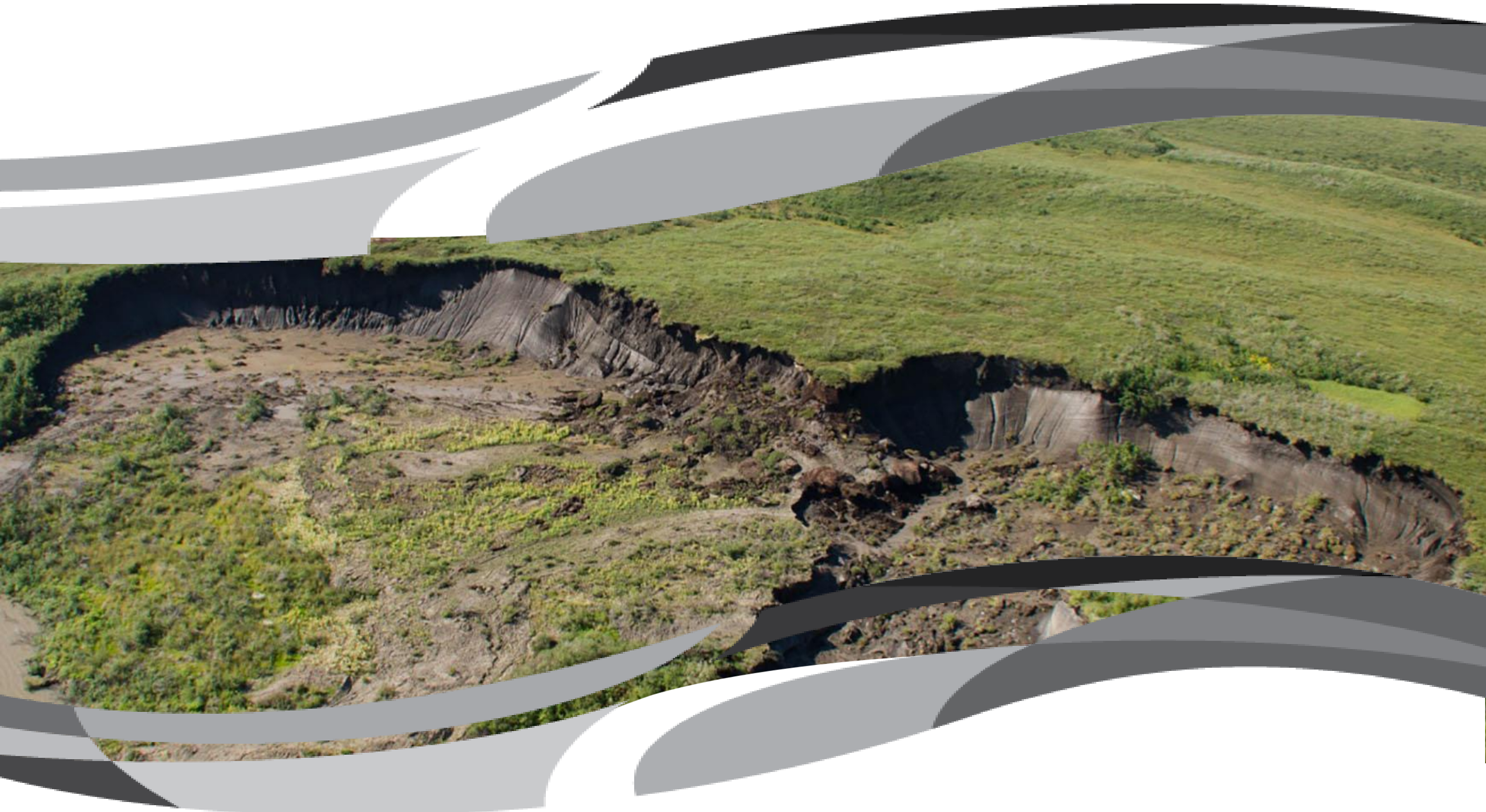
Northwest Territories Geological Survey – Permafrost 101



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NORTHWEST TERRITORIES
GEOLOGICAL SURVEY

Government of
Northwest Territories

Cover photo:
Retrogressive thaw slump near Tuktoyaktuk Coastlands, Northwest Territories, showing characteristic headwall feature. Photo courtesy of Trevor Lantz.

Workshop

Northwest Territories Geological Survey – Permafrost 101

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Permafrost:

What is permafrost?

Permafrost is the frozen ground that underlies terrain throughout subarctic, Arctic and mountainous regions of Canada. Permafrost is the cement that holds northern landscapes together, providing the foundation for northern ecosystems, communities and roads. The extent of permafrost increases northward with a decrease in mean annual air temperatures. Northwest Territories fall within the zones of continuous, discontinuous, and sporadic permafrost (Figure 1). In Arctic tundra regions, permafrost underlies almost all of the land area. The Yellowknife area is within the extensive discontinuous permafrost zone, where 50 to 90% of the land is underlain by frozen ground. In contrast, Hay River on the southern side of Great Slave Lake is in the sporadic permafrost zone where only 10 to 50% of the land is underlain by permafrost. Further south, permafrost persists in patches of organic soils to comprise less than 10% of the land area.

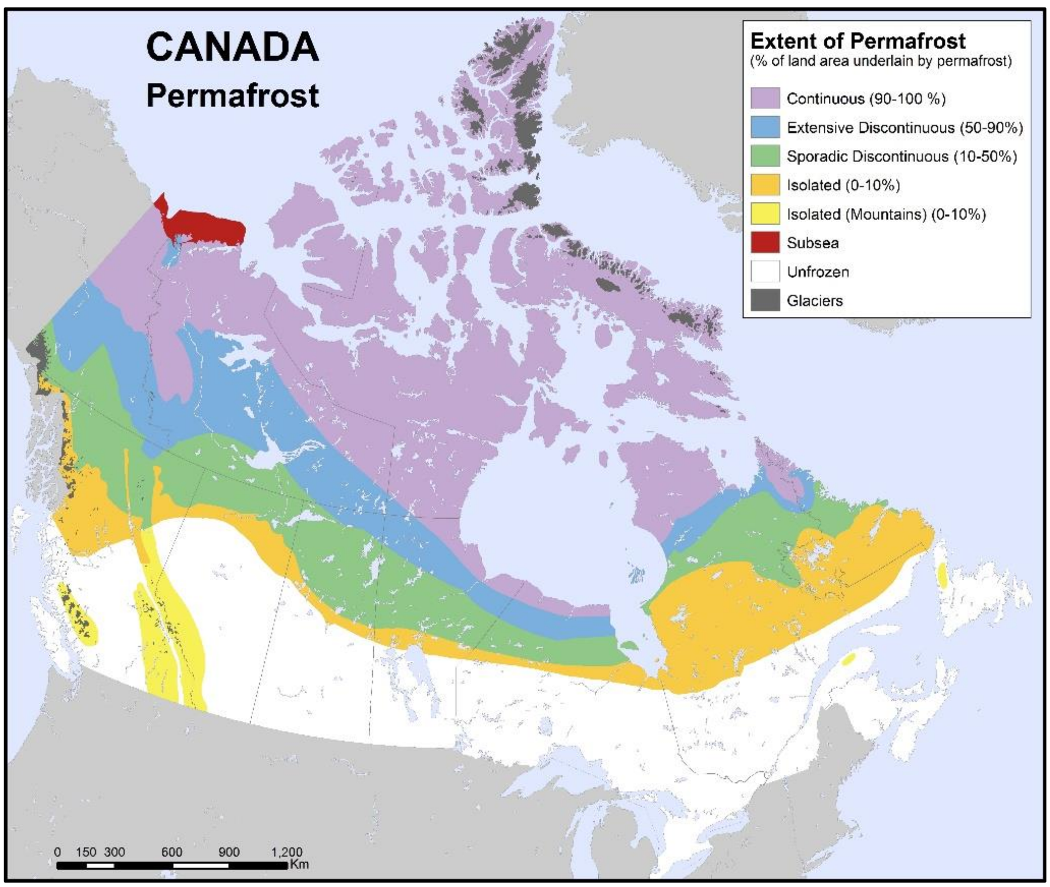

Figure 1. Permafrost map of Canada (Heginbottom, J.A., Dubreuil, M.A., Harker, P.A., 1995. Canada — permafrost, National Atlas of Canada, 5th edition. National Atlas Information Service, Natural Resources Canada, Ottawa. MCR 4177).

Characteristics of permafrost

Geographical variation of permafrost thickness and temperatures

Permafrost thickness relates primarily to air temperature, thermal properties of earth materials and the geothermal gradient. The age of the terrain surface, proximity to water bodies, surface drainage, vegetation and snow cover are also factors that contribute to local variation in permafrost conditions. On the barrenlands north of Yellowknife, continuous permafrost is about 400 m thick. Permafrost thickness decreases southward with increasing mean annual air temperatures (Figure 2), and when encountered in the Yellowknife area it is typically less than 50 m thick. Within the southern zone of discontinuous permafrost, isolated patches may be only a few metres thick. In permafrost areas, the lakes and rivers that exceed the depth of maximum winter ice thickness are underlain by unfrozen ground called a talik.

Permafrost is the result of cold climate conditions, so there are direct associations between air and permafrost temperature. Generally, the permafrost gets colder northward, but the temperatures vary locally due to differences in soils, vegetation, snow cover and proximity to water bodies. The mean annual ground temperature provides one index of permafrost thermal conditions that can be compared between sites and regions. In the High Arctic, mean ground temperature may be as low as -15 °C. In the Slave Geological Province north of Yellowknife, the lowest permafrost temperatures are about -5 °C but in the discontinuous permafrost around Yellowknife, the permafrost temperatures are typically above -2 °C.

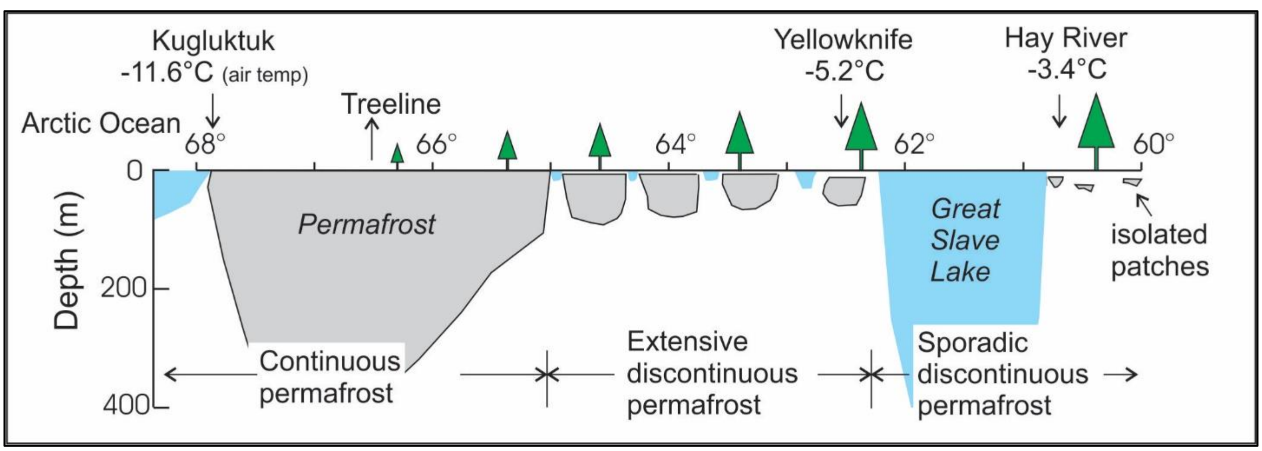

Figure 2. Permafrost thicknesses across a latitudinal gradient from north to south (Adapted from Brown, R.J.E., 1970. Permafrost in Canada. University of Toronto Press, 234 pages).

Ground temperature profiles

The ground thermal regime is described by an annual ground temperature envelope (Figure 3). The near-surface which thaws in summer and freezes in winter is called the active layer. Seasonal temperature variations decrease to the depth of zero annual amplitude, where the temperature remains constant throughout the year. Variation in air temperatures and the nature of the underlying earth materials influence the depth of zero annual amplitude. In warm permafrost comprised of icy, fine-grained soils, the depth of zero annual amplitude can be close to the ground surface because energy is consumed as water in soil pores thaws or freezes. In cold, continuous permafrost or in bedrock, ground temperatures may vary seasonally to depths exceeding 15 m. Under equilibrium conditions, ground temperatures increase below the depth of zero annual amplitude to the base of permafrost due to the geothermal heat flux.

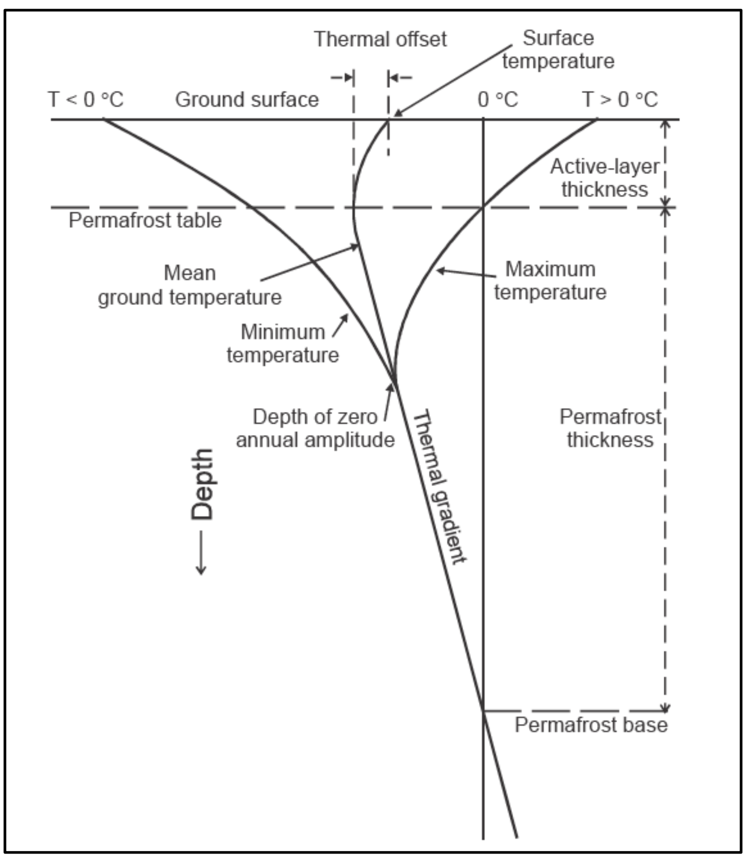

Figure 3. The typical ground temperature profile in a permafrost area (Burn C.R., 2004). The thermal regime of cryosols. (In Cryosols: Permafrost-affected Soils, Kimble J.M. (ed.). Springer-Verlag: Berlin, Germany; pp. 391-413.)

Disturbance at the ground surface or climate change can increase permafrost temperature. As permafrost temperatures approach 0 °C they respond more slowly to the effects of warming due to the absorption of latent heat as pore ice is thawed. In contrast, cold permafrost does not approach the phase change temperature of water, so that ground surface warming can more rapidly increase the temperatures of colder permafrost. As a result, permafrost near 0 °C may not appear to be warming, but its geotechnical properties may be changing as pore ice converts to water at temperatures near 0 °C. This is typically observed with thawing permafrost.

Active layer

The active layer is near-surface earth materials that freeze and thaw annually (Figures 3 & 4). The main factors that influence the thickness of the active layer are summer air temperature, soil conditions, vegetation cover, and slope aspect. In continuous permafrost, the active layer thicknesses range from about 0.3 m in organic soils to more than 1.0 m in dry sandy soils. The active layer in bedrock may be several metres thick. Figure 4 indicates the depth of the active layer and top of permafrost beneath forests in the Yellowknife area.

Active layer thicknesses generally increase with decreasing latitude. This relates to a southward increase in summer air temperatures, however differences in soil, vegetation and drainage conditions cause significant local variation. Sub-arctic spruce forests with thick organic soils may have maximum active layers less than 0.6 m, but barren tundra can thaw to depths of 2.0 m in coarse-grained soils or shallow bedrock areas with a southern exposure.

Figure 4. Exposure of permafrost soils in the Yellowknife area. The active layer is about 1.2 m thick beneath the forest cover. The ice content increases significantly with depth within the permafrost. The zone of permafrost between the base of the active layer and the underlying ice-rich ground is called the transient layer. Photograph by S. Wolfe.

Disturbance or removal of the surface organic layer can cause active-layer thicknesses to increase and near-surface permafrost to thaw. This can have a major effect on the stability in ice-rich terrain.

There is a zone at the top of the permafrost, which can become part of the active layer during periods of climate warming or following disturbance such as fire, then revert back to permafrost as the active layer thins after vegetation recovery or climate cooling. This is called the transient or intermediate layer.

Ground ice

Permafrost derives its environmental and geotechnical significance from the occurrence and characteristics of ground ice within it. In some environments, near-surface permafrost is comprised mostly of ice. Thawing of permafrost and melting of ground ice causes the terrain to subside and reduces slope stability. The consequences of permafrost thaw greatly depend on the nature and distribution of ground ice, soil conditions and characteristics of the landscape.

Excess ice is the volume of ice in the ground that exceeds the total pore volume of the soil under natural unfrozen conditions. Permafrost thaw and melting of excess ice can lead to ground surface subsidence and slope instability. Thermokarst refers to the suite of processes that produce characteristic landforms that result from the thawing of ice-rich permafrost or melting ground ice. These landforms include thaw slumps, pits, ponds, and thermokarst lakes. In forested areas, thawing permafrost is often associated with leaning spruce trees that begin to topple as the underlying ice-rich permafrost thaws. The "drunken forest" can be a good indicator of underlying ice-rich permafrost.

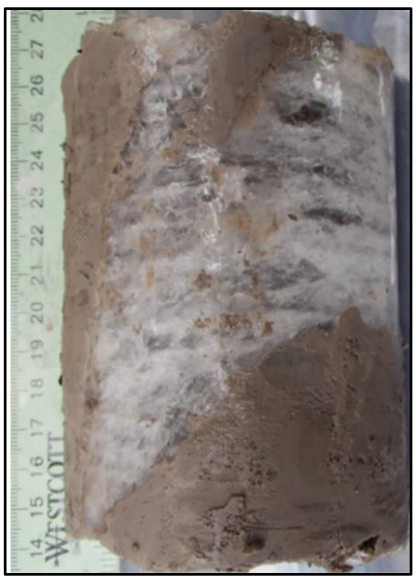

Figure 5. Segregated ice lens in clayey silt core sample, Yellowknife region.

Ground ice can be classified by its appearance. Pore ice occurs within interstices of soil and rock and acts to bond earth materials. Larger horizontal or vertical bodies of mostly pure ice can range from segregated ice lenses that are only millimetres thick, to massive ice several metres thick. Some of this ice forms with the initial development of permafrost. Ice types include pore ice and segregated ice. The later develops due to temperature-induced suction gradients that draw water from saturated sediments into the freezing ground. Some ground ice types can develop after permafrost is established. Thermal contraction cracking of the ground in winter and infilling of cracks with snowmelt can form veins of ice, and repeated cracking over many years can cause ice wedges to develop. Polygonal terrain is the surface expression of an ice-wedge network. Some of the ground ice may consist of buried ice including snowbanks, river or lake ice, and remnant glacier ice. This is relict ice and it can be preserved by permafrost for millennia.

Climate change and permafrost

Permafrost temperatures are increasing due to recent climate warming. Field evidence indicates that rapidly rising air temperatures since the 1970s have caused permafrost in the subarctic boreal forest regions of the Northwest Territories to warm by about 2 °C. The rate of temperature increase has been lower in discontinuous permafrost due to the latent heat effects associated with melting ground ice just below 0 °C. However, in this region, there is growing evidence of increasing thermokarst and eradication of thin permafrost.

The anticipated climate warming will cause ground temperatures to continue increasing; thin permafrost in isolated patches and the sporadic discontinuous zone will eventually disappear. Thawing of near-surface ground ice will cause terrain subsidence leading to a cascade of ecosystem and hydrological affects. Thaw-driven settlement of terrain will damage roads and may compromise building foundations (Figure 6). An increase in active-layer thicknesses may also promote greater seasonal frost heave effects at sites with frost-susceptible soils.

Figure 6. Abandoned section of Highway 4, east of Yellowknife. The paved road surface has continued to settle due to permafrost thaw after it was abandoned in 1999.

Measuring ground temperature in a variety of different terrains provides baseline information for planning infrastructure, calibrating permafrost models and predicting effects of climate warming. Mapping thermokarst terrain can provide valuable information on sensitive landscapes as well characterizing the environmental consequences of thawing permafrost.

General circulation models are tools that allow scientists to explore how global climate may change with future increases in atmospheric greenhouse gasses. Most current general circulation models (GCMs) project global average air temperatures to warm by 0.6-0.7 °C by 2030 relative to the 1980-1999 period. The models indicate that most of this projected increase in air temperature is due to the emission of greenhouse gases into the atmosphere.

All GCMs indicate that climate change will be greater in the Arctic than in other regions of Canada and that warming will become more pronounced over time. Given moderate emissions scenarios, mean annual air temperatures in the Arctic are expected to increase by an average of 5 °C in the next 100 years. Winter air temperatures will likely be affected the most, while summer temperature increases will be more modest.

Glossary

Permafrost: Ground (soil or rock) that remains at or below 0 °C for at least two years.

Active layer: The top layer of ground subject to annual thawing and freezing in areas underlain by permafrost.

Ice-rich permafrost: Permafrost containing excess ice, defined as the volume of ice in the ground which exceeds the total pore space that the ground would have under natural unfrozen conditions.

Thaw slump: A slope failure feature caused by the melting of ground ice and downslope sliding and flowing of the resulting debris.

Figure 7. Mega thaw slump on the Peel Plateau.

Thermokarst: The process by which characteristic landforms result from thawing of ice-rich permafrost. Thermokarst processes may cause lakes to enlarge, peatlands to collapse and landslides or thaw slumps to develop.

Talik: A layer or body of unfrozen ground in a permafrost area.