# Past and present permafrost as an indicator of climate change

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The permafrost history of the high northern latitudes over the last two million years indicates that perennially frozen ground formed and thawed repeatedly, probably in close synchronicity with the climate changes that led to the expansion and subsequent shrinkage of continental ice sheets. The early stages of the Pleistocene are the least known and the changes that occurred in the Late Pleistocene and early Holocene are the best known.

Evidence that permafrost is degrading in response to the current global warming trend is difficult to ascertain. The clearest signals are probably provided by changes in permafrost distribution in the sub-Arctic regions, at the extreme southern fringes of the discontinuous permafrost zone.

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## Introduction

At high latitudes today, permafrost forms under current climatic conditions. A map recently compiled and published under the auspices of The International Permafrost Association (Brown et al. 1998) indicates that permafrost occupies approximately 20–25% of the Earth's land surface in the Northern Hemisphere. In the case of the North American continent, field observations in both Canada (e.g. Brown 1967; National Atlas of Canada 1995) and Alaska (e.g. Ferrians 1994) indicate that the southern limit of continuous permafrost coincides with the general position of the −6 to −8°C mean annual air temperature (MAAT) isotherm. This relates to a ground temperature of about −5°C measured just beneath the depth at which seasonal fluctuations are minimal. The discontinuous permafrost zone lies to the south of the continuous zone. Its southern limit approximates the −1°C MAAT isotherm and ground temperatures vary from just below 0°C to −3 or −4°C. The most extreme, or southern, occurrences of permafrost are found beneath peaty materials, the result of the unusual insulating properties of such material.

## Past permafrost

Permafrost has undergone growth and decay at various times during Earth's history. There is convincing evidence to suggest that much of today's permafrost probably originated during the fluctuating climate of the Pleistocene. Some of the most striking evidence includes the remains of woolly mammoths and other Pleistocene animals found preserved in permafrost in Siberia, Alaska and north-western Arctic Canada. Another line of evidence is cryostratigraphic: in some areas, the upper boundary of permafrost lies below the depth of modern seasonal freezing and the temperature of permafrost sometimes decreases with increasing depth. Both phenomena indicate residual (i.e. relict) cold. Another clue lies in the fact that the thickest permafrost occurs in areas which escaped glaciation and which were not protected from cold subaerial conditions by a thick ice cover. Finally, offshore or submarine permafrost exists on the continental shelves beneath both the Kara and Beaufort seas and could only have formed when sea level was lower (i.e. during the cold periods of the Pleistocene).

Cryostratigraphic evidence for Pleistocene-age

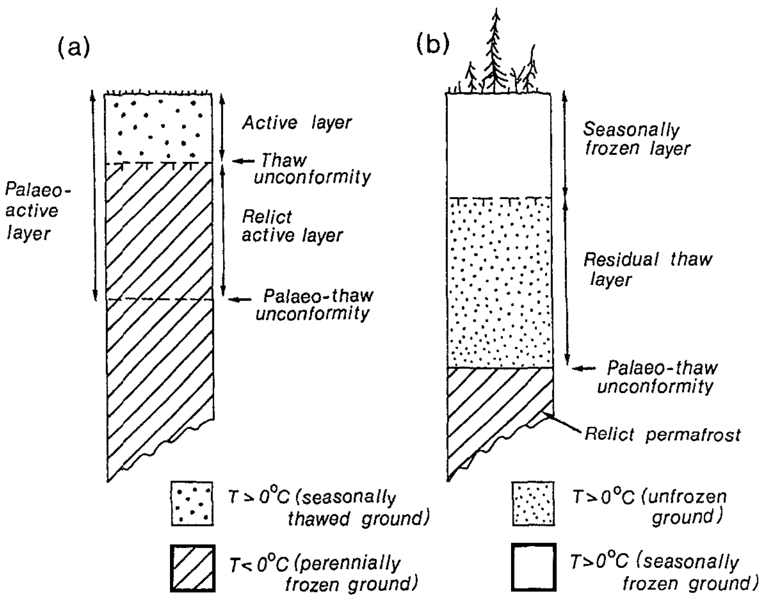


*Fig. 1.* Diagram illustrating the types of ice discontinuities commonly found within perennially frozen sediments in (a) the continuous permafrost zone of the Arctic, or the tundra region, and (b) the discontinuous permafrost zone of the sub-Arctic region.

permafrost is provided by the study of the ice discontinuities (e.g. Murton & French 1994; French 1998) commonly found within perennially frozen sediments. Most permafrost, especially that which has formed in unconsolidated sediments, contains ice. This may be as much as 30–50% by volume in the upper few metres. Discontinuities in the ice are usually the result of either the thaw of frozen material or the subsequent refreezing of previously thawed materials. The significance of these discontinuities, termed "thaw unconformities," are explained below.

Figure 1 shows the typical permafrost conditions which might exist in (a) the continuous permafrost zone of the Arctic, or the tundra region, and (b) the discontinuous permafrost zone of the sub-Arctic, or the boreal forest (taiga) region. In (a), the "active layer" is shown as the surficial horizon of permafrost terrain which thaws during the summer months. A "relict active layer" is shown as ground immediately below the modern active layer that was once part of the active layer but which is now perennially frozen. A "palaeo-active layer" is shown as the horizon between the ground surface and the base of the relict active layer. In (b), a "residual thaw layer" is shown as referring to an unfrozen layer, formerly permafrost, lying between the modern depth of seasonal frost penetration and an underlying permafrost body.

The base of the current active layer, as in (a), is the simplest and most obvious example of a thaw unconformity.

From the viewpoint of permafrost history, it is possible to distinguish between primary (i.e. present-day) and secondary (i.e. palaeo-) thaw unconformities. Both are shown in (a), but in (b) a palaeo-thaw unconformity overlies permafrost unrelated to the present surface conditions. As such, the permafrost is "relict."

The manner in which permafrost degrades and subsequently reforms, and the cryostratigraphic evidence which it leaves, is illustrated in Fig. 2, which considers a scenario of permafrost terrain being subject to warming and subsequent cooling. It depicts an initial permafrost sequence (a), that is subject to degradation from the surface downwards, possibly the result of regional climate warming (b). As thaw proceeds, a primary thaw unconformity (T-U1) forms at depth below a residual thaw layer. At this time, the ground surface experiences only seasonal freezing and thawing. In the process, an ice wedge is truncated and is no longer active. When the climate subsequently deteriorates, as in (c), permafrost aggrades and the base of the active layer again becomes the primary thaw unconformity. Renewed thermal contraction cracking at the ground surface permits a new ice wedge to form. During this process, the original thaw unconformity at depth becomes a secondary (i.e. palaeo-) thaw unconformity (T-U2). The latter can be recognized

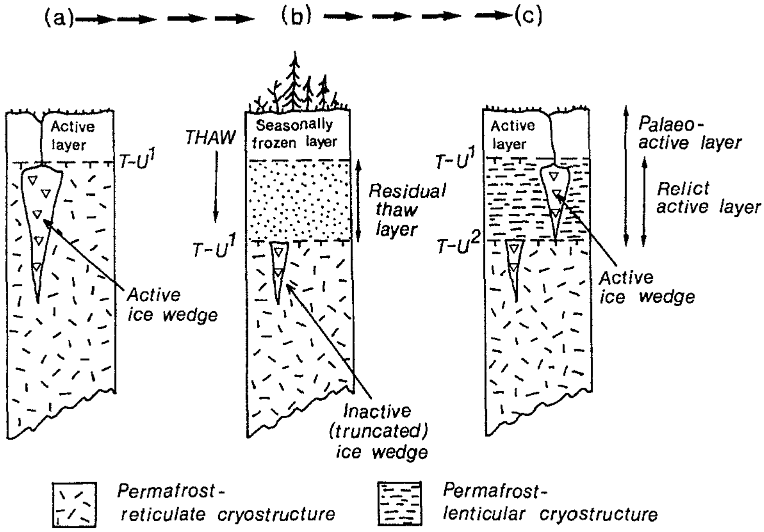


*Fig. 2.* Diagram illustrating the cryostratigraphic evidence associated with the degradation and subsequent aggradation of permafrost. (a) An initial permafrost sequence is (b) subjected to degradation from the surface downwards, possibly the result of regional climate warming. As thaw proceeds, a primary thaw unconformity (T-U1) forms at depth below a residual thaw layer. (c) When the climate subsequently deteriorates, permafrost aggrades and the base of the active layer again becomes the primary thaw unconformity.

by both the truncated ice wedge and by different ice structures (cryostructures) in the sediments above and below.

Using this kind of evidence, Russian geographers (e.g. Gerasimov & Velichko 1982; Rozenbaum & Shpolyanskaya 1998) have undertaken large-scale palaeo-environmental reconstructions for the last two million years. For Europe and northern Eurasia they suggest four stages of permafrost evolution, the earliest being the least known.

During the earliest stage, between approximately 2.0–0.7 Mya, permafrost probably existed without interruption throughout much of Yakutia and north-eastern Siberia. By contrast, in northern Europe, western Siberia and mainland North America, permafrost probably formed and thawed on several occasions, but little is known of these conditions.

Between approximately 190 Kya and 10 Kya, extensive regions dominated by permafrost conditions existed once again in both Eurasia and North America to the south of the Late Pleistocene ice sheets. Isotopic data (Klimenko et al. 1996) indicate that global air temperatures probably dropped by as much as 4°C on several occasions during the last 223 Ky. This was sufficient to cause significant expansion of areas underlain by permafrost at about 150 Kya, 70 Kya and 25 Kya.

One example of all these changes is found near Fairbanks in central Alaska. There, the Eva Forest Bed (Péwé et al. 1997) lies buried within frozen loess-like materials. The organic remains indicate that the last interglaciation of the North American continent, about 125 000 years ago, was a major warm period when there was erosion of loess and the deep and rapid thawing of previously formed permafrost. During the 100 Ky that followed, a treeless steppe-like tundra environment returned to northern Alaska and the deposits were refrozen as permafrost once again developed.

In this time period, permafrost attained its greatest thickness and its lowest temperature in those high-latitude areas of the Northern Hemisphere that escaped glaciation. Thicknesses in excess of 500 m formed with temperatures at the depth of zero annual amplitude of greater than −15°C. In addition, and in response to the lower sea level in the Arctic Basin, the continental shelves of the Beaufort and Kara seas, together with the Bering Strait, were exposed to permafrost forming, cold-climate subaerial conditions. At this time, the extreme maximum southern limits of permafrost probably extended as far south as 50°N in European Russia and Kazakhstan.

During the Holocene, or the last 10 Ky, there is evidence to indicate that the climate ameliorated, causing permafrost to partially thaw but to then subsequently refreeze towards the end of the Holocene. These conditions can be demonstrated with reference to the lowlands of the western Canadian Arctic. There, observations indicate the existence of a thick palaeo-thaw layer (see e.g. Burn 1988, 1997; Harry et al. 1988; Murton & French 1994). It occurs at a depth of 125–150 cm

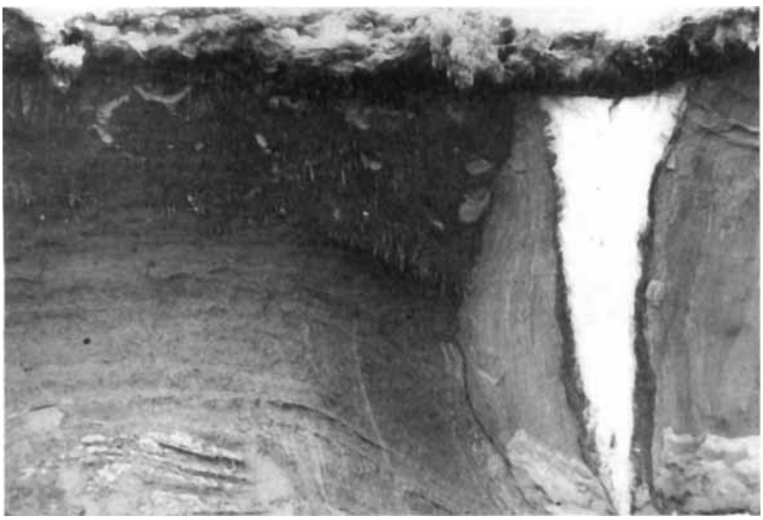

*Fig. 3.* Perennially frozen sediments exposed at Crumbling Point, Pleistocene Mackenzie Delta, western Canadian Arctic. The early Holocene thaw unconformity truncates icy sediments penetrated by sand wedges. Photo by J. B. Murton.

in the Tuktoyaktuk region and can be recognized by distinct cryostructural contrasts and, in places, by truncated ice bodies. A good example is from the cliffs at Crumbling Point, in the Pleistocene Mackenzie Delta (Fig. 3). Recent years have exposed a massive icy body penetrated by remarkably large inactive sand wedges and large active ice wedges, and overlain by sand and diamicton. Radiocarbon dates from here and elsewhere in north-western Arctic Canada suggest that the active layer was deepest about 8.0–9.0 Kya and that it was approximately 2.5 times thicker than the present active layer. A similar early Holocene thaw unconformity can be recognized on eastern Melville Island, at 77°N, at a depth of approximately 113 cm (French et al. 1986).

## Permafrost and past climate

The early Holocene thaw unconformity in the Western Canadian Arctic can be used to illustrate the relationship between permafrost and inferred past climate. Burn (1997) has shown that, with care, it is possible to make inferences about the palaeo-climate prevailing at this time of maximum thaw. He stresses that certain assumptions are critical to the analysis. One must assume that (a) any increase in the active layer is the result of summer thaw, and (b) that the thawing of frozen ground is linked to the thawing index of degree-days above 0°C. Using such assumptions, the Stefan solution can be used to predict the depth of thaw (see e.g. Mackay 1995; Burn 1997). According to the Stefan solution, a doubling of active-layer thickness corresponds to a fourfold increase in thawing index, and an active layer 2.5 times as thick as today implies an increase in the thawing factor by 6.25.

This analysis can be applied to the climatic records obtained from the five settlements of Whitehorse, Inuvik, Tuktoyaktuk, Sachs Harbour and Rae Point, the latter being an oil company logistics base on eastern Melville Island (Table 1). These localities typically record thawing indices today of 1900, 1200, 800, 400 and 300 degree-days per year, respectively. The current active layer at each locality is approximately 150 cm, 100 cm, 50 cm and 30–25 cm, respectively. These data reflect the progressively shorter and cooler summers with increasing latitude. The current treeline is located just north of Inuvik and south of the Arctic coast. However, during the early Holocene climatic optimum, trees probably existed at the location of the present Arctic coast. Therefore, the most appropriate thawing-index comparison for the present Arctic coast (i.e. Tuktoyaktuk) is with Inuvik. The Stefan solution for the maximum depth of the thaw unconformity observed at Tuktoyaktuk indicates a thawing index of about 1.5 times current conditions at Inuvik; in other words, approximately 1800 thawing degree-days. Thus, permafrost considerations enable one to conclude that, in the early Holocene, the

*Table 1.* Data showing average active layer depths, the depth of the Early Holocene thaw unconformity (where recognized), typical annual thawing degree-days, and bio-climatic zonations for 5 localities in the western and high Arctic of Canada (sources: French et al. 1986; Burn 1998).

| Locality | Latitude | Thawing degree-days (°C) | Active layer (cm) | Early Holocene thaw unconformity | Ecozone |
|---|---|---|---|---|---|
| Whitehorse | 61°N | 1900 | 125–150 | | Boreal forest |
| Inuvik | 68°N | 1200 | 100 | | Treeline |
| Tuktoyaktuk | 69°N | 800 | 50 | 125–150* | Tundra |
| Sachs Harbour | 72°N | 400 | 30–50 | | |
| Eastern Melville Island | 77°N | 300 | 25–50 | 113** | Polar semi-desert |

Stefan solution: z = bI 1/2 where z = depth of thaw (cm)
b = soil thermal properties
I = thawing degree-days (°C)

*Thaw unconformity at 125–150 cm depth corresponds to approx. 1800 thawing degree-days.

**Thaw unconformity at 113 cm depth corresponds to approx. 600 thawing degree-days.

summer climate at the location of the present Arctic coast was typical of that which exists today near Whitehorse, in central Yukon. Likewise, the thaw unconformity that can be observed at a depth of 113 cm on eastern Melville Island corresponds to approximately 600 thawing degree-days; that is, a value typical of the climate that forms the low Arctic tundra in the southern Beaufort Sea region (i.e. between Tuktoyaktuk and Sachs Harbour).

## Permafrost and climate change

Today, clear evidence that permafrost is degrading in response to current global climate change is limited. More time is required before definite trends can be detected. Possible indicators of climate warming in the permafrost regions of northern latitudes are summarized by Maxwell (1997). They include: (a) increases in the thickness of the active layer; (b) increases in the frequency of occurrence of active layer failures and slope instability; and (c) increased thermokarst activity, especially related to an increased frequency of forest fires in the summer in the boreal forest and taiga.

In addition to these parameters, however, probably one of the clearest signals will be provided by changes in permafrost distribution in the sub-Arctic regions, at the extreme southern fringes of the discontinuous permafrost zone. In such areas the permafrost is typically less than −1 to −2°C. There, in addition to the thermal influence of peat bodies, the boreal forest acts to maintain permafrost in marginal situations since, by restricting the depth of snow on the ground in winter, it enhances winter frost penetration. Subtle variations in surface vegetation characteristics can also produce significant permafrost changes, as illustrated by the permafrost degradation that follows upon forest fires (e.g. Mackay 1995; Burn 1998). Therefore, if climate warming is occurring, the marginal permafrost present at the extreme southern fringes of the discontinuous zone appears to be especially sensitive.

## Conclusions

The history of permafrost over the last two million years suggests that permafrost has grown and decayed in response to global climate change. The techniques of cryostratigraphy can be used to infer past climate changes from the permafrost record. If global climate warming is occurring today, and once the buffering thermal effect of the active layer has been overcome, marginal permafrost bodies located at the extreme southern fringes of the discontinuous permafrost zone will be the first to disappear.

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