Glacial ice accumulates when the average winter snowfall exceeds the amount of snow and ice lost in summer by ablation.

Ablation occurs through sublimation, melting, and evaporation.

When winter snowfall exceeds summer ablation, a layer of snow is added each year to what has already accumulated.

As the snow compacts by melting and refreezing, it turns into granular ice that is gradually compressed into hard crystalline ice by overlying layers.

When the ice mass is so thick that the lower layers become plastic, outward or downhill flow starts, and the ice mass is now an active glacier.
Glaciers

Typically, mountain glaciers are long and narrow because they occupy former stream valleys (alpine glacier).

Smaller glaciers that persist in mountain basins are called cirque glaciers.

Others, called hanging glaciers, end as icefalls when they no longer extend down to the main valley.

A regionally extensive ice accumulation in a mountain region that feeds several glaciers is known as an icefield.

In arctic and polar regions, prevailing temperatures are low enough that snow can accumulate over broad areas, eventually forming a vast ice sheet several thousand metres thick.

The largest ice sheets are in Greenland and Antarctica.

At some locations, long tongues extend from ice sheets as outlet glaciers or tidewater glaciers that reach the sea at the heads of fjords.

Huge masses of ice break off from the floating edge of the glacier and drift out to open sea with tidal currents to become icebergs.
Glaciers

Alpine Glaciers

An alpine glacier begins in a bowl-shaped depression, called a cirque, and occupies a sloping valley between steep rock walls.

Snow collects in the zone of accumulation where layers of snow are compacted and recrystallized.

The lower part of the glacier lies in the zone of ablation where the ice wastes away.

The equilibrium line marks the boundary between the accumulation zone and the ablation zone.

Changes in gradient of the underlying rock surfaces also influence glacier movement.

Where the gradient is steeper, a glacier will accelerate and thin; this is called extending flow.

Areas of extending flow are usually characterized by large tensional cracks, known as crevasses.

Conversely, compressive flow occurs in response to a reduction in gradient.

Here, the ice thickens and pressure ridges deform the surface.

A Glacier as a System of Matter and Energy

In the zone of accumulation, snowfall provides input to the glacier as it becomes compacted and recrystallized.

During warm periods, some snow is lost to melting, evaporation, and sublimation, but the annual balance favours accumulation.

When the glacier reaches lower elevations, it loses more water.

The balance shifts at the equilibrium line to a net loss of ice over the year, and the glacier enters the zone of ablation.
Glaciers

A Glacier as a System of Matter and Energy

Solar energy provides water at high elevations through precipitation, thus contributing potential energy as an input - gravity powers the downhill motion of the ice (potential energy is converted to kinetic energy, and the kinetic energy is dissipated as heat generated by friction).

The surface of a glacier is subjected to short-wave heat flows from solar radiation - provides a positive net radiation balance during the day.

Most of the energy flow melts the ice, leaving less energy available to warm the overlying air through sensible heat transfer (less energy remains to sublimate the snow and evaporate the meltwater - reduces the flow of latent heat to the atmosphere, making the local climate colder).

Glaciers

Landforms Made by Alpine Glaciers

Glacial ice normally contains abundant rock fragments, ranging from huge angular boulders to pulverized rock flour - the combined actions of abrasion and plucking smooth and chip the bedrock.

Abrasion by very fine particles can polish the surface of the bedrock; more pronounced scratches or striations are cut by larger particles.

As the calibre of the transported material increases, grooves and furrows may be formed.

Crescentic gouges or chattermarks can also be chipped out of the bedrock.
Glaciers
Landforms Made by Alpine Glaciers

Cirques grow steadily larger - their rough, steep walls replace the smooth slopes of the original highland mass.

Where two cirque walls approach from opposite sides, a jagged, knife-like ridge, or arête, is created.

When three or more cirques grow together, the remnant highland is left as a sharply pointed pyramid peak, or horn.
Glaciers
Landforms Made by Alpine Glaciers

Debris carried in, on, or under the ice is eventually deposited as ridges or piles of rock.

A lateral moraine is a debris ridge formed along the edge of the ice adjacent to the trough wall.

Where two ice streams join, marginal debris is dragged as a narrow band on the ice surface (medial moraine).

At the terminus of a glacier, rock debris accumulates in a terminal moraine.

Recessional moraines mark the positions where the snout of a receding glacier remained stationary long enough to produce a depositional ridge.
Glaciers
Landforms Made by Alpine Glaciers

A valley is constantly deepened and widened as a glacier passes along it.

After the ice has disappeared, a deep, steepwalled glacial trough remains.

The trough typically has a U-shaped cross-profile.

In coastal areas, deeply excavated glacial troughs are usually flooded with sea water as the ice recedes, creating fjords.

The Late-Cenozoic Ice Age

The present ice sheets in Greenland and Antarctica provide an impression of the landscape that would have existed over much of Canada at the peak of the Late-Cenozoic ice Age (Ice Age).

Began in late Pliocene time, perhaps 2.5 to 3.0 million years ago.

The Ice Age is associated with the last three epochs of the Cenozoic Era: the Pliocene, Pleistocene, and Holocene.
The Late-Cenozoic Ice Age

A period during which continental ice sheets grow and spread outward over vast areas is known as a glaciation.

Eventually, the ice sheets may melt completely (deglaciation).

Following a deglaciation, but before the next glaciation, is a period in which a milder climate prevails; such a period is referred to as an interglaciation or interstadial.

A succession of alternating glaciations and interglaciations, spanning a period of several million years, constitutes an ice age.

Glaciation During an Ice Age

During the Wisconsinan Glaciation, most of Canada was engulfed by the vast Laurentide Ice Sheet that was centered in the general vicinity of what is now Hudson Bay.

Ice spread into the United States, covering most of the land lying north of the Missouri and Ohio rivers, and extending eastward into New England.

Alpine glaciers from the western mountains coalesced to form the Cordilleran Ice Sheet that spread to the Pacific shores and met the Laurentide sheet lying to the east.
The Late-Cenozoic Ice Age

Wisconsinan Glaciation

Isostatic Rebound

Isostatic mound created a raised coastal region in late high stands, later falling after melting of the Laurentide Ice Sheet.
Landforms Made by Ice Sheets

Like alpine glaciers, ice sheets are highly effective agents of erosion, and several landscape features are common to both environments.

For example, the slowly moving ice scrapes and grinds away solid bedrock, leaving behind smoothly rounded rock masses.

These show countless grooves and striations trending in the general direction of ice movement.
Deposits Left by Ice Sheets

The term glacial drift includes all varieties of rock debris deposited as a result of continental glaciation.

Two major types of drift are distinguished according to the degree of sorting and layering that occurred during deposition.

Till or non-stratified drift is made up of a mixture of rock fragments, ranging in size from clay to boulders, that is deposited directly from the ice without subsequent water transport.

Stratified drift consists of layers of clays, silts, sands, or gravels that were deposited by meltwater streams or settled out in bodies of water adjacent to the ice.
Deposits Left by Ice Sheets

Ablation till shows no sorting, and often consists of a mixture of sand and silt with many angular stones and boulders.

Beneath this residual material, there may be a basal layer of dense lodgement till, consisting of clay-rich debris previously dragged forward beneath the moving ice.

Where ablation till forms a thin, more-or-less even cover, it is called a ground moraine.
Deposits Left by Ice Sheets

Glacial till usually does not form prominent landscape features, but tends to obscure, or entirely bury, the landscape that existed before glaciation.

Where the deposits are thick and smoothly distributed, they form a level till Plain.

Thicker deposits of glacial till that accumulate in a narrow zone at the ice margin form a terminal moraine comprising heaps of unsorted debris.

Small lakes may occupy depressions within this undulating landscape of mounds and ridges; such terrain is often referred to as knob-and-kettle topography.

Terminal moraines reflect the shape of the ice margin, which consisted of a series of great ice lobes, each with a curved front.

Where two lobes come together, the moraines curve back and fuse together into a single interlobate moraine.

A drumlin is another common feature formed from glacial till; these smoothly rounded, oval hills have the general shape of an inverted spoon.

Drumlins invariably lie in a zone behind the terminal moraine.

The long axis of each drumlin parallels the direction of ice movement, with the steeper, broader end facing the oncoming ice.
Stratified Glacial Deposits

In front of the ice margin, a smooth, gently sloping outwash plain or sandur accumulates from stratified drift left by braided streams issuing from the ice.

Outwash plains are built of layer upon layer of sands and gravels distributed and sorted by the continuous lateral shifting of the meltwater streams.

Because they develop beyond the margin of an ice sheet, an outwash plain is classed as a proglacial deposit.

Stratified Glacial Deposits

In some cases, large meltwater streams flowing within (englacial streams) and beneath (subglacial streams) the ice sheet emerge from tunnels at the ice margin.

After the ice has disappeared, the positions of such streams are marked by long, sinuous ridges of sediment.

These features are called eskers and represent the deposits of sand and gravel on the tunnel floors.
Stratified Glacial Deposits

When ice sheets advance toward higher ground, outlet valleys may become blocked with ice. Under these conditions, meltwater can collect in marginal glacial lakes that form along the ice front. Meltwater streams draining from the ice are able to build glacial deltas into these marginal lakes.

After the ice has disappeared and the proglacial lake has dried, several distinctive features remain in the landscape. Exposed lake beds remain as glaciolacustrine plains underlain by soils that are predominantly clay; these plains often contain extensive areas of marshland.
**Stratified Glacial Deposits**

In many locations, the sediments deposited in former glacial lakes contain *varves*.

Varved sediments consist of alternating layers of clay and silt, usually only 1 to 2 cm thick.

The layers reflect seasonal deposition in the lakes at the ice margin.

**Investigating the Late Cenozoic Ice Age**

Deep-sea cores reveal a long history of alternating glaciations and interglaciations going back at least 2 million years, and possibly 3 million years BP.

The cores show that more than 30 glaciations occurred in Late-Cenozoic time, spaced at intervals of about 90,000 years.
Causes of the Late Cenozoic Ice Age

Three principal causes are postulated for the Ice Age cycle of glaciations and interglaciations.

First is a change in the relative positions of continents on the Earth’s surface as a result of plate tectonic activity.

Second is an increase in the number and severity of volcanic eruptions.

Third is a reduction in the sun’s energy output and other aspects of the radiation budget, based on cyclical changes in Earth’s orbit (astronomical hypothesis).

Causes of the Late Cenozoic Ice Age

Causes of Glaciation Cycles

Several timing and triggering theories have been proposed for the glacial cycles of the Ice Age.

The most widely accepted of these is the astronomical hypothesis, which is based on well-established motions of the Earth in its elliptical orbit around the sun.

Causes of the Late Cenozoic Ice Age

Causes of Glaciation Cycles

The varying shape of Earth’s orbit is referred to as eccentricity - changes the distance between the Earth and the sun, and will affect the amount of solar energy the Earth receives at each point of the annual cycle.

The Earth’s axis of rotation also experiences cyclic motions. The tilt of the axis or obliquity varies from about 22 to 24 degrees over a 41,000-year cycle - affects seasonal insolation by changing the angle at which solar rays strike the Earth’s surface.

Earth’s axis slowly progresses through a circular path that changes its orientation over cycles of 22,000 to 24,000 years - change in the direction of the axis in space is called precession, or axial precession to distinguish it from apsidal precession.
Causes of the Late Cenozoic Ice Age

Holocene Environments

The elapsed time span of about 10,000 years since the end of the Wisconsinan Glaciation is called the Holocene Epoch - began with a rapid warming of ocean surface temperatures.

Three major climatic periods occurred during the Holocene Epoch leading up to the last 2,000 years.

The cool Boreal stage that followed the initial ice retreat - persisted from about 9,000 to 7,500 years BP.

A general warming accompanied by moister conditions gave rise to the Atlantic stage, noted for temperatures somewhat warmer than they are today, which peaked about 8,000 years BP.

The Atlantic stage was replaced by the Sub-boreal stage about 4,500 years BP - the transition to the present Sub-Atlantic stage occurred about 2,000 years BP.
Processes and Landforms of the Permafrost Regions

The periglacial system is governed by the flow of energy into and out of the ground's surface layer, which seasonally changes water from ice to liquid then back to ice.

The expansion and contraction of water as it changes state, coupled with the pressure that ice crystals can exert as they grow, provides the mechanism for the movement of mineral particles that characterizes periglacial processes.

Ground with temperatures perennially below 0 °C is called permafrost, while the ice that is commonly present in pore spaces or as lenses is known as ground ice.

A distinctive feature of permafrost terrain is the shallow surface layer, called the active layer, which freezes and thaws each year.

Four permafrost zones are recognized in the northern hemisphere:

- Continuous permafrost zone,
- Discontinuous permafrost,
- Sub-sea permafrost
- Alpine permafrost
Forms of Ground Ice

Ice lenses are more or less horizontal layers of ice that form as the active layer freezes again at the end of the warm season.

Another common type of ground ice is the ice wedge formed where ice accumulates in deep cracks in the sediment.

The cracks develop when permafrost contracts during the extreme winter cold - because the cracking relieves strain across a large area, the cracks and wedges are often interconnected in a network of surface troughs, called ice-wedge polygons.

Pingos are conspicuous ice-formed features of the arctic tundra. These conical mounds have an ice core and slowly grow in height as more ice accumulates, forcing the overlying sediment upward.
Processes and Landforms of the Permafrost Regions

Thermokarst Lakes

Many areas of ice-rich permafrost are marked with shallow lakes formed by thawing of permafrost. These features are called thermokarst lakes. Topographic relief in thermokarst areas develops by melting of ground ice and subsequent settling of the ground.

Processes and Landforms of the Permafrost Regions

Retrogressive Thaw Slumps

A unique form of mass wasting in permafrost terrain is the retrogressive thaw slump, which may develop where erosion exposes the ice-rich upper layer of permafrost or massive icy beds. These slumps typically occur along eroding river banks and lake and ocean shorelines.

Processes and Landforms of the Permafrost Regions

Patterned Ground and Solifluction

The growth of ice lenses usually causes stones to move upward or sideways within the soil profile through a process of cryoturbation. In arctic environments, cryoturbation can produce regular surface forms, such as circles, polygons, and nets of stones, or fields of low mounds of soil. These features are collectively known as patterned ground. Circles, polygons, and nets are common features of permafrost terrain on flat or gentle slopes, but often become elongated into stripes on steeper slopes.
Processes and Landforms of the Permafrost Regions

Patterned Ground and Solifluction

A special type of earth flow characteristic of cold regions is solifluction.

This occurs in late summer, when the ice-rich layer at the bottom of the saturated active layer melts to form mud.

The active layer above then moves downslope as a single mass.

Environmental Problems of Permafrost

The permafrost environment is in many ways a delicate one in which small changes can have large impacts.

Even a minor disturbance of the ground surface can change the thermal environment, leading to degradation of permafrost and overlying structures.
Sea Ice and Icebergs

Free-floating ice on the sea surface is of two general types: sea ice and icebergs.

Sea ice is formed by direct freezing of ocean water, which due to salinity, occurs at about −1.8 °C.

Sea ice that has frozen along coasts is referred to as fast ice. Pack ice consists of extensive areas of freely floating sea ice that is detached from land.

Wind and currents break up pack ice into smaller patches called ice floes. The narrow strips of open water between these floes are known as leads.

Sea Ice and Icebergs

Icebergs are bodies of land ice that have broken away from glaciers and ice shelves.

Because they are composed of glacial ice, icebergs are differentiated from sea ice.

Being slightly less dense than sea water, icebergs float low in the water so that about 80 percent of their bulk is submerged.
A Look Ahead

The next section discusses soils and vegetation, both of which have been greatly affected by human activity, mainly because of the ever-pressing demand for sufficient food and other agricultural products to sustain the growing human population.