Chapter 1

THE QUATERNARY: CONCEPT AND DEVELOPMENT

1.1 INTRODUCTION

Quaternary is the latest Period in the Geological Time Scale. The Cenozoic Era includes Quaternary (above) and Tertiary (below). The Quaternary Period comprises Pleistocene and Holocene Epochs. The Holocene Epoch spans only the last 10,000 years. The whole of the Quaternary covers a small span of geological time, only 2.5ma.

Traditionally, a little focus has been given to the Quaternary and this has been neglected for a long time. Unfortunately, most of the authors of last century considered the Quaternary as an integral part of the Tertiary. Some of them state that the Quaternary does not exist. The Quaternary is continuation of the Tertiary. They argue that traditional Periods are subdivided based on either sychronous major tectonic movement all over the world or the guide fossils that demarcate the Period boundaries. In addition, the duration of earlier Periods covers long geological time. Indeed, duration of the Quaternary Period is so short that the duration of a single unconformity, sometime, is much longer than the Quaternary Period. On the other hand, Quaternary has not been separated in a traditional way. There was no major important universal orogenic movement that could make a sharp tectonic or stratigraphic boundary with the underlying Tertiary Period. The subdivision of Quaternary based mainly on the climatic changes contradicts the principles and conventional practices of Geochronologic or chronostratigraphic classification.

The next debate concerns the subdivision of the Quaternary into Pleistocene and Holocene Epochs. Edward Forbes (1815-1854) in his short life span worked on plant and animal life, and equated the Pleistocene with the Glacial Epoch. During the Pleistocene Epoch, cold phase (glacial) was alternated with the warm phase (Interglacial). The warm phase of present day, or Interglacial, which started at about 10,000 years ago, is called Holocene. The last glacial phase (Weischel Glaciation in Europe) of the Pleistocene was followed by the Interglacial phase of the present day in a similar fashion as the cold and warm phases alternated during the whole Pleistocene Epoch. In this sense, Holocene can be considered as the part or continuation of Pleistocene Eoch. Hence, giving the Epoch status (Holocene) to the last warm phase is questionable.

However, the Quaternary Period has its own special characteristics that separate this Period from the Tertiary. Quaternary (which includes present day) processes and sediments are well preserved, and quite fresh. The data obtained from the Quaternary sediments are relatively more accurate and informative. 'Present is the key to the past'. The Quaternary environments and processes may precept and unravel the geological ambiguities of the long past.

1.2 GENERAL CHARACTERISTICS OF THE QUATERNARY

1.2.1 Climatic Changes

Climatic change is unequivocally the dominating characteristics of the Quaternary. Global climate changes due to the variation of solar radiation received at the earth's surface. Global temperature changes periodically in some long-term, intermediate-term and short-term climatic cycles. The Quaternary climatic fluctuations followed a cyclic pattern. At the end of nineteenth century, Croll (1875) developed the 'Astronomical Theory' which was subsequently elaborated by the Yugoslavian geophysicist Milankovitch in 1920 (figure 1.1; Milankovitch, 1941). The theory was put forward on the premise that the surface temperature of the earth changes in a cyclic way in response to the periodic changes in the earth's orbit and axis. It was thought that there were three regular variations in the earth's orbit and axis which resulted in some climatic cycles of different amplitudes. The earth rotates about its own axis and at the same time it revolves around the sun. Milankovitch calculated that there were three very important and regular variations in the earth's orbit and axis, resulting in different length of climatic cycles. The path of the earth in moving around the sun (called as orbit) is not always circular. Approximately, over 96,000 years, the shape of earth's orbit changes from more elliptical to less elliptical and vice-versa. This phenomenon is called Eccentricity (figure 1.2). It produces a change in the surface temperature of earth in a cycle of 96,000 years. The second variable is called 'Axial tilt or Obliquity'. The axis of the earth tilts from about 22.1 to 24.5 degrees and back over a period of around 42,000 years. This is the angle between equatorial plane and orbital plane. Infact, it is the angle between an object's rotational axis and its orbital axis. The third variable is called Precession of the equinoxes. Precession is a change in the orientation of the rotational axis of a rotating body. The rotational motion of the axis of a spinning body, such as, the wobbling of a spinning top, caused by torque applied to the body along its axis of rotation. The motion of this kind makes by the earth's axis, causes mainly by the gravitational pull of the sun, moon, and other planets. The precession of the equinoxes happens due to the wobbling of the earth's axis. The time when the earth is nearest to the sun is called Perihelion. At present, the Northern Hemisphere winter occurs in perihelion, while the summer occurs at the furthest point on the orbit and is called aphelion. To shift the position from perihelion to aphelion, it takes about 10500 years and further back to perihelion to complete the cycle it takes about 21000 years (figures 1.2 and 1.3).

The pattern of Milankovitch climatic curve (figure 1.1) did not appear to accord with the number and frequency of glacial and interglacial cycles observed at that time in the terrestrial record of sediments. Therefore, the Milankovitch hypothesis was rejected at that time. Penck and Bruckner introduced the classical model, 'The Alpine Glaciation' in 1909. Globally, the model was well accepted. Merit of Penck and Bruckner's scheme rests on four-fold classification of Quaternary System.

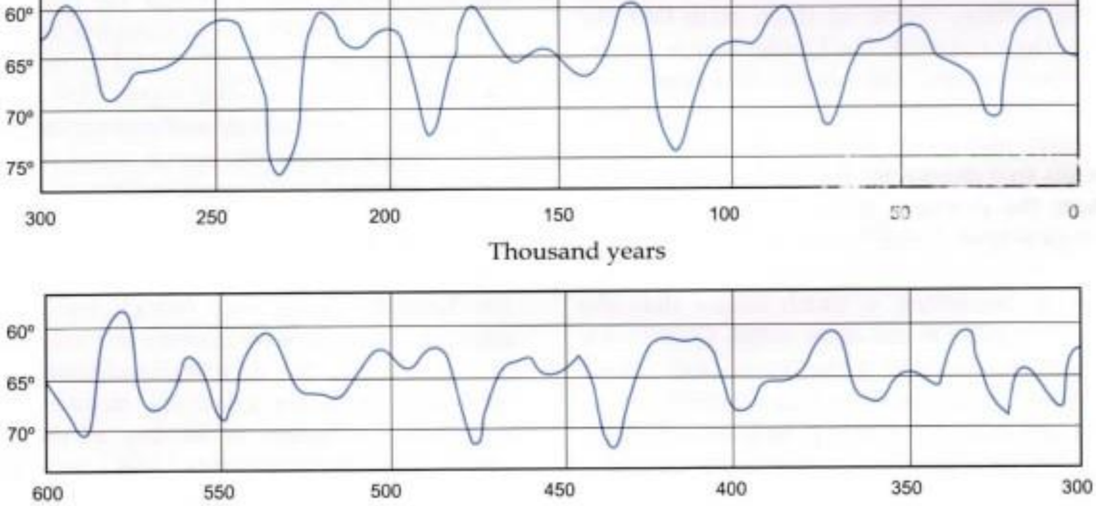

Figure 1.1 Milankovitch climatic curve showing the variations of solar radiation.

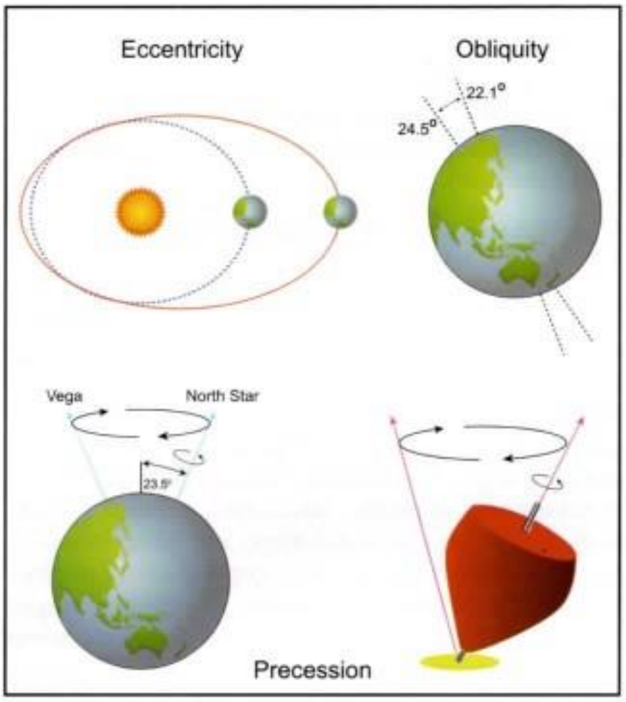

Figure 1.2 Milankovitch cycles.

Instead of a single glaciation in Quaternary Period (what was the initial presumption), Penck and Bruckner (1909) introduced four Glacial Periods in the Quaternary System. It was a breakthrough. Each Glacial Period alternated with an Interglacial Period of relatively warm climatic cycle in our planet. The variation of climate is directly related to the sea level changes. The oxygen isotope analysis of deep ocean core sediments provided sea level curve with some long term and short-climatic cycles. Long term climatic cycles can be fitted with the glacial- interglacial and short term cycles accounted for the stadial and interstadial. Thus, oxygen isotope curve has led to the re-establishment of Milankovitch hypothesis.

1.2.2 Ice Age: Glacial and Interglacial Periods

Glacial and Interglacial Periods (phases) are the major characteristics of the Quaternary. An ice age is a period of long-term reduction in the temperature of the earth's surface and its atmosphere, resulting in the appearance or expansion of continental and polar ice sheets as well as mountain glaciers. Within a long-term ice age, individual

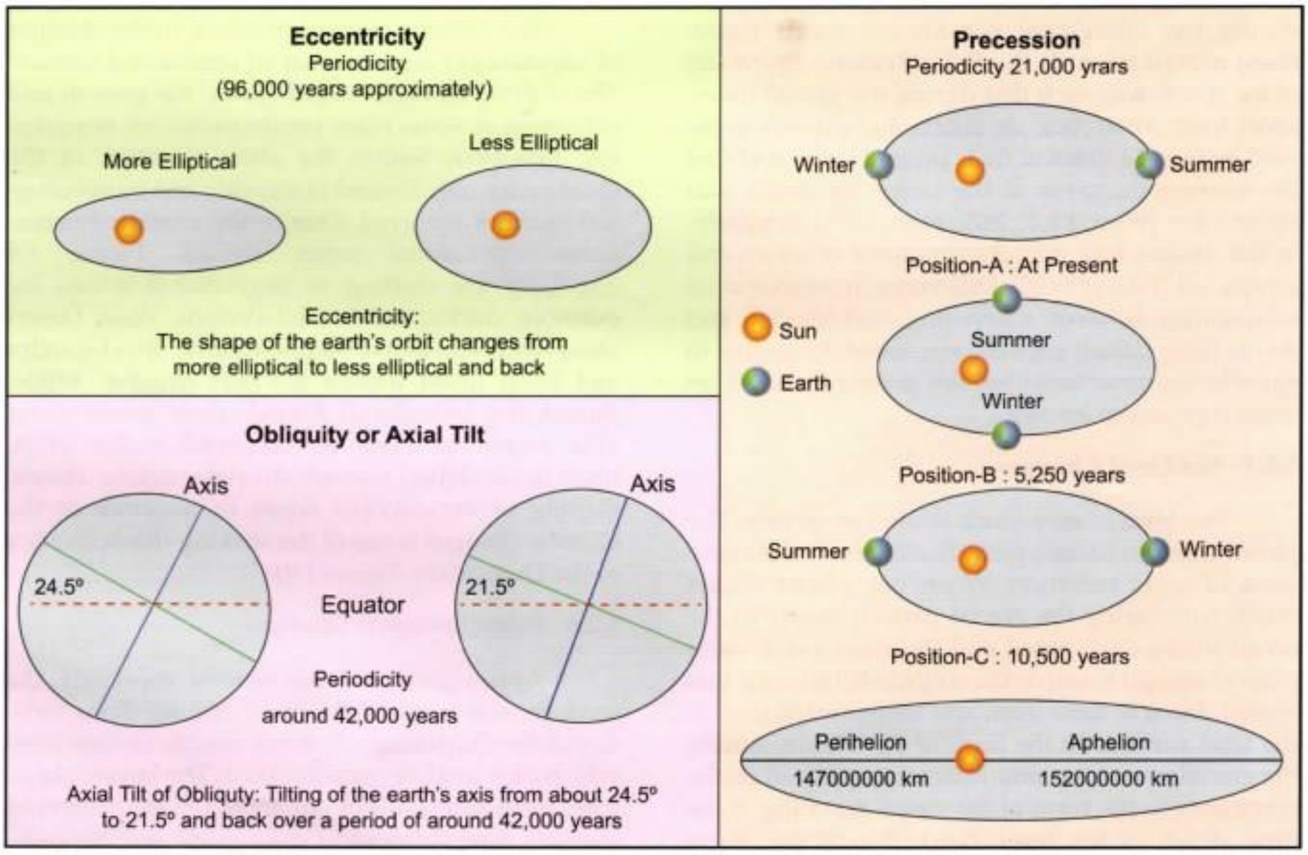

Figure 1.3 Orbital and axial variations affecting receipt of solar radiation at the earth's surface.

pulses of cold climate are termed glacial periods (or alternatively glacials or glaciations or colloquially as ice age) and intermittent warm periods are called interglacials. Glaciologically, ice age implies the presence of extensive ice sheets in the northern and southern hemispheres (Imbrie, 1979). By this definition we are now in an interglacial period (called the Holocene) of the ice age that began 2.5 million years ago at the start of the Pleistocene Epoch. This is justified by the present day existence of ice sheets in the Greenland, Arctic and Antarctic regions.

At the end of Pliocene Epoch and in the beginning of the Quaternary Period, the earth started to cool down and ice started to accumulate on two poles (North and South). Further cooling of global climate resulted in the expansion of ice sheets of the two Polar Regions, i.e., ice sheets from the two poles extended towards the equator. The Mean Sea Level fell. Subsequent, warming up of the global climate caused melting of continental ice, the melted water discharged into the lakes or ocean basins. Sea level rose up. The ice sheets retreated towards the poles. Hence, during the glacial periods, continental ice sheets (snow lines) moved towards the equator and during the interglacial periods ice sheets (snow lines) moved towards the Polar Regions. Extension of ice sheets was such that during the glacial times, apart from Antarctica, ice sheets and glaciers occupied an area 13 times of their present sizes, and that the average thickness of the larger ice sheets was about 2 km (West, 1968, 1977; Flint, 1971). Similarly, in hot deserts, lake margins expanded (Pluvial) and contracted (Interpluvial). Difference in mean annual temperature between alternating cold (glacial) and warm (interglacial) periods was about 0.5 degree in equable maritime locations, but greater than 10^{0}C in some continental interiors.

1.2.3 Sea Level Changes

Sea level is very much related to climate. The global climate changes periodically due to the variations of solar radiation. When our planet cooled down (i.e. during the glacial period), water in the ocean basins evaporated and the evaporated water (vapor) moved towards the continental interior that cooled down to form frost; and then precipitated on the land surfaces in the form of ice. Hence, during the glacial period, oceanic water accumulated on the continents in the form of ice sheets resulting in the drop down of sea level. Next, during the warm period, i.e. during the interglacial period, ice sheets on the continental surfaces melted down and melt water again returned to the ocean basin. As a result, sea level rose up. Therefore, eustatic sea level changes (changes of water volume in the ocean basin) due to the climatic fluctuation is another characteristic of the Quaternary.

1.2.4 Changes of Relief and Landscapes

One of the striking characteristics of the Quaternary is glacial and post-glacial landforms resulted by the occurrence of ice sheets and melt water. The resulting erosional landforms include striations, glacial horns, arêtes, trim lines, U-shaped valleys, hanging valleys, cirques, erratics, striations, corries pingos, hummocks, truncated spurs, roches moutonnées, morainic landforms, eskers, kames, kettles, tills, etc. Accumulations and movements of the Quaternary glaciers also created these distinct relief and topography. Along the coastline, changes of sea level during the Quaternary created some coastline topographic features, such as, raised beach, coastal plains and related coastal morphology.

1.2.5 Vegetational Changes

The climatic changes resulted in the changes of vegetational environment in continental surface. The shifting of vegetational zones, the growth and extinction of some plant communities are remarkable. However, within the short duration of the Quaternary only limited taxonomic and morphological changes occurred. Due to the climatic fluctuations vegetational zones shifted. Figure 1.4 illustrates the shifting of vegetational zones, for example, during the Glacial Periods, Polar Desert along with successive steppe-tundra, shrub-tundra and birch forest moved towards equator. While, during the Interglacial Period, these zones along with deciduous mixed forest, boreal conifer forest, birch forest shifted towards the polar egions. Hence, shifting of vegetational zones in response to the climatic changes is one of the striking characteristics of the Quaternary (figure 1.4).

1.2.6 Paleontological Changes

Appearance of Homo sapiens, especially, the modern man is one of the most striking characteristics of the Quaternary. It is not exactly certain from which race modern man evolved. The bones, skeletons, teeth and skulls of our ancestors are preserved in caves, river valleys and in some volcanic deposits. The East African Rift and Olduvai Gorge (Tanzania)

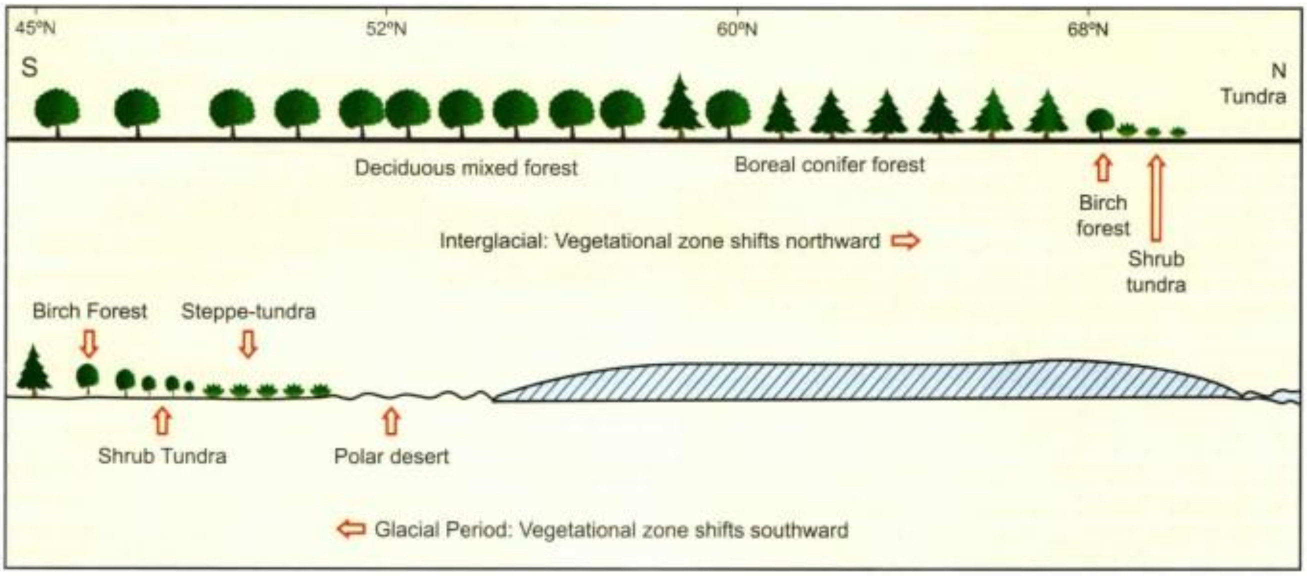

Figure 1.4 Development of vegetation during the glacial and Interglacial Periods in Europe (after Van der Hammen et al., 1971, modified).

in Africa, and the Siwalik Hills in the Himalayas were the best sites for our ancestors. The oldest bones and skeleton remains of our ancestors are found in East Africa. During the 1960s and 1970s hundreds of fossils were discovered in East Africa in the regions of the Olduvai Gorge and Lake Turkana.

Ramapithecus (believed to be a member of the Hominidae), was found in India, Pakistan, China, Greece and Kenya. *Ramapithecus* was considered to be a distinct genus that was the first direct ancestor of modern humans *(Homo sapiens)* before it had been regarded as that of the orangutan ancestor *Sivapithecus*. It is beyond doubt that the australopithecines were hominids. They appeared at the end of the Miocene, about 5.5 ma (million years ago). The *Australopithecus africanus* is an extinct species of the australopithecines, the first of an early ape-form species to be classified as hominin. *Australopithecus afarensis* is an extinct hominin that lived between 3.9 and 2.9 ma ago. *A. afarensis* were slenderly built, like the younger *Australopithecus africanus*. *A. afarensis* is thought to be more closely related to the genus Homo (which includes the modern human species *Homo sapiens*), whether as a direct ancestor or a close relative of an unknown ancestor, than any other known primate from the same time. Their evolution was confined to Africa, not appearing elsewhere until the Late Pliocene and Early Pleistocene. It is likely that several taxonomic categories existed: *A. africanus, A. robustus and A. boisei*, but they disappeared from the fossil record about 1 to 1.5 ma ago. At Olduvai Gorge, remains of *A. robustus* and an early form of Homo *(Habilis)* were found together, dated ca. 1.8 ma. Early Homo fossils have larger brain sizes than australopithecines and had lower limb bones more alike modern man. *Homo sapiens* (modern man) are the important ancestor, appeared about 0.4 ma ago; descended from *Homo habilis* and migrated from Africa to Asia and Europe.

Some other mammalian faunas are important in the Quaternary Period. Appearance of *Elephus*, *Equus* and *Leptobos* is one of the characteristics of the Quaternary. Reboul (1833) defined Quaternary as the Period, which includes deposits with fauna or flora of still living species. Lyell (1830-33, 1839) put forward a paleontological approach. According to Lyell (1839), the Quaternary contains more than 70% of the Tertiary molluscan fauna, still living species. Hence, paleontological changes are also the characteristics of the Quaternary, despite its limited application.

1.3 DEVELOPMENT OF GLACIAL THEORY

Initially, the Quaternary Period was thought to be the Period of glaciation, because the people were astonished to observe the evidences of glaciations and glacial deposits in those places, especially in the Alpine regions, that never witnessed permanent glaciations at the present times. Appearance of glacier during the Quaternary Period is the major characteristic. At the end of the Tertiary Period, global climate started to cool down and ice started to accumulate in and around the two poles of our planet. The continental ice sheet extended towards the equator during the cold Period (Glacial Period) and retreated during the warm period (Interglacial Period). The evidence of glaciation was first observed at the end of eighteenth century when James Hutton (1726-1797), a Scottish farmer and naturalist (he is known as the founder of modern geology), identified erratic blocks in the Jura mountainous region in France in 1795. He thought that the erratic blocks were glacier-borne deposits. In 1815, Perraudin, a Swiss peasant, inferred Alpine glaciation (Imbrie, 1979; Bolch et al., 2013). In 1824, Esmark recognized former mountain glaciation in Norway. In 1829, Venetz argued that most of the Europe was glaciated, as he recognized European glaciation beyond the Alps. First continental glaciation in Germany was recognized by Bernhardi in 1832. In 1837, Agassiz delivered a lecture to Helvetic Society on 'A Great Ice Period'. In 1838, Buckland was convinced that Britain was glaciated. In this way, the concept of widespread glaciation at the end of the Tertiary, started to develop (Bowen, 1978; Matthews, 2014; Bolch et al., 2013).

Jules Desnoyers (a French geologist) first introduced the term 'Quaternary' in 1829 (Imbrie, 1979; Bolch et al., 2013). He applied the term to the youngest deposits overlying Tertiary strata while he was working in the Paris Basin in France. Desnoyers followed an antiquated method of referring to geologic eras as Primary, Secondary, Tertiary, and so on. The Quaternary was again defined by Reboul in 1833 on the basis of paleontological evidences. Reboul stated that the Quaternary deposits contained fauna or flora which were still living being. A Scottish geologist Charles Lyell in 1839 introduced the term 'Pleistocene'. The term Pleistocene is derived from two Greek words, *pleistos* (meaning 'most') and *kainos* (meaning 'new' or 'recent'). Hence, Pleistocene means 'Most Recent'. Lyell introduced this term to describe the strata exposed in Sicily (type section, southern Italy) that had at least 70% of their molluscan fauna still living today. He also distinguished these deposits containing the youngest fossil from the deposits of older Pliocene Epoch (initially C. Lyell thought that those were the Pliocene deposits).

After the general acceptance of the glacial theory, another geologist Edward Forbes (1946) redefined the Pleistocene as the same age of glacial epochs. Lyell noticed that between the layers of rock or within the same layer, there was a distinct change between fossils of marine mollusks of warm water species and fossils which were like modern cold water species. After further investigation, it was confirmed that these geologic strata contained almost 70% of Molluscan fauna which were still living species. Forbes in 1846, suggested the post-glacial time as Recent. In 1885, International Geological Congress (IGC) accepted the term Holocene (meaning wholly recent). In 1869, Paul Gervais, a French paleontologist, introduced a term Holocene (wholly recent) for the last 10,000 years. The Holocene is indeed the 'Age of Man'.

Pleistocene should be synonymous with the Glacial Epoch. The Epoch Pleistocene started about 2.5 ma BP and the Holocene Epoch (Interglacial) started at about 10,000 years BP. The present author believed that the Holocene Epoch in Bangladesh started about 2000 years earlier than the start of Holocene in Europe. Hence, Holocene started about 12,000 years BP in Bangladesh.

1.4 CLASSICAL MODELS FOR SUBDIVISION OF THE QUATERNARY

There are some models for the classification of the Quaternary. These models were established following the antiquated method based on inadequate data. Hence, each model has its own characteristics and cannot be correlated easily. Among the classical models, the Alpine scheme of glaciation, proposed by Albrecht Penck and Eduard Bruckner (1909) is the most prevalent, as it has been accepted worldwide and has been practiced for more than a century now. The classical, long-established classification of the Pleistocene is still used in: i. the Alpine regions of Germany, Austria, France and Italy, ii. Northern Europe, Belgium, the Netherlands, Denmark, Norway and Sweden, iii. the British Isles, iv. The United States of America and Canada, and v. East Africa. All these classifications of Pleistocene Epoch were not based on universally accepted set of rules of practices. Those are not integrated and have contradictory mass of data. Some models did not follow the *Law of Superposition* for stratigraphic classification. Those were based on geomorphologic positions and the concept of terrace system. The emphasis was given to climatic changes that should not be used in stratigraphic classification. In the

African model, changes of lake level due to climatic fluctuation were improperly used for the Quaternary stratigraphic classification. Nevertheless, some important classical models (Bowen, 1978; Flint, 1971) are briefly reviewed.

1.4.1 The Alpine Model

Initially, the Quaternary Period was presumed to be a single event of cold phase. It was thought that during the Period, our planet cooled down and ice accumulated on two poles and mountain tops. The ice caps on the mountainous regions extended down to the foot hills or even extended over the outwash plains and to the continental interiors. The glacial deposits were not subdivided into lithostratigraphic or microstratigraphic units. It was Penck and Bruckner (1909) who subdivided the Quaternary Period into four events of glaciation. Each glacial event (Glacial Period) alternated with an event of warm period (Interglaciation). In 1885, Albrecht Penck recognized three terraces of glacial moraine deposits exposed in the Bavarian Plateau and around Lake Constance between Lech and Iller

Photo 1.1 Photograph of the famous geologists Albrecht Penck (right) and Eduard Brückner (left).

rivers of North German plain, south of Ulm, Augsburg and Munich. Penck believed that those were the glacier-drifted moraines (during the Glacial Period) and were deposited as glacio-fluvial deposits (moraines and tills) that formed a glacio-fluvial outwash terrace during the warm period (Interglacial Period). During this fieldwork, Penck morphologically mapped the extensions of these four outwash terraces of four glaciations. In 1886, Eduard Bruckner (photo 1.1) also recognized the same outwash terraces in the Sal Zach valley farther east in the Alpine region. The up-valley terrace, formed by moraines and till deposits, were merged with the end moraines of the contemporaneous glacier. The first glaciation (cold phase) was indicated by the outer end moraine, downstream from which the upper outwash plain filled the valley floor. Subsequently, after deglaciation, the outwash plain was eroded and valley deepening dissected it into a terrace. Such down cutting, and dissection were deemed to have occurred during an Interglacial interval. Therefore, the interglacial time is not represented by any deposits, rather by an erosional episode. Thus, Interglacial Period (warm phase) was the time of erosion. The entire process repeated during a subsequent glaciation. Hence, each Glacial Period (glaciation) alternated with an Interglacial Period (Erosion). Originally only the two lowest terraces were linked with the end moraines of subsequent glaciation. Finally, end moraines of the later glaciations were linked, and four glaciations were recognized by Penck and Bruckner (1909), as mentioned earlier.

In 1909, Albrecht Penck and Eduard Bruckner (photo 1.1) published their classic work in German Language. The name of the book is DIE ALPEN IM EISZEITALTER (The Alpine Glaciation). These four glaciations were named after four rivers: Wurm, Riss, Mindel and Gunz, flowing in the Bavarian region (table 1.1).

Initially, Penck (1985) described three gravel units: i. Cover Gravel, ii. High Terrace and iii. Low Terrace. The Cover Gravels were further subdivided into two separate units: Older Cover Gravel (Gunz Glaciation) and Younger Cover Gravels (Mindel Glaciation), representing two separate glaciations. The cover gravels were highly weathered and subdued losing their original morphology and could not be recognized by naked eyes. The gravels of high terrace (Riss Glaciation) were partially subdued, comparatively less weathered and the gravels of Low Terrace (Wurm Glaciation) were quite fresh and retained their original morphology.

After a long time, two more glaciations discovered and added to the original scheme of Penck and Bruckner. In fact, those glaciations were not incorporated into the original scheme. Eberl (1930) and Schaefer (1953) added these two more glaciations: Donau (older than Gunz glaciation) and Biber (older than Donau glaciation) to the Peck and Bruckner's classical model. The glacial deposits (moraines) of the Donau and Biber glaciations were isolated terraces and were not interconnected with the deposits of Penck and Bruckner's original scheme. Notwithstanding, a total of six glaciations were recognized.

Merits and Demerits:

The classical model of Alpine region after Penck and Bruckner (1909) was well accepted by the geologists all over the world. In fact, it was the first attempt to subdivide the Quaternary Period into four glacial and four interglacial events. Each Glacial Period was separated by an Interglacial Period, i.e. the time of warm period. Penck and Bruckner's (1909) classical work was strengthened and supported by Milankovitch (1924). It became a powerful tool for classification of Quaternary deposits.

However, Penck and Bruckner's method of classification was based on faulty assumption. It does not follow the normal rules and procedures of stratigraphic classification, i.e., it does not comply with the Law of Superposition. In organizing sedimentary sequence, Penck and Bruckner (1909) followed the principle of morphostratigraphy, i.e., terrace system (older one up and younger below). In addition, climatic fluctuation cannot be the basis for lithostratigraphic classification. Bowen (1978) strongly criticized the method of classification of Penck and Bruckner's (1909) Classical Model. According to Bowen (1978), the Alpine classification is clearly unsatisfactory.

Table 1.1 Penck and Bruckner's (1909) scheme of Glaciation in the Alpine region.

Name of Glacial/ Interglacial Period	Erosional Feature
Wurm Glaciation	Low Terrace
Riss-Wurm Interglacial	Erosion
Riss Glaciation	High Terrace
Mindel-Riss Interglacial	Erosion
Mindel Glaciation	Younger Cover Gravel
Gunz-Mindel Interglacial	Erosion
Gunz Glaciation	Older Cover Gravel

1.4.2 Northern European Model

The Northern European classical model (table 1.2) being largely used in Western Europe for long time with some modifications. This classical model, based on the subdivision of the Scandinavian Ice Sheet, extended beyond the North German plain. During the glacial period the ice sheet extended and in the interglacial period, the ice sheet was retreated leaving the end moraine and ice-contact deposits. The subdivision was based on the recognition of the end moraine system. End moraine system approach effectively delimits successive glaciations. Hence, one series of end moraine system represents one event of glaciation. These successive glaciations were named after the different rivers flowing in the North German plain, such as, the Elster, Saale, Warthe and Weichsel glaciations. The end moraines of these glaciations were weathered differentially. For example, the end moraines of the Warthe and Weichsel glaciations are quite fresh in appearance and still retain, to a large extent, their original morphology as well as numerous depressions on their surfaces. The moraines of the Saale Glaciation

Table 1.2 The classical Sequence of Glaciations and Interglaciations In northern Europe.

Name of Glaciation/Interglaciation		Cold Period	Warm Period
Weichselian Glaciation		Glacial	
Emian Interglaciation			Interglacial
Saale Glaciation	Warthe	Glacial	
	Drenthe		
Holsteinian Interglaciation			Interglacial
Elsterian Glaciation		Glacial	
Cromerian Interglaciation			Interglacial

also retain their original morphology, but those are somewhat subdued and have been dissected to a greater degree. On the other hand, end moraines of the Elster Glaciation have been denuded to such an extent that they have lost their original morphology (Bowen, 1978).

It is to be mentioned that the Europeans remain the pioneers of the Quaternary researches. The concept of the Quaternary and its development started from Europe. Since, the Quaternary is the last Period and the Period covers only a small span of time in comparison with the early Periods of Geological Time Scale, the data and information preserved in the Quaternary sediments are quite fresh. The Lower Pleistocene Quaternary deposits are well exposed in the Campine area of Belgium. These units are briefly discussed in subsequent sections. Table 1.3 shows the lithostratigraphic units present in the Campine area in Belgium.

Pretiglian Stage (Glacial Period)

The first cold period, known as the Pretiglian, based on pollen data from the Netherlands, began about 2.5 million years ago. Reuver deposits of Pliocene are exposed in the Netherlands. These deposits are of fluvial origin. On the top of the Ruverian deposits signature of cold climate has been noticed. The onset of a cold climatic condition resulted in the extinction of the warm loving trees. The appearance of some pollen species, such as Pinus, Betula, Picea etc. indicated that the climate changed from warmer to colder. In Belgium, the shallow marine Markshem Sands were overlain by the Mol sands. The upper and lower Mol Sands are separated by a lignite member, viz., (namely) Arendonk Lignite Member. The Pliocene-Pleistocene boundary is placed on the top of the Arendonk Lignite Member.

Tiglian Stage (Interglacial Period)

The Tegelen clay pits are now-a-days considered a 'classical' locality for mammalian fauna. In 1904, Dubois described the locality in the Netherlands as a suite for fossil mammals. It is the type locality of the Tiglian Stage - a warm period of the Early Pleistocene. The deposit of Tiglian Stage is represented by Tegelen Clay in the Netherlands. The Tegelen Clay is a bluish clay of shallow marine origin. In Belgium, the upper Mol Sands (above Arendonk Lignite) belong to the Tiglian Stage. The Mol Sands are shallow marine deposits. The Mol Sands are used as raw materials for making the famous Belgian Glass. In the Campine area, near the port city Antwerp, the Campine Clay and Sand Formation is exposed. The Formation is composed of three Members (from bottom to top): Rijkevorsel

Table 1.3 Lithostratigraphic units in the Campine area in Belgium.

Epoch (ma)	Glacial/Interglacial Stages (Periods)	Depositional, climatic and vegetational characteristics	
Lower Pleistocene (2.45 – 0.40)	Menapian (Glacial)	Thin layer of eolian deposits, thickness about 0.5m. in Belgium.	
	Waalian (Interglacial)	Turnhout Clay Member: Heavy bluish tidal clay, deposited during marine transgression	*Azolla filiculoides* is a small, free floating freshwater fern
	Eburonian (Glacial)	Beerse Sand Member: Eolian and fluvio-glacial deposits having ice-wedge and cryoturbatin. Pinus, Betula, Abies, Picea etc.	
	Tiglian (Interglacial)	Rijkevorsel Clay Member. Sallow marine deposits represented by bluish heavy clay containing several humic layers and siderite nodules. At least two marine transgressions.	Campine Clay and Sand Formation (Campine area in Belgium, in and around port City Antwerp)
	Pretiglian (Glacial)	Extinction of some Tertiary vegetation, such as Taxodium, Nyssa and Sciadopitys. Appearance of Pinus, Betula, Abies etc. cold loving trees. Plio-Pleistocene Boundary rests on Arendonk Lignite Member (between Upper and Lower Mol Sand) in Belgium	

Clay Member (Lower), Beerse Sand Member (Middle) and Turnhout Clay Member (Upper). All the three members of this Formation is well exposed in and around the Beerse township at Nova (brick field). The Lower Member, called the Rijkevorsel Clay Member represents the deposits of Tiglian Stage. The Rijkevorsel Clay is represented by compacted bluish clay of shallow marine origin. It contains several humic horizons. Siderite nodules formed below the humic horizons. Paleomagnetic results show negative polarity of the Rijkevorsel Clay Member and indicate the Matuyama Magnetozone. There were several marine transgressions during the Tiglian Age.

Eburonian Stage (Glacial Period)

The Beerse Sand Member, middle unit of the Campine Formation belongs to the Eburonian Stage. The deposits are represented by coarse to medium sands, in some places, contain smooth and small gravels. These are the composite layers of eolian and glacio-fluvial deposits. The deposits have many glacial features, such as, ice-wedge, frost wedge, cryoturbation and load-cast structures.

Waalian Stage (Interglacial Period)

The youngest member of the Campine Formation is the Turnhout Clay Member. The Member is represented by dark bluish thinly laminated clay and contains primary sedimentary structures, viz., herringbone crossbedding, indicates the tidal influences. The deposits are exposed around the township Turnhout. These deposits are designated as of the Waalian Interglacial Stage.

Menapian Stage (Glacial Period)

The Menapian Glacial Stage followed the Waal Interglacial Stage and preceded the Cromerian Interglacial Stage, both periods of relatively moderate climatic conditions. The Menapian eolian deposits in the Campine area of Belgium overlie the Bearse Sand Member. Menapian sediments contain the remains of fossil animals and plants (preserved as spores and pollen) adapted to cold climates.

Cromerian Stage (Interglacial Period)

The name 'Cromerian Interglacial or Cromerian Stage' has been derived from Cromer Forest Bed Series Norfolk in the British Isles. Here, the Cromerian Stage has been subdivided into three Sub-Stages: Pastonian (Interstadial), Beestonian (Stadial) and Cromerian (Interstadial). The Cromerian Stage is the lower Interglacial of the Middle Pleistocene which started from about 400,000 yrs. BP. Wet and humid climate favored the growth of that luxuriant forest. In Germany, on the basis of palynological evidences, Cromerian Stage has been subdivided into Waardenburg (Interstadial), Glacial-A, Westerhoven (Interstadial), Glacial-B, Rosmalen (Interstadial), Glacial-C and Noodburghum (Interstadial). It has been suggested that during the Middle Pleistocene warm and humid climate was prevailing in the tropics and subtropics, resulting in the Rubification or brownification (oxidation) of Quaternary sediments.

Elsterian Stage (Elster Glacial Period)

The Elster Glaciation was interpreted to represent the most severe and widespread glaciation in the Alpine region. It has been noticed that the Netherlands was glaciated during this time. The deposits of the Elster Glaciation are found in Hamburg area where the thickness of the deposits locally attains up to 70m (Bowen, 1978). The Elster deposits are also exposed in the Upper Saxony and in Thuringia areas. The Elster deposits are younger than the Cromerians. In northwest Germany, there is a marker horizon, represented by clay and sand, which is called the Lauenburg Clay. Lauenburg Clay is melt water sediments, deposited on Elster till immediately after deglaciation. The Lauenburg Clay has been correlated with the Pokclei (pottery clay) in the Netherlands.

Holsteinian Stage (Holstein Interglacial Period)

There is evidence of marine transgressions during the Holstein Interglaciation. Pollen analyses indicated a pulse of cold climate (subartic), Melbech or Fuhne stadial (middle), which prevailed in between two warm pulses: Hoxnian (Bottom, interstadial) and Wacken (Top, Interstadials).

Saalian Stage (Saale Glacial Period)

The deposits of the Saale Glaciation are morphologically subdued but still clearly recognizable. These moraines form Middle Terrace in the northerly flowing German rivers. In places, Saalian Glaciation has been subdivided into Drenthe and Warthe colder peaks. The moraines of Drenthe Glaciation are somewhat subdued, whereas the moraines of Warthe Glaciation are quite fresh.

Table 1.4 Classical Model of Central North America (after Bowen, 1978).

Stage	Glacial/Interglacial Period	Type Locality
Wisconsin	Glacial	State of Wisconsin
Sangamon	Interglacial	Sangamon County and Illinois. Presence of soil between Wisconsin loess and Illinoian till deposits.
Illinoian	Glacial	State of Illinois. All deposits between the Yarmouth and Sangamon soils.
Yarmouth	Interglacial	Yourmouth, Des Moines County and Iowa. Soil separating Kansas and Illinoian glacial deposits.
Kansan	Glacial	Upper till at Afton Junction Pit, Union County, Iowa.
Aftonian	Interglacial	Gravels at Afton Junction Pit, Union County, Iowa
Nebraskan	Glacial	Lower till at Afton Junction Pit, Union County, Iowa.

Eemian Stage (Eemian Interglacial Period)

The Eemian Interglacial is called the last Interglacial, named after a stream flowing in Netherlands. The marine deposits of this interglacial are younger than the deposits of Warthe Glaciation, overlain by the moraine beds of Weichsel Glaciation in northern Germany. The last Interglacial Period started at about 127,000 BP. There was a marine transgression when the sea level was about 8m higher than the present sea level.

Weichselian Stage (Weichsel Glacial Period)

This is the last glacial period. The lower boundary of Weichsel Glacial Period has been fixed at 73,000 yrs. BP. The moraines of the last glaciation are quite fresh and easily identifiable. The last glacial period has been subdivided into Early (73,000–50,000 yrs. BP), Middle (50,000–32,000 yrs. BP) and Late (32,000 - 10,000 yrs. BP). The peak of the last ice age is called Last Glacial Maximum, at about 18,000 years BP when the Mean Sea Level (MSL) was about 120m below the present MSL. Major part of English Channel remained dry and the British Isles were connected to the main continent. Bering Strait was dry. It was thought that during this Last Glacial Maximum, i.e., at about 18,000 years BP, Homo sapiens crossed the Bering Strait and migrated from Asia to the America. Palynological data indicate some Stadials and Interstadials in the Weichselian Glacial Period.

1.4.3 Classical Model of Central North America

Canada and the northernmost parts of America were glaciated during the Quaternary Period. The classical model of Central North America (table 1.4) was based on till sheets (rock stratigraphic units), landforms (morphostratigraphy) and paleosols (soil stratigraphic units).

1.4.4 East African Pluvial and Interpluvial

During the glacial period solar insolation reduced, ice sheet advanced towards the equator and mountain glaciers extended up to the foot hills and/or adjacent to outwash plain. During the interglacial, ice sheets melted and ice front retreated toward the polar region or mountain tops. Then question arises, what happened to the tropical countries? What would be evidences of cold and warm phases? It was observed that in the tropical regions wet phases alternated with dry phases. The wet phase is called Pluvial and dry phase Interpluvial. It was observed that during the Pluvial, East African lakes were filled up with water, i.e., lake levels rose up (high). On the other hand, the Interpluvials were marked by falling of lake levels. Evidences of shrinkage and desiccation of lakes were recorded by several groups of geologists. Pluvial and Interpluvial in tropical regions were correlated with the glacial and interglacial in the frigid, temperate and subtropical zones. Initial concept was that when Glacial Period was prevailing in the high latitudes, there was heavy rainfall in the low latitudes (tropical regions). This heavy rainfall or Pluvial in the tropics resulted in the rise of lake level. On the other hand, during the Interglacial Period in the frigid and temperate regions, there was dry climatic condition in the tropical region, favored shrinkage and desiccation of the East African lakes. This concept was not based on relevant sufficient data and lack of positive sign of climatic change. But unfortunately, in 1947, the Pluvial and Interpluvial concept was ratified by the first Pan African Congress on Prehistory at Nairobi, and in the following year (in 1948), it was accepted by the International Geological Congress (IGC) in London. Thus, this misconception was approved by an important international body.

Table 1.5 East African Pluvial and Interpluvials Sequence (Bowen, 1978).

Pluvial/Interpluvial	Evidence	Type Locality
Nakurian Pluvial	Lake deposits and shorelines	Lake Nakuru, Kenya
Dry phase	Red blown sand, Gamblian Cave	Gambles Cave, Kenya
Makalian Pluvial	Lake deposits and shorelines	Makalia River Valley, Kenya
1st Post-Pluvial (dry phase)	Red soil and blown sand	Gamblian Cave and Makalia Valley
Gamblian Pluvial	Lake deposits and shorelines	Gamblian Cave and Gamblian Drift, Kenya
3d Interpluvial	Paleosol (Red) and lag (alluvial) gravel; Unconformity at top of Olduvai Bed 4	Uganda; Olduvai Gorge, Tanzania
Kanjeran Pluvial	Lake deposits and shorelines	Kanjera area, Kenya
2nd Interpluvial	Red Bed (Fluvial), Olduvai Bed 3	Olduvai Gorge, Tanzania
Kamasian Pluvial	Lake deposits (unfossiliferous)	Kamasian Plateau, Kenya
1st Interpluvial	'Bone Beds' indicating desiccation.	Lake Albert Basin, Uganda
Kageran Pluvial	Fluvial gravels (unfossiliferous)	Kagera River Valley, Uganda

In fact, the climatic cycles 'Pluvial and Interpluvial' do not represent a stratigraphic sequence (table 1.5). A stratigraphic sequence, mainly, represents lithologic characters: lithology, physical characteristics of sediments, grain sizes etc. Therefore, it is not a scheme based on the stratigraphic succession of Quaternary deposits. It is a scheme of series of inferred climatic cycles. When these climatic cycles are placed in a vertical column, they give the notion of a stratigraphic sequence, which is quite misleading. Sometimes, the identified units were referred to as 'stratigraphic units' or 'climatic stratigraphic units'. Climatic unit should not be considered as geologic or stratigraphic unit.

The present palynological investigation gives an opposite concept. It has been confirmed by pollen studies that when there was Glacial Period in the high latitudes (subtropical and temperate regions), dry climatic condition prevailed in the low latitudes or tropical countries. On the other hand, when there was Interglacial Period in the high latitudes, there was heavy rainfall in the tropical regions (lower latitudes).

1.5 PLIOCENE-PLEISTOCENE BOUNDARY

1.5.1 Introduction

It has been discussed that the major characteristic of the Quaternary is the climatic fluctuations. The cooling of global climate resulted in the accumulation of ice sheets in and around two poles. Further cooling accelerated the movement or extension of ice sheets towards the equator and their accumulation on mountain tops. The terminal moraines of the first Glaciation in the frigid zone are much older than those of the same Glaciation in the temperate zone. Hence, the time of inception of a single Glacial Period varies from latitude to latitude. In addition, the tropical regions were not glaciated except for the high mountains. Now, question arises, if climatic deterioration should be considered as the basis for subdivision of the Cenozoic Era, and then why the time when ice just started to accumulate on two poles, should not be taken as the lower boundary of the Pleistocene Epoch? In addition, question arises, where to fix the Plio-Pleistocene boundary in the tropical region where no signature of glaciation could be ascertain?

Before going through the fixation of Plio-Pleistocene boundary, it is to discuss the principles of chronostratigraphic classification. Traditionally, the classification is based on the presence of guide fossils or unequivocal universal tectonic evidences. The Quaternary Period was separated from the Tertiary on the basis of climatic evidences more than hundred years ago. Bowen (1978) describes three schools of thoughts: i. there is no reason to regard the Quaternary Period fundamentally different from the Tertiary as similar rocks were deposited. Hence, classification should be the same for both the Quaternary and Tertiary, ii. there are certain distinguishing features that make the Quaternary Period and the rock a special case. If that be true, then, special rules should apply. These are usually a combination of stratigraphic and other criteria, such as, geomorphology and periglacial criteria. Moreover, in some instances, use of assemblages of flora or fauna should be considered for a means of dating. iii. This thought views stratigraphic classification as something of a hindrance, and instead advocates the use of radiometric dates as a means of subdivision, correlation and dating.

Some important recommendations were adopted by the General Assembly of the 18th Geological Congress held in London in 1948. The following recommendations were suggested by the temporary Commission on the Pliocene-Pleistocene Boundary (Zagwijn, 1974):

i. The Type Area should be selected prior to the fixation of Pliocene-Pleistocene Boundary and the Boundary should be drawn following the stratigraphic principles.

ii. It is customary to group the fossiliferous strata for stratigraphic classification, the Commission suggested that the Pliocene-Pleistocene Boundary should be based on the evolutionary changes in marine faunas. The Commission recommended that the area of marine sedimentation in Southern Italy be regarded as the best area for the implementation of this principle. The Commission also suggested that the terrestrial equivalents of the marine faunas under consideration could be determined.

iii. To eliminate the then existing ambiguities, the Commission recommended that the Lower Pleistocene should be included as its basal member in the type area the Calabrian Formation (marine) together with its terrestrial equivalent the Villafranchian (this proposal was rejected by a Sub-committee of INQUA, after a field Conference on the Boundary, held in Punjab and Kashmir in 1979).

iv. The Commission noted that the Pliocene-Pleistocene Boundary should be place at the horizon of the first indications of climatic deterioration in the Italian Neogene (this proposal was rejected by a Subcommittee of INQUA, after a field conference on the Boundary, held in Punjab and Kashmir in 1979).

These recommendations followed the most traditional way of stratigraphic classification. These were valuable because the recommendation established the stratigraphic scope of the Pleistocene Epoch. The resolution has emphasized the importance of marine faunas in defining stratigraphic boundary. The third suggestion regarding the correlation of Calabrian Formation (marine) with the Villafranchian faunal assemblages (terrestrial) has become more ambiguous. However, the environments of deposition of marine and continental (terrestrial) sediments are quite different and their correlation is not so easy.

1.5.2 Plio-Pleistocene Boundary in Italy

a) Calabrian Stage in Italy

The name 'Calabrian Stage' was introduced by the French stratigrapher Maurice Gignoux in 1910. A sequence of marine deposits is exposed in Calabria in southern Italy. Initially, the whole sequence was thought to be the deposits of the Pliocene time. The beds of the upper part of these deposits constitute the Calabrian Stage, initially considered as upper Pliocene, precedes the Sicilian Stage and are more or less, continuously overlie older Pliocene deposits, called Austian Stage. These Calabrian beds are characterized by the absence of typical Pliocene molluscan species and presence of some modern forms. Among the modern forms that can be found in Calabrian Beds, there are some special forms that normally live in cold sea. These modern special forms are called the 'Northern immigrants'. Among the modern forms, *Cyprina islandica*, a molluscan fauna is most important. Hence, the concept of Calabrian Stage is characterized by a particular faunal assemblage rather the presence of index fossil.

In the foraminiferal assemblages, some cold loving foraminifera were recorded. Among them, *Hyalinea baltica* is most important. This species of foraminifera is, presently, living in the Bering Strait (cold sea). This is a cold species of foraminifera and can be found in the Calabrian beds. Hence, the presence of these two cold loving species (*Cyprina islandical* and *Hyalinea baltica*) in the Calabrian Formation, indicates the first appearance of the Glacial Period and this level has been considered the base of Pleistocene. *Cyprina islandica* is a shallow water Molluscan fauna, on the other hand, *Hyalinea baltica* is deep water benthic foraminifera. Therefore, these two species cannot be found together in one layer. The 18th International Geological Congress, held in London in 1948, recognized the Pliocene-Pleistocene boundary at the base of the Calabrian Stage. Hence, Calabrian deposits, defined by Gignoux (1913) do not represent upper Pliocene rather they represent Pleistocene, the base of the Quaternary.

Initially, the section at Santa Maria di Catanzaro in southern Italy was selected as Type Section for Pliocene-Pleistocene Boundary. However, the base of the Pleistocene Series is defined formally in a Strato-type at Vrica, Calabria, southern Italy. Biostratigraphic criteria for correlating the boundary level are well supported by magnetostratigraphic and geochronologic data (Aguirre and Pasini, 1985).

b) The Villafranchian Stage

In 1865, a famous Italian geologist Lorenzo Pareto defined Villafranchian Stage. Villafranchian age designated geologic time (3.50 – 0.80 ma), overlapping the end of the Pliocene and the beginning of the Pleistocene, used more specifically with European Land Mammal Ages. The Villafranchian deposits are terrestrial sequences. In these deposits plenty of different species of mammalian faunas were found. The Type Section is situated near Villafranca d'Asti, a town near Turin in northern Italy. In 1948, the temporary Commission on Plio-Pleistocene Boundary recommended this terrestrial Villafranchian Stage partially equivalent to the marine Calabrian Stage. But ultimately, this proposal was rejected by a Subcommittee of INQUA, after a field Conference on the Boundary, held in Punjab and Kashmir in 1979. The Villafranchian Stage has been subdivided into three substages from older to younger: Lower (3.50 to 2.43 ma), Middle (2.43-1.80 ma) and Upper (1.80-0.80 ma). Among the Villafranchian faunal assemblages, viz., *Elephas, Leptobos* and *Equus*, immigrants from Asia hold importance as these mammals are deemed to be representatives of Pleistocene Epoch. Some most important mammalian faunas found in the Villafranchian deposits are given in the table 1.6.

1.5.3 Tiberian Limit

A dramatic climatic change at certain level was noticed in the Netherlands. It was traced by means of pollen studies. In the Reuver Clay (Pliocene) several Taxa, such as, *Sequoia, Taxodium, Sciadopitys, Nyssa, Liquidamber* and others were found. But these taxa are absent in the Pleistocene Tegelen Clay. There was a change in the floral composition at certain level. It was believed that an advent of cold phase during this time caused the extinction of *Taxodium, Sciadopitys, Nyssa* etc. Pollen analyses of several Plio-Pleistocene sequences in northern and central Italy indicated this horizon. The partial floral extinction of *Taxodium, Sciadopitys, Nyssa* was also noticed in the Reuver Clay in Netherlands. This level was named as 'Tiberian limit' after the Tiber basin in Italy, where the section of fresh-water deposits at Pietrafita distinctly showed this phenomenon. A cold phase caused the extinction of *Taxodium, Sciadopitys, Nyssa* and others. Several warm phases afterward followed this cold phase where significant presence of *Carya, Pterocarya, Tsuga, Eucommia* and *Celtisare* was observed, but *Taxodium, Sciadopitys, Nyssa* etc. permanently disappeared and was never found again (Bowen, 1978).

1.5.4 INQUA's Proposal on Plio-Pleistocene Boundary

In 2009, the International Commission on Stratigraphy has adopted the classification (SQS/INQUA's Proposal) of the Quaternary Period (see table 1.7). The Commission also approved the Plio-Pleistocene Boundary at the Type Section at Monte San Nicola in Italy. The section crops out in the badlands (Calanchi) on the southern slope of the Monte San Nicola, some 10km N-NW of the town of Gela (Caltanissetta Province). The base of the Gelasian Stage is defined as the base of the marl layer overlying sapropel MPRS 250. The astronomical age of sapropel MPRS 250 (mid-point), corresponding to precessional cycle 250 from the present, is 2.588 Ma, which can be designated as the age of the boundary (MPRS - Mediterranean Precession Related Sapropel).

In the Type Section, the lower 36m of the succession comprises rhythmically bedded marls and limestones of the Trubi Formation, grading upward into marly-silty Monte Narbonne Formation. The Monte Narbonne Formation is characterized by brownish red laminated intervals (sapropels) and by brownish non-laminated manganiferous levels. Both the units are important for regional correlations; the sapropels being an important tool for astronomical calibration.

There are some marker horizons in the Type Section at Monte San Nicola

i. Precessional Cycle

In the boundary interval, a cluster of six sapropel or manganiferous levels is recognized and correlated to coeval sections in Sicily, Calabria and Northern Italy. The single sapropels of this cluster have been coded as the Mediterranean Precession Related

Table 1.6 Showing only some important Villafranchian mammalian faunal assemblages.

Stage	Absolute age (Million Years)	Mammals
Upper Villafranca	1.80 to 0.80	Farneta zone: Archid. *Meridionalis, Equus stehlini, Leptobos etruscus, Homotherium.* Tasso zone: *Canis arnensis, Mimomys pliocaenicus, Lepus valdarnensis.* Liva zone: *Eq. stenonis, Leptobos ectruscus, Panthera toscana, Canis etruscus.*
Middle Villafranca	2.43 to 1.80	Saint Vallier zone: *Mimomys Pliocaenicus, Mimomys polinicus, Lept. Stenometopon, Anancus avernensis, A. Meridionalis.*
Lower Villafranca	3.50 to 2.43	Monopoli Zone: *Anancus avernensis, D. jeanvireti, Ceruus pardinensis, Leptobos. Stenometopon. Triversa Zone: Tapirus avernensis, Anancus avernensis.*

Sapropels (MPRS) and linked to the corresponding precessional cycle. The base of the Gelasian Stage is defined as the base of the marly layer overlying the sapropel MPRS 250. According to Rio et al., (1998) the astronomical age of the sapropel MPRS 250 (mid-point) is 2.588 Ma, which is assigned to be the age of the boundary.

ii. Paleomagnetics:

The section represents the interval between the upper part of the Gilbert Chron (C2Ar) and the Matuyama Chron above the Olduvai Subchron (C1r). The Gauss/Matuyama boundary is clearly recognized and placed 1 meter below the GSSP.

iii. Nannofossils:

The last appearance of *Discoaster pentaradiatus* occurs in most low and mid-latitude areas close to the isotopic stage 99, 80kyrs above the boundary.

iv. Isotope

Matuyama/Gauss boundary (C2r/C2An) is placed 1m below GSSP horizon is within the Marine Isotope Stage 103.

(Abbreviations: GSSP: Global Boundary Stratotype Sections and Points, MPRS: Mediterranean Precession Related Sapropel).

1.5.5 Plio-Pleistocene Boundary in the Bengal Basin

The reddish-brown clastic deposits exposed in the Lalmai Hills, Madhupur and Barind tracts are called Madhupur Clay Formation. The lower member of the Madhupur Formation is represented by bidirectional (herringbone type) cross-bedded, highly micaceous sand (deposits). At the bottom of this sand, quartz-chalcedony gravel bed is present. This quartz-chalcedony gravel bed, named as Cumilla Gravel Bed, represents a marker horizon in the Bengal basin. The Plio-Pleistocene boundary has been placed at the top of this Quartz-chalcedony Gravel Bed. This Bed is well exposed in the Ranirbanglow section of Lalmai hills. This Bed can also be seen in the Rupban Mura hill-slope section. In the Bengal Basin, it has been assumed that the Pleistocene started around 1.6 million years ago.

1.6 GLACIAL GEOLOGY

1.6.1 Introduction

It has already been discussed that the concept of the Quaternary developed owing to the extension of continental glaciers and their advancements from the Artic region (Polar regions) towards the temperate region (Subtropical regions) or extension of glacier from the mountain tops downward the valley trains and outwash plains. It has been found that green agricultural lands in some temperate regions were glaciated in the long past. At present, only 10% of land surface is covered with ice. During the last glacial maximum 32% of land area was covered with ice. Hence, the Quaternary geology, especially, Quaternary geomorphology, its relief and landforms, processes of deposition and so forth are very much related to the glacial geology.

There are two types of glaciers: continental glacier and mountain glacier. Glacier is not a morphological feature. Glaciation is the development and spreading of glacier or ice sheet on surface. Glaciation means the effect of glacier or ice sheet on bed rock, eroding and depositing rock debris. On the undulated surfaces, hill slopes and valley trains, ice sheets move downward, eroding bed rock by abrasion. There are some distinct zones of activities: i. a zone very close to the center of dispersion of ice sheet. Here, the erosional debris are dispersed and the zone can be recognized by a bare bedrock surface, ii. the zone of deposition of the glacial drift; the load of debris picked up by the eroding ice sheet is deposited, iii. the third zone is the zone of end moraine formation or the zone of accumulation of till deposits, iv. last zone is the zone of proglacial deposition. Melt water transports finer sediments (gravels, sand, silt and clay) which settle out over the outwash plain.

Meltwater carries outwash from the ice front. The sediments deposited by meltwater depend on the marginal landscape. If it slopes steeply away, no outwash may be accumulated as the meltwater velocity is sufficient to carry all types of sediments. In this case, river-valley cutting becomes prominent. For the gentle slope ice front, sediments may be deposited above the local standing water level to form layers of different grain sizes or bands of outwash. These are called glacio-fluvial deposits. The outwash may be discharged into an ice-marginal lake to form glacio-lacustrine deposits or into the sea to form glacio-marine deposits. Grain size of the deposits depends on the outwash load, whether it is rich in gravel, sand, silt or clay. The grain size decreases away towards the distal slope. In this chapter, only the important aspects of glacial geology will be briefly focused for the Quaternary geologists of plainland, like Bangladesh.

1.6.2 Glacial and Proglacial Deposits & Landforms

A. Glacial and Proglacial Deposits: Moraines

Moraines are the glacier-borne unsorted

Table 1.7 ICS-Approved Quaternary (SQS/INQUA) Proposal, 2009.

ERA	PERIOD	EPOCH & SUBEPOCH		AGE	AGE (Ma)	GSSP
CENOZOIC	QUATERNARY	HOLOCENE			0.012	
		PLEISTOCENE	Late	Tarantian	0.126	
			M	Ionian	0.781	
			Early	Calabrian	1.806	Vrica Calabria
				Gelasian	2.588	Monte San Nicola, Sicily, Italy.
	TER	PLIOCENE		Piacenzian	3.600	
				Zanclean	5.332	

deposits of different grain sizes, large boulders to fine-grained unconsolidated debris deposited in the glaciated or formerly glaciated areas. The particles are angular or sub angular to rounded in shape. Moraines may be found on the surfaces of glaciers or may be deposited as piles or sheets of debris in the areas of ice front or along areas of snow line where ice melts. At places, glaciers or icebergs transport rocks into water bodies (lake or sea) and deposit the transported debris (moraines) when ice melts. There are different kinds of moraines: i. Lateral moraines, ii. Ground moraines, iii. End or Terminal moraines, iv. Medial moraines, v. Supra-glacial moraines, vi. Washboard moraines and vii. Veiki moraines.

i. Lateral moraines: This type of moraines is deposited along the sides of an advancing glacier. These unconsolidated debris may be deposited on top of the glacier and may form parallel ridges along the sides of a glacier. Since the lateral moraines are deposited on top of the glacier, their position is always on top of the valley floor and also partially on top of the ground moraines after deglaciation. When the glacier melts, lateral moraines preserve as high ridges parallel to the direction of the ice movement. The repetition of glacier movements, i.e. advancement and retreats of glaciers form some multiple lateral high ridges.

ii. Ground moraines: These are the deposits forming some irregular surfaces or rolling hills or rolling elevated plains. In fact, these are the lodgment tills, accumulated at the base of glacier ice. At places ground moraines are found between two terminal moraines.

iii. End or Terminal and recessional moraines: This type of moraine is deposited at the end of a glacier. They form some ridges of unconsolidated debris. The end moraines are of two types: a. terminal moraines and b. recessional moraines. The terminal moraines represent the maximum advance of the glacier. On the other hand, recessional moraines mark the retreat of glacier. The recessional moraines are unconsolidated debris, perpendicular to the lateral moraines. These are deposited during the time of temporary halting of glacial retreat. These moraines are eroded by postglacial erosional activities (figure 1.5).

iv. Medial moraine: Medial moraines are formed when two glaciers meet at one point. When the glaciers melt, the debris are deposited and form a ridge down the middle of the valley floor.

v. Supraglacial moraines: Supraglacial moraines are deposited on the top of the ice sheet. The oblation debris can accumulate due to ice flow toward the surface. The melting of surface ice or debris that falls onto the glacier from valley sidewalls.

vi. Washboard moraines: These are low-amplitude geomorphic features. The name came from the fact that they resemble wash-board.

vii. Veiki moraines: It is a kind of hummocky moraine that forms irregular landscapes of ponds and plateau surrounded by banks. Discontinuous melting of ice forms this kind of feature. Ice is thus covered with thick layer of debris. These are quite common in Sweden and Canada.

The glacial deposits and landforms largely differ from the products of other geological processes. Hence, the studies of glacial deposits unravel the history of glaciation of a region. Sorting, sphericity and roundness, angularity and degree of stratification are most important in defining glacial deposits. Ice drifted deposits are not stratified and sorted. Melt water plays an important role for stratification. Hence, the ice drifted deposits (moraines) under the glacier or at the terminal zone of a glacier (end moraines and tills) naturally are not sorted and stratified. On the other hand, melt water deposits in the outwash plain are more or less sorted and are stratified. Hence, there are mainly two categories of deposits:

a. Unstratified: Till deposits; accumulate at or near the ice front. These are unsorted and unstratified deposits.

b. Stratified deposits: Proglacial deposits-deposits of outwash plain and lake at distal slope, e.g. gravel, sand, silt and clay. Between these two extremes, there are ice-contact stratified deposits, formed near to the ice sheet, but washed to some degree by melt water.

Tills

Tills are the unstratified and unsorted boulders to clay size bulk materials drifted by ice sheets and accumulate on or near the ice front. When ice sheet moves over bedrocks, it picks up all sorts of eroded materials including rock flour resulting from glacial abrasion. When ice melts the drifted unsorted materials laid down along the ice front or snow line. The particles are of all size grades from clay to boulders being mixed together in the deposit. There are different kind of till: i. Lodgement till: During melting of ice, the unsorted debris drifted by ice sheet are laid down at the base of glacial ice are called Lodgement till. ii. Oblation and flow tills: During the movement of glacier oblation tills accumulate near the margins of glacial ice. The oblation tills are sometimes non-graded. Fine grained sediments are removed by meltwater streams. iii. Shearplane till: Shearplane tills are accumulated at the fractured planes of moving glaciers.

Varves

The varves are the deposits having distinct layers of annual increments of sediments. The word 'varve' derives from the Swedish word *varv* whose meanings and connotations include 'revolution', 'in layers', and 'circle'. Initially, the word was used for laminated clays formed in proglacial standing water. The layers of laminations are formed by the winter and summer cycles and the layers or laminations are differentiated by textures and colors. During the summer times, high flow of meltwater discharged into the lakes or proglacial standing water where coarse to fine sediments were deposited. At the onset of winter, melting of continental ice sheet ceased and the finest particles were precipitated. In the next summer, again the coarsest sediments started to settle down. This annual climatic cycle results a sharp winter-to-summer transition and then a gradual summer-to-winter one, and hence the sediments layer between the sharp dividing lines represents one year's sedimentation. These are called varves. Sometimes, counting of the layers of varve sediments are used for chronologic dating in geology.

B. Glacial and Proglacial Landforms

Broadly, there are three kinds of glacial landforms: i. Constructional landforms, form by the direct action of ice. These categories of landforms are composed of moraines and tills. ii. Ice-contact landforms and features which consist of predominantly of ice-contact deposits, but which may also contain some tills. Such features are usually formed by deposition from meltwater in close contact with ice. iii. Landforms and features associate with proglacial sediments. For example, outwash plain and valley trains.

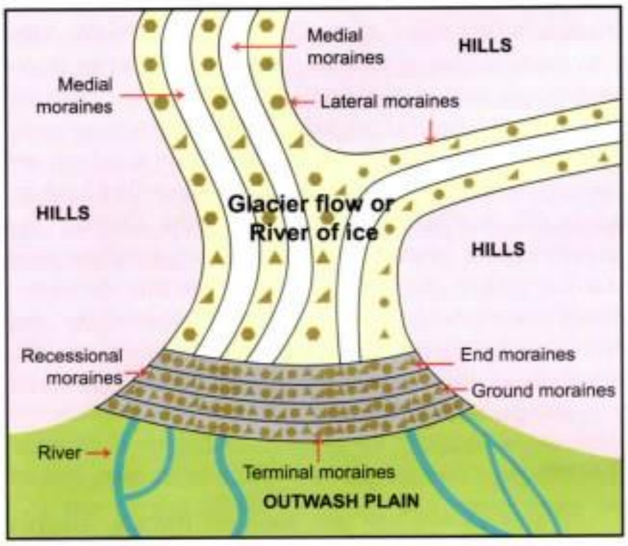

Figure 1.5 Types of moraines.

Morainic Landforms

The constructional landforms are formed by the direct action of ice. These are the morainic landforms. Behind the end moraines of ice front, drumlins are found. Drumlins indicate the advancement of ice sheet.

Ice-contact Landforms

The most important landforms are: i. Eskers, ii. Kames, iii. Kame terraces, iv. Kettle holes, v. Drumlins, vi. Outwash Plain (figure 1.6).

i. Eskers

Eskers are elevated ridges those can be found in the proglacial regions (figure 1.6). These elevated

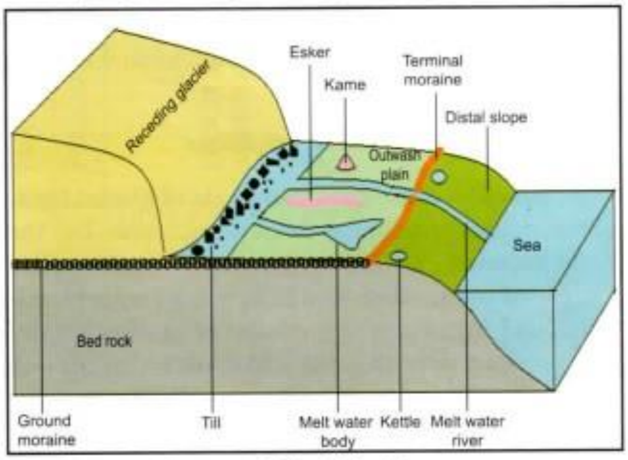

Figure 1.6 Glacial landforms.

ridges, formed by the till deposits, parallel to the direction of movement of ice sheets. Eskers are formed within ice-walled tunnels by flowing streams. The day/night or annual temperature variation causes melting of top of ice sheet and meltwater flows on top surface of glacier creating a deep ice-walled tunnel. During the meltwater flow, the sediments were accumulated on the stream beds. When ice sheets along with ice-walled tunnels, were melted down, the deposits were remaining as winding ridges. In this way, the bedload sediments of the paleochannel flowing on top of ice sheet formed this kind of elevated ridge, called Esker. The eskers are almost symmetrical. The lineation of eskers indicates the paleostream flow on the ice sheets or within ice-walled tunnels.

ii. Kames

Kames are low hills with steep slopes (figure 1.6). They are formed by the ice contact stratified drift. The kames are mounds of sands and gravels in the areas of slowly melting or stationary ice sheets. The debris built up into mounds as the ice melt and more sediments were deposited on top of old debris.

iii. Kame terraces

The kame Terraces are also composed of sands and gravels, but form along the sides of the glacier. The kame terraces are formed laterally to ice sheet by meltwater streams (West, 1968). They are formed by the actions of meltwater streams. These streams were flowing along the sides of the ice, trapped against it by the valley walls. The valley walls were warmed up in summer, the warmed rock helped to melt the ice nearest to it, forming a long depression or trough along which meltwater flowed. Since, the kame terraces are formed by the action of flowing water, the sediments are sorted. The sorted sediments of kames terraces differ from unsorted lateral moraine deposits.

iv. Kettle holes

Kettle holes form by the block ice, separated from the main glacier when the ice sheet retreats. Sometimes, the ice blocks are partially buried in meltwater sediments. When the ice blocks ultimately melt they leave behind holes or depressions. These holes are filled up with water. Sometimes, kettle holes form small lakes in the outwash plain.

v. Drumlins

Drumlins form under moving glaciers. These are elongated tear dropped hills or hillocks, composed of glacial deposits, aligned in the direction of ice flow.

vi. Outwash plain

After deglaciation, meltwater flows over a flood plain through the numerous streams and rivers. This flood plain is called Outwash plain (figure 1.6). These streams and rivers discharge the water into some lakes or sea. The sediments deposited by the streams and rivers in the outwash plain are called fluvio-glacial deposits. The point at which the melt water discharges into lake or sea is called 'Distal Slope'. The environment of deposition at the distal slope is called glacio- fluvio-deltaic Environment.

1.6.3 Glacial and Periglacial Effects (only some important zones and features)

i. Permafrost

Permanently frozen ground is called Permafrost (figure 1.7). In the permafrost area, the sediments below the surface remains frozen for a period more than a year. In this area, the saturated sediments are undergone in a frozen state. Soil becomes very hard like stones where no vegetation can grow. In most cases, periglacial areas are underlain by permafrost. Permafrost occurs where the Mean Annual Temperature of ground remains less than 0⁰C. Normally, the depth of permafrost can be up to several hundred meters. In some regions, it can be up to 1500 meters. There are different types of permafrost. i. continuous permafrost: The area has never undergone the process of thawing. ii. discontinuous permafrost: When the area is sometimes thawed, is called discontinuous permafrost. These areas are the marginal zones at the edge of the continuous permafrost (Flint 1971). The top part of permafrost, sometimes, is subject to a cyclic thaw during the warm season. This top part is called Active layer. The Active layer is disturbed by cyclic freezing and thawing process. The thickness of Active layer varies from one meter to three meters. Permafrost areas are found in Russia and Canada.

ii. Polar Desert

Polar deserts are the areas where annual precipitation is less than 250 millimeters and a mean temperature during the warmest month is less than 10°C. Polar deserts on earth cover nearly 5 million square kilometers and are mostly hard bedrock or gravel plains. Polar desert climatic condition was prevailing in wide areas of land surfaces during the last glacial periods. Loess is an important deposit of the polar desert area. Loess is an aeolian deposit. The loess particles having the sizes less than 60 micrometers are transported by wind before settling down. The loess particles get deposited when wind velocity decreases. A wide area of Belgium (Beerse Sand) and France was covered by loess deposits during the last glacial period. The source of loess sediments was the dried up coastal region of the North Sea. The eolian deposits were deposited from source as per grain sizes: sand to clay. Those aeolian (windblown) sediments are called cover sand (sand dominates), loam (sand, silt and clay) and loess (dominantly, silt and clay). A series of buried paleosol horizons can be found in loess deposits. Chinese Loess Plateau has a thickness of about 100 meters having a series of paleosols layers.

iii. Talik

Taliks are the unfrozen rocks, layers or masses in the permafrost (figure 1.7). Talik can be found on top or within the masses of permafrost. In most cases, taliks are found under lakes. Taliks are formed because of the ability of water to store and vertically transfer heat energy. Open taliks can be found in the permafrost under lake water and closed taliks are seen under the active layer of permafrost areas. The closed taliks are formed due to the groundwater flow. Closed taliks can also be formed under a lake when the lake filled up with sediments.

iv. Ice Wedges

The most important feature that can be found in the periglacial areas is the ice wedge. Ice wedges are the cracks in soil surface narrowed downward filled with ice. These cracks are formed due to the differential expansion and contraction of saturated or unsaturated soil material by cryogenic effect. The cracks penetrate up to the depth of about 3 to 4 meters. In fact, these are the features indicative for the formerly glaciated areas. In the polar deserts or in the permafrost areas, ground surfaces are fractured in different shapes (polygons) like mud cracks, due to the cryogenic effect (figure 1.8).

During the glacial periods, extreme cold temperatures caused soil contraction and these kinds of cracks were developed. Periodical changes of weather resulted in the widening and deepening of cracks or fractures. In the polar deserts, these cracks were filled up with aeolian sediments. And that is why, the sediments of these fossil ice wedges are different from the adjacent sediments and the wedges become quite distinct in the stratigraphic sections. In the stratigraphic cross section, the fossil crack appears like a 'wedge'. These wedges are called Fossil Ice Wedges or Frost Wedges (figure 1.9).

v. Pingo

Pingos are ice-cored hills or hillocks (figure 1.10). The height of pingos varies from 3 to 70 meters with a diameter between 30 to 1000 meters. Sometimes, large pingos have a curved ice top. This top sometimes melts and creates a lake on top. Ice accumulate at the core of the pingos due to the cryostatic pressure and artesian groundwater. The cryostatic pingos are developed with some lakes. The lakes fill up with sediments. Water then inside the sediments gradually freezes and volume increases to form such dome shaped hillocks.

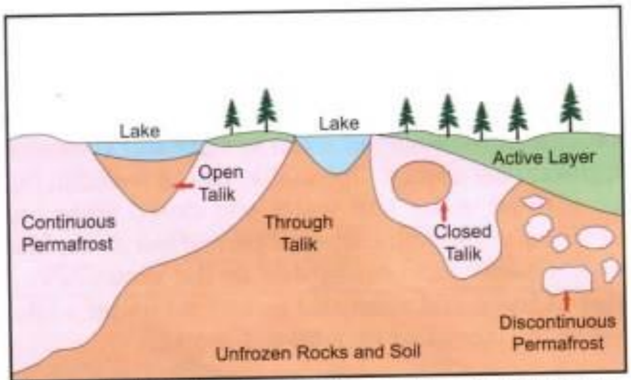

Figure 1.7 Sketches of permafrost, talik and active layer. (The figure is drawn sharing the concept of Dr. Michael Pidwirny & Scott Jones University of British Columbia Okanagan Vertical cross section of the transition zone between continuous and discontinuous permafrost. The graphic also shows the various types of talik or unfrozen ground).

Figure 1.8 Sketches of patterned ground with polygonal cracks in the permafrost area.

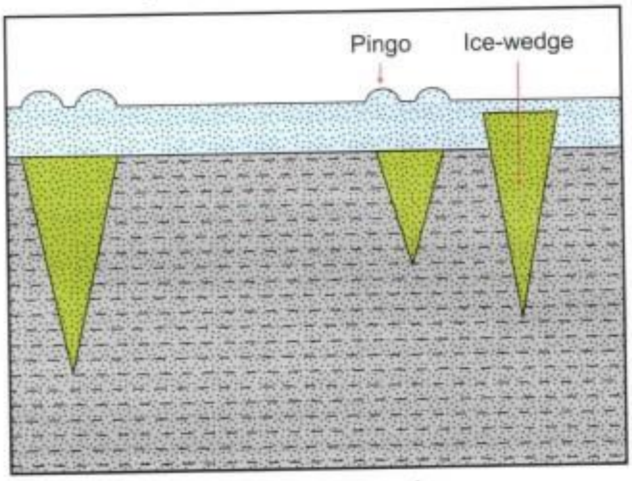

Figure 1.9 An ice-wedge.

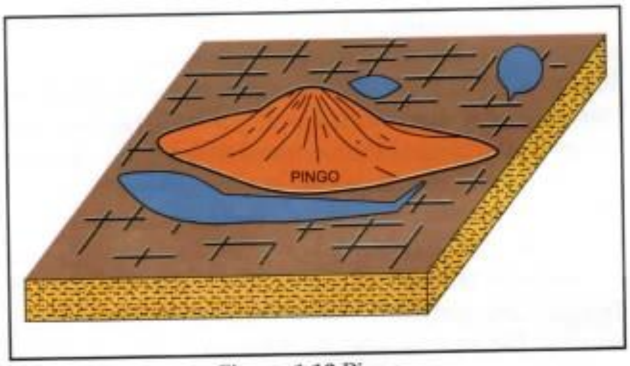

Figure 1.10 Pingo.