the rivers would have not always been the same. The amount of salt brought by the rivers through erosion to the oceans would have gradually decreased due to continuous decrease in the rate of denudation of the mountains because of continuous lowering of their height consequent upon continued subaerial erosion. The rate of deposition of salt in the oceans would have again increased after the creation of new mountains during the next period of global mountain building. Based on this premise, the advocates of the above concept have determined the age of the oceans to be 1500 million years. They have further assumed that the earth was originated before about one quarter of the age of the oceans (i.e. 375 million years). Thus, the age of the earth may be calculated as 1500+375 =1875 million years.

It may be pointed out that this method of the determination of the age of the earth is not without faults. It is very difficult rather impossible task to measure total amount of salt in the world oceans and to determine the annual rate of salt deposition in the oceans. The rate and amount of subaerial erosion is neither equal everywhere nor is the same every year, rather it varies both spatially and temporally. Thus, the rate of deposition of salt in the oceans may not be same every year. It is erroneous to believe that the land areas are the only source of oceanic salinity. It has been established that thermal convective currents bring salt to the oceanic crust which, thus, also contributes to the oceanic salinity.

3.4 On the Basis of Sedimentation

There are several methods for the calculation of the age of the earth on the basis of the formation of sedimentary rocks and their period of formation. The first igneous rocks were formed due to cooling and solidification of hot and liquid magma and lava after the origin of the earth. These igneous rocks were disintegrated and decomposed and thus the resultant sediments of various sorts were transported and deposited by denudational agents (geological agents *e.g.* rivers, wind etc.) into water bodies to form first sedimentary rocks on the earth's surface. Since then the processes of sedimentation and the formation of sedimentary rocks continued throughout geological periods and are still operative. Continuous sedimentation resulted into thickening of sedimentary rocks and thus their thickness continued to increase. If we can find out the total thickness and annual rate of deposition of sedimentary rocks, then we can calculate the age of the formation of the first sedimentary rocks on the earth's surface and by applying common sense the age of the earth may be roughly estimated.

$$\text{Age of first sedimentary rocks} = \frac{\text{total thickness of sedinentary rocks}}{\text{annual rate of deposition}}$$

Various scientists have attempted to calculate the age of the earth on the basis of above method but their results are not compatible because of variations in the thickness of sedimentary rocks at different places. A few calculations are presented below.

(1). The stone statue of Ramses II was found buried under 9-foot thickness of sediments in Egypt (now U.A.R.) in the year 1854. The statue of Ramses II was installed about 3000 years before it could be discovered in 1854. Based on this fact it may be safely argued that 9-foot thick sediments were deposited in 3000 years. Thus, the annual rate of sedimentation may be calculated. It is believed that the known depth of sedimentary rocks on the earth's surface is about 100 miles (160 km). The following calculation may be made to compute the age of the first sedimentary rocks.

9-foot deposition = in 3000 years
3-foot deposition = in 1000 years
total depth of sedimentary rocks = 100 miles or 528,000 feet
3-foot deposition = 1000 years
528,000-foot deposition = in 176 million years

Thus, the age of the first sedimentary rock is determined to be 176 million years. It may be pointed out that the sedimentary rocks were formed at much later date from the time of the origin of the earth. If the age of the earth may be taken 3 times to that of the age of the first sedimentary rock then the age of the earth may be estimated at roughly 500 million years but this age is much lower than the expected age of the earth and hence this method is not acceptable.

(2). Attempt has been made to calculate the age of the earth on the basis of sedimentary deposits in the valleys of Colarado and Wyoming of the USA. It has been estimated that half mile-thick sediments were deposited in about 6.5 million years. Based on this estimate the following calculation may be made to find out the age of the first sedimentary rocks.

1/2 mile thick deposits = in 6.5 million years
100-mile thick deposits = 1300 million years

If the age of the earth is taken to be 3 times to that of the age of the first sedimentary rocks then the age of the earth becomes 3900 million years or 3.9 billion years. This calculation more or less gives fairly good idea about the age of the earth which is generally accepted to be in the range of 4 to 5 billion years. Some scientists argue that the age of the earth may not be more than double the age of the first sedimentary rocks. If we accept this connotation, then the age of the earth is calculated as 2600 million or 2.6 billion years. This calculation nearly matches with the result of 'radioactive mineral method' according to which the age of the earth has been estimated at 2000 million years.

(3) The rate of sedimentation in England has been determined as one foot deposit per 4000 years.

Thus, the age of the first sedimentary rocks may be calculated as follows - 1 foot deposit = in 4000 years

528,000 feet deposit = in 2112 million years

As stated earlier, if we take the age of the earth 3 or 2 times more than the age of the first sedimentary rocks, then the age of earth becomes 6336 million (or 6.33 billion years) or 4224 million (4.22 billion years) years but the computed age of the 6.33 billion years is so high that it cannot be accepted. It appears from the aforesaid calculations on the basis of the sedimentation that the age of the earth is beyond doubt more than 2000 million years.

It appears from the above descriptions that the age of the earth calculated on the basis of sediementary deposits of different places varies significantly. Thus, these conclusions may not be acceptable. Besides differences in the results, this method also suffers from some defects and errors. It is argued that the annual rate of sedimentation is not uniform every year. The rate of sedimentation also varies from one place to another and from one climatic region to another climatic region. Similarly, the rate of sedimentation also varies in accordance with the lithological and structural characteristics of the region concerned. Continuous sedimentation in particular place causes thickening of sediments and therefore decrease in the thickness of sedimentary rocks due to weight of superincumbent load of fresh sedimentation. Thus, the thickness and depth of sedimentary rocks at present is not real one because it has been lessened due to the pressure exerted by the overlying recent deposits. It is, therefore, obvious that it is not possible to measure real depth of sedimentary rocks. Consequently, the age of the earth calculated on the basis of sedimentary rocks cannot be relied upon.

3.5 On the Basis of Erosion

Some scientists have attempted to calculate the age of the earth on the basis of the rate of erosion of the land areas. This method is based on this belief that the continental areas are regularly eroded by the exogenous or denudatonal processes every year. If we can find out the total amount of denundation of the surficial materials till now and the annual rate of denudation, then the age of the earth can be estimated. It has been generally believed that one-foot thick surface of the earth is generally eroded down in about 10,000 years. It is also true that the eroded sediments are deposited by the fluvial processes as sedimentary rocks. The known thickness of sedimentary rocks is about 100 miles (528,000 feet). Thus, based on above facts the following calculation can be made-

1-foot erosion = in 10,000 years
528,000 feet erosion = in 5280 million years
(100 miles) (5.28 billion years)

If we take the age of the earth to be double of the age of the thickness of deposited seidments derived through continuous denudation of land areas, then the age of the earth may be estimated at 10,560 million (or 10.5 billion) years. This estimation is not acceptable because the age of the earth may not be so much in any case. This method also suffers from numerous inherent defects. The rate of erosion varies both spatially and temporally. In fact, the rate of erosion of surficial materials is affected by such a host of environmental factors (*e.g.* lithology, structure, relief, vegetation, gradient, efficiency of denudational processes, climate and so on) which also vary form one place to another and from one climatic region to another region. Thus, it is very difficult, rather impossible task to determine the rate of erosion.

5.6 On the Basis of Tidal Force of the Moon

The age of the earth, based on tidal force of the moon, is calculated in a variety of ways. **First method-** It is commonly believed that the moon was originated from the earth because it is her satellite as the moon revolves around the earth (now this old concept has been refuted as many scientists claim that the moon is not the satellite of the earth). If this is so, the moon might have been very close to the earth at the time of its birth from the earth and the tidal friction of the moon might have been maximum. With the passage of time the moon gradually moved away from the earth and hence the tidal friction of the moon also gradually decreased. The age of the moon and ultimately the age of the earth is calculated on the basis of the rate of decrease of the tidal friction of the moon. The scientists have calculated the age of the earth, on this basis, as 4000 million (4 billion) years. **Second method-** It is believed that the rotational force of the earth is reduced due to tidal friction of the moon. In other words, the time of the rotation of the earth increases (due to decrease in the speed of earth's rotation) due to tidal friction of the moon. Thus, on the basis of the calculation of the tidal friction of the moon and the change in the speed of the rotation of the earth it has been concluded that the moon moves away from the earth at the rate of about 13 cm per year. The present distance of the moon from the earth is 3,84,000 km. Thus, the moon would have taken 2,953,846,000 years to move 3,84,000 km away from the earth. On this basis the age of the earth has been estimated as 4000 million (4 billion) years.*

3.7 The Concept of Lord Kelvin

Though Lord Kelvin proposed scientific base for the calculation of the age of the earth but now his concept is not tenable. He has suggested to calculate the age of the earth on the basis of the rate of the cooling of the earth. On an average the temperature increases with increasing depth of the earth at the rate of 1^0 C per 32m. Thus, there is very high temperature in the core of the earth. Consequently, there is continuous transfer of heat from the core of the earth to its outer cells from where the heat is lost to the atmosphere through the mechanism of radiation. The amount of lost heat from the earth through radiation can be determined on the basis of underground temperature gradient, thermal conductivity of the crustal rocks and the surface area of the earth. The time of the solidification of the earth's crust can be found out on the basis of the rate of the loss of heat from the earth's crust. Based on above considerations Lord Kelvin assumed that the whole earth was solidified at the temperature of $7{,}000^0$ F. Thus, the outer part of the earth was solidified on cooling about 40,000,000 years ago. Lord Kelvin, thus, estimated the age of the earth as 40 million years but this little age of the earth cannot be accepted. Moreover, this method also suffers from certain defects. It may be pointed out that radioactive elements were not discovered at the time of the postulation of Kelvin's concept of the determination of the age of the earth. Heat is generated due to disintegration of radioactive minerals and thus the heat of the core of earth is increased. Lord Kelvin did not consider this fact in his concept and thus his concept is not acceptable.

3.8 On the Basis of Radioactive Elements

The method of the calculation of the age of the earth on the basis of radioactive elements has gained maximum success in the modern scientific world because this method is more convincing than other methods. Radioactive elements generate heat after their disintegration. This fact was first discovered by Pierre Curie in the year 1903 while renowned scientist Rutherford presented his scheme of the calculation of the age of the rocks on the basis of the radioactive elements in the year 1904. Uranium, thorium etc. contain maximum amount of radioactive elements in them. Uranium and thorium are found in all types of rocks though their amount varies significantly from one type of rock to the other type. When the rocks are disintegrated, the radioactive elements are also disintegrated, and decayed and in the process emit different types of rays which generate heat. Thus, the radioactive minerals play a major role in supplementing the heat of the earth's interior. When uranium is disintegrated, it is changed into lead becase of excessive heat generated during its disintegration. If we can know the time of the transformation of uranium to lead, we can easily find out the time of the formation of uranium and radioactive elements. It may be pointed out that uranium after being disintegrated generates alpha particles. Thus, the rate of metamorphism of uranium into lead can be determined by counting the alpha particles coming out from the rocks. It is estimated that 1/67th part of uranium is changed into lead in 100 million years. It may be pointed out that the quantity of lead in different rocks varies significantly and hence the leads of different rocks were transformed in different times. Inspite of this problem the exact quantity of lead present in each rock is determined on the basis of available scientific techniques. Based on above considerations it has been concluded that the radioactive minerals were present at least 1500 million years B.P. (before present). Thus, the age of any rock may not be older than 2000 million years. Based on above considerations, thus, the age of the earth is estimated to be between 2000 to 3000 million years.

3.9 Conclusions

Besides aforesaid methods, some scientists have developed their own methods to calculate the age of the earth. For example, Joly has attempted to estimate the age of the earth on the basis of the age of the minerals. According to him there are several concentric rings around mica minerals. These concentric rings have been called by Joly as 'halo'. According to Joly the age of the minerals can be calculated on the basis of the diameter of these concentric rings and the rate of disintegration of their atoms. The oldest mineral may be used to estimate the age of the earth. H.N. Russell has calculated the age of the earth on the basis of uranium-lead and thorium-led as 2250 million and 4600 million years respectively. According to Russell, thus, the age of the earth ranges between 2.0 to 5.0 billion years. The biologists have calculated the age of the earth on the basis of biological evolution as 1000 million years.

It appears from the aforesaid discussions that several concepts and methods have been proposed to calculate and estimate the age of the earth but none of them could be accepted by the majority of scientific community. Some concepts and methods are so confusing and erroneous that these present wrong notion about the age of the earth. Most of the concepts and methods are based on deductions and estimations. It may be pointed out on the basis of available information that the age of the earth may not be, in any case, less than 2000 million years. Most likely, the age of the earth may be put between 3000 to 8000 million years. Recently the age of the earth has been estimated between 4 and 4.5 billion years.

3.10 Earth's Climate in its Childhood Paradoxical Question : "The Faint Early Sun Paradox"

Why the earth's surface was not covered with ice in its childhood in spite of the fact that sun's rays were much fainter in its fragile beginning than today?

This 'faint early sun paradox' was formulated by astronomer Carl Sugan and his colleague George Mullen in 1972.

This paradox consisted of the following :

- The earth's age ranging between 4 to 4.5 billion years,
- The earth's climate has been fairly consistent during its 4 billion out of 4.5 billion years age inspite of the fact that solar radiation increased by 25-30 per cent.

Then paradoxical question arises —

Why the earth's surface in its childhood was not covered with ice?

Explanation

1. JAIM KASTING'S EXPLANATION

American atmospheric scientist Jim Kasting presented his explanation in 1993. According to him 4 billion years ago 30 percent of the earth's atmosphere consisted of greenhouse gas carbon dioxide (CO_2). Thus CO_2 formed a protective greenhouse gas thick layer around the earth. This resulted in the warming of ocean surface which in turn prevented the earth's surface from freezing.

2. MINIK ROSTING'S EXPLANATION

Minik Rosting of Natural History Museum of Denmark propounded that it was not high concentration of CO_2 in the atmosphere in the earth's early history which

prevented the earth's early surface from being covered whith ice layers but it was **thin cloud cover** which prevented early ice age on the basis of the following facts :

- Cloud layer in the earth's childhood was much thinner than today, and
- Most of the earth's surface was covered with water with the result oceans were warmed uninterruptedly and hence water surface of the earth could not be frogen.

3. PARADOX OF FAINT SUN AND ICE-FREE OCEANS SOLVED

The team of Carl Sugan, George Mullen and Minik Rosting analysed the samples of 3.8 billion year-old mountain rocks from world's oldest bedrocks of Isua in western Greenland to solve the said **paradox.** The analysis revealed the maximum concentration of **one part per thousand** of CO_2 in the childhood of the earth. Thus, this CO_2 concentration was only 3 to 4 times more than the present CO_2 concentration in the atmosphere.

Thus they refuted the earlier finding of 30 percent share of CO_2 in the composition of the atmosphere. They finally concluded that the concentration of CO_2 contenent in the atmosphere has not changed substantially through billions of geological history of the earth.

It was thin cloud cover and dominance of water surface on the early earth's surface which prevented the earth's surface from being frozen in the beginning of the earth's geological history.

3.11 Geological History of the Earth (Geological Clock)

The geological history of the earth or the 'geological clock' refers to the reconstruction of evolutionary sequence of the geological events involving the information of various zones (crust, mantle and core) of the earth, formation and evolution of geomaterials (rocks), formation and development of mountains and faults, evolution of different lives etc. The whole geological history right from the origin of the earth to its present form has been divided into major and minor periods on the basis of forms of life (organic remains), characteristic rock deposits, places of rock formation, major tectonic events etc. The whole geological history of the earth has been divided into five eras (the largest time division of the earth's history has been termed Era) based on five major groups of deposits as follows-

Major Groups of Deposits (from youngest to oldest)	Eras
Cenozoic group	Cenozoic (era of recent life)
Mesozoic group	Mesozoic (era of medieval life)
Proterozoic	proterozoic (era of earlier life)
Archeozoic	Archaeozoic (era of primeval life)

Each era is numbered in sequence as first (primary), second (secondary), third (tertiary) and fourth (quaternary) and is named period. Further, each period is divided into several epochs. The names of epochs have been assigned on various grounds *e.g.* names of the places of characteristic systems of deposits, the names of tribes, the characteristics of deposits, dominance of certain elements and minerals etc. as follows-

Palaeozoic	palaeo (ancient), zoe (German)- life
Mesozoic	mesos (German) means middle
Cenozoic	Kainos (German) means new
Cambrian	Cambria or Wales (place) in U.K.
Ordovician	Ordovices (a British tribe in N. Wales)
Silurian	Silurs (a British tribe in S. Wales)
Devonian	Devonshire (place and region in U.K.)
Carboniferous	dominance of carbon (coal)
Permian	perm (a province in earstwhile USSR)
Triassic	three-fold division of deposits in Germany, 'trias' means triple.
Jurassic	after Jura mountans in Switzerland
Cretaceous	creta (Latin) means chalk, dominance of abundant deposits of white writing chalk
Eocene	Eos means day break
Oligocene	Oligos (German) means little
Miocene	Meion (German) means smaller
Pliocene	Pleion (German) means greater
Pleistocene	Pleistos means most
Holocene	Holo means complete

Some scientists have put together all the geological events of the past history of the earth in the form of a clock. Thus, the spiral system representing the whole geological and geomorphic history together is called as '**geological clock**' wherein one billion years represent each revolution of the clock's arm. Each revolution is further subdivided into '**hours**' where each division (hour) corresponds to 100 million years and '**minutes**' represent the time period of 10 million years. F.g.3.1 represents the geological clock suggested by Frank Press and Raymond Siever (1974).

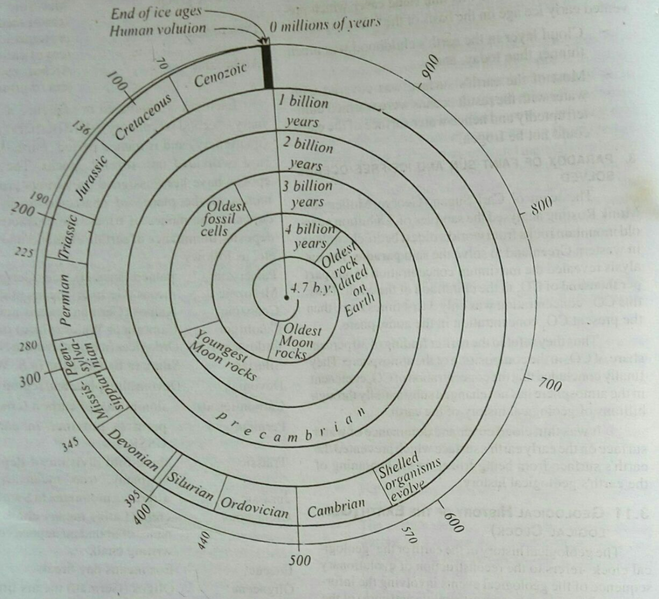

Fig. 3.1 : The geological clock (modified after F. Press and R. Siever, 1974). Numbers denote years in millions before present.

Table 3.1: Geological Time Table (from youngest to oldest)

Eras	Periods	Epochs	Duration (million years)	Starting time before present (million years)
Neozoic	Quaternary	2.Holocene or Post-glacial		
		1.Pleistocene	0.990	1.000
Cenozoic	Tertiary	4.Pliocene	10.000	11.000
		3.Miocene	14.000	25.000
		2.Oligocene	15.000	40.000
		1.Eocene	30.000	70.000
Mesozoic	Secondary	3. Cretaceous	65.000	135.000
		2. Jurassic	45.000	180.000
		1. Triassic	45.000	225.000
Palaeozoic	Primary	6. Permian	45.000	270.000
		5. Carboniferous	80.000	350.000
		4. Devonian	50.000	400.000
		3. Silurian	40.000	440.000
		2. Ordovician	60.000	500.000
		1. Cambrian	100.00	600.000
Pre-Palaeozoic		Pre-Cambrian or Algonican	-	700.000
Azoic or Archaean		Archaean	-	800.000

Precambrian Period

The Precambrian period started 700 million year B.P. (before present). The earth changed from gaseous state to liquid state. The solid outer crust was formed due to cooling and solidification of liquid materials. This phase was followed by the formation of dense atmosphere surrounding the earth. Due to gradual but continued cooling and contraction of the earth and resultant condensation of water vapour there began the precipitation process which ultimately resulted into the formation of rivers and seas. The sequence of warm climate was broken by many glacial periods. The rocks were subjected to maximum metamorphism due to heat and pressure. Among the plant kingdom only marine grasses were evolved. Soft bodied invertebrate animals were evolved in warm seas but the land areas were devoid of animals.

Cambrian Period

The Cambrian Period lasted from 600 million years B.P. to 500 million years B.P. The earth's surface was characterized by shallow seas and the land areas were frequented by transgression and regression of seas. Cambrian rocks of Wales, north-west Scottland, western England, Canada and USA were formed during this period. Europe was characterized by vulcanicity but no trace of any mountain building could be found. The earth's surface was characterized by warm and uniform climate. Evolution of plants was still confined to the seas only. Most of the vertebrate animals including 1000 species were evolved in the seas but they are not found at the present time. These animals depended on marine grasses for their food. No land animals could evolve during this period.

Ordovician Period

The Ordovician Period continued from 500 million years B.P. to 440 million years B.P. The transgressional and regressional phases of seas continued. Many shallow seas became dry because of deposition of sand and mud. Ordovician rocks were formed in north-west Europe and North America. This period was characterized by the initiation of mountain building. Marine areas were affected by active vulcanicity. The climate on the entire earth's surface was warm and hence no zonal pattern of climate was evolved. Vegetation and animals were still confined to the seas only. Animals species included only vertebrates.

Silurian Period

The Silurian Period spread from 440 million to 400 million years B.P. Sea level was characterized by periodic rise and fall which introduced changes on earth's crust. The mountain building continued but the vulcanicity was less active than during ordovician period. On an average the climate was warm but some areas were also characterized by relatively dry climate. Leafless plants were evolved on the land areas. The remains of such vegetation have been found in Australia. There was increase in the species of vertebrate animals of marine environment. The plant community was diversified because of evolution of new species. Corals were evolved at large scale. Plants were evolved for the first time on land areas.

Devonian Period

The Devonian Period continued from 400 to 350 million years B.P. and experienced increase in land and decrease in marine areas. Mountain building and vulcanicity were more active. The newly formed mountains were subjected to denudation and eroded materials were deposited as pebbles, sands and red sandstones. Most of the areas of North-West Europe and North America were characterized by warm and semi-arid climate. The remaining areas were dominated by uniform climate. The earth's surface was covered with green vegetation as the plants developed their leaves, branches, stems and roots. The vegetation comprised of small shrubs to tall trees measuring 14-15 m in height. Fern vegetation was evolved by the end of this period. Marine vertebrate animals were again evolved. This period was characterized by the evolution of a large number of species of fish. Amphibians were evolved towards the end of this period. There was dispersal of vertebrate animals (mites, spiders etc.) from seas to the land areas due to evolution of such flora on land areas which could provide them food.

Carboniferous Period

The carboniferous period spread from 350 million to 270 million years B.P. and was characterized by numerous small and shallow seas on the earth's surface. Most of the areas of Europe including Russia were submerged under water. Some land areas in North America and Europe were depressed and thus were covered with water giving birth to swamps. The coal formation of northern hemisphere was accomplished during this period. Dry climate continued for most period but some areas were characterized by warm and wet climate which became responsible for dense vegetation cover over such areas. Land areas were covered with green tall trees measuring more than 30m in height. The number and species of amphibious animals continued to increase in water areas. Reptiles were evolved on land areas. Smaller animals were evolved in swamps and marshes but their length increased upto 4-5m by the end of this period.

Permian Period

The Permian period continued from 270 million to 225 million years B.P. Inland lakes were formed due to faulting. The evaporation of these lakes resulted into the formation of major potash reserves of the world. High mountains were formed due to great tectonic movements in Europe, Asia and eastern North America (Applachians). Different climatic conditions prevailed over the earth's surface. British Isles were characterized by semi-arid climate. The most parts of the northern hemisphere were dominated by dry climate but were periodically frequented by warm and wet climate. Most parts of the southern hemisphere were under the influence of glacial period. With increasing seasonal variations in the climatic conditions the ratio of evergreen trees continued to decrease. Consequently, deciduous trees, which could resist dry weather and frost, were evolved. The number and species of land animals further increased and numerous species of insects were evolved on land areas.

Triassic Period

The Triassic Period continued from 225 million to 180 million years B.P. Most of the mountains were covered with deserts and bushes. The entire Britain was covered with saline lakes which were surrounded by desert areas. Marl and sandstones were formed in warm seas. Warm and dry climate was dominant over entire areas but the climate became wet by the end of this period. Consequently, coniferous trees and ferns were developed in the northern hemisphere. Carnivore fishes like reptiles and lobsters were evolved in seas. The land areas were still dominated by reptiles. For the first time, mammals evolved from reptiles on land areas. Flies and termites also appeared on the land.

Jurassic Period

The Jurassic Period spread from 180 million to 135 million years B.P. and was characterized by reextension in marine areas. Land areas were dominated by forests and swampy plains having lakes and meandering rivers. The mountains were transformed into low hills due to continued denudation. Major areas of Asia and Europe and surrounding areas of Great Britain were submerged under sea water. This period is characterized by widespread deposition of lime mostly in France, southern Germany, Switzerland etc.The climate became subtropical towards the end of this period. The rainfall was such that dense vegetation could be evolved and developed in many areas. For the first time, flowering plants were evolved during this period.

Cretaceous Period

The cretaceous period continued from 135 million to 70 million years B.P. Coastal lands were covered with large swamps. Rivers' flow was sluggish and delta formation became more active. The deposition of chalk was the main feature of this period. Mountain building again became active. The process of formation of tertiary or alpine mountains (Rockies, Andes, Alps, Himalayas etc.) was initiated. This period was characterized by widespread vulcanicity. The peninsular India was covered with thick basaltic lava. The growth of vegetation became possible upto Greenland due to warm and wet climate. Deciduous trees flourished because of seasonal regime of climate. Fishes

like modern shork and herring, large turtles, mosasauros etc. were evolved in seas. The period was characterized by the evolution of flying reptiles, feathered and feathereless birds, overdominance by reptiles like dirosaurs and pterosaurs.

Eocene Epoch

This epoch includes a time span from 70 million to 40 million years B.P. Major parts of Europe were transgressed by sea due to subsidence of land areas and sauthern England was characterized by tropical vegetation similar to present Malaysia. The tertiary mountains formed during cretaceous period were further uplifted and grew in height. The Indian and Atlantic Oceans were extended due to sea floor spreading. Arctic area, Scottland, Ireland and peninsular India received thick cover of basaltic lava. Warm climate extended upto Greenland and hence tropical palm trees grew upto Greenland. Reptiles disappeared from the seas but two species of mammals viz. early whales and sea cows were evolved. Most of the sea fishes got their present form. Several primates of modern mammals were evolved on land areas *e.g.* elephants, horses, rhinoceros, pigs etc. Early monkeys and gibbons were evolved in Burma (Myanmar). The process of the formation of the Himalayas was initiated.

Oligocene Epoch

The Oligocene epoch spread from 40 million to 25 million years B.P. during which land areas experienced extension while there was decrease in oceanic areas. America and Europe experienced intense earth movements and the process of the formation of Alps was initiated. Most of the areas were dominated by warm and temperate climates but the cycle of cold climate also started in this period. The onset of cold climate resulted in the obliteration of forests in some areas but there was expansion in grasslands which became responsible for the evolution of many species of grass eater mammals. Several species of crabs, snails and mussels were evolved in water areas. Ancestors of modern cats, dogs and bears were evolved on land areas. Apes were originated probably as acestors of man.

Miocene Epoch

This epoch extended from 25 million to 11 million years B.P. and was characterized by decrease in oceanic areas and increase in land areas due to strong earth movements. Mediterranean sea was surrounded by lands from all sides. Asia and Europe were connected and were subjected to rapid rate of denudation due to increased rainfall. The Alps were originated and the second upheaval of the Himalayas resulted in the origin of lesser Himalaya and Greater Himalaya was further uplifted. The orogeny was accompanied by volcanic activity. The earth's surface was characterized by varying climatic conditions as these varied from dry and desert climate to wet and cold climate. Humid climate became responsible for the growth and development of deciduous trees like maple, oak and poplar in North America and Europe while cedar grew on high lands. The plains of North America were covered by prairie grasses. Boney fishes were evolved in water areas. There was maximum growth in shork (upto 18m in length). Proconsuls migrated from Africa to Asia and Europe. The elephants grew in size and migrated from Africa to Europe, Asia and North America. Penguins evolved in Antarctica.

Pliocene Epoch

The pliocene epoch continued from 11 million to 1 million years B.P. when the continents and ocean basins attained their present position. North Sea, Black Sea, Arabian Sea and Caspian Sea were formed due to drifting of land areas and filling of the resultant gaps with water. The Himalayan orogeny registered third upheaval resulting in the origin of the Siwalik ranges. Temperate zone covered larger areas. Marine plants and animals attained their present life-forms.

Pleistocene Epoch

The pleistocene epoch extended from one million to 10,000 years B.P. during which major areas of the northern hemisphere were covered with extensive ice sheets followed by fall in sea level. This period is also known as Pleistocene Ice Age comprised of four glacial and four interglacial periods. The four glacial periods of North America are known as (from south to north) Nebraskan, Kansan, Illinoin and Wisconsin which were separated by three interglacial periods *e.g.* Aftonian, Yarmouth and Sangaman. Similarly, four glacial periods in Europe have been identified as Gunz, Mindel, Riss and Wurn. Retreat of ice sheets brought several changes in North American and European scenery viz. evolution of Great Lakes (Superior, Michigan, Huron, Erie and Ontario) in North America, numerous glacial lakes in Norway, Sweden, Switzerland and north Italy, origin of fiords of Norwagian coasts.

Holocene Epoch

The present epoch is known as post-pleistocene or holocene period which started 10,000 years B.P. Marine organisms attained their present life-forms and man began farming and animal domestication.

3.12 Important Definitions

Cambrian period : is a geological period, named after the place 'Cambria' or Wales in U.K. This period continued from 600 to 500 million years B.P. (before present).

Carboniferous period : is a geological period, named due to large-scale widespread carbon (coal) formation during this period, which continued from 350 to 270 million years B.P.

Cretaceous period : is a geological period and is named after 'creta' (Latin word) which means chalk, dominance of abundant deposits of white writing chalk. It continued from 135 to 70 million years B.P.

Devonian period : is named after Devonshire of U.K. and continued from 400 to 350 million years B.P.

Eocene epoch : is a geological period and is named after the word 'eos' meaning thereby day break (dawn). This epoch continued from 70 to 40 million years B.P.

Epoch : is a particular period of time marked by distinctive features, events etc.

Era : is a period of time of very longer duration marked by distinctive features, events etc.

Geological clock : The spiral system representing the whole geological and geomorphic history of the earth is called geological clock.

Holocene epoch : represents the present period which is in fact post-pleistocene epoch. It started 10,000 years B.P.

Jurassic period : is a geological period, named after Jura mountain of Europe, which continued from 180 to 135 million years B.P.

Miocene epoch : is a geological period and is named after German word 'meion' meaning thereby smaller. This period continued from 25 to 11 million years B.P.

Oligocene epoch : is a geological period and is named after German word 'oligos' meaning thereby 'little'. This period continued from 40 to 25 million years B.P.

Ordovician period : is a geological period and is named after the 'ordovices' tribe in N. Wales of U.K. This period continued from 500 to 440 million years B.P.

Period : is 'the basic unit of time, during which a standard rock system is formed comprising two or more epochs and included with other period in an area' (Webster's EU Dictionary).

Permian Period : is a geological period which continued from 270 to 225 million years B.P. This period is named after 'perm', a province in the earstwhile USSR.

Pleistocene epoch : extended from 1,000,000 years B.P. to 10,000 years B.P. during which major areas of the northern hemisphere were covered with extensive ice sheets. This epoch is named after 'pleistos' meaning thereby most.

Pliocene epoch : continued from 11 million years B.P. to 1 million years B.P. This epoch, derived its name from German word 'pleion' meaning thereby greater.

Radiocarbon dating : is the method of 'determination of the age of objects of organic origin by measurement of the radioactivity of their carbon content. This method is also called C-14 dating'.

Silurian period : is a geologic period which extended from 440 to 400 million years B.P. This period got its name from 'Silurs', a British tribe in South Wales.

Triassic period : is a geological period which continued from 225 to 180 million years B.P., it is named after three-fold ('trias' means triple) division of deposits in Germany.

4

STRUCTURE OF THE EARTH'S INTERIOR

4.1 Introduction

Though the study of constitution of the interior of the earth is out side the domain of geography but its elementary knowledge is necessary for the geographers because the nature and configuration of the reliefs of the earth's surface largely depend on the nature, mechanism and magnitude of the endogenetic forces which originate from within the earth. It is decidedly true that it is very difficult task to have accurate knowledge of the constitution of the earth's interior because it is beyond the range of direct observation by man but recently **seismology** has helped to have some authenticated knowledge about the mystery of the earth's interior. The sources which provide knowledge about the interior of the earth may be classified into 3 groups.

1. Artificial sources
2. Evidences from the theories of the origin of the earth
3. Natural sources

e.g. volcanic eruption, earthquakes and seismology

4.2 Artificial Sources

Numerous inferences can be drawn about the constitution of the interior of the earth on the basis of density of rocks, pressure of superincumbent load (weight of overlying rocks) and increasing trend of temperature with increasing depth inside the earth. It is commonly believed that the outer thinner part of the earth is composed of sedimentary rocks the thickness of which ranges between half a mile to one mile (0.8 km to 1.6 km.) Just below this sedimentary layer there is the second layer of crystalline rocks, the density of which ranges between 3.0 and 3.5 at different places. The average density of the whole earth is about 5.5. Thus, it appears that the density of the core of the earth will be, wihtout doubt, more than 5.5. Generally, the density of the core of the earth is around 11.0. Cavendish attempted to calculate the average density of the earth in 1798 on the basis of the Newton's gravitational law. According to him the average density of the earth is 5.48. Poynting calculated the average density of the earth as 5.49 g cm^{-3} in the year 1878. Since 1950 several attempts are being made to calculate the density of the earth on the basis of satellites. The satellite studies have revealed the following results about the density of various parts of the earth-average density of the earth = 5.517 g cm^{-3}, average density of the earth's surface = 2.6 to 3.3 g cm^{-3} and average density of the core = 11g cm^{-3}.

Thus, it is proved that (i) ***the density of the core of the earth is highest of all parts of the earth.***

PRESSURE

Now question arises, what is the reason for very high density of the core? Previously it was believed that very high density of the core was because of heavy pressure of overlaying rocks. It is common principle that pressure increases the density of rocks. Since the weight and pressure of rocks increase with increasing depth and hence the density of rocks also increases with increasing depth. Thus, it is proved that *(ii) very* *high density of the core of the earth is due to very high pressure prevailing there because of superincumbent load.* This inference is proved wrong on the ground that there is a criticial limit in each rock beyond which the density of that rock cannot be increased inspite of increasing pressure therein. It may be, thus, forwarded that (*iii*) *very high density of the core of the earth is not because of very high pressure prevailing there.* If the high density of the core of the earth is not because of high pressure of overlying rocks then (*iv*) *the core must be composed of intrinsically heavy metallic materials of high density.* The experiments have revealed that the core of the earth is made of the mixture of iron and nickel. This inference is also validated on the basis of geocentric magnetic field. The metallic core is surrounded by a zone of such rock materials, the upper part of which is composed of crystalline rocks.

TEMPERATURE

It is evident on the basis of information available from the findings of bore holes and deep mining that temperature increases from the surface of the earth downward at the rate of 2° to 3°C for 100 metres. It may be pointed out that it becomes very difficult to find out the rate of increase of temperature beyond the depth of 8 km. The rate of increase of temperature in the continental crust has been calculated based on geothermal graphs and the following generalization has been made. In the tectonically active areas (like the Basin and Range Province of the USA) temperature remains 1000°C at the depth of 43 km from the surface of the earth while the temperature remains only 500°C at the depth of 40 km from the surface in tectonically stable areas. This information provides significant knowledge about the nature and behaviour of the continental crust. It is evident that high temperature of 1000°C at the depth of 43 km in the tectonically active areas is nearer to the initial melting point of the rocks of lower crust and mantle mainly basalt and peridotite.

The temperature of the upper part of the magma slab representing the upper portion of the oceanic crust has been estimated to be 0°C where as the temperature of the lower part of the magma slab which comes in contact with the asthenosphere remains 1200°C which is quite nearer to the melting point. If we believe the rate of general increase of temperature with increasing depth the temperature should be around $25,000^{\circ}$C at the depth of 2,900 km but under such circumstances most part of the earth would have melted but this has not so happened. It is evident form this discussion that most part of the radioactive minerals are concentrated in the uppermost layer of the earth. This fact explains the situation of high temperature in the continental crust as described above because disintegration and decay of radioactive minerals generate more heat in the crustal areas. It, thus, appears that the rate of increase of temperature downwards decreases with increasing depth. The following facts may be presented about the thermal condition of the interior of the earth-

(i) The asthenosphere is partially molten. The temperature is around 1100°C at the depth of 100 km which is nearer to initial melting point.

(ii) The temperature at the depths of 400 km and 700 km (from the earth's surface) has been estimated to be $1,500^{\circ}$C and $1,900^{\circ}$C respectively.

(iii) The temperature at the junction of mantle and outer molten core standing at the depth of 2,900 km is about 3700°C.

(iv) The temperature at the junction of outer molten core and inner solid core standing at the depth of 5,100 km is $4,300^{\circ}$C.

Generation and transfer of heat inside the earth-It may be pointed out that the heat in the interior of the earth is generated through the disintegration of radioactive minerals and conversion of gravity force into thermal energy. It is believed that about 4.7 billion years ago the initial temperature of the earth generated by planetary accretion and adiabatic compression would have been around 1000°C. Later on the heat of the interior of the earth would have gradually but substantially increased due to heat supplied by the disintegration of radioactive minerals. About 4.0 to 4.5 billion years ago the core and mantle would have been separated and their boundary would have evolved when the temperature would have increased to reach the melting point of iron. Thus, due to foundering of molten iron into core the gravity force equivalent to 2×10^{37} erg (one calorie = 4.9×10^{7} erg) in the form of heat energy might have been released. Large scale melting and rearrangement of material inside the earth consequent upon high thermal energy, as stated above, probably became responsible for the formation of different zones of the earth *e.g.* crust, mantle and core.

On an average there is gradual flow of heat from the inner part of the earth to its outer part. It may be pointed out that the heat energy in the solids is in the form of vibrations of atoms. It is to be remembered that the rocks are poor conductor of heat. The transfer of heat from only 10m thick rock layer takes 3 years. The 100m thick lava flow takes 300 years to cool down and solidify. The transfer of heat from the lower part to the upper part of a 400km thick layer of rocks would take a long period of 5 billion years. If we take conduction as the only mechanism of the cooling of the earth, the heat from the depth of 400 km would have not reached the earth's surface till now.

The transfer of heat from the interior of the earth towards its outer part may also not be effectively performed by radiation because most of the minerals of the interior of the earth are opaque. Such materials cannot effectively transfer or lose heat through radiation. The third alternative possibility for the transfer of heat may be the process of convection but convective mechanism is more effective in liquid materials.

The earth's surface receives heat from two sources *e.g.* from the sun and from its interior part itself. The heat received from these two sources is ultimately sent into the space. Solar heat drives the atmospheric and hydrological processes and generates denudational processes whereas the internal heat of the earth performs constructive works *e.g.* formation of mountains, plateaux, faults etc., vulcanicity, seismic events and other tectonic events. 'In a real sense, the earth's internal heat engine builds mountains and its external heat engine, the sun, destroys them' (F. Press and R. Siever, 1974).

4.3 Evidences from the Theories of the Origin of the Earth

Various exponents of different hypotheses and theories of the origin of the earth have assumed the original form of the earth to be solid or liquid or gaseous. According to the 'Planetesimal Hypothesis' the earth was originated due to accretion and aggregation of solid dust particles known as 'planetesimals'. Based on this corollary the core of the earth should be in solid state. According to the 'Tidal Hypothesis' the core of the earth should be in liquid state because the earth has been taken to have been formed, according to this hypothesis, from the tidal materials ejected from the primitive sun. According to the 'Nabular Hypothesis' of Laplace the core of the earth should be in liquid state. Zoeppritz and Ritter have opined that the core of the earth is made of gases but this concept may not be accepted because if we assume the core of the earth in gaseous state many more problems will emerge. There may be only two possibilities viz. either the core may be in solid state or liquid state. This problem would be dealt with while dealing with the evidences of seismology.

4.4 Natural Sources

Vulcanicity

Some scientists believe on the basis of upwelling and spread of hot and liquid lava on the earth's surface during volcanic eruption that there is at least such a layer below the earth's surface which is in liquid state. Such molten layer has been termed as 'magma chamber' which supplies magma and lava during volcanic eruptions. It may be, thus, surmised, on the basis of above connotation, that some part of the earth should be in liquid state but this inference is refuted if one considers the increasing pressure with increasing depth inside the earth. It is known to all that increasing pressure increases the melting point of the rocks. Thus, the inner part of the earth may not be in molten state inspite of very high temperature prevailing therein because the enormous weight and pressure of the overlying materials (superincumbent load) increases the melting point of the rocks. It, thus, appears that the core of the earth should be in solid state. Now question arises, where hot and liquid lavas come from during volcanic eruption? It may be pointed out that when the pressure of superincumbent load is released due to fracturing and faulting in the crustal surface, the melting point of underlying rocks is reduced (lowered) and thus the rocks are instantaneously melted because required degree of high temperature is already present there. It, thus, appears that no authenticated knowledge about the composition of the earth's interior is obtained from the evidences of volcanic activities.

EVIDENCES OF SEISMOLOGY

Seismology is the science which studies various aspects of seismic waves generated during the occurrence of earthquakes. Seismic waves are recorded with the help of an instrument known as **seismograph.** It may be pointed out that seismology is the only source which provides us authenticated information about the composition of earth's interior. The place of the occurrence of an earthquake is called **'focus'** and the place which experiences the seismic event first is called **'epicentre'**, which is located on the earth's surface and is always perpendicular to the 'focus'. On the other hand, the focus or the place of the origin of an earthquake is always inside the earth. The deepest focus has been measured at the depth of 700 km from the earth's surface. The different types of tremors and waves generated during the occurrence of an earthquake are called **'seismic waves'** which are generally divided in 3 broad categories *e.g.* primary waves, secondary waves and surface waves.

(i) Primary waves also called as longitudinal or compressional waves or simply 'P' waves, are analogous to sound waves wherein particles move both to and fro in the line of the propagation of the ray. P waves travel with fastest speed through solid materials. Though these also pass through liquid materials but their speed is slowed down.

(ii) Secondary waves are also called as transverse or distortional or simply S waves. These are analogous to water ripples or light waves wherein the particles move at right angles to the rays. S waves cannot pass through liquid materials.

(iii) Surface waves are also called as Long Period waves or simply L waves. These waves generally affect only the surface of the earth and die out at smaller depth. These waves cover longest distances of all the seismic waves. Though their speed is lower than P and S waves but these are most violent and destructive.

When an earthquake occurs the seismic waves are recorded at the epicentre with the help of seismograph. In the beginning a few small and weak swings are recorded. Such tremors are called **'first preliminary tremors.'** After a brief interval the **'second preliminary tremors'** are recorded and finally the **'main tremors'** of strong waves are recorded (fig. 4.1).

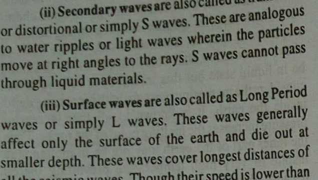

Fig. 4.1 : Recorded seismic waves by a seismograph.

The nature and properties of the composition of the interior of the earth may be successfully obtained on the basis of the study of various aspects of seismic waves mainly the velocity and travel paths of these waves while passing through a homogeneous solid body but these waves are reflected and refracted while passing through a body having heterogenous composition and varying density zones. If the earth would have been composed of homogenous solid materials the seismic waves should have reached the core of the earth in a straight path but this is not the case in reality. In fact, the recorded seismic waves denote the fact that these waves seldom follow straight paths rather they adopt curved and refracted paths. Thus, it becomes obvious that the earth is not composed of homogenous materials rather there are variations of density inside the earth. The seismic waves are refracted at the places of density changes. A regular change of density inside the earth causes a curved path to be followed by the seismic waves. Thus, the seismic waves become concave towards the earth's surface (fig. 4.2)

As stated earlier S waves cannot pass through liquid. After indepth study of seismic waves Oldhum demonstrated in the year 1909 that S waves disappear at the angular distance of 120^0 from the epicentre and P waves are weakened. It is evident from fig. 4.2 that S waves are totally absent in the core of the earth. It appears from this observation that there is a core in liquid state which is located at the depth of more than 2900 km from the earth's surface and surrounds the nucleus of the earth. Based on this finding the scientists have estimated that the iron and nickel of the core of the earth may be in liquid state.

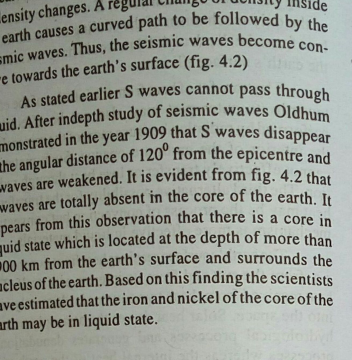

Fig. 4.2 : Paths followed by seismic waves through the earth's interior.

Not only this, if we study the nature, characteristics and velocity of seismic waves, we may find the presence of several density zones inside the earth. Detailed studies of seismic waves of different epicentres all over the world have revealed the fact that there are extra sets of seismic waves which are similar to P and S waves but with slower rate of velocity. It is a known fact that the velocity of seismic waves changes only when there are changes in the density of rocks. On the basis of velocity seismic waves are divided in three sets of waves *e.g.* (i) first set of P-S waves of maximum velocity, (ii) second set of Pg-Sg waves of minimum velocity, (iii) third set of p*-S* waves of medium velocity falling between the first and the second sets of waves. Thus, on the basis of changes of velocity of seismic waves it is proved that there are major changes in the velocity of waves at three places inside the earth and hence it can be safely inferred that there are three distinict zones or layers of varying densities inside the earth below the outer thin layer of sedimentary rocks.

(1) **Upper layer-** Jeffreys discovered a different set of seismic waves termed as Pg-Sg waves on the basis of the record of the earthquake of the Kulpa valley in Croatia in the year 1909. On an average, Pg and Sg waves travel at the rate of 5.4 km and 3.3 km per second respectively in the upper part of the earth. The density of the rocks through which these waves travel is about 2.7. It is proved on this basis that the upper layer is composed of granitic rocks.

(2) **Intermediate layer-**Conard identified another set of seismic waves termed as P*-S* waves on the basis of the study of Tauern earthquake of 1923. The velocities of these waves are intermediate between P-S and Pg-Sg sets of waves. P* and S* waves travel at the rate of 6-7 km and 3-4 km per second respectively in the middle zone of the earth. It has been inferred on the basis of intermediate velocity of these waves that there is an intermediate layer with average density of 3 inside the earth. There is difference of opinion about the nature and type of the rocks of this intermediate layer. According to Daly and Jeffreys the intermediate layer consists of glassy basalt whereas Wegener and Holmes have identified amphibolite as constituent rock of this layer. But most of the scientists are of the view that the intermediate layer is composed of basalt.

(3) **Lower layer-** P and S waves penetrate upto greatest depth inside the earth. The velocity of P and S waves is 7.8 km and 4.5 km per second respectively. The highest velocity of seismic waves in the innermost part of the earth indicates an inner or lower layer of heavier materials, most probably peridotite or dunite. It is also possible that materials may be in non-crystalline, glassy state. The depth of this layer is estimated to be about 2900 km from the earth's surface.

4.5 Chemical Composition And Layering System Of The Earth

According to Suess

E. Suess has thrown light on the chemical composition of the earth's interior. The crust is covered by a thin layer of sedimentary rocks of very low density. This layer is composed of crystalline rocks, mostly silicate matter. The dominant minerals are felspar and mica. The upper part of this layer is composed of light silicate matter while heavy silicate matter dominates in the lower part. Suess has identified three zones of different matter below the outer thin sedimentary cover.

(i) **SIAL** located just below the outer sedimentary cover is composed of granites. This layer is dominated by silica and aluminium (SIAL = SI + AL). The average density of this layer is 2.9 whereas its thickness ranges between 50 to 300 km. This layer is dominated by acid materials and silicates of potassium, sodium and aluminium are abundantly found. Continents have been formed by sialic layer.

(ii) **SIMA** is located just below the sialic layer. This layer is composed of basalt and is the source of magma and lava during volcanic eruptions. Silica (si-silica+ma-magnesium) and magnesium are the dominant constituents. Average density ranges between 2.9. to 4.7 whereas the thickness varies from 1,000 km to 2,000 km. There is abundance of basic matter. The silicates of magnesium, calcium and iron are most abundantly found.

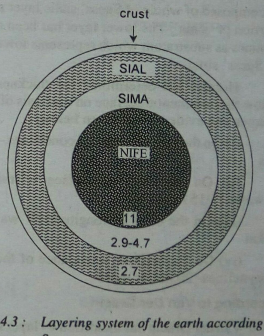

Fig. 4.3 : Layering system of the earth according to E. Suess.

(iii) **NIFE** is located just below the 'sima' layer. This layer is composed of nickel (NI) and ferrium (Fe). It is, thus, apparent that this layer is made of heavy metals which are responsible for very high density (11) of this layer. The diameter of this zone is 6880 km. The presence of iron (ferrium) indicates the magnetic property of the earth's interior. This property also indicates the rigidity of the earth (fig. 4.3)

4.6 Thickness And Depth Of Different Layers Of The Earth

According to Daly

Daly has recognized three layers of different density in the earth. (i) Outer zone is composed of silicates. Average density is 3.0 and the thickness is 1,600 km. (ii) Intermediate layer is composed of the mixture of iron and silicates. Average density is from 4.5 to 9 and the thickness is 1,280 km. (iii) Central zone is made of iron and is in solid state. Average density and diameter are 11.6 and 7,040 km respectively.

According to Harold Jeffreys

Jeffreys has identified, on the basis of the study of seismic waves, four layers in the earth *e.g.* (i) outer layer of sedimentary rocks, (ii) second layer of granites, (iii) third layer of thachylyte or diorite and (iv) fourth layer of dunite, peridotite or eclogite.

According to Holmes

Arthur Holmes has recognized two major layers in the earth. The upper layer is termed as crust which is composed of whole of Suess' sialic layer and upper portion of 'sima'. The lower layer has been named by Holmes as substratum which represents lower portion of Suess' sima.

Holmes has determined the thickness of sial below the continental surface on the basis of different sources and evidences as given below.

(i) On the basis of thermal conditions - 20 km or less

(ii) On the basis of surface seismic waves (L waves) - 15 km or more

(iii) On the basis of longitudinal waves - 20-30 km

(iv) On the basis of subsidence of the deepest geosynclines- 20 km or more

According to Van Der Gracht

Van der Gracht has identified 4 - layer system of the composition of the interior of the earth. He has summarized the various properties of the earth's interior in the following manner-

Layer	Thickness	Density
(i) Outer sialic crust	60 km (under continents) 20 km (under Atlantic Ocean) Absent (under Pacific Ocean)	2.75 to 2.9
(ii) Innersilicate mantle	60 - 1140 km	3.1 to 4.75
(iii) Zone of mixed metals and silicates	1,140-2,900 km	4.75 to 5.0
(iv) Metallic nucleus	2,900 - 6371 km	11.0

It appears from the foregoing discussion that there is difference of opinions about the number, thickness and various properties of the layers of the earth. In order to avoid confusion the following generalized pattern of the layering system of the earth's interior is commonly accepted by majority of the scientists.

(i) **Lithosphere** with a thickness of about 100 km is mostly composed of granites. Silica and aluminium are dominant constituents. Average density is 3.5.

(ii) **Pyrosphere** stretches for a thickness of 2780 km having an average density of 5.6. The dominant rock is basalt.

(iii) **Barysphere** is composed of iron and nickel. Average density ranges between 8 and 11 and this layer stretches from 2800 km to the nucleus of the core.

4.7 Recent Views

The aforesaid views about the composition and structure of the earth's interior have now become obsolete. The scientific study and analysis of various aspects of seismic waves (mainly velocity and travel paths) of natural and man-induced earthquakes have enabled the scientists to unravel the mystery of the earth's interior based on authentic information. Three zones of varying properties have been identified in the earth on the basis of changes in the velocity of seismic waves while passing through the earth (fig. 4.4) *e.g.* **crust, mantle** and **core.** It may be pointed out that there is still difference of opinions about the thickness of these zones, mainly about the thickness of the crust. Various sources put the thickness of the crust between 30 km and 100 km. On the basis of the change in the velocity of seismic waves crust is further divided into

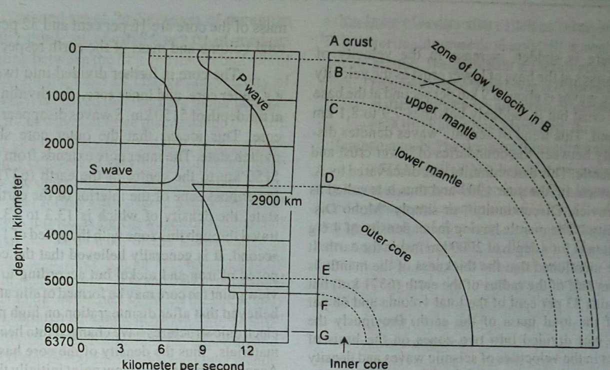

Fig : 4.4 : Presentation of velocities of seismic waves from the crust of the earth to its interior and relationships between the velocities of seismic waves and different zones of the earth (after K.E. Bullen).

(i) **upper crust** and (ii) **lower crust** because the velocity of P waves suddenly increases in the lower crust. For example, the average velocity of P waves in the upper crust is 6.1 km per second while it becomes 6.9 km per second in the lower crust, Fig. 4.4 depicts the different velocities of P and S waves in different parts of the earth and the relationship between velocities of seismic waves and different zones of the earth.

CRUST

The average density of the outer and lower crust is 2.8 and 3.0 respectively. It may be pointed out that in the beginning vast difference between the structure and composition of upper and lower crust was reported by the scientists but now the evidences of seismology have revealed almost identical structure and composition of these two sub-zones of the crust. The difference of density between the upper (2.8) and lower crust (3.0) is because of the pressure of supperincumbent load. The formation of the minerals of the upper crust was accomplished at relatively lower pressure than the minerals of the lower crust.

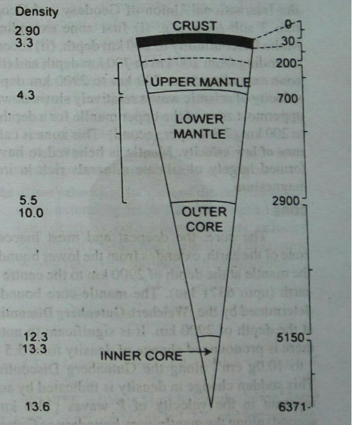

Fig. 4.5: Diagramatic presentation of different zones of the earth, their densities and thickness on the basis of the information of International Union of Geodesy and Geophysics.

MANTLE

There is sudden increase in the velocity of seismic waves at the base of lower crust as the velocity of seismic waves is about 6.9 km per second at the base of lower crust but it suddenly becomes 7.9 to 8.1 km per second. This trend of seismic waves denotes discontinuity between the boundaries of lower crust and upper mantle. This discontinuity was discovered by A. Mohorovicic in the year 1909 and thus it is called as 'Mohorovicic Discontinuity', or simply 'Moho Discontinuity.' The mantle having mean density of 4.6 g cm^{-3} extends for a depth of 2900 km inside the earth. It may be mentioned that the thickness of the mantle is less than half of the radius of the earth (6371 km) but it contains 83 per cent of the total volume and 68 per cent of the total mass of the earth. Previously the mantle was divided into two zones on the basis of changes in the velocities of seismic waves and density *e.g.* (i) **upper mantle** from Moho Discontinuity to the depth of 1000 km and (ii) **lower mantle** from 1000 km to 2900 km depth but now the mantle is divided on the basis of the information received from the discovery of the International Union of Geodesy and Geophysics into 3 sub-zones *e.g.* (i) first zone extending from Moho Discontinuity to 200 km depth, (ii) second zone extending from 200 km to 700 km depth and (iii) third zone extending from 700 km to 2900 km depth. The velocity of seismic waves relatively slows down in the uppermost zone of the upper mantle for a depth of 100 to 200 km (7.8 km per second). This zone is called the **zone of low velocity.** Mantle is believed to have been formed largely of silicate minerals rich in iron and magnesium.

CORE

The core, the deepest and most inaccessible zone of the earth, extendes from the lower boundary of the mantle at the depth of 2900 km to the centre of the earth (upto 6371 km). The mantle-core boundary is determined by the **'Weichert-Gutenberg Discontinuity'** at the depth of 2900 km. It is significant to note that there is pronounced change of density form 5.5 g cm^{-3} to 10.0g cm^{-3} along the Gutenberg Discontinuity. This sudden change in density is indicated by sudden increase in the velocity of P waves (13.6 km per second) along the mantle-core boundary or Gutenberg Discontinuity. The density further increases from 12.3 to 13.3 and 13.6 with increasing depth of the core. It, thus, appears that the density of the core is more than twice the density of the mantle but the volume and mass of the core are 16 per cent and 32 per cent of the total volume and mass of the earth respectively.

The core is further divided into two sub-zones *e.g.* **outer core** and **inner core,** the dividing line being at the depth of 5150 km. S waves disappear in this outer core. This means that the outer core should be in molten state. The inner core extends from the depth of 5150 km to the centre of the earth (6371 km). This lowermost zone of the interior of the earth is in solid state, the density of which is 13.3 to 13.6. P waves travel through this zone with the speed of 11.23 km per second. It is generally believed that the core is composed of iron and nickel but according to the second view point the core may be formed of silicates. It is also believed that after disintegration on high pressure the electronic structures have changed into heavy metallic materials, thus the density of the core has increased. According to the third view point initially the core was composed of hydrogen but later on hydrogen was transformed into metallic materials due to excessive pressure (over 3 million atmospheres). This possibility is questioned on the ground that though the transformation of silicate or hydrogen due to very high pressure in the core may be believed tentatively but this process cannot increase the density of the core as high as it is at present. For example, the planet Mercury is smallest of all the planets of our solar system. It may be argued that least compression and pressure cannot generate highest density in the core of Mercury. Most of present-day geophysicists and geochemists believe that the core is made of metallic materials mainly iron and nickel.

4.8 Important Definitions

Barysphere : represents the innermost zone of the interior of the earth and extends from 2800 km. depth to the nucleus of the core. The average density ranges between 8 and 11.

Core : is the deepest and most inaccessible zone of the interior of the earth and extends from the lower boundary of the mantle at the depth of 2900 km. to the center of the earth i.e. upto 6371 km. The density increases from 10 at the mantle-core boundary downword to 11.6 at the center of the core. The core has two subzones i.e. outer core (from 2900 km. to 5150 km. depth) and inner core (from 5150 to 6371 km. depth).

Crust : is the outermost layer (zone) of the earth with average density of 2.8 to 3.0 and average thickness of 30 km.

Density : refers to the amount of mass per unit volume of substance, usually measured in gram per cubic centimeter (g/cm^3).

Lithosphere : literally means rocksphere (lithos means rock) which represents the solid portion of the continents having a thickness of about 100 km. and average density of 3.5. It is composed of mostly silicate minerals.

Mantle : represents the second zone of the interior of the earth and extends from 30 km. to 2900 km. depth. The lower crust and upper mantle is separated by Moho-discontinuity. Mantle is divided into 2 subzones i.e. upper mantle (200 km. to 700 km. depth), and lower mantle (700 km. to 2900 km. depth). Mantle is formed of silicate minerals.

Moho-discontinuity : The boundary between lower crust and upper mantle, where there is sudden increase in density and velocity of seismic waves downward is called Moho-discontinuity after A. Mohorovicic who discovered it in the year 1909.

Primary waves : also called as **longitudinal** or **compressional** waves or simply 'P' waves, are analogous to sound waves wherein particles move both to and fro in the line of the propagation of the ray. P seismic waves travel with fastest speed through solid materials, but with low speed in liquid.

Pyrosphere : is the middle zone of the earth with a thickness of 2780 km. having an average density of 5.6.

Secondary waves : also called as **transverse** or **distortional waves** or simply 'S' waves are such seismic waves which are analogous to water ripples or light waves wherein particles move at right angles to the rays. S waves cannot pass through liquid materials.

Seismic waves : The waves generated by the occurrence of earthquakes are called seismic waves.

Seismology : is the science that deals with different aspects of seismic waves.

Seismograph : is an intrument which records the seismic waves generated by the occurrence of earthquakes.

Surface waves : are such seismic waves which generally affect only the surface of the earth and die out at low depth. Also called as 'long period waves' or simply 'L' waves, surface seismic waves cover longest distance of all the seismic waves.

Vulcanicity : is a process which includes all those processes and mechanisms which are related to the origin of magmas, gases and vapour, their ascent and appearance on the earth's surface in various forms.

Wichert-Guttenberg discontinuity : The sudden change in the composition and structure of the interior of the earth at mantle-core boundary is called Wichert-Guttenberg discontinuity. There is sudden change of average density from 5.5 to 10 at the depth of 2900 km. which separates lower mantle from outer core.

Zone of low velocity : The zone of the interior of the earth extending from 100 km. depth to 200 km. depth is called zone of low velocity because of the fact that the velocity of seismic waves relatively slows down in this zone.