PHYSICAL GEOGRAPHY

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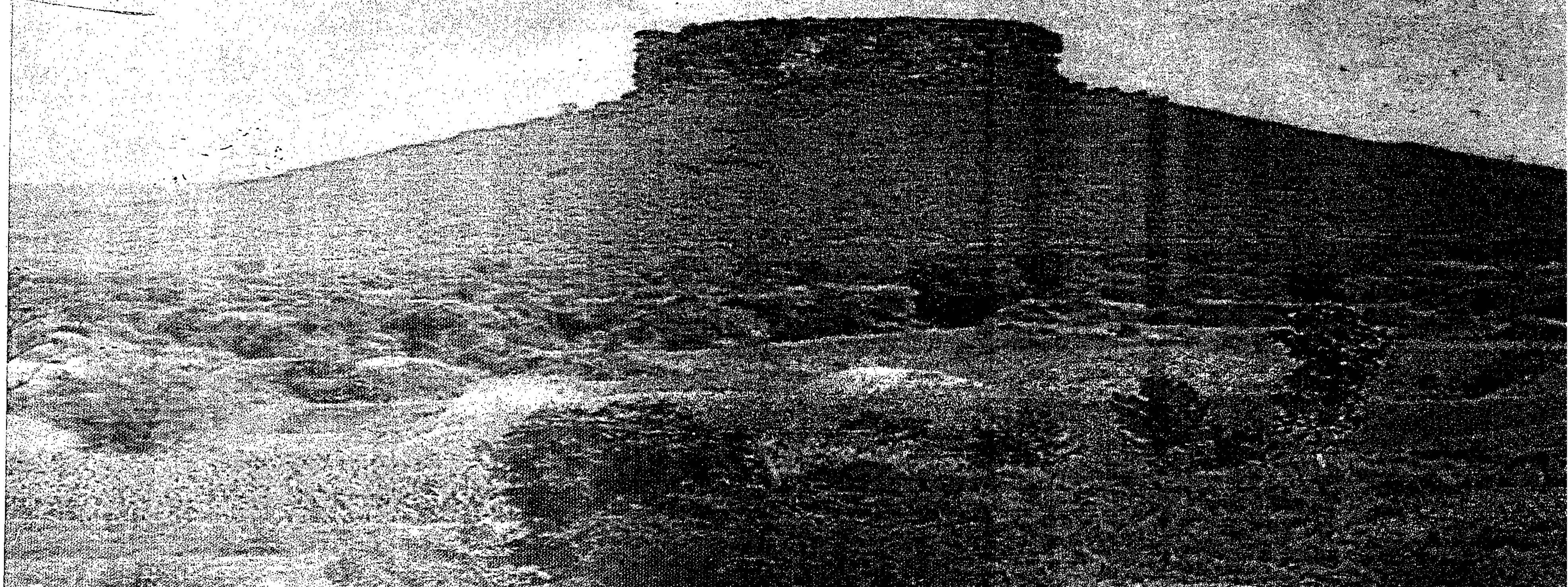

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NATURE OF PHYSICAL GEOGRAPHY

(Definition, Scope and Development)

1.1 DEFINITION

Physical geography is one of the two branches of geography viz. physical geography and human geography. In fact, the study of physical aspects of the earth represents the core of spatial science i.e. geography. Most of geographers have pleaded for bifurcation of geography into physical and human geography but it is rather unwise to ingnore biotic aspect of the biospheric ecosystem of the earth and hence there should be trifurcation of geography into physical geography, human geography and biogeography. Physical geography in terms of its meaning and definition, scope (subject matter) and methods of study has undergone seachange in the past few decades. In the beginning, physical geography was defined as the study of only physical environment (namely reliefs, air and water) of the earth e.g. *'the study of physical environment by itself is physical geography which includes consideration of surface relief of the globe (geomorphology), of the seas and the oceans (oceanography) and of the air (meteorology and climatology)'* (Arthur Holmes).

Physical geography was considered as the agglomeration of different branches of earth sciences or natural sciences viz. sciences of atmosphere (meteorology and climatology); science of seas and oceans (oceanography); science of solid earth (geology); science of soil (pedology); science of plants (botany) and science of landforms (geomorphology). Arthur Holmes further remarked that *'physical geography is simply the study of unification of a number of earth sciences which give us a general insight into the nature of man's environment. Not in itself a distinct branch of science physical geography is a body of basic principles of earth sciences selected with a view to include primarily the environmental influences that vary from place to place over the earth surface'* (Arthur Holmes, 1960).

It may be pointed out that presently physical geography is not only the agglomeration and unification of earth sciences as referred to above but it also studies the patterns of interactions between human activities and physical environment. As a distinct branch of geography physical geography studies the spatial patterns and spatial relationships of environmental components of the globe in regional context, it also studies the causes of regional patterns of such spatial relationships, simultaneously it incorporates the explanation of spatial and

temporal changes of environmental components and causes thereof. It is evident that the focus of the study of physical geography is the biosphere (life layer) comprising the envelope of land, air and water around the globe which supports the life of all biota (plants and animals) on the earth surface.

Thus, we include the study of all such physical elements and factors in physical geography which provide suitable habitats for the living organisms of the biosphere (plants and animals including man). It may be mentioned that the quality of biosphere is determined by the physical environment, the quality of which in itself is determined by the interactions between endogenetic forces (coming from within the earth) and exogenetic forces (originating from the atmosphere i.e. denudational processes which include the processes of erosion and weathering). The solid earth's surface (crust) provides different types of habitats to living organisms of the biospheric ecosystem. Different reliefs (tectonically originated) are created (like mountains and hills, plateaus, lakes, plains etc.) on the earth's surface by endogenetic forces which introduce diversity in the habitats. The outer solid crustal surface also provides nutrients to the biosphere. On the other hand, atmosphere provides essential elements (namely carbon, hydrogen, oxygen, nitrogen etc.) to the biosphere and gives birth to different types of climate on the earth's surface. The exogenetic processes originating from the atmosphere on one hand help in the circulation and exchange of heat between the atmosphere and the earth's surface, on the other hand they create different types of landforms through their denudational works and these landforms in turn further introduce diversity in the habitats produced by endogenetic forces. Thus, physical environment affects life forms (plants and animals) of the biosphere while man also modifies and changes physical environmental conditions through his economic activities.

1.2 SCOPE OF PHYSICAL GEOGRAPHY

It is evident from the foregoing discussion on the nature of physical geography that the detailed consideration of four components of the earth viz. lithosphere, atmosphere, hydrosphere and biosphere, are included in physical geography wherein characteristic features of these components are studied spatially and temporally.

First, the origin, age and structure of the interior of the earth, isostasy and evolution of continents and ocean basins are studied inorder to understand the characteristic features of the aforesaid four components. The study of forces or movements of the earth, both endogenetic (originating from within the earth) and exogenetic (originating from the atmosphere) becomes significant to understand the interactions between these two forces and resultant features. In fact, endogenetic forces (termed as constructive forces) coming from within the earth, create reliefs of varying dimensions on the earth's surface (e.g. mountains, folds, faults, volcanic cones etc.) which provide habitats for living organisms of the biospheric ecosystem on the one hand, and present initial reliefs for the interplay of exogenetic forces originating from the atmosphere, termed as destructive forces (denudational processes e.g. fluvial, marine, glacial, aeolian, periglacial etc. processes and weathering agents) on the other hand. The study of evolution of continents and ocean basins and their drifting (continental drift as evidenced by plate tectonics) helps in the understanding of evolution and dispersal of plants and animals.

The characteristics, origin and distribution of constructional reliefs namely mountains, faults, folds etc. are thoroughly investigated. The distribution, characteristics and origin of vulcanicity and landforms resulting therefrom are studied as physical features and natural hazards which adversely affect both human being and plants and animals.

The study of features resulting from the interactions between endogenetic and exogenetic forces involves the discussion of mode of denudational processes (weathering and erosion), hetherto termed as geomorphic processes, their mechanism of operation (machanism of erosion, transportation and deposition by running water-river, groundwater, sea waves, wind, glacier and periglacial agent) and resultant landforms.

The study of **hydrospheric component** involves the consideration of reliefs of the ocean basins (continental shelves, submarine canyons, continental slope, deep sea plains, ocean deeps etc.); thermal characteristics of ocean water; salinity (composition of seawater, sources and distribution of oceanic salinity); ocean deposits; ocean tides; ocean currents and

coral reefs and atolls (their distribution and origin, coral bleaching etc.).

The study of **atmospheric component** includes the discussion of composition and structure of atmosphere, elements of weather and climate, insolation and heat balance, terrestrial radiation balance and anthropogenic factors causing imbalance, air temperature, air pressure and winds (permanent or planetay winds, seasonal and local winds), characteristics and origin of monsoon, humidity and precipitation, airmasses, frontogenesis, cyclones and anticyclones, world climate etc.

The study of **biospheric component** involves the consideration of components of biosphere (both abiotic and biotic), soil system, ecological production and energy flow in the biospheric ecosystem, circulation of elements in the ecosystem, biogeochemical cycles, evolution, dispesal and extinction of plants and animals, biomes and man, ecosystem stability and man, man and atmospheric environment (global radiation balance, ozone depletion, greenhouse effects and global warming), man and environmental processes, main-induced soil erosion and sedimentation, environmental degradation and pollution, extreme events, hazards and disaster, environmental planning and management, global environmental problems and international co-operations.

It is evident from the aforementioned discussion that the scope of physical geography includes the consideration of systematic study of physical environment as well as the study of interactions between man and physical environment. Major changes have taken place in the subject matter and methodology of physical geography due to following factors :

(1) Universal desire to make physical geography more meaningful and applicable for human welfare and to integrate it more intimately with human geography inorder to redefine and to keep the discipline of geography intact and to make it more relevant to society.

(2) More attention of man towards natural hazards and disaster and greater emphasis on the evaluation of adverse impacts of human activities on physical environment and environmental problems resulting therefrom and remedial measures therefor.

(3) Greater emphasis on instrumentation and measurement of operation of different geomorphic processes and mathematical analysis of data derived through field and laboratory studies.

(4) More attention towards the study of certain aspects of physical geography e.g. ecosystem and ecological stability and instability, hydrology, plate tectonics etc.

(5) Recent trends of increasing emphasis on micro-temporal scale (i.e, graded and steady state time scale) in place of macro-temporal scale (*i.e,* cyclic time involving geological time *i.e.,* millions of years) and on shorter microspatial scale (10 to 100 km^2) in place of large or macro-spatial scale (mega scale, millions of square kilometres) in the study of geomorphic and environmental processes to make such study more relevant to society inorder to solve immediate environmental problems.

1.3 DEVELOPMENT OF PHYSICAL GEOGRAPHY

The discipline of physical geography has evolved through successive stages of its development in terms of methodology and approaches to study. After taking its birth in the philosophical ideas and reports of ancient thinkers, philosophers and historians of the ancient seats of civilization and culture *e.g.* Greece, Rome and Egypt, the science of physical environment attained its present status wherein different components were added from time to time. Previously physical geography concerned with only three components *i.e.,* lithosphere, hydrosphere and atmosphere but biosphere has been recently added to this discipline. It is desirable that the historical development of four distinct branches of physical geography *e.g.,* geomorphology, oceanography, climatology and biogeography should be discussed separately dealing with lithosphere, hydrosphere, atmosphere and biosphere respectively.

1. Geomorphology

Geomorphology is a significant branch of physical geography. The term of geomorphology stems from three Greek words *i.e., ge* (meaning earth), *morphe* (meaning form) and *logos* (meaning discourse). 'Geomophology may be defined as the scientific study of surface features of the earth's surface involving interpretative description of landforms, their origin and development and nature

and mechanism of geomorphological processes which evolve the landforms' (Savindra Singh, 1998).

The subject matter of geomorphology is organized on the bases of (i) dimension and scale of relief features (landforms), (ii) processes that shape the landforms, and (iii) the approaches to the geomorphic studies. The systematic study of landforms requires some fundamental knowledge of geology as the genesis and development of all types of landforms primarily depend on the materials of the earth's crust (rocks) and partly on the forces coming from within the earth. Certain principles of structural and dynamic geology are included in geomorphic studies. Theoretical geology helps in understanding the nature of landforms and, therefore, the origin of different types of reliefs like mountains, plateaus, faults, folds, continents and ocean basins cannot be properly understood because it helps in understanding the denudational landforms which develop on them. Endogenetic forces particularly diastrophic and sudden (vulcanicity and seismic events) should be taken note of as these introduce irregularities on the earth's surface which generate variety in landforms. **First order relief features** include continents and ocean basins while mountains, plateaus, plains, faults, rift valleys etc. are included in relief features of the second order. Micro-level landforms developed on **second order relief features** by exogenetic denudational processes (both erosional and depositional landforms) *e.g.* running water, groundwater, sea waves, wind, glacier and periglacial agents, are included in the categories of **relief features of third order** .

'The rapidly evolving discipline of geomorphology has undergone seachange in methodology and approaches to the study of landforms and related processes since 1945 when R.E. Horton introduced quantitative methods for the analysis of morphometric characteristics of fluvially originated drainage basins' (Savindra Singh, 1998). The present status of geomorphology is the result of grandual but successive development of geomorphic thoughts postulated in different periods by innumerable philosophers, experts and geoscientists in the subject and outside the subject. In the **ancient period** some ideas of landforms were presentd by philosophers and historians of Greece, Rome and Egypt *e.g.* Herodotus (485 B.C.-425 B.C., he named depositional features at the mouth of a river as delta and propounded that 'Egypt is the gift of Nile'), Aristotle (384 B.C.-322 B.C., he described the features developed on limestones, origin of springs and streams), Strabbo (54 B. C.-25 A.D., according to him the size of delta varies depending on the nature of rocks of the region through which the river makes its course) etc. No significant development of geomorphology could take place during **dark age** (1st Century A.D. to 14th Century A.D.) as a lull prevailed in the development of geographical knowledge with the fall of Roman empire.

The long continued academic silence of 1400 years was suddenly broken by the emergence of catastrophism which believed in the quick and sudden origin and evolution of all animate and inanimate objects in very short period of time and thus new pages of peculiar and fantastic concepts were added to the treasure of geomorphological and geographical literature. The **age of catastrophism** was dominated by the concept of sudden occurrence and evolution of all types of features but this concept was soon rejected by the advocates of uniformitarianism. The emergence of **age of uniformitarianism** resulted in the outright rejection of the concept of catastrophism and gradual cyclic nature of earth's history was postulated by James Hutton (1726-1797 A.D.) in the 18th century. His concept of uniformitanrianism was based on the basic tenet 'that the same geological processes which operate today operated in the past and therefore the history of geological events repeats in cyclic manner.' His concept of **'present is key to the past'** aimed at the reconstruction of past earth history on the basis of the present. He was the first geologist to observe cyclic nature of earth's history. He also propounded the concept of 'no vestige of a beginning : no prospect of an end'. His two disciples John Playfair (1748-1819 A.D.) and Charles Lyell (1797-1873 A.D.) further developed and propagated the concept of uniformitarianism.

Geomorphology became an independent discipline and a major branch of geology at the beginning of the 19th century when the development of geomorphic thoughts took place at regional level and two distinct schools of geomorphic thoughts can well be identified *e.g* (1) European School and (2) American School.

European School was characterized by significant contributions in the fields of recognition and identification of Pleistocene Ice Age and glaciation, glacial erosion, marine erosion, fluvial processes and erosion, arid and karst landscapes. Louis Agassiz (1807-1873 A.D.), Jean de Charpentier, John Playfair, Venetz, Esmark etc. made significant contributions in the development of glacial geomorphology. Jean de Charpentier and Louis Agassiz postulated the concept of continental glacier and ice ages while James Geikie published his book 'The Great Ice Age' in 1894. According to him an ice age involving longer geological period is comprised of distinct several glacial periods separated by warm interglacial periods. A. Penck and Bruckner identified four glacial periods during Pleistocene Ice Age (Gunz, Mindel, Riss, Wurm) which were separated by three warm interglacial periods. Sir Andrew Ramsay (1833-1905 A.D.) made significant contributions in marine geomorphology while J. Walther, Passarge etc. developed aeolian geomorphology. W. Penck postulated the concepts of cycle of erosion and slope replacement through his 'morphologishe analyse.'

American School is credited for making maximum contributions in the field of geomorphology. In fact, the last two decades of 19th century and first two decades of 20th century (*i.e.,* from 1875 to 1920) are considered as **'golden age'** not only of American geomorphology but also of world geomorphology because it was this period when for the first time general theory of landscape development was propounded by W.M Davis and landform analysis attained its final shape. The concept of sequential changes of landforms through scuccessive developmental phases in terms of time based on the basic tenet of time-dependent concept of Davisian model of geographical cycle of erosion became the core of landform analysis and guideline for geomorphologists and geologists not only in North America but world over. Powell, Gilbert, Dutton and Davis made significant contributions in the field of subaerial denudation.

Major J.W. Powell (1834-1902 A.D.) postulated the concept of limit of maximum vertical erosion by streams to which he proposed the term **base level,** which is determined by sea level. G.K. Gilbert (1843-1918 A.D.) propounded the concept of **dynamic equilibrium** and introduced quantitative methods of the analysis of landforms W.M. Davis (1850-1934 A.D.) is given credit to synthesize and integrate hitherto scattered ideas of American geomorphologists to present them in coherent and well defined framework. Davis is given credit for postulation of first general theory of landscape development which is in fact a synthesis of his three major concepts viz. 'cpmplete cycle of river life' (1889), **'geographical cycle'** (1899) and 'slope evolution'. He emphasized progressive development of erosional stream valleys through the concept of 'complete cycle of river life' while sequential changes of landscapes through time involving historical evolution of landsforms (time-dependent series of landforms) or cyclic development of landforms were highlighted through the concept of geographical cycle.

The beginning of the 20th century was heralded by methodological revolution in geomorphological studies brought by W.M. Davis and his followers at home (U.S.A.) and geographical cycle was variously termed, popularised and applied by his followers worldover *e.g.* normal cycle of erosion, geomorphic cycle, humid cycle etc. His concept of geographical cycle was later on applied with all other processes by Davis and his followers *e.g.* arid cycle of erosion (Davis, 1903, 1905 and 1930), glacial cycle of erosion (Davis, 1900 and 1906), marine cycle of erosion (Davis, 1912, D. W. Johnson, 1919), karst cycle of erosion (Bedee, 1911, Cvijic, 1918), periglacial cycle of erosion (Peltier, 1950) etc. Davis' concept of historical evolution of landscape became the pivot for the development of classical concept of **denudation chronology** and **erosion surfaces** in U.K. British geomorphologists made their independent identity and there emerged an entirely different school of geomorphology which laid emphasis on the chronological (historical) study of landscape development in historical perspective better known as denudation chronology based on the **concept of palimpsest.** The Davisian model of geographical cycle met with strong criticism and rapid and erosionless upliftment became the crux of criticisms by the opponents of cyclic concept of landscape evolution particularly by German geomorphologists. W. Penck, through his 'morphological analysis' and 'morphological system', attempted to reconstruct and interpret past events of

crustal movements on the basis of exogenetic processes and morphological characteristics and postulated the concept of time independent landscape evolution.

A new branch of geomorphology in the form of **climatic geomorphology** was developed in France and Germany based on basic tenet that 'each climatic type produces its own characteristic assemblage of landforms'. Sauer (1925), Wentworth (1928), Saper (1935), Friese (1935), Budel (1944, 1948), L.C. Peltier (1950), Tricart and Cailleux etc. made significant contributions in this field.

Post-1950 geomorphology has undergone seachange in methods and approaches to the study of landforms, conceptual framework, paradigm and thrust areas of study. The recent trends in the field of geomorphological studies since 1950 include increasing criticism of Davisian model of cyclic development of landforms, concerted efforts for the replacement of cyclic model by non-cyclic (dynamic equilibrium) model, descriptive geomorphology (qualitative treatment of landforms) by quantitative geomorphology, inductive method of landforms analysis by deductive method, introduction of models and system approach, emergence of process geomorphology, climatic geomorphology, applied geomorphology, environmental gemorphology, shift from larger spatial scale (mega geomorphology) and longer temporal scale to smaller spatial and shorter temporal scale (micro-geomorphology) etc.

The decade 1950-60 was devoted more for the quantitative study of landforms and processes and the consideration of geomorphic theories occupied a back seat. The rejection of Davisian concept of **'cyclic model'** culminated in the postulation of **'dynamic equilibrium theory'** of landscape devlopment by J.T. Hack, R.J. Chorley and others but the conceptual vacuum caused by the rejection of Davisian model could not be filled up even by dynamic equilibrium model. Recently, a few alternative geomorphic theories have been postulated *e.g.* 'geomorphic threshold model', 'tectonic geomorphic model' (M. Morisawa), 'episodic erosion model' (S.A. Schumm) etc. The most outstanding contribution to the advancement of geomorphological knowledge has been replacement of **'form geomorphology'** by **'process geomorphology'** and postulation of **'functional theory'** in place of **'evolution theory'** and emergence of **'environmental geomorphology'** as a new branch of geomorphology. As regards Indian contributions to geomorphology four centres of geomorphology have developed at Allahabad university, Calcutta university, Poona university and Central Arid Zone Research Institute (CAZRI), Jodhpur.

2. Oceanography

About three-fourth of the globe (70.8 per cent) is covered by hydrosphere. Out of the total surface area of the globe (509,950,000 km^2) lithosphere and hydrosphere cover 361,060,000 km^2 and 148,890,000 km^2 respectively. The study of hydrosphere (oceans and seas) is called oceanography which includes the consideration of description and analysis of physical and biological aspects of hydrosphere. According to J. Proudman fundamental principles of dynamics and thermodynamics are also studied in relation to characteristics of ocean water and biological aspects. The science of oceans *i.e.*, oceanography includes marine geology, marine geomorphology, physical oceanography, chemistry of ocean water and bio-oceanography. The origin of ocean basins (continental drift and seafloor spreading), structure of crust and mantle, characteristics of ocean deposits and characteristics and origin of marine landforms are studied in marine geology and geomorphology. Physical oceanography includes the consideration of physical properties of ocean water (*e.g.* temperature, pressure, salinity, density, compressibility, viscosity, water masses and their distributional patterns) and dynamics of ocean water (*e.g.* sea waves, currents, tides, tsunamis etc.). Recently, marine meteorology is also included in oceanography wherein atmospheric conditions over ocean water are studied. Bio-oceanography includes the study of the characteristics, evolution, distribution and dispersal of marine organisms.

The study of seas and oceans dates back to the ancient period of before Christ though early descriptions were based on empirical observations of individuals. The long period of 1200 years from 1000 B.C. to 2nd century A.D. is divided into 3 phases of development of knowledge of marine environment. (1) Early period of 500 years from the age of Homer (1000 B.C.) to the age of Hecatius includes the knowledge of Mediterranean sea based on individual voyages, (2) period of the study of tides by Pytheas (4th Century B.C.), a contemporary of Alexander; detailed description of land and sea by Strabbo (54 B.C.-25 A.D.) and measurement of ocean depths upto 1000 fathoms near Sardinia by Posidonius, (3) presentation of the map of the world and Indian Ocean as closed sea by Ptolemy (2nd Century A.D.), dark age continued from 2nd century A.D. to 14th century when no significat contribution could be made in the science of oceanography. The period from 15th to 16th century is called **Great Age of Discovery and Exploration** because efforts were made to discover and explore new areas. Columbus discovered America and Vasco de Gama reached India and Magellan circumnavigated the globe during this period. The map presented by Ortelius in 1570 gave new knowledge about the distribution of land and seas. Significant contributions were made in the fields of origin of coastal geomorphology, theoretical base of tides, ocean currents and sea waves during this **period of renaissance.**

The study of seas and oceans began on theoretical basis since 17th century and mathematical methods and scientific principles were used for the interpretation of empirical knowledge and description. Ocean tides became the focal theme of study. Detailed studies were carried out regarding the mapping of ocean depth, variation in horizontal and vertical distribution of salinity, pressure of ocean water, ocean tides and currents on the basis of investigation of these variables in Gibralter Strait. Newton presented his theory of the origin of ocean tides. In spite of such attempts the period of 17th and 19th century remained a period of inactivity in this field because of greater emphasis on physics, mathematics and astronomy. The study of the subject again received attention with the exploration of South Pacific Region by Captain James Cook (1728-1779). Marsigli for the first time presented the description of **regional oceanography** based on his studies of bottom relief, temperature, salinity, water pressure, tides and currents of Mediterranean sea.

The development of the science of oceanography gained currency in 19th century. This period is divided into three stages of the development of knowledge of oceanography as follows :

(1) Period of Edward Forbes (1815-1854)—Forbes was a marine biologist. His contributions to the development of oceanography included the study of sea animals upto the depth of 230 fathoms near Great Britain, Hebrides and Mediterranean Sea, study of bottom reliefs of some parts of the Atlantic Ocean; discovery of sites of 18 submerged ancient cities near Lycian coast; distribution of marine life in the Aegean Sea; preparation of map showing world distribution of marine life etc.

(2) Period of Challenger Expedition—Wayville Thompson (1830-1882) made significant contributions in oceanography through his different expeditions' viz. **Lightening** (1868), **Porcupine** (1869, 1870) and **Challenger** (1872-76). He explored the depth of oceans from Faroes in the north to Gibralter in the south through his first two expeditions while Challenger expedition was undertaken to study the bottoms of the oceans all over the world wherein he covered the distance of 1,10,400 km (69,000 miles) of the oceans and accomplished dredging at 362 centres. The results of this great expedition (pertaining to bottom reliefs, sea water temperature, marine deposits etc.) were published in a book entitled Voyages of the Challenger-the Atlantic in 1877. He also studied the formation and origin of coral reefs and presented a world map of the distribution of pelagic deposits.

John Murray (1841-1914) laid the foundation of modern oceanography. His major contributions based on **Triton** (1882) and **Challenger Expedition** (1872-76) include discovery of submarine ridge of Wayville Thompsons Ridge located to the northwest of Scotland; study of planktons, deposits on seabottoms, formation and origin of coral reefs; formulation of theory of the origin of atolls; determination of fish zones and mud lines (based on Michael Sars Expedition in 1910) and presentation of map of ocean deeps of the Atlantic Ocean.

(3) Post-Challenger Period—Louis Agassiz made detailed study of Florida Reefs and Keys. He studied different aspects of ocean from Florida to Sansfransisco around south American coast. Alexander Agassiz, son of Louis Agassiz undertook coastal surverys covering a distance of 1,60,000 km (1,00,000 miles) through Black and Albatross Expeditions. His major contributions include location and origin of Gulf Stream between Newfoundland and Florida, studies of coral reefs near Bahamas and Cuba, Bermuda and Florida, Great Barrier Reef of Australia,

Fizi Islands, and Maldives etc. He rejected the Darwinian theory of subsidence of the origin of coral reefs and atolls. According to him atolls and barrier reefs are formed due to biological, mechanical and chemical processes.

Several expeditions were launched to study different aspects of seas and oceans in the first half of the 20th century *e.g.* Gazelle Expedition in the North Atlantic Ocean, Fishing Commission and Albatross Expedition in the East Pacific Ocean, Meteor Expedition in the South Atlantic Ocean, Michael Sars Expedition in the South Atlantic Ocean, Carnegie Expedition in the Pacific and Indian Oceans, Discovery (2nd) Expedition in Southern Seas (1950-51), Challenger Expedition and Danish Expedition in Southern Seas etc.

Several renowned oceanographers namely Nansen, Amundsen, Pettersson, Shepard etc. enriched the science of oceanography through their elaborate studies of different aspects of oceans and seas. F.B. Taylor and A.G. Wegener postulated the concepts of continental drift to account for the origin of continents and ocean basins. In the 1960s Hary Hess (1960) propounded the concept of sea floor spreading which further validated the hypothesis of continental drift. With the postulation of plate tectonic theory the riddle of origin of ocean basins, bottom reliefs of the oceans, displacement and drifting of continents and ocean basins could be successfully solved. Recently, new information about marine environment and marine ecology are forthcoming through the institutes of oceanography, ocean departments and ocean expeditions established and funded by several countries and organizations like Naval Hydrographic Office, the Coast and Geodetic Survey, the Scripps Institute of Oceanography (U.S.A.); the Geophysical Institute, the Hydrographic Biological Commission in Scandinavia; the Marine Biological Association of U.K.; the Oceanographic Institute in Paris; Institute of Oceanography in Canada and Russia etc. The first co-operative work for the study of Indian oceans was initiated with the launch of the International Indian Ocean Expedition (IIOE) comprising 20 countries and 38 research ships in 1960. Naval Hydrographic Office (at Dehra Dun) and the Department of Ocean Development (Goa) have been assigned the task of investigation of Indian ocean and all aspects of its marine environment.

It may be pointed out that recently the study of oceanography has gained currency because the economic and strategic importance of seas and oceans is increasing very fast. Thus, more attention is paid towards applied oceanography which includes the consideration of delineation, mapping, exploitation, utilization and management of marine biotic and abiotic resources. Marine ecology and marine ecosystem have become the focal themes of oceanography. There is a need to introduce and develop 'economic oceanography' (resource oceanography) as a new branch of oceanography.

3. Climatology

The gaseous envelop surrounding the earth is called atmosphere while the science dealing with the study of the atmospheric components and charactristics is called meteorology and climatology. Climatology includes the systematic and regional studies of the atmospheric conditions *i.e.* weather and climate. **Weather** refers to the sum total of the atmospheric conditions in terms of temperature, pressure, wind, moisture, cloudiness, precipitation and visibility of a particular place at any given time. In fact, weather denotes short term variations of atmospheric conditions and it is highly variable. On the other hand, **climate** is defined as aggregate weather conditions of any region in long-term perspective. According to Trewartha 'climate represents a composite of day to day weather conditions and of the atmospheric elements, within a specified area over a long period of time.' According to Critchfield 'climate is more than a statistical average; it is the aggregate of the atmospheric conditions involving heat, moisture, and air movement. Extremes must always be considered in any climatic description in addition to means, trends, and probabilities'. According to Koeppen and De Long, 'climate is a summary, a composite of weather conditions over a long period of time; truly portrayed, it includes details of variations, extremes, frequencies, sequences of the weather elemens which occur from year to year, particularly in temperature and precipitation. Climate is (thus) aggregate of the weather'. G.F Taylor has maintained that 'climate is the integration of weather, and weather is the differentiation of climate. The distinction between weather and climate is, therefore, mainly one of time.' According to Critchfield climatology is that science which studies the nature of climate, the causes and interpretation of its spatial variations and its association with the elements of natural environment and human activities.

There are three distinct branches of climatology *e.g.* (1) **physical climatology,** (2) **regional climatology,** and (3) **applied climatology.** Physical climatology deals with the interpretation of factors responsible for the spatial and temporal variations of exchange of air circulation, heat and humidity. It studies various elements of weather namely insolation, temperature, air pressure, wind, evaporation and humidity, precipitation, fogs, visibility etc. Different climates are formed due to combinations of these weather elements. The occurences of different combinations of these weather elements are accomplished through different processes and mechanisms. Thus, these processes of exchange of heat, humidity and momentum between atmosphere and earth's surface are also studied thoroughly. It is, thus, evident that physical climatology studies the factors and processes of regional variations of climatic conditions.

Regional climatology includes the study of types, distribution, pattern and characteristic features of world climates. Regional climatology is studied in three ways on the basis of spatial scales viz. (1) macro-climatic regions, (2) meso-climatic regions, and (3) micro-climatic regions. **Applied climatology** studies the application of climatic knowledge to solve various problems faced by human society *e.g.* global warming and climatic changes. It studies the interactions between climate and biosphere *i.e.* how does climate influence and control plants and animals including man and in turn how does man modify climate by introducing advertent and inadvertent changes in the physical environment and by making certain weather modifications *e.g.* cloud seeding and induced precipitation. Further, applied climatology includes the study of variability of climate, climatic changes, air pollution, climate and comfort, climate and health, climate and society, extreme weather events (*e.g.* floods, drought etc.) and their impacts, climate and agriculture, climate and manufacturing industries, climate and recreation, climate and urban planning, weather forecasting, climate and transport and communication, weather modifications etc.

Human biometeorology, which studies the reactions of human bodies to the changes in the atmospheric environment, has gained currency recently. It lays emphasis on to 'establish how much of the overall biological variability is the result of changes in weather, climate and season' (J.E. Hobbs, 1980). The study of climate is also divided into three categories based on influences of climatic environment on human health and behaviour on different spatial scales viz. micro-climate, ecoclimate and geoclimate. According to M. Bates (1966) three levels of climatic environment affect human behaviour viz. (1) **microclimate,** which represents weather conditions surrounding an individual organism; (2) **ecological climate** or **ecoclimate,** which represents weather elements of the habitats of the organisms, in the case of man the habitat may be his house and working places like factory, office, mine, agricultural farm, pasture etc. and (3) **geographical climate** or **geoclimate,** which represents weather conditions of larger areal unit and longer temporal span.

4. Biogeography

Biosphere is a life supporting layer which surrounds the earth and makes plants and animal life possible without any protective device. The organic world or biosphere is that part of the earth which contains living organisms-the biologically inhabited soil, air and water' (J. Tivy, 1982). According to A.N. and A.H. Strahler (1977) all the living organisms of the earth and the environment to which these organisms interact make biosphere. Thus, the biosphere consists of all the living organisms (the biotic component), energy (the energy component) and physical environment (abiotic component) and there are continuous interactions between living organisms and physical environment and among the living organisms themselves. The average thickness of biosphere or life supporting layer consisting of land, air, water, soil and rock is about 30 km. The upper limit of biosphere is determined by the availability of oxygen, moisture, temperature and air pressure which are necessary for the existence of organisms. Decrease in oxygen, temperature, moisture and air pressure with increase in height in the atmosphere limits the upper boundary of the biosphere. Though the NASA has discovered the presence of bacteria

upto the height of 15 km in the atmosphere but the lower layer of the atmosphere upto a few hundred metres accounts for most of the living organisms because favourable environmental conditions are available for the growth and development of living organisms in the lower part of the atmosphere. The depth of the biosphere over the land is upto the depth of deepest roots of trees or the depth upto which can live the burrowing organisms or the depth at which lie the parent rocks. The biosphere extends upto greater depth in the oceans. The existence of life has been detected upto a depth of 9,000 m in the deep oceanic trenches and deep sea plains.

The study of biosphere is called **biogeography,** which includes the consideration of physical environment, soil, animals and plants. 'Biogeography as the term indicates, is both a biological and a geographical science. Its field of study is the biologically inhabited part of the lithosphere, atmosphere and hydrosphere-or, as it has become known—the biosphere' (J. Tivy, 1982). Since the living organisms of the biosphere are studied in botany, zoology, biochemistry and geography with different view points and focus and hence there are variations in the meaning and scope (subject matter of study) of biogeography in the aforesaid disciplines. If a geographer studies the distribution patterns of plants and animals of the biosphere in spatial and temporal contexts and attempts to analyse the processes and factors which are responsible for such spatial and temporal variations, the biologists limit themselves to the study of physiological, morphological, behavioural and functional aspect of an individual organism. A geographer beside studying the distributional patterns of community of plants and animals also emphasises two more aspects viz. (1) intimate interrelationships between the abiotic and biotic components and (2) reciprocal relationship between man and biosphere. It may be pointed out that the discipline of biogeography cannot be exclusive domain of either biology or geography as its boundary is overlapping not only with these two subjects but also with other subjects. J. Tivy (1982) has aptly remarked, 'the geologist, climatologist, pedologist, geomorphologist as well as the botanist, zoologist, geneticist and geographere all 'cultivate' or 'crop', as the case may be, particular parts of this very large and varied field (biosphere) : and in doing so they are, to a greater or lesser extent, essential to as well as being dependent on, an understanding of biogeography'. Thus, the meaning, subject matter and approach to study vary according to the interest and objective of the investigator.

The primary goal of a geographer is to present a vivid picture of spatial patterns of distribution of plants and animals, their temporal variations and processes and causes thereof. Margaret Anderson defined biogeography as the essence of 'biological relations between man (considered as animal) and the whole of his animate and inanimate environment'. Since plants and animals are major components of biogeography and hence the subject is divided into two branches viz. (1) plant geography and (2) animal geography but in geographical studies plant geography is given more attention while animal geography or zoogeography occupies back seat. This is because of the fact that the study of distribution pattern of animals becomes difficult due to mobility of animals, very micro-forms of animal species and very high variability in their behaviour while the study of distribution patterns of plants becomes easy due to their static nature and their aggregation in static community. Simultaneously, plants represent most of total biomass of the world (say biosphere). In comparison to animals plants depend more on physical environment of their habitats, they are more affected by their environment and in turn they also affect their environment. Plants provide food to all animals including man because they are primary producers and become most valuable resource to human society.

It may be pointed out that though biotic components of the biosphere are most significant aspect of the study of biogeography but abiotic components involving land, air and water are also studied in this discipline. Land or **lithospheric component** includes (from smaller to higher) elements (iron, nickel, oxygen, nitrogen, hydrogen, carbon etc.), minerals (hematite, dolomite, felspar etc.), rocks and soils, microlandforms (relief features of 3rd order viz erosional and depositional landforms produced by exogenetic denudational processes like running water-fluvial process, groundwater, sea waves-marine process, wind-aeolian process, glaciers and periglacial process), meso-landforms (relief features of 2nd order produced by endogenetic forces namely, mountains, plateaus, faults, folds etc.) and macro-landforms (relief features of 3rd order *e.g.* continents and ocean basins).

The atmosphere is a significant component of the biospheric ecosystem because it provides all the gases necessary for the sustenance of all life forms in the biosphere. It also filters the incoming solar radiation and thus prevents the ultraviolet solar radiation waves to reach the earth's surface and hence protects it from becoming too hot. The atmospheric component includes the consideration of the composition and structure (troposphere, stratosphere, mesosphere, thermosphere-ionosphere and exosphere) of the atmosphere and the elements of weather and climate (insolation, temperature, air pressure, winds, humidity and precipitation, airmasses, frontogenesis and fronts, cyclones and anticyclones etc.).

The water or **hydrospheric component** is very important component of the abiotic or physical components because it is very essential element for all types of life in the biosphere. Water plays very important role in the circulation of nutrients in the various components of the ecosystems and it makes biogeochemical cycles effective in the biosphere. The water components consist of surface water, subsurface or groundwater and oceanic water. Surfacewater of the earth surface is found in static state (*e.g.* water of lakes, ponds, tanks, reservoirs etc.) and in dynamic (in motion) state (*e.g.* surface runoff, streams, springs etc.). The groundwater is found in the pore spaces of regolith known as aquifers. The oceanic water or hydrosphere covers about 71 per cent of the total surface area of the globe. On the basis of size and location the hydrosphere is divided into oceans, seas, small enclosed seas, bays etc. The hydrospheric component includes the consideration of origin and characteristics of botom reliefs (continental shelves, continental slopes,deep sea plains, deeps, submarine canyons etc.), temperature, salinity, ocean deposits, waves and currents, coral reefs and atolls because these determine different types of habitats of marine organisms.

Biotic components of the biosphere consist of 3 subsystems *e.g.* plant system, animal system including man and micro-organisms. Of these three subsystems plants are most important because these alone produce organic matters which are used by themselves and by animals including micro-organisms either directly or indirectly. Plants also make the cycling and recycling of organic matter and nutrients possible in different components of the biospheric ecosystem. The study of plant component includes the consideration of classification of plants, major divisions of plant kingdoms, plant system, plants and their environment, structure and composition of plant communities, evolution, distribution, dispersal and extinction of plants etc. The study of animal component includes the consideration of classification, distribution, dispersion and extinction of animals.

The develoment of biogeography is closely linked with biological sciences (botany, zoology and ecology) which have themselves come out of the earth sciences and natural history as is aptly remarked by J. Tivy, 'biogeography is firmly rooted in the biological sciences on whose data, concepts and methods the geographer is obliged to draw and whose developments have inevitably influenced his particular interest in and approach to the biosphere' (J. Tivy, 1982). Thus, the history of the development of biogeography is traced from biological sciences. In fact, the development of biological sciences and thus biogeography began with the contributions of early explorers and naturalists like Carl von Linne, Alexander von Humbolt, Edward Forbes, Joseph Hooker, Louis Agassiz, Alfred Wallace, Charles Darwin etc. Initially, different aspects of plants (e.g. classification, taxonomy, evolution etc.) were given more significance. The development of two basic concepts for the explanation of biological diversity and anomalies in the distribution of different types of plant and animal species on the basis of information of plants and animals gathered by early explorers and naturalists made revolution in biological sciences and biogeography mainly plant geography together. These two basic concepts were (i) the concept of **adaptation** of species to their physical environmental conditions, and (2) concept of **natural selection** and survival of the fittest. It may be mentioned that these two basic concepts became the basis of Darwinian Theory of evolution and origin of species in 1859. In fact, the Darwinian theory of origin of species, propounded by Charles Darwin, is related to the concept of progressive evolution of species (gradual speciation).

Charles Darwin (1859) postulated the principles and mechanisms of evolution of species by the process of natural selection wherein the heritable variations in the populations (here population means a community of individuals of sexually reproducing species) form the basis of evolution of species. The process of natural selection simply means that a few of the advantageous qualities inherited from the parents of a species by a few populations of that species are such that these qualities enable a few individual members of that species to survive in their environment and to become adapted to the physical environmental conditions. On the other hand, some individual members of the species lack in the advantageous qualities because these could not be inherited by them from their parents. In such cases the individuals which possess the advantageous qualities which are useful for their adaptation to their physical environmental conditions eliminate those plants and animals which do not possess those advantageous qualities.

In the early stages of the development of biogeography two aspects were more emphasized viz. taxonomic aspect and ecological aspect. The classification (taxonomy) of plants, their nomenclature and distribution, dispersion and evolution of individual plants became the centre of investigation and study by botanists whereas geographers attached more importance to the ecological aspects (relationships between plants and physical environmental factors) and geographical factors responsible for spatial variations in plant species.In fact, 'plant geography has made and condinues to make important contributions to the elucidation and assessment of the relative importance of the factors which determine floristic (plants) distribution' (J. Tivy, 1982). Plant geographer, as influenced by the Huttonian theory of **uniformitarianism** based on two concepts of 'present is key to the past' and 'no vestige of a beginning and no prospect of an end' (as propounded by Scottish geologist James Hutton), also attempted to study the influences of past events and environmental conditions on present distribution of plants.

Plant geographers were more influenced by the ecological concepts of interactions between biotic components (plants and animals including man) and abiotic (physical) environment and among the biotic components themselves. **Ecology**, in a very simple term, is a science that studies the independent, mutually reactive and interconnected relationships between the organisms and their physical environment on the one hand and among the organisms on the other hand. Though the term 'oecology' (oekologie or oecologie, oiko=home) was first coined and used by German biologist, Ernst Haeckel in 1869, a few conceptual terms were already proposed to reveal relationships between organisms and their environment, for example, **'ethology'** by French Zoologist, Isodore Geoffroy St. Hilaire in 1859 (for the study of relations of the organisms within the family and society in the aggregate and in the community); **lexicology** by British naturalist St. George Jackson Mivart (for the study of relations which exhist beween organisms and their environment) etc. Since then the scope of ecology and its objectives have expanded enormously with the development of ecological concepts and thoughts consequent upon growing interest in man-envirnment relationships due to increasing pressure on natural resources to sustain and enhance economic development.

The field and the scope of ecology have changed during various phases of methodological development of the subject. In the beginning ecology was exclusively associated with biological sciences e.g. botany and zoology and hence plants and animals were studied separately. This approach led to the emergence of **plant ecology and animal ecology.** The second approach of the study of relationships between organisms and physical environment (*i.e.* ecology) was based on habitats in terms of their physical characteristics (*e.g.* topography, soils, insolation and temperature, water, minerals, weather and climate etc.). This approach of ecological study led to the development of **habitat ecology.** The third approach to ecological studies is to study either individual organisms or groups of organisms of a particular ecosystem. This approach led to the development of **autecology** and **synecology**. Autecology is the study of relationships of individual species to its environment while synecology is the study of complex interrelationships of groups of organisms known as biological communities because organisms (plants, animals and micro-organisms) affect each other in reciprocal manner and interact with habitat or natural environment. Synecology was further divided

into population ecology, community ecology, biome ecology, ecosystem ecology etc. Though synecology is given more attention in biogeography but autecology also does not lose its relevance. It may be mentioned that biogeography became more concerned with the ecological studies of plants than animals. In fact, plant geography was also referred to as ecological plant geography. Simultaneously, plant geography was replaced by more specific term of **vegetation geography** so as to differentiate it from botany. In fact, 'the study of vegetation geography, however, developed nearly a century before the rcognition and acceptance of ecology as an academically respectable branch of the biological sciences' (J. Tivy, 1982).

Climate was accepted as a significant ecological variable during 18th and 19th centuries, consequently attempts were made to divide vegetation of the world into vegetation zones on the basis of climatic conditions. For example, C.H. Merriam divided the world into life zones on the basis of climatic parameters mainly temperature in1894. A.W.F. Schimper attached reasonable importance to climate while dealing with various aspects of vegetation in his famous book entitled 'Plant Geography on a Physiological Basis'. 'The vegetation-climate relationship also reflected in the classification of world climates by W.K. Koeppen (1918) and divisions of the world into natural regions by A.H. Herbertson (1905). It may be mentioned that by this time vegetation was taken (studied) as static component of the biosphere. In other words, vegetaion was studied at a given time and no attempt was made to study its changing form with time *i.e.* its dynamic aspect (temporal changes in vegetaion) was altogether ignored.

Thus, with the march of time other factors were also taken into consideration which could conrol and determine the nature of vegetation. Consequently, the importance of time in influencing dynamic aspect of vegetation gained currency and the process of succession was introduced in the study of vegetation geography which gave a new direction to biogeography. **'Succession'** simply means the entire process of directional and sequential changes of either plant community (groups of plants adapted to a particular habitat) or the whole ecosystem through time. The sequence of successional development (changes) of vegetation community is called **'sere'**. In other words, the transitional stages of sequential changes from one vegetation community to another vegetation community are called 'sere'. The succession of vegetation community in any habitat of an ecosystem is classified into two types on the basis of temporal changes in the environmental conditions of that habitat viz. **autogenic succession** (due to changes in the environmental conditions effected by vegetation itself) and **allogenic succession** (due to variations in physical components of habitats *e.g.* global climatic changes, rapid rate of siltation of lakes, ponds etc., accelerated rate of erosion of the region concerned, upliftment or subsidence of ground surface etc.).

F.E. Clements introduced genetic approach to the study of vegetation community and gave more emphasis to time factor to strengthen dynamic nature of vegetation geography. He further enriched and elaborated the concept of 'succession'. After elaborating two processes of succession (*e.g.* primary and secondary succession) he propounded the concept of **'climax'** to indicate last stage of successional development of vegetation community. **Primary succession** refers to the developmental sequence of vegetation in those bare areas where there were no vegetation and animals earlier whereas **secondary succession** refers to the developmental sequences of vegetation in those areas which had vegetation cover earlier but now have been rendered nude or bare, due to destruction of vegetation (either partly or completely) either by natural processes (like lava flow, prolonged drought, glaciation, natural widespread forest fires, severe storms, catastrophic floods etc.) or by human interferences (like intentional burning of vegetation, massive land use changes, mass felling of trees, overgrazing etc.). It may be pointed out that such disturbed ecosystems or habitats still contained mature soils and some original vegetation and therefore the initial stage of **'sere'** of secondary succession of plant community is quite different from the initial stage or sere of primary succession which starts on a bare rocky surface, having no earlier plants and animals. The end product of the process of succession of vegetation community was given the term of **climax succession, climax vegetation, climatic climax** etc.

A.G. Tansely defined the **'climax'** on the basis of main dominant factor which controls the maximum growth of vegetation of habitat. According to him the climax should be identified as (1) **climatic climax** (when climate is the most dominant factor), (2) **edaphic climax** (when soil is the most dominant factor), (3) **relief climax** (relief being the most dominant factor), (4) **anthropogenic climax** (human activities being the most dominant factor), (5) **biotic climax** (biotic factors being the most dominant factors) etc. It may be pointd out that the concept of succession and climax stage as propounded by Henry Cowles and F.E. Clements denoting development of successive stages of vegetation evolution in terms of time was in conformity with Darwin's theory of evolution of species and William Morris Davis' concept of cycle of erosion. Similarly, time concept was also used for the explanation of pedogenesis and developmental stages of evolution of soils. It may be mentioned that there began a major shift from larger spatial and longer temporal scales to smaller spatial and temporal scales in geomorphology, pedology and climatology in the beginning of the 20th century but biogeography was still seized by zonal approach and the concept of climatic climax which laid more emphasis on major vegetation zones in association with soil zones at world level and evolution of vegetation communities involving geological time scale.

But soon there began a shift in research methodology in biogeography due to new emphasis on field study, collecton of vegetation data from smaller areas and laboratory experimentation, with the result data and information obtained through controlled areas and experiments in the laboratories enabled the investigators to examine empirical hypotheses and modify earlier hypotheses. During this course of new emphasis there emerged two aspects of detailed study namely **plant sociology and ecological energetics**. Secondly, two distinct schools of ecological studies emerged at world level *e.g.* (1) the American School (led by F.E. Clements) and British School (led by A.G. Tansely) of ecological studies which emphasized the study of habitats and vegetation communities and (2) European School which gave more attention to the study of floristic composition of plant community.

The post-first world war period registered a sea-change in the subject matter and methodology in biogeography and ecology. The larger spatial scale involving larger areal extent was replaced by small spatial scale involving small areal extent for intensive study of vegetation. Secondly, the study of ecological relationship was prefered to vegetation taxonomy and ecosystem was accepted as a convenient ideal areal unit for ecological study.

Since 1970 the environmentalists, ecologists, conservationsists and planners became more and more aware about the process of environmental degradation and ecological imbalance caused by depletion of natural resources (both biotic and aboitic) due to their rapacious exploitation and irrational utilization by man. Consequently, the study of components, circulation of energy, circulation and cycling and recycling of nutrients, soil systems etc. in the biospheric ecosystems of various orders gained currency. The systematic study of different aspects (e.g. classification, evolution, distribution, dispersion and extinction) of plant and animal systems and characteristic features of biomes is more emphasized. Simultaneously, the study of man-environment relationships and ecological equilibrium has become the focal theme of ecology and biogeography. Recently, more and more attention is paid towards the study of processes and factors of environmental degradation and pollution, stability and instability of ecosystem and ecological inbalance. Environmental planning and management involving remedial measures of environmental degradation and pollution, reduction in the impact of natural hazards and disaster, conservation and preservation of ecological resources etc. has become centre of ecological study. **Biosphere reserve** (nature reserve) with three roles (e.g. logistic role, development role and conservation role) programme has been launched world over for the management of abiotic and biotic resources of the nature which has been least impacted by human activities.

Since 1970 numerous books have been published on ecological conservation and resource management *e.g.* Biological Conservation by D.W. Ehrenfield, (1970), Conservation in Practice by A. Warren and F.B. Goldsmith (1974), Grassland Ecology and Wildlife Management by E. Duffey et. al (1974), Conservation of Nature by E. Duffey (1970),

the Scientific Management of Animal and Plant Communities for Conservation by E. Duffey and A.S. Watt (1971), Ecology and Environmental Planning by J.M. Edington and M.A. Edington (1977), Environmental Conservation by R.F. Dasmann (1977), Biological Management and Conservation by M.B. Usher (1973), The Ecosystem Concept in Resource by G.M. Van Dyne (1969), Environmental Geography by Savindra Singh (1991), etc. The siginficant books on biogeography are Basic Biogeography (N.V. Pears, 1968), Biogeography-An Ecological and Evolutionary Approach (G.B. Cox, I.N. Halley and P.D. More, 1973), Biogeography-A study of Plants in the Ecosphere (J. Tivy, 1971), Biogeography (H. Robinson, 1972), Principles of Biogeography (D. Watts, 1974), Geography of the Biosphere (P.A. Furley and W.W. Newey, 1983) etc.

It may be conluded that physical geography has recently become more relevant to society because of increasing interest of geographers to strengthen the core of geography i.e. physical geography and greater emphasis on the study of spatial pattern of physical environment and complex interrelationships of its components which may be more relevant and conducive for regional planning and development. In fact, environment has always been at the centre stage of geography but unfortunately it was overshadowed by tilt of geographers towards sociology and economics during 1960-1980 but now they have realised the risk of leaving their core subject i.e. physical environment and are now giving due importance to the study of physical geography. The introduction and development of **'environmental geography'** as a new branch of geography by Savindra singh (1989 and 1991) is a positive welcome step in this direction.

2

ORIGIN OF THE EARTH

2.1 SOLAR SYSTEM

Our solar system is the only planetary system which is known to us at present though there may be numerous such systems scattered in the space. The earth is a member planet of our solar system. It is, therefore, necessary to have some elementary knowledge of the solar system to understand the origin of the earth. Planets are non-luminous bodies whereas stars are luminous bodies of the universe around us. In other words, the planets do not have their own light, rather they reflect the light of the stars while the stars have their own light and energy due to thermonuclear reactions wherein hydrogen nuclei combine under intense temperature and pressure to form helium nuclei which reelease vast amount of energy.

The congregation of stars and planets is known as **solar system.** Our solar system having a disc-like shape consists of nine planets (e.g. Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Naptune and Pluto) and one star (the Sun). Besides, there are numerous minor planets (planetoids or asteroids). All these bodies revolve around the sun almost in the same plane and in the same direction along the near circular elliptical orbits. Most of the sattellites of the planets also revolve in the same direction. The planetoids with some exceptions have their orbits between the orbits of Mars and Jupiter. The rotatory motion of the planets (except Venus and Uranus) is in the same direction as their revolution around the sun i.e. anticlockwise for one who looks at the earth from the north pole to the south pole. According to the **Titius Bode Rule** the distance of each planet from the sun is approximately twice that of the next planet close to the sun (table 2.1).

The diameter of the whole solar system is about 1,173 crore kilometres. The earth is about 149,600,000 km (1.496×10^8 km) away from the sun. The diameter and average density of the earth are 12,742 km and 5.52 respectively. Average distances from the sun, period of orbital revolution, period of rotation, diameter, average density and number of satellites of the member planets of our solar system are presented in table 2.1.

Table 2.1 : Characteristics of Solar System

Sun and its family	Average distance from the Sun (AU)	Orbital period	Rotation period (days)	Radius with reference to the earth's radius (6371 km)	Average density with reference to the density of water ($10^3 kgm^{-3}$)	No. of satellites	Angle of inclination of axis
Sun	...	...	25.4	109	1.40	...	...
Mercury	0.387	88 days	58	0.38	5.50	0	7^0
Venus	0.723	225	–243	0.96	5.27	0	3.5^0
Earth	1.000	365.26	1.00	1.00	5.52	1	23.5^0
Mars	1.524	1.88 years	1.03	0.53	3.95	2	2^0
Jupiter	5.200	11.86	0.41	11.23	1.33	16	1^0
Saturn	9.520	29.50	0.43	9.50	0.69	22	2.5^0
Uranus	19.160	84.00	0.45	3.70	1.70	15	0^0
Naptune	30.000	164.00	0.66	3.90	1.60	2	2^0
Pluto	40.000	247.00	6.40	0.50	4.00	1	17^0

AU = Astronomical Unit means average distance between the sun and the earth (1.496×10^8 km). The distances of the planets from the sun have been shown with reference to the average distance between the sun and the earth (e.g. the distance of the Pluto from the sun is 40 times to that of the distance between the sun and the earth).

The planets of our solar system are divisible in two groups, e.g. (i) the planets of the inner circle or the **terrestrial planets** and (ii) the planets of the outer circle or the **'giant planets'**. The inner circle consists of four planets (Mercury, Venus, Earth and Mars) having smaller and denser bodies while the outer circle comprises 5 planets (Jupiter, Saturn, Urananus, Naptune and Pluto) having larger size and less dense materials (of low density). These five planets are more like the sun than like the terrestrial planets. Pluto is an exception (small size but relatively high density). If we take Jupiter, the biggest planet, as the centre of the planets of our solar system, the size of the planets becomes smaller as we go away from either side of Jupiter (Mars being the exception).

Our solar system is a small part of the system of stars collectively known as the **spiral nebula** or the **galaxy.** The diameter of our galaxy or the **milky way** is about 10^5 light years. It contains more than thousand million stars. Our sun with its solar system is about 30,000 light year away from the centre of the Milky Way. Like other stars, the sun with its solar system is revolving around the centre of the Milky Way, the period of revolution is about 224×10^6 years. In other words, since the beginning of Palaeozoic era, the sun has made only two complete rounds around the centre of the Milky Way (Galaxy). The

* A light year is the distance covered by the rays of light in one year in vacuum travelling at the speed of 2,99,792.5 km per second or about 1,86,000 miles per second. The value of the light year is thus 5.88×10^6 miles.

solar system revolves around the Milky Way with a speed of 285 km per second.

There are several globular and spiral nebulae (stellar islands) around our Milky Way. Andromeda nebula is relatively closer to us i.e. 6.8×10^5 light years. The distance of one such far off nebula (Maffei I) is 140×10^6 light years which means that the light rays which started from the nebula at the beginning of the Mesozoic era are reaching us only now. The galaxies, 'relatively near' to us form **'archipilago of stellar islands'** i.e. system of galaxies, Greater Universe comprises the system of millions of **'archipilagos'**. The diameter of the Greater Universe is measured in many thousands of millions of light years. According to modern astronomy there are countless greater universes. It means that 'the universe is infinte in space and time.'

2.2 ORIGIN OF THE EARTH

Various scientists and philosophers have propounded from time to time their concepts, hypotheses and theories to unravel the mystery and to solve the riddle of the problems of the origin and evolution of our solar system in general and of the earth in particular but none of these could be accepted by majority of the scientific community. Though there is no common consesus among the scientists about the origin of our solar system but it can be safely argued that all planets of our solar system are believed to have been formed by the same process.

It means that all the concepts, hypotheses and theories propounded for the origin of the solar system are also applicable for the origin of the earth. All the views and concepts pertaining to the origin of the earth may be divided into two groups e.g. (i) **religious concepts** and (ii) **scientific concepts.** Since the religious concepts do not have any logical and scientific basis, these are discarded by modern scientific community. For example, the view of Archbishop Usher (1664, in Annals of the World) that the earth was created at 9.00 A.M. (presumably Greenwich Mean Time?) on October 26, 4004 B.C. is merely a fantasy.

Scientific concepts—the scientific concepts, generally based on sound principles of hard sciences, are usually divided into two schools e.g. (i) **'hot origin concepts'** and (ii) **'cold origin concepts'.** According to the school of 'hot origin' our solar system and therefore the earth is believed to have been formed from the matter which was either initially hot or was heated up in the process of the origin of the earth. On the other hand, according to the school of 'cold origin' our solar system together with the earth was formed of the matter which was either initially cold or always remained cold. After the formation the earth might have been heated up due to the presence of radioactive elements or only the interior of the earth might have been heated up due to intense pressure exerted by the superincumbent load of the upper layers.

On the basis of the number of heavenly bodies involved in the origin of the solar system and the earth the scientific concepts are further divided into three groups e.g. (i) **monistic concept** (involving only one heavenly body, (ii) **dualistic concept** (involving two heavenly bodies) and (iii) **binary star concept** or **trihybrid concept** (involving more than two heavenly bodies).

2.3 GASEOUS HYPOTHESIS OF KANT

Immanuel Kant, the German philosopher, presented his treatise entitled 'The General Natural History and Theory of the Heaven or the Essay on the Working and Mechanical Origin of the Entire Universe on the Basis of Newtonian Laws' in 1755. Kant claimed that his 'gaseous hypothesis' of the origin of the earth was based on the sound principles of Newton's laws of gravitation and rotatory motion. In the beginning his hypothesis acclaimed world-wide appreciation but later on it was disproved as it was based on erroneous concepts and wrong application of Newtonian laws of gravitation. Inspite of severe criticism the hypothesis was considered a great step forward in the field of cosmogony and 'he almost reverberated the mid-18th century with his words...Give me matter and I will build a world out of it.'

Kant postulated his gaseous hypothesis of the origin of the earth on the basis of a few assumptions. He assumed that supernaturally created primordial hard matter was scattered in the universe. In fact, according to Kant there was a primeval, slowly rotating cloud of gas (now called a nebula) and matter comprised of very cold, solid and motionless particles. In terms of modern scientific language it can be said (but not described by Kant) that the

temperature of primordial matter was near about 273^0 C or absolute zero or 0^0k. This was the reason that cold matter was initially motionless (according to the molecular theory of matter). He further assumed that the particles began to collide against each other under their mutual gravitational attractions.

This mutual attraction and collision between the particles generated random motion in the primordial matter. Collision of the particles also generated friction which generated heat, with the result the temperature of the primordial matter started rising. He further argued that the random motion of the particles also generated rotatory motion in the primordial matter. Thus, the original cold and motionless cloud of matter became in due course a vast hot nebula and started spinning (rotating) around its axis.

According to Kant with the increase in temperature, the random motion as well as the rate of collision among the particles also increased. This gave extra impetus of the rate of rotatory motion (spinning) of the primordial matter. The rise in temperature also changed the state of primordial matter from solid to gaseous particles. Thus, the initial primordial matter gradually changed in hot rotating nebula. With continuous rise in temperature and rate of rotatory motion the nebula started expanding in size.

According to Immanuel Kant as the heat increased, the size of nebula increased and as the size of nebula increased, the angular velocity or rotatory speed further increased. Due to continuous increase in the size of nebula the rotatory speed became so fast that the centrifugal force (away from the centre) exceeded the attractional or centripetal force (directed towards the centre). The nebula started spinning so rapidly that an irregular ring was separated from the middle part of the nebula and was ultimately thrown off due to centrifugal force. By the repetition of the same process a system of concentric rings (nine) were separated from the nebula. The residual central mass of the nebula remained as the sun. The irregularity of the rings caused the development of the cores (knots) for the formation of the corresponding planets. In other words, all the matters of each ring were aggregated at a point to form a core or a knot which ultimately grew as a planet in due course of time. Thus, it is apparent that according to Kant the earth was formed due to aggregation of all the matter of the ring which was separated from the nebula due to centrifugal force. By the repetition of same process rings were separated from the newly formed planets and the materials of each ring were condensed to form satellites of the concerned planets. Thus, the whole solar system comprised of the sun (residual part of the rotating nebula), nine planets and their satellites were formed.

Evaluation

Though Immanuel Kant based his gaseous hypothesis on scientific principles (Newton's law of gravitation)to solve the problem of the origin of the solar system and the earth but his hypothesis has been rendered baseless because it is based on several erroneous facts of science. In fact, Kant's hypothesis was declared dynamically unsound. (1) It was one of the basic assumptions of Kant's hypothesis that there was primordial matter in the universe but he never explained the source of the origin of the primordial matter. (2) Kant did not explain the source of energy to cause random motion of the particles of the primordial matter which were cold and motionless in the initial stage. According to Newton's first law of motion 'a body remains at rest, or if in motion it remains in uniform motion with constant speed, unless or until an external force is applied on it.' The particles of the primordial matter,as assumed by Kant, were at rest and no external force was applied on them, then what was the cause for the random motion among the particles of primordial matter? (3) The collision among the particles of the primordial matter can never generate rotatory motion in it. It is an erroneous statement of mechanism. (4) Kant's assumption that the rotatory speed of the nebula increased with the increase of its size was against the law of conservation of angular momentum. According to the law of conservation of angular momentum, 'the total angular momentum of an isolated system remains constant.' It means that if any body is rotating, the total amount of its angular momentum will always remain constant unless an external force is applied on the rotating body.Let us undestand angular momentum. Angular momentum is the product of the mass, angular velocity and the square of the radius of the rotating body.

$$\text{Angular Momentum} = \begin{bmatrix}\text{mass of}\\ \text{the body}\end{bmatrix} \times \begin{bmatrix}\text{angular}\\ \text{velocity}\\ \text{of the}\\ \text{rotating}\\ \text{body}\end{bmatrix} \times \begin{bmatrix}\text{the square}\\ \text{of the radius}\\ \text{of the}\\ \text{rotating}\\ \text{body}\end{bmatrix}$$

No one can change the mass of the rotating body, that is why it is constant. Angular momentum of any rotating body can never be changed unless an external force is applied. Thus, the above equation can also be expressed in the following manner Angular velocity α 1/radius (or size)

The second equation shows that there is an inverse relation between angular velocity or the speed of rotatory motion and the radius or the size of the rotatory body. If the radius of any rotating (spinning) nebula increases or if the nebula expands in size, the angular velocity or the velocity of the rotation of the nebula will decrease. Kant's hypothesis envisages that 'as the heat increased the size of the nebula (or radius of the nebula) increased and as the size of the nebula increased, the angular velocity or the rotatory speed further increased.' This statement is erroneous as it is against the law of conservation of angular momentum. Thus, the very foundation, on which Kant's hypothesis was based, is proved unsound and wrong. However, the importance of Kant's hypothesis lies in the fact that it was first scientific attempt for the explanation of the origin of the earth . In fact, Kant's hypothesis paved the way for the postulation of nebular hypothesis by Laplace.

2.4 NEBULAR HYPOTHESIS OF LAPLACE

French mathematician Laplace propounded his 'nebular hypothesis' in the year 1796. He elaborted his concepts about the origin of the solar system and the earth in his book entitled 'Exposition of the World System'. Laplace's nebular hypothesis was in some way similar to the gaseous hypothesis of Kant. It appears that Laplace's hypothesis is just the modified version of Kant's hypothesis. It may be pointed out that Laplace propounded his hypothesis without mathematical formulation. In fact, Laplace postulated his hypothesis after removing the inherent weak points and erroneous concepts of Kant's hypothesis which suffered from three basic defects e.g. (1) Large amount of heat cannot be generated due to the collision of cold particles of primordial matter. (2) Mutual collision of particles cannot generate motion in the primordial matter and the random motion of the particles cannot generate circular motion (rotatory motion) in the primordial matter. (3) The angular velocity of rotatory speed of the nebula cannot increase due to increase in the size of the nebula.

In order to remove the aforesaid defects Laplace assumed certain axioms for the postulation of his nebular hypothesis to solve the riddle of the origin of the earth. (1) He assumed that there was a huge and hot gaseous nebula in the space. Thus, he solved the problem of heat of the nebula through this assumption. (2) From the very beginning huge and hot nebula was rotating (spinning) on its axis. (3) The nebula was continuously cooling due to loss of heat from its outer surface through the process of radiation and thus it was contiunuously reducing in size due to contraction on cooling.

Based on aforesaid assumptions Laplace maintained that there was a hot and rotating huge gaseous nebula in the space. There was gradual loss of heat from the outer surface of the nebula through radiation due to circular motion or rotation of the nebula. Thus, gradual loss of heat resulted into the cooling of the outer surface of the nebula. Gradual cooling caused gradual contraction in the size of the nebula. These processes e.g. gradual cooling and contraction, resulted into continuous decrease in the size and volume of the nebula. Thus, reduction in the size and volume of the nebula increased the circular velocity (rotatory motion) of the nebula. As the size of the nebula continued to decrease, the velocity of rotatory motion continued to increase. Thus, the nebula started spinning at very fast speed and consequently the centrifugal force became so great that it exceeded the centripetal force. When this stage was reached the materials at the equator of the nebula became weightless. Consequently, the outer layer was condensed due to excessive cooling and so it could not rotate with the still cooling and contracting central nucleus of the nebula and thus the outer ring (layer) was separated from the remaining part of the nebula. This separated ring of material started moving around the nebula. It is to be remembered that according to Laplace only one ring of material was separated from the nebula and not nine rings as conceived by Immanuel Kant. Laplace further maintained that the original ring was divided into nine

rings and each ring moved away from the other ring. All the materials of each ring condensed at a point or knot in the form of 'hot gaseous agglomeration'. Each such agglomeration was later on cooled and condensed to form planet. Thus, nine planets were formed from nine rings and the remaining central nucleus of the nebula became the sun. Satellites were formed from the planets due to repetition of the aforesaid processes and mechanism.

'This simple hypothesis offered an explanation of the facts that (with a few exceptions among the satellites) each celestial body possesses acquired motions of rotation and evolution in one and the same sense, and that the several planetary orbits are nearly in the same plane' (S.W. Wooldrige and R.S. Morgan. 1959).

French scientist Roche suggested modification in the nebular hypothesis of Laplace during mid-19th century. He opined that nine rings were separated from the nebula itself and these rings were condensed to form nine planets.

Evaluations

The nebular hypothesis of Laplace commanded continued great respect for more than 150 years due to its simplicity but as the knowledge about the universe and its related phenomena as well as the knowledge of science and technology of the modern world increased, the nebular hypothesis began to fade away due to severe criticisms of the hypothesis by the scientists on various grounds. It is significant to point out that the nebular hypothesis not only tried to explain and slove the problems of the origin of the earth but it also described the constitution of the earth. According to this hypothesis the planets and also the earth were initially in gaseous state. The earth was changed into liquid state on cooling and ultimately the solid crust was formed. But some scientists claimed that the earth retained a solid condition throughout its period of growth. However, the nebular hypothesis is renderd untenable on the basis of the following demerits.

(1) Laplace assumed that initially there was a hot and rotating nebula but he did not describe the source of the orgin of the nebula. Where did heat and motion in that nebula come from? He did not offer any explanation.

(2) What was the reason behind the formation of certain fixed number of planets from the irregular ring? Why did only 9 rings come out from the irregular ring detached from the nebula? Why not more or less than 9 rings? He could not explain the formation of fixed number of planets (9). It is quite unreasonable to imagine the situation that all matter of one ring could condense into one incandescent gaseous mass to form one planet. According to dynamical theory the ring may break up into several parts and thus several planets may be formed due to condensation of small parts.

(3) 'The small degree of cohesion between the particles of the nebula would make the formation of rings a continuous not an intermittent process, as the theory requires' (S. W. Wooldrige and R.S. Morgan, 1959).

(4) If the sun is the remaining nucleus of the nebula as claimed by Laplace, it should have a small bulge around its middle part (equator) which would point out the probable separation of irregular ring from the sun but there is no such bulge in the middle part of the sun.

(5) If we accept the tenet of Laplace that the planets were formed from the nebula, then the planets must have been in liquid state in their initial stage. But the planets in liquid state cannot rotate and revolve around the sun properly because the rotatory motion of different layers of the liquid is not always equal. Only the solid mass of matter has the property to perform rotatory and revolutionary motions along a near circular path without losing its original shape.

(6) According to the nebular hypothesis all the satellites should revolve in the direction of their father-planets but contrary to this a few satellites of Saturn and Jupiter revolve in the opposite direction of their father planets.

(7) About one hundred years later from the date of the postulation of Laplace hypothesis great British physicists James Clerk Maxwell and Sir James Jeans showed that the mass in the rings was not enough to provide gravitational attraction for condensation to form individual planets.

(8) The nebular hypothesis is unable to explain the peculiar distribution of the present day angular momentum in our solar system. The sun

possesses about 99.9 per cent of the total mass of our solar system whereas the planets contain only 0.1 per cent of the total mass. As far as the angular momentum (product of mass, angular velocity and the square of the radius of solar system) of our solar system is concerned, more than 99 per cent is concentrated in the revolving nine planets and the remaining one per cent is contained by our sun. According to the law of conservation of angular momentum the total angular momentum of an isolated system remains constant. Laplace's nebula was also an isolated system, therefore, it should have conserved its total angular momentum even after the separation of irregular ring but this is not the case as the sun contains only one or less than one per cent of total angular momentum. Thus, this hypothesis is against established mathematical formulation. In fact, the sun must have acquired most of the angular momentum of our solar system but this did not happen. Laplace did not explain the causes for this anomaly. It may be concluded that the present day total angular momentum of our solar system, originally concentrated in the nebula, is not quite sufficient for the separation of ring from the nebula by excess of rotatory motion.

Based on above arguments the nebular hypothesis of Laplace is rendered untenable.

2.5 PLANETESIMAL HYPOTHESIS OF CHAMBERLIN

The conroversy of peculiar redistribution of angular momentum in our solar system from the original angular momentum of Laplace's nebula shattered the very basis of mono-parental or monistic concepts of the origin of the earth (and the planets). That is why , the idea of biparental or dualistic concept of the origin of the earth started gaining currency and respect among the scientists of the 1st quarter of the 20th century. Planetesimal hypothesis propounded jointly by Chamberlin and Moulton belongs to the dualistic concepts of the origin of the earth.

T.C. Chamberlin, a geologist, in collaboration with Forest Ray Moulton, an astronomer (both belonged to the University of Chicago, USA) postulated a new hypothesis popularly known as 'planetesimal hypothesis' for solving the problem of the earth in the year 1905. In fact, the 'planetesimal hypothesis' was the revival of earlier 'collision hypothesis' (1749) of the French natural scientist Count de Buffon. Planetesimal hypothesis not only explains the origin of the earth but also throws light on the structure of the earth, the origin of its atmosphere and continents and ocean basins.

Origin of the Earth

Unlike monistic concept (e.g. gaseous hypothesis of Immanuel Kant and nebular hypothesis of Laplace) the planetesimal hypothesis envisaged the origin of the solar system (and the earth) with the help of two heavenly bodies. According to Chamberlin initially there were two heavenly bodies (stars) in the universe-proto-sun and its companion star. The behaviour and properties of the proto-sun were not like other stars. It was formed of very small particles which were cold and solid. Thus, the proto-sun, unlike Laplace's nebula, was not hot and gaseous rather it was formed of solid particles and was cold and circular in shape. There was another star, termed as **'intruding star'** or **'companion star'** which was destined to pass very close to the proto-sun. When the intruding star came very close to the proto-sun infinite number of small particles were detached from the outer surface of the proto-sun due to massive gravitational pull exerted by the giant intruding star. Chamberlin termed these detached small particles as planetesimals.

Initially, the detached particles or planetesimals were just like dust particles. The planetesimals were not of uniform size rather a few planetesimals around the proto-sun were of fairly big size. These larger planetesimals became nuclei for the formation of future possible planets. Gradually, large planetesimals started attracting small planetesimals. Thus, numerous small planetesimals were accreted (added) to the nuclei of large planetesimals and ultimately these large planetesimals grew in the form of planets due to continuous accretion of infinite number of planetsimals. With the passage of time, the remaining proto-sun changed into the present-day sun. The satellites of the planets were created due to the repetition of the same processes and mechanisms.

According to the planetesimal theory the main force of the ejection of small jets or planetesimals from the proto-sun was the tidal force exerted by the approaching or intruding star on the outer surface of

the proto-sun. "It was not necessary to assume that the earth as a whole was ever in molten condition. It grew from small beginnings by the addition of planetesimal matter, rapidly at first, but with decreasing speed' (S.W. Wooldrige and R.S. Morgan, 1959).

Evolution of the Earth

T.C. Chamberlin has attempted to describe and explain the evolution of different components of the earth e.g. continents and ocean basins, folds and faults, volcanoes and earthquakes, mountains and plains, heat of the interior of the earth and its structure and the origin and evolution of its atmosphere through specific periods or stages. (1) **first stage**-'the period of planetesimal accession' or 'the period of acquisiton of the present shape and size by the earth'. (2) **second stage**—"the period of dominant vulcanism' or 'the period of the evolution of the earth's interior and the evolution of continents and ocean basins'. (3) **third stage**—'the actual geological period' or 'the period of the formation of the folds and faults, mountains and plateaux etc.' It may be pointed out that these stages of the evolution of the earth are separated from each other only for the sake of convenience, otherewise these are so interlinked with each other that it is quite difficult to differentiate one stage from the other.

1. Period of planetesimal accession.—As the solar tides caused by the gravitational force of the intruding star became greater and greater, huge quantity of planetesimals (jets) were thrown out of the surface of the proto-sun and these planetesimals began to whirl. Some planetesimals followed the intruding star which ultimately vanished in the space while others were attracted by proto-sun and thus started moving around it. The great solar tide subsided when the intruding star moved away from the proto-sun and ultimately vanished in the space. Gradual accretion of smaller planetesimals around larger planetesimals ultimately gave birth to the planets and the earth. The mechanism of the accretion of planetesimals has already been described above.

Evolution of the earth's atmosphere—Chamberlin maintained that in the initial stage of the origin of the earth there was no atmosphere on it but as the earth grew in size it captured 'atmospheric material and elements' by gravitational force which was continuously increasing due to everincreasing size of the earth. The earth's atmosphere was formed from two basic sources. (1) External Source-When the earth grew in size it became successful in capturing free atmospheric molecules. The supply of atmospheric molecules was more but it decreased with the passage of time as most of the molecules were already captured by the earth. (2) Internal sources provided carbon dioxide, water vapour and nitrogen gases. Another source of the 'atmospheric material' was occluded gases carried by the planetesimals captured by the 'nucleus' of the earth. These occluded gas particles came out of the interior of the earth through volcanic and fissure eruptions and became part and parcel of the present day atmosphere. Oxygen was, thus, provided by the volcanic eruption.

Origin of heat—The heat inside the earth was originated gradually with the increase in the size of the earth consequent upon more and more accretion of planetesimals. The heat of the earth could be possible from various sources. (1) Heat was originated due to mutual collision of planetesimals during the phase of their active accretion. Gradually, the molecules of the earth started heating mainly because of intensive pressure exterted by constantly increasing aggregation of planetesimals on the surface of the earth. (2) As the accretion (aggregation of planetesimals increased, the pressure on the nucleus of the earth also increased, with the result there was further increase in the heat of the earth. (3) some amount of heat was also generated by the re-arrangement of different molecular compounds of the interior of the earth into heavier (and hence denser) compounds due to intensive pressure of superincumbent load and involved exothermic (release of heat) chemical reactions. Gradually, the interior of the earth acquired temperature more than 20,000^{0}C which decreased outwards (towards the outer parts of the earth). It may be pointed out that inspite of very high temperature the interior of the earth did not melt because of high pressure of superincumbent load. It my be remembered that high pressure increases the melting point of the matter. As the heat moved from the nucleus of the earth towards its outer zone of low pressure and hence zone of low melting point, the rocks started melting in patches.

2. Period of dominant vulcanism—Gradual accumulation of heat inside the earth during its early stage of evolution resulted into selective melting of rocks in the outer parts of the earth and thus began widespread volcanic activity. It may be pointed out that in the initial stage of the evolution of the earth, its surface was very much rough and fragmented due to 'infalling' of planetesimals. There were huge crevices between the planetesimals. The fragments of the earth's surface were also not well cemented. The escape of volatile substances of the interior of the earth resulted into violent volcanic explosions which created 'crater-like hollows' on the surface of the earth.

Evolution of continents and ocean basins—Chamberlin opined that the primitive oceans were first formed under the fragmented and crevice-ridden outer permeable zone of the earth's surface. Later on the crevices were cemented and thus water derived through the condensation of water vapour accumulated in these crevices and volcanic craters and the earth's surface, thus, looked as if filled with numerous lakes. Gradually and gradually these lakes were connected due to their expanding areal extents and thus different oceans were formed. Basic materials were weathered and eroded and were ultimately carried away by running water from the upstanding land masses (continents) and were deposited in the submerged areas of the earth (oceans). Thus, there was gradual increase in the acidic material of the landmasses because most of the basic material was removed in solution form from the landmasses. This caused reduction of the specific gravity of the continental material. In other words, the weight of continental material started decreasing whereas there was increase in the weight of oceanic material. This caused further submergence of the lowlying parts of the continents. Continuous deposition of weathered and eroded debris and the weight of the water itself further depressed the submerged parts of the earth (oceans). This process caused further extension of the oceans. According to J.A. Steers 'as long as the earth as a whole continued appreciably to grow by the accession of the planetesimals, the oceanic regions expanded and deepened.'

3. Actual geological period—The final stage of the evolution of the earth was characterized by dominant tectonic events including dominant vulcanicity, folding and faulting and submergence and emergence and thus the ancient surface features of the earth's surface were formed.

Evaluation

No doubt, Chamberlin made a sincere effort through his 'planetesimal hypothesis' to solve the riddle of the origin of the earth, the structure of its interior, the evolution of continents and ocean basins and the origin of mountains and faults but he committed certain mistakes while doing so because of the fact that he attempted to paint avery large canvas (several problems of the earth) with a single stroke of a brush. Had he concentrated on the single problem of the origin of the earth he might not have left a long fissure of loop-holes unplugged. The following are a few major points on which his hypothesis was criticised and discarded by various scientists.

(1) According to many astronomers the planetesimals would have so volatilized (converted into gaseous mass from the solid state) due to excessive heat of friction and collision at the time of their ejection from the 'proto-sun' that it would have been impossible for them to condense in the form of orbits around the 'protosun' without being deffused violently in the universe. Under these circumstances the question of accretion and aggregation of planetesimals around the 'protosun' in the condensed form of planets does not arise.

(2) According to the 'planetesimal hypothesis' of Chamberlin, the size of the planets was dependent upon (i) the amount of accretion and aggregation of planetesimals around the nucleus, (ii) amount of planetesimals available in the particular orbit and (iii) the attractional force of the so-called nucleus of the planets. Thus, the nucleus of any orbit would have acquired and accreted any number of planetesimals and would have gained any size accordingly depending upon the aforesaid factors and thus the planets should have not been arranged in any order. However, the planets of our present-day solar system are arranged according to their size around the sun in a systematic order. The increase in the size of the planets away from the sun continues upto Jupiter (except Mars) and then the size decreases regularly away from Jupiter. Chamberlin's hypothesis, thus, does not offer any explanation for this type of arrangement of the planets in our solar system.

(3) Why only nine planets were formed? Why not one more or one less? No answer is offered by Chamberlin.

(4) According to the planetesimal hypothesis, the planets always remained in solid state (if we assume that Chamberlin proposed such situation only for the planets of the inner circle of the solar systems). According to many scientists the planets of the inner circle of the solar system (Mercury, Venus, Earth and Mars) were initially in liquid state. There is no explanation in Chamberlin's hypothesis about the planets of the outer circle which are of very low densities and are in gaseous state.

(5) The planetesimal hypothesis does not explain the present higher amount of angular momentum in the planets of our solar system. According to many astronomers the angular momentum imparted by the 'intruding star' to the planets was high enough to surpass the amount imparted by the nebula of Laplace but was not high enough to match the existing angular momentum of the planets of our solar system.

(6) The infinite space of the universe makes such a close encounter between the stars a remote possibility.

(7) The mechanism of the evolution of the continents and ocean basins as described by Chamberlin is unreasonable because our primitive earth was initially in liquid state. The compressional force provided for mountain building was not sufficient.

The planetesimal hypothesis presents wrong notion about the origin and evolution of the atmosphere. According to Jeffreys initial nucleus of the planets did not possess enough attractional pull to catch and hold the planetesimals or 'atmospheric material' around it. If the nucleus carried some water and vapour at all, these could not have come out as these were buried in the nucleus under thousands of kilometres of depth of planetesimals. It may also be pointed out that the atmospheric material could also not be provided by the surrounding planetesimals (external source) of the primitive planets because the recent studies of meteorites show that they are completely dry and atmosphereless.

2.6 TIDAL HYPOTHESIS OF JAMES JEANS

Sir James Jeans, a British scientist, propounded his 'tidal hypothesis' to explain the origin of the earth in the year 1919 while another British scientist, Harold Jeffreys, suggested modifications in the 'tidal hypothesis' in 1929 and thus made it more relevant and significant in the context of increasing knowledge of the cosmogonic ideas of the 1st quarter of the 20th century. Tidal hypothesis is one of the modern hypotheses of the origin of the earth and the solar system. Jeans postulated his hypothesis on the basis of certain axioms (self proved facts) as given below.

(1) The solar system was formed from the sun and another intruding star.

(2) In the beginning the sun was a big incandescent gaseous mass of matter.

(3) Besides the sun, there was another star termed as 'intruding star' in the universe. This intruding star was much bigger in size than the primitive sun.

(4) The primitive sun was stationary and was rotating on its axis.

(5) The 'intruding star' was moving along such a path in such a way that it was destined to come nearer to the primitive sun.

(6) There was a great impact of the tidal force of the intruding star on the surface of the primitive sun.

James Jeans postulated that due to massive gravitational force of the 'intruding star', huge amount of matter was ejected from the primitive sun, which later on became the building material of future planets. According to the Newton's law of universal gravitation (1687) every body in the universe attracts every other body with a force which is directly proportional to the product of the masses of the two bodies and inversely proportional to the square of the distance between them. It means that the intensity of the gravitational force of the 'intruding star' and the 'primitive sun' would depend upon two factors e.g. (i) product of the masses of the intruding star and the primitive sun, and (ii) the distance between the two stars. There is direct relation between the product of the masses of the 'intruding star' and the primitive sun (equation 3).

Gravitation Force α Product of the mass of the two stars.........(3)

It means that if the product of the masses of the 'intruding star' and the 'primitive sun' is high,

the amount of gravitational force between them will also be high and if the product of masses of the two stars is low the amount of gravitational force will also be low. In simple words, it also means that if the mass of the 'introding star' is high, the gravitational force exerted by it will also be high. Since James Jeans assumed the 'intruding star' to be much bigger than the 'primitive sun', the former exerted larger amount of gravitational pull on the surface of the 'primitive sun' than the gravitational pull of the 'primitive sun' which caused ejection of matter from the 'primitive sun'.

Secondly, there is an inverse relation between the gravitational force of two stars and the distance between them (equation 4).

$$\text{Gravitation Force} \;\alpha\; \frac{1}{\text{distance between the intruding star and the primitive sun}} \quad \ldots(4)$$

It means that as the distance between two stars decreases, the amount of gravitational force between them increases and as the distance between two stars increases, the gravitational force between them decreases. Since the 'intruding star' was coming closer to the 'primitive sun' and hence the amount of gravitational force between them was also increasing.

Evolution of filament—According to James Jeans the 'intruding star' was continuously moving along such a path that it was coming nearer to the primitive sun and thus exerted gaseous tidal force (gravitational pull) on the surface of the 'primitive sun'. As the 'intruding star' came nearer and nearer to the 'primitive sun', its gravitational force went on increasing with the result tidal force also increased. When the 'intruding star' came nearest to the 'primitive sun' its gravitational force became maximum, with the result a giant cigar-shaped tide, thousands of kilometres in length, was created on the outer surface of the 'primitive sun' and ultimately huge mass of matter, in the shape of a cigar, was ejected from the 'primitive sun'. James Jeans called this cigar-shaped matter as **filament** which was much thicker in the centre and thinner and sharper at the ends (tapering ends) (see fig. 2.1).

The shape of the ejected filament with thick middle portion and tapering ends may be explained in the following manner.

(i) When the 'intruding star' was at distant place from the 'primitive sun' (but not so distant that it could not exert attractional pull on the surface of the 'primitive sun') the gravitational attraction exerted by it on the surface of the primitive sun was also low due to greater distance between them. Therefore small quantity of the first part of the incandescent matter came out from the surface of the primitive sun. (2) When the intruding star came nearest to the primitive sun, maximum amount of gravitational attraction was exerted by it on the surface of the primitive sun due to minimum distance between them. This attractional and tidal force resulted into the ejection of maximum amount of the incandescent matter (which represented the middle portion of the filament). (3) When the 'intruding star' moved away from the primitive sun (but not so away that it could not exert attractional pull on the primitive sun), the gravitational attraction exerted by it on the primitive sun became low due to greater distance between them. Thus, again small quantity of incandescent matter came out from the surface of the primitive sun. Thus, the shape of matter ejected from the primitive sun became like a cigar which was called by James Jeans as 'filament.' (4) Gradually and gradually the intruding star moved far away from the primitive sun and thus went out of the domain of the gravitational field of our primitive sun. In the beginning, when the filament was detached from the primitive sun it followed the intruding star as it was pulled by the intruding star. The filament tried to keep pace with the intruding star for

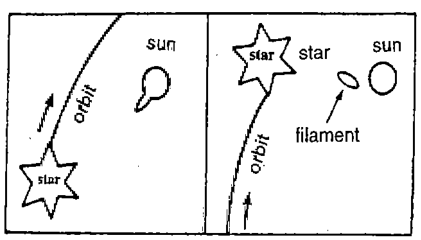


Fig. 2.1 : Formation of planets according to tidal hypothesis.

some time but could not succeed and ultimately it (filament) started revolving around the primitive sun.

Formation of planets from the filament—According to James Jeans nine planets of our solar system were formed due to cooling and condensation of the incandescent mass of gaseous matter of the filament. The filament, after being detached from the sun, began to cool down. Thus, the filament started contracting in size on cooling. The contraction of the filament led to its breaking in several pieces and each piece was condensed to form one separate planet. This process led to the formation of nine planets.

The filament of incandescent gaseous matter allowed bigger planets to form in its middle portion (like Jupiter and Saturn) and smaller ones towards its tapering ends. The reamining part of the primitive sun became our sun. The satellites of the planets were formed due to gravitational pull and tidal effect exerted by the sun on the outer surfaces of the newly formed planets. The processes of the formation of satellites ceased when the amount of matter ejected from the planets for the formation of new satellites became so low that it was not able to hold together its matter by its central gravitational force/attraction. The rate of cooling of the primitive incandescent gaseous planets was dependent upon the size of the planet. The planets of greater mass cooled very slowly while the smaller planets and satellites condensed to liquid and then to solid forms within very short period. This may be the possible reason for larger number of satellites of bigger planets and fewer number of satellites of smaller planets. Very small planets were cooled and condensed soon, so no matter could be ejected from their surface due to tidal effect and thus no satellite could be formed. This is why Mercury, Venus and Pluto do not have any satellite.

Evidence in Fvour of the Hypothesis

The 'tidal hypothesis' of James Jeans has not only explained the origin of the solar system and the earth but has also attempted successfully to some extent, to solve various problems of the solar system related to its shape, size, structure and peculiar motion. The following characteristics of the solar system are more or less explained on the basis of this hypothesis.

(1) **Shape and ordering of planets**—The filament ejected from the primitive sun was cigar-shaped. It was thick in the middle portion and thin at the ends. The planets formed from the condensation of the incandenscent gaseous matter of the middle portion of the filament were bigger in size than the planets formed from the condensation of matter at the tapering ends of the filament (fig. 2.2). This arrangement of the planets formed of the filament clearly matches with the present planetary arrangement of our solar system. If we start from the sun, the size of the planets (Mercury, Venus, Earth, Mars-which is an exception) inceases upto Jupiter which is the biggest planet and occupies almost the central position in the solar system. The size of the planets after Jupiter (Saturn, Uranus, Naptune and Pluto) again decreases till the location of the smallest planet-Pluto at the extreme end. It may be pointed out that James Jeans propunded his hypothesis before the discovery of Pluto. Thus, the discovery of planet Pluto having smallest size and its location at the extreme end further enhanced the significance of tidal hypothesis.

(2) **Ordering and arrangement of satellites**—According to this hypothesis the satellites of the planets were formed through the condensation of incandescent gaseous matter ejected from the planets in the same manner as the planets were formed through the condensation of incandescent gaseous matter ejected from the sun. Thus, there is almost the same type of arrangement of satellites around the planets as is the arrangement of planets around the sun in our solar system i.e. smaller ones at the end and bigger ones in the middle. For example, if a planet has several satellites, the biggest satellite is placed in the middle and smaller ones are placed at the end. The arrangement of satellites of Jupiter and Saturn confirms the above fact.

(3) **Number and size of satellites**—According to tidal hypothesis bigger planets remained in gaseous form for longer time in the space because their cooling took longer time due to their large size. On the other hand, smaller planets were cooled and condensed within very short period of time because of their small size. Thus, larger number of satellites were formed from bigger planets but the size of such satellites was relatively small whereas fewer number of satellites were formed from medium-sized planets but the size of such satellites was relatively

larger. Very small planets occupying the end location of planetary system were cooled and condensed within very short period of time and hence no satellites could be formed from them. The existing planetary arrangement of the solar system confirms the above fact. For example, Jupiter and Saturn (biggest planets) have 14 and 15 satellites respectively while Mercury, Venus and Pluto, which are smallest planets of our solar system do not have any satellite (table 2.1).

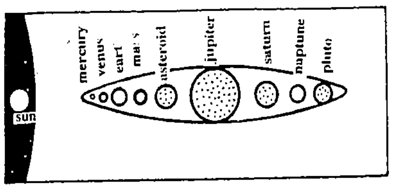


Fig. 2.2 : Cigar-shaped arrangement of the planets of our solar system.

(4) Rotation, revolution and inclination of the planets' axis—According to James Jeans the planets were formed from the filament which was revolving around the sun. Thus, the planets of our solar system should also revolve around the sun. In our present day solar system all the planets are revolving around the sun in the same direction and also in the same orbital plane (the orbital plane of Pluto is however slightly inclined). Similarly, almost all their satellites of the planets are also revolving around their respective planets in the same direction as their father planets are revolving around the sun. James Jeans also proposed that the rotational motion of the planets should also be in the same direction. Except Venus and Uranus all the planets of the present solar system rotate on their axis in the same direction as their revolution around the sun.

As per tidal hypothesis the encounter of the primitive sun and the intruding star was not in the same planes of their rotation. The filament, which was ejected from the primitive sun by the gravitational attraction of the intruding star, was slightly inclined. Thus, the axis of rotation of the planets, which were formed from the inclined filament (inclined from the plane of the rotation of our sun), should also be inclined. It is apparent from table 2.1 that all the axes of the planets of the present solar system are inclined. However, the planes of the orbital paths of various planets are also not matching with the plane of rotation of our sun.

Modification by Jeffreys

Harold Jeffreys, a British scientist, modified the original tidal hypothesis of James Jeans in 1929 and presented his concept as **'collision hypothesis'**. According to Jeffreys there were three stars in the universe before the origin of our solar system. One was our **primitive sun**, the second one was its **'companion star'** and the third one was **'intruding star'** which was moving towards 'companion star'. Thus, the intruding star collided against the 'companion star'. Due to head-on collision the companion star was completely smashed and shattered, some shattered portions were scattered in the sky while remaining debris started revolving around the primitive sun. However, the impact of collision and explosion enabled the intruding star to clear itself off from the gravitational attraction of the primitive sun and gradually vanished in the universe. The planets of our solar system were formed from the remaining debris of the companion star. It may be pointed out that Jeffreys suggested modifications in the tidal hypothesis of James Jeans with the intention to remove major inherent weak points of the tidal hypothesis so that it can withstand the criticisms of the modern scientific world.

Evaluation

The tidal hypothesis as propounded by James Jeans and modified by Harold Jeffreys enjoyed a long lease of popularity and wide appreciation till the end of the 1st half of the 20th century because of its simplicity, inherent logic and scientific appeal but the hypothesis was severely criticised on various grounds. Even Jeffreys accepted in Guttenberg (1951) that his modified version of tidal hypothesis needed substantial modifications and in some places was completely wrong. The following criticisms have been labelled against this hypothesis.

(1) According to B. Levin the universe is infinite in space and time and the stars are so distant from each other that such a close encounter between them is a remote possibility.

(2) James Jeans did not explain the whereabout and destiny of the intruding star which caused tidal

eruption on the surface of the primitive sun in the form of filament.

(3) N.N. Parisky has proved on the basis of mathematical calculation that tidal hypothesis fails to explain the real distances between the sun and the planets in our present solar system. Hoyle has maintained that if 'we reduce the solar system to scale, representing the sun by a ball of the size of a large grape fruit, the bulk of the planetary material lies at a distance of some 100 yards from it.' That is why American astronomer Russell expressed serious doubts about the fact that such a huge amount of material of the filament would have come out from the primitive sun to form planets at much greater distances from the sun, some times more than 500 to 3000 times the diameter of the sun (the distances of Jupiter and Naptune from the sun respectively). In fact, according to this hypothesis the planets should have been very close to the sun but in reality they are far away from the sun.

(4) According to Wooldrige and Morgan 'the fundamental difficulty is that the planets comprising but a small fraction of the total mass of the system, yet at great distances from the sun, carry most of the angular momentum of the system'. Many modern astrophysicists are of the opinion that the angular momentum imparted by the intruding star to the planets was not high enough to match the existing angular momentum of the planets of our present solar system.

(5) The planets of our solar system are largely formed of the elements having high atomic weight but the constituent elements of the sun (from which the planets are supposed to have been formed) are of lighter atomic weight e.g. hydrogen and helium. The tidal hypothesis fails to offer convincing explanation for such anomalous situation.

(6) Another problem is that of the formation of satellites from the planets. If for the time being we accept the view that satellites were formed from the tidal effect exerted by the primitive sun on the newly born planets, then question arises, why no satellite was formed from Mercury and Venus though these planets were nearest to the sun. In the circumstances the sun should have exerted maximum gravitational force on the outer surfaces of Mercury and Venus. The argument that small planets were condensed to solid form within very short period of time and hence there was no time for the ejection of matter from these planets does not appear sound.

(7) James Jeans could not elaborate the process and mechanism of the condensation of matter ejected from the primitive sun.

1.7 BINARY STAR HYPOTHESIS OF RUSSELL

It may be pointed out that the hypothesis based on dualistic concept failed to explain the high amount of angular momentum of the planets of present solar system, high atomic weight of the constitutent elemens of the planets of inner circle and lighter atomic weight of the planets of outer circle of the solar system and the distances of different planets from the sun. In order to solve these problems the scientists tried to explain the origin of the earth and the solar system with the help of three heavenly bodies.

H.N. Russell, an American astronomer, propounded his **'binary star hypothesis'** in the year 1937 to remove the shortcomings of tidal hypothesis of Sir James Jeans. Russell opined that there were two stars near the primitive sun in the universe. In the beginning the **'companion star'** was revolving around the primitive sun. Later on one giant star (the third one) named as **'approaching star'** came near the companion star but the direction of revolution of the approaching star was opposite to that of the companion star. It was believed that the distance between two stars might have been about 48,00,000 to 64,00,000 km. It means that the approaching star might have been at a far greater disance from the primitive sun. Thus, there would have been no effect of tidal force of the giant approaching star on the

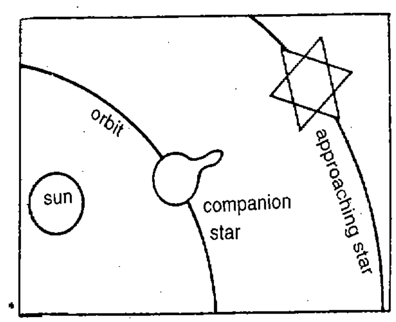


Fig. 2.3 : Origin of the earth according to the binary star hypothesis of H.N. Russell.

primitive sun but large amount of matter of the companion star was attracted towards the giant approaching star because of its massive tidal force (gravitational pull) (fig. 2.3).

As the giant approaching star came nearer to the companion star, the gravitational and tidal force continued to increase and hence the bulge on the outer surface of the companion star started growing towards the giant approaching star. When the giant approaching star came nearest to the companion star, large amount of matter was ejected from the companion star due to maximum gravitational force exerted by the giant approaching star. The ejected matter started revolving in the direction of the giant approaching star and thus opposite to the direction of revolution of companion star. Later on planets were formed from the ejected matter. In the beginning the planets might have been nearer to each other and thus matter might have been ejected from these planets due to their mutual attraction and thus satellites might have been ejected from these planets due to their mutual attraction and thus satellites might have been formed from these matter.

Evaluation

Though Russell solved, to some extent, the problems of distances between the planets and the sun and angular momentum of different members of the solar system by assuming the origin of the earth with the help of two stars besides the sun and by ejecting the required matter from the companion star (and not from the sun as assumed by James Jeans) to form planets but the hypothesis has been criticised on the basis of the following points.

(1) Russell has explained the formation of planets out of the matter ejected from the companion star due to gravitational and tidal force of the giant intruding star but he did not throw light on the fate of the remaining portion of the companion star. What happened about the residual part of the companion star? Russell could not answer this question.

(2) According to Russell the planets, at the time of their formation, were far off from the primitive sun. Even they were also distantly placed from each other but after the disappearance of the giant intruding star the planets were brought under the gravitational domain of the primitive sun. On the other hand, the residual companion star, which was nearest to the primitive sun, could not come within the gravitational field of the sun. In fact, the residual companion star should have come within the sun's gravitational domain but it did not happen. Russell was unable to resolve this contradiction.

(3) Russell did not elaborate the process and mechanism through which the planets, after their formation, were brought within the gravitational field of the sun.

2.8 SUPERNOVA HYPOTHESIS OF HOYLE

F. Hoyle, a mathematician of Cambridge University (U.K.) presented his speculative theory known as **'supernova hypothesis'** in the year 1946. His hypothesis was based on the principles of **'nuclear physics'** and was described in his essay entitled **'Nature of the Universe'**. According to Hoyle initially there were two stars in the universe viz. (i) the primitive sun and (ii) the companion star. The companion star was of giant size and later on became supernova due to nuclear reaction.

It may be pointed out that energy, which is emitted by any star in the form of light, heat, etc., is generated by the process knowns as 'nuclear fusion' wherein atoms of lighter elements combine under intense heat and pressure to form atoms of heavier elements, releasing vast amount of energy. The stars generally contain hydrogen. The hydrogen nuclei slowly and slowly combine with each other to form helium. In the process comparatively heavier element helium is formed and vast amount of energy is also released.* The same type of nuclear fusion was also going on in Hoyle's primitive sun and the companion star but the rate of nuclear fusion was many times greater in the core of the companion star than the primitive sun. With the passage of time all of the hydrogen nuclei of the companion star were consumed in the process of nuclear reaction and it collapsed (in modern and cosmogonic language) and violently exploded.

* The atomic weight of four hydrogen atoms is 4.032 while that of one helium atom is 4.003. Thus, there is loss of 0.7 per cent of mass during the conversion of every four hydrogen atoms into one helium atom through nuclear fusion. What happens to the lost mass? According to Einstein the lost mass of matter of four hydrogen atoms is converted into energy which is the prime source of energy of the stars. One kilogram of lost matter during nuclear fusion gives 5×10^{14} joules of energy which is sufficient enough to keep the sun shining for a very long time.

The violent explosion of the companion star (now supernova) resulted into the spread of enormous mass of dust which started revolving around the primitive sun. Hoyle maintained that when the companion star was violently exploded, the recoil of the gigantic stellar explosion threw the nucleus of the companion star out of the gravitational field of

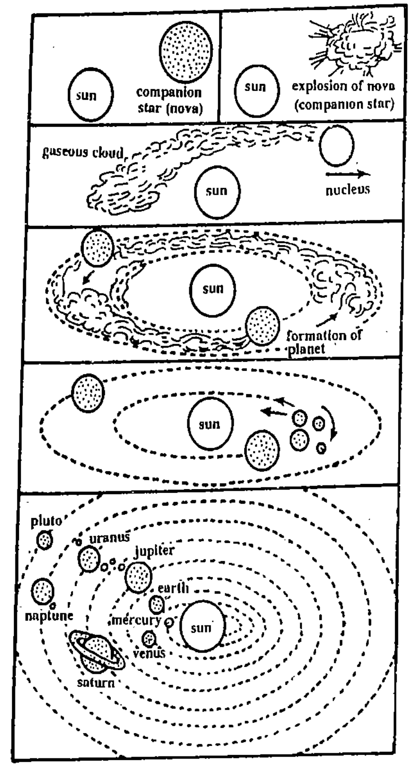


Fig. 2.4 : Origin of the solar system according to F. Hoyle (1946).

the primitive sun. The gaseous matter comming out due to violent explosion of the companion supernova star changed into a circular moving disc which started revolving around the primitive sun. Thus, the matter of this disc became building material for the formation of future planets. The main constituent elements of the aforesaid building material were formed during the explosion of the companion star of supernova. It may be pointed out that the explosion of the companion star or supernova generated intense heat equivalent to 5×10^9 degree C which was sufficient enough to start the process of nuclear fusion. The intense heat and nuclear fusion became responsible for the formation of heavy elements (e.g. helium, carbon, oxygen, silicon, nitrogen, etc.). In fact, the degree of heat and pressure decides the level of heaviness of the elements in the process. The explosion of the supernova (companion star) generated intense heat and pressure which formed heavy elements of which our primitive earth was made. Thus, the planets of our solar system were formed due to condensation of the matter of the disc formed of the matter thrown out of the supernova due to its violent explosion. It is, thus, obvious that the planets of our solar system were not formed from the primitive sun but were formed from the heavy elements which were formed from the matter thrown out of the supernova due to nuclear reactions and violent explosion (fig. 2.4.).

Evaluation

The **'supernova hypothesis'** of F.Hoyle helps us in solving 3 basic problems of the origin of the earth and the solar sytem raised by the critics since the time of the postulation of 'tidal hypothesis' of James Jeans viz. (i) the problem of great distance between the planets and the sun, (ii) the problem of the angular momentum of the planets and (iii) the problem of heavier elements of the material of the planets than the sun. Hoyle has tried to solve these problems through his superenova concept. (i) The shattered matter of the violently exploded supernova were thrown upto great distant locations and thus the planets were also formed at great distances. (ii) The large amount of angular momentum of the planets was provided by the violent explosion of the supernova. (iii) The materials were rendered denser and heavier due to intense heat and pressure generated from the nuclear fusion and violent explosion of the supernova.

If the supernova hypothesis solves the intricate problems of the solar system, it fails to explain the peculiar arrangement of the planets on the basis of their size, similar direction of rotation as well as the plane of revolution and path of the planets and the lighter constituent elements of the planets of the outer circle of our solar system on the other hand.

2.8 INTER-STELLAR DUST HYPOTHESIS

Otto Schimidt, a Russian scientist, proposed his 'Inter-Stellar Dust Hypothesis' in 1943 to explain the complex problems of the origin and characteristics of the solar system and the earth. The most outstanding characteristic feature of this hypothesis is that the earth and the solar system have been taken to have been formed from gas and dust particles, the genesis of which has not been explained by Schimidt.

The scientific researches about the universe have given ample evidences of the presence of **'dark matter'** in the form of gas and dust particles known as **'gas and dust cloud'** in the universe. Though Schimidt did explain the mode of origin of these dark matter but it may be safely assumed that these gaseous clouds and dust particles might have been formed from the matter coming out of the stars and meteors. According to the 'interstellar dust hypothesis' our sun during its **'galactic revolution'*** captured the dark matter of the universe. The dark matter of gaseous cloud and dust particles had their own angular momentum. The dark matter after being attracted by the sun during its 'galactic revolution' started revolving around the primitive rotating sun. These dark matter were called 'inter-stellar dusts' by Schimidt. It may be pointed out that in the beginning the gaseous cloud and dust particles were not well arranged and stabilized and hence these were revolving around the sun separately. Gases being less in volume were more destabilized and less systematically arranged while the dust particles being more in amount and quantity were more stabilized and systematically arranged. Thus, the dust particles after being combined and condensed were changed into a flat disc which started revolving around the sun. It may be pointed out that flat disc of captured dark matter started revolving around the sun under the combined impacts of three types of motions *e.g.* (i) the rotational motion of the sun itself, (ii) gravitational force exerted by the sun on the disc of dark matter and (iii) the angular momentum of dark matter of the disc. Thus, under the combined impact of these three types of motions each and every particle of dark matter of the universe (fig. 2.5) started redistributing itself on the basis of mass, density, dimension and the existing amount of centrifugal force (generated due to the revolution of matter around the sun) tending to push the particles away from the sun and the centripetal force (generated due to gravitational pull of the sun) tending to push the particles towards the sun. Thus, the particles having larger amount of centrifugual force were thrown out towards the margins of the rotating disc of dark matter around the sun while the particles having small amount of centrifugal force were attracted towards the band of the disc nearer to the sun.

* Our sun with its planetary system is revolving (one revolution in 224×10^6 years) around the central part of our Milky Way along its gigantic two arms because the solar system is located in one of the arms of our Milky Way about 30,000 light years away from its core (the radius of our rotating Milky Way is 50,000 light years). This is called 'galactic revolution' of our sun.

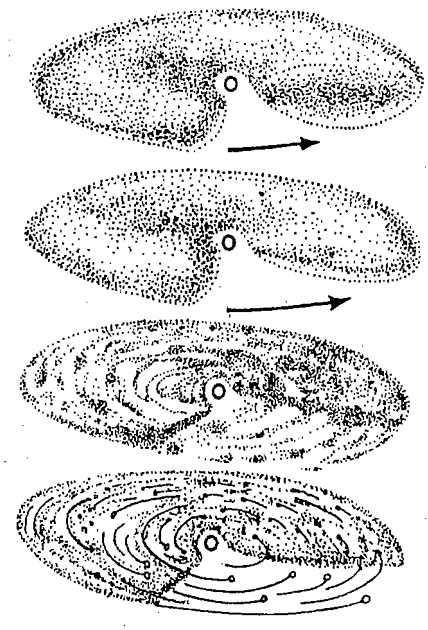


Fig 2.5 : Formation of disc of dark matter and embryos of the planets according to Schimidt.

The intense heat of the sun dispersed the gaseous particles towards the margins of the disc (except oxygen which combines with iron chemically). The intense heat also formed heavy particles

which remained in the inner bands of the disc. Collision among the dust particles started the process of aggregation and accretion around the bigger particles which became the embryos of the future planets but the gas particles could not condense as they could not be organized due to their continued motion. With the passage of time these embryos captured more and more matter and thus grew in size to become **asteroids.** It may be pointed out that the asteroids were still inside the disc and were revolving in the evolutionary direction of the disc. These asteroids further grew in size due to continuous accretion of nearby matter around them and thus they became planets. Some matter still remained in the disc after the formation of the planets. These matter were condensed to form satellites of the planets.

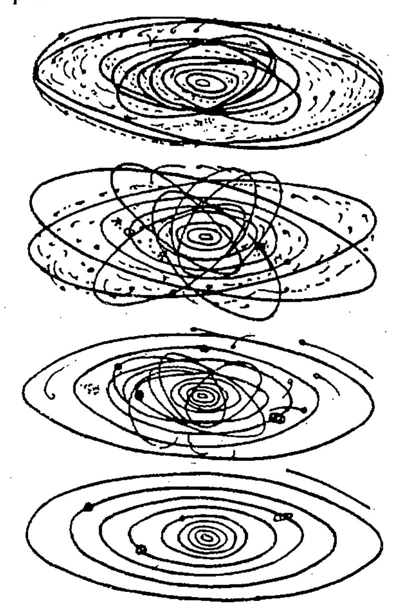


Fig. 2.6 : Final stage of the formation of planets according to Schimidt (after B. Levin).

It may be pointed out that since the lighter matters were pushed towards the margins of the disc (as explained above) and heavy matters were pushed towards the inner bands of the disc, the planets formed in the inner bands of the disc were also of higher density than the planets of the outer bands of the disc.

The planets of the outer bands of the disc were of low density because they were formed by the **'freezing out'** process of the gaseous matter. The redistribution of matter and 'averaging of the dynamic characteristics' of the disc resulted in the placement of the planets according to well known Titius-Bode law of planetary distances (equation 2.5).

$$D = 0.4 + 0.3 \times z^n \qquad \ldots\ldots.(2.5)$$

Where D is the distance of planets from the sun in astronomical unit and n is a coefficient, the value of which for each planet is constant *e.g.* Mercury ∞ Venus o, Earth 1, Mars 2 etc.

Evaluation

The outstanding merit of the 'inter-stellar dust hypothesis' of Otto Schimidt is that it solves almost all of the problems of the peculiar characteristic features of our solar system like (i) near circular and similar planes of orbits of the planets ; (ii) revolution in the equatorial plane of the sun closely matching with the orbital planes of the planets; (iii) placement of planets according to their size on the basis of well founded laws ; (iv) high density planets in the outer circle of the solar system and (v) large and peculiar distribution of angular momentum among the planets of sloar system.

According to the current cosmogonic ideas there are a few disputable points in the 'interstellar dust hypothesis' of Schimidt. (1) The gravitational force of the primitive sun was incapable of capturing dark matter scattered in the universe. Calculations show that only the binary star system (two stars) can capture dark matter. (2) According to some astrophysicists 'meteorites and asteroids were formed as a result of the distintegration of some planets and not the planets were formed out of meteorites and asteroids'. (3) Till now no trace of rennants of dark matter could be discovered either in the archaeological drilling on the earth's surface or on any planet.

1.9 RECENT THEORIES

Among the recent hypotheses and theories of the origin of our solar system and the earth significant are (1) Fon Vaischcer's Hypothesis; (2) Alfven's Inter-Stellar Cloud Hypothesis, (3) Rossgunn's

Rotational and Tidal Hypothesis; (4) Cepheid Hypothesis of A.C. Banerjee (of Allahabad University); (5) Kuiper's Hypothesis (1949); (6) Fosenkov's Globule Concept (1951); (7) Voitkevich's Protoplanetary Chondrule's Concept (1971); (8) Jupiter-Sun Binary System Hypothesis of E.M. Drobyshevski (1974) etc.

The latest ideas of the modern astrophysics indicate that there was initially a big rarified cloud of inter-stellar matter which started rotation around its axis. Later on, at the stage of redistribution of matter in the rotating disc of cloud of matter maximum mass was accumulated in its central part which increased the luminocity of the core (central part) of the disc. This core of the disc became our primitive sun. Relatively lesser masses of the outer zones of the disc became planets after being condensed. This is the summary of the latest 'Nuclear Disc Model' (neo-Laplacean model) of the origin of the sun and its planets. The formation of the planets of different constituent materials and size is explained with the help of 'Chemical-Condensation-Sequence Model' of the American scientists.

1.10 BIG BANG THEORY

The Big Bang Theory postulated in 1950's and 1960's and validated in 1972 (May) through convincing evidences received from COBE (Cosmic Background Explorer) explains the origin of universe and every thing in it including ourselves on the premise that the universe contained many million of gallaxies, each one 'having thousands of millions of stars and each star having numerous planets around them'. According to this theory every thing in the universe emerged from a point known as singularity, 15 billion years ago. The galaxies moved apart from one another as the empty space between them expanded. In the beginning the universe was much smaller as there was less space between the galaxies. All of the matter in the universe was created in one instant at a fixed moment in time. "As the universe expanded for 15 billion years, the hot radiation in the original fireball also expanded with it, and cooled as a result." It may be summerized that there was a single fireball some 15 billion years ago. 'There were already wispy clouds of matter stretching across vast distances, upwards 500 million light years across. As those clouds collapsed in upon themselves, pulled together by their own gravity, they would have broken up and formed clusters of galaxies with the galaxies themselves breaking up into stars like those of the Milky Way' (John Gribbin). The stars might have broken up to form their planets as our earth.

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 geological 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. x 10^{22} grams. He has further maintained that about 1.56 x 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.

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

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.

3.6 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

* It may be pointed out that the study of rocks of the moon brought to the earth during Appolo 9 expedition of the USA in 1969 has revealed that the rocks of the moon are older than the rocks of the earth and hence the concept of the origin of the moon from the earth stands rejected. If this is so, the method of the calculation of the age of the earth on the basis of moon's tidal force is proved baseless.

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.

3.10 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-

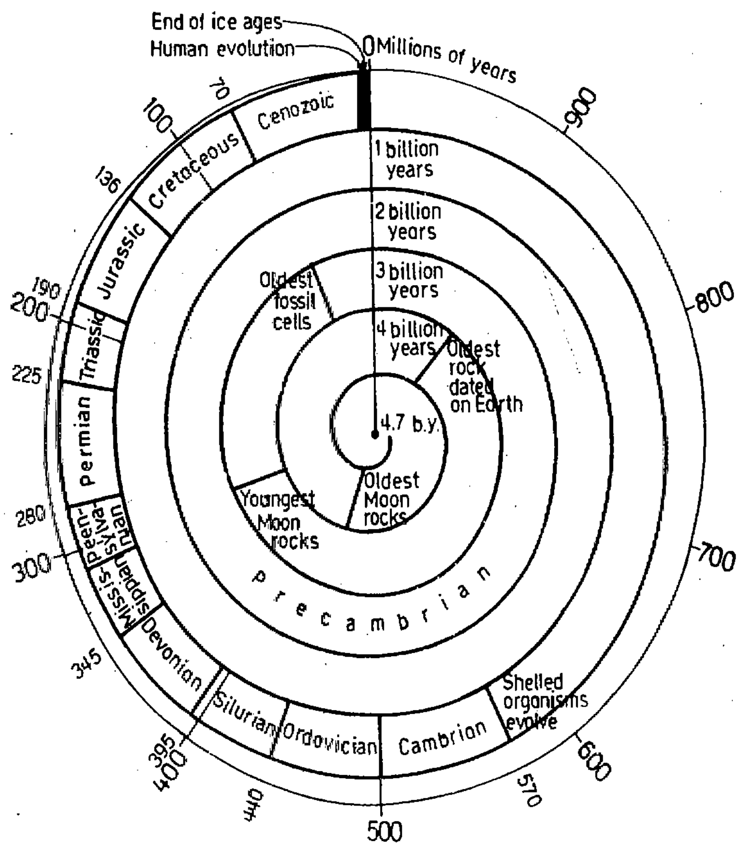


Fig. 3.1: The geological clock (modified after F. Press and R. Siever, 1974). Numbers denote years in millions before present.

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). Further, each epoch is divided into several periods. The names of periods 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).

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

Eras	Epochs	Periods	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 Scotland, 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 featherless

birds, overdominance by reptiles like dirosaurs and pterosaurs.

Eocene Period

This period 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 Period

The Oligocene period 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 Period

This period 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 Period

The pliocene period continued from 110 million to 10 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 Period

The pleistocene period extended from one million to 9,90,000 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 Period

The present period 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.

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

DENSITY

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 = 11 g 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°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°C and 1,900°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°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 $= 4.9 \times 10^{7}$ 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 pres-

sure 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).

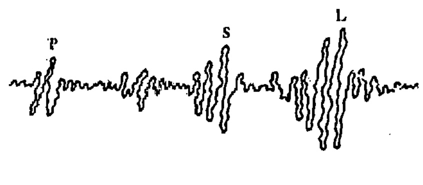


Fig. 4.1 : Recorded seismic waves by a seismograph.

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.

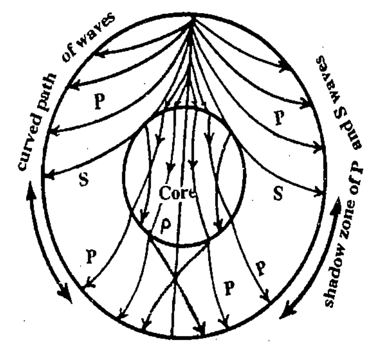


Fig. 4.2 : Paths followed by seismic waves through the earth's interior.

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.

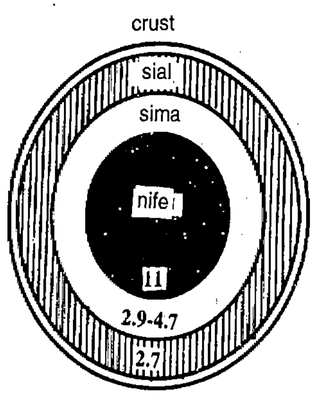


Fig. 4.3 : Layering system of the earth according to E. Suess.

(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 Homles

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.

Homles 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

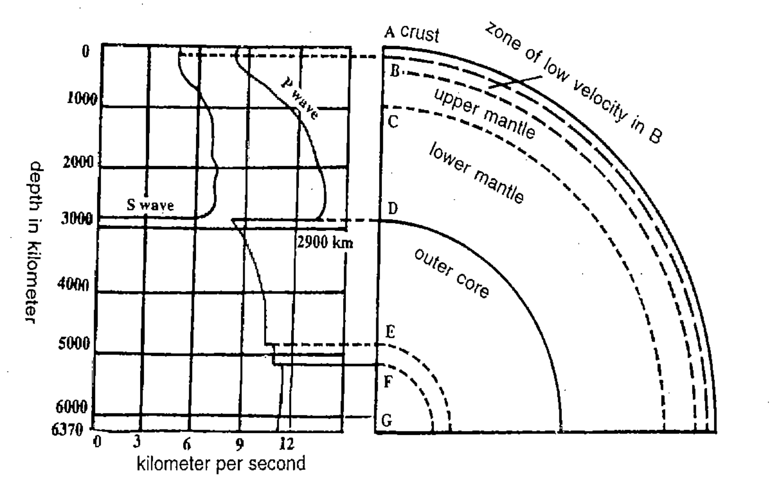


Fig : 4.4 : Presentation of velocities of seismic waves from the crust of the earth to its interior and relationships between the velocities of seismic waves and different zones of the earth (after K.E. Bullen).

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 **(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

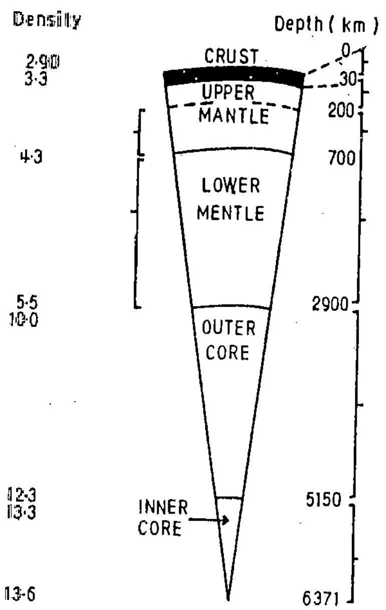


Fig. 4.5: Diagramatic presentation of different zones of the earth, their densities and thickness on the basis of the information of International Union of Geodesy and Geophysics.

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.

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.

5

CONTINENTS AND OCEAN BASINS

5.1 INTRODUCTION

Continents and ocean basins being fundamental relief features of the globe are considered as **'relief features of the first order'**. It is, therefore, desirable to inquire into their mode of possible origin and evolution. Different views, concepts, hypotheses and theories regarding the origin of the continents and ocean basins have been put forth by the scientists from time to time. Before examining these views about their origin we should know the characteristic features of the distributional patterns and arrangement of the continents and ocean basins as seen at present. About 70.8 per cent of the total surface area of the globe is represented by the oceans whereas remaining 29.2 per cent is represented by the continents. Even the distribution of different continents and oceans in both the hemispheres is not uniform. The following characteristic features of the distributional pattern of the continents and ocean basins may be highlighted.

(1) There is overwhelming dominance of land areas in the northern hemisphere. More than 75 per cent of the total land area of the globe is situated to the north of the equator (*i.e.* in the northern hemisphere). Contrary to this water bodies dominate in the southern hemisphere. If we devide the globe in two such hemispheres where the north pole stands located in the English Channel and the south pole near New Zealand, then the northern hemisphere would be **'land hemisphere'** while the southern hemisphere as **'water hemisphere'**. Thus, the land hemisphere would represent 83 per cent of the total land area of the globe while the water hemisphere would carry 90.6 per cent of the total oceanic areas of the globe.

(2) Continents are arranged in roughly triangular shape. Most of the continents have their bases (of triangle) in the north while their apices are pointed towards south. If we take North and South Americas together, they represent equibilateral triangles, the base of which would be along the arctic sea while the apex would be represented by Cape Horn. If we take these two continents separately, again they form two separate triangles. Similarly, Eurasia also assumes the form of a triangle the base of which is along the arctic sea while its apex is near East Indies. The base of African triangle is towards north while its apex is the Cape of Good Hope. Australia and Antarctica are the exceptions to this rule.

(3) Roughly, the oceans are also triangular in shape. Contrary to the continents the bases of oceans are in the south while their apices are in the north. The base of the Atlantic Ocean extends between Cape Horn and Cape of Good Hope while its apex is located to the east of Greenland. The base of the

Indian Ocean is in the south but its two apices are located in the Bay of Bengal and Arabian Sea. The apex of the Pacific Ocean is near Aleutian Islands while its base lies in the south.

(4) The north pole is surrounded by oceanic water while south pole is surrounded by land area (of the Antarctic continent).

(5) There is antipodal arrangement (situation) of the continents and oceans. Only 44.6 per cent oceans are situated opposite to oceans and 1.4 per cent of the total land area of the globe is opposite to land area. More than 95 per cent of the total land area is situated diametrically opposite to water bodies. There are only two cases of exceptions to this general rule *i.e.* (i) Patagonia is situated diametrically opposite to a part of north China and (ii) New Zealand is situated opposite to Portugal and Spain (the Iberian Peninsula)

(6) The great Pacific Ocean basin occupies almost one-third of the entire surface area of the globe.

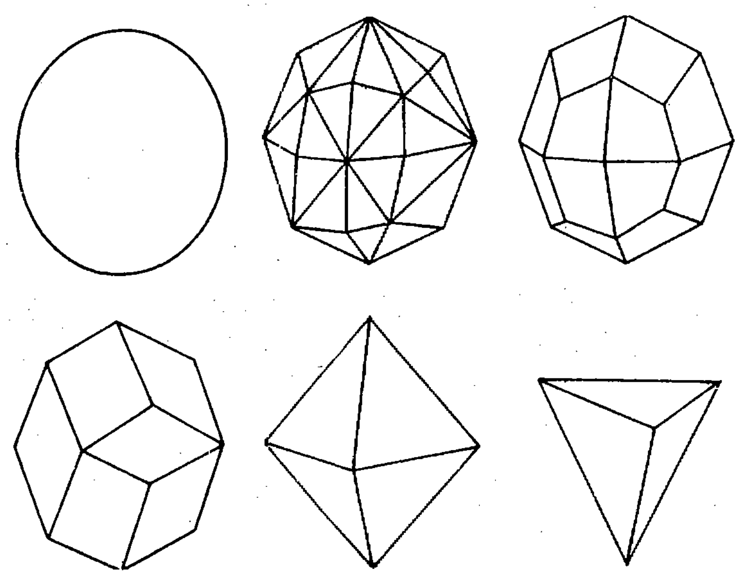


Fig. 5.1 : Different geometrical shapes which were used to postulate the hypotheses of the origin of the continents and ocean basins. The last one is a tetrahedron.

The validity and authenticity of any hypothesis or theory dealing with the origin and evolution of the continents and the ocean basins would be determined in the light of aforesaid characteristics of the distributional pattern of the continents and ocean basins. The presence of the great Pacific Ocean basin and island arcs and festoons of the Pacific Ocean is teething problem before scientists who venture in the precarious field of the postulation of the relevant theory of the origin of the continents and ocean basins. Keeping the above facts in mind Lowthian Green postulated his 'Tetrahedral Hypothesis' to explain the intricate problems of the origin of the continents and oceans and characteristic features of their distributional pattern. Besides, Lord Kelvin, Sollas, Love etc. have also attempted to explain the

origin of the continents and ocean basins but their views are not discussed here because they are based on discarded and obsolete arguments and assumptions. In fact, all the previous hypotheses and theories dealing with the origin of the continents and ocean basins have faded away after the posulation of plate tectonic theory. We will examine here only the concepts of Lowthian Green, F.B. Taylor, A.G. Wegener and of course plate tectonic theory.

5.2 TETRAHEDRAL HYPOTHESIS

A few scientists have attempted to solve the problems of the origin of the continents and ocean basins on the basis of fundamental principles of geometry. The **pantagonal dodecahedral hypothesis** (dodeca is a Greek word which means twelve) of Elie de Beaumont is considered to be the first attempt in this field but the **tetrahedral hypothesis** of Lowthian Green is most significant of all the hypotheses based on geometrical principles. 'An attractive hypothesis which has enjoyed a considerable vogue was initiated by Lowthian Green in 1875' (S.W. Wooldridge and R.S. Morgan, 1959). His hypothesis is based on the characteristics of a tetrahedron which is a solid body having four equal plane surfaces, each of which is an equilateral triangle (fig. 5.1)

Lowthian Green postulated his hypothesis after considering the characteristics of the distributional pattern of land and water over the globe. Barring a few drawbacks and defects the tetrahedral hypothesis successfully explains the following characteristics of the continents and ocean basins.

(1) Dominance of land areas in the northern hemisphere and water areas in the southern hemisphere; (2) triangular shape of the continents and oceans; (3) situation of continuous ring of land around north polar sea and location of south pole in land area (Antarctica) surrounded by water from all sides; (4) antipodal arrangement of the continents and oceans; (5) largest extent of the Pacific Ocean covering one third area of the globe and (6) location of chain of folded mountains around the Pacific Ocean.

The hypothesis of Lowthian Green propounded in the year 1875 is based on the common characteristics of a tetrahedron. He based his hypothesis on the following two basic principles of geometry-

(1) 'A sphere is that body which contains the largest volume with respect to its surface area ;

(2) 'A tetrahedron is that body which contains the least volume with respect to its surface area'.

After many experiments Lowthian Green opined that a sphere if subjected to uniform pressure on all its sides would be transformed into the shape of a tetrahedron. He applied this principle in the case of the earth. According to him when the earth was originated it was in the form of a sphere. In the beginning the earth was very hot but it gradually began to cool down due to loss of heat. First, the outer part of the earth cooled down and thus was formed the crust but inner part of the earth continued to cool down. Consequently, the inner part of the earth was subjected to more contraction due to continued cooling and thus there was marked reduction in the volume of the inner part of the earth. Since the upper part, the crust, was already cooled and solidified and hence it could not be subjected to further contraction. This resulted into possible gap between the upper and inner parts of the earth. Consequently, the upper part collapsed on the inner part and ultimately the earth began to assume the shape of a tetrahedron. Lowthian Green has further maintained that the earth has not been as yet changed into a complete tetrahedron rather as it is being

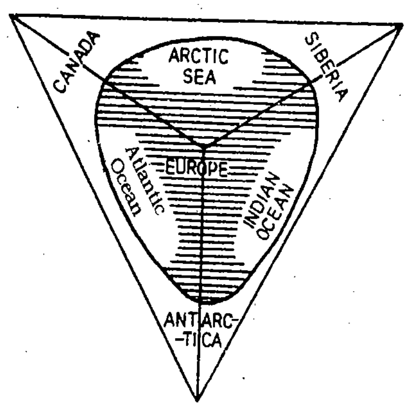


Fig. 5.2 : Distribution of land and water on a tetrahedron.

cooled, it is proceeding towards attaining the true shape of a tetrahedron. He has further opined that the earth cannot be in the shape of a real tetrahedron because of its structural variations and thus it is natural that there may be some deviations from a true tetrahedron.

In a tetrahedron a plane face remains always opposite to an apex or coign. The apex or coign is more sharpened in the case of a real tetrahedron. In the case of the earth oceans represent the plane faces of the tetrahedron and land masses represent the apices or coigns but in the case of the earth the coigns are not much sharpened, rather they are flat and convex. According to Lowthian Green oceans were created on the plane faces of the terrestrial tetrahedron whereas the coigns became continental masses

Four oceans (*e.g.* the Pacific Ocean, the Atlantic Ocean, the Indian Ocean and the Arctic ocean) were created on the four plane faces of the terrestrial tetrahedron. These plane faces could retain water because of the fact that these were lower than the level of the apices or coigns of the terrestrial tetrahedron. Continents were formed along the apices or coigns of the tetrahedron. This fact may also be proved on the basis of an experiment. If we submerge a tetrahedron in a hemisphere of water, the flat surfaces of the tetrahedron would retain water while the edges or apices or coigns will project above the water.

Lowthian Green claimed to see a tetrahedral arrangement in the distribution of the continents and oceans in such a way that the earth was linked to a tetrahedron having four flat faces and standing on one point (fig. 5.2). The upper flat face represents the Arctic Ocean while the remaining three faces represent the Pacific Ocean, the Atlantic Ocean and the Indian Ocean. Similarly, three vertical meridional edges represent North and South America, Europe and Africa and Asia while the lower point is represented by Antarctica. Thus, the presence of water around north pole and the location of south pole in land area (Antarctic continent) are very well explained on the basis of tetrahedral hypothesis. Three coigns out of four coigns of four equilateral triangles are located in the northern hemisphere. Only the fourth coign is located in the southern hemisphere. These three coigns present the oldest rigid masses around which the present continents have grown. These three ancient shields are the Laurentian or Canadian shield, Baltic shield and Siberian shield. The fourth coign or the pivot of the tetrahedron represents the Antarctic shield. The present continents have grown out of these four ancient shields represented by four coigns of the tetrahedron. All the continents developed along the edges of the tetrahedron taper southward and thus triangular shape of the continents is proved. The location of the oceans along four plane faces and the continents along the edges or coigns of the plane faces of the tetrahedron proves antipodal position of land and water.

Though Gregory accepted the tetrahedral hypothesis of Lowthian Green but he suggested certain modifications. According to Gregory due to shrinkage of the earth because of contraction on cooling 'the portion of the vertical tetrahedral edges should be fairly constant, but three edges around the polar depression might develop sometimes in the northern and at others in the southern hemisphere'.

Evaluation

Though the tetrahedral hypothesis throws light on the problems of the continents and ocean basins and to major extent it successfully explains the characteristic features of the distributional pattern of the present-day continents and ocean basins but because of certain basic defects and errors the hypothesis is not acceptable to the modern scientific community. It is argued that the balance of the earth in the form of a tetrahedron while rotating on an apex cannot be maintained. Secondly, the earth is rotating so rapidly on its axis that the spherical earth cannot be converted into a tetrahedron while contracting on cooling. Thirdly, this hypothesis belives more or less in the permanency of continents and ocean basins while the plate tectonic theory has validated the concept of continental drift.

5.3 CONTINENTAL DRIFT THEORY OF TAYLOR

F.B. Taylor postulated his concept of 'horizontal displacement of the continents' in the year of 1908 but it could be published only in the year 1910. The main purpose of his hypothesis was to explain the problems of the origin of the folded mountains of tertiary period. Infact, F.B. Taylor wanted to solve the peculiar problem of the distributional pattern of tertiary folded mountains. The north-south arrange-

ment of the Rockies and the Andes of the western margins of the North and South Americas and west - east extent of the Apline mountains (Alps, Caucasus, Himalayas etc.) posed a serious problem before Taylor which needed careful explanation. He could not find any help from the **'contraction theory'** to explain the peculiar distribution of tertiary folded mountains and hence he propounded his **'drift or displacement theory'**. The concept of Taylor, thus, is considered to be first attempt in the field of continental drift though Antonio Snider presented his views about **'drift'** in the year 1858 in France. Main purpose behind the postulation of **'drift hypothesis'** of Snider was to explain the similarity of the fossils of the coal seams of carboniferous period in North America and Europe.

Taylor started from cretaceous period. According to him there were two land masses during cretaceous period. Lauratia and Gondwanaland were located near the north and south poles respectively. He further assumed that the continents were made of sial which was practically absent in the oceanic crust. According to Taylor continents moved towards the equator. The main driving force of the continental drift was tidal force. According to Taylor continents were displaced in two ways e.g. (i) equatorward movement and (ii) westward movement but the driving force responsible for both types of movement was tidal force of the moon.

Lauratia started moving away from the north pole because of enormous tidal force of the moon towards the equator in a radial manner. This movement of land mass resulted into tensional force near the north pole which caused stretching, splitting and rupture in the landmass. Consequently, Baffin Bay, Labrador Sea and Davis Strait were formed. Similarly, the displacement of the Gondwanaland from the south pole towards the equator caused splitting and disruption and hence the Gondwanaland was split into several parts. Consequently, Great Australian Bight and Ross Sea were formed around Antarctic Continent. Arctic sea was formed between Greenland and Siberia due to equatorward movement of Lauratia. Atlantic and Indian oceans were supposed to have been formed because of filling of gaps between the drifting continents with water. Taylor assumed that the landmasses began to move in lobe form while drifting through the zones of lesser resistance. Thus, mountains and island arcs were formed in the frontal part of the moving lobes. The Himalayas, Caucasus and Alps are considered to have been formed during equatorward movement of the Lauratia and Gondwanaland from the north and south poles respectively while the Rockies and Andes were formed due to westward movement of the landmasses.

Evaluation

Since F.B. Taylor's main aim was to explain the origin of the tertiary folded mountains and hence he made the continents to move at a very large scale. In fact, some sort of horizontal movement of the land masses was essential for the origin of mountains but the displacement of land masses upto 32-64 km would have been sufficient enough for the purpose. Contrary to this Taylor has described the displacement of the landmasses for thousands of kilometres. Secondly, the mode of drift as suggested by Taylor has also been erroneous. If the tidal force of the moon was so enormous during cretaceous period that it could displace the landmasses for thousands of kilometers apart then it might have also put a break on the rotatory motion of the earth and thus the rotation of the earth might have stopped within a year. According to A. Holmes neither tidal force nor any external force can drift the continents apart and can help in the formation of mountains. The responsible force must come from within the earth. Though the concept of F.B. Taylor is not acceptable but his hypothesis is considered to be significant on the ground that Taylor raised his voice very forcefully through deductive postulation against the prevalent concept of the permanency of the continents and ocean basins and forcefully objected to the **'contraction theory'** and showed a new direction to solve the problem of the origin of the continents and ocean basins. A. Holmes has rightly remarked, 'but Taylor must be given credit for making an independent and slightly an earlier start in this precarious field.'

5.4 CONTINENTAL DRIFT THEORY OF WEGENER

Aim of the Theory

Professor Alfred Wegener of Germany was primarily a meteorologist. He propounded his concept on continental drift in the year 1912 but it could

not come in light till 1922 when he elaborated his concept in a book entitled 'Die Entstehung der Kontinente and Ozeane' and his book was translated in English in 1924. Wegener's displacement hypothesis was based on the works and findings of a host of scientists such as geologists, palaeo-climatologists, palaeontologists, geophysicists and others. The main problem before Wegener, which needed explanation, was related to climatic changes. It may be pointed out that there are ample evidences which indicate widespread climatic changes throughout the past history of the earth. In fact, the continental drift theory of Wegener 'grew out of the need of explaining the major variations of climate in the past'. The climatic changes which have occurred on the globe may be explained in two ways.

(1) If the continents remained stationary at their places throughout geological history of the earth, the climatic zones might have shifted from one region to another region and thus a particular region might have experienced varying climatic conditions from time to time.

(2) If the climatic zones remained stationary the land masses might have been displaced and drifted.

Wegener opted for the second alternative as he rejected the view of the permanency of continents and ocean basins. Thus, the main objective of Wegener behind his **'displacement hypothesis'** was to explain the global climatic changes which are reported to have taken place during the past earth history.

Basic Premise of the Theory

Following Edward Suess, Wegener believed in three layers system of the earth e.g. outer layer of **'sial'**, intermediate layer of **'sima'** and the lower layer of **'nife'**. According to Wegener sial was considered to be limited to the continental masses alone whereas the ocean crust was represented by upper part of sima. Continents or sialic masses were floating on sima without any resistance offered by sima. He assumed, on the basis of evidences of palaeoclimatology, palaeontology, palaeobotany, geology and geophysics, that all the landmasses were united together in the form of one landmass, which he named **Pangaea**, in carboniferous period. There were several smaller inland seas scattered over the Pangaea which was surrounded by a huge water body, which was named by Wegener as **'Panthalasa'**, representing primeval Pacific Ocean. Lauratia consisting of present North America, Europe and Asia formed northern part of the Pangaea while Gondwanaland consisting of South America, Africa Madagascar (now Malagasy), Peninsular India, Australia and Antarctica represented the southern part of the Pangaea. South pole was located near present Durban (near Natal in southern Africa) during carboniferous period. Thus, Wegener's theory of continental drift begins from carboniferous period, he does not describe the conditions during pre-carboniferous times "but the postulation of a carboniferous Pangaea does not mean that he disbelieves in pre-carboniferous drift: events before this time are known with much less certainty, and the distribution of plants and animals can largely be explained by movements which have taken place since the carboniferous' (J.A. Steers, 1961, p. 160). The Pangaea was disrupted during subsequent periods and broken landmasses drifted away from each other and thus the present position of the continents and ocean basins became possible.

Evidences in Support of the Theory

Wegener has successfully attempted to prove the unification of all landmasses in the form of a single landmass, the Pangaea, during carboniferous period, on the basis of evidences gathered from geological, climatic and floral records. He claimed that all the present-day continents could be joined to form Pangaea. The following evidences support the concept of the existence of Pangaea during carboniferous period.

(1) According to Wegener there is geographical similarity along both the coasts of the Atlantic Ocean. Both the opposing coasts of the Atlantic can be fitted together in the same way as two cut off pieces of wood can be refitted (jig-saw fit) (fig. 4.3).

(2) Geological evidences denote that the Caledonian and Hercynian mountain systems of the western and eastern coastal areas of the Atlantic are similar and identical (fig. 5.4). The Applachians of the north-eastern regions of North America are compatible with the mountain systems of Ireland, Wales and north-western Europe.

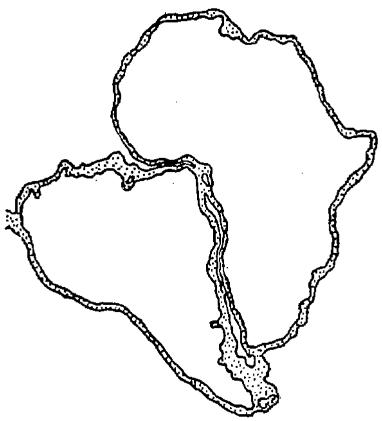


Fig. 5.3 : Jig-saw fitting (juxtaposition) of South America and Africa.

(3) Geologically, both the coasts of the Atlantic are also identical. Du Toit, after detailed study of the eastern coasts of South America and western coast of Africa, has said that the geological structures of both the coasts are more or less similar. According to Du Toit both the landmasses (i.e. South America and Africa) cannot be actually brought together but near to each other because a gap of 400-800 km would separate them due to the existence of continental shelves and slopes of these two landmasses.

(4) There is marked similarity in the fossils and vegetation remains found on the eastern coast of South America and the western coast of Africa.

(5) It has been reported from geodetic evidences that Greenland is drifting westward at the rate of 20 cm per year. The evidences of seafloor spreading after 1960 have confirmed the movement of landmasses with respect to each other.

(6) The lemmings (small sized animals) of the northern part of Scandinavia have a tendency to run westward when their population is enormously increased but they are foundered in the sea water due to absence of any land beyond Norwagian coast. This behaviour of lemmings proves the fact that the landmasses were united in the ancient times and the animals used to migrate to far off places in the western direction.

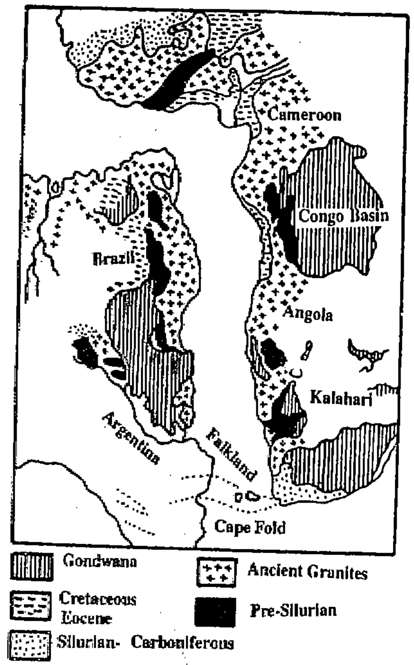


Fig. 5.4 : Geological similarity on the eastern coast of South America and the western coast of Africa.

(7) The distribution of glossopteris flora in India, South Africa, Australia, Antarctica, Falkland islands etc. proves the fact that all the landmasses were previously united and contiguous in the form of Pangaea.

(8) The evidences of carboniferous glaciation of Brazil, Falkland, South Africa, Peninsular India, Australia and Antarctica further prove the unification of all landmasses in one landmass (Pangaea) during carboniferous period.

Process of the Theory

As stated earlier the main aim of Wegener behind the postulation of his 'drift theory' was to explain major climatic changes which are reported to have taken place in the past geological history of the earth, such as carboniferous glaciation of major parts of the Gondwanaland. Besides, Wegener also attempted to solve other problems of the earth e.g. origin of mountains, island arcs and festoons, origin and evolution of continents and ocean basins etc.

(1) Force responsible for the drift—According to Wegener the continents after breaking away from the Panagaea moved (drifted) in two directions e.g. (i) equatorward movement and (ii) westward movement. The equatorward movement of sialic blocks (continental blocks) was caused by gravitational differential force and force of buoyancy. As already stated the continental blocks, according to Wegener, were formed of lighter sialic materials (silica and aluminium) and were floating without any friction on relatively denser 'sima'. Thus, the equatorward movement of the sialic blocks (continental blocks) would depend on the relation of the centre of gravity and the centre of buoyancy of the floating continental mass. Generally, these two types of forces operate in opposite directions. 'But because of the ellipsoidal form of the earth, these forces are not in direct opposition, but are so related that, if the buoyancy point lies under the centre of gravity, the resultant (force) is directed toward the equator' (J.A. Steers, 1961, p.164).

The westward movement of the continents was caused by the tidal force of the sun and the moon. According to Wegener the attractional force of the sun and the moon, which was maximum when the moon was nearest to the earth, dragged the outer sialic curst (continental blocks) over the interior of the earth, towards the west. It may be pointed out that in any drift theory the weakest point and the most difficult problem is related to the competent force responsible for the movement of the continents. 'Such a force (tidal force/attractional force of the sun and the moon) is extraordinarily small, but, as in the case of other forces, the question of time is all important: given sufficient time, it is claimed that even these very small forces are able to cause movements'. (J.A. Steers, 1961, p.164).

(2) Actual drifting of the continents—The disruption, rifting and ultimately drifting of the continental blocks began in carboniferous period. The movement of the continental blocks away from the poles was dramatically called by Wegener as **'the flight from the poles'.** Pangaea was broken into two parts due to differential gravitational force and the force of buoyancy. The northern part became **Lauratia (Angaraland)** while the southern part was called by Wegener as **Gondwanaland.** The intervening space between these two giant continental blocks was filled up with water and the resultant water body was called **Tethys Sea.** This phase of the disruption of Pangaea is called **'opening of tethys'.** Gondwanaland was disrupted during cretaceous period and Indian peninsula, Madagascar, Australia and Antarctica broke away from Pangaea and drifted apart under the impact of tidal force of the sun and the moon. North America broke away from Angaraland and drifted westward due to tidal force. Similarly, South America broke away from Africa and moved westward under the impact of tidal force. Due to northward movement of Indian Peninsula Indian Ocean was formed while the Atlantic Ocean was formed due to westward movement of two Americas. It may be mentioned that North and South Americas were drifting westward at different rates and hence 'S' shape of the Atlantic Ocean could be possible. Arctic and North Sea were formed due to flight of the continental blocks from north pole. The size of the **panthalasa** (primitive Pacific Ocean) was remarkably reduced because of the movement of continental blocks from all sides towards Panthalasa. Thus, the remaining portion of Panthalasa became the Pacific Ocean. It may be mentioned that disruption, rifting and displacement (drifting) of continental blocks continued from carboniferous period to pliocene period when the present pattern and arrangement of the continents and ocean basins was attained (fig. 5.5). There have been frequent changes in the positions of the equator and the poles as given in table 5.1.

Table 5.1 : Shifting of the Positions of the Poles

Period	North Pole	South Pole
Silurian	14^0N latitude 124^0W longitude	to the north-west of Madagascar
Carboniferous	16^0N latitude 147^0W longitude	near Durban in Natal
Tertiary	51^0N latitude 153^0W longitude	near 53^0S latitude to the south of Africa

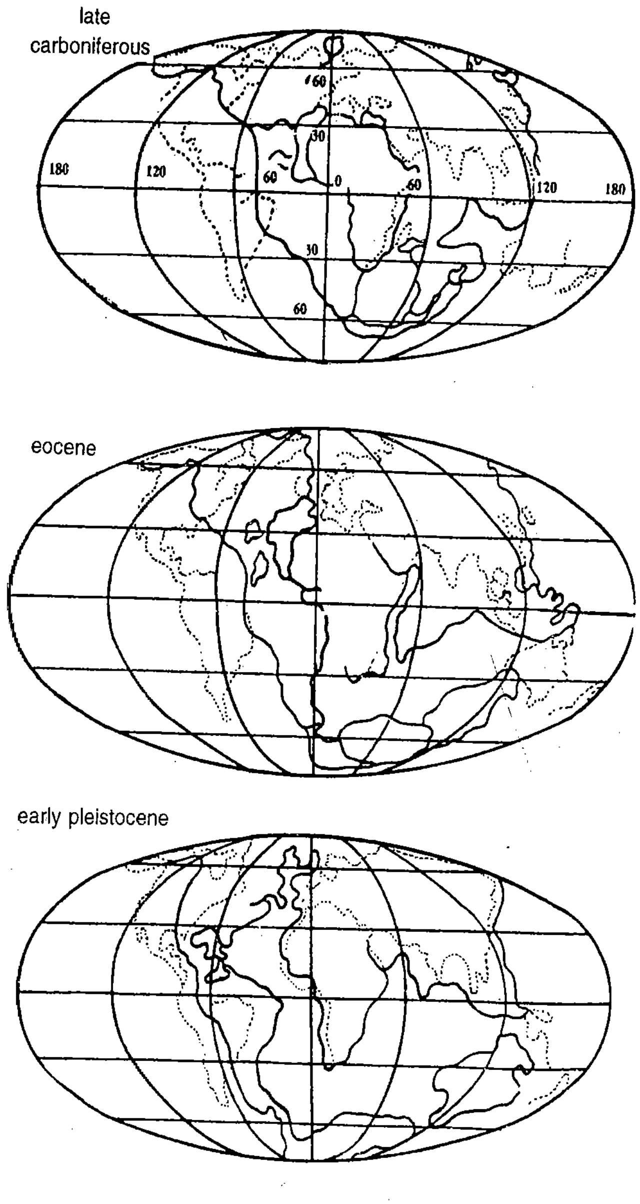


Fig. 5.5 : Disruption of Pangaea and drifting of continents. The dotted lines denote the present position of contine and ocean basins.

Equator was located at the most northerly location during silurian period as it passed north of Norway. It passed through London during carboniferous period and through present locations of the European Alpine mountains during tertiary period (fig. 5.6.). 'The south pole and equator obviously moved into accordant positions. The prevailing westward and equatorward movement must be referred to these positions' (J.A. Steers, 1961, p.166).

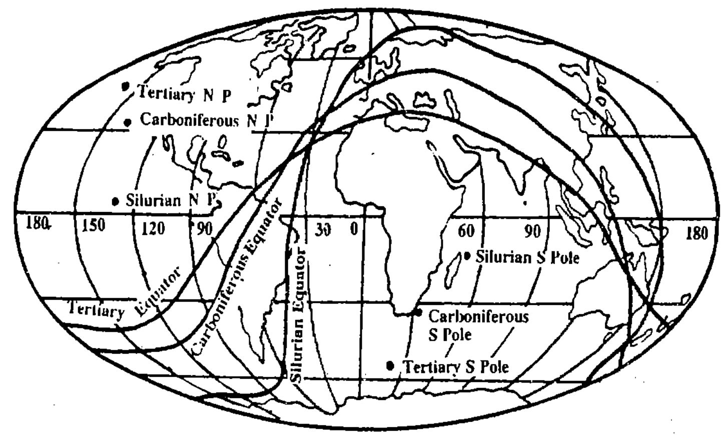


Fig. 5.6 : Different positions of Poles and Equator.

(3) **Mountain building-** A.G. Wegener also attempted to solve the problem of the origin of folded mountains of tertiary period on the basis of his continental drift theory. The frontal edges of westward drifting continental blocks of North and South Americas were crumpled and folded against the resistance of the rocks of the sea-floor (sima) and thus the western cordilleras of the two Americas (*e.g.* Rockies and Andes and other mountain chains associated with them) were formed. Similarly, the Alpine ranges of Eurasia were folded due to equatorward movement of Eurasia and Africa together with Peninsular India (equator was passing through Tethys sea at that time). Here, Wegener postulated contrasting view points. According to Wegener sial (continental blocks) was floating upon sima without any friction and resistance but during the later part of his theory he pointed out that mountains were formed at the frontal edges of floating and drifting continental blocks (sialic crust) due to friction and resistance offered by sima. How could it be possible? The question remains unanswered. Inspite of this serious flaw in the continental drift theory of Wegener, S.W. Wooldridge and R.S. Morgan have remarked, 'certainly the problem of mountain building is one in which the hypothesis of continental drift solves more difficulties than it creates.'

(4) **Origin of island arcs**—Wegener has related the process of the origin of island arcs and festoons (of eastern Asia, West Indies and the arc of the southern Antilles between Tierra del Fugo and Antarctica) to the differential rates of continental drift. When the Asiatic block (part of Angaraland) was moving westward, the eastern margin of this block could not keep pace with the westward moving major landmass, rather lagged behind, consequently the island arcs and festoons consisting of Sakhalin, Kurile, Japan, Phillippines etc. were formed. Similarly, some portions of North and South Americas, while they were moving westward, were left behind and the island arcs of West Indies and southern Antilles were formed.

(5) **Carboniferous glaciation**—There are ample evidences to demonstrate that there was large-scale glaciation during carboniferous period when Brazil, Falkland, Southern Africa, Peninsular India, Australia, Antarctica etc. were extensively glaciated. According to Wegener all the continental blocks were united together in the form of one land mass called as Pangaea. South pole was located near the present position of Durban in Natal. Thus, south pole was located in the middle of Pangaea. Consequently, ice sheets might have spread from south pole outward at the time of glaciation and the aforesaid land areas, which were closer to south pole, might have been covered with thick ice sheets. At much later date, these land areas might have parted away due to disruption of Pangaea and related continental drift. Glossopteris flora might have also been distributed over the aforesaid areas when these were united together.

Evaluation of the Theory

It may be pointed out that Wegener's continental drift theory widely departed from the contemporary orthodox geological ideas of the nineteenth century and the time-honoured thermal contraction theory of the mountain building and thus it was obvious that the believers of contraction theory should also discard it. 'It is now widely agreed that he (Wegener) handled his case as an advocate rather than as an impartial scientific observer, appearing to ignore evidences unfavourable to his ideas and distort other evidences in harmony with the theory' (S.W. Wooldridge and R.S. Morgan, 1959, p. 40). The critics of Wegener's continental drift theory fall in two broad categories *e.g.* (i) the crictics and writers who always attempted to search errors and discrepancies in Wegener's original synthesis and (ii) the scientists who attempted to modify, enlarge and correct the original theory of Wegener while retaining its basic tenet. The following flaws and defects have been pointed out by different scientists in Wegener's theory of the continental drift.

(1) The forces applied by Wegener (differential gravitational force and the force of buoyancy and tidal force of the sun and the moon) are not sufficient enough to drift the continents so apart. 'The tidal force as invoked by Wegener to account for the supposed westerly drift of the continents would need to be 10,000 million times as powerful as it is at present to produce the required effects, and, if it had such a value, it would stop the earth's rotation completely in a year' (S.W. Wooldridge and R.S. Morgan, 1959, p.40). Similarly, the differential gravitational force and the force of buoyancy are also not adequate to cause equatorward movement of the continents, instead the force, if so enormous, might have caused the concentration of the continents near the equator.

(2) Wegener has described several contrasting view points. Initially, sialic masses (continents) were considered by Wegener as freely floating over **'sima'** without any friction offered by **'sima'** but in later part of his theory he has described forceful resistance of offered by 'sima' in the free movement of sialic continents to explain the origin of mountains along the frontal edges of floating continents. Moreover, 'it is difficult to show how the sial blocks, in their passage through the sima, would crumple at their frontal edges and produce mountains' (J.A. Steers, 1961, p. 165). According to Willis no compression could be possible to form the Rockies and the Andes if the 'sima' is more rigid than the 'sial'. Bowie has maintained that sima has no strength to crumple sial to form mountains.

(3) Both the coasts of the Atlantic Ocean cannot be completely refitted. Thus, the concept of juxtaposition' or 'jig-saw fit' cannot be validated.

(4) Wegener has not elaborated the direction and chronological sequence of the displacement of the continents. He did not describe the situations of pre-carboniferous times. Many questions remain unanswered such as, What kept Pangaea together till its disruption in mesozoic era? Why did the process of continental drift not start before mesozoic era? etc. Some writers argue that 'it is not a fair criticism to say that any pre-carboniferous mountain building cannot be explained on Wegener's hypothesis merely because he does not develop his scheme in earlier geological times' (J.A. Steers, 1961, pp. 161-162).

It may be concluded that 'even if all the matter of his theory is wrong, geologists and others can but remember that it is largely to him that we owe our more recent views on world tectonics' (J.A. Steers, 1961, p. 174). Though most point of Wegener's theory was rejected but its central theme of horizon-

tal displacement was retained. In fact, the postulation of plate tectonic theory after 1960 is the result of this continental drift theory of Wegener. Wegener is, thus, given credit to have started thinking in this precarious field.

5.5 PLATE TECTONIC THEORY

The rigid lithospheric slabs or rigid and solid crustal layers are technically called **'plates'**. The whole mechanism of the evolution, nature and motion of plates and resultant reactions is called **'plate tectonics'**. In other words, the whole process of plate motions is referred to as plate tectonics. 'Moving over the weak asthenosphere, individual lithospheric plates glide slowly over the surface of the globe; much as a pack of ice of the Arctic Ocean drifts under the dragging force of currents and winds' (A.N. Strahler and A.H. Strahler, 1978, p. 373). Plate tectonic theory, a great scientific achievement of the decade of 1960s, is based on two major scientific concepts *e.g.* (i) the concept of continental drift and (ii) the concept of sea-floor spreading. Lithosphere is internally made of rigid plates (fig. 5.7). Six major and 20 minor plates have been indentified so far (Eurasian plate, Indian-Australian plate, American plate, Pacific plate, African plate and Antarctic plate).

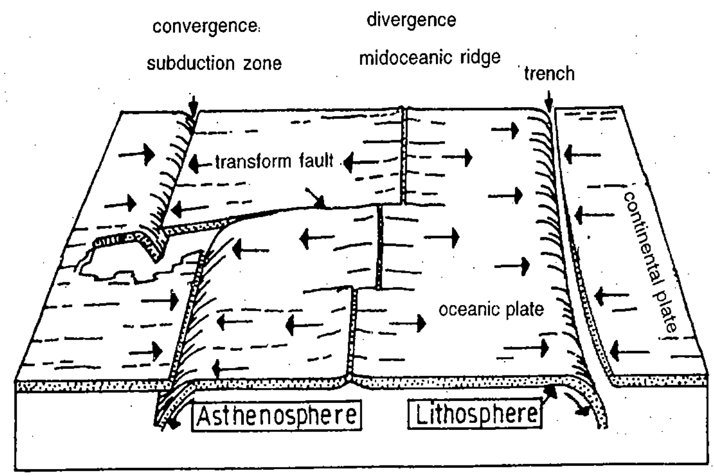


Fig. 5.7 : Diagramatic presentation of main aspects of plate tectonics (based on A.N. Strahler 1971).

It may be mentioned that the term 'plate' was first used by Canadian geophysicist J.T. Wilson in 1965. Mckenzie and Parker discussed in detail the mechanism of plate motions on the basis of Euler's geometrical theorem in 1967. They postulated **'a paving stone'** hypothesis wherein the oceanic crust was considered to be newly formed at mid-oceanic ridges and destroyed at the trenches. Isacks and Sykes confirmed the 'paving stone hypothesis' in 1967. W.J. Morgan and Le Pichon elaborated the various aspects of plate tectonics in 1968. Now the continental drift and displacement are considered a reality on the basis of plate tectonics.

It may be highlighted that tectonically plate boundaries or plate margins are most important because all tectonic activities occur along the plate margins *e.g.* seismic events, vulcanicity, mountain building, faulting etc. Thus, the detailed study of plate margins is not only desirable but is also necessary. Plate margins are generally divided into three groups, as follows:

(1) **Constructive plate margins** are also called as **'divergent plate margins'** or **'accreting plate mar-**

gins'. Constructive plate margins (boundaries) represent zones of divergence where there is continuous upwelling of molten material (lava) and thus new oceanic crust is continuously formed. In fact, oceanic plates split apart along the mid-oceanic ridges and move in opposite directions (fig. 5.8).

(2) **Destructive plate margins** are also called as **'consuming plate margins'** or **'convergent plate margins'** because two plates move towards each other or two plates converge along a line and leading edge of one plate overrides the other plate and the overridden plate is subducted or thrust into the mantle and thus part of crust (plate) is lost in the mantle (fig. 5.8).

(3) **Conservative plate margins** are also called as shear plate margins. Here two plates pass or slide past one another along transform faults and thus crust is neither created nor destroyed.

H. Hess prostulated the concept of 'plate tectonics' in 1960 in support of continental drift. The continents and oceans move with the movement of these plates. The present shape and arrangement of the continents and ocean basins could be attained because of continuous relative movement of different plates of the second Pangaea since carboniferous period. Plate tectonic theory is based on the evidences of (1) sea-floor spreading and (ii) palaeomagnetism.

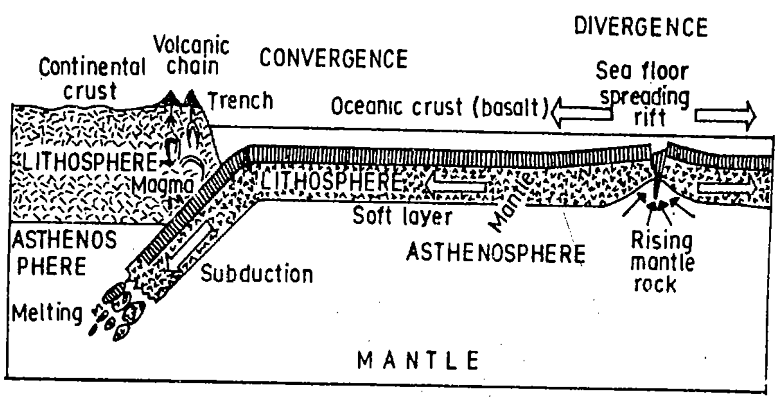


Fig. 5.8 : Diagramatic presentation of different types of plate margins.

Sea-Floor Spreading

The concept of sea floor spreading was first propounded by professor Hary Hess of the Princeton University in the year 1960. His concept was based on the research findings of numerous marine geologists, geochemists and geophysicists. Mason of the Scripps Institute of Oceanography obtained significant information about the magnetism of the rocks of sea-floor of the Pacific Ocean with the help of magnetometer. Later on he surveyed a long stretch of the sea-floor of the Pacific Ocean from Mexico to British Columbia along the western coast of North America. When the data of magnetic anomalies obtained during the aforesaid survey were displayed on a chart, there emerged well defined patterns of stripes (fig. 5.9). Based on these information Hary Hess propounded that the mid-oceanic ridges were situated on the rising thermal convection currents coming up form the mantle (fig. 5.10). The oceanic crust moves in opposite directions from mid-oceanic ridges and thus there is continuous upwelling of new molten materials (lavas) along the mid-oceanic ridges. These molten lavas cool down and solidify to form new crust along the trailing ends of divergent plates (oceanic crust). Thus, there is continuous creation of new crust along the mid-oceanic ridges. This, according to Hess, proves the fact that sea-floor spreads along the mid-oceanic ridges and the

expanding crusts (plates) are destroyed along the oceanic trenches. These facts prove that the continents and ocean basins are in constant motion.

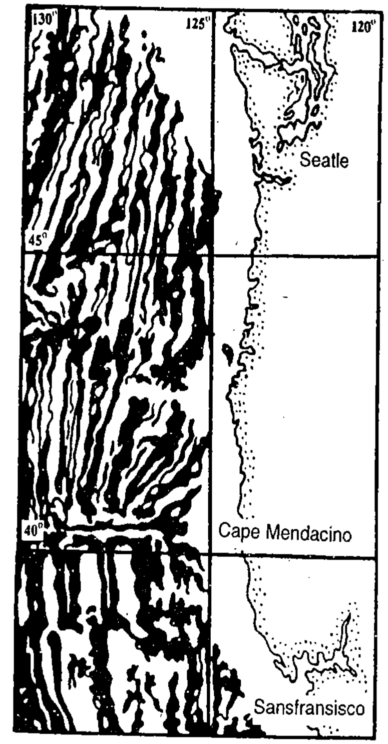


Fig. 5.9 : Patterns of positive magnetic anomalies off the coast of Sanfransisco.

W.G. Vine and Mattheus conducted the magnetic survey of the central part of Carlsberg Ridge in Indian Ocean in 1963 and computed the magnetic profiles on the basis of general magnetism. When he compared the computed magnetic profiles with the profiles of magnetic anomalies plotted on the basis of actual data obtained during the survey, he found sizeable difference between the two profiles. When he plotted the magnetic profiles on the basis of alternate bands of normal and reverse magnetism in separate stripes of 20 km width on either side of the ridge, he found complete parallelism between the computed profiles and observed profites.

Vine and Mattheus have opined on the basis of the evidences of temporal reversal in the geomagnetic filed and the concept of sea-floor spreading as propounded by Deitz and Hess that when molten hot lavas come up with the rising thermal convection current along the mid-oceanic ridges and get cooled and solidified, these (lavas) also get magnetized, at the same time, in accordance with the then geomagnetic field and thus alternate bands or stripes of magnetic anomalies are formed on either side of the mid-oceanic ridge. In other words, when molten lavas are upwelled along the mid-oceanic ridges, these divide the earlier basaltic layer into two equal halves and these basaltic layers slide horizontally on either side of the mid-oceanic ridges. The findings of Cox, Doell and Dalrympal (1964), Opdyke (1966) and Heritzler (1966) have validated the following facts-(i) there is reversal in the main magnetic field of the earth (known as geocentric dipole magnetic field), (ii) normal and reverse magnetic

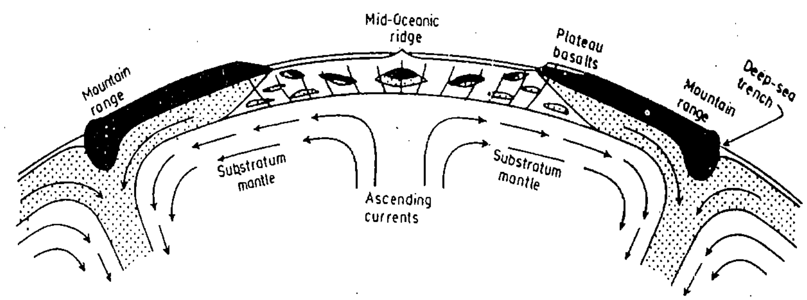


Fig. 5.10 : Pattern of thermal convective currents and plate movements.

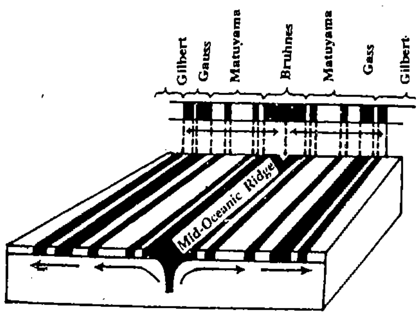


Fig. 5.11: Diagramatic presentation of magnetic stripes on either side of the mid-oceanic ridge according to Vine and Matheus. The periods of the formation of these stripes have been named after known scientists (e.g. Gillbert, Gass, Matuyama and Bruhnes).

anomalies are found in alternate manner on either side of the mid-oceanic ridges, (iii) there is complete parallelism in the magnetic anomalies on either side of the mid-oceanic ridges and (iv) there is parallelism in the time sequence of palaeomagnetic epochs and events calculated for 4.5 million years on the basis of magnetism of basaltic rocks or sedimentary rocks. Fig. 5.11 depicts the position of magnetic stripes on either side of the mid-oceanic ridge along with the time-scale of their formation.

It may be concluded, on the basis of above discussion, that there is continuous spreading of sea-floor. New basaltic crust is continuously formed along the mid-oceanic ridges. The newly formed basaltic layer is divided into two equal halves and is thus displaced away from the mid-oceanic ridge. Alternate stripes of positive and negative magnetic anomalies are found on either side of the mid-oceanic ridges. Such magnetic anomalies (postive and negative) are formed because of temporal reversal in the geomagnetic field. The rocks formed during normal magnetic field contain positive magnetic anomalies while the rocks formed during reverse polarity (reversed geomagnetic field) denote negative magnetic anomalies.

The age of magnetic stripes, the rate of sea floor spreading and the time of drifting of different continents are calculated on the basis of above facts. The dating of the magnetic stripes formed upto 4.5 million years before present has been completed on the basis of information obtained from the survey of palaeomagnetism of the sea floors of different oceans. The rate of sea floor spreading is calculated on two bases *e.g.* (i) on the basis of the age of isochrons (isochrons are those lines which join the points of equal dates of the magnetic stripes plotted on the map) and (ii) on the basis of distance between two isochrons. Thus, the rates of spreading (drifting) of different oceans have been determined on the basis of above principles. The Atlantic and Indian Oceans are spreading (expanding) very sluggishly i.e. at the rate of 1.0 to 1.5 cm per year while the Pacific Ocean is expanding at the rate of 6.0 cm per year. It may be pointed out that the rate of seafloor spreading always means the rate of expansion only on one side of the mid-oceanic ridge. For example, if the rate of sea-floor is reported to be 1.0 cm per year, the total spreading of the concerned ocean would be 1+1=2 cm per year. The recent studies have shown that (i) the maximum spreading of the Pacific Ocean is 6 to 9 cm per year (total expansion 12 to 18 cm/year) along the eastern Pacific ridge between equator and 30°S latitude, (ii) the southern Atlantic ocean is spreading along the southern Atlantic ridge at the rate of 2 cm per year (total expansion 4 cm/year) and (iii) the Indian Ocean is expanding at the rate of 1.5 to 3 cm per year (total expansion being 3 to 6 cm/year).

Plate Tectonics and Continental Displacement

On the basis of the evidence of palaeomagnetism and sea floor spreading it has been now validated that the continents and ocean basins have never been stationary or permanent at their places rather these have always been mobile throughout the geological history of the earth and they are still moving in relation to each other. The scientists have discovered ample evidences to demonstrate the opening and closing of ocean basins. For example, the Mediterranean sea is the residual of once very vast ocean (Tethys sea) and the Pacific Ocean is continuously contracting because of gradual subduction of American plate along its ridge. On the other hand the Atlantic Ocean is continuously expanding for the last 200 million years. Red Sea has started to open (to

expand). It may be mentioned that continental masses come closer to each other when the oceans begin to close while continents are displaced away when the oceans begin to open (expand).

Though the sequence of events of continental displacement based on the evidences of palaeomagnetism and sea floor spreading is available only for the last 200 million years but on the basis of general mechanism of plate tectonics and the evidence from the continents the sequence of earlier events may be reconstructed. Valentine and Moors (1970) and Hallam (1972) have attempted to reconstruct the chronological sequence of the conti-

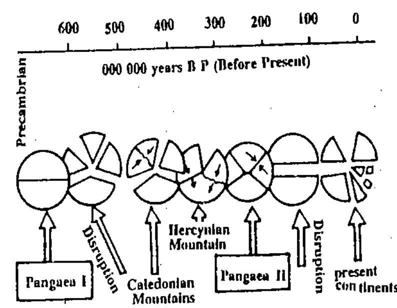


Fig. 5.12 : The probable pattern of continental movement during the last 700 million years (based on Valentine and Moors. 1970)

nents and ocean basins from the beginning to the present time. About 700 million years ago all the landmasses were united together in the form of one single giant landmass known as **Pangaea I**. About 600-500 million years before present first Pangaea was broken because of thermal convective currents coming from within the earth, most probably from the mantle and different landmasses drifted apart. These landmasses were again united together due to plate motions in one land mass known as **Pangaea II** about 300-200 million years before present. According to A. Hallam Second Pangea began to break during early Jurassic period and N.W. Africa broke away from N. America and drifted away. The zone of sea floor spreading continued to extend

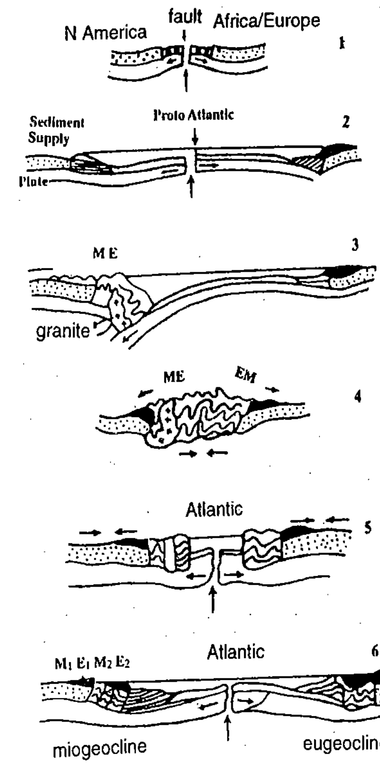


Fig. 5.13 : Evolutionary history of the Atlantic Ocean during the past 700 million years. 1. Formation of new ocean basins 700 million years ago. 2. Deposition of miogeocline and eugeocline on the margins about 500 million years ago. 3. Closing of the Atlantic Ocean and the formation of part of the Applachians due to convergence of Eurasian and American plates about 400 million years ago. 4. Atlantic closed completely and the formation of the Applachians of North America and Hercynian mountains of Europe was completed about 300 million years ago. 5. Reopening of the Atlantic due to plate motion about 150 million years ago. 6. Present situation, beginning of the formation of new geosynclines (after Dietz, 1973).

towards north and south. The separation of South America and Africa was accomplished during middle cretaceous period, and North America and Europe began to move away from each other (Fig.5.12).

The opening of North Atlantic was accomplished in many phases. After the separation of North America from Africa, Europe and Greenland broke away from Labrador during late cretaceous period (about 80 million years before present) and thus Labrador sea was formed. This newly formed sea continued to remain for some time as northern extension of the Atlantic Ocean. Rockall plateau was separated from Greenland during Tertiary period (about 60 million years before present). Labrador Sea and North Atlantic continued to expand

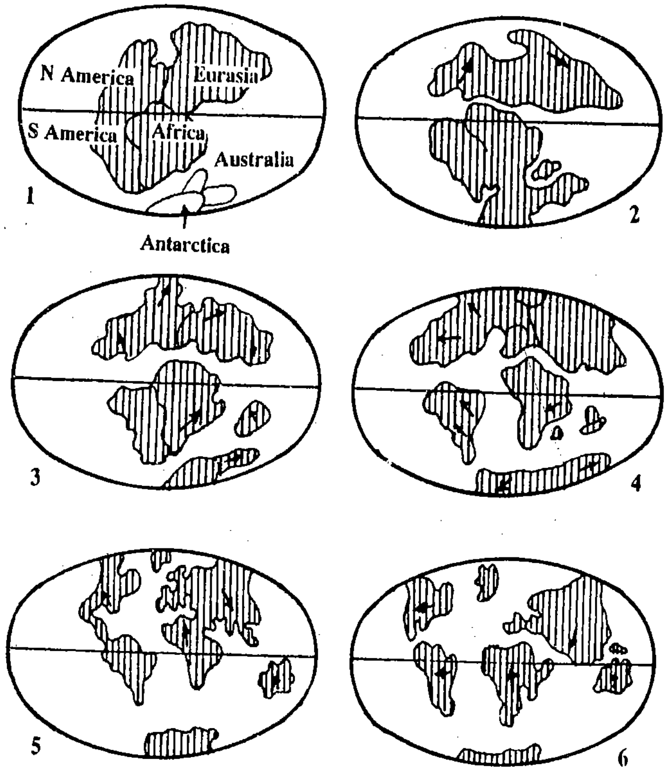


Fig. 5.14 : The evolution of the continents and ocean basins on the basis of plate tectonics since Triassic period and the probable future pattern of events upto 50 million years hence. 1. Triassic period, 200 million years ago, 2. Late Triassic period, 180 million years ago, 3. Late Jurassic period, 135 million years ago, 4. Late Cretaceous period, 65 million years ago, 5. Present position and 6.50 million years hence. Arrows indicate the directions of movement of the continents (after Dietz and Holden, 1973).

between Europe and Greenland upto middle miocene period because the European and American plates continued to move eastward and westward respectively. The spreading of Labrador Sea stopped by middle miocene period (about 47 million years before present) but North Atlantic continued to expand.

Indian Ocean did not exist before cretaceous period. Indian plate began to move towards Asiatic plate through 'Tethys Sea' and Australian-Antarctic plates after breaking away from African plate began to move southward during cretaceous period. Dan Mackenzie and John Sclater have presented the chronological sequence of the evolution of Indian Ocean on the basis of the study of magnetic anomalies. According to them Indian plate began to move northward at the rate of 18 cm per year during early tertiary period but the movement stopped during eocene period. The same time Antarctica broke away from Australia. Thus, the Pacific Ocean began to shrink in size because of expansion of the Atlantic and Indian Oceans. Fig. 5.13 depicts the

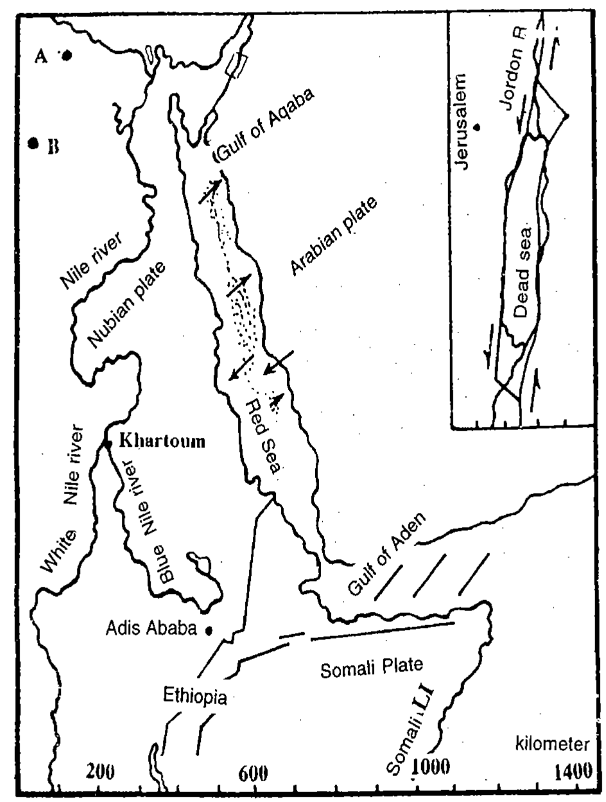


Fig. 5.15 : Diagramatic presentation of the separation of Africa and Arabia due to spreading of Red Sea and Gulf of Aden. Arrows indicate directions of the movement of the plates and spreading of Red Sea and Gulf of Aden. A and B denote the poles of rotation (after A.M. Quennel, 1958).

chronological events of the Atlantic Ocean during past 700 million years. The Atlantic Ocean began to open about 700 million years before present because of breaking of **First Pangaea** when the American and Africa-European plates began to move in divergent directions and thus the Atlantic continued to expand till 400 million years before present when the Atlantic again began to close. Because of the closing of the Atlantic Ocean Applachian mountains of North America were formed. The Atlantic Ocean again began to open up about 150 million years before present when **Second Pangaea** was broken into several landmasses and it still continues to expand because of the movement of American and European plates in opposite directions. It may be pointed out that the Atlantic Ocean is continuously expanding for the past 200 million years but the Pacific Ocean is contracting in size because of westward movement of the Pacific Ocean. Fig. 5.14 depicts the probable situation of the continents and ocean basins during 50 million years hence.

The following examples demonstrate the trends and patterns of continental displacement, sea-floor spreading and contraction in the size of the oceans.

Red Sea and the Gulf of Aden—Red Sea is an example of axial trough which is located between Africa and Arabian peninsula (fig. 5.15). The surveyed magnetic anomalies in this area show, as observed by A.W. Girdler, the pattern of stripes and these are similar to the magnetic anomalies of the ocean basins. F.J. Vine calculated the rate of the spreading of Red Sea on the basis of the data of magnetic anomalies in the year 1966. According to him the Red Sea is spreading at the rate of one centimeter per year (total spreading 2 cm/year) since the past 3-4 million years. Alen and Morelli calculated the spreading rate in 1969 as 1.1 cm/year (total spreading 2.2 cm/year). Similarly, the rate of spreading of the Gulf of Aden has been calculated on the basis of stripped magnetic anomalies as 0.9 to 1.1 cm/year (total spreading 1.8 to 2.2 cm/year). The Red Sea and the Gulf of Aden are located at the junction of three plates viz. Nubian plate, Somali plate and Arabian plate. Nubian and Somali plates are separated by Ethiopian fault. Fig. 5.15 denotes the location of Red Sea, Gulf of Aden, Arabian, Nubian and Somali plates and the pole of rotation.

Gulf of California—The Pacific Ocean is a waning ocean because it is continuously being contracted in its size because of gradual encroachment of westward moving American plates. It is believed that like mid-Atlantic ridge there might have been a mid-oceanic ridge in the Pacific Ocean but it has now been remarkably deformed due to plate movement. The magnetic survey of the Gulf of California revealed the presence of stripped magnetic anomaly. This situation validates two facts viz. (i) East Pacific Rise (ridge) is also located in the Gulf of California and there has been continuous spreading of the gulf along the ridge since the past four million years and (ii) Baja, the Californian peninsula, was previously united with the mainland of North America but later on it broke away from the continent due to spreading of sea floor.

Evaluation

It is commonly agreed by the majority of the scientists that plate tectonics has validated the concept of continental drift, rather continental drift has now become a reality. The only point of argument and question is related to the competent force responsible for the drifting of the continents. Most of the scientists still rely on the thermal convective currents coming from the mantle as the probable adequate force to move the plates (continents) in different directions.

6

THEORY OF ISOSTASY

6.1 INTRODUCTION

Different relief features of varying magnitudes *e.g.* mountains, plateaux, plains, lakes, seas and oceans, faults and rift valleys etc. standing on the earth's surface are probably balanced by certain difinite principle, otherwise these would have not been maintained in their present form. Whenever this balance is disturbed, there start violent earth movements and tectonic events. Thus, 'isostasy simply means a mechanical stability between the upstanding parts and lowlying basins on a rotating earth'.

The word isostasy, derived from a German word 'isostasios' (meaning thereby 'in equipoise'), was first proposed by American geologist Dutton in 1859 to express his view to indicate 'the state of balance which he thought must exist between large upstanding areas of the earth's surface, mountain ranges and plateaux, and contiguous lowlands, etc.' (S.W. Wooldridge and R.S. Morgan, 1959). According to Dutton the upstanding parts of the earth (mountains, plateaux, plains and ocean basins) must be compensated by lighter rock material from beneath so that the crustal reliefs should remain in mechanical stability. According to J.A. Steers (1961) 'this doctrine states that wherever equilibrium exists on the earth's surface, equal mass must underlie equal surface areas'.

6.2 DISCOVERY OF THE CONCEPT

Though the concept of isostasy came in the mind of geologists all of sudden but its concept grew out of gradual thinking in terms of gravitational attraction of giant mountainous masses. Pierre Bouguer during his expedition of the Andes in 1735 found that the towering volcanic peak of Chimborazo was not attracting the plumb line as it should have done. He thus maintained that the gravitational attraction of the Andes 'is much smaller than that to be expected from the mass represented by these mountains'. Similar discrepancies were noted during the geodetic survey of the Indo-Gangetic plain for the determination of latitudes under the supervision of Sir George Everest, the then Surveyor General of India, in 1859. The difference of latitude of Kalianpur and Kaliana (603 km due northward) was determined by both direct triangulation method and astronomical method. Kaliana was only 96 km away from the Himalayas. The difference between two results amounted to 5.23 seconds as given below-

Result obtained through triangulation	$= 5^0\ 23'\ 42.294''$
Result obtained through astronomical method	$= 5^0\ 23'\ 37.058''$
difference	$= 5.236''$

This discrepancy between two methods was attributed to the attraction of the Himalayas due to which the plumb bob used in the astronomical determination of latitude was deflected.

This interpretation, thus, brought the fact before the scientists that the enormous mass of the Himalayas was responsible, through its attractional force, for the difference in the results of two methods. Later on the matter was referred to Archdeacon Pratt for further investigation and clarification. He attempted to estimate the amount of attraction of the Himalayas on the basic assumption that all the mountains had the average denisity of 2.75. Thus, Pratt based on minimum estimate of the mass of the Himalayas calculated the gravitational effects on the plum-bob at two places (Kaliana and Kalianpur) and to his dismay he discovered that the difference was surprisingly more than actually worked out during the survey.

Gravitational deflection at Kaliana = 27.853"

Gravitational deflection at Kalianpur = 11.968"

difference = 15.885"

Thus, the difference of 15.885" was infact more than 3 times the observed deflection of 5.236" during the survey. Pratt's calculation of the difference of the gravitational deflections brought another fact before the scientists that the Himalaya was not exerting the attraction according to its enormous mass. This interpretation gave birth to another problem-what is reason behind low attractional force of the Himalayas? The following explanations were offered for this question.

(1) The Himalayas are hollow and are composed of bubbles and not the rocks. Due to this fact the weight and denisity of the Himalayas would be low and thus their gravitational force would also be low. This was the reason for the difference in the results of two locations as referred to above. This explanation cannot be accepted because such a high mountain, if composed of bubbles, cannot stand on the earth's surface.

(2) If the mountains are not hollow, the visible mountain mass must be compensated by defficiency of mass from below. In other words, the density of the rocks of the mountains 'must be relatively low down to considerable depth.' Thus, the total weight would be low and consequently the attractional force would also be low.

(3) The rocks of the Himalayas are of low density in themselves and thus their attraction is also low.

(4) It was suggested 'that there is such a level below the surface of the earth below which there is no change in the density of the rocks', density varies only above this level. Thus, all columns have equal mass along this level. It was therefore suggested on this basis that *'bigger the column, lesser the density, and smaller the column, greater the density'.*

Thus, the debate on the discrepancies of the gravitational deflections of the plumb line and numerous explanations for these discrepancies resulted into the postulation of the concept of isostasy by different scientists, the views of a few of them are presented below-

6.3 CONCETP OF SIR GEORGE AIRY

According to Airy the inner part of the mountains cannot be hollow, rather the excess weight of the mountains is compensated (balanced) by lighter materials below. According to him the crust of relatively lighter material is floating in the substratum of denser material. In other words, 'sial' is floating in 'sima'. Thus, the Himalayas are floating in denser glassy magma. According to Airy 'the great mass of the Himalayas was not only a surface phenomenon : the lighter rocks of which they are composed do not merely rest on the level surface of denser material beneath, but, as a boat in water, sink into the denser material' (J.A. Steers, 1961). In other words, the Himalayas are floating in the denser magma with their maximum portion sunk in the magma in the same way as a boat floats in water with its maximum part sunk in the water. This concept in fact involves the principle to floation. For example, an iceberg floats in water in such a way that for every one part to be above water level, nine parts of the iceberg remain below water level. If we assume the average density of the crust and the substratum to be 2.67 and 3.0 respectively, for every one part of the crust to remain above the substratum, nine parts of the crust must be in the substratum. In other words, the law of floatation demands that 'the ratio of

freeboard to draught is 1 to 9.' It may be pointed out that Airy did not mention the example of the floation of iceberg. He simply maintained that the crustal parts (landmasses) were floating, like a boat, in the magma of the substratum.

It we apply the law of floatation, as stated above, in the case of the concept of Airy, then we have to assume that for the 8848m height of the Himalaya there must be a root, 9 times more in length than the height of the Himalaya, in the substratum. Thus, for 8848 m part of the Himalaya above, there must be downward projection of lighter material beneath the mountain reaching a depth of 79,632m (roughly 80,000 m).

Joly applied the principle of floation for the crust of the earth taking the freeboard to draught ratio as 1 to 8. According to him 'for every emergent part of the crust above the upper level of the substratum there are eight parts submerged' (J.A. Steers, 1961). If we apply Joly's view of floation to the concept of Airy, there would be downward projection of the Himalaya upto a depth of 70,784m (8848m x 8) in the substratum.

Thus, according to Airy the Himalayas were exerting their real attractional force because there existed a long root of lighter material in the substratum which compensated the material above. Based on above observation Airy postulated that 'if the land column above the substratum is larger, its greater part would be submerged in the substratum and if the land column is lower, its smaller part would be submerged in the substratum.' According to Airy the density of different columns of the land (*e.g.* mountains, plateaux, plains etc.) remains the same. In other words, density does not change with depth, that is, **'uniform density with varying thickness.'**

This means that the continents are made of rocks having uniform density but their thickness or length varies from place to place. In order to prove this concept Airy took several pieces of iron of varying lengths and put them in a basin full of mercury. These pieces of iron sunk upto varying depths depending on their lengths. The same pattern may be demonstrated by taking wooden pieces of varying lengths. If put into the basin of water these would sink in the water according to their lengths (fig. 6.1).

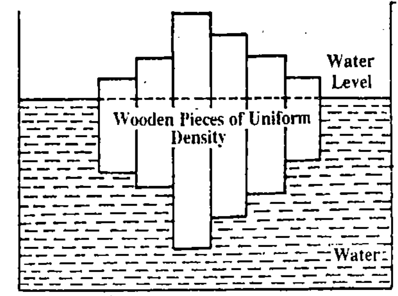


Fig. 6.1 : Illustration of the concept of Airy on isostasy.

Though the concept of Sir George Airy commands great respect among the scientific community but it also suffers from certain defects and errors. If we accept the Airy's views of isostasy, then every upstanding part must have a root below in accordance with its height. Thus, the Himalayas would have a root equivalent to 79,632m (if we accept the freeboard to draught ratio as 1 to 9) or 70,784m (if the freeboard to draught ratio is taken as 1 to 8). It would be wrong to assume that the Himalaya would have a downward projection of root of lighter material beneath the mountain reaching such a great depth of 79,634m or 70,784m because such a long root, even if accepted, would melt due to very high temperature prevailing there, as temperature increases with increasing depth at the rate of 1^0c per 32m.

"Quite recently, however, the fundamental concept of Airy, the continental masses floating as lighter (sial) blocks in a heavier (sima) substratum, has been rejuvenated, largely through the influence of Heiskanen's work, so that is now probably true to say that most geologists favour Airy's explanation' (J.A. Steers, 1961, p. 75).

6.4 CONCEPT OF ARCHDEACON PRATT

While studying the difference of gravitational deflection of 5.236 seconds during the geodetic survey of Kaliana and Kalianpur Archdeacon Pratt calculated the gravitational force of the Himalaya after taking the average density of the Himalaya as 2.75 and came to know that the difference should have been 15.885 seconds. He, then, studied the

rocks (and their densities) of the Himalaya and neighbouring plains and found that the density of each higher part is less than a lower part. In other words, the density of mountains is less than the density of plateaux, that of plateau is less than the density of plain and the density of plain is less than the density of oceanic floor and so on. This means that there is inverse relationship between the height of the reliefs and density.

According to Pratt there is a level of compensation above which there is variation in the density of different columns of land but there is no change in density below this level. Density does not change within one column but it changes from one column to other columns above the level of compensation. Thus, the central theme of the concept of Pratt on isostasy may be expressed as **'uniform depth with varying density'**. According to Pratt equal surface area must underlie equal mass along the line of compensation. This statement may be explained with an example (fig. 6.2).

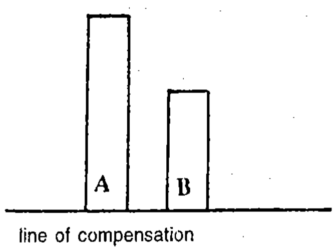


Fig. 6.2 : Line of compensation according to Archdeacon Pratt.

There are two columns, A and B, along the line of compensation. Both the columns, A and B, have equal surface area but there is difference in their height. Both the columns must have equal mass along the line of compensation, so the density of column A should be less than the density of column B so that the weight of both the columns become equal along the line of compensation. Thus, Pratt's concept of inverse relationship between the height of different columns and their respective densities may be expressed in the following manner-*'bigger the column lesser the density and smaller the column, greater the density.'* According to Pratt density varies only in the lithosphere and not in the pyrosphere and barysphere. Thus, Pratt's concept of isostasy was related to the **'law of compensation'** and not to **'the law of floatation.'** According to Pratt different relief features are standing only because of the fact that their respective mass is equal along the line of compensation because of their varying densities. This concept may be explained with the help of an example (fig. 6.3).

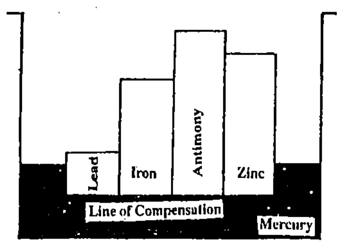


Fig. 6.3 : Explanation of the concept of Pratt on isostasy.

Bowie has opined that though Pratt does not believe in the law of floatation, as stated by Sir George Airy but if we look, minutely, into the concept of Pratt we certainly find the glimpse of law of floatation indirectly. Similarly, though Pratt does

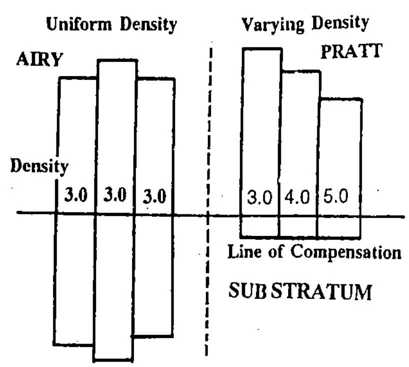


Fig. 6.4 : Comparison of the views of Airy and Pratt on isostasy.

not believe directly in the concept of **'root formation'** but very close perusal of his concept on isostasy, does indicate the glimpse of such idea (root formation) indirectly. While making a comparative analysis of the views of Airy and Pratt on isostasy Bowie has observed that *'the fundamental difference between Airy's and Pratt's views is that the former postulated a uniform density with varying thickness, and the latter a uniform depth with varying density.'* Fig. 6.4 explains the fundamental difference between the concepts of Airy and Pratt on isostasy.

6.5 CONCEPT OF HAYFORD AND BOWIE

Hayford and Bowie have propounded their concept of isostasy almost similar to the concept of Pratt. According to them there is a plane where there is complete compensation of the crustal parts. Densities vary with elevations of columns of crustal parts above this plane of compensation. The density of the mountains is less than the ocean floor. In other words, the crust is composed of lighter material under the mountains than under the floor of the oceans. There is such a zone below the plane of compensation where density is uniform in lateral direction. Thus, according to Hayford and Bowie there is inverse relationship between the height of columns of the crust and their respective densities (as assumed by Archdeacon Pratt) above the line of

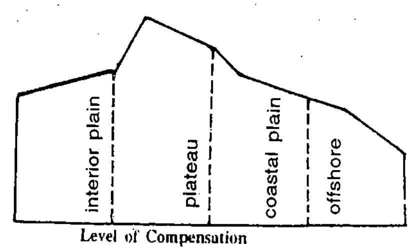


Fig. 6.5 : Explanation of views of Hayford and Bowie on isostasy. The densities mentioned in the different columns (e.g. inland plain, plateau, coastal plain and off shore region) are imaginary.

compensation. The **plane of compensation** (level of compensation) is supposedly located at the depth of about 100 km. The columns having the rocks of lesser density stand higher than the columns having the rocks of higher density. This statement may be understood with the help of fig. 6.5

There are four imaginary columns (interior plain, plateau, coastal plain and offshore region) in fig. 6.5 which reach the level of compensation. Their height varies but they are balanced by their varying densities. 'The assumption is that the varying volume of matter in the several columns is compensated by their density, in such a fashion that they exert equal downward pressure at the level of compensation and thus balance one another' (S.W. Wooldridge and R.S. Morgan, 1959). Fig. 6.6 explains the above concept. It is apparent from fig. 6.6 that different columns of equal cross-section cut from various metals and ores having varying densities are seen floating in a basin of mercury but all of them reach the same line (level of compensation) and thus exert equal weight along the line of compensation.

Bowie made a comparative study of the views of Airy and Pratt on isostasy and concluded that there was a great deal of similarity in their views. In fact, 'both the views appeared to him similar but not the same.' Bowie could observe a glimpse of the concept of root formation and law of floatation of Airy, though indirectly, in the views of Pratt. The concept of Hayford and Bowie, that the crustal parts (various reliefs) are in the form of vertical columns, is not tenable because the crustal features are found in the form of horizontal layers.

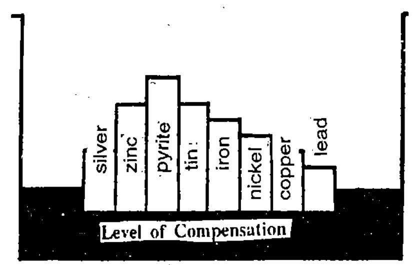


Fig. 6.6 : Illustration of the concept of Bowie on isostasy.

6.6 CONCEPT OF JOLY

Joly, while presenting his views on isostasy in 1925, contradicted the concept of Hayford and Bowie. He disapproved the view of Hayford and Bowie about the existence of level of compensation at the depth of about 100 km on the ground that the temperature at this depth would be so high that it would cause complete liquefaction and thus level of compensation would not be possible. He further refuted the concept of Hayford and Bowie that 'density varies above the level of compensation but remains uniform below the level of compensation' on the ground that such condition would not be possible in practice because such condition would be easily disturbed by the geological events and thus the level of compensation would be disturbed. According to Joly there exists a layer of 10-mile (16 km) thickness below a shell of uniform density. The density varies in this zone of 10-mile thickness. It, thus, appears that Joly assumed the level of compensation as not a linear phenomenon but a zonal phenomenon. In other words, he did not believe in a **'line (level) of compensation'** rather he believed in a **'zone of compensation'** (of 10-mile thickness). Thus, we also find a glimpse of the law of floatation (it may be remembered that Joly did not mention this, we only infer the idea of floatation from Joly's concept) and his concept is closer to the Airy's concept rather than the concept of Hayford and Bowie.

'This is in close agreement with floatation idea; the areas of low density in the 10-mile layer correspond with downward projections of the light continental crust, while those of high density represent the intervening areas filled with material of the heavier understratum' (S.W. Wooldridge and R.S. Morgan, 1959) (fig. 6.7).

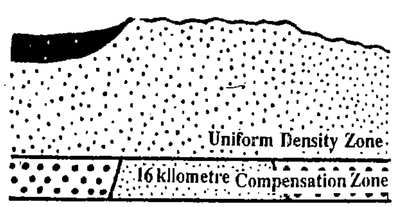


Fig. 6.7 : Compensation zone of 10-mile thickness (after Joly). Finer dots indicate lighter materials while larger dots represent denser materials.

6.8 CONCEPT OF HEISKENEN

Heiskenen presented a new concept of isostasy in 1933 in which he combined the concepts of both Airy (uniform density with varying thickness) and Pratt (varying density in different columns). According to him density of rocks varies within the column (section of the earth) and between the columns. For example, rocks of a column at sea level have higher density (say 2.76 gram cm^{-3}) than at higher elevation of the same column (say 2.70 gram cm^{-3}) which means as we go downward the rocks of a section of the earth's crust become denser *i.e.* density increases downward. Similarly, density of rocks of different sections (columns) of the earth's crust also varies. Thus, it appears that **density of rocks varies both vertically and horizontally.**

6.7 CONCEPT OF HOLMES

The views of Arthur Holmes on isostasy, to a greater extent, are compatible with the views of Airy. Following Airy Holmes has also assumed that

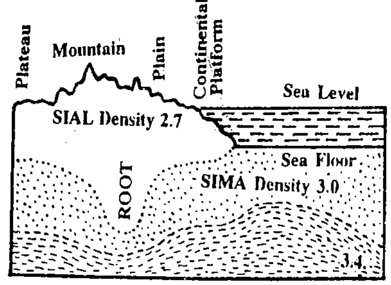


Fig. 6.8 : Diagramatic presentation of the earth's crust and the upper part of the mantle to illustrate the relationship between surface features and crustal structure and the concept of isostasy (based on A. Holmes and D.L. Holmes, 1978).

upstanding crustal parts are made of lighter materials and inorder to balance them major portions of these higher columns are submerged in greater depth of lighter materials (of very low density). According to Holmes the higher columns are standing because of the fact that there is lighter material below them

for greater depth whereas there is lighter material below the smaller columns upto lesser depth. (fig. 6.8).

A. Holmes and D.L. Holmes (1978) have tried to explain and illustrate the concept of isostasy through a diagram (fig. 6.9) which 'shows characteristic examples of crustal columns, each of which has the same area and extends downward to the same depth below sea level, the same depth at which the weight of each column exerts approximately the same pressure on the underlying material, irrespective of its surface elevation' (A. Holmes and D.L. Holmes, 1978, P. 21). They have taken the depth of 50 km for isostatic compensation in those areas which have not been disturbed by geological events for fairly longer duration. A. Holmes and D.L. Holmes have attempted to explain and illustrate the concept of equal weight along the 'level of equal pressure' through the examples of 4 columns of equal cross-section through characteristic parts of the continents and ocean floor (fig. 6.9). These four columns are (i) plateau, 4 km high; (ii) plateau, 1 km high; (iii) plain at sea level and (iv) ocean, 5 km deep. Each column has a thickness of 50km. The figures to the right of each column denote density (average). M indicates Mohorovicic Discontinuity. The weight of each column along the level of equal pressure is almost the same, ranging between 150.0 to 151.2. According to Holmes and Holmes the total weight of each column along the level of equal pressure can be obtained by summing up the product of the density and corresponding thickness down to the depth of 50 km as given below-

(i) For the plateau (4 km high from sea level (fig. 6.9 A) – 54×2.8 (average density) = 151.2

(the whole section is continental crust)

(ii) For the plateau (1 km high) (fig. 6.9 B)- 36 x 2.8 (continental crust) + 15.33 (mantle sima, probably basaltic rock) = 150.3

(iii) For the plain near the sea level (fig. 6.9 C).

30×2.8 (continental crust) x 20 x 3.3 (mantle sima) = 150.0

(iv) For the ocean (5 km deep, fig. 6.9 D)-

5×1.03 (sea water) + 1×2.4 (sediments) + 5×2.9 (crustal sima, probably basaltic rock) + 39×3.3 (mantle sima) = 150.75

6.9 GLOBAL ISOSTATIC ADJUSTMENT

It may be pointed out that there is no comple isostatic adjustment over the globe because the ea is so unresting and thus geological forces (endogene forces) coming from within the earth very oft disturb such isostatic adjustment. Moreover, recent a few scientists have even questioned the concept isostasy. Even there is disagreement among th scientists about local or regional nature of isostas It appears from the result of various expedition experiments and observations that if the isostati adjustment does not occur at local level, it does exis at extensive regional level. It is necessary that ther must be balance at local level, it may be and it ma not be. The endogenetic forces and resultant tectoni events cause disturbances in the ideal condition o isostasy but nature always tends towards the isostatic adjustment.

For example, a newly formed mountain due to tectonic activities is subjected to severe denudation. Consequently, there is continuous lowering of the height of the mountain. On the other hand, eroded sediments are deposited in the oceanic areas, with the result there is continuous increase of weight of sediments on the sea floor. Due to this mechanism the mountainous area gradually becomes lighter and the oceanic floor becomes heavier, and thus the state of balance or isostasy between these two areas gets disturbed but the balance has to be maintained. It may be stated that the superincumbent pressure and weight over the mountain decreases because of continuous removal of material through denudational processes. This mechanism leads to gradual rise in the mountain. On the other hand, continuous sedimentation on the sea floor causes gradual subsidence of the sea floor. Thus, inorder to maintain isostatic balance between these two features there must be slow flowage of relatively heavier materials of substratum (from beneath the sea floor) towards the lighter materials of the rising column of the mountain at or below the level of compensation (fig. 6.10). Thus, the process of redistribution of materials ultimately restores the disturbed isostatic condition to complete isostatic balance. Commenting on

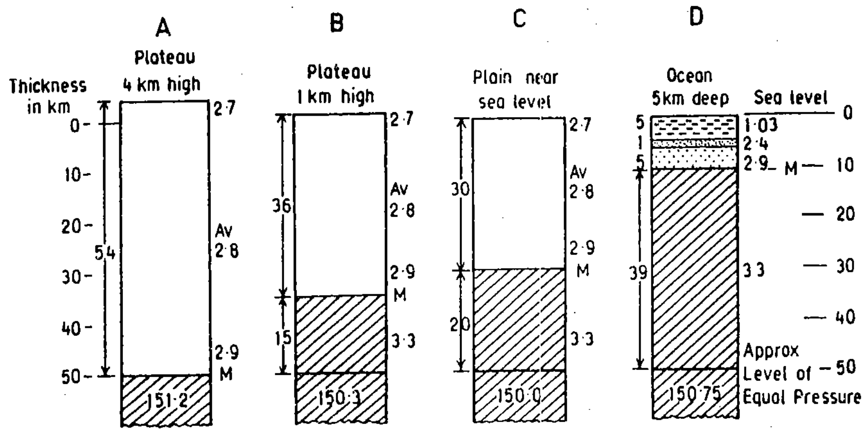


Fig. 6.9 : Columns of equal cross section through characteristic parts of the continents and ocean floor. White portion (unshaded) denotes continental crust while larger dots represent mantle sima. Broken line shows sea water, dense tiny dots reveal sediments and sparse tiny dots indicate crustal sima, probably basaltic rock. After A. Holmes and D.L. Holmes, 1978.

the validity of the above mechanism of the isostatic adjustment, Wooldridge and Morgan (1959) have remarked, 'That some such mechanism operates is indeed very likely; geologists have irrefutable evidence that sediments can depress the floor of a loaded sea to a limited extent, and some species of sub-crustal flow has been invoked on many other grounds. But clearly we are not justified in regarding

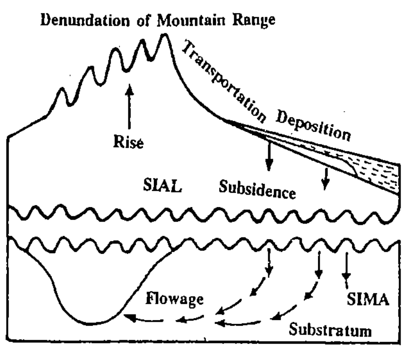


Fig. 6.10 : Mechanism of isostatic adjustment at global scale (based on A. Holmes).

the crust as composed of columns, moving up and down independently; such a conception flouts the facts of observation, and even it did not, it would on the geological side, create many more problems than it solved' (S.W. Wooldridge and R.S. Morgan, 1959, p. 26).

Some times the endogenetic forces act so suddenly and violently that the state of isostatic balance is thrown out of gear all of sudden and hence the isostatic adjustment through the process of flowage of materials from the substratum is not maintained. Similarly, some times climatic changes occur at such an extensive global scale that there is accumulation of thick ice sheets on the land surface and thus increased burden causes isostatic disturbance. For example, extensive parts of North America and Eurasia were subsided under the enormous weight of accumulation of thick ice sheets during Pleistoncene glaciation but the landmasses began to rise suddenly because of release of pressure of supereincumbent thick load of ice sheets due to deglaciation and consequent melting of ice sheets about 25,000 years ago and thus the isostatic balance was disturbed. According to an estimate major parts of Scandinavia and Finland have risen by 900 feet. The land masses are still rising at the rate of one foot per 28 years under the process of isostatic recovery. The isostatic adjustment in these areas could not be achieved till now.

7

EARTH'S MOVEMENTS

7.1 INTRODUCTION

The study of forces affecting the crust of the earth or geological processes is of paramount significance because these forces and resultant movements are involved in the creation, destruction, recreation and maintenance of geomaterials and numerous types of relief features of varying magnitudes. These forces very often affect and change the earth's surface. In fact, the change is law of nature. The geological changes are generally of two types e.g. (i) long-period changes and (ii) short-period changes. Long-period changes occur so slow that man is unable to notice such changes during his life period. On the other hand, short-period changes take place so suddenly that these are noticed within few seconds to few hours, e.g. seismic events, volcanic eruptions etc. The forces, which affect the crust of the earth, are divided into two broad categories on the basis of their sources of origin e.g. (1) endogenetic forces and (ii) exogenetic forces (fig. 7.1).

7.2 ENDOGENETIC FORCES

The forces coming from within the earth are called as endogenetic forces which cause two types of movements in the earth viz. (1) **horizontal movements** and (ii) **vertical movements.** These movements motored by the endogenetic forces introduce various types of vertical irregularities which give birth to numerous varieties of relief features on the earth's surface (e.g. mountains, plateaux, plains, lakes, faults, folds etc.). Volcanic eruptions and seismic events are also the expressions of endogenetic forces. Such movements are called **sudden movements** and the forces responsible for their origin are called **sudden forces.** We do not know precisely the mode of origin of the endogenetic forces and movement because these are related to the interior of the earth about which our scientific knowledge is still limited. On an average the origin of endogenetic forces is related to thermal conditions of the interior of the earth. Generally, the endogenetic forces and related horizontal and vertical movements are caused due to contraction and expansion of rocks because of varying thermal conditions and temperature changes inside the earth. The displacement and readjustment of geomaterials some times take place so rapidly that earth movements are caused below the crust. The endogenetic forces and movements are divided, on the basis of intensity, into two major categories viz.

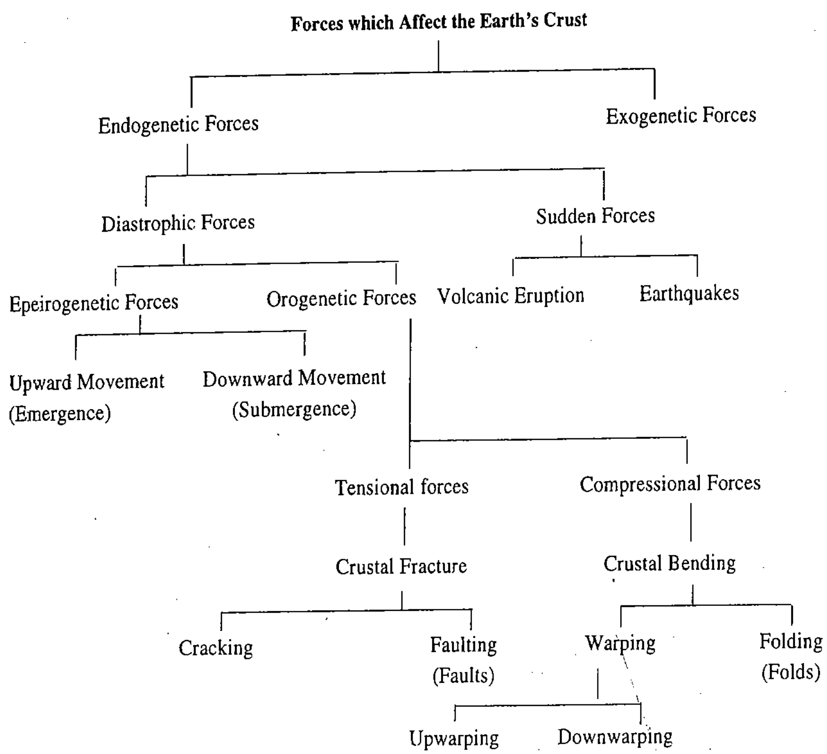


Fig. 7.1 : Schematic presentation of forces (endogenetic) affecting the earth's crust.

(1) diastrophic forces and (2) sudden forces.

1. Sudden Forces and Movements

Sudden movements, caused by sudden endogenetic forces coming from deep within the earth, cause such sudden and rapid events that these cause massive destructions at and below the earth's surface. Such events, like volcanic eruptions and earthquakes, are called **'extreme events'** and become disastrous hazards when they occur in densely populated localities. 'These forces work very quickly and their results are seen within minutes. It is important to note that these forces are the result of long period preparation deep within the earth. Only their cumulative effects on the earth's surface are quick and sudden' (Savindra Singh, 2001, Environmental Geography, p. 68). Geologically, these sudden forces are termed as **'constructive forces'** because these create certain relief features on the earth's surface. For example, volcanic eruptions result in the formation of volcanic cones and mountains while fissure flows of lavas form extensive lava plateaux (e.g. Deccan plateau of India, Columbia plateau of the USA etc.) and lava plains. Earthquakes create faults, fractures, lakes etc.

2. Diastrophic Forces and Movements

Diastrophic forces include both vertical and horizontal movements which are caused due to forces deep within the earth. These diastrophic forces operate very slowly and their effects become discernible after thousands and millions of years. These forces, also termed as constructive forces, affect larger areas of the globe and produce meso-level

reliefs (e.g. mountains, plateaux, plains, lakes, big faults etc.). These diastrophic forces and movements are further subdivided into two groups viz. **(i) epeirogenetic movements** and (ii) **orogenetic movements.**

1. Epeirogenetic movements — The epeirogenetic word consists of two words viz. **'epiros'** (meaning thereby continent) and **'genesis'** (meaning thereby origin). Epeirogenetic movements cause **upliftment and subsidence** of continental masses through upward and downward movements respectively. Both the movements are, infact, vertical movements. These forces and resultant movements affect larger parts of the continents. These are further divided into two types viz. (i) **upward movement** and (ii) **downward movement.** Upward movement causes upliftment of continental masses in two ways e.g. (a) upliftment of whole continent or part thereof and (b) upliftment of coastal land of the continents. Such type of upliftment is called **emergence.**

Downward movement causes subsidence of continental masses in two ways viz. (ii) subsidence of land area. Such type of downward movement is called as **subsidence.** (ii) Alternatively, the land area near the sea coast is moved downward or is subsided below the sea level and is thus submerged under sea water. Such type of downward movements is called as **submergence.**

(2) Orogenetic movement—The word orogenetic has been derived from two Greek words, **'oros'** (meaning thereby mountain) and 'genesis' (meaning thereby origin or formation). Orogenetic movement is caused due to endogenetic forces working in horizontal manner. Horizontal forces and movements are also called as **tangential forces.** Orogenetic or horizontal forces work in two ways viz. (i) in opposite directions and (iii) towards each other. This is called **tensional force** when it operates in opposite directions. Such types of force and movement are also called as **divergent forces** and **movements.** Thus, tensional forces create rupture, cracks, fracture and faults in the crustal parts of the earth. The force, when operates face to face, is called **compressional force** or **convergent force.** Compressional force causes crustal bending leading to the formation of folds or crustal warping leading to local rise or subsidence of crustal parts.

Crustal bending—When horizontal forces work face to face the crustal rocks are bent due to resultant compressional and tangential force. In other words, when crustal parts move towards each other under the influence of horizontal or convergent forces and movements, the crustal rocks undergo the process of 'crustal bending' in two ways e.g. (i) **warping** and (ii) **folding.** The process of crustal warping affects larger areas of the crust wherein the crustal parts are either warped (raised) upward or downward. The upward rise of the crustal part due to compressive force resulting from convergent horizontal movement is called **upwarping** while the bending of the crustal part downward in the form of a basin or depression is called **downwarping.** When the processes of upwarping or downwarping of crustal rocks affect larger areas, the resultant mechanism is called **broad warping.** When the compressive horizontal forces or convergent forces and resultant movements cause buckling and squeezing of crustal rocks, the resultant mechanism is called folding which causes several types of folds.

FOLDS

Wave-like bends are formed in the crustal rocks due to tangential compressive force resulting from horizontal movement caused by the endogenetic force originating deep within the earth. Such bends are called **folds** wherein some parts are bent up and

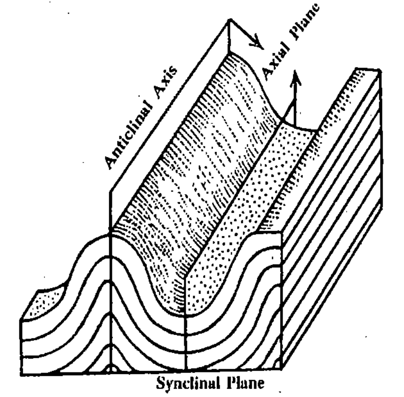


Fig. 7.2 : Different components of a fold.

some parts are bent down. The upfolded rock strata in arch-like form are called **anticlines** while the down folded structure forming trough-like feature is called **syncline** (fig. 7.3). In fact folds are minor forms of broad warping. The two sides of a fold are called **limbs** of the fold. The limb which is shared between an anticline and its companion syncline is called **middle limb**. The plane which bisects the angle between two limbs of the anticline or middle limb of the syncline is called the **axis of fold** or **axial plane** (fig. 7.2). On the basis of anticline and syncline these axial planes are called as **axis of anticline** and **axis of syncline** respectively.

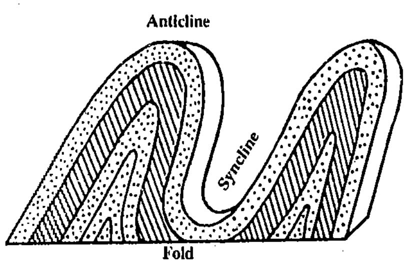


Fig. 7.3 : Anticlines and synclines.

It is desirable to explain the characteristics of **dip and strike** as it becomes absolutely necessary to understand them in order to understand the structural form. The inclination of rock beds with respect to horizontal plane is termed as 'dip' (fig. 7.4). It is apparent that we derive two information about the dip e.g. (i) the direction of maximum slope down a bedding plane and (ii) the angle between the maximum slope and the horizontal plane. The direction of dip is measured by its true bearing in relation to east or west or north e.g., 60^0N.E.; while the angle of dip is measured with an instrument called clinometer. For example, if any rockbed is inclined at the angle of 60^0 with respect to horizontal plane and the direction of slope is N then the dip would be expressed as 60^0N. 'The strike of an inclined bed is the direction of any horizontal line along a bedding plane' (A. Holmes and D.L. Holmes). The direction of dip is always at right angle to the strike (fig. 7.4).

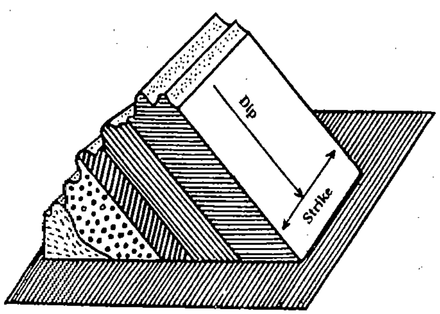


Fig. 7.4 : Dip and Strike .

Anticlines—The upfolded rock beds are called anticlines. In simple fold the rock strata of both the limbs dip in opposite directions. Some times, folding becomes so acute that the dip angle of the anticline is accentuated and the fold becomes almost vertical. When the slopes of both the limbs or sides of an anticline are uniform, the anticline is called as **symmetrical anticline** but when the slopes are unequal, the anticline is called as **asymmetrical anticline**. Anticlines are divided into two types on the basis of dip angle e.g. (i) gentle anticline when the dip angle is less than 40^0, some times 1^0 or 2^0 and (ii) steep anticline when the dip angle ranges between 40^0 and 90^0.

Synclines—Downfolded rock beds due to compressive forces caused by horizontal tangential forces are called synclines. These are, in fact, trough-like form in which beds on either side 'incline together' towards the middle part. If folded intensely, the syncline assumes the form of a canoe.

Anticlinorium—Anticlinorium refers to those folded structures in the regions of folded mountains where there are a series of minor anticlines and

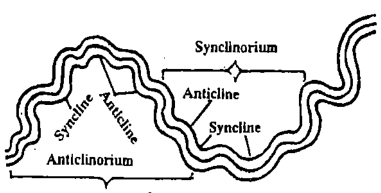


Fig. 7.5 : Illustration of anticlinorium and synclinorium.

synclines within one extensive anticline (fig. 7.5). Anticlinorium is formed when the horizontal compressive tangential forces do not work regularly. Consequently, due to difference in the intensity of compressive forces such structures are formed. Such type of folded structure is also called as fan fold.

Synclinorium represents such a folded structure which includes an extensive syncline having numerous minor anticlines and synclines. Such structure is formed due to irregular folding consequent upon irregular compressive forces (fig. 7.5).

Types of Folds

The nature of folds depends on several factors e.g. the nature of rocks, the nature and intensity of compressive forces, duration of the operation of compressive forces etc. The elasticity of rocks largely affects the nature and the magnitude of folding process. The softer and more elastic rocks are subjected to intense folding while rigid and less elastic rocks are only moderately folded. The difference in the intensity and magnitude of compressive forces also causes variations in the characteristics of folds. Normally, both the limbs of a simple fold are more or less of equal inclination but in most of the cases of different folds the inclinations of both the limbs are different. Thus, based on the inclination of the limbs, folds are divided into 5 types (fig. 7.6).

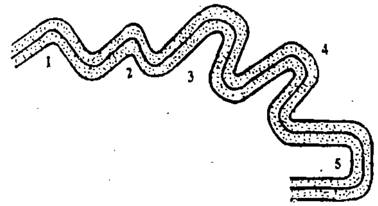


Fig. 7.6 : Types of folds—1. symmetrical folds, 2. asymmetrical folds. 3. monoclinal folds. 4. isoclinal folds and 5. recumbent folds.

(1) Symmetrical folds are simple folds, the limbs (both) of which incline uniformly. These folds are an example of open fold. Symmetrical folds are formed when compressive forces work regularly but with moderate intensity. In fact, symmetrical folds are very rarely found in the field.

(2) Asymmetrical folds are characterized by unequal and irregular limbs. Both the limbs incline at different angles.One limb is relatively larger and the inclination is moderate and regular while the other limb is relatively shorter with steep inclination. Thus, both the limbs are asymmetrical in terms of inclination and length.

(3) Monoclinal folds are those in which one limb inclines moderately with regular slope while the other limb linclines steeply at right angle and the slope is almost vertical. It may be pointed out that vertical force and movement are held responsible for the formation of monoclinal folds. There is every possibility for the splitting of the limbs of such folds because of intense folding. Splitting of limbs gives birth to the formation of faults. It is also opined that monoclinal folds are also formed due to unequal horizontal compressive forces coming from both the sides.

(4) Isoclinal folds are formed when the compressive forces are so strong that both the limbs of the fold become parallel but not horizontal.

(5) Recumbent folds are formed when the compressive forces are so strong that both the limbs of the fold become parallel as well as horizontal.

(6) Overturned folds are those folds in which one limb of the fold is thrust upon another fold due to intense compressive forces.Limbs are seldom horizontal.

7. Plunge folds are formed when the axis of the fold instead of being parallel to the horizontal plane becomes tilted and forms plunge angle which is the angle between the axis and the horizontal plane.

8. Fan folds represent an extensive and broad fold consisting of several minor anticlines and synclines. Such fold resembles a fan. Such feature is also called as anticlinorium or synclinorium (fig. 7.5).

(9) Open folds are those in which the angle between the two limbs of the fold is more than 90^0 but less than 180^0 (i.e. obtuse angle between the two limbs of a fold). Such open folds are formed due to

wave-like folding because of moderate nature of compressive force (fig. 7.7).

(10) Closed folds are those folds in which the angle between the two limbs of a fold is acute angle. Such folds are formed because of intense compressive force.

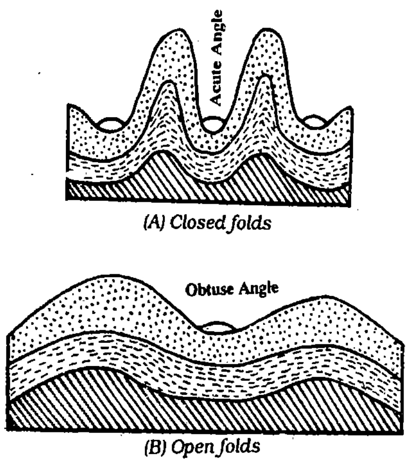


Fig. 7.7 : (A) closed folds and (B) open folds.

NAPPES

Nappes are the result of complex folding mechanism caused by intense horizontal movement and resultant compressive force.Both the limbs of a recumbent fold are parallel and horizontal. Due to further increase in the continued compressive force one limb of the recumbent folds slides forward and overrides the other fold. This process is called **thrust** and the plane along which one part of the fold is thrust is called **thrust plane**. The upthrust part of the fold is called 'overthrust fold'. When the compressive force becomes so actute that it crosses the limit of the elasticity of the rock beds, the limbs of the fold are so acutely folded that these break at the axis of the fold and the lower rock beds come upward. Thus, the resultant structure becomes reverse to the normal sructure. Due to continued horizontal movement and compressive force the broken limb of the folds is thrown several kilometres away from its original place and overrides the rock beds of the distant place. Such type of structure becomes unconformal to the original structure of the place where the broken limb of the fold of the other place overrides the rock beds. Such broken limb of the fold is called **nappe** (fig. 7.8).

Several examples of nappes are traceable in the present folded mountains. The nappes of the Alps have been more systematically studied. Four major nappes have been identified in the Alps mountains. The structure has become very much complex because of superimposition of one nappe upon another nappe. The four major groups of Alpine nappes from below upward are (i) Helvetic nappe, (ii) Pennine nappe, (iii) Austride nappe and (iv) Dinaride nappe. In fact, these nappes are located like a series of earth-waves. In most of the localities the overriding nappes have been eroded away because of dynamic wheels of denudational processes and thus

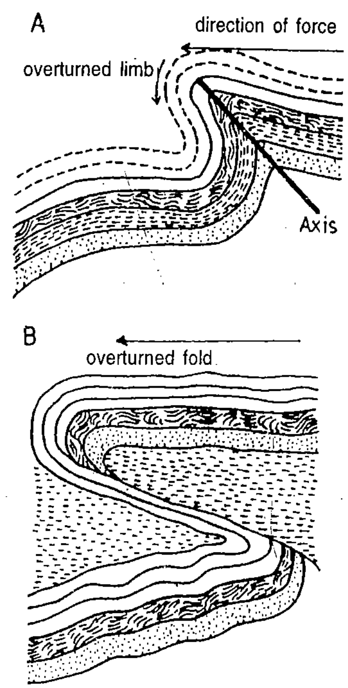


Fig. 7.8 : Formation of nappe : (A) stage of overturned fold, (B) overriding of one limb of the fold on the other limb.

burried basic structure has been exposed. When the portion of lower nappe is seen because of denudation of overriding nappe, the resultant open structure is called **structural window**. Several examples of **complete window** have been discovered in eastern Alps.

A few examples of nappes have also been traced out in the Himalayas. The existence of nappes has been discovered by Wadia from Kashmir Himalaya, by Pilgrim from Simla Himalaya, by Auden from Garhwal Himalaya and by Heim and Gansser from Kumaun Himalaya. It is desirable to mention some facts about nappe structure. When the broken limb of a fold overrides the other fold near to the broken fold, the resultant nappe is called **autochthonous nappe.** On the other hand, when the limb of a fold, after being broken, overrides the other fold at a distant place (several kilometres away), the resultant nappe is called **exotic nappe.**

CRUSTAL FRACTURE

Crustal fracture refers to displacement of rocks along a plane due to tensional and compressional forces acting either horizontally or vertically or some times even in both ways. Crustal fracture depends on the strength of rocks and intesity of tensional forces. The crustal rocks suffer only cracks when the tensional force is moderate but when the rocks are subjected to intense tensional force, the rock beds are subjected to dislocation and displacement resulting into the formation of faults. Generally fractures are divided into (i) **joints** and (ii) **faults.** A joint is defined as a fracture in the crustal rocks wherein no appreciable movement of rock takes place, whereas a fracture becomes fault when there is appreciable displacement of the rocks on both sides of a fracture and parallel to it.

Faults

A fault is a fracture in the crustal rocks wherein the rocks are displaced along a plane called as **fault plane.** In other words when the crustal rocks are displaced, due to tensional movement caused by the endogenetic forces, along a plane the resultant structure is called a **fault.** The plane along which the rock blocks are displaced is called **fault plane.** In fact, there is real movement along the fault plane due to which a fault is formed (fig. 7.9). A fault plane may be vertical, or inclined, or horizontal, or curved or of any type and form. The movement responsible for the formation of a fault may operate in vertical or horizontal or in any direction. During the formation of a fault the vertical displacement of rock blocks may occur upto several hundred metres and horizontally the rock blocks may be displaced upto several kilometres but it does not mean that the total displacement occurs at a single time. In fact, fault-movement or the displacement of rocks occurs only upto a few metres only at a time. Fault, in fact, represents weaker zones of the earth where crustal movements become operative for longer duration. A few terms regarding an ideal fault should be understood before going into the details of the mode of formation of various types of faults.

(1) Fault plane is that plane along which the rock blocks are displaced by tensional and compressional forces acting vertically and horizontally to form a fault. A fault plane may be vertical, inclined, horizontal, curved or of any other form.

(2) Fault dip is the angle between the fault plane and horizontal plane (fig. 7.9).

(3) Upthrown side represents the upper most block of a fault.

(4) Downthrown side represents the lowermost block of a fault. Some times it becomes difficult to

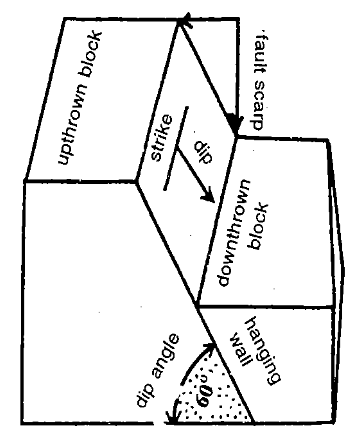


Fig. 7.9 : Different components of a fault.

find out, which block has really moved along the fault plane?

(5) **Hanging wall** is the upper wall of a fault.

(6) **Foot wall** represents the lower wall of a fault.

(7) **Fault scarp** is the steep wall-like slope caused by faulting of the crustal rocks. Some times the fault scrap is so steep that it resembles a cliff. It may be pointed out that scarps are not always formed due to faulting alone, rather these are also formed due to erosion, but whenever these are formed by faulting (tectonic forces), these are called 'fault-scarpts.

Types of Faults

The different types of faulting of the crustal rocks are determined by the direction of motion along the fracture plane. Generally, the relative movement or displacement of the rock blocks or the slip of the rock blocks occurs approximately in two directions viz. (i) either to the direction of the dip or (ii) to the direction of the strike of the fault plane. Thus, the displacement or movement of rock blocks may be distinguished as (a) **dip slip movements** and (b) **strike slip movements.** Thus, on the basis of the direction of slip or displacement faults are divided into (i) **dip-slip faults** and (ii) **strike-slip faults**. Again, the displacement of rock block-mainly upper blocks may be either down the direction of the dip (then the resultant fault is called **normal fault**) or up the dip (the resultant fault becomes **reverse** or **thrust fault**). In the case of strike-slip movement and fault, the relative displacement of the rock blocks may be either to the right (then the resultant fault will be **right-lateral** or **dextral fault**) or to the left-side (the resultant fault becomes **left-lateral** or **sinistral fault**). Strike slip faults are also called as **wrench faults, tear faults** or **transcurrent faults**. The combinations of normal and wrench faults or reverse and wrench faults are called as **oblique slip faults.**

(i) **Normal faults** are formed due to the displacement of both the rock blocks in opposite directions due to fracture consequent upon greatest stress. The fault plane is usually between 45^0 and the vertical. The steep scarp resulting from normal faults is called fault-scarp or fault-line scarp the height of which ranges between a few metres to hundreds of metres. It may be mentioned that it becomes very difficult to find out the exact height of the fault-scarps in the field because the height is remarkably reduced due to continued denudation (fig. 7.10).

(ii) **Reverse faults** are formed due to the movement of both the fractured rock blocks towards each other. The fault plane, in a reverse fault, is usually inclined at an angle between 40 degree and the horizontal (0 degree). The vertical stress is minimum while the horizontal stress is maximum. It may be mentioned that in a reverse fault the rock beds on the upper side are displaced up the fault plane relative to the rock beds below. It is apparent that reverse faulting results in the shortening of the faulted area while normal faults cause extension of the faulted area. It is, thus, also obvious that some sort of compression is also involved in the formation of reverse faults. Reverse faults are also called as **thrust faults.** Since the reverse fault is formed due to compressive force resulting from horizontal movement and hence this is also called as **compressional fault.** When the compressive force exceeds the strength of the rocks, one block of the fault overrides the other block and the resultant fault is called as **overthrust fault** wherein the fault plane becomes almost horizontal.

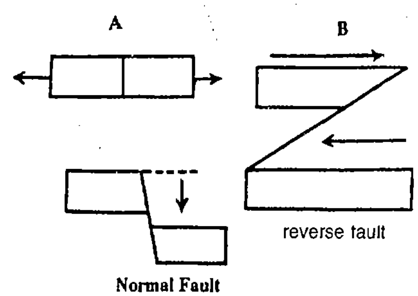


Fig. 7.10 : (A) Normal fault and (B) reverse fault.

(iii) **Lateral or strike-slip faults** are formed when the rock blocks are displaced horizontally along the fault plane due to horizontal movement. These are called **left-lateral** or **sinistral faults** when the displacement of the rock blocks occur to the left on the far side of the fault and **right-lateral** or **dextral faults** when the displacement of rock blocks takes place to the right on the far side of the fault (fig. 7.11). In majority of the cases there are no scarps in such faults, if they occur at all, they are very low in height..

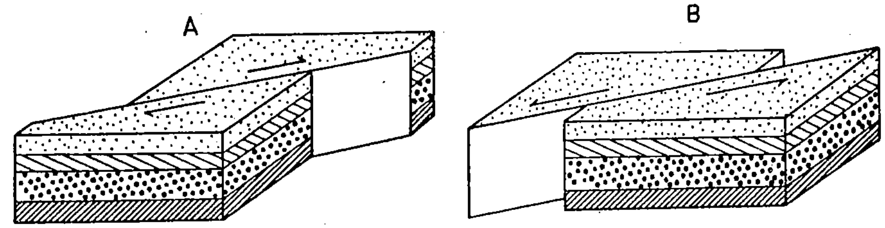


Fig. 7.11 : Formation of strike-slip or transcurrent faults : (A) right-lateral or dextral fault and (B) left-lateral or sinistral fault (after A. Holmes and D.L. Holmes, 1978).

(iv) **Step faults :** When a series of faults occur in any area in such a way that the slopes of all the fault planes of all the faults are in the same direction, the resultant faults are called as step faults (fig. 7.12). It is a prerequisite condition for the formation of step faults that the downward displacement of all the downthrown blocks must occur in the same direction.

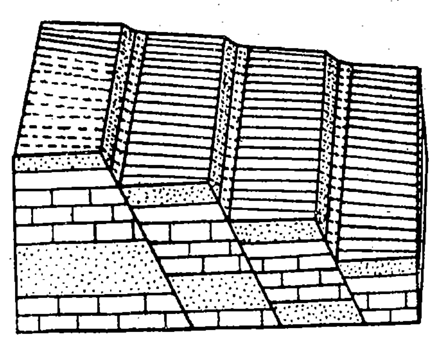


Fig. 7.12 : Illustration of step faults.

RIFT VALLEY AND GRABEN

Rift valley is a major relief feature resulting from faulting activities. Rift valley represents a trough, depression or basin between two crustal parts. In fact, rift valleys are long and narrow troughs bounded by one or more parallel normal faults caused by horizontal and vertical movement motored by endogenetic forces. Rift valleys are actually formed due to displacement of crustal parts and subsidence of middle portion between two normal faults. Rift vallyes are generally also called as **graben** which is a German word which means a trough-like depression. These two terms are synonymously used in various parts of the world. 'Tensional crustal forces, literally pulling the crust apart, are responsible for these downdropped fault blocks' (F. Press and R. Siever, 1974) (fig. 7.13). A few scientists have attempted to differentiate a graben from a rift valley on the basis of size and dimension. They believe that a graben is relatively smaller in size than a rift valley but this minor difference of size is not acceptable to others. Thus, both the terms, graben and rift valley should always be considered as synonym.

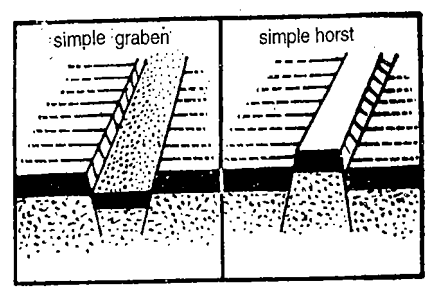


Fig. 7.13 : Illustration of rift valley and graben.

A rift valley may be formed in two ways viz. (i) when the middle portion of the crust between two normal faults is dropped downward while the two blocks on either side of the downdropped block remain stable and (ii) when the middle portion between two normal faults remains stable and the two side blocks on either side of the middle portion are raised upward.

Normally, a rift valley is long, narrow but very deep. Rhine rift valley is the best example of a well defined rift valley. It stretches for a distance of 320 km having an average width between the cities of Basel and Bingen. The one side of this great rift valley is bounded by Vosges and Hardt mountains (block mountains-horst) and the other side is bordered by Black Forest and Odewnwald mountains. The example of the longest rift valley is the valley that runs from the Jordon river valley through Red Sea basin to Zambezi valley for a distance of 4,800 km. A few of the rift valleys are so deep that their bottom/floor is below sea level. Death Valley of the southern California (USA) is a good example of such graben. Dead Sea of Asia presents an ideal example of typical rift valley. The floor of the Dead Sea is about 867 m below sea level. The floors of the Jordon rift valley and Death Valley are also 433 m below sea level. The Narmada valley, the Damodar valley and some stretches of the Son Valley, the Tapi valley etc. are considered to be examples of rift valleys but this view is still controversial and is not acceptable to all geologists.

It may be mentioned that the rift valleys are not only confined to the continental crustal surfaces but they are also found on sea floor. In fact, the deepest grabens are found in the form of **ocean deeps** and **trenches.** The Bortlet Trough located to the south of Cuba is 4.8 km deep while Java Deep is 6.4 km deep from the sea floor. The central plain of Scotland, Spencer Bay of south Australia etc.are examples of rift valleys.

Origin of Rift Valleys

The riddle of the problem of the origin of the rift valleys and grabens, typical topographic expressions of faulting, still remains a mystery. Though many scientists have propounded their views regarding the origin of the rift valleys based on their studies of respective rift valleys but their concepts and theories are still controvercial and no commonly acceptable theory could be propounded as yet. The hypotheses regarding the origin of the rift valleys are generally grouped in two categories e.g. (1) tensional hypothesis and (2) compressional hypothesis.

(1) Tensional hypothesis—The earlier hypothesis of the origin of the rift valleys was based on the basic concept of the **'dropped keystone of the arch'** of a building. According to this concept the rift valleys were related to the hollow space created by the dropping of the keys stone of an arch of a building downward. In other words, an open space is formed at the middle portion of an arch of a building when the keystone or keybrick falls downward due to cracks developed in the arch. Similarly, when two parallel cracks develop in the crustal surface due to tensional forces and when the side blocks on either side of the two cracks or fractures are pulled apart due to tensional forces, the middle portion between two parallel normal faults moves downward and thus an open space is formed. This open space becomes a rift valley.

This **'key stone hypothesis'** was severely criticized because it was based on erroneous concepts and beliefs. For example, there is wide open space below the arch of a building and hence the keystone or keybrick, after the arch develops cracks, can easily fall down but there is no open space beneath the crustal rocks and thus there would be difficulty for the middle block between the two parallel normal faults to slip downward. The faulted middle block can only be slipped downward when it would be able to displace the magma lying below the crustal blocks. If this process is accepted then the formation of the rift valley must be followed by volcanic activities because the displaced magma would try to ascend through the faults. Some times, the mechanism may be so sudden that there may be sudden violent volcanic eruption, but the observations of several deep rift valleys denote the fact that rift valley formation is not necessarily always associated with volcanic eruptions. The observations and several experiments have revealed the fact that already existing volcanic activities and active volcanoes ceased to operate at the time of the formation of rift valleys. It might have become possible only when the exit of the ascent of magma would have been pluged due to faulting activity. This explanation is also refuted on

the ground that if we accept the mode of formation of a rift valley due to horizontal tensional forces and resultant pulling of bounding faulted side blocks of two normal faults apart, then the upwelling of magma in the form of lava cannot be stopped, rather the pouring of lava can be stopped due to compressive forces. Thus, the tensional hypothesis of the origin of the rift valleys is rejected on this ground.

(2) Compressional hypothesis—In order to remove the difficulties of the tensional hypothesis of the origin of the rift valleys compressional hypothesis was postulated by a number of scientists e.g. Wayland, Baily Willis, Waren D. Smith, E.C. Bullard etc. Wayland through his studies of Lake Albert and Ruwenzori section and Baily Willis based on his studies of Dead Sea have postulated the concept that the rift valleys are not formed by tensional forces but are formed due to compressional forces at greater depth. Due to intense compression the side blocks are thrown up along the thrust faults in the form of **horsts.** These upthrown blocks are called **overthrusting rift blocks.** The middle portion is forced to slip downward because of the pressure resulting from the rising side blocks. Thus, the downward slipping middle portion between two faults is called **rift block** which is narrow upward but broader downward. In other words, the rift block gradually broadens out downward. Thus, the rift valleys are formed due to slipping of middle block or rift block downward between two rising side blocks caused by thrust faulting under the impact of convergent compressional forces.

(3) Hypothesis of E.C. Bullard.—E.C. Bullard, while conducting the gravity survey, postulated his new concept of the origin of the rift valleys in 1933-34. According to him the rift block cannot slip downward under the impact of gravity, like a keystone of an arch of a building. Thus, the rift valley can be formed only due to compression coming from two sides. According to Bullard the formation of a rift valley is not completed during a single phase but is completed through a series of sequential phases. **First stage,** there is compression in the crustal rock beds of the rigid part of a plateau due to active horizontal movement. The horizontal compressive forces work face to face from both the sides of the land. This lateral compression causes buckling of the crustal rocks. As the compressive forces continue to increase, the buckling and squeezing of the crustal rocks also continue to increase. When the compression becomes so enormous that it exceeds the strength of the rocks, a crack is developed at a place (A in fig. 7.14) in the crustal rocks. This crack is gradually enlarged due to continuous increase in the compressive force.

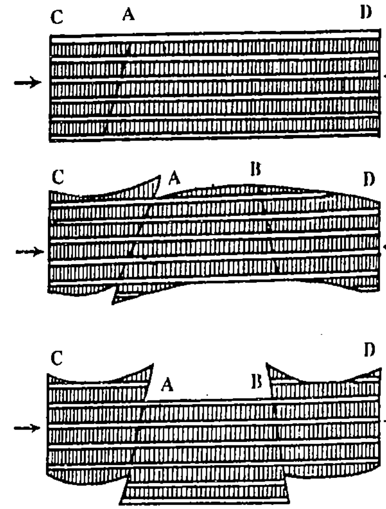


Fig. 7.14 : Formation of a rift valley according to E.C. Bullard.

Second stage, due to the formation of a crack (at A place, fig. 7.14), one portion overrides the other portion. This process is called as **thrusting.** On the other hand, the second part is thrown downward relative to the first part. This process is called **downthrusting.** A-C part (fig. 7.14) has gone upward because of overthrusting. Due to upthrusting of the side block (A-C) upto a height of a few thousand metres the downthrust block (A-D) develops crack at a place (B) due to resultant compressive force. The place of the crack is located at the highest point of downthrust block. This newly formed crack continues to increase gradually.

Third stage, the crack developed in downthrust block at B place (fig. 7.14) becomes enlarged due to increased compression with the result B-D part of the downthrust block overrides its other part (A-B). Thus, the position of downthrust A-B part between

the two upthrust blocks (A-C and B-D) become a rift valley. A-B in fig. 7.14 denotes the width of the upper portion of the rift valley.

According to E.C. Bullard the width of the rift valley (A-B) depends upon the elasticity of the rocks, depth of the rift valley and the density of the substratum. If the density of the substratum is taken to be 3.3. then the width of the rift valley would be 40 km if the depth of the valley is 20 km. Similiarly, for a 40 km deep valley the width would be 65 km.

It may be concluded that neither the tensional hypothesis nor the compressional hypothesis could be able to slove many of the intricate problems of the origin of the rift valleys.

7.3. EXOGENETIC FORCES

The exogenetic forces or processes, also called as **denudational processes,** or **destructional forces or processes** are originated form the atmosphere. These forces are continuously enganged in the destruction of the relief features created by the endogenetic forces through their weathering, erosional and depositional activities. Exogenetic processes are, therefore, planation processes. Denudation includes both weathering and erosion where weathering being a static process includes the disintegration and decomposition of rocks in situ whereas erosion is dynamic process which includes both, removal of materials and their transportation to different destinations. Weathering is basically of three types viz. (i) physical or mechanical weathering, (ii) chemical weathering and (iii) biological weathering. Weathering is very important for the biospheric ecosystem because weathering of parent rocks results in the formation of soils which are very essential for the sustenance of the biotic lives in the biosphere . The erosional processes include running water or river, groundwater, sea waves, glaciers, periglacial processes and wind. These erosional processes erode the rocks, transport the eroded materials (except periglacial processes) and deposit them in suitable places and thus form several types of erosional and depositional landforms of different magnitudes and dimensions. The description of the mechanisms of these exogenetic processes and resultant landforms would be attempted in the succeeding 15th and 16th chapters of this book.

8

ROCKS

8.1 INTRODUCTION

The materials of the crust or lithosphere are generally called as rocks. The word lithosphere, in fact, means **rocksphere** as the literal meaning of **'lithos'** is rock. The smallest component of the crust or the lithosphere is element. As regards the whole earth eight most abundant elements (iron, oxygen, sillicon, magnesium, nickel , sulphur, calcium and ammonium, table 8.1) constitute 99 per cent of the total mass of the earth whereas only four elements (iron, oxygen, silicon and mangesium) account for 90 percent of total mass of the earth. On the other hand, the eight most abundant elements which constitute 99 per cent of total mass of the crust are oxygen, silicon, aluminium, iron, magnesium, calcium, postassium and sodium (table 8.1).

Table 8.1 : Important Elements of the Whole Earth and the Crust

Whole Earth		Earth's Crust	
Elements	Percentage	Elements	Percentage
1. Iron	35	1. Oxygen	46
2. Oxygen	30	2. Silicon .	28
3. Silicon	15	3 Aluminium	8
4. Magnesium	13	4. Iron	6
5. Nickel	2.4	5. Magnesium	4
6. Sulphur	1.9	6. Calcium	2.4
7. Calcium	1.1	7. Potassium	2.3
8. Aluminium	1.1	8. Sodium	2.1
Others, less than	1.0	Others, less than	1.0

More than one element of the earth's crust are organized to form compounds which are known as minerals and minerals are organized to form rocks. The important mineral groups are silicates, carbonates, sulphides, metal oxides etc.

(1) The silicate minerals are very important rock making minerals. The most outstanding rock-forming silicate mineral groups are quartz, feldspar, and ferromagnesium. Quartz is composed of two elements viz. silicon and oxygen and is generally a

hard and resistant mineral. The most abundant and most important rock-forming silicate mineral is feldspar which is also very important economically because it is used in ceramics and glass industry. Feldspar is very weak mineral and is easily broken down and decomposed due to chemical weathering and is changed into clays as hydrated aluminosilicates. When silicon and oxygen combine with iron and magnesium, ferromagnesium minerals are formed. Ferromagnesium minerals are easily weathered and eroded away and are easily altered and removed. The rocks having abundant ferromagnesium minerals provide weak structure for the construction of buildings, roads, dams, reservoirs, tunnels etc.

(2) **Carbonate group of minerals** is very much succeptible to chemical weathering and erosion in humid areas. Calcite is the most important mineral of this group. Limestones and marbles having abundant calcite are corroded by the surface and groundwater and extensive caves are formed below the ground surface. Such areas provide very weak structures for construction sites e.g. construction of buildings, roads, dams reservoirs, air strips, tunnels etc.

(3) **Sulphide minerals** include pyrites, iron sulphides etc. When these minerals come in contact with water or air, these form ferric hydroxides and sulfuric acids which cause serious environmental problems.

(4) **Metallic elements** like iron, aluminium etc. after reacting with atmospheric oxygen form metal oxides which are commercially very important.

Rocks, thus, representing the geomaterials of the earth's crust, are composed of two or more minerals. Rocks play very important role in determining the characteristic features of several types of erosional landforms because the nature and magnitude of erosion largely depends upon the structure and composition of rocks. The fundamental dictum of famous American geomorphologist W.M. Davis that the 'landscape is a function of structure, process and time (stages)' lays more emphasis on the dominant role of rocks in the evolution of landforms. According to A.K. Lobeck, 'a rock should be conceived as a product of its environment. When the environment is changed, the rock changes'. Rocks are also very helpful in dating the age of the earth as rocks are the books of earth history and fossils are the pages. S.W. Wooldridge and R.S. Morgan (1959) have aptly remarked, 'Rocks whether igneous or sedimentary, constitute on the one hand the manuscripts of the past earth history on the other, the basis for contemporary scenery.'

8.2 CLASSIFICATION OF ROCKS

The crustal rocks are classified on several grounds e.g. mode of formation, physical and chemical properties, locations etc.

1. Classification on the basis of mode of formation—The rocks are divided into three broad categories on the basis of their mode (method) of formation.

(i) **Igneous rocks,** formed due to cooling, solidification and crystallization of molten earth materials known as magma (below the earth's surface) and lava (on the earth's surface), e.g. basalt, granites etc.

(ii) **Sedimentary rocks,** formed through the lithification and compression and cementation of the sediments deposited in a particular place mainly aquatic areas, e.g. sandstones, limestones, conglomerates etc.

(iii) **Metamorphic rocks,** formed due to change either in the form or composition of either igneous or sedimentary rocks provided that there is no disintegration of pre-existing rocks, e.g. slate, quartzite, marble etc.

8.3 IGNEOUS ROCKS

The word igneous has been derived form a Latin word **'ignis'**,meaning thereby fire. It does not mean that the origin of igneous rocks is associated with fire in any way. In fact, the igneous rocks are formed due to cooling, solidification and crystallization of hot and molten materials known as magmas and lavas. Since the magmas and lavas are so hot that they look like the red pieces of fire and hence there is a confusion of fire but this is not the case. Igneous rocks are also called as **primary rocks** because these were originated first of all the rocks during the formation of upper crust of the earth on cooling, solidification and crystallization of hot and liquid magmas after the origin of the earth. Thus, all the subsequent rocks were formed, whether directly or indirectly, from the igneous rocks in one way or the

other. This is why igneous rocks are also called as **parent rocks.** It is believed that the igneous rocks were formed during each period of the geological history of the earth and these are still being formed.

Characteristics of Igneous Rocks

(1) In all, the igneous rocks are roughly hard rocks and water percolates with great difficulty along the joints. Some times the rocks become so soft, due to their exposure to environmental conditions for longer duration, that they can be easily dug out by a spade (e.g. basalt).

(2) Igneous rocks are granular or crystalline rocks but there are much variations in the size, form and texture of grains because these properties largely depend upon the rate and place of cooling and solidification of magmas or lavas. For example, when the lavas are quickly cooled down and solidified at the surface of the earth, there is no sufficient time for the development of grains/crystals. Consequently, either there are no crystals in the resultant basaltic rocks or if there are some crystals at all, they are so minute that they cannot be seen without the help of a microscope. Contrary to this, if magmas are cooled and solidified at a very slow rate inside the earth, there is sufficient time for the full development of grains, and thus the resultant igneous rocks are characterized by coarse grains.

(3) Igneous rocks do not have strata like sedimentary rocks. When lava flows in a region occur in several phases, layers after layers of lavas are deposited and solidified one upon another and thus there is some sort of confusion about the layers or strata but actually these are not strata rather these are layers of lavas. Such examples may be seen anywhere in the Western Ghats where several lava flows during Cretaceous period resulted into the formation of thick basaltic cover having numerous layers of lavas of varying compositions. One can see such lava layers near Khandala or along the deeply entrenched valleys of Koyna river, Krishna river, Saraswati river etc.in and around Mahabaleshwar plateau.

(4) Since water does not penetrate the rocks easily and hence igneous rocks are less affected by chemical weathering but basalts are very easily weathered and eroded away when they come in constant touch with water. Coarse grained igneous rocks are affected by mechanical or physical weathering and thus the rocks are easily disintegrated and decomposed.

(5) Igneous rocks do not contain fossils because (i) when the ancient igneous rocks were formed due to cooling and solidification of molten rock materials at the time of the origin of the earth, there was no life on newly born earth and (ii) since the igneous rocks are formed due to cooling and solidification of very hot and molten materials and hence any remains of plants or animals (fossils) are destroyed because of very high temperature.

(6) The number of joints increases upward in any igneous rock. The joints are formed due to (i) cooling and contraction, (ii) expansion and contraction during mechanical weathering, (iii) decrease in superincumbent load due to removal of materials through denudational processes and (iv) earth movement caused by isostatic disturbances. Whenever these joints are plugged by minerals, the rocks become quite hard and resistant to weathering and erosion.

(7) Igneous rocks are mostly associated with the volcanic activities and thus they are also called as volcanic rocks. Igneous rocks are generally found in the volcanic zones.

Classification of Igneous Rocks

There are vast variations in the igneous rocks in terms of chemical and mineralogical characteristics, texture of grains, forms and size of grains, mode of origin etc. Thus, the igneous rocks are classified on several grounds in a variety of ways as follows :

(1) The most traditional method of the classification of the igneous rocks is based on the amount of silica ($Si\ O_2$). Thus, the igneous rocks are devided into two broad categories e.g. (i) **acidic igneous rocks** having more silica, e.g. granites, and (ii) **basic igneous rocks** having lower amount of silica, e.g. gabbro. It may be pointed out that silica content is not a measure of acidity.

(2) On the basis of the chemistry and mineralogical composition (light and dark minerals) the igneous rocks are classified into two dominant groups e.g. (i) **felsic igneous rocks** composed of the dominant minerals of the light group such as quartz and feldspar having rich content of silica. The word **felsic** has been derived from fell(s), feldspar plus ic., meaning

there by the dominance of feldspar mineral (ii) **mafic igneous rocks** composed of the dominant mineral of dark group such as pyroxenes, amphiboles and olivines, all of which have rich contents of magnesium and iron. The word **'mafic'** has been derived from magnesium and f (ferrous) for iron and ic meaning thereby the dominance of magnesium and ferrous (iron), (iii) **ultramafic igneous rocks** are characterised by the abundance of pyroxenes and olivine minerals, examples, peridotite (rich in pyroxene and olivine),and dunite (rich in olivine).

(3) The igneous rocks are also classified on the basis of texture of grains into 5 major groups.

(i) **Pegmatitic igneous rocks** (very coarse-grained igneous rocks) include very large crystals, several metres across. Examples, granites.

(ii) **Phaneritic igenous rocks** (coarse grained igneous rocks). The word phaneritic has been derived from Greek word **'phanero'**, meaning thereby visible.

(iii) **Aphanitic igneous rocks** (fine grained igneous rocks). The word aphanitic has been derived from the Greek word **'aphan'**, meaning thereby invisible, that is the grains of the aphanites are so minute that they cannot be seen by bare eyes.

(iv) **Glassy igneous rocks** (without grains of any size).

(v) **Porphyritic igneous rocks** (mixgrained igneous rocks).

(4) The igneous rocks are more commonly classified on the basis of the mode of occurrence into two major groups.

(i) **Intrusive igneous rocks**—(a) plutonic igneous rocks, (b) hypabyssal igneous rocks.

(ii) **Extrusive igneous rocks**—(a) explosive type, (b) quiet type.

1. Intrusive Igneous Rocks

When the rising magmas during a volcanic activity do not reach the earth's surface rather they are cooled and solidfied below the surface of the earth, the resultant igneous rocks are called intrusive igneous rocks. These rocks are further subdivided into two major groups of plutonic intrusive igneous rocks and hypabyssal intrusive igneous rocks on the basis of the depth of the place of cooling of magmas from the earth's surface. When the magmas are cooled and solidified very deep within the earth, the resultant rocks become plutonic but when the magmas are cooled just below the earth's surface , the rocks are called as hypabyssal igneous rocks.

(i) **Plutonic igneous rocks** are formed due to cooling of magmas very deep inside the earth. Since the rate of cooling of magmas is exceedingly slow because of high temperature prevailing there and hence there is sufficient time for the full development of large grains. Thus, the plutonic igneous rocks are very coarse-grained (pegmatites) rocks. Granite is best representative example of this category.

(ii) **Hypabyssal igneous rocks** are formed due to cooling and solidification of rising magma during volcanic activity in the cracks, pores, crevices, and hollow places just beneath the earth's surface, the resultant rocks are called as hypabyssal igneous rocks. The magmas are solidified in different forms depending upon the hollow places such as batholiths, laccoliths, phacoliths, lopoliths, sills, dikes etc. It should be remembered that these should not be taken as the types of igneous rocks because these are different shapes of solidified magmas.

(A) **Batholiths** are long irregular and undulating forms of solidified intruded magmas. They are usually dome-shaped and their side walls are very steep, almost vertical. The upper portions of batholiths are seen when the superincumbent cover is removed due to continued denudation but their bases are never seen (fig. 8.1) because they are buried deep within the earth. When exposed to the surface they are subjected to intense weathering and erosion and hence their surfaces become highly irregular and corrugated. Numerous batholithic domes were intruded below the Dharwarian sedimentaries in many parts of the peninsular India during pre-Cambrian period. Many of such batholithic domes have now been exposed well above the surface in many parts of the Chotanagpur plateau of India mainly Ranchi plateau where such batholithic domes are called as **Ranchi batholiths**. Murha pahar near Pithauriya village, to the north-west of Ranchi city, is a typical example of exposed Ranchi batholithic domes.

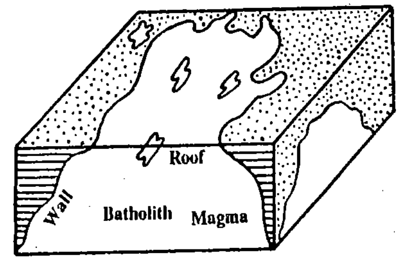


Fig. 8.1 : Diagramatic presentation of a granitic batholith.

(B) **Laccoliths**—The world laccolith has been derived from German word, **'laccos'** meaning thereby 'lithos' or rocks. Laccoliths are formed due to injection (intrusion) of magmas along the bedding planes of horizontally bedded sendimentary rocks. Loccoliths are of mushroom shape having convex summital form. The ascending gases during a volcanic eruption force the upper starta of the flat layered sedimentary rocks to arch up in the form of a convex arch or a dome. Consequently, the gap between the arched up or domed upper starta and the horizontal lower starta is injected with magma and other volcanic materials (fig. 8.2).

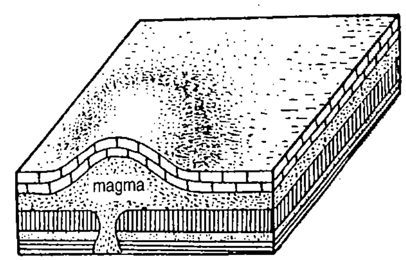


Fig. 8.2 : Diagramatic illustration of a typical laccolith.

(c) **Phacoliths** are formed due to injection of magma along the anticlines and synclines in the regions of folded mountains (fig. 8.3).

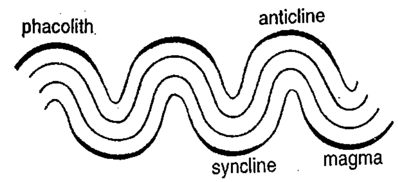
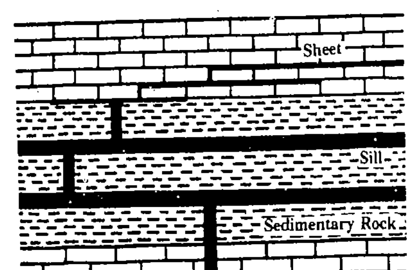


Fig. 8.3 : An example of phacoliths.

(D) **Lopoliths**—The word lopolith has been derived from German word 'lopas' meaning thereby a shallow basin or bowl shape body. When magma is injected and solidified in a concave shallow basin whose central part is sagged downward, the resultant form of solidified magmas is called a lopolith. The rocks of lopoliths are generally coarse-grained because of slow process of cooling of magmas.

(E) **Sills**—The word 'sill' has been derived from an Anglo-Saxon word 'syl' meaning thereby a ledge. The sills are usualy parallel to the bedding planes of sedimentary rocks. In fact, sills are formed due to injection and solidification of magmas between the bedding planes of sendimentary rocks. Thick beds of magmas are called sills whereas thin beds of magma are termed as **'sheets'**. The thickness of sills ranges between a few centimetres to several metres. When sills are tilted together with the sendimentary beds due to earth movements and are exposed to exogenous denudational processes, they form significant landforms like cuesta, hogbacks and ridges (figs. 8.4 and 8.8).



Intrusion of Lava

Fig. 8.4 : Intrusion of sills between the horizontal bedding planes of sedimentary rocks.

(F) **Dykes** represent wall-like formation of solidified magmas. These are mostly perpendicular to the beds of sedimentary rocks. The thickness of dykes ranges from a few centimetres to several hundred metres but the length extends from a few metres to several kilometres. A well defined dyke is observable across the palaeochannel and valley of the Narmada river near Dhunwadhar Falls (Bheraghat) near Jabalpur city. The relative resistance of dykes in comparison to the surrounding country rocks gives birth to a few interesting landforms e.g. (1) If the rocks of dykes are weaker and less resistant than the country rocks, the upper portion of dykes is more eroded than the country rocks, with the result a depression is formed, which, when filled up with water, is called a 'dyke lake' (fig. 8.5); (ii) If the rocks of dykes are more resistant than the country rocks, upstanding ridges and hills are formed because of more erosion of the country rocks (fig. 8.6) and (iii) If the rocks of dykes and country rocks are of uniform resistance, both are uniformly dissected and hence no significant landform is developed but the height is gradually reduced (fig. 8.7).

2. Extrusive Igneous Rocks

The igneous rocks formed due to cooling and solidification of hot and molten lavas at the earth's surface are called extrusive igneous rocks. Generally, extrusive igneous rocks are formed during fissure eruption of volcanoes resulting into **flood basalts.** These rocks are also called as **volcanic rocks.** Extrusive igneous rocks are generally fine-grained or glassy basalts because lavas after coming over the earth's surface are quickly cooled and solidified due to comparatively extremely low temperature of the atmosphere and thus there is no enough time for the development of grains or crystals. Basalt is the most significant representative example of extrusive igneous rocks. Gabbro and obsidian are the other important examples of this group. Extrusive igneous rocks are further divided into two major

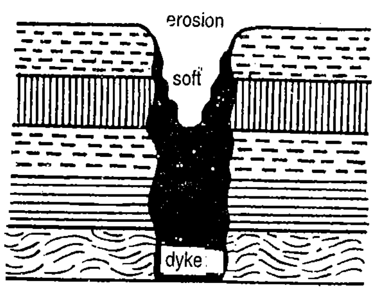


Fig. 8.5 : The resultant feature on dyke after erosion (the rocks of dykes being less resistant than the surrounding country-rocks).

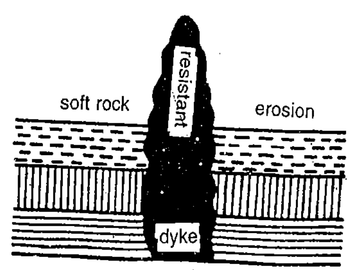


Fig. 8.6 : Form of a dyke after erosion (when the rocks of dyke are more resistant than the country-rocks).

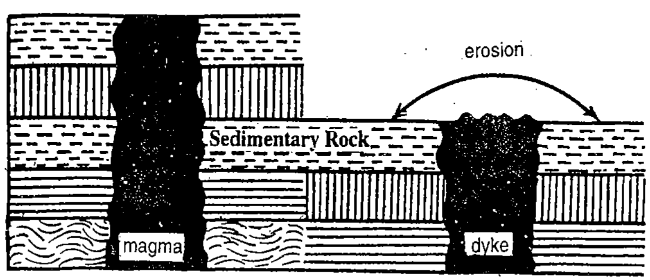


Fig. 8.7 : Form of a dyke after erosion (when the rocks of dyke and country-rocks are of uniform resistance).

subcategories on the basis of the nature of the appearance of lavas on the earth's surface e.g. (i) explosive type and (ii) quiet type.

(i) Explosive type—The igneous rocks formed due to mixture of volcanic materials ejected during explosive type of violent volcanic eruptions are called explosive type of extrusive igneous rocks. Volcanic materials include **'bombs'** (big fragments of rocks), **'lapilli'** (fragments of the size of a peas) and volcanic dusts and ashes. Fine volcanic materials, when deposited in aquatic condition, are called 'tuffs'. The mixture of larger and smaller particles after deposition is called **'breccia'** or **'agglomerate.'** These are more susceptible to erosion because these are not well consolidated.

(ii) **Quiet type**—The appearance of lavas through minor cracks and openings on the earth's surface is called **'lava flow'**. These lavas after being cooled and solidified form basaltic igneous rocks. Flood basalts resulting from several episodes of lava flow during fissure flows of volcanic eruption form extensive **'lava plateau'** and **'lava plains'** wherein several layers of basalts are deposited one upon another.

The thickness of lavas of the Columbia plateau of the states of Washington and Oregon (USA), spread over an area of about 6,45,000 km^2 (2,50,000 square miles), measures about 1,216 m (4,000 feet). The extensive lava flows during Cretaceous period covered an area of about 7,74,000 km^2 (3,00,000 square miles) of Peninsular India. Several beds of basaltic lavas are clearly observable all along the exposed sections of the Western Ghats mainly near Khandala (between Mumbai and Pune) and over Mahabaleshwar plateau.

Classification of Igneous Rocks on the Basis of Chemical Composition

Though the chemical composition of igneous rocks varies significantly from one group to another group but each type of igneous rock contains some amount of silica. Thus, on the basis of silica content, igneous rocks are divided into the following four types.

(i) **Acid igneous rocks** are those which carry silica content between 65 to 85 per cent. The average density varies from 2.75 to 2.8. Quartz and white and pink feldspar are the dominant minerals. Acid igneous rocks generally lack in iron and magnesium. On an average acid igneous rocks are hard and relatively resistant to erosion. Granite is the most significant example of this group of rocks. These rocks are light in weight and are used as building materials because of their less erosivity.

(ii) **Basic igneous rocks** contain silica content between 45 to 60 per cent. Their average density ranges from 2.8 to 3.0. Such igneous rocks are dominated by ferro-magnesium minerals. There is very low amount of feldspar. The rock is heavy in weight and dark in colour because of the dominance of iron content. Basic igneous rocks are easily eroded away when these come in regular contact with water. These rocks are fine grained igneous rocks. Basalt, gabbro, dolerite etc. are the typical examples of this group.

(iii) **Itremediate igneous rocks** are those in which silica content is less than the amount present in the acid igneous rocks but more than the basic igneous rocks. The average density ranges between 2.75 and 2.8. Diorite and andesite are the representative examples of this group of rocks.

(iv) **Ultra basic igneous rocks** carry silica conent less than 45 per cent but their average density varies from 2.8 to 3.4. Peridotite is the typical example of this group of rocks.

Classification of Igneous Rocks on the Basis of the Texture of Grains

The texture of the crystals (grains) of igneous rocks depends on 3 basic factors viz. (i) source region of the origin of magmas and lavas and places of their cooling and solidification; (ii) rate of cooling and solidification of magmas and lavas and (iii) quantity of water and gases (vapour) with hot and molten magmas and lavas. If magmas and lavas are cooled slowly and gradually the grains are well developed but if they are cooled and solidified at a very faster rate, grains are not well developed. The rate of cooling of magmas and lavas also depends upon several factors viz. (i) When magmas are cooled deep within the earth, the rate of cooling is exceedingly slow because of very high temperature prevailing there and hence very large and coarse grains are formed. (ii) If lavas are cooled at the surface of the earth, the rate of cooling is very fast because of very low temperature (in comparison to

the temperature of lavas) of outside environment and hence either grains are not formed at all, or if they are formed, they are so minute that they cannot be seen without the aid of a microscope. (iii) If magmas and lavas are associated with larger proportion of water vapour and gases, the rate of their cooling and consequent solidification is slowed down and hence larger grains are formed.

On the basis of the size of grains (texture) igneous rocks are generally divided into (i) **coarse-grained igneous rocks** (plutonic igneous rocks come under this category, grainite is the example), (ii) **fine-grained igneous rocks** (extrusive igneous rocks fall under this group, basalt is the example) and (iii) **medium-grained igneous rocks** (hypabyssal rocks are generally medium grained igneous rocks).

Alternatively, igneous rocks are divided into six sub-types on the basis of textural characteristics of the rocks e.g. (1) **pegmatitic igneous rocks** (or very coarse-grained igneous rocks; examples : plutonic igneous rocks e.g. pegmatitic granites, pegmatitic diorite, pegmatitic synite etc.); (2) **phaneritic igneous rocks** (or coarse-grained igneous rocks; plutonic igneous rocks; examples, granites, diorites etc.); (3) **aphanitic igneous rocks** (or fine grained igneous rocks; grains are so minute that they cannot be seen without the help of a microscope; examples basalt, felsite and the rocks of sills and dykes); (4) **glassy igneous rocks** (or grainless igneous rocks; usually there is general absence of grains; examples-pitchstones, obsidians, pumice, perlyte etc.); (5) **porphyritic igneous rocks** (or mixgrained igneous rocks and (6) **fragmental igneous rocks** (consisting of bombs, lapilli, breccia, volcanic dusts and ashes, tuffs etc.).

It is desirable to discuss in brief the major characteristics of granites and basalts which represent the intrusive and extrusive igneous rocks respectively.

Granites

Granites are the most significant example of the plutonic intrusive igneous rocks which are formed deep within the earth. Since the rate of cooling and solidification of magmas inside the earth is very slow because of very high temperature prevailing underground and hence granites become coarse-grained due to full development of large-sized grains. Granites are composed essentially of the minerals of quartz, feldspar, and mica but the most abundant mineral is feldspar, mainly orthoclase. Some times, the minerals are uniformly distributed and all of them are almost of the same size. Besides, albite, biotite, muscovite and hornblende are also found in granite rocks.

The granite family includes numerous types of rocks. These granitic rocks are differentiated on the basis of their texture and mineral composition. For example, hornblende granite (when hornblende mineral is most dominant), rhyolite granite, pumice granite, absidian granite, pitchstone granite etc. From the standpoint of chemical composition granites are acidic rocks wherein silica content ranges between 65 to 85 per cent. Granites are generally light in weight as their density varies from 2.75 to 2.8. Table 8.2 denotes percentage composition of different minerals in granites.

Table 8.2 : Mineral Composition of Granites

Minerals	feldspar	quartz	mica	hornblende	iron	others
Percentage	52.3	31.3	11.5	2.4	2.0	0.55

There is also wide range of colour variation in different types of granites. The colour variation is caused mainly because of the number of different minerals present in the rocks and the size of grains. Generally, granites are of light colour but if orthoclase mineral is present in abundance, the granites become pink to yellow of slightly reddish in colour. If dark coloured hornblende or biotite is a dominant mineral, the granites become of dark black or dark grey colour. Granites are generally resistant to erosion but when the rocks are well jointed, they are easily weathered and a very peculiar landform, **'tor'** is formed.

Basalts

Basalt is a very fine-grained, dark coloured extrusive igneous rock which is formed due to cooling and solidification of molten lavas at the suface of the earth. Some times, the cooling of lavas takes place so rapidly that no time is available for the

crystallization of basalt and hence no grains are formed, with the result the rock becomes **glassy basalt**. Basalts having grains, though very small rather minute, are called **aphanitic basalts**. Chemically basalts contain 45 to 65 per cent of silica content. Though the rock is heavy in weight but is more susceptible to chemical weathering and fluvial erosion. The dark colour of basalts is because of the abundance of iron. Feldspar is the most dominant mineral (46.2 per cent). Besides, augite (36.9 per cent), olivine (7.6 per cent), mineral iron (9.5 per cent) etc. (others-2.4 per cent) are other constituent minerals of basalts. Some times, polygonal cracks are developed in basalts due to contraction on cooling of lavas. Columnar jointings in basalts give birth to peculiar landforms characterized by uneven terrain surfaces.

Igneous Rocks and Landforms

Wide range of variations in the structure and composition of different types of igneous rocks largely controls the landscape characteristics of a given region. Basaltic plateaux and plains give birth to picturesque landscapes after continued weathering and erosion. Very deep and long gorges and canyons have been formed by the source segments of the Sarswati (draining towards Arabian Sea) and the Krishna rivers (draining towards the Bay of bengal(through their vigorous vertical erosion in the massive and thick basaltic covers of Mahabaleshwar plateau (about 100 km south-west of Pune). Similarly, Ullahas river has entrenched a very deep gorge in the basaltic plateau near Khandala (between Mumbai and Pune). The Yellowstone river has dug out a large canyon in the Columbian lava plateau of the U.S.A.

If the sills are intruded in the tilted or inclined sedimentary layers and if they are more resistant than the surrounding sedimentary rocks, the latter are enoded more than the former and thus resistant sills project above the general ground surface as **cuestas and hogbacks** (fig. 8.8).

Granitic rocks when subjected to **exfoliation** or **onion weathering** give birth to domeshaped landforms known as **exfoliation domes**. Several exfoliation domes of granite-gneisses are seen over the Ranchi plateau, for example, Kanke Dome near Ranchi city, a group of gneissic domes near Buti village (near Ranchi city).

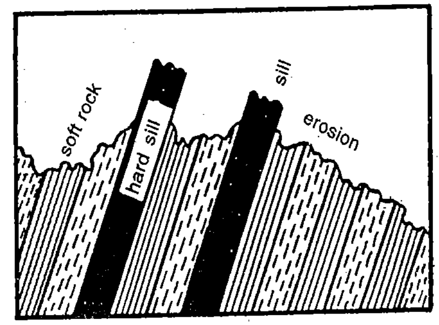


Fig. 8.8 : Landforms resulting from differential erosion of sills and surrounding rocks.

Massive granitic batholiths, when exposed to the earth's surface due to removal of superiencumbent load of overlying rocks through continued erosion, become interesting landforms. These dome-shaped hills project above the general surface. Such exposed granite-gneissic domes are very often found on Ranchi plateau. The granitic batholiths were intruded in the Dharwarian sedimentaries during Archaean period. After a long period of prolonged subaerial erosion the Dharwarian sedimentaries have been removed and the batholiths, regionally known as Ranchi batholiths, have been exposed well above the ground surface (50 to 100 m from the ground surface). Murha Pahar near Pithauria village, located to the north-west of Ranchi city, is a typical example of exposed grantic-gneissic batholithic domes. These exposed batholithic domes have suffered intense fracture because of the removal of superincumbent load of Dharwarian sedimentaries and hence resultant massive joints have been responsible for the development of different types of **'tors'**.

The differential erosion of the basaltic 'cap rocks' (fig. 8.9) produces interesting features like **mesas** and **buttes**. Mesa is a Spanish word meaning thereby a table. Mesas, in fact, is such a hill which is characterized by almost flat and regular top-surface but by very steep slopes (wall like) from all sides. When mesas are reduced in size due to continuous weathering and erosion, they are called buttes. Mesas are locally called as **'pats'** or **'patland'** on the

Chotanagpur plateau of Jharkhand. Jamira pat, Netarhat Pat, Bagru pat, Khamar pat, Raldami pat, Lota pat etc. are typical examples of lava-capped mesas of the western Chotanagpur High Lands. Mahabaleshwar plateau and Panchgani plateau (of the Western Ghats, Maharashtra) are characteristic representatives of well developed basaltic mesas. Grand Mesa and Raton Mesa of the state of Colorado, USA, are typical examples of extensive mesas. Grand Mesa rises more than 1500 m (5,000 feet) above the valley-floor of the Colorado and Gunnison rivers, Raton Mesa is more than 1824 m (6,000 feet) higher than the surrounding ground surface.

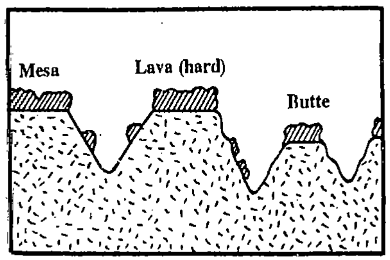


Fig. 8.9 : Lava-capped mesa and butte.

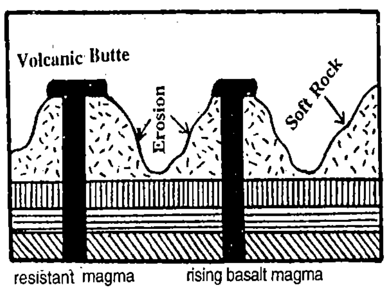


Fig 8.10 : An example of volcanic butte.

Some times magma is injected in a vertical columnar form in the sedimentary rocks. The upper portion of vertical column of magma appears as butte when the overlying rocks are eroded down, Such butte is called as **'volcanic butte'** (fig. 8.10).

The granitic rocks having rectangular joint patterns are weathered and eroded along the interfaces of their joints and thus smaller tables or blocks are separated by the eroded narrow clefts developed along the joints. Such granitic topography develops retangular drainage pattern (fig. 8.11).

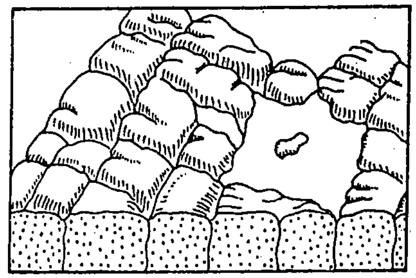


Fig. 8.11 : Development of rectangular topographic features on granitic rocks having rectangular joint pattern.

The igneous rocks having columnar joints give birth to hexagonal landforms after weathering and erosion (fig. 8.12).

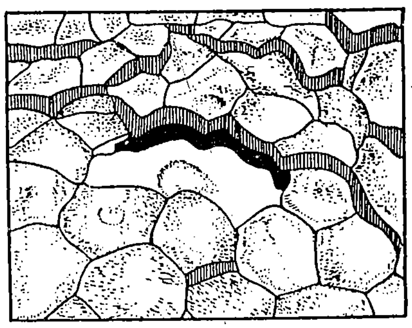


Fig. 8.12 : Development of hexagonal landforms on igneous rocks having columnar joints.

Well jointed granitic rocks give birth to very peculiar landforms such as **tors** which are piles of broken and exposed masses of hard rocks particularly granites having a crown of rock-blocks of different sizes on the top and clitters (trains of blocks) on the sides. The rock-blocks, the main components of tors, may be cuboidal, rounded, angular etc. in shape. They may be posted at the top of the hills, on the flanks of the hills facing a river valley or on flat basal platform (Savindra Singh, 1977, p. 93, National Goegrapher, Vol. 12 (1) (fig. 8.13).

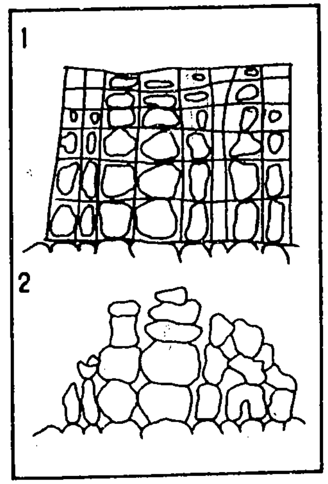


Fig. 8.13 : Formation of tors.

8.4 SEDIMENTARY ROCKS

Sedimentary rocks, as the word implies, are formed due to aggregation and compaction of sediments. The word 'sedimentary' has been derived from Latin word **sedimentum** which means **settling down.** Sedimentary rocks are also called as **stratified** or **layered rocks** because these rocks have different layers or strata of different types of sediments. Some times, layers are absent in some sedimentary rocks, for example loess. The sediments and debris derived through the disintegration and decomposition of the rocks by the agents of weathering and erosion are gradually deposited in water bodies. Thus, layers after layers of sediments and debris are regularly deposited. Continuous sedimentation increases the weight and pressure and thus different layers are consolidated and compacted to form sedimentary rocks.

According to P.G. Worcester (1948) 'sedimentary rocks, as sediment implies, are composed largely of fragments of older rocks and minerals, that have been more or less throughly consolidated and arranged in layers and strata.'

Characteristics of Sedimentary Rocks

Though most of sedimentary rocks are deposited due to continuous deposition of sediments in water bodies (lakes, ponds, basins, rivers and seas) but some times these are also formed at the land surface, e.g. loess, rocks of sand dunes, alluvial fans and cones. The following are the main characteristics of sedimentary rocks.

(1) Sedimentary rocks are formed of sediments derived from the older rocks, plant and animal remains and thus these rocks contain fossils of plants and animals. The age of the formation of a given sedimentary rock may be determined on the basis of the analysis of the fossils to be found in that rock.

(2) Sedimentary rocks are found over the largest surface area of the globe. It is believed that about 75 per cent of the surface area of the globe is covered by sedimentary rocks whereas igneous and metamorphic rocks cover the remaining 25 per cent area. Inspite of their largest coverage the sedimentary rocks constitute only 5 per cent of the composition of the crust whereas 95 per cent of the crust is composed of igneous and metamorphic rocks. Thus, it is obvious that the sedimentary rocks are important for extent, not for depth in the earth's crust.

(3) The deposition of sediments of various types and sizes to form sedimentary rocks takes place in certain sequence and system. The size of sediments decreases from the littoral margins to the centre of the water bodies or sedimentation basins. Different sediments are consolidated and compacted by different types of cementing elements e.g. silica, iron compounds, calcite, clay etc.

(4) Sedimentary rocks contain several layers or strata but these are seldom crystalline rocks.

(5) Like igneous rocks sedimentary rocks are not found in massive forms such as batholiths, laccoliths, dykes etc.

(6) Layers of sedimentary rocks are seldom found in original and horizontal manner. Sedimentary layers are generally deformed due to lateral compressive and tensile forces. The beds are folded and found in anticlinal and synclinal forms. Tensile and compressive forces also create faults due to dislocation of beds.

(7) Sedimentary rocks may be well consolidated, poorly consolidated and even unconsolidated. The composition of the rocks depends upon the nature of cementing elements and rock forming minerals.

(8) Sedimentary rocks are characterized by different sizes of joints. These are generally perpendicular to the bedding planes.

(9) The connecting plane between two consecutive beds or layers of sedimentary rocks is called **bedding plane.** The uniformity of two beds along a bedding plane is called **conformity** (i.e. when beds are similar in all respect). When two consecutive beds are not uniform or conformal, the structure is called **unconformity**. In fact, 'an unconformity is a break in a stratigraphic sequence resulting from a change in conditions that caused deposition to cease for a considerable time' (J.D. Collinson and D.B. Thompson, 1982). There are several types of unconformity e.g. (i) **non-conformity** (where sedimentary rocks succeed igneous or matamorphic rocks), (ii) **angular unconformity** (where horizontal sedimentary beds are deposited over previously folded or tilted strata), (iii) **disconformity** (where two conformable beds are separated by mere changes of sediment type), (iv) **paraconformity** (where two sets of conformable beds are separated by same types of sediments) etc.

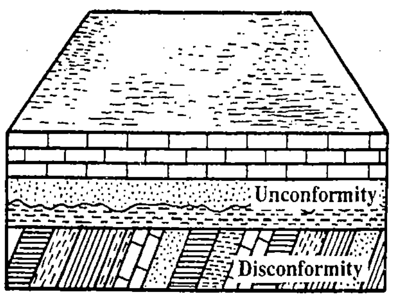


Fig. 8.14 : (A) disconformity and (B) angular unconformity.

(10) Sedimentation units in the sedimentary rocks having a thickness of greater than one centimetre are called **beds**. The upper and lower surfaces of a bed are called **bedding planes** or **bounding planes.** Some times the lower surface of a bed is called **sole** while the upper surface is known as **upper bedding surface.** There are further sedimentary units within a bed. The units having a thickness of more than one centimetre are called as layers or strata whereas the units below one centimetre thickness are known as **laminae.** Thus, several strata and laminae make up a bed. When the beds are deposited at an angle to the depositional surface, they are called **cross beds** and the general phenomena of inclined layers are called **cross lamination** or **cross bedding.**

(11) Soft muds and alluvia deposited by the rivers during flood period develop cracks when baked in the sun. These cracks are generally of polygonal shapes. Such cracks are called as **mud cracks** or **sun cracks.**

(12) Most of the sedimentary rocks are permeable and porous but a few of them are also non-porous and impermeable. The porosity of the rocks depends upon the ratio between the voids and the volume of a given rocks mass.

Classification of Sedimentary Rocks

1. On the basis of the nature of sediments

(1) Mechanically Formed or Clastic Rocks
- (i) Sandstones
- (ii) Conglomerates
- (iii) Clay rock
- (iv) Shale
- (v) Loess

(2) Chemically Formed Sedimentary Rocks
- (i) Gypsum
- (ii) Salt rock

(3) Organically Formed Sedimentary Rocks
- (i) Limestones
- (ii) Dolomites
- (iii) Coals
- (iv) Peats

2. On the basis of transporting agents

(1) Argillaceous or Aqueous Rocks
- (i) Marine rocks
- (ii) Lacustrine rocks
- (iii) Riverine rocks

(2) Aeolian Sedimentary Rocks
- (i) Loess

(3) Glacial Sedimentary Rocks
- (i) Till
- (ii) Moraines

(1) Mechanically Formed Sedimentary Rocks

Previously formed rocks are subjected to mechanical or physical disintegration and thus the rocks are broken into fragments of different sizes. These are called fragmental rock materials or clastic materials which become source materials for the formation of **clastic sedimentary rocks.** These materials are obtained, transported and deposited at suitable places by different exogenous processes (geological agents) like running water (rivers), wind, glaciers, and sea waves. These materials are further broken down into finer particles due to their mutual collision during their transportation. These materials after being deposited and consolidated in different water bodies (sedimentation basins, lakes, seas, rivers etc.) form sedimentary rocks known as clastic sedimentary rocks. Sandstones, conglomerates, silt, shale, clay etc. are important members of this group.

(1) **Sandstones** are formed mostly due to deposition, cementation and consolidation of sand grains. Sand grains are divided into five categories on the basis of their size. When sand grains are deposited in water bodies and are aggregated and consolidated by cementing elements (e.g. silica, calcium, iron oxide, clay etc.), sandstones are formed. The colour of sandstones varies according to the nature and amount of cementing elements and minerals. Sandstones become red or gray when cemented by iron oxides but these become white or gray when calcium carbonate dominates. Sandstones become hard and resistant to erosion when cemented by silica. On an average sandstones are porous rocks and water easily percolates through them. On the basis of textural and mineralogical characteristics sandstones are classified into (i) **quartz arenites** (arenite from Latin word arena, meaning thereby sand) composed entirely of quartz grains, (ii) **arkose sandstones** (feldspar being the dominant mineral), (iii) **lithic arenites** (composed of fine grained rock fragments, mostly derived from shales, slates, schists and volcanic rocks) and (iv) **graywackes sandstones** (composed of quartz, feldspar and rock fragments surrounded by a fine-grained clay matrix).

Table 8.3 : Classification of Sands by Grain Size

Sand Types	Grain Size (mm)
(i) Very coarse sand	1.0 to 2.0
(ii) Coarse sand	0.5 to 1.0
(iii) Medium sand	0.25 to 0.5
(iv) Fine sand	0.125 to 0.25
(v) Very fine sand	0.0625 to 0.125

(2) **Conglomerates** are formed due to cementation and consolidation of pebbles of various sizes together with sands. 'The term conglomerate is applied to cemented fragmental rocks containing rounded fragments such as pebbles and boulders; if the fragments are angular or subangular, the rock is called breccia' (A. Holmes and D.L. Holmes, 1978). Polished and rounded fragments are called pebbles having a diameter upto 4-64 mm while those fragments which have the diameter upto 256 mm or more are called boulders. The rock fragments after being cemented by clay form **gravels.** Though gravels are found in layers but there is general absence of uniformity. When the rounded fragmental materials are cemented by quartz, the resultant rocks become conglomerates. If conglomerates are formed due to their cementation by silica, they become very hard rocks and resistant to erosion.

Table 8.4 : Classification of gravels by grain size

Gravel type	Grain size (mm)
Boulder	more than 256
Cobble	256-64
Pebble	64-4
Granule	4-2

(3) **Clay rock and shale**—Clay rocks are formed due to deposition and cementation of fine sediments. The rocks formed of the sediments having the grain size of 0.0312 mm to 0.004 mm are called **silts** whereas **clays** are formed when the sediments of the grain size of 0.004 mm to 0.00012 mm are cemented and consolidated. Silt and clay are soft and weak rocks but they are definitely impervious. Clay rocks are formed exclusively of kaolin minerals. Since clay rocks are not soluble and hence these are least affected by chemical weathering but these are easily eroded away. Pure clay rocks are of white colour but they change in colour when they are mixed with the impurities of other materials. Shales are formed due to consolidation of silt and clay. Shales are formed of

thin laminae which are easily separated. Shales are impermeable rocks and therefore they hold mineral oil above them.

(2) Chemically Formed Sedimentary Rocks

Running water contains chemical materials in suspension. When such chemically active water comes in contact with the country rocks in its way, soluble materials are removed from the rocks. Such materials are called chemically derived or formed sediments. These chemical materials after being settled down and compacted and cemented form chemical sedimentary rocks such as gypsum and salt rocks.

(3) Organically Formed Sedimentary Rocks

The sediments derived from the disintegration or decomposition of plants and animals are called organic sediments. These sediments after being deposited and consolidated form organic sedimentary rocks. On the basis of lime and carbon content these rocks are divided into 3 categories e.g. (i) clacareous rocks, (ii) carbonaceous rocks and (iii) siliceous rocks.

(1) **Calcareous rocks** are formed due to deposition and consolidation of sediments derived from the skeletons and remains of those animals and plants which contain larger portion of lime. Limestone is the most significant characteristic example of calcareous rocks. Limestones are formed in the following manner—

(i) Calcium oxide (CaO) reacts with water (H2O) to form calcium hydroxide ($Ca(OH)_2$)

$$CaO + H_2O \rightarrow Ca(OH)_2$$

(ii) Calcium hydroxide reacts with carbon dioxide (CO_2) to form calcium carbonate ($CaCO_3$)

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The calcareous rocks are collectively called as **carbonate rocks** or simply **carbonates.** Lime stones ($CaCO_3$) or calcium carbonate, magnesium carbonate, ($MgCO_3$) and dolomite ($CaMg(CO_3)_2$) are important carbonate rocks. Limestones are found in both the forms-thinly bedded and thickly bedded. They are formed of both fine sediments as well as coarse sediments. The most dominant minerals are calcite (of hexagonal shape) and argonite (of orthorhombic shape). Since limestones are formed of chemically soluble materials and hence these are most susceptible to chemical weathering as follows:

(i) Carbon dioxide (CO_2) after being dissolved in water form carboric acid (H_2CO_3).

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

(ii) Carbonic acid reacts with limestone ($CaCO_3$) to form calcium bi-carbonate ($Ca(HCO_3)_2$)

$$H_2CO_3 + CaCO_3 \rightarrow Ca(HCO_3)_2$$

Though limestones are very weak rocks in humid regions because these easily dissociate when they come in contact with water but these become resistant rocks in hot and dry climate because of the fact that limestones have uniform and homogeneous structure and hence these are not affected by differential expansion and contraction due to temperature changes. The rocks having the carbonates of both calcium and magnesium are known as dolomites which are less soluble than limestones. These carbonate rocks, after weathering and chemical erosion, give birth to **karst topography.** Chalk is another form of carbonate rocks but it is softer and more porous than limestone. Chalks are formed due to precipitation of carbonate materials which are derived from micro-organisms like foraminifera.

(2) **Carbonaceous rocks** are dominated by carbonic materials which represent vegetation remains. These rocks are formed due to transformation of vegetations because of their burial during earth movements and consequent weight and pressure of overlying deposits The initial form of carbonaceous rocks is peat which is of a dark gray colour. Vegetation remains can be seen with the help of microscope. The other subsequent forms of carbonaceous sedimentary rocks are lignite, bituminous and anthracite coals with greater proportion of carbon and darker colour. Coals are also found in stratified form wherein coal layers are known as **coal seams.** Carbonaceous rocks are more important economically than geomorphologically.

(3) **Siliceous rocks** are formed due to dominance of silica content. Siliceous rocks are formed due to aggregation and compaction of wastes derived from sponge and radiolarian organisms and diatom plants. Geysreites are also deposits of silica around geysers. Geyserites have different colours

e.g. white, gray or pink due to impurities of deposition of various types of sediments.

Classification on the Basis of Transporting Agents

Sedimentary rocks are also classified on the basis of transporting agents or geological agents (e.g. running water or rivers, wind, glaciers, oceanic currents and sea waves). These agents of transportation obtain different types of sediments and deposit them in suitable places where sediments are consolidated and cemented to form sedimentary rocks of various sorts. Based on major transporting agents, sedimentary rocks are divided into argillaceous, aeolian and glacial rocks.

(1) **Argillaceous rocks** are also called as **aqueous rocks** because these are formed in water areas. Aqueous word has been derived from Latin world **'aqua'** which means **'water'**. Aqueous rocks are called argillaceous rocks because of the dominance of clay in the rocks. In fact, the word argillaceous has been derived from Latin word **'argyll'** or **'argill'** meaning thereby clay. Argillacous rocks are characterized by their general softness. These are essentially impervious rocks. Argillaceous rocks are further divided into 3 sub-types on the basis of the places of their formation. (i) **Marine argillaceous sedimentary rocks** are formed due to deposition and consolidation of sediments in the oceans and seas mainly in their littoral zones. The process of sedimentation in marine environment is well ordered and sequential in character. In other words, the size of particles deceases progressively from the coastal lands towards the seas or the oceans e.g. the order of the particles from the coast lands towards the sea is of boulders, cobbles, pebbles, granules, sands, silts, clay and lime.It is evident that as we go away from the coast lands towards the sea, the size of sediments becomes so fine that they are kept in suspension with oceanic water. Sandstones, limestones, dolomites and chalk are the most important examples of marine argillaceous sedimentary rocks. (ii) **Lacustrine argillaceous sedimentary rocks** are formed due to deposition and consolidation of sediments in lake environment. Generally, the sediments are deposited at the floor of the lakes. The lacustrine rocks may be seen in 3 conditions viz. (a) if the lake becomes dry, (b) if the floor of the lakes is raised due to earth movements and (c) if the whole lake is filled up with sediments. It may be pointed out that there is no ordering in the size of sediments as is the case with the seas and the oceans. (iii) **Riverine argillaceous sedimentary rocks** are those which are formed due to deposition of sediments in the riverine environment. The sediments may be deposited in the beds of the rivers and in the flood plains. Such deposition includes alluvia which are dominated by clay. Alluvia are deposited on either side of the alluvial rivers during floods. It may be pointed out that alluvial deposits are renewed almost every year. Alluvial deposits develop polygonal cracks due to their exposure to insolation.

(2) **Aeolian sedimentary rocks** are formed due to deposition of sands brought down by the wind. Pre-existing rocks are greatly disintegrated due to mechanical weathering in the hot and dry regions. This process resuls in the formation of immense quantity of sands of different sizes. Winds pick up these sands and deposit them at various places. The particles are further comminuted into finer particles due to attrition while they are being transported from one place to another. Continuous deposition of sands results in the formation of different layers but these layers are not well consolidated as is the case with the argillaceous rocks. Sometimes, there is complete absence of layers in the airborn or aeolian sedimentary rocks. Loess is the most important member of this group. Loess is, in fact, the heaps of unconsolidated fine materials. There is general absence of laminae and layers in the loessic formation. These are soft and porous rocks. Water can easily infiltrate in the loessic deposits. Thus, loess is easily eroded away. Thus, most outstanding characteristic feature of loess is that the entire loessic mass may stand like a vertical cliff or wall. The best example is observable on the left and right banks of the palaeochannel and valley of the Narmada river at Dhunwadhar falls (Bheraghat) near Jabalpur (M.P.) where the loessic banks rise 20 to 25 m from the valley floor and form complete vertical free-face cliff section. The sediments are so loosely arranged that they can be removed even by using fingers. The most extensive loessic deposits are found in north China where the thickness of sediments is of several hundred metres. The deposits are of yellow colour and are rich in lime and hence these look like fine loam soils. The Yellow river (formerly Hwang Ho) and its tributaries easily erode the loessic deposits and hence the river be-

comes overloaded and causes frequent severe floods. It may be pointed out that the Yellow river of China carries the largest amount of sediments (1640 million tonnes per year) in the world. The river is called "Yellow" because of the yellow colour of the sediments which are derived through the erosion of yellow coloured Chinese loess.

(3) **Glacial rocks:** The materials deposited by glaciers are called glacial drifts which are deposited in four conditions and therefore there are four types of morainic deposits viz. (i) **lateral moraines,** when glacial materials are deposited on either side of a glacier, (ii) **medial moraines,** when glacial sedimentary materials are deposited along the joining glaciers (the lateral moraines of joining ice streams merge and form a single medial moraine in the middle of larger flows—F. Press and R. Siever, 1978), (iii) **ground moraines,** when the glacial materials are deposited in the bed of the glacier and (iv) **terminal moraines** (these are formed when the glacier is ablated and materials are deposited therein (fig. 8.15).

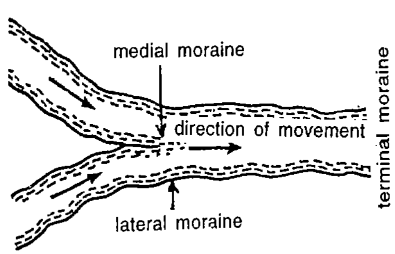


Fig. 8.15 : Different types of moraines.

8.5 METAMORPHIC ROCKS

Meaning and Characteristics

'Metamorphic rocks include rocks that have been changed either in form or composition without disintegration' (P.G. Worcester, 1948). Metamorphic rocks, as the word 'metamorphism' implies, are formed due to changes in the forms of other rocks. Originally, the word metamorphism has been derived from the word **'metamorphose'** which means change in form. In fact, metamorphic rock means complete alteration in the appearance of pre-existing rocks due to change in mineral composition and texture through temperature and pressure. Metamorphic rocks are generally formed due to changes in form of sedimentary and igneous rocks. Some times, even previously formed metamorphic rocks are again metamorphosed.

It may be mentioned that the process of metamorphism simply means change in form but in geology this is used for specific meaning and condition. For example, the form and composition of a rock may change during the process of metamorphism but there is no disintegration and decomposition of the rock. When already formed metamorphic rocks are again metamorphosed, the process is known as **remetamorphism.** This becomes possible only when the temperature becomes exceedingly high and the weight and pressure of overlying rocks becomes enormous due to orogenetic movements. When the rocks are metamorphosed to the greatest intensity, the process is known as **intense metamorphism.** Dharwarian sedimentary rocks of peninsular India have suffered intense metamorphism.

The change in the form of the rocks during the process of metamorphism takes place in two ways viz. (i) **physical metamorphism** pertaining to changes in textural composition of the rocks and (ii) **chemical metamorphism,** leading to changes in the chemical composition of the rocks. Some times, both the processes of metamorphism become operative together. It may be pointed out again that during the process of metamorphism there may be complete alteration in the form of the rocks, the form and nature of minerals may change, old minerals may be rearranged and changed in new minerals, new minerals may be added, pre-existing minerals may be transformed into other forms due to melting caused by very high temperature, pre-existing crystalline rocks may be recrystallized but there would be no disintegration and decomposition of the rocks in any circumstance.

Some times, the form of the rocks is so changed due to intense metamorphism that it becomes difficult to find out the original form of the rocks. Some rocks, after metamorphism, become harder than their original forms, such as marbles from limestones and quartzites from sandstones. Marbles and

quartzites are relatively more resistant to erosion than their parent rocks, limestones and sandstones. Fossils of sedimentary rocks are also destroyed during the process of metamorphism.

'Unlike igneous rocks, the texture of metamorphic rocks is the result of recrystallization or conversion of one mineral to another in the solid state' (Presss and Siever, 1978). Foliation, defined as streaking or parallel arrangement of the constituent crystals (of metamorphic rocks) which generally 'cut the rocks at an angle to the bedding planes of the original sediments of the parent rocks' is the most common characteristic feature of metamorphic rocks. The coarse grained metamorphic rocks are imperfectly foliated (e.g. gneisses from granites) while fine-grained metamorphic rocks are perfectly foliated (e.g. schists from shales). The property of metamorphic rocks to part or split along the bedding planes is known as **fissility.** The structure of the presence of numerous closely spaced parallel planes of splitting is known as **cleavage.** In fact, cleavage is a special type of foliation which denotes the tendency of a rock to cleave or break or split into moderately thin sheets or laminae. Schistocity refers to the growth of larger crystals and segregation of some minerals into lighter and darker bands.

Agents of Metamorphism

(i) **Heat** is the most important factor for the development of metamorphic rocks from pre-existing parent rocks. It may be pointed out that mineral composition is entirely changed due to intense heat but the rocks are seldom melted. The required heat for metamorphism is available during vulcanicity when hot and molten magmas ascend through the crustal rocks.

(ii) **Compression** resulting from convergent horizontal movement caused by endogenetic forces causes folding in rock beds. Thus, the resultant pressure from compressive forces and consequent folding changes the form and composition of parent rocks. This factor becomes operative during mountain building.

(iii) **Solution**—Chemically active hot gases and water while passing through the rocks change their chemical composition. Magmatic water and water confined in the beds of sedimentary rocks also help in introducing chemical changes in the rocks.

Types of Metamorphism

The agents and factors of metamorphism some times operate separately and some times work together. The processes of metamorphism may be classified on the bases of (i) the nature of the agents of metamorphism and (ii) place and area involved in metamorphism.

(1) On the basis of the nature of agents

(i) Thermal metamorphism (due to heat)

(ii) Dynamic metamorphism (due to pressure)

(iii) Hydro-metamorphism (due to hydro-static pressure.

(iv) Hydro-thermal metamorphism (due to water and heat)

(2) On the basis of place or area

(i) Contact metamorphism (localized in area)

(ii) Regional metamorphism (involving larger area)

(3) Composite classification

(i) Contact or thermal metamorphism

(ii) Dynamic and regional metamorphism

(iii) Hydro-metamorphism

(iv) Hydro-thermal metamorphism.

1. Contact Metamorphism

Contact metamorphism takes place when the mineral composition of the surrounding rocks known as **aureoles** is changed due to intense heat of the intruding magmas. This process of metamorphism is called contact metamorphism because of the fact that metamorphism occurs when the rocks come in contact with the intruding magmas. This process is also called as **thermal metamorphism** because the rocks are changed in their forms due to high temperature of the intruding magmas. Such metamorphism occurs during volcanic activity when the physical properties of the surrounding rocks are changed due to intense heat of the rising magmas of dykes (fig. 8.16). Some times, the rocks coming in contact with the intruding magmas are also changed in their chemical composition due to some water and water vapour associated with the intruding magmas. Limestones are changed to marbles due to contact metamorphism.

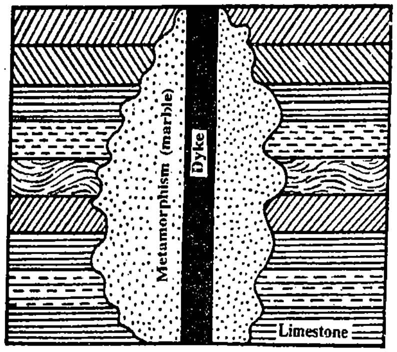


Fig. 8.16 : Illustration of contact or thermal metamorphism.

As stated above, the rocks surrounding the igneous intrusions are altered due to intense heat of magmas. The margins of the altered rock around igneous intrusions are called **aureoles** the width of which (i.e. the dimension of metamorphosed rocks) depends upon mainly two factors e.g. (i) the temperature of intruding magma, and (ii) the depth of magma intrusions in the crust.

2. Regional Metamorphism

When the rocks are altered in their forms in extensive area the process is called regional metamorphism. Such metamorphism is also known as **dynamic metamorphism** because pressure plays dominant role in the alteration of the form of the rocks though temperature is also an important factor. The sedimentary rocks are folded due to compressive forces during the period of mountain building. This process results in intense pressure and heat which ultimately alter the original form of the concerned rocks. Dynamic metamorphism leads to crystallization in the rocks and if the rocks are already crystallized, they are recrystallized. Regional metamorphism is a characteristic feature of mountainous area. Regional metamorphism is further divided into two sub-types viz. (i) **dynamic regional metamorphism,** when the rocks are metamorphosed due to compressive forces and resultant high pressure caused by convergent horizontal movements (fig. 8.17), and (ii) **static regional metamorphism,** when the

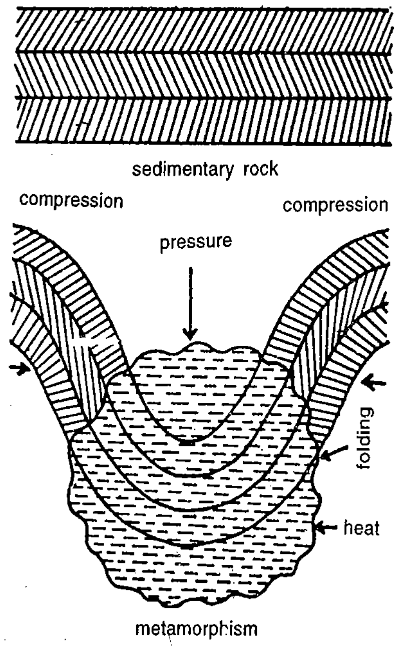


Fig. 8.17 : Example of dynamic regional metamorphism.

rocks are metamorphosed at greater depth due to intense pressure and weight of overlying rocks (superincumbent load) (fig. 818).

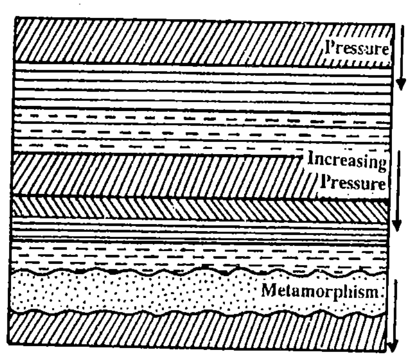


Fig. 8.18 : Example of static regional metamorphism.

3. Hydro-Metamorphism

The alteration in the composition of the rocks due to hydrological factor takes place in a number of ways e.g. (i) When the chemically active water (solvent) passes through the countryrocks, there occur several chemical changes in the rocks due to varied chemcial reactions. (ii) The storage of immense volume of water in big reservoirs exerts high pressure on the underlying rocks and thus the rocks are altered in their forms due to pressure of overlying huge volume of water. Such type of metamorphism is known as hydrostatic matamorphism.

4. Hydro-Thermo-Metamorphism

The minor alteration in the physical and chemical composition of the rocks caused by the weight and pressure of water mass and chemically active hot gases and water vapour is called hydro-thermo-metamorphism which is, in fact, geographically less important.

Classification of Metamorphic Rocks

The classification of metamorphic rocks is easier and less complicated because generally these are classified on the basis of those original or parent rocks from which they have been formed. It is obvious that the parent rocks in relation to metamorphic rocks are sedimentary and igneous rocks. Some times the process of metamorphism becomes so intense and the parent rocks are so greatly metamorphosed that it becomes very difficult to trace the true nature of the rocks before their metamorphism. Besides such conditions, metamorphic rocks are divided into 2 broad categories.

(1) **Meta-sedimentary or para-metamorphic rocks** are those metamorphic rocks which are formed due to alteration of the forms of sedimentary rocks, e.g. marbles from limestones, quartzites from sandstones, slates from shales and clays etc.

(2) **Meta-igneous or ortho-metamorphic rocks** represent those metamorphic rocks which are formed due to changes in the form of igneous rocks, e.g. gneisses from granites, serpentine from gabbro, basic granulites from amphibolites, eclogite from basaltic rocks etc.

Metamorphic rocks are also classified on the basis of foliation into (i) foliated metamorphic rocks e.g. slates, gneisses and schists and (ii) non-foliated metamorphic rocks, e.g.quartzites, marbles, serpentines etc.

Important Metamorphic Rocks

Marbles

Marbles are generally formed due to changes in limestones because of temperature changes. Limestones are transformed into marbles due to contact thermal metamorphism during volcanic activity. Limestones are also metamorphosed due to dynamic regional metamorphism wherein calcium carbonates and other finer particles are changed into calcite. In fact, the metamorphism of limestones to marble involves a number of changes in the mineralogical characteristics of limestones. For example, the reaction between calcium carbonate of limestone during the process of metamorphism produces a new mineral known as wollastonite or calcium silicate. The colour of marbles depends upon the nature of parent limestones. If the original limestones are devoid of any impurities, the resultant marbles become pure white in colour. The colour changes due to impurities of other materials in the parent limestones. The marbles of Carrara region of Italy are pure white while the marbles exposed along both the banks of magnificent and stupendous gorge of the Narmada river at Bheraghat near Jabalpur (M.P.) show different grades of colour though white and pink colours dominate.

Dolomites and chalks are also metamorphosed to marbles due to excessive heat but these have only local importance. Marbles are more resistant to erosion than their parent limestones. Besides, they are economically valuable rocks because they are used as building materials for the construction of very important buildings as monuments. For example, Tajmahal of Agra and Dilwara temple of Mount Abu (Rajasthan) have been built of marbles.

Schist

Schists are fine grained metamorphic rocks and are characterized by well developed **foliation.** The word schist has been derived from French word **schiste** and German word **schistose** which means to split. When shale sedimentary rocks are subjected to intense compressive force and consequent folding and pressure, the clay and other minerals of the original shale rocks are changed to mica minerals due to high pressure and temperature and thus shales

are changed to schists. During the process of regional metamorphism the schists get foliated. Schists are named on the basis of dominant minerals e.g. mica-schists, hornblende schists, quartz schists etc.Mica-schist is the comonest type of schist rocks because it is formed from argillaceous shale sedimentary rock which is a very common rock and is abundantly found on the earth's surface.Mica-schist is composed of muscovite, biotite, plagioclase and some times garnet. Hornblend schists are formed from basaltic rocks and contain hornblende, plagioclase and some quartz minerals. Green schists are composed of green minerals such as hornblende and chlorites, provided that the rocks are well foliated. If the schists rich in green minerals are poorly foliated,they are called greenstones. The term **metabasite** is used to name those schists which are formed from basalts or dolerites.

Slate

Slates are formed due to dynamic regional metamorphism of shales and other argillaceous rocks. Slates are characterized by the 'presence of numerous closely-spaced parallel planes of splitting or **cleavage**' but the splitting planes of slates are not parallel to the bedding planes rather they form angle with the bedding planes. Some times the angle between the splitting planes and bedding planes becomes obtuse angle. Such structure of slates is known as slaty cleavage (fig. 8.19) which is formed due to compressive pressure exerted on the rocks. The cleavage is always at right angle to the direction of compression. Slates, if subjected to further intense metamorphism due to immense compression, are changed to phyllites or fine-grained mica-schist. 'Slates, in fact, may be regarded as a special type of fine-grained schist' (S.W. Wooldridge and R.S. Morgan), Slates are not as much resistant to erosion as are schists and gneisses. They are of varied colours.

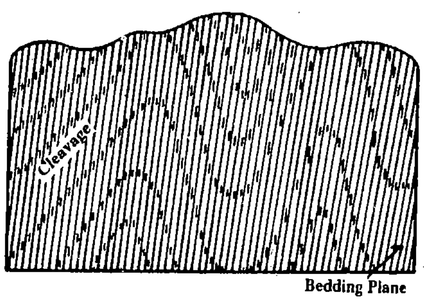


Fig. 8.19 : Relationship between cleavage planes and bedding planes of slates.

Gneiss

Gneisses are coarse-grained metamorphic rocks which are formed due to metamorphism of conglomerates (sedimentary rocks) and coarse gained granites (igneous). Feldspar is the most dominant mineral of gneisses. Like schists, gneisses are also foliated rocks but the foliation is open and is some times absent. There are several types of banded gneisses, which some times pass into augen gneiss. The process of granitization or granitification means the transformation of mica-schist to gneiss. Gneissic rocks produce, after weathering and erosion, rounded topography.

Quartzites

Quartzites are generally formed from sandstones which are dominated by the abundance of quartz mineral. During the process of metamorphism the voids within the sandstones are compacted due to excessive compression and heat and are also filled with silica, with the result quartzites become very hard and resistant to erosion. When quartzites lie over weaker sedimentary rocks like shales or limestones as caprocks, they form stupendous wall-like escarpments. Kaimur escarpment along the left bank of the Son river (in M.P. and Bihar), Bhander escarpments (Satna and Panna districts of M.P.), Rewa escarpments facing the Ganga plains etc. have been formed due to resistant caprocks of quartzitic sandstones resting over shale lithology. 'The term quartzite is also extended to sandy rocks which have been subjected to cementation by silica deposited from solution. Such rocks are generally softer than the true metamorphic quartzites and often behave more like normal sandstones, breaking down into sandy soils' (S.W. Wooldridge and R.S. Morgan, 1959).

9

VULCANICITY AND VOLCANOES

9.1 CONCEPT OF VULCANICITY

The terms volcanoes, mechanism of volcanoes and vulcanicity are more or less synonymous to common man but these have different connotations in geology and geography. 'A volcano is a vent, or opening, usually circular or nearly circular in form, through which heated materials consisting of gases, water, liquid lava and fragments of rocks are ejected from the highly heated interior to the surface of the earth' (P.G. Worcester, 1948). According to A. Holmes and D.L. Holmes (1978) a volcano is essentially a fissure or vent, communicating with the interior, from which flows of lava, fountains of incandescent spray or explosive bursts of gases and volcanic ashes are erupted at the surface. On the other hand, 'the term vulcanicity covers all those processes in which molten rock material or magma rises into the crust or is poured out on its surface, there to solidify as a crystalline or semicrystalline rock' (S.W. Wooldridge and R.S. Morgan, 1959). Some scientists have also used the term of vulcanism as synonym to the term of vulcanicity. For example, P.G. Worcester (1948) has maintained that 'vulcanism includes all phenomena connected with the movement of heated material from the interior to or towards the surface of the earth.'

It is apparent from the above definitions of volcano and vulcanicity (vulcanism) that the later (vulcanicity) is a broader mechanism which is related to both the environments, endogenetic and exogenetic. In other words, vulcanicity 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. It is evident that the vulcanicity has two components which operate below the crustal surface and above the crust. The endogenetic mechanism of vulcanicity includes the creation of hot and liquid magmas and gases in the mantle and the crust, their expansion and upward ascent, their intrusion, cooling and solidification in various forms below the crustal surface (*e.g.* batholiths, laccoliths, sills, dykes, lopoliths, phacoliths etc.) while the exogenous mechanism includes the process of appearance of lava, volcanic dusts and ashes, fragmental material, mud, smoke etc. in different forms *e.g.* fissure flow or lava flood (fissure or quiet type of volcanic eruption), violent explosion (central type of volcanic eruption), hot springs, geysers, fumaroles, solfatara, mud volcanoes etc. It may be, thus, concluded that the vulcanicity is a broader mechanism which includes several events and processes which work below the crust as well as above the crust whereas volcano is a part of vulcanicity (vulcanism).

9.2 COMPONENTS OF VOLCANOES

Volcanoes of explosive type or central eruption type are associated with the accumulated vol-

canic materials in the form of **cones** which are called as **volcanic cones** or **simply volcanic mountains.** There is a vent or opening, of circular or nearly circular shape, almost in the centre of the summital part of the cone. This vent is called as volcanic vent or volcanic mouth which is connected with the interior part of the earth by a narrow pipe, which is called as **volcanic pipe.** Volcanic materials of various sorts are ejected through this pipe and the vent situated at the top of the pipe. The enlarged form of the volcanic vent is known as **volcanic crater** and **caldera.** Volcanic materials include lavas, volcanic dusts and ashes, fragmental materials etc. (fig. 9.1).

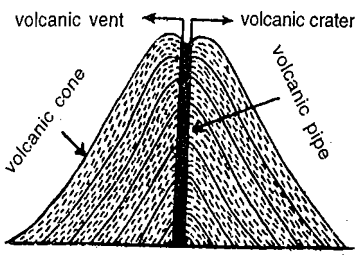


Fig. 9.1 : Different components of a volcano.

9.3 TYPES OF VOLCANOES

There is a wide range of variations in the mode of volcanic eruptions and their periodicity. Thus, vocanoes are classified on the basis of (i) the mode of eruption and (ii) the period of eruption and the nature of their activities.

(1) Classification on the Basis of the Mode of Eruptions

(i) Central eruption type or explosive eruption type.

(a) Hawiin type

(b) Strombolian type

(c) Vulcanian type

(d) Peleean type

(e) Visuvius type

(ii) Fissure eruption type or quiet eruption type

(a) Lava flood or lava flow

(b) Mud flow

(c) Fumaroles

(2) Classification on the Basis of Periodicity of Eruptions

(a) Active volcanoes

(b) Dormant volcanoes

(c) Extinct volcanoes

Classification on the basis of the nature of volcanic eruptions

Volcanic eruptions occur mostly in two ways viz. (i) violent and explosive type of eruption of lavas, volcanic dusts, volcanic ashes and fragmental materials through a narrow pipe and small opening under the impact of violent gases and (ii) quiet type or fissure eruption along a long fracture or fissure or fault due to weak gases and huge volume of lavas. Thus, on the basis of the nature and intensity of eruptions volcanoes are divided into two types *e.g.* (1) central eruption type or explosive eruption type and (2) fissure eruption type or quiet eruption type.

(1) Volcanoes of central eruption type- Central eruption type or explosive eruption type of volcanoes occurs through a central pipe and small opening by breaking and blowing off crustal surface due to violent and explosive gases accumulated deep within the earth. The eruption is so rapid and violent that huge quantity of volcanic materials consisting of lavas, volcanic dusts and ahses, fragmental materials etc. are ejected upto thousands of metres in the sky. These materials after falling down accumulate around the volcanic vent and form volcanic cones of various sorts. Such volcanoes are very destructive and are disastrous natural hazards. Explosive volcances are further divided into 5 sub-types on the basis of difference in the intensity of eruption, variations in the ejected volcanic material and the period of the action of volcanic events as given below-

(i) Hawaiin type of volcanoes-Such volcanoes erupt quietly due to less viscous lavas and non-violent nature of gases. Rounded blisters of hot and glowing mass/boll of lavas (blebs of molten lava) when caught by a strong wind glide in the air like red and glowing hairs. The Hawaiin people consider these long glassy threads of red molten lava as **Pele's hair** (Pele is the Hawaiin goddess of fire). Such volcanoes have been named as Hawaiin type because of the fact that such eruptions are of very common occurrence on Hawaii island. The eruption of Kilavea volcano of the southern Hawaii island in 1959-60 continued for seven days (from November 14 to 20, 1959) when about 30 million cubic metres of lavas poured out. The intermittent eruptions continued upto December 21, 1959, when the volcano became dormant. It again erupted on January 13, 1960 and about 100 million cubic metres of lavas were poured out of one kilometre long fissure.

(ii) Strombolian type of volcanoes- Such volcanoes, named after Stromboli volcano of Lipari island in the Mediterranean Sea, erupt with moderate intensity. Besides lava, other volcanic materials like pumice, scoria, bombs etc. are also ejected upto greater height in the sky. These materials again fall down in the volcanic craters. The eruptions are almost rhythemic or nearly continuous in nature but some times they are interrupted by long intervals.

(iii) Vulcanian type of volcanoes- These are named after Vulcano of Lipari island in the Mediterranean Sea. Such volcanoes erupt with great force and intensity. The lavas are so viscous and pasty that these are quickly solidified and hardened between two eruptions and thus they crust over (plug) the volcanic vents. These lava crusts obstruct the escape of violent gases during next eruption. Consequently, the violent gases break and shatter the lava crusts into angular fragments and appear in the sky as ash-laden volcanic clouds of dark and often black colour assuming a convoluted or cauliflower shape (fig. 9.2c).

(iv) Peleean type of volcanoes-These are named after the Pelee volcano of Martinique Island in the Caribbean Sea. These are the most violent and most explosive type of volcanoes. The ejected lavas are most viscous and pasty. Obstructive domes of lava are formed above the conduits of the volcanoes. Thus, every successive eruption has to blow off these lava domes. Consequently, each successive eruption occurs with greater force and intensity making roaring noise. The most disastrous volcanic eruption of Mount Pelee on May 8,1902 destroyed the whole of the town of St. Pierre killing all the 28,000 inhabitants leaving behind only two survivors to mourn the sad demise of their brethren. Such type of disastrous violent eruptions are named as **nuee ardente** meaning thereby 'glowing cloud' of hot gases, lavas etc. coming out of a vocanic eruption. The nuee ardente spread laterally out of the mountain (Mount Pelee) with great speed which caused disastrous avalanches on the hillslopes which plunged down the slope at a speed of about 100 kilometres per hour. The annihilating explosive eruption of Krakatoa volcano in 1883 in Krakatoa Island located in Sunda Strait between Java and Sumatra is another example of violent volcanic eruption of this type.

(v) Visuvious type of volcanoes-These are more or less simiiar to Vulcanian and Strombolian type of volcanoes, the difference lies only in the intensity of expulsion of lavas and gases. There is extremely violent expulsion of magma due to enormous volume of explosive gases. Volcanic materials are thrown up to greater height in the sky. The ejected enormous volume of gases and ashes forms thick clouds of 'cauliflower form.' The most destructive type of eruption is called as **Plinian type** because of the fact that such type of eruption was first observed by Plini in 79 A.D.

(2) **Fissure eruption type of volcanoes-**Such volcanoes occur along a long fracture, fault and fissure and there is slow upwelling of magma from below and the resultant lavas spread over the ground surface. The speed of lava movement depends on the nature of magma, volume of magma, slope of ground surface and temperature conditions. The Laki fissure eruption of 1783 in Iceland was so quick and enormous that huge volume of lavas measuring about 15 cubic kilometers was poured out from a 28-km long fissure. The lava flow was so enormous that it travelled a distance of 350 kilometres.

Classification on the basis of periodicity of eruptions

Volcanoes are divided into 3 types on the basis of period of eruption and interval period between two eruptions of a volcano *e.g* (i) active volcanoes, (ii) dormant volcanoes and (iii) extinct volcanoes.

(i) **Active volcanoes** are those which constantly eject volcanic lavas, gases, ashes and fragmental materials. It is estimated that there are about more than 500 volcanoes in the world. Etna and Stromboli of the Mediterranean Sea are the most significant examples of this category. Stromboli Volcano is known as Light House of the Mediterranean because

of continuous emission of burning and luminous incandescent gases. Most of the active volcanoes are found along the mid-oceanic ridges representing divergent plate margins (constructive plate margins) and convergent plate margins (destructive plate margins represented by eastern and western margins of the Pacific Ocean). The latest eruption took place from Pinatubo volcano in June 1991 in Phillippines. Mayon of Phillippines re-erupted in Feb. 2000.

(ii) **Dormant volcanoes** are those which become quiet after their eruptions for some time and there are no indications for future eruptions but suddenly they erupt very violently and cause enormous damage to human health and wealth. Visuvious volcano is the best example of dormant volcano which erupted first in 79 A.D., then it kept quiet upto 1631 A.D., when it suddenly exploded with great force. The subsequent eruptions occurred in 1803, 1872, 1906, 1927, 1928 and 1929.

(iii) **Extinct volcanoes-** The volcanoes are considered extinct when there are no indications of future eruption. The crater is filled up with water and lakes are formed. It may be pointed out that no volcano can be declared permanently dead as no one knows, what is happening below the ground surface.

9.4 VOLCANIC MATERIALS

Volcanic materials discharged during eruptions include gases and vapour, lavas, fragmental materials and ashes.

(1) **Vapour and gases-** Steam and vapour constitute 60 to 90 per cent of the total gases discharged during a volcanic eruption. Steam and vapour include (i) **phreatic vapour** and (ii) **magmatic vapour** whereas volcanic gases include carbon dioxide, nitrogen oxides, sulphur dioxide, hydrogen, carbon monoxide etc. Besides, certain compounds are also ejected with the volcanic gases *e.g.* sulphurated hydrogen, hydrochloric acid, volatile chlorides of iron, potassium and other metallic matter.

(2) **Magma and lava-** Generally, molten rock materials are called magmas below the earth's surface while they are called lavas when they come at the earth's surface. Lavas and magmas are divided on the basis of silica percentage into two groups *e.g.* (i) **acidic magma** (higher percentage of silica and (ii) **basic lava** (low percentage of silica). Lavas and

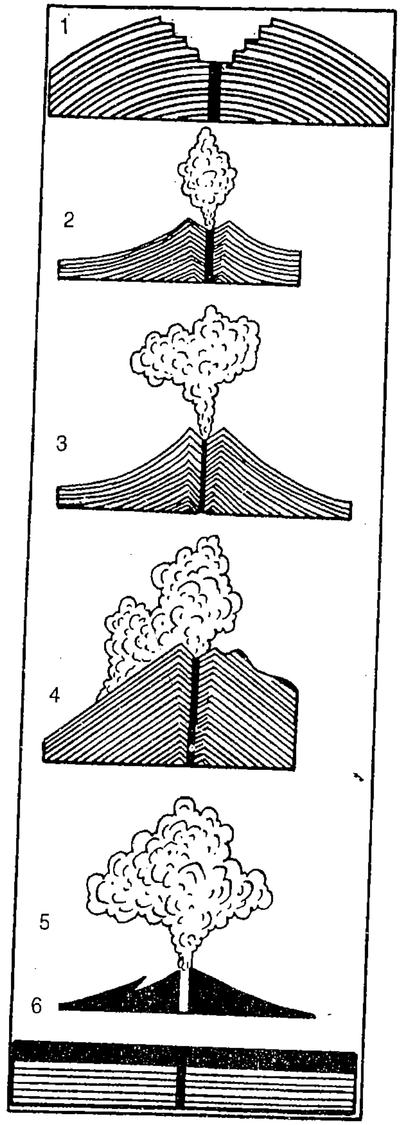


Fig. 9.2 : Types of Volcanoes(1) Hawaiin type, (2) Strombolian type, (3) Vulcanian type, (4) Peleean type, (5) Visuvian type and (6) Fissure type or Icelandic type.

magmas are also classified on the basis of light and dark coloured minerals into (1) **felsic lava** and (ii) **mafic lava.** Basaltic or mafic lava is characterized by maximum fluidity. Basaltic lava spreads on the ground surface with maximum flow speed (from a few kilometres to 100 kilometres per hour, average flow speed being 45 to 65 km per hour) due to high fluidity and low viscosity. Basaltic lava is the hottest lava (1,000^0 to 1,200^{0}C). Lava flow is divided into two types on the basis of Hawaiin language *e.g.* (i) **pahoehoe** and (ii) **As Aa lava flow** or block lava flow. Pahoehoe lava has high fluidity and spreads like thin sheets. This is also known as **ropy lava.** On the other hand aa aa lava is more viscous. Pahoehoe lava, when solidified in the form of sacks or pillow, is called **pillow lava.**

(3) **Fragmental or pyroclastic materials** thrown during explosive type of eruption are grouped into three categories. (i) Essential materials include consolidated forms of live lavas. These are also known as **tephra** which means ash. Essential materials are unconsolidated and their size is upto 2 mm. (ii) Accessory materials include dead lavas. (iii) Accidental materials include fragmental materials of crustal rocks. On the basis of size pyroclastic materials are grouped into (i) **volcanic dust** (finest particles), (ii) **volcanic ash** (2 mm in size), (iii) **lapilli** (of the size of peas) and (iv) **volcanic bombs** (6 cm or more in size), which are of different shapes viz. ellipsoidal, discoidal, cuboidal, and irregularly rounded. The dimension of average volcanic bombs ranges from the size of a base ball or basket ball to giant size. Some times the volcanic bombs weigh 100 tonnes in weight and are thrown upto a distance of 10 km.

9.5 WORLD DISTRIBUTION OF VOLCANOES

Like earthquakes, the spatial distribution of volcanoes over the globe is well marked and well understood because volcanoes are found in a well defined belt or zone (fig. 9.3). Thus, the distributional pattern of volcanoes is zonal in character. If we look at the world distribution of volcanoes it appears that the volcanoes are associated with the weaker zones of the earth's crust and these are closely associated with seismic events say earthquakes. The weaker zones of the earth are represented by folded mountains (western cordillera of North America, Andes, mountains of east Asia and East Indies) with the exceptions of the Alps and the

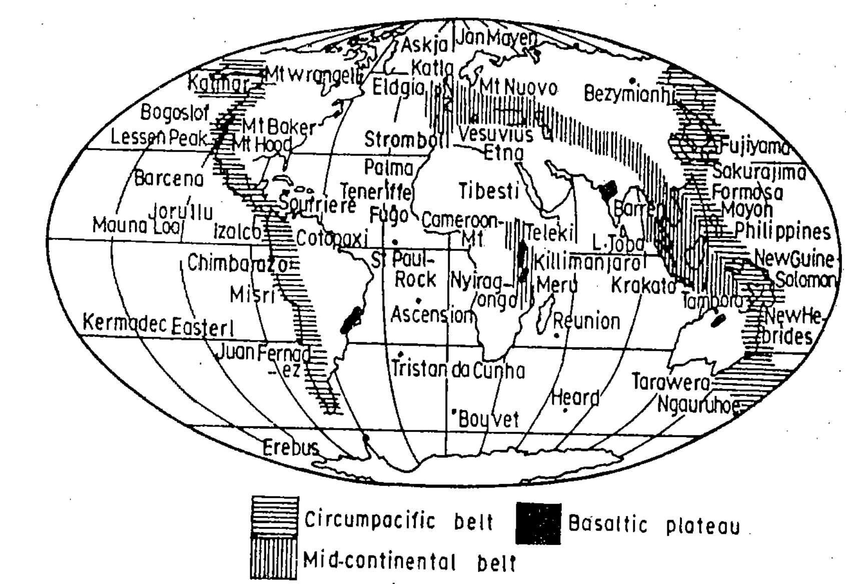


Fig. 9.3 : World distribution of volcanoes.

Himalayas, and fault zones. Volcanoes are also associated with the meeting zones of the continents and oceans. Occurrences of more volcanic eruptions along coastal margins and during wet season denote the fact that there is close relationship between water and volcanic eruption. Similarly, volcanic eruptions are closely associated with the activities of mountain building and fracturing.

Based on **plate tectonics,** there is close relationship between plate margins and vulcanicity as most of the world's active volcanoes are associated with the plate boundaries. About 15 per cent of the worlds' active volcanoes are found along the **constructive plate margins** or **divergent plate margins** (along the mid-oceanic ridges where two plates move in opposite directions) whereas 80 per cent volcanoes are associated with the **destructive** or **convergent plate boundaries** (where two plates collide). Besides, some volcanoes are also found in intraplate regions *e.g.* volcanoes of the Hawaii Island, fault zones of East Africa etc.

Like earthquakes, there are also three major belts or zones of volcanoes in the world viz. (1) circum-Pacific belt, (ii) mid-continental belt and (iii) mid-oceanic ridge belt (fig. 9.3)

(1) Circum-Pacific belt- The circum-Pacific belt, also known as the 'volcanic zones of the convergent oceanic plate margins', includes the volcanoes of the eastern and western coastal areas of the Pacific Ocean (or the western coastal margins of North and South Americas and the eastern coastal margins of Asia), of island arcs and festoons off the east coast of Asia and of the volcanic islands scattered over the Pacific Ocean. This volcanic belt is also called as the **fire girdle of the Pacific** or the **fire ring of the Pacific.** This belt begins from Erebus Mountain of Antarctica and runs northward through Andes and Rockies mountains of South and North Americas to reach Alaska from where this belt turns towards eastern Asiatic coast to include the volcanoes of island arcs and festoons (*e.g.* Sakhalin, Kamchatka, Japan, Phillippines etc.). The belt ultimately merges with the mid-continental belt in the East Indies. Most of high volcanic cones and volcanic mountains are found in this belt. Most of the volcanoes are found in chains *e.g.* the volcanoes of the Aleutian Island, Hawaii Island, Japan etc. About 22 volcanic mountains are found in group in Ecuador wherein the height of 15 volcanic mountains is more than 4560 m AMSL. Cotopaxi is the highest volcanic mountain of the world (height being 19,613 feet). The other significant volcanoes are Fuziyama (Japan), Shasta, Rainier and Hood (western cordillera of North America), a valley of ten thousand smokes (Alaska), Mt St. Helens (Washington, USA), Kilavea (Hawaiiland), Mt. Taal, Pinatubo and Mayon (re-eruption in Feb. 2000) of Phillippines etc.

Here volcanic eruptions are primarily caused due to collision of American and Pacific plates and due to subduction of Pacific plate below the Asiatic plate.

(2) Mid-continental belt is also known as 'the volcanic zones of convergent continental plate mergins'. This belt includes the volcanoes of Alpine mountain chains and the Mediterranean Sea and the volcanoes of fault zone of eastern Africa. Here, the volcanic eruptions are caused due to convergence and collision of Eurasian plates and African and Indian plates. The famous volcanoes of the Mediterranean Sea such as Stromboli, Visuvious, Etna etc. and the volcanoes of Aegean Sea are included in this belt. It may be pointed out that this belt does not have the continuity of volcanic eruptions as several gaps (volcanic-free zones) are found along the Alps and the Himalayas because of compact and thick crust formed due to intense folding activity. The important volcanoes of the fault zone of eastern Africa are Kilimanjaro, Meru, Elgon, Birunga, Rungwe etc.

(3) Mid-Atlantic belt includes the volcanoes mainly along the mid-Atlantic ridge which represents the splitting zone of plates. In other words, two plates diverge in opposite directions from the mid-oceanic ridge. Thus, volcanoes mainly of fissure eruption type occur along the constructive or divergent plate margins (boundaries). The most active volcanic area is Iceland which is located on the mid-Atlantic ridge. This belt begins from Hekla volcanic mountain of Iceland where several fissure eruption type of volcanoes are found. It may be pointed out that since Iceland is located on the mid-Atlantic ridge representing the splitting zone of American plate moving westward and Eurasian plate moving eastward, and hence here is constant upwelling of magmas along the mid-oceanic ridge and wherever the crust becomes thin and weak, fissure flow of lava occurs because of fracture created due to divergence of plates. The Laki fissure eruption of 1783 A.D. was so quick and enormous that huge volume of lavas measuring about 15 cubic kilometres was poured out from 28-km long fissure. Recently, Hekla and Helgafell volcanoes erupted in the year 1974 and 1973 respectively. Other more active volcanic areas are Lesser Antilles, Southern Antilles, Azores, St. Helena etc. The dreadful and disastrous eruption of Mount Pelee occurred on May 8, 1902 in the town of St. Pierre on the Martinique Island of West Indies in the Caribbean Sea. All the 28,000 inhabitants, except two persons, were killed by the killer volcanic eruption.

(4) Intra-plate volcanoes— Besides the aforesaid well defined three zones of volcanoes, scattered volcanoes are also found in the inner parts of the continents. Such distributional patterns of volcanoes are called as intraplate volcanoes, the mechanism of their eruption is not yet precisely known. Fig. 9.4 depicts the location of volcanoes of Pacific plate where one branch of volcanoes runs from Hawaii to Kamchatka. Vulcanicity also becomes active in the inner parts of continental plates. Massive fissure eruption occurred in the north-western parts of North America during Miocene period when 1,00,000 cubic kilometres of basaltic lavas were spread over an area of 1,30,000 km^2 to form Columbian plateau. Similarly, great fissure flows of lavas covered more than 5,00,000 km^2 areas of Peninsular India. Parana of Barazil and Paraguay were formed due to spread of lavas over an area of 7,50,000 km^2.

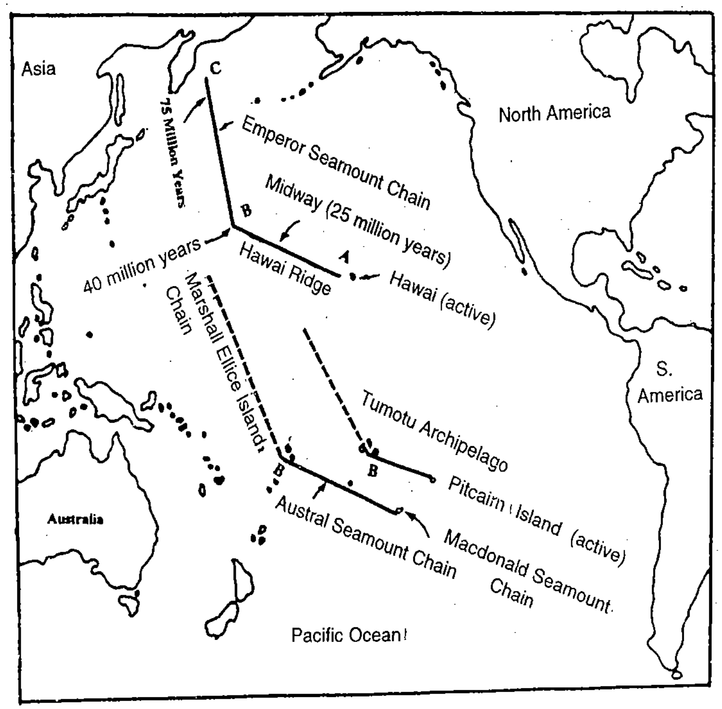


Fig. 9.4 : Volcanic-ridge-chain on Pacific plate.

9.6 MECHANISMS AND CAUSES OF VULCANISM

As stated earlier the volcanic eruptions are associated with weaker zones of the earth surfaces represented by mountain building at the destructive or convergent plate margins and fracture zones represented by constructive or divergent plate bounda-

ries at the splitting zones of mid-oceanic ridges and the zones of transform faults represented by conservative plate boundaries. The mechanism of vulcanicity (vulcanism) and volcanic eruptions is closely associated with several interconnected processes such as (i) gradual increase of temperature with increasing depth at the rate of 1^0C per 32 m due to heat generated from the disintegration of radioactive elements deep within the earth, (ii) origin of magma because of lowering of melting point caused by reduction in the pressure of overlying superincumbent load due to fracture caused by splitting of plates and their movement in opposite direction, (iii) origin of gases and vapour due to heating of water which reaches underground through percolation of rainwater and melt-water (water derived through the melting of ice and snow), (iv) the ascent of magma forced by enormous volume of gases and vapour and (v) finally the occurrence of volcanic eruptions of either violent explosive central type or quiet fissure type depending upon the intensity of gases and vapour and the nature of crustal surface.

Theory of plate tectonics now very well explains the mechanism of vulcanism and volcanic eruptions. In fact, volcanic eruptions are very closely associated with the plate boundaries. It may be pointed out that the types of plate movements and plate boundaries also determine the nature and intensity of volcanic eruption. Most of the active fissure volcanoes are found along the mid-oceanic ridges which represent splitting zones of divergent plate boundaries (fig. 9.5). Two plates move in opposite directions from the mid-oceanic ridges due to thermal convective currents which are originated in the mantle below the crust (plates). This splitting and lateral spreading of plates creates fractures and faults (transform faults) which cause pressure release and lowering of melting point and thus materials of upper mantle lying below the mid-oceanic ridges are melted and move upward as magmas under the impact of enormous volume of accumulated gases and vapour. This rise of magmas along the mid-oceanic ridges (constructive or divergent plate boundaries) causes fissure eruptions of volcanoes and there is constant upwelling of lavas. These lavas are cooled and solidified and are added to the trailing ends of divergent plate boundaries and thus there is constant creation of new basaltic crust. The volcanic eruptions of Iceland and the islands located along the mid-Atlantic ridge are caused because of sea-floor spreading and divergence of plates. It is obvious that divergent or constructive plate boundaries are always associated with quiet type of fissure flows of lavas because the pressure release of superincumbent load due to divergence of plates and formation of fissures and faults is a slow and gradual process.

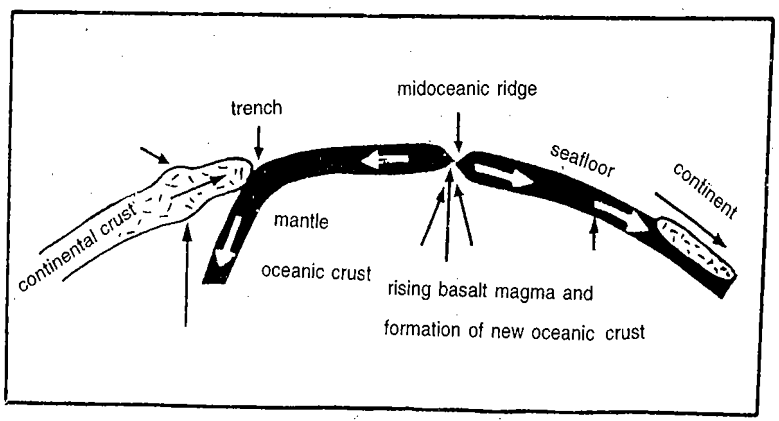


Fig. 9.5 : Illustration of constructive (divergent) and destructive (convergent) plate boundaries and their relationship with vulcanicity.

It is apparent from the above discussion that the mid-oceanic ridges, representing splitting zones, are associated with active volcanoes wherein the supply of lava comes from the upper mantle just below the ridge because of differential melting of the rocks into tholeiitic basalts. Since there is constant supply of basaltic lavas from below the mid-oceanic ridges and hence the volcanoes are active near the ridges but the supply of lavas decreases with increasing distance from the mid-oceanic ridges and therefore the volcanoes become inactive, dormant and extinct depending on their distances from the source of lava supply. *e.g.* mid-oceanic ridges. This fact has been validated on the basis of the study of the basaltic floor of the Atlantic Ocean and the lavas of several islands. It has been found that the islands nearer to the mid-Atlantic Ridge have younger lavas whereas the islands away from the ridge have older lavas. For example, the lavas of Azores islands situated on either side of the mid-Atlantic Ridge are 4-million years old whereas the lavas of Cape Verde Island, located far away from the said ridge, are 120-million years old.

Destructive or convergent plate boundaries are associated with explosive type of volcanic eruptions. When two convergent plates collide along Benioff zone (subduction zone), comparatively heavier plate margin (boundary) is subducted beneath comaparatively lighter plate boundary. The subducted plate margin, after reaching a depth of 100 km or more in the upper mantle, is melted and thus magma is formed. This magma is forced to ascend by the enormous volume of accumulated explosive gases and thus magma appears as violent volcanic eruption on the earth's surface. Such type of volcanic eruption is very common along the destructive or convergent plate boundaries which represent the volcanoes of the Circum-Pacific Belt and the Mid-Continental Belt. The volcanoes of the island arcs and festoons (off the east coast of Asia) are caused due to subduction of oceanic crust (plate) say Pacific plate below the continental plate, say Asiatic plate near Japan Trench.

9.7 HAZARDOUS EFFECTS OF VOLCANIC ERUPTIONS

Volcanic eruptions cause heavy damage to human lives and property through advancing hot lavas and fallout of volcanic materials; destruction to human structures such as buildings, factories, roads, rails, airports, dams and reservoirs through hot lavas and fires caused by hot lavas; floods in the rivers and climatic changes. A few of the severe damages wrought by volcanic eruptions may be summarized as given below.

(1) Huge volumes of hot and liquid lavas moving at considerably fast speed (recorded speed is 48 km per hour) bury human structures, kill people and animals, destroy agricultural farms and pastures, plug rivers and lakes, burn and destroy forest etc. The great eruption of Mt. Loa on Hawaii poured out such a huge volume of lavas that these covered a distance of 53 km down the slope. Enormous Laki Lava flow of 1783 A.D. travelled a distance of 350 km engulfing two churches, 15 agricultural farms and killing 24 per cent of the total population of Iceland. The cases of Mt. Pelee eruption of 1902 in Martinique Island (in Caribbean Sea) (total death 28,000) and St. Helens eruption of 1980 (Washington, USA) are representative examples of damages done by lava movement. The thick covers of green and dense forests on the flanks of Mt. St. Helens were completely destroyed due to severe forest fires kindled by hot lavas.

(2) Fallout of immense quantity of volcanic materials including fragmental materials (pyroclastic materials), dusts and ashes, smokes etc. covers large ground surface and thus destroys crops, vegetation and buildings, disrupts and diverts natural drainage systems, creates health hazards due to poisonous gases emitted during the eruption, and causes killer acid rains.

(3) All types of volcanic eruptions, if not predicted well in advance, causes tremendous losses to precious human lives. Sudden eruption of violent and explosive type through central pipe does not give any time to human beings to evacuate themselves and thus to save themselves from the clutches of death looming large over them. Sudden eruption of Mt. Pelee on the Island of Martinique, West Indies in the Caribbean Sea, on May 8, 1902 destroyed the whole of St. Pierre town and killed all the 28,000 inhabitants leaving behind only two survivors to mourn the sad demise of their brethren. The heavy rainfall, associated with volcanic eruptions, mixing with falling volcanic dusts and ashes causes enormous mudflow or **'lahar'** on the steep slopes of

volcanic cones which causes sudden deaths of human beings. For example, great mud flow created on the steep slopes of Kelut volcano in Japan in the year 1919 killed 5,500 people.

(4) Earthquakes caused before and after the volcanic eruptions generate destructive **tsunamis** seismic waves which create most destructive and disastrous sea waves causing innumerable deaths of human beings in the affected coastal areas. Only the example of Krakatoa in 1883 would be sufficient enough to demonstrate the disastrous impact of tsunamis which generated enormous sea waves of 30 to 40 m height which killed 36,000 people in the coastal areas of Java and Sumatra.

(5) Volcanic eruptions also change the radiation balance of the earth and the atmosphere and thus help in causing climatic changes. Greater concentration of volcanic dusts and ashes in the sky reduces the amount of insolation reaching the earth's surface as they scatter and reflect some amount of incoming shortwave solar radiation. Dust veils, on the other hand, do not hinder in the loss of heat of the earth's surface through outgoing longwave terrestrial radiation. The ejection of nearly 20 cubic kilometres of fragmental materials, dusts and ashes upto the height of 23 km in the sky during the violent eruption of Krakatoa volcano on August 27, 1883 formed a thick dust veil in the stratosphere which caused a global decrease of solar radiation received at the earth's surface by 10 to 20 per cent.

(6) A group of scientists believes that volcanic eruptions and fallout of dusts and ashes cause mass extinction of a few species of animals. Based on this hypothesis the mass extinction of dinosaurs about 60 million years ago has been related to increased world-wide volcanic activity. **Acid rains** accompanied by volcanic eruptions cause large-scale destruction of plants and animals.

9.8 TOPOGRAPHY PRODUCED BY VULCANICITY

Numerous types of landforms are created due to cooling and solidification of magmas below the earth's surface and lavas at the earth's surface and due to accumulation of fragmental materials, dusts and ashes with lavas such as different types of volcanic cones. The cones and craters are not always permanent landforms because they are changed and modified during every successive eruption. Explosive type of volcanic eruptions helps in the formation of several types of volcanic cones whereas fissure flows result in the formation of lava plateaux and lava plains due to accumulation of thick layers of basaltic lavas over extensive areas. The topographic features produced by the entire process of vulcanicity are grouped into two broad categories viz. (1) extrusive topography and (ii) intrusive topography. Fig. 9.6 depicts major characteristic volcanic landforms.

(1) Extrusive Volcanic Topography

(i) From Explosive Type of Eruptions

(a) Elevated forms, *e.g.* volcanic cones

(b) Depressed form, *e.g.* craters and calderas

(ii) From Fissure Eruptions

(a) Lava plateaux and domes

(b) Lava plains

(2) Intrusive Volcanic Topography

(i) intrusive lava domes, (ii) batholiths, (iii) laccoliths, (iv) phacoliths, (v) lopoliths, (vi) sills, (vii) dikes, (viii) volcanic plugs and stocks etc.

1. Elevated Forms : Volcanic Cones

(i) Cinder or ash cones are usually of low height and are formed of volcanic dusts and ashes and pyroclastic matter (fragmental materials). The formation of cinder cones is initiated due to accumulation of finer particles around the volcanic vent in the form of tiny mound, say 'ant mount' which varies in height from a few centimetres to a few metres in the beginning. The size of the cone gradually increases due to continuous accumulation of volcanic materials minus lavas. Some times, the rate of growth of the cone is so high that it gains height of 100 m or more within a week. The slopes of cinder cones range between 30^0 and 45^0. Larger particles are arranged near the craters and rest at the angle between 40^0 and 45^0 and the finer particles are deposited at the outer margins of the cones. Since such cones are formed of unconsolidated larger particles and are seldom compacted by lavas and hence they are permeable to water.

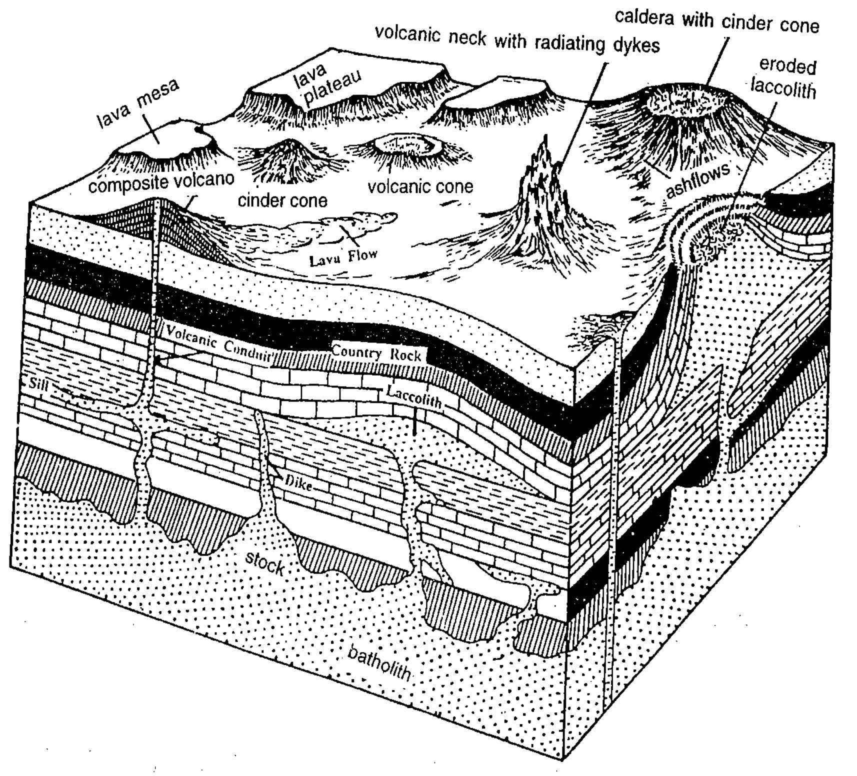


Fig. 9.6 : Different types of landforms produced during volcanic activities.

Such cones are on an average less suscepitble to erosion and hence they maintain their original forms for hundreds of years provided that they are not destroyed by ensuing violent explosion. The volcanic cones of Mt. Jorullo of Mexico, Mt. Izalco of San Salvador, Mt. Camiguin of Luzon Island of Phillippines etc. are typical examples of cinder cones (fig. 9.7(1)).

(ii) Composite cones are the highest of all volcanic cones. These are formed due to accumulation of different layers of various volcanic materials and hence these are also called as **strato-cones** (fig 9.7(2). In fact, these cones are formed due to deposition of alternate layers of lava and fragmental (phyroclastic) materials wherein lava acts as cementing material for the compaction of fragmental materials. The cone becomes comparatively resistant to erosion if it is coated by thick layer of lava. On the other hand, if the outer layer is composed of fragmental materials, the composite cone is subjected to severe erosion. Most of the highest symmetrical and extensive volcanic cones of the world come under this category e.g. Mt. Shasta, Mt. Ranier, Mt. Hood (USA), Mt. Mayon of Phillippines, Mt. Fuziyama of Japan, Mt. Cotopaxi of Ecuador etc.

(iii) Parasite cones- Several branches of pipes come out from the main central pipe of the volcano when the volcanic cones are enormously enlarged. Lavas and other volcanic materials come out from these minor pipes and these materials are deposited

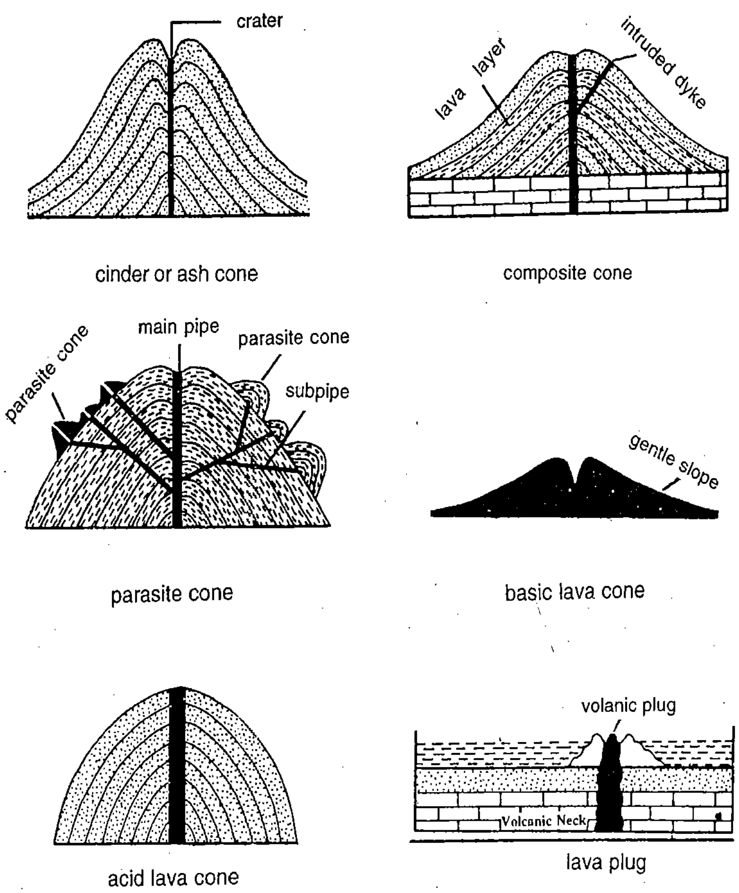


Fig. 9.7 : Different types of volcanic cones.

around newly formed vents located on the outer surface of the main cone and thus several smaller cones are formed on the major cone (fig. 9.7(3)). These cones are called parasite cones because the supply of lava for these cones comes from the main pipe. These cones are also known as **adventive** or **lateral cones.** Shastina cone is a parasite cone of Mt. Shasta of the USA.

(iv) **Basic lava cone** is formed of light and less viscous lava with less quantity of silica. In fact, when the lava coming out of fissure flows is deficient in silica and is characterized by high degree of fluidity, it cools and solidifies after spreading over larger area. Thus, a long cone with significantly low height is formed. Such cones are also called as shield cones because of their shapes resembling a shield. Since these cones are composed of basaltic lavas, they are also called as **basic lava cones.** These are also known as Hawana type of cones (fig. 9.7(4)).

(v) Acid lava cones are formed where the lavas coming out of volcanic eruptions are highly viscous and rich in silica content. In fact, such viscous lavas have very low mobility and hence they are immediately cooled and solidified after their appearance on the earth's surface. Thus, high cones of steep slopes are formed. Such cones are very often known as Strombolian type of cones (fig. 9.7(5)).

(vi) Lava domes are in fact similar to shield cones in one way or the other. Lava domes differ from shield cones as regards their size. Actually, lava domes are larger and more extensive in size than the shield cones. These are formed due to accumulation of solidified lavas around the volcanic vents. Based on the mode of origin and the place of formation lava domes are divided into 3 categories *e.g.* (A) **plug dome** (formed of lavas due to filling of volcanic vents), (B) **endogenous dome** (formed of silica rich viscous lavas) and (C) **exogenous dome** (formed of silica-deficient lava with high degree of fluidity.)

(vii) Lava plugs are formed due to plugging of volcanic pipes and vents when volcanoes become extinct. These vertical columns of solidified lavas appear on the earth's surface when the volcanic cones are eroded away. The lava-filled volcanic piple is called as **volcanic neck** (fig. 9.7(6)). Generally, volcanic necks are cylindrical shaped and measure 50 to 60 m in height (above the ground surface) and 300 to 600 m in diameter. Some times **diatreme** term is used to indicate volcanic neck or pipe filled with breccia. '**Shiprock** which towers 515 metres (1700 feet) over the surrounding flat-lying sedimentary rocks of New Mexico, is an excellent example of a diatreme exposed by the erosion of its enclosing sedimentary rocks' (F. Press and R. Siever 1974) (fig. 9.8).

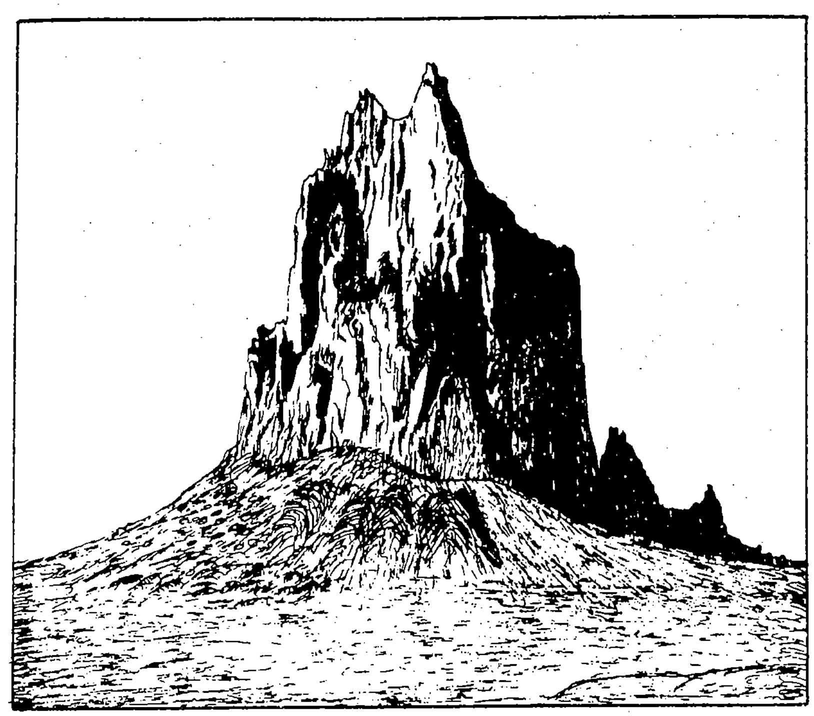


Fig. 9.8 : Shiprock (New Mexico, USA), an example of diatreme or volcanic neck.

2. Depressed Forms

(i) Craters-The depression formed at the mouth of a volcanic vent is called a crater or a volcanic mouth, which is usually funnel shaped. The slope of the crater depends upon the volcanic cone in which crater is formed. Normally, a crater formed in a cinder cone slopes at the angle between 25^0 and 30^0. The size of a crater increases with increase and expansion of its cone. A crater may be differentiated from a caldera on the basis of size and mode of formation. An average crater measures 300 m in diameter and 300 m in depth but there are wide range of variations in craters from the standpoint of their size *e.g.* craters range from small **craterlets** having a diameter of a few hundred metres to large craters having the diameter of a few kilometres. The crater of extinct Aniakchak volcano of Alaska has a diameter of 9.6 km (6 miles) and the side walls are 364 m to 912 m (1200 to 3000 feet) high. If the Crater Lake of the state of Oregon (USA) is accepted as a crater, it becomes one of the most extensive craters of the world, though many scientists consider it as an example of a caldera. When a crater is filled with water, it becomes a crater lake.

When the crater of volcano becomes very extensive and if there are few eruptions of very small intensity after long time, several smaller cones are formed within the extensive older crater and thus several small-sized craters are formed at the mouth of each volcanic vents inside the extensive crater. Such craters or craterlets are called **'nested craters'** or **'craters within the crater'** or **'grouped craters'.** Such craters are formed only when the next eruption is smaller in intensity than the previous one. The craters formed at the mouth of volcanic vent of parasite cones developed over an extensive volcanic cone is called **adventive crater.** Three smaller craters are found within the extensive crater of Mt. Taal of Phillippines. Similarly, three and two craters are found within the craters of Visuvius and Etna volcanoes.

(ii) Calderas- Generally, enlarged form of a crater is called caldera. There are two parallel concepts for the origin of calderas. According to the first group of scientists a caldera is an enlarged form of a crater and it is surrounded by steep walls from all sides. The caldera is formed due to subsidence of a crater. This concept has been propounded by the U.S. Geological Survey. It is believed according to this concept that Aso crater of Japan and Crater Lake of the USA are the result of subsidence. The second group of scientists has opined that the calderas are formed due to violent and explosive eruptions of the volcanoes.

Daly, the leading advocate of 'eruption hypothesis' of the origin of calderas, believes that the topographic features formed by subsidence are 'volcanic sinks. According to the advocates of this hypothesis if calderas are formed due to subsidence there should not be any deposit of pyroclastic materials and volcanic ashes related to a particular volcanic cone near the caldera but evidences have revealed that the remains of volcanic materials related to a particular cone are found not only near the concerned caldera but are also found several kilometres away from the caldera. For example, volcanic materials have been found at the distance of 128 km from the caldera of Crater Lake (USA). The significant calderas of the world are (figures in the brackets denote dimension in kilometres) Lake Toba of Sumatra (50 km × 50 km) in Sumatra, Aira (25 km × 24 km) in Japan, Lake Kutchaio (26 km × 20 km) in Japan, Tarso Yega (20 km × 17 km) in Sahara (Africa), Aso San (23 km × 14 km) in Japan, Alban (11 km × 10 km) in Italy, Crater Lake (10 km × 10 km in USA, Krakatoa (7 km × 6 km) in Indonesia, Kilauea (5 km × 3 km) in Hawaii etc. Smaller calderas housed in a big caldera are called **nested calderas** or grouped calderas (fig. 9.9).

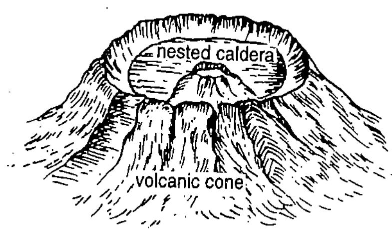


Fig. 9.9 : Example of nested caldera.

Intruusive Topography

When gases and vapour are not very much strong during volcanic activity, the ascending magmas to not erupt as lavas rather these are intruded in voids below the crustal surface and after cooling and solidification assume several interesting forms like batholiths, laccoliths, phacoliths, lopoliths, sills and dykes. These instrusive volcanic forms are seen only when the superincumbent loads of overlying country rocks are removed through prolonged erosion. These features have already been discussed in the preceding chapter 8 on **Rocks.**

9.9 GEYSERS

Geyser, in fact, is a special type of **hot spring** which spouts hot water and vapour from time to time. The word geyser has been derived from an Icelandic word **'geysir'** which means **gusher or spouter.** This word was used to indicate the spouting water of a hot spring of Iceland known as Great Geyser or Gesir.

Geyser, representing a minor form of the broader process of vulcanicity, has been variously defined by the scientists. For example, Arthur Holmes has defined geyser in the following manner, "geysers are hot springs from which a column of hot water and steam is explosively discharged at intervals, spouting in some cases to heights of hundreds of feet." According to P.G. Worcester "Geysers are intermittent hot springs that from time to time spout steam and hot water from their craters."

The difference between hot springs and geyser lies in the fact that there is continuous spouting of hot water from the former while there is intermittent (with interval) spouting of water from the latter. A geyser spouts water from a small and narrow vent which is connected by a circuitous pipe with the underground aquifers. This pipe is called as **geyser pipe** or **geyser tube.** The length of geyser tube ranges between 30 to 100m at different places. The temperature of water coming out of geyser ranges between 75^0 to 90^0C.

Geysers are classified into two types viz. (i) pool type of geyser and (ii) nozzle type of geyser. When a geyser spouts water through an open and relatively large pool, it is called **pool type of geyser.** Such geysers spout larger volume of water and vapour through long geyser tubes. No deposits are possible around the geyser **pools. Nozzle type of geysers** spout water and vapour through a very small and constricted vent. Emitted materials are deposited around the geyser vents and thus **geyser cones** are formed.

Some scientists do not agree to accept hot springs and geysers as two separate forms of vulcanicity rather they believe that both are the same, the difference is only of periodicity of spouting of water. Thus, they have grouped geysers into two categories viz. (1) Non-continuous geysers or geysers with intermittent spouting and (2) continuously active geysers. The intermittent geysers are further divided into (i) geysers of equal intervals between two successive periods of spouting (wherein interval period between two successive active periods of spouting is certain and fixed, such geysers are, thus, considered to be reliable as regards the periods of interval and spouting, example, Old Faithful Geyser of the Yellow Stone National Park, USA), (ii) variable geysers (wherein the interval period between two successive periods of spouting is not certain), (iii) long-period geysers (wherein the active period of spouting is longest of all the geysers, ranging between a few minutes to one hour, example, Grand Geyser of Iceland spouts water for 30 minutes in continuation before the next interval period starts) and (iv) feeble geyser (wherein the active period of water spouting is very short). Continuously active geysers are, in fact, hot springs which spout water without any interval. The Excelsior Geyser of the Yellow Stone National Park of the USA is the example of this category.

There is no certain observable distributional pattern of geysers over the globe as they are found in almost all the continents and in almost all the climatic zones. The geysers of the USA, Iceland and New Zealand are most widely studied geysers. Geysers are found in groups in the Yellow Stone National Park (USA). About one hundred geysers have been named and another hundred geysers are known to the scientists. There are four major basins of geysers viz. (i) Norris Basin, (ii) Upper Lake Basin, (iii) Lower Lake Basin and (iv) Heart Lake Basin. The major geyser of New Zealand is located in the western region of the northern Island which is also dominated by volcanic activities. The geysers and hot springs are spread over an area of 1786 km^2 (5000 square miles) in Iceland. The most significant geyser of Iceland is Grand Geyser.

9.10 FUMAROLES

Fumarole means such a vent through which there is emission of gases and water vapour. It appears from a distant place that there is emission of enormous volume of smokes from a particular centre. Thus, smoke or gas emitting vents are called fumaroles. In fact, fumaroles are directly linked with volcanic activities. Emission of gases and vapour begins after the emission of volcanic materials is terminated in an active volcano. Some times the emission of gases and vapour is continuous but in majority of the cases emission occurs after intervals. It is believed that gases and vapour are generated due to cooling and contraction of magma after the termination of the eruption of a volcano. These gases and vapour appear at the earth's surface through a narrow and constricted pipe (tube). It may be pointed out that fumaroles are the last signs of the activeness of a volcano.

Numerous fumaroles are found in groups near Katmai volcano of Alaska (USA). Here fumaroles are found in groups in extensive valley zone, which is called a Valley of Ten Thousand Smokes which means fumaroles appear from 10,000 vents the diameter of which is around 3 metres. Here fumaroles are found along a linear fracture. Elsewhere, fumaroles are found along the volcanic craters. The temperature of vapour emitted from fumaroles is around 645°C. It may be mentioned that vapour constitutes 98.4 to 98.99 per cent of the total gases emitted from fumaroles. Other gases include carbon dioxide, hydrochloric acid, hydrogen sulphide, nitrogen, some oxygen and ammonia. Some minerals are also emitted with gases and vapour from fumaroles. Sulphur is the most important mineral. Fumaroles dominated by sulphur are called **solfatara** or **sulphur fumaroles.**

10

EARTHQUAKES

10.1 INTRODUCTION

An earthquake is a major demonstration of the power of the tectonic forces caused by endogenetic thermal conditions of the interior of the earth. 'An earthquake is a motion of the ground surface, ranging from a faint tremor to a wild motion capable of shaking buildings apart and causing gaping fissures to open in the ground. The earthquake is a form of energy of wave motion transmitted through the surface layer of the earth in widening circles from a point of sudden energy release, the focus' (A.N. Strahler and A.H.. Strahler, 1976). 'An earthquake is a vibration or oscillation of the surface of the earth caused by a transient disturbance of the elastic or gravitational equilibrium of the rocks at or beneath the earth the surface.'

The magnitude or intensity of energy released by an earthquake is measured by the **Richter Scale** devised by Charles F. Richter in 1935. The number indicating magnitude or intensity (M) on Richter scale ranges between 0 and 9 but in fact the scale has no upper limit of number because it is a logarithmic scale. 'It is estimated that the total annual energy released by all earthquakes is about 10^{25} ergs, most of this is from a small number of earthquakes of magnitude over 7' (A.N. Strahler and A.H. Strahler, 1976). The 1934 Bihar earthquake measuring 8.4 and Good Friday Earthquake of March 27, 1964 in Alaska (USA) measuring 8.4 to 8.6 on Richter scale are among the greatest earthquakes of the world ever recorded.

The place of the origin of an earthquake is called **focus** which is always hidden inside the earth but its depth varies from place to place. The deepest earthquake may have its focus at a depth of even 700 km below the ground surface but some of the major Himalayan earthquakes, such as the Bihar-Nepal earthquake of August 21, 1988, have their focus around 20-30 km deep. The place on the ground surface, which is perpendicular to the buried 'focus' or 'hypocentre', recording the seismic waves for the first time is called **epicentre.** The waves generated by an earthquake are called 'seismic waves' which are recorded by an instrument called seismograph or seismometer at the epicentre. The science, that deals with the seismic waves, is called **seismology**.

10.2 CAUSES OF EARTHQUAKES

Earthquakes are caused mainly due to disequilibrium in any part of the crust of the earth. A number of causes have been assigned to cause disequilibrium or isostatic imbalance in the earth's crust such as volcanic eruptions, faulting and folding, upwarping and downwarping, gaseous expansion and contraction inside the earth, hydrostatic pressure of man-made water bodies like reservoirs and lakes, and plate movements. If we look at the world distribution of earthquakes (fig. 10.2) it ap-

pears that the earthquake belts are closely associated with the weaker zones and isostatically disturbed areas of the globe. It was generally believed that isostatically balanced and old and stable rigid masses were free from seismic events but the devastating earthquake of Koyna on 11 December, 1967, in Satara district of Maharashtra, Latur-Kilari earthquake of Sept. 30, 1993 of Maharashtra, disproved this old connotation and made us believe that no part of the earth is immune from seismic events. A host of possible causes have been suggested to cause disequilibrium in the earth's crust which trigger earth tremors of various sorts.

1. Vulcanicity

Volcanic activity is considered to be one of the major causes of earthquakes. In fact, vulcanicity and seismic events are so intimately related to each other that they become cause and effect for each other. In other words, each volcanic eruption is followed by earthquakes and many of the severe earthquakes cause volcanic eruptions. In fact, earth tremors are major precursor events of possible volcanic eruption in immediate future in any region. The explosive violent gases during the process of vulcanicity try to escape upward and hence they push the crustal surface from below with great force and thus is caused severe earth tremor of high magnitude. Whenever these gases become successful in breaking the weak crustal surface they appear on the earth's surface with violent explosion and great force causing devastating volcanic eruption which causes sudden desequilibrium in the crustal surface to invite severe earth tremors. It may be pointed out that the magnitude of such earthquakes depends upon the intensity of volcanic eruptions. The violent eruption of Krakatoa volcano (between Java and Sumatra) caused such a severe earthquake the impact of which was experienced as far away as Cape Horn (some 12,800 km away). The devastating earthquake generated 30 to 40 m high tsunamis waves which killed 36,000 people in the coastal areas of Java and Sumatra.

2. Faulting and Elastic Rebound Theory

The horizontal and vertical movements caused by endogenetic forces result in the formation of faults and folds which in turn cause isostatic disequilibrium in the crustal rocks which ultimately causes earthquakes of varying magnitudes depending on the nature and magnitude of dislocation of rock blocks caused by faulting and folding. In fact, sudden dislocation of rock blocks caused by both tensile and compressive forces trigger immediate earth tremors due to sudden maladjusment of rock blocks. The 1950-earthquake of Assam was believed to have been caused due to disequilibrium in crustal rocks introduced by crustal fracture. The 1934-earthquake of Bihar was also considered to have been triggered by faulting activity underneath. Underground active fault zone was suggested as one of the possible causes of Koyna earthquake (Maharashtra) of December 11, 1967.

The occurrence of severe devastating earthquake of San Francisco (USA) in 1906 led H.F. Reid, one of the official investigators of the San Fransisco earthquake disaster, to advance his famous and much appreciated **elastic rebound theory** to explain the mode and causes of earthquakes mainly caused by fractures and faults in the earth's crust and upper mantle. According to Reid the underground rocks are elastic like rubber and expand when stretched and pulled. The stretching and pulling of crustal rocks due to tensile forces is slow process. The rocks continue to be stretched so long as the tensile forces do not exceed the elasticity of the rocks but as the tensile forces exceed the rocks elasticity, they are broken and the broken rock blocks try immediately to occupy their previous positions so that they may adjust themselves. All these processes occur so rapidly that the equilibrium of the concerned crustal surface is suddenly disturbed and hence earth tremors are caused.

Reid's elastic rebound theory very well explains the occurrences of seismic events in Californian valley which is very much frequented by faulting activity. The famous earthquake of 1872 of California was caused due to creation of a massive fault in the Oven Valley. Similarly, the Californian earthquake of April 18, 1906, was caused due to the formation of 640 km long San Andreas Fault. The 1923 earthquake of Sagami Bay of Japan was also believed to have been triggered by big fault.

N. Krishna Brahman and Janardhan G. Niyogi, the two scientists of the National Geophysical Research Institute, have opined that the seismic events near Bhatsa Dam and Koyna Dam are very much active due to active faulting beneath the Deccan Traps. They have claimed to have identified two active rift faults in Maharashtra beneath the Deccan Traps viz. Kurduvadi rift and Koyna rift. According to them Koyna rift begins from Kaladgi in Karnataka and runs for a distance of 540 km through Koyna and terminates 40 km west of Nasik. The 390 km long Kurduvadi rift begins from 40 km south-west of Solapur and after running through Kurduvadi it merges with the Koyna rift to the north of Pune. According to them Bhatsa Dam is located at the junction of Tawi and Koyna faults. They are of the opinion that gradual increase in the seismic events in Bhatsa Dam area since 1983 is because of active faulting beneath the basaltic crust. The 1950 Assam earthquake, 1934 Bihar earthquake and 2001 Bhuj earthquake (Gujarat) of India were caused mainly by faulting.

3. Hydrostatic Pressure and Anthropogenic Causes

Though the earthquakes are natural phenomena and are caused by the endogenetic forces coming from within the earth but certain human activities such as pumping of groundwater and oil, deep underground mining, blasting of rocks by dynamites for constructional purposes (e.g. for the construction of dams and reservoirs, roads etc.), nuclear explosion, storage of huge volume of water in big reservoirs etc. also cause earth tremors of serious consequences. The introduction of additional artificial superincumbent load through the construction of large dams and impounding of enormous volume of water in big reservoirs behind the dams cause disequilibrium of already isostatically adjusted rocks below the reservoirs or further augment the already fragile structures due to faults and fractures underneath.

Many major seismic events have been correlated with dams and reservoirs all over the world such as earthquake of 1931 in Greece due to Marathon Dam constructed in 1929; initiation of earth tremors since 1936 around Hoover Dam (USA) due to creation of Mead Lake in 1935; Koyna earthquake of 1967 (in Satara district of Maharashtra) due to Koyna reservoir constructed in 1962; other examples of earthquakes caused by dams and reservoirs are of Monteynard and Grandvale in France, Mangla in Pakistan, Kariba in Zambia, Manic in Canada, Hendrick Verwoerd in South Africa, Nourek in earst-while USSR, Kurobe in Japan etc. It may be pointed out that the intensity of earthquake has been positively correlated with the levels of water in the reservoirs. The earthquakes caused by hydrostatic pressure of reservoirs are called 'reservoir-induced earthquakes'.

4. Plate Tectonic Theory

Recently, plate tectonic theory has been accepted as the most plausible explanation of the causes of earthquakes. As per theory of the plate tectonics the crust or the earth is composed of solid and moving plates having either continental crust or oceanic crust or even both continental-oceanic crust. The earth's crust consists of 6 major plates (Eurasian plate, American plate, African plate, Indian plate, Pacific plate and Antarctic plate) and 20 minor plates. These plates are constantly moving in relation to each other due to thermal convective currents originating deep within the earth. Thus, all the tectonic events take place along the boundaries of these moving plates. From the stand point of movement and tectonic events and creation and destruction of geomaterials the plate boundaries are divided into (1) constructive plate boundaries, (ii) destructive plate boundaries and (iii) conservative plate boundaries. **Constructive plate boundaries** represent the trailing ends of divergent plates which move in opposite directions from the mid-oceanic ridges, **destructive plate boundaries** are those where two convergent plates collide against each other and the heavier plate boundary is subducted below the relatively lighter plate boundary and **conservative plate boundaries** are those where two plates slip past each other without any collision. Major tectonic events associated with these plate boundaries are ruptures and faults along the constructive plate boundaries, faulting and folding along the destructive plate boundaries and transform faults along the conservative plate boundaries. All sorts of disequilibrium are caused due to different types of plate motions and consequently earthquakes of varying magnitudes are caused.

Normally, moderate earthquakes are caused along the consructive plate boundaries because the rate of rupture of the crust and consequent move-

ment of plates away from the mid-oceanic ridges is rather slow and the rate of upwelling of lavas due to fissure flow is also slow. Consequently, shallow focus earthquakes are caused along the constructive plate boundaries or say along the mid-oceanic ridges. The depth of 'focus' of earthquakes associated with the constructive plate boundaries ranges between 25 km to 35 km but a few earthquakes have also been found to have occurred at the depth of 60 km. It is, thus, obvious that the earthquakes occurring along the mid-Atlantic Ridge, mid-Indian Oceanic Ridge and East Pacific Rise are caused because of movement of plates in opposite directions (dirvergence) and consequent formation of faults and ruptures and upwelling of magma or fissure flow of basaltic lavas (fig. 10.1).

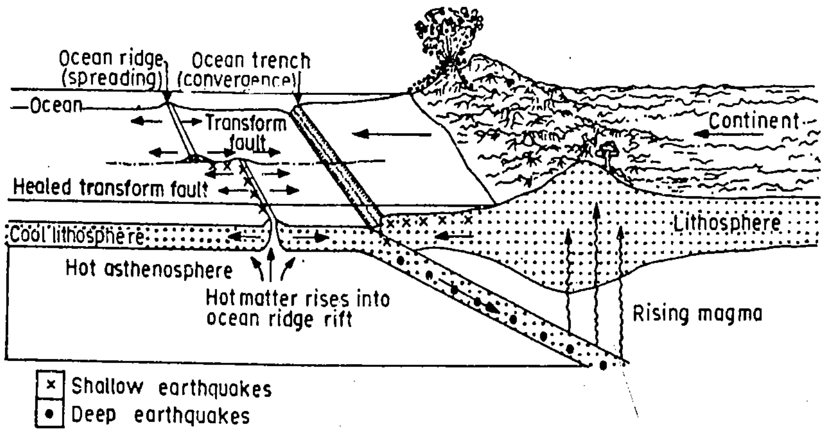


Fig. 10.1 :Relationship between earthquakes and plate boundaries, after, F. Press and R. Seiver, 1978.

Earthquakes of high magnitude and deep focus are caused along the convergent or destructive plate boundaries because of collision of two convergent plates and consequent subduction of one plate boundary along the Benioff zone. Here mountain building, faulting and violent volcanic eruptions (central explosive type of eruptions) cause severe and disastrous earthquakes having the focus at the depth upto 700 km. This process, convergence of plates and related plate collision, explains the maximum occurrence of earthquakes of varying magnitudes along the Fire Ring of the Pacific or the Circum-Pacific Belt (along the western and eastern margins of the Pacific Ocean or say along the western coastal margins of North and South Americas and thus the Rockies to Andes Mountain Belt and along the eastern coastal margins of Asia and island arcs and festoons parallel to the Asiatic coast). The earthquakes of the Mid-Continental Belt along the Alpine-Himalayan chains are caused due to collision of Eurasian plates and African and Indian plates. The earthquakes of the western marginal areas of North and South Americas are caused because of subduction of Pacific plate beneath the American plate and the resultant tectonic forces whereas the earthquakes of the eastern margins of Asia are originated because of the subduction of Pacific plate under Asiatic plate. Similarly, the subduction of African plate below European plate and the subduction of Indian plate under Asiastic plate cause earthquakes of the mid-continental belt. The severe earthquake of Bhuj of Jan. 26, 2001 (Gujarat, India) was caused due to reactivated subsurface faults due to subduction of Indian plate below Asiatic plate.

Creation of transform faults along the conservative plate boundaries explains the occurrence of severe earthquakes of California (USA). Here one part of California moves north-eastward while the other part moves south-westward along the fault plane and thus is formed transform fault which causes earthquakes.

10.3 CLASSIFICATION OF EARTHQUAKES

It has become apparent after the discussion of the causes of seismic events that there is wide range of variation in the nature and magnitude of earthquakes. Each earthquake differs from the other and thus it becomes difficult to classify all the earthquakes into certain categories. Inspite of these limitations earthquakes are classified on the basis of common characteristics as given below.

1. Classification on the basis of causative factors

(A) **Natural earthquakes** are those which are caused by natural processes i.e. due to endogenetic forces. These are further divided into four subcategories.

(i) **Volcanic earthquakes** are caused due to volcanic eruptions of explosive and fissure types. Generally, volcanic earthquakes are confined to volcanic areas. The intensity and magnitude of such earthquakes depend on the intensity and magnitude of volcanic eruptions. Examples, severe earthquakes caused by violent explosions of Krakatao volcano in 1883 and Etna volcano in 1968.

(ii) **Tectonic earthquakes** are caused due to dislocation of rock blocks during faulting activity. Such earthquakes are very severe and disastrous. Examples, 1872 earthquake and 1906 earthquake of California (USA), 1923 earthquake of Sagami Bay (Japan), 2001 earthquake of Gujarat etc.

(iii) **Isostatic earthquakes** are triggered due to sudden disturbance in the isostatic balance at regional scale due to imbalance in the geological processes. Generally, the earthquakes of active zones of mountain building are included in this category.

(iv) **Plutonic earthquakes** are infact deep-focus earthquakes which occur at greater depths. The centres (foci) of these earthquakes are generally located within the depths ranging from 240 km to 670 km.

(B) **Artificial or man-induced earthquakes** or anthropogenic earthquakes are caused by human activities such as pumping of water and mineral oil from underground aquifers and oil reserves respectively, deep underground mining, blasting of rocks by dynamites for constructional purposes (e.g. for the construction of dams and reservoirs, roads etc.), nuclear explosion, storage of huge volume of water in big reservoirs etc. Examples, 1931 earthquake of Greece due to Marathon Dam, 1936 earthquake of Hoover Dam (USA) due to Lake Mead, Koyna earthquake (Maharashtra, India) of 1967 due to Koyna reservoir etc.

2. Classification on the basis of focus

Guttenberg has divided the world seismic centres on the basis of the depths of their foci into 3 types viz. (i) moderate earthquakes—foci are located at the depths from the ground surface (0 km) to 50 km, (ii) intermediate earthquakes-seismic foci at the depths between 50 km and 250 km and (iii) deep focus earthquakes-seismic foci at the depths between 250 km and 700 km. Moderate and intermediate earthquakes are also called as shallow focus and intermediate focus earthquakes respectively.

3. Classification on the basis of human casualities

Earthquakes are grouped into 3 categories on the basis of their hazardous impacts in terms of human casualities. (i) **Moderately hazardous earthquakes**-When human deaths caused by severe seismic tremors are below 50,000 mark. Examples, Kamakura earthquake of Japan of 1293 A.D. (22,000 deaths), Tabas earthquake of Iran of 1978 A.D. (25,000 deaths), Armenian earthquake of earstwhile USSR of 1988 (26,000 deaths), Lisbon earthquake of Portugal in 1531 A.D. (30,000 deaths), Chile earthquake of 1939 A.D. (40,000 deaths), Quito earthquake of Ecudador in 1797 A.D. (41,000 deaths), Calabria earthquakes of Italy in 1783 A.D. (50,000 deaths), North Iranian earthquake of 1990 A.D. (50,000 deaths) etc. (ii) **Highly hazardous earthquakes** causing human deaths ranging between 51,000 and 1,00,000 occurred in 1268 (in Silicia, Asia Minor, death toll, 60,000), in 1667 (in Shemaka, Caucasia, death toll 60,000), in 1693 (Catania, Italy, 93,000 deaths), in 1693 (Naples, Italy, 93,000 deaths), in 1932 (Kansu, China, human deaths, 70,000), in

1935 (Quetta, Baluchistan, death toll, 60,000), in 1970 (Chimbote, Peru, 67,000 deaths), in 2001 (Bhuj, Gujarat, 50,000-1,00,000 death) etc. (iii) **Most hazardous earthquakes** causing human casualitis above 1,00,000 mark occurred in the year 1290 (in Chihli, China, 1,00,000 deaths), in 1556 (in Shen-Shu, China, 8,30,000 deaths), in 1737 (Kolkata, India, 3,00,000 deaths), in 1908 (in Messina, Italy, 1,60,000 deaths), in 1920 (in Kansu, China 1,80,000 deaths), in 1923 (in Tokyo, Japan, 1,63,000 deaths), in 1967 (in Tang-Shan, China 7,50,000) deaths etc.

10.4 WORLD DISTRIBUTION OF EARTHQUAKES

If we look at the world distribution map of earthquakes (fig. 10.2) it appears that the seismic centres are closely related to certain zones of the globe. Earthquakes are, in fact, associated with the weaker and isostatically disturbed areas of the globe. Most of the world earthquakes occur in (i) the zones of young folded mountains, (ii) the zones of faulting and fracturing, (iii) the zones representing the junction of continental and oceanic margins, (iv) the zones of active volcanoes, and (v) along different plate boundaries.

The world map of the distribution of earthquakes prepared by the seismologists on the basis of computer analysis and simulation of 30,000 earthquakes that occurred between 1961 and 1967 very much coincides with the traditional map of world distribution of earthquakes (fig. 10.2) e.g. (1) Circum-Pacific Belt surrounding the Pacific Ocean, (2) Mid-Continental Belt representing epicentres located along the Alpine-Himalayan Chains of Eurasia and northern Africa and epicentres of East African Fault Zones, and (3) Mid-Atlantic Belt representing the earthquakes located along the mid-Atlantic Ridge and its offshoots. 'The high-quality seismicity maps showed that narrow belts of epicentres coincide almost exactly with the crest of mid-Atlantic (Ridge),

Table 10.1 : Devastating severe earthquakes of 20th and 21st centuries of the world

Year	Place of Occurrence	Magnitude (Richter Scale)	Deaths (maximum estimates)
1905	Kangra Valley, India	8.6	20,000
1907	Afganistan	8.1	12,000
1908	Messina, Italy	7.5	200,000
1915	Avenzzaro, Italy	7.5	30,000
1917	South Java		15,000
1918	South-East China	7.3	10,000
1920	Kansu, China	8.5	180,000
1923	Tokyo-Yakohama	8.3	163,000
1927	Nanshan, China	8.0-8.3	180,000
1933	North-Central China	7.4	10,000
1934	Bihar, India	8.4	10,700
1935	Quetta, Pakistan	7.5-7.6	60,000
1939	Chillan, Chile	8.3	40,000
1939	Erzincan, Turkey	8.0	40,000
1948	Kagi, Formosa (Taiwan)	7.3	19,800
1960	Agadir, Morocco	5.6-5.9	14,000
1962	Buyin-zara, Iran	7.3	14,000
1968	Dasht-e-Bayaz, Iran	7.3-7.8	18,600

1970	Chimbote, Peru	7.8-7.9	67,000
1974	West Central China	6.8	20,000
1975	Haicheng, China	7.3-7.4	10,000
1976	Guatemala	7.5	23,000
1976	Tang-Shan, China	7.8-8.1	750,000
1978	Tabas, Iran	7.7-7.8	25,000
1985	Mexico city, Mexico	-	10,000
1988	Armenia	-	26,000
1988	Darbhanga (Bihar, India) and Nepal	6.5	850
1990	Northern Iran	7.3	50,000
1990	Manila, Phillippines	7.7	500
1990 (June)	Iran	7.3	40,000 5,00,000 homless
1995 (January)	Kobe, Japan	7.2	5,502 2,80,000 homeless
1997 (May)	Jabalpur (India)	6.0	50
1997 (May)	Iran	7.1	2,500
1998 (February)	Afghanistan	6.1	4,400 15,000 families homeless
1998 (29 May)	Afghanistan	6.9	More than 5000
1998 (17 January)	Kobe, Japan	...	over 5000 23,600 injured
1999 (17 August)	Turkey	7.4	over 40,000 more than 19,000 wounded
1999 (12 November)	Turkey	7.2	550 dead
1999 (21September)	Taiwan	7.3	more than 2000
20001 (26 January)	Bhuj, India	8.1	50,000-100,000

the east Pacific, and the other oceanic ridges, where plates separate. Earthquake epicentres are also aligned along the transform faults, where plates slide past each other. But the earthquakes that occur at depths greater than about 100 km typically occur near margins where plates collide. It is a basic tenet of the theory of plate tectonics that these deep earthquakes actually define the positions of subducted plates which are plunging back into the mantle beneath an overriding plate (F. Press and R. Seiver, 1978).

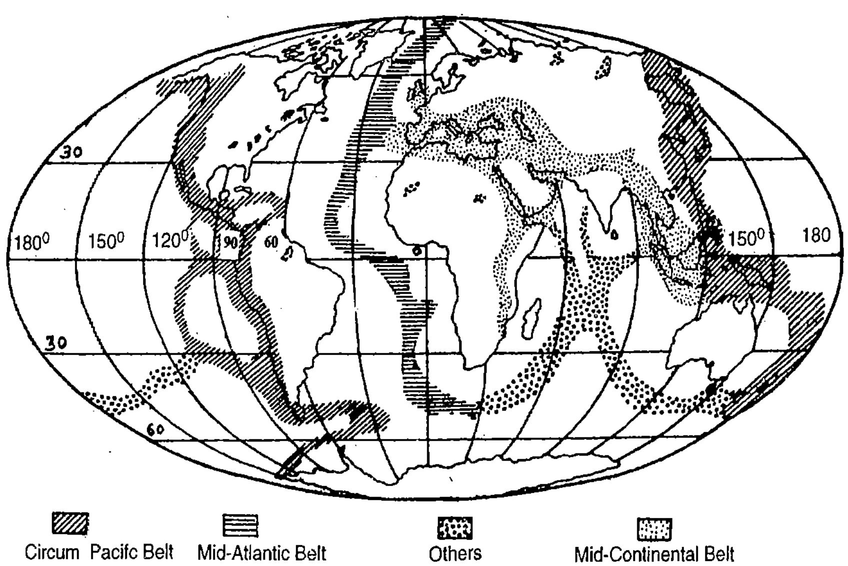


Fig. 10.2 : World distribution of earthquakes.

(1) **Circum-Pacific Belt** includes the epicentres of the coastal margins of North and South Americas and East Asia representing the eastern and western margins of the Pacific Ocean respectively. This belt accounts for about 65 per cent of the total earthquakes of the world. This belt presents 4 ideal conditions for the occurrences of earthquakes viz. (i) junction of continental and oceanic margins, (ii) zone of young folded mountains, (iii) zone of active volcanoes and (iv) subduction zone of destructive or convergent plate boundaries. The western marginal zones of North and South Americas are represented by Rockies and Andes folded mountain chains respectively. These zones are isostatically very sensitive zones because they are also the zones of convergent plate boundaries where the Pacific Oceanic plate is being continuously subducted below the American plates. Besides, these zones are also the areas of strong volcanic activity. The earthquakes associated with the eastern coastal margins of Asia and the island arcs and festoons (Kamchatka, Sakhalin, Japan, Phillippines) are caused due to the collision of the Pacific and Asiatic plates and consequent vulcanicity. Japan records about 1500 seismic shocks every year.

The recent earthquake of Mexico city in 1985 reveals the impact of collision of convergent (destructive) plate boundaries on the occurrences of earthquakes. The damage done by the devastating earthquake included death of 5,000 people, disappearance of 2,000 persons, injuries to 40,000 people, destruction of 4000 buildings, damages to 6,000 buildings, lesser damage to 50,000 buildings etc.

(2) **Mid-continental belt** is also known as Mediterranean Belt or Alpine-Himalayan Belt which represents the collision or subduction zones of continental plates. About 21 per cent of the total seismic events of the world are recorded in this belt. This belt includes the epicentres of the Alpine mountains and their offshoots in Europe, Mediterranean Sea, northern Africa, eastern Africa and the Himalayan mountains and Burmese hills. This belt represents the

weaker zones of folded mountains where isostatic and fault-induced earthquakes are caused due to subduction of African and Indian plates below Eurasian plate.

The Indian seismic foci are grouped into 3 zones viz., (i) Himalayan region, (ii) plain region and (iii) plateau region. **The Himalayan region** is a zone of maximum intensity in terms of the magnitude of seismic tremors because this zone is located in the subduction zones of the Asiatic and Indian plates where the process of mountain building is still in progress. Uttar Kashi earthquake of October 20, 1991 and Chamoli earthquake of 29 March, 1999 (all in Uttaranchal of India) are latest examples. **The plain seismic region** is a zone of comparatively moderate intensity. Even the earthquakes of Assam are also included in this zone. The significant earthquakes recorded in the past in this region are 1934 earthquakes of Bihar, Assam earthquake of 1950, Kolkata earthquake of 1737 and Darbhanga earthquake (Bihar) of 1988. **The peninsular Indian region** is considered to be a zone of minimum intensity.

The Indian earthquakes along the Himalayas and foothill zones may be explained in terms of plate tectonics. The Asiatic plate is moving southward whereas the Indian plate is moving northward and hence the northern margin of the Indian plate is being subducted below the Asiatic plate. The collision of Asiatic and Indian plates and resultant subduction of Indian plate and consequent folding and faulting and gradual rise of the Himalayas at the rate of 50 mm per year cause earthquakes of northern India, Tibet and Nepal. According to J.G. Negi, P.K. Agrawal and O.P. Pandey (as reported in Hindu, September 8, 1988) the Indian subcontinent has deformed at places due to the Indian Ocean floor spreading process. India folds at places and when the energy reaches the elastic limit the rocks break up and trigger strike-slip and thrust fault earthquakes. The Himalayan fault zone is not actually one fault but a broad system of interactive faults. It consists of a complex grid of faults extending all along this colliding zone. The earthquake belt extends through Sulaiman and Kirthar shear zones in the west, the Himalayas in the north and Burmese arc in the east. These tectonic events caused by plate movements cause earthquakes in the northern and north-eastern parts of India. Even the earthquakes of Peninsular India have been related to the active faults below deccan traps.

On the basis of magnitude of **damage risk** India is divided into **five damage risk zones** : 1. Zone I of **least damage risk** includes the places of some parts of Punjab and Haryana, plain areas of Uttar Pradesh, portions of plains of Bihar and west Bengal, delta area of the Godavari, coastal plain areas of Maharashtra and Kerala, desert areas of Rajasthan and most areas of Gujarat except Kutch area. 2. Zone II of **low damage risk** includes southern Punjab and Haryana, southern parts of plains of Uttar Pradesh, eastern Rajasthan, coastal districts of Orissa, Tamil Nadu etc. 3. Zone III of **moderate damage risk** represents the areas of southern and south-eastern Rajasthan, most of Madhya Pradesh, Maharashtra and Karnataka, southern Bihar (Jharkhand), northern and northwestern Orissa etc. 4. Zone IV of **high damage risk** covers Jammu and Kashmir, Himachal Pradesh, northern Punjab and Haryana, Delhi, eastern Uttar Pradesh, 'tarai' and 'bhabar' regions and Himalayan regions of Uttaranchal and Bihar and Sikkim areas. 5. Zone V of **very high damage risk** includes parts of Jammu and Kashmir, some parts of Himachal Pradesh, Uttaranchal, western north Bihar (including Munger-Darbhanga), entire north eastern India and Kutch areas of Gujarat.

Though the plains of west Bengal comes under the zone of least damage risk but the devastating severe earthquake of Kolkata of 11 October, 1737, killing 300,000 people, puts a question mark against this concept. The zone of very high damage risk of Kutch region of Gujarat registered most devastating killer earthquake on Jan. 26, 2001 in its seismic history of past 182 years killing 50,000 to 100,000 people. The epicenter was located near Bhuj town.

Table 10.2 : Major Earthquakes of India

Time	Location	Effects
October 11, 1737	Kolkata	3,00,000 deaths of human beings , the worst earthquake of India in its seismic history.
September 1, 1793	Mathura	Adversely affected larger areas including Garhwal, Kumaun and Simla hills
June 16, 1819	Kutch	2,000 people died, Bhuj city destroyed, famous mosque of 15th century in Ahmedabad city broken, rise of land in a length of 15 km in the Rann of Kutch known as Allah Bund.
June 16, 1828	Kashmir	1,000 people died.
August 26, 1833	Bihar	Adversely affected the areas from Bihar to Nepal; 1000 houses destroyed.
February 19, 1842	Jalalabad	Adversely affected the areas from Delhi to Kabul city of Afghanistan.
April 1, 1843	Deccan India	Carnool, Solapur, Belgaon and Bellary cities greatly damaged
January 10, 1869	Assam	Adversely affected a large area of 2,50,000 square miles.
May 30, 1885	Kashmir	3,000 people died
July 14, 1886	Dacca (Bangladesh) & W. Bangal	Adversely affected large area of West and East Bengal, Assam, Sikkim, Bhutan and Chotanagpur covering an area of 2,30,000 square miles.
June 12, 1887 (8.7)	Shillong (Meghalaya)	1500 people died; houses even of stones in the cities of Naogaon, Shillong, Gauhati (Guwahati), Golpara etc. heavily damaged and destroyed; affected area 17,50,000 squae miles; a great fault of 35 feet width and 12 miles length formed in the ground.
June 15,1890	Kutch	1500 people died
April 4, 1905 (8.6)	Kangra	20,000 people killed,whole Punjab was affected
July 8, 1918	Assam	...
July 3, 1930	Assam (Dhubri)	Dhubri town destroyed
January 5, 1934 (8.4)	Bihar-Nepal	8.4 magnitude on Richter scale; 10,700 people killed
June 26, 1941	Andman	...
August 15, 1950 (8.7)	Assam	1500 people killed; 60 after shocks; floods in the rivers of Assam
May 18, 1955	Nicobar (Andman)	...
August, 1956	Kutch	...
September, 1956	Bulandshar	...
December 11, 1967 (6.5)	Koyna (Satara)	1000 people killed; 2063 wounded and 10,000 homeless
August 21, 1988 (6.7)	Darbhanga (Bihar), Nepal	Magnitude 6.7 on Richter scale, 850 people died, 25000 houses damaged
October 20, 1991 (6.6)	Uttar Kashi (Uttaranchal)	Over 2500 dead
September 30, 1993 (6.3)	Latur (Maharashtra)	11,000 dead
May 22,1997 (6.0)	Jabalpur (M.P.)	50 dead
March 29, 1999 (6.8)	Chamoli (Uttaranchal)	
Jan. 2001 (8.1)	Bhuj (Gujarat)	50,000-100,000 dead

Bhuj Earthquake (2001)

While the people of India were busy in celebrating the first republic day on Jan. 26, 2001 of the new century in different parts of the country and the programme of display of might of armed forces of the country was in progress in New Delhi, the nature demonstrated its might by rocking Kutch region of Gujarat when a severe earthquake struck at 8.45 A.M. and shook the region for almost a minute. Within no time the villages and towns were flattened, high rise buildings collapsed, many villages and towns became heaps of debris, communication and power lines were completely disrupted, transport system was thrown out of gear and settlements became ruins. This was the second most devastating quake in the earthquake history of India after 1737 killer earthquake of Kolkata (300,000 people dead). The epicentre of this earthquake was located near Bhuj town (population, 150,000). A moderate quake measuring 4.2 on Richter scale was registered on 24 December, 2000. The epicentre of this precursor quake was located only 22 km away from Bhuj town but no attention was paid to this precursor seismic event either by experts or by govt. agencies. The Bhuj quake of Jan. 26, 2001 was measured 6.9 on Richter scale by the Indian Meteorological Department (IMD) while the quake was measured 7.9 which was subsequently upgraded to 8.1 by the U.S.A, France and China. National Geophysical Research Institute (NGRI) of India and Bhabha Atomic Research Centre (BARC) also confirmed the American measurement (8.1). According to Indian Meteorological Department the main reason for the difference in the magnitude of the quake was the application of different methodologies for the measurement of seismic magnitude by different countries and organizations. It may be pointed out that the IMD uses body wave for the measurement of seismic magnitude while the USA uses shock waves for this purpose.This severe devastating earthquake killed 50,000 to 100,000 people and adversely affected 5,000,000 people. Bhachau and Anjar towns were totally flattened, 90, 60 and 50 per cent houses collapsed in Bhuj, Rajkot and Ahmedabad respectively.

If we look at the past seismic history of Gujarat, it appears that a severe earthquake occurs every 30 years e.g. Bhawnagar earthquake, 1872; Kutch earthquake, 1903; Dwarka earthquake, 1940; Broach earthquake, 1970 and Bhuj earthquake, 2001. Between 1845 and 1956 sixty six moderate earthquakes were registered in Kutch area but no one was killed, five severe and one very severe earthquakes rocked the area. In fact, the sequence of destruction of Kutch began with the severe earthquake of June 19, 1819 (7.1 on Richter scale) when 2000 people were killed, Bhuj town was destroyed, famous mosquake of Ahmedabad was damaged, a 100 km long ridge known as Allah Bund was created (most of which is now in Sind of Pakistan, only 15 km ridge is in India) was formed etc.

The main reasons for the recent Bhuj earthquake of 2001 are : sea floor spreading of Indian Ocean at the rate of 5 cm per year, gradual northward movement of Indian plate and reactivated faults below the surface. Two major connecting faults have been located in Kutch region. A 200 km long and 100 km wide fault runs east-west between Bhuj and Ahmedabad. The second fault measuring 500 km in length and 100 km in width runs in north-south direction through Ahmedabad, Mehsana and Baroda and is known as Combay Graben. These subterra-

nean faults intersect each other near Viramgam, Santhalpur and Radhanpur towns and become the pivot of seismic events whenever these are activated due to plate movement.

(3) Mid-Atlantic Ridge Belt includes the epicentres located along the mid-Atlantic Ridge and several islands nearer the ridge . This belt records moderate and shallow focus earthquakes which are essentially caused due to the creation of transform faults and fractures because of splitting of plates and their movement in opposite directions. Thus, the spreading of sea floor and fissure type of volcanic eruption cause earthquakes of moderate intensity.

It may be pointed out that the earthquakes that occur along the plate margins (boundaries) are well explained on the basis of plate tectonic theory but the earthquakes originating within the plates are difficult to be explained on the basis of this revolutionary theory. For example, the earthquakes of New Madrid (Missouri, USA, 1812), Charleston (South Carolina, USA, 1886), Boston (Massachusetts, USA, 1755), Tang-Shan (China, 1976), Koyna (Maharashtra, India, 1967) etc. are a few examples of intraplate earthquakes. Similarly, 'the seismicity of the Indian Shield as revealed from Kutch (1819), Koyna (1967), Bhadrachalam (1969) and Broach (1970) cannot be explained easily by plate tectonics since they occurred away from plate boundary' (J.G. Negi, in the Hindu, September 18, 1988).

10.5 HAZARDOUS EFFECTS OF EARTHQUAKES

It may be pointed out that the intensity of earthquakes and their hazardous impacts are determined not on the basis of the magnitude of seismic intensity as determined by Richter scale but are decided on the basis of quantum of damages done by a specific earthquake to human lives and property. An earthquake becomes hazard and desaster only when it strikes the populated area. The direct and indirect disastrous effects of earthquakes include deformation of ground surfaces, damage and destruction of human structures such as buildings, rails, roads, bridges, dams, factories, destruction of towns and cities, loss of human and animal lives and property, violent devastating fires, landslides, floods, disturbances in groundwater conditions etc.

(1) Slope instability and failures and landslides—The shocks produced by earthquakes particularly in those hilly and mountainous areas which are composed of weaker lithologies and are tectonically sensitive and weak cause slope instability and slope failure and ultimately cause landslides and debris falls which damage settlements and transport systems on the lower slope segments. The shocks generated by Peruvian earthquake of May, 1970 triggered off the collapse of ice caps seated on the peak of high mountain called Huascaran of 6654 m height near the town of Yungay in Peru. The huge masses of falling ice dislodged thousands of tonnes of rock mass from the said mountain and thus was generated a gigantic debris flow down the slope of Huascaran mountain travelling at the speed of 320 km per hour. The enormous mass of debris flow covered a distance of 15 km within few minutes and buried many buildings and human structures of Yungay town and killed about 25,000 people.

(2) Damage to human structures—Earthquakes inflict great damage to human structures such as buildings, roads, rails, factories, dams, bridges, and thus cause heavy loss of human property. It may be pointed out that in the ground surface composed of unconsolidated geomaterials, such as alluvium, colluvium, artificially infilled and levelled depressions, swamp deposits reclaimed through the dumping of coarse sands and city garbages the vibrations of earthquakes last longer and the amplitudes of seismic waves are greater than in the structures of consolidated materials, and bedrocks. Thus, the earthquakes cause more damages in the areas of unconsilidated ground than their counterparts in the regions of solid structures and bedrocks.

Two major earthquakes of Bihar-Nepal border in 1934 and 1988 can explain the impact of earthquake disasters on human structures and human lives. The damage caused by the Bihar earthquake of 15 January, 1934, measuring 8.4 on Richter scale, include 10,700 human deaths, landslides and slumping in an area of 250 km length and 60 km width, ruptures and faults in the ground surface etc. which caused irreperable damage to human structures. The Darbhanga (Bihar) earthquake of 21 August, 1988 measuring only 6.5 magnitude on Richter scale (1000 times smaller than the great earthquake of 1934 in intensity) damaged 25,000 houses due to unconsolidated Gangetic alluvium which in fact acted as a seismic amplifier. The disastrous earthquake of Mexico city of 1985 (September) caused total collapse of 400 buildings, damage to 6,000 buildings and moderate damage to 50,000 buildings. Besides, the infrastructures of the city were seriously damaged, for example, water pipes were broken, telecommunication lines and systems were severely damaged, power and water supplies were disrupted, inner vehicular transport was halted etc. The severe earthquake of 9 February, 1971 in the San Fernando valley, located to the north-west of Los Angeles (USA) caused total collapse of Olive New Hospital in Sylmar. This damage shocked every body because this building was constructed in conformity with the earthquake resistance standards. Uttar Kashi (Uttaranchal) earthquake of 1991 and Latur-Kilari quake (Maharashtra) of 1993 (India) flattened many buildings.

(3) Damages to the towns and cities—Earthquakes have their worst effects on towns and cities because of highest density of buildings and large agglomerations of human populations. The earth tremors of higher magnitudes shake the ground to such an extent that large buildings collapse and men and women are burried under large debris and rubbles of collapsed structural materials of buildings, ground water pipes are bent and damaged and thus water supply is totally disrupted, electric poles are uprooted and electric and telephone wires and cables are heavily damaged causing total disruption of electric supply, obstruction and destruction of sewer systems causes epidemics, road blocks throw the transport systems out of gear etc.

Kolkata city was severely damaged due to severe earthquake of 11 October, 1737 as thousands of buildings were severely damaged and 3,00,000 people were killed. The sad tale of the destruction of Mexico city due to the earthquake of 1985 has already been described. Recent Bhuj earthquake of Gujarat (Jan. 26, 2001) flattered towns of Anjar and Bhuj destroying more than 90 percent buildings.

(4) Loss of human lives and property—It may be pointed out that it is not the intensity (magnitude of Richter scale) of earthquake alone which matters more as regards the human casualities but it is the density of human population and houses which matter more in terms of human deaths and loss of property. For example, the Kangra earthquake of India in 1905 recorded 8.6 magnitude on Richter scale but it could cause deaths of only 20,000 people whereas 1976 Tang-Shan earthquake of China measuring 7.8 to 8.1 on Richter scale killed 7,50,000 people. More than 40,000 people lost their lives in the devastating earthquake of Turkey (August 17, 1999) which recorded 7.4 on Richter scale. The loss of human lives caused by earthquakes has been enumerated in the preceding section on the classification of earthquakes based on human casualities (see also tables 10.1, 10.2, 10.3).

Table 10.3 : Human casualities

Moderately Hazardous Earthquakes (human deaths below 50,000)

Earthquakes	Deaths
1. West Central China, 1971	20,000
2. Kamakura, Japan, 1293	22,000
3. Peking, China, 1731	22,000
4. Shen-Shu, China, 1556	25,000
5. Tabas, Iran, 1978	25,000
6. Armenia, earstwhile USSR, 1988	26,000
7. Sanriku, Japan, 1896	30,000
8. Zenkoji, Japan, 1847	34,000
9. Quito, Ecuador, 1797	41,000
10. Northern Iran, 1990	50,000
11. Kobe Quake, 1995 (Jan.) Japan	5,000
12. Iran, Feb., 1997	1180
13. Jabalpur (India), May, 1997	2,500
14. Turkey, 17 Aug., 1999 (7.4)	more than 40,000

Table 10.4 : Human casualities

Highly Hazardous Earthquakes (human deaths between 50,000 and 1,00,000)

Earthquakes	Deaths
1. Silicia, Asia Minor, 1268	60,000
2. Shemaka, Caucasia, 1667	60,000
3. Catania, Italy, 1693	93,000
4. Kansu, China, 1932	70,000
5. Quetta, Baluchistan, 1935	60,000
6. Chimbote, Peru, 1970	67,000
7. Bhuj, Gujarat, 2001 (8.1)	50,000-100,000

Table 10.5 : Human Casualities

Most Hazardous Earthquakes (human deaths above 1,00,000)

Earthquakes	Deaths
1. Chihli, China, 1290	1,00,000
2. Kolkata, India, 1737	3,00,000
3. Messina, Italy, 1908	1,60,000
4. Kansu, China, 1920	1,80,000
5. Tokyo, Japan, 1923	1,63,000
6. Sagami Bay, Japan, 1923	2,50,000
7. Tang-Shan, China, 1976	7,50,000

(5) **Fires**—The strong vibrations caused by severe earthquakes strongly shake the buildings and thus strong oscillations cause severe fires in houses, mines and factories because of overturning of cooking gas cylinders, contact of live electric wires, churning of blast furnaces, displacement of other electric and fire-related appliances. For example, the house wives were cooking their lunches in the kitchens when disastrous killer earthquake struck in the vicinity of Tokyo and Sagami Bay in 1923. Consequently, severe fire broke out which claimed the lives of 38,000 people out of total fatalities of 1,63,000 caused by the earthquake through various processes. This earthquake resulted into total loss of property worth 2,500 million US dollars. The severe earthquake of San Fransisco (USA), which occurred on April 18, 1906, caused widespread fires in several parts of the city. No water could be made available immediately to extinguish the fire because water pipes were also broken and displaced by the earthquake.Two biggest oil refineries of Turkey were completely devastated due to fire caused by the killer earthquake of August 17, 1999 (7.4).

(6) **Deformation of ground surface**—Severe earth tremors and resultant vibrations caused by severe earthquakes result in the deformation of ground surface because of rise and subsidence of ground surface and faulting activity. For example, the Alaska (USA) earthquake of 1964 caused displacement of ground surface upto 10-15 metres. The 1897-Assam earthquake caused a large fault measuring 10.6 m (35 feet) wide and 19.3 km (12 miles) long. Several faults were created in the mouth areas of the Mississippi river because of the earthquakes of 1811, 1812 and 1813 in the Mississippi valley. The alluvial-filled areas of the flood plains of the Mississippi were fractured at many places which forced ground surface at few places to collapse. This process resulted in the formation of lakes and marshes.

The ground surface was greatly deformed in the delta area of the Indus river (in Pakistan) due to the earthquake of 1819 as an area of 4,500 square kilometres was submerged beneath sea water and this land area disappeared for ever. It may be pointed out that subsidence in one area is followed by emergence of the land in other area. This also happened in the Indus delta area as a large area measuring 80 km in length and 26 km in width was raised by 3 m from the surrounding area. Similarly, the coastal land of Chile was raised from 6m to 13 m because of the earthquake of 1835. The seafloor of Sagami Bay of Japan was subsided from 305 m to 457 m because of the earthquake of 1923.

(7) **Flash floods**—Strong seismic events result in the damages of dams and cause severe flash floods. Severe floods are also caused because of blocking of water flow of rivers due to rock blocks and debris produced by severe tremors on the hillslopes facing the river valleys. Sometimes, the blockade of the rivers is so immense that even the main course of the river is changed. The 1950 earthquake of Assam produced barrier in the Dihang river, the tributary of the Brahmaputra river, due to accumulation of huge debris caused by landslides triggered by earth tremors and thus caused severe flash floods in the upstream sections. Similarly, the dam on Subansiri river broke in and resultant flash flood submerged an area of 770 square kilometres.

(8) **Tsunamis**—The seismic waves, caused by the earthquakes travelling through sea water, generate high sea waves and cause great loss of life and property. Since the Pacific Ocean is girdled by the ring of earthquakes and volcanoes tsunamis are more common in the Pacific with a minimum frequency of 2 tsunamis per year. The Kutch earthquake of June 16, 1819 generated strong tsunamis which submerged the coastal areas and inflicted great damage to ships and country-made boats of the fishermen. The land area measuring 24 km in length was raised upward because of tectonic movement triggered by the said earthquake which provided shelter to the stranded and marooned people. This is why the people called this raised land as **Allah's Bund** (bund created by the God). The great tsunamis caused by the Lisbon earthquake of the year 1755 (in Portugal) generated about 12 m high sea waves which damaged most parts of Lisbon city and killed 30,000 to 60,000 people. The impact of this earthquake was so enormous that the waters of inland lakes like Looh Lomond and Looh Ness continued to oscillate for several hours. The strong tsunamis triggered by Lisbon earthquake also caused 3.5 m to 4.5 m high waves as far away as the West Indies. The earthquake caused by violent volcanic eruption of Karakatoa in 1883 caused enormous tsunamis which generated 36.5 m high sea waves which ravaged the coastal areas of Java and Sumatra and killed 36,000 people.

Tsunami : Historical Perspective

The waves generated in the oceans triggered by high magnitude earthquakes in the ocean floors (exceeding 7.5 on Richter scale), or by violent central volcanic eruptions (such as Krakatao eruption in 1883), or by massive landslides of the coastal lands or of submerged continental shelves and slopes or in deep oceanic trenches, are called tsunami, which is a Japanese word meaning thereby **harbour waves.** The tsunamis are long waves (with longer wavelengths of 100 km or more) which travel at the speed of hundreds of kilometers per hour but are of shallow in depth in deeper oceans and seas. As these waves approach coastal land, the depth of oceanic water decreases but the height of tsunamis increases enormously and when they strike the coast, they cause havoc in the coastal areas. The best example of tsunami induced by violent volcanic eruption is from Krakatao eruption which occurred in 1883. Severe earthquake caused by Krakatao eruption generated furious tsunami waves ranging in 30 to 40 meters in height (average being 120 feet or 36.5 m). These waves were so violent that they ravaged the coasts of Java and Sumatra and killed 36,000 people.

Since the Pacific Ocean is girdled by convergent plate boundaries and the ring of earthquakes and volcanoes, tsunamis are more common in the Pacific with a minimum frequency of 2 tsunamis per year. The great tsunamis caused by the Lisbon earthquake (Portugal) of the year 1755 generated about 12 m high sea waves which damaged most parts of Lisbon city and killed 30,000 to 60,000 people. The Kutch earthquake of June 16, 1819 generated strong tsunamis which submerged the coastal areas. The land area measuring 24 km in length was raised upward because of tectonic movements. The raised land was called as **Allah's Bund** (bund created by the God).

The following are the significant tsunamis in the second half of the 20th century and 21st century :

(1) **Aleutian tsunami :** April 1, **1946**, generated by Aleutian earthquake of the magnitude of 7.8 on Richter scale, the resultant tsunami with a height of 35 m killed many people in Alaskan and Hawaiian coastal areas.

(2) **Kamchatka tsunami :** Nov. 4, **1952**, earthquake of the magnitude of 8.2, generated Pacific-wide tsunami with a wave height of 15 m.

(3) **Aleutian tsunami** : March 9, **1957**, earthquake of the magnitude of 8.3 on Richter scale, generated a Pacific-wide tsunami of 16 m height and adversely affected Hawaii islands.

(4) **Chilean tsunami :** May 22, **1960**, a strong earthquake of the magnitude of 8.6 on Richter scale, generated Pacific-wide tsunamis and claimed 2,300 human lives in Chile.

(5) **Alaskan tsunami :** March 28, **1964**, a strong earthquake of the magnitude of 8.4 on Richter scale, generated 15 m high tsunami and killed more than 120 people, in Alaska.

(6) **Papua New Guirea tsunami :** July 17, **1998**, a moderate intensity (7.00n Richter scale) submarine earthquake followed by massive submarine landslides generated 30m high tsunami killing thousands of people living along the lagoon.

(7) **Sumatra tsunami :** December 26, **2004**, a powerful earthquake of the magnitude of 9 on Richter scale, off the coast of Sumatra with its epicenter at **Simeulue** in the Indian Ocean occurred at 00:58:53 (GMT), 7:58:53 (Indonesian Local Time) or 6.28 a.m. (Indian Standard Time, IST) and generated a powerful tsunami with a wavelength of 160 km and initial speed of 960 km/hr. The deep oceanic earthquake was caused due to sudden subduction of **Indian plate** below **Burma plate** upto 20 meters in a boundary line of 1000 km or even more (2000 km upto southern China). This tectonic movement caused 10 m rise in the oceanic bed which suddenly displaced immense volume of water causing killer tsunami. This earthquake was largest (highest on Richter scale) since 1950 and the 4th largest since 1900 A.D. The Andman and Nicobar group of islands were only 128 km (80 miles) away from the epicenter (Simeulue) and the east coasts of India were about 1920 km (1200 miles) away from the epicenter. The furious tsunami with a height of about 10 m adversely affected 12 countries bordering the Indian Ocean, worst affected areas included Tamil Nadu coast and Andman-Nicobar Islands of India, Sri Lanka, Indonesia and Thailand. The strong tsunami took about 3 hours to strike Tamil Nadu coast. The killer tsunami clained more than 200,000 human lives in the affected countries wherein Indonesia, Sri Lanka and India stood 1st, 2nd and 3rd in the number of human casualities.

11

MOUNTAIN BUILDING

11.1 MEANING

Mountains are significant relief features of the second order on the earth's surface. A mountain may have several forms viz. (i) mountain ridge, (ii) mountain range, (iii) mountain chain, (iv) mountain system, (v) mountain group and (vi) cordillera. A **mountain ridge** is a system of long, narrow and high hills. Generally, the slope of one side of a ridge is steep while the other side is of moderate slope but a ridge may also have symmetrical slopes on both the sides. **A mountain range** is a system of mountains and hills having several ridges, peaks and summits and valleys. In fact, a mountain range stretches in a linear manner. In other words, a mountain range represents a long but narrow strip of mountains and hills. All of the hills of a mountain range are of the same age but there are structural variations in different members of the range. **A mountain chain** consists of several parallel long and narrow mountains of different periods. Some times, the mountain ranges are separated by flat upland or plateaux. **A mountain system** consists of different mountain ranges of the same period. Different mountain ranges are separated by valleys. **A mountain group** consists of several unsystematic patterns of different mountain systems. **Cordillera** consists of several mountain groups and systems. In fact, cordillera is a community of mountains having different ridges, ranges, mountain chains and mountain systems. The mountainous region of the western part of North America is the best example of a cordillera.

11.2 CLASSIFICATION OF MOUNTAINS

1. On the basis of height

(i) Low mountains; height ranges between 700 to 1,000 m.

(ii) Rough mountains; height-1000 m to 1,500 m

(iii) Rugged mountains; height-1,500 to 2,000 m.

(iv) High mountains; height above 2,000 m.

2. On the basis of location

(i) Continental mountains

(a) **Coastal mountains,** examples : Applachians, Rockies, Alpine mountain chains, Western and Eastern Ghats of India etc.

(b) **Inland mountains :** examples, Ural mountains (Russia), Vosges and Black Forest block mountains (Europe), Himalayas, Aravallis, Satpura, Maikal, Kaimurs etc. (India), Kunlun, Tienshan, Altai etc. (Asia) etc.

(ii) **Oceanic mountains**—Most of the oceanic mountains are below the water surface (below sea level). Oceanic mountains are located on continental shelves and ocean floors. Some oceanic mountains

are also well above sea level. If the height of the mountains is considered from the oceanic floor and not from the sea level, many of the oceanic mountains will become much higher than the Mount Everest. For example, Mauna Kea volcanic mountain of Hawaii Island is 4200 m high from the sea level but if its height is considered from the sea bottom, its height becomes 9140 m which is higher than the highest mountain, Mount Everest (8848m AMSL) of the continent. Similarly, the Antilean Mountain system is 3000 m above sea level but it is also 5400 m below sea level, and thus its total height from the oceanic floor becomes 8400 m. Most of the oceanic mountains are volcanic mountains.

3. On the basis of mode of origin

(1) **Original or tectonic mountains** are caused due to tectonic forces e.g. compressive and tensile forces motored by endogenetic forces coming from deep within the earth. These mountains are further divided into 4 types on the basis of orogenetic forces responsible for the origin of a particular type of mountain.

(i) **Folded mountains** are further divided into 3 sub-types on the basis of their area. These are originated by compressive forces.

(A) Young folded mountains

(B) Mature folded mountains

(C) Old folded mountains

(ii) **Block mountains** are originated by tensile forces leading to the formation of rift valleys. They are also called as horst mountains.

(iii) **Dome mountains** are originated by magmatic intrusions and upwarping of the crustal surface. Examples, normal domes, lava domes, batholithic domes, laccolithic domes, salt domes etc.

(iv) **Mountains of accumulations** are formed due to accumulation of volcanic materials. Thus, these are also called as volcanic mountains. Different types of volcanic cones (e.g. cinder cones, composite cones, acid lava cones, basic lava cones etc.) come under this category.

(2) **Circum-erosional or relict mountains :** examples, Vindhyachal ranges, Aravallis, Satpura, Eastern Ghats, Western Ghats etc. (all from India).

4. On the basis of period of origin

(1) **Pre-cambrian mountains :** examples, Laurentian mountains, Algoman mountains,. Kilarnean mountains etc. (North America), mountains of Feno-Scandia, North-West Highlands and Anglesey etc. (Europe).

(2) **Caledonian mountains :** mountains formed during Silurian and Devonian periods, examples: Taconic mountains of the Applachian system, mountains of Scottland, Ireland and Scandinavia (Europe), Brazilides of South America, Aravallis, Mahadeo, Satpura etc. of India.

(3) **Hercynian mountains** formed during Permian and Permocarboniferous periods, examples : mountains of Iberian peninsula, Ireland, Spanish Messeta, Brittany of France, South Wales, Cornwall, Mendips, Paris basin, Belgian coalfields, Rhine Mass, Bohemian plateau, Vosges and Black Forest, plateau region of central France, Thuringenwald, Frankenwald, Hartz mountain, Donbas coal field (all in Europe); Variscan mountains of Asia include Altai, Sayan, Baikal Arcs, Tien Shan, Khingan, mountains of Dzungarian basin, Tarim basin, Nanshan, Alai and Trans Alai mountains of Amur basin, Mongolia and Gobi etc; Astralian Variscan mountains include the scattered hills in the Eastern Cordillera, New England of New Southwales; North American Variscan mountains include Applachians; South American Variscan mountains are Austrian and Saalian folds of San Juan and Mendoza, mountains of Puna area of Atacama, Gondwanides of Argentina etc.

(4) **Alpine mountains :** mountains formed during Tertiary period, examples, Rockies (North America), Andes (South America), Alpine mountain systems of Europe (main Alps, Carpathians, Pyrenees, Balkans, Caucasus, Cantabrians, Appenines, Dinaric Alps etc.), Atlas mountains of north-west Africa; Himalayas and mountains coming out of Pamir Knot of Asia (Taurus, Pauntic, Zagros, Elburg, Kunlum etc).

Block mountains

Block mountains, also known as fault block mountains, are the result of faulting caused by tensile and compressive forces motored by endogenetic

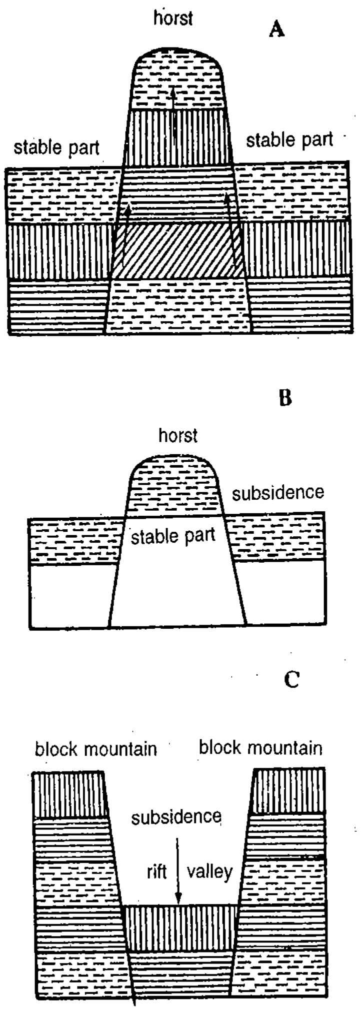


Fig. 11.1 : A-Block mountain formed due to rise of middle block, B-formation of block mountains due to downward movement of side blocks and C-formation of block mountain due to downward movement of middle block-due to rift valley formation.

forces coming from within the earth. Block mountains represent the upstanding parts of the ground between two faults or on either side of a rift valley or a graben. Essentially, block mountains are formed due to faulting in the ground surface. Block mountains are generally of two basic types e.g. (i) **tilted block mountains** having one steep side represented by fault scarp and one gentle side and (ii) **lifted block mountains** represent real **horst** and are characterized by flattened summit of tabular shape and very steep side slopes represented by two boundary fault scarps. Block mountains are also calld as **horst mountains.**

Block mountains are found in all the continents e.g. (i) young block mountains around Albert, Warner and Klamath lakes in the Steens Mountain District of Southern Oregon, Wasatch Range in the Utah province etc. in the USA, (ii) Vosges and Black Forest mountains bordering the faulted Rhine Rift valley in Europe, (iii) Salt Range of Pakistan etc. Sierra Navada mountain of California (USA) is considered to be the most extensive block mountain of the world. This mountain extends for a length of 640 km (400 miles) having a width of 80 km (50 miles) and the height of 2,400 to 3,600 m (8,000 to 12,000 feet). There is difference of opinions among the scientists regarding the origin of block mountains. There are two theories for the origin of these mountains viz. (1) fault theory and (ii) erosion theory.

Fault Theory—Most of the geologists are of the opinion that block mountains are formed due to faulting. The structural patterns of Great Basin Range mountains of Utah province (USA) were closely studied by Clarence King and G.K. Gilbert who named these mountains as faulted blocks (between 1870 and 1875 A.D.). Since then the mountains formed due to large-scale faulting were named block mountains. Later on G.D. Louderback opined that Basin Range mountains were formed due to faulting and tilting in the ground surface. W.M. Davis also advocated for the fault theory of the origin of block mountains. Block mountains are formed in a number of ways.

(i) Block mountains are formed due to upward movement of middle block between two normal faults (fig. 11.1 A). The upthrown block is also called as horst. The summital area of such block mountain is of flat surface but the side slopes are very steep.

(ii) Block mountains may be formed when the side blocks of two faults move downward whereas the middle block remains stable at its place (fig. 11.1 B). It is apparent that the middle block projects above the surrounding surface because of downward movement of side blocks. Such block mountains are generally formed in high plateaux or broad domes.

(iii) Block mountains may be formed when the middle block between two normal faults moves downward. Thus, the side blocks become horsts and block mountains (fig. 11.1C). Such mountains are associated with the formation of rift valleys.

Erosion theory—J.F. Spurr, on the basis of detailed study of Great Basin Range mountains of the USA, opined that these mountains were not formed due to faulting and tilting. rather they were formed due to differential erosion. According to Spurr the mountains, after their origin in Mesozoic era, were subjected to intense erosion. Consequently, differential erosion resulted into the formation of existing denuded Great Basin Range mountains. It may be pointed out that erosion theory of the origin of block mountains is not acceptable to most of the scientists because they believe that denudation may modify mountains but cannot form a mountain. In fact, deformatory process play major role in the origin of block mountains.

Folded Mountains

Folded mountains are formed due to folding of crustal rocks by compressive forces generated by endogenetic forces coming from within the earth. These are the highest and most extensive mountains of the world and are found in all the continents. The distributional pattern of folded mountains over the globe denotes the fact that they are generally found along the margins of the continents either in north-south direction or east-west direction. Rockies, Andes, Alps, Himalayas, Atlas etc. are the examples of folded mountains. Folded mountains are classified on various bases a follows :

(1) Folded mountains are divided into 2 broad categories on the basis of the nature of folds. (i) **simple folded mountains with open folds**—Such mountains are characterized by well developed system of anticlines and synclines wherein folds are arranged in wave-like pattern. These mountains have open and relatively simple folds. (ii) **complex folded mountains** represent very complex structure of intensely compressed folds. Such complex structure of folds is called 'nappe'. In fact, complex folded mountains are formed due to the formation of recumbent folds caused by powerful compressive forces.

(2) Folded mountains are classified into (i) **young folded mountains** (which are least affected by denudational processes) and (ii) **mature folded mountains.** It may be pointed out that it is difficult to find true young folded mountains because the process of mountain building is exceedingly slow process and thus denudational processes start denuding the mountains right from the beginning of their origin. Mature folded mountains are characterized by monoclinal ridges and valleys. This classification is based on the age factor.

(3) On the basis of the period of origin, folded mountains are divided into (i) **old folded mountains** and (ii) **new folded mountains.** All the old folded mountains were originated before Tertiary period. The folded mountains of Caledonian and Hercynian mountain building periods come under this category. These mountains have been so greatly denuded that they have now become relict folded mountains, for example, Aravallis, Vindhyachal etc. The Alpine folded mountains of Tertiary period are grouped under the category of new folded mountains, for example, Rockies, Andes, Alps, Himalayas etc.

Characteristics of Folded Mountains

(1) Folded mountains are the youngest mountains on the earth's surface.

(2) The lithological characteristics of folded mountains reveal that these have been formed due to folding of sedimentary rocks by strong compressive forces. The fossils found in the rocks of folded mountains denote the fact that the sedimentary rocks of these mountains were formed due to deposition and consolidation of sediments in water bodies mainly in oceanic environment because the argillaceous rocks of folded mountains contain marine fossils.

(3) Sediments are found upto greater depths, thousands of metres (more than 12,000 metres). Based on this fact some scientists have opined that the sediments involved in the formation of sedimentary rocks of folded mountains might have been deposited in deep oceanic areas but the marine fossils found in the rocks belong to such marine organisms which can survive only in shallow water

or shallow sea. It means that the sedimentary rocks of folded mountains were deposited in shallow seas. The sea bottoms were subjected to continuous subsidence due to gradual sedimentation. Thus, the greater thickness of sediments could be possible due to continuous sedimentation and subsidence and consequent consolidation of sediments due to ever-increasing superincumbent load.

(4) Folded mountains extend for greater lengths but their widths are far smaller than their lengths. For example, the Himalayas extend from west to east for a length of 2400 km (1500 miles) but their north-south width is only 400 km (250 miles). It means that folded mountains have been formed in long, narrow and shallow seas. Such water bodies have been termed geosynclines and it has been established that '*out of geosynclines have come out the mountains*' or '*geosynclines have been cradles of mountains*'. According to P.G. Worcester 'all great folded mountains stand on the sites of former geosynclines'.

(5) Folded mountains are generally found in arc shape having one side concave slope and the other side convex slope.

(6) Folded mountains are found along the margins of the continents facing oceans. For example, Rockies and Andes are located along the western margins of North and South Americas respectively and face Pacific Ocean. They are located in two directions e.g. north-south (e.g. Rockies and Andes) and west-east directions (e.g. Himalayas). The Alpine mountains are located along the southern margins of Europe facing Mediterranean sea. If we consider former Tethys Sea, then the Himalayas were also located along the margins of the continent.

11.3 GEOSYNCLINES

Meaning and Concept

The geological history of the continents and ocean basins denotes the fact that in the beginning our globe was characterized by two important features viz. (i) **rigid masses** and (ii) **geosynclines.** Rigid masses representing the ancient nuclei of the present continents, have remained stable for considerably longer periods of time. These rigid masses are supposed to have been surrounded by mobile zones of water characterized by extensive sedimentation. These mobile zones of water have been termed '**geosynclines**' which have now been converted by compressive forces into folded mountain ranges.

On an average, a geosyncline means a water depression characterized by sedimentation. It has now been accepted by majority of the geologists and geographers that all the mountains have come out of the geosynclines and the rocks of the mountains originated as sediments were deposited and later on consolidated in sinking seas, now known as geosynclines. If we consider the height and thickness of sediments of the young folded mountains of Tertiary priod (*e.g.* Rockies, Andes, Alps, Himalayas etc.), then it appears that the geosynclines should have been very deep water bodies but the marine fossils found in the sedimentary rocks of these folded mountains belong to the category of marine organisms of shallow seas. It is, thus, obvious that the geosynclines are shallow water bodies characterized by gradual sedimentation and subsidence. Based on above facts geosynclines can now be defined as follows-

'Geosynclines are long but narrow and shallow water depressions characterized by sedimentation and subsidence'.

J.A. Steers (1932) has aptly remarked, 'the geosynclines have been long and relatively narrow depressions which seem to have subsided during the accumulation of sediments in them.'

The following are the general characteristics of geosynclines-

(1) Geosynclines are long, narrow and shallow depressions of water.

(2) These are characterized by gradual sedimentation and subsidence.

(3) The nature and patterns of geosynclines have not remained the same throughout geological history rather these have widely changed. In fact, the location, shape, dimension and extent of geosynclines have considerably changed due to earth movements and geological process.

(4) Geosynclines are mobile zones of water.

(5) Geosynclines are generally bordered by two rigid masses which are called forelands.

Evolution of the Concept

The concept of geosynclines was given by James Hall and Dana but the concept was elaborated and

further developed by Haug. J.A. Steers (1932) has remarked, "while the theory of geosynclines is due to Haug, the concept of idea belongs to Hall and Dana'. It is desirable to discuss the concepts of geosynclines developed by different exponents.

(1) **Concept of Hall and Dana**-Dana studied the folded mountains and postulated that the sediments of the rocks of folded mountains were of marine origin. These rocks were deposited in long, narrow and shallow seas. Dana named such water bodies as geosynclines. He defined, for the first time, geosynclines as long, narrow and shallow and

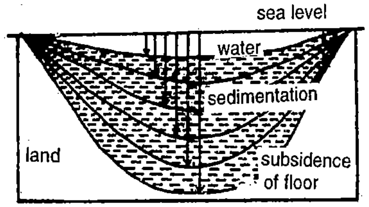


Fig. 11.2 : Sinking beds of geosynclines due to sedimentation and subsidence.

sinking beds of seas. Hall elaborated the concept of geosynclines as advanced by Dana. He presented ample evidences to show relationship between geosynclines and folded mountains. He opined that the rocks of folded mountains were deposited in shallow seas. According to Hall the beds of geosynclines are subjected to subsidence due to continuous sedimentation but the depth of water in the geosynclines remains the same (fig. 11.2). Geosynclines are much longer than their widths.

(2) **Concept of E. Haug**-'If the idea of geosynclines is due to Hall and Dana, the theory of their development is really due to Haug'. He defined geosynclines as long and deep water bodies. According to Haug 'geosynclines are relatively deep water areas and they are much longer than they are wide'. He drew the palaeogeographical maps of the world and depicted long and narrow oceanic tracts to demonstrate the facts that these water tracts were subsequently folded into mountain ranges (fig. 11.3). He further postulated that the positions of the present-day mountains were previously occupied by oceanic tracts *i.e.* geosynclines. Geosynclines existed as mobile zones of water between rigid masses. He identified 5 major rigid masses during Mesozoic era *e.g.* (i) North Atlantic Mass, (ii) Sino-Siberian Mass, (iii) Africa-Brazil Mass, (iv) Australia-India-Madagascar Mass and (v) Pacific Mass. He located 4 geosynclines between these ancient rigid masses *e.g.* (i) Rockies geosyncline, (ii) Ural geosyncline, (iii) Tethys geosyncline and (iv) Circum-Pacific geosyncline.

According to Haug there are systematic sedimentation in the geosynclines. The littoral margins of the geosynclines are affected by transgressional and regressional phases of the seas. The marginal areas of the geosynclines have shallow water wherein larger sediments are deposited whereas finer sediments are deposited in central parts of the geosynclines. The sediments are squeezed and folded into mountain ranges due to compressive forces coming from the margins of the geosynclines. He has further remarked that it is not always necessary that all the geosynclines may pass through the complete cycle of the processes of sedimentation, subsidence, compression and folding of sediments. Some times, no mountains are formed from the geosynclines inspite of continuous sedimentation for long duration of geological time.

Though the contributions of Haug in this regard are praiseworthy as he developed the concept of geosynclines but his theory suffers from certain serious drawbacks and confusing ideas about them. His palaeogeographical map (fig. 11.3) of Mesozoic era depicted unbelievable larger extent of rigid masses (land areas) in comparison to geosynclines (oceanic areas). Questions arise, as to what happened to such extensive land masses after Mesozoic era? Where did they disappear? Haug could not explain these and many more questions. His geosyclines as very deep oceanic tracts are also not acceptable because the marine fossils found in the folded mountains belong to the group of marine organisms of shallow seas.

(3) **Concept of J.W. Evans**—According to Evans the geosynclines are so varied that it becomes difficult to present their definite form and location. The beds of geosynclines are subjected to gradual subsidence because of sedimentation. The form and shape of geosynclines change with changing environmental conditions. A geosyncline may be narrow or wide. It may be of different shapes. There may be several alternative situations of geosynclines

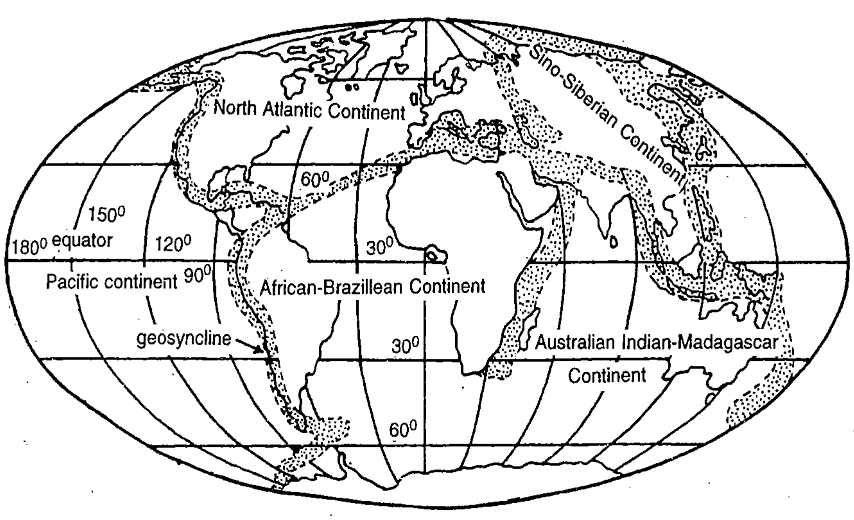


Fig. 11.3: Distribution of rigid masses and geosynclines during Mesozoic era as depicted by E. Haug.

e.g. (i) it may be between two land masses (example, Tethys geosyncline between Laurasia and Gondwanaland), (ii) it may be in front of a mountain or a plateau (for example, resultant long trench after the origin of the Himalayas, this depression was later on filled with sediments to form Indo-Gangetic Plains), (iii) it may be along the margins of the continents, (iv) it may be in front of a river mouth etc. According to Evans all the geosynclines irrespective of their varying forms, shapes and locations are characterized by twin processes of sedimentation and subsidence. Geosynclines, after long period of sedimentation, are squeezed and folded into mountain ranges.

(4) **Views of Schuchert**—He attempted to classify geosynclines on the basis of their characteristics related to their size, location, evolutionary history etc. He has divided the geosynclines into 3 categories. **(i) Monogeosynclines** are exceptionally long and narrow but shallow water tracts as conceived by Hall and Dana. The geosynclinal beds are subjected to continuous subsidence due to gradual sedimentation and resultant load. Such geosynclines are situated either within a continent or along its borders. These are called mono because they pass through only one cycle of sedimentation and mountain building. Applachian geosyncline is considered to be the best example of monogeosynclines. In place of the Applachains (USA) there existed a long and narrow Applachain geosyncline during Pre-cambrian-period. The geosyncline was bordered by highland mass known as Applachia in the east. Applachian geosynclines were folded from Ordovician to Permian periods.

(ii) Polygeosynclines were long and wide water bodies. These were definitely broader than the monogeosynclines. These geosynclines existed for relatively longer period than the monogeosynclines and these have passed through complex evolutionary histories. "These are considered to have experienced more than one phase of orogenesis, consequently they may have been diversified by the production of one or more parallel geanticlines arising from their floors in the squeezing process". They originated in positions similar to those of monogeosynclines. Rocky and Ural geosynclines are quoted as the representative examples of polygeosynclines.

(iii) Mesogeosynclines are very long, narrow and mobile ocean basins which are bordered by continents from all sides. They are characterized by great abyssal depth and long and complex geological histories. These geosynclines pass through several geosynclinal phases *e.g.* phases of sedimentation, subsidence and folding. Mesogeosynclines are similar to the geosynclines conceived by Haug. Tethys geosyncline is the typical example of such type. Mediterranean Sea is the remnant of Tethys geosyncline. This geosyncline was folded into Alpine mountains of Europe and the Himalayas of Asia. The unfolded remaining portion of Tethys geosyncline became Mediterrancean sea, an example of median mass of Kober.

(5) **Concept of Arthur Holmes**-Besides describing main characteristics of geosynclines, A. Holmes has also elaborated the causes of the origin of different types of geosynclines. He has also described the detailed processes and mechanisms of sedimentation and subsidence and consequent orogenesis. According to him no doubt sedimentation leads to subsidence but this process cannot account for the greater thickness of sediments in geosynclines rather earth movements can cause subsidence of high magnitude in the geosynclinal beds. He further pointed out that the process of subsidence of the geosynclinal beds was not a sudden process rather it was a gradual process. The deposition of sediments upto the thickness of 12,160 m (40,000 feet) in the Applachian geosyncline could be possible during a long period of 300,000,000 years from Cambrian period to early Permian period at the rate of one foot of sedimentation every 7,500 years. Holmes has identified 4 major types of geosynclines and has described the mode of their origin separately as given below-

(i) **Formation of geosynclines due to migration of magma**-According to Holmes the crust of the earth is composed of 3 shells of rocks. Just below the outer thin sedimentary layer lies (i) outer layer of granodiorite (thickness, 10 to 12 km), followed by (ii) an intermediate layer of amphibolite (thickness, 20-25 km), and (iii) a lower layer of eclogite and some peridotite. He has further pointed out that migration of magmas from the intermediate layer to neighbouring areas causes collapse and subsidence of upper or outer layer and thus is formed a geosyncline. It may be summarized that some geosynclines are formed due to displacement of light magmas and consequent subsidence of crustal surface. Present Coral Sea. Tasman Sea, Arafura Sea, Weddell Sea and Ross Sea have been quoted as typical examples of such geosyncline. This concept of Holmes has been severely criticised because the transfer and displacement of magmas cannot cause subsidence to form geosynclines.

(ii) **Formation of geosynclines due to metamorphism**—According to Holmes the rocks of the lower layer of the crust, as referred to above, are metamorphosed due to compression caused by converging convective currents. This metamorphism increases the density of rocks, with the result the lower layer of the crust is subjected to subsidence and thus a geosyncline is formed. Caribbean Sea, the western Mediterranean Sea and Banda Sea have been quoted as examples of this category of geosynclines. This concept has been rejected on the ground that compression caused by convergent convective currents would not cause metamorphism rather it would cause melting of rocks due to resultant high temperature.

(iii) **Formation of geosynclines due to compression**- Some geosynclines are formed due to compression and resultant subsidence of outer layer of the crust caused by convergent convective currents. Persian Gulf and Indo-Gangetic trough are considered to be typical examples of this group of geosyclines.

(iv) **Formation of geosynclines due to thinning of sialic layer**- According to Holmes there may be two possibilities if a column of rising convective currents diverges after reaching the lower layer of the crust in opposite directions. (i) The sialic layer is stretched appart due to tensile forces exerted by diverging convective currents. This process causes thinning of sialic layer which results in the creation of a geosyncline. The former Tethys geosyncline is considered to have been formed in this manner. (ii) Alternatively, the continental mass may be separated due to enormous tensile force generated by divergent convective currents. Former Ural geosyncline is supposed to have been formed due to this mechanism.

(6) **View of Others**—Dustar has classified geosynclines into 3 types on the basis of structure of mountain ranges.

(i) **Inter-continental geosynclines** are always situated between two continental or land masses. Schuchert's mesogeosyncline is similar to this type. Ural geosyncline is quoted as the representative example. (ii) **Circum-continental geosynclines** are generally situated along the margins of the continents. Schuchert's **monogeosyncline** is the example. **(iii) Circum-oceanic geosynclines** are generally found along the marginal areas of the oceans where continental margins meet with the oceanic margins. Stille has named such geosyncline as **marginal geosyncline** while others have called it special type of geosyncline or unique geosyncline. More extensive geosynclines have been named by Stille as **orthogeosynclines.** Stille has further classified the geosynclines on the basis of intermittent volcanic activity during their infilling into **(i) eugeosynclines** and **(ii) miogeosynclines.** Eugeosynclines have relatively high amount of volcanic products (Greek prefix eu means high status of igneous activity) while miogeosynclines have low volcanic products (mio means low).

Stages of Geosynclines

The geosynclinal history is divided into three stages viz. (i) lithogenesis (the stage of creation of geosynclines, sedimentation and subsidence of the beds of geosynclines, fig. 11.4), (ii) orogenesis (the stage of squeezing and folding of geosynclinal sediments into mountain ranges, figs. 11.5 and 11.6),

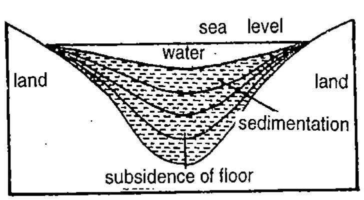


Fig. 11.4: The stage of lithogenesis: creation of geosyncline followed by sedimentation and subsidence.

and (iii) gliptogenesis (the stage of gradual rise of mountains, and their denudation and consequent lowering of their heights). These stages would be elaborated during the discussion of geosynclinal theory of Kober.

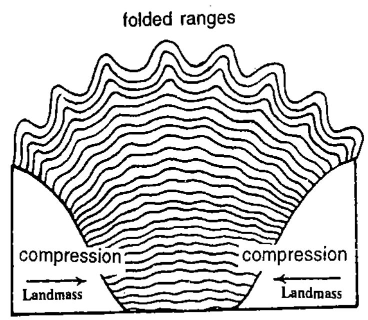


Fig. 11.5: The stage of orogenesis: squeezing and folding of geosynclinal sediments due to compressive forces; the whole of geosyndinal sediments are folded when the compressive forces coming from the sides of geosyncline is enormous and acute.

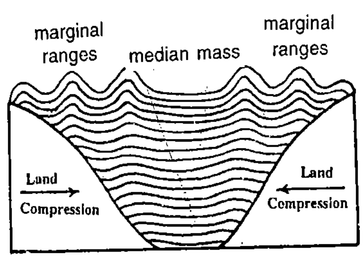


Fig. 11.6: Folding of marginal sediments into marginal ranges and formation of median mass when the compressive forces are moderate.

11.4 THEORIES OF MOUNTAIN BUILDING

The process of the origin of block mountains, dome mountains, and volcanic mountains (mountains of accumulation) is more or less well understood but the problem of the origin of folded mountains is very much complex and complicated. Different hypotheses and theories have been postulated from time to time by various scientists for the explanation of the origin of folded mountains but none of them could become commonly acceptable to majority of the scientists. Recently, plate tectonic theory has to a larger extent solved the problem of mountain building at global scale. The hypotheses and theories related to mountain building are divided into two

groups. (i) theories based on horizontal forces and (ii) the theories based on vertical forces.

(1) The first group includes those theories which postulate the origin of mountains due to horizontal crustal movements and consequent contraction and folding of crustal surface into mountains. This group is further subdivided into two subgroups *e.g.* (i) the group of contraction theories (*i.e.* horizontal movements are caused due to contraction of the earth because of cooling) and (ii) the group of the drift theories (*i.e.* the horizontal movements are caused due to continental displacement and drift). Thermal contraction theory of Jefferys and Geosynclinal Theory of Kober belong to the group of contraction theories whereas Continental Drift theories of F.B. Taylor, and A.G. Wegener, Thermal Convection Current Theory of A. Holmes, Sliding Continents Theory of Daly, Radioactivity Theory of Joly and Plate Tectonic Theory are included in the group of drift theories. (2) The second group includes those theories which are based on vertical movements coming from within the earth, *e.g.* Undulation and Oscillation Theory of Harmon. The theories of F.B. Taylor and A.G. Wegener have already been discussed in chapter 5 of this book.

1. GEOSYNCLINAL OROGEN THEORY OF KOBER

Objective

Famous German geologist Kober has presented a detailed and systematic description of the surface features of the earth in his book 'Der Bau der Erde'. His main objective was to establish relationship between ancient rigid masses or tablelands and more mobile zones or geosynclines, which he called **orogen.** Kober not only attempted to explain the origin of the mountains on the basis of his geosynclinal theory but he also attempted to elaborate the various aspects of mountain building *e.g.* formation of mountains, their geological history and evolution and development. He considered the old rigid masses as the foundation stones of the present continents. According to him present continents have grown out of rigid massess. He defined the process of mountain building or orogenesis as that process which links rigid masse with geosynclines. In other words, mountains are formed from the geosynclines due to the impacts of rigid masses.

Orogenetic Force

Kober's geosynclinal theory is based on the forces of contraction produced by the cooling of the earth. He believes in the contraction history of the earth. According to J.A. Steers (1932) "Kober is definitely a contractionist, contraction providing the motive force for the compressive stress". In other words, the force of contraction generated due to cooling of the earth causes horizontal movemenets of the rigid masses or forelands which squeeze, buckle and fold the sediments into mountain ranges.

Base of the Theory

According to Kober there were mobile zones of water in the places of present-day mountains. He called mobile zones of water as geosynclines or **orogen** (the place of mountain building). These mobile zones of geosynclines were surrounded by rigid masses which were termed by Kober as **kratogen.** The old rigid masses included Canadian Shield, Baltic Shield or Russian Massif, Siberian Shield, Chinese Massif, Peninsular India, African Shield, Brazilian Mass, Australian and Antarctic rigid masses. According to Kober mid-Pacific geosyncline separated north and south forelands which were later on foundered to form Pacific Ocean. Eight morphotectonic units can be identified on the basis of the description of the surface features of the earth during Mesozoic era as presented by Kober *e.g.* (i) Africa together with some parts of Atlantic and Indian Oceans, (ii) Indian Australian land mass, (iii) Eurasia, (iv) North Pacific continents, (v) South Pacific continents, (vi) South America and Antarctica etc.

Kober has identified 6 major periods of mountain building. Three mountain building periods, about which very little is known, are reported to have occurred during pre-Cambrian period. Palaeozoic era saw two major mountain building periods-the Caledonian orogenesis was completed by the end of Silurian period and the Variscan orogeny was culminated in Permo-Carboniferous period. The last (6th) orogenic activity known as Alpine orogeny was completed during Tertiary epoch.

Kober has opined that mountains are formed out of geosynclines. According to Kober geosynclines, the places of mountain formation (known as orogen) are long and wide water areas characterized by

sedimentation and subsidence. According to J.A. Steers (1932) 'Kober's views (on geosynclines and orogenesis) are, then, a combination of the old geosynclinal hypothesis of Hall and Dana, which was developed later by Haug, and his own views on orogenesis.'

Mechanism of the Theory

According to Kober the whole process of mountain building passes through three closely linked stages of lithogenesis, orogenesis and gliptogenesis. The first stage is related to the creation of geosynclines due to the force of contraction caused by cooling of the earth. This preparatory stage of mountain building is called **lithogenesis.** The geosynclines are long and wide mobile zones of water which are bordered by rigid masses, which have been named by Kober as **forelands, or kratogen.** These upstanding land masses or forelands are subjected to continuous erosion by fluvial processes and eroded materials are deposited in the geosynclines. This process of sediment deposition is called **sedimentation.** The ever increasing weight of sediments due to gradual sedimentation exerts enormous pressure on the beds of geosynclines, with the result the beds of geosynclines are subjected to gradual **subsidence.** This process is known as the process of subsidence. These twin processes of sedimentation and resultant subsidence result in the deposition of enormous volume of sediments and attainment of great thickness of sediments in the geosynclines.

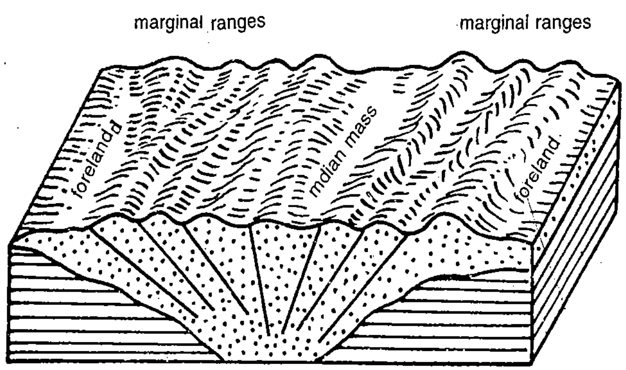


Fig. 11.7: Illustration of Kober's geosynclinal theory of mountain building through a block diagram.

The second stage is related to mountain building and is called the stage of **orogenesis**. Both the forelands start to move towards each other because of horizontal movements caused by the force of contraction resulting from the cooling of the earth. The compressive forces generated by the movement of forelands together cause contraction, squeezing and ultimately folding of geosynclinal sediments to form mountain ranges. The parallel ranges formed on either side of the geosyncline have been termed by Kober as **randketten** (marginal ranges) (figs. 11.6 and 11.7).

According to Kober folding of entire sediments of the geosyncline or part thereof depends upon the intensity of compressive forces. If the compressive forces are normal and of the moderate intensity, only the marginal sediments of the geosyncline are folded to form two marginal randketten (marginal ranges) and middle portion of the glosyncline remains unaffected by folding activity (thus remains unfolded). This unfolded middle portion is called **zwischengebirge** (betwixt-mountains) or **median mass** (figs. 11.6 and 11.7). Alternatively, if the compressive forces are acute, the whole of geosynclinal sediments are compressed, squeezed, buckled and ultimately folded (fig. 11.5) and both the forelands are closeted. This process introduces complexity in the mountain because acute compression results in the formation of recumbent folds and nappes.

Kober has attempted to explain the forms and structures of folded mountains on the basis of his typical median mass. 'Really, Kober's typical "orogen" (geosynclines) well explains the origin of mountains'. 'The idea of median mass of Kober fully explains the process of mountain building'. According to Kober the Alpine mountain chains of Europe can well be explained on the basis of median masses. According to him Tethys geosyncline was bordered by European land mass in the north and by African rigid mass in the south. The sediments of Tethys geosycline were compressed and folded due to movements of European landmass (foreland) and African rigid mass (foreland) together in the form of Alpine mountain system. According to Kober the Alpine mountain chains were formed because of compressive forces coming from two sides (north and south). Betic Cordillera, Pyrenees, Provence ranges, Alps proper, Carpathians, Balkan mountains and Caucasus mountains were formed due to northward movement of African foreland (fig. 11.8). On the other hand, Atlas mountain (north-west Africa), Apennines, Dinarides, Hellenides and Taurides were formed due to southward movement of European land mass (fig. 11.8).

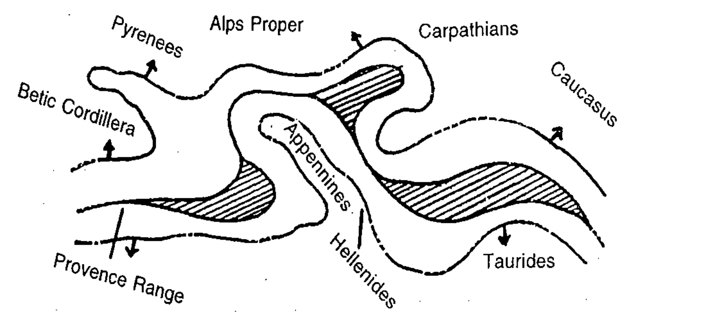


Fig. 11.8: The directions of folding in Alpine mountains of Europe. Arrows indicate directions (based on Kober).

The median masses located in the Alpine mountain system very well explain the mechanism of mountain building. It is apparent from fig. 11.8 that the direction of folding in the Carpathians and Dinaric Alps (Dinarides) is north and south respectively, which means that Hungarian median mass is located between two mountain ranges having opposite directions of folding. Mediterranean Sea is in fact an example of median mass between Pyrenees-Provence Ranges in the north and Atlas mountains and their eastern extension in the south. Corsica and Sardinia are remnants of this median mass. Anatolian plateau between Pantic and Taurus ranges is another example of median mass. Similarly, further eastward, Iranian plateau is a median mass between Zagros and Elburz mountains.

Alpine mountains further extend into Asia where mountain ranges follow latitudinal direction *e.g.* west-east orientation but the latitudinal pattern is broken in north-eastern hill region of India where mountain ranges take southerly trend in the form of Burmese hills. Asiatic Alpine ranges begin from Asia minor and run upto Sunda Island in the East Indies. Kober has also explained the orientation of thrust or compression of Asiatic folded mountains on the basis of his **foreland theory**. Asiatic folded mountains including the Himalayas were formed due to compression and folding of sediments of Tethys geosyncline caused by the movement of Angaraland and Gondwana forelands together (fig. 11.9). Two marginal ranges (randketten) were formed on either side of the geosyncline and unfolded middle portion remained as median mass. According to Kober Asiatic Alpine folded mountains can be grouped into two categories on the basis of orientation of folds. (i) The ranges, which were formed by the northward compression, include Caucasus, Pantic and Taurus (of Turkey), Kunlun, Yannan and Annan ranges. (ii) The ranges, which were formed by the southward compression, include Zagros and Elburz of Iran, Oman ranges, Himalayas, Burmese ranges etc. Tibetan plateau is a fine example of median mass between Kunlun-Tien-Shan and the Himalayas.

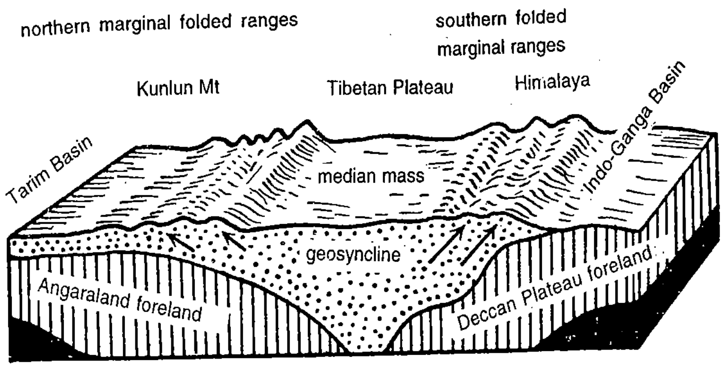


Fig. 11.9 : Illustration of Kober's median mass through Tibetan plateau between Kunlun and Himalaya.

The **median mass** may be of various forms *e.g.* (i) in the form of plateau (examples, Tibetan plateau between Kunlun and Himalaya. Iranian plateau between Zagros and Elburz, Anatolian plateau between Pantic and Taurus, Basin Range between Wasatch ranges and Sierra Navada in the USA; (i) in the form of plain (example, Hungarian plain between Carpathians and Dinaric Alps) and (iii) in the form of seas (examples, Mediterranean Sea between African Atlas mountains and European Alpine mountains, Caribbean Sea between the mountain ranges of middle America and West Indies).

Third stage of mountain building is characterized by gradual rise of mountains and their denudation by fluvial and other processes. Continuous denudation results in gradual lowering of the height of mountains.

Evaluation of the Theory

Though Kober's geosynclinal theory satisfactorily explains a few aspects of mountain building but the theory suffers from certain weaknesses and lacunae.

(1) The force of contraction, as envisaged by Kober, is not sufficient to cause mountain building. In fact, very extensive and gigantic mountains like the Alps, the Himalayas, the Rockies and the Andes cannot be formed by the force of contraction generated by cooling of the earth.

(2) According to Suess only one side of the geosyncline moves whereas the other side remains stable. The moving side has been termed by Suess as **backland** whereas stable side has been called **foreland.** According to Suess the Himalayas were formed due to southward movement of Angaraland. The Gondwanaland remained stationary. This observation of Suess gained much favour previously but after the postulation of **plate tectonic theory** his views have become meaningless and the concept of Kober, that both the forelands move together, has been validated because ample evidences of palaeomagnetism and sea-floor spreading have shown that both Asiatic and Indian plates are moving towards each other.

(3) Kober's theory some how explains the west-east extending mountains but north-south extending mountains (Rockies and Andes) cannot be explained on the basis of this theory. Inspite of a few inherent limitations and weaknesses Kober is given credit for advancing the idea of the formation of mountains from geosynclinal sediments because geosyncline found berth in almost all the subsequent theories even in plate tectonic theory.

2. THERMAL CONTRACTION THEORY OF JEFFEREYS

Objectives

Jeffreys, a strong exponent of contraction theory, postulated his 'thermal contraction theory' to explain the origin and evolution of major reliefs of the earth's surface (continents, ocean basins, mountains, island arcs and festoons) but his major objective was to explain the origin and distributional patterns of mountain systems of the globe. Jeffreys was a contractionist. His theory was based on mathematical reasoning. He postulated his contraction theory because he could not find any strong reasons in the continental drift theory which advocated horizontal movement of the continents due to tidal force of the sun and the moon and the gravitational force as envisaged by A.G. Wegener.

Orogenetic Force

Jeffreys used the force of contraction resulting partly from cooling of the earth due to loss of heat through radiation from the earth's surface and partly from the decrease of the speed of the earth's rotation. In fact, the forces invoked by Jeffreys are divided into two groups. (1) Force coming through the cooling of the earth. The earth, after being formed, started cooling due to loss of heat through radiation. This process resulted in the gradual decrease of the size of the earth due to contraction on cooling. The resultant contraction provided adequate force (as believed by Jeffreys) to form various relief features including mountains. (2) Force coming through the decrease in the speed of earth's rotation. About 1600 million years ago the earth completed its one rotation in about 0.84 hour whereas it presently completes one rotation in about 24 hours. The decrease in the rotational speed caused contraction in the equatorial circumference of the earth. It may be concluded that the force of contraction was derived through the contraction of the earth due to (i) cooling of the earth and (ii) due to decrease in the speed of earth's rotation.

Mechanism of the Theory

Jeffrey's theory is based essentially on the history of the contraction of the earth. According to Jeffreys the earth began to shrink because of contraction caused by gradual cooling of the earth due to loss of heat through radiation from the very beginning of its origin. He has mathematically calculated the extent of contraction on cooling. A decrease of temperature upto 400^0C in the 400 km thick outer shell of the earth would cause shortening of the diameter of the earth by 20 km and the circumference by 130 km due to cooling and resultant contraction. He calculated the maximum shortening of the crust due to contraction to be 200 kilometres and the reduction in surface area upto 5×10^{16} cm^2.

According to Jeffreys the earth is composed of several concentric shells (layers). The cooling and resultant contraction take place layer after layer but the cooling is effective upto the depth of only 700 km from the earth's surface. 'The region of the earth from the centre to somewhere about 700 kilometres from the surface may have undergone no appreciable change of temperature, and consequently no marked change in volume' (J.A. Steers, 1932). Within the zone of 700 km from the earth's surface every upper layer has cooled earlier and more than the layer immediately below the upper layer. Thus, each upper layer contracted more than the layer just below it. Further, each upper layer continued to cool unless obstructed by the immediate lower layer. The outer layer began to cool first due to loss of heat through radiation. It may be pointed out that there is a limit of cooling beyond which no further cooling is possible. After maximum cooling and resultant contraction of the upper layer lower layer just lying below the upper layer begins to cool and contract, with the result already cooled and contracted upper layer becomes too large to fit in with the still cooling and contracting lower layer. The core of the earth is not affected by cooling because of exceptionally high temperature prevailing there. Thus, the core obstructs the contraction of the layer lying above it. The cooling and contracting layer lying below the already cooled and contracted upper layer becomes too short to fit in with the core of the earth. There is such a layer between the upper and lower layer where contraction is such that the intermediate layer can fit in with the lower layer. This layer is called **level of no strain.**

The layer lying over the level of no strain is too big to fit with the lower layer and hence the upper layer has to collapse on the lower layer so that it can fit with the lower layer. This process (collapse of upper layer on lower layer) results in the decrease in the radius of the earth which causes horizontal compressive stress which leads to buckling and folding of the rocks of upper layer. Thus, the mountains are formed. The lower layer below the level of no strain is too short to fit with the core of the earth and hence the lower layer has to stretch horizontally. This process implies a lateral spreading and thinning

out of the materials of the lower layer below the level of no strain. The spreading and thinning of the lower layer introduces a state of stress which causes fractures and fissures resulting into breaking of rocks. This mechanism allows further collapse of the already cooled outer layer and thus already formed mountains are subjected to further rise in height.

Jeffreys has also explained various aspects of mountain building *e.g.* period of mountain building, zones of mountain building, direction of mountains etc.

Period of mountain building-According to Jeffreys the process of aforesaid mechanism of mountain building is not always active throughout the geological periods rather is confined to certain periods only. There is continuous accumulation of compressive and tensile forces resulting from contraction of the earth due to cooling and this process continues until the accumulated forces exceed the rock strength. When this state (when accumulated compressive and tensile forces exceed the rock strength) is reached, folding and faulting are introduced and the process of mountain building sets in and this process continues till the compressive and tensile forces are strong and active. When these forces become weak, mountain building stops and the period of quiescence sets in. Again the process of accumulation of compressive and tensile forces starts and the next process of mountain building begins when these forces again become strong enough to fold the crustal rocks. Thus, two periods of mountain building are separated by a long period of quiescence.

Zones of mountain building-According to Jeffreys mountain building depends upon the nature and strength of rocks. The areas having soft and elastic rocks are most affected by the process of mountain building as the rocks are easily folded by compressive forces caused by contraction but the regions having hard and less elastic rocks are affected by tensile forces and thus several faults and fractures are formed because such rocks are easily broken into blocks. It is, thus, apparent that mountain building is localized in certain zones of the globe.

Direction of force-According to Jeffreys not all the areas below the earth surface are equally affected by the mechanism of cooling and contraction. The cooling process was more active below the oceanic crust than the continental crust because of dissimilar structure of these two zones. Thus, the rocks below the oceanic crust experienced more cooling and contraction than the rocks below the continental crust. Thus, the force of contraction is directed from oceanic crust towards the continental crust. This mechanism results in the formation of mountains along the continental margins parallel to the oceans. Rockies and Andes are the examples of such situation.

Direction of mountains-According to Jeffreys the compressive force generated by contraction of the earth due to cooling was directed from oceanic areas towards the continental areas almost at right angle and thus the mountain ranges were formed parallel to the oceanic areas. The layout and direction of the Rockies and Andes mountains are very well explained on the basis of this theory because these mountains run north to south along the western margins of North and South America respectively and are parallel to the Pacific Ocean but the west-east extent of the Alps and the Himalayas cannot be explained on the basis of this theory.

Evaluation of the Theory

Though Jeffreys has attempted to explain the origin and evolution of surface features of the earth and has presented several evidences in support of his thermal contraction theory but his theory has been severely criticised and attacked on the following grounds.

(1) The force of contraction resulting from the cooling of the earth is not sufficient enough to account for the origin and evolution of major surface reliefs of the globe. A. Holmes has remarked that 'the calculated reduction of area (by Jeffreys) is seriously in deficit of the amount to explain mountain building.'

(2) The concept of cooling of the earth in the system of concentric shells (layers) is erroneous and is not acceptable.

(3) The impact of decrease in the speed of rotation of the earth on mountain building is doubtful. J.A. Steers (1932) has aptly remarked, 'It may, in fact, be safely concluded that whatever effects the changing speed of rotation in geological times may have had, it was totally inadequate to influence mountain building in any marked way.' (4) It is improper to believe that contraction would have been so immense about 200 million years ago so that it might have formed such gigantic mountains of Tertiary period as the Rockies, the Andes, the Alps, the Himalayas etc.

(4) As per thermal contraction theory of Jeffreys the continents and oceans should have been uniformly distributed as the earth was contracted from all sides but presently there is uneven distribution of continents and oceans.

(5) According to this theory the situation of mountains should always be parallel to the oceans. The arrangement of the Rockies and Andes is justified on the basis of this theory but the arrangement of European Alpine mountains and the Himalayas cannot be explained.

(6) If we believe in the competence of the force of contraction to form mountains it cannot produce great ranges of mountains as they are found at present over the globe but it would produce a larger number of small puckers or minor folds.

(7) According to this theory there should not be any definitive distributional pattern of mountains as they may be formed everywhere because all parts of earth's crust experienced contraction but contrary to this mountains are found in certain patterns *e.g.* along the margins of the continents extending either north-southward or west-eastward.

3. SLIDING CONTINENT THEORY OF DALY

Objectives

Daly postulated his theory of sliding continents in his book 'Our Mobile Earth' in the year 1926 to explain the origin and evolution of different relief features of the earth's surface. Though Daly attempted to throw light on major reliefs of the globe but his main objective was to explain the causes and processes of mountain building. He attempted to explain salient aspects of folded mountains *e.g.* origin, successive upheavals, distributional patterns and orientation and extent.

Orogenetic Force

The main force implied by Daly for the origin of the mountains has been the force of gravity. The whole theory of Daly is based on the nature and rate of downward slide of the continents fostered by gravitational force. 'The key to the Daly's views is the idea that there has been downhill sliding movement of continental masses. In other words, the controlling factor has been gravity' (J.A. Steers, 1932). Daly himself proclaimed that his theory based on gravitational force was competent to deal with all the problems of mountain building satisfactorily.

Axioms of the theory

Daly has assumed certain axioms (self proved facts) in support of his theory. If we look into his theory it appears that 'a major part of the theory is based on self proved facts or axioms'. It may be pointed out that Daly did not elaborate his axioms. He admitted himself that 'his theory can well explain the problems of orogenesis on the force of gravity alone.'

According to Daly a solid crust was formed just after the origin of the earth. He named this solid crust as **primitive crust.** In early times there existed a series of ancient rigid masses which were generally situated near the poles and around the equator. These rigid masses have been named by Daly as **polar** and **equatorial domes.** Thus, there were three belts of rigid masses *e.g.* (i) north polar domes, (ii) equatorial domes and (iii) south polar domes. These three belts of rigid masses were separated by depressed regions which were called by Daly as **mid latitude furrows** and **primeval Pacific ocean.** These depressed regions were in fact oceanic areas (or say geosynclines) the beds of which were formed of **primitive crust** which was formed with the origin of the earth.

The crust, according to Daly, composed of granites, was heavier than the rocks of substratum below the crust. The crust was composed of heavier granites while the substratum was formed of lighter glassy basalt. It may be pointed out that this view of Daly is isostatically totally wrong. He further assumed that the water bodies occupied about half of the globe and Tethys geosycline (northern mid-latitude furrow between north polar dome and equatorial dome) 'was a marked feature throughout much of geological time'. Land masses (polar equatorial domes-rigid masses) projected above the water bodies and the polar and equatorial domes were sloping towards mid-latitude furrows (which were in fact geosynclinal tracts) and the Pacific Ocean.

Mechanism of the Theory

Daly has believed in the collapse of the primitive crust but has not elaborated the mechanism of collapse. It may be surmised that the primitive crust would have been probably bad conductor of heat and so the surface temperature would have fallen soon to that of the present time but the loss of heat from the interior into the exterior part continued and hence the interior part contracted away from the outer shell or crust. Consequently, crust would have collapsed on the still contracting interior due to (i) the weight of the oceanic water, (ii) the weight of geosynclinal sediments and (iii) gravitational force of the centre of the earth. It may be pointed out that the impact of gravitational force was more under the oceanic crust than the continental domes because the former was nearer to the earth's centre. It appears (though not described by Daly) that the mid-latitudinal furrows were formed as geosynclines due to collapse of outer crust on the contracting interior of the earth and due to the gravitational force coming from the centre of the earth.

The sediments derived through the erosion of polar and equatorial domes (more precisely continental domes) were deposited by the rivers into the mid-latitudinal furrows and the Pacific Ocean (geosynclines). Continuous sedimentation and weight of the oceanic waters exerted enormous pressure on the beds of oceans (geosynclines) with the result their beds were subjected to continuous subsidence. Thus, downward pressure on the oceanic (geosynclinal) beds due to continuous sedimentation and resultant subsidence of geosynclinal beds caused lateral pressure on the continental masses, with the result they were transformed into broad continental domes known as polar and equatorial domes. As the oceanic beds were depressed downward due to gravitational force of the earth's centre, and weight of oceanic water and geosynclinal sediments, the size of domes continued to increase. It may be pointed out that gradual increase in the lateral pressure resulting from continuous downward movement of geosynclinal beds was responsible for increase in the size and height of continental domes.

The sediments of the continental domes began to expand because of increase in the size and height of the domes and consequently sediments of the domes began to lose weight and became lighter in weight. In order to compensate the loss of weight of sediments of the continental domes there began underground flowage of dense materials from below the oceanic (geosynclinal beds) beds towards the continental domes. Because of this process denser materials began to accumulate in the continental domes from below. Because of the repetition of the above processes the continental domes continued to grow in size and height, 'probably not as rapidly in the centre as towards their peripheries'. The increase in the size of domes caused pressure on the crust under the oceanic beds (geosynclinal beds). As the size of domes continued to expand, the resultant pressure on oceanic beds also continued to increase. When the tolerance limit of the oceanic crust to withstand the everincreasing pressure was crossed, the oceanic beds began to rupture and break. Thus, the support of the continental domes was removed due to rupture of the oceanic beds which introduced strong tensional movements due to which larger blocks of continental mass began to slide towards the geosynclines. The geosynclinal sediments were thus squeezed and folded due to compressive force coming from the sliding continental blocks. (fig. 11.10) giving birth to folded mountains.

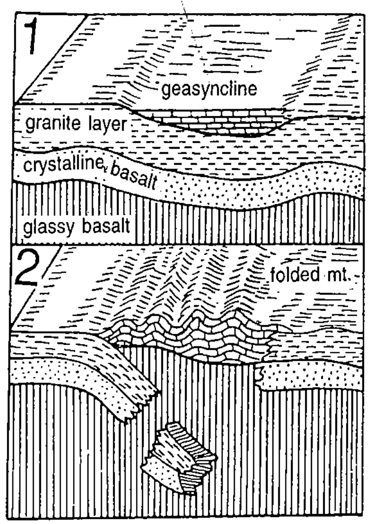


Fig. 11.10 : Illustration of sliding continents theory of R.A. Daly.

According to Daly the broken continental blocks and parts of oceanic crust founder in the substratum because the density of outer crust is more than the substratum. On the other hand, the geosynclinal sediments do not founder in the substratum rather these float on the substratum because these are less dense than the substratum. Because of this fact geosynclinal sediments are more folded by the compressive forces generated by sliding continental blocks. It is thus obvious that greater the amount of slipping of continental blocks, the more geosynclinal sediments are squeezed and more and greater folded mountains are formed. Daly has further pointed out that the foundered continental blocks in the substratum are melted due to high temperature and thus rise in the volume of molten continental blocks causes further rise in the mountains.

The sliding continental theory of Daly also well explains the distributional patterns of folded mountains *e.g.* north-south and west-east extents. According to Daly folded mountains are formed because of squeezing and folding of geosynclinal sediments by compressive forces caused by sliding of the continental blocks towards the geosynclines. Thus, west-east extending mountains (*e.g.* Alpine chains and the Himalayas) were formed due to sliding of polar and equatorial domes towards mid-latitude furrow (Tethys geosyncline) and north-south extending mountains (*e.g.* Rockies and Andes) were formed due to sliding of continental masses towards Pacific Ocean. Similarly, the island arcs and festoons parallel to the Asiatic coast were formed due to sliding of Asiatic mass towards Pacific Ocean.

Evaluation of the Theory

Though the 'sliding continent theory' by Daly is based on well known principle of gravitational force and tries to explain the problem of mountain building in a simple manner yet it does not present coherent account of the problem as the theory does not go into details and there is a wide gap between theoretical and practical aspects of the theory. Major part of the theory is based on self proved facts (axioms). The theory suffers from the following limitations-

(1) The sliding continent theory presents erroneous concepts about the structure of the interior of the earth. His concept, that the outer crust is denser than the substratum, is against the evidences of seismology because it is now proven fact that the density increases with increasing depth in the interior of the earth.

(2) Daly's theory is based on several guesses and surmises. Why did the earth's crust become asymmetrical? Why the continental domes were sloping towards mid-latitude furrows (geosynclines)? How was the Pacific Ocean formed? Daly does not offer any convincing explanation to these and many more questions.

(3) This theory presents erroneous views about geosynclines because these are generally considered as long, narrow and relatively shallow depressions of water but Daly's geosynclines were in fact oceans (*e.g.* mid-latitude furrows and Pacific Ocean). If these are accepted as geosynclines, they would have never been filled with sediments and thus no mountains could have been formed.

(4) Daly has also presented confusing ideas and erroneous concepts about the mechanism of mountain building. In fact, this theory does not care for the extension and depth of oceans and amount of sediments deposited in them but expects mountains from every ocean (geosyncline).

(5) The theory provides wrong views about the mechanism and process of gravity. The theory does not throw light on the termination of pulling effects of gravity and the beginning of the rupture of the beds of the geosynclines. Thus, there is no coherence between different events related to mountain building as envisaged by the sliding continent theory. In fact, the theory presents some piecemeal analysis of mountain building rather than a complete or perfect perspective.

(6) The theory to certain extent believes in such distribution of land and sea (midlatitude furrows and Pacific Ocean and polar and equatorial continental domes) as to suit its own purpose.

Wooldridge and Morgan have aptly remarked, 'complete rejection of the idea may be premature, but it is a fair comment to say that the cause of primary "bulges" which start the slipping has in no sense been satisfactorily indicated.'

4. THERMAL CONVECTION CURRENT THEORY OF HOLMES

Objectives

Arthur Holmes postulated his thermal convection current theory in the year 1928-29 to explain the intricate problems of the origin of major relief features of the earth's surface. Holmes' major objectives were not confined to search the mechanism of mountain building based on sound scientific background but were also directed towards finding scientific explanation for the origin of the continents and ocean basins in terms of continental drift as he was opposed to the concept of permanency of the continents and ocean basins as envisaged by the advocates of thermal contraction of the earth. Wooldrige and Morgan have aptly remarked. "The only unifying theory which shows a hopeful sings of reconciling certain of the divergent hypotheses of mountain building and continental drift is that due to Holmes' (S.W. Wooldrige and R.S. Morgan, 1959).

Orogenetic Force

The driving force of mountain building implied by Arthur Holmes is provided by thermal convection currents originating deep within the earth. The main source of the origin of convective currents is excessive heat in the substratum wherein disintegration of radioactive elements generates heat regularly. In fact, the whole theory depends exclusively on the mechanism of thermal convective currents.

Base of the Theory

According to Holmes the earth consists of 3 zones or layers *e.g.* (i) upper layer of granodiorite (10 to 12 km), (ii) intermediate layer (20 to 25 km) of amphibolite and (iii) lower layer of eclogite. He has further grouped these three layers into two zones *e.g.* (i) **crust** consisting of upper and middle or intermediate layers and crystalline upper part of lower layer and (ii) **substratum** representing molten part of lower layer. Crust and substratum are composed of **sial** and **sima** respectively. Generally, sial is absent in the oceanic areas.

The origin of thermal convective currents within the earth depends on the presence of radioactive elements in the rocks. The disintegration of radioactive elements generates heat which causes convective currents. According to Holmes there is maximum concentration of radioactive elements in the crust but temperature is not so high because there is gradual loss of heat through conduction and radiation from the upper surface at the rate of 60 calories per square centimetre per year. 'This is approximately equal to the radioactive energy produced by a layer 14 km thick of granite, 16.5 km of granodiorite, 52 km of plateau basalt or gabbro and 60 km of peridotite' (J.A. Steers, 1932). According to Holmes the loss of heat from the earth's surface is compensated by the heat produced by a crustal shell of 60 km thickness. Thus, there is no accumulation of additional heat in the earth's crust inspite of maximum concentration of radioactive elements. On the other hand, though there is very low concentration of radioactive elements in the substratum but the gradual accumulation of heat produced by the radioactive elements causes convective currents. The convective currents depend on two factors *e.g.* (i) thickness of the crust near the equator and the poles and (ii) uneven distribution of radioactive elements in the crust. Ascending convective currents originate under the crust near the equator because of greater thickness of crust whereas descending convection currents are originated under the polar crust because of its shallow depth. The rising convective currents originating from below the continental crust are more powerful than the convective currents originating from below the oceanic crust because of greater concentration of radioactive elements in the continental crust.

Mechanism of the Theory

Convective currents, thus, are generated at some places in the substratum. Because of difference of temperature gradient from the equator (greater) towards the poles (low) rising convective currents are formed under the equatorial crust while downward moving (descending) convective currents are generated under the polar crust. The convective currents originating under the continental crust are more powerful than the convective currents originating under the oceanic crust. It may be pointed out that the currents originating under the equatorial crust move towards the poles *i.e.* towards north and south and thus the crusts are carried away with the convective currents.

There are two situations of rising convective currents when they reach the lower limit of the crustal masses. (i) The crustal mass, where two

rising convective currents diverge in opposite directions, is stretched and thinned due to tensional forces and ultimately the crust is ruptured and broken into two blocks which are carried away by lateral divergent convective currents and the opening between two blocks becomes seas. Thus, divergent convective currents cause continental drifts. (ii) Where two lateral convective currents originating under the continental and oceanic crusts converge (fig. 11.11),

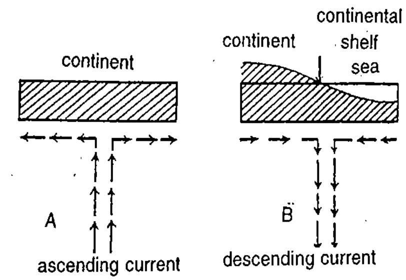


Fig. 11.11: Illustration of rising and descending convective currents under the crust. A- Divergent convective currents cause opening of the landmass and creation of oceans. B- convergent convective currents cause closing of land masses and oceans and create mountains.

compressive force is generated which causes subsidence in the crustal zones giving birth to **geosynclines** and closing of sea. It is apparent that divergent convective currents move the crustal blocks away in opposite directions and thus create seas and oceans while convergent convective currents bring crustal blocks together and thus form mountains.

The convective currents are divided into two groups on the basis of their locational aspect *e.g.* (i) **convective currents of rising columns** and (ii) **convective currents of falling columns.** The rising convective currents after reaching the lower limit of the crust diverge in opposite directions. This outward or divergent movement introduces tensional force due to which the crust is stretched, thinned and ultimately broken and the broken crustal blocks are moved apart. The wide open area between two drifting crustal blocks in opposite directions is filled with water and thus an ocean is formed. According to Holmes the equatorial crust was stretched and ruptured due to divergence of rising convective currents which carried the ruptured crustal blocks towards the north and south and Tethys Sea was formed. This phase is called **'opening of Tethys'** Again two sets of convergent or downward moving (descending) currents brought Laurasia and Godwnaland together and thus Tethys was compressed and folded into Alpine mountains. This phase is called **'closing of Tethys'.**

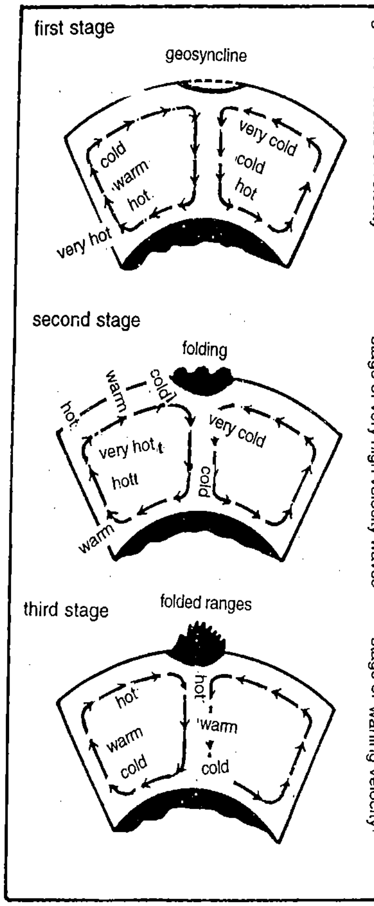


Fig. 11.12: Illustration of successive stages of thermal convective currents under the crust and mountain building.

'The convective mechanism is not a steady process but a periodic one, which waxes and wanes and then begins again with a different arrangement of centre' (A. Holmes, 1952). It means that the convective currents originate at several centres which are not permanent. Geosynclines are formed due to subsidence of crustal blocks mainly continental shelves due to compressive force generated by convergent convective currents moving laterally together under continental and oceanic crusts. In other words, when the continental and oceanic crusts move together and converge under the continental shelves, they descend downward and thus cause immense compression due to which the crust is subjected to subsidence to form geosyncline. The convective currents of rising columns under continental and oceanic crusts bring materials in the geosynclines which are always located above the descending convective currents of falling column. Continuous compression and sedimentation causes gradual subsidence of geosynclines. Holmes has described a cyclic pattern of thermal convective currents which includes the origin of convective currents, formation of geosynclines, sedimentation and orogenesis and further rise in the mountains. According to Holmes the cyclic pattern of convective currents and related mountain buildings pass through three phases or stages (fig. 11.12).

First stage is of the longest duration during which convective currents are originated in the substratum. The rising convective currents of two centers converge under the continental shelves and thus form geosynclines due to compression coming from the convergence of two sets of lateral currents. Geonsynclines are subjected to continuous sedimentation and subsidence. As the sediments are pressed downward into geosynclines, these go further downward and are intensely heated and metamorphosed. Metamorphism of sediments causes rise in their density which further causes downward movement of the metamorphosed materials. Thus, the falling column of downward moving convective currents is the column of increasing density. Amphibolites are metamorphosed into eclogites. A portion of heat is spent during the process of metamorphism and hence the heat does not accumulate to greater extent. The first stage, characterized by high velocity convective currents, is in fact the preparatory stage of mountain building which is marked by the creation of geosynclines, sedimentation and subsidence of materials partly caused by compression resulting from convergence of convective currents and partly by increase in the density of materials due to metamorphism.

Second stage is marked by phenomenal increase in the velocity of convective currents but this stage is relatively of short duration. The main cause for the phenomenal increase in the velocity of convective currents is the downward movement of cold materials in the falling column and upward movement (rise) of hot materials in the rising column of convective currents. Increased pressure due to metamorphism of geomaterials in the falling column of descending currents increases the velocity of downward moving convective currents. The high velocity convergent convective currents buckle geosynclinal sediments and thus initiate the process of mountain building (fig. 11.12). This stage, thus, is called the **stage of orogenesis.**

Third stage is characterized by waning phase of thermal convective currents due to incoming hot materials in the falling column and upward movement (rise) of colder materials in the rising column. Gradually, the rising column becomes a cold column *i.e.* cold materials are accumulated at the centre of the origin of rising (upward moving) convective currents due to which these currents cease to operate and the whole mechanism of convective currents comes to an end. The termination of the mechanism of conective currents yields several results *e.g.*(i) The materials of the falling column start rising because of decrease in the pressure at the top of the falling column due to the end of deposition of materials. This mechanism causes further rise in the mountains. (ii) The depressed and subsided heavier materials in the falling column of descending convective currents start rising due to decrease in the weight and pressure at the top of the falling column. (iii) Eclogite, which was depressed downward, gets melted due to immense heat and thus it expands. This expansion in the volume of molten eclogite causes further rise in the mountains. This stage is known as the **stage of gliptogenesis.** It is, thus, apparent that the thermal convective currents of Holmes explain all the three stages of mountain building *e.g.* **lithogenesis, orogenesis and gliptogenesis.**

Griggs through his experiments has validated the mechanism of convective currents and consequent mountain building.

Evaluation of the Theory

Commenting on Holmes' thermal convective current theory J.A. Steers (1932) has remarked, 'the theory is interesting, but it depends upon such factors about which little is known'. It may be pointed out that this comment of Steers about 80 years ago is not valid today as there are ample convincing scientific evidences which validate the mechanism of convective currents originating from within the mantle. Even much appreciated plate tectonic theory is based on thermal convective currents. The theory was criticised, at the time of its postulation in 1928-29, on the following grounds-

(1) Convective currents theory, no doubt, is a leading theory in a new direction but whole of the theory depends on such factors about which very little is known. Rising and falling columns are doubtful phenomena and therefore doubtful stage can never be taken for the explanation of natural phenomena.

(2) The whole mechanism of convective currents depends on the heat generated by radioactive elements in the substratum (now mantle) but several scientists have raised doubt about the availability of required amount of heat generated by radioactive elements. If heat, thus, is insufficient, convective currents may not be generated and, therefore, the whole mechanism and working of the theory would not be possible. It may be further pointed out that the rising currents pass on their heat into the crust through conduction. This process also causes loss of heat which may weaken the currents.

(3) The horizontal flow of thermal convective currents under the continental and oceanic crusts is also a doubtful phenomenon because of lack of required amount of heat to drive these currents. If horizontal flow of convergent movement of convective currents is not possible, then the falling column would not exist and hence mountain cannot be formed.

(4) The metamorphism of amphibolites into eclogites and resultant downward movement of relatively denser eclogites is also a doubtful phenomenon. Even we accept the metamorphism of amphibolites into eclogites but the resultant increase in density from 3.0 to 3.4 would not be enough to depress and sink eclogites in the falling column. If desired sinking of eclogites is not possible, there would not be proper accommodation of materials brought by the horizontal convergent convective currents into the falling column. If this is so, the whole falling column would be filled with eclogites and the next stage of the mechanism of the convective currents would not work. It is, thus, argued that the theory does not make proper provision for the accommodation of additional materials.

(5) According to this theory convective currents are originated at few centres only under the continental and oceanic crusts but question arises, why are not they originated at all places? If this so happens, the horizontal movement of these currents would not be possible. The whole of the continents would be divided into several blocks as the rising convection currents originating from numerous centres would break the crusts and would give birth to volcanic eruptions of various sorts. This observation has been now validated on the basis of plate tectonics as rising convective currents diverge under the mid-oceanic ridges and thus the plate is ruptured and two plates move in opposite directions due to divergent convective currents and fissure flows of lavas occur along the mid-oceanic ridges representing the rupture zone. It may be concluded that the idea of thermal convective currents conceived by A. Holmes about 80 years ago (in 1928-29) proved its worth in 1960s when the scientists were looking forward to search such a force which can explain the movement of plates. Now, the process of mountain building can be very satisfactorily explained on the basis of convective currents though not in the way as conceived by A. Holmes in 1928-29 but on the lines of plate tectonics.

5. RADIOACTIVITY THEORY OF JOLY

objectives

Joly postulated his theory based on radioactivity of certain radioactive minerals in the year 1925 in his book, 'Surface History of the Earth' to account for the origin and evolution of surface features of the earth. His theory is also known as **thermal cycle theory** or **theory of the surface of the earth.** Though the main objective of Joly's theory was to present a

detailed account of the thermal history of the earth and mathematical explanation of the structure of the interior of the earth but he also attempted to explain the problems of mountain building and the continental drift. In fact, 'Joly's views on the earth's surface history are based on such reasonable premises, and are so simple in their conception, that they have met with a great deal of favour' (J.A. Steers, 1932). While commenting on Joly's theory of radioactivity he has remarked, 'it should not be accepted as proved, but retained as an hypothesis which probably contains a certain elements of truth'.

Orgogenetic Force

The driving force of the mountain building as invoked by Joly is provided by expansion and contraction of the substratum of the earth resulting into transgressional and regressional phases of the seas (geosynclines). The expansion and contraction of the substratum are based on the mechanism of heat generated by radioactive elements of the rocks. It may be pointed out that the theory of A. Holmes and Joly are based on radioactive elements but they sought their help differently *e.g.* Holmes used radioactive elements to explain the origin of thermal convective currents in the substratum while Joly used them to explain the melting and resolidification of the substratum. He also implied tidal force and friction to explain continental drift.

Bases of the Theory

The whole mechanism of Joly's theory is based on the presence of radioactive elements of the rocks of the earth. In order to explain various aspects of the mechanism of radioactive elements Joly has described first the structure of the earth. According to him continents are made of lighter sialic materials the density of which is 2.67 while the oceanic beds are formed of heavier materials of sima having average density of 3.0. Thus, the crust has been assumed to have been composed of sial and substratum of basalt (sima). Besides a few exceptions, sial is not found in oceanic beds.

According to Joly the rocks of the earth contain radioactive elements but their distribution is not uniform in all zones of the earth. Radioactive elements are found in abundance in sialic zone or the continental rocks but the rocks of sima forming the oceanic crusts are less radioactive. Continuous breakdown of certain radioactive elements like uranium, thorium etc. generates heat. It may be pointed out that the actual rate of heat production by radioactive elements is exceedingly small but it becomes sufficient enough to produce appreciable result after long period of accumulation. Though the production of heat is comparatively higher in the continental crust because of more radioactive elements than the oceanic beds but there is no large-scale accumulation of heat in the continental crust due to continuous loss of heat through radiation.

Mechanism of the Theory

According to Joly the disintegration of radioactive elements of sialic or continental rocks produces heat but it does not accumulate in the continents or sial because the total loss of heat through radiation from the sialic crust is more than the total heat produced by the radioactive elements. He has further pointed out that temperature increases with increasing depth. After detailed mathematical calculation Joly estimated the amount of temperature at the depth of 30km to be 1050^0C. He estimated the maximum thickness of sial to be 30km. According to him there is no transfer of heat from sima to overlying sial. He has also estimated the amount of temperature at the outer limit of sima under the continents to be 1050^0C. The conditions under the oceans are rather different. Since there is no sial in the oceanic beds, so the heat produced by radioactive elements, though very small, is lost to the oceanic water through conduction but such situation does not exist at greater depths in the substratum (sima) under the oceans. Temperature increases with increasing depth in the substratum (sima) under the oceans because of accumulation of heat produced by radioactive elements. This mechanism causes temperature gradient at greater depth in sima (substratum). The temperature becomes equal to the melting point of basalt. There is no transfer of heat from the lower part of sima to the upper part of sima so there is accumulation of heat in the lower layers of sima beneath the oceans. The melting point is 1150^0C whereas the temperature at the top of substratum (sima) is 1050^0C. If the temperature of the substratum rises to 1150^0C it would attain its melting point but the substratum would still remain in solid state unless required amount of **latent heat of fusion** is provided. Joly has calculated that the required amount of heat to liquefy the substratum would be available

in 33,000,000 to 56,000,000 years. If such conditions become possible i.e. if the substratum reaches the molten condition, several changes take place in the earth's structure.

Period of transgressional sea— Several interesting events take place when the substratum reaches the molten condition due to accumulation of greater amount of heat produced by the breakdown of radioactive elements. (1) The expansion of sima due to melting causes increase in the radius of the globe. (2) Continental masses or sialic masses are raised relative to the centre of the globe. (3) The density of sima decreases due to melting and hence sialic masses begin to sink in molten sima. (4) The level of oceanic water rises due to sinking of sialic or continental masses into liquid sima. This mechanism causes extension of oceanic water over the continental margins. This process of expansion of oceanic waters and their encroachment on continental margins is called transgression of sea and the concerned stage is known as the phase of transgressional sea. (5) Transgression of sea results in sedimentation on the submerged continental margins. Thus, this theory of radioactivity accounts for the origin of geosynclines due to submergence of continental margins during transgressional phase of sea. (6) The conditions under the oceans are different because there is absence of sial. The increase in the radius and the circumference of the globe due to melting of sima produces tension in the oceanic beds which causes cracks and faults. Molten materials or molten basalts come upward through these cracks and faults. These molten basalts are then solidified and thus oceanic islands are formed. The radioactivity theory, thus, explains the islands of the Pacific and other oceans. (7) Continental masses easily float over molten sima, consequently they are more affected by tidal force which causes westward movement of the continents. It is in this way that the radioactivity theory also describes the process of continental drift. (8) Continental drift changes the position of the continents and the oceans as the former occupy the positions of the latter. This process allows the escape of heat and thus the transgressional phase comes to an end.

Period of regressional sea—The phase of regressional sea is characterized by the following events-(1) The temperature of the substratum decreases because of loss of heat due to continental drift. Thus, the cooling of the substratum results in the resolidification of molten substratum. The cooling of the substratum begins from its upper layer and continues downward and ultimately the whole of the substratum becomes solid on cooling. (2) The density of the substratum, which was relatively decreased during its molten stage, again increases to regain its previous value. (3) The radius and the circumference of the globe, which were increased due to melting of the substratum, are again shortened to their previous position, with the result the continents, which were raised relative to the centre of the globe, are again brought to their previous positions. (4) Relative increase in the density of the substratum due to resolidification causes contraction of the oceanic bed which results in the withdrawal of oceanic waters from the continental margins. This is called the **phase of regressional sea.** Because of the withdrawal of oceanic water previously submerged continental margins (during the phases of transgressional sea) rise upward and the deposited sediments are exposed above the water level. (6) It may be remembered that the oceanic beds were subjected to maximum expansion during the period of transgressional phase due to melting of the substratum. Similarly, the oceanic beds are also subjected to maximum contraction during the period of regressional sea due to resolidification of molten substratum. Thus, contracting beds of two oceans exert lateral compression on the sediments deposited on the continental margins (geosynclines), consequently the sediments deposited during the period of transgressional sea are squeezed, buckled and folded and thus mountains are formed.

Joly has described two parallel processes of mountain building. (i) The sediments deposited in the shallow seas of the continental margins are squeezed and folded due to lateral compression caused by two contracting oceanic beds. (ii) Vertical force is produced during the process of resolidification of the substratum. This vertical force raises the whole mountains system formed during the first process. It is obvious that according to this theory mountains are always formed along the margins of the continents facing oceans. The intensity of lateral pressure and consequent magnitude of folding depend on the amount of contraction of oceanic beds.

It may be argued that large oceans would produce more powerful lateral compression and hence greatest mountain would face largest ocean. To some extent this statement is true as the Rockies and the Andes mountains face the Pacific Ocean.

Joly also explains the period of quiescence between two periods of mountain building. The total period of two solid phases of the substratum (solid phase, molten phase and resoldification phase of the substratum) is called a **revolution** wherein the melting of substratum (sima) takes total time period of 33,000,000 to 56,000,000 years. It may be, thus, inferred that the process of mountain building occurs in cyclic manner wherein the period of mountain building is alternated by the period of quiescence.

Evaluation of the Theory

Though the radioactivity theory of Joly based on scientific facts and mathematical calculation was widely appreciated by several scientists but simultaneously it was also severely criticized. A few critics of the theory do not grant theoretical status to the views of Joly rather they take his views as merely descriptive accounts of the earth's interior. In fact, the theory of Joly is a well developed geomorphic story of the earth rather than a theory. J.A. Steers (1932) has remarked that 'the theory is, at first sight, convincing and it certainly does give adequate explanations of many features of the earth's surface'. The following shortcomings have been pointed out by the critics of the theory.

(1) The theory is based on radioactive elements of the rocks of the earth at different depths about which very little is known. Thus, the force of expansion and contraction of the substratum (sima) due to melting and cooling respectively based on radioactive elements is doubtful and perhaps is not enough to form mountains.

(2) Jeffreys did not agree with the 30km thickness of the continental masses as envisaged by Joly. According to Jeffreys the thickness of the continental crust may not be more than 16km. If the thickness of the continental crust is accepted to be 16 km then the whole mechanism of Joly's theory would come to a grinding halt as required amount of heat of 1150°C would not be possible at the depth of 16km

(3) The Joly's concept of cyclic nature of mountain building has been disputed by some critics. The theory envisages uniform periods of quiescence between two periods of mountain building but this concept has also been disputed. J.A. Steers has commented that "in short very essence of the theory, the approximately equally spaced recurrence of similar conditions, seems to be one of its main drawbacks." He has further remarked that "there seems to be little doubt that mountain building periods have been recurrent to some extent, but it is very doubtful if they have been so regular as Joly's theory would make them" (J.A. Steers, 1932).

(4) This theory envisages two facts about mountain building. (i) 'The greatest mountains must face the greatest oceanic beds'. (ii) Both the margins of the continent must have mountains of the same period and both the margins should be regular. The first is validated to some extent but the second fact is not validated.

(5) This theory presents erroneous concept about geosynclines. As per this theory geosynclines are always formed due to submergence of continental margins due to transgression of seas. It means that geosynclines should always be located around the continents. On the other hand, it has been generally accepted that geosynclines are long, narrow and shallow water bodies which are characterized by continuous sedimentation and subsidence but Joly's geosynclines receive sediments but do not undergo the process of subsidence. Without subsidence the enormous thickness of sediments of the present Alpine mountains cannot be explained.

(6) Jeffreys has demonstrated that sima (substratum) if melted at all cannot resolidify if we accept the capacity of radioactive agencies to liquefy sima.

6. PLATE TECTONIC THEORY

Objective

Plate tectonic theory is a comprehensive theory which offers explanations for various relief features and tectonic events viz. mountain building, folding and faulting, continental drift, vulcanicity, seismic events (earthquakes) etc. The theory belongs to a host of scientists of different disciplines. Plate tectonic theory is, in fact, the outcome of combined efforts of many scientists of different countries working together and separately. The theory came into light in the 1960s. It envisages the formation of mountains due to collision of plate boundaries.

Orogenetic Force

The orogenetic force to form mountains is provided by the compressive forces caused by the collision of two convergent plates along the destructive plate boundaries. Thermal convective currents originating in the mantle have been accepted as the competent force for the movement of plates. The plates move in different directions relative to each other under the impact of thermal convective currents. Plate movements take place in accordance with the **Euler's geometrical theorum** which envisages the movement of plates in the form of simple rotation along a pole of rotation (see fig. 5.10 in chapter 5).

Base of the Theory

The rigid lithospheric slabs or rigid and solid land masses having a thickness of about 100km composed of earth's curst and some portion of upper mantle are technically called **'plates'**. The term 'plate' was first used by Canadian geologist J.T. Wilson in 1965. The whole mechanism of the evolution, nature and motion and resultant reactions of plates is called **'plate tectonics'**. Plate tectonic theory, a great scientific achievement of the decade of 1960s, is based on two major scientific evidences *e.g.* (i) evidence of palaeomagnetism and (ii) evidences of sea-floor spreading. Six major and 20 minor plates have been identified so far (*e.g.* Eurasian plate, Indian-Australian plate, American plate, Pacific pate, African plate and Antarctic plate).

McKenzie and Parker discussed in detail the mechanism of plate motions on the basis of Euler's geometrical theorum in 1967. Hary Hess (1960) elaborated the mechanism of plate movement on the basis of the evidences of sea-floor spreading. W.J. Morgan and Le Pichon elaborated the various aspects of plate tectonics in 1968.

Three types of plate boundaries (see fig. 5.7 in chapter 5 on the Origin of Continents and Ocean Basins) have been identified *e.g.* (i) destructive plate boundaries, (ii) constructive plate boundaries and (iii) conservative plate boundaries.

(1) Constructive plate boundaries also called as **'divergent plate boundaries'** or **'accreting plate boundaries'** represent zones of divergence along the mid-oceanic ridges and are characterized by continuous addition (accretion) of materials as there is constant upwelling of molten materials (basaltic lavas) from below the mid-oceanic ridges. These basaltic lavas are cooled and solidified and are added to the trailing margins of the divergent plates and thus new oceanic crust is continuously formed. In fact, oceanic plates split appart along the mid-oceanic ridges and move in opposite direction (see fig. 5.7) and thus transform faults are formed.

(2) Destructive plate boundaries also known as **'consuming plate boundaries'** or **'convergent plate boundaries'** are those where two plates collide against each other and the leading edge of one plate having relatively lighter material overrides the other plate and the overriden plate boundary of relatively denser material is subducted or thrust into the upper mantle and thus a part of the crust is lost in the mantle (see fig. 5.8 in chapter 5). This mechanism results in constant loss of crustal materials.

(3) Conservative plate boundaries also known as **'shear plate boundaries'** are those where two plates slip past each other without any collision along the transform fault and thus crust is neither created nor destroyed.

Mechanism of the Theory

According to plate tectonic theory mountains are formed due to collision of two convergent plates. Mountains are always formed along the destructive plate boundaries. It is obvious that the process of mountain building is associated with destructive plate boundaries of two convergent plates. The plate tectonic theory envisages the formation of mountains due to compression of sediments caused by the collision of two convergent plate boundaries. Two plates moving together under the impact of thermal convective currents collide against each other and the plate boundary having relatively denser materials is subducted under the other plate boundary of relatively lighter materials. This subduction zone is also called Benioff zone. The subduction of plate boundary causes lateral compressive force which ultimately squeezes and folds the sediments and materials of the margins of the plates and thus

mountains are formed. The subducted part of the plate after reaching a depth of 100km or more in the mantle is liquefied and thus expands in volume because of conversion of the portion of plate into magma. This expansion of molten materials causes further rise in the mountains.

The convergence and consequent collision of plate boundaries occurs in three situations viz. (i) collision of two oceanic plates, (ii) collision of two continental plates and (iii) collision of oceanic-continental plates.

(1) Convergence of two oceanic plates-The collision of two oceanic plates and subduction of the boundary of the plate of relatively denser materials results in the formation of the fold mountain ranges of island arcs and festoons, for example, island arcs and festoons formed by Japanese islands, Phillippines etc. around the western margin of the Pecific Ocean off the east coast of Asia. The fold mountain ranges of island arcs and festoons 'form where a section of the ocean floor is subducted in the ocean basin away from a continent *i.e* where ocean floor crust is on either side of the convergent plate boundary' (M.J. Bradshaw et al. 1978).

The best example of the formation of mountains due to collision of two oceanic plates is the situation of Japanese island arc. Mountains of Japan range in height from 3000m to 4000m AMSL. It may be pointed out that all the mountains of Japan are of volcanic origin. Though Japanese mountains exhibit a number of characteristic features of folded mountains but they can no longer be regarded as fold mountains like the Alps and the Himalayas. Honshu Island represents the most characteristic example of the situation of the convergence of two oceanic plates.

Honshu is bordered by Japan Trench in the east and Japan Sea in the west. The western part of the island is more frequented by volcanic activities than the eastern part. The island is characterized by two belts of metamorphic rocks on either side. It is believed that the Japan Trench was formed due to the subduction of Pacific Oceanic plate under the oceanic crust to the east of Japan. According to plate tectonic theory the subducted portion of plate after reaching a depth of 100km or more starts melting due to high temperature prevailing in the upper mantle. The magma, thus formed, ascends and appears as volcanic eruption about 200km away from the oceanic trench. Since Japan is very close to the Japan Trench and hence western part of Japan is more frequented by volcanic activities. This process is still continuing as the Pacific plate is being continuously subducted under the oceanic crust along the Japan Trench. The eruption of volcano in the month of June, 1991 in Japan after a dormant period of about 200 years and the eruption of Mt Pinatubo on June 9, 1991 in Manila, Phillippines, validate the authenticity of this theory of plate tectonics. The volcanic eruptions caused by subduction of oceanic plates under the oceanic crust off the Japanese coast resulted into continuous accumulation of volcanic rocks and consequent increase in the height of island arc and thus the formation of volcanic mountains could be possible.

(2) Convergence of continental and oceanic plates-The collision of continental and oceanic convergent plates results in the formation of cordillera type of folded mountains, *e.g.* the western cordillera of North America (including the Rockies). When one continental and the other oceanic plates collide due to their convergence along subduction or Benioff zone, the oceanic plate boundary being heavier due to comparatively denser materials is subducted below the continental plate boundary. The sediments deposited on the continental margins are squeezed and folded due to compressive forces caused by the subduction of oceanic plate (see fig. 5.8 in chapter 5). The Rockies and the Andes mountains were formed due to subduction of the Pecific ocean plate under the American continental plate.

(3) Convergence of two continental plates-When two convergent plates composed of continental crusts collide against each other, the continental plate having relatively denser materials is subducted under the other continental plate having comparatively lighter materials than the former. The resultant lateral compression squeezes and folds the sediments deposited on either side of continental plate margins and the sediments of the geosynclines lying between two convergent continental plates and thus forms gigantic folded mountains *e.g.* the Alps and the Himalayas.

The origin of the Alpine mountains of Europe and Asia is well explained on the basis of this mechanism (collision of two convergent continental plate boundaries) of plate tectonics. There existed a long Tethys geosyncline between Eurasian plate in

the north and African-Indian plate in the south during Mesozoic Era. The geosynclinal sediments of Tethys sea were squeezed and folded into Alpine-Himalayan mountain chains due to lateral compressive forces caused by the convergence and collision of Eurasian and African-Indian continental plates during Cenozoic Era. It may be pointed out that the formation of Alpine-Himalayan mountain chains could be possible due to continued collision of continental plates and consequent orogenesis along several subduction zones for long period of time.

About 70-65 million years ago there was an extensive geosyncline, known as Tethys geosyncline, in the place of the Himalayas. Tethys geosyncline was bordered by Asiatic plate in the north and Indian plate in the south. Tethys geosyncilne began to contract in size due to movement of Indian and Asiatic plates together. About 60-30 million years ago the Indian plate came very close to Asiatic plate. The Indian plate began to actively subduct under the Asiatic plate. The convergence and collision of Asiatic and Indian plates and consequent subduction of Indian plate under the former caused lateral compression due to which the sediments of Tethys geosyncline were squeezed and folded into three parallel chains of the Himalayas about 30-20 million years ago. It has been estimated that the crust has been shortened by 500km between Asiatic and Indian plates due to convergence of two plates and subduction of Indian plate.

Alpine mountains of Europe were formed due to convergence and collision of European and African plates. Since the collision of these two continental plates was very complex and hence the structure of the European Alpine mountains is also very complex. The African plate is still moving northward and is being subducted under European plate to the south of Aegean arc. Similarly, Indian plate is also being continuously subducted under Asiatic plate.

Evaluation of the Theory

The overwhelming majority of the scientists all over the world is of the view that plate tectonic theory has almost solved the problems of the origin of continents and ocean basins and of mountain building. In fact, the continental drift has now become a reality on the basis of evidences of palaeomagnetism and sea-floor spreading. Plate tectonic theory also satisfactorily explains the cyclic pattern of mountain building.

It may be pointed out that 4 major periods of mountain building have been identified *e.g.* (i) pre-Cambrian Orogeny, (ii) Caledonian Orogeny, (iii) Hercynian Orogeny and (iv) Tertiary Orogeny. All the earlier theories of mountain building, as discussed in the preceding pages, suffer from a common defect that they, some how, do attempt to explain the origin of the folded mountains of Tertiary period but they do not throw any light on the mountains older than Tertiary period. It may be mentioned that plates are always in motion due to which some times all the land masses unite together to form **Pangaea** and again break up and move away relative to each other and new distributional pattern of continents and ocean basins is evolved. The past history of the earth upto 200 million years has been reconstructed on the basis of evidences of palaeomagnetism. About 200 million years before present all the continents were united together in the form of **Pangaea II** (a super continent). It is believed that before the situation of Pangaea II, the continents were separated from each other. These continents might have moved relative to each other in such a way that they might have united together to form a super continent. It is believed that the continents moved together due to plate motions and were united together in the form of **Pangaea I** during Pre-Cambrian period, about 700 million years ago. About 600-500 million years ago Pangaea I was disrupted. About 460 million years ago the Atlantic Ocean began to close down due to convergence of American and Eurasian plates and the Caledonian mountains were formed. About 300 million years ago the Atlantic Ocean was completely closed and the orogenesis of the Applachian mountains was completed during Permian period. At the same time Hercynian mountains of Europe were formed (see figure 5.12 in chapter 5). About 200 million years ago all the continents were again united to form Pangaea II. About 150 million years ago Pangaea was again distupted and the Atlantic ocean was reopened. The Alpine mountains were formed due to plate movements during Tertiary period.

The only point of argument and question is related to the competent force responsible for the movement of plates and drifting of continents. Most of the scientists still rely on the thermal convective currents originating from the mantle as the probable adequate force to move the plates (continents) in different directions relative to each other.

12

PLATEAU

12.1 MEANING

Plateaux are significant relief features of the second order as these cover about 33 per cent of the surface area of the globe (plains, hills and mountains cover about 41, 14 and 12 per cent of the total surface area of the globe respectively). According to Finch and Trewartha "tabular uplands having a relief of more than 500 feet may be arbitrarily defined as plateau". Plateau may be defined as that upland which has atleast one side of very steep slope standing well above the neighbouring surface and the upper part is extensive and almost flat, examples, Ranchi plateau, Hazaribagh plateau, Shillong plateau etc. There is wide range of variation in the heights of plateaux, *e.g.* Applachian plateau rises for 1000 m AMSL, Colorado plateau has a mean height of 2500 m AMSL and Tibetan plateau is the highest (5,000 m AMSL) plateau in the world.

12.2 GENERAL CHARACTERISTICS

On an average, plateaux are extensive upland areas characterized by flat and rough top surface, steep side walls which rise above the neighbouring ground surface at least for 300 m. "The surfaces of plateau may be plain like in quality, very flat, rolling or hilly, or they may be so dissected by streams and glaciers that it is difficult to recognise their original plateau characteristics" (P.G. Worcester, 1948).

From locational point of view plateaux vary from one place to another place. Some plateaux are surrounded by hills and mountains (*e.g.* Tibetan plateau), some plateaux are bordered by hills and mountains on one side while they are bordered by plains or coastal areas on the other side *e.g.* piedmont plateau of the USA (it is bordered by middle Applachian mountains in the west and Atlantic coastal plains in the east), Cumberland and Alleghany plateaux in the USA (surround by Applachian mountains in the east and Mississippi plains in the west), Iranian and Anatolian plateaux and Colorado plateau of the USA are also bordered by mountain ranges.

Some plateaux are very extensive in areal context *e.g.* Deccan plateau of India, Siberian plateau, Arabian plateau etc. The most characteristic features of plateaux are their flat and rolling top surfaces. Generally, the slopes of the side walls are very steep but the top surfaces, except minor reliefs, are more or less flat. Ranchi plateau abruptly rises from the Damodar valley and the northern side-walls are about 300m high from the Damodar plain (300m AMSL). The flat top surface of the Ranchi plateau is characterized by scattered hills and batholithic granite-gneissic domes which rise upto 50 to 100m from the ground surface. Plateau surface is also dotted with hill ranges and river valleys. The rivers while descending from the plateau form long, narrow and

deep valleys (*e.g.* gorges and canyons). For example, all the major rivers while descending through Rawa plateau (in Madhya Pradesh) and draining northward to meet the Yamuna or the Ganga rivers have entrenched deep valleys *e.g.* Chachai gorge of Bihar river (127 m deep), Kevati gorge of Mahana river (98m deep), Odda gorge (145m deep) on Odda river (in Rewa district, M.P.) etc. The Colorado plateau in Arizona State (USA) attains the height of 2100 m AMSL. Its top surface has been deeply entrenched by Colorado river. The world famous Colorado gorge and canyon is 1000m deep.

From the stand point of surficial materials plateaux also register wide range of variations. Some plateaux have thick covers of basaltic lavas *e.g.* plateaux in an area of 7,74,000 km^2 (*e.g.* Deccan plateaux in an area of 7,74,000 km^2 (*e.g.* Mahabaleshwar plateau and Panchagani plateau in Maharashtra have thick covers of basaltic lavas topped by massive laterite covers). Some plateaux are composed entirely of sedimentary rocks *e.g.* Rewa plateau (composed of sandstones, shales and limestones), Bhander plateau having sandstone capping, Rohtas plateau (Bihar) having sandstone capping etc. Some plateaux are so dissected by the network of streams that they are segmented into numerous parts *e.g.* **patlands** of Ranchi and Palamau uplands (in Jharkhand) have been segmented by the North Koel river and its tributaries into several flat-topped mesas and buttes having steep side slopes from all sides. Such lava-capped mesas are locally called 'Patlands', examples, Netarhat Pat, Jamira Pat, Khamar Pat, Rudni Pat, Raldami Pat, Bagru Pat (having bauxite capping) etc.

12.3 ORIGIN AND EVOLUTION OF PLATEAUX

Plateaux are originated in a number of ways as follows-

(1) Due to downwarping of surrounding areas. For example, if the southern part of the Ganga plain is downwarped by a few hundred metres but the northern part remains stable, then the remaining plain area associated with the Himalaya would become a plateau.

(2) Due to upwarping of some portion of an extensive land mass by a few hundred metres in relation to surrounding ground surface *e.g.* Western Patlands of Ranchi and Palamau.

(3) Due to deposition of thick covers of basaltic lavas *e.g.* Columbian plateau (USA), Mahabaleshwar plateau, Panchgani plateau etc.

(4) Some times, the adjoining areas of mountains are not folded but are raised during the process of mountain building. Such unfolded but upwarped regions become plateau *e.g.* Cumberland plateau to the west of Applachian mountains. It may be pointed out that perfect horizontality of coal beds has been preserved in Cumberland plateau.

(5) The marginal sediments of geosynclines are folded into parallel marginal ranges and the middle portion of the geosynclines remains unaffected by compressive forces. Such unfolded middle portion of geosynclines bordered by marginal mountain ranges becomes median mass which may assume the form of a plateau (it may also be a plain) *e.g.* Tibetan plateau between Kunlun-Tienshan and the Himalayas, Iranian plateau between Zagros and Elburz mountains, Anatolian plateau (in Turkey) between Pantic and Taurus mountains etc.

(6) Some plateaux are also formed when extensive mountains are transformed into low uplands having extensive rugged surfaces due to prolonged denudation. Several examples of such mountain-cum-plateau may be seen in the Applachian mountain.

(7) Thick deposits of loose materials by wind also form plateaux *e.g.* Loess plateau of China.

12.4 CLASSIFICATION OF PLATEAUX

1. According to mode of origin

(A) Simple Plateaux

(1) Plateaux formed by exogenetic processes

(i) Glacial plateau *e.g.* Garhwal plateau

(ii) Aeolian plateau *e.g.* Potawar plateau, Loess plateau

(B) Compound Plateaux

(2) Plateaux formed by endogenetic processes

(i) Intermontane plateau *e.g.* Tibetan plateau

(ii) Piedmont plateau *e.g.* Applachian Piedmont Plateau

(iii) Dome plateau *e.g.* Ozark Massif (USA), Chotanagpur plateau (Jharkhand, India).

(iv) Lava plateaux, examples, Columbia plateau (USA), Mahabaleshwar plateau, Panchagni tableland etc.

2. Classification according to geographical situation

(1) Intermontane plateaux, examples: Tibetan plateau, Bolivian plateau, Peru plateau, Columbian plateau, Mexican plateau, Iranian plateau, Anatolian plateau etc.

(2) Piedmont plateaux, examples : Applachian Piedmont plateau, Patagonian plateau etc.

(3) Continental plateaux, examples : Deccan plateau of India, Ranchi plateau, Shillong plateau, Columbian plateau (USA), Mexican plateau, Tibetan plateau etc.

(4) Coastal plateaux, example: Coromandal Coastal upland of India.

3. Classification on the basis of size and shape

(1) Dome-shaped plateau, example : Chotangpur plateau (in Jharkhand)

(2) Dissected plateau, example : Deccan plateau of India

(3) Step-like plateau, example : Kaimur plateau consisting of (from west to east, height decreases eastward) Panna plateau, Bhander plateau, Rewa plateau and Rohtas plateau

(4) Flat-topped plateau, examples : Tibet plateau, Bhander plateau (M.P.), Rewa plateau etc.

(5) Rejuvenated peneplain plateau, example : Missouri plateau of USA, Patlands of Ranchi and Palamau (Jharkhand)

4. Classification on the basis of surface configuration

(1) Uneven plateau, example : Applachian plateau

(2) Tableland plateau, example : Mahabaleshwar plateau, Panchgani tableland (Maharashtra)

5. Classification on the basis of climate

(1) Desert or arid plateau, example : Arabian plateau

(2) Humid plateau, example : Shillong plateau, Mahabaleshwar plateau, Assam plateau etc.

(3) Ice-capped plateau, example : Greenland plateau

6. Classification on the basis of stage of erosion

(1) Young plateau, examples : Idaho plateau (USA), Colorado plateau (USA), Mahabaleshwar plateau, Khandala upland (Maharashtra)

(2) Mature plateau, examples : Ranchi plateau, Hazaribagh plateau (all in Jharkhand) : Applachian plateau

(3) Old plateau

(4) Rejuvenated plateau, example : Missouri plateau (USA)

7. On the basis of mode of origin

(1) Glacial plateaux-It may be pointed out that glacial plateau does not mean a plateau formed by the glaciers rather it means a plateau modified and transformed by glacial actions because all the plateaux, in one way or the other, are the result of endogenetic forces and related tectonic events. When mountains are greatly modified and transformed by glacial erosion, they are lowered in height and their sharp reliefs are rounded to such an extent that they become the example of a plateau. Glaciers have formed numerous plateaux through their erosional work on Greenland and Antarctica. According to Chhibber Garhwal plateau of India has been formed due to glacial actions. The deposition of glacial moraines also forms low plateaux. Such plateaux have been formed in Germany because of morainic deposits during Pleistocene Ice Age. **'Marg'** of Kashmir is supposed to have been formed of glacial moraines.

(2) Fluvial plateaux are formed due to continuous deposits of fluvial sediments brought by the rivers. The sediments are gradually consolidated and stratified into sedimentary rocks of great thickness. These sedimentaries are raised upward due to earth movements relative to surrounding regions and thus upland plateau with extensive flat top surface is formed. Extensive Kaimur plateau consisting of Panna plateau, Bhander plateau, Rewa plateau, Rohtas plateau etc. is the best example of fluvial plateau. This extensive plateau region consists of a series of descending plateaux beginning

from Panna plateau in the west (M.P.) and ending into Rohtas plateau (Bihar) in the east. These plateaux consist of sedimentary rocks (sandstones, shales and limestones) which were deposited in Vindhyan Sea during pre-Cambrian period and were subsequently raised by earth movements. The rocks of these plateaux belong to Vindhyan formations.

(3) Aeolian plateau is formed because of deposition of fine sediments brought by winds. Enormous volumes of sediments are consolidated in due course of time and plateau is formed. Potawar plateau of Pakistan and Loess plateau of China are considered to have been formed due to deposition of fine sediments by wind.

Most extensive, highest and most complex plateaux are originated through endogenetic forces coming from deep within the earth. The plateaux formed by horizontal and vertical movements caused by endogenetic forces are called **diastrophic plateau** which include intemontane plateaux, piedmont plateau, continental plateaux and dome-shaped plateau. Diastrophic plateaux, in fact, are true plateaux. They are also called **tectonic plateaux.**

(4) Internontane plateaux are, in fact, the highest and most extensive plateaux of the globe. These are called intermontane because they are surrounded by hills and mountains almost from all sides. Intermontane plateaux are originated together with the origin of folded mountains, Generally, intermontane plateaux are formed due to upwarping of middle portion of the geosynclines known as **median mass,** after the formation of mountain ranges along both the margins of the geosynclines. Tibetan plateau is the best example of intermontane plateaux. Bolivian plateau, Peruvian plateau, Columbian plateau, Mexican plateau etc. are other significant examples of intermontane plateaux.

Tibetan plateau, having an average height of 5,000 m (16,000 feet), is the highest plateau of the world. At some places the plateau rises upto 6,000 m AMSL. As regards areal extent, Tibetan plateau is also the most extensive plateau of the world as it covers an area of about 20,64,000 km^2 (8,00,000 square miles). Tibetan plateau, surrounded by Kunlun mountains in the north, the Himalayas in the south, Kunlun-Himalayas in the west and Chinese mountains in the east, is the best example of a **median mass** (unfolded upland). From the stand point of reliefs, Tibetan plateau is divided into 4 regions *e.g.* (i) the northern region is a mixture of low hill ranges, valleys and plains with an average height of 4,800 m (16,000 feet). There are several enclosed salt lakes which are spread over an area of 2,580 km^2. (ii) The southern plateau region is the source area of the Indus and the Brahmaputra rivers. (iii) The eastern plateau region is comparetively lower than the northern and the southern plateau regions. This region has the sources of Yellow river (Hwang Ho), Yangtze river, Salween river, Meeking river etc. (iv) North-eastern plateau region consists of several enclosed basins, playa lakes and saline lakes (salt lakes). Tsaidan Swamps are the characteristic features of this region.

Mexican plateau, another fine example of an intermontane plateau, is surrounded by Sierra Madre Occidental range in the west and Sierra Madre Oriental mountain range in the east. The plateau slopes northward as its average height near Mexico city is about 2250m (7410 feet) while it decreases to 1216m (4000 feet) near its international border with the USA. The whole plateau is covered with valleys, low hills, playa lakes, salt lakes etc. The southern part of the plateau is characterized by several volcanic mountains. Tectonically and seismically the plateau is very much sensitive and unstable. The devastating Mexico earthquake of September, 1985 proves the validity of this concept.

The plateaux of Bolivia and Peru (South America) are also surrounded by mountain ranges of tertiary period. The Peruvian-Bolivian plateuax are surrounded by Cordillera Central Ranges and Cordillera Occidental Ranges in the east and west respectively. These plateaux, exhibiting an example of median mass, were originated together with the origin of the Andes mountains during tertiary period. The average height of these plateaux from sea-level is 3,648 m (12,000 feet). Some parts of the plateaux are plains while some parts are hilly regions. Lake Titicaca is fresh water lake which is 264 km long and 96 km wide and 12,370 feet (3761 m) high (AMSL).

(5) Piedmont plateau-Plateau formed at the foothill zone of extensive mountains is called piedmont plateau, which is surrounded by mountain range on one side while by plain topography or coastal plain on the other side. The side of the plateau facing the plains is of steep slope and thus forms an

escarpment. Piedmont plateaux are also formed due to upliftment during the origin of mountains. The piedmont plateau representating the eastern margins of the Applachian mountains (USA) and Patagonian plateau of South America are the representatives of piedmont plateaux. The Applachian piedmont plateau abruptly terminates into Atlantic coastal plains. The sudden break in slope along the junction of the piedmont and the coastal plains makes sudden decrease in the channel gradients of the Atlantic-bound rivers of the Applachians, with the result all the rivers which originate in the Applachians and descend through the escarpment of the piedmont plateau and enter the coastal plains to drain into the Atlantic Ocean, make stupendous waterfalls of varying magnitudes. There is a world famous fall line along the eastern margin of the piedmont plateau from Alabama in the south-west to New England in the north-east. This fall-line is associated with numerous waterfalls, the most of which have been tapped for the generation of hydroelectricity which has accelerated the place of industrial development along the fall-line.

(6) **Dome shaped plateaux** are formed when the landmass is uplifted in such a manner that the middle portion is upwarped and the sides are rounded. Dome-shaped plateaux are generally formed due to endogenetic forces mainly during volcanic activities. In fact, the batholithic and laccolithic intrusions of magmas beneath the crustal rocks cause large-scale doming of the ground surface which rises upto several hundred metres from the surrounding neighbouring ground surface. Chotanagpur plateau of Bihar is quoted as a typical example of domal plateau because it is studded with numerous batholithic domes which were intruded in the Dharwarian sedimentaries during Archaean period. Prolonged denudation has removed the superincumbent Dharwarian covers and these batholithic domes have been exposed on the surface. Ozark plateau (USA) is considered to be the best example of dome-shaped plateau. Ozark was formed due to upliftment of ground surface caused by Applachian Revolution (Applachain mountain building) during Permain period. This plateau was vigorously denuded and hence it was transformed into a peneplain before Tertiary period. It was again uplifted and was again transformed into second peneplain due to prolonged denudation by the end of Tertiary period. It is apparent that Ozark plateau has passed through two phases of cycle of erosion and peneplanation. Presently, Ozark plateau consists of three separated plateaux *e.g.* (i) Salem plateau, (ii) Springfield plateau and (iii) Boston plateau. The Ozark plateau has given birth to radial drainage pattern. The sides of the plateau have been deeply entrenched by the radiating streams.

(7) **Continental plateaux** are very extensive plateaux and are generally away from mountainous areas but are surrounded by coastal plains. Some times, these plateaux are bordered by mountains on one or two sides. Deccan plateau of Peninsular India is a typical example of such plateau. Deccan plateau, covering an area of hundreds of thousands of square kilometres, is one of the oldest plateaux of the world. The plateau composed of different rocks of Dharwar, Cuddapah, Vindhyan and Gondwana formations has been widely dissected and is characterized by elongated hill ranges. The plateau is bordered by the Western Ghats in the west and by the Eastern Ghats in the east. The plateau is surrounded by the hill ranges of the Aravallis, Vindhyachal, Parasnath and Rajmahal, Mahadeo, Maikal, Kaimurs, Sahyadri, Ajanta, Nilgiri, Nallamalai, Nimgiri etc. Hill ranges are the prominent reliefs of the plateau. Rivers have dissected and segmented the plateau into several independent plateaux. Arabian plateau, Australian plateau, South African plateau etc. are other examples of continental plateaux. Antarctica and Greenland may be considered as the examples of new continental plateaux.

(8) **Volcanic plateaux** are those plateaux which are formed due to accumulation of thick layers of basaltic lavas. Lava plateau was formed over an area of 7,74,000 km^2 (3,00,000 square miles) in the Peninsular India due to accumulation of enormous volume of basaltic lavas erupted during Cretaceous period. The examples of volcanic plateaux formed due to deposition of basaltic lavas coming up through fissure flows are also found in New Zealand, South Africa, northern and southern Argentina, Brazil, western USA (Columbian plateau), France, Siberia etc. The Columbian plateau of the USA is the best example of lava plateaux in the world. This plateau is surrounded by the Rockies in the east, by Cascade mountains in the west, by Basin and Range Province

in the south and by the plateau of British Columbia (Canada) in the north. Columbian plateau may also be accommodated in the group of intermontane plateaux because it is surrounded by mountains from three sides. The plateau covers an area of 258,000 km^2 (1,00,000 square miles) wherein the thickness of basaltic lavas ranges between 608m to 1520m (200 to 5000 feet). Columbia river and its tributaries have dissected the plateau to great extent. It is believed that about 300m thick basaltic lavas have already been eroded away by fluvial processes. The presence of 20 layers of lava in the Columbian plateau denotes the fact that there were 20 episodes of lava eruptions.

8. Classification on the basis of cycle of erosion

A.K. Lobeck has divided the plateaux on the basis of stages of cycle of erosion into 3 types *e.g.* (i) young plateau, (ii) mature plateau and (iii) old plateau. A fourth type, rejuvenated plateau, may also be added to this group.

Young plateaux are characterized by almost horizontal beds of rocks. Though the rivers are few but they form deep and narrow valleys through vertical erosion. Such young plateaux are generally bordered by escarpments. **Colorado plateau** is a fine example of young plateaux where Colarado river has dug out a stupendous world-famous canyon, known as **Grand Canyon,** which stretches for a distance of 200 km with remarkable depth of 1600m (1.6 km).

Mature plateaux are formed when they are so greatly dissected that their surfaces become highly corrugated, undulating and uneven and the surface is dominated by pointed peaks. It may be pointed out that these pointed, sharp and angular peaks are maintained only in arid and semi-arid regions. These are greatly rounded in the warm and moist regions.

Old plateaux are formed due to prolonged erosion of mature plateau. The peaks are so denuded that they are eliminated and the plateaux are transformed into **peneplains.** The **mesas** and **buttes** scattered over the plateau surface are the characteristic relief features. Rejuvenated plateaus are formed due to upliftment of an old plateau. Missouri plateau of the USA is an example of rejuvenated plateau.

13

PLAINS

13.1 MEANING

Plains are the simplest relief features of all the reliefs of the second order. These are easily identifiable and are easily classified into distinct categories. Plains are flat areas with low height. The height of plains cannot be precisely defined in reference to the sea-level because some plains are some times even below sea-level *e.g.* coastal plains of Netherlands (where sea walls and sea embankments of concrete have been constructed to protect the coastal plains against possible submergence during high tidal waves), some plains are only a few metres above the sea-level *e.g.* southern deltaic plains of Bangladesh (the most devastating hazardous cyclonic storms of the century hit the coast in May, 1991 and submerged most part of the deltaic coastal plains killing more than 5,00,000 people) while some plains are hundreds of metres above mean sea-level *e.g.* eastern Mississippi plain is 450m high which is definitely higher than the piedmont plateau situated to the east of the Applachians. It may be mentioned that plains may be above or below sea-level but they cannot be higher than the surrounding regions. The plains are generally characterized by almost flat surface but it also becomes undulating because of erosion. Plains are also dominated by level to gentle slopes. On an average, plains are composed of same type of rocks but these are generally overlain by sediments. There is a wide range of variations in the plains in relation to their height, situation, size and extent, topographic forms, lithological characteristics, mode of origin etc. It may be pointed out that plains are formed mainly in two ways *e.g.* (i) through endogenetic forces and (ii) through exogenetic processes. The plains grouped under the category of the reliefs of the second order include only those plains which are formed due to endogenetic forces coming from within the earth whereas the plains formed through erosional and depositional works of exogenetic processes (denudational processes) are grouped under the category of the reliefs of the third order. This chapter includes plains of both the categories.

13.2 ORIGIN AND DEVELOPMENT OF PLAINS

Plains found on the earth's surface have been formed in different ways as follows-

(1) Most of the plains have been originated due to upliftment or emergence of submerged landmasses under epicontinental seas due to diastrophic movements. The Great Plains Province of the USA is a burning example of this process of the origin of plains. Northern portion of the Atlantic coastal plains is also supposed to have been formed due to emergence of submerged coastal land having marine deposits.

(2) Plains are formed due to filling of depressions with sediments, which are created in front of the mountains during the process of orogenesis. In other words, the land areas in front of a newly originated mountain are depressed due to diastrophic movements and an extensive trench-like depression or foredeep is formed. This foredeep is filled with sediments in due course of time and ultimately a broad and extensive depositional plain is formed. The northern plains or the Ganga-Yamuna plains of India are typical examples of such plains.

(3) Some times, the middle part of the geosynclines remain unfolded after the formation of bordering ranges on both the margins of the geosynclines. Such area unaffected by folding activities, very often known as median mass, becomes plains. It may be pointed out that not all the median masses become plains, rather most of them become plateau (like Tibetan plateau, Iranian plateau, Anatolian plateau, Colorado plateau etc.). A median mass becomes plain only when it is characterized by flat surface and comparatively lower height. Hungarian plain between Dinaric Alps and Carpathian Alps is an example of plain formed by a median mass.

(4) Some times, coastal lands are submerged under sea water because of transgressional phase of sea. Such coastal lands submerged under shallow water receive sediments regularly and after long time of continuous sedimentation narrow coastal plains are formed. The eastern coastal plains of India, mainly North Circar, are supposed to have been formed due to sedimentation over submerged coastal lands.

(5) Submerged coastal lands emerge as marine coastal plains due to withdrawal of sea water during regressional phase of sea. The Kutch plain of India is the example of such plain. It may be pointed out that Rann of Kutch is gradually prograding (extending) towards sea and hence the marshy plain is also gradually extending in area.

(6) Extensive plateaux after prolonged denudation become plains.

(7) Deposition of enormous volume of lavas over extensive area gives birth to lava or volcanic plains.

13.3 CLASSIFICATION OF PLAINS

1. **According to morphological and structural characteristics**
   - (1) Flat plains
   - (2) Undulating plains
   - (3) Rolling plains
   - (4) Dissected plains
2. **According to mode of origin**
   - (1) Plains formed due to diastrophic forces (diastrophic plains)
     - (i) formed due to upliftment, coastal plains
     - (ii) formed due to subsidence and sedimentation, coastal plains
     - (iii) lava plains or volcanic plains
   - (2) Plains formed due to denudational processes
     - (i) erosional plains
       - (a) peneplains
       - (b) glacio-fluvial plains
       - (c) pediplains
       - (d) desert plains
       - (e) karst plains
     - (ii) depositional plains
       - (a) alluvial plains (piedmont alluvial fan plains and flood plains)
       - (b) glacial-depositional plains (till plains and outwash plains)
       - (c) aeolian-depositional plains (sandy plains and loess plains)
       - (d) Marine-depositional plains
   - **(3) According to location**
     - (1) Inland plains
     - (2) Coastal plains
   - **(4) Simplified classification**
     - (1) Constructional or diastrophic plains
     - (2) Erosional plains
     - (3) Depositional plains

Diastrophic Plains

It may be pointed out that a particular plain is seldom formed by a single process. Erosion or deposition, in one way or the other, always plays an

important role in the development of plains. Thus, the nomenclature of a plain is based on the dominant process playing the most significant role in the origin and evolution of that plain. Under the diastrophic events plains are formed due to upliftment or subsidence of land areas or emergence of land areas from beneath the oceanic water or submergence of coastal lands under oceanic water caused by epeirogenetic movements.

The Great Plains (USA) are the examples of plains formed due to upliftment or emergence of submerged landmasses under epicontinental sea. The great plains are bordered by the Rockies in the west, by Central Lowland Province or Mississippi-Missouri plains in the east and by Rio Grande river in the south. The plains further extend northward into Canada. It is believed that the Great Plains remained under water in Cretaceous period for fairly long period and hence horizontal thick beds of marine sediments were deposited. The submerged land mass began to rise due to diastrophic movement and the landmass appeared above sea-level by the end of Cretaceous period and thus the plains were formed which soon developed various lakes, ponds, swamps and marshes and vegetations. These plains were further uplifted along with the origin of the Rockies during Tertiary period. To some extent the Cretaceous sedimentaries were folded and faulted due to orogenetic force coming from the west. Erosional agencies deposited alluvial materials over lowlying Cretaceous formations. The northern part of Great Plains falling in the states of North Dakota and Montana (USA) was greatly modified by southward advancing ice sheets during Pleistocene glaciation. It is obvious that the Great Plains were definitely originated due to diastrophic movements but they have also been developed and modified by fluvial erosion and deposition and glaciation from time to time.

Plains are also formed due to upliftment or emergence of submerged coastal lands caused by diastrophic movements. The Atlantic Coastal Plains of the USA are considered to have been formed under this process. It is believed that the present Atlantic Coastal Plains were submerged under oceanic water upto Miocene period, with the result there was continued deposition of marine sediments on the submerged landmass. The emergence and upliftment of submerged landmass began by the end of Miocene period and was completed by Pliocene. The Atlantic Coastal Plains extend from New York to the Gulf of Mexico. These plains together with the continental shelves extend for an average width of 480km. It may be pointed out that there is unique relationship between the widths of the coastal plains and the continental shelves. The narrow coastal plains are associated with wider continental shelves whereas wider coastal plains are associated with narrow continental shelves. The coastal plains gently slope towards Atlantic Ocean with average gradient of 10 feet per mile. The distinct marine terraces along the coast denote the phases of upliftment or emergence of submerged landmasses above sea water.

Coastal plains are also formed due to deposition of sediments over submerged continental shelves. Such plains are not placed under the category of diastrophic plains. Some times, land area along the sea coast is subjected to mild subsidence and thus the submerged land area gets sediment deposits to such extent that it rises above sea water. The Coromandal and Northern Circar Coastal Plains were formed due to mild subsidence and consequent sedimentation. It is believed that the north-western part of Peninsular India was raised upward with the result the south-eastern part was submerged due to mild subsidence. The eastern coastal plain was thus formed due to subsidence, sedimentation and then upliftment due to diastrophic movements.

Erosional Plains

(1) Erosional plains formed by river erosion-Peneplains are the most characteristic plains formed by river erosion at the end of 'normal cycle of erosion'. Peneplains are characterized by convexo-concave residual hills, known as monadnocks, which project above the general surface. The peneplains are formed by lateral erosion by the rivers and weathering processes. The weathered materials are deposited over the peneplains. Rivers are well adjusted to the structure.

(2) Glaciated plains-Glaciers transform highland areas through their slow but continued erosive works into lowland with flat surface but with sufficient low reliefs of rounded shape. Glaciated plains are characterized by rounded peaks, broad and flat valleys and small depressions which become lakes

when filled with water. Swamps and marshes are also developed over glaciated plains. Several examples of glaciated plains are found in the northern part of North America and north-western Eurasia because of advancement and retreat of ice sheets during Pleistocene glaciation.

(3) Wind eroded plains-Rocks become loose due to disintegration caused by mechanical (physical) weathering in the hot desert areas. Strong winds pick up these weathered and communited fine particles and deposit them elsewhere. The repetition of this process over longer period of time results in the transformation of stony areas into plains. Wind eroded plains are called **reg, serir** and **hamada** in Sahara. Hamada is, in fact, nude stony flat surface. Hamada is formed due to joint actions of wind erosion and sheet erosion during floods caused by occasional strong rainstorms. The plains developed at the hillslopes due to twin processes of scarp retreat and pedimentation (pediment formation) are called **pediplains.**

(4) Karst plains- The plateaux composed of massive limestones are subjected to chemical weathering and erosion by groundwater and are ultimately transformed into subdued topographic surface of very low relief. Such plains are called karst plains which are formed at the end of karst cycle of erosion. The surface of karst plain is corrugated and undulating.

Depositional Plains

Depositional plains are formed due to gradual deposition of sediments by different geological agents *e.g.* rivers, wind, glaciers etc. Depositional plains range in size and extent which depend upon area and nature of sedimentation. The Ganga-Yamuna plains, Mississippi-Missouri plains, Yangtze plain, Yellow plain (Hwang Ho plain) etc. are very extensive depositional plains which have been formed due to alluviation by big rivers and their tributaries. Depositional plains include alluvial plains (by rivers), aeolian plains or loess plains (by wind), outwash plains (by gleciers) wave-built platforms (by sea waves), lacustrine plains, lava plains etc.

(1) River deposited plains—The alluvial plains deposited by rivers are most extensive depositional plains. Nearly all the alluvial plains of the major rivers of the world are the members of this group. Alluvial plains are formed due to filling of extensive and deep trenches or depressions caused by tectonic movements with sediments of various sorts brought by the rivers. The North Indian Plains or the Ganga-Yamuna Plains were formed due to deposition of eroded materials into extensive foredeep which was formed due to Himalayan orogenetic movements. River-deposited plains include piedmont alluvial plains, flood plains and delta plains.

(i) Piedmont alluvial plains are formed at the foothill zones of the mountains. The gradient of the rivers is remarkably reduced at the foothill zones where the river leaves the mountain and enters the plains topography of level to gentle slope (less than 5 degree of slope), with the result sediments of fairly large size, *e.g.* cobbles, pebbles, boulders together with silt and gravels are deposited at the foot of the mountains because the rivers are unable to carry them further downstrearm due to decrease in transportation capacity because of marked decrease in the channel gradient. Thus, the materials are deposited at the foothill zones in the form of alluvial cones and alluvial fans which grow in size with time. If several rivers descend through a mountain range numerous alluvial fans are formed parallel to the mountain range. These alluvial fans gradually and gradually grow in size and thus coalesce to form one extensive fan which becomes **piedmont alluvial fan plain.** The apex of the fans is characterized by larger particles, the size of which decreases further away from the appicers of the alluvial fans. The mountainward portion of the piedmont alluvial plains is called Bhabar in India. The rivers coming from the Himalayas generally disappear in the **bhabar** zone because water disappears in the large-sized materials like boulders, cobbles and pebbles. These rivers repappear in the **Tarai region** to the south of bhabar region. **Bhabar plain** is also called **dry delta plain.**

(B) Flood plains are formed due to deposition of fine sediments consisting of sands, silts, muds, clays etc. in the flood zones of the rivers. Flood plains are also known as alluvial plains because they are formed of the argillaceous sediments or alluvial soils. Agriculturally, flood plains are very significant because they have become the **granaries of the world** *e.g.* flood plains of Mississippi, Yangtze, Ganga, Yellow, Salveen, Meekong etc. The flood plains are very fertile because their fertility is re-

newed every year due to yearly alluviation during flood period. In India flood plains are divided into (i) **khadar plains** and (ii) **bhangar plains.** Khadar plains are those which are submerged under flood waters almost every year. These are always situated on either side of the river. Bhangar plains are not affected by flood waters.

(C) Delta plains—Rivers while debouching in the seas and oceans form deltas through gradual deposition of sediments brought by them. The Ganga delta is the largest delta of the world as it covers an area of 1,29,000 square kilometres (50,000 square miles). The Ganga delta is shared by both India and Bangladesh but the latter accounts for the largest area. The delta plains are drained by numerous tributaries of the master river. These tributaries are called distributaries. In West Bengal, higher parts of the delta are called **'char'** and lowlying areas are called **'beels'.**

(2) Lacustrine plains are formed when the lakes are filled with sediments. Plains are formed in two ways *e.g.* (i) due to filling of lakes by the sediments brought by the rivers and (ii) due to upliftment of the beds of lakes due to diastrophic movements caused by endogenetic forces.

(3) Lava plains are formed due to deposition of thin sheets of lavas coming out through fissure flows. Several examples of lava plains are found in France, New Zealand, Iceland, USA, Argentina etc. Lava plains are economically very important because black soils are formed due to weathering of lavas. These black soils (regur soils) support good cotton crops.

(4) Wind deposited plains fall in two categories *e.g.* (i) sandy plains or desert plains and (ii) loess plains. Sahara Desert of Africa, Thar Desert of India etc. are characterized by extensive sandy plains or desert plains. The surfaces of desert plains are irregular and undulating because of the presence of numerous sand dunes and ripple marks. Loess plains are formed away from the deserts. Loess plains of Shansi province of China are most extensive loess plains of the world. Loess plains are divided into (i) **desert loess plains,** when the sands are derived from the deserts and (ii) **glacial loess plains,** when the sediments are of glacial origin. Glacial loess plains are found in North America and North West Europe.

(5) Glacial plains are formed due to deposition of glacial and other debris by glacial ice sheets mainly during ice ages. Extensive glacial plains were formed in North America and North-West Europe during Pleistoncene glaciation of the northern hemisphere. Glacial plains are generally uneven, undulating and marshy and are of two types *e.g.* (i) **true glacial plains** formed of pure glacial materials and (ii) **outwash plains,** which are formed due to deposition of materials after the ablation of glaciers and ice sheets. Glacial plains are divided into 3 types on the basis of composition and structure. (i) **Till plains**- Finer to coarser materials brought by glaciers are called **'tills'.** The plains formed of tills are called till plains which are characterized by undulating wave-like surface having small ridges and peaks. Eskers and drumlins are significant landforms of **till plains.** (ii) **Morainic plains** are deposition of finer glacial materials. (iii) **Outwash plains** are composed of the mixture of sands, gravels, silts and clays.

Finch and Trewartha have classified plains into four types *e.g.* (i) **flat plains,** relative reliefs not more than 15m, (ii) **undulating plains,** relative reliefs ranging between 15m and 50m, (iii) **rolling plains,** relative reliefs between 50m 75m and (iv) **dissected plains,** relative reliefs between 75m and 100m.

13.4 GREAT PLAINS OF NORTHERN INDIA

The great plains of northern India, also known as Ganga-Satlej Plains, are, in fact, transitional belt between the Himalayas and Peninsular India. The great plains cover an area 7,74,000 km^2(3,00,000 square miles) having west-east length of 2400 km and north-south width of 144 km. Except Aravallis in the Rajasthan plains no part of these extensive plains is higher than 150m AMSL. The plains have been formed by the deposition of alluvia brought by the rivers. The exact depth of alluvia could not be ascertained as yet though the evidences of borings of tubewells have revealed the thickness of 400 to 500m but the basal rocks have not been encountered even during deepest borings. As per scheme of R.L. Singh (1971) the great plains of India are divided into the following regions of three orders *e.g.* meso-level regions, first-order regions and second-order regions.

Table 13 : Regional Classification of Great Plains of India

Meso-Level Regions	First Order Regions	Second Order Regions
I. Rajashthan Plain	1. Marusthali	(a) Jaisalmer Marusthali
		(b) Barmer Marusthali
		(c) Bikaner-ChuruMarusthali
	2. Rajasthan Bagar	(d) Ghaggar Plain
		(e) Shekhawati Region
		(f) Nagaur Region
		(g) Luni Basin
II. Punjab Plain	3. Punjab Plain North	(a) Hoshiarpur-Chandigarh Plain
		(b) Upper Bari Doab
		(c) Jullundur Plain
		(d) Punjab Malwa
	4. Punjab Plain South	(e) Ambala Plain
		(f) Kurukshetra Plain
		(g) Western Haryana
		(h) Southern Haryana
III. Upper Ganga Plain	5. Upper Ganga Plain North	(a) Rohilhand Plain
		(b) Awadh Plain
	6. Upper Ganga Plain South	(c) Upper Ganga-Yamnaa Doab
		(d) Trans-Yamuna Plain
		(e) Lower Ganga-Yamuna Doab
IV. Middle Ganga Plain	7. Middle Ganga Plain North	(a) Ganga-Ghaghra Divide
		(b) Saryupar Plain
		(c) Mithila Plain
		(d) Kosi Plain
	8. Middle Ganga Plain South	(e) Son-Ganga Divide
		(f) Mgadh-Ganga Tract
V. Lower Ganga Plain	9. North Bengal Plain	(a) Duras (Barind) Tract
		(b) Tista Flood Plain
	10. Delta Proper	(c) Moribund Delta
		(d) Mature Delta
		(e) Active Delta
	11. Rarh Plain	(f) Mayurakshi Plain
		(g) Bankura Upland
		(h) Midnapur Upland
VI. Assam Valley	12. Upper Assam Valley	(a) Upper Assam Valley North
		(b) Upper Assam Valley South
	13. Lower Assam Valley	(c) Lower Assam Valley North
		(d) Lower Assam Valley South

Origin of the Great Plains

Though apparently the origin of the 'great plains' of India appears to be simple and less complicated as people think of their origin and development due to sedimentation of the foredeep created in front of the Himalayas during Alpine (Tertiary) mountain building but the process of the origin of the plains is still debatable as several scientists have postulated contrasting view points.

(1) Concept of E. Suess- According to E. Suess an extensive foredeep was formed between the Himalayas and Peninsular India due to Himalayan orogeny. The foredeep was in the form of an extensive syncline the bed of which being irregular and undulating was a broad **synclinorium** (consisting of numerous small anticlines and synclines). The rivers coming from the Himalayas started to deposit sediments into the fore deep. The sediments were derived through the erosion of the Himalayas by southward flowing rivers. In due course of time the foredeep was filled with the sediments and thus the 'great plains' were formed. According to Suess the bed of the foredeep was irregular, as its slope was gentle towards north but very steep towards south. It appears that Suess assumed greater depth of the foredeep in the south probably to explain the greater thickness of alluvia in the southern part of the 'great plains'. He did not offer any explanation for the irregular bed of the foredeep. He further maintained that the Himalayas and Peninsular India were connected by consolidated parent rocks below the 'great plain'.

(2) Concept of S. Burrard- According to S. Burrard an extensive rift valley was formed at the time of the origin of the Himalayas. The northern and the southern blocks of this rift valley were formed by the southern ranges of the Himalayas and the foreland of Indian peninsula respectively. According to him this rift was formed due to formation of two normal faults. He has presented the examples of Himalayan rift valley and Normada rift valley as evidences in support of his concept. Thus, according to Burrard an extensive rift valley, measuring 2400 km in length and 500 m in depth, formed due to the origin and upliftment of the Himalayas, was filled with the sediments brought by the rivers coming from the Himalayas and thus the great plains were formed due to gradual sedimentation in due course of time. Burrard's views of rift valley formation in front of the Himalayas are not tenable as no evidence could be found which can validate the idea of the formation of rift valley along the northern foreland of Indian Peninsula.

(3) General Concept- The origin of the great plains of India should be considered as the outcome of several interconnected processes and mechanisms *e.g.* sedimentation, subsidence, upliftment, recession of sea etc. Evidences show that in geological past the Arabian Sea extended upto the present position of Garhwal and Kumaun regions as indicated by the presence of massive limestones and dolomites (these carborate rocks are always formed under marine conditions). Similarly, the Bay of Bengal extended upto present Shillong plateau in the form of Eastern Gulf. It is believed that an extensive trench was formed in front of the Himalayas due to Himalayan orogeny. The rivers started to erode the Himalayan rocks and thus the sediments, so obtained, were deposited in the trench. The everincreasing weight of continuous sedimentation of enormous volume of eroded materials (alluvia) caused gradual subsidence of the trench. Thus, the repetition of twin processes of sedimentation and subsidence over long period of time resulted into the deposition of sediments upto great thickness (hundreds of metres). The trench was ultimately filled with the sediments and the 'great plains' were formed. Arabian sea continued to withdraw, with the result new land areas were freed from the sea and were added to plains. There are still evidences to demonstrate the recession of the Arabian Sea and progradation of coastal lands. The saline lakes, *e.g.* Panchbhadra and Sambhar Lakes, in Rajasthan validate the existence of sea in the geological past.

13.5 GANGA PLAIN

Location

The Ganga plain is a major part of the Great Plains of north India which comprise the Rajasthan plain, the Punjab plain and the Ganga plain and have been formed through the process of alluviation by the Satluj, the Ganga and the Brahmaputra drainage systems during late Tertiary and Quaternary periods. In fact, the great plains are in the form of a transitional belt between the Himalayas in the north and the Deccan plateau in the south covering an area of more than 7,77,000 km^2 from Rajasthan to West

Bengal. The great plains run for a distance of 2400 km from west to east and have a width of 480 km in the west and 144 km in the east.

Geological Formation

Lithologically, the Ganga plain is characterized by Quaternary alluvia with varying combinations of clay, silt, sand and gravels. It is, thus, evident that lithologically the Ganga plain is monotonous except some variations in the northern part where the Bhabars of the Himalayas grade into the plains and in the southern part. In fact, 'alluvium is one continuous and conformable series of fluviatile and subaerial deposits, mainly composed of unconsolidated beds of clay, sand, gravel, and their mixture in varying proportion' (R.N. Mathur, 1961). The basement of alluvial deposits and their exact thickness could not be ascertained inspite of several attempts. According to Oldham the thickness of alluvium ranges between 4000-6000m whereas Glennie's estimate of alluvium depth comes to about 2000m. Ganga alluvia are classified into **khadar** and **bhangar.** Khadar represents alluvial deposits in the riverine tracts or the flood plains of the rivers where the constituents of khadar *i.e.* silt, caly and sand, are renewed almost every year due to alluviation followed by floods. On the other hand, bhangar represents older alluvium of relatively higher lands which are not submerged under water during floods. The Bhabar and Tarai regions contain gravel deposits comprising coarse sands, pebbles and cobbles with clay and silt. 'One distinctive character of the **bhangar** is the formation of **kankarpans** (hardpans) in the subsoil zone through capillary action owing to the alternating calcareous sand and clay beds here as also elsewhere in the zone of seasonal rainfall, which adds to soil moisture retention in the subsoil zone' (R.L. Singh, 1971).

D.C. Dassarma and S. Biswas (1971-72) established the following stratigraphic successions of the Quaternary alluvium deposits resting over the Vindhyan basement in the alluvial-filled Belan basin (Allahabad district, U.P.) from below upward-- (i) gravel-mottled clay formation, (ii) red brown gravel-sand formation, (iii) yellow silt formation, (iv) caliche formation, (v) buried soil layer, (vi) aeolian sand formation, and (vii) modern soil horizon.

The sequence of older and newer alluvia is repeated throughout upper, middle and lower Ganga plains but 'there is conspicuous absence of older alluvium in the delta region, which is quite extensive in the northern parts of the region' (R.L. Singh, 1971).

Physiographic Regions and Morphological Characteristics

Geomorphologically, the entire Ganga plain is monotonous as no significant bold reliefs of mountainous and dissected plateau regions are found. Extensive flood plains, natural levees, sharp meanders, ox-box lakes, gullied riparian tracts, braided channels, bluffs etc. are the only morphological features of the Ganga plain. Though the entire Ganga plain exhibits geomorphological homogeneity but it is divided into three regions following R.L. Singh (1971) viz. (1) upper Ganga plain, (2) middle Ganga plain, and (3) lower Ganga plain.

(1) Upper Ganga Plain lies between the Yamuna valley in the west and 100m contour in the east covering an area of 1,49, 029 km^2 of Uttar Pradesh. The drainage of the area comprises two drainage systems of the Ganga and the Yamuna (It may be mentioned that the Yamuna is also a tributary of the Ganga and hence the upper Ganga plain is drained by a single drainage system *i.e.* the Ganga drainage system). Most of the streams adopt parallel courses and join the master streams at acute angles. Extremely low channel gradient because of almost level plain country makes the rivers sluggish and their erosive power is markedly reduced. The drainage pattern is pinnate but the overall pattern is dendritic. Significant rivers are the Yamuna, the Ganga, the Ramganga, the Gomati, the Ghaghra and their numerous tributaries.

Though linear erosion is very limited but the areal erosion in the form of soil erosion is more widespread in the Ganga plain. 'Soil erosion is the most common widespread geo-environmental problem of the major catchment areas of big rivers in Uttar Pradesh. Micropedogenic erosional processes are the primary and basic mechanism responsible for the soil loss. During the rainy season rill and interrill erosion causes soil loss from the **bhangar** (older alluvial areas) and the **khadar** (new alluvial area) and the eroded sediments are brought to the main rivers

via rills, gullies, nalas, and tributary streams which in due course partly deposit them in the flood plains and partly entrain the sediments from Uttar Pradesh (upper Ganga plain) to Bihar (middle Ganga plain). Foothill zones of the Himalayas (in the north) and the foreland of the Indian Peninsula (in the south) and riparian tracts of major alluvial rivers are the main sites of active and rapid rate of fluvial erosion whereas vast alluvial tract is washed out through surface runoff. Rill and gully erosion is responsible for accelerated rate of soil erosion and increase in sediment discharge and sediment load factor in the major rivers' (Savindra Singh and A. Dubey, 1988).

'Total amount of average annual silt carried away from Uttar Pradesh to Bihar by the Ganga system (including the Yamuna system) is about 23,456 ha meters or 328.384 million tonnes and average annual runoff of the Ganga system at U.P.-Bihar border is 21,328 thousand ha meters or 213.38 thousand million m^3. The average annual silt load factor is about 3.476 ha m/100 km^2/year. It means that every year about 3.476 mm of upper soil of Uttar Pradesh (upper Ganga plain) is eroded and carried away to the state of Bihar (middle Ganga plain) by the Ganga river system' (Savindra Singh and A. Dubey, 1988).

The topographic features include alluvial fans and cones in the submontane or piedmont zone to the north of plains, river bluffs, natural levees, flood plains, meanders, meander cut-off, ox-bow lakes, uplands or bhangar lands, sandy stretches or **'bhurs'**, gullied riparian tracts of major and tributary streams, broken river banks, braided channels, micro-seasonal forms on river beds (*e.g.* sand bars, sand islands, shoals etc.), dense network of gullies and badland in the Yamuna-lower Chambal tract and in the intervening zones between the Ganga plain and the foot-hill zone of the foreland of Indian Peninsula etc.

'Thus, the micro-level topographic facets and their regional characteristics render possible delineation of as many as four physiographic units *i.e.* (i) the submantane belt, (ii) the Ganga-Ghaghra doab region, (iii) the Ganga-Yamuna doab, and (iv) Yamunapar in the ravine tract' (R.L. Singh, 1971).

(2) **Middle Ganga Plain** covering an area of 1,44,409 km^2 is spread over Eastern Uttar Pradesh and whole of Bihar plains. 'The western and eastern sides of the region are wide open forming as it does, the central part of the east-west continuum of the vast isotropic Ganga Plain-there is no physical boundary as the plain imperceptibly opens up in the west from out of the Upper Ganga plain and so invisibly dies out into the lower Ganga plain in the east. As such, it is a transitional region, par excellence, interposed in the enormity of the Ganga valley, and all its physical, human and economic fabric seems to have been woven out of the various unique phenomena interplaying in transition' (R.L. Singh, 1971).

The region is drained by the Ganga and its major tributaries like the Ghaghra, the Gandak, the Kosi and their numerous tributaries in the north middle Ganga plain and the Son, the Punpun, the Mohani etc. drain the south middle Ganga plain. Geologically, the region has more or less the same alluvial formations as those of the upper Ganga plain. The rivers have developed highly sinuous and meandering courses and they are notorious for furious floods and frequent changes in their courses. The Kosi river has registered continuous westward shifting in its course but now the channel has been stabilized by artificial levees (embankments). Similarly, there have been significant changes in the channels of the Ganga, the Ghaghra, the Son etc. The Ganga channel becomes braided during post-monsoon period and the river bed morphology comprises numerous riffles, pools, braids, sand bars, sand islands, sand flats and seasonal bed sand dunes. The north middle Ganga plain is characterized by the presence of numerous palaeochannels, ox-bow lakes, tanks and ponds locally known as **tals** (formed due to shifting in river courses) which are of very rare occurrence in the south middle Ganga plain. Other morphological features include natural levees, ravines and badlands in the riparian tracts of the rivers, flood plains, meander loops, eroded but unstable river banks, sandy features like **dhus** etc.

'Obviously, it is difficult to divide the region into physical sub-units on any prominent foundation of reliefs, except through the help of the river systems which generally carve out somewhat inter-distinguishable relief and slope, differential nature of drainage based on rainfall regimes and the proximity of the hills, and the all-resultant sub-soil water table of varying depths in different parts of the

region' (R.L. Singh, 1971). Thus, following R.L. Singh (1971) the Middle Ganga Plain is divided into two broad subregions viz. (A) the Ganga Plain North and (B) the Ganga Plain South. The Ganga Plain North is further subdivided into (i) the Ganga-Ghaghra Doab, (ii) the Saryupar Plain (the Ghaghra-Gandak interfluve), (iii) the Mithila Plain (the Gnadak-Kosi interfluve), and (iv) the Kosi Plain (the Kosi-Mahananda interfluve); while the Ganga Plain South is subdivided into (i) the Ganga-Son divide, (ii) the Magadh Plain, and (iii) the Anga Plain.

(3) **Lower Ganga Plain**-'The Lower Ganga Plain, in real sense of the term, includes the Kishanganj tahsil of Purnea district (Bihar), whole of the West Bengal State (excluding the Purulia district and the mountainous parts of Darjeeling district) and most of East Pakistan (now Bangladesh) as well. Though the whole of this plain is now perceived as deltaic, the real delta constitutes about two-third of this plain lying to the south of the Rajmahal-Garo alignment....The region embraces an area of about 80,968 km^2, extending from the foot of the Darjeeling Himalaya in the north to the Bay of Bengal in the south (maximum stretch about 580 km) and from the edge of the Chotanagpur Highlands, in the west to the border of East Pakistan (Bangladesh) and Assam in the east (maximum stretch about 200 km)' (R.L. Singh, 1971).

The region is drained by the streams of two major drainage systems of the Ganga and the Brahmaputra and a few minor systems viz. the Kasai system, the Subarnarekha system, the Mahananda system, the Karatoya system, the Tista system, the Sankosh system, etc. The Rarh Plain is drained by the Mayurakshi, the Damodar, the Dwarkeshwar, the Kasai, the Subarnarekha etc. Geomorphologically, the region, like the upper and middle Ganga Plains, is monotonous as the entire region is almost featureless plain except a few local reliefs of 10 to 30 m rising above the general surface. Malda-West Dinajpur tract, the tracts bordering the Chotanagpur plateau, coastal areas of Midnapur, and duars (equivalent to tarai of Uttar Pradesh) of Jalpaiguri and Darjeeling are the areas where some reliefs are noted. For example, lateritic alluvium in the Malda-Dinajpur tract has been dissected to produce prominent reliefs; the bordering areas of the Chotanagpur have been gullied and ravinated; coastal areas of Midnapur are characterized by a series of sand dunes and the lateritic alluvium has been intensively gullied to form badland; the **duars** of Jalpaiguri and Darjeeling are characterized by swamps, marshes, **bills**, levees etc. The alluvial morphological characteristics of the region have been conditioned by the tectonics, changes in river courses and sea levels. R.L. Singh (1971) divided the Lower Ganga Plain, on the basis of micro-order diversities within the apparently homogenous surface configuration, into the following physiographic subdivisions : (i) the northern plain characterized by **duars** (tarai) and Barind tract; (ii) the Delta proper comprising (a) the land of dead and decaying rivers (Moribund delta) in the north (Murshidabad and Nadia), (b) the active Delta of the Sundrabans and (c) the mature delta (parts of Birbhum, Burdwan, Midnapur, and entire districts of Hooghly and Howrah); (iii) the western margin of the delta is called the **Rarh** plain where the lateritic alluvial landscape along with the coastal scenery at Digha beach has developed (R.L. Singh, 1971).

14

LAKES

14.1 MEANING

Lakes are those static bodies of water on the land surface which are surrounded by lands on all sides and are always located on the land surface. There is wide range of variation in the size of lakes. Some lakes are as small as ponds having a meagre areal extent of a few square metres while some lakes are as large as the Great Lakes (comprised of Superior, Michigan, Huron, Onatario and Erie Lakes) of North America. Lakes are also called as **inland standing water** but this is not always true as some lakes are also located along the sea coasts e.g. Chilka lake in Orissa. Lakes are not permanent features on the earth's surface. Lakes are formed, developed and are ultimately obliterated due to siltation and upliftment of lake beds due to diastrophic movements, for example, several lakes have disappeared in the Kumaun region of Uttaranchal e.g. Sukha Tal ('tal' means lake or pond, Sukha Tal means dry lake) and Saria Tal (means rotten lake) around Nainital town. Lakes, thus, may be defined as non-permanent features of static waters on the land surface.

14.2 SPATIAL DISTRIBUTION OF LAKES

If we look at the distributional pattern of lakes over the globe it appears that they do not have any specific spatial pattern of their distribution. They are found over the mountains, plateaux, plains alike. The highest lake of the world, Tso Sekuru, is located at the height of 18, 284 feet AMSL (Tibetan plateau). On the other hand, Dead Sea, the lowest lake of the world, is located 1300 feet below sea level. Normally, lakes are found more in the following regions (i) humid regions, (ii) glaciated regions, (iii) flood plain areas, (iv) sea coastal areas, (v) rift valley zones etc. Though lakes are found in all continents from equator to the poles including Antarctica continent and from humid through arid and semiarid regions to polar regions but lakes are more abundantly found in (i) the high latitude areas of North America, (ii) South America, (iii) Western Europe, and (iv) rift valley zones of east Africa. The important lakes of the world include Caspian Sea, Chad Lake, Great Lakes of the USA and Canada (Superior, Michigan, Huron, Ontario and Erie lakes), Victoria lake, Aral Sea, Nyasa lake, Lake Baykal, Lake Tanganyika, Great Bear lake, Titicaca lake, Dead Sea, Crater Lake (USA) etc. The Himalayas are studded with numerous lakes. In fact, Kumaun region of Uttaranchal may be called as Lake Region because of the presence of numerous lakes (eg. Naini tal Lake, Bhimtal, Khurpatal, Sattal, Naukuchiatal, Sukhatal, Sariatal etc.). The highest glacial lake of India is Devtal which is located at the height of 17,745 feet AMSL in Garhwal Himalaya, Gaurikund is the second highest lake (height 18,200 feet AMSL) of the world.

14.3 CHARACTERISTIC FEATURES OF LAKES

It may be pointed out that each lake has its own characteristics and hence it becomes difficult to

enumerate such characteristics which may be common to all lakes. Inspite of this limitation some common characteristic features may be identified. (i) Lakes are variables and change with time. Each lake has its own life history or life-cycle which includes origin, development and obliteration (extinction). (2) Some lakes are found at higher heights (thousands of metres from sea level) of the mountains and plateaux for example, Tso Sekuru Lake of Tibetan plateau (at 18,284 feet AMSL), Devtal of Garhwal Himalaya (at 17,745 feet AMSL), Rakastal, Mansarovar Lake (Tibet) etc. whereas some lakes are found below sea level e.g. Dead Sea (1300 feet below sea level). (3) Some lakes are characterized by greater depth e.g. Baykal Lake of Siberia (more than 1.6 km deep) whereas many of the lakes are very shallow which become almost dry during dry summer season and thus such lakes are also called **seasonal lakes.** (4) Lakes range in areal extent from a tiny **tarn** glacial lake having an areal extent of a few square metres to very extensive lakes like Caspian Sea (area, 4,30,000 km^2), Great Lakes of North America etc.

Two favourable conditions are required for the origin and development of lakes e.g. (i) suitable places where water may collect and may remain stationary, basins or troughs or depressions are the most ideal places for the development of lakes. (ii) There should be proper and regular supply of water. If the water table of groundwater is higher than the beds of the basins, there is sufficient supply of water from underground sources. Each lake is characterized by inlet and outlet. The inlet allows influx of water in the lake through those rivers which debouch into the lake, while the outlet allows exit of lake water through streams and 'nalas' which emerge or take their sources from the lake. The volume of water depends on the ratio between the input and output of water. The level of a lake is determined by the level of outlet of that lake as there may not be any water above the level of outlet because in such case water would flow out of the lake through streams and 'nalas' which emerge from the lake. The main sources of lake water are (i) seepage water from groundwater reservoirs, (ii) direct rainwater, (iii) water brought by the rivers which debouch in the lakes, (iv) meltwater (through melting of glaciers, ice, ice caps etc.) etc. Evaporation largely affects the volume of water in the lakes. The volume of lake water is remarkably reduced in the arid and semi-arid regions mainly during summer season because of loss of water due to excessive evaporation.

The nature of lake water also gives definite status to a particular lake. Salinity is a significant characteristic feature of lakes. Salts are taken out from the rocks and are brought to the lakes through surface runoff, rivers, seepage of groundwater etc. Salts are, thus, gradually and gradually accumulated in the lakes which in due course of time become saline. Some of the lakes, having greater proportion of salinity, have been named as Salt Lakes. The salinity varies from one lake to another. In fact, salinity of lakes depends on the climate of the concerned place, the nature of inlets and outlets and fluctuating trends of water during various seasons of the year. Marked reduction in the volume of lake water in the hot desert areas due to excessive evaporation causes high salinity. Lakes are divided into two broad categories on the basis of presence or absence of salt in the lake water e.g. (i) saline lakes and (ii) freshwater lakes.

14.4 CLASSIFICATION OF LAKES

1. On the basis of salinity

(1) Freshwater lakes

(2) Saline lakes

- (i) Alkali lakes (having sodium and potassium carbonates)
- (ii) Bitter lakes (having sodium sulphate)
- (iii) Borax lakes
- (iv) Mixed lakes (having several types of salts)

2. On the basis of mode of origin

(3) Glacial lakes

- (i) Lakes formed due to glacial deposits
  - (a) Ground moraine lakes
  - (b) Terminal moraine lakes
  - (c) Lateral maraine lakes
- (ii) Lakes formed due to glacial erosion
  - (a) Cirque lakes or tarn lakes
  - (b) Rock-basin lakes
  - (c) Cock lakes
  - (d) Clint lakes

(4) Fluvially originated lakes
- (i) Plunge basin lakes
- (ii) Oxbow lakes
- (iii) Raft-dammed lakes
- (iv) Delta lakes
- (v) Alluvial fans lakes

(5) Aeolian lakes
- (i) Sand dune lakes
- (ii) Blowout lakes

(6) Volcanic lakes
- (i) Lava dam lakes
- (ii) Crater lakes

(7) Diastrophic lakes
- (i) Relic lakes
- (ii) Synclinal lakes
- (iii) Fault lakes
  - (a) Normal fault lakes
  - (b) Rift Valley lakes

(8) Lakes formed due to masstranslocation
- (i) Landslide basin lakes
- (ii) Mudflow basin lakes
- (iii) Slump basin lakes
- (iv) Solution basin lakes

(9) Lakes formed by groundwater
- (i) Cave lakes
- (ii) Karst lakes

(10) Periglacial lakes
- (i) Thermokarst lakes
- (ii) Cauldron subsidence lakes.

(11) Anthropogenic lakes
- (i) Reservoir lakes

14.5 GLACIAL LAKES

Several lakes are formed due to glacial erosion and deposition. Morainic deposits some times dam the flow of rivers and glaciers and thus form **morainic lakes.** It may be pointed out that there are largest number of glacial lakes in the world. The regions which were affected by Pleistocene glaciation are studded w numerous lakes of varying dimensions and are called **gardens of lakes.** Such lake gardens are abudnantly found in Canada, Norway, Sweden and Finland. Though most of the glacially originated lakes are small in size but the Great Lakes of North America, the result of Pleistocene glaciation, denote the fact that glacial action can form even one of the most extensive lakes of the globe.

Ground moraine lakes are formed due to collection of water in the irregular smaller depressions formed due to deposition of moraines in the bed of the glacial valleys when either the ice sheets retreat or glaciers are ablated (melted). The depressions receive either the meltwater or seepage water coming as springs. These lakes are called ground moraine lakes because of the fact that these are formed in the depressions which are created due to irregular deposits of moraine in the beds of the glacial valleys. Generally, ground moraine lakes are **enclosed lakes** as they do not have any outlet. Such lakes are of small size and shallow depth. They range in area from a few acres to several square kilometres (20 to 30 square kilometres). Thousands of such lakes are found in the areas glaciated during Pleistocene ice age.

Lateral moraine lakes are formed in two ways e.g. (i) Due to damming of the mouths of tributary glacial valleys by the accumulation of lateral moraines and filling of these tributary valleys by water. Such lakes are purely temporary because these are drained out when the morainic dams are breached due to accumulation of huge volume of water, (ii) Due to accumulation of water between the walls of glacial valleys and the lateral moraines parallel to the valleys.

Terminal moraine lakes are formed when the glaciers are ablated. In fact, several successive morainic ridges parallel to each other are formed due to recession of ice sheets during great ice ages. The water, when located between two morainic ridges, forms such lakes. Grand Lake of the state of Colorado (USA) is an example of such lakes. Several terminal moraine lakes are found in Wisconcin and Minnesota states of the USA where these lakes were formed during the recession of ice sheets at the time of Pleistocene glaciation of North America.

Rock basin lakes (fig 14.1) are formed due to filling of depressions and hollows, formed by glacial erosion in the beds of glacial valleys, with water. The water collecting in cirques forms **cirque or tarn lakes.** Naina or Nainital lake of India (in Kumaun region of Uttaranchal) is considered as an example of corrie or cirque lake but many geologists refute this hypothesis and consider Naina lake as the result of tectonic movements.

14.6 FLUVIAL LAKES

Like glaciers, rivers also form several types of lakes through their erosional and depositional works. It may be pointed out that rivers are generally destroyers of lakes rather than creaters of lakes. Lakes are often obliterated due to filling of sediments and headward erosion by rivers. Fluvially originated lakes are generally temporary and are soon obliterated. Fluvially originated lakes include plunge pool lakes, structural lakes, oxbow lakes, alluvial fan lakes, delta lakes, flood plain lakes, and raft-dammed lakes.

Plunge pool lakes are formed in the plunge pools which are formed at the bases of major waterfalls. Such lakes are formed in the beds of river valleys due to recession of waterfalls. **Structural lakes** are those which are formed due to damming of river water because of major obstructions caused by the exposure of resistant rock beds across the river channels. These lakes are drained out as the resistant rock beds are eroded away. **Oxbow lakes** are more frequently found with the alluvial rivers. These lakes are formed when a meandering river straightens its course and the acute meander loops are left out. These left-out or separated meander loops become oxbow lakes (fig. 14.1). Such lakes are abundantly found in the Ganga plains wherein nearly all the major rivers like the Ganga, the Rapti, the Gomti, the Gandak, the Ghaghra, the Kosi, the Hoogly etc. are associated with numerous oxbow lakes. The situation of oxbow lakes quite away from the rivers gives clues for the palaeochannels of the river concerned. Wular lake of Kashmir is considered to be an ox-bow lake.

Alluvial fan lakes are formed due to obstruction of free flow of the rivers offered by the alluvial fans developed at the foothill zones of the mountains. Such smaller lakes have been formed in fan areas all along the foothill zones of the Sivalik Ranges of the Himalaya. **Delta lakes** are formed due to collection of water in the lowlying areas between two distributaries of the main river draining the delta. Such delta lakes are more frequently formed in bird-foot deltas because the seaward projecting narrow branches of delta are bent by sea and tidal waves and thus water is locked between the branches of delta and lakes of smaller sizes are formed. Colair lakes of Godawari delta have been formed between two deltas. Such lakes in the Ganga delta are called **beels.** Ponchastrian lakes of Mississippi in Luisiana state are fine examples of delta lakes. Mayeh Lake of Nile delta and Marigot Lake of Niger delta are other significant examples of delta lakes.

Flood plain lakes are small and temporary lakes which are formed due to collection of water in the depressions formed during the uneven deposition of alluvia at the time of floods. **Raft lakes** are formed when several larger wooden logs and rafts obstruct the free flow of water as they form temporary dams across the river channels. Such lakes become hazardous when the dams formed by wooden rafts are breached and lake water gushes downstream with very high velocity causing severe flash floods

14.7 VOLCANIC LAKES

Volcanic lakes include lava-dammed lakes and crater lakes. The outflow of enormous volume of lavas during fissure flow of volcanic eruption blocks the free flow of the rivers as lavas after being solidified due to rapid cooling form dams across the river valleys and thus the waters are obstructed and blocked upstream from the lava dams to form lava dammed lakes. Lake Tine of Abyssina and Lake Nicaragua of middle America are examples of lava-dammed lakes. **Crater lakes** are very common types of lakes which are associated with most of the volcanic craters. Crater lakes are formed when the craters and calderas are filled with water. Crater Lake of the state of Oregon (USA) is the best example of this category. This lake has a diameter of 10.2 km with a depth of 3,975 feet.

14.8 DIASTROPHIC LAKES

Diastrophic movements caused by endogenetic forces are perhaps the most potent factors for the origin of many of the lakes all over the world. The **synclinal lakes** are formed when some of the depressions are filled with water. Edward and George lakes of South Africa are the examples of synclinal lakes. **Anticlinal lakes** are formed due to damming of river flow when the anticlines are formed across

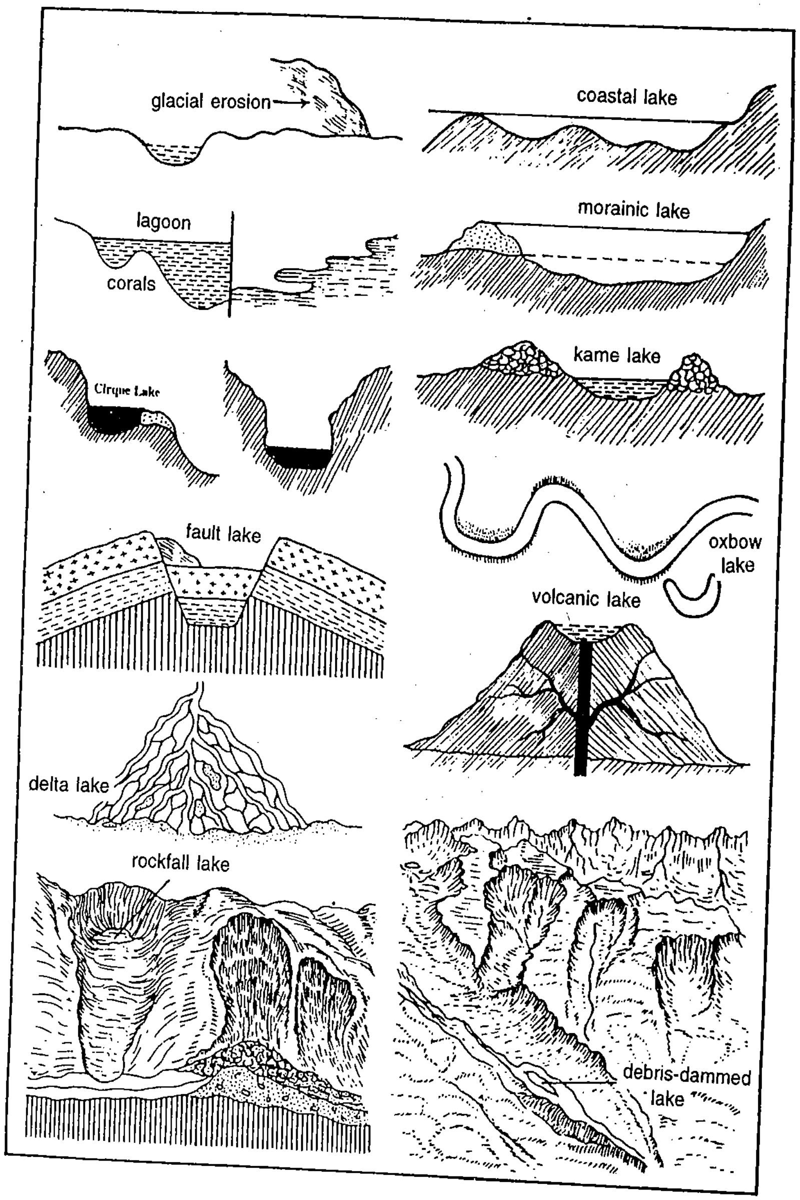


Fig. 14.1 : Different types of lakes.

the rivers. Faulting and fracturing very often form lakes of various dimensions. San Andreas Lake and Crystal Spring Lake are the examples of **fault lakes.** Many of the lakes in the East African rift valley zone are the result of faulting events e.g. Lake Tanganyika, Lake Victoria, Lake Nyasa, Lake Albert, Lake Rudolf etc. Dead Sea, Jordan Valley etc. are also the examples of **rift valley lakes.** Several lakes have been formed in the 8-km wide Rocky Mountain Trench.

14.9 LAKES FORMED DUE TO MASS-TRASNSLOCATION OF ROCK WASTES

Mass-translocation of rockwastes includes landslides, rockslides, rockfalls, debris slides, debris fall, mudflow etc. Temporary lakes are formed due to damming of the rivers caused by accumulation of huge volume of debris coming down from the nearby hills due to major landslides. These lakes are drained out when the dams created by landslide are breached due to accumlation of excessive volume of water upstream from the dams. Such temporary and ephemeral lakes are very often formed in the Himalayas where landslides and mudflow are of very common occurrence. Lake San Cristobal of south western Colorado state was formed by Slumgullion Mudflow. The catastrophic landslides of October 1968 in Darjeeling formed two lakes through the damming of Tantakhola, a tributary of Jaldhaka river.

14.9 FRESHWATER LAKES

Freshwater lakes are characterized by very low amount of salt in the water and high rate of influx (inflow) and outflow of water. Freshwater lakes receive water from direct rainfall, surface runoff and water springs in humid regions and from melt-water in glaciated regions. The inflow of water in the lakes is of high order, so several streams and nalas emerge from these lakes, and thus salt contents are also drained out with outflowing streams. So there is no regular accumulation of salt in freshwater lakes. Most of the lakes of Kumaun region of Uttaranchal are freshwater lakes. Dal and Wular lakes of Kashmir are freshwater lakes.

14.10 SALINE LAKES

The lakes having relatively larger proportion of salt content say salinity are called **salt lakes** or **saline lakes.** Generally, salt lakes are found in semi-arid and arid regions of warm climate where the rate of evaporation is very high. On the basis of variations of types and contents of salt, saline lakes are divided into four types e.g. (i) **alkali lakes** having the dominance of salts of sodium and potassium carborates (ii) **bitter lakes** contain salts of sodium sulphate, (iii) **borax lakes** having high proportion of borax and (iv) **mixed lakes** hving mixture of different salts. Sambhar and Panchbhadra lakes of Rajasthan, Salt lakes of Lingtzi Tang of Kashmir etc. are the examples of salt lakes of India. Chilka Lake of Orissa is also a saline lake. Saline lakes are abundantly found in the western arid and semi-arid regions of the USA, Chile, Peru, Sahara and arid and semi-arid regions of Asia. Most of the present day salt lakes are, infact, the remnants of older freshwater lakes, for example Great Salt Lake of the state of Utah (USA) is the remnant of Bonneville lake which was a freshwater lake. Similarly, saline lakes of western Nevada (USA) such as Curson, Pyramid, Winnimuca, Walkar and Honey lakes are the remnants of earlier freshwater lakes. Lakes Lahontan, Caspian Sea, Dead Sea, Aral Sea etc. are the examples of salt lakes.

14.11 OBLITERATION OF LAKES

Each lake has its own life history or life cycle including its origin, development and obliteration (extinction). These successive and sequential changes pass through three stages of youth, mature and old. It may be pointed out that it is not necessary that all the lakes should pass through all the three stages of their evolution. It is believed that except flood plain lakes and delta lakes almost all the lakes of the world are in youthful stage of their evolution because most of them were formed during and after Pleistocene glaciation. Lakes are generally obliterated because of deposition of sediments by the rivers. It is believed that the Great Lakes (Superior, Michigan, Huron, Erie and Ontario) of the USA and Canada would be obliterated due to sedimentation in the coming 45,000 years. Lakes are obliterated because of (i) lowering of outlet, (ii) sedimentation and siltation and (iii) diastrophic movements.

15

WEATHERING AND MASS MOVEMENT

15.1 MEANING AND CONCEPT

The process of disintegration and decomposition of rocks in situ is generally called weathering. It means weathering is a static process. According to C.D. Ollier (1969) 'weathering is the breakdown and alteration of minerals near the earth's surface to products that are more in equilibrium with newly imposed physico-chemical conditions.' According to P.Reiche (1950) 'weathering is the response of minerals which were in equilibrium within the lithosphere to conditions at or near its contact with the atmosphere, the hydrosphere, and perhaps still more importantly, the biosphere.' It may be pointed out that rocks are never in parmanent equilibrium rather they are in equilibrium only momentarily and thus W.D. Keller (1957) has pleaded for the deletion of 'which were in equilibrium' from Reiche's above definition of weathering. B.B. Polynov (1937) has very precisely defined weathering as 'the change of rocks from the massive to the clastic state.'

Arthur Holmes has presented more elaborate definition of weathering which also includes the processes of weathering. According to him 'weathering is the total effect of all the various subaerial processes that cooperate in bringing about the decay and disintegration of rocks, provided that no large-scale transport of the loosened products is involved. The work of rainwash and wind, which is essentially erosional, is thus excluded' (A. Holmes, 1952).

It appears from the above definitions that weathering is essentially the breakdown of rocks due to chemical and mechanical processes at their places. The definition of weathering by B.W. Sparks highlights the above facts. According to him, 'weathering may be defined as the mechanical fracturing or chemical decomposition of rocks by natural agents at the surface of the earth.'

It is obvious that weathering involves two types of changes in the rocks *e.g.* (i) **physical** or **mechanical changes,** wherein rocks are **disintegrated** through temperature changes (heat factor), frost action (frost factor), biological activities (biotic factor), and wind actions; (ii) **chemical changes** wherein rocks are **decomposed** through static water, oxygen, carbon dioxide and biological activities. Secondly, the breakdown of rocks occurs at the place of rocks (in situ). Thirdly, there is no large-scale transport of weathered materials except massmovement or masstranslocation of weathered materials (rockwastes) down the slope under the force of gravity. Weathering, thus, may be defined so as to include all aspects of the mechanism of breakdown of rocks as follows-

'Weathering refers to the breakdown or disintegration and decomposition of rocks in situ through mechanical and chemical changes in the rocks and their minerals effected by water, temperature, wind, different atmospheric gases and organisms provided

that there is no large-scale transport of weathered products by denudational processes except massmovement of rockwastes (weathered products) down the slope under the impact of gravity'-Savindra Singh.

15.2 CONTROLLING FACTORS OF WEATHERING

The nature and magnitude of weathering differs from place to place and region to region. Weathering of rocks is affected and controlled by the agents of weathering, lithological and structural characteristics of rocks, height and slope factors. Besides, climatic conditions, topography and reliefs, flora and microfauna also affect different processes of weathering to greater extent. For example, disintegration of rocks is more effective in hot and dry region and in the regions where frost action is more dominant while chemical decomposition is more prevalent in hot and humid and temperate humid regions.

1. Composition and Structure of Rocks

Since weathering involves disintegration and decomposition of rocks and hence mineral composition, joint patterns, layering system, faulting, folding etc. largely affect the nature and intensity of weathering. For example, carbonate rocks (*e.g.* calcium carbonate, magnesium carbonate etc.) having more soluble minerals are easily affected by chemical weathering. Well jointed rocks are more subjected to mechanical disintegration. Rocks having vertical strata are easily loosened and broken down due to temperature changes, frost action, water and wind actions. On the other hand, the rocks having horizontal beds are more compact and are less affected by the mechanisms of disintegration and decomposition.

2. Nature of Ground Slope

Ground slope controls mechanical disintegration of rocks and massmovement of weathered products down the slope. The rocks in the regions of steep hillslope are easily disintegrated due to mechanical weathering and the weathering materials are instantaneously moved down the hillslope in the form of rockfall, debris fall and slide, talus creep etc. Instantaneous removal of weathering products allows continuous exposure of rocks to atmospheric conditions for further weathering. The regions of gentle and moderate ground slope are less affected by mechanical disintegration.

3. Climatic Variations

Climate is considered to be very important factor of all types of weathering. Climatic geomorphologists are of the view that each climatic type produces definite conditions for a particular type of weathering. For example, chemical weathering is more dominant in humid tropical areas because of more available water and high temperature. Because of abundance of moisture and high temperature **leaching process** and solution of rocks are more effective in the humid tropics. Mechanical weathering is less effective. On the other hand, mechanical disintegration of rocks is more dominant in the tropical and semi-arid regions. Rocks are weakened due to alternate expansion on heating during daytime and contraction on relative cooling during nights because of diurnal change of temperature. It may be pointed out that limestones are very weak rocks in humid climatic regions but they are relatively more resistant to weathering and erosion in hot desert climate. The rocks in dry temperate climates are more susceptible to mechanical weathering than chemical weathering because alternate expansion and contraction of cracks, fractures and joints of rocks due to alternate freeze and thaw of water accumulated in these cracks and fractures weaken the rocks. Rocks are least affected by mechanical disintegration in cold climate but chemical decomposition of rocks may be effective provided that the ground surface is not covered by ice cover for longer duration in a year. Both, mechanical and chemical weathering cease when the ground surface is covered by permanent ice sheets. Not only this, seasonal variations in climate of a region generate different conditions for weathering. For example, in monsoon climate rocks are subjected to mechanical disintegration during hot and dry summer months whereas chemical and biochemical weathering is more dominant during wet monsoon months.

4. Floral Effects

The nature of weathering is largely determined by the presence or absence of vegetations in a particular region. It may be pointed out that vegetation is partly a factor of weathering and partly a

protector of rocks. In fact, vegetations bind the rocks through their network of roots and thus protect them from weathering and erosion but the same time the penetration of roots weakens the rocks by breaking them into several blocks. Dense vegetations protect the ground surface from the direct impact of sun rays. The micro-organisms associated with the roots of plants and trees encourage decomposition and disintegration of rocks through physico-biochemical weathering.

15.3 TYPES OF WEATHERING PROCESSES

Generally, weathering processes are conveniently divided into physical, chemical and biochemical processes but these are so intimately interrelated that it is practically difficult to isolate one process from the other. In fact, 'no chemical weathering takes place without the production of physical stresses, disintegration of rocks by thermal expansion probably does not occur in the absence of the chemical process associated with the presence of water; in the country of even sparsest vegetation chemical weathering is replaced in part by biochemical (process)' (R.J. Chorley, et al. 1985). Inspite of this limitation one has to divide weathering into physical weathering, chemical weathering and biochemical weathering on the basis of dominant agent of weathering and weathering process. The **weathering agents** are divided into 3 types as follows.

1. Physical or mechanical weathering agents
   - (i) Moisture and water
   - (ii) Frost
   - (iii) Insolation (temperature)
   - (iv) Wind
2. Chemical weathering agents
   - (i) Oxygen
   - (ii) Carbon dioxide
   - (iii) Hydrogen
3. Biological weathering agents
   - (i) Vegetation
   - (ii) Animals, mainly micro-organisms

Thus, weathering processes or simply weatherings are divided, on the basis of weathering agents, into 3 major types.

1. Physical or Mechanical Weathering
   - (i) Block disintegration due to temperature
   - (ii) Granular disintegration due to temperature
   - (iii) Block disintegration due to frost
   - (iv) Exfoliation or onion weathering due to temperature and wind
2. Chemical Weathering
   - (i) Oxidation
   - (ii) Carbonation
   - (iii) Solution
   - (iv) Hydration
   - (v) Chelation
   - (vi) Hydrolysis
3. Biotic weathering and biochemical weathering
   - (i) Plant weathering
   - (ii) Animal weathering
   - (iii) Biochemical weathering
   - (iv) Anthropogenic weathering

15.4 PHYSICAL WEATHERING

The physical or mechanical weathering leads to fragmentation and breakdown of rock masses into big blocks and boulders, cobbles and pebbles, sands and silts and feldspar and mica minerals are chemically decomposed and clay is formed. Physical weathering may be defined as the disintegration of rocks due to temperature variations, frost action, wind action and unloading of confining superincumbent pressure. Though temperature variation is a key factor in physical weathering but pressure release, freeze and thaw of water and gravity also play major roles.

1. Block disintegration due to temperature change- Temperature changes have been reported to have great impact upon many rocks but there are also some rocks which are least affected by temperature changes such as clastic sedimentary rocks (*e.g* shales and sandstones) because the particles are separated by thin cementing laminae of silica. On the other hand, crystalline rocks, like granites, are more affected by temperature changes as particles are closely associated with each other and these particles expand and contract with increase and decrease of temperature respectively. It has been experimentally demonstrated that if the temperature of granite

rocks is increased by 65.5^0C, the rock expands by 2.54cm per 30.48m distance. Contrary to this Black Welder in 1925 found no impact of temperature change on granite when he dropped granitic blocks into hot oil at the temperature of 200^0C It may be pointed out that contrasting results have been reported about the impact of temperature changes on the rocks.

The products of weathering in hot desert areas are different from those of more humid areas as they are coarser and deficient in clay and organic matter. Generally, it is accepted that the bare rock surfaces are heated during day time due to which their outer layers expand. During nights the rocks are cooled due to relative decrease in temperature which leads to contraction in the outer layer of the rocks. Thus, the repetition of expansion and contraction of outer rock layers due to diurnal range of temperature in the hot desert areas causes tension and stresses which introduce parallel joints in the rocks. The rocks, then, are disintegrated along these joints and broken big blocks of rocks are dislodged from the main rock mass and fall down the slope under the impact of gravity. This process of physical weathering is called **block disintegration.** It may be pointed out that block disintegration should not be considered as the result of only temperature changes, rather unloading of superincumbent load or release of confining pressure also helps in this process.

2. Granular disintegration due to temperature changes- The coarse-grained rocks are more affected by shattering process in those hot deserts which are characterized by high range of daily temperature. If the rocks are coarse-grained and are of different colours, they absorb insolation differently. Thus, the different parts of the same rock mass receive and absorb different amount of insolation, consequently the different parts of the rock are affected by differential expansion and contraction which cause stresses within the rocks due to which they are disintegrated into smaller particles. Such type of shattering of rocks is called granular disintegration which is more active in hot desert areas.

3. Shattering due to rain shower and heat-The outer shells of the rocks are shattered due to sudden light showers in hot climatic regions mainly in hot desert areas. Griggs has remarked after experiments that small cracks are developed at the outer surface of the highly heated rocks when light drizzles suddenly strike them. It may be mentioned that Griggs' experiments involving purely thermal changes equivalent to diurnal changes of 110^0C over 244 years could not produce any change in the rock strength and thus could not cause disintegration of rocks. In another experiment Griggs used water sprinkles to cool highly heated rocks instead of reducing the temperature. The result was imminent as the rocks developed cracks and surface spalling. This process works when there is sudden light showers in the hot desert areas. The highly heated rocks when struck by sudden drizzles develop numerous cracks. The repetition of this mechanism causes **spalling** and granular disintegration of rocks.

4. Block disintegration due to frost-Disintegration of rocks into large size blocks due to freeze and thaw of water is of common occurrence in the temperate and cold climatic regions. In fact, this process is more active in those areas which are very often characterized by alternate processes of freezing and thawing of water mainly during night and day respectively. Frost action weakens the rocks in two ways *e.g.* (i) due to freeze and thaw of water between the particles of the rocks and (ii) due to freeze and thaw of water in the crevices and pore spaces The more compact and highly consolidated rocks, like granites, are least affected by freeze-thaw actions while less compact and loosely consolidated rocks are more affected by frost actions, for example, sedimentary rocks being more porous are highly susceptible to the mechanism of weathering. Water present between the particles of porous rocks freezes during night due to fall of temperature below freezing point and thus expands due to increase in its volume by about 10 per cent and thaws during day time due to relative increase in the temperature and hence it contracts in volume by 10 per cent. This diurnal freeze and thaw cycle causes alternate expansion and contraction which introduce tension and stresses due to which rocks are disintegrated into smaller particles. This process, known as granular disintegration due to frost action, is an exceedingly slow process and rocks are least affected by this process.

Alternatively, alternate expansion and contraction of crevices, pores and cracks in the rocks due to diurnal freeze and thaw of water causes block

disintegration of rocks wherein rocks are broken down into larger blocks which are dislodged from the main rock mass. When such process operates over the hillslopes of well jointed massive rocks, the dislodged rock blocks tumble down the slope in the form of rockslides and rock falls and collect at the base of hillslopes.

The disintegration of rocks due to diurnal freeze-thaw cycles in the periglacial areas is called **frost weathering** or **congelifraction** which forms very interesting landforms like frost-riven polygons.

5. Exfoliation due to temperature and wind-Exfoliation weathering, also known as **onion weathering**, refers to peeling off concentric shells of rocks due to combined actions of heat and wind in hot arid and semi-arid regions and monsoon lands. Exfoliation is more common over crystalline rocks. The outer shells of rocks become loose due to alternate expansion and contraction due to high temperature during day time and comparatively low temperature during night respectively and these loosened shells are removed (peeled off) by strong winds. Differential heating of outer and lower shells of a rock mass causes **flaking.** The solar radiation penetrates upto a few centimetres only in the rocks having low thermal conductivity. Thus, the outer shells of such rocks expand more than the shells lying just below. This differential expansion of rock shells causes flaking wherein the thin rock sheets are detached from the rock mass. These detached rock sheets are later on removed by strong winds. Thus, sheets after sheets of rocks are peeled off and the rocks continue to be bare. Many of the granitic batholiths, which are exposed above the ground surface, are being continuously affected by exfoliation weathering. Kanke dome near Ranchi city exhibits a fine example of such weathering process.

6. Disintegration and exfoliation due to unloading-The rocks, which are buried under thick covers of overlying rocks, are disintegrated when they are exposed to the surface due to removal of superincumbent load and consequent release of confining pressure. The removal of superincumbent load, very precisely known as **unloading,** may be effected through gradual denudation of overlying rocks. In fact, the buried rocks, when relieved of the confining pressure due to unloading, develop cracks and joints and ultimately breakup along these cracks and joints. Granites, massive sandstones, massive arkose, conglomerates and limestones are more affected by **sheeting, spalling** and block disintegration due to reduction in the confining pressure because of removal of superincumbent load by uplift and erosion.

Sheeting refers to the development of cracks and fractures parallel to the ground surface caused by removal of superincumbent load resulting into reduction of confining pressure. Such parallel cracks and fractures are developed in massive rocks such as granites and other igneous intrusives, quartzites and thickly bedded sandstones because of expansion of rocks consequent upon unloading of superincumbent load. R.H. Jahns (1943) has enumerated seven processes which cause sheeting in the rocks-

(i) Tensional or contractional strains set up during cooling of an igneous mass,

(ii) Local or regional compressional stresses due to tectonic movements,

(iii) Insolation, with attendant daily and secular temperature changes,

(iv) Progressive hydration and formation of chemical alteration products in susceptible minerals,

(v) Mechanical action of fire, frost, and vegetation,

(vi) Diminution of primary confining pressure by removal of superincumbent load, and

(vii) Combinations of the above causes.

Cambering process refers to fracturing of brittle sandstone beds along vertical joints due to expansion caused by unloading of superincumbent load and consequent release of confining pressure. G.W. Bain (1931) has reported the case of flying rock-sheets or spalls known as rock-bursts in limestone quarries due to spontaneous mechanical rock expansion caused by unloading of superincumbent load. "As new faces are cut in the walls of (limestone) quarries the dense limestone expands, producing cracks parallel to the surface. In some instances quarries had to be closed down because of the danger of flying rock-sheets or spalls" (C.D. Ollier, 1969).

The process of **spalling** refers to the development of platy rock fragments, lozenge-shaped or irregular, in the rocks due to unloading of superincumbent load.

7. Other types of physical weathering-boulder cleaving refers to breaking and splitting of boulders of granites and basalts and complex boulders due to thermal expansion. Another type of **insolation weathering** is **'dirt cracking'** wherein the boulders containing **'dirt'** are fractured and split due to thermal expansion and contraction. Fire, mainly brushfire, also causes insolation weathering due to thermal expansion and contraction of rocks which cause exfoliation and thus numerous spalls and flakes of rocks are produced. **Slaking weathering** refers to disintegration of rocks due to alternate wetting and drying of rocks wherein consequent expansion and contraction of rock shells result in the disaggregation of rocks. Disaggregation of rocks due to growth of salt crystals from solution is called **salt weathering** which generally occurs in hot arid areas. It may also be important in the rocks of coastal areas.

15.5 CHEMICAL WEATHERING

Decomposition and disintegration of rocks due to chemical reactions is called chemical weathering wherein the minerals of the rocks weather away. Water vapour and water are the media which activate several types of chemical reactions within the rocks. Pure water, distilled water, is chemically inert but when it mixes with the atmospheric gases, mainly with CO_2, it becomes potent solvent. Oxidation, carbonation, solution, hydration, chelation, hydrolysis, base exchange etc. are the important chemical reactions which cause various chemical changes in the minerals of rocks which ultimately lead to decomposition and disintegration of rocks.

1. Solution is considered to be the first step in the chemical decomposition and disintegration of rocks. Solution refers to the dissolution of soluble particles and minerals from the rocks with the help of water in motion but a thin film of water around a solid particle also leads to chemical dissolution. Solution of rocks depends on the nature of rocks, solubility of rocks or solids and the ratio between the volumes of solvent (water) and the solids. Common salts are most soluble whereas carbonate rocks (limestones-calcium carbonate, dolomites-magnesium carbonates etc.) are of moderate solubility.

Limestones are more susceptible to solution process which depends on temperature, CO_2 (carbon dioxide) content of water and pH of the solution. When rainwater mixes with atmospheric CO_2 it becomes active solvent and when it comes in contact with the carbonate rocks, such as limestones and dolomites, it dissolves the rocks through a set of chemical reactions occurring through various stages. The various stages of the chemistry of limestone solution may be presented in a simplified form as follows-

According to R.M. Garrels (1960) there are seven variables which control the equilibria involved in the solution of limestones-

(i) Partial pressure of CO_2

(ii) [H_2CO_3] carbonic acid

(iii) [HCO_3^-] bicarbonate ion

(iv) [CO_3^{2-}] carbonate anion

(v) [H^+] hydrogen ion

(vi) [OH^-] hydroxyl ion

(vii) [Ca^{2+}] calcium cation

Calcium hydroxide, $Ca(OH)_2$, is formed due to reaction of calcium oxides (CaO) with water (H_2O) in the following manner of reversible exothermic reaction-

$CaO + H_2O \leftrightarrow Ca(OH)_2$......eq. 15.1

Calcium carbonates, $CaCO_3$, is formed due to reactions of calcium hyxroxide ($Ca(OH)_2$ with carbon dioxide (CO_2) in the following manner of reversible exothermic reactions-

$Ca(OH)_2 + CO_2 \leftrightarrow CaCO_3 + H_2O$ ...eq. 15.2

Carbonic acid (H_2CO_3) is formed when CO_2 is dissolved in water-

$CO_2 + H_2O \leftrightarrow H_2CO_3$ ...eq. 15.3

Carbonic acid is also dissociated into positive hydrogen ion and negative bicarbonate ion-

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ ...eq. 15.4

Calcium carbonate (limestones) dissociates to limited extent in pure water into a metal cation (Ca^{2+}) and carbonate anion (CO_3^{2-}) during the process of dissolution in the following manner-

$CaCO_3 \xrightarrow{\text{dissociation}} Ca^{2+} + CO_3^{2-}$ ...eq. 15.5

It may be pointed out that limestone can be dissolved in water only when it is transformed into calcium bicarbonate, $Ca(HCO_3)_2$, with the help of carbonic acid (H_2CO_3) as follows-

$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$...eq. 15.6

or

$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$

The carbonate ion (CO_3^{2-}) can react with water when it accepts proton from acid and then the carbonate becomes base (which accepts the proton). The ultimate reactions yield hydroxyl ions and thus the calcium carbonate becomes an alkaline substance as follows-

$$CO_3^{2-} + H_2O \xrightarrow{\text{hydrolysis}} HCO_3^- + OH^- \quad \text{...eq. 15.7}$$

The actual quantity of limestone dissolved in water depends on temperature, CO_2 content of water, partial pressure of CO_2, pH of the solution and kinetics of reactions. The solubility of CO_2 is directly related to pressure (partial pressure) and is inversely related to temperature. In other words, the solubility of CO_2 increases and decreases with increase and decrease of partial pressure whereas it (solubility of CO_2) increases with decrease in the temperature and vice versa. On the other hand, the solubility of solids (say limestones) is directly related to temperature *i.e.* total solution of limestone increases with increase in temperature and vice versa. More and more limestones can be dissolved in water either by increasing the temperature or CO_2 content of water or by decreasing the pH of the solution. The solution of limestones and dolomites gives birth to very interesting landscapes known as **karst topography** characterized by various solution holes (sink holes, swallow holes, uvalas, dolines and polje) and various types of caves and galleries.

2. Oxidation—The chemical process of oxidation simply means a reaction of atmospheric oxygen to form oxides. When water is mixed with oxygen its reaction with the minerals of the rocks forms hydroxide. In other words, the atmospheric oxygen after reacting with the rocks produces several types of oxides, iron oxide being the most important, which weakens the rocks to disintegrate. The oxidation of minerals of the rocks by gaseous oxygen becomes possible when oxygen is dissolved in water. Most of the iron bearing rocks commonly contain iron in ferrous state (Fe) *e.g.* major iron sulphide (pyrite, FeS_2), iron carbonate (siderite, $FeCO_3$), and various iron silicates.

When water mixed with atmospheric oxygen comes in contact with iron bearing rocks, the iron oxidizes to form ferrous oxides (FeO). Further oxidation of ferrous oxides produces ferric oxides (Fe_2O_3) or ferric hydroxides ($Fe(OH)_2$). The oxidation of iron-bearing rocks produces rusts in the following manner.

$$Fe + H_2O + O_2 \rightarrow Fe_2O_3 \cdot 3H_2O \text{——eq 15.8}$$

(rust)

The rusting of rocks weakens them and ultimately the rocks are disintegrated. The ferric oxides and ferric hydroxides give red and yellow colours to many rocks and soils. The oxidation of iron-rich Vindhyan sandstones of the Kaimur ranges and Rewa scarps (M.P.) has helped in the block disintegration of massively bedded and well jointed sandstone capping.

3. Carbonation—'Carbonation is the reaction of carbonate or bicarbonate ions with minerals'. The process of carbonation is also known as **solution** wherein atmospheric carbon dioxide after mixing with water forms carbonic acid (H_2CO_3, see equation 15.3) which after reacting with carbonate rocks, say limestones ($CaC0_3$) forms calcium bicarbonate ($Ca(HCO_3)_2$) (see equation 15.6) which is easily dissolved in water. The mechanism of solution of carbonate rocks has already been discussed above. The rainwater having dissolved carbon dioxide (CO_2aq) percolates through the different horizons of the soils to reach underlying limestones. Thus, more and more organic carbon dioxide is dissolved in groundwater which then becomes a more active solvent because dissolution of more carbon dioxide produces more carbonic acids which dissolve more carbonate rocks after transforming calcium carbonates into calcium bicarbonates.

4. Hydration—The process of hydration is related to the addition of water to the minerals. The rocks after having absorbed water undergo the process of positive change of their volume. In other words, the volume of the hydrated rocks (rocks which have absorbed water) increases remarkably. Some times, the increased volume becomes about twice of the original volume. Thus, the increase in the volume of rocks due to increase in the volume of

minerals causes stresses and strains in the minerals of the rocks which ultimately lead to physical disintegration of rocks. "Hydration is an exothermic reaction, and involves a considerable volume change which may be important in physical weathering-exfoliation and granular disintegration. Hydration prepares mineral surfaces for further alteration by oxidation and carbonation, and enables the transfer of ions to take place with greater ease" (C.D. Ollier, 1969). The process of hydration changes feldspar minerals into kaolinite clays, the process being known as **kaolinization.**

5. Hydrolysis—'Hydrolysis is chemical reaction between mineral and water, that is between hydrogen (H) ions or hydroxyl (OH) ions, and the ions of the mineral' (C.D. Ollier, 1969). In fact, the hydrolysis is that process wherein both the minerals of the rocks and water molecules decompose and react in such a way that new mineral compounds are formed. Silicate minerals are most affected by hydrolysis. This reaction starts immediately when a mineral comes in contact with water. The hydrolysis of magnesium silicate minerals (Mg_2SiO_4) in contact with 4 ionized water molecules ($4H_2O \longrightarrow 4H^+ + 4OH^-$) takes place in the following manner-

$$Mg_2SiO_4 + 4H^+ + 4OH^- \xrightarrow{\text{hydrolysis}} 2Mg^{++} + 4OH^- + H_4SiO_4 \text{ (silicic acid in solution)}$$

Hydrolysis of potassium feldspar (orthoclase, $2KAlSi_3O_2$) with carbonic acid (H_2CO_3) in water is perhaps the most common type of chemical weathering process wherein the end product of the reaction of potassium feldspar with carbonic acid in water is potassium and bicarbonate ions in solution. The mechanism of the hydrolysis of potassium feldspar is given below-

$$2KAlSi_3O_2 + H_2CO_3 + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 +$$

orthoclase + carbonic acid + water kaolinite, a clay mineral

$$4H_4SiO_4 + 2K^+ + 2HCO_3^-$$

silicic acid in solution + Potassium and bicarbonate in solution

6. Chelation-According to D.S. Lehman (1963) "chelation is a complex organic process by which metallic cations are incorporated into hydrocarbon molecules". In fact, the word **chelate** means a co-ordination compound in which a central metallic ion is attached to an organic molecule at two or more positions. In other words, chelation means 'holding of an ion, usually a metal, within a ring structure of organic origin' (C.D. Ollier, 1969). We may safely say that chelation is a form of chemical weathering by plants. Plants extract minerals or say nutrients from the soils with the result mineral lattices are disrupted and crystal lattices are fragmented and thus mineral weathering takes place at a much faster rate.

The products of chemical weathering are classed under three catagories--

(i) Solutes of sodium, potassium, calcium, magnesium etc. produced by the process of carbonation or solution of carbonate rocks, which are brought to the lakes and seas and are reprecipitated to form limestones, dolomites and other carbonate rocks.

(ii) Clays, derived from the weathering of feldspar and ferromagnesian minerals, form argillaceous sedimentary rocks like shales.

(iii) Mineral residuals, such as silica, unweathered feldspar and mica and other heavy minerals, form clastic sedimentary rocks such as sandstones.

15.6 BIOTIC WEATHERING

Plants and animals including man largely control breakdown of rocks. It may be pointed out that in all types of weathering in all climatic regions biotic communities play some roles in one way or the other. This is why B.B. Polynov (1937) believed that completely **sterile weathering** was impossible. It may be mentioned that it does not mean that biotic communities always indulge in destructive work by disintegrating and decomposing the rocks but the burrowing animals definitely help in the transfer of soils from lower to upper and upper to lower horizons and thus the mixing of geomaterials activates weathering. Though vegetations protect the rocks by binding them through their roots but different types of acids (*e.g.* humic acids, bacterial acids, microfloral acids etc.) produced by them facilitate **biochemical weathering.** Recently, man has become the most powerful weathering agent because of the development of modern technologies. Biotic weathering, thus, is divided into 3 types *e.g.* (i) faunal weathering, (ii) floral weathering and (iii) anthropogenic weathering.

1. Faunal weathering—The burrowing animals, worms and other organisms help in gradual breakdown of rocks or fragments thereof. Burrowing animals include gophers, prairie dogs, foxes, rabbits, jackals, termites, rats etc. which dug out burrows and tunnels in the rocks and unconsolidated geomaterials as their living places (homes). By doing so they weather the rocks and geomaterials to great extent. Small organisms play more important roles in rock and soil weathering. These organisms repeatedly mix up the soil materials and thus always expose fresh materials to weathering agents. They also help in moving the organic matter downward into the soil profiles and thus extend the weathering at greater depths which otherwise would have not been possible.

It is believed that there are about 1,50,000 creatures, big and small, in one acre of land and these organisms bring about 15 tonnes of soils at the surface from below every year. According to the estimate of Charles Darwin the soil organisms bring about 25.4 thousand kilograms of soil at the surface every year in the English gardens. Termites play very important role in sorting and rearranging the soil materials in the upper horizons of soil profiles in tropical regions. Termitaria are the evidences of soil weathering by termites. According to Ponomareva (1950) earthworms burrow to about 1.5m and pass 10 tons per acre per year as a mean and 20 tons per acre per year as a maximum of soil materials. Rabbits, prairie dogs etc. destroy the soil structure and they obstruct the leaching and other horizon forming processes by constantly remixing the soil materials.

2. Floral weathering—Weathering of rocks by vegetations takes places in two ways viz. (i) physical weathering and (ii) chemical weathering which is called as biochemical weathering, which will be discussed under separate heading. It may be pointed out that floral weathering does not take place independently rather it helps the physical and chemical processes of weathering. Larger plants affect and control weathering in a number of ways. (i) Cracks are widened by root penetration and consequent root pressure. (ii) Dense vegetation cover generates distinct microclimate at the ground surface. The soil atmosphere is largely affected by root respiration, humus content, increased moisture due to low rate of evaporation, increased content of organic CO_2, low temperature, all of which activate chemical weathering. It may also be mentioned that vegetations also protect the rocks and soils from weathering processes.

3. Anthropogenic weathering—Man being a biological agent accelerates and decelerates the natural rates of weathering by many folds. The 'economic and technological man' lashed with modern technologies has become the most powerful weathering and erosion agent. Mining activities for extraction of minerals, blasting of hills and ridges by dynamites for road and dam construction and mineral extraction, quarrying for industrial (limestones from cement) and building materials etc. result in such a fast rate of disintegration of geomaterials (rocks) that this may be accomplished by natural weathering processes in thousands to millions of years. Man accelerates the rate of weathering on hillslopes by modifying the ground surface through deforestation which reduces the mechanical reinforcement and cohesion of unconsolidated geomaterials and thus increases slope instability which causes slope failures and massmovement of materials down the slope in the form of landslides, slumping and debris fall and slides.

15.7 BIOCHEMICAL WEATHERING

Biochemical weathering refers to decompositions and disintegration of rocks due to organic materials of both flora and fauna. A complex set of different biochemical processes such as **cation root exchange, chelation, solution** by root exudates and production of different kinds of organic acids such as humic acids, bacterial acids, microfaunal acids etc. produced by organic materials help in the decomposition and disintegration of rocks and soils.

Humic acids activate **chelation** and help in the decomposition of silicate minerals. Fulvic acids, humic acids derived from peat, play important role in decomposing rock minerals. Bacterial acids, including lactic, acetic, oxalic and gluconic, attack a wide range of rock minerals important being magnesium carbonate, calcium and magnesium silicates, feldspar and kaolinites. Bacterial acids also produce sulphides, oxidize iron and help in the solution of silica when the rocks are constantly submerged under water (perpetual waterlogging). Microfaunal acids such as oxalic and citric acids are produced by fungi and lichens. These acids weather silicate minerals and clays.

Chemotrophic bacteria manufacture sulphides and remove silica in the tropical soils and help in the carbonate mineralization in caves. The colonization by blue-green algae forms **desert varnish** and mobilize ferrous irons and help in the concentration of oxides on rock surfaces. Micro-organisms also form **varnish incrustations** on rocks. Lichens introduce the alteration of mineral composition of rocks both mechanically and chemically. The organic carbon dioxide produced by plants accelerates the rate of carbonation on carbonate rocks *e.g.* limestones and dolomites.

15.8 GEOMORPHIC IMPORTACE OF WEATHERING

1. Production of rockwastes-Rocks are disintegrated and decomposed and ultimately are broken down into smaller pieces due to the operation of different weathering processes *e.g.* physical weathering, chemical weathering, biotic weathering and biochemical weathering. Thus, different weathering processes produce immense volume of rockwastes or weathered materials. These weathered materials lying over the unweathered fresh rocks are called regoliths. The depth of weathered rocks from the ground surface to the unweathered fresh rocks is called **weathering zone.** The depth of weathering zones varies from place to place and from region to region depending mainly on the depth of water table of groundwater and the duration of weathering. The weathered materials are very important economically because they help in the process of soil formation, they expose minerals etc. Weathering generates mass movement of rockwastes down the hillslope and thus causes damage to human settlements in the foothill zones, causes obstructions in the river flow and thus forms lakes (by damming the rivers through debris fall).

2. Weathering helps erosional processes—Weathering loosens the rocks by disintegrating and decomposing them and thus paves the way for erosional processes to operate easily. Different agents of erosion like running water (rivers) in humid regions, wind in hot arid and semi-arid regions, glaciers in cold regions and sea waves operating along coastal zones obtain these weathered materials and move them to other places. The rapid rate of weathering due to mass felling of trees (deforestation) has accelerated the rate of erosion of nude rocks of hill ranges with the result most of the rivers have become overloaded and sluggish because millions of tones of eroded sediments are reaching the major rivers every year. For example, Garhwal and Kumaun Himalayas and other parts of the Himalayas have been extensively deforested and thus the weathered rocks have increased the rate of fluvial erosion, consequently most of the Himalayan rivers like the Yamuna, the Ganga, the Ghaghra, the Kosi etc. have become overloaded in the plains due to supply of huge volume of sediments every year. This process has caused rapid rate of siltation of river beds of major alluvial rivers of north India and the resultant siltation has increased the frequency and dimension of recurring floods.

3. Lowering of surface-Continuous removal and transfer of weathered materials through different processes of masstranslocation of rockwastes such as landslides, debris slides, rockfall, rockslides, talus creep etc. and by the agents of erosion causes gradual lowering of the height of the affected area.

4. Evolution of landforms and their modifications—Differential weathering helps in the evolution of different types of landforms. Weathering plays important role in the development of stone lattice (in hot deserts), tors, buttes, talus cones, talus fans, sandstone anvils etc. It may be pointed out that weathering and erosion go hand in hand and thus it is not wise to separate the inseparable, so it is difficult to ascertain the quantum of work done by weathering and erosion in the development of a particular type of landform.

15.9 MASS MOVEMENT (MASS WASTING)

The study of mass movement of rockwastes involves the analysis of meaning and concept, classification, causes, and geomorphic significance of mass movement or mass transtocation of rockwastes.

1. Meaning and Concept

Disintegrated and fragmented rock materials due to mechanism of weathering processes (mechanical, chemical, biotic and biochemical) are called **rockwastes.** Generally, movement of rockwaste enblock down the hillslope is called massmovement

of rockwaste or simply mass movement. 'Mass movement is the detachment and downslope transport of soil and rock material under the influence of gravity. The sliding or flowing of these materials is due to their position and to gravitational forces, but mass movement is accelerated by the presence of water, ice and air. This definition of mass movement permits consideration of the movement of earth materials at all scales and at all rates' (R.J. Chorley, et. al, 1985). It is evident from the above definition that mass movement includes both, detachment of rock materials and their downslope transport enblock. 'The collective term for gravitational or downslope movements of weathered rock debris is **masswasting**. The term implies that gravity is the sole important force and that no transporting medium such as wind, flowing water, ice or molten lava is involved. Although flowing water is excluded from the process by definition, water nevertheless plays an important role in masswasting by over steepening slopes through surface erosion at their bases and by generating seepage forces through groundwater flow' (A.L. Bloom, 1978).

If we look at the aforesaid two definitions of R.J. Chorley et. al and A.L. Bloom it appears that the term **mass movement** is more sound and appropriate than **mass wasting** to describe enblock downslope transport of weathered materials ranging from very fine (soils) to very coarse and large sized rock materials (boulders). In fact, the definition by R.J. Chorley and others is comprehensive one because it includes both the aspects of mass movements, viz. detachment of rock materials and their downslope transport whereas Bloom's mass wasting describes only the process of downslope transport of weathered rock debris.

Emphasising the significance of tectonics in mass wasting (may be rock disintegration) and mass movements R.J. Chorley and others (1985) have remarked, that, 'the relation between mass wasting and tectonics is a relatively clear one. Where rocks are shattered and relief is high, this is where mass movement is common and, in fact, the denudation of high mountains may.......be the result of mass wasting rather than fluvial or glacial process'.

It is, thus, evident that mass movement of rock wastes includes the mechanisms of detachment of rock materials through different weathering processes, and enblock downslope transport of weathered rock debris by gravity force without any medium of transport (*e.g.* running water, wind, sea waves, glacier etc.) except some lubricating role of water or ice. The rocks debris coming through mass movement are deposited at the foot-hill zone as **scree or talus**. The deposit of large boulders in conical shape is called **talus cone.** It is, thus, apparent that the most significant stimulating factor of mass movements is gravity force.

2. Classification of Mass Movements

A wide range of variations in terms of rate, direction and type of movements is noted in mass movements in different places having varying environmental conditions. It is generally believed that mass movement of rock wastes occurs suddenly and instantaneously and hence all mass movements cannot be witnessed by man. But in reality mass movements have long preparatory period and there are certain precursor events which herald the occurrence of mass movements but these are generally unnoticed. It may be mentioned that most of mass movements occur in mountainous areas and hence it is not possible to notice the precursor events such as restlessness of animals, deserting of hives by bees etc. 'Hence, if a landslide comes as a surprise to eyewitness, it would be more accurate to say that the observers failed to detect the phenomena which preceded the slide' (R.J. Chorley et. al, 1985). Mass movements are generally classified on the basis of causative factors *e.g.* rate of movement, direction of movement, type of movement, lubricating substance *e.g.* water, ice etc.

The direction of mass movement of rockwaste down the slope may be (i) vertical, (ii) lateral, and (iii) diagonal. Based on direction mass movement may be divided into vertical movement, lateral movement and diagonal movement of rockwaste. **Vertical mass movement** is further divided into (a) rockfall, (b) collapse earthfall. **Lateral mass movement** includes (a) block slide, (b) spread, (c) cambering, (d) sackung etc. **Diagonal mass movement** is divided into (a) soil creep, (b) rockcreep, (c) talus creep,

(d) rockslide, (e) debris slide, (f) slump, (g) debris flow, (h) mud flow, (i) solifluction, (j) avalanche etc.

R.J. Chorley et. al (1985) have presented exhaustive classification of mass movement and mass wasting phenomena on the basis of direction of movement, type of movement and presence of transporting agent as given below-

Table 15.1 : Mass Movement-Mass Wasting Phenomena

Direction of movement	Vertical		Lateral		Diagonal		
Type of movement	Fall	Subsidence	Slide	Spread	Creep	Slide	Flow
Presence of transporting agent	No	No	Minor in basal layer or on sliding surface	Moderate in basal layer	Minor	Minor to moderate	Major
Types of mass movement	Rockfall, earthfall, topple	collapse settlement	Block slide	Spread cambering	soil creep, rock creep, talus creep	rock slide debris slide, soil slip, slump	solifluction mudflow rock glacier, rock avalanche

Source : R.J. Chorley et. al, 1985.

Based on the rate of movement and water content mass movements are classified in 3 types-

(1) Large-scale rapid slide of rock waste. Water is needed as lubricating agent for such type of mass movement. Landslide is the typical example of this type.

(2) Slow flowage of rock waste and weathered debris. Partial saturation of rock debris is required for such mass movement and hence moderate quantity of water is needed as lubricating and stimulating agent. Rock creep, soil creep, solifluction etc. are typical examples of this type.

(3) Rapid flowage of weathered debris. Sufficient quantity of water is needed as lubricant. Earth flow, mudflow etc. are representatiives of this type of mass movement.

A generalized classification of mass movement of rock wastes is presented as follows:

Table 15.2 : Classification of mass movement

1. **Very rapid movement**
   (no water is required)
   - (i) Landslides
     - (a) slump
     - (b) debris slides
     - (c) debris fall
     - (d) rock fall
     - (e) rock slides
2. **Slow movement (flowage or slide)**
   (little water is required)
   - (i) Rock creep
   - (ii) Soil creep
   - (iii) Solifluction
3. **Rapid movement (flowage or slide)**
   (enough water is required)
   - (i) Earthflow
   - (ii) Mudflow
   - (iii) Sheetwash

On the basis of direction and type of movement the following types of mass movement of rock waste may be identified (simplified scheme of R.J. Chorley et. al, 1985)-

Table 15.3 : Classification of Mass Movement

1. **Vertical movement**
   (A) **Fall** (of earth materials from very steep slopes like steep scarps and cliffs)
   On the basis of materials
   (a) rockfalls
   (b) earthfalls (of alluvia, soils, colluvia)
   (c) debrisfall (soils, alluvia, colluvia, vegetation and human structures)
   (d) topple (rotational fall of rock slabs, or of earthen material)
   (B) **Subsidence** (of the ground surface)
   Sinking (a) **collapse** (of roofs of underground caves or cavities or lava tubes)
   (b) **settlement** (collapse of ground surface due to withdrawal of water, crude oil etc.)
2. **Lateral movement**
   (A) **Slides** (sliding) (movement of materials along a horizontal fracture or interface between two rock strata of varying resistance *e.g.* sandstones-shales or limestones-shales)
   (a) **block slide** (bock glide) (downslope movement of a single large block of massive rock on such a surface which has been lubricated by water)
   (B) **Spreading** (lateral displacement of a series of rock blocks (multiple blocks) or mud block downslope)
   (a) **cambering** (draping of sedimentary units)
   (b) **sackung** (lateral spreading away from anticlinal crests)
3. **Diagonal movement**
   (A) **Creeping** (downslope movement of earthen materials at slow velocity)
   (a) **soil creep** (movement of moistened soils downslope)
   (b) **rock creep** (movement of rock upon rock)
   (c) **talus creep** (rearrangement of scree and downslope movement)
   (B) **Slide** (rapid rate of downslope movement of large quantities of debris of varying sizes) (on the basis of materials)
   (a) **rock slides** (b) **debris slides** (c) **soil creep**
   (d) **slumping** (movement of fine materials along a curved plane)
   (C) **Flows** (dominant role of water, downslope transport of water-soaked fine debris)
   (a) **earthflow** (b) **slides** (c) **mudflow**

Table 15.4 : **Simplified classification of mass movement (land slides)**

1. **Fall**
   (a) Rock fall (b) Debris fall (c) Earth fall
2. **Slides**
   (a) **Slump**
   (i) rock slump (ii) debris slump (iii) earth slump
   (b) **Slides**
   (i) rock slides (ii) debris slides (iii) earth slides
3. **Topples**
   (i) rock topples (ii) debris topples (iii) earth topples
4. **Flows**
   (a) Rock flow

   (b) Soil flow
   (i) debris flow (ii) earth flow
5. **Lateral spreads**
   (i) rock spreads (ii) debris spread (iii) earth spread

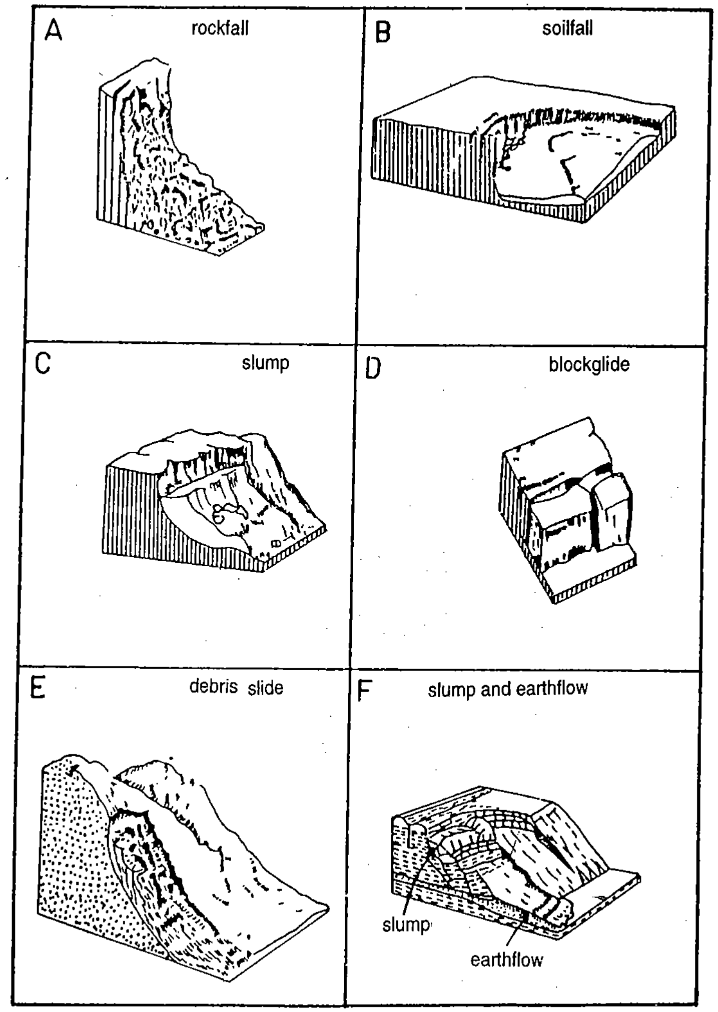


Fig. 15.1 : Different types of mass movements, rock fall (A), soil fall (B), slump (C), block glide (D), debris slide (E) and slump and earth flow (F), Source : D.J. Varnes (1978), M.J. Selby (1982) and R.J. Chorley et. al (1985).

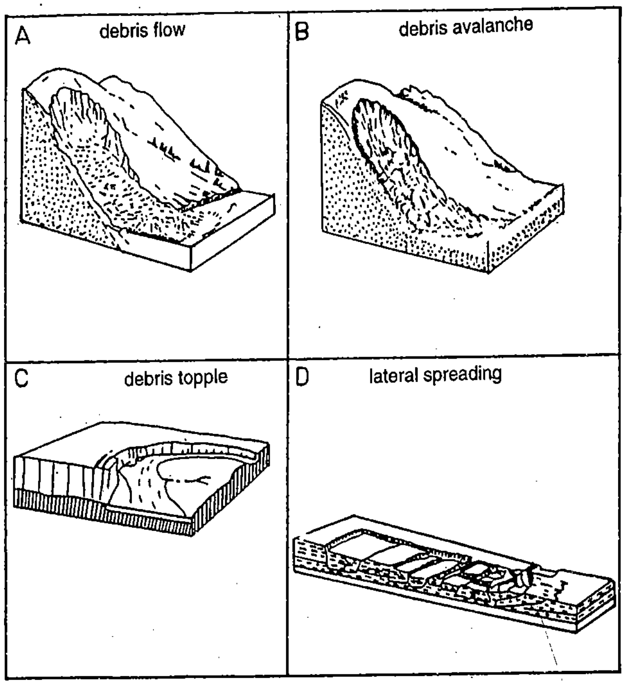


Fig. 15.2 : Different types of mass movement : debris flow (A), debris avalanche (B), debris topple (C) and lateral spreading (D), Source : D.J. Varnes, (1978), M.J. Selby (1982) and R.J. Chorley et. al (1985).

3. Factors of Mass Movement

Any sort of mass movement of weathered debris with any rate whether on hillslope or valley side slope depends on the ratio between shearing forces (simply known as stress) and resistance of materials to shearing forces (*i.e.* shearing resistance of materials) as follows-

$$Fs = \frac{\text{strength or shearing resistance of materials}}{\text{magnitude of shearing forces}}$$

where Fs = factor of safety

When the quotient of shearing resistance of materials (simply strength of materials) and magnitude of shearing force *i.e.* safety factor (Fs) is less than 1.0 (*i.e.* when magnitude of shearing forces of hillslope or valley side slope exceeds the shearing resistance of materials resting on slopes) materials begin to move downslope and thus mass movement of weathered debris occurs. It is apparent that mass movement may occur when either shearing forces increase or shearing resistance of materials decreases. It may be pointed out that either of the two processes (increase in stress and decrease in resistance of materials to stress) may operate or both the processes may operate together.

Based on this corollary D.J. Varnes (1978) classified the factors which control mass movement of rockwastes in two broad categories and many subcategories- (1) factors which increase shearing forces (shear stress) and (2) factors which reduce resistance of materials to shear stress. The summarized form of Varne's classification of factors of mass movement have been presented in table 15.5.

Table 15.5 : Factors of Mass Movement

Category I

Factors which increase the shear strength

(External Processes)

1. **Removal of lateral support** (undercutting-steepening of slope)
   (A) (Natural)
   - (a) stream erosion, (b) glacial erosion,
   - (c) marine erosion by sea waves,
   - (d) weathering (these factors lead to removal of lateral support) and
   - (e) previous rockfall or slide, subsidence or faulting (these factors steepen the slope)

   (B) (Anthropogenic factors)
   - (a) Construction of quarries, pits, canals, roads
   - (b) alteration of water levels in lakes and reservoirs
2. **Surcharge** (loading of slope)
   - (a) (natural) weight of rain, snow, (anthropogenic) water from pipelines, sewers, canals
   - (b) accumulation of talus
   - (c) vegetation, trees
   - (d) seepage pressure of percolating water
   - (e) (anthropogenic) construction of fill, waste piles, buildings
3. **Transitory earth stress** (endogenetic processes)
   - (a) earthquakes
   - (b) vibrations, blasting, traffic
   - (c) swaying of trees in wind
4. **Removal of underlying support**
   - (a) undercutting by rivers and waves
   - (b) solution at depth, mining (anthropogenic)
   - (c) loss of strength of underlying sediments
   - (d) squeezing out of underlying plastic sediments
5. **Lateral pressure**
   - (a) water in cracks
   - (b) freezing of water in cracks
   - (c) swelling (hydration of clay)
   - (d) mobilization of residual stress (pressure release)

Category II

Factors which decrease (reduce) the shear strength of materials

1. **Weathering and other physico-chemical reactions**
   - (a) softening of fissured clays
   - (b) physical disintegration of granular rocks (frost action, thermal expansion etc.)
   - (c) hydration of clay mineral causing decrease in particles cohesion, swelling
   - (d) base exchange (changes in physical properties)
   - (e) drying (desiccation) of clays and shales (racking, loss of cohesion)
   - (f) removal of cement by solution
2. **Changes in intergranular forces due to water content**
   (porewater pressure)
   - (a) saturation
   - (b) softening of material
3. **Changes of structure**
   - (a) fissuring of shales and consolidated clays
   - (b) remoulding of loess, sand and sensitive clay
4. **Organic**
   - (a) burrowing animals
   - (b) decay of roots

Source : D.J. Varnes, 1978, in R.J. Chorley et. al, 1985

Recently, man has emerged as a significant factor of mass wasting and mass movement in almost all of the environmental conditions. His activities (*e.g.* deforestation for commercial wood and increase in agricultural land; construction of roads, dams, reservoirs; urbanization on fragile hillslope; manipulation of rivers, coastal areas etc.) destabilize hillslopes as well as valley side slopes and accelerate the process of mass wasting and mass movement and increase frequency and magnitude of different mechanisms of mass movement. Increased deforestation, cultivation on cleared hillslope, construction of roads and reservoirs in the Himalayas have made the mountain ecosystem more fragile and vulnerable to increase frequency and magnitude of different types of mass movement.

1. Landslides

It may be mentioned that generally all types of mass movements of rock wastes including soils

and ice are collectively called as landslides which are variously classified on different bases *i.e.* direction of movement, type and rate of movement, nature of materials, presence or absence of lubricants etc. (tables 15.1 to 15.4). On an average, landslides (downslope movement of different types of debris enblock) are divided into five major categories *e.g.* fall, slide, topple, flows and lateral spreads. On the basis of nature of materials these are further subdivided into several types (table 15.4).

(1) Falls

Instantaneous fall of weathered rock materials including large blocks from steep hillslopes or earthen materials from steep and cliffed valleysides of streams under the influence of gravity is called fall. The size of rock fragments depends on the size and pattern of rock joints. This type of movement involves vertical displacement of materials without water. The velocity of fall is greatest of all other types of mass movement. According to A.L. Bloom, 'fall is a distinct landslide process, but it is rarely independent of subsequent events.' On the basis of materials fall is subdivided into rock fall, debris fall and earthfall.

Rock falls are relatively small landslides confined to the removal of individual and superficial blocks from a cliff base (M.J. Selby, 1982). Rock fall (fig. 15.1A) is facilitated by granular and block disintegration of rocks under the processes of mechanical weathering and limited action of oxidation in sandstones. According to M.J. Selby (1982) 'most rockfalls are promoted by hydrofacturing, stress release, the wedging action of tree roots, and other weathering processes........a common cause of rock falls is undercutting of a face by streams or the more rapid weathering of an underlying weak rock such as shale or mudstone.' The frequency of rock falls depends on certain environmental conditions such as aridity/humidity factor, lithological and structural characteristics of rocks, nature of slope and vegetation etc. In humid areas rock falls are very common features but in hot arid areas they are of very rare occurrence. **Debris fall** involves rapid rate of fall of weathered rock materials (which are finer than the materials involved in rock fall) downslope (it may be hillslope or steep valley side slope of streams) from great height. The fallen materials collect at the foot-hill or cliff base and form small mounds and ridges. **Earthfall** involves downslope movement of finer materials than debris fall.

(2) Slides

Slides, very often known as **landslides** among general public, are most significant of all types of mass movements. 'Mass-wasting wherein a mass of rock or weathered debris moves downhill along discrete shear surfaces is defined as a slide' (A.L. Bloom). It may be pointed out that slides involve downslope displacement of both types of materials-weathered rock materials and soils. Slides in rock or soil are characterized by movement above a sharply defined shear plane. In rocks such as slate, schist, and many sedimentary formations the shear plane follows a structural plane within the rocks such as a plane of foliation or bedding-and it is often straight' (M.J. Selby, 1982). Slides are promoted by a host of controlling variables such as nature of slopes (vertical and cliff slope is essential for slides), moderate lubrication by water, earth tremors, gravity, vertical and steeply inclined rock beds, base removal etc. Slides are more frequent in certain locations having favourable condition viz. (1) steep hillslope or steep valleysides of streams, (2) fault scarps, (3) rejuvenated fluvially eroded valleys, (4) sea coasts, (5) alluvial river valleys, (6) degraded hills and mountains (due to deforestation, road construction, settlement expansion etc.).

On the basis of nature of materials, direction and rate of movement (intensity) slides are divided into (1) slump (which is further divided into rock slump, debris slump and earth slump), (2) rock slides, (3) debris slide, and (4) earth slide.

(i) **Slumping** involves intermittent sliding of rock fragments, rock blocks or soils downslope along a curved plane caused by rotational movement (figs. 15.1 C and 15.3) and displaced blocks (whether rock blocks or soil blocks) cover very short distance. Slump is promoted by undercutting of slope base (with hillslope or valley side slope of streams) by streams, seawaves (in case of coast land) and by human activities (quarrying). In fact, 'slump is the form of slide most common in thick, homogeneous, cohesive materials such as clay. The surface of failure beneath a slump block is spoon-shaped, concave upward or outward' (A.L. Bloom, 1978, fig. 15.3).

Slumping of alluvial deposits of valley sides of alluvial rivers of north India through undercutting of valley sides by hydraulic action of the steams during wet monsoon period is of common occurrence. Slumping is consuming a large chunk of rich agricultural lands every year along the Ganga valley in U.P. and Bihar. Based on the nature of materials involved slump is subdivided into rock slump, debris slump and earth slump.

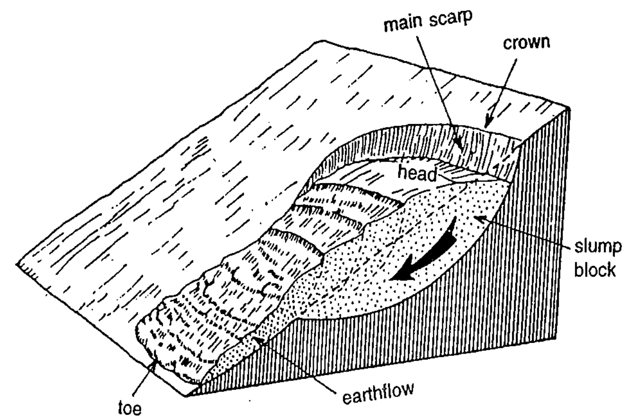


Fig. 15.3: Slump and earthflow (After A.L. Bloom, 1978).

(ii) **Rock slide** (also known as **rock glide** or **block glide**) is most significant of all types of slides wherein large rock blocks slide down the hillslope. 'Rock slides may be very large and catastrophic in mountain regions where the large available relief permits accelerations of rock debris to velocities as great as those of rock falls and rock avalanches,' (M.J. Selby, 1982). Rock slides involve rapid movement of materials downslope. Some times, the velocity is so high and mass of materials is so enormous that 'rock slides can be dramatic forms of sliding mass-wasting if large masses of unweathered rock slide downhill along a sloping joint or a bedding surface' (A.L. Bloom, 1978). The Cross Ventre Slide of 1925 in Wyoming, USA and Turtle Mountain Slide of 1903 in Alberta, Canada, are typical examples of devastating landslides. The very massive landslides (rock slide), which occurred in the north-western side of Naini Lake (Nainital, Uttaranchal) in 1884, was so enormous that the debris filled a sizeable portion of the lake.

(iii) **Debris slide** is more extensive and occurs at larger scale than slump but there is little amount of water. Debris slide is promoted because of two basic factors-(1) saturation of rocks due to water, and (2) sudden downslope movement of unconsolidated mantle rock. The materials involved in debris slide is a mixture of soils and rock fragments (boulders). The debris collects at the foot-hill or the base of the valleys and forms interesting morphological features.

3. Flow

Diagonal downslope movement of rock fragments and soils along sliding plane with enough water is called flow (which is further divided into solifluction, debris flow, mud flow, earthflow, rock avalanche etc.). Flow involves downslope rapid movement of rock debris or soils saturated with water like viscous fluid. 'Dry flows in sand or silt are known, but most flows are saturated with water. Rates of movement are greater than for creep but range from imperceptibly slow to tragically rapid mud flows and avalanches. Flows typically move as lobes or tounges' (A.L. Bloom, 1978).

(i) **Debris flow** involves downslope movement of enormous amount of viscous soils and boulders either separately or mixed together, and occurs mostly along river valley sides. The difference between debris flow, earth flow and mud flow is related to size of particles and amount of water. The size of particle decreases from debris flow to mudflow. The three terms form a series of progressively higher water content (*i.e.* water content increases from debris flow through earth flow to mud flow) but are often used interchangeably. Debris flows have 20-80 percent particles coarser than sand sizes, whereas

earth flows and mud flows are 80 per cent or more mud and sand. Mud flow is the most liquid "end member" of the series (A.L. Bloom, 1978). 'Debris flow occurs mostly due to availability of water, presence of loosely deposited soils and fine rock materials, lack of vegetation cover, clay minerals in the soils, unstable slope, undercutting of slope (valley sides) by streams, earth tremors etc. Debris flows range in size from a few meters to over 1000 meters in width and may be tens of meters thick in places; more commonly they are 1 to 5 m thick' (M.J. Selby, 1982). Debris flow is most common on gully heads in the riverine tracts of major alluvial rivers.

(ii) **Earth flow** is promoted by excessive water received mostly through rainfall so that the materials are oversaturated. Earth flow is more common on planar hillsides or valleysides having alluvium, rich in clay minerals.

Debris flow of volcanic materials saturated with water on volcanic cones is called **lahar.** Heavy downpour mixing with falling volcanic dusts causes enormous mud flow as lahar on the steep slopes of volcanic cones which inflicts great damage to human health and wealth. For example, great lahar created on the steep slopes of Kelut Volcano in Japan in 1919 killed 5500 persons.

(iii) **Mud flow** differs from earth flow in that former may be noticed by the observer while the latter cannot be noticed because earth flow is not very common. The water content is more in mud flow than in debris flow and earth flow. Mud flow is most common along valleysides of alluvial rivers and the debris (mud) so produced is transported by the rivers. The necessary conditions which promote mud flow include (1) steep and vertical slope, (2) presence of unconsolidated materials on the upper surface so that these, when mixed with water, become viscous fluid and slippery, (3) intermittent supply of sufficient water as lubricant, and (4) absence of vegetation. Based on these factors Elliot Blackwelder (1928) considered arid regions as most favourable for mud flow. C.F.S. Sharpe (1938) has divided mud flow into three categories on the basis of spatial characteristics *e.g.* (1) mud flow of arid regions, (2) Alpine mud flow, and (3) volcanic mud flow.

4. Creep

Very slow and imperceptible downslope movement of materials (colluvium) is called creep. On the basis of materials involved in such movement creep is divided into (1) soil creep (fine weathered rock debris as well as soil) and (2) rock creep (unweathered joint blocks). It may be pointed out that the rate of movement of materials (colluvia) under creep is so slow (a few millimeters per year) that it becomes practically difficult for the observers to notice it.

(i) **Soil creep** is also called as solifluction which occurs in a variety of climatic conditions ranging from tropical humid to periglacial climates. The process of debris movement in periglacial regions has been variously defined and a number of terms have been suggested. First J.G. Anderson (1906) proposed the term **solifluction** (solum-soil, fluere-flow) for slow movement of debris, soaked with water, from higher to lower slopes. Solifluction term was replaced by **congelifluction** of J.Daylik (1951) to incorporate only soil flow in the periglacial climate having permafrost below an active layer. K. Bryan (1946) used the term **cryoturbation** which included all types of mass movement of regoliths under periglacial environment. Recently, **gelifluction** is used in place of congelifluction.

(iii) **Rock creep** involves downhill movement of rock debris having relatively great depth (upto 300m) but the movements is very slow and ranges between one meter to ten meters per year. 'It is distinguished from soil creep by its great depth and isolation from daily and seasonal climatic conditions, and from land sliding by the lack of a single clearly defined failure plane and slow rate of deformation' (M.J. Selby, 1982). The following conditions promote rock creep-deformation of rocks through bending, folding, bulging, fracturing, spreading; distortion and buckling of inclined rock beds of varying resistance, mechanical disintegration of rocks etc.

15.10. TOPOGRAPHIC EXPRESSIONS OF MASS WASTING AND MASS MOVEMENT

Different types of mass wasting and mass movement create distinctive morphological features on hillslope and river valley sides and coastal lands. It may be pointed out that on one hand there is wide range of variation in mass movement because of varying controlling factors and conditions, on the other hand, there is almost uniformity in the resultant morphological features. The topographic features produced by mass movement say landslides include scars, ripple marks, terraces, meander widening etc.

16

CYCLE OF EROSION, REJUVENATION AND POLYCYCLIC RELIEFS

16.1 ORIGIN AND EVOLUTION OF THE CONCEPT

Cyclic concept was probably postulated first in geology by Scottish geologist James Hutton in 1785 when he propounded the concept of 'cyclic nature of the earth history' and the dictum of 'no vestige of a beginning; no prospect of an end' and 'present is key to the past'. The concept of cyclic nature of the earth history was later on transformed into the concept of **'uniformitarianism'** which states that 'the same physical processes and laws that operate today, operated throughout geologic time, although not necessarily always with the same intensity as now.' Probably based on this inheritance of Hutton's concept of the cyclic nature of the earth history and the evolutionary concepts of Charles Darwin (Origin of Species through natural selection) William Morris Davis (1850-1934 A.D.) presented his concept of cycle of erosion under the title of **geographical cycle of erosion** in the year 1899 though the concept of **'complete cycle of river life'** was already propounded in the year 1889. The Davis' model of geographical cycle of erosion was based on the basic concept of 'sequential change in landforms through time like the evolution of an organic life.'

According to Davis landforms undergo sequential changes through time (passing through three stages of youth, mature and old). The earth's surface is affected by two types of forces viz. (i) endogenetic forces and (ii) exogenetic forces wherein endogenetic forces create vertical irregularities on the earth's surface by forming several types of relief features of different dimensions whereas exogenetic processes originating from the atmoshpere (rivers, wind, glaciers, seawaves, groundwater, periglacial processes etc.) try to remove the vertical irregularities created by the endogenetic forces and ultimately become successful in bringing down the reliefs to low featureless plain called as a peneplain. The whole period of the creation of relief features by endogenetic processes and their destruction by exogenetic processes is called cycle of erosion which Davis defined as follows : "geographical cycle is the period of time during which an uplifted landmass undergoes its transformation by the process of land sculpture ending into a low featureless plain-a peneplane."

The concept of 'geographical cycle' of Davis was severely criticised by German geographers and the term 'cycle' was described as confusing and hence untenable. Walther Penck though accepted the basic concept of cycle of erosion but rejected the Davisian model of geographical cycle and propounded his own model of cycle of erosion. Inspite of severe criticism in Germany the Davisian model of geo-

graphical cycle of erosion was adopted by most of the contemporary and subsequent geomorphologists all over the world. It may be safely argued that Davisian model of cycle of erosion, say the first general theory of landform development, dominated the entire field of geomorphology and geomorphological investigations right from its inception in 1899 to 1950 throughout the world. His 'cycle of erosion' was basically concerned with the evolution of landforms in humid temperatte areas but the cyclic concept was later on applied to almost all the geomorphic processes e.g. arid cycle of erosion (W.M. Davis, 1905), glacial cycle of erosion (Davis, 1900, 1906), marine cycle of erosion (Davis 1912 and D.W. Johnson, 1919), karst cycle of erosion (Beede, 1911 and Cvijic, 1918), periglacial cycle of erosion (L.C. Peltier, 1950) etc.

C. H. Crickmay suggested modifications in Davisian model of 'geographical cycle' in 1933 and described the process of **panplanation** to be more powerful and effective than Davis' process of **peneplanation** in the evolution of landforms. According to Crickmay the end product of the cycle of erosion would be **panplain** and not the peneplain. L.C. King proposed a new cycle of erosion named as **'the cycle of pediplanation'** to explain the characteristics and evolution of landforms of arid and savanna regions of Africa as he found Davisian model of geographical cycle unfit to explain the landforms of the aforesaid regions. J.C. Pugh (1966) and M.F. Thomas (1966) propounded the concept of **savanna cycle of erosion** to account for the development of landforms of semi-arid savanna regions of Africa. A.N. Strahler (1950), J.T. Hack (1960) and R.J. Chorley (1962) rejected the evolutionary concept of landform development as advanced by W.M. Davis and his followers and pleaded for the concept of 'time—independent landforms' instead of Davisian concept of **'time-dependent landforms'** and advanced the concept of **'dynamic equilibrium model'** of landform development. Recently, **'tectonogeomorphic model'** of Marie Morisawa (1975, 1980), **'episodic erosion theory'** of S.A. Schumm and R.W. Lichty (1965) etc. have been suggested to explain the landform development. These models are, in fact, modified forms of Davisian model of landform development

16.2 GEOGRAPHICAL CYCLE OF DAVIS

William Morris Davis, an American geomorphologist, was the first geomorphologist to present a general theory of landform development. In fact, his theory is the outcome of a set of theories and models presented by him from time to time e.g. (i) 'complete cycle of river life', propounded in his essay on 'The Rivers and Valleys of Pennsylvania' in 1889, (ii) 'geographical cycle' in 1899, (iii) 'slope evolution' etc. He postulated the cyclic concept of progressive development of erosional stream valleys under the concept of 'complete cycle of river-life', while through 'grographical cycle' he described the sequential development of landforms through time.

The general theory of landform development of Davis is not the 'geographical cycle' as many of the geomorphologists believe. His theory may be expressed as follows :

'There are sequential changes in landforms through time (passing through youth, mature and old stages) and these sequential changes are directed towards a well defined end product-development of peneplain.'

The basic goal of Davisian model of geographical cycle and general theory of landform development was to provide basis for a systematic description and genetic classification of landforms. The reference system of Davisian general theory of landform development is 'that landforms change in an orderly manner as processes operate through time such that under uniform external environmental conditions an orderly sequence of landform develops' (R.C. Palmquist, 1975). Various models were developed on the basis of this reference system e.g. normal cycle of erosion, arid cycle of erosion, glacial cycle of erosion, marine cycle of erosion etc. Thus, 'geographical cycle' is one of the several possible models based on Davis' reference system of landform development.

Davis postulated his concept of 'geographical cycle' popularly known as 'cycle of erosion' in 1899 to present a genetic classification and systematic description of landforms. His 'geographical cycle' has been defined in the following manner.

'Geographical cycle is a period of time during which an uplifted landmass undergoes its transformation by the process of landsculpture ending into low featureless plain or peneplain (Davis called peneplane)."

According to Davis three factors viz. structure, process and time play important roles in the origin and development of landforms of a particular place. These three factors are called as 'Trio of Davis' and his concept is expressed as follows :

"Landscape is a function of structure, process and time" (also called as stages by Davis' followers).

Structure means lithological (rock types) and structural characteristics (folding, faulting, joints etc.) of rocks. **Time** was not only used in temporal context by Davis but it was also used as a process itself leading to an inevitable progression of change of landforms. **Process** means the agents of denudation including both, weathering and erosion (running water in the case of geogrpahical cycle).

The basic premises of Davisian model of 'geographical cycle' included the following assumptions made by Davis.

(1) Landforms are the evolved products of the interactions of endogenetic (diastrophic) forces originating from within the earth and the external or exogenetic forces originating from the atmosphere (denudational processes, agents of weathering and erosion-rivers, wind, groundwater, sea waves, glaciers and periglacial processes).

(2) The evolution of landforms takes place in an orerly manner in such a way that a systematic sequence of landforms is developed through time in response to an environmental change.

(3) Streams erode their valleys rapidly downward until the graded condition is achieved.

(4) There is a short-period rapid rate of upliftment in land mass. It may be pointed out that Davis also described slower rates of upliftment if so desired.

(5) Erosion does not start until the upliftment is complete. In other words, upliftment and erosion do not go hand in hand. This assumption of Davis became the focal point of severe attacks by the critics of the cyclic concept.

Davis has described his model of georaphical cycle through a graph (fig. 16.1).

The cycle of erosion begins with the upliftment of landmass. There is a rapid rate of short-period upliftment of landmass of homogeneous structure. This phase of upliftment is not included in the cyclic time as this phase is, in fact, the preparatory stage of the cycle of erosion. Fig. 16.1 represents the model of geographical cycle wherein UC (upper curve) and LC (lower curve) denote the hill-tops or crests of water divides (absolute reliefs from mean sea level) and valley floors (lowest reliefs from mean sea level) respectively. The horizontal line denotes time whereas vertical axis depicts altitude from sea level. AC represents maximum absolute relief whereas BC denotes initial average relief. Initial relief is defined as difference between upper curve (summits of water divides) and lower curve (valley floors) of a landmass. In other words, relief is defined as the difference between the highest and the lowest points of a landmass. ADG line denotes **base level** which represents sea level. No river can erode its valley beyond base level (below sea level). Thus, base level

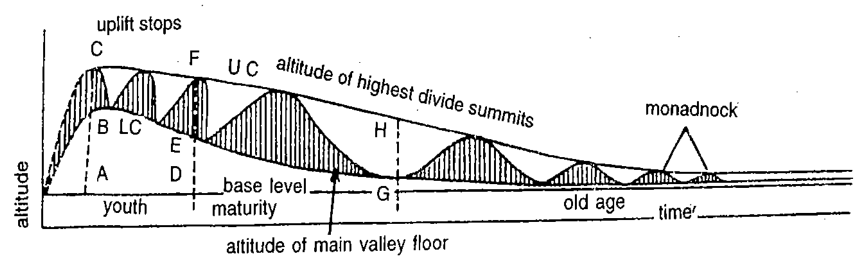


Fig. 16.1 : Graphical presentation of geographical cycle presented by W.M. Davis.

represents the limit of maximum vertical erosion (valley deepening) by the rivers. The upliftment of the landmass stops after point C (fig. 16.1) as the phase of upliftment is complete. Now erosion starts and the whole cycle passes through the following three stages :

(1) **Youthful stage**—Erosion starts after the completion of the upliftment of the landmass. The top-surfaces or the summits of the water divides are not affected by erosion because the rivers are small and widely spaced. Small rivers and short tributaries are engaged in headward erosion due to which they extend their lengths. The process is called **stream lengthening** (increase in the lengths of the rivers). Because of steep slope and steep channel gradient rivers actively deepen their velleys through vertical erosion aided by **pothole drilling** and thus there is gradual increase in the depth of river valleys. This process is called **valley deepening.** The valleys become deep and narrow characterized by steep valley side slopes of convex plan. The youthful stage is characterized by rapid rate of vertical erosion and valley deepening because (i) the channel gradient is very steep, (ii) steep channel gradient increases the velocity and kinetic energy of the river flow, (iii) increased channel gradient and flow velocity increases the transporting capacity of the rivers, (iv) increased transporting capacity of the rivers allow them to carry big boulders of high calibre (more angular boulders) which help in valley incision (valley deepening through vertical erosion) through pothole drilling. The lower curve (LC valley floor) falls rapidly because of valley deepening but the upper curve (UC summits of water divides or interestream areas) remain almost parallel to the horizontal axis (AD, in fig. 16.1) because the summits or upper parts of the landmass are not affected by erosion. Thus, relative relief continues to increase till the end of youthful stage when **ultimate maximum relief** (EF, in fig. 16.1) is attained. In nutshell, the youthful stage is characterized by the following characteristic features.

(i) Absolute height remains constant (CF is parallel to the horizontal axis) because of insignificant lateral erosion.

(ii) Upper curve (UC) representing summits of water divides is not affected by erosion.

(iii) Lower curve (LC) falls rapidly because of rapid rate of vally-deepening through vertical erosion.

(iv) Relief (relative) continues to increase.

(v) Valleys are of V shape characterized by convex valley side slopes.

(vi) Overall valley form is gorge or canyon.

(vii) Long profiles of the rivers are characterized by rapids and water falls which gradually diminish with march of time and these practically disappear by the end of late youth. The main river is graded.

(2) **Mature stage**—The early mature stage is heralded by marked lateral erosion and well integrated drainage network. The graded conditions spread over larger area and most of the tributaries are graded to base level of erosion. Vertical erosion or valley deepening is remarkably reduced. The summits of water divides are also eroded and hence there is marked fall in upper curve (UC) i.e. there is marked lowering of absolute relief. Thus, absolute relief and relative relief, both decrease. The lateral erosion leads to valley widening which transforms the V shaped valleys of youthful stage into wide valleys with uniform or rectilinear valleys sides. The marked reduction in valley deepening (vertical erosion or valley incision) is because of substantial decrease in channel gradient, flow velocity and transporting capacity of the rivers.

(3) **Old stage** is characterized by almost total absence of valley incision but lateral erosion and valley widening is still active process. Water divides are more rapidly eroded. In fact, water divides are reduced in dimension by both, downwasting and backwasting. Thus, upper curve falls more rapidly, meaning thereby there is rapid rate of decrease in absolute height. Relative or available relief also decreases sharply because of active lateral erosion but no vertical erosion. Near absence of valley deepening is due to extremely low channel gradient and remarkably reduced kinetic energy and maximum **entropy.** The valleys become almost flat with concave valley side slopes. The entire landscape is dominated by graded valley-sides and divide crests, broad, open and gently sloping valleys having extensive flood plains, well developed meanders, residual convexo-concave **monadnocks** and extensive undulating plain of extremely low relief. Thus, the entire landscape is transformed into **peneplain.** As revealed by fig. 16.1 the duration of old stage is many times as long as youth and maturity combined together.

Evaluation of the Davisian Model of Geographical Cycle

Davisian model of geographical cycle received world-wide recognition and the geomorphologists readily applied his model in their geomorphological investigations. The academic intoxication of Davis' model of cycle of erosion continued from its inception in 1899 to 1950 when the model had to face serious challenges though his model was being criticised from the very beginning of its postulation. S. Judson (1975) while commenting on Davis' geographical cycle remarked,"his grasp of time, space and change; his command of detail and his ability to order his information and frame his arguments remind us again that we are in the presence of a giant." C.G. Higgins (1975) admitted that "Davis system came to dominate both teaching and research in the descriptive and genetic-historical aspects of geomorphology. Its continued validity is attested in part by continuing objections to it by recent critics such as R.C. Flemal (1971) and C.R. Twidale (1975) that such an obviously flawed doctrine could have enjoyed such prolonged popularity among large segment of the geomorphic community suggests that there must be compelling reasons for its appeal" (Charles G. Higgins, 1975).

Positive Aspects of Davis' Model

(1) Davis' model of geographical cycle was highly simple and applicable.

(2) He presented his model in a very lucid, compelling and disarming style using very simple but expressive language. Commenting on the language of Davis used in his model Bryan remarked, "Davis rhetorical style is just admired and several generations of readers became, slightly bemused by long though mild intoxication of the limpid prose of Davis remarkable essay."

(3) Davis based his model on detailed and careful field observations.

(4) Davis' model came as a general theory of landform development after a long gap after Hutton's cyclic nature of the earth history.

(5) This model synthesized the current geological thoughts. In other words, Davis incorporated the concept of 'base level' and genetic classification of river valleys, the concept of 'graded streams' of G.K. Gilbert and French engineers' concept of 'profile of equilibrium' in his model.

(6) His model is capable of both predictions and historical interpretation of landform evolution.

Negative Aspects of Davis' Model

(1) Davis' concept of upliftment is not acceptable. He has described rapid rate of upliftment of short duration but as evidenced by plate tectonics upliftment is exceedingly a show and long continued process.

(2) Davis' concept of relationship between upliftment and erosion is erroneous. According to him no erosion can start unless upliftment is complete. Can erosion wait for the completion of upliftment? It is a natural process that as the land rises, erosion begins. Davis has answered this question. He admitted that he deliberately excluded erosion from the phase of upliftment because of two reasons : (i) to make the model simple and (ii) erosion is insignificant during the phase of upliftment.

(3) The Davisian model requires a long period of crustal stability for the completion of cycle of erosion but such eventless long period is tectonically not possible as is evidenced by plate tectonics according to which plates are always in motion and the crust is very often affected by tectonic events. Davis has also offered explanation to this objection. According to him if crustal stability for desired period is not possible., the cycle of erosion is interrupted and fresh cycle of erosion may start.

(4) Walther Penck objected to over emphasis of time in Davis' model. In fact, Davisian model envisages **'time-dependent series'** of landform development whereas Penck

pleaded for **'time-independent series'** of landforms. According to Penck landforms do not experience progressive and sequential changes through time. He, thus, pleaded for deletion of **'time'** (stage) from Davis' **'trio'** of **'structure, process** and **time'**. According to Penck "geomorphic forms are expressions of the phase and rate of upliftment in relation to the rate of degradation" (Von Engeln, 1942).

(5) A.N. Strahler, J.T. Hack and R.J. Chorley and several others have rejected the Davisian concept of **'historical evolution'** of landforms. They have forwarded the **dynamic equilibrium theory** for the explanation of landform development. It may be pointed out that non-cyclic concept of 'dynamic equilibrium' as valid substitute of Davis' cyclic concept of landform development and other so called **'open system'** and non-cyclic models of landform development could not arouse any enthusiasm among the modern geomorphologists.

It may be concluded in the words of Charles Higgins (1975) that "If the desire for a cyclic, time-dependent model stems from an unacknowledged fundamental postulate that the history of the earth is itself cyclic, then no non-cyclic theory of landscape development can win with general acceptance until this postulate is unearthed, examined, and possibly rejected."

16.3 PENCK'S MODEL OF CYCLE OF EROSION

It may be pointed out that German scientist Walther Penck pleaded for the rejection of Davisian model of geographical cycle based on time-dependent series of landform development and presented his own model of 'morphological system' or 'morphological analysis' for the explanation of landscape development. The main goal of Penck's model of morphological system was to find out the mode of development and causes of crustal movement on the basis of exogenetic processes and morphological characteristics. The reference system of Penck's model is that the characteristics of landforms of a given region are related to the tectonic activity of that region. The landforms, thus, reflect the ratio between the intensity of endogenetic processes (i.e. rate of upliftment) and the magnitude of displacement of materials by exogenetic processes (the rate of erosion and removal of matrials).

Penck is perhaps the most misunderstood geomorphologist of the world: It is not yet sure whether he used the word 'cycle' or not in his model of landform development. Penck's views could not be known in true sense and could not be interpretted in right perspective because of (i) his incomplete work due to his untimely death, (ii) his obscure composition in difficult German language, (iii) ill-defined terminology, (iv) misleading review by W.M. Davis and (v) some contradictory ideas.

According to Penck landform development should be interpretted by means of ratios between diastrophic processes (endogenetic, or rate of uplift) and erosional processes (exogenetic, or rate of vertical incision).

Penck is supposed to have deliberately avoided the use of stage concept in his model of landscape development either to undermine the cyclic concept of W. M. Davis or to present a new model. According to O.D. Von Engeln (1960) "Penck found escape from the concept of cyclic change marked by the stages youth, maturity and old age." In the place of 'stage" he used the term **entwickelung** meaning thereby **development**. Thus, in the place of youth, maturity and old stages he used the terms aufsteigende entwickelung (waxing or accelerated rate of development), gleichformige entwickelung (uniform rate of development) and absteigende entwickelung (wanning or decelerating rate of development).

Penck used the term **primarumpf** to represent the characteristic landscape before upliftment. Primarumpf is, in fact, initial surface or primary peneplain representing either newly emerged surface from below sea level or a **fastenbene** or 'peneplain' type of land surface converted into featureless landmass by uplift. According to Von Engeln (1942) the "primarumpf is a primary peneplain, one which could, in either case, exhibit truncated beds and structures, and yet need never have had a greater altitutde or a higher relief." In other words, primarumpf is the initial landscape with evidences of erosion but with low altitude.

Contrary to the concept of W.M. Davis, 'that landscape is a function of structure, process and time (stage)', Walther Penck postulated that, 'geomorphic forms are an expression of the phase and rate of uplift in relation to the rate of degradation. It is assumed that ineraction between the two factors, uplift and degradation, is continuous. The landforms observed at any given site give expression to the relation between the two factors (uplift and degradation) that has been or is in effect, and not to a stage in a progressive sequence' (O.D. Von Engeln. 1960. pp. 261-62).

The landscape development (we may say the cycle of erosion) begins with the upliftment of primarumpf (initial landscape with low height and relief) representing an initial featureless broad land surface. In other words, **primarumpf** is initial geomorphic unit for the beginning of the development of all sorts of landforms. Penck is supposed to have assumed varying rates of upliftment of primarumpf for the development of landforms. In the beginning the uplift is characterized by exceedingly slow upheaval of long duration and thereafter the rate of uplift is accelerated and ultimately it stops after passing through the intermediate phases of uniform and declerating rates of upheaval. In fact, "the most tectonic movements began and ended slowly, and that the common pattern of such movements involved a slow initial uplift, an accelerated uplift, a deceleration in uplift and, finally, quiescence" (R.J. Chorley, et. al., 1985, p. 28). The initial uplift begins with regional updoming and the landform development passes through the following three phases.

(1) Aufsteigende entwickelung means the phase of waxing (accelerating) rate of landform development. Initially, the land surface rises slowly but after some time the rate of upliftment is accelerated. Because of upliftment and consequent increase in channel gradient, flow velocity and kinetic energy and of course increase in discharge (not due to uplift) the rivers continue to degrade their valleys with accelerated rate of downcutting (valley deepening or incision) but the rate of upliftment far exceeds the rate of valley deepening (say degradation of uplifted landmass). Continuous active downcutting and valley deepening results in the formation of deep and narrow V shaped valleys. As the rate of uplift (aufsteigende entwickelung) continues to increase the V shaped valleys are further deepened and sharpened. Since valley deepening does not keep pace with the upliftment of landmass the absolute height continues to increase. In other words, the altitudes of divide summits as well as the altitudes of valley bottoms continue to increase as the rate of upliftment far exceeds the rate of vertical erosion (fig. 16.2) but the relative or available reliefs continue to increase due to everincreasing rate of vertical erosion or valley deepening. Thus, both maximum altitude (absolute height from sea level) and maximum relief (relative) increase (1 in fig. 16.2). The slopes of valley sides are convex in plan.

The valley side slopes are continuously steepened due to continued valley deepening. The radius of convexity of slopes is reduced with passage of time due to parallel retreat of the steeper slope segments. With the passage of time and more accel-

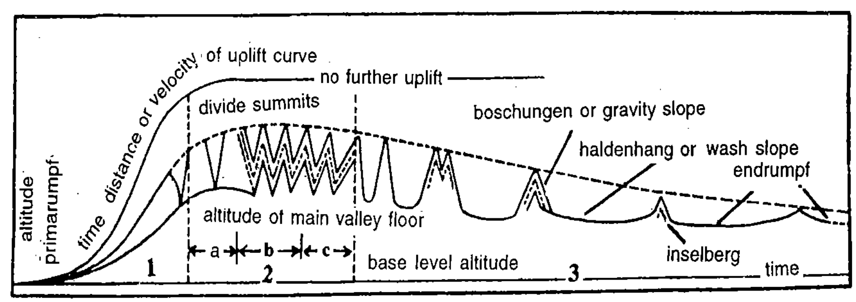


Fig. 16.2 : Graphic presentation of Penck's model of landform development.

erated uplift and degradation the primary peneplain or say primarumpf is surrounded by a series of benches called as **piedmont treppen.** Each of such benches develops as a piedmont flat, called in German as **piedmontflache** on the slowly rising margins of the dome.

(2) Gleichformige entwickelung means uniform development of landforms. This phase may be divided into 3 subphases on the basis of rate of uplift and degradation (2 in fig. 16.2). **Phase (a)** is characterized by still accelerated rate of uplift. Absolute height still increases because the rate of erosion is still less than the rate of upliftment. Altitudes of both summits of water divides and valley floors continue to increase but at relatively lower rate than in the phase of Aufsteigende entwickelung. Maximum altitude (absolute relief) is attained but relative relief remains constant because the rate of valley deepening equals the rate of lowering of divide summits. The valley sides are characterized by straight slopes (2a in fig. 16.2). This phase is called the phase of uniform development probably because of uniform rate of valley deepening and lowering of divide summits. **Phase (b) :** Altitude (absolute relief) neither increases nor decreases i.e. remains constant due to matching of upliftment by the lowering of divide summit due to denudation. It means that upliftment still continues. Relative relief also remains constant because the rate of erosion of divide summits matches with the rate of valley deepening while both are uplifted uniformly. The slopes of valley sides are still straight as in phase 2a because of parallel retreat. This phase is, thus, characterized by constant absolute and relative reliefs and thus uniform development of landforms. **Phase (c) :** Upliftment of the land stops completely. Absolute reliefs or altitudes of summit divides start decreasing because of absence of upliftment but continued erosion of summits of divides. Relative reliefs also remain constant because the rate of the lowering of divide summits equals the rate of valley deepening. Thus, this subphase is also characterized by uniform development of landscape.

(3) Absteigende entwickelung means wanning development of landscape during which the landscape is progressively dominated by the erosional process of lateral erosion and consequent valley widening and marked decrease in the rate of valley deepening through vertical downcutting. This phase is marked by progressive decline of landforms. Absolute relief (altitude from sea level) decreases remarkably because of total absence of upliftment but continued downwasting of divide summits. Relative relief also decreases because the divide summits are continuously eroded down and lowered in height while downcutting of valley floor decreases remarkably due to decrease in channel gradient and kinetic energy. Parallel retreat of valley side slopes still continues. Now the valley side slope consists of two segments. The uppermost segment maintains its steep angle inspite of continuous lowering of ridge crests. This slope is called **gravity slope** or **boschungen.** The lower segment of the valley sides is called **wash slope** or **haldenhang.** Haldenhang, composed of talus materials of lower inclination, is formed at the base of the valley sides due to rapid parallel retreat of gravity slope or boschungen and consequent elimination of much of the convex waxing slopes. Divide summits are continuously lowered by the intersection of the retreating boschungen of adjoining valleys. Thus, the intersection of boschungen and haldenhang produces sharp knick (break in slope). Haldenhang or wash slope continues to expand at the cost of upper gravity slopes. In the advanced stage of the phase of absteigende entwickelung the gravity slopes or boschungen are reduced to steep-sided conical residuals called **inselbergs** (fig. 16.2). Eventually, inselbergs are also consumed and the whole landscape is dominated by a series of concave wash slopes or haldenhang. Such extensive surface produced at the end of absteigende entwickelung is called **'endrumpf'**, which may be considered equivalent to Davis' **peneplain.**

Evaluation of Penck's Model

The Penck's model of landscape development, as pointed out in the beginning, could not be correctly interpretted because of its publication in obscure German language and wrong interpretation of his ideas by English translators. Penck's morphological system was severely criticised in the USA in the same way as the 'geographical cycle' was criticised in Germany. Penck's concepts of parallel retreat of slope and continued crustal movements became the most sensitive points of attacks by American geologists. It may be pointed out that earlier

transaltion of Penck's work in English revealed that Penck believed in parallel retreat of slopes but subsequent English translations showed that Penck believed in slope replacement wherein each upper slope unit of hillslope and valley sides was considered to be replaced by lower slope unit of gentler slope. It may be, thus, forwarded that most of the criticisms of Penck's morphological system came out of the faulty interpretations of his views. Some of the American critics stooped down to such an extent that they remarked that "his peculiar notions owed to his incomplete recovery from a head wound suffered in World War I" (quoted by C.G. Higgins, 1975). His concept of long continued upliftment and tectonic speculations could not find any support but his concepts of slope development and weathering processes are definitely of much geomorphological significance.

16.4 NORMAL CYCLE OF EROSION

The cycle of erosion by fluvial processes (running waters or rivers) is called normal cycle of erosion because of the fact that fluvial processes are most widespread (covering most parts of the globe) and most significant geomorphic agent. Even water also plays important roles in glacial, and arid regions. W. M. Davis considered humid temperate areas as the most normal case for fluvial cycle of erosion but this claim is debatable.

The normal cycle of erosion begins with the upliftment of any landmass with reference to sea level. As the land rises, the rivers are originated and their erosional work starts. The rate of uplift in the beginning far exceeds the rate of erosion with the result absolute relief (absolute altitude from sea level) and relative relief register increase. After some time upliftment of the land stops and erosion becomes more active. The land area, teconically, remains stable i.e. there is crustal stability for long period of time during which there is neither upliftment nor subsidence of land area. There is progressive development of river valleys in sequential order and the whole land area progressively passes through three successive stages of youth, mature and old (senile or penultimate) and is ultimately transformed into low featureless plain of undulating surface. Thus, the penultimate end product of normal cycle of erosion is called **peneplain** which is characterized by undulating surface with residual convexo-concave low hills known as **'monanocks'**, **'unakas'** and **'mosores'**.

Thus, the land area has to pass through the successive stages of its development right from the upliftment of landmass to its transformation into peneplain of exceedingly low reliefs. W.M. Davis has divided the whole duration of normal cycle of erosion into three successive stages of youth (juvenile), mature (equilibrium) and old (penultimate or senile) and each stage has been further divided into three substages e.g. early, middle and late (for example, early youth, middle youth and late youth and so on). Thus, the landscapes also become young, mature and old with the advancement of normal cycle of erosion. Like landscape development through three sucessive stages, the development of river valleys also passes through three successive stages of their development and the rivers become young or youthful rivers, mature rivers and old rivers (fig. 16.3). The following are the characteristic features of successive stages of the normal cycle of erosion.

1. Youthful Stage

Consequent streams (which follow the regional slope) are originated with the upliftment of land area due to endogenetic forces. In the beginning, the streams are less in number and short in length. Very few tributaries of the master consequent streams are originated. The slopes are dominated by numerous rills and gullies rather than big streams. These rills and gullies lengthen their longitudinal profiles (increase their lengths) through **headward erosion.** Gradually and gradually the main streams deepen their valleys. The origin and evolution of tributaries of master streams give birth to the development of dendritic drainge pattern. The rivers are continuously engaged in rapid rate of downcutting of their valleys (valley incision) because the transporting capacity of the rivers is maximum due to high velocity of flow rate and kinetic energy because of very steep channel gradient. High transporting capacity enables the rivers to carry big boulders (tools of erosion) of fairly good size (large size)

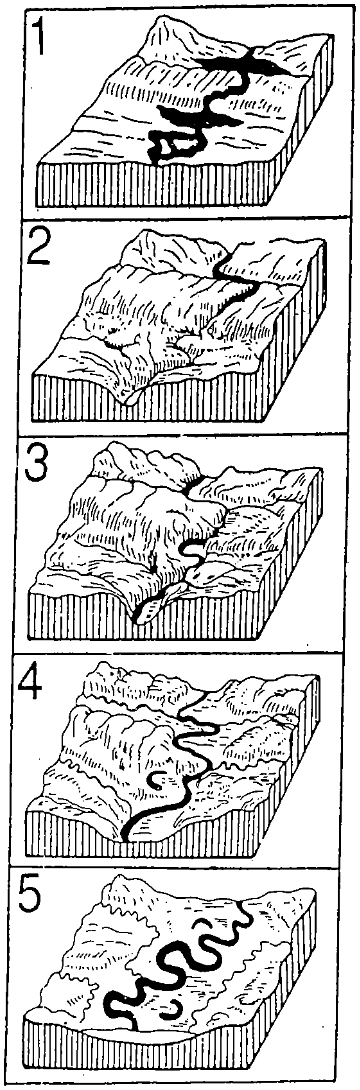


Fig. 16.3 : Stages of river cycle or life history of rivers—1. early youthful stage (lakes and falls), 2. youthful stage, 3. early maturity. 4. maturity and 5. old stage.

and high calibre (angular boulders) which help in the **pothole drilling** of the river beds. It may be mentioned that pothole drilling is the most active and powerful process of vertical erosion (valley deepening) in the juvenile stage of the normal cycle of erosion.

The valley becomes very narrow and deep with almost vertical side walls due to continuous active downcutting of the valley floors at exceedingly fast rate. The valley side slopes are convex in plan. Thus, the resultant juvenile valleys are V-shaped and are called **gorges and canyons.** The valley floors are studded with numerous **pot holes** which are the result of pothole drilling. The interstream areas or **water divides** (land area between the valleys of two major streams) are extensive and wide and these are least affected by denudational processes because **valley widening** by lateral erosion is less effective in the early and middle youth stages. The valley thalwegs (longitudinal profiles of the rivers) are characterized by numerous rapids and waterfalls which always recede upstream. Most of the water falls and knick points disappear by late youth. The rivers are underloaded (not having the required amount of sediment load) according to their transporting capacity and thus available energy is more than the work to be done. The rivers are well integrated by the end of youth when maximum relative reliefs are formed.

River capture is the most characteristic feature of the juvenile stage of the normal cycle of erosion. Main rivers having steeper channel gradients and more volume of water capture smaller streams of relatively low channel gradient through headward erosion.

2. Mature Stage

Marked valley deepening through vertical erosion during youthful stage results in pronounced decrease in channel gradient and consequent decrease in flow velocity with the result the arrival of early maturity is heralded by marked decrease in valley deepening due to (i) decrease in channel gradient, (ii) decrease in the velocity of river flow, (iii) decrease in the transporting capacity etc. Consequently, valley widening through active lateral erosion dominates over valley incision through downcutting. The convex slope of valley sides is progressively transformed into uniform or rectilin-

ear slope and the gorges and canyons characterized by deep and narrow valleys are replaced by broad and flat valleys.

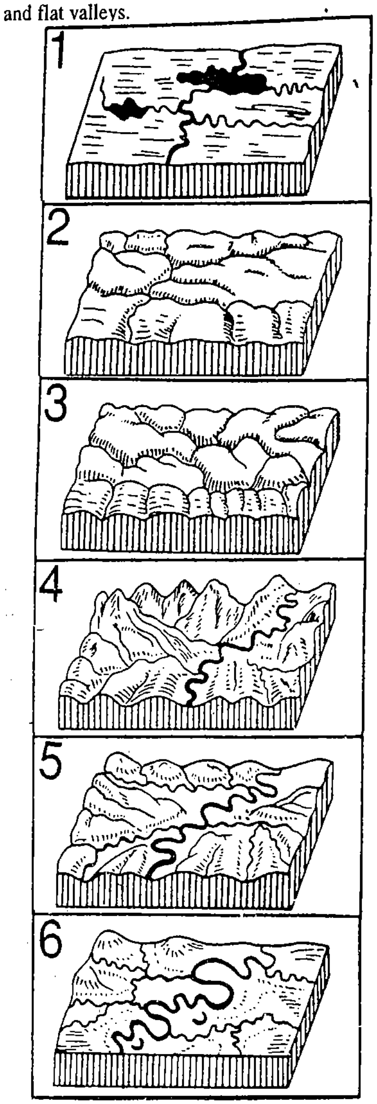


Fig. 16.4 : Stages of normal cycle of erosion—1. initial stage. 2. early youth, 3. late youth, 4. early maturity, 5. maturity and 6. old stage (peneplain).

The rivers deposit big boulders at the foothill zones due to sudden decrease in channel gradient and hence marked decrease in the transporting capacity of the rivers. These materials form **alluvial fans and alluvial cones.** The gradual expansion of of these fans and cones due to their continuous growth result in the formation of extensive **peidmont plains** through the coalescence of several fans and cones. Interstream areas or water divides are continuously narrowed due to **backwasting** caused by active lateral erosion and valley widening. Thus, interstream areas are transformed into narrow ridges. The major river erodes down to its base level (sea level) and becomes **'graded'**. Thus, the longitudinal profile of the master river becomes the **profile of equilibrium** wherein there is balance between available energy and the work to be done i.e. balance between the transporting capacity and total sediment load to be transported. Because of marked decrease in channel gradient rivers adopt sinous courses and develop numerous **meanders** and **loops** in their courses. Extensive **flood plains** are formed due to sedimentation of alluvia. Rivers frequently change their courses because of gentle to level slopes of the flood plains. Numerous **ox bow lakes** are formed due to straightening of highly meandering loops. Deposition of sediments on either side of the river valleys leads to the formation of **natural levees.**

3. Old Stage

The old stage is characterized by further decrease in channel gradient, almost total absence of valley deepening, decrease in the number of tributary streams and flattening of valleys. Tributary streams also attain the base level of erosion and are graded. Lateral erosion and consequent backwasting eliminates most of interstream areas. Valleys become broad and flat characterized by concave slopes of valley sides. Downcutting of the valleys is totally absent. Weathering processes are most active. Thus, lateral erosion, downwasting and weathering continuously degrade the land resulting into gradual lowering of absolute altitude and water divides. Interstream areas and water divides are remarkably reduced in height and are changed to lowland but they still rise above the surrounding areas. Transporting capacity of the rivers becomes minimum because of very low channel gradient and thus the rivers become overloaded. Consquently, sedimenta-

tion becomes most active during this stage. The rivers adopt highly meandering courses. The extensive flood plains with level to gentle slopes (2^0-5^0) and very low channel gradient make the river flow so sluggish that the main channel of the river is divided into numerous distributaries and thus the river becomes **braided.** Valley sides are bordered by extensive natural levees which are also known as bluffs which denote the farthest limit of recurrent floods of the concerned rivers. Rivers deposit and form extensive **deltas** at their mouths if other environmental conditions remain favourable for delta formation.

The entire landscape is converted into extensive flat plain of undulating surface except a few residual convexo-concave hills which project above the general flat surface and thus break the monotony of reliefless flat plain, called as **peneplain.** These residual hills, the result of differential erosion, are called **monadnocks** on the basis of Monadnock hills of the North-East Applachians in New England region (USA). The whole landscape is dominated by concave slope, minimum available energy, both potential (because of very low height) and kinetic energy (due to very low channel gradient) and maximum entropy (means maximum disorder of relief, as the whole area is characterized by featureless peneplain).

This ideal normal cycle of erosion can pass through its all the three stages (i.e. youth, mature and old) and the peneplain can be formed only when the region remains in stand still position for longer duration of crustal stability but the availability of such condition is of remote possibility because the earth is very much unstable. The plate tectonics have also revealed that plates are always mobile and hence long period of crustal stability is not possible. Thus, the smooth functioning and completion of normal cycle of erosion is very often disturbed due to tectonic events and also due to climatic changes. The disturbance in the cycle of erosion is called **interruption of normal cycle of erosion** which is caused by changes in sea level (either due to upliftment or subsidence of oceanic bottoms or due to glaciation and deglaciation during great ice ages, like Carboniferous glaciation of the Gondwanaland during Carboniferous period and Pleistocene glaciation of the northern hemisphere during Pleistocence period), upliftment or subsidence of land areas, volcanic eruptions and climatic changes. The interruption of normal cycle of erosion by volcanic eruptions or climatic changes is called **'accident'**. The interruptions caused by negative changes in base level (lowering of base level-maximum limit of vertical erosion by rivers) due to fall in sea level (because of the subsidence of the oceanic floors) and upliftment of landmass are called **rejuvenation**, which means renewed vigour of erosive capacity of the rivers. Rejuvenated rivers are again engaged in valley deepening at much faster rate and thus the cycle of erosion is driven back to youthful (juvenile) stage. Several interesting landforms, like valley in valley topography or multi-storeyed valleys, paired terraces, incised meanders, nick points and nickpoint water falls, uplifted peneplains, deeply entrenched gorges and canyons within broad flat valleys etc. are formed due to rejuvenation. The landforms resulting from several cycles of erosion, whether complete or incomplete, are called **polycyclic landrorms** or multicyclic landforms. e.g. Chotanagpur region represents multicyclic landforms.

16.5 INTERRUPTIONS IN CYCLE OF EROSION

Meaning

Davisian cyclic concept envisages gradual sequential changes in uplifted landmass through the stages of youth, mature and old culminating into the development of low featureless plain called as **peneplain.** The completion of such generalized and ideal form of cycle of erosion depends on tectonic stability of longer period of time, which is seldom possible in the nature as the earth is unstable. Thus, the cycle of erosion is liable to frequent interruptions which cause inequilibrium condition in the cyclic model. Any sort of obstacle in the normal functioning of cycle of erosion is called **interruption of cycle.** The basic causes of interruption may be climatic or tectonic or both. Tectonic factors are related to positive and negative movement of base levels of erosion. The interruptions in cycle of erosion caused by positive movement of base level (due to susidence of landmass or rise in sea level) shortens the cyclic time as it advances forward e.g. if the cycle is in youth stage, it may advance (due to positive movement of base level) to mature stage or if it is in the mature stage it may advance to old stage. Conversely, negative change in base level of erosion

(due to upliftment of landmass or fall in sea level) lengthens the cyclic time as the cycle is pushed backward e.g. if the cycle is running through late mature stage and there is either sudden upliftment of landmass or fall in sea level, the cycle goes back to youth stage characterized by renewed vigour of valley incision known as rejuvenation. Thus, the cycles punctuated by interruptions are called as **interrupted cycles** which lead to occurrences of several cycles in a region. Such cycles are called **polycycles.** If the polycycles (multi-cycles) occur in succession, they are called **successive cycles of erosion** and the landscapes resulting therefrom are called polyclic or multi-cyclic landscapes. Applachian regions of the U.S.A. and Chotonagpur region of India present typical examples of polycyclic landscapes where several cycles have been completed. Paired terraces, valley in valley topography, and incised meanders of the Damodar Valley at Rajroppa in Hazaribagh (Jharkhand) and valley in valley topography and paired terraces, Dhunwadhar falls and incised meander of the Narmada river at Bheraghat near Jabalpur (M.P.) are indicative of rejuvenation and polycyclic reliefs.

It may be pointed out that the interruption of cycle of erosion is generally divided into two categories i.e. if the interruption is such that the period of cycle is either lengthened (due to rejuvenation) or shortened it is simply called as interruption of cycles. It may also be called as **base level change interruption.** If the interruption is such that the chapter of ongoing cycle is closed and a new cycle is initiated after a gap of long time, such interruption is called as **accident** which is caused either due to climatic changes or volcanic eruptions. Suppose, a fluvial cycle of erosion is running through mature stage, and if there is a widespread volcanic fissure flow leading to pouring of immense volume of lava resulting in the obliteration of all the existing streams, then the chapter of cycle of erosion would be closed. New set of streams would appear on new surface after the lava is cooled and solidified and a fresh cycle of erosion would start.

1. Interruptions due to vulcanicity and climatic changes (accidents)

The chapter of any cycle of erosion is closed due to permanent interruptions caused by volcanic eruption and climatic changes. The widespread volcanic fissure flows cause upwelling and pouring of immense volume of basaltic lava which covers larger areas and obliterates surface drainage and reliefs which results in the permanent interruption and closure of the existing chapter of existing fluvial cycle of erosion. The fresh cycle of erosion may start only when the fissure flow ceases, lavas are cooled and solidified, new surface is formed and new sets of streams are initiated. It may be pointed out that such interruptions in the fluvial cycle occurred over Indian peninsula during Cretaceous period when Deccan lava flows covered vast areas of the Deccan plateau including Chotanagpur plateau and even southern parts of the Vindhyan upland causing closure of the Jurassic cycle of erosion. The new Tertiary cycle was initiated only after the Deccan trappean lavas were cooled and solidified and monsoon climate set in.

Climatic interruptions (accidents) occure due to major changes in the climate of the concerned region, for example, if the fluvial cycle of erosion in a humid region is passing through mature stage, and there is sudden climatic change leading to onset of either extreme dry conditions or extreme cold conditions, then the cycle of erosion is interrupted to such an extent that the chapter of current cycle of erosion is closed and another set of cycle either arid cycle (if the climate becomes extreme hot and arid) or glacial or periglacial cycle (if the climate becomes glacial/periglacial or subglacial) sets in. It may be mentioned that if there are minor changes in the climate, then the chapter is not closed, rather it (cycle) is either augemented or slowed down. Suppose, if the climate becomes more humid leading to increased amount of rainfall, then the surface runoff and stream discharge will automatically increase which would cause local interruption in the cycle by accelerating the rate of erosion (case of rejuvenation), the effects of which may spread over larger areas.

2. Interruptions due to base level changes

Any change in the base level of erosion (determined by the sea level) causes interruptions in the cycle of erosion or may initiate new cycle whether the previous cycle is complete or not. Changes in base level of erosion are basically of two types i.e. **positive change** (due to rise in sea level) and **negative**

change (due to fall in sea level). The base level changes caused due to sea level changes are eustatic (wide spread). Base level of erosion also changes due to tectonic factors i.e. subsidence of landmass causes positive change whereas upliftment of landmass is responsible for negative change. It may be mentioned that such type of subsidence or upliftment of landmass may be or may not be related to sea-level. Positive change of base level (or rise in base level) shortens the cyclic time. Secondly, positive change of base level of erosion is indicative of accelerated alluviation (deposition) whereas negative change causes accelerated erosion (rejuvenation). It is evident that rejuvenation is the most important factor of interruption in the fluvial cycle of erosion and genesis of polycyclic (multi-cyclic) reliefs and hence it needs detailed discussion.

16.6 REJUVENATION

Rejuvenation simply means accelaration of erosive power of the fluvial process (rivers) caused by a variety of factors. Rejuvenation lengthens the period of cycle of erosion. For example, if the cycle of erosion is passing through senile stage (old stage) characterized by gentle channel gradient, sluggish river flow and broad and shallow alluvial valleys, after rejuvenation (caused either due to substantial fall in sea level or due to upliftment of landmass) the cycle is interrupted and is driven back to juvenile (youth) stage characterized by steep channel gradient and accelerated valley incision. Rejuvenation is of 3 types—

1. Dynamic rejuvenation

Causes :

(i) upliftment in the landmass
(ii) tilting of land area
(iii) lowering of outlet

2. Eustatic rejuvenation

Causes :

Changes in sea level due to :

(i) diastrophic events (subsidence of sea floor or rise of coastal land)
(ii) glaciation causing fall in sea level

3. Static rejuvenation

Causes :

(i) decrease in the river load
(ii) increase in the volume of water and consequent stream discharge due to increased rainfall or melt-water
(iii) increase in water volume of the main river due to river capture

Causes of Rejuvenation

As pointed out earlier, the basic cause for rejuvenation of fluvial cycle of erosion (acceleration of erosive power of the river) is negative change in the base level of erosion (which is determined by the sea level) which is caused by a host of factors. Negative change of base level of erosion is always related to negative change in sea level (fall in sea-level) which is also called as **eustatic movement** as it is widespread and global phenomenon. It may be pointed out that fall in sea level (and hence causing negative movement/change in base level of erosion) steepens the channel gradient resulting into increased kinetic energy of the fluvial process which resorts to valley incision with renewed vigour.

The eustatic negative change in sea level is caused during glacial ages when most of seawater is locked on the continents as thick cover of ice sheets. The consequent lowering of sea level causes steepening of channel gradient of streams which are infact rejuvenated and are engaged in active downcutting of their valleys. The Pleistocene glaciation of the northern parts of N. America and Eurasia caused widespread rejuvenation in the temperate and tropical zones. Four river terraces of the Red river of the U.S.A. have been related to four periods of advancement of ice sheets i.e. Nebraskan, Kansan, Illinoin and Wisconcin glacial periods of the Pleistocene Ice Age.

Negative change in sea level causing rejuvenation locally and regionally is also caused because of subsidence of sea floor in relation to coastal land due to tectonic factors.

Local or regional upliftment of landmass causes interruption in the flivial cycle of erosion and rejuvenates the fluvial processes (streams). Such type of regional rejuvenation caused by secular rise in the landmass has been reported from several parts of the Chotanagpur Highlands of Jharkhand which experienced 3 phases of upliftment in response to three episodes of upliftment of the Himalayas during Tertiary period. The Patlands of the Ranchi plateau and Palamau uplands (Jharkhand) were subjected to an upliftment of 305 m resulting in the interruption of fluvial cycle of erosion and rejuvenation of

N. Koel river and its tributaries. The **nick points** and resultant waterfalls on Burha river (Burhaghaugh falls 142 m, Gutamghaugh falls, 36.57 m and Ghoraghughra falls 7.62 m), a tributary of the N. Koel river, on Pandra river (Ghagri falls of 43 m), on Sankh river (Sadnighaugh falls of 61 m). on Jori river (Jalimghaugh falls of 37 m), on Ghaghra river (Nindighaugh falls of 45.72 m) etc. indicate rejuvenation.

Lowering of outlets of streams also causes rejuvenation due to release of extra volume of water in the concrned river. Such rejuvenation (due to increase in the volume of water) also occurs when the water supply suddenly increases due to river capture (supply of extra water of the captured stream to the captor stream).

16.7 TOPOGRAPHIC EXPRESSIONS OF REJUVENATION (POLY (MULTI) CYCLIC RELIEFS)

The typical landforms resulting from interruptions in the fluvial cycle of erosion and from rejuvenation resulting in the formation of mossaic of poly or multi-cyclic landforms include topographic discordance, valley in valley or multi-storeyed valleys, uplifted peneplains, incised meanders, paired terraces, nick points etc.

Topographic discordance refers to the creation of older topographic forms above and younger forms below. In other words, when the topographic accordance or uniformity from the top of the river valley to its bottom is not maintained rather is disturbed due to interruption in fluvial cycle of erosion caused by rejuvenation, the resultant topographic expression is called **topographic unconformity** or discordance wherein the upper part of the valley reveals the sign of senile or mature stage whereas the lowest part of the valley belongs to youth stage. The river develops flat and shallow valley at the end of mature and beginning of senile stage but if there is sudden negative change in the base level of erosion caused either by fall in sea level or upliftment of landmass, the river is rejuvenated and begins active downcutting of its valley due to increased erosive power. Thus, a deep and narrow valley is formed within flat and broad valley. This new deep and narrow valley is flanked by terraces on its either side which represent earlier older valley. Such topography is called **'valley in valley topography'** or **'two storeyed valley'** or **'two cycle valley'**. By the march of time the rejuvenated river deepens its valley to the new base level and thus forms second broad and flat valley within the first broad and flat valley formed during first cycle of erosion. Suppose, if there is again upliftment of landmass or fall in sea level, the cycle is again interrupted and the river is rejuvenated. Consequently, again a narrow and deep valley is formed within previously formed two storeyed valley. Now there are two paired terraces on either side of the new deep and narrow valley. Thus, the resultant form of the valley is called **three storeyed valley**. Such topographic forms, where there are more than one valley in a single river's cross profile, are called **'multi storeyed or multi-cyclic valleys'**.

Examples—The Damodar valley at Rajroppa in Hazaribagh (Jharkhand) is a typical example of poly-cyclic valley or topographic discordance which is characterized by two-storeyed valley. The Damodar river developed its broad and flat valley of senile stage before the onset of Tertiary upliftment. The river was rejuvenated due to upliftment of landmass during Tertiary period caused by the side effects of the Himalayan orogeny and thus the Damodar excavated its new deep and narrow valley of youthful stage within its broad and flat valley of senile stage. The Bhera river coming from over the Ranchi

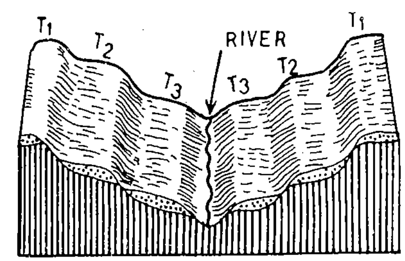


Fig. 16.5 : Example of poly cyclic valleys and paired river terraces-T-Terraces.

plateau makes a water fall while joining the Damodar river and thus presents an example of a hanging valley. Such topographic discordance is also observable in the valley of the Narmada river at Bheraghat (downstream from Dhunwadhar falls, 15 km away from Jabalpur city in M.P.).

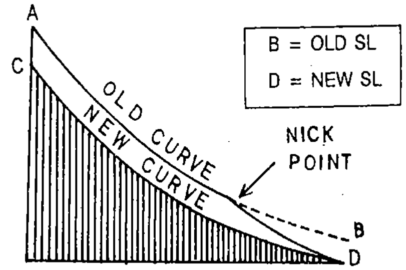


Fig. 16.6 : Graphic presentation of nick points.

Three storeyed valleys have been located in the Himalayas where the rivers were rejuvenated thrice due to three major episodes of upliftment of the Himalayas during Tertiary orogeny. Nearly all the major rivers of the Uttaranchal Himalayas are flanked by three sets of terraces on their either side.

Uplifted peneplains are formed due to interruption caused by rejuvenation consequent upon regional upliftment. The uplifted peneplains are represented by their remnants of accordant summit levels which rise above the general ground surface of the present-day planation surface. Uplifted peneplains are in fact the results of successive cycles of erosion wherein several fluvial cycles of erosion are completed in succession. Three uplifted peneplains have been identified in the Applachians (which are indicative of successive phases of upliftment, consequent rejuvenation and cycles of erosion) e.g. (from older to younger) Schooley peneplain (after Schooley mountain), Harrisburg peneplain (after Harrisburg mountain), and Sammerville peneplain. The Patlands of the Ranchi plateau is a typical example of uplifted peneplain which is higher than the central Ranchi plateau (610 m a.m.s. 1). The granitic-gneissic surface (910 m. a.m.s.1) of the western highlands has a capping of 154m thick basaltic lava (now weathered to laterites) cover of Cretaceous period. Prior to Cretaceous lava flow the entire Ranchi plateau, including the present western highlands, was peneplained by Jurassic period, the western part of which received lava cover of 154 m thickness during Cretaceous period. This western part (610 m + 154 m lava) was uplifted by 305 m in Tertiary epoch and thus the granitic-gneissic surface of 915 m height lying below 154 m thick lateritic basalt is an example of uplifted peneplain (fig. 16.7). The North Koel and its numerous tributaries have dissected patlands and segmented them into several small tableaux locally known as 'pats' (which are fine examples of mesas and buttes) such as Netarhat pat, Khamar pat, Rudni pat, Jamira pat, Raldami pat, Bangru pat etc.

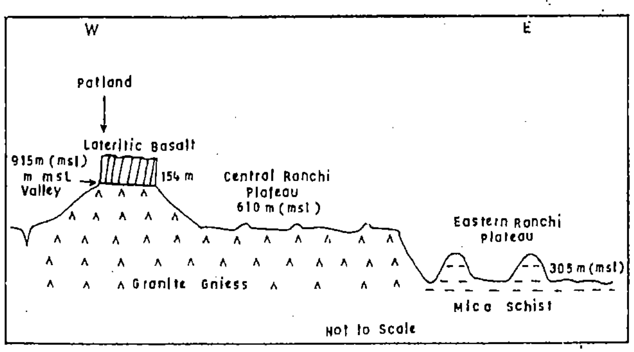


Fig. 16. 7 : Sketch map of Patlands and Ranchi plateau, Jharkhand.

Incised meanders—Five alternative terms are in use for river meanders viz. incised meanders, entrenched meanders, intrenched meanders, inclosed meanders and ingrown meanders. Incised meanders are the representative features of rejuvenation and polycyclic reliefs and are developed through vertical erosion leading to valley incision consequent upon renewed erosive power due to rejuvenation. The

narrow and deep meanders formed due to accelerated rate of valley incision caused by rejuvenation within simple broad meanders (having wide and shallow valleys) developed by lateral erosion during 1st cycle of erosion are called incised meanders which are further divided into (i) entrenched meanders (having uniform slopes of both the valley sides of meander loops), and (ii) ingrown meanders which have unequal slopes of valley sides wherein one side of the valley representing concave side is deeply undercut and the outer side (convex side) is characterized by gentle valley side slopes. The meandering valley of the Karo river downstream from Pheruaghaugh falls at the southern margin of the Ranchi plateau has been considerably incised due to rejuvenation and hence presents an ideal example of incised meander. The Damodar gorge near Rajroppa is typical example of incised meander. Similarly, Bheraghat gorge of the Narmada near Jabalpur (M.P.) is fine example of incised meander.

Knick point, simply called as nick point or only 'nick' represents breaks in slope in the longitudinal profile of a river caused by rejuvenation (fig. 16.6). This is why nick point is also called as **head of rejuvenation** which registeres gradual recession upstream. These breaks in channel gradient or nick points denote sudden drops of elevation in the longitudinal profile of the rivers and allow water to fall down vertically giving birth to waterfalls of varying dimensions. These are called as **nick point falls** or simply **nickfalls.** Hundru falls (76.67 m) on the Subarnarekha river (near Ranchi city), Johna or Gautamdhara falls at the confluence of the Raru and the Gunga rivers (to the east of Ranchi city), Dassam falls (39.62 m and 15.24 m) on the Kanchi river (east of Ranchi city), Burhaghaugh falls (148 m) on the Burha river, a tributary of the North Koel river, Dhunwadhar falls on the Narmada river (near Jabalpur, M.P.), major falls of Rewa plateau, M.P. (e.g. Chachai falls, 127 m on the Bihar river, Kevti falls, 98 m on the Mahana nadi, Tons or Purwa falls, 75 m on the Tons river, Odda falls, 145 m on the Odda nadi etc.) are the examples of nick points caused by rejuvenation.

Paired terraces (fig. 16.5) are also significant features of poly-cyclic reliefs. Three pairs of terraces are found in the Himalayas indicating three phases of uplift and consequent rejuvenation.

17

DRAINAGE SYSTEMS AND PATTERNS

17.1 MEANING AND CONCEPTS

The study of the charactristics of drainage network of a particular region is approached in two ways e.g. (1) descriptive approach and (2) genetic approach . The descriptive approach involves the study of the characteristics of the forms and patterns of the streams of a given region while the genetic approach involves the investigation of the evolution of streams of a region in relation to tectonics, lithologies and structures. Thus, **drainage system** refers to the origin and development of streams through time while **drainage pattern** means spatial arrangement and form of drainage system in terms of geometrical shapes in the areas of different rock types, geological structure, climatic conditions and denudational history e.g. trellis pattern, dendritic pattern, parallel pattern etc. The examples of drainage systems are consequent streams, subsequent streams, obsequent streams, resequent streams, antecedent and superimposed streams etc.

The origin and subsequent evolution of any drainage system in a region are determined and controlled by two main factors viz. (1) nature of initial surface and slope and (2) geological structure (e.g. folds, faults, fractures, joints, dips and strikes of rock beds and types of rocks). Streams or drainage systems are divided in two broad categories on the basis of the adjustment of the streams to the initial surface and geological structures e.g. (1) **sequent streams** (which follow the regional slope and are well adjusted to geological structures) such as consequent streams, subsequent streams, obsequent streams and resequent streams and (2) **insequent streams** (which do not follow the regional slope and are not adjusted to geological structures) such as antecedent streams and superimposed streams.

17.2 MAJOR DRAINAGE SYSTEMS

(A) Sequent Drainage Systems

1. Consequent streams

Consequent streams are the first streams to be originated in a particular region. These streams have their courses in accordance with the initial slope of land surface. In other words, the consequent streams follow the regional slope. These are also called **dip streams.** In a region of folded structure (when the crustal rocks are folded due to lateral compressive forces into parallel anticlines and synclines) consequent streams are formed in the synclinal troughs. Such consequent streams are called **synclinal consequent streams,** which become the master consequent streams of **trellis drainage pattern** at much later date.

The first streams to be initiated on a newly emerged coastal plain are consequent streams which are parallel to each other and thus form **parallel drainage pattern.** The longest stream of the whole

system of consequent streams is called master consequent (fig. 17.1). Most of the streams draining the coastal plains of India are the examples of consequent streams. The most ideal landscapes for the origin and development of consequent drainage system are domes and volcanic cones. Consequent streams are divided in two types e.g. (1) **longtudinal consequent** (which follows the axis of the depression or syncline in a folded structure) and (2) **lateral consequent** (which follows the sides of the depressions or the sides of the anticlines). Lateral consequent streams generally join the master or logitudinal or synclinal consequent more or less at right angle.

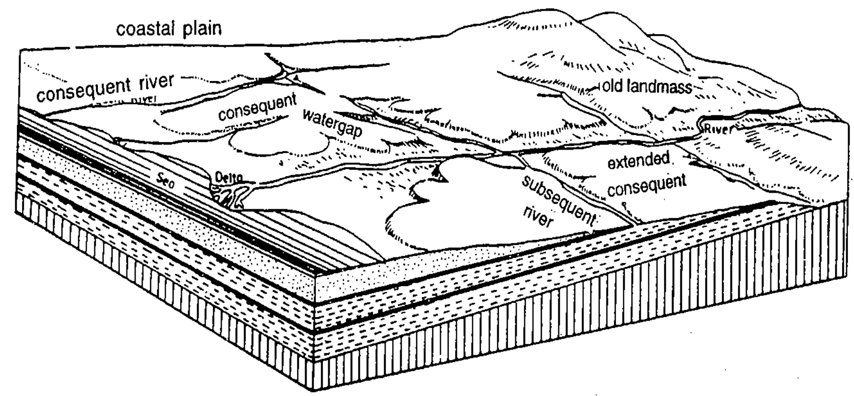


Fig. 17.1 : Development of master consequent and subsequent streams over a coastal plain.

2. Subsequent streams

The streams originated after the master consequent stream and following the axis of the anticlines or ridges and the strikes of beds are called subsequent streams. Some of the scientists have opined that the subsequent streams originate on the flanks of the anticlines and join the master consequent at almost right angle (which means that the lateral consequents, as referred to above, are the subsequents) while others maintain that the subsequents are parallel to the master consequent. S.W. Wooldridge and R.S. Morgan (1960) have opined that it should be noted that all the first generation tributaries to consequent streams are subsequent in the sense that they arise subsequently to the establishment and incision of the consequent streams. According to them 'such streams, starting as gullies on the sides of the primary consequent valleys, discover and explore belts of structural weakness, due to softer strata, fault, or joint-planes, and shatter zones' (Wooldridge and Morgan, 1960, pp. 173-74). E Ahmad (1985) has remarked that "the term subsequent may be used generally not to indicate a chronological sequence but a relation between drainage on the one hand and geology, structure and tectonics on the other. Generally, it refers to the streams transverse to the master consequents." The Asan river, a tributary of the Yamuna river and the Song river, a tributary of the Ganga river in the Dehra Dun valley (infilled alluvial plain) are the examples of subsequent streams while the Yamuna and the Ganga are the master consequents (fig. 17.2).

3. Obsequent streams

The streams flowing in opposite direction to the master consequent are called obsequent streams. In fact, obsequent streams are also consequents because they also follow the slopes of the ranges. The streams originating from the northern slopes of the west-east stretching ranges of the Himalayas flow northward to meet the east-west flowing tributaries (subsequent streams) of the southward draining master consequent streams. For example, the Mahabharat Range of the Lesser Himalaya has issued several streams from its northern slopes. These northward flowing streams join the subsequent stream

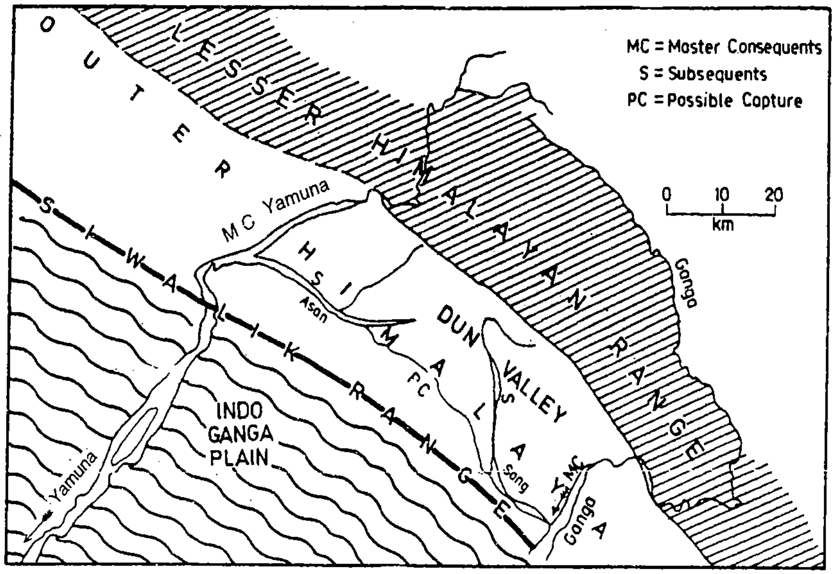


Fig. 17.2 : Development of master consequent and subsequent streams in Dehra Dun valley.

Sun Kosi which runs west to east, as obsequent streams because these are opposed to the directions of the master consequents like the Ganga and the Yamuna. Similarly, several streams originating from the northern slopes of the Siwalik Range drain due northward to join east-west subsequent streams of the southward flowing master consequents of the Ganga and the Yamuna, north of the Someshwar Range of Dundwa Range (of the Siwalik Range). These northward flowing tributaries are the examples of obsequent streams.

4. Resequent streams

The tributary streams flowing in the direction of the master consequents are called resequents. These are originated at much later date in comparison to the master consequents. Since they are of recent origin, and hence they are called resequent.

The resequent streams are originated during the initiation of second cycle of erosion in a folded structure. The gradual denudation of folded mountains during the first cycle of erosion results into **inversion of relief** with the passage of time wherein anticlinal ridges and synclinal valleys are converted into anticlinal valleys and synclinal ridges respectively (fig. 17.3). Thus, logitudinal streams are developed in the anticlinal valleys. These features are peneplaned by the end of the first cycle of erosion. The initiation of second cycle of erosion begins with the excavation of new valleys in the synclines. Thus, the streams developed in the synclinal portions become resequent streams which though analogous to the original longitudinal consequents developed during the first cycle of erosion but, in fact, they are hundreds of metres below the initial surface (fig. 17.3).

(B) Insequent Drainage System

The streams which do not follow the regional slopes and drain across the geological structures are called insequent or inconsequent streams. Antecedent and superimposed streams are the best representative examples of insequent drainage systems.

1. Antecedent drainage system

Antecedent streams are those which are originated prior to the upliftment of land surface. In other

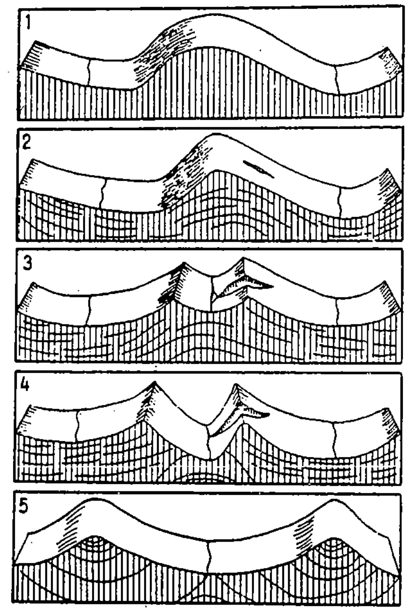


Fig. 17.3 : Inversion of relief. The syncline and anticline of stage I have become synclinal ridge and anticlinal valley in stage 5 which denotes the end of the first cycle of erosion.

words, antecedent streams antedate the upliftment of an upland or mountain across which they have maintained their present courses through continuous downcutting of their valleys. It is, thus, obvious that if a river has developed in a particular region and if the subsequent uplift or upwarping of the land area across the pre-existing river does not divert or deflect the course of the river and the river maintains its previous course through downcutting its valley at the rate equivalent to the rate of uplift of the land area, the river is called antecedent or **anticonsequent.** It may be pointed out that the concept of antecedence of a particular river is based on guesses and conjectures because neither the rate of the uplift of land area nor the rate of downcutting by the rivers is known.

The nature and the rate of upliftment of land area is very important parameter for the development of antecedent drainage system because rivers cannot maintain their previous courses during all types of upliftment. For example, if the upliftment of the area occurs very rapidly and is completed within a very short period of time, the rivers draining through that area cannot maintain their previous courses because the rate of downcutting of their valleys cannot keep pace with the rate of the upliftment and thus the rivers are dismembered and adopt

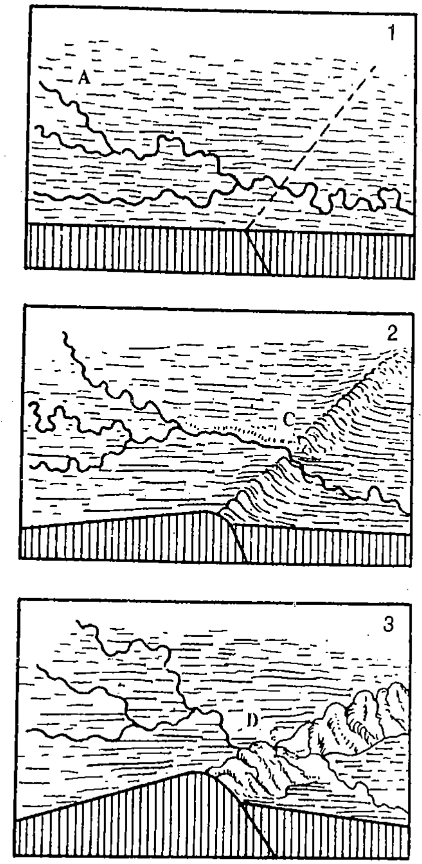


Fig. 17.4 : Stages of the development of antecedent stream.

different courses depending on local (new) conditions. On the other hand, if the rate of upliftment is such that the rivers are able to degrade their valleys through active downcutting (valley incision) at the

rate equal to the rate of the upliftment, they become able to maintain their previous courses and thus they become antecedent streams. The nature and dimension of the upliftment also determine the antecedence of the rivers. It is the local and not the regional upliftment which gives birth to the development of antecedent streams.

The origin and development of antecedent drainage system can be explained with the help of a diagram (fig. 17.4). 'A' river (fig. 17.4 (1) has fully developed its valley and course in a region of almost flat topographic surface. The river is flowing from west to east. At a later date there is upliftment of land area across river 'A' at point B. The land is rising in a form of a ridge with slow rate of upliftment. This local upliftment of the land rejuvenates the river 'A' due to which it deepens its valley with accelerated rate of downcutting. If the rate of downcutting (valley deepening) equals the rate of uplift the bed of the river valley remains constant and the river maintains its usual flow direction. River 'A' in the second stage (fig. 17.4(2) has deepened its valley so much so to match the rate of upliftment. It is apparent from figure 17.4(2) that 'A' river has cut across the newly uplifted ridge at 'C' and has maintained its previous course. The river continues to deepen its valley through active downcutting so long as the upliftment continues. Thus, the river develops very deep and narrow gorges across the uplifted land area (ridge) wherein the valley sides are of convex slope and rise almost vertically from the valley floor (fig. 17.4 (3). It may be pointed out that tributaries of the master antecedent streams cannot deepen their valleys at par with their master streams and hence their valleys are at higher level than the valleys of their master streams. Thus, the tributary valleys become hanging valleys.

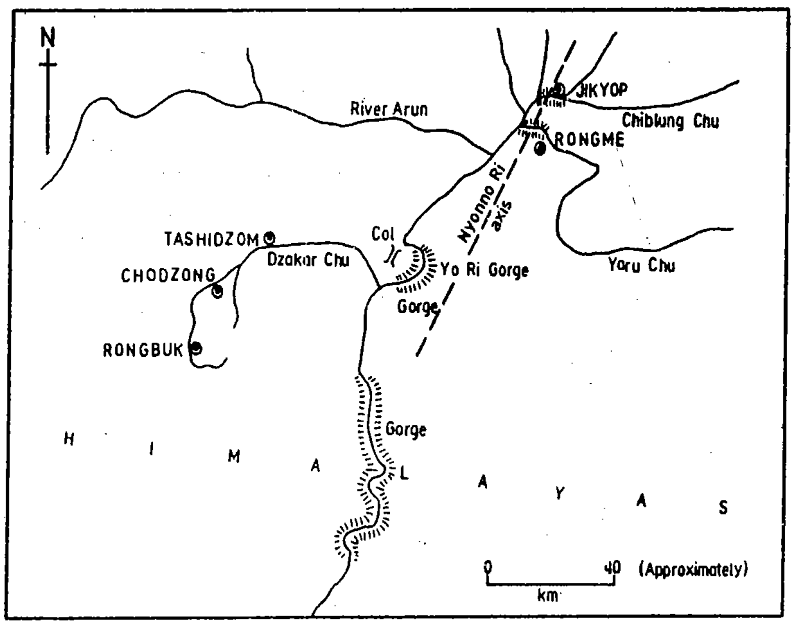


Fig. 17.5 : The upper reaches of the Arun river (after L.R. Wager, 1937).

Examples : Examples of antecedent streams are found in almost all of the folded mountains of the world. Many of the major Himalayan rivers are the examples of antecedent streams e.g. the Indus, the

Sutlej, the Ganga, the Ghaghra, the Kali, the Gandak, the Kosi, the Brahmaputra etc. It may be pointed out that the Himalayan mountain system consists of three parallel ranges running from west to east viz. (from north to south) the Greater Himalaya, the Lesser Himalaya and the Outer Himalaya or Siwalik Range. Three kinds of antecedent streams are identified in terms of their antecedence to the aforesaid three ranges of the Himalayas. (1) The Indus, the Sutlej, the Ganga, the Ghaghra, the Kosi, the Brahmaputra etc. are antecedent to all of the three ranges of the Himalayas as they cut across the Greater, the Lesser and the Outer Himalayan ranges. It is believed that these rivers were present before the folding and upliftment of the Himalayan ranges. With the upliftment of these ranges during Tertiary period these rivers maintained their southward courses through downcutting their valleys in harmony with the rate of upliftment. All of these rivers have formed deep and narrow gorges while cutting across the Himalayan ranges. The Indus river has dug out a 17,000- foot deep gorge across the Greater Himalayas near Gilgit. It may be pointed out that a group of geologists does not believe in the antecedence of the Indus river. According to them the Indus is an example of consequent stream because consequent streams might have developed on the southern slopes of the Himalayas. These rivers might have extended their courses northward through the process of headward erosion resulting into gradual backward shifting of their water divides. Ultimately, the streams of the southern slopes of the Himalayas might have captured the streams of the northern slopes and thus they might have extended their courses across the Himalayan ranges. The Arun river has been quoted as the best example of antecedent river by L.R. Wager (1937). The Arun river (fig. 17.5) flows from west to east in its uper reaches following the structural grain of the region to the north of the Himalayas. It suddenly turns due southward and drains across the Himalayas through several deeply entrenched narrow gorges (fig. 17.5). A few geologists opine that the sudden southward bend of the Arun river is due to river capture. The advocates of the antecedent origin of the Arun river maintain that the convex course of the river across the Himalayas could be possible only through active downcutting of the valley in accordance with the rate of upliftment. A series of terraces on either side of the valley of the Arun river also validate its antecedent origin.

(2) The rivers, which are antecedent to only two ranges of the Himalayas viz. the Lesser and the Outer (Siwalik Range) Himalayas, are the Jhelum, the Yamuna, the Ravi, the Ramganga etc. (3) The streams, which are antecedent only to the Outer Himalaya or Siwalik Range, include the Kamla, the Rapti, the Gola etc.

2. Superimposed drainage system

Like antecedent streams superimposed streams are also not adjusted to regional geological structures and slope and thus are insequent or anti-consequent streams. Superimposed stream means a river which, flowing on a definite geological formation and structure, has inherited the characteristics of its previous form developed on upper geological formation of entirely different structural characteristics. In other words, a superimposed drainage is formed when the nature and characteristics of the valleys and flow direction of a consequent stream developed on the upper geological formation and structure are superimposed on the lower geological formation of entirely different characteristics. It is not necessary that the upper geological formation is conformal to the lower geological formation, rather it happens that some times the upper rock cover is entirely different from the underlying geological formation viz. the upper cover may consist of horizontally bedded sedimentary rocks while the lower cover may be composed of folded sedimentary beds, or domed structure or batholithic intrusives. The consequent streams are developed on almost flat ground surface of the horizontally bedded sedimentary rocks. These streams develop their valleys through vertical erosion (downcutting). With the passage of time the lower structure is exposed to the river which continues its downcutting and extends its valley downward on the lower geological structure (say anticlinal folds, domes or batholiths) and thus the valley developed on the upper structure is superimposed on the lower structure. The lower structure has to accept the form of the valley already developed on the entirely different upper structure Thus, the river maintains the form of its valley, the flow direction and its drainage patterns as usual. Such rivers are called superimposed rivers. Had the lower structure

been present on the ground, the nature of drainage system would have certainly been entirely different but the buried different geological structure has no alternative other than to adapt the nature of valley and flow direction developed on the upper structure. Such streams are unconformal to the local geological structure and slopes. Such unconformal valleys have been named as **'superimposed'** by J.W. Powell (1857) and D. Maw (1886) and **'superposed'** by W.J. McGee (1888).

The mechanism of the development of a superimposed stream and valley can be explained with the help of a diagram (fig. 17.6). Figure 17.6 depicts such a region which is characterized by a flat ground surface consisting of horizontally bedded sedimentary rocks and the lower structure of anticlinal fold. First of all a consequent stream (fig. 17.6(1) develops on the upper horizontally bedded sedimentary formation. The river is flowing in harmony with the geological formation and structure and local slope.

With the passage of time the consequent stream digs out its valley with slow process of valley deepening. In the second stage (fig. 17.6(2) the consequent stream fully develops its valley on horizontally bedded sedimentary rocks. Now the anticlinal part (third stage, fig. 17.6(3) is exposed to the river as the upper horizontal beds of sedimentary rock have been removed due to gradual downcutting. This anticlinal lower structure is entirely different from the upper structure of the horizontal beds of sedimentary rocks but the river extends its valley on this lower unconformal structure of anticline in accordance with its already developed valley on the upper structure i.e. the river degrades the anticline through downcutting and continues to develop its valley further downward. The development of river valley goes on unhindered because the anticline becomes a passive factor in controlling the development of the river valley as it has no option other than to accept the form of the valley already developed in the upper structure. Now the consequent river and its valley are superimposed on the anticline and the river maintains its usual course. Had this anticline been initially exposed to the ground surface, the drainage system would have been entirely different.

The fundamental difference between superimposed and antecedent drainage systems lies in the fact that the former represents the superimposition

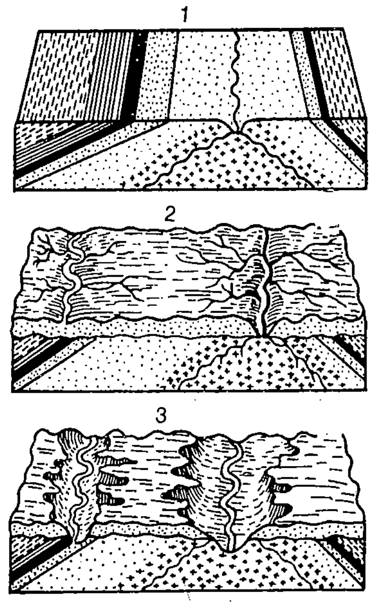


Fig. 17.6 : Stages of the development of superimposed drainage system.

of the valley developed in the upper geological formation and structure on the lower structure irrespective of its types and complexities but without any upliftment of the land area while the latter represents the maintenance of former course of the river and its valley inspite of upliftment of the land area across the river course due to concomitant valley deepening and upwarping of the land.

Most of the rivers of the Deccan trap (lava) region of Peninsular India are superimposed because new drainage system was evolved on the new surface formed due to cooling and solidification of lavas erupted during late Cretaceous and early Tertiary periods and these rivers were superimposed on the lower formation after the removal of lava covers. For example, the Subarnarekha river is superimposed on Dalma and phyllite hills to the west of Chandil in the south-eastern Chotanagpur plateaue region of Jharkhand.

Example : The Son river flowing across the Khainjua ridges in the southern part of Rewa plateau (Madhya Pradesh) is a fine example of superimposed river (fig. 17.7). The Son river flows parallel and very close to the Khainjua ridge between $81^0 15'$ E logitude and Deolond (fig. 17.7). In fact, the Khainjua ridge of quartzitic sandstones makes the southern bank of the Son valley. The river suddeny cuts across the Khainjua ridge at Deolond and then flows in south-easterly direction (fig. 17.7). After its confluence with the Banas river it again turns northward and cuts across the Khainjua ridge and flows in easterly direction.

The Son cannot be an antecedent river, though it cuts across Khainjua ridges at two places, because (i) the Khainjua ridges are composed of lower Vindhyans sedimentaries, (ii) there are no evidences to support any localized rise in the ridges after Cambrian period, (iii) the evidence of laterites to the north of Kaimur scarps denotes the spread of basaltic lava of the Deccan trappean age of Cretaceous period which might have buried and obliterated previous drainage lines, and (iv) the absence of any significant stream to the north of the Son does not support the idea of the Son being older than the Crectaceous lava flow.

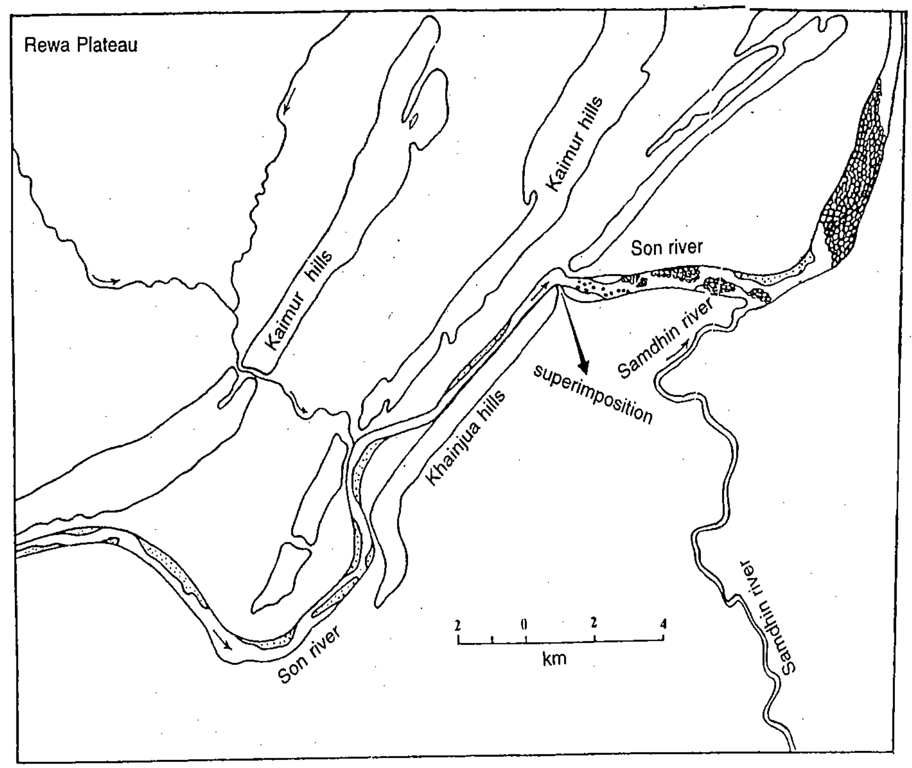


Fig. 17.7 : Superimposition of the Son river over Khainjua ridges of lower Vindhyans in southern part of the Rewa plateau (M.P.).

Thus, the Son appears to be superimposed river. It may be argued that the Deccan lava flows during Cretaceous period covered the whole of the Rewa Plateau and consequently buried the pre-existing drainage network and reliefs including Kaimurs and Khainjua ridges. With the initiation of sub-aerial conditions during Tertiary period new drainage lines began to develop over the solidified lava cover (basaltic lava) and the Son developed its present course through several stages. The lava cover might have been removed through continuous but gradual fluvial erosion. Once the Son established its course over the lava covered surface, it continued to erode its valley over the buried structures and thus its valley became superimposed over the Khainjua ridges.

17.3 DRAINAGE PATTERNS

The drainage pattern means the 'form' (geometrical forms) of the drainage systems and the spatial arrangement of streams in a particular locality or region. The location, number and flow directions of different streams of a particular region depend on the nature of slope, structural control, lighological characteristics, tectonic factors, climatic conditions, vegetal characteristics etc. Since there are much variations in the environmental conditions of different regions and hence there are also spatial variations in drainage patterns. Though the drainage patterns of some regions may be similar but not the same, but there are some common characteristics which enable us to distinguish different drainage patterns. Generally, the drainage patterns are divided into the following types, (1) trellised pattern, (2) dendritic pattern, (3) rectangular pattern, (4) parallel pattern, (5) centrifugal or radial pattern, (6) centrepetal pattern, (7) annular pattern, (8) barbed pattern, (9) indeterminate or confused pattern, (10) herringbone pattern, (11) pinnate pattern etc.

1. Trellised Drainage Pattern

Trellised drainage patterns are formed by the network of tributaries and master consequent streams which follow the regional slope and are well adjusted to the geological structures. Such patterns are developed in the area of simple folds charactriszed by parallel anticlinal ridges alternated by parallel synclinal valleys. Several master consequent longitudinal streams are developed in the elongated longitudinal synclinal valleys. These longitudinal rivers and their valleys occupying the furrows between parallel ridges are parallel to each other. Several streams develop on both the flanks of the ridges and join the longitudinal synclinal streams at right angle. These tributary streams are called as lateral consequent streams. Thus the resultant network of numerous longitudinal streams and transverse or lateral consequents is called trellised pattern. This pattern also resembles the rectangular pattern. In fact, the trellised and rectangular patterns are differentiated on the basis of spacing between the streams. If the streams are closely spaced the resultant pattern becomes trellised while rectangular pattern is formed when the streams are widely spaced. Trellised drainage patterns are generally formed in the regions of cuesta topography where hard beds become escarpments and soft beds are eroded to become valleys or lowlands.

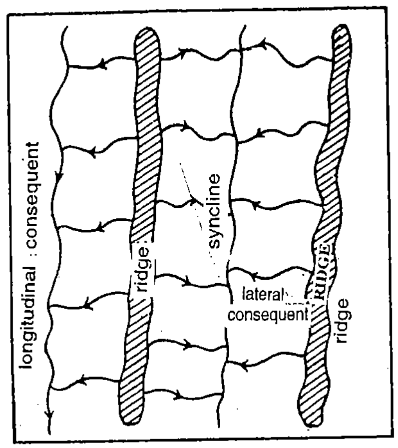


Fig. 17.8 : Development of trellised drainage pattern on folded structure.

2. Dendritic Drainage Pattern

Dendritic or tree-shaped drainage pattern is the most common and widespread pattern to be found on the earth's surface. The pattern is called dendritic on the ground that the network of tributaries of various orders and magnitudes of the trunk or master stream resembles the branches and roots and rootlets of a tree. The dendritic pattern is associated with the areas of homogeneous lithologies, horizon-

tal or very gently dipping strata, flat and rolling extensive topographic surface having extremely low reliefs. Though dendritic pattern is independent of structural and lithological controls but almost uniform lithology (presence of same type of rocks in extensive area) presents most ideal condition for the development of dendritic drainage pattern. This pattern develops in a variety of structural and lithological environments such as in the mountainous and hilly areas (e.g. dendritic pattern is one of the dominant patterns in the Himalayas), on extensive plateau surfaces (e.g. Deccan plateau), on peneplain surfaces (e.g. the Peninsular peneplains of India, mostly in the basins of the Mahanadi, the Godavari, the Krishna, the Cauvery, the Domodar etc.), in the alluviated plains (e.g. Great Plains of North India), in the desert plains (e.g. Rajasthan desert), in the glaciated lowland regions (e.g. North European plains and northern lowlands of North America) etc.

The evolution of dendritic pattern is guided by the lithological characteristics mainly the permeability of underlying rocks, the amount and regime of rainfall and resultant surface runoff and the time factor. First of all the master or trunk consequent stream develops on gently sloping topographic surface. The master consequent gradually but slowly lengthens its longitudinal course through headward erosion. Major tributary streams of the master stream develop on either side of the trunk stream (fig. 17.9). These tributaries also lengthen their longitudinal courses through headward erosion and branches of tributaries are developed in due course of time (fig. 17.9 (2). In the beginning the dendritic pattern is **'open'** because the streams are few in number and are widely spaced (fig. 17.9 (1) but with the passage of time a dense mesh of multitudes of tributaries of various hierarchical orders is developed and thus the initial open network becomes a **'closed pattern'** as the streams are very closely spaced. At a much later date, i.e. in the penultimate stage of drainage development, the dendritic pattern becomes **'simplified'** due to 'surface abstraction' because many of the tributaries are integrated due to active river capture.

Slope and permeability of rocks very effectively control the number and extension of streams of dendritic drainage pattern. The drainage network of dendritic pattern becomes most extensive if the land surface is characterized by flat surface, level to gentle slopes and impermeable rocks. In such environmental conditions the pattern extends both in length and width but if the region is characterized by higher slope angles, the pattern extends more in length than in width. The extensive plateau surfaces of the Panna plateau, Bhander plateau and Rewa plateau (M.P.) composed of sandstones capping and the peneplained surface of the central Ranchi plateau composed of granite-gneisses have favoured extensive dendritic drainage pattern while elongated dendritic pattern has developed along the middle and lower segments of the escarpments associated with these plateaux.

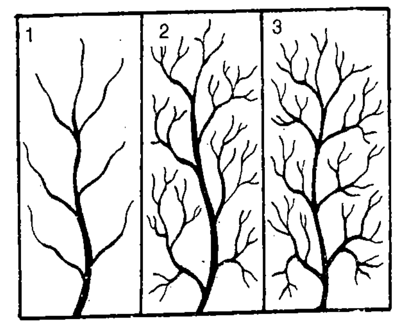


Fig. 17.9 : Stages of the development of dendritic drainage pattern.

3. Rectangular Drainage Pattern

Rectangular pattern shows some degree of resemblance to trellised drainage pattern as tributary streams in both the patterns join their master streams almost at right angle but the confluence angle in the trellised pattern is guided by the strikes and dip angle of the rock beds while it is determined by the lines of weaknesses (e.g. faults and fractures and joints) of the rocks in the rectangular pattern. The second line of difference between these two drainage patterns is related to the spacing of streams i.e. the rectangular pattern is characterized by widely spaced trbutaries while trellised pattern has a dense mesh of closely spaced tributaries.

Rectangular pattern is generally developed in the regions where the rock joints form rectangular pattern. The rocks are weathered and eroded along the interfaces of joints, fractures and faults and thus

surface runoff collects in such long and narrow clefts (resulting from the weathering and erosion of joints) and forms numerous small rills. These rills are further extended in length and width and become channels. With the march of time a network of streams is developed wherein streams follow the lines of weakness (joints and fractures). The tributaries join their master streams almost at right angles and thus a rectangular drainage pattern is formed (fig. 17.10).

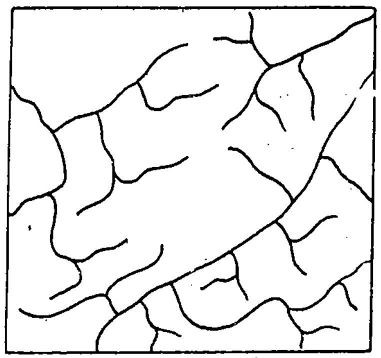


Fig. 17.10 : An example of rectangular drainage pattern.

4. Radial Drainage Pattern

Radial drainage pattern, also known as centrifugal pattern, is formed by the streams which diverge from a central higher point in all directions. It is obvious that dome structures, volcanic cones, batholiths and laccoliths, residual hills, small tablelands, mesas and buttes, and isolated uplands favour the development of ideal radial pattern (fig. 17.11). The streams emerge at the central point of the aforesaid reliefs and drain down the slopes in all directions. Since the streams follow the slopes and hence they are basically consequent streams. These streams resemble the spokes of a wheel or the radii of a circle. If we take the entire drainage network of Sri Lanka, it exhibits the best example of radial drainage pattern at macro-level. The local upland situated to the south-west of Ranchi city has given birth to radial drainage pattern wherein the South Koel, the Subarnarekha, the Kanchi and the Karo rivers take their sources and radiate in different directions.

Hazaribagh plateau, Parasnath hill, Panchet hill and Dalma lava upland (all in Jharkhand) have

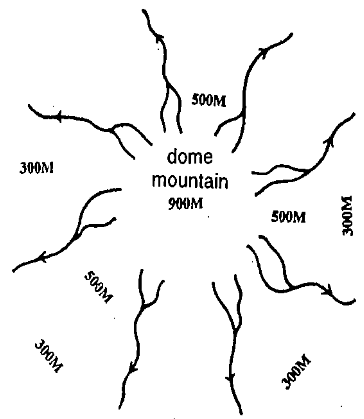


Fig. 17.11 : Example of radial drainage pattern.

issued radial drainage pattern. Morcha pahar and Lugu hill of Hazaribagh, Mt. Abu (Rajasthan) etc. present ideal examples of radial drainage pattern. At a regional level the Rohtas plateau of S.W. Bihar province presents a good example of radial drainage pattern wherein the Karamnasa and the Durgawati rivers and their source tributaries emerge from the south-western corner of the plateau and flow in the western, north-western, northern, and north-eastern directions whereas the tributaries of the Son river flow in the southern direction.

5. Centripetal Drainage Pattern

Centripetal or inland drainage pattern (fig. 17.12) is opposite to the radial drainage pattern because it is characterized by the streams which converge at a point which is generally a depression or a basin. This pattern is formed by a series of streams which after emerging from surrounding uplands converge in a central low land which may be a depression, or a basin or a crater lake. The Kathmandu valley of Nepal presents an ideal example of centripetal drainage pattern wherein the tributary streams of the Baghmati converge in the tectonically formed circular basin. The depression formed at the top of Raigarh Dome in the Lower Chambal Basin has given birth to centripetal drainage pattern.

6. Annular Drainage Pattern

Annular pattern, also known as **'circular pattern'** is formed when the tributaries of the master

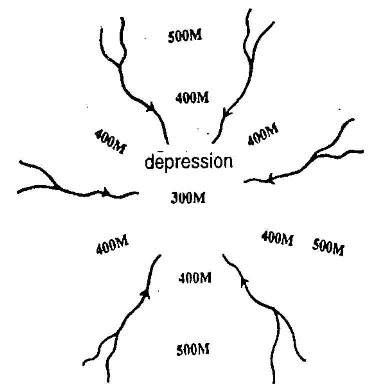


Fig. 17.12 : An example of centripetal drainage pattern.

consequent streams are developed in the form of a circle. Such pattern (fig. 17.13) is developed over a mature and dissected dome mountain characterized by a series of alternate bands of hard and soft rock beds. The differential erosion of hard and soft rock beds results in the truncation of the beds which

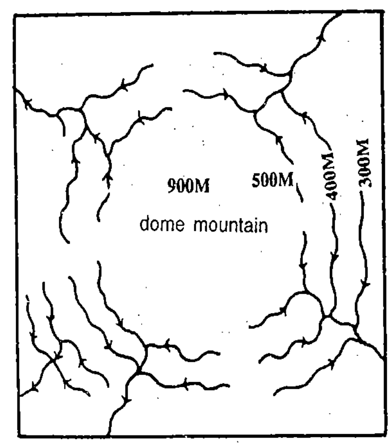


Fig. 17.13 : An example of annular drainage pattern.

produces **ringed belted structure** wherein relatively resistant beds project outward whereas the weaker (soft) beds form circular clefts. The master consequent streams emerge at the top of the dome and rediate in all directions down the slope like radial drainage pattern whereas tributary streams develop in the clefts formed due to erosion of soft beds, assume arcuate shape and join the master consequent streams and thus annular drainage pattern is formed. At a much later date tributaries of circular subsequent streams, which join the radial consequents, are also developed and thus the drainage pattern becomes a special case of trellised pattern. Annular drainage pattern has developed over denuded domes in the Weald of England. The mature dissected Sonapet dome of Uttaranchal presents an ideal example of annular drainage pattern.

7. Barbed Drainage Pattern

Barbed drainage pattern, a rare kind of

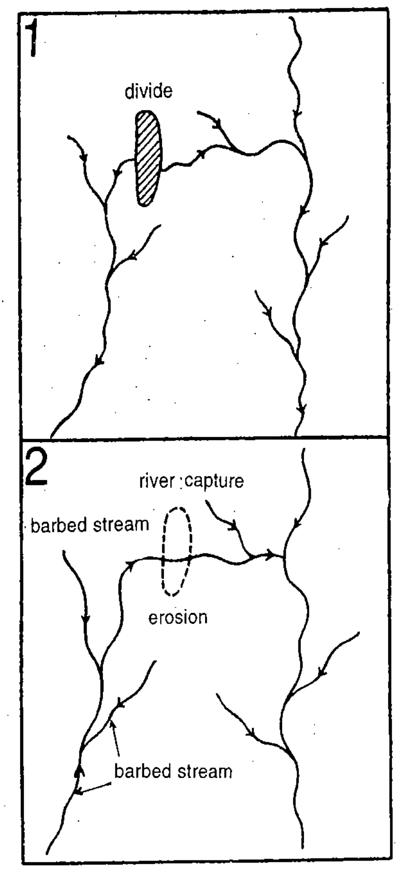


Fig. 17.14 : Stages of the development of barbed drainage pattern.

drainage pattern, is formed when the tributaries flow in opposite direction to their master streams. The tributaries join their master streams in a hook-shaped bend. Such pattern is generally developed due to river capture (fig 17.14).

8. Pinnate Drainage Pattern

Pinnate pattern is developed in a narrow valley flanked by steep ranges. The tributaries originating from the steep sides of parallel ridges join the longtitudinal master consequent occupying the valley at acute angles (fig. 17.15). The drainage network of the upper Son and Narmada rivers denotes the example of pinnate drainage pattern. This pattern resembles the veins of a leaf.

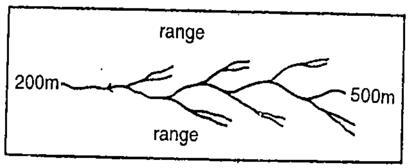


Fig. 17.15 : Example of pinnate drainage pattern.

9. Herringbone Drainage Pattern

Herringbone drainage pattern, also known as **rib pattern** (like the rib bones of human beings), is developed in mountainous areas where broad valleys are flanked by parallel ridges having steep hillside slopes. The longitudinal consequent streams, as master streams, are developed in the longitudinal parallel valleys while tributaries, as lateral consequents, after originating from the hillslopes of the bordering parallel ridges join the longitudinal consequents almost at right angle. The courses of the tributaries are straightened because of slope factor and little distance between the ridges and the longitudinal consequents occupying the valleys and thus the tributaries are not allowed to adapt sinuous course and join the longitudinal consequents at acute angles (fig. 17.16). The term herringbone has been derived from the pattern of bones of herring fish (mainly spine bones). The upper Jhelum river in the Vale of Kashmir receives numerous tributaries from both the sides and thus forms herringbone drainage pattern. The rivers occyping east-west trenches in the Himalayas form herringbone pattern. The Tamar Kosi, a left bank tributary of the Kosi river, the upper Rapti (a tributary of the Ghaghra river), the Rapti (another one), the left bank tributary of the Gandak river etc. have formed such drainage pattern.

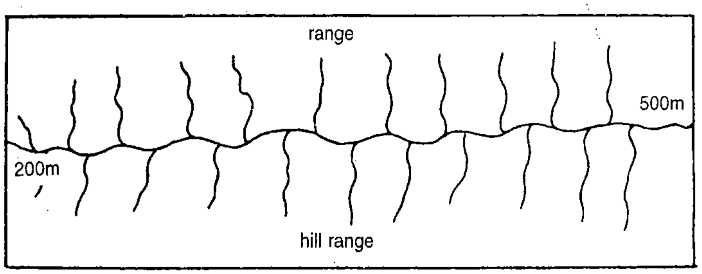


Fig. 17.16 : An example of herringbone drainage pattern.

10. Prallel Drainage Pattern

Parallel drainage pattern comprises numerous rivers which are parallel to each other and follow the regional slope. This pattern is more frequently developed on uniformly sloping and dipping rock beds such as cuestas or newly emerged coastal plains. The western coastal plains of India represent several examples of parallel drainage patterns where the streams after taking their sources from the western flanks of the Western Ghats drain in straight courses towards west to empty into the Arabian Sea. Parallel drainage pattern has also developed on the Eastern Coastal Plains of India. It may be pointed out that a subparallel pattern is, threrefore, essentially an **'initial drainage pattern'** (fig. 17.17).

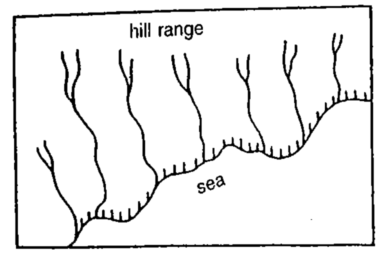


Fig. 17.17 : Example of parallel drainage pattern.

17.4 RIVER CAPTURE

Meaning and Concept

The diversion of the part of the course of a river by another river is called **stream diversion** or **stream capture** or **stream piracy** . The river which captures the course of another river is called the **capturing** or **captor stream** while the part of the stream which has been divested of its course and water is called the **captured stream.** River capture is a natural process which is more active in the youthful stage of the valley development because the streams are actively engaged in **headward erosion** and **valley lengthening** but river capture also occurs during mature and senile stages of the valley development through the process of lateral erosion and **meander intersection**. The stronger and more powerful streams (in terms of channel gradient, stream velocity and discharge and kinetic energy) capture the upper courses of weak and sluggish streams. Figure 17.18 depicts the stages of the capture of the Saraswati river by the Yamuna river.

There are four major evidences of river capture viz. (i) **elbow of capture,** (ii) **cols, or wind gaps,** **(iii) watr gaps, and (iv) misfit or underfit streams and valleys.** The elbow of capture denotes the point (fig. 17.19 (E)) where the course of the captured sream has been diverted to the course of the captor stream. Generally, the ellbow of capture denotes sharp turn in the course of a river almost at right angle. The water gap denotes the deep and narrow valley in the form of a gorge formed by the captor stream through headward erosion across the ridge (fig. 17 : 19 w.g.).

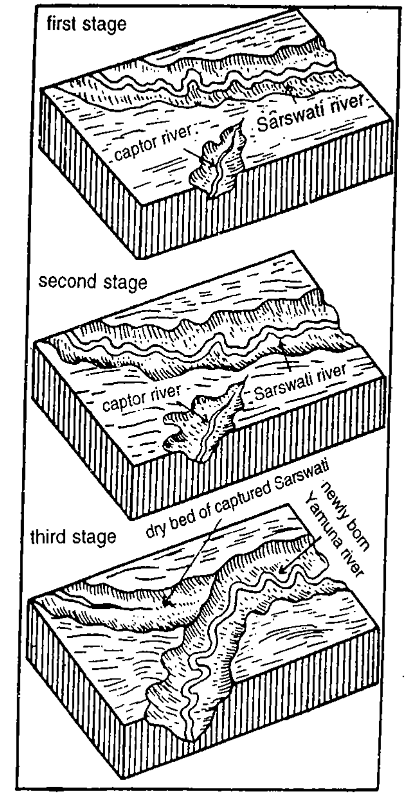


Fig. 17.18 : Stages of the capture of the Saraswati river through the process of headward erosion.

Wind gap is the dry portion of the beheaded stream just between the elbow of capture (fig. 17.19 (wg). The wind gap is also called as col. The misfit or underfit stream is the lower course of the captured stream. It is called misfit because of the fact that the former valley of the captured stream becomes too large and wide for the beheaded stream because of substantial decrease in the volume of water due to diversion of its water to the captor stream.

Ideal conditions for River Capture

Though the river capture is a natural process, but it does not take place in all circumstances rather it requires certain necessary conditions. In fact, the process of river capture depends on channel gradi-

ent, depth of river valley, volume of water, velocity and discharge, lithological characteristics and geological structures, stage of cycle of erosion or the stage of river development. A particular river of a locality having deeper valley, more volume of water, steeper channel gradient and hence higher velocity and kinetic energy and flowing over less resistant and softer rocks than the other river of that region resorts to more powerful headward erosion than the latter, and thus may usurp the water and upper reaches of the weaker river. It may be, thus, inferred that river capture occurs under the following conditions—(1) steep channel gradient, (2) relatively narrow valley so that water may not spread in the otherwise wide and flat valleys, (3) higher volume of water so that velocity and discharge may be sufficiently high, (4) soft rocks so that the river may resort to rapid rate of headward erosion, (5) deeper valley than the valleys of other neighbouring rivers, (6) low sediment load so that the river may resort to active erosion etc.

Types of River Capture

It is apparent from the above discussion that the process of river capture is effected by erosion of different sorts viz., headward erosion (valley lengthening), vertical erosion (valley deepening or downward cutting), lateral erosion (valley widening), and intersection of meanders (lateral erosion). Headward and lateral erosion is the most powerful geomorphological process of river capture. It may also be pointed out that headward erosion is more effective in terms of river capture during juvenile stage (youthful stage) of river development while lateral erosion becomes more operative during mature stage. The capture of the course of a particular river by the other river through the intersection of meanders occurs mostly during late maturity and senile stage (old stage). Thus, the forms of river capture may be grouped in 3 broad categories viz. (1) capture through headward erosion, (2) capture through latral erosion, and (3) capture through the intersection of meanders.

(1) River capture through headward erosion

Most of the river captures occur due to headward erosion. In the initial stage of their development most of the streams and their tributaries are engaged in active headward erosion resulting into continuous creeping or shifting of water divides and lengthening of their valley thalwegs. The nature and intensity of headward erosion of any stream largely depends on the potential energy (height of the divide) and the steepness of the side slope of the water divide. Generally, the side slopes of the divide are unequal. The streams originating from the steeper slopes of the divide having relatively softer rocks and more precipitation and relatively short channel lengths degrade their valleys through the process of valley deepening more powerfully and resort to headward erosion at more accelerated rate than those streams which originate from the other side of the divide having less steep slope relatively resistant rocks and low precipitation. Consequently, the erosive power of the former becomes much more than the latter. The powerful stream pushes the water divide backward towards the side of gentle slope through active headward erosion. Prolonged headward erosion by more powerful stream flowing on the steeper hillside of the divide results in the coalescence of the sources of both the streams on opposite sides of the divides. Since the valley floor of the stream of the steeper side of the divide is lower than the valley floor of the stream of the gentler side of the divide and hence the former captures the headwater of the latter.

The process of river capture may be explained with the help of an example. Consequent streams originate on the slopes of any uplifted landmass. The most active and the longest consequent is called the master consequent. 'A' is the **master consequent** (fig. 17.19-1) while 'B' is the other consequent stream shown in figure 17.19. 'A' stream is flowing through steeper slope and channel gradient than B stream and thus the former has deepened its valley much more than the latter, with the result the valley floor of A stream is lower than the valley floor of B stream. It is, thus, apparent that A stream is more active than B stream. A few subsequent or lateral consequent streams emerge from the ridge (fig. 17.19 I) and join the longitudinal consequent A and B streams at almost right angles. For example, C and D are the tributaries of streams A and B respectively. These two tributaries take their sources on both the slopes of the same ridge. The valley of C would be also deeper than the valley of D stream because the valley of the master stream of C(A) is deeper than the valley of the receiving stream of D(B). Thus, the headward erosion by C stream would be more active and vigorous than the headward erosion by D stream. The water divide is gradually pushed back (towards the source of the stream D) because of more active headward erosion by C stream. A time comes when the C stream cuts across the ridge and extends its course through deep and narrow valley (gorge) and captures the course of D stream (fig. 17.19 II). Now the water of the upper course of the longitudinal consequent B stream also flows into the master consequent A stream via the integrated D and C tributary streams. Now the water of BEDC in the form of one channel drains into A stream. This example illustrates the capture of two streams at two stages. First, D stream, a tributary of B stream, was captured by C stream, a tributary of A stream through active headward erosion. Secondly, the headwaters of B stream (from the source to E point, the elbow of capture) were diverted towards A stream via D and C streams due to fallout of the first stage. C-D streams now flow through deeply entrenched narrow valley known as gorge (fig. 17.19 II). This narrow passage through the ridge is called **water gap** (WG in Fig. 17.19). B-E portion of the former B consequent stream has become **captured stream** which turns at right angle forming an **elbow of capture** (E in fig. 17.19 II). H-B portion of the former B consequent has now become a **beheaded stream,** the upper part of which is called **wind gap** (wg. in fig. 17.19 II) because of dry bed of the river due to capture of the upper portion of the river. The H-B portion of the former B consequent stream has now become **misfit** or **underfit river** because now the existing H-B stream is unable to adjust itself in its former valley because of marked reduction in the volume of water due to diversion of its headwaters to A stream via D-C streams as a result of river capture. There are two evidences which enable the investigators to identify the captured streams in the field viz. (i) elbow of capture and (ii) wind gap just to the downstream side of the elbow. The erosional work of the beheaded stream becomes almost nil because of marked reduction in the volume of water. Some times, the valley of the beheaded stream becomes almost dry. On the other hand, the **captor streams** (fig. 17.19, C and A) resort to more vertical erosion resulting into accelerated rate of valley deepening because of marked increase in the volume of water due to additional supply of water of D stream and headwaters of B stream (B-E portion) because of river capture. It may be pointed out that C and D tributary streams were formerly flowing in opposite directions (fig. 17.19 I) but now the waters of D stream flow in the direction of C stream. Thus, such streams of reversed flow direction are called **inverted streams.**

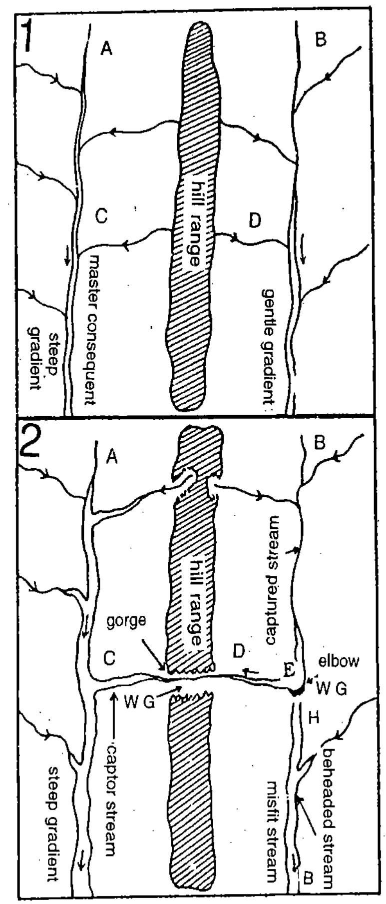


Fig. 17.19 : Illustration of river capture through headward erosion. WG = water Gap, wg = wind gap.

Examples : A group of geologists and geomorphologists believe that the present drainage system of the Himalayas is the outcome of progressive river piracy during various stages of drainage development. The Arun Kosi, a head tributary of the Kosi river, has captured the Phung Cho, a southern tributary of the Tsangpo (the upper part of the Brahmaputra river is called Tsangpo) river. Two head-tributaries of the Ganga e.g. the Bhagirathi and the Vishnuganga have captured the source tributaries of the Sutlej river. The water divide between the tributaries of Song river (a tributary of the Ganga river) and Asan river (a tributary of the Yamuna river) is only a few metres wide near Dehra Dun (fig. 17.2). It is expected that the Song river may capture the Asan river and thus the upper course of the Yamuna may be diverted to the Ganga via the Asan and the Song rivers.

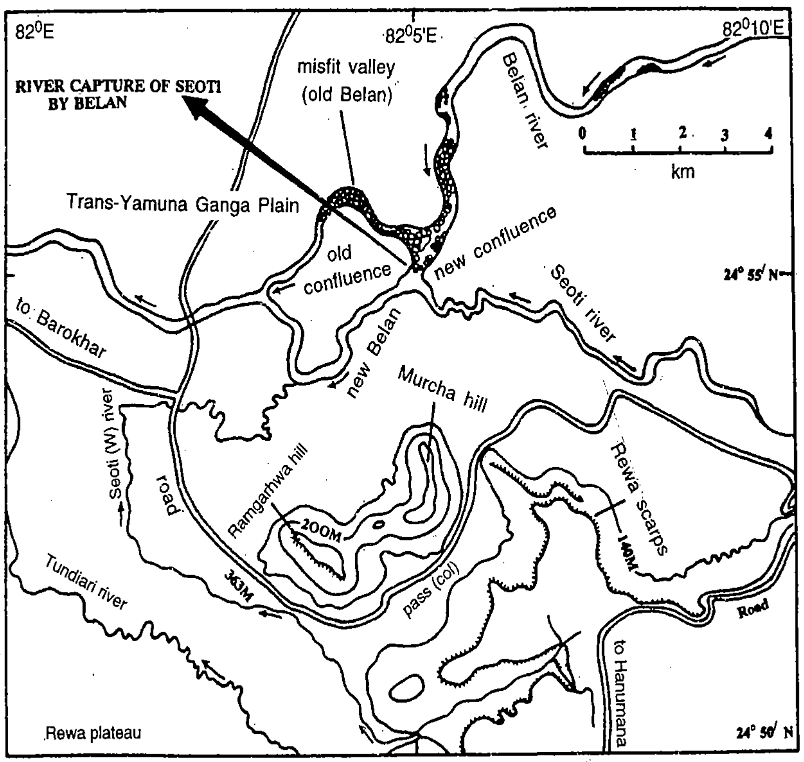


Fig. 17.20 : Example of river capture through lateral erosion and consequent meander intersection.

(2) River capture through lateral erosion

Lateral erosion and consequent valley widening becomes more active and significant during mature stage of river development than vertical erosion and valley deepening. The water divides between parallel streams developed on sedimentary rocks of the coastal plains are gradually narrowed down due to lateral erosion and valley widening. The streams having more volume and discharge of water and relatively steeper channel gradient than the other streams resort to more lateral erosion due to which smaller parallel tributaries are consumed by the larger parallel streams. This process of river capture is called **stream abstraction** or **natural selection.**

3. River capture through the intersection of meanders

The streams adopt highly sinuous and meandering courses during their late mature and old stages of development because of the development of level to gentle slopes (0^0-5^0) over major part of the area concerned. The meanders of two closely spaced streams are gradually sharpened due to continuous lateral erosion and ultimately they intersect each other and thus relatively more powerful stream captures the waters of the other stream. The Belan river, a tributary of the Tons river (which is itself a tributary of the Ganga river), has captured the lower course of its tributary, the Seoti river near Deoghat (about 80 km south of Allahabad city) through meander intersection and now has pushed its course through the course of the Seoti while its older course, now an example of a palaeochannel, has become quite narrow due to sedimentation and anthropogenic processes (cultivation) (fig. 17.20). Due to this unique process of river capture the confluence of the Belan-Seoti rivers has been pushed about 6 km upstream. The older (palaeo) valley of the Belan now has become **misfit valley** (fig. 17.20).

Numerous cases of river capture have occurred in the Himalayan region. In fact, the present drainage system of the Himalayas is, to greater extent, the result of progressive stream piracy. The headward erosion has been the most active process of river capture in the Himalayas and the Western Ghats. The water divide between the headwaters of the Savitri river (draining into the Arbian Sea) and the Krishna river)draining into to the Bay of Bengal) at the margin of the Mahabaleshwar plateau (Maharashtra) is very narrow. The Krishna river may capture the headwaters of the Savitri in near future. The process of river capture through lateral erosion and interesection of meanders is more active in the coastal plains and the Great Northern Plains (India).

18

RUNNING WATER (RIVER) AND FLUVIAL LANDFORMS

18.1 MEANING

The work of running water in the form of surface runoff or overland flow and streams is most important of all the exogenetic or planation processes (*e.g.* groundwater, sea waves, glaciers, wind, periglacial processes etc.) because the running water is the most widespread exogenetic process on this planet earth. The landforms either carved out (due to erosion) or built up (due to deposition) by running water are called **fluvial landforms** (both erosional and depositional) and the running waters which shape them are called **fluvial process** which include overland flow (surface runoff) and steam flow.

The rainwater reaching the earth's surface becomes **surface runoff** when it spreads laterally on the ground surface. The surface runoff becomes a stream when water flows from certain height down the slope under the impact of gravity. Streams are generally divided into four broad categories viz. perennial or permanent streams, non-permanent or seasonal streams, intermittent streams and ephemeral streams. The geological works of fluvial processes or rivers are called **three-phase work** comprising **erosion, transportation** and **deposition.** The fluvial landforms are divided into two major groups *e.g.* 1. **erosional landforms** and 2. **depositional landforms.** The landforms resulting from progressive removal of the bedrock mass are called erosional landforms *e.g.* various types of valley (viz. gorges, canyons, broad and flat, mature and senile valleys, multi-storeyed valleys etc.), pot holes, rapids and water falls, structural benches, terraces, meanders etc. The landforms shaped by the deposition of different types of eroded materials become depositional landforms such as alluvial fans and cones, natural levees, flood plains, terraces, deltas etc.

18.2 EROSIONAL WORK OF RIVERS

The word **'erosion'** has been derived from a Latin word, **'erodere'** which means to gnaw. Erosion is, in fact, a dynamic process which involves the removal of geomaterials from the rocks and other deposited materials. Though weathering greatly assists in the erosion of rocks but it is not a prerequisite condition as remarked by W.D. Thornbury. 'It is true, of course, that weathering is a preparatory and may make erosion easier, but it is not prerequisite to nor necessarily followed by erosion.' In fact, erosion is that process in which various erosive agents (running water-river, wind, glacier, periglacial, sea waves and groundwaters) obtain and remove rock debris from the earth's crust and transport them for long distance (Savindra Singh, 1973).

The erosional work of the rivers depends on channel gradient, volume of water, velocity and thus kinetic energy, water discharge, sediment load (tools of reosion) etc. The sediment load of the rivers

includes gravels, sands, silt and clay. Gravels include boulders (256 mm diameter), cobbles (64-256 mm), pebbles (4-64mm) and granules (2-4mm). The quantity, size and calibre (angularity) of erosional tools (river load) largely control the nature and magnitude of fluvial erosion. The erosional tools of fairly big size and high calibre (with high degree of angularity) help in active down cutting of valleys. The size of river load is of paramount significance because if the load consists of very fine sediments, they move with the water in suspension (suspended sediment load) and hence becomes passive in fluvial erosion but if they are of fairly big size, they roll down along the valley floor and help in valley deepening. The amount of load should be of optimal level *i.e.* the rivers should neither be overloaded nor underloaded because if the river is overloaded in relation to its transporting capacity, it would start deposition of additional load and if the river is underloaded, the erosional work becomes negligible. The following relationships may be identified between the rate of fluvial erosion and river load-

(1) Erosion becomes minimum in the absence of required amount of river load (underloaded river).

(2) Erosion also becomes minimum when the river has maximum load (overloaded river).

(3) Erosion becomes maximum when the river carries load according to its transporting capacity.

The **law of erosion** states that the rate and amount of erosion increases before the attainment of equilibrium between the transporting capacity of the river and its load while it decreases after the attainment of their equilibrium condition.

It may be pointed out that besides the river load, velocity and channel gradient are also significant parameters which effectively control fluvial erosion. Erosion becomes maximum when the river having steep channel gradient and optimal amount of load of good size and high cablibre flow with high velocity. The velocity of water flow depends on (i) channel gradient and (ii) volume of water. Normally, the erosional power of the stream is proportional to the square of the velocity which (**erosional power α (velocity of the stream)2** means if the velocity is doubled, the erosinal power of the streams increases four times, if the velocity is increased 4 times, the erosional power increases 16 times and so on. Besides, lithological and structural characteristics of geomaterials also affect the nature and magnitude of fluvial erosion.

18.3 TYPES OF FLUVIAL EROSION

The erosional work of the rivers is performed in two ways viz. (i) through chemical erosion and (ii) through mechanical erosion. **Chemical erosion** involves corrosion or solution and carbonation while **mechanical erosion** comprises corrasion or abrasion, hydraulic action and attrition. Fluvial erosion is also divided into (i) vertical erosion or downcutting (which leads to valley deepening) and lateral erosion (which causes valley widening).

(1) **Solution** or **corrosion** involves the dissolution of soluble materials through the processes of disintegration and decomposition of carbonate rocks. The soluble materials are removed from the parent rocks and are mixed with the running water of the streams. Most of the salts are removed from the bedrocks through the process of carbonation (see chemical weathering in chapter 15 of this book) and are suspended in river water. According to the estimate of Murray every cubic mile water of the river contains about 7,62,587 tons of suspended minerals of which about 50 per cent is calcium carbonate. On an average the world rivers discharge about 6,500 cubic miles of water into the oceans every year. On the basis of Murray's estimate it may be inferred that about 5 billion tons of minerals are removed from the bedrocks by the world rivers each year and these minerals are carried to the seas and oceans in solution.

(2) **Abrasion** or **corrasion** involves the removal of loosened materials of the rocks of valley walls and valley floors with the help of erosional tools (boulders, pebbles, cobbles, etc.). The erosional tools or river loads move down the channel gradient along with water and thus strike against the rocks which come in contact with them. The repetition of this mechanism weakens the rocks which are ultimately loosened and broken down. Thus, abrasion is the mechanism of breakdown of rocks occasioned by erosional tools carried by the rivers. The nature and magnitude of abrasion depends on the nature, size and calibre (angularity) of erosional tools. Boulders, cobbles and pebbles of various sizes and angularity are by far the most important tools of

erosion which are generally called **drilling tools.** The erosional mechanism of abrasion operates in two ways *e.g.* (i) vertical erosion leading to the erosion and deepening of valley floors and (ii) lateral erosion leading to the erosion of valley walls. Lateral abrasion causes valley widening while the vertical abrasion leads to valley deepening wherein the erosional tools drill the valley floor though the mechanism of **pot hole drilling** resulting into the formation of numerous pot holes (cylindrical depressions) of various sizes in the valley floors. Vertical abrasion (downcutting) becomes more effective during the juvenile stage (youthful) of river and valley development when channel gradient and velocity are very high.

(3) **Attrition** is the mechanical tear and wear of the erosional tools in themselves. The boulders, cobbles, pebbles etc. while moving with water collide against each other and thus are fragmented into smaller and finer pieces in the transit. Thus, the rock particles are so broken down that ultimately they are communitted into coarse to fine sand particles which are transported down the channel in suspension.

(4) **Hydraulic action** involves the breakdown of the rocks of valley sides due to the impact of water currents of channel. In fact, hydraulic action is the mechanical loosening and removal of materials of rocks by water alone. It may be pointed out that chemical weathering, abrasion and hydraulic action are so intimately interrelated that it is unwise to think of pure hydraulic action without chemical erosion and abrasion.

18.4 BASE LEVEL OF EROSION

There is a limit for maximum vertical erosion by a river beyond which it cannot degrade its valley. This limit of maximum downward erosion by a river is called **base level of erosion** or simply a **base level.** Base level, in fact, is the ultimate limit of vertical erosion by a river. J.W. Powell postulated the concept of base level in 1875. According to him the sea level becomes the **grand base level** beyond which no dryland can be further degraded. Besides grand base level, there are local and temporary base levels in a particular river.

(1) **Grand base level** is also called general or ultimate or permanent base level which is determined by the sea level. Base level is a smooth curve which rises and becomes concave upstream. In other words, grand base level is such an imaginary smooth curve below the land the slope of which gradually decreases downstream towards the sea where the river enters the sea. This imaginary smooth curve of the grand base level denotes the limit of maximum downward erosion by a particular river. The sea level is a tangent on this smooth curve of the grand base level of erosion. The grand base level depends on the position of sea level. In other words, it changes with changes in the sea level. When a river degrades its valley upto sea level near its mouth, the river is said to have attained its base level. The rise and fall in sea level also causes rise and lowering of base level. Thus, changes in base level of erosion in response to sea level changes produces different suites of landforms.

(2) **Temporary base level-** There may be several temporary base levels in a particular river due to a variety of factors *e.g.* due to the presence of lakes, different beds of hard and soft rocks etc. in the longitudinal course of the rivers. The temporary base levels are eliminated when the whole course of the river attains its grand base level or permanent base level determined by the sea level.

(3) **Local base level** is in fact the level of the confluence of a tributary stream with its receiving master stream. The tributary streams first erode their valleys according to the level of their confluences and thus grade their longtitudinal profiles. Ultimately, the sea level becomes the grand base level of erosion for the entire drainage basin.

Changes or Movements of Base Level

The changes or movements in the base level of erosion are guided by the changes in sea level. Sea level changes are generally of two types viz. (i) **eustatic changes** (which have global impacts) and (ii) **local changes.** Sea level changes are divided in two categories on the basis of timal factor *e.g.* (i) long-term changes and (ii) short-term changes. Sea level changes and consequent changes and movements in the base level of erosion are always considered in terms of relative position of the coastal land and sea level. Thus, changes in sea level and base level are grouped into two categories viz. (i) **positive change** and (ii) **negative change.** Postive change in the sea level and hence in the base level of erosion occurs when either there is subsidence of the coastal land in relation to the sea level or there is upheaval of the sea floor. On the other hand, the negative change in sea level and base level of erosion occurs when either there is emergence of the coastal land in relation to the sea level or there is subsidence of the sea floor. The above mentioned causes of sea level and base level changes are related to tectonic factors. Besides, glaciation and deglaciation during ice ages at global level also cause lowering (negative change) and rise (positive change) of sea levels and base levels respectively. It is apparent from the above discussion that negative change in sea level and base level (lowering of base level) causes emergence of coastal land while positive change (rise) leads to submergence of coastal land.

The positive change or upward movement of base level due to rise in sea level causes the following geomorphic events in a particular river profile- (i) interruption in the fluvial cycle of erosion leading to shortening of cyclic time because the stage of cyle of erosion is advanced forward, (ii) formation of ria coasts and estuaries because of the submergence of valleys of the rivers at their mouths, (iii) filling of river mouths leading to the formation of buried valleys or channels, (iv) formation of flood plains because of increased sedimentation and alluviation due to lowering of channel gradient and decrease in the transporting capacity of the rivers because of rise or upward movement of base levels, (v) filling of lowlands by aggradation, (vi) formation and development of sea islands near the coasts due to transgression of sea water on the coastal land etc.

The negative change in base level caused by lowering of sea level brings the following geomorphic changes in the affected areas : (i) interruption in the fluvial cycle of erosion leading to lengthening of cyclic time because the stage of cycle of erosion is pushed back (*i.e.* from old to mature or from mature to young stage), (ii) rejuvenation leading to accelerated rate of downward (vertical) erosion and active valley deepening, (iii) evolution of topographic discordance having young topographic features in the lower segments of the valleys and old features in the upper part of the valleys, (iii) formation of multistoreyed valleys and paired terraces on either side of the valley, (iv) development of polycyclic reliefs, (v) development of knick points, knick point waterfalls, and incised meanders, (vi) breaks in slope in the longitudinal profiles of the rivers etc.

18.5 EROSIONAL LANDFORMS

The significant landforms resulting from fluvial erosion by streams include river valleys, water falls and rapids, pot holes, structural benches, river terraces, meanders, peneplians etc.

River Valleys

The valleys carved out by the rivers are significant erosional landforms. The shape and dimension of fluvially originated valleys change with the advancement of the stages of fluvial cycle of erosion. The valley formed in the youthful stage of fluvial cycle of erosion and in the initial stage of valley development is V-shaped having steep valley side slope of convex element. The valley is very deep and narrow, both the valley sides meet together at the valley floor and thus water always touches the valley sides. Such type of V-shaped valleys are the result of accelerated rate of downcutting (vertical erosion or valley deepening). The valleys are gradually widened due to lateral erosion with the advancement of the stage of cycle of erosion and they become quite broad with flat valley floor and uniform or rectilinear valley side slopes during mature stage or valley development and fluvial cycle of erosion. They are further transformed into very broad and shallow valleys having concave valley side slope of very gentle gradient during old stage. V-shaped valleys are divided into two types viz (1) gorges and (2) canyons.

(1) **Gorges** and **canyons** represent very deep and narrow valleys having very steep valley side slopes say wall-like steep valley sides. It is difficult to draw a line of distinction between these two types of valleys. Normally, a very deep and narrow valley is called a gorge and the extended form of a gorge is called a canyon (fig. 18.1). Gorges are formed due to active downcutting of the valleys through the mechanism of pothole drilling during juvenile (youth) stage of the fluvial cycle of erosion. Gorges are also formed due to recession of water falls. Most of the Himalayan rivers have carved out deep and narrow gorges. The significant gorges formed due to

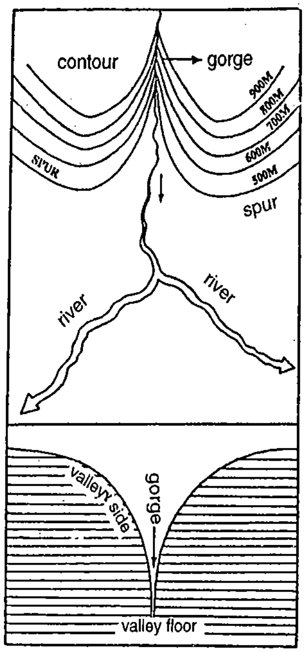


Fig. 18.1 : Contour plan of gorge and spurs and cross section of a gorge.

recession of waterfalls include Hundrughagh gorge on the Subarnarekha river (near Ranchi), gorge of the Raru river below Johna or Gautamdhara falls (east of Ranchi), Dassamghagh gorge below Dassamghagh falls on the Kanchi river (east of Ranchi), Pheruaghagh gorge on the South Koel river (south of Ranchi), Chachai gorge on the Bihar river (Rewa, M.P.), Kevti gorge on the Mahana river (Rewa, M.P.), gorge of the Odda river (Rewa, M.P.) etc.

(2) **Canyons** are extended form of gorges. Canyons represent very deep, narrow but long valleys. The steepness of the valley sides depends on the nature of the rocks. Relatively resistant rocks support steep valley sides whereas resistant rocks alternated by soft rocks give birth to undulating valley sides. The Grand Canyon of the Colorado river in the state of Arizona (USA) having a length of 482.8 kilometres and depth of 2088.3 m is one of the most important canyons of the world. The Indus river has cut across the Himalayan ranges and flows through 17,000-foot deep gorge and canyon.

Waterfalls

Waterfalls or simply falls are caused because of sudden descents or abrupt breaks in the longitudinal course of the rivers due to a host of factors *e.g.* variation in the relative resistance of rocks, relative difference in topographic reliefs, fall in the sea level and related rejuvenation, earth movements etc. A waterfall may be defined as a vertical drop of water of enormous volume from a great height in the long profiles of the rivers. Rapids are of much smaller dimension than waterfalls. Generally, they are found upstream from the main falls but they are also found independently. There is a chain of waterfalls along the junction of the Piedmont and Atlantic coastal plain from New England Region in the north-east to central Alabama in the south-west (USA) wherein all the Atlantic bound streams while descending through the Piedmont make numerous waterfalls. This chain of water falls is called fall line in the USA. There is also a well marked **fall line** in India. This **Indian fall line** extends between the Purwa or Tons falls on the Tons river (in the north-west part of the Rewa district of Madhya Pradesh) in the west and Sasaram (Bihar) in the east along the junction of the northern foreland of Peninsular India and the Ganga plains. Hundreds of waterfalls ranging in height between 15m and 180m are found along this fall line as all the major streams emerging from the Kaimur ranges and draining due northward make stupendous water falls while descending through the rim of the northern foreland of the Indian Peninsula. Significant waterfalls of this fall line are Purwa or Tons falls (70m) on the Tons river (in Rewa district, M.P.), a tributary of the Ganga river, Chachai falls (127m) on the Bihar river (Rewa district), tributary of the Tons river, Kevti falls (98m) on the Mahana river (Rewa district), a tributary of the Tons river, Odda falls (145m) on the Odda river (Rewa district), a tributary of the Belan river (which is itself a tributary of the Tons river), Devdari falls (58m) on the Karamnasha river (Rohtas plateau, Bihar), Telharkund falls (80m) on the Suara West river (Rohtas plateau), Suara falls (120m) on the Suara East river, Durgawati falls (80m) on the Durgawati river (Rohtas plateau), Okharean Kund falls (90m) on the Gopath river (Rohtas plateau), Dhuan Kund

falls (30m, Rohtas plateau, near Sasaram) on the Dhoba river, Kuaridah falls (180m) on the Ausane river (a tributary of the Son river, Rohtas Plateau), Rakim Kund falls (168m on the Gayghat river, a tributary of the Ausane river (Rohtas plateau) etc.

Table 18.1 : Important Waterfalls of the World

Name of the Falls	Height in metres	Location
	(A) Highest Waterfalls	
Angel Falls	979.00	Venezuela
Browne Falls	837.00	New Zealand
Kjeifossen Falls	792.00	Norway
Yosemite Falls	739.00	California (USA)
Southerland Falls	579.34	New Zealand
Roraima Falls	457.20	British Guiana
Kalambo Falls	426.72	South Africa
Takkaku Falls	400.26	British Columbia (Canada)
Gersoppa (Jog) Falls	253.00	Sharavati (Karnataka, India)
Multnomah Falls	250.85	Oregon (USA)
Bridalveil Falls	188.97	Yosemite, California (USA)
	(B) Falls with high volume of water	
Niagra Falls	62.00	USA and Canada
Victoria Falls	108.00	Zimbabwe
Iguazu Falls	70.00	Argentina
Kaieteur Falls	-	British Guiana
Lower Yellowstone Falls	-	Wyoming (USA)
Grand Falls	-	Labrador (Canada)

Types of Waterfalls-The waterfalls vary so greatly in terms of their height, shape and size, dimension and volume of water that it becomes difficult to classify them in certain categories. Generally, waterfalls are divided into two broad categories on the basis of mode of their origin viz. (1) normal waterfalls and (2) minor waterfalls. Normal waterfalls include those falls which are formed due to variation in the resistance of rocks. These waterfalls are indicative of youthful stage of stream development and ungraded long profiles of the streams. Minor waterfalls include the falls which are originated due to interruption in the cycle of erosion caused by rejuvenation. Such water falls are called knick-point falls. The following is the detailed scheme of the classification of fluvially originated waterfalls.

1. Normal waterfalls

- (i) Step waterfalls
- (ii) Caprock falls
- (iii) Barrier falls
- (iv) Plateau falls

2. Minor waterfalls

- (A) Falls originated due to endogenetic forces
  - (i) Fault falls
  - (ii) Falls due to upliftment
- (B) Falls originated due to changes in the level of valley floors

(1) Due to lowering of valley floor
- (i) Hanging valley falls
- (ii) Glacial hanging valley falls
- (iii) Falls due to river capture
- (iv) Coastal hanging valley falls
- (v) Knickpoint falls

(2) Due to obstructions in the river courses
- (i) Falls due to landslides
- (ii) Falls due to lava dams
- (iii) Falls due to glacial moraines

(1) **Waterfalls due to structural and lithological variations**—The waterfalls originated due to variations in the structural and lithological characteristics of terrestrial rocks are called normal waterfalls. Various hierarchical orders of water falls (*e.g.* catracts, rapids and cascades) depend on the relative resistance and disposition of the beds of different rocks. The cliffs formed due to the presence of hard and soft rocks in the courses of the rivers form large waterfalls which are called **cataracts.** Alternate bands of hard and soft rocks give birth to a series of small step-like falls which are called **cascades.** The disposition of rock beds gives birth to waterfalls of varying dimensions in the following manner.

(i) **When the rock beds dip upstream**—When the alternate bands of hard and soft rocks dip upstream in the longitudinal course of the river and if the caprock is resistant the underlying soft rocks are eroded more rapidly due to cliffing and thus the resistant rock beds form precipitous wall-like scarps which allow the river water to fall downstream vertically and ultimately a stupendous waterfall is formed. Such waterfall recedes at faster rate due to cliffing and tumbling down of hanging head walls of the falls (fig. 18.2). Such falls, called as caprock falls, disappear when the river attains its graded profile of equilibrium.

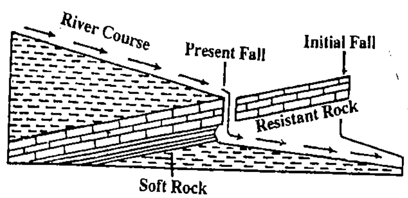


Fig. 18.2 : Origin of waterfalls when the rocks dip upstream.

(ii) **When the rock beds dip downstream-** Rapids are formed when the alternate bands of hard and soft rocks dip downstream and the caprock is resistant to erosion. Such falls are called **caprock rapids** (fig. 18.3).

(iii) **When the rock beds are horizontal-**Very massive and stupendous waterfalls are formed when the rock beds are arranged in horizontal manner and the caprock is quite resistant such as quartzitic sandstones, dolomitic limestones, granite-gneisses and the underlying rocks are soft and vulnerable to quick fluvial erosion such as shale, volcanic ash and unconsolidated geomaterials, because soft rocks are eroded more than the overlying resistant caprocks and thus resistant rocks form wall-like scarps which allow river water to fall down vertically. Niagra Falls come under this category of waterfalls. The

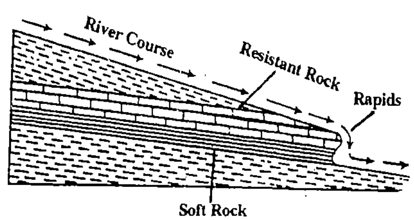


Fig. 18.3 : Formation of rapids when the rock beds dip downstream.

caprock of this waterfall is dolomitic limestones which are succeeded below by the successive beds of shales, limestones, sandstones, sandstones intercalated with shales, sandstones, and shales (fig. 18.4). The height of the fall is now 52m and the water discharge is 17,000 cumecs (cubic metres per second). The fall is supposed to have been formed about 10,000 years ago. It is receding at the rate of 3 to 4 feet per year. It is estimated that the Niagra fall has registered a total recession of about 7 miles (11.2 km) till now, Kaieteur falls (British Guiana) also fall under this category of **caprock falls.** The caprock is of resistant conglomerates. The Potaro river has cut deep through conglomerates and thus has formed 225.5 m high waterfall.

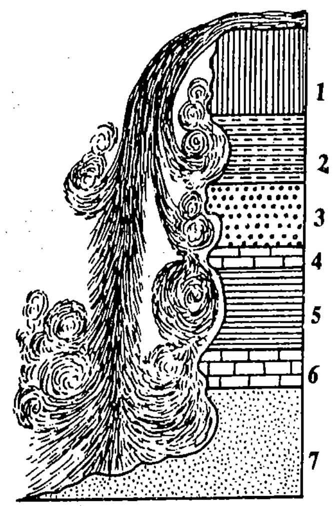


Fig. 18.4 : Formation of waterfalls when the rock beds are horizontal and the caprock is resistant to erosion. Example of Niagrafalls; (1) dolomitic limestones, (2) shales, (3) limestones, (4) sandstones, (5) sandstones and shales, (6) sandstones, and (7) shales.

The waterfalls of the Rewa (Madhya Pradesh) and Rohtas (Bihar) plateaux (as mentioned above) also come under this category as the caprocks are sandstones and quartzitic sandstones underlian by weaker shales of Vindhyan formations. Chachai falls (127m, on Bihar river), Kevti falls (98m, on Mahana river), Odda falls (145m, on Odda river), Kuaridah falls (180m, on Ausane river), Rakimkund falls (168m, on Gayahat river) etc. are typical examples of caprock waterfalls.

(iv) **When the rock beds are vertical**—When alternate resistant and soft rocks are arranged in vertical manner, soft rocks are eroded away rapidly but the resistant rock beds are less eroded and hence form precipitous scarps in the course of the river which give birth to waterfalls of steep slope. The intrusive dykes also form waterfalls because of their less (fig. 18.5) erosion than the surrounding rocks. Such waterfalls are called **vertical barrier falls.** Great Fall of the Yellowstone river of the Yellowstone National Park (USA) is a typical example of vertical barrier fall. Several such waterfalls have been formed in the 'Patlands' of Ranchi and Palmau (Jharkhand) but their heights range between 3m and 30m only. These waterfalls have been formed because of structural and lithological controls and differential erosion.

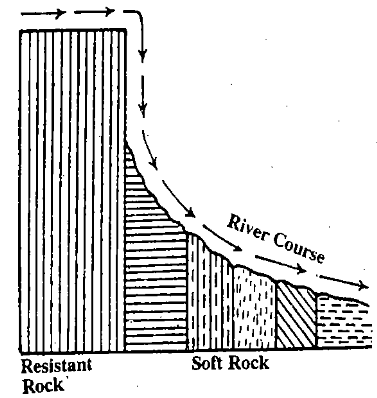


Fig. 18.5: Origin of waterfalls when the rock beds are vertical.

(v) **Plateau waterfalls-**The rivers coming from over the plateau surface form waterfalls when they descend through the precipitous escarpments of the plateau and enter the region of significantly lower height. The Congo river has formed 275 m high Livingstone Falls while descending through the African Plateau. Similarly, the Orange river has formed 140 m high Aughrabies Falls at the margin of the plateau. Nearly all of the significant northward drain-

ing streams and their tributaries have formed waterfalls at the northern margin of the Rewa plateau (M.P.) *e.g.* Chachai Falls (127 m) on Bihar river, Kevti Falls (98 m) on Mahana river, Odda Falls (145m) on Odda river etc. Karo river has formed 17 m high Pheruaghaugh Falls at the southern margin of the Ranchi plteau. Such falls are called as **scarp falls.** Hundru falls (75 m) on Subaranrekha river (near Ranchi), Dasam falls (39.62 m) on Kanchi river (east of Ranchi), Sadni falls (60m) on Sankh river (Ranchi plateau) etc. are the examples of **scarp falls** or **knick line falls.** The Tons river while descending through the Rewa plateau and draining northward to meet the Ganga makes a vertical falls of 70m known as Purwa falls. Similarly, its tributary the Bihar river makes a stupendous Chachai falls of 127 m height.

Yenna falls (180m) on Mahabaleshwar plateau, Gokak falls (54 m) in Belgaun district (Karnataka), Gersoppa falls (253m) on the Sharavati (in North Kanara), Sivasamudram (90m) on the Cauvery river etc. are also examples of scarp falls.

(vi) **Step falls**-The arrangement of alternate bands of horizontal beds of hard and soft rocks in the course of the rivers produces a series of low water falls due to differential erosion. These falls are in fact rapids. Bhagawati falls on the Krishna river in the Raichur district of Karnataka (India) is an example of step (cascade) falls.

(2) **Waterfalls due to faults and fractures**-Waterfalls are formed along the fault scarps which are created due to faulting across the river valleys. Victoria falls on the Zambezi river (110 m high) is a typical example of fault falls.

(3) **Waterfalls due to upliftment**- Waterfalls of varying dimensions are formed due to upliftment of local nature in the courses of the rivers. These waterfalls are obliterated when the rivers regrade their longitudinal profiles. A series of waterfalls on the rivers along the junction of Palamau upland and the northern flat plain (Palamau district, Jharkhand) are said to have been formed due to origin of escarpment caused by the upliftment of southern Palamau during Tertiary period. Patam falls (45.72 m) and Datam falls (30.45 m) on the Patam river (in Bhandaria Anchal, Palamau, Bihar) are typical examples of such categories. Gersoppa falls (253m) or Jog falls is also believed to have been formed due to upliftment. The waterfalls on the eastern margin of the Ranchi plateau (*e.g.* Hundru falls on the Subarnarekha river, Dasam falls on the Kanchi river, Jonha or Gautamdhara falls on the Gunga river etc.) are also quoted as the examples of waterfalls resulting from upliftment.

(4) **Hanging valley falls**-Some times, waterfalls of varying dimensions are formed when the tributary streams join their master streams from great height forming hanging valleys (fig. 18.6). In other words, hanging valley falls are formed when the level of the junction of the tributary streams is

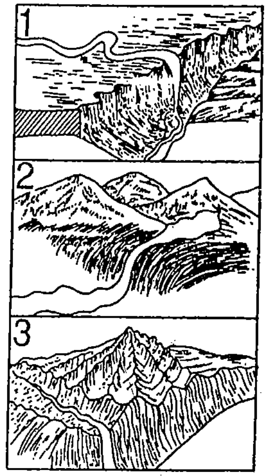


Fig. 18.6 : Origin of waterfalls due to (1) hanging valley, (2) lava dam and (3) glacial hanging valley.)

much higher than the level of the main valley of the master stream. The Rajroppa falls (10m) at the junction of the Bhera nadi and the receiving Damodar river (located to the north of Ranchi city) is a typical example of **hanging valley waterfalls** as the Bhera nadi after coming from over the Ranchi plateau hangs above the Damodar river at its confluence with the latter. The Gautamdhara or Jonha falls (25.9m) is another example of this category of falls. In fact, the Gunga river hangs above its master stream, Raru river, (to the east of Ranchi city) and forms the said falls.

(5) **Glacial hanging valley falls**-The fluvially originated river valleys are largely modified by

glaciers during ice ages. The glaciers flowing through the main valleys deepen them more due to erosion than the tributary valleys. Thus, the tributary valleys hang over the main valleys and discordant levels are formed. These valleys are again occupied by the rivers after the ice age is over and glaciers are ablated. Consequently, the tributary streams hang over the main rivers at their junctions and waterfalls are formed (fig. 18.6). Such glacial hanging valley waterfalls are found in Norway, Sweden, Finland, Canada etc.

(6) **Waterfalls due to river capture**-Some times, waterfalls are formed when the streams flowing over higer but flat lands are captured by the streams of relatively lower height. Thus, the captured streams drain into the captor streams by making waterfalls. Such falls are abundantly found in the Himalayas.

(7) **Coastal hanging valley falls**-The rivers while descending through sea cliffs or cliffed coast form vertical waterfalls before debouching into the sea (fig. 18.7). Such waterfalls are also called coastal hanging valley falls as the river hangs through the vertical cliffed coast.

(8) **Knickpoint falls**-The breaks in channel gradient caused by rejuvenation (either due to upliftment or fall in sea level) are called knick points or heads of rejuvenation. These breaks in channel gradient or knickpoints denote sudden drops of elevation in the longitudinal profile of the rivers and allow the water to fall down vertically giving birth to waterfalls of varying dimensions. Hundru falls (76.67 m) on the Subarnarekha river (near Ranchi city), Jonha or Gautamdhara falls at the confluence of the Raru and the Gunga rivers (to the east of Ranchi), Dasam falls (39.62 m and 15.24 m) on the Kanchi river (east of Ranchi), Burhaghaugh falls (148 m) on the Burha river, a tributary of the North Koel (Palamau upland, Jharkhand), Dhunwadhar falls on the Narmada river (near Jabalpur, M.P.), major falls of Rewa plateau (*e.g.* Chachai falls-127 m on the Bihar nadi, Kevti falls-98 m on the Mahana nadi, Tons or Purwa falls-75m on the Tons river, Odda falls - 145 m on the odda nadi etc.) etc. are the examples of knick point waterfalls.

(9) **Waterfalls due to obstructions in the river flow**-Some times, temporary water falls are formed due to temporary damming of the river flow through natural processes in a number of ways.

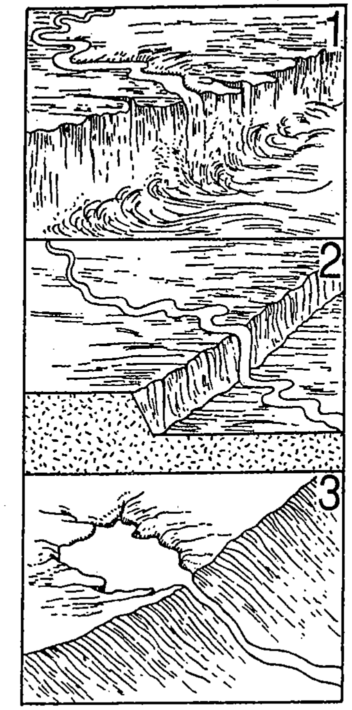


Fig. 18.7 : Origin of waterfalls due to (1) cliffed coast, (2) faults and (3) upliftment.

(i) **Lava-dammed waterfalls** are formed when the flow of river water is obstructed due to formation of lava barrier across the valley. Such falls are almost permanent.

(ii) **Landslide-dammed waterfalls** are originated when huge volume of debris slides down from the nearby hillslopes into the river and obstructs the free flow of the river by making barrier across the valley.

(iii) **Moraine-dammed waterfalls** are formed due to damming of river flow by morainic debris. The rivers make falls while crossing through the morainic ridges formed across the valleys.

Recession of waterfalls—It may be pointed out that waterfalls and rapids are not permanent landforms. They disappear when the rivers attain their graded curves and profiles of equilibrium during mature

stage of valley development and normal cycle of erosion. In fact, the rivers try to grade themselves through vertical erosion (valley deepening) in relation to base level of erosion (sea level). The obliteration of waterfalls takes place through two processes viz. (1) horizontal recession through backwasting and (2) lowering of height through downwasting. Niagra falls are receding at the rate of 1.2 to 1.4 m per year. It has been estimated that Niagra falls have receded upto about 11 km till now. No attempts have been made to record the recession of waterfalls in India.

Pot Holes

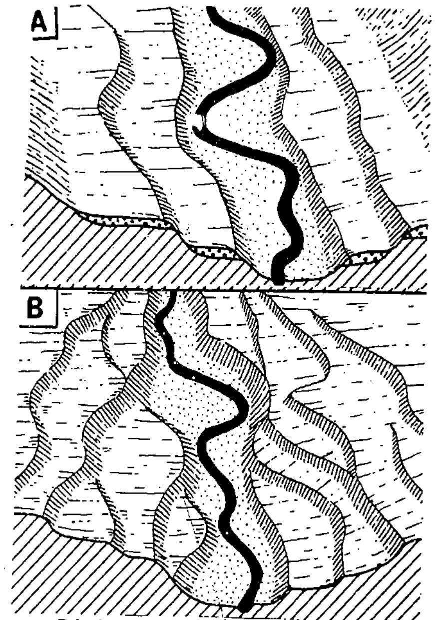
The kettle-like small depressions in the rocky beds of the river valleys are called potholes which are usually cylindrical in shape. Potholes are generally formed in coarse-grained rocks such as sandstones and granites. Potholing or pothole drilling is the mechanism through which the grinding tools (fragments of rocks *e.g.* boulders and angular rock fragments) when caught in the water eddies or whirling water start dancing in circular manner and grind and drill the rock beds of the velleys like drilling machine and thus form small holes which are gradually enlarged by the repetition of the said mechanism. The potholes go on increasing in both diameter (and perimeter) and depth. The diameter of pot holes ranges from a few centimetres to several metres. The depth of potholes is far more than their diameters. Potholes of much bigger size are called **plunge pools.** In fact, plunge pools are generally formed at the base of waterfalls due to pounding of rocks by gushing water of the falls (waterfalls). Many of the river valleys are studded with numersous potholes in Chotanagpur highlands where the rivers have been rejuvenated due to upliftment effected during Tertiary period. The basaltic bed of the Gaur nadi near Bhadbhada (east of Jabalpur, M.P.) presents a magnificent view of numerous potholes of various dimension. Pothole drilling is the effective mechanism of valley deepening.

Structural Benches

The step-like flat surfaces on either side of the present lowest valley floors are called terraces. The benches or terraces formed due to differential erosion of alternate bands of hard and soft rock beds are called structural benches or terraces because of lithological control in the rate of erosion and consequent development of benches (fig. 18.8).

River Terraces

The narrow flat surfaces on either side of the valley floor are called river terraces which represent



Paired (A) and unpaired (B) river terraces

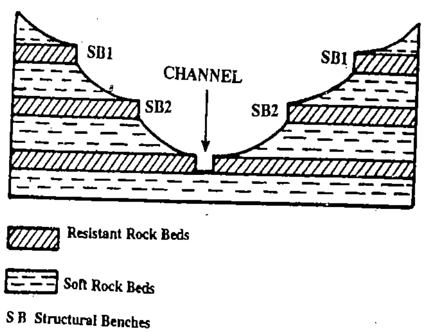


Fig. 18.8 : Structural Benches : SB=Structural Benches.

the level of former valley floors and the remnants of former (older) flood plains. Some times, the river

valleys are frequented by several terraces on either side wherein they are arranged in step-like forms. River terraces are generally formed due to dissection of fluvial sediments of flood plains deposited along a valley floor. There are much variations in terraces as regards their morphology, structure and mode of origin. River terraces are classified in various ways. For example, terraces are divided into (1) **paired terraces** and (2) **unpaired terraces** on the basis of nature of erosion. Paired terraces are formed due to rapid rate of vertical erosion resulting into the occurrence of terraces on both the sides of the river valley almost at the same level (fig. 18.9). It may be pointed out that paired terraces mean occurrence of terraces on both the sides of valley at the same height. Unpaired terraces are formed due to concamitant vertical erosion (valley deepening) and lateral movement of the channel. River terraces are also divided into (1) **rock terraces** and (2) **aggradational terraces.** Rock terraces are characterized by bedrock platform covered by fluvial deposits whereas aggradational terraces consist of very thick deposits of fluvial sediments. River terraces are generally formed due to erosion of former flood plains consequent upon rejuvenation caused by either upliftment of the landmass or fall in sea level. Alternatively, river terraces are divided into alluvial terraces and strath terraces (stony terraces).

The mechanism of the formation of river terraces may be explained in the following manner. The rivers form extensive flood plains during late mature stage and attain their graded curve of profile of equilibrium. The flood plains consist of thick deposits of alluvia and gravels. The rivers are rejuvenated due to sudden negative change (fall) in sea-level. Consequently, the erosive capacity of the rivers is increased substantially. Thus, rejuvenated rivers deepen their valleys due to accelerated rate of vertical erosion. Now the rivers form their new narrow valleys within former flat valleys and thus terraces (fig. 18.9) are formed on both the sides. The rivers are again rejuvenated due to fall in sea level and new narrow valleys are formed due to vigorous valley deepening consequent upon second rejuvenation. This process leads to the formation of second pair of terraces (fig. 18.9) and so on.

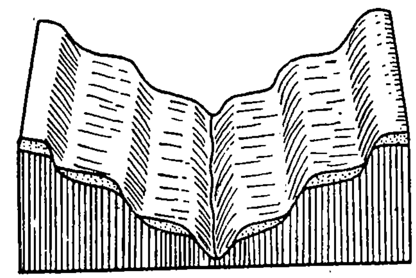


Fig. 18.9: Examples of paired rivers terraces.

River Meanders

River meanders refer to the bends of longitudinal courses of the rivers. The bends of sinous rivers have been named meanders on the basis of Meander River of Asia Minor (Turkey) because it flows through numerous bends. Each bend of a meander belt has two types of slopes of valley sides. (1) One side is characterized by concave slope where the channel strikes the valley sides directly, with the result concave side is subjected to severe erosion resulting into the formation of vertical cliffs. This side of the meander belt is also called as cliff-slope side. The other side of the meander belt is characterized by convex slope which receives deposition mostly of sands and gravels but some times alluvium is also deposited. This convex side is characterized by gentle slope and is called the side of **slip-off slope** (fig. 18.10). The shape of meander is usually semi-circular but some times it is also circular. The length of a meander belt can be found out on the basis of the channel width because meander belt is usually about 15 to 18 times the width of bankfull channel.

It may be pointed out that the meandering is a natural process which is governed by a number of environmental factors viz. lithological characteristics, topographic characteristics, general slope, vegetation, annual precipitation, stream discharge and of course the stage of river development and cycle of erosion (i.e. timal factor). All streams meander in all types of terrains (*e.g.* mountainous and hilly terrains, dissected upland, alluvial plains, plateaux, coastal plains etc.) but their magnitude varies according to ground slope and nature of geomaterials. Meandering is most pronounced in the regions characterized

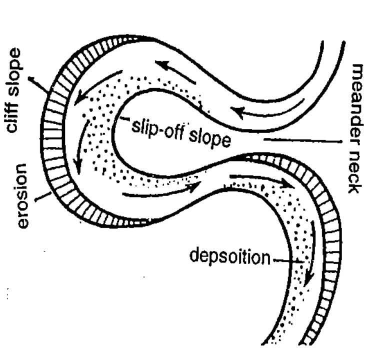


Fig. 18.10 : Components of a meander loop.

by even surface and gentle slope, alluvial deposits and sufficient stream discharge. Theoretically, the streams should adopt straight path (referred to as expected path) but no streams adopt straight paths rather they register significant departures from expected straight paths. The degree of deviation of observed path (actual course of a stream) from expected path (theoretical straight course), known as sinuosity index tells the magnitude of meandering. If the value ranges between 1 and 1.3, the stream is said to be sinuous and the stream becomes meandering if the value exceeds 1.3.

The gradient of highly meandering streams ranges between 20 cm to 10 m per kilometre. All of the alluvial streams of the Northern Plains of India have developed meandering courses. The Gomti river (Uttar Pradesh) is a typical example of highly meandering stream of alluvial plains because of the fact that its channel gradient is very low (9 cm per kilometre between Lucknow and Sultanpur). The Ganga river has developed highly meandering course between Allahabad and Varanasi due to very low channel gradient (6 cm per kilometre). Besides, Ramganga, Sai (a tributary of the Gomti river), Rapti, Ghahghra, Punpun, Burhi Gandak, Kosi etc. have also developed highly meandering courses.

Meanders are the result of erosion and deposition both. Meanders are divided into two major types on the basis of the nature of fluvial erosion *e.g.* (1) meanders developed through lateral erosion (normal meanders) and (2) meanders developed by vertical erosion or valley deepening (incised meanders). (3) Misfit or unfit meander is also identified as the third type of meanders. Morphologically, river meanders are divided into 3 types viz. (1) wavy type of meanders, (2) horse-shoe type of meanders and (3) ox-bow or bracelet type of meanders. The wavy meanders are very simple in plan (fig. 18.11(2)) wherein the meander necks are wide apart. Such meanders have been developed by the major streams in the Himalayas. The horse-shoe types of meanders are those in which the beds are highly curved (fig. 18.11 (3) and the arms of meanders are brought closer to each other with the result the meander necks become very narrow. The ox-bow or bracelet (a type of ornament of women) types of meanders are those which have almost circular bends with high curvature. Most of the alluvial rivers of the Northern Plains of India have developed horse-shoe and ox-bow types of meanders.

(1) **Simple meanders**—The meanders developed during first cycle of erosion by a stream are called simple meanders. These are formed by lateral erosion. Simple meanders or say monocyclic meanders are divided into three types on the basis of their morphological characteristics *e.g.* (i) **wavy meander**, (ii) **horse-shoe type** of meander and (iii) **ox-bow**

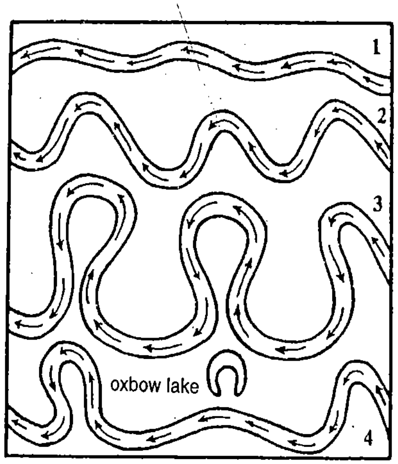


Fig. 18.11: Stages of the formation and development of meanders. 1-2. wavy meander, 3. horse-shoe meander and 4. ox-bow or bracelet type of meander.

or bracelet type of meander. There are certain necessary conditions for the development of simple meanders. (a) Over-loaded streams cannot form meanders because their total power is spent in the transportation of huge amount of sediments. Such rivers are always engaged in depositional activity. The streams in youthful stage are also not capable of forming meanders because they are actively engaged in incising their valleys through downcutting and related valley deepening. Thus, mature streams are more capable of forming meanders because they resort to lateral erosion and consequently valley widening more than valley deepening. The most ideal conditions required for development of meanders are alluvial plains, gentle slope, sufficient amount of precipitation and general absence of vegetation. A minor obstruction in the free flow of the streams in flood plains diverts their courses from straight course and thus the process of meander formation begins with the initiation of very minor bends in the longitudinal courses of the alluvial streams (formation of wavy meanders, fig. 18.11 (1 and 2)). The channel currents strike against the concave side of the open meander bends and cut the loose geomaterials (alluvium) and thus there is continuous sharpening of meander bends resulting into high degree of curvature of meander loops (formation of horse-shoe type of meander, fig. 18.11 (3). The processes of erosion of concave sides and deposition of sediments on convex sides of meander loops. (fig. 18.10) continue and the curvatures of meander loops are made more and more circular (formation of ox-bow or bracelet type of meanders, fig. 18.11 (4) and the river course becomes highly meandering with several ox-bow lakes.

(2) **Incised meanders** are the representative features of rejuvenation and are developed through vertical erosion leading to valley incision or deepening. The narrow and deep meanders formed due to accelerated rate of valley incision caused by rejuvenation (either due to upliftment of land area or fall in sea level) inside simple meanders (having wide and shallow valleys) developed by lateral erosion during first stage of cycle of erosion are called incised meanders (fig. 18.12).

It may be pointed out that simple meanders develop over loose geomaterials (such as alluvium) as well as over resistant bedrocks but incised meanders are always dug out in bedrocks. Five terms are in use to indicate incised meanders which are

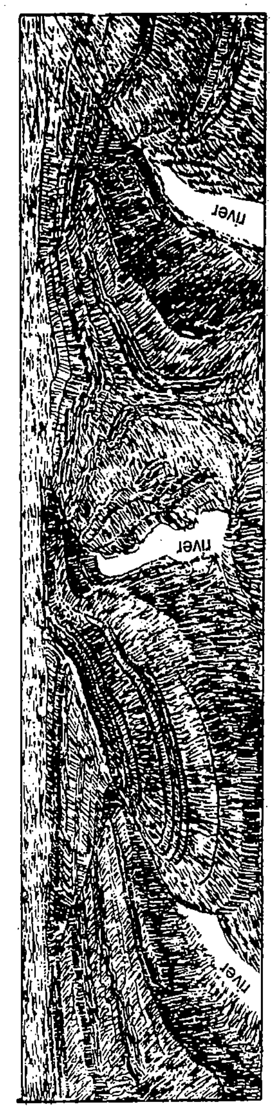


Fig. 18.12 : Incised meanders of San Juan river (Utah, USA).

developed due to vertical erosion (downcutting or valley incision) of bedrock viz. (i) incised meanders,

(ii) entrenched meanders, (iii) intrenched meanders, (iv) inclosed meanders and (v) ingrown meanders.

Inclosed and incised meanders represent those meanders of deep and narrow valleys which are inclosed by rocky walls. In fact, incised meanders mean the formation of meanders in older meanders through downcutting of valley floors. Further, incised meanders can be divided on the basis of nature and slope of valley sides into (i) **entrenched** or **intrenched meanders** having uniform slopes of both the valley sides of meander loops and (ii) **ingrown meanders,** which have unequal slopes of valley sides wherein one side of the valley representing concave side is deeply undercut and the other side (convex side, slip-off slope) is characterized by gentle valley side slope and deposition of sediments mainly sands. Thus, it is apparent that entrenched meanders represent those incised meanders in which the valley floors have been deeply entrenched through vertical erosion consequent upon rejuvenation whereas ingrown meanders are those incised meanders in which one side of the valley has been deeply undercut resulting into the formation of hanging cliff.

Misfit meanders represent those meanders which are formed within the extensive former meanders due to substantial decrease in the volume of water. The rivers develop extensive meander loops and belts in alluvial plains and are braided into several channels which wander in the extensive broad and flat valleys. When, by any reason, the volume of water in the concerned rivers decreases substantially, the channels become narrow. These narrow channels becomes unable to fit themselves in the broader former valleys and hence they develop their own meandering course of narrow valleys within the older wider meanders. Such narrow meanders within the wider meanders are called misfit meanders because they cannot fit with the latter.

Ox-bow Lakes

The lakes formed due to impounding of water in the abandoned meander loops are called ox-bow or horse-shoe lakes. When the curvature of the meander loops is so accentuated due to lateral erosion, the meander loops become almost circular and the two ends of meander loops come closer, consequently, the streams straighten their courses and meander loops are abandoned to form ox-bow lakes (fig. 18.13). It may be pointed out that the formation of oxbow lakes owes to erosion (straightening of river course through the intersection of two ends of meander loops at the meander neck due to lateral erosion) and deposition both (filling and plugging of cut off ends of meander loops through deposition (fig. 18.13). There is frequent sedimentation (alluviation) of oxbow lakes during floods and thus they are converted into swamps in due course of time. The meandering course of the Ganga river in Uttar Pradesh and its gradual southward shifting has left out a series of palaeochannels and oxbow lakes to the north of the present course of the Ganga. Such palaeochannels and oxbow lakes are now seen in the forms of tanks, ponds and lakes. Several examples of palaeochannels and palaeo-oxbow lakes are still observable in Pratapgarh district of Uttar Pradesh.

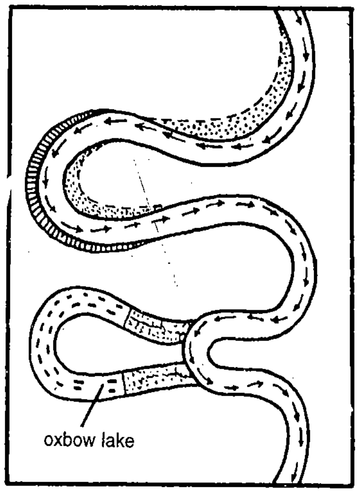


Fig. 18.13: Formation of oxbow lakes due to sharpening of meander loop.

Peneplains

Peneplains represent low featureless plain having undulating surface and remnants of convexo-concave residual hills. These are, in fact, the end products of normal cycle of erosion. These are frequented with low residual hills known as **monadnocks** (named by W.M. Davis after Monadnock hills of New England region, USA) which are left out due to less erosion of relatively resistant rocks.

The end product of normal or fluvial cycle of erosion has been variously named by different geomorphologists. *e.g.* peneplain (W.M. Davis), **endrumpf** ((W. Penck), **panplain** (C.H. Crickmay), **pediplain** (L.C. King), **etchplain** (Pugh and Thomas), **panfan** (A.C. Lawson) etc.

18.6 TRANSPORTATIONAL WORK OF STREAMS

Rivers obtain the eroded materials and transport them from one place to another place. Rivers have their limits to transport materials, they cannot transport loads if they exceed the transporting power of the streams. The size and amount of load and the velocity of streams determine their transporting power. The velocity of streams depends on channel gradient, form and nature of valley floors and valley walls, sinuosity of river course and volume and discharge of water. Steep channel gradient, less sinuous course, smooth valley floor and required amount of volume of water increase the velocity of streams which in turn increases the transporting power of streams.

G.K. Gilbert has propounded a law of stream transportation based on the relationship between stream velocity and its transporting power. The law is known as **Gibert's sixth power law** according to which the transportation power of the streams is proportional to the sixth power of their velocity. In other words, if the stream velocity is doubled, the transportational power of the stream increases 64 times. This law can be expressed in the following form-

$$\text{Transportation Power } \alpha \text{ (stream velocity)}^6$$

Rivers transport their load in different ways *e.g.* (1) by traction, (2) by saltation, (3) by suspension and (4) by solution. **Saltation** involves the transportation of rock pieces and boulders of bigger size which move as bedload close to channel floor by rolling or sliding. The bedload does not always touch the valley floor. The bedload being transported by **traction** method consists of gravels, pebbles, cobbles and boulders. The mechanism of saltation involves the transport of load with water currents wherein coarse load moves downward by leaping and jumping through the valley floors. This mechanism is extremely slow. The materials of medium size are suspended in water due to its buoyancy. Such load is called suspended load which is easily carried away by the streams for longer distances. The soluble materials are dissolved in water and become invisible. Thus, such materials are transported in solution form and the involved mechanism is known as transportation by solution.

18.7 DEPOSITIONAL WORK OF STREAMS

The deposition of load carried by the streams is effected by a varivery of factors *e.g.* (1) decrease in channel gradient, (2) spreading of stream water over larger area, (3) obstruction in channel flow, (4) decrease in the volume and discharge of water, (5) decrease in the velocity of streams, (6) increase in the load etc. It may be pointed out that aforesaid factors of river deposition may be grouped into two categories *e.g.* (1) decrease in stream velocity and (2) increase in river load. The decrease in stream velocity reduces the transporting power of the streams which are forced to leave additional load to settle down. The stream velocity is decreased because of decrease in channel gradient (effected by subsidence of land or tilting of land due to diastrophic forces, expansion in the delta of the master stream, increase in sinuosity of the river course and tendency of streams to attain graded stage due to more and more erosion), spreading of water over larger area (due to decrease in channel gradient and overtopping of river banks at the time of floods), obstruction in the channel flow (due to damming of streams through accumulation of debris caused by landslides, formation of sand dunes in the river beds of alluvial streams, accumulation of logs and other wood pieces carried by the streams across the valley and transverse to the direction of channel flow, and sudden deposits of huge volume of materials), and decrease in the volume and discharge of water (caused by decrease in annual precipitation and consequent surface runoff due to climatic change, substantial loss of water through evaporation in hot dry regions, downward seepage of river water, diversion of substantial volume of water to other streams due to river capture, diversion of water through canals for irrigation, braiding of stream channel etc.).

Increase in river load is effected through (i) accelerated rate of erosion in the source catchment areas consequent upon deforestation and thus increase in the sediment load in the downstream sections of the rivers, (ii) supply of glacio-fluvial materials, (iii) supply of additional sediment load by tributary streams, (iv) gradual increase in the sediment load of the streams due to rill and gully erosion etc.

18.8 DEPOSITIONAL LANDFORMS

Rivers deposit sediments in different parts of their courses and thus form various types of landforms which are called constructional landforms such as alluvial fans and alluvial cones, sand banks, natural levees, flood plains, sand bars and deltas.

Alluvial Fans and Cones

Alluvial fans (fig. 18.14) and cones (fig. 18.15) due to accumulation of materials are always formed at the base of foothills where there is abrupt drop (decrease) in the channel gradient. The transporting capacity of the streams decreases enormously at the foothill zones while they leave the mountains and enter the plain topography because of substantial decrease in their velocity consequent upon decrease in channel gradient. Consequently, load consisting of finer to coarser and big-sized materials coming from upstream is deposited at the point of break in slope or foothill zone and thus alluvial fans are formed. There is sorting of materials in the alluvial fans. The size of sediments decreases outward from the apex (which is towards the hills) of the fans towards their outer margins (distal side)

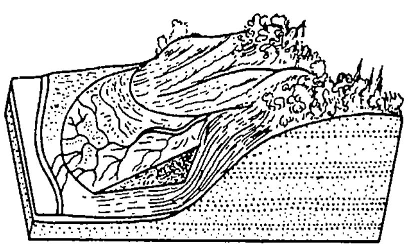


Fig. 18.14 : Alluvial fan.

Morphology of alluvial fans—The shapes of alluvial fans are usually semi-circular or arcuate, the apex of which is located at the mouth of narrow opening through which the stream comes out of the hills and enter the surface of low height and gentle slope. The shape of alluvial fans is described in two perspectives, planimetric and volumetric. The planimetric consideration involves two dimensional shape whereas volumetric perspective involves three dimensional shape of the fans. The alluvial fan, in planimetric perspective, is similar to the shape of a sector of a circle. In volumetric perspective an alluvial fan has a shape of a part of a cone. The longitudinal profile of an alluvial fan is concave at its apex while the transverse profile (which is parallel to the mountain front) is convex. Though the size of alluvial fans varies significantly but generally the diameter of fans ranges from a few kilometres to several hundred kilometres. A.B. Mukerji has studied the Chandigarh Dun Alluvial Fans developed at the foothills of Siwalik Range. According to him the Balad, Kiratupur and Banasar alluvial fans have the area of 20.75 km^2, 26.5 km^2. and 22 km^2 respectively. Several examples of palaeo-alluvial fans are seen in the Dun Valley of Uttaranchal. Similarly, numerous alluvial fans are found along the Himalayan piedmont in the northern part of the Brahmaputra valley.

The slopes of fans are much gentler than those of alluvial cones. Larger alluvial fans have average slope of less than one degree but smaller fans are characterized by gentle to moderate slopes (5 degree). Alluvial cones have average slopes of about 15 degree. Alluvial cones are made of coarser materials than the alluvial fans. The belts of alluvial fans and cones developed at the foothill belt of the Siwalik Himalayas (sub-Himalayan belt) are composed of gravels, pebbles, cobbles, shingles and coarse sands. These depositional, features at the foothills of the Himalayas are called 'bhabar'.

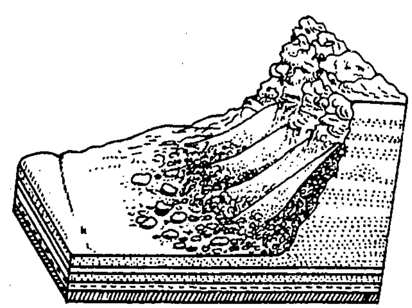


Fig. 18.15 : Alluvial cone.

Structure and origin of alluvial fans-Alluvial fans and cones are more or less similar except difference in their gradients. Alluvial fans have

gentler slopes than the cones. Alluvial cones are formed when the slope of hill or mountain front through which the stream descends is steep (fig. 18.15) so that debris collect at the foot of the hills. The formation of alluvial cones requires more debris but little water. On the other hand, alluvial fans are formed when the slope of hill or mountain front is gentle and water is more than debris so that debris spread away to assume arcuate shape. The origin and development of alluvial fans is simple. The velocity of streams while descending through the hill or mountain front is remarkably reduced due to sudden decline in slope gradient. This phenomenon causes substantial decrease in the transporting capacity of the streams. Consequently, streams become overloaded in relation to their reduced transporting power and thus they unload enormous quantity of debris at the foothill zone (at the point of break in slope) and thus fans are formed. There is gradual growth and development of alluvial fans in two ways. Firstly, the fans grow in size due to continuous increase in their areal extent because of regular supply of debris from upstream section. Secondly, the alluvial fans grow in height because of gradual deposition of debris upon debris. The gradual increase in height causes increase in slope gradient. An alluvial fan may be transformed into an alluvial cone if the slope gradient is significantly increased. Some times, a series of alluvial fans are formed along the piedmont zone. They grow in size and are ultimately coalesced to form an extensive fan which is called **compound alluvial fan.** The most extensive compound alluvial fans form undulating and sloping alluvial plain in front of peidmont zone. Such plain is called **piedmont alluvial plain.**

Natural Levees

The narrow belt of ridges of low height (fig 18.16) built by the deposition of sediments by the spill water of the stream on its either bank is called natural levee or natural embankment. It may be pointed out that not all the streams build natural levees. Levees are formed due to deposition of sediments during flood periods when the water overtops the river banks and spreads over adjoining flood plains. Long ridges of low height are formed parallel to the river valleys. Average height of natural levees is within 10 metres. The natural levees of the Mississippi river ranges between 6m and 7.6m. Natural levees limit the lateral spread of river water except during severe and widespread floods. Natural levees are more or less stabilized landforms which attract human settlements. Some times, natural levees are also used for agricultural purposes because water table of groundwater is very high. Generally, natural levees help in checking the floods but when breached they cause severe catastrophic floods inflicting heavy loss of human health and wealth. Since the channel

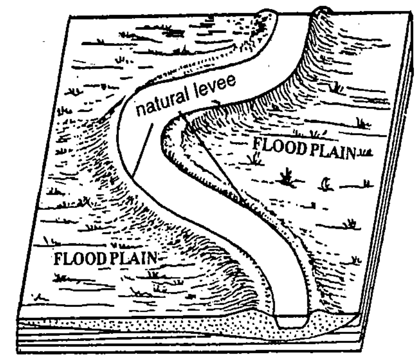


Fig. 18.16 : Natural levees.

is more or less confined within the natural levees and hence there is continuous sedimentation which causes gradual rise of the river beds (valley floor). Consequently, some times the bed of the stream becomes higher than the adjoining flood plain. Breach of natural levees in such situation causes sudden catastrophic floods because the river water gushes in the flood plains and settlements with high velocity beyond imagination. Such cases of breaches of natural levees and consequent severe floods are very often reported from the Yellow river (formerly Hwang Ho) of China. This was the reason that the Hwang Ho was called "Sorrow of China".

Delta

The depositional feature of almost triangular shape at the mouth of a river debouching either in lake or a sea is called delta. The word delta, derived from Greek letter, was first used by Greek historian Herodotous (485-425BC) for the triangular depositional feature at the mouth of the Nile river.

Whether small or large, almost every river forms delta. The size of delta of major and small rivers all over the world varies from a few square kilometres to thousands of square kilometres (*e.g.* Ganga delta in India and Bangladesh). The size of delta depends on the rock characteristics, vegetal cover, rate of erosion, amount of annual rainfall etc. The depth of sediments has been reported to be hundreds of metres. For example, the average depth of sediments in Mississippi delta is about 610m. The shape of delta also varies from one river to the other. Common shapes of delta are arcuate shape, bird-foot shape, elongated shape etc.

1. Conditions for Delta Formation

The ideal favourable conditions for the formation and growth of delta include (1) suitable place in the form of shallow sea and lake shores, (2) long courses of the rivers (*i.e.* long rivers so that they bring enough amount of sediments), (3) medium size of sediments (because if the sediments are very fine, they would be carried in the sea in suspension for longer distances and if they are very coarse, they would soon settle down at the sea bottom, and hence no delta would be formed), (4) relatively calm or sheltered sea at the mouths of the rivers (so that ocean currents, strong waves or high tidal waves do not interfere with the natural process of gradual sedimentation and delta formation), (5) large amount of sediment supply, (6) accelerated rate of erosion in the catchment area of the concerned river, (7) almost stable condition of sea coast and oceanic bottom (because sea coast subjected to frequent emergence or submergence caused by tectonic movements does not allow regular sedimentation and thus disfavours delta formation) etc.

2. Delta Formation

The formation of delta starts with the deposition of sediments if the aforesaid favourable conditions are available. The sedimentation takes place regularly at the mouth of the river, on the sides of stream channel, in the bed of the river and in front of river mouth where the river debouches in the sea. Thus, an extensive fan is formed which slopes towards the sea. Several such fans are formed at the mouth of the river. These fans gradually grow towards the sea. Ultimately these fans are coalesced and a delta is formed. These deposits obstruct the free flow of main river and hence it is divided into several branches. This process of segmentation of main stream is known as bifurcation. Thus, the main channel is bifurcated into numerous small and narrow subchannels which are called **distributaries** and the stream with numerous distributaries is called **braided stream**

3. Structure of Delta

The deposition of sediments or say materials takes place in such a way that larger materials (*e.g.* gravels, pebbles, cobbles etc.) are deposited towards the coastal land and the size of sediments gradually decreases with increasing distance from the coastal land towards the sea. An average delta consists of three beds of sediments *e.g.* (1) **topset beds,** (2) **foreset beds** and (3) **bottomset beds.** The topset beds represent the uppermost bed of sediments of a delta. These are quite extensive, wide and gentle in slope. These represent delta plains. The topset beds are relatively higher than sea level. The series of steeply dipping beds inclined towards the sea are called foreset beds which are always under sea water. The lowest beds are called bottomset beds because they rest on sea bottoms. Deltas undergo subsidence because of (1) gradual sedimentation and consequent increase in the weight of delta materials, (2) compaction of sediments caused by load of sediments, (3) enormous thickness of sediments, (4) isostatic adjustement etc.

4. Growth of Delta

No doubt, there is growth in al types of delta towards the sea but the rate of growth varies considerably from one situation to the other. The nature and rate of delta growth depends on a variety of factors *e.g.* (1) velocity of the stream flow, (2) nature of sea waves, (3) supply of sediments, (4) oceanic currents, (5) slope and height of deltas etc. Most of the sediments are unloaded at the mouths of the rivers if their velocity is extremely low and thus the growth of deltas towards the sea becomes sluggish. On the other hand, streams with greater velocity transport their load far greater distance in the sea and thus allow faster rate of delta growth, but deltas formed in such situation are narrow and long. Strong sea waves and oceanic currents retard the growth of deltas because they erode and remove the sediments away. The sliding of materials from higher deltas towards

the sea also encourages the seaward growth of deltas.

5. Classification of Delta

Deltas are generally classified on the basis of common characteristics of shape, structure, size, growth etc. The shape of deltas is determined by the physical conditions such as discharge of water, velocity of stream flow, supply and amount of sediments, rate of subsidence, tidal waves, sea waves, oceanic currents, rate of growth etc. Some scientists have related the shapes of deltas to hydrodynamics. If the river is overloaded with sediments and the river water is heavier than the sea water, an elongated submarine delta is formed. A lobate or fan-shaped delta is formed if the river water is as dense as the seawater. Alternatively, a bird-foot delta is formed when the river water is lighter than sea water. Generally, deltas are divided on the following two bases-

(1) On the basis of shape
- (i) arcuate delta
- (ii) bird-foot delta
- (iii) estuarine delta
- (iv) truncated delta

(2) On the basis of growth
- (i) growing delta
- (ii) blocked delta

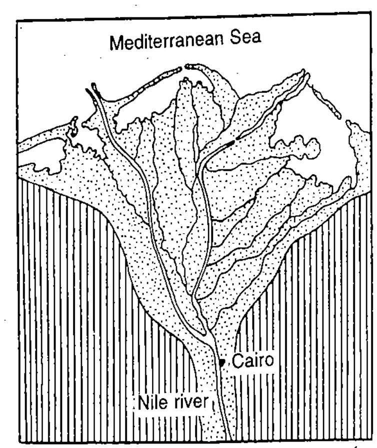


Fig. 18.17 : arcuate delta; Nile delta.

(1) Arcuate Delta

Such deltas are like an arc of a circle or a bow and are of lobate form in appearance wherein middle portion has maximum extent towards the sea whereas they narrow down towards their margins. Such deltas are formed when the river water is as dense as the

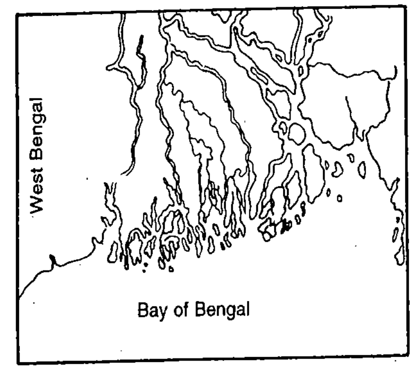


Fig. 18.18 : Ganga delta (example of arcuate delta).

sea water. The arcuate or semi-circular shape is also given to such deltas by sea waves and oceanic currents. The Nile Delta is the best example of arcuate deltas (fig. 18.17), which is also called as Nile type of delta. Arcuate deltas are formed of

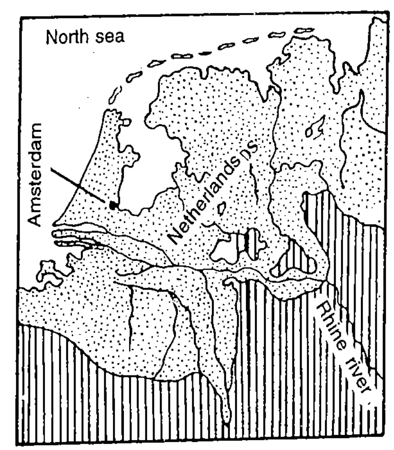


Fig. 18.19 : Rhine delta (example of arcuate delta).

coarser materials including gravels, sands and silt. The main river is bifurcated into numerous channels known as distributaries. Such deltas are very often formed in the regions of semi-arid climate. Significant examples of arcuate delta include Ganga delta, Rhine delta, Niger delta, Yellow (Hwang Ho) delta, Irrawaddy delta, Volga delta, Indus delta, Danub Delta, Meekong Delta, Po delta, Rhone Delta, Leena delta etc. Arcuate delta is an example of growing delta as it grows towards the sea every year but the annual rate of growth varies from one delta to another. This process of seaward growth of deltas is called progradation.

(2) Bird-Foot Delta

Bird-foot deltas resembling the shape of foot of a bird are formed due to deposition of finer materials which are kept in suspension in the river water which is lighter than the sea water. The rivers with high velocity carry suspended finer load to greater distances inside the oceanic water. The fine materials after coming in contact with saline oceanic water settle down on either side of the main channel and thus a linear delta is formed. It is interesting to note that the distributaries of the main channel also form linear segments of delta. These linear bars of sediments on either side of the distributaries of the main channel resemble the fingers of human hand. Such delta is, thus, also called **finger delta.** The Mississippi delta exhibits the best example of bird-foot delta (fig. 18.20).

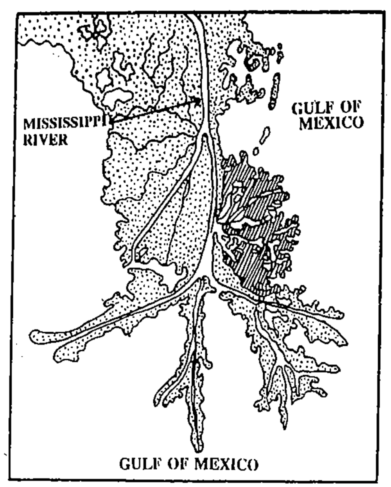


Fig. 18.20 : Bird-foot delta of Mississippi River.

(3) Estuarine Delta

The deltas formed due to filling of estuaries of rivers are called estuarine deltas. Those mouths of the rivers are called estuaries which are submerged under marine water and sea waves and oceanic currents remove the sediments brought by the rivers. There is continuous struggle between the rivers and sea waves wherein the former deposit sediments while the latter remove them. Whenever rivers succeed in depositing sediments at their submerged mouths, long and narrow deltas are formed. Such deltas are called estuarine deltas. The deltas of Narmada and Tapi (formerly Tapti) rivers of India are the examples of estuarine deltas. The other significant examples of estuarine deltas include Mackenzie delta, Vistuala delta, Elb delta, Ob delta, Seine delta, Hudson delta etc.

(4) Truncated Delta

Sea waves and ocean currents modify and even destroy deltas deposited by the river through their erosional work. Thus, eroded and dissected deltas are called truncated deltas.

(5) Blocked Delta

Blocked deltas are those whose seaward growth is blocked by sea waves and ocean currents through their erosional activities. The progradation of deltas may also be hampered due to sudden decrease in the supply of sediments consequent upon climatic change or management of catchment areas of concerned rivers.

(6) Abandoned Delta

When the rivers shift their mouths in the seas and oceans, new deltas are formed, while the previous deltas are left unnourished. Such deltas are called abandoned deltas. The Yellow (formerly Hwang Ho) river of China has changed its mouths several times and thus has formed several deltas. For example, the present delta of the Yellow river is to the north of Shantung Peninsula while the previous delta was deposited to the south of the peninsula. The western part of the Ganga delta, which is drained by the Hoogli river is an example of abandoned delta.

6. Major Deltas of Indian Rivers

Major deltas of Indian rivers include Ganga delta, Mahanadi delta, Godawari delta, Krishna delta, and Cauvery delta. The Ganga delta is the most extensive delta of the world, the arc of which extends for 400 km from Hoogli to Meghna rivers. The outer margin is highly indented and the delta is frequented by numerous north-south distributaries and tidal (marine) inlets. The lands between marine inlets are marshy lands which are partly transgressed by marine water during high tidal water. There are several evidences which indicate gradual subsidence and sinking of the delta. It is showly prograding towards the sea. There are numerous small and tiny islands bordering the outer margin of the Ganga delta (*e.g.* Sagar island, Bangaduni island etc.). Moore island is the example of newly emerged island due to progradation.

"The Mahanadi delta is triple delta where deltaic sediments of the Mahanadi, the Brahmani, and the Baitarni are dropped" (E. Ahmad, 1972). The arc of the arcuate shaped Mahanadi delta, on Orissa coast, stretches for a lengh of about 300 km. The enormous delta has been formed due to supply of huge quantity of sediments consequent upon accelerated rate of fluvial erosion of the rugged terrain of the catchment area of the Mahanadi basin. There are also a few deltaic lakes such as Sar lake (24 km^2) and Samang lake (4.5 km^2) of fresh water.

The Godawari delta extends upto 35 km in the Bay of Bengal off the coast of Andhra Pradesh but the maximum length of the longer side through the middle portion of the delta is 90 km while the other two sides are 35 km long. The deltaic shore stretches for a distance of 150 km. This is also an example of arcuate shaped delta. The strong monsoon-generated ocean currents, long-shore drifts and sea waves obstruct in the free growth of the delta towards the sea.

19

GROUNDWATER AND KARST TOPOGRAPHY

19.1 GROUNDWATER : MEANING AND COMPONENTS

The water present in the pore spaces of **regolith** (the layer of loose and unconsolidated materials lying over the bedrocks is called regolith) and bedrocks (bedrocks are those rocks which have not been weathered and eroded) below the ground surface is called **groundwater.** The main source of groundwater is rainwater and meltwater which infiltrates downward through the pore spaces of surficial materials and collects in large quantity in **aquifers** of varying sizes and locations. Aquifers refer to the storage pools of groundwater lying below the ground surface. The groundwater is also called **subsurface water** or underground water but the latter is not in use. Sands form most ideal aquifers but permeable sandstones also form extensive aquifers. The percolating water fills the pore spaces of regoliths and permeable rocks. This process is known as saturation of regoliths and rocks. When almost all of pore spaces are filled with water, the zone is called **saturated** or **phreatic zone.** The upper level of the saturated zone is called **groundwater table** or simply water table (fig. 19.1). The zone lying above the water table is unsaturated and is called **unsaturated zone** or **vadose zone** or **aeration zone** because the pore spaces of the regoliths and permeable rocks are partly filled with water and partly with air (fig. 19.2).

The position and movement of groundwater become complicated when there is arrangement of alternating aquifers and impermeable beds. The impermeable bed separating two aquifers is called **aquiclude** because it obstructs or impeds water movement between two aquifers (fig. 19.2). When an aquifer is zagged between two impermeable beds or aquicludes there is produced a **confined water reservoir** which gives birth to **artesian wells.** When an aquiclude lies between two aquifers, the water table of upper aquifer is called **perched water table** (fig. 19.2). There is seasonal and annual fluctuation in the depth of water table of groundwater through percolation of rainwater and therefore water table rises but during long period of drought there is considerable fall in water table.

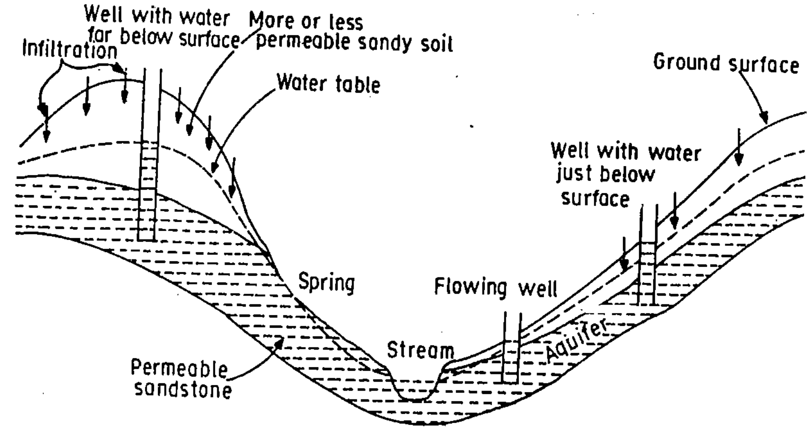


Fig. 19.1 : Components of groundwater.

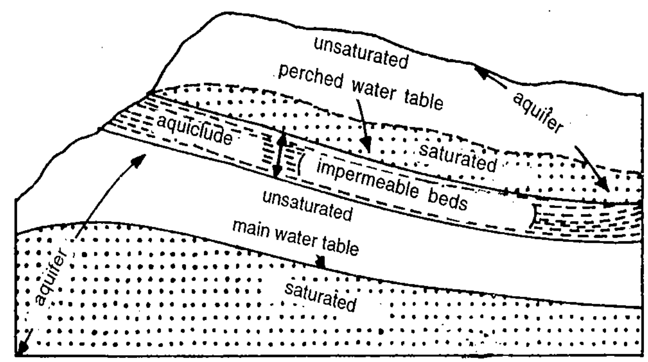


Fig. 19.2 : Components of groundwater.

19.2 GEOMORPHIC WORK OF GROUNDWATER

The geological or geomorphic work of groundwater includes chemical erosion of soluble rocks at the surface by surface water and below the surface by percolating and moving groundwater, limited transport of eroded materials in suspended form and deposition of solutes. It may be pointed out that the geological work of groundwater is exceedingly slow because of its very slow rate of movement. Only that part of chemical erosion of carbonate rocks at the ground surface is included in the geological work of groundwater which is related to the infiltration of rainwater.

1. Erosional Work

Besides erosional work, groundwater also facilitates slumping, debris slides and fall and landslides on steeply inclined hillslopes because groundwater acts as lubricator. The erosional work of groundwater is performed through the mechanism of corrosion or solution, corrasion or abrasion, attrition and hydraulic action but the last three types of erosion are not effective because of exceedingly

slow movement of groundwater and thus corrosion or chemical erosion is the only effective method of denudation of carbonate rocks (such as limestones, dolomites, chalk etc.) by surface and subsurface water (groundwater).

Rainwater mixed with atmospheric carbon dioxide (CO_2) and organic CO_2 becomes active solvent agent and disintegrates and dissolves carbonate rocks at the surface and below the surface to form numerous types of solutional landforms. According to R.M. Garrels there are seven variables which control limestone solution viz. (1) partial pressure of CO_2, (2) H_2CO_3 (carbonic acid), (3) HCO_{3^-} (bicarbonate ion), (4) CO_3^{2-} (carbonate anion), (5) H^+ (hydrogen ion), (6) OH^- (hydroxyl ion) and (7) Ca^{2+} (calcium cation).

The following chemical processes reveal the chain of exothermic reversible and non-reversible reactions right from the formation of limestone ($CaCO_3$) to its dissociation (solution).

Calcium hydroxide ($Ca(OH)_2$ is formed due to reaction of water (H_2O) with calcium oxides (CaO) in the following manner :

$$CaO + H_2O \leftrightarrow Ca\,(OH)_2 \qquad \ldots\ldots\ldots\ldots(1)$$

Calcium carbonate ($Ca\,CO_3$) is formed due to reaction of $Ca(OH)_2$ with carbon dioxide (CO_2) in the following manner :

$$Ca(OH)_2 + CO_2 \leftrightarrow CaCO_3 + H_2O \ldots\ldots\ldots\ldots(2)$$

(insolubie)

Carbon dioxide (CO_2) when dissolved in water forms carbonic acid ($H_2\,CO_3$).

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \qquad \ldots\ldots\ldots\ldots(3)$$

Carbonic acid is easily dissociated into positive hydrogen ion (H^+) and negative bicarbonate ion or hydrogen carbonate ion (HCO_3^-which produces source of acidity in the solution as given below :

$$H_2CO_3 \leftrightarrow H^{++} + HCO_{3^-} \qquad \ldots\ldots\ldots\ldots(4)$$

Calcium carbonate dissociates in pure water into a metal cation (Ca^{2+}) and carbonate anion (CO_3^{2-}) during the process of dissolution in the following manner :

$$CaCO_3 \xrightarrow{\text{dissociation}} Ca^{2+} + CO_3^{2-} \ldots\ldots\ldots\ldots(5)$$

Calcium carbonate reacts with CO_2 and H_2O or say carbonic acid (H_2CO_3) to form calcium bicarbonate ($Ca(HCO_3)_2$ which is soluble in water.

$$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca\,(HCO_3)_2 \ldots\ldots(6)$$

It may be pointed out that the amount of carbonate rocks depends on temperature, partial pressure of atmospheric carbon dioxide, organic carbon dioxide, the chemical composition of carbonate rocks (calcium carbonate-limestones, magnesium carbonate - dolomite, and chalk), joints of the rocks, nature and rate of flow of groundwater, contact time of solvent (water) and carbonate rocks, route of water flow etc. There is inverse relationship between temperature and solubility of carbon dioxide and positive relationship between the dissolution of carbonate rocks and temperature.

2. Depositional Work

As the chemical erosion (dissolution) of carbonate rocks continues, the groundwater or say solvent receives more and more solutes and becomes saturated with sediments. Since the movement of groundwater is exceedingly slow it cannot transport enough materials. Thus, chemical erosion and deposition go together. Larger sediments immediately settle down whereas suspended fine materials kept in solution form are deposited due to following factors : (1) due to obstruction in the flow path of groundwater and consequent decrease in the flow velocity of the solvent, (2) due to evaporation of water because of increase in temperature and consequent decrease in the volume of groundwater and increase in solute-water ratio, (3) due to decrease in solution capacity of groundwater etc. Deposition of sediments takes place at various places in various forms e.g. (i) at the floor of caves, (ii) along the ceiling of caves, (iii) in the rock joints etc.

19.3 LIMESTONE TOPOGRAPHY (KARST TOPOGRAPHY)

1. Meaning

Landforms produced by chemical weathering or chemical erosion of carbonate rocks mainly calcium carbonate ($CaCO_3$, limestones) and magnesium carbonate (dolomites) by surface and subsurface water (groundwater) are called **karst topography** which refers to characteristic landforms produced by chemical erosion on crystalline jointed

limestones of Karst region of earstwhile Yugoslavia situated along the eastern margin of Adriatic Sea. The Karst region of the earstwhile western Yugoslavia extends for 480 km in length and 80 km in width. The region having folded limestones rises to the

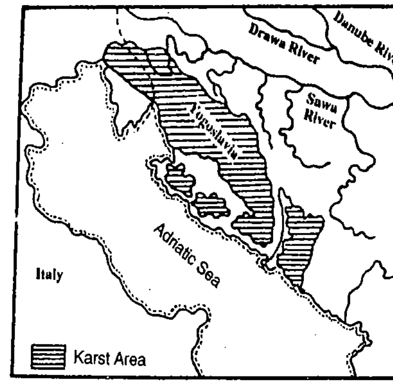


Fig. 19.3 : Karst Region of earstwhile Yugoslavia.

height of 2,500m AMSL. The surface studded with numerous solution holes, ravines, gullies, clefts, lapies and narrow valleys has become so corrugated and rough that it becomes practically impossible to walk with bare feet. Numerous caves and stalagmites and stalactites have been formed below the surface. Thus, the limestone topography all over the world having characteristic features similar to the **karst region** of earstwhile Yugoslavia is universally called karst topography.

2. Distribution of Karst Areas

Karst topography generally develops in those areas where thick beds of massive limestones lie just below the layer of surficial materials. Besides, karst topography also develops on dolomite, dolomitic limestones and chalks. Besides typical karst region of earstwhile Yugoslavia, karst topography has well developed in Causes Region of southern France; Spanish Andalusia; northern Puertorico; western Cuba; Jamaica; southern Indiana, west-central Kerntucky, Virginia, Tennessee and central Florida of the USA. These areas are classified as major karst areas. Besides, there are a few minor karst areas e.g. Carlsbad area of the USA, chalk area of England (Peak District), chalk area of France, Parts of Jura mountains, some parts of Alps and Apennines. Limestone topography in India has not been properly identified and studied because of non-existence of extensive thick limestone formations near the surface. Most of limestones of Vindhyan formations are buried under thick covers of sandstones and shales. For example, Rohtas stage limestones having famous Guptadham cave in Rohtas plateau (south-western Bihar) are buried under 90-m thick cover of massive sandstones. A few areas of limestone topography have been identified in the Himalayas (mainly Jammu and Kashmir; Sahasradhara, Robert Cave and Tapkeshwar temple near Dehra Dun in Uttaranchal; Eastern Himalayas; Pachmarhi (Madhya Pradesh), Bastar district (Chhattisgarh); coastal area near Visakhapatnam etc.

3. Essential Conditions for the Development of Karst Topography

The following conditions alone favour the development of true karstic topography :

(1) The limestones must be massive, thickly bedded, hard and tenaceous, well cemented and well jointed (high density of joints).

(2) Limestones should not be porous wherein permeability is largely controlled by joints and not by the mass of rocks because if limestones are porous, the water may pass through the rock mass and thus whole rock mass will become weak and will collapse. On the other hand, if limestones are non-porous and thickly bedded, water will infiltrate through joints resulting into effective corrosion of limestones along the joints and solution holes would be formed.

(3) The position of limestones should be above the groundwater table so that surface drainage may disappear through sinks, blind valleys and sinking creeks to have subterranean (subsurface) drainage so that cave, passages and galleries and associated features may be formed.

(4) The limestones should be widely distributed in both areal and vertical dimensions.

(5) The carbonate rocks should be very close to the ground surface so that rainwater may easily and quickly infiltrate into the beds of limestones and may corrode the rocks to form solutional landforms.

(6) The limestones should be highly folded, fractured or faulted.

(7) There should be enough rainfall so that required amount of water is available to dissolve carbonate rocks.

19.4 EROSIONAL LANDFORMS

Lapies

The highly corrugated and rough surface of limestone lithology characterized by low ridges and pinnacles, narrow clefts and numerous solution holes is called lapies (a French term). In fact, lapies (fig. 19.4) represent a fretted and fluted topography marked by small rills and gullies, minor ridges or pinnacles and deep clefts. Lapies are variously named in different parts of the world e.g. **clints** or **grykes** in North England, **karren** in Germany, **bogaz** in earstwhile Yugoslavia etc. Lapies are generally formed due to corrosion of limestones along their joints when limestones are well exposed at the ground surface. The weathering residues left at the surface are called **terra rosa** which means red residual soils or red earth.

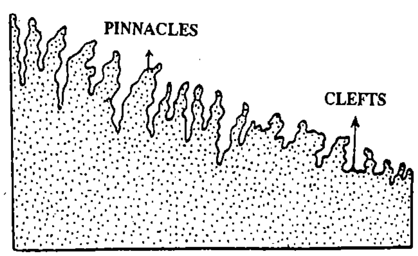


Fig. 19.4 : Lapies.

Solution Holes and Associated Features

Chemically active rainwater (charged with atmospheric carbon dioxide) dissolves limestones and other carbonate rocks along their joints and thus numerous types of solution holes (e.g. sink holes, dolines etc.) are developed at the ground surface when limestones are directly exposed to the atmospheric processes. Smaller holes are called sink holes which are generally of two types viz. (i) funnel shaped sink holes and (ii) cylindrical sink holes. The depth of sink holes ranges from a few centimetres to 10 metres but generally average depth remains between 3 to 10 m. Area varies from a few square metres to few acres. Gradual enlargement of sink holes due to continuous dissolution of limestones results in the coalescence of closely spaced sink holes into one large hole which is called **swallow hole** (fig. 19.5). Some swallow holes are further enlarged due to continuous solution into larger depressions which are called **dolines** (fig. 19.5) in the Karst Region and **doline** in Serbia. The solution holes enlarged due to collapse of some portion of upper surface because of formation of cavities below the ground surface are called **collapse sinks**. The diameter of doline ranges from a few metres to 1000 metres while the depth varies from a few metres to 300 metres.

A feature almost similar to doline in appearance but with shallow depth and larger areal extent is called **solution pan**. The solution pan of the Lost River of Indiana (USA) is 30 acres in area. Some times, the floor of dolines is plugged due to deposition of clay, with the result water cannot percolate downward and thus doline is filled with water. Such dolines full of water are called **karst lakes**. Rock-walled steep depressions caused by the collapse of ground surface are called **cockpits**.

Karst window is formed due to collapse of upper surface of sink holes or dolines. These windows enable the investigators to observe sub-surface drainage and other features formed below the ground surface.

Extensive depressions are called **uvalas** which are upto one kilometre across. They are formed in a number of ways e.g. (1) due to coalescence of several dolines due to continuous solution and enlargement of dolines, (2) due to collapse of upper roof of large cavities formed underground, (3) due to coalescence of various sink holes etc. Elongated uvalas are formed either due to (i) the elongated pattern of joints or (ii) due to coalescence of numerous sink holes aligned in a line. Smaller uvalas are called **jamas**. Uvalas are so extensive that surface drainage is lost in them and takes subterranean course. C.A. Malott has termed such uvalas as **karst windows**. Uvalas are called as **compound sinks** because of coalescence of several sink holes (fig. 19.5). The sides of uvalas are very steep. They are generally dry depressions. The floors are generally characterized by the deposition of clay but they are usually of even surface.

Poljes

Most extensive, larger than **dolines**, depressions are called 'poljes'. They are characterized by vertical side walls, flat alluvial floors, independent surface drainage systems on their floors, irregular borders and central lake. Poljes are, in fact, closed basins of elliptical shape (fig. 19.5) having an area up to 258 km^2. They are frequently found in Karst Region of earstwhile Yugoslavia and in Jamaica. The Livno Polje of the Balkan Region of Europe is 64 km long and 5 to 11 km wide. There is difference of opinions about the formation of polje. They are believed to be formed due to downfolding and downfaulting of limestone areas due to earth movements. The resultant grabens are then modified by solution work of water. According to B.W. Sparks (1972) 'the poljes are probably not solution forms at all but tectonic depressions modified by solution of limestone preserved in them.'

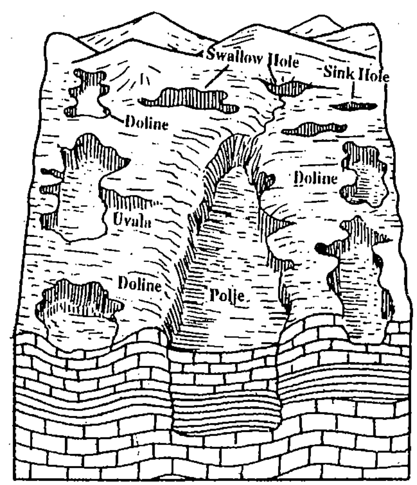


Fig. 19.5 : Sink holes, swallow holes, dolines, uvalas and poljes.

Valleys of Karst Region

The upper surface having several sink holes in the region of limestones having horizontal beds or slightly inclined beds is called **karst plain** on which surface drainage systems develop various types of valleys and typical landforms. Almost all of the valleys are related to sink holes or swallow holes in one way or the other. The following types of valleys are more important (fig. 19.6).

(1) Sinking creek—The surface of the karst plain looks like a sieve because of development of closely spaced numerous sink holes. These sink holes act as funnels because surface water disappears to go underground through these holes. When surface water disappears through numerous sink holes located in a line, the resultant feature is called **sinking creek** and the point through which water goes downward, is called **sink** (fig 19.6). The water of short rivers disappears through a single 'sink' while that of large streams disappears through many 'sinks'.

(2) Blind valley refers to the valley of that surface stream which disappears in limestone formation through a swallow hole or sink hole. In other words, that valley is called blind valley the flow of which terminates at a swallow hole and the valley looks dry valley. According to O.D. Von Engeln blind valleys are developed on uvala floors (fig. 19.6).

(3) Karst valley—Surface streams develop their U-shaped valleys on limestone formation. Such wide U-shaped valleys developed on limestones are called **solution valleys** or **karst valleys**. Such valleys are always temporary because generally water disappears through swallow or sink holes and the valleys become dry.

Caves or Caverns

Caves or caverns are voids of large dimension below the ground surface. In fact, caves are the most significant landforms produced by erosional work (mainly corrosion or solution and abrasion) of groundwater in limestone lithology. Caves vary in sizes and shape ranging from smaller size to larger caves. Large caves are formed in the regions of pure, massive and thickly bedded limestones. Carlsbad and Mammoth caves of the USA are the examples of very extensive caves. Carlsbad cave of New Mexico State of the USA, having a dimension of 1219 m length, 190.5m width and 300m depth, consists of several chambers. The ceiling is about 83.3 m high

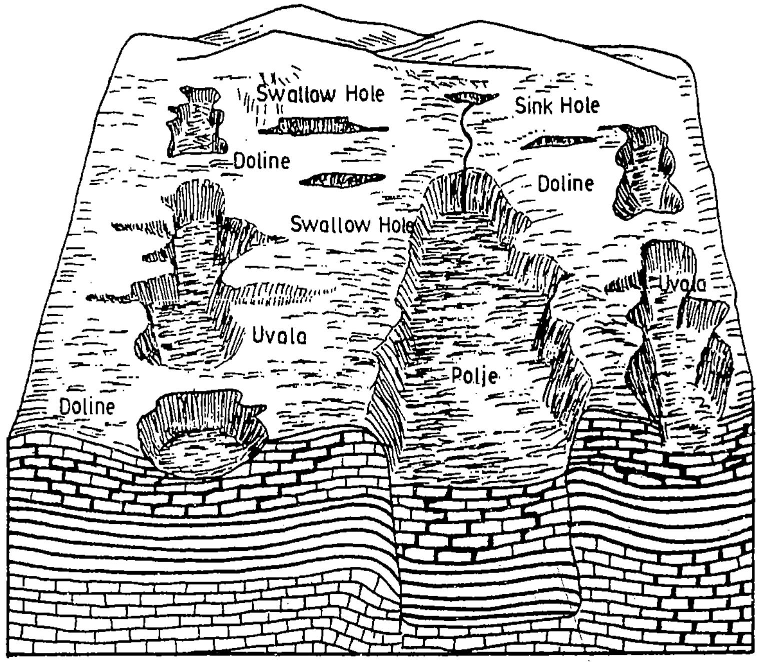


Fig. 19.6 : Development of sink holes, swallow holes, uvalas, sinking creek, blind valley and karst valley.

from the floor. The largest chamber is known as Big Room.

Limestone caves are found in India near Dehra Dun in Uttar Pradesh (Robert Cave, Sahasradhara), in south-western Bihar (Guptadham Cave, 1.5 km long), in Bastar district of Chhattisgarh (Kutumbsar Cave), in Pachmarhi hill, in Chitrakut area of Satna district of Madhya Pradesh (Gupta Godavari Cave), near Visakhapatnam coast etc.

The Guptadham cave of the Rohtas plateau (located in the south-western corner of Bihar) is an example of galleried cave and has been formed due to dissolution of Rohtas stage limestones of Vindhyan formations lying below 90m thick capping of quartzitic sandstones. The cavern is characterized by horizontal passages and amphitheatre-like extensive areas at the junctions of tunnels (cave crossings) (fig. 19.7)

The formation and development of limestone caverns is most debatable of all the karstic landforms. Various contrasting theories have been put forward by different geomorphologists to account for the origin and development of limestone caves viz. (1) corrasion theory of Lapparent, Martonne, Martel, Weller and C.A. Malott, (2) two-cycle theory of W.M. Davis and supported by J.H. Bretz, (3) water table theory of A.C.. Swinnerton, (4) static water zone theory of J.H. Gardner, (5) invasion theory of C.A. Malott etc. It may be pointed out that difference of opinions about the formation of caverns and galleries is related to solution process, water table of groundwater and corrasion process.

According to **'corrasion theory'** caves are formed due to corrasion (abrasion) of limestones by groundwater in the **vadose zone** above the water table of groundwater. W.M. Davis contradicted the

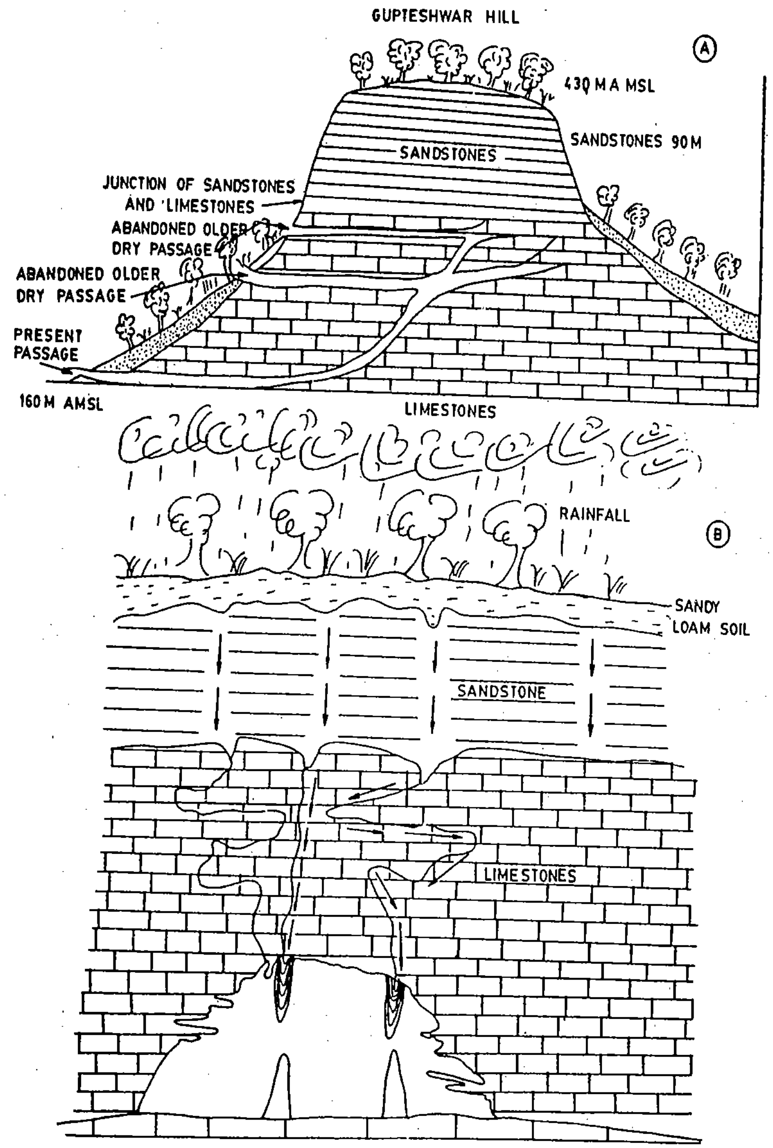


Fig. 19.7 : A-Probable sequence of cave passages and B-dissolution of limestones and formation of Guptadham cave (Bihar).

corrasion theory in 1930 and postulated his **two-cycle theory** for the development of limestone caverns. According to him caves are formed by **phreatic water** i.e. water under hydrostatic pressure below water table. In the first cycle or stage caves are formed due to solution of limestones in the phreatic zone below water table. In the second cycle or stage the area is uplifted and thus the cave comes under vadose zone because of lowering of water table and the cavern becomes dry resulting into the formation of depositional landforms (speleothems). **'Water table theory'** of A.C. Swinnerton states that caves are not formed by phreatic water under hydrostatic pressure but are formed by lateral flow of water in the vadose zone or by freely moving water at the level of water table. According to **'static water zone theory'** of J.H. Gardner caves are formed due to solution of limestone above the water table. The **'invasion theory'** of C.A. Malott states that most of the present caverns and galleries in limestone regions have been formed by the subterranean streams. According to Malott surface streams disappear at sink holes and take underground courses where they dissolve and abrade limestones to form their passages. These passages are gradually enlarged due to corrosion and abrasion of limestones and thus caverns and galleries are formed.

Ponores

The vertical pipe-like chasms or passages that connect the caves and the swallow holes are called 'ponores' in Serbia and **'avens'** in France. Ponores are formed due to downward extension of sink holes through continuous solution of carbonate rocks. Ponores may also be inclined (fig. 19.8)

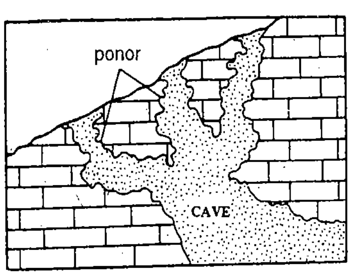


Fig. 19.8 : Cave and ponore.

Natural Bridge

Natural bridges in limestone areas are formed in two ways viz. (1) due to collapse of the roofs of caves and (2) due to disappearance of surface streams as subterranean streams, formation of valleys below the ground surface and reappearance of disappeared (subterranean) stream on the ground surface. Like caves various theories have been put forth to account for the origin of natural bridges and natural tunnels in limestone regions e.g. (1) solution theory of F.W. Gilmer, (2) theory of C.D. Walcott, (3) subterranean stream piracy theory of H.P. Woodward, (4) subterranean stream cut off theory of C.A. Malott and R.R. Shrock etc.

19.5 DEPOSITIONAL LANDFORMS

All types of deposits in the caverns are collectively called **speleothems** of which calcite is the common constituent. Banded calcareous deposits are called **travertines** whereas the calcareous deposits, softer than travertine, at the mouth of the caves are called **tufa** or **calc-tufa**. The calcareous deposits from dripping of water in dry caves are called **dripstones.** The columns of dripstones hanging from the cave ceiling are called **stalactites** while the calcareous columns of dripstones growing upward from the cave floor are known as **stalagmites. Cave pillars** are formed when stalactites and stalagmites meet together (fig. 19.9). Numerous needle-shaped dripstones hanging from the cave ceiling are called **drapes** or **curtains.** The dripstones growing sideward from stalactites and stalagmites are called **helictites** and **heligmites** respectively. The helictites of globular structure are called **globulites.** Floor deposits

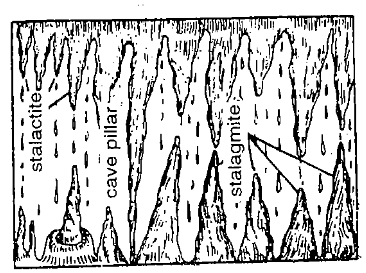


Fig. 19.9 : Formation of stalactites, stalagmites and cave pillars (various forms of speleothems).

caused by seepage water and water flowing out of stalagmites are called **flowstones.**

Stalactites are formed due to deposition of calcareous solutes which are carried by water dripping through the cave ceilings in dry environment. The water is evaporated and solutes are deposited in incicle-like or needle-like forms. These structures have broad bases stuck to the cave ceiling and tapering ends hanging downward from the cave ceiling. There is gradual increase in the length and thickness of stalactites. The shapes of stalactites are controlled by the shape of cave ceiling. The stalactites become uniform and their tapering lower ends are directly pointed towards the cave floor when the cave ceiling is flat or is uniformly arched (fig. 19.10, C and F respectively). The stalactites hanging downward are almost perpendicular to the cave ceiling. When the cave ceiling is steeply inclined, inclined and elongated stalactites are formed (fig. 19.10, D). When the cave ceiling is flat but is gently inclined towards one side, slightly inclined and elongated stalactites are formed (fig. 19.10 E).

The solution that drops on the cave floor is also precipitated and crystallized and forms a column-like structure of stalagmites at various centres. When a group of stalagmites is formed together from closely spaced centres the resultant stalagmites are called **compound stalagmites.**

19.6 KARST CYCLE OF EROSION

The concept of cycle of erosion was also applied in limestone area by J.W. Beede in 1911 and by Jovan Cvijic in 1918. W.M. Davis (1930) regarded karst cycle of erosion as a special phase of the normal fluvial cycle of erosion characterized by the development of surface drainage, disappearance of surface drainage underground and reappearance of substerranean drainage as surface drainage. The karst cycle of erosion is simpler than other geomorphic cycles because of uniformity of structure (generally limestones) and dominance of mono-process (solution process). The difficulties are related to the nature of movement of groundwater and base level of erosion which are not precisely known. Most of the geomorphologists believe that the water table of groundwater should be taken as the base level of erosion. According to some geomorphologists the rainwater infiltrates through the joints of the rocks in vertical manner until it reaches the surface of the water table and thereafter it moves horizontally below the surface of water table.

Two types of conditions have been recommended for the initiation of karst cycle of erosion e.g. (1) exposure of thick limestone cover at the ground surface and (2) limestone cover overlain by non-soluble rocks (e.g. sandstones, shales etc.). Karst cycle of erosion becomes more operative over two types of structures viz. (1) folded limestones and (2) faulted beds of limestones. It may be pointed out that karst cycle of erosion becomes more effective where thick beds of limestones, whether folded or faulted, are exposed on the ground surface because rainwater immediately comes in contact with the rocks and starts dissociating them. Beede postulated 3-stage karst cycle (e.g. youth, mature and old stages) whereas Cvijic presented 4-stage karst cycle (e.g. youth, maturity, late maturity and old stage). The characteristic features of different stages of karst cycle of erosion are summarized below.

1. Youth

The karst cycle starts with the initiation of surface drainage in the regions of thickly bedded limestones of folded or faulted structure or even of horizontal structure (fig. 19.11(1). The limestones are directly exposed at the ground surface. If the limestones are overlain by thin deposits of insoluble or non-calcareous formations, the surface runoff first removes these formations. The rainwater mixed with atmospheric carbon dioxide now reacts with limestones along the interfaces of their joints and thus form **sink holes** and **swallow holes** through the mechanism of solution process. These sink holes gradually increase in number and are enlarged due to continuous solution of limestones. The ground surface is characterized by rough terrain due to development of **lapies** because of dissolution of limestones along their joints. With the enlargement of sink holes and swallow holes into **dolines** surface drainage starts disappearing underground through different **sinks** or **blind valleys.** The underground drainage initiates the formation of caves and caverns through underground solution and abrasion. The characteristic geomorphic features of this stage are sink holes, swallow holes, dolines, lapies, blind

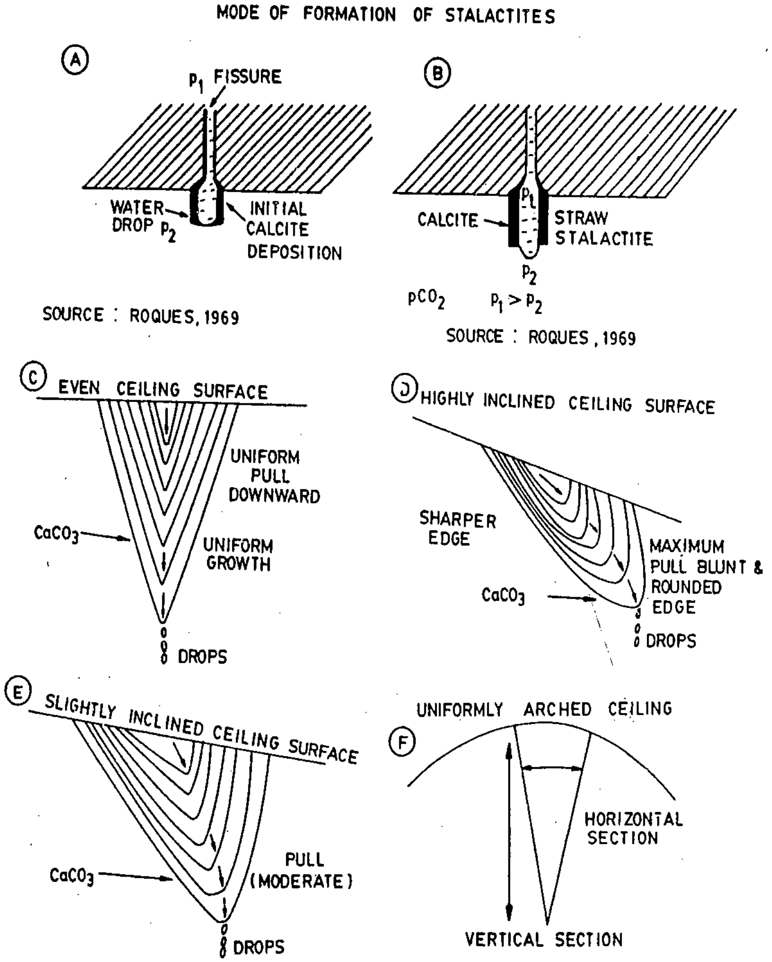


Fig. 19.10 : Nature of cave ceiling and formation of stalactites.

valleys, sinking creeks, caves and caverns of smaller dimension. The termination of youth stage is marked by total disappearance of surface drainage.

(2) Maturity

The initiation of early maturity is heralded by total disappearance of surface drainage underground. Thus, the ground surface is characterized by dry waterless condition. The surface drainage disappears underground through dolines and blind valleys. Thus, numerous **sinking creeks** are formed. The processes of underground solution and abrasion are augmented because of increased volume of water

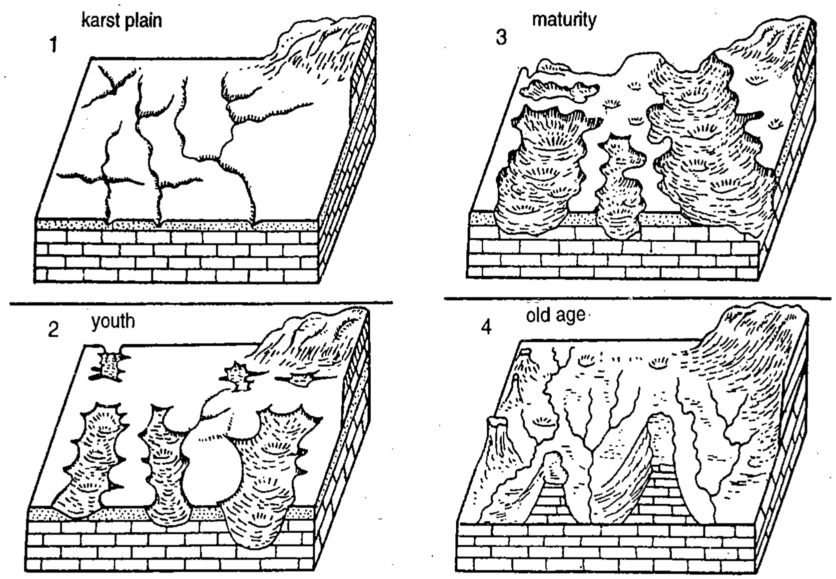


Fig. 19.11 : Development of Karst Cycle of erosion—1. Karst plain, 2. Youth, 3. Maturity and 4. Old stage, after A.K. Lobeck.

due to maximum development of subterranean drainage. Increased solution of carbonate rocks results in gradual enlargement of caves, galleries and passages. The covering roofs of caves and caverns undergo the process of thinning because of alround enlargement of caves. The thinning of cave roofs causes their colapse giving birth to **uvalas, poljes** and **karst windows** (fig. 19.11(3). The residual uplands with highly pitted surface between uvalas become ridges. The late maturity is characterized by the destruction of most of solutional landforms.

(3) Old Stage

The cave roofs are totally collapsed and ridges with pitted surface between uvalas are considerably narrowed down (fig. 19.11 (4)) and reduced in height. The residuals of carbonate rocks project slightly above the ground. These are called **hums** . Most of the ground surface is levelled and thus resembless the **peneplain** of normal fluvial cycle of erosion (river cycle of erosion). The subterranean drainage again appears on the ground surface. Nearly all of the karst valleys, solution holes and sinking creeks are eliminated. The second karst cycle of erosion may start with fresh upliftment of karst plain.

19.7 TYPICAL LANDFORMS OF KARST REGIONS

Cockpits, cone karst, polygonal karst and tower karst are important typical landforms of karst regions. Carbonate rocks are quickly dissolved in tropical humid regions. If the dolines, which are cone-shaped solution depressions, are closely spaced, they expand in size due to fast rate of solution and change into star-shaped depressions. Such star-shaped solution features are called **cockpits** which have developed in Jamaica, Vietnam, China, Java, New

Zealand etc. The polygon-shaped depressions are called **polygonal karsts** which are formed due to coalescence of several dolines and development of numerous arms in their perimeter which give the shape of polygon. Polygonal karsts have developed in New Zealand, southern China, New Guinea etc. When a few closely spaced cockpits coalesce, the ridges between them become conical in shape. Such conical ridges developed in carbonate rocks are called **cone karsts** which, when attain greater height, are called **tower karsts,** which have developed in Cuba, Puertorico, Vietnam, south China etc. It may be pointed out that cone and tower karsts are formed in humid tropical regions. If they are presently found in extra-tropical areas (e.g. Poland, Canada and New Zealand), it means, they are not the result of present climate but are palaeo landforms indicating climatic change.

20

SEA WAVES AND COASTAL LANDFORMS

20.1 AGENTS OF COASTAL EROSION

The work of sea water is performed by several marine agents like sea waves, oceanic currents, tidal waves and tsunamis but the sea waves are most powerful and effective erosive agent of coastal areas. Sea waves are defined as undulations of sea water characterized by well developed crests and troughs (fig. 20.1). The mechanism of the origin of sea waves is not precisely known but it is commonly believed that waves are generated due to friction on water surface caused by blowing winds. The undulations of sea water at the place of their origin are called **swells** which are low, broad, regular and rounded ridges and troughs of water. In other words, 'the regular pattern of smooth, rounded waves that characterizes the surface of the ocean during fair weather is called swell' (A. Bloom, 1978).

The height of wind generated sea waves depends on (i) wind speed, (ii) the duration of wind from one direction and (iii) the extent of **fetch** which represents the length of water surface over which the wind blows. The upper and lower parts of the waves are called wave crests and wave troughs respectively. The straight horizontal distance between two successive crests or troughs is called **wavelength** which is expressed in terms of length unit of metres in the case of sea waves. The time taken by a sea wave to cover the distance of one wavelength or wave cycle is called **wave period.** The number of sea waves (one sea wave is equal to one wavelength) passing through a certain point per unit time (usually one second) is called **wave frequency** which varies according to the wavelengths of sea waves. There is inverse relationship between the wavelength and wave frequency *i.e.* shorter the wavelength, higher the wave frequency and longer the wavelength, lower the wave frequency (fig. 20.1).

Wave velocity is directly related to wavelength, *i.e.* the wave velocity increases with increasing wavelength or decreases with decreasing wavelength if the wave frequency is constant.

It may be pointed out that only the form of wave moves forward in seas and oceans through the water and the water does not move forward. Water particles within a wave in the seas and oceans do not move forward with coastward or landward advancing wave itself but move in circular orbit (fig. 20.2A). In an open sea the orbital motion of water particle associated with the passage of a wave decreases rapidly from the water surface downwards (towards the sea floor). The orbit of particles decreases with increasing depth from the water surface (fig. 20.2A) with the result orbits become more and more elliptical towards sea bottom and there is only horizontal movement of water particles (back and forth movement of water particles) (fig. 20.2B).

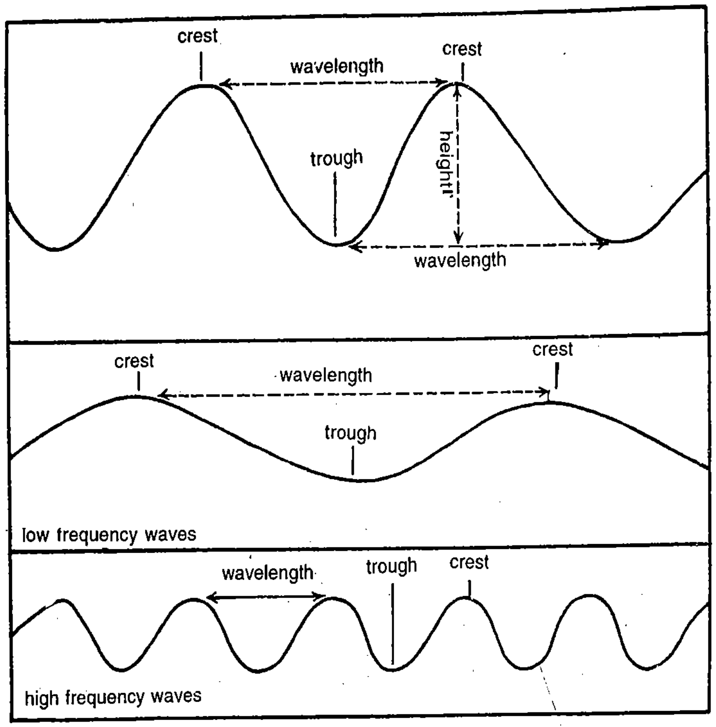


Fig. 20.1 : Patterns and components of sea waves.

The sea waves after being generated radiate outward from generating area of the sea. The longest wavelengths move most rapidly. Steep waves with shorter wavelengths but greater heights decay more rapidly while moving away from generating area while waves with longer wavelengths and lower heights radiate for thousands of kilometres across the oceans with little energy loss. As the waves advance towards the coast the depth of water decreases, the wave height increases and the wavelength decreases.

As the waves move in shallow water they lose energy because they suffer from friction and distortion caused by the bottom surface. The waves begin to **feel bottom** (touch the bottom) when the depth of water becomes equivalent to about the half of the wavelength. As the waves approach the shore the wavelength continues to decrease while the wave height increases to such an extent that the crest of the wave, topples over and the wave is transformed into **breaker** which then collapses. The turbulent water, known as **swash** or **uprush** rushes shoreward with great velocity and force. The distance from the shore where the waves break is called **plunge line** where the depth of sea water and the wave height are approximately equal. The turbulent forward moving **swash** or **breaker** is also called **surf.**

Breakers are of 3 types viz. (1) spilling breakers, (2) plunging breakers and (3) surging breakers. **Spilling breakers** are those in which water does not fall but regularly spills down the front of the sea waves and forms prominent foaming coast. **Plunging breakers** are those in which water falls vertically and rushes shoreward in the form of turbulent foaming water mass. **Surging breakers** are those in which water moves rapidly shoreward.

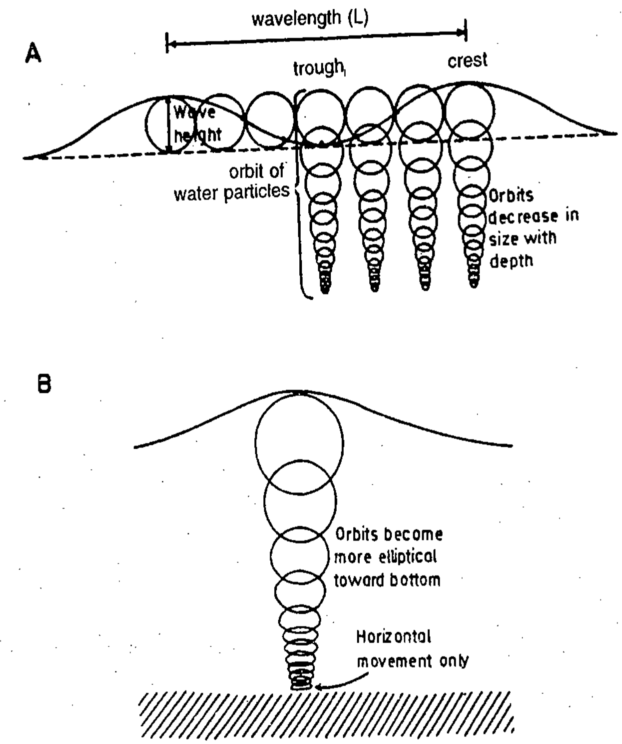


Fig. 20.2 : A- Generation of wave forms by orbital motion of water particles. Each water particle continues orbitting about the same position while the wave form advances forward.

B- The size of orbits of water particles decreases and orbits become more and more elliptical downwards or as they approach a shallow bottom where the movement of water particles becomes horizontal i.e. water particles move back and forth only.

Spilling breakers are associated with steep waves and are caused when the velocities in the wave crest and wave body are almost equal. Plunging breakers are caused when the velocity of water in the wave crest exceeds the velocity of wave body (of intermediate waves). Surging breakers are associated with gentle waves (in terms of steepness of wave crest).

The breakers or swash or surfs after reaching the sloping beach return towards the sea as **backwash** or **undertow currents** and **rip currents.** It may be pointed out that surf currents or swash or breakers and undertow currents or backwash are significant geomorphic agents. The sea waves become geomorphoic agent only when they **feel bottom** at the plunge line.

Sea waves are classified into two types on the basis of depth of oceanic water viz. (1) waves in deep water are called **oscillatory waves** and (2) waves of shallow water are called **translatory waves.** In oscillatory waves water particles move in circular orbit and they return very nearly to their original position after the passage of waves while in translatory waves

water particles move forward approximately at the same velocity as the wave form.

From geomorphological point of view sea waves are divided into two major types viz. (1) **constructive waves** and (2) **destructive waves.** Low-frequency waves approaching the shore and beach are constructive in character because they lose volume and energy rapidly while moving up the beach because water percolates in the shingles and other beach materials and thus the backwash is weakened. It is, thus, obvious that low-frequency waves help in the building of beaches. On the other hand, high-frequency waves with short wavelengths and high wave crests occurring on a more steeply sloping shore are destructive in character because instead of spilling they plunge and generate a powerful backwash which combs down the beach (removes the beach materials and transport them towards the sea).

Wave refraction results in the formation of **littoral** or **longshore currents** which move parallel to the sea coast. These are generated in two ways *e.g.* (i) when sea water under the influence of gusty winds strikes the coast, there is mass transport of sea water parallel to the coast or (ii) when powerful sea waves under the influence of high-velocity winds strike the coast obliquely, most of water moves parallel to the coast.

20.2 SEA COAST AND SEA SHORE

Generally, sea coast and sea shore are taken as synonymous but geomorphologically these two terms have quite different meanings. Sea shore represents the zone of land between high tide water (HTW) and low tide water (LTW) (fig. 20.3) while the **shoreline** represents the actual landward limit of sea water at a given moment of time. 'The shoreline is the line of demarcation between land and water. It fluctuates from moment to moment influenced by waves and tides' (A. Bloom, 1979). The coast represents the land-zone immediately behind the cliff. The coastline represents the cliff-line or the margin of land rising above the sea water. The shore zone or simply shore is divided into 3 zones : (1) **back shore** represents the beach zone starting from the limit of frequent storm waves to the cliff base, (2) **foreshore** extends from low tide water to high tide water and (3) **offshore** represents the zone of shallow bottom of the continental slope.

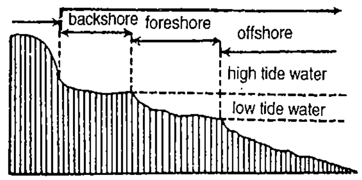


Fig. 20.3 : Divisions of sea coast and sea shore.

20.3 PROCESSES AND MECHANISM OF MARINE EROSION

Sea waves resort to erosion of the coastal land and backshore zone through the processes and mechanism of hydraulic action, corrasion or abrasion, attrition, corrosion or solution and water pressure. When the sea waves break at plunge line, the potential energy of the waves is converted into kinetic energy and the resultant **breakers** or **swash** or **surf currents** strike the coast land with enormous power and erode the geomaterials in different manner as stated above. It may be pointed out that the coastal rocks are immensely affected by weathering processes resulting into disintegration and decomposition and thus weakening of rocks. Such weakened rocks are easily plucked and eroded away by the hydraulic pressure and turbulence of breaking waves (swash).

The nature and magnitude of coastal erosion are affected and determined by the following factors- (1) Wavelength, wave velocity, wave frequency and wave period. Long enduring waves with longer wavelength and high velocity become effective erosive agent. (2) Structure and composition of bedrocks of coast land. Well jointed and fractured rocks are more easily plucked, quarried and abraded by sea waves. Rock types (lithological characteristics) determine the nature of erosion. (3) More or less stable coastline is subjected to more erosion than unstable coastline. (4) Vertical coast land (cliffs) having deep water is less eroded because the sea waves are reflected back without causing much harm to the cliff. On the other hand, the cliffs, which rise moderately from wide basal platform and if the sea water is of shallow depth, are prone to more hydraulic action and plucking because the breakers or swash

strike the cliff with great ferocity and enormous power and thus hammer the rocks. (5) Availability of erosion tools (sands, gravels, pebbles and cobbles and sometimes boulders) and (6) Duration of marine erosion.

Hydraulic action refers to the impact of moving water on the coastal rocks. Large storm waves attack the coastal rocks with erormous hammer blows amounting to 50 kgf per square centimetre (gravity force (f) is 9.81 and hence sea waves, normally, hurl a force of 50 kgf per square centimetre of the coastal rocks). Repeated blows of striking sea waves enlarge the incipient joints, fracture patterns and thus help in breaking the rocks into smaller joint-bounded blocks. The waves are capable of dislodging larger fragments of rocks weighing several tonnes in weight. This process of displacement of rock fragments is also called as **quarrying** and **plucking.** In fact, wave quarrying and wave plucking caused by the hydraulic pressure and turbulence of breaking waves is very effective mechanism of erosion of weathered and joint-bounded fresh bedrocks. The striking breaking waves also exert enormous pressure on the air trapped in the crevices and hollows within the coastal rocks. Thus, alternate process of compression (when the waves strike the rocks as swash) and decompression (when the waves return as backwash) causes pressure changes and weakens the rocks to break into the blocks of several tonnes.

Abrasion or **corrasion** is another effective mechanism of coastal erosion by marine waves with the help of tools of erosion (coarse sands, pebbles, cobbles and some time boulders). High-energy storm waves charged with large cobbles drill out circular potholes and abrade the standing bedrocks. **Attrition** involves mechanical tear and wear and consequential breakdown of fragments due to their mutual collision effected by backwash and rip currents which remove the fragments from the cliff base and transport them towards the sea.

Corrosion or solution refers to the chemical alteration of rocks mainly carbonate rocks (limestones, dolomites and chalks) due to their contact with sea water. Besides hydraulic action, abrasion and corrosion, coastal rocks are also weakened and disintegrated due to alternate processes of wetting (hydration) and drying (dehydration) because these promote a wide range of chemical processes which help in the disintegration and decomposition of coastal rocks. Alternate freeze and thaw actions in the foreshore zones in the cold climates cause disintegration of joint-bounded rocks.

It may be mentioned that lithological characteristics of coastal zones and their layout largely control the mechanism of marine erosion. It is argued that basalts and obsidian weather far more in marine water than in freshwater. This factor explains the unusual width of continental shelf west of the Deccan basalt region of Peninsular India. The west coast of Maharashtra is characterized by rias, coves, caves, stacks, inlets etc. because the waves strike the joints and fissures of basalts transversely and thus have caused differential erosion while the south coast of Kathiawar having the same lithology (basalt) is almost devoid of such features because the waves do not attack the coast transversely as they move parellel to the coast.

20.4 EROSIONAL LANDFORMS

Significant coastal features formed due to marine erosion by sea waves and other currents and solutional processes include cliffs, coves, caves, indented coastline, stacks, chimneys, arch, inlets, wave-cut platforms etc.

Cliffs

Steep rocky coast rising almost vertically above sea water is called sea cliff which is very precipitous with overhanging crest (fig. 20.4). The steepness of true vertical cliffs depends on variations of lithology and geological structure and relative rate of subaerial weathering and erosion of cliff face and crest and marine erosion of cliff base. If marine erosion at the base of cliff is much faster than the subaerial weathering of cliff face and crest,

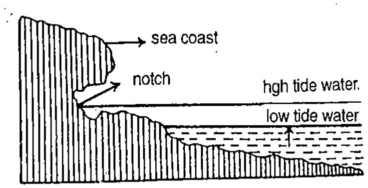


Fig. 20.4 : An example of sea cliff.

overhanging cliff with steep vertical face is formed. On the other hand, if the subaerial processes dominate over marine processes the verticality of cliff disappears and the cliff loses its true cliff character.

True cliffs are generally formed where bedrocks are affected by low rate of subaerial weathering and massmovement viz. limestones, chalk, horizontally bedded sandstones, massively jointed igneous rocks and metamorphic rocks. In fact, the morphology of sea cliffs is determined by (i) the influences of bedrocks lithology and structure and (ii) balance between marine and subaerial erosional processes. A Guilcher (1958) has identified 4 types of cliffs on the basis of their morphology determined by the aforesaid two factors (fig. 20.5) viz. (1) **resistant cliffs** formed on chalk (fig. 20.5A) and horizontally bedded sandstones (fig. 20.5B), (2) **weak cliffs** developed on clays and shales (fig. 20.5C), (3) **composite cliffs** of chalk overlying clay (fig, 20.5D) and of interbedded sandstones and shales (fig. 20.5E) and (4) **complex cliffs.**

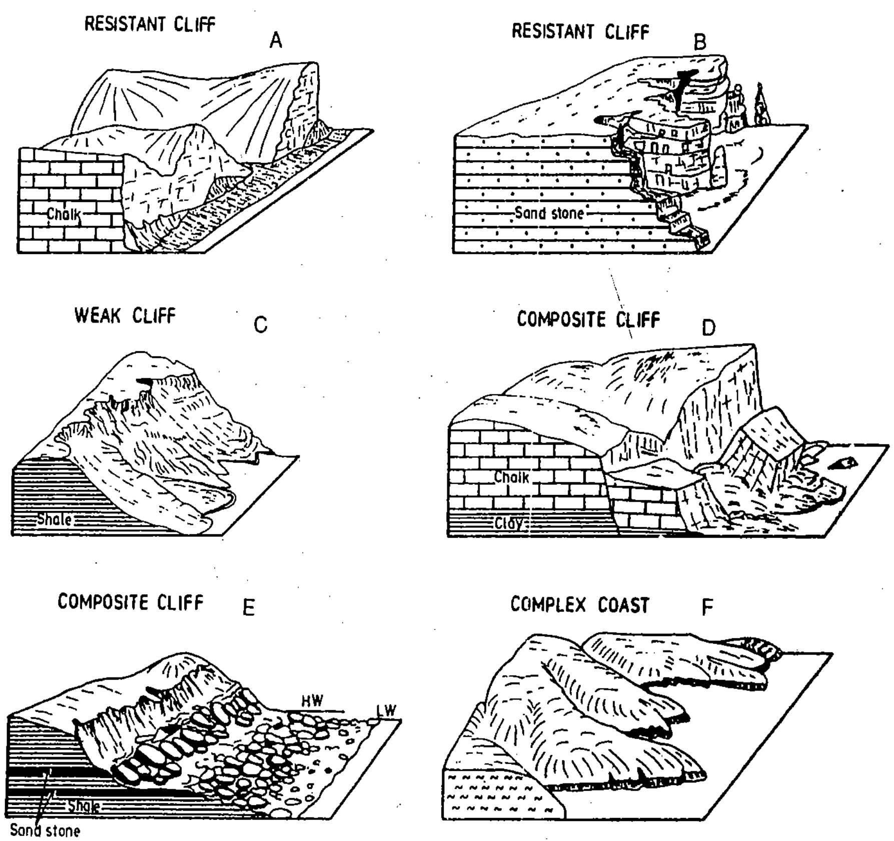


Fig. 20.5 : Types of cliffs, (a) resistant cliff, (B) resistant cliff, (C) weak cliff, (D) composite cliff, (E) composite cliff and (F) complex cliffs (after A. Guilcher, 1958).

The formation of sea cliff begins with the erosion of coastal rocks through the mechanisms of hydraulic actions and abrasion by breaker waves (swash or surf currents). This results in the formation of notch and the coast becomes vertical. There is gradual extension of notch landward due to continuous wave attack with the result the crest of the cliff overhangs the notch. If the notch at the base of the cliff is extended landward to such an extent that the support to the cliff crest is weakened the overhanging head of the cliff breaks and falls down resulting into gradual recession of the cliffs landward. The rate of cliff recession varies both in space and time depending on the following conditions- (i) rock lithology and structure, (ii) susceptibility to chemical erosion, mass movement and subaerial erosion, (iii) cliff height, (iv) orientation of the coast, (v) wave energy, (vi) offshore topography, (vii) rate of removal of debris from the cliff base by the backwash or the undertow currents etc.

Wave-Cut Platform

Rock-cut flat surfaces in front of cliffs are called wave-cut platforms or simply **shore platforms** (fig. 20.6) which are slightly concave upward. The origin and development of wave-cut platforms is related to cliff recession. These are also called **wave-cut benches.** Shore platforms are formed where cliff recession is active due to powerful bombardment of cliff base by uprushing breaker waves and effective removal of eroded materials by backwash (undertow currents). The forms of wave-cut platforms depend on geological factors. Extensive platforms are developed where the rocks are least resistant to wave erosion. In other words, thinly bedded and densely jointed, and horizontally disposed rocks with strike parallel to the coastline are more vigorously eroded by uprushing breaker waves and thus are associated with extensive shore platforms. On the other hand, narrow and steeper platforms with high mean elevation are developed over resistant rocks. As regards the processes and mechanism of the development of wave-cut platforms, quarrying and plucking by large and high-energy storm waves and water-level weathering are effective marine processes of shore platform development.

Wave-cut platforms are generally divided into 3 zones viz. (1) **mesolittoral zone** between high and low tide water, (2) **supralittoral zone** above high tide water but within the range of spray and (3) **sublittoral zone** below low tide water. On the basis of morphology wave-cut platforms are classified into 3 types *e.g.* (1) **shore platforms** with inclined plane (about 1m above highest tide level), (2) **stepped platforms** (are formed by tropical water-level weathering, biological action and small tidal ranges), and (3) **storm wave platforms.** A fourth type of shore platform is distinguished as solution platform which is developed on carbonate rocks in the shore zone by chemical processes mainly solution.

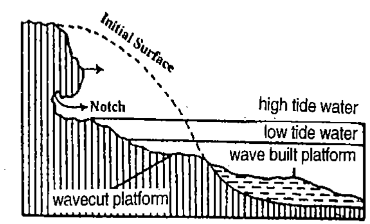


Fig. 20.6 : Wave-cut and wave-built platforms.

Sea Caves And Associated Features

Sea caves are formed along the coast due to gradual erosion of weak and strongly jointed rocks by uprushing breaker waves (surf currents). The joints are widened into large cavities and hollows which are further enlarged due to gradual wave erosion into well developed coastal caves. Sea caves are more frequently formed in carbonate rocks (mainly limestones and chalks) because they are eroded more by solutional processes. It may be pointed out that sea caves are not permanent features as they are very often destroyed by uprushing high-energy storm waves. When the caves are enlarged to such an extent that their roofs become remarkably thin, they ultimately collapse and fall and the debris are removed by powerful backwash and thus resultant long narrow inlets are called **'geo'** in Scottland. Some times, the air in the cave is compressed by uprushing powerful storm waves and finding no other route to escape it breaks open the roof of the cave and appears with great force making unique whistling. Such holes are called **natural chimneys** or **blow holes** or **gloup.** "The name blow hole refers to the fact that during storms spray is forcibly blown

into the air each time a breaker surges through the cave beneath" (A. Holmes and D.L. Holmes, 1978). When caves are formed on opposite sides of the seaward projecting headland, a natural arch is formed due to coalescence of two caves (fig. 20.7). It may be mentioned that natural arches are not permanent coastal features because the roof, after becoming very thin, collapses and thus the seaward part of the arch stands detached from the coast. Such isolated remnant of headland projecting well above sea level is called **stack** (fig. 20.8). This is also called as **chimney rock.** Stacks are also called **needles, columns, pillars, skerries** etc. The Old Man of Hoy (137 m high) in the Orkney

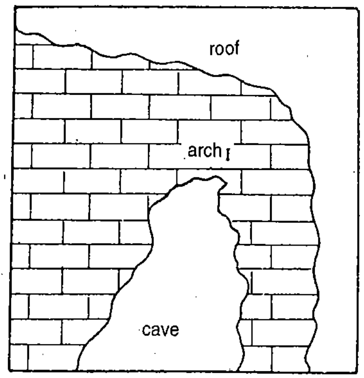


Fig. 20.7 : An example of sea arch.

Island of British Isles is widely quoted example of sea stack. The elliptical hollows formed in the coastal area alternated by hard and weak rocks are called **coves** or **mini bays** (fig. 20.9).

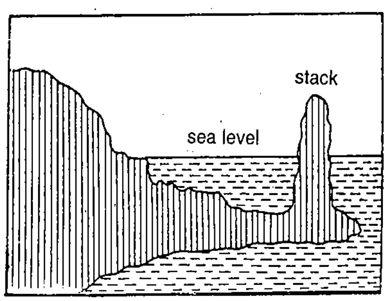


Fig. 20.8 : Formation of stack.

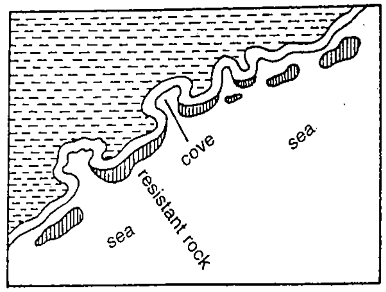


Fig. 20.9 : Formation of coves and island.

Nearly all of the aforesaid coastal erosional features are found along the western and eastern coasts of Peninsular India. The author noticed the examples of cliffs, wave-cut platforms, caves, arches, tidal inlets, chimneys etc. along the eastern coast in the environs of Visakhapatnam. Such features are frequently observed on the western Indian coast mainly between Mumbai and Mangalore. B. Arunachalam has studied 3 headlands near Ratnagiri. These headlands are marked by overhanging cliffs ranging in height from 45m to 90m.

20.5 TRANSPORTATIONAL WORK

The eroded materials are transported by sea waves in different manner but the transportational work of sea waves varies significantly from other agents of erosion and transportation. For example, the **backwash,** or **undertow currents** (moving from the coast and beach towards the sea) pick up the eroded materials and transport them seaward but the uprushing **breaker waves** or **surf currents** pick up these materials and bring them again to the coast and beaches. Thus, the transportation of materials takes place from coastland towards sea and from sea towards the coast. When oblique waves strike the coast, longshore currents are generated. These longshore currents transport the materials parallel to the shoreline. The materials involved in the transportation by sea waves include sands, silts, gravels, pebbles, cobbles and sometime boulders. When there is equilibrium between incoming supplies of sediments by uprushing breaker waves and removal of sediments by backwash or undertow currents on the wave-cut platforms, a **profile of equilibrium** is achieved. If the wave-cut rock platform is characterized by steep

slope towards the oceanic slope, the destructive waves become very active and thus resultant powerful backwash removes the materials from the landward side so that the slope of the platform is lessened. On the other hand, if the slope of the wave-cut platform is less steep, constructive waves become more effective as they favour sedimentation and beach deposition on the landward side so that the slope of the platform becomes steeper. 'The surface is therefore continually modified, and in such a way that at each point it tends to acquire just the right slope to ensure that incoming supplies of sediment can be carried away just as fast as they are received. A profile so adjusted that this fluctuating state of balance is approximately achieved is called a **profile of equilibrium**' (A. Holmes and D.L. Holmes, 1978, p. 516).

20.6 DEPOSITIONAL LANDFORMS

Significant depositional landforms developed by sea waves include sea beaches, bars and barriers, offshore and longshore bars, spits, hooks, loops, connecting bars, looped bars, tombolo, barrier island, tidal inlets, winged headlands, progradation, wave-built platforms etc.

Besides, mangroove swamps, **sabkha** and delta are also included in the category of depositional coastal landforms, though deltas are formed due to deposition of sediments brought by the rivers.

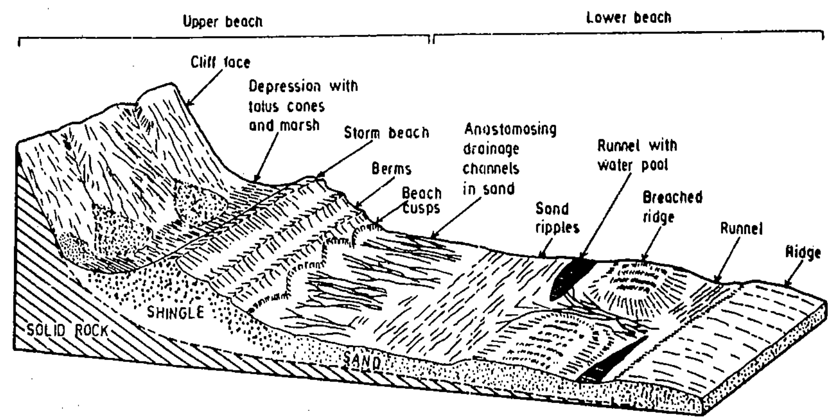


Fig. 20.10 : Different elements of an ideal beach (after A. Goudie, 1984).

Beaches

Temporary or short-lived deposits of marine sediments consisting of sands, shingles, cobbles etc. on the sea shore are called beaches. According to A. Bloom (1979) 'the sediment in motion along a shore is the beach'. Beaches are deposited by breaker waves between high and low tide water. Beaches are infact wedge-shaped sediment deposits on sea shore. In width beaches vary from a few metres to several kilometres. Beaches are generally formed when sea is calm and winds are of low velocity. Beach materials consist of fine to coarse sands, shingles (pebbles), cobbles and boulders. The major sources of the supply of beach materials are erosion of headlands and cliffs, sediments brought by the rivers and nallas at their mouths, mass wasting and massmovement (landslides and slumping) of cliffs, scouring of the offshore zone by storm waves, erosion of pre-existing beaches etc. The significant beaches developed on the west coasts of India include Juhu beach (Mumbai coast), Colba, Kalangut, Anjana etc. along Goa coast, Koblam beach along Kerala coast etc. Marina beach on Tamil Nadu coast (Chennai), Vishakhapatnam beach on Andhra coast and Puri beach at Puri along Orissa coast etc. are important beaches developed along eastern coast of India.

An ideal beach consists of two main elements *e.g.* **upper beach** and **lower beach** and several minor elements *e.g.* **storm beach, beach ridges,** or **berms, beach cusps, small channels, ripples, ridges** and **runnels** etc. (fig. 20.10). The **upper beach** representing the landward section of the beach is composed of coarser and larger materials such as pebbles, cobbles and boulders and the slope ranges between 10^0 to 20^0. On the other hand, the **lower beach** representing the seaward section of the beach is composed of sands and has low gradient of 2^0 or even less. The **storm beach** is a semi-permanent ridge which stands well above the level of highest spring tides. The successive low ridges built by constructive waves parallel to the coastline and below the level of high spring tides are called **beach ridges** or **berms. Beach cusps** are small regular embayments and a series of headlands composed of shingles. Small anastomosing drainage channels are developed in the sands below the cusps. Sand ripples are developed on the lower beach section by wave action or by tidal currents. Ridges and runnels are broad and gentle rises and depressions which are developed at the seaward side of the sand beach and are aligned parallel to the shoreline.

Beaches are generally classified on the basis of beach materials into (1) **sand beach** (sand grains ranging in size between 0.5 to 2mm), (2) **shingle beach** (composed of pebbles ranging in size from 2 to 100mm) and (3) **boulder beach** (more than 100mm in diameter). The regular increase in the width of sea beaches towards the sea is called **progradation** while depletion of beaches due to erosion and thus their narrowing or beach cutting is called **retrogradation.**

Bars and Barriers and Associated Features

The ridges, embankments or mounds of sands formed by sedimentation through sea waves parallel to the shoreline are called **bars.** The larger forms of bars are called **barriers.** The formation of bars and barriers starts with the development of shoals due to deposition of sands. These shoals grow in height by addition of sediments until they appear above sea-level. Bars and barriers may be formed near the coast or away from the coast, parallel to the coastline or transverse to the coast. There are different forms of sand bars and barriers. If the bars are formed in such a way that they are parallel to the coast but are not attached to the land, they are called **offshore** or **longshore bars** (fig. 20.11). If the sand bars are formed in such a way that their one end is attached to the land while the other end projects or opens out towards the sea, they are called **spits** (fig. 20.11). A few spits have been reported from the eastern and western coasts of India. For examples, 50 km long spit in the mouth of Chilka lake (Orissa coast), 16 km long spit near Kalinagapatnam, a well developed spit growing at the rate of 12 km per century to the east of Kakinada Bay, 60 km long spit to the east of Pulicat lake-all along the east coast; 22 km and 55 km long two spits enclosing the Vembanad Lake and converging at the port of Cochin on the east coast of India. Rameshwaram spit projecting seaward from Tamil Nadu coast is very important spit which is so stabilized that it bears human settlements.

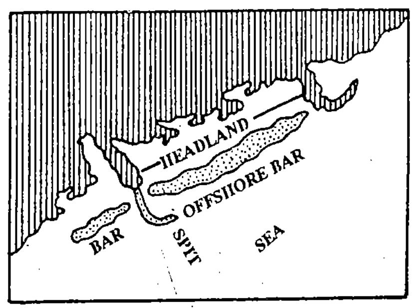


Fig. 20.11: Offshore bars and spits.

High-energy storm waves very often modify the shape of spits by bending them towards the

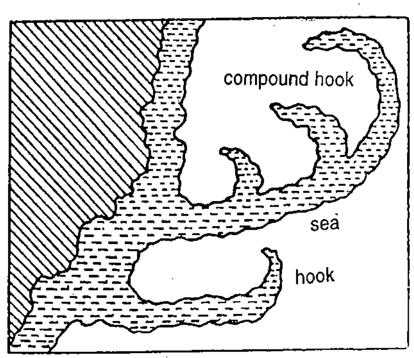


Fig. 20.12 : Simple and compound hooks.

coast.. The curved spits assume the shape of hook and thus such spits are called **hooked spits** or simply **hooks** (fig. 20.12). Hooks are stabilized when there is equilibrium between constructive and destructive waves.

When the opposing currents become more dominant than the littoral currents, the spits are bent to such an extent that they are attached to the mainland (coast) and thus form complete loop which encloses sea water in the form of lagoons. Such form of a spit is called **loop** (fig. 20.13). When such loop is formed around and an island, it is called **looped bar** (fig. 20.13).

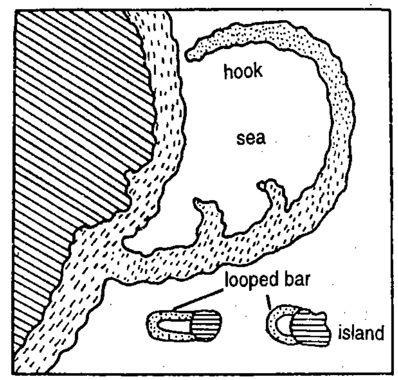


Fig. 20.13 : Loop and looped bar.

Connecting bars are formed when bars are so extended that they either join two headlands or two islands (fig. 20.13). Connecting bars are variously named on the basis of their shapes and forms. For example, a bar connecting two headlands is called connecting bar while a bar becomes **tombolo** when it connects the mainland with an island or connects a headland with the island (fig. 20.14). Thus, a tombolo acts as a bridge between the coast and an island. A few examples of tombolo are observed along the western coast of India between Ratangiri and Malvan. When bars of pebbles and cobbles are formed on either side of a headland, such headland is called a **winged headland.** There may be 3 locations of bars in the bays viz. (1) **bay head bars,** formed at the head (landward) of the bay, (2) **mid-bay bars,** formed in the middle portion of a bay and (3) **bay-mouth bars,** formed at the opening of a bay. **Lagoons** are formed when the coves or bays are completely enclosed by bars. Chilka lake and Pulicat lake on the east coast of India are examples of lagoons.

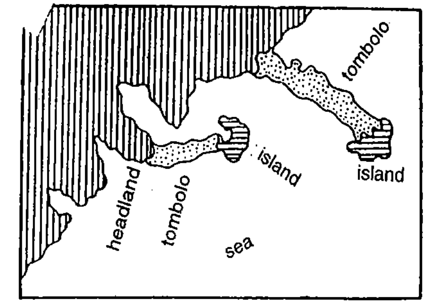


Fig. 20.14 : Tombolo.

Coastal Wetlands

Flat and rolling marshy lands developed in the coastal areas of humid tropics are called **coastal wetlands,** which are generally formed behind spits or bars. There is absence of reliefs and sea water remains stagnant in these wetlands. Sediments are fine and water is saline. The floral environment is dominated by mangrooves. Such wetlands are found extensively in the coastal zones of West Bengal where the mangrooves of the wetlands are known as **Sundarban.**

Sabkha

Depositional coastal areas having flat surface in the dry tropical zones are called **sabkhas** which are flat but barren coastal lands. Sabkhas have developed in the coastal zones of UAR (Egypt), UAE, Mexico, Baja of California (USA) etc. Sabkhas are also called as **saltflats.**

20.8 MARINE CYCLE OF EROSION ALONG A SHORELINE OF SUBMERGENCE

Initial Stage

The initial stage of marine cycle of erosion of shoreline of submergence beghins with the submergence of coastal land under sea water. Submergence of coast land takes place in two ways viz. (i) either due to rise in sea level (positive change in sea level)

or (ii) subsidence of coast land so that most of the coast land is submerged under sea water due to its transgression on main land. Rise in sea level may be either due to rise in the oceanic floor due to tectonic factors or due to return of melt-water locked in the form of ice sheets on the continents during ice age. The initial form of shoreline of submergence may be **a ria coast** or **a fiord coast.** The lower segments of the rivers at their mouths are dismembered due to submergence of coast land. The initial submerged coastline is highly irregular characterized by numerous embayments, coves, bays, headlands, inlets, islands etc. (fig. 20.16).

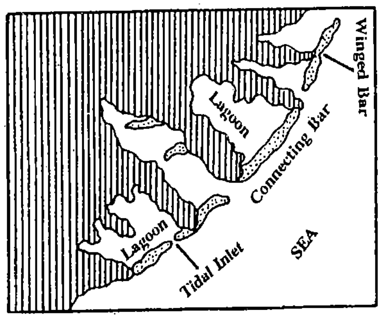


Fig. 20.15: Different types of bars.

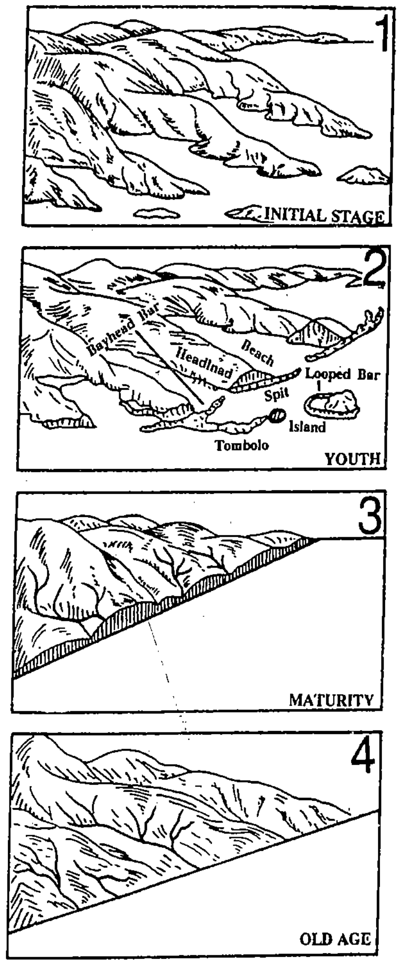


Fig. 20.16 : Stages of marine cycle of erosion along the shoreline of submergence.

Youth

Marine waves mainly **swash** or **breaker waves** or **surf currents** erode the exposed coastal land through the mechanisms of hydraulic action and corrasion (abrasion). The uprushing high-energy storm waves bombard the densely jointed rocks and dislodge larger rock blocks. Consequently, the coastline is highly indented and becomes crenulated and irregular. Numerous caves and headlands are formed due to differential erosion of coastal rocks. The breaker waves notch the rocks at water level and thus initiates the formation of sea cliffs. In the beginning the cliffs are of low height and are imperfectly developed. Gradually, the cliffs are sharpened due to regular erosion at the cliff base. Wave-cut platforms (shore platforms) are formed in front of cliffs due to regular landward recession of cliffs. Though the early youth is dominated by erosional work but some depositional features are also developed such as beaches in the back shore zone. Wave-cut platforms are characterized by several coastal features such as **arch, stacks, caves, natural chimneys** etc. Late youth is characterized by maximum development of wave-cut platforms as they become most extensive due to progressive recession of cliffs. Most of the erosional features start disappearing and numerous depositional features are formed *e.g.* bars, offshore bars, connecting

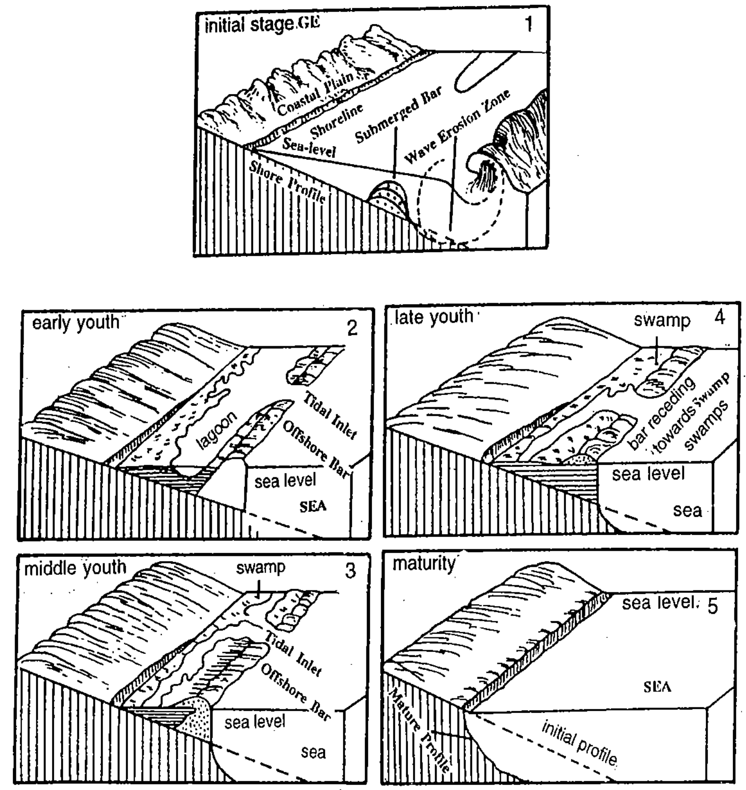


Fig. 20.17 : Stages of marine cycle of erosion on the shoreline of emergence.

bars, spits, hooks, loops, looped bars, tombolo, beaches etc. Several types of beaches such as shore beaches, headland beaches, bay-head beaches, berms, cusp beaches etc. are developed. Most of the bays are enclosed by bars and thus lagoons are formed. Cliffs are fully developed and thus the coast becomes almost vertical.

Maturity

Most of the features developed during youthful stage are obliterated. Profile of equilibrium is attained due to balance in the rate of erosion and deposition. Most of the depositional features are destroyed by late maturity and thus the coast line becomes almost straight and regular. The height and gradient of coastland decrease significantly.

Old Stage

Coast and shore are significantly lowered in height because of continued weathering and erosion. Adjoining land areas are eroded down to sea level. Thus, the coast and shore become straight and slope very gently towards the sea. It may be pointed out that this may be possible only when there is crustal

stability for long period. It is obvious that the conditions of old stage are only theoretically possible because coasts are affected by emergence and submergence due to diastrophic forces.

20.9 CYCLE OF EROSION ON SHORELINE OF EMERGENCE

Initial Stage

Shoreline of emergence is evolved in two ways viz. (i) due to upliftment of coastland in relations to sea level because of tectonic events or (ii) due to fall in sea level because of subsidence of oceanic floor. Initially, shorelines of emergence are straight and regular. Coastal plains extend for greater distance in sea water but their gradient is quite gentle. Since the depth of water is shallow, most of the sea waves break in off-shore zone. The breakers erode the coast to form 'notch' and small cliffs. Such small cliffs are called 'nips'. Submarine bars are formed due to deposition of sediments on submerged coastal plains. These submarine bars gradually grow in height and are aligned parallel to the shoreline.

Youth

The youthful stage of marine cycle of erosion on shoreline of emergence begins with the appearance of submarine bars above sea level. Numerous independent small bars are united and thus form offshore bars. These offshore bars protect the coast from wave erosion. Sea water locked between the coast and offshore bars becomes lagoon (fig. 20.17). Sea waves break offshore bars at some places and thus make their way to the lagoons. Such openings in the offshore bars are called tidal inlets. Legoons are filled with sediments brought by the rivers (which debouch in the lagoons) and wind. Sometimes, lagoons become swamps and marshes because of vegetation.

Late youth is characterized by migration of offshore bars towards the coast. Seaward side of these bars is steepened due to their erosion by storm waves. Eroded materials are deposited by sea waves on the landward side of these bars. This process causes gradual shifting of offshore bars coastward with the result lagoons become narrower.

Maturity

Offshore bars, lagoons, swamps and marshes, tidal inlets etc, are distroyed by the beginning of mature stage. Sea waves erode the submerged coastal platform upto wave base. Most of the coastal irregularities are obliterated and the coastline becomes simple and straight. The slope of the coast becomes steep and the depth of water increases.

Old Stage

The development of old stage of marine cycle of erosion on shoreline of emergence can be deduced theoretically only as its practicability is not possible.

21

WIND AND AEOLIAN LANDFORMS

21.1 AEOLIAN ENVIRONMENTS

Wind is, no doubt, an important geomorphic agent but it is not as much effective process of erosion as rivers and sea waves. "Wind is a comparatively minor agent of geomorphic change because of the low density of air as compared to rock and water" (A. Bloom, 1979). Aeolian processes involving erosion of dry, loose and unprotected geomaterials, transportation and deposition of fine sediments mainly sands, are most active in arid and semi-arid regions of tropical and temperate environments. Aeolian processes are generally associated with desert areas but one should keep in mind that deserts (defined as barren, desolate and plantless areas) are of two types viz. hot and warm deserts and cold deserts. Aeolian processes are not active in cold deserts because the surfaces are always covered with permanent ice sheets. Thus, winds are active in those arid and semi-arid environments where the ground surface is covered with loose and friable geomaterials. About one third of the land surface area of the earth is characterized by arid and semi-arid environment wherein extremely arid, arid and semi-arid areas account for 4 per cent, 15 per cent and 14.6 per cent respectively.

Desert environments are characterized by very low mean annual rainfall (less than 250 mm, average being 100 mm), practical absence of vegetation, very high daily and annual ranges of temperature, dust storms, high velocity winds, dominance of sands, highly variable annual rainfall (years without rainfall), occasional torrential rainfall through strong rainstorms resulting into stream floods and sheetfloods etc. Semi-arid environment is characterized by mean annual rainfall of 250 mm to 500mm. UNEP (United Nations Environment Programme) in 1992 divided arid regions into 3 categories on the basis of aridity index (AI) *e.g.* (1) semi-arid regions, (AI = 0.2 - 0.5), (2) arid regions (AI = 0.05 - 0.20) and (3) hyper arid regions (AI = less than 0.05) when AI = P/PET, where P = annual precipitation, PET = potential evapo-transpiration. The largest stretches of true deserts are found in five great provinces *e.g.* (1) Sahara-Central Asia Province (Sahara desert, Arabian desert, Indian desert, Kara Kum and Kizil Kum deserts, Takla Makan desert and Gobi desert), (2) Southern African Province (Namib desert, Karroo desert, Kalahari desert etc.), (3) South American Dry Zone (Atacama desert of Peru and Chile along the west coast and Patagonian desert of south Argentina along east coast), (4) North American Desert Province (Mojave desert of California and Arizona and Sonoran desert of Mexico) and (5) Australian Desert Province.

The deserts having mobile sands are called **ergs** (Arabic word erg means region of shifting sands). The model size of erg is about 188,000 km^2 whereas the largest erg of the world is Rub Khali in Arabia (560,000 km^2). The sands of deserts are

derived from ephemeral river valleys, other fluvial deposits, coastal deposits, pre-existing sand dunes and from mechanical weathering of sandstones.

Winds are the most widespread geomorphic agent in the deserts of arid and semi-arid regions of tropical and subtropical environments. Besides, ephemeral and intermittent streams resulting from occasional rainstorms also become important agents of erosion and transportation. Most of the drainage in the extensive deserts is of inland drainage pattern. Thus, besides aeolian process, fluvial processes, though of limited extent, are also operative in the arid and semi-arid regions.

21.2 WEATHERING IN ARID AREAS

The tropical desert areas are characterized mainly by mechanical (physical weathering) weathering which includes the processes of block disintegration due to temperature change (during day and night), granular disintegration due to temperature change, shattering due to occasional light shower during day time, exfoliation (onion weathering) due to heat and wind etc. Besides, chemical weathering involving decomposition of rocks during occasional wet condition also becomes effective.

Tafoni is a typical cavernous topography developed in siliceous rocks mainly sandstones in the tropical deserts. Amorphous network of holes are developed in sandstones due to decomposition of rocks under the mechanism of chemical weathering during infrequent wet periods. The decomposed materials are blown away by the wind and thus the holes are gradually enlarged. Such tafoni are found in Jodhpur-Ajmer part of Thar desert of India.

The chemical weathering in the tropical deserts having stony surfaces produces encrustation of varnish of dark reddish or blackish colour on the exposed surfaces of rocks mainly sandstones laving ferrous and silica contents in abundance. Such coloured encrustations on big rock blocks, boulders, extensive stony surfaces are called **desert varnish.**

Chemical weathering associated with eluviation of certain mineral contents under the process of leaching and illuviation (accumulation) of such minerals below gives birth to the formation of hardened cuirasses known as **duricrusts.** On the basis of dominant constituents they are classified as alcrete (of aluminium), silicrete (silica), ferricrete (iron), calcrete (calcium carbonate), salcrete (salt), gypcrete (gypsum) etc.

21.3 EROSIONAL WORKS OF WIND

Wind erosion in the arid and semi-arid regions is assisted by mechanical weathering. Expansion of rocks due to high daytime and summer temperature and contraction consequent upon lower night and winter temperature result in the disintegration of crystalline rocks which facilitates aeolian erosion. Wind erosion is largely controlled and determined by (i) wind velocity, (ii) nature and amount of sands, dusts and pebbles (tools of erosion), (iii) composition of rocks, (iv) nature of vegetation and (v) humidity, rainfall amount and temperature.

It may be mentioned that wind erosion generally takes place above the ground and thus wind velocity plays a major role in determining the degree of aeolian erosion. It is now generally agreed that wind is of relatively minor significance in the evolution and development of landforms of any significance. The quantity and size of materials lifted and moved by wind determine the degree of wind abrasion. Wind erosion is believed to be effective only upto 180 cm above the ground surface. Maximum wind erosion occurs at a short distance above the ground, say at a height of 20-25 cm because here wind velocity and sediment movement are moderate whereas 'at the ground sediment transport is high but velocity of transport is low. At a height velocity is high but the quantity of sand available for abrasion is small' (R.J. Chorley et al., 1984).

Unlike rivers and glaciers winds erode the rocks from all sides because of their variable directions. Wind erosion occurs in three ways viz. (1) deflation, (2) abrasion or sandblasting and (3) attrition. The process of removing, lifting and blowing away dry and loose particles of sands and dusts by wind is called **deflation** (derived from Latin word deflatus, which means blowing away). Long continued deflation removes most of loose materials and thus depressions or hollows known as **blow outs** are formed and bedrocks are exposed to wind abrasion (corrasion). Deflation also attacks rock surfaces mainly of sandstones, detaches small fragments and helps in forming small depressions in rock surfaces but the process of depression formation through deflation in bedrock surfaces is exceedingly slow.

Since deflation removes mostly fine particles (mainly sands) larger particles such as gravels are left over the surface. Thus, accumulation of gravels over thousands of years forms **desert pavements** which protect the rocks below from further wind erosion.

Wind armed with entrained sand grains as tools of erosion attacks the rocks and erodes them through the mechanims of abrasion, fluting, grooving, pitting and polishing. The combined effects of these mechanisms are collectively called **abrasion** or **sandblasting.** As stated earlier wind abrasion is minimum at ground level because wind velocity is retarded by friction. Similarly, wind ceases to become an erosive agent beyond the height of 180 cm from the ground levels because normal wind cannot lift and carry particles of average size. Thus, maximum abrasion occurs at the height between 20-25 cm from the ground surface. Abrasion undoubtedly undercuts the upstanding objects from all sides because wind very often changes its direction. It may be, thus, stated that wind abrasion decreases drastically with increasing height from the ground and becomes inactive beyond 180 cm height except during strong gales and storms.

Attrition involves mechanical tear and wear of the particles suffered by themselves while they are being transported by wind through the processes of saltation and surface creep. **Saltation** involves the movement of sands and gravels through the mechanisms of bouncing, jumping and hopping by turbulent air flow. Saltating grains (saltation is derived from Latin word **saltare** which means to leap) frequently rise to a height of 50 centimetres over a sand bed and upto 2 metres over pebbly surface by the combined action of aerodynamic lift and the impact of other saltating grains which return back to the ground surface. **Surface creep** involves movement of relatively bigger particles along the ground surface by strong winds. Thus, the particles, while they are moving, collide against each other and are further comminuted in finer particles.

21.4 EROSIONAL LANDFORMS

Long-continued erosional works through the mechanisms of abrasion or sandblasting and deflation produces some characteristic landforms in desert areas such as blowouts or deflation basins, mushroom rocks or pedastal rocks, inselbergs, demoiselles, yardangs, zeugen, ventifacts, dreikanters, stone lattice, wind windows etc. but 'probably no modern geomorphologist would accept that wind action has been of any real importance in the evolution of features such as inselbergs, pediments, and wider erosional plains' (R.J. Small, 1970).

Deflation basins—Depressions formed in the deserts due to removal of sands through the process of deflation are called deflation basins or blow-outs or desert hollows, the depth of which is determined by goundwater table. The size of these enclosed depressions varies from smaller ones like **buffalo wallows** of the American Great Plains (where thousands of small enclosed depressions mark sandy deserts) to very large depressions such as **pang kiang** hollows of the Mongolian Desert, great Quattara depression of the Western Egyptian Desert and Big Hollow near Laramine in Wyoming state of the USA (5 km wide, 15 km long and 100 m deep). The Quattara depression is estimated to have an excavated volume of 3200 km^3 and a depth of 134 m below sea level.

Mushroom rocks—The rocks having broad upper part and narrow base resembling an umbrella or mushroom are called mushroom rocks or **pedastal rocks** or **pilzfelsen** (named by J. Walther)

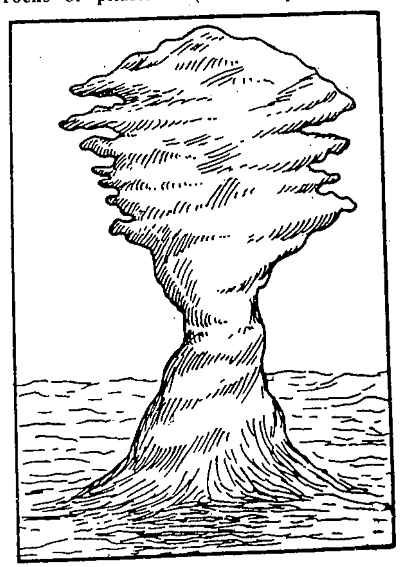


Fig. 20.1 : Example of mushroom rock or gara.

(fig. 21.1). These undercut, mushroom-shaped pedastal rocks are formed due to abrasive works of wind. The base of the individual rock block is abraded vigorously from all sides because of variable directions of wind and active abrasion limited to six feet height from the ground while the upper part is least affected by abrasion. These pedastal rocks are called **gara** in Sahara and **pilzfelsen** in Germany.

Inselbergs are very controvercial landforms. Inselberg, a German word, was used by Passarge in 1904 to indicate sharply rising residual hill above the flat surfaces in South Africa. Such residual hills and mounds of relatively resistant rocks in the arid regions are also called **bornhardts** after the name of famous geomorphologist Bornhardt. Passarge and Davis have taken inselbergs as the representative landforms of the penultimate stage of the arid cycle of erosion. Inselbergs have now been also located in subhumid and humid climates. Thus, the origin of inselbergs only through wind erosion has been refuted. According to L.C. King the inselbergs are formed due to twin processes of scarp retreat and pedimentation over coarse-grained igneous rocks. It may he pointed out that inselbergs are the product of weathering and erosion in different climatic regions.

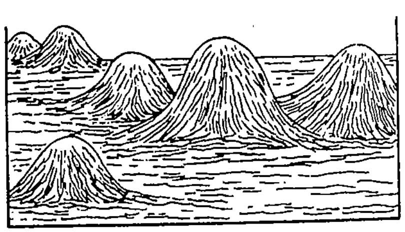


Fig. 21.2 : Inselbergs (bornhardts).

Demoiselles represent rock pillars having relatively resistant rocks at the top and soft rocks below (fig. 21.3). These features are formed due to differential erosion of hard rocks (less erosion) and soft rocks (more erosion). The demoiselles are maintained so long as the resistant caprocks are seated at the top of the pillars.

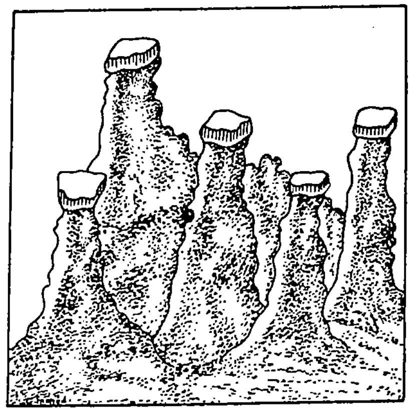


Fig. 21.3 : Demoiselles.

Zeugen—Rock masses of tabular form resembling a capped inkpot standing on softer rock pedestal of shale, mudstone etc. are called zeugen

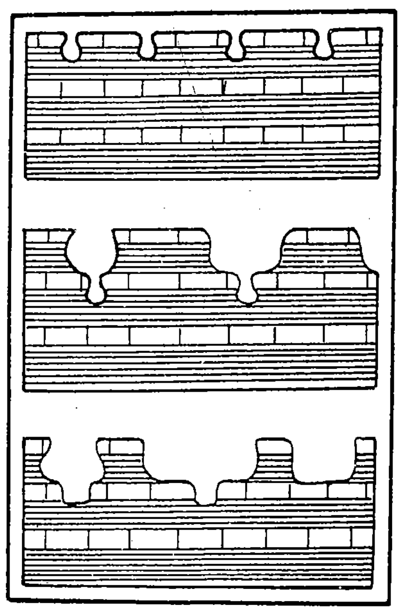


Fig. 21.4 : Stages of the formation of zeugen.

(fig. 21.4). The bases of such features are broader than their tops. These are formed in those desert areas where temperature during night becomes so low that the moisture in the joints and crevices of rocks freezes. The frozen moisture again thaws during day time. The alternate freeze and thaw of moisture cause expansion and contraction of volume respectively. This mechanism causes disintegration of rocks along the joints. The disintegrated fine materials are blown away by the wind. The repetition of this mechanism results in the formation of zeugen.

Yardangs are steep-sided deeply undercut overhanging rock ridges separated from one another by long grooves or corridors or passageways cut in desert floors of relatively softer rocks (fig. 21.5). They range in size from a metre to kilometre. The yardangs are usually 8m high from the corridor floor but they attain the height of 60 m in the Lutt desert of Iran. They are formed where alternate bands of hard and soft rocks are vertical or inclined to the horizontal plane. The intervening beds of softer rocks are abraded and eroded materials are blown away by deflation process. The most characteristic feature of yardangs is their parallelism. They are usually formed in the areas which are characterized by directional steady winds. Yardangs have been called **cockscomb** by A. Holmes.

Fig. 21.5 : Yardangs.

Dreikanter—Faceted rock boulders, cobbles and pebbles abraded by long periods of wind erosion are called **ventifacts.** A ventifact or faceted rock block may have as many as eight abraded facets. The rock pieces (boulders) having three abraded facets are called **dreikanter** while the boulders with two abraded facets are called **zweikanter.**

Stone lattice—The rocks of varying compositions and resistance when abraded by powerful wind charged with erosion tools (rock particles) become of uneven surface as the powerful wind abrades weaker sections of rocks and removes the abraded materials while relatively resistant sections are least affected by abrasion. Such pitted and fluted rock surfaces are called stone lattice.

Wind bridges and windows—Holes are formed due to continuous abrasion of stone lattice by powerful wind. These holes are gradually widened and ultimately they ıeach the opposite side of the rocks. Such holes formed through abrasion across the rocks are called **wind windows.** The holes are further widened and enlarged through the processes of abrasion and deflation in such a way that an arch like features having intact roof are formed. These are called **window bridges.**

21.5 TRANSPORTATIONAL WORKS OF WIND

The transportational work of wind differs from other agents of erosion (viz. rivers, glaciers and sea waves) substantially because the direction of wind is highly variable. Wind transport involves entrainment of loosened grains of sands and dust in the air and their movement to new locations of deposition. Wind transports the materials through the mechanisms of **suspension, saltation** and **traction.** Very fine materials with a diameter of less than 0.2 mm are kept in suspension by upward moving air. Such materials kept in suspension are called dusts and extremely fine particulate matters are called **haze** or **smoke.** The suspended matters are carried by wind for greater distances. The materials larger than 0.2 mm in diameter are transported through the mechanism of bouncing, leaping or jumping. This mechanism of wind transport is called **saltation.** The mechanism of transport of loosened materials on the ground surface is called **surface creep** or **traction** wherein the materials always touch the ground and move forward without saltating. The following are the main characteristics of wind transport. (1) The direction of wind transport is variable because wind very often changes its direction. (2) Wind transport involves larger areas and greater distances (thousands of kilometres). (3) Wind transports the mate-

rials at the ground surface and above the ground (in the air). (4) Only very fine materials are transported to greater distances in one step while coarser materials are transported in stages and steps by rolling, leaping and jumping.

21.6 DEPOSITIONAL WORK OF WIND

Depositional work of wind is geomorphologically important because significant features like sand dunes and loess are formed. Deposition of wind blown sediments occurs due to marked reduction in wind speed and obstructions caused by bushes, forests, marshes and swamps, lakes, big rivers, walls etc. Sands are deposited on both windward and leeward sides of fixed obstructions. The accumulated sand mounds on either side of the obstructions are called **sand shadows.** Accumulations of sands between obstacles are called **sand drifts.**

21.7 DEPOSITIONAL LANDFORMS

Ripple Marks

Ripple marks are small-scale depositional features of sands. These wave-like features are formed mainly by saltation impact. Ripples are divided into (i) transverse ripples and (ii) longitudianl ripples.

Sand Dunes

Heaps or mounds of sands are generally called sand dunes or simply dunes. Though sand dunes are significant depositional features of desert areas but they are also formed in all those areas where sands are available in profusion and wind is capable of transporting and depositing them in suitable areas. Thus, dunes are also formed in coastal areas (called as coastal dunes), along the river banks (riverine dunes), along the lake shores (lacustrine dunes) etc. There is a wide range of variation in the shape, size and structure of different types of dunes. They also vary in height and length. On an average, their height ranges between a few metres and 20 metres but some time they are several hundred metres in height and 5-6 km in length. The windward slope is generally gentle (5^0-15^0) while leeward slope is steep (20^0-30^0).

Formation of sand dunes begins with the accumulation of sands in the form of low sand mounds due to obstruction in the wind speed caused by fixed obstructions (*e.g.* trees, bushes, grasses, rocks, hills etc.). These accumulated low sand mounds become obstacles in themselves and cause gradual accumulation of sands. Thus, sand mounds gradually grow in height and length and ultimately become typical sand dunes. It may be pointed out that most of sand dunes are mobile landforms as they generally move forward in the direction of wind. Formation of sand dunes requires (i) abundance of sands, (ii) high velocity wind, so that huge quantity of sands may be blown and transported to form dunes, (iii) obstacles of trees, bushes, forests, rock outcrops, walls, rock boulders etc. so that sand may be trapped and forced to settle down and (iv) suitable places for the accumulation of sands. Dunes are generally formed in groups. Such dune areas are called **dune complex, dune colony** or **dune chain.**

Dunes formed due to the obstacles of shrubs are called **nebkhas** while the dunes developed in the lee of desert depressions are called **lunettes.** It may be emphasized that most of dunes do not require an obstacle for their formation. Regular dunes are developed on most regular desert surfaces where winds have a single dominant direction. The axes of dunes are oriented at right angles to the wind direction.

Migration of dunes—Most of dunes are not stable at the place of their formation rather they are mobile. Migration of dunes involves movement of whole sand mound downwind (fig. 21.6) wherein sand grains are saltated (moved) up the low-angle windward slope to the crest by the wind then they fall over into the wind shadow on the leeward slope of the dune. Thus, the leeward slope or slip face of the dune becomes steep. The repetition of this mechanism results in constant movement of sand grains forward which causes gradual migration or shifting of sand dunes resulting into desert spread. The rate of dune migration varies from place to place. On an average, dunes migrate at the rate of a few metres per year but at places they migrate at the rate of 30-40 m per annum. Dune migration is very harmful as vast

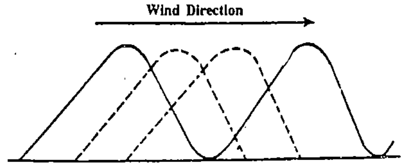


Fig. 21.6 : Migration of sand dunes.

areas of agricultural fields, human settlements (villages and towns), forests etc. are buried under immense cover of sands. It is reported that Thar Desert is spreading towards Uttar Pradesh due to gradual migration of sand dunes.

Dune types—Dunes are classified on various bases viz. morphology, structure, orientation, location, ground pattern, internal structure, number of slip faces etc.

(1) R.A. Bagnold (1953) recognized two basic types of dunes on the basis of forms viz. (i) crescentic dunes or barchans and (ii) longitudianl dunes or seifs.

(2) J.T. Hack (1941) classified sand dunes of the western Navajo County (USA) into 3 types *e.g.* (i) transverse dunes, (ii) parabolic dunes and (iii) longitudinal dunes.

(3) Melton (1940) identified 3 types of dunes—(i) simple dunes formed by unidirectional wind, (ii) dunes formed by wind in conflict with vegetation and (iii) complex dunes formed by variable wind.

(4) E.D. Mckee (1979) after his global study of sand dunes classified them on the basis of their morphology, ground pattern and their internal structure involving the number of slipfaces into (i) dome dune, (ii)barchan, (iii) barchanoid, (iv) transverse dune, (v) parabolic dune, (vi) linear or longitudinal dune (seif), (vii) reversing dune (2 slipfaces), and (viii) star dune (having central peak with 3 or more arms).

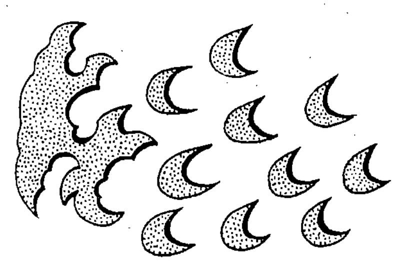


Fig. 21.7 : Seif dunes.

(5) Another general classification involves the following main types of dune forms at global level-(i) obstacle or topographic dunes : (a) small dune or **nebka** formed in the lee of a shrub, (b) crescentic lunette formed in the lee of a small desert depression (playa), (c) wind-shadow dunes formed in the lee of a hill, (d) dune formed to the windward side of a hill, (e) dune formed in the proximity of plateau, (ii) linear or longitudinal dunes or seifs, (iii) star dunes, (iv) dome dunes, (v) reversing dunes, (vi) parabolic dunes, (vii) barchan dunes, (viii) barchanoid ridge dunes, and (ix) transverse dunes.

(6) Classification based on location- (i) coastal sand dunes, (ii) inland or desert sand dunes, (iii) riverine sand dunes.

(7) Classification based on shape- (i) longitudinal sand dunes or seifs, (ii) transverse sand dunes or barchans, and (iii) parabolic sand dunes.

Longitudinal sand dunes—Sand dunes formed parallel to the wind direction are called longitudinal dunes. They are huge aeolian landforms extending hundreds of kilometres in length with average width of a kilometre or more and average height of several hundred metres. Windward slope of these dunes is gentle while leeward slope is steep. These dunes are formed in the inner parts of the great deserts where high velocity winds are constant in direction (unidirectional) or they change their direction seasonally. Thus, longitudinal dunes are generally formed in the heart of trade-wind deserts. Great systems of longitudianl sand dunes are found in Australian, Lybian, Saharan, South African and Thar desert (India). Active longitudinal dunes are developed in the areas devoid of vegetation and persistent winds. Longitudinal dunes are almost parallel to each other and they are separated by sand-free bare surfaces known as **reg** or **hammada.** Such **sand-free corridors** between parallel dunes are called **gassi** in Sahara (fig. 21.8). Such corridors in the deserts are used as paths known as **caravans.** Such dunes are also called **linear dunes, sand ridges, seif, alab dunes** etc. The height of such dunes in Thar desert of India varies between 5 and 45m while the length and width are upto 300m and 350 m respectively.

Transverse sand dunes—Dunes formed transverse to the direction of prevailing winds are called transverse dunes. These are formed by ineffective winds along the coasts and margins of deserts. They are not very common depositional features in extensive deserts. They appear as wave-like features. The

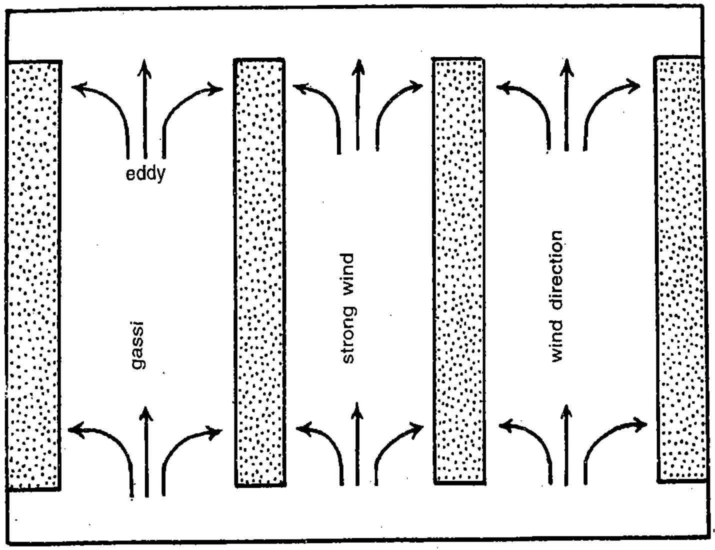


Fig. 21.8 : Sand-free corridors or gassi.

height of transverse dunes in Thar desert of India is 3 to 25m while the length and width are upto 750m and 150m respectively.

Barchan dunes—Sand dunes of crescentic shape having two horns (fig. 21.9) are called barchans. In fact, barachans are special types of transverse dunes. The windward side having gentle slope is convex in plan while the leeward side is concave in plan with steep slope. The horns always project downwind. Transverse dunes are transformed into barchans (Turkish word barkan meaning thereby sandhill) when sand supply becomes more limited downwind. They are formed in groups when there is ample supply of sands. Isolated barchans are formed when the supply of sands is inadequate. The crest of a barchan is divided into two horns downwind due to dominant prevailing winds, wind eddies and limited supply of sands.

It may be pointed out that mechanism of the formation of two horns of barchans is not properly understood. Wind eddies transform the leeward slope into concave element and remove the sands from the middle portion and deposit them along the sides to form horns. These horns are sharpened and extended downwind by the prevailing wind and thus crescentic shape of barchans is developed.

Isolated barchans migrate freely across the desert plains. In fact, barchans 'are large enough to maintain themselves as they migrate and represent a remarkable balance between accumulation, transportation, and erosion' (A. Bloom). Seven Hedin has observed three cases of migration of active barchans. (1) Barchans advance regularly with constant rate when the sand supply is constant. (2) They advance with decelerating rate when the sand supply goes on increasing but the height continues to increase. (3) They advance with accelerated rate when the sand supply continues to decrease. Regular advancement or migration of barchans results in gradual spreading of deserts. Desert spread engulfs vast areas of bordering inhabited regions and oases within deserts. It becomes difficult to cross deserts when barchans are found in groups and colonies. Sand-free corridors or **gassi** between two ranges of barchans are used as **caravan routes.** The height, average length and width in Thar desert are 2-15m, 350m and 250m respectively.

Nearly all types of sand dunes are found in India. Large longitudinal sand dunes are found abundantly in the western part of Great Indian Desert

(Thar Desert). These sand dunes attain the height of about 5-45m. Coastal sand dunes are found along Malabar coast, Orissa coast, Kutch, Tinnevalli coast etc. where mainly longitudinal dunes have developed. Transverse dunes are found along the riverine banks of Ganga, Kosi, Krishna, Godavari rivers etc.

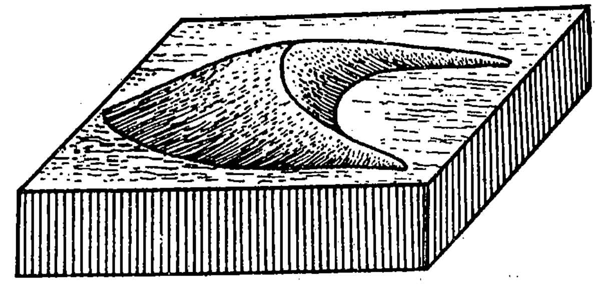


Fig. 21.9 : Barchan.

Parabolic dunes generally develop in the partially stabilized sandy terrains. They are usually U-shaped having convex nose which migrates downwind. These dunes are much longer and narrower than barchans but are always associated with a blowout.

Other forms of dunes—The dunes having multiple slipfaces, high central peak, radially extending three or more arms are called **star dunes.** These dunes are formed by variable winds. Unlike other dunes, star dunes grow vertically and thus do not migrate laterllay. The dunes having intermediate characteristics between star dunes and transverse dunes are called **reversing dunes** which are formed when winds blowing from opposite directions are balanced in strength and duration. These dunes have two slipfaces opposite to each other. The dunes formed of coarser sands left behind due to migration of longitudinal dunes are called **whalebacks** or **whaleback dunes.** Very large whaleback dunes are called **draas.** They are usually longitudinal in plan having great heights reaching 400m or more. They are characteristic features of the Saharan and Namibian deserts but they are uncommon in the Australian deserts. They grenerally appear to be compound or complex dunes.

Loess

Loess is the example of most significant wind-blown deposits. Loess (German term loss meaning thereby fine loam, loose or unconsolidated material) represents thick deposits of unstratified, non-indurated, buff-coloured, wellsorted, fine grained sediments consisting of quartz silt (0.05mm-0.02mm or less in diameter) with small clay fraction and higher content of carbonate minerals (about 40 per cent). There is total absence of laminae in the loessic deposits. Loess deposits generally occur at very distant places from the source areas of their sediment supply. Sediments required for the accumulation of loess are derived from desert areas, flood plains of river valleys, coastal areas and glacial outwash. The initial reliefs are eliminated due to deposition of loess but some times higher peaks and hills project well above the loessic surface. In fact, the depositional surface becomes featureless. Loess is readily eroded in humid climates and thus dense network of rills and gullies are formed.

Loess is divided into (1) **desert loess** and (2) **glacial loess** on the basis of sources of supply of sediments for its formation. According to M. Pecsi (1968) about 10 per cent of the land area of the globe is covered by loess deposits of varying thicknesses (1m to 100m). According to R.V. Ruhe (1974) about one third area of the USA is covered by aeolian deposits. The most extensive deposits of loess are found in North China where loess is spread over an area of 7,74,000 km^2 (3,00,000 square miles) having a thickness from 90m to 300m. Chinese loess is yellow in colour, very soft and impermeable. The loess terrain (spread in the Yellow basin) has been heavily ravinated and gullied resulting into the de-

velopment of **badland topography**. Rivers form natural levees along their banks due to deposition of sediments derived through the erosion of loess. This phenomenon causes siltation and rise of river beds. Some times the river beds become higher than the surrounding ground surface. There occurs severe flash flood whenever the levees are breached. This is the reason that the Hwang Ho (now Yellow river) was considered **'Sorrow of China'.** The Yellow river transports the largest amount of silt load (1640 million tonnes per year) of all the major rivers of the world. Chinese loess is the example of desert loess as the deposits have occurred due to deposition of dusts blown from the deserts of central Asia.

The loess areas of Europe include Borde area of Germany, low plateau area of central Belgium and eastern France. Loess is known as 'limon' in France and Belgium. European loess is the example of glacial loess. North American loessic areas are spread over semi-arid region and the basins of the Mississippi and Missouri. Here loessic deposit is called **'adobe'.** Loess is extensively found in Illinois, Iowa Nebraska etc. American loess is partly glacial and partly desert loess. A very fine example of thick loess (18 to 25m) deposits is found along the right bank of the present valley and both the banks of the palaeochannel of the Narmada river at Bheraghat (near Jabalpur in M.P.)

21.8 FLUVIAL DESERT LANDFORMS

Badland, pediments, bajadas and playas are special types of landforms of arid and semi-arid regions caused by mechanical disintegration of rocks and water action.

Badland Topography

The regions of weak sedimentary formations are extensively eroded by numerous rills and channels which are occasionally developed due to occasional rainstorms. The linear fluvial erosion results in the formation of ravines and gullies which are divided by numerous undulating narrow ridges. Thus, the ground surface becomes so uneven and corrugated due to numerous gullies and ravines that it becomes entirely difficult to walk on it. Such type of landscape is called badland topography.

Bolsons and Playas

The intermontane basins in arid or semiarid areas are generally called bolsons. Such basins are characterized by 3 unique landforms which from the mountain front downward are **pediments, bajadas** and **playas** (fig. 21.10). Numerous ephemeral streams after originating from the surrounding mountain fronts drain into the bolsons. Some water collects in the centre of the bolsons and form temporary lakes. Such temporary lakes are called **playas.** For example, Lake Lap Nor is a playa in the centre of the

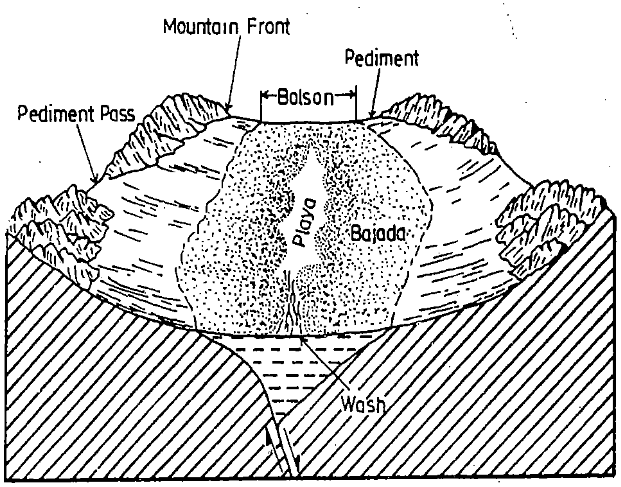


Fig. 21.10 : Mouuntainous desert landforms-mountain front, pediments, bajada, bolson and playa.

Tarim Basin. The playas range in areal extent from a few square metres to tens of square kilometres. These are called **'khabari'** and **'mamlaha'** in Arabian deserts while they are known as **'shatts'** in Sahara. Playa lakes may last for days, weeks or even longer before they are completely dried up by evaporation. Evaporation of playa lake water results in the formation of encrustation of alkaline materials (sodium bicarbonate or sodium carbonate), salt deposits such as borax. Such salt-covered playa beds are called **salinas.**

Bajada

Gently sloping depositional plain between pediments and playa is called bajada. Bajada is formed due to coalescence of several alluvial fans. Thus, bajada is a wholly depositional feature. The slope in its upper part ranges between 8^0 and 10^0 but it becomes 1^0 to zero in its lowermost portion touching the playa (fig. 21.10).

Pediments

Pediments situated between mountain front and bajada in intermontane basin are broad, extensive, and gently sloping areas of rockcut surfaces which spread as aprons around the bases of mountains. The term (pediment) was first used by G.K. Gilbert (1882) for the surfaces of the alluvial fans that encircle mountains in deserts. According to Kirk Bryan (1922) 'pediments are slopes of transportation cut on bedrock, usually covered with a veneer of alluvium in transit from high to lower levels. In form and function, a pediment is similar to an alluvial fan, the difference being that a pediment is an erosional landform and a fan is constructional' (A. Bloom). It may be pointed out that pediments are now not considered to be confined only to the arid and semiarid regions rather they are found widely in tropical and temperate climate. A true pediment represents rockcut surfaces of mountain side. This feature is, in fact, a slope of derivation or transportation as thin veneer of debris also moves through this surface down the slope. These bare rock surfaces extend for several kilometres in length. The general gradient ranges between 1^0 - 7^0. Several theories have been postulated to account for the development of desert pediments.

(1) Lawson's recession theory—According to A.C. Lawson (1915) pediments are developed because of gradual recession of mountain front caused by weathering and erosion. Due to backwasting of mountain front through mechanical disintegration of rocks and consequent aeolian and fluvial erosion mountain front is subjected to gradual recession. This process results in the formation of more and more smooth rock-cut plains. As the mountain front recedes debris is deposited in the lower segment of the pediment and thus the alluvial deposits in the form of alluvial fans extend upslope on the pediments. Thus, the thickness of the veneer of deposits also increases. Pediments are exhumed due to removal of deposits under the impact of diastrophic movements. The thin cover resting on the pediment may also be removed through climate changes or from long continued aeolian deflation (fig. 21.11).

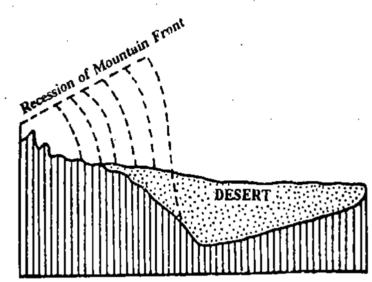


Fig. 21.11 : Formation of pediments due to recession of mountain front.

(2) Sheet-flood theory of McGee—According to W.J. McGee (1897) pediments are formed due to erosion of weathered bedrocks by sheetfloods originating from occasional torrential rainfall in deserts. The eroded materials are transported downslope and are deposited as **bajadas.** The advocates of this concept do not attach any importance to lateral erosion in the development of pediments because, according to them, concave surface of pediments cannot be formed by lateral erosion. The critics maintain that sheetfloods may have ancillary influence on pediments once they are formed but they cannot initiate the formation of pediments.

(3) Lateral erosion theory—G.K. Gilbert attributed the formation of pediments to lateral corrasion by streams. Later on S. Paige (1912), Eliot

Blackwelder (1931), D.W. Johnson (1932), Berkey, Morris etc. also advocated for lateral erosion by streams as powerful mechanism of pediment formation. According to D.W. Johnson there are 3 zones along the mountains encircling an itermontane basin viz. (i) inner zone, (ii) outer zone and (iii) intermediate zone (fig. 21.12). **Inner zone** represents the mountain front where downcutting (vertical erosion) by streams is most active. This zone is, thus, **zone of degradation. Outer zone** represents the lower segment which extends upto the margin of the intermontane basin (playa). In fact, this zone is characterized by deposition to form bajada. This zone, thus, is the **zone of aggradation. Intermediate zone** represents the zone between degradational zone (inner zone) and aggradational zone (outer zone) where lateral erosion is most active. This zone is also called as **zone of pedimentation.** The formation of pediment is initiated by active downcutting of inner zone resulting into rapid rate of erosion of mountain front. The eroded materials are removed and deposited by ephemeral streams resulting from occasional strong rainstroms in the basins. Thus, several alluvial fans are formed on the lower segments of hillslopes. These alluvial fans gradually coalesce to form bajadas. Gradually, the streams are graded and braided in the intermediate zone. Rock fans are formed in the intermediate zone due to lateral erosion by the steams. These rock fans gradually extend to become pediments.

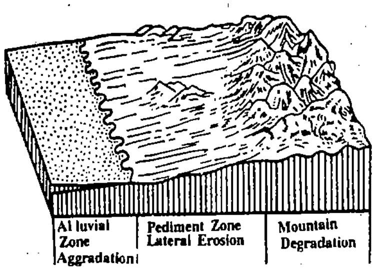


Fig. 21.12 : Formation of pediment according to D. W. Johanson.

(4) Composite theory—It may be mentioned that the above mentioned theories of pediment formation are based on the mechanism of monogeomorphic process. On the other hand, some geomorphologists have opined that pediments are formed by more than one geomorphic process. For example, Kirk Bryan, W.M. Davis, R.P. Sharp, James Gilluly, J.L. Rich, W.H. Bradley, L.C. King, T.J.D. Fair etc. have pleaded for composite origin of pediments.

(i) Kirk Bryan (1923) has postulated that pediments are developed in three ways viz. (a) due to lateral erosion by streams coming out from the mountain front, (b) due to erosion of foothill zones by rills, and (c) due to disintegration of mountain fronts under the impact of mechanical weathering.

(ii) According to W.M. Davis (1938) first the mountain front is disintegrated due to mechanical weathering and then the weathered materials are transported downslope by sheetfloods. These twin processes cause gradual recession of mountain front and consequent development of rockcut pediment surface. It is evident that Davis' concept involves the views of A.C. Lawson (recession of mountain front) and McGee (sheetflood erosion) for the development of pediments.

(iii) According to R.P. Sharp (1940) lateral erosion, weathering and rill wash play their relative roles in the development of pediments. According to him the pediments of Nevada (USA) owes their existence 40 per cent to rainwash.

21.9 ARID CYCLE OF EROSION

The concept of arid cycle of erosion was postulated first by W.M. Davis in 1905. It may be pointed out that this concept is applicable only in the cases of mountainous deserts and not in the case of open low-level deserts. Further, besides wind, water also plays very important role in arid cycle of erosion.

Initial Stage

The initial stage of arid cycle of erosion of mountain-grit deserts is characterized by extremely dry climate (mean annual rainfall less than 25 cm), upliftment of deserts by folding or faulting, development of intermontane basins, initiation of inland and centripetal drainage etc. Initially, the intermontane basins (of tectonic origin) have their independent drainage system and there is no drainage communication among the basins. The centres of isolated intermontane basins become base level of erosion. Evaporation is very active. Playa is formed due to accumulation of some water in the centre of the basins.

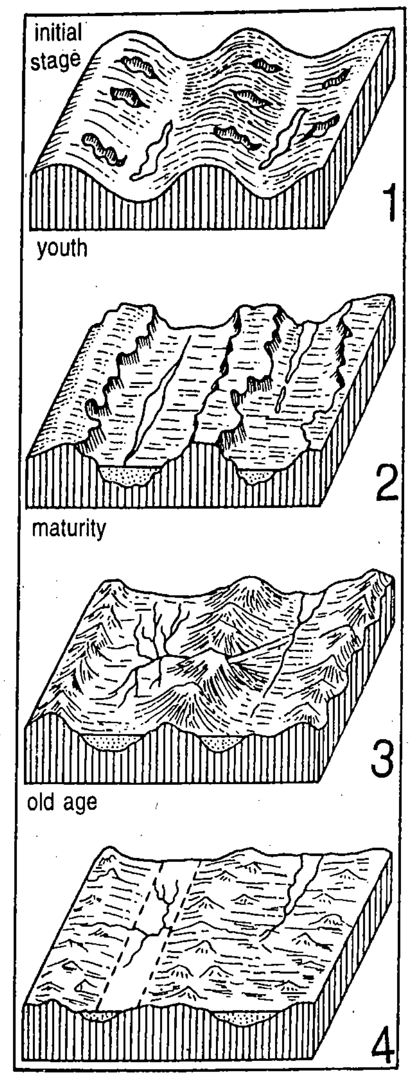


Fig.21.13 : Stages of cycle of erosion in arid regions: (1) initial stage, (2) youth, (3) maturity, and (4) old stage.

Nearly all of the streams are consequent and drain into the enclosed basins. The cycle of erosion begins with the degradation of mountains and filling (through sedimentation) of the basins.

Youth

Erosion and deposition both go hand in hand and thus the initial reliefs are gradually reduced because of erosion of the mountains and filling of the basins (fig. 21.13(2). The water divides are gradually narrowed and lowered because of backwasting and downwasting respectively. The lower segments of hillslopes are more vigorously dissected by rill and gully erosion caused by occasional rainstorms. It is evident that there are two zones of geomorphic significance viz. (i) zone of degradation on higher lands and (ii) zone of aggradation (of the basins). Alluvial fans are formed at outer margins of the enclosed basins. Bajadas are formed due to coalescence of several alluvial fans. Deflation by wind becomes active whenever loose sands are available. Deflation causes smaller depressions known as blowouts. Playa lake is formed in the centre of the basin. Some sand dunes are formed here and there along the margins of playa. Relief is remarkably reduced by the end of youthful stage.

Maturity

Relief decreases rapidly because of progressive erosion of mountain divides and filling of enclosed basins. The progressive recession of water divides increases the size of enclosed basins. The level of these basins also rises because of gradual sedimentation. Bajadas are further enriched, widened, and extended upslope. Extensive rock-cut pediments are formed between the receding mountain fronts and bajada zone. Mountain divides are breached due to their progressive recession. This process leads to the integration of basins and drainage system. The higher basins become tributary to the lower basins as the water of the former is drained into the latter by the streams which have breached the divides between them (fig. 21.13(3). Deflation of sands by winds becomes more active. This process causes the formation of bare surfaces-desert pavements.

Old Stage

All the highlands are reduced to almost plain surface of very low height. Numerous residual hills project above the general flat desert surface. These low hills known as inselbergs or bornhardts look like islands in the vast deserts. Deflation of sands by wind is most active. Several pediments are coalesced and form extensive pediplains.

22

GLACIERS AND GLACIATED TOPOGRAPHY

22.1 ICE AND RELATED PHENOMENA

The moving ice mass downslope under the impact of gravity is called glacier. About 10 per cent of earth's surface is now covered by glaciers. About 2-3 million years BP glaciers extended over almost one-third of the earth's lithospheric surface. Glaciers are formed due to accumulation of ice above **snow line** under extreme cold climate. Snow line is generally defined as a zone between permanent and seasonal snow. In fact, snow line denotes that height above which there is permanent snow cover and thus it corresponds to the level where average temperature is always below freezing point during the warmest month of the year. The snow line is at the lowest height (0m or sea level) in the polar region and increases equatorward where it tends to occur between 5000 to 6000m. The snow line is found at the highest elevation in the drier part of the Tibetan plateau and Andes (6500m). The estimated number of all types of glaciers all over the world ranges between 70,000 and 200,000. The areas of accumulation of huge volume of ice are called **snow fields** which generate glaciers of different dimensions. The glaciers grow by gradual transformation of snow into **granular snow,** then into **firn** or **neve** and finally into **solid glacial ice.** Snow is a fluffy mass of loosely packed snowflakes of very low density having an open feather-like appearance. Semi-compacted snow due to the weight of overlying snow is transformed into granular snow of denser form. Such granular snow is called firn or neve. Further compaction of granular snow produces pure solid glacial ice.

22.2 TYPES OF GLACIERS

Glaciers are generally divided into 2 broad categories viz. (i) mountain or valley glaciers and (ii) continental glaciers. H.W. Ahlmann (1953) classified world glaciers on the basis of their thermal and morphological characteristics. He divided glaciers into 3 broad categories (continental glaciers, valley glaciers and piedmont glaciers) and into 11 subtypes as follows—

1. Glaciers without geomorphological constraints or glaciers of extensive ice sheets characterized by glacial movements in all directions

These glaciers have been further divided into 3 subtypes—

(i) Continental glaciers

(ii) Ice caps

(iii) Highland glaciers

2. Glaciers with geomorphological constraints or confined to more or less marked courses

(iv) Valey glaciers of Alpine type

(v) Cirque glaciers

(vi) Glacier tongues

(vii) Wall-sided glaciers

(viii) Transection glaciers

3. Cake-like ice sheets

(ix) Piedmont glaciers

(x) Foot glaciers

(xi) Shelf ice

Ice sheets or ice caps—The biggest glaicers on the earth's land surface are called ice sheets which are broad domes with flattened cross-section covering thousands of square kilometres. These are hundreds of kilometres in width. They submerge underlying topography. Ice radiates outward from the centre of the ice mass. These radiating ice masses are called ice sheets. The difference between ice sheets and ice caps is that of areal extent *e.g.* dome-shaped ice masses spreading over more than 50,000 km^2 are called ice sheets while small ice sheet with an area less than 50,000 km^2 is called ice cap. The central part of an ice cap or ice sheet is called ice dome. The most extensive ice sheets are Antractic and Greenland ice sheets.

Continental glaciers are in fact extensive ice sheets. These are called continental because they cover most part of the continent. Extensive ice sheets radiate outward from the centre and move downslope. During Pleistocene Ice Age extensive ice sheets moved from two centres (viz. Labrador and Keewatin) and covered about one half of North American continent. At present the biggest continental glaciers are Antarctic and Greenland ice sheets. The Antarctic continental glacier having an average thickness of 4000m covers an area of 8 million square kilometres. The ice sheets rise about 4500m above mean sea level. The Greeland continental glacier with the thickness of 3000 m at its central dome is spread over an area of 1,30,000 km^2 which is about three-fourth of the island. Smaller ice caps occur in Arctic Canada, Iceland, Norway etc.

Mountain or valley glaciers—The body of ice moving downslope under the impact of gravity through the valley bordered by rock valley walls in the mountains is called mountain glacier or valley glacier or Alpine glacier. The length of these glaciers ranges from a few kilometres to 2000 km. They are located generally above snow line as they are ablated while descending down the snowline. The important glaciers of the Himalayan regions are (figures in brackets denote the lenght of valley glaciers) : Rupal glacier (16km), Punmah glacier (27km), Rimo glacier (40km), Himarche glacier, Barche glacier, Minapin glacier (all located in the Kashmir Himalaya); Hispar glacier (60km), Baifo glacier (62km), Baltoro glacier (58km), Siachen glacier (72km), Batura glacier (58km), Sasaini glacier (158km), Mohil Yaz glacier (29km), Yaz Ghil glacier (29km), Khurdopin glacier (41.6km) (all in Karakoram range); Milan glacier (19km), Kedarnath glacier (14km), Gangotri glacier (25km), Kosa glacier (11km) (all in Kumaun Himalaya); Zemu glacier (25km) and Kanchenjunga glacier (16km) (all in Sikkim).

Piedmont glaciers—The glaciers formed due to coalescence of several mountain or valley glaciers at the foothill zone are called piedmont glaciers. Such glaciers are found only in colder areas and not in the tropical or temperate regions because they melt when they reach the foothill zone. Melaspina glacier of Alska (USA) is typcial example of piedmont glaciers.

Ice shelf is a floating thick ice sheet or ice cap attached to the coast. Since there is no friction of ice with the bed and hence ice can spread freely. Such glaciers are abundantly found along the Antarctic coasts *e.g.* Ross Ice Shelf, Ronne-Filchner Ice Shelf etc.

Ice field is comparatively flat and extensive mass of ice sheets.

Cirque glaciers—The ice occupying an arm-chair-shaped cirque in the mountains is called cirque glacier.

Niche glacier represents a small upland ice mass which rests upon a sloping rock face.

22.2 MOVEMENT OF GLACIERS

Glacier moves under the impact of the force of gravity which is the result of the thickness of ice mass and the gradient of the bed. In technical terms glacier advances because 'it deforms to stress set up in the ice mass by the force of gravity'. The stress is set up because of the weight of overlying ice. Hydrostatic pressure and shear stresses are the two main components of internal stress. The hydrostatic pressure representing the weight of overlying ice is the same in all directions of the ice mass. Thus, it is the shear stress which, being the outcome of the weight of the superincumbent ice and surface slope of the

glacier, causes the particles of ice to slip past one another.

There are three types of movment of glaciers e.g. (i) by sliding over bedrock, (ii) by internal deformation (known as creep) of the ice and (iii) by alternate compression and extension of the ice mass. The rate of movement of glacier depends on the thickness of glacial ice and its slope *e.g.* the greater the thickness of glacial ice, and steeper its slope, the faster the movement of the glacier and vice versa. The rate of movement of glacial ice decreases from the centre line towards the sides or edges of the glaciers becasue the friction of the ice against rockwalls retards the flow from the surface towards the bottom or the bed. The average velocity of most of the glaciers ranges between 3m and 300m per year. The internal deformation of the ice makes the glaciers sluggish in their movement. For example, Meserve Glacier in Victoria Land of Antarctica moves at the rate of 3-4m per year. On the other hand, more active basal sliding of the ice causes higher velocity of the galciers. For example, Franz Josef Glacier of New Zealand moves at the rate of 300m per year. Jakobshavn Isbrae Glacier of Greeland moves at much faster velocity (viz. 7-12 km per year). Sudden increase in the velocity of the glaciers causing velocities of 4-7km per year is called **periodic glacial surge.** The occasional glacial surge is characterized by the movement of ice at the rate of 5m per hour. The forward movement of glacier is called **advancement of glaciers** while withdrawal of glacier is known as **retreat of glacier.** The destruction of glacial front due to melting of ice consequent upon increase of temperature is called **ablation of glacier.**

22.3 EROSIONAL WORK OF GLACIERS

Normally, a glacier is supposed to erode the rocks, transport the eroded materials and deposit the eroded materials at suitable places like other agents of erosion and depostion but there are two contrasting view points as regards glacial erosion. One group of glaciologists, very often called as protectionists, believes that glacier instead of eroding the rocks protects them as it covers the bedrocks. This **protection concept** is based on the belief that glacial ice is softer than the rocks and hence it cannot erode them. The second group of glaciologists does not accept the glaciers as impotent agents of erosion rather take them as active potent agents of erosion and deposition. On an avergae, glaciers modify the pre-existing landscapes through their erosional and depositional works. The term **glacierization** means the coverage of an area by moving glacial ice while **glaciation** refers to the action of moving ice on land. It may be pointed out that glaciation may include both the processes of occupation of land by ice masses and erosional and depositional works of advancing glaciers.

The erosional work of the glaciers is accomplished through the mechanisms of **abrasion, plucking and polishing.** Pure ice mass is geomorphologically inactive but when coarse debris is carried by the glacier at its base it becomes active agent of erosion. Thus, the glacier erodes its bed and side walls with the help of tools of erosion (coarse debris) through the mechanism of abrasion. Large particles of well jointed rocks are detached by the moving glacial ice. This mechanism is called plucking.

22.4 EROSIONAL AND RESIDUAL LANDFORMS

The landforms carved out of glacial erosion iclude bumps (whaleback, rock drumlin) and depressions, U-shaped valleys, hanging valleys, cirques, aretes, horns, nunataks, crag and tail, glacial stairway, Roches moutonnees, trough lakes, tarn, fiords etc.

U-shaped valleys—The cross-section of glacial valleys or glacial troughs of mountain glaciers is U-shaped which is characterized by steep valley walls with concave slope and broad and flat valley floor (figs. 22.1 and 2). Some times, U-shaped valleys are associated with tributary valleys called as **hanging valleys**. According to one group of glaciologists glaciers do not form their own valleys but flow through pre-existing fluvially originated valleys. They modify pre-existing river valleys through the mechanism of abrasion and plucking and thus they transform them into U-shaped valleys. On the other hand, the advocates of extreme glacial erosion believe that glaciers dig out their own valleys through which they flow. It may be pointed out that if we look at the depth and width of glacial valleys it becomes clear that such enormous valleys cannot be dug out by glaciers alone. It may be concluded that glacial valleys are modified forms of pre-existing valleys.

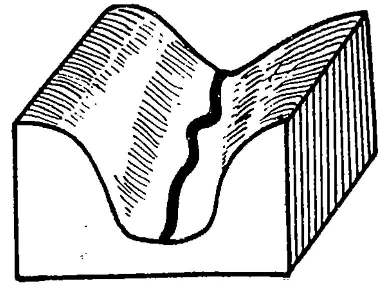


Fig. 22.1 : U-shaped valley.

Hanging valleys—The valleys of tributary glaciers which join the main glacial valleys of much greater depth are called hanging valleys (fig. 22.2) After deglaciation the meltwater of hanging valleys makes waterfalls while joining the main valley. There are two contrasting opinions about the origin and development of hanging valleys. (1) According to **glacial erosion school** hanging valleys are carved out entirely by glacial erosion. The hanging valleys, according to this concept, are the result of difference between the levels of main and tributary glacial valleys because of differential over-deepening between the main and tributary valleys. The main glacier being longer, wider and more extensive than its tributaries erodes its valley more than the tributary glaciers and hence the valley of the main glacier becomes much deeper and hence the tributary valleys hang over the main valley. (2) According to **glacial protection school** the main valleys are water eroded and their tributaries originating from higher mountains carry ice with them. The main valleys are more and more deepened because of water action. On the other hand, the tributaries are unable to deepen their valleys like the main valleys because they are full of ice. Thus, the level of the tributary glacial valleys becomes higher than the main valleys. Consequently, the tributary valleys appear hanging over the main valleys. This school presents the following evidences in its support, (i) Not all the tributary glacial valleys uniformly hang over the main valleys. (ii) Not all the glacial valleys are associated with hanging valleys. (iii) Not all the tributary glacial valleys are hanging valleys. (iv) Hanging valleys are found only in those areas where tributary glaciers originate from higher height than the main glacier.

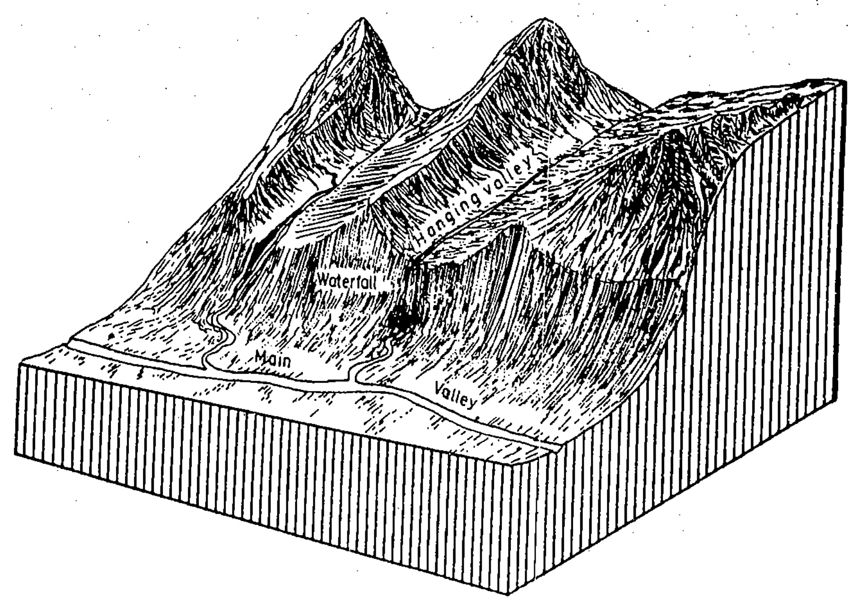


Fig. 22.2 : Hanging valley.

Cirques—The armchair-shaped or amphitheatric cirque or corrie is a horseshoe-shaped, steepwalled depression representing a glaciated valley head. Cirques are variously named in different countries e.g. **cwm** in Wales, **corrie** in Scotland, **kar** in Germany, **botn** in Norway etc. There are four main types of cirques viz. (i) simple cirques, (ii) compound cirques, (iii) hanging cirques and (iv) nivation cirques. There are 3 main components of an open cirque (fig. 22.3). (1) Head wall is almost vertical from the cirque basin and may attain the height of 600 m to 900 m with wall-like steep slope. There is no accumulation of debris at its base. It may be noted that the absence of any debris (talus) denotes the fact that there is no role of weathering in the development of cirques and thus glacial erosion is responsible for their formation. (2) The second component of cirques is their basins which represent the floors of cirques. After deglaciation the cirque basin may form lakes if water collects in it. (3) The third component is threshold which is the outer margin of cirque.

Theories of cirque formation—The following conditions favour the formation and development of cirques. (i) The water-eroded valleys should be widely spaced before the initiation of glaciation. (ii) There should be widespread intense snowfall so that snow field can be formed and glaciers may be initiated. (iii) The lithology should be homogeneous in composition. If cirques are most significant and interesting landforms of glacial erosion their origin is also complex and is still uncertain. Various geomorphologists have postulated their contrasting hypotheses to account for the origin of cirques e.g. (i) Glacial Protection Theory of Garwood, (ii) Bergschrund Nivation Theory of W.D. Johnson, (iii) Cyclic Theory of Hobbs, (iv) Meltwater and Rainwater Theory of Lewis and (v) Rotational Slip Theory.

(1) According to **glacial protection theory** of Garwood depressions are formed by frost action and water-erosion and soil creep during interglacial period before the formation of cirques (corries). These depressions are later modified by glaciers to form corries. In fact, glacial ice offers protection to corries.

(2) According to **bergschrund theory** of D.W. Johnson **basal sapping** is the most active process of corrie excavation. A crevasse or a bergschrund is caused in the glacial ice due to its movement (fig. 22.3). Alternate freeze and thaw at the interesecting point of the cirque wall and bergschrund causes mechanical disintegration of rocks and thus deepens the depression. This mechanism is called basal sapping. Gradual increase in the bergschrund and consequent acceleration of basal sapping results in the formation of well developed corrie. This theory is criticised on two main counts viz. (i) most of the bergschrunds are very small and they do not reach the rock wall or head wall and (ii) most of the glaciers contain very few bergschrunds.

(3) The **glacial erosion theory** or very often known as **cyclic theory of cirque formation** of W.H. Hobbs (1910) advocates that cirques are formed according to the various stages of the cycle of mountain glaciation. First, a small hollow is formed. Later, this hollow increases in size due to glacial erosion according to the **bergschrund theory** of W.D. Johnson. Gradually, the wall of the hollow recedes and ultimately semicircular armchair shaped depression or cirque is formed. If cirques are formed on both the sides of a mountain, they recede back and form sharp mountain peak. The intersection of receding cirques forms **cols**. Ultimately, the whole upland is dissected by the recession of corries and is transformed into fretted upland.

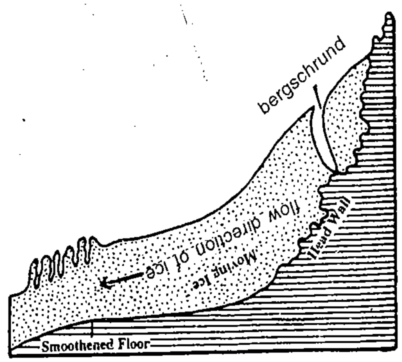


Fig. 22.3 : Cirque and its components.

Tarn—A rock basin is formed at the floor of the cirque basin due to erosion consequent upon greater thickness of ice mass and its enormous pressure. After deglaciation this rock basin is filled up with water and thus forms a small glacial lake which is called as a cirque lake or simply a tarn.

Col, aretes and horns—A high plateau or a mountain range after being eroded rather incompletely by glaciers mainly through the process of cirque recession remains 'as remnants between the steep, concave glaciated forms'. Such imperfectly glaciated upland surface is called **scalloped upland** or **biscuits board topography**. The scalloped upland is transformed into **fretted upland** by complete dissection of the terrain through cirque recession.

The mountain divide is sharpened due to recession of cirques on its both sides. Such sharpened peaks resembling saw-teeths are called **aretes.** An arete is, in fact, 'a saw-toothed divide consisting of a series of cols and intervening ridge segments.' The gap formed due to cutting of headwalls because of intersection of two steep-sided cirques is called col. Arete is called a **serrate range** in England. A pyramidal or triangular-faceted peak formed due to recession and intersection of three or more cirques is called **horn** on the basis of Matterhorn Peak of Switzerland (fig. 22.4). The crest-line of aretes and pyramidal peaks is called **col-and-peak topography.** Converging aretes looking like a star fish in plan are called **star-fish aretes.** Several examples of pyramidal peaks or horns are found in the Himalayas e.g. Mt. Godwin Austen and Broad Peak in the Karakoram Range, Badrinath and Nanda Devi in Uttaranchal Himalaya, Mt. Kailash in Tibet, Mt. Everest and Makalu in Nepal etc.

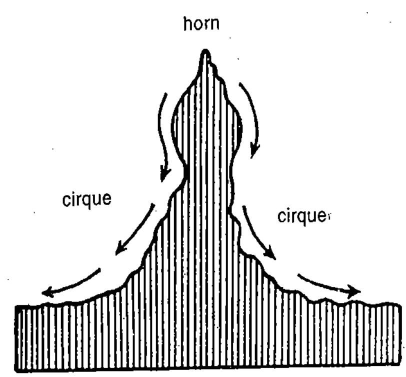


Fig. 22.4 : An example of a horn.

Nunatak—The higher peaks and mounds surrounded by ice from all sides are called nunataks. They look like scattered small islands amid extensive ice masses. That is why they are also called glacial islands. They decrease in size due to erosion caused by glacial lateral erosion and frost action.

Crag and Tail—A peculiar landform having vertical eroded steep side upglacial side and tail-like appearance with lower height downglacial side is called crag and tail (fig. 22.5). Such landform is developed over old volcanic or basaltic plugs which project above the ground surface as resistant knots. These volcanic plugs offer resistance in the flow direction of glacial ice and hence the side facing the direction from which the ice comes becomes steep due to erosion and is called crag. On the other hand, the other side being sheltered by glacial ice becomes elongated with gentle slope and appears like a tail.

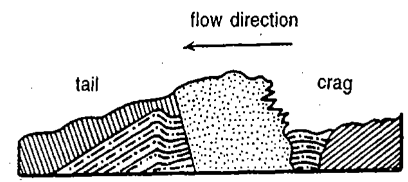


Fig. 22.5 : Crag and tail.

Roches moutonnees are streamlined asymmetrical hillocks, mounds or hills having one side smoothly moulded with gentle slope (onset or stoss side) and the steepened and craggy lee side (fig. 22.6). The term roches moutonnee was first used by de Saussure in 1804 for the streamlined rocky eminences resembling a sheep in lying posture. The onset or stoss side is smoothened through the mechanisms of abrasion and polishing by the advancing ice while the lee side is steepened due to plucking out of joint blocks by descending ice mass. There is wide range of variation in the dimension of roches moutonnees. (i) At the smallest scale they are one metre in length having ice-smoothed convex surface. (ii) At large scale roches moutonnees are several hundred metres in their dimension. They are very often aligned to structural weakness. (iii) At the largest scale roches moutonnees represent complete hills whose onset sides have been smoothed by advancing ice while

the lee sides have been steepened by descending ice. Several roches moutonnees are found in the glaciated valleys of Kashmir Himalaya.

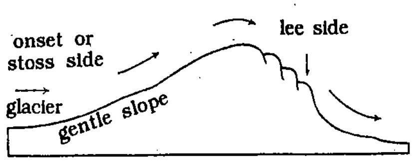


Fig. 22.6 : Roches moutonnees.

Glacial stairways also known as **giant stairways** or **cyclopean stairs,** are very picturesque and bewildering glaciated landforms. The length of each stair ranges from a few metres to several kilometres. Each stair is separated from the other by vertical cliffs measuring 30 to 300 metres. These stairs are formed in a veriety of manner. The advancing ice. of glaciers carves out giant stairway through the processes of abrasion and plucking of step faults which come across the paths of moving glaciers. The plucking of rocks at the foot of faults forms vertical cliffs. Smaller depressions are formed at the bases of cliffs. These depressions become lakes when they are filled with melt-water. These smaller lakes are called **paternoster lakes** (fig 22.7). These lakes appear as **beaded lakes** because they are associated with almost step or stair.

Glacial grooves—Small-scale streamlined depressions are called glacial grooves. Individual groove may measure 12 km in length, 100m in width and 30 m in depth.

Fiords are glacial troughs which have been occupied by the sea. In fact, fiords are the arms of the sea which have occupied U-shaped glaciated valleys which were dug out below sealevel through the mechanisms of abrasion and plucking by valley glaciers descending from coastal mountains. Fiords are characterized by steep side walls and several hanging valleys. They are very deep towards the coastal land and become shallow for some distance towards the sea but they again become deep. Thus, there is slightly raised part between the fiords and the sea. This raised part is called threshold of fiords. According to some geomorphologists these thresholds are in fact submerged terminal moraines. Most of fiords have developed during the period of intense glaciation of dissected coastal plateaus and

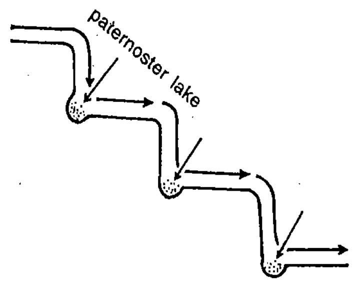


Fig. 22.7 : Glacial stairways and paternoster lakes.

mountains in Scotland. Norway, Greenland, Labrador, British Columbia, Alaska, Patagonia, New Zealand etc. The world distribution of fiords is conditioned by (A. Holmes and Dorris L. Holmes, 1978) (i) tectonic structures in upland regions near the sea, (ii) pre-existing valleys which follow these structures, and (iii) heavy glaciation by seaward moving ice of sufficient thickness. There are three views regarding the origin of fiords. (1) Deep valleys were carved out by glaciers descending from the coastal mountains above sealevel. At much later date these glaciated valleys were submerged under sea water to form fiords. (2) Fiords were formed by glacial erosion below sealevel. Sea level was significantly lowered during Pleistocene Ice Age and thus pre-existing fluvially originated valleys were further deepened by glaciers. These valleys were later submerged under sea water because of rise in sealevel due to deglaciation and these submerged glaciated valleys became fiords. (3) Fiords are supposed to have been formed due to tectonic factors. According to this concept fiords have been formed due to submergence of grabens which were formed near the coast because of faulting of the coastal land.

22.5 TRANSPORTATION AND DEPOSITIONAL WORKS OF GLACIERS

The rock debris carried by the glaciers are collectively called **glacial drifts.** Some times, the

term **moraine** is used for the debris transported by the glaciers and also for the landforms made by the deposition of glacial debris. Moraine, in fact, is a collective term which should be used for depositional landforms of direct glacial origin. The glacial drifts include (1) **till,** (2) **ice-contact stratified drift,** (3) **outwash,** etc. The unsorted and nonstratified glacial drifts are called **tills** which are further divided into (i) **basal** or **lodgment till** and (ii) **ablation till.** The **basal** or **lodgment tills** are compact, tough, dense and rich in clay. They are deposited at the base of the glaciers. The ablation tills are poorly consolidated and lack in fine grain sizes. The **ice-contact stratified drifts** are modified glacial debris by meltwater. Till is also known as **boulder clay.**

The glacial debris is divided into 3 types on the basis of location e.g. (1) **englacial debris,** which is transported within the glacier, (2) **supraglacial debris,** which exists on the surface of the glacier and (3) **subglacial debris,** which is found at the base of the glacier. Glacial sediments are transported along the sides, floor and snout of the glacier. The debris falling directly into a glacier is transported without touching the bottom of the glacier. The debris falling on to the surface of a glacier is transported downslope along with the moving ice mass. The materials derived from the bed by subglacial erosion are transported by touching the bottom.

22.6 DEPOSITIONAL LANDFORMS

Depositional landforms formed due to setting down of glacial drifts (glacial sediments of varying sizes) include moraines or morainic ridges and drumlins.

Moraines are ridge-like depositional features of glacial tills. They are long but narrow ridges with height more than 30m. Moraines are generally divided into 4 main categories on the basis of locational aspect of glacial deposits viz. (1) end or terminal and recessional moraines, (2) lateral moraines, (iii) medial moraines and (iv) ground moraines (see figures 8.15 and 22.8) V.K. Prest (1968) classified moraines in 3 main types on the basis of orientation of moraines with respect to ice movement :

(1) **Moraines deposited transverse to ice movement**

(i) ground moraines, (ii) end moraines-terminal moraines, recessional moraines and push moraines, (iii) ice-thrust moraines, (iv) ribbed moraines, (v) De Geer or cross valley moraines and (vi) linear ice-block ridge.

(2) **Moraines deposited parallel to ice movement**

(i) ground moraines-flutted and drumlinized. (ii) marginal and medial moraines, (iii) interlobate and kame moraines and (iv) linear ice block ridge.

(3) **Non-oriented moraines**

(i) Ground moraines-ablation moraines, (ii) disintegration moraines, (iii) interlobate and kame moraines and (iv) irregular ice-block ridge and rim ridge.

(1) Terminal moraines, also known as end moraines, are formed due to deposition of glacial till across the moving ice sheets at the snouts of glaciers after ablation of ice. Terminal moraines are horse-shoe shaped or crescentic ridges having concave slopes facing glacial valleys. They stretch for hundreds of kilometres in length and more than 100 metres in height. The recession of glaciers or ice sheets results in the deposition of several irregular ridges, mounds separated by basins. Such landscape is called **'knob and basin topography',** (2) **Lateral moraines** are parallel ridges of till on either side of a glacier. They are formed due to deposition of sediments along the margins of a glacier when it contracts in size due to melting of ice. Lateral moraines are generally long, narrow and steep sided ridges parallel to the glacial valleys. They are several hundred metres in height. (3) **Medial moraines** are formed due to deposition of glacial sediments along the internal margins of two glaciers at their confluence (fig. 22.8). They project above the surface of glacial valley. (4) **Ground moraines** are formed when glacial sediments (till) are deposited at the floor of glacial valleys. The sediments are not sorted because coarse and fine sediments are deposited together. The non-oriented moraines are usually formed due to mixture of ablation till and ice-contact stratified glacial drift.

Drumlins

The swarms of rounded hummocks resulting from the deposition of glacial till are called drumlins (fig. 22.9). They look like an inverted boat or spoon.

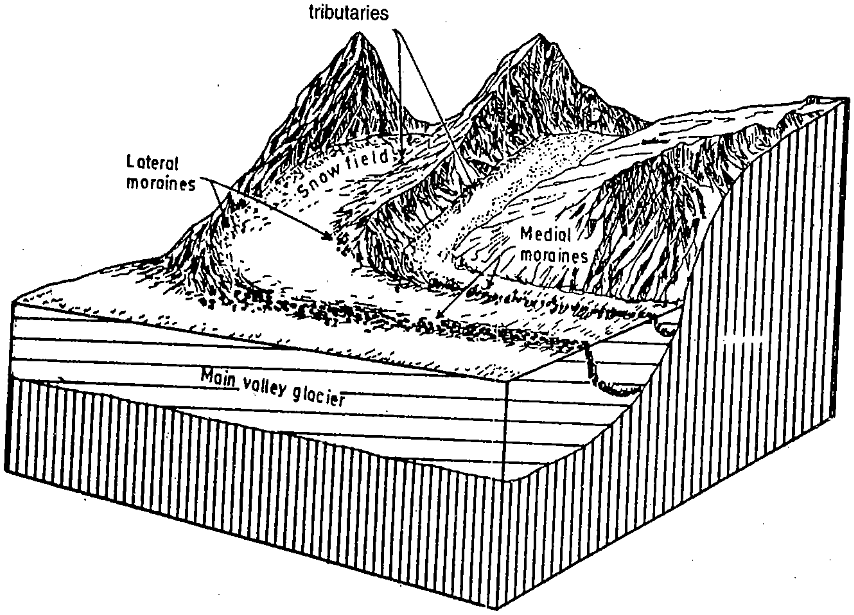


Fig. 22.8 : Different forms of morainic ridges.

In fact, drumlins "are elliptical or ovoid hills, blunt on the upglacier end (steeper slope), with an elongate downglacier tail" (A. Bloom, 1978). These are streamlined hills which vary in size ranging from a few metres to 60-100 metres in height and from a few hundred metres to one-two kilometres in length. Usually, these occur in cluster and regular pattern. Such topography is called **'basket of egg topography'**. Colonies of drumlines are found in Finland, Northern Ireland and Wisconcin State of the USA where 10,000 drumlines are found in group. Drumlin clusters have also developed in middle New York and Southern Michigan states of the USA. Drainage pattern becomes irregular and indeterminant in the areas dominated by drumlin clusters. Drumlins resemble roches moutonnees in shape as both have one side with steep blunt slope and the other side with gentle slope with long tail but they differ in origin as the former are the result of deposition of glacial till (boulder clay) while the latter are erosional in character. It may be further pointed out that the upglacier side of drumline is steep while roches moutonnees' downglacier side is steep. Though most of the geomorphologists consider drumlins as the outcome of glacial deposits but some consider them as the result of fluvial erosion. The following are the prevalent viewpoints regarding the origin of drumlins.

(1) According to some geomorphologists drumlins have been formed due to modification in the terminal moraines by the glaciers. Several recessional terminal moraines parallel to each other are formed due to recession of glaciers during interglacial period. These morainic ridges are later modified by advancing glaciers during next glacial period. The advancing glaciers erode the upglacier sides of the pre-existing terminal moraines and deposit the eroded materials on the downglacier sides. Thus, the upglacier side is steepened and the downglacier side is smoothened and lengthened (fig. 22.9).

(2) Some geomorphologists believe that drumlines are formed due to deposition of glacial till (boulder clay) below the ice under special circumstances. According to this viewpoint when the

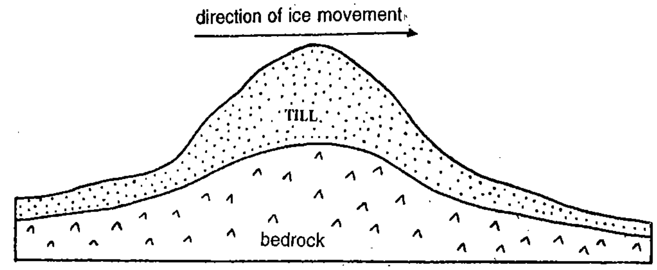


Fig. 22.9 : Drumlin.

glacier is overloaded with sediments, these are not carried upto the snout but are deposited below the ice and form mounds. These mounds attract more sediments to be deposited because they obstruct the movement of ice. These till mounds grow in size and become drumlins.

(3) The third group of geomorphologists is of the view that drumlins are formed due to fluvial erosion. According to them mounds are formed due to deposition of huge amount of boulder clay during glacial period. These mounds are later modified by fluvial erosion during interglacial period. Water erodes the onward side of these mounds and deposit them on the leeward side. Thus, the onward side is steepened and the leeward side is smoothened and lengthened.

(4) According to Leverett drumlins are formed due to deposition of glacial till (boulder clay) by the glaciers.

22.7 GLACIO-FLUVIAL DEPOSITS AND LANDFORMS

The snout of a glacier starts melting due to increase in temperature when it descends below **snow line**. The process of melting of a glacier is called **ablation.** Meltwater escapes through numerous but small and temporary streams. These streams carry sediments for longer distances and deposit them in various forms. These streams still carry some ice. Thus, the deposition of sediments after the ablation (melting of a glacier) is called **glaciofluvial deposit** and the landforms resulting from such deposit are called **glaciofluvial landforms.** The sediments are deposited in the form of low alluvial fans (if deposited on land) or deltas (if deposited in standing water). The fans spread out and coalesce into plains called as outwash plains. The glaciofluvial landforms include eskers, kames, kame terrace, kettle, kettle holes, outwash plains etc. (fig. 22.10).

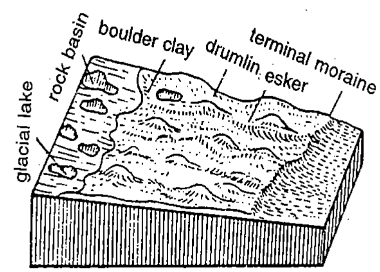


Fig. 22.10 : Depositional landforms by glaciers.

Eskers are long, narrow and sinuous ridges of sands and gravels and are situated in the middle of ground moraines. The sides of eskers are very steep. They vary in height and width ranging from a few metres to tens of metres and extend for kilometres in length parallel to the direction in which ice moved previously. Eskers are formed in the region of varying reliefs. They are extended through valleys, swamps, lakes and undulating terrains and thus they are very useful from the point of transportation as roads are easily constructed along eskers. Several hypotheses have been postulated for the origin of eskers.

(1) It is generally believed that water channel is issued from the snout of glacier due to melting of ice. This channel transports glacial fine sediments down the slope. The free flow of this channel is obstructed because of any obstacle. Consequently, sediments are deposited in the middle of the valley parallel to the main channel. Thus, long and narrow but low esker is formed.

(2) Water channel of meltwater is formed at the surface of the glacier and thus finer sediments are deposited at the ice surface. When the whole ice gets melted, sediments settle down at the floor of the glacial valley and thus esker is formed.

(3) Hollow tunnels are formed due to melting of ice at the bottom of melting glaciers. Thus, long but narrow water channels are formed below the surface of ice of the glaciers. The sediments carried by these subglacial channels, when obstructed, settle down to form eskers. The eskers can be observed after the melting of all of the overlying ice.

Sometimes, a series of swellings are strung along the eskers at regular intervals. Such eskers are called **beaded eskers** (fig. 22.11).

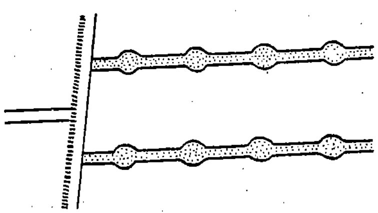


Fig. 22.11 : An example of beaded eskers.

Kames are small hills or irregular mounds of bedded sands and gravels which are deposited by meltwater near or at the edge of the retreating ice sheets. They are, in fact, small alluvial cones if deposited on the land or small alluvial deltas if deposited in the lakes. So, kames are classified into **cone kames** and **delta kames.** They are characterized by steep side slopes. Narrow flat topped terrace-like ridges formed along the trough between the glacier and the valley side are called **kame terraces.** The mounds formed in hollows and perforations in decaying ice are called **moulin kames** or **perforation kames.**

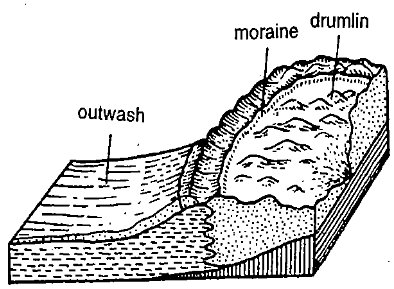


Fig. 22.12 : Moraines, drumlins and outwash.

Kettles and hummocks—Kettles are depressions in the outwash plains. Kettles are formed due to melting of large blocks of ice. Large kettles are dotted with numerous low mounds which are called **hummocks.**

Outwash—The meltwater caused due to ablation of a glacier at its snout descends through the terminal moraine and spreads like sheet water. This spreading water erodes the terminal moraines and deposits the eroded sediments in front of the terminal moraines and thus forms a plain which is called outwash plain (fig. 22.12). Outwash plains are characterized by well sorted sediments. Outwash plains also known as **'sandar'** (in Icelandic language) are characterized by multi-thread channels which are called **'braids'.** Outwash plains are, in fact, formed due to coalescence of several alluvial fans in front of terminal moraines.

23

PERIGLACIAL PROCESSES AND LANDFORMS

23.1 MEANING AND CONCEPT

The term periglacial literally means around the ice or peripheral to the margins of the glaciers but now this term is used for both **'periglacial landscape'** and **'periglacial climate'.** Periglacial areas are those which are in permanently (perennially) frozen condition but without permanent ice cover on the ground surface. The periglacial climate is characterized by mean annual temperature ranging between 1^0C and -15^0C and mean annual precipitation of 120 mm to 1400 mm (mostly in solid form). In fact, periglacial areas are characterized by permanently frozen subsoil **(permafrost)**, seasonally thawed topsoil (**active layer**), frequent changes of temperature and an incomplete vegetation cover. The term periglacial was first used by W. Lozinski in 1906, though some subglacial processes were already described by earlier scientists e.g. nivation process by F.E. Matthes in 1900, subglacial climate and process (dominanted by solifluction) by J.G. Anderson in 1906 etc. Later on D.D. Cairnes (equiplanation), H.M. Eakin (altiplanation), B. Hogbom (frost heave) etc. studied different periglacial processes.

Periglacial areas are of two types viz. (a) the present day periglacial zones are found in the Arctic regions of Alaska, Canada, Greenland and Siberia and also in Antarctica, and (b) the fossil zones of Pleistocene and other past Ice Ages. **Permafrost** and **active layer** are the two most striking features of periglacial areas.

23.2 PERMAFROST

The most striking feature of periglacial areas is the permafrost or permanently fronzen ground without permanent ice cover. The term **permafrost** was first used by S.W. Muller while K. Bryan used **pergelisol** (pergelisol = per, meaning permanently + gelare, meaning to freeze + solum, meaning soil=permanetly frozen soil). The depth of permafrost varies from place to place. The greatest depth of 600 m has been discovered near Nordvic (northern Siberia). The depth of permafrost has been noted as 500 m in Taymyr Peninsula of Siberia, 314 m near Cape Simpson in Alaska and 450 m in northern Canada.

Permafrost is classified in 3 categories e.g. (i) continuous permafrost, (ii) discontinuous permafrost and (iii) sporadic permafrost. About 50 per cent and 47 per cent areas of Alaska and Canada and earstwhile USSR are covered by continuous and discontinuous permafrost. Nearly 20 to 25 per cent of the geographical area of the globe is covered by permafrost.

23.3 ACTIVE LAYER

The top layer of permafrost is called active layer which is characterized by diurnal freeze (dur-