Chapter 2*

GEOLOGICAL PROCESSES

2.1 INTRODUCTION

2.1.1 *Branches of Geology*

Geology is the science that studies the earth. Geology (from the Greek, *gia* or *ge*, the Goddess Earth, and *logos*, denoting logical speech or science) deals not only with landforms but also with the structure and behaviour of the earth. Modern geology tries to explain the whole evolution of the earth and its inhabitants from the time of the earliest record, which can be recognized in the rocks, right down to the present day (Holms 1986).

Geology has several branches. Geomorphology (from the Greek, *ge-* earth, *morpha-* shape, *logos-* science) is that branch of geology which deals mainly with the landforms and processes of the earth's surface. The geological processes that are responsible for the changes in the features of the earth's surface are studied in physical geology. Hydrogeology evaluates the geological controls on the occurrence and movement of groundwaters. The architecture of the rocks is studied by structural geology. The earth's structure, the arrangement and form of materials composing it, the movements of the earth's crust, and deformations caused by them are studied in geotectonics or tectonics (from the Greek, *tectonikos-* builder). Geophysics applies physical methods to study rocks and the globe as a whole. Seismology (*seisma-* tremor) is the science of earthquakes.

The materials of the earth's rocky crust are studied by mineralogy (from the French- *minêral*) and petrology (from the Greek *petra-* rock). Magmatism (*magma-* dough) deals with the composition of magma, its role and activity. Metamorphism (*meta-* after; *morpha-* appearance, shape) concerns itself with the changes that rocks undergo in the interior of the earth under high temperature and pressure.

The erosion and deposition of rock fragments as well as the processes involved are studied in sedimentology. The study of various layers of rocks in space and time and their relationship with rocks of other regions is called stratigraphy (from the Latin, *stratum* - cover). The science that deals with the origin and evolution of life on earth, and the classification of fossil records, is called paleontology (*paleo-* ancient, *ontos-* existence, *logos-* science). The dating of rocks by radioactive and other methods is studied under geochronology (*ge-* earth, *chronos-* time). Historical geology studies the history of evolution of the organisms, our continents, and the oceans.

Engineering geology is a part of applied geology and is more closely related to civil engineering. It deals with the identification and assessment of the problems due to the inherent geologic setting that may arise during the planning, design, and construction of engineering structures in order to evolve suitable remedial measures.

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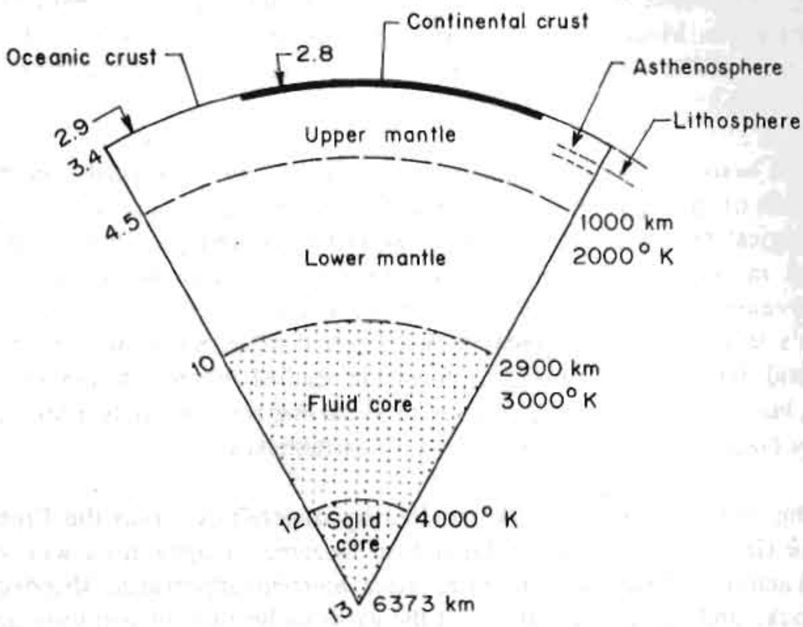
2.1.2 *The Earth's Outer Zones*

The earth can be described as a ball of rock (the crust), partly covered by water (the hydrosphere) and wrapped in an envelope of air (the atmosphere). The biosphere (*bio-* life) is another important aspect of the earth's crust. It is the site of organic activity. This system of crust, hydrosphere, atmosphere, and biosphere is a closed system. This means that losses from any part of the system are balanced by additions to others (Holms 1986).

The crust is the outer shell (Fig. 2.1) of the earth. It is made up of various kinds of rock. The uppermost part of the cover is composed of loose soil which is a product of the disintegration of the rocks themselves.



Source: Blyth and de Freitas 1985

Fig. 2.1 Composition of the earth

2.1.3 *The Earth's Inner Zones*

Apart from the outermost envelope called the crust, the earth's interior is divided into mantle and core as inferred from the seismological data (Fig. 2.1). The boundary between the crust and the mantle is called the Moho Discontinuity. It was discovered by Mohorovicic in 1909 by observing the break in the velocity of seismic waves. In passing through the rocks immediately above this surface, earthquake waves reach a velocity of about 7.2 km/sec, whereas in the rocks below the Moho Discontinuity the velocity jumps to about 8.1 km/sec. The core is divisible into two parts - the outer fluid core and the inner solid core, having a very high density (10.72 gm/cm^3).

2.1.4 *The Shape of the Earth*

The earth is more or less shaped like a sphere. The reason for this shape is that the gravitational force pulls all the particles towards the centre. Because of the earth's daily rotation, its matter is also affected by the centrifugal force. The opposing centrifugal force pulls in a direction perpendicular to the axis of rotation. It is proportional to the distance of the object from the axis of rotation, and, therefore, is maximum at the equator and minimum (almost zero) at the poles. Hence, the earth has an equatorial bulge, and the equatorial axis is 42.8 km longer than the polar axis.

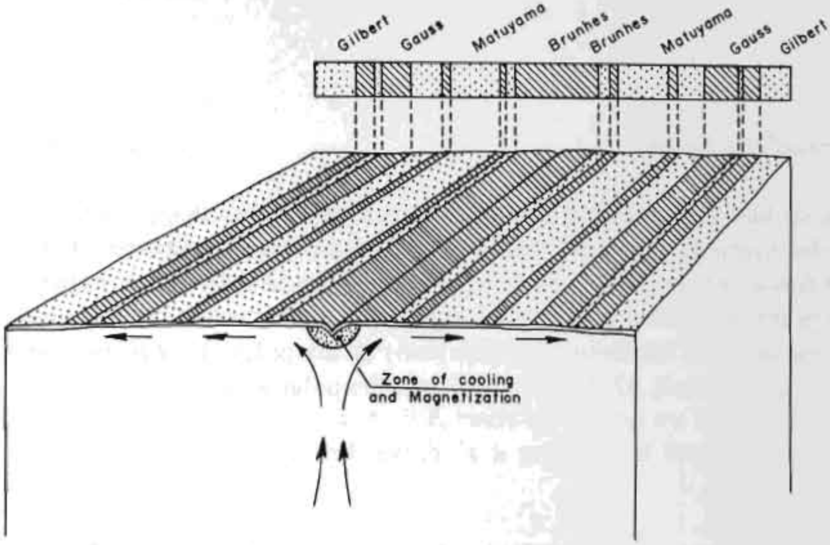
2.1.5 *Isostasy*

The ideal condition of gravitational equilibrium that controls the heights of continents and ocean floors in accordance with the densities of their underlying rocks is called isostasy.

If a wooden block is put into water, it floats, but a part of the block remains under water. The height of the submerged part of the block is proportional to the buoyant height of the block. The same concept is applicable to the mountains. In other words, as the mountains are raised there should be a proportional part of that mountain in the earth's crust. This is called the root of the mountain. Then what about the oceans? How to explain the depressions on the earth's crust? This problem is solved if we consider several wooden blocks of different heights floating together. The shorter block will have a lower level than the higher one.

Continents and mountains are composed of low-density rock, and they stand high because they are thick and light; ocean basins are topographically low because the thin oceanic crust is composed of dense rock. Isostasy and difference in the density of rocks beneath the continents and oceans, therefore, are the reasons why the earth has two pronounced topographic levels. The depth at which rock is weak enough to flow like a viscous fluid in order to produce the buoyancy effects of isostasy is called the **depth of compensation**. It is defined as that depth above which segments of crust and upper mantle act as blocks that rise or sink depending upon the mass and density of the individual blocks. The depth of compensation corresponds approximately to the bottom of the lithosphere where rock is hot enough to be weak and easily deformed (Skinner and Porter 1987).

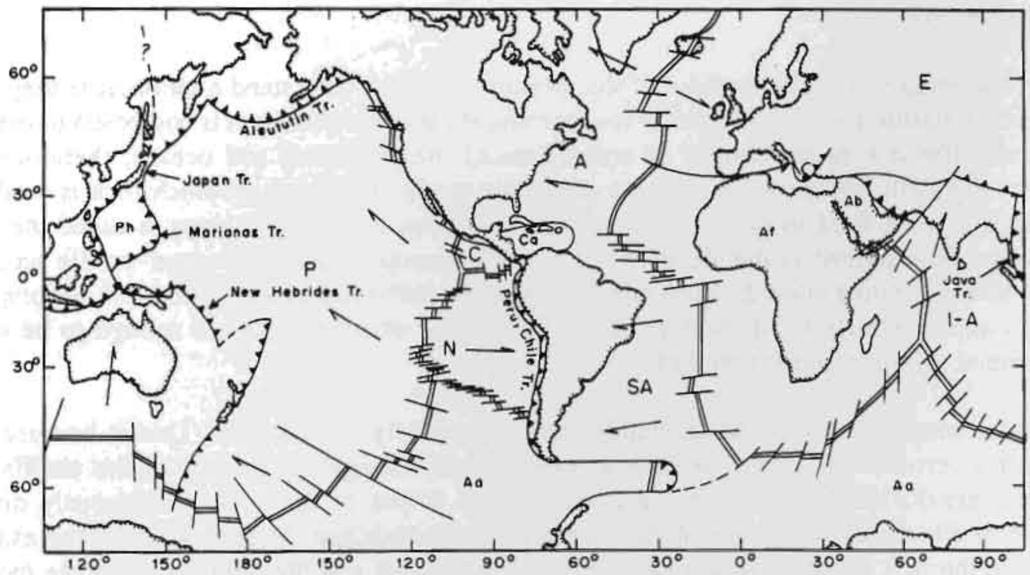
Under natural conditions, the isostatic equilibrium is generally not reached. This is because external forces, such as erosion and mass movement, continuously change the heights of the earth's crust to maintain the gravitational equilibrium, and the internal forces of the earth continuously disturb the equilibrium. It clearly shows the possibility of vertical movements in the earth's crust. For example, in the *Himalaya* the isostatic equilibrium has not yet been reached and the lighter root of the mountain is 'pushing' the mountain chain upwards, and the rivers and glaciers are eroding the mountain slopes. There are some rivers such as the Ganges and Brahmaputra which are older than the Himalayan mountains and have been cutting through them from the time of origin. The mountains are rising so rapidly that these rivers do not have enough time to cut wide valleys and can only make very narrow gorges. The *Himalaya* is a young (about 40 million years old in comparison to the earth which is 4.5 billion years) mountain chain, and the steep mountain slopes are basically caused by the faster speed of uplift and slower erosion rates.



Source: Cox et al. 1967

Fig. 2.2 Sea floor spreading and magnetic anomaly patterns

Convection currents bring molten material up under the mid-ocean ridge, where it cools, becomes magentized and then spreads laterally away from the ridge. Symmetrical bands of normal and reversed magentic anomalies in rocks would be produced by the combined effect of field reversal and spreading.



Source: Modified from Oxburgh 1974 in Blyth and de Freitas 1985

Fig. 2.3 Plate boundaries in the earth's crust

Plate boundaries in the Earth's crust. P. Pacific Plate. A. North American Plate. SA. South American Plate. Af. African Plate. E. Eurasian Plate. I-A. Indo-Australian Plate. Aa. Antarctica. Ph. Philippine. Ca. Caribbean. N. Nazca. C. Cocos. Ab. Arabian. The plate boundaries largely coincide with zones of seismic and volcanic activity. Oceanic ridges shown by double lines, transcurrent faults by single lines. ▲▲▲ = zones of subduction.

2.1.6 *Plate Tectonics*

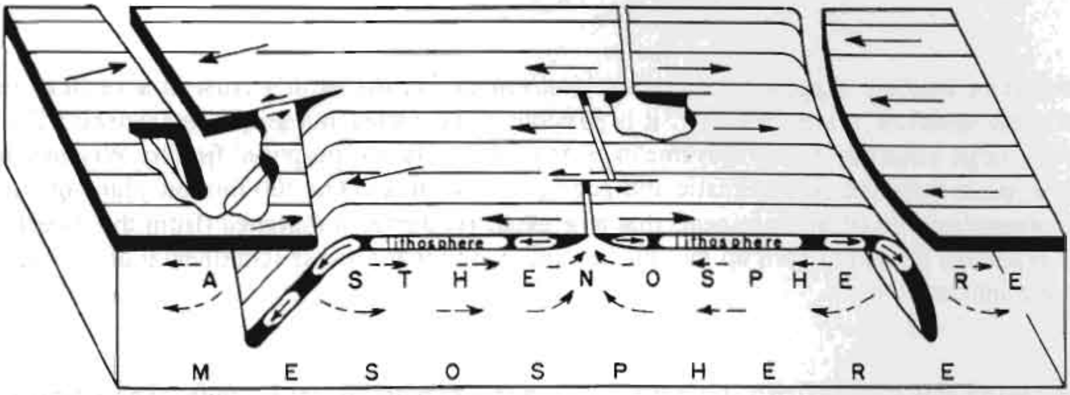
The principle of isostasy suggests that there are movements in the earth's crust in a vertical direction. Obviously, the question arises whether it is possible to have some horizontal movements. The answer is yes. Very large-scale horizontal movements of the continents was proposed first by Wegener in 1912. He tried to prove from the paleoclimatic and geological data that about 300 million years ago there was a supercontinent joining all the continents that now exist. He named it *Pangaea* (from the Greek : whole earth). It gradually started to split up into pieces, and due to that process (continental drift), the Atlantic Ocean came into existence.

Many geologists and geophysicists did not believe in this hypothesis until 1960. The geophysical and geologicial findings of the 1960s showed that the ocean floor is quite young (about 150 million years). Scientists also discovered that the magnetic poles flip back and forth from N to to S after a certain interval. This property is called the **magnetic reversals**.

If we make a geological map of the magnetic reversals in the ocean, it will look like a zebra crossing (Fig. 2.2). The youngest of the strips are found in the central portion of the ocean and are called the mid-oceanic ridge. They become successively older away from the ridge. This clearly shows that the ocean floor is spreading. In other words, a new oceanic crust, formed by eruption of lava at the ridges, slowly moves away on either side. But a question arises concerning what happened to the ocean floor that was older than 150 million years (as there is no floor older than that)? It means that there is some way of destroying the ocean floor. This destruction occurs at the margins of the continents where we find deep trenches. The depth of some of the trenches is more than 10,000 m. The moving ocean floor vanishes down the trenches. This process is called **subduction**. The hypotheses dealing with all these interpretations are called **plate tectonics**.

According to plate tectonics, the earth can be subdivided into six large rigid plates and several smaller ones (Fig. 2.3). The boundary of the plates is fixed by the foci of the earthquake epicentres. The plates, about 100 km thick, consist of crust and the uppermost part of the mantle and together are called the **lithosphere** (Fig. 2.1). The lithosphere moves along a more or less ductile zone called the **asthenosphere** (Fig. 2.1). As the lithosphere moves, a new crust is generated at the mid-oceanic ridges, and the older crust is partly destroyed at the trenches (Fig. 2.4). Thus the ocean floor is continuously renewed. In other words, the ocean floor is slowly moving away from both sides of the mid-oceanic ridge and disappearing in the trenches, like a conveyer belt. The continental crust, being lighter than the oceanic crust, floats and generally cannot be subducted. Sometimes, two continental blocks come close to each other and collide. A typical example of a collided mountain range is the Himalayan Range where the Indian subcontinent collided with the Eurasian continent about 40 million years ago (Fig. 2.5). The process of convergence is still continuous and, therefore, earthquakes are frequent in this region.

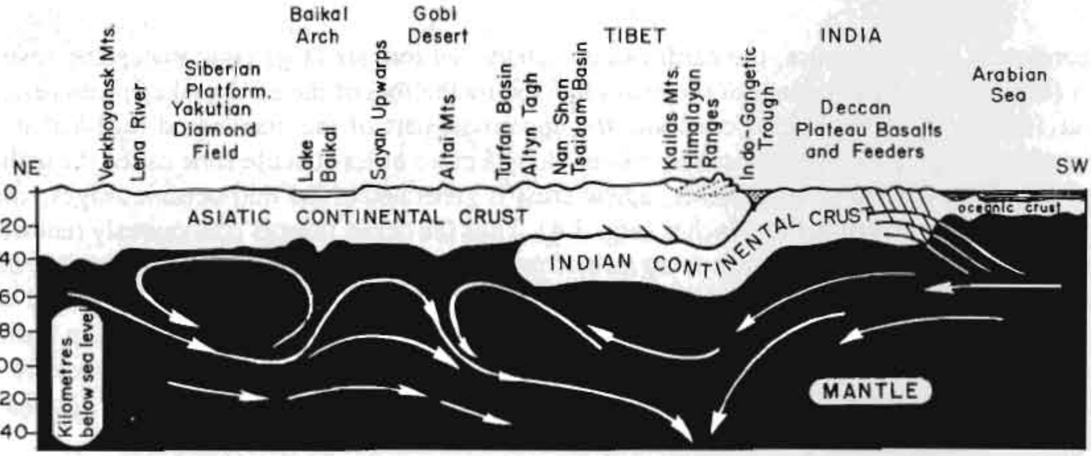
The mechanism that drives a moving plate is not known. Probably it results from a combination of convection currents in the mantle and the forces that act on a plate of lithosphere. The convective mixing was probably vigorous in the early earth and it resulted in a less clear distinction between continental and oceanic crust than is the case for the present-day earth.



Source: Isacks et al. 1968

Fig. 2.4 Block diagram illustrating schematically the configurations and roles of the lithosphere, asthenosphere, and mesosphere

Arrows on lithosphere indicate relative movements of adjoining blocks. Arrows in asthenosphere represent possible compensating flow in response to downward movement of segments of lithosphere.



Source: Holms 1986

Fig. 2.5 Schematic cross-section across Asia illustrating continental collision and partial under thrusting

2.1.7 *The Geological Time Scale*

Since the earth came into existence about 4,600 million years ago, its outer layer, called the crust, has changed significantly. As soon as the atmosphere and hydrosphere were formed, the earth's outer surface was subjected to an endless cycle of erosion and deposition. This interaction between the earth's crust, atmosphere, and hydrosphere led to the creation of the first organisms in the sea. The traces of the primitive organisms were subsequently lost in the sediments as they did not possess any resistant skeleton or shell.

The long timespan taken for the evolution of life on earth gave rise to successively more and more complex animal and plant species. Owing to natural selection, the old species that could not survive in a changing environment were lost and new, more advanced ones, appeared. As the evolution of life progressed, unicellular and multicellular organisms with hard shells or skeletons came into existence. The observation that sedimentary rocks deposited at various time intervals contain the remains of organisms that flourished during that period and the principle of superposition of strata (i.e., that in an undisturbed rock succession, the beds lying below are older than those lying above) make it possible to prepare a relative time scale. That means relative in the sense that it is possible only to say, for example, that the Cambrian period is older than the Ordovician as the latter overrides the former in undisturbed rock succession.

The discovery of radioactivity in 1896, by French physicist Becquerel, made it possible to get precise data concerning the formation of igneous and some sedimentary rocks containing radioactive isotopes. From these 'fossil watches' we can date the rocks in terms of the time that has elapsed after their formation. The common radioactive elements found in rocks are uranium (U), radium (Ra), thorium (Th), rubidium (Rb), potassium (K), and their isotopes. With time, they undergo spontaneous decay and change into other elements such as lead (Pb) and helium (He) as given below:

$$U^{235} \quad - \quad 7He^{4} + Pb^{207}$$

$$U^{238} \quad - \quad 8He^{4} + Pb^{206}$$

$$Th^{232} \quad - \quad 6He^{4} + Pb^{208}$$

The process of decay is constant and not affected by external forces. The decay of some radioactive elements continues for a long time. For example, a half of all the uranium atoms decay over 7×10^{8} years. A precise count of new atoms of lead or helium together with the parent uranium present in the rock enables us to determine the absolute age of that rock.

Geologists have sub-divided the geological time scale into larger and smaller time units termed respectively era, period, epoch, and age. A short description of eras and periods with corresponding duration and age and organisms of that time is presented in Table 2.1.

Table 2.1 The geological time scale

ERA		PERIOD		DURATION AND AGE (million years)		EVOLUTION OF LIFE
CAINOZOIC (CENOZOIC) (*Kainos* = recent *zoe* = life)		Quarternary		2	2	Homo sapiens
		Tertiary	Neogene	23	25	Ancestral pigs and apes
			Paleogene	40	65	Ancestral horses and elephants
MESOZOIC (*Mesos* = middle)		Cretaceous		79	144	Flowering plants
		Jurassic		69	213	Early mammals
		Triassic		35	248	Birds, flying reptiles, dinosaurs
PALAEOZOIC (*Palaios* = ancient)		Permian		38	286	Conifers and beetles
		Carboniferous		74	360	Abundant plants, early reptiles
		Devonian		48	408	Ammonites, trees
		Silurian		30	438	Plants, jawed fish
		Ordovician		67	505	Early fish
		Cambrian		85	590	Brachiapods, Trilobites, Corals
PRE-CAMBRIAN	PROTEROZOIC (*Proteros* = earlier)			~1910	~2500	Worms, Algae, Bacteria
	ARCHAEAN (*Archaeos* = primaeval)			~2100	~4600	Oldest algae and bacteria

Source: Modified from Holms 1986

2.2 EXOGENOUS AND ENDOGENOUS PROCESSES

From the beginning of its existence, the earth has gone through a continuous series of changes. These changes are never ending. The first group of processes causing the changes is known as exogenous (from the Greek *exo-* outside) processes and they take place on the surface of the earth. The second group of processes takes place inside the globe and they are governed by the forces inherent in the earth. These are the endogenous processes.

2.2.1 *Exogenous Processes*

Exogenous processes consist of continuous movements of water and air masses, of the circulation of water in the atmosphere, on the surface, and inside the earth. These processes also include the chemical and physical transformation of matter under the action of weathering reactions, destruction, transportation and redeposition of rocks, the life activity of organisms, and the like.

The exogenous processes can be divided into three stages. They are: (1) the breakdown of the primary rock exposed on the surface, (2) the stripping and transport of the liberated particles, and (3) the accumulation of the material or sedimentation. The totality of the processes involving the disintegration of rocks and the stripping of decomposed products and transport down to low-lying areas is called denudation (from Latin, *denudare*- to lay bare).

2.2.2 *Endogenous Processes*

The sediments deposited in the ocean, sea, or lake show horizontal or nearly horizontal layers. This property is related to the gravitational force of the earth. But, as soon as the sediments are deposited, they begin to undergo a series of changes in their geometry and composition.

At first they gradually become compact and solid without much change in mineral composition or internal arrangement of the grains. This kind of change is called **diagenesis**. Later, due to **tectonic movements**, as well as higher temperatures in the earth's crust and the pressure of the overlying rocks, the **sedimentary rocks** gradually transform into **metamorphic rocks**. Further change in temperature and pressure may lead to melting and formation of **magma**.

Crystallization of magma in the interior of the earth gives rise to **intrusive igneous rocks** and if the magma pours out from volcanoes it solidifies into **volcanic igneous rocks**. Thus, the three major rock groups (1) sedimentary, (2) metamorphic, and (3) igneous come into existence. They are discussed in Chapter Three.

The process of transformation of sedimentary, metamorphic, and igneous rocks into one another is called the rock cycle. The rock cycle is continuously taking place in the earth's crust (Fig. 2.6a and Fig. 2.6b).

When the rocks undergo deformation, folds may be generated. But when the rock cannot be deformed, it ruptures and the fracture is called the fault. Folds and faults are discussed in Chapter Four.

2.3 WEATHERING

Weathering is an aggregate of exogenous processes involving the physical destruction and chemical decomposition of minerals and rocks at the site of their occurrence and caused by the variations in temperature, by the chemical action of water, by gases (e.g., oxygen and carbon dioxide), by the biochemical action of organisms in the course of vital activity, and by the products of their decomposition after they have died off (Gorshkov and Yakushova 1977).

Weathering processes can be divided into two types: (1) physical weathering and (2) chemical weathering. However these two types always work together in nature and there is no sharp boundary between them.

2.3.1 *Physical Weathering*

Physical weathering is caused by a variety of factors that lead to the mechanical breakdown of rocks into smaller and smaller fragments. One type of physical weathering is caused by variations of temperature (thermal weathering). The periodic contraction and expansion of rocks, due to the diurnal variations of temperature, lead to the formation of cracks parallel to the heated surface and later to the flaking off of the upper layer. The process of temperature breakdown in rocks is called **exfoliation**.

Temperature weathering may also occur because of intensive heating, by sunshine, of rocks of different coloured minerals. Since the dark minerals are more intensely heated than the light ones, the difference in their volumetric expansion leads to the development of cracks.

Another form of physical weathering is mechanical weathering. One of the examples is frost weathering in which rocks are broken down by the freezing and thawing of water that has penetrated pores and cracks. The roots of plants, capillary water, and crystallization of minerals have the same effect.

2.3.2 *Chemical Weathering*

Chemical weathering is the chemical decomposition of rocks by the effect of atmospheric factors. The most important factors are the oxygen, carbon dioxide, and water contained in the atmosphere and the active role of organisms. The main reactions causing chemical weathering are oxidation, hydration, dissolution, and hydrolysis.

An example of oxidation is the change of sulfides into oxides:

$$FeS_2 \text{ (Pyrite)} + nH_2O + mO_2 = FeSO_4 = Fe_2(SO_4)_3 = Fe_2O_3.nH_2O.$$

Hydration consists of the formation of new minerals containing water of crystallization: $CaSO_4$ (anhydrite) + $2H_2O$ = $CaSO_4.2H_2O$ (gypsum). Hydrolysis is the chemical decomposition or alteration of minerals into other compounds by taking up molecules of water.

$$K_2Al_2SiO_{16} \text{ (feldspar)} + nH_2O + CO_2 = H_4Al_2Si_2O_9 \text{ (kaolinite)} + K_2CO_3 + SiO_2.\ nH_2O.$$

All the processes involving physical and chemical weathering result in the formation of various weathering products. These may be (1) mobile ones, which are transported over varying distances under the action of gravity, sheet flow, erosion by water, etc and (2) residual products that remain on the site of destruction of the parent rocks.

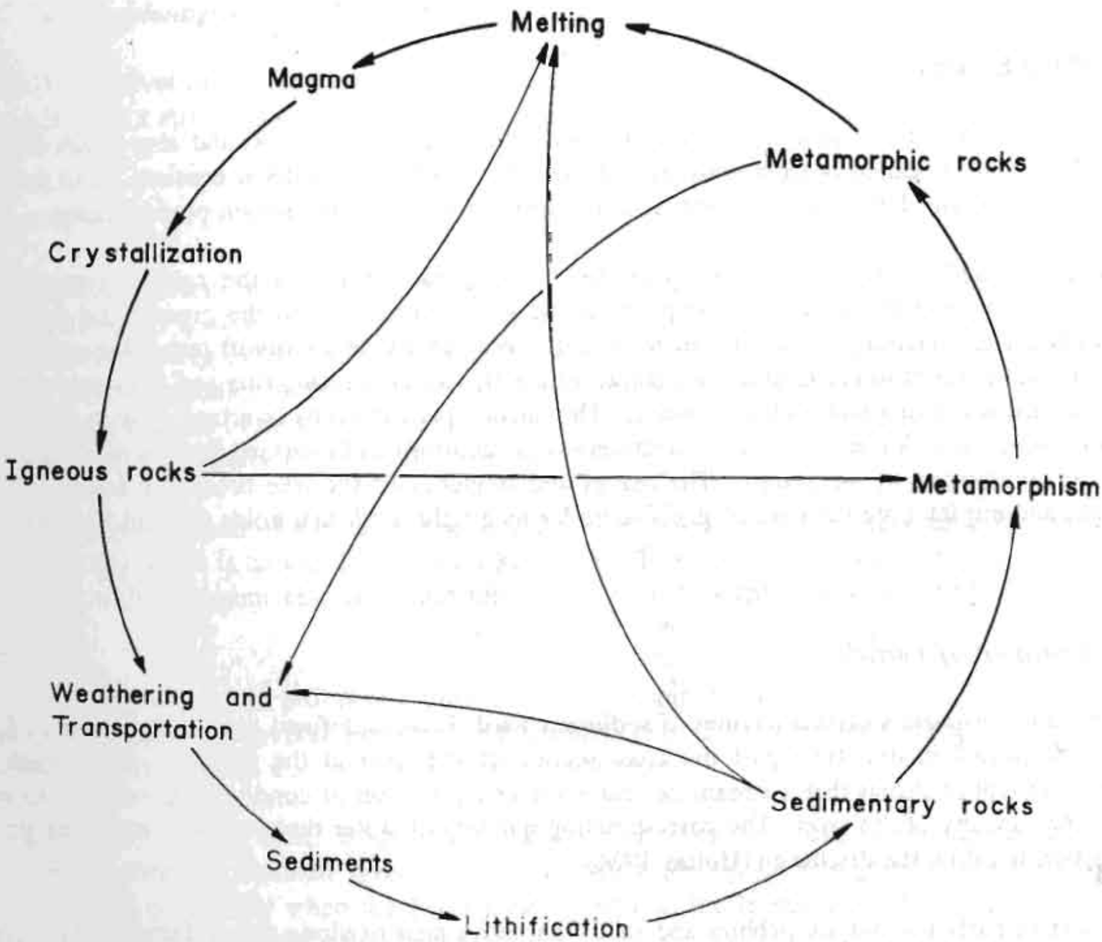


Fig. 2.6 Rock cycle

2.4 GEOLOGICAL ACTION OF RIVERS

A river or stream is a body of water which carries rock particles and dissolved substances and which flows down a slope along a clearly defined path called the stream's channel (Skinner and Porter 1987). The material the stream moves or carries is called the load.

Rivers and streams shape the continents. The work done by rivers is of three kinds: the destruction of rocks (erosion), the transport of particles by water, and their subsequent deposition (accumulation).

2.4.1 *River Erosion*

Rivers erode the bottom of their channels, gradually cutting into the bedrock, and also break down the banks. The former is called **bottom erosion** and the latter is known as **lateral erosion**. Both processes always take place together, but, in the initial stages of the river, bottom erosion predominates.

The water supplied to streams and rivers comes from rainfall. Some of the rainfall returns to the atmosphere through evaporation and transpiration and some infiltrates into the ground and remains as groundwater. The remaining portion forms the runoff. We can divide the runoff into (1) overland flow, the movement of runoff in broad sheets or groups of small, interconnecting rills and (2) streamflow, the flow of surface water in a well-defined channel. The erosion performed by overland flow is called **sheet erosion** (Skinner and Porter 1987). The effectiveness of raindrops and overland flow in eroding the land are greatly diminished by vegetation. The leaves and branches of the tree break the force of falling raindrops, and the intricate network of grass roots forms a tight mesh that holds the soil in place.

2.4.2 *Transport of Particles*

Every stream transports a certain amount of **sediment load**. Load is defined as the total weight of solid detritus transported in unit time past the cross-section of the river at the place of observation. The maximum amount of debris that a stream can carry under a given set of conditions is referred to as the transporting capacity of the river. The corresponding quantity of water that passes in unit time past the cross-section is called the discharge (Holms 1986).

The amount of particles (mainly pebbles and sand) that move near or along the surface of a river bed is called **bed load**. The quantity of fine particles that are carried away in suspension is called the **suspended load**. However, there is no sharp boundary between the two categories. The third load, in the form of dissolved substances, is called the **dissolved load**.

The particles of bed load generally move down current by saltation, a forward movement of the particles by intermittent jumps. In this process, the particles spin and bounce. As a result, the pebbles of the river become well rounded in contrast to the angular fragments of colluvium. The suspended load is diffused in water due to turbulence. The upward moving currents within a turbulent stream hold the particles in suspension as long as the energy, that the silt and clay particles settle, is less than that of the turbulent eddies.

2.4.3 *Accumulation*

The process of erosion and transport is accompanied by accumulation or deposition. Even in the early stages, when erosion and transport prevail over accumulation, the material carried by the river is deposited in some of its sections. As the river loses its transporting capacity, the bed load and the suspended load begin to accumulate. The deposits accumulating in river valleys are called alluvial deposits or simply alluvium (from the Latin, *alluvius*).

2.4.4 *Geomorphological Features of Rivers*

The water of a river or stream moves along a channel and the channel continuously modifies its course. Downcutting by a stream is called **vertical erosion**.

Channel Pattern

Depending upon geological conditions the stream may have **straight, meandering**, or **braided channels**. Straight channels (Fig. 2.7) are rare and, if present for a long distance, are probably controlled by joints or faults. The **thalweg** is the line connecting the deepest part of a stream along its direction of flow. Generally it is not parallel to the banks. A bar (or point bar) is the feature produced by the deposition of sediments at the side of the stream due to decrease in stream velocity. The deepest part of the channel, called the pool, is generally found opposite the bar.

A smooth, loop-like bend of a river channel is called a meander (from the Latin name for the Meander River in Turkey which is famous for its loop-like course). The meandering pattern (Fig. 2.8) is the result of the flow with minimum resistance and the energy is distributed almost uniformly along the river course.

If a river is overloaded with sediment it cannot transport material downstream in which case the material is deposited as bars with several interconnected channels (Fig. 2.9). This braided pattern is observed in rivers with highly variable discharge and easily erodible banks.

A **flood plain** is that area which is inundated in flood. Generally the banks of a stream are bordered by a small rise called the **natural levée**. The levees are made up of fine-grained sediments, and the deposition takes place only when the flood plain as well as the levees are submerged in flood and a temporary lake is formed on the flood plains.

River Terrace

In the process of lateral and vertical erosion, the river channel abandons its older flood plain which then becomes a river terrace. In some areas, the terraces occur at a number of levels. The lowest part of the river terrace is made up of coarse gravel with rounded pebbles representing the channel and/or bar deposits. The highest part of the terrace is composed of fine sand, silt, and clay representing the deposits of the natural levee and flood plain. If the river occasionally changes its course laterally and vertically, the terraces show a cyclic deposition of coarse and fine sediments (Fig. 2.10).

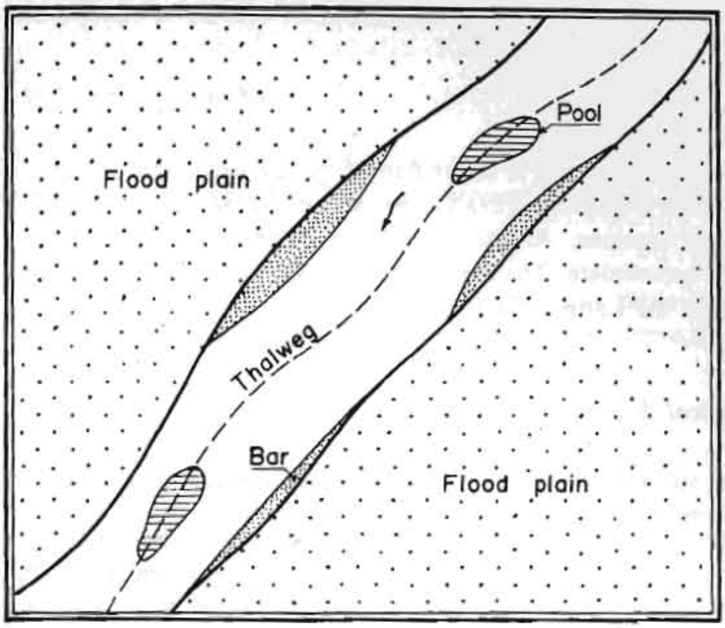


Fig. 2.7 Features of a straight channel

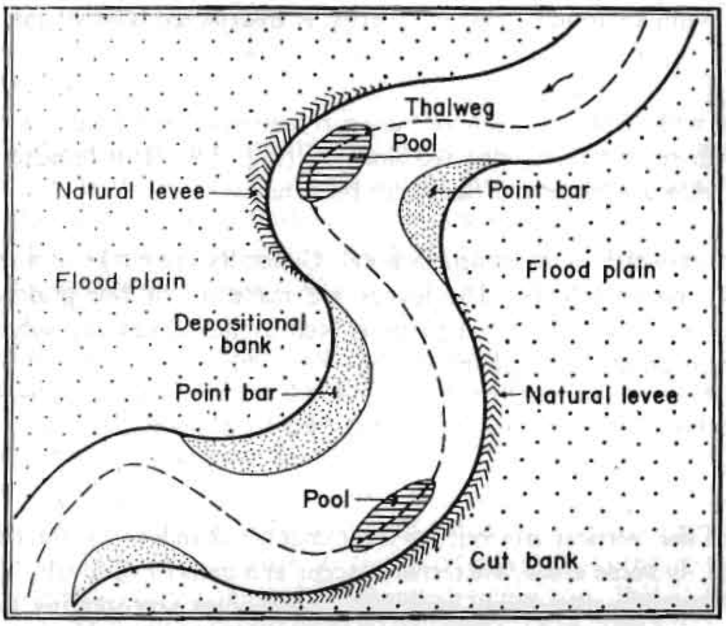


Fig. 2.8 Features of a meandering channel

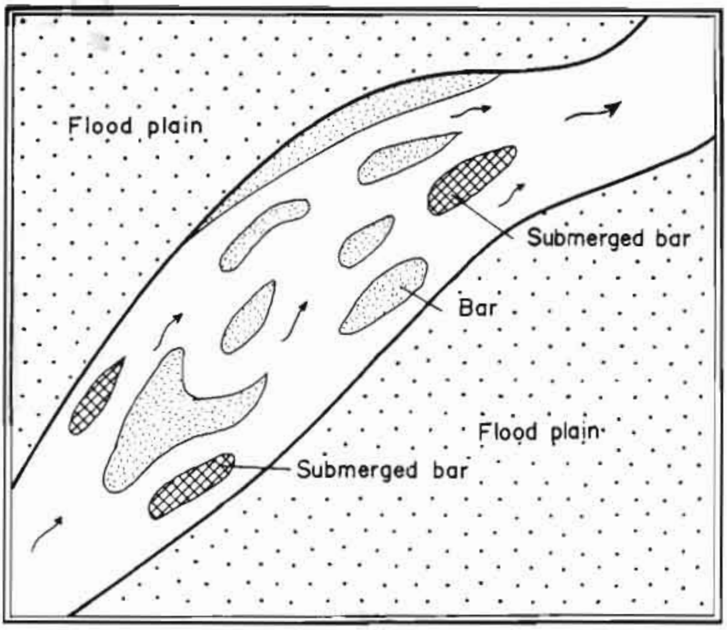


Fig. 2.9 Features of a braided channel

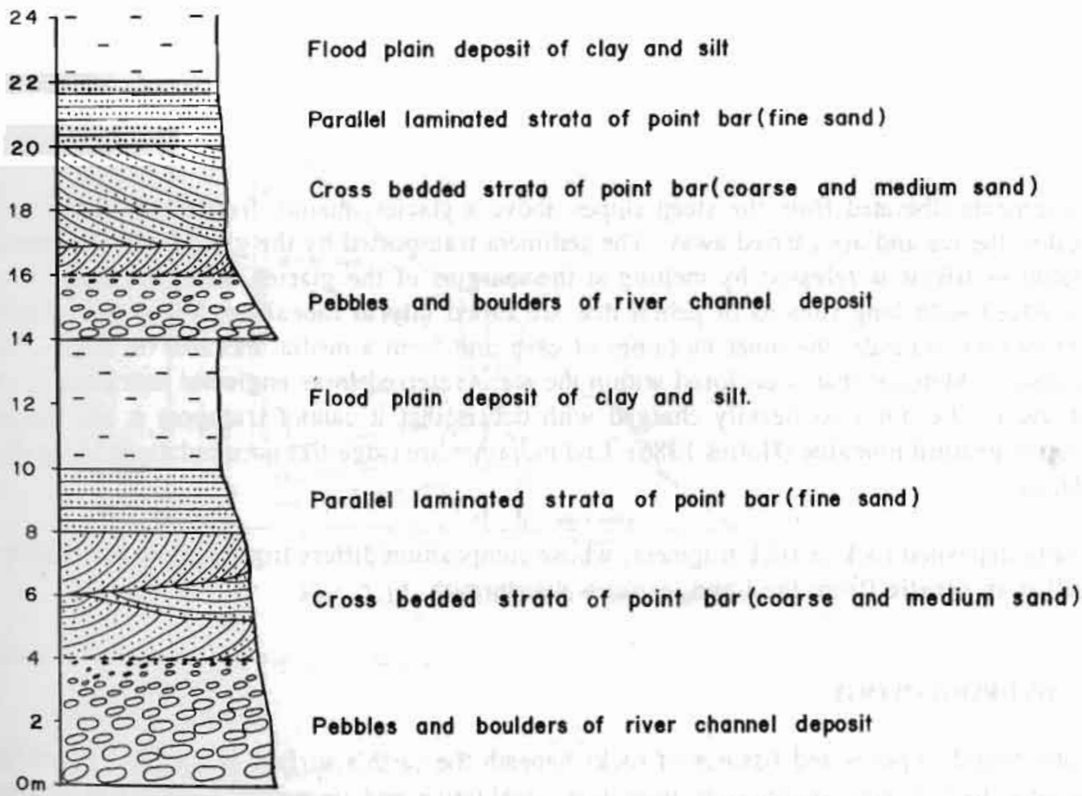


Fig. 2.10 Cyclic deposition in a river terrace

2.5 GEOLOGICAL ACTIVITY OF GLACIERS

A glacier is a large natural body of crystal ice, formed as a result of accumulation and subsequent transformation of snow. A glacier moves constantly down a slope.

Transformation of snowflakes into glacier ice is a kind of low-temperature metamorphism. As the loose feathery snow is buried by later falls it gradually passes into neve, a closely compact form with a density of from 0.8 units of air free ice to 0.917 units. With further compaction more air is squeezed out until the deeper layers are transformed into ice (Holms 1986). The loss of glacier ice by evaporation, melting, or calving is called **ablation** (from the Latin *auferre-ablatum-* to carry away). As the ice moves down slowly the glacier exhibits a tongue-like shape. The glacier advances until its front reaches a point where the accumulation is balanced by ablation.

2.5.1 *Types of Glacier*

Generally glaciers are classified into three major groups: (1) ice-sheets or thin sheets of ice which are spread over the flat surfaces of continents and plateaux, (2) mountain or valley glaciers occupying the valleys of high mountains, and (3) piedmont glaciers resulting from the coalescence of several valley glaciers (Holms 1986).

Glaciers erode rock by plucking, quarrying, and abrasion. They transport the waste and deposit it as glacial drift. Mountain glaciers erode the valley floor into U-shaped troughs with hanging tributaries (Refer to Section 2.7.5).

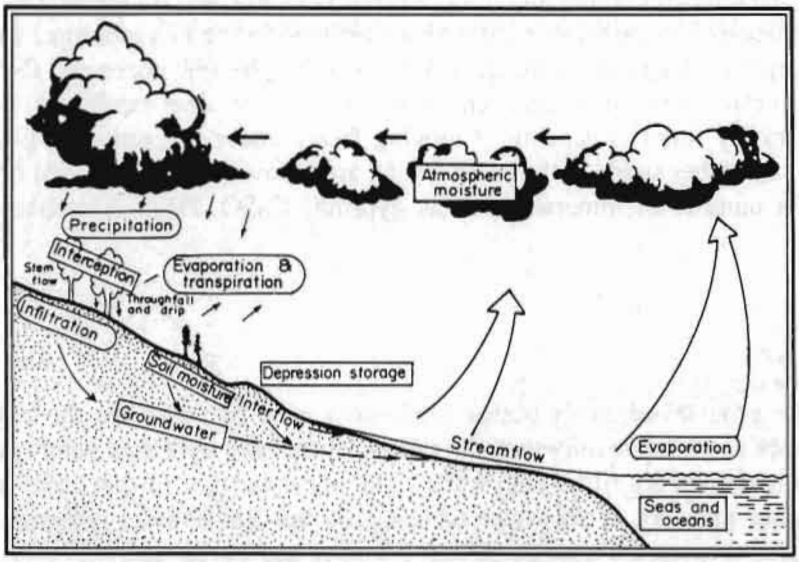
2.5.2 *Deposits of a Glacier: Moraines*

Rock fragments liberated from the steep slopes above a glacier, mainly from frost shattering, tumble down on to the ice and are carried away. The sediment transported by the glacial ice is plastered on to the ground as **till** or is released by melting at the margins of the glacier. Thus the sides of a glacier become edged with long ribbons of debris that are called **lateral moraines**. When two glaciers from adjacent valleys coalesce, the inner moraines of each unit form a medial moraine on the surface of the united glacier. Material that is enclosed within the ice is referred to as **englacial moraine**. If the lower part of the ice becomes so heavily charged with debris that it cannot transport it all, the excess is deposited as **ground moraine** (Holms 1986). End moraines are ridge-like accumulations along the margin of a glacier.

A glacially deposited rock or rock fragment, whose composition differs from that of the bedrock beneath it, is called an **erratic** (from the Latin, *erratus-* wandering).

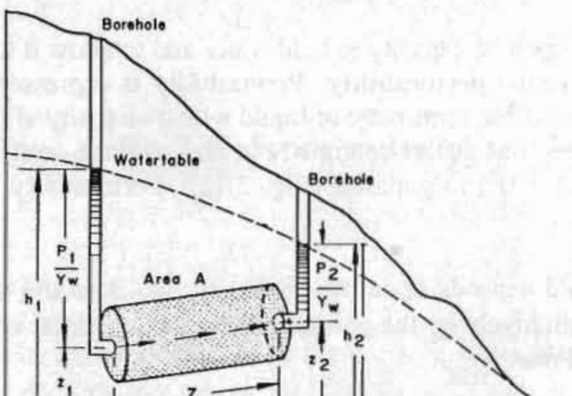
2.6 HYDROGEOLOGY

The water found in pores and fissures of rocks beneath the earth's surface is studied by hydrogeology. This covers their origin, distribution, migration, qualitative and quantitative variations in time, and geological effects (Gorshkov and Yakushova 1977). The hydrological cycle is shown in Fig. 2.11.



Source: Selby 1982

Fig. 2.11 The hydrological cycle



Source: Hoek and Bray 1981

Fig. 2.12 Definition of permeability

Permeability $K = Ql/A(h_1-h_2)$ (see Fig. 2.12), where:

K = permeability coefficient,
Q = discharge (m_3),
A = cross-sectional area of the sample (m_2),
(h1 - h2) = head, i.e., difference in water table (m) elevation between the ends of the sample, and
l = length of the sample (m).

2.6.1 *Types of Water in Rocks*

Water in the form of vapour is contained in the air that fills pores and fissures. It is in a dynamic equilibrium with other types of water. **Hygroscopic water** forms when molecules of water vapour are adsorbed (from the Latin *(ad)sorbere-* to swallow up) or retained on the surface of minerals. It forms a thin monomolecular envelope around the mineral grain and is firmly held on the surfaces of the particles. Film water forms a thicker envelope around the rock particles and the hygroscopic layer. It can move from one particle to another. Capillary water fills fully or partly the fine pores and fissures in rocks and is held in them by surface tension forces. The water rises over fine capillaries upwards from the groundwater table. Gravity water is capable of moving freely under the action of gravity through and along pores, fissures, and other voids in the rocks which are below the melting point of ice. Crystallized water forms part of a number of minerals such as gypsum: $CaSO_4.2H_2O$ (Gorshkov and Yakushova 1977).

2.6.2 *Water Table*

A hole penetrating the ground ordinarily passes first into a **zone of aeration**, the zone in which open spaces in soil or bedrock are filled mainly with air and moisture. The hole then enters the saturated zone, the zone in which all openings are filled with water. The upper surface of that zone is called the water table and the pore water pressure at the water table equals the atmospheric pressure. The water table generally slopes towards the nearest river or stream (Skinner and Porter 1987).

2.6.3 *Reservoir Properties of Rocks*

The water content of rock depends upon its capacity to hold water and to allow it to pass through it. This capacity for transmitting fluids is called **permeability**. Permeability is expressed in darcy or units of permeability equal to the flow of one cubic centimetre of liquid with a viscosity of one centipoise through the cross-section of a porous medium, one square centimetre in area and one centimetre in length, within one second at a pressure differential of 0.1 megapascal (Fig. 2.12). Permeability is generally expressed in millidarcies.

The capacity of rocks to hold liquid depends upon their porosity, which is the total volume of all the voids in them. It is measured quantitatively by the porosity ratio, i.e., the total void space expressed as a percentage of the rock's total volume:

$$n = (V_p/V_o) \times 100\%$$

where,

n is the porosity ratio; V_p is the total pore space in the rock; and V_o is the volume of the rock.

Permeability and porosity play a major role in slope movement. The rate of infiltration and percolation (slow infiltration) of surface runoff depends mainly on the permeability and porosity of materials. Based on the permeability and porosity, the rocks and soils can be broadly classified into three categories.

1. Pervious and non-porous: a. hard rocks with tight fractures - igneous and metamorphic rocks,
b. hard rocks with wide fractures and solution cavities-limestone.

2. Pervious and porous: porous rocks and soils - sandstone, conglomerate, sand, gravel, and cobble.

3. Impervious and porous: impervious and porous rocks and soils - claystone, siltstone, clay, marl, and fine silt.

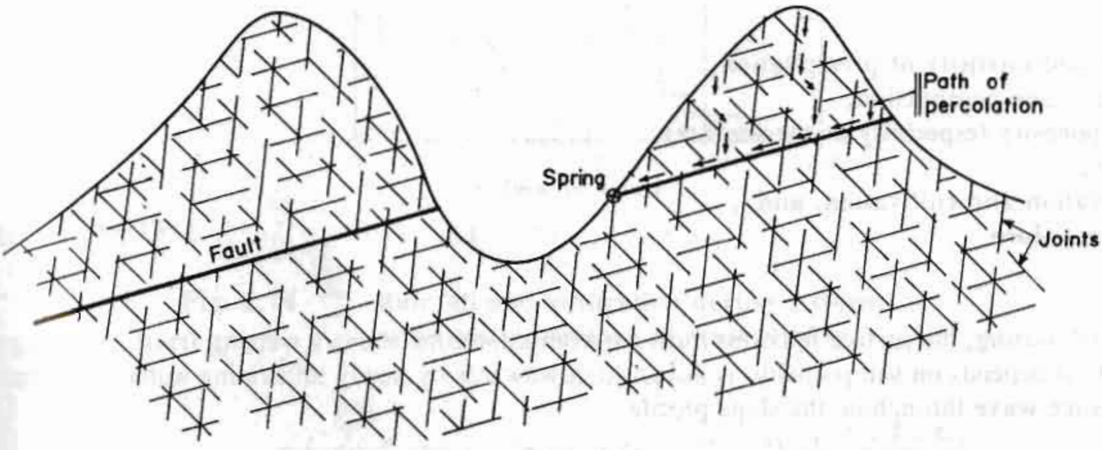


Fig. 2.13 Spring controlled by a fault

2.6.4 *Aquifer*

An aquifer is a layer of rock or soil in which the pores, cavities, and fissures are saturated with water and through which the groundwater moves.

2.6.5 *Spring*

A spring is the natural outflow of underground water on to the surface. Often springs are confined to depressed sectors of the relief where the aquifers outcrop on the surface. The quantity of water discharged by a spring is called its yield.

A general emission of water along the line of interception is called **seepage**. The diagram in Figure 2.13 illustrates an example of structures favouring the development of springs.

2.6.6 *Water and Soil Slope Movements*

Before the infiltration process, rainfall may be intercepted by the leaves of trees or shrubs or may become stem flow as it runs down the trunks of plants. This phase occurs at the beginning of a storm, during which water may be directly absorbed or evaporated from the plant surface. The capacity of the plant to store and lose water by evaporation declines with the increasing duration of the storm. Under prolonged rainfall the canopy may become saturated, the interception loss declines to virtually nothing, and the infiltration process starts.

Infiltration is a process by which water enters the surface horizon of soil. **Percolation** down to the water table occurs beneath the surface horizons. Infiltration may be controlled by a variety of factors. The most important are:

- **type and intensity of precipitation,**
- **surface soil compaction,**
- **soil porosity (especially at the surface),**
- **slope,**
- **vegetation and cultivation, and**
- **soil moisture.**

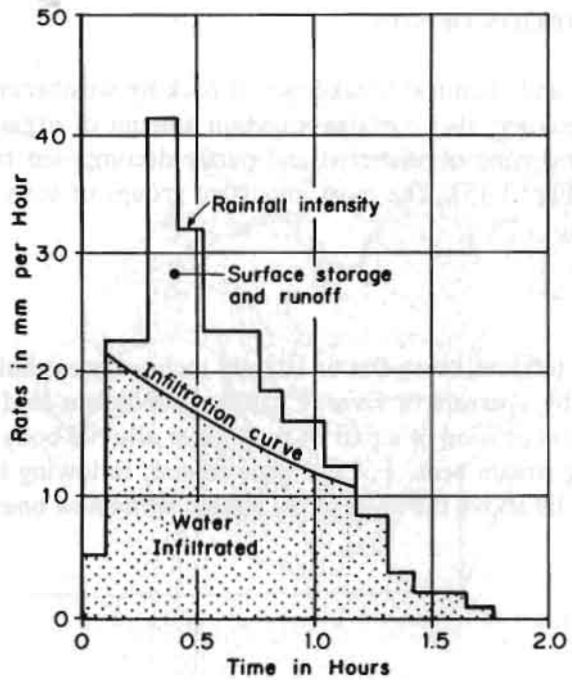
After initial wetting, the surface horizons form a transmission zone above a **wetting front**. Existing soil water, which depends on soil porosity, is displaced downwards by newly infiltrating water which moves as a **pressure wave** throughout the slope profile.

In multi-layered soils, **permeabilities** vary so that saturated layers may form above each less permeable horizon. A steady rate of infiltration is achieved when the entire profile is transmitting water at the maximum rate permitted by the least permeable horizon. This infiltrated water then forms the water table through percolation.

Excess water which cannot infiltrate is stored initially in surface depressions and once these are filled the excess spills downslope as **overland flow**. The changing rate of infiltration may be represented by a curve (Fig. 2.14).

When rainfall is intense, runoff and storage is high. The intensity of a storm is therefore one of the main causes of erosional processes such as **sheet erosion**, **rilling**, **gullying**, and other slope movements.

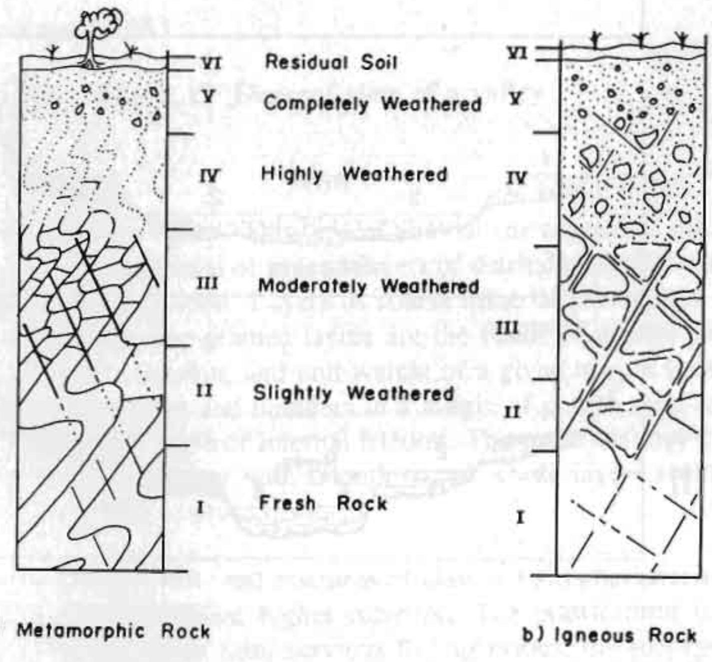
Infiltration and, therefore, runoff is strongly influenced by the texture of the soil as sands and gravels may be several times more permeable than clays. Permeability alone, however, does not control infiltration. It is also controlled by land use practices, vegetation cover, and slope. Compaction by animals or machinery may reduce the porosity and permeability. The range of infiltration in relation to vegetation, slope, and antecedent moisture content has to be taken into account when erosion hazard is assessed.



Source: Selby 1982

Fig. 2.14 Rainfall and infiltration during a storm

At low rainfall intensities, all water infiltrates.



Source: Deere and Patton 1971

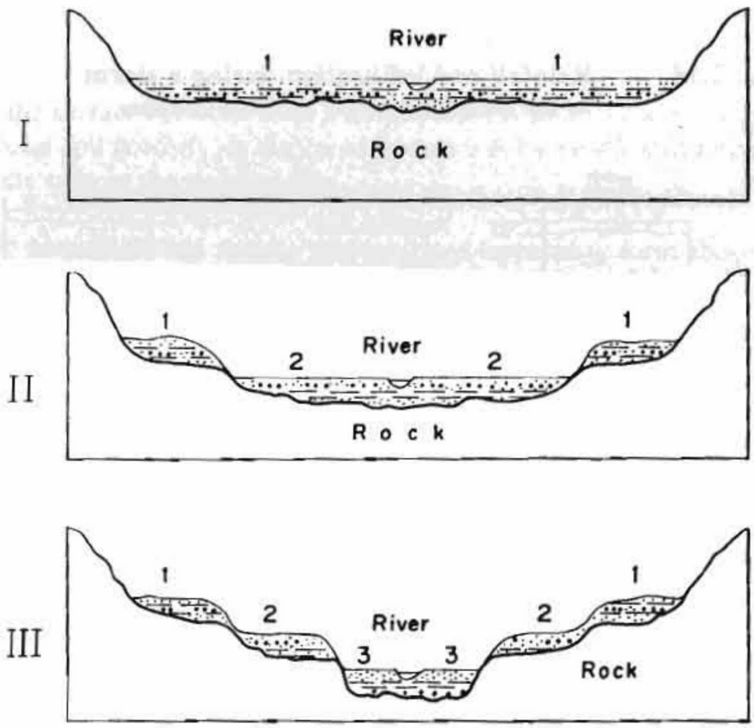
Fig. 2.15 Typical weathering profiles in igneous and metamorphic rocks

2.7 ORIGIN AND DESCRIPTION OF SOIL

Soil is formed by the physical and chemical breakdown of rock by weathering processes. However, the soil (topsoil in engineering geology) also contains a certain amount of organic matter. The soil passes gradually downwards through a zone of shattered and partly decomposed rock (called subsoil) to the bedrock, which is still fresh (Fig. 2.15). The most important groups of soils are described below.

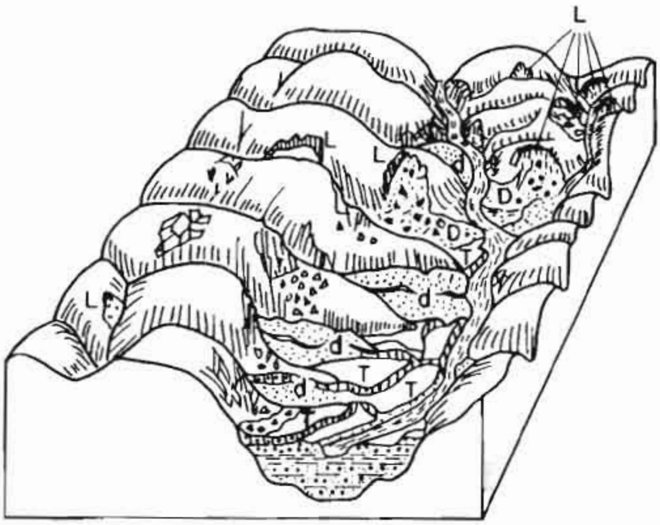
2.7.1 *Alluvium*

Alluvial soil is found on river terraces or on flat or slightly inclined areas built up over a period of time by detrital material deposited by a stream or river. Changing conditions lead to shifts in the position of the stream bed and to consequent erosion of a part of the former alluvial body. This is why alluvial cliffs are frequently found bordering stream beds. For the same reason, following long periods of erosion and uplift, former alluvial terraces lie above the level of the stream while new ones are deposited below (Fig. 2.16).



Source: Krähenbuhl and Wagner 1983

Fig. 2.16 Deposition of successive alluvial terraces



d delta
D facing deltas (may dam the main river)
T alluvial terraces
l landslide
L landslide (may dam tributary)

Source: Krähenbuhl and Wagner 1983

Fig. 2.17 General view of a valley

Fig. 2.17 depicts a general view of a valley. This type of alluvial site represents one or more successive terraces, each of which is usually composed of several layers of detrital material which vary in thickness and in the size of the elements they contain. Layers of coarse material correspond to periods of strong current and heavy erosion, whereas fine-grained layers are the result of quieter periods. The physical parameters such as friction angle, cohesion, and unit weight of a given terrace consequently vary from one layer to another. Layers of pebbles and boulders in a matrix of coarse sand are very porous, pervious, cohesionless, and have a high angle of internal friction. The materials they contain are generally rounded but can frequently be semi-angular with smooth edges. These layers are often poorly graded, particularly when the material is very coarse.

Layers of fine material such as sand, silt, and mixtures of clay and silt characteristically have a rather low angle of internal friction but somewhat higher cohesion. The plastic limit is sometimes critical. Because layers of fine material vary from semi-pervious to impervious, the seepage of water is slowed down or stopped altogether, which sometimes leads to the formation of more or less perennial aquifers. These aquifers frequently determine the stability of alluvial cliffs and adjacent areas and influence the unit weight of the material.

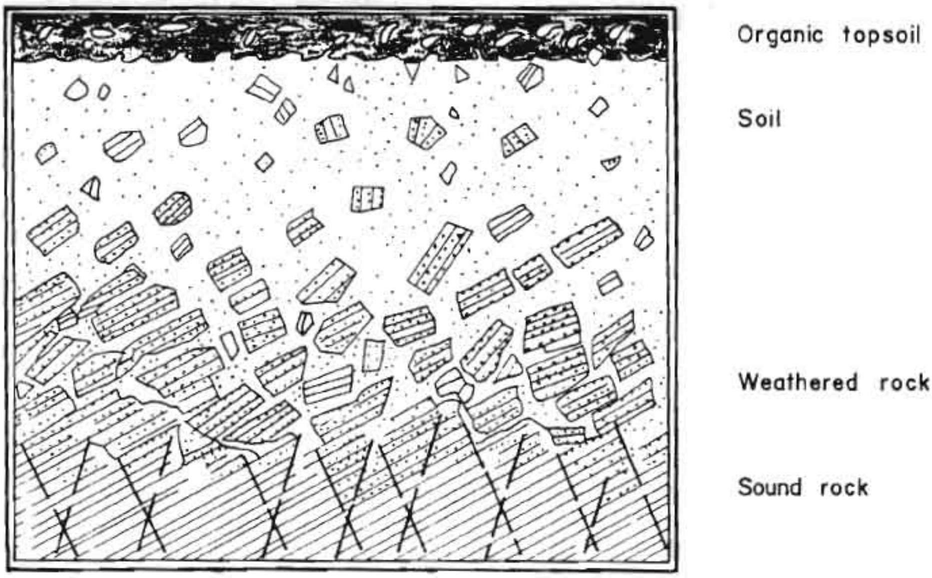
2.7.2 *Alluvial Fan or Delta*

An alluvial fan or delta (Fig. 2.17) is an alluvial deposit, triangular in shape, at the mouth of a tributary stream emerging into a larger river. Like the alluvial terrace an alluvial fan consists of eroded material brought to the tributary. The bulk of the alluvial material is considerably increased when the catchment area of the tributary is affected by landslides and gully erosion. In such cases, during the monsoon periods, heavy rains and the swelling of the tributary cover the fan with angular pebbles and blocks. Damming may also alter the tributary's course. Should two fan terminals of such eroded basins face both banks of a main river, they may temporarily dam the latter and thus dangerously threaten the downstream channel of the river when the dam bursts. Except when such events take place, the material of the fan is rounded to sub-angular but is poorly graded, rather coarse, and poor in fines. A strong increase in the water level of the main river where the fan emerges may destroy important features of the fan's body.

2.7.3 *Eluvial Soils or Regoliths*

Eluvial soils originate from the weathering of the underlying rock. For our purpose, only thick eluvial soils are considered. In the case of thin eluvial soils, when rock can be reached by excavation, the site must be considered a rocky site (Fig. 2.18). Thick regoliths appear on rather weak slopes into which surface water may penetrate deeply leading to weathering of the rock. Near the surface, these soils contain small rock debris. The grain size of this debris frequently increases with depth below the surface.

Because the composition of the soil matrix depends on the nature of the parent rock, parameters such as cohesion, permeability, friction angle, and unit weight may vary greatly from one soil to another.



Source: Krähenbuhl and Wagner 1983

Fig. 2.18 Eluvial soil or regoliths

2.7.4 *Colluvium*

These soils originate from landslides or transported eluvial soils. They are characterized by angular stones and blocks in a matrix of clay, silt, sand, or gravel. No grading or horizontal continuity is visible (except for weathered, rock-rotational slides where relicts of lamination remain). This is the main criterion distinguishing colluvium from alluvial soils (Fig. 2.19).

Fig. 2.19 Alluvium and colluvium.

Parameters such as cohesion and friction angle are highly dependent on the rock from which they originate and on the type of movement which has occurred. These types of soil are often unstable and should be considered with caution. Due to weathering, impervious horizons may be formed in the colluvium which leads to the formation of perched water tables. This water table may control rotational slides. In general, the colluvium is thicker at the toe of the slope.

2.7.5 *Moraine*

A moraine (Fig. 2.20) is a drift deposited by glacial action having a topography different from that of the surface on which it lies. Morainic soils are confined to relatively high altitudes in the Himalayan terrain, though they may be present down to 2,000 m and lower. Moraine consists of gravels, pebbles, and boulders (the latter sometimes reaching large proportions), within a clayey, silty, or sandy matrix. The edges of material are frequently polished by glacial action, distinguishing them from old stabilized landslides. The stones and boulders sometimes exhibit glacial striae or scratches due to the friction and compression they underwent while being transported by the glacier. Often huge boulders (erratic boulders) appear within or on the surface of the moraine. As only glaciers are capable of displacing such material, the presence of huge boulders, especially if they bear striations, is proof of deposits of glacial origin. Moraines sometimes reach great thickness. They generally have poor grading and horizontal continuity, except where they have been reworked by stream action during the glacial period. Glacial valleys characteristically have U shapes, cirque-shaped catchment areas, and horns (Fig. 2.20). As the morainic soils on the slopes are rather unstable, they should be surveyed and tested carefully.

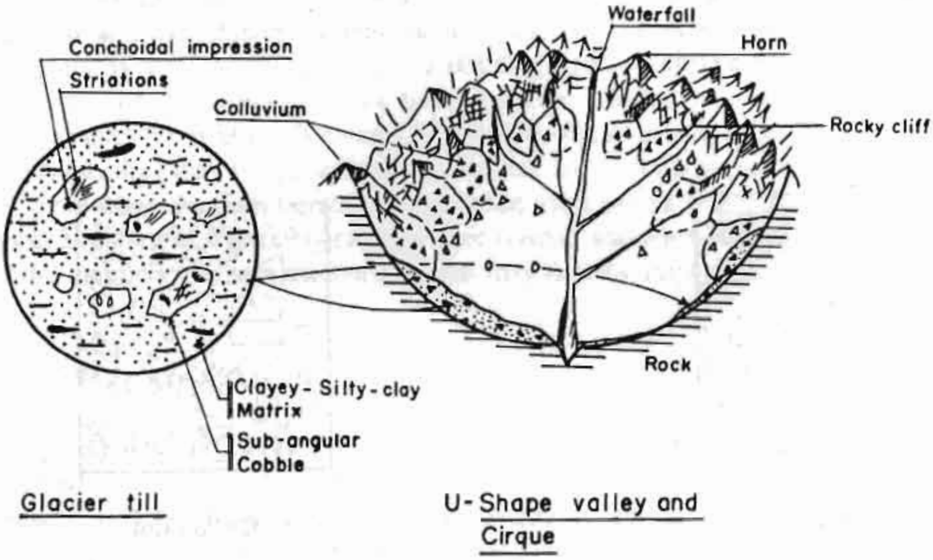


Fig. 2.20 Moraine and Glacial Valley Features