

# Land and Permafrost



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Many thanks to Jerry Brown for text, images, and enthusiasm.

Further permafrost resources can be found at the end of this page.

*The following text and selected figures are based mainly on excerpts from a chapter entitled Permafrost and Periglacial Environments by J. Alan Heginbottom (Canada), Jerry Brown (USA), Ole Humlum (Norway) and Harald Svensson (Denmark). It is scheduled for publication later in 2008 in the U.S. Geological Survey Professional Paper 1386-A edited by Richard S. Williams, Jr. and Jane G. Ferrigno.*

## Definitions and Distribution

Permafrost constitutes one of the major components of the perennial cryosphere, complementing ice sheets, ice caps, and other glaciers on land; snow patches; and sea ice and ice shelves of the polar oceans. Unlike ice and snow covers that are easily observed by the human eye and on satellite imagery, permafrost terrains are not as easily detected from their surface characteristics. Indirect indicators of present-day and ancient permafrost include surface features such as sorted and non-sorted patterned ground, pingos, ice-wedge polygons, and thermokarst features; such features range in size from small, pitted terrain to large deep lakes. Ice wedge polygons, pingos, and rock glaciers are indicators of an underlying, perennially frozen substrate.

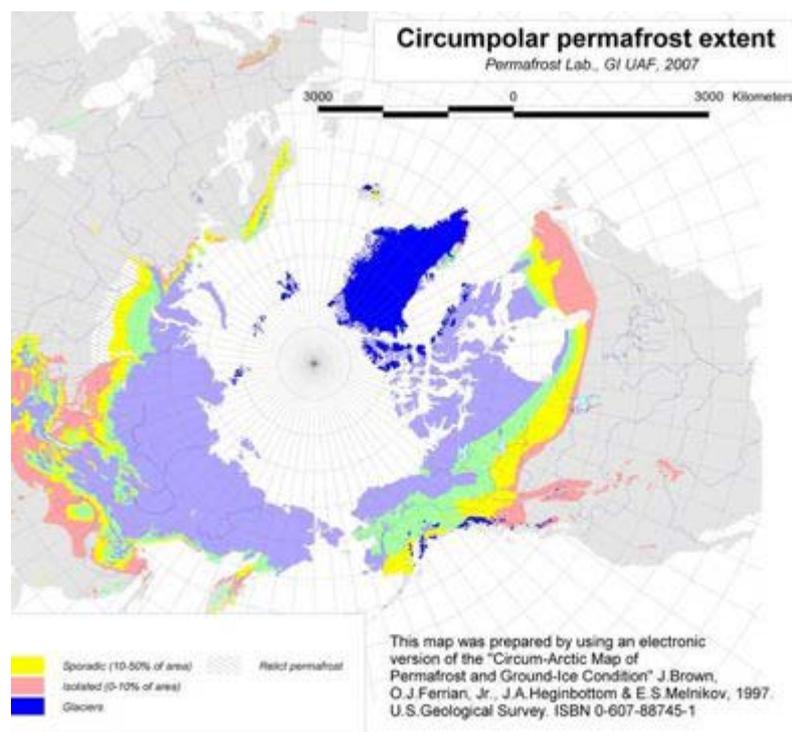
Permafrost or perennially frozen ground is earth material that remains frozen (at or below 0°C) for at least two consecutive years. In the Northern Hemisphere, the permafrost regions occupy approximately 23 million square kilometers (24% of the land). In the Southern Hemisphere, permafrost occurs in the Andes mountains of South America and all ice-free land in the Antarctic. Seasonal freezing and thawing of ground without permafrost occurs both within the permafrost regions and in extensive areas beyond the permafrost regions. The average maximum extent of seasonally frozen ground in the Northern Hemisphere is estimated to be 48 million km<sup>2</sup>.

Between the permafrost and the ground surface is found a layer, typically about 20 to 150 cm in

thickness, which thaws during the summer and refreezes each winter. This is referred to as the active layer. Should the winter freezing (temperature at or below 0°C) not penetrate to the underlying permafrost, the residual unfrozen layer is designated a talik. Taliks also occur beneath water bodies, such as deep lakes and rivers.

Permafrost ranges from very cold (temperatures of -10°C and lower) and very thick (more than 500 m to as much as 1,400 m) in the Arctic, to warm (within one or two degrees below 0°C) and thin (a few decimeters or less in thickness) in Subarctic and boreal regions.

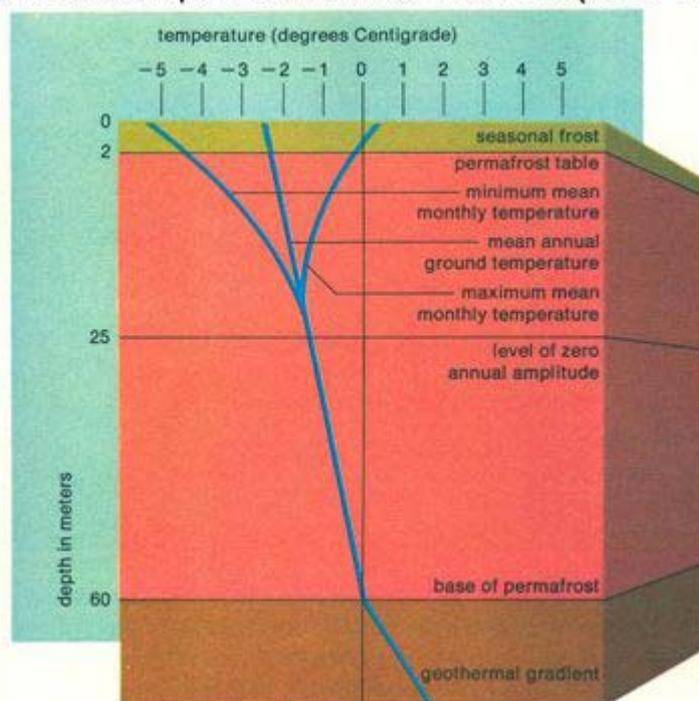
The permafrost region of the Northern Hemisphere is commonly divided into broad zones based on the proportion of ground area that is underlain by permafrost. The northernmost zone is where permafrost is found essentially everywhere beneath exposed land areas and forms the continuous permafrost zone. To the south of this is the discontinuous permafrost zone, where permafrost is absent from some areas of the landscape. In the continuous permafrost zone, permafrost occupies the entire area of exposed land, except beneath large rivers and deep lakes. In the discontinuous permafrost zone, including the sporadic zone, anywhere from 10 to 90 percent of the surface is underlain by permafrost. Permafrost in lower-latitude mountainous regions and plateaus is commonly referred to as mountain (or alpine) permafrost and plateau permafrost.



Compared to the Northern Hemisphere, relatively little is known about the distribution, thickness, and properties of permafrost in the Southern Hemisphere. In the Southern Hemisphere permafrost occurs at high elevations throughout the length of the Andes of South America from Ecuador, through Bolivia and Perú, to Argentina and Chile, in the Subantarctic islands of the Southern Ocean, and in Antarctica.

The periglacial environments are cold, non-glacial land regions, typically without tree cover and with significant freezing and thawing of the surface soils. Many periglacial features are observable on high-resolution imagery and thus can be used as indicators of permafrost-dominated terrains.

**Permafrost depth near Barrow 1330 feet (-10.6°C)**



### Permafrost Formation and Age

The existence of permafrost is dependent principally on climatic conditions. The occurrence of permafrost depends on the heat balance at the Earth's surface. When the depth of seasonal freezing exceeds the depth of seasonal thaw of the soil, permafrost begins to grow downward at the base of seasonal frost. The lower limit of permafrost eventually reaches an equilibrium depth when the heat flow from the interior of the Earth offsets the surface temperature. The permafrost temperature regime (at depths of 10 to 200 m) is a sensitive indicator of decade-to-century climatic variability and long-term changes in the surface-energy balance. From temperature measurements in abandoned oil wells in northern Alaska, it was possible to detect a 20th century warming in permafrost that began in the late 19th century. During the "Little Ice Age," permafrost cooled and expanded in extent in mountains and in regions of discontinuous permafrost.

Permafrost temperatures respond to changes in surface climate, hydrology, vegetation, and landscape changes, such as those caused by erosion (for example, lake drainage, or marine transgressions), wildfire, and human-induced changes including disruption of the surface or change in surface cover during construction.

Permafrost is more extensive and thicker in the colder, high-latitude and high-altitude regions of Planet Earth. Large areas of subsea permafrost are also found beneath the continental shelves bordering the Arctic Ocean, especially along the Siberian coast. During glacial intervals, permafrost

attained thicknesses in excess of 1,500 m in unglaciated parts of Siberia and northwestern North America. The colder and deeper permafrost is likely to have survived several interglacial periods during at least the last 1,000,000 years. In high northern latitudes, permafrost probably developed during the Pliocene Epoch (3.5 million years ago) and may be older in Antarctica.

During the numerous glacial intervals of the Pleistocene Epoch, when global sea levels were as much as 125 m lower than today, large areas of the Arctic continental shelves of northern Russia and North America were exposed to the full glacial climate of sub-zero °C temperatures. Permafrost developed in those exposed subsea areas to thicknesses in excess of 700 m, and relict permafrost still survives beneath the sea floor.

In areas that were glaciated, much of the permafrost developed in post-glacial time (for example, during the late Pleistocene and Holocene Epochs). In unglaciated parts of northern Russia, Alaska, and Yukon, permafrost may be much older. In Svalbard, permafrost in the high mountains is thought to be perhaps as much as 800,000 years old or even older. Permafrost also developed in periglacial environments around the southern margins of the continental ice sheets in the Northern Hemisphere, and also on the eastern margin of the Patagonian ice sheet in southern South America, as evidenced by the widespread occurrence of a range of diagnostic landforms, such as casts of former ice wedges and circular ridges formed by the collapse of pingos.

The monitoring of permafrost temperatures in a large number of existing boreholes is underway as part of the International Polar Year (IPY) and its Project 50: Thermal State of Permafrost.



### **Ground Ice: A Component of the Cryosphere**

A key characteristic of permafrost is the presence of ice in the upper tens of meters of the permafrost. This ice occurs in many forms and often in large masses of relatively pure ice. The widespread presence of ice in permafrost creates challenges for construction since when the ice melts the ground becomes unstable. This excess ice, when thawed, yields water that exceeds the

void volume; this water will accumulate at the surface as the newly thawed ground consolidates and subsides. Freezing and thawing processes and the presence of excess ice are responsible for the many landscape features associated with ground ice.

Ground ice is one of the most important attributes of the terrain. Its presence influences topography, geomorphic processes, vegetation, and the response of the landscape to environmental changes, whether natural or technogenic. Ground ice may form more or less simultaneously with the enclosing sediments, as syngenetic ice; or it may form later, as epigenetic ice. In areas of seasonal frost, ice occurs primarily as lenses that causes frost heaving of the ground surface.

Ground ice is generally more abundant near the surface and decreases with depth; most ground ice in permafrost is found within 10 m of the ground surface. In the Russian Arctic, the ice content is up to 80 percent in silty deposits, particularly in the “edoma” deposits of Siberia where the ice complex is as much as 40 m in thickness.

Ice wedges consist of vein ice, and typically take the form of vertical wedge-shaped dykes penetrating downwards into the permafrost. They vary in size from less than 10 cm to more than 3 m in width at the top, commonly tapering to at depths between 1 m and 10 m or even up to 25 m deep. Winter cracking of the frozen ground results in a polygonal network of vertical cracks. Meltwater percolates into them during spring and then refreezes. Ice wedges thereby grow as each successive phase of contraction cracking is accompanied by filling of the open crack with more ice. Radiocarbon dating of organic remains in ice wedges, pollen analyses, and the isotopic composition of the ice, provides evidence for the Pleistocene age of these deposits.



### **Periglacial Landscapes Dominated by Ground Ice**

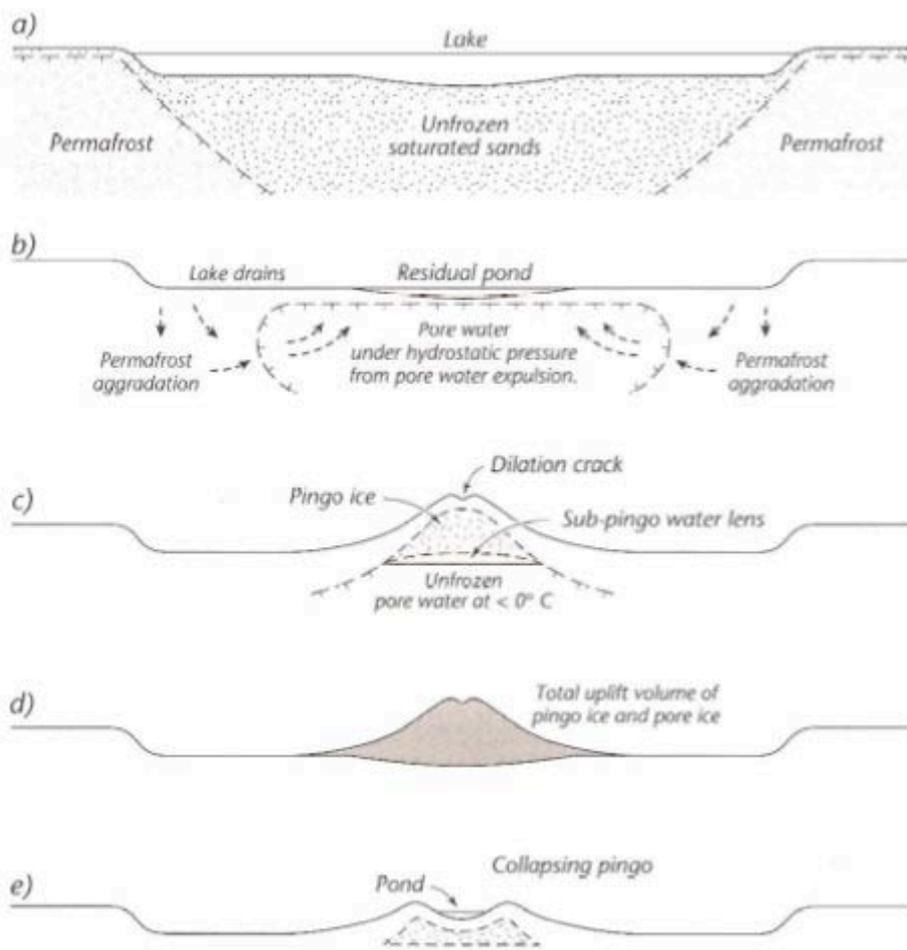
Ice-wedge polygons are striking features of many flat regions. Surface troughs mark the locations of the underlying ice wedges. The polygons generally range from 15 to 50 m in diameter. On flat terrain, low-centered polygons frequently form shallow ponds. Polygon fields are among the most widespread and visible permafrost features of the landscape of arctic regions.

Pingos are perennial frost mounds, comprising a core generally of massive ice, produced principally by injection of water, and with a covering of soil and vegetation. The word pingo is a local Inuit or Eskimo term for a hill. Pingos occur in both the continuous and discontinuous permafrost zones, and the scars of former pingos (relict pingos), identified in mid-latitudes, are evidence of the previous extent of permafrost. Two types of pingos are recognized: closed-system and open-system. Most pingos are domed to conical in shape, somewhat asymmetric, with a circular to oval base and a fissured top that may be cratered. The world's largest concentration of closed-system pingos is found in the Mackenzie Delta region of northwestern Canada, where some 1,450 are known.



Closed-system pingos are found most commonly in areas of low-lying, poorly drained terrain in regions of continuous permafrost. In such regions, bodies of unfrozen ground (taliks) exist beneath the larger water bodies such as lakes and rivers. When a lake drains newly exposed sediments of the lake-bed cool, and permafrost begins to grow in this unfrozen soil. As the freezing and heaving continues over time a mound is formed which continues to grow. The largest closed-system pingos known are about 50-m high.

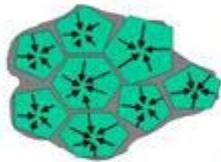
Open-system pingos are found in hilly to mountainous regions, where they occur in valleys and at the base of slopes, and primarily in areas of discontinuous permafrost. Open-system pingos tend to be smaller than closed-system pingos, even though examples from Svalbard attain heights in excess of 40 m. If the ice core begins to melt, the ice and thawing of the surrounding soil can lead to complete collapse of the pingo. Collapsed pingos are recognizable by their ringed shape. the resulting crater will often contain its own residual pond.



Frost mounds or palsas, with heights of a few meters and diameters of 5 to 20 m, are smaller than pingos, and the frozen core generally is formed of ice lenses in frozen peat and soil. The growth of a palsa is due to the development of the ice layers. The frozen cores of palsas and peat plateaus are protected from thawing during the summer by an insulating, dry surface layer of peat. Their maximum height is 6 or 7 m.

Rock glaciers are characteristic large-scale flow features of frozen material in high-relief permafrost regions. They are located at the foot of rock faces with an abundant supply of talus. The length of rock glaciers may be as much as several kilometers, but the typical length is 200 to 800 m measured parallel to the flow direction. The surface of rock glaciers is covered by coarse (0.2–5 m) rock fragments, and displays a 1 to 5 m high furrow-and-ridge topography.

# Ice Wedge Formation



The ground gets very cold in the winter and cracks into large polygon shapes the size of a swimming pool -- similar to mud cracks drying in a puddle. The cracks fill with water in spring. The wedge grows in the permafrost over many hundred of years.



Winter



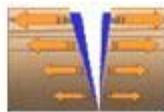
Spring



Spring



Spring



Winter



Over many years

[http://www.crrl.unacc.arizona.edu/permafrost/ice\\_wedge\\_formation.htm](http://www.crrl.unacc.arizona.edu/permafrost/ice_wedge_formation.htm)

Link to animation: "[Ice Wedges, Polygons, and Pingos](#)"

## Thermokarst Processes and Periglacial Landscapes

The so-called karst phenomenon, or melting of ground ice, is termed thermokarst. The thawing of ice-rich permafrost beneath the active layer may strongly alter the surface morphology, resulting in subsidence and cave-in formations of the ground surface. Ice-rich permafrost, upon thawing, is subject to thaw consolidation. Depending on the texture of the soil, if thawing proceeds relatively slowly and the resulting meltwater can drain away, the ground surface will be lowered by an amount related to the excess ice content—a process referred to as thaw subsidence. If, however, thawing occurs more rapidly than meltwater can be expelled from the thaw zone, ground failure condition can develop, with the water carrying part of the overburden load.

Thermokarst landscapes are dependent primarily on the amount of ground ice initially present, the form in which it occurred, and the rate of thaw. On level terrain, natural thermokarst typically begins as one or more small depressions, commonly containing meltwater, and often developing at the intersections of ice wedge polygons. These small thermokarst ponds enlarge by thermal erosion of the surrounding banks. Adjacent thermokarst ponds may coalesce, forming thaw lakes. Beaded streams or pitted drainage form as ice wedges melt at their intersection under the influence of stream runoff, a process termed thermal erosion.

The formation of thaw lakes is strongly dependent upon the ice content of the ground, so that their optimal development is in areas of ice-rich, fine-grained silty and sandy soils. Thaw lakes can drain, often quite suddenly, due to lake tapping or truncation by coastal retreat. Lake tapping often occurs by means of thermal erosion along ice wedges.

Where ice-rich soils are exposed in cliffs along the Arctic coast, wave erosion can lead to

undercutting of the cliff face, forming a thermo-erosional niche. Such niches can be many meters deep. Under the tensional strain, the overhanging frozen ground of the cliff eventually collapses, often along the line of an ice wedge, allowing a large block of frozen soil to fall into the ocean. The same process occurs on a smaller scale along Arctic rivers. The fallen blocks of frozen ground initially protect the cliff face from further undercutting, but thermal abrasion thaws and erodes this material until a fresh face is exposed. Late summer storms have the greatest effect in forming niches.

Some terraces along Siberian rivers are covered with oval thermokarst depressions which may reach dimensions of 10 m deep and as much as 15 km long. Such depressions are called *alasses*, a Yakutian word in origin. Viewed from the air, *alasses* stand out as open, grass-covered, closely spaced, and flat-bottomed basins in the taiga, often containing lakes or swampy areas, which have developed from former lakes. It is possible that some of the larger systems of *alasses* in central Yakutia started to develop during climatically favorable periods of the late Pleistocene or Holocene Epochs.



### **Slope Movement and Failures**

Freezing and thawing of slopes in ice-rich permafrost and related failures produce specific landforms. Detachment failures occur when a thawed active layer and vegetation mat separate from the underlying permafrost table. The causes of such failures may include an unusually warm summer with deeper than normal thawing of the ground, wildfire, unusually heavy rain, etc.

Thaw-slumps are deeper and larger developing where ice-rich soil or massive ground ice is exposed at the ground surface. A thaw-slump forms a bowl in a slope with a steep headwall, in which the massive ice or ice-rich soil is exposed. During the summer thaw, a debris flow of soupy mud flows away from the ice face.

Solifluction is the slow, downslope creep of fine-textured soils involves several components. Solifluction leads to the formation of lobate-shaped debris masses or solifluction lobes.



### **Other Periglacial Features and Processes**

Repeated freezing and thawing of the soil produces ground patterns including circles, stripes, and polygons. The coarse cobbles and boulders form the outside of the ring and the finer sediments form the center. Unsorted circles, often in the form of hummocks, or vegetated mounds, are found in a variety of environments. Large stone stripes occur on slopes, where the circular or polygonal pattern

becomes elongated.

Nivation hollow is a common phenomenon created by periglacial processes enhanced by the presence of snow. The development of the hollows requires two ingredients: a snow patch that persists or reforms in the same area year after year and a slope to allow for erosional transport of material out of the developing depression. As the summer season progresses, the patch of snow reduces in size and the excavation of material continues inward.

In permafrost areas, vast surface sheets of ice develop during the fall and winter by freezing of river or ground water which has flowed across cold ground or snow surfaces and build up large parallel-layered accumulations of ice. The Russian word *naledi* has long been used for this special type of ice accumulation; it was directly translated to *aufeis* in German. The corresponding Inuit name in Greenland is *sersinaq*.

The Arctic is characterized by wind-polished rocks, wind-oriented lakes, sand dunes, and loess deposits that owe their formation to eolian processes controlled by frost and snow cover. Wind erosion and deposition are important factors in cold climates because of the open landscape and sparse vegetation. Dust storms are frequent and may result in the accumulation of thick eolian deposits along such braided river plains. The removal of the fine particles by wind from the ground surface results in surfaces covered with lag gravels.

In very arid areas with permafrost, extreme winter temperatures can result in ground cracking by thermal contraction. Windblown fine sand and silt can be deposited in these cracks and, lead to the growth of sand wedges and polygonal patterned ground. Excellent examples of sand wedges associated with ice wedges and composite wedges of sand and ice are known from the McMurdo Dry Valleys region of Antarctica.

### **Observational Networks**

The establishment of long-term, records of permafrost temperatures and seasonal soil thaw at the same locations and across diverse land types are required to identify the changes in the polar lands. Widespread, systematic changes in the thickness of the active layer and warming of permafrost terrains could have profound effects on the flux of greenhouse gases, and on the human built infrastructure in cold regions, and on landscape processes. Within the past decade, several polar land-based observing networks have been established under the coordination of the International Permafrost Association (IPA) and the IPY Coordinated Project 33, 50, 90, and 363. A full list of IPY projects related to Land and Life can be found [here](#).)

The Thermal State of Permafrost (TSP, Project 50) network is designed to record the temperature of permafrost at various depths and time periods. Temperatures are measured in more than 500 boreholes in 16 countries in continental and mountainous regions of both hemispheres. Most of these boreholes range in depth between 25 and 100 m.

In Alaska there are about 80 borehole sites, many of which borehole have automatic weather stations and soil-temperature measurement probes for the estimation of site-specific active-layer depths. In Canada, there are about 100 reporting sites from the Mackenzie Valley and Delta, the

High Arctic Islands, and in northern Québec. In Russia many boreholes are in central and southern Yakutia, northern West Siberia, European Russia, and some in the 'Far East.' Other Asian sites are in China, Mongolia, Kazakhstan, and Japan. In Europe, an expanding network exists in the Swiss and Austrian Alps, Svalbard, Norway, Sweden, and Iceland. The Norwegian monitoring program is underway as part of its International Polar Year program. Additional sites are being installed as part of IPY Schoolyard and PYRN projects.

The [Circumpolar Active Layer Monitoring](#) (CALM) network consists of more than 160 sites in both polar and subpolar regions and involves 14 participating countries. Most sites in the CALM network are located in Arctic and Subarctic lowlands, although 20 sites are situated in high-mountain regions of the Northern Hemisphere, >1,300 m in elevation. A new Antarctic component includes 14 identified sites. CALM represents the only coordinated and standardized program of observations designed to observe and detect decadal changes in the timing of seasonal thawing and freezing of high-latitude soils. Although the main purpose of CALM is to measure late-summer thaw depths, many sites include seasonal measurements of soil temperature and moisture and of ground heave and subsidence. Several methods are used to determine thickness of the active layer: physical probing with a metal rod and soil temperature measurements are the most common.

IPY Project 90 (ACCO-Net) include the Arctic Coastal Dynamics (ACD) network is observing erosion rates of permafrost-dominated coastlines, particularly those containing massive ground ice. Thirty permanent "key" sites are located along the coasts bordering the Arctic Basin. Erosional rates are established by repeated ground measurements or analysis of sequential aerial photographs and direct field measurements.

Carbon Pools in Permafrost Regions (CAPP, Project 90) is assessing the quantity and quality of carbon in peats and soils across high latitude and mountain regions characterized by the presence of isolated to continuous permafrost. Site along transects are being developed in the Northern Hemisphere representing the range of climatic and permafrost regions, complemented by several transects in the sub-Antarctic and Antarctic regions, and additional altitudinal transects in high alpine environments.

A baseline set of data from these monitoring measurements and the establishment of a permanent network of observations will be part of the IPY-IPA legacy.

The Permafrost Young Researchers Network (PYRN) is a membership organization of over 500 permafrost researchers, engineers, and educators from more than 40 countries around the world. The [PYRN website](#) hosts information on events, jobs, fellowships, and scientific support. It features blogs, pictures galleries, a newsletter and contributes to strengthening bonds between members.



### **Permafrost Hazards and Engineering Considerations**

Since people first started to build in permafrost regions, dwellings and other man-made structures have experienced damage mainly from cumulative subsidence due to thawing of permafrost. Ground temperatures affect the strength and deformation properties of frozen ground. However, the presence of excess ground ice and subsequent thawing of ice-rich soil are the primary causes of instability problems and associated loss of ground strength. The loss of strength can lead to critical problems for engineering structures, such as highways, railways, pipelines, dams, and building foundations, unless they have been designed and built to withstand these effects. The growth of ground ice, both seasonal and perennial, and the associated frost heave of the ground can also create design and maintenance problems, particularly for linear structures such as pipelines, roads, and airfields.

Special precautions and engineering designs are required for construction on permafrost and especially on ice-rich terrain. These involve measures to prevent the thawing of the underlying frozen ground (passive techniques), such as elevation of buildings and pipelines on piles placing insulation on the ground surface, and use of cooling systems. More aggressive approaches required removing ice-rich soil and replacing it with non-frost susceptible material or allowing the excess ice to melt before construction begins (active techniques). Examples of large constructions projects using passive techniques are the Trans-Alaska Pipeline) and the new Qinghai-Tibet Railway. Natural warming of permafrost in mid-latitude mountainous regions and subsequent melting of the ground ice in bedrock foundations affect ski facilities and slopes. Avalanches such as occurred in the Kolka-Karadon area, Caucasus Mountains and rock slides triggered by permafrost thaw in rock walls, such as occurred on the Matterhorn in July 2003, are becoming increasingly common occurrences.



### **Permafrost and the 21st Century**

Changes in climate have both short-term and long-term effects on near-surface permafrost and are mediated by changes in snow, vegetation, and soil covers. Locally the spatial distribution of warmer permafrost is decreasing under the current phase of climatic warming. Although some shifts in permafrost boundaries may occur, hundreds to even thousands of years are required to substantially degrade thick deposits of ice-rich permafrost. Even permafrost close to the thawing point, can persist for many centuries or millennia.

Recent observations reveal that permafrost degradation is occurring in Alaska, Canada, Mongolia, and China. In Russia, during the last 30 to 35 years, a tendency toward warming is observed in permafrost temperatures, although with distinct regional differences. Northern peatlands and frozen, organic-rich sediments contain large amounts of carbon. Deep, perennially frozen sediments, both on land and beneath the Arctic shelves, contain methane hydrates. Active thermokarst and thermal erosion releases organic matter from thawing permafrost into anaerobic lake bottoms resulting in exceptionally high rates of methane production and emission.

The actual response of the terrain at a specific locality is difficult to forecast, because of the complex interactions of climate, snow cover, vegetation, and soil conditions, as well as the existing ground-ice regime. Climate warming, generally would lead to a thickening of the active layer, loss of the uppermost ice-rich layer of permafrost, increased talik formation, and a reduction in the areal extent of near-surface permafrost in the warmer discontinuous permafrost zone. Frozen peatlands and palsas will undergo degradation—easily visible by surface changes. In areas with high ground-ice content and extensive thermokarst, widespread slope failures can be expected to develop. This loss of ground ice and of any buried glacial ice will be irreversible. Even with a much colder climate, it would take centuries to millennia for significant quantities of ground ice to redevelop.

Thawing of ice-rich permafrost, regardless of its location has a considerable effect on the landscape and natural ecosystems and on human social and economic activities. Erosion or subsidence of ice-rich landscapes, alterations to hydrological processes, and release of greenhouse gases to the atmosphere will occur. The stability of buildings, linear structures, including roads and pipelines, and communication links will be affected. The observed and forecasted changes in permafrost stress the necessity to monitor permafrost dynamics on the ground (particularly temperatures) and by remote sensing for timely assessment and forecasts of the possible negative effects of permafrost degradation on ecosystems and built infrastructures.

**Permafrost- related Resources:**

[Circumarctic Permafrost and Ground Ice Map](#)

[Permafrost Activity](#)

**Networks:**

[Thermal State of Permafrost](#) (TSP)

[International Permafrost Association](#) (IPA)

[Global Terrestrial Network for Permafrost](#) (GTN-P)

[Circumpolar Active Layer Monitoring](#) (CALM)

[Thermal State of Permafrost in Norway and Svalbard](#) (TSP)

[Arctic Coastal Dynamics](#) (ACD)

[Carbon Pools in Permafrost Regions](#) (CAPP)

[Cryosol Working Group](#) (RASCHER)

[UAF Permafrost Laboratory](#)

**Hazard:**

[Glacier and Permafrost Hazards in Mountains](#) (GAPHAZ)

**Antarctic:**

[Antarctic Permafrost and Soils](#) (ANTPAS)

**Outreach:**

[UAF Permafrost Outreach](#)

[LATITUDE 60!](#) (in Portuguese)

[Permafrost Young Researchers Network](#) (PYRN)

[Ice Wedges, Polygons, and Pingos](#)