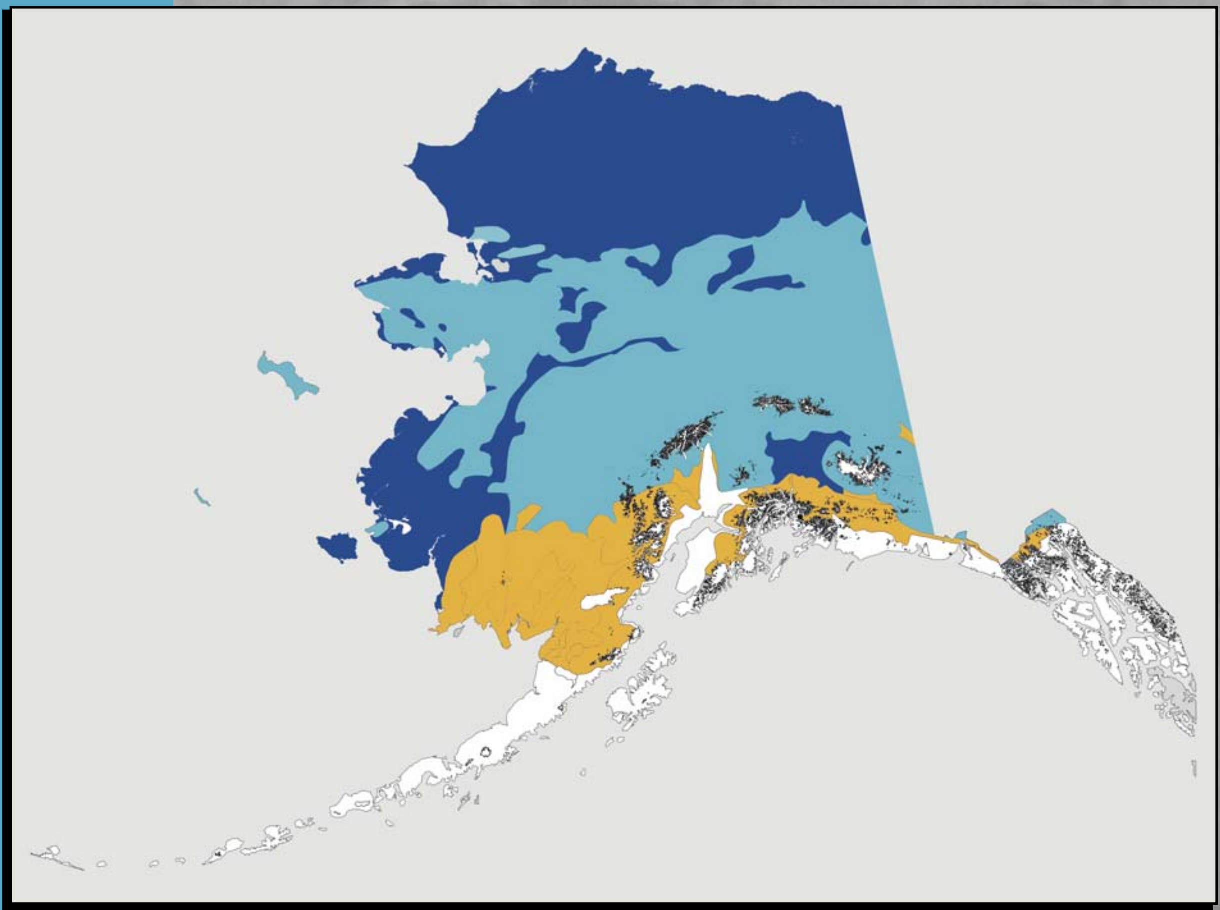
Climate Change, Permafrost, and Impacts on Civil Infrastructure



U.S. Arctic Research Commission

Permafrost Task Force Report

December 2003

Special Report 01-03

Executive Summary

Permafrost, or perenially frozen ground, is a critical component of the cryosphere and the Arctic system. Permafrost regions occupy approximately 24% of the terrestrial surface of the Northern Hemisphere; further, the distribution of subsea permafrost in the Arctic Ocean is not well known, but new occurrences continue to be found. The effects of climatic warming on permafrost and the seasonally thawed layer above it (the active layer) can severely disrupt ecosystems and human infrastructure such as roads, bridges, buildings, utilities, pipelines, and airstrips. The susceptibility of engineering works to thaw-induced damage is particularly relevant to communities and structures throughout northern Alaska, Russia, and Canada. It is clear from the long-term paleographic record in these areas that climatic warming can lead to increases in permafrost temperature, thickening of the active layer, and a reduction in the percentage of the terrestrial surface underlain by near-surface permafrost. Such changes can lead to extensive settlement of the ground surface, with attendant damage to infrastructure.

To advance U.S. and international permafrost research, the U.S. Arctic Research Commission in 2002 chartered a task force on climate change, permafrost, and infrastructure impacts. The task force was asked to identify key issues and research needs to foster a greater understanding of global change impacts on permafrost in the Arctic and their linkages to natural and human systems. Permafrost was found to play three key roles in the context of climatic changes: as a record keeper (temperature archive); as a translator of climatic change (subsidence and related impacts); and as a facilitator of climatic change (impact on the global carbon cycle). The potential for melting of ice-rich permafrost constitutes a significant environmental hazard in high-latitude regions. The task force found evidence of widespread warming of permafrost and observations of thawing—both conditions have serious, long-term implications for Alaska's transportation network, for the Trans-Alaska Pipeline, and for the nearly 100,000 Alaskan citizens living in areas of permafrost. Climate research and scenarios for the 21st century also indicate that major settlements (such as Nome, Barrow, Inuvik, and Yakutsk) are located in regions of moderate or high hazard potential for thawing permafrost. A renewed and robust research effort and a well-informed, coordinated response to impacts of changing permafrost are the responsibilities of a host of U.S. federal and state organizations. Well-planned, international polar research, such as the International Polar Year, is urgently needed to address the key scientific questions of changing permafrost and its impacts on the carbon cycle and overall global environment.

Key task force recommendations include: review by funding agencies of their interdisciplinary Arctic programs to ensure that permafrost research is integrated in program planning and execution; development of a long-term permafrost research program by the U.S. Geological Survey; enhanced funding for permafrost research at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory; adoption of the Global Hierarchical Observing Strategy in all permafrost monitoring programs; development of a high-resolution permafrost map of Alaska, including the offshore; development of new satellite sensors optimized for monitoring the state of the surface, temperature, moisture, and ground ice; full incorporation of permafrost hydrology, hydrogeology, and geomorphology in new Arctic research programs of the U.S. National Science Foundation; incorporation of permafrost research in all U.S. and international programs devoted to the global carbon cycle; enhanced and long-term funding for the U.S. Frozen Ground Data Center; and substantially increased federal funding for contaminants research in cold regions, including studies on the impacts of regional warming, predictive modeling, and mitigation techniques.

The task force report makes specific recommendations to eight U.S. federal agencies, the State of Alaska, and the U.S. National Research Council. Many of the recommendations will be incorporated in future Arctic research planning documents of the Commission, including its biennial *Report on Goals and Objectives*. The task force report will also be presented to the U.S. Interagency Arctic Research Policy Committee and to appropriate international bodies, including the International Arctic Science Committee and the Arctic Council.

Cover: Map of permafrost zonation in Alaska (modified from Brown et al., 1997, 1998). Dark blue: zone of continuous permafrost. Light blue: zone of discontinuous permafrost. Yellow: zone of sporadic permafrost. Background shows a network of active ice-wedge polygons on the North Slope of Alaska.

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MESSAGE FROM THE CHAIR

This report on *Climate Change, Permafrost, and Effects on Civil Infrastructure* is the result of the outstanding efforts of a team of experts serving as Special Advisors to the Arctic Research Commission. The Commissioners authorized this report in order to bring the Nation's attention to the connections between climate change research and the changes to civil infrastructure in northern regions that will come about as permafrost changes.

The Commission believes strongly that basic research has important connections to the way our citizens live and work. The study of climate change is an interesting discipline, but it is important to carry the results and predictions of these changes through to their effects on roads, bridges, buildings, ports, pipelines, and other infrastructure. This report suggests future research programs for the federal agencies, programs that the Commission will incorporate into our recommendations to the Interagency Arctic Research Policy Committee in our biennial *Report on Goals and Objectives for Arctic Research*.

The Commission is grateful for the effort and enthusiasm of the Task Force on Climate Change, Permafrost, and Civil Infrastructure and commends their efforts. Without this voluntary effort by the community of researchers, the Commission would be unable to help the residents of the North to cope with the changing and occasionally extreme environment in which they live.

George B. Newton, Jr.
Chair

Climate Change, Permafrost, and Impacts on Civil Infrastructure

Contents

Chapter 1

PERMAFROST AND ITS ROLE IN THE ARCTIC

1.1 Introduction

Climate-change scenarios indicate that human-caused, or *anthropogenic*, warming will be most pronounced in the high latitudes. Empirical evidence strongly indicates that impacts related to climate warming are well underway in the polar regions (Hansen et al., 1998; Morison et al., 2000; Serreze et al., 2000; Smith et al., 2002). These involve air temperature (Pavlov, 1997; Moritz et al., 2002), vegetation (Myneni et al., 1997; Sturm et al., 2001), sea ice (Bjorgo et al. 1997), the cumulative mass balance of small glaciers (Dyurgerov and Meier, 1997; Serreze et al., 2000; Arendt et al., 2002), ice sheets and shelves (Vaughan et al., 2001; British Antarctic Survey, 2002; Rignot and Thomas, 2002), and ground temperature (Lachenbruch and Marshall, 1986; Majorowicz and Skinner, 1997).

Many of the potential environmental and socioeconomic impacts of global warming in the high northern latitudes are associated with *permafrost*, or perennially frozen ground. The effects of climatic warming on permafrost and the seasonally thawed layer above it (the *active layer*) can severely disrupt ecosystems and human infrastructure and intensify global warming (Brown and Andrews, 1982; Nelson et al., 1993; Fitzharris et al., 1996; Jorgenson et al., 2001). Until recently, however, permafrost has received far less attention in scientific reviews and media publications than other cryospheric phenomena affected by global change (Nelson et al., 2002).

Throughout most of its history, permafrost science in western countries was idiosyncratic, performed by individuals or small groups of researchers, and not well integrated with other branches of cold regions research. Owing to the importance of permafrost for development over much of its territory, the situation in the former Soviet Union was distinctly different, with a large institute in Siberia and departments in the larger and more prestigious universities devoted exclusively to permafrost research.

Several factors converged in the late 1980s and early 1990s to integrate permafrost research into the larger spheres of international, systems, and global-change science:

- Easing of Cold-War tensions facilitated interactions between Soviet and western scientists. Conferences held in Leningrad (Kotlyakov and Sokolov, 1990), Yamburg, Siberia (Tsibulsky, 1990), and Fairbanks (Weller and Wilson, 1990) during the late 1980s and early 1990s were instrumental in achieving international agreements.
- Publicity about the impacts of climate warming in the polar regions followed several decades of unprecedented resource development in the Arctic and raised concerns about the stability of the associated infrastructure (Vinson and Hayley, 1990).
- The global nature of climate change made apparent the need for widespread cooperation, both within the permafrost research community and between permafrost researchers and those engaged in other branches of science (Tegart et al., 1990).
- Permafrost scientists became increasingly aware of the benefits accruing from the development of data archives and free exchange of information (Barry, 1988; Barry and Brennan, 1993). Moreover, the increasingly integrated nature of arctic science

The Ground Temperature Profile

Figure 1 shows a typical temperature profile through permafrost, from the ground surface to the base of the permafrost. Higher temperatures are to the right and lower to the left; 0°C is represented as a dashed vertical line. The heavier curves show current conditions. The summer profile curves to the right, indicating above-freezing temperatures near the ground surface. The winter profile curves to the left, indicating that the lowest temperatures are experienced at the surface, with higher temperatures deeper in the permafrost. The summer and winter profiles intersect at depth; below this point, temperatures are not affected by the seasonal fluctuations at the surface. The ground warms gradually with depth in response to the geothermal gradient. The base of the permafrost is situated where the temperature profile crosses 0°C. The *active layer* is a layer of earth material between the ground surface and the permafrost table that freezes and thaws on an annual basis.

In its simplest approximation, climate warming can be envisioned as a shift of the temperature profile to the right, as shown by the gray curves. The surface temperatures in summer and winter are higher, the active layer is thicker, and the mean annual temperature at the thermal damping depth is higher. In time, the base of the permafrost thaws and moves toward the surface. Thus, the permafrost body warms and thins as thaw progresses both above and below.

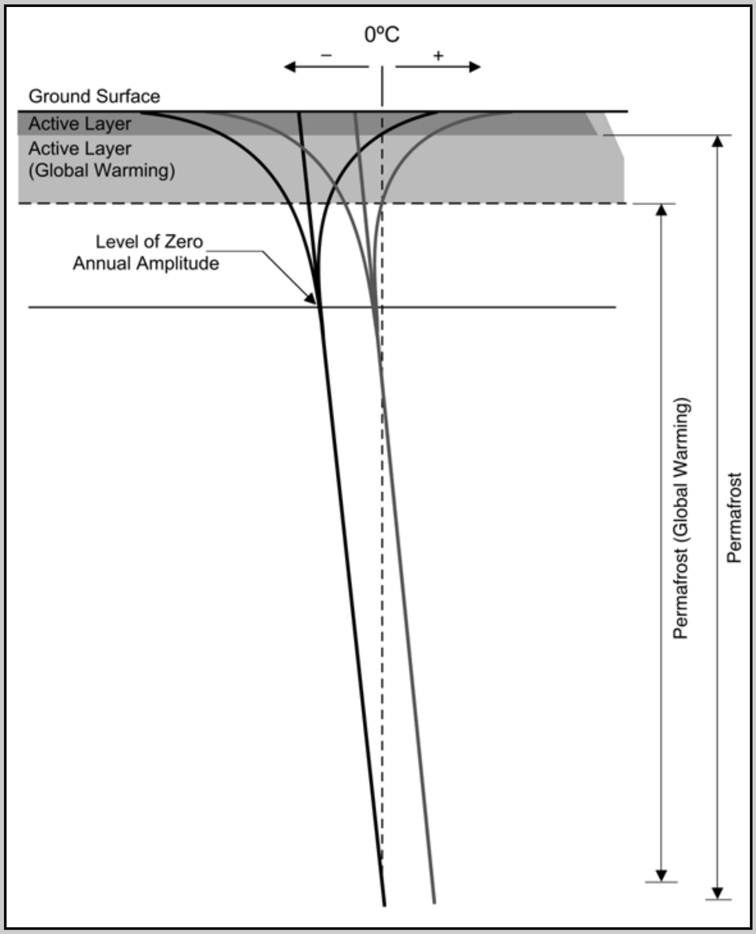


Figure 1. Ground temperature profile.

demands widespread cooperation and collaboration. Some funding agencies, such as the U.S. National Science Foundation, now require, as a condition of funding, that data be made accessible to all interested parties.

U.S. scientists have made major contributions to the study of frozen ground (*geocryology*), particularly since World War II. Useful English-language reviews, many with emphasis on Alaska, have been provided by Muller (1947), Black (1950), Terzaghi (1952), Stearns (1966), Ives (1974), Washburn (1980), Andersland and Ladanyi (1994), Davis (2001), and Hallet et al. (2004). Péwé (1983a) reviewed the distribution of permafrost in the cordillera of the western U.S.; Walegur and Nelson (2003) discussed its occurrence in the northern Appalachians. Péwé (1983c) outlined the distribution of permafrost and associated landforms in the U.S. during the last continental glaciation.

Permafrost science employs a complex and occasionally confusing lexicon derived from several languages and scientific disciplines. A brief Glossary and a List of Acronyms at the end of this document provide assistance for navigating unfamiliar terminology. A more comprehensive glossary, published under the auspices of the International Permafrost Association (IPA), is readily available (van Everdingen, 1998).

1.2 Background and Concepts

1.2.1 Thermal Regime

Two classes of frozen ground are generally distinguished: *seasonally frozen ground*, which freezes and thaws on an annual basis, and *perennially frozen ground* (permafrost), defined as any subsurface material that remains at or below 0ºC continuously for at least two consecutive years. The term *permafrost* is applied without regard to material composition, phase of water substance, or cementation. Permafrost can be extensive in areas where the mean annual temperature at the ground surface is below freezing. Because the temperature at the surface and the temperature in the air often differ substantially (Klene et al., 2001), and because of differences in the thermal conductivity of many soils in the frozen and unfrozen states (the *thermal offset*), permafrost can exist for extended periods at locations with mean annual air temperatures above 0ºC (Goodrich, 1982). Climate statistics do not, therefore, provide a reliable guide to the details of permafrost distribution. Although ultimately a climatically determined phenomenon, the presence or absence of permafrost is strongly influenced by local factors, including microclimatic variations, circulation of ground water, the type of vegetation cover, and the thermal properties of subsurface materials.

The range of temperatures experienced annually at the ground surface in typical permafrost terrain decreases with depth, down to a level at which only minute annual temperature variation occurs, termed the damping depth or *level of zero annual amplitude*. The active layer above permafrost often experiences complex heat-transfer processes (Hinkel et al., 1997; Kane et al., 2001). Below the *permafrost table*—the upper limit of material that experiences a maximum annual temperature of 0ºC—heat transfer occurs largely by conduction. In situations where, unlike Figure 1, the bottom of the active layer is not in direct contact with the top of the permafrost, the permafrost is a relic of a past colder interval and may be substantially out of equilibrium with the contemporary climate.

1.2.2 Landforms

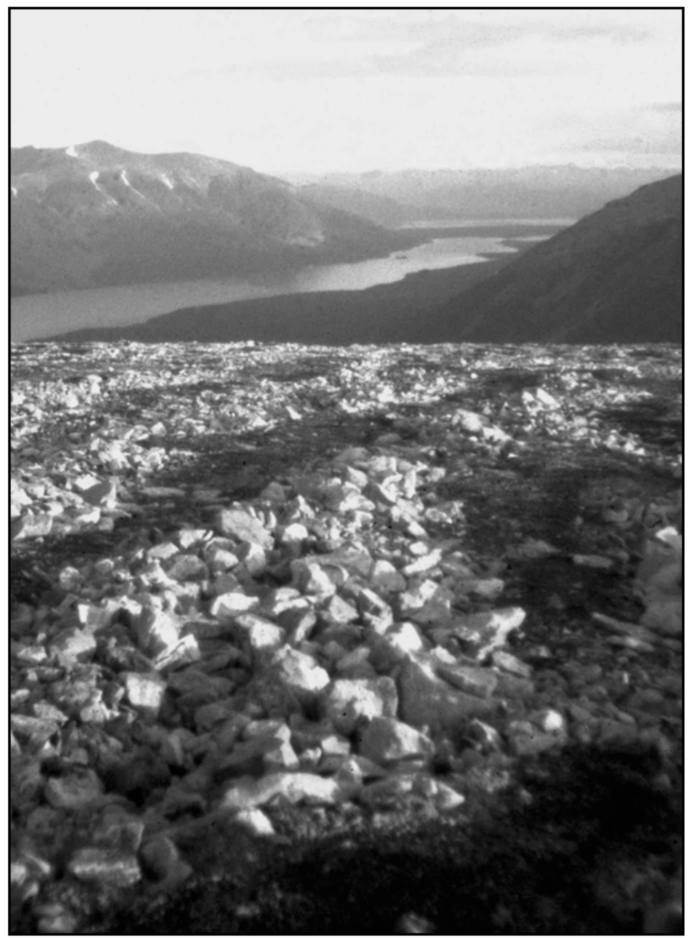
Many distinctive landforms exist in permafrost regions, although only some unambiguously indicate the presence of permafrost. Surface features formed under cold, nonglacial conditions are known as *periglacial landforms* (Washburn, 1980; French, 1996) (Fig. 2). One periglacial feature that serves as a good indicator of the presence of permafrost is *ice wedges*—vertical ice inclusions created when water produced from melting snow seeps into cracks formed in fine-grained sediments during severe cold-weather events earlier in winter. Repeated many times over centuries or millennia, this process produces tapered wedges of foliated ice more than a meter wide near the surface and extending several meters or more into the ground. Viewed from the air, networks of ice wedges form striking polygonal patterns over extensive areas of the Arctic (Lachenbruch, 1962, 1966). Other landforms diagnostic of the presence of permafrost are *pingos*—ice-cored hills frequently over 10 m in height that can form when freezing fronts encroach from several directions on saturated sediments remaining after drainage of a deep lake (Mackay, 1998). *Palsas*—smaller, mound-shaped forms often found in subarctic peatlands—can form through a variety of mechanisms (Nelson et al., 1992).

Other periglacial landforms occur frequently in association with permafrost but are not necessarily diagnostic of its presence. When *ice-rich permafrost* or another impermeable layer prevents infiltration of water, the soil on a hillside may become vulnerable to a slow, flow-like process known as *solifluction*, giving rise to a network of lobes and terraces that impart a crenulated or festooned appearance to the slope. Other small landforms frequently encountered in subpolar and polar regions, collectively referred to as *patterned ground*, include small

a. Large pingo near Prudhoe Bay, Alaska.

b. Palsa at MacMillan Pass, near the Yukon–NWT border.

c. Detachment slide in the Brooks Range foothills.



d. Large-diameter sorted patterned ground, Cathedral Massif, northwestern British Columbia.

Figure 2. Periglacial landforms often associated with permafrost.

hummocks and networks of striking geometric forms arranged into circles, polygons, or stripes of alternating coarse- and fine-grained sediment.

1.2.3 Permafrost Distribution

The permafrost regions occupy approximately 24% of the terrestrial surface of the Northern Hemisphere (Brown et al., 1997; Zhang et al., 1999, 2003). Substantial areas of subsea permafrost also occur around the land margins of the Arctic Ocean, much of it ice rich (Brown et al., 1997; Danilov et al., 1998). The distribution of offshore permafrost is not well known, and new occurrences are found frequently. As shown in Figure 3, the distribution of permafrost is often classified on the basis of its lateral continuity. In the Northern Hemisphere the various classes form a series of

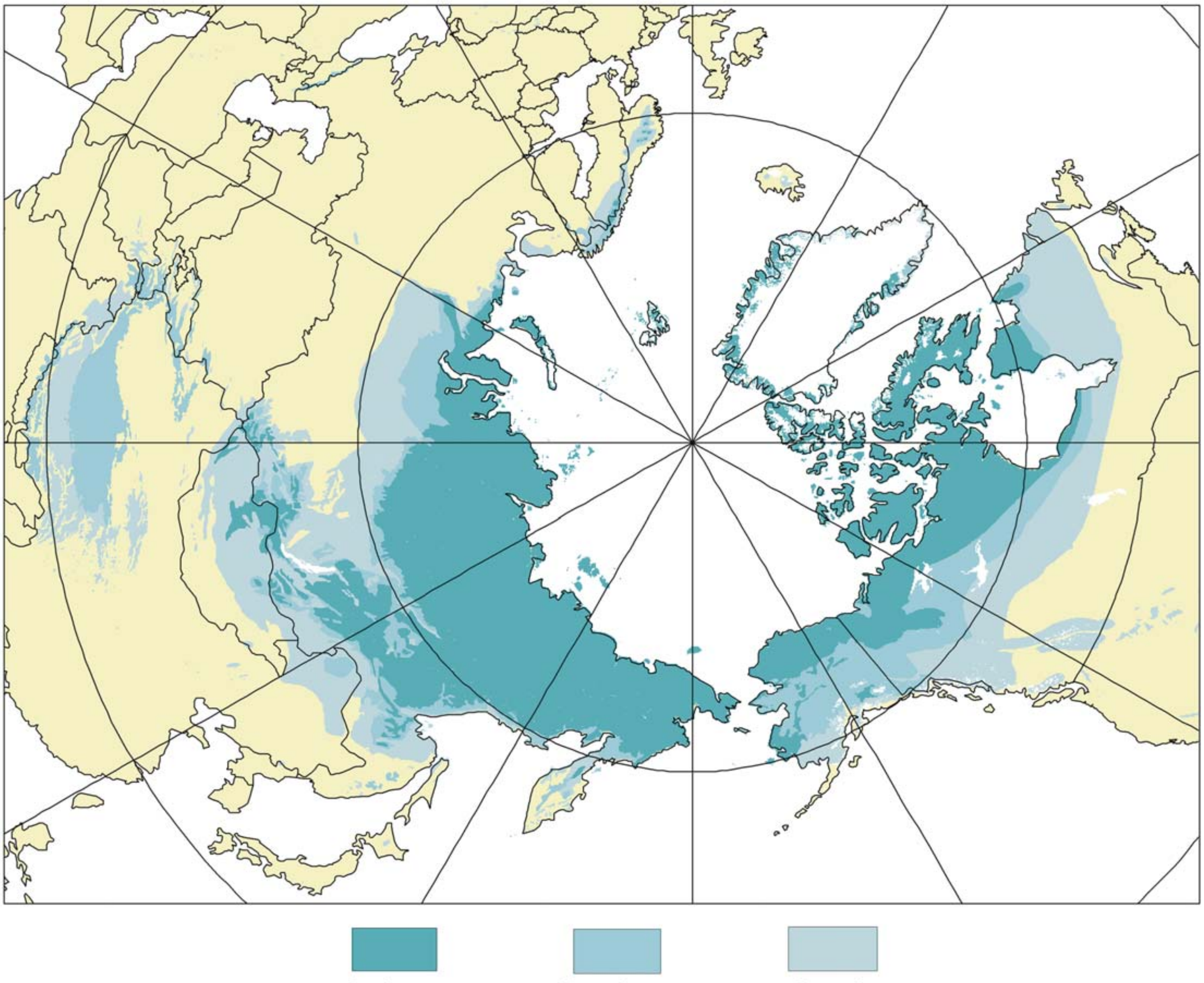


Figure 3. Permafrost zonation in the Northern Hemisphere. Zones are defined on the basis of percentage of land surface underlain by permafrost: continuous zone, 90–100%; discontinuous zone, 50–90%; sporadic zone, 10–50%; isolated patches, 0–10%. The 1997 map on which this figure is based is the first detailed document to show permafrost distribution in the Northern Hemisphere based on standardized mapping criteria. [After Nelson et al. (2002) adapted from Brown et al. (1997, 1998).]

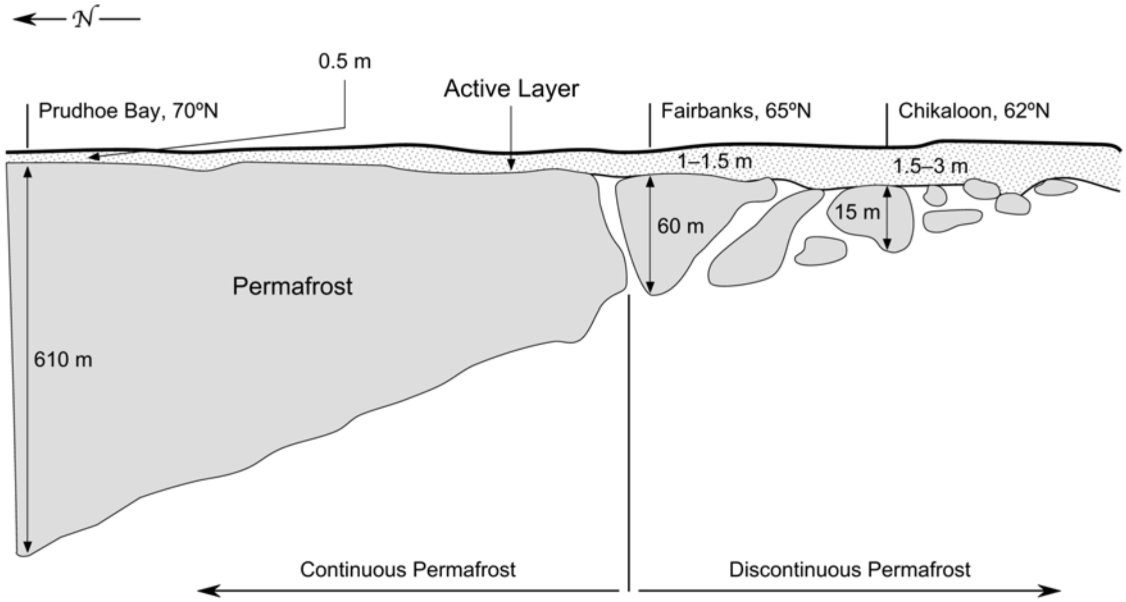


Figure 4. Latitudinal profile through the permafrost zones in Alaska, extending from the vicinity of Chikaloon in the Interior to Prudhoe Bay near the Arctic Ocean. Near the southern boundary, where the average annual temperature is around 0°C, isolated permafrost bodies may exist sporadically at depth. As the mean annual temperature decreases with increasing latitude, discontinuous permafrost bodies become larger and thicker, existing where local conditions are favorable, for example, on north-facing slopes. At average annual temperatures around –5°C, permafrost in Alaska is essentially continuous, and in northern Alaska it extends to depths of over 400 m, although local unfrozen zones (taliks) may exist beneath large rivers and lakes. The active layer can be quite thick in the sporadic permafrost zone, and it decreases in thickness with latitude, although local factors can make it highly variable (Nelson et al., 1999). Near the coast of the Arctic Ocean the active layer reaches a maximum mean thickness of only about 60 cm in mid- to late August.

concentric zones that conform crudely to the parallels of latitude (Fig. 4). Southward deviations in the extent of permafrost in Siberia and central Canada are a response to lower mean annual temperatures in the continental interiors.

In the *zone of continuous permafrost*, perennially frozen ground underlies most locations, the primary exception being under large bodies of water that do not freeze to the bottom annually. In the *discontinuous zone*, permafrost may be widespread, but a substantial proportion of the land surface can be underlain by seasonally frozen ground, owing to variations in such local factors as vegetation cover, snow depth, and the physical properties of subsurface materials. Some authors also refer to a zone in which permafrost is *sporadic*, occurring as isolated patches that reflect combinations of local factors favorable to its formation and maintenance. Because the thermal properties of peat are conducive to the existence of frozen ground, subarctic bogs are the primary locations of permafrost in southerly parts of the subarctic lowlands (Zoltai, 1971; Beilman and Robinson, 2003). In the Southern Hemisphere, permafrost occurs in ice-free areas of the Antarctic continent and in some of the subantarctic islands (Bockheim, 1995). Permafrost is also extensive in such midlatitude mountain ranges as the Rockies, Andes, Alps, and Himalayas, a response to progressively lower mean annual temperatures at higher elevations. Given sufficient altitude and favorable local conditions, patches of permafrost can exist even in the subtropics, such as in the crater of Mauna Kea (4140 m above sea level) on the island of Hawaii (Woodcock, 1974).

The thickness of permafrost is determined by the mean annual temperature at the ground surface, the thermal properties of the substrate, and the amount of heat flowing from the earth's interior. Permafrost thicknesses range from very thin layers only a few centimeters thick to about 1500 m in unglaciated areas of Siberia (Washburn, 1980). In general, the thickness of lowland permafrost increases steadily with increasing latitude.

1.2.4 Ground Ice and Thermokarst

Although the presence of ice is not a criterion in the definition of permafrost, ground ice is responsible for many of the distinctive features and problems in permafrost regions. Ice can occur within permafrost as small individual crystals within soil pores, as lenses of nearly pure ice parallel to the ground surface, and as variously shaped intrusive masses formed when water is injected into soil or rock and subsequently frozen. The origin and morphology of ground ice are varied (Mackay, 1972), ranging from thick layers of buried glacier ice, through horizontally oriented ice lenses formed by the migration of moisture to freezing fronts (*segregation ice*), to the distinctive polygonal networks of vertical veins known as *ice wedges*. If their thermal stability is preserved, perennially frozen ice-bonded sediments can have considerable bearing capacity and are often an integral part of engineering design in cold regions (Andersland and Ladanyi, 1994; Yershov, 1998). Figure 5 shows the generalized distribution of ground ice in the Northern Hemisphere. A digital database on ground ice is under development at Moscow State University (Streletskaya et al., 2003).

Changes in the thickness and geographical extent of permafrost have considerable potential for disrupting human activities if substantial

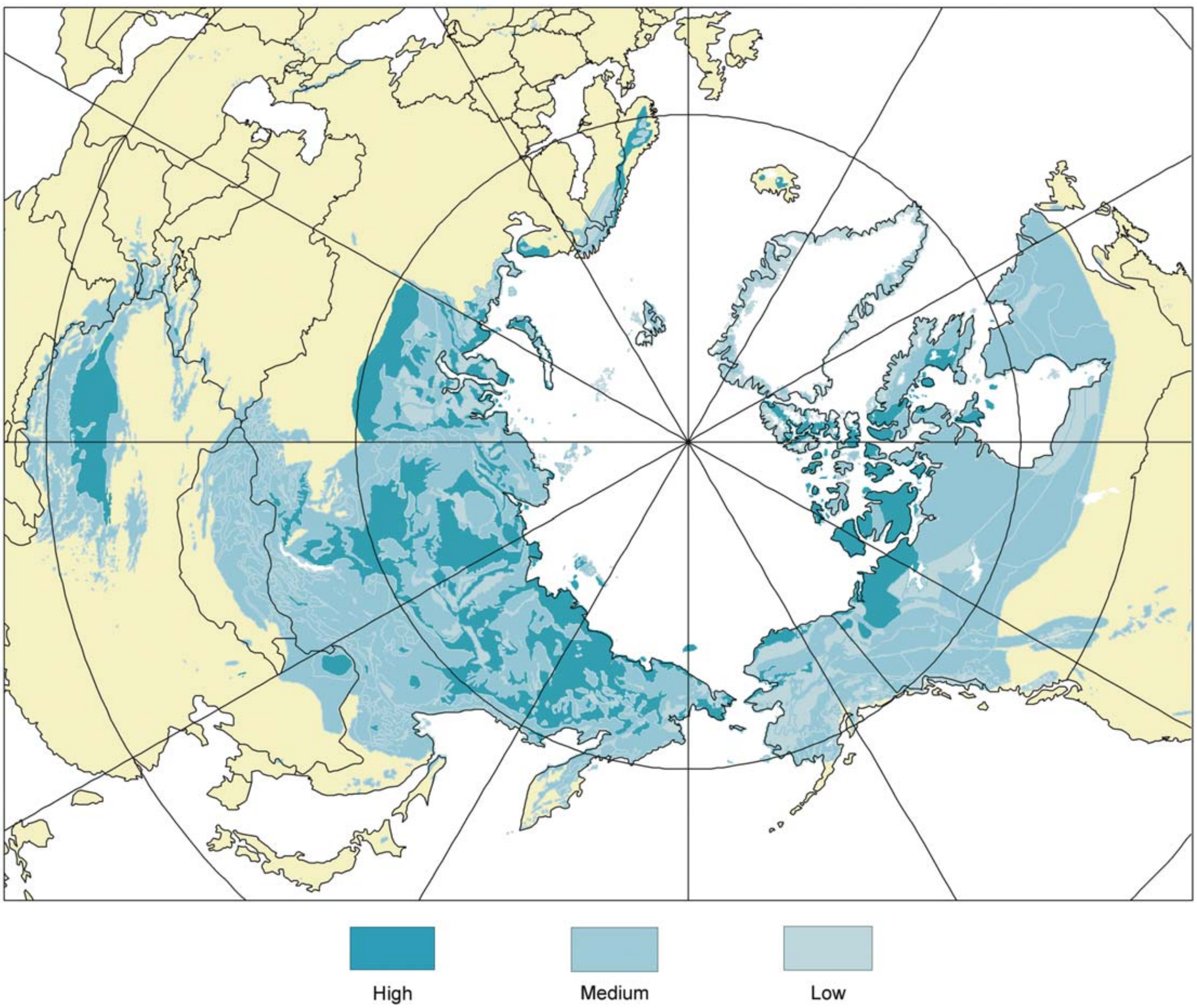


Figure 5. Generalized distribution of ground ice in the Northern Hemisphere. Ground-ice content is expressed on a relative volumetric basis: low: 0–10%; medium: 10–20%; high: >20%. Ice-cored landforms of limited extent (e.g., pingos) are not shown. [From Nelson et al. (2002) and adapted from Brown et al. (1997, 1998).]

Thermokarst and Ground Subsidence

Thickening of the active layer has two immediate effects. First, decomposed plant material frozen in the upper permafrost thaws, exposing the carbon to microbial decomposition, which can release carbon dioxide and methane to the atmosphere. Second, the ice in the upper permafrost is converted to water. In coarse materials such as sand and gravel, this is not necessarily a problem. However, fine-grained sediments often contain excess ice in the form of lenses, veins, and wedges. When ice-rich permafrost thaws, the ground surface subsides; this downward displacement of the ground surface is termed *thaw settlement* (Fig. 6). Typically, thaw settlement does not occur uniformly over space, yielding a chaotic surface with small hills and wet depressions known as *thermokarst terrain*; this is particularly common in areas underlain by ice wedges (Fig. 7). When thermokarst occurs beneath a road, house, pipeline, or airfield, the structural integrity is threatened. If thermokarst occurs in response to regional warming, large areas can subside and, if near the coast, can be inundated by encroaching seas.

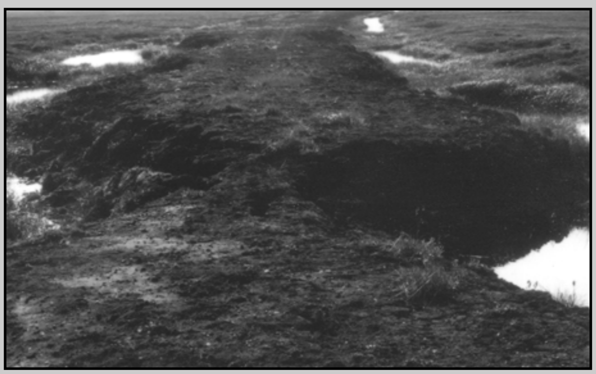


Figure 6. Thaw settlement, which develops when ice-rich permafrost thaws and the ground surface subsides.

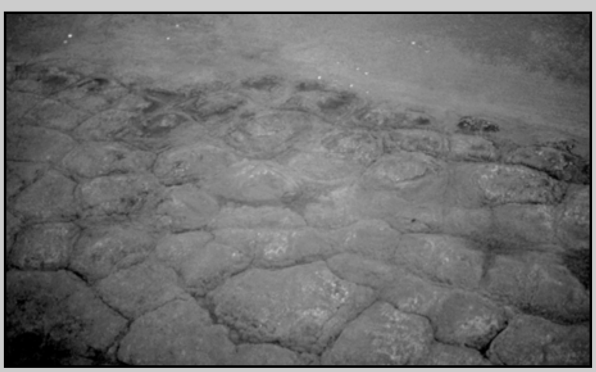


Figure 7. High-centered polygons near Prudhoe Bay, Alaska. This form of thermokarst terrain develops through ablation of underlying ice wedges.

amounts of ground ice are present. Because the volume is reduced when ice melts and because pore water is squeezed out during consolidation, thawing of ice-rich sediments leads to subsidence of the overlying ground surface, often resulting in deformation of an initially level surface into irregular terrain with substantial local relief. By analogy with terrain developed by chemical dissolution of bedrock in areas underlain extensively by limestone, the irregular surface created by thawing of ice-rich permafrost is known as *thermokarst terrain*. Thermokarst subsidence occurs when the energy balance at the earth's surface is modified such that heat flux to subsurface layers increases. The process occurs over a wide spectrum of geographical scale, ranging from highly localized disturbances associated with the influence of individual structures to depressions tens of meters deep and occupying many square kilometers (Washburn, 1980, p. 274).

On slopes, particularly in mountainous regions, thawing of ice-rich, near-surface permafrost layers can create mechanical discontinuities in the substrate, leading to *active-layer detachment* slides (Figure 8b) and *retrogressive thaw slumps* (Lewkowicz, 1992; French, 1996), which have a capacity for damage to structures similar to other types of rapid mass movements. Thermokarst subsidence is amplified where flowing water, often occurring in linear depressions, produces *thermal erosion* (Figure 8e; Mackay, 1970). Similarly, wave action in areas containing ice-rich permafrost can produce extremely high rates of coastal and shoreline erosion (Walker, 1991; Wolfe et al., 1998).

Anthropogenic disturbances in permafrost terrain have been responsible for striking changes over relatively short time scales. Removal or disturbance of the vegetation cover for agricultural purposes (Péwé, 1954), construction of roads and winter vehicle trails (Claridge and Mirza, 1981; Nelson and Outcalt, 1982; Slaughter et al., 1990), and airfields (French, 1975) have resulted in subsidence severe enough to disrupt or prevent the uses for which land was developed. A controlled experiment at the Permafrost National Test Site near Fairbanks, Alaska, caused the permafrost table to

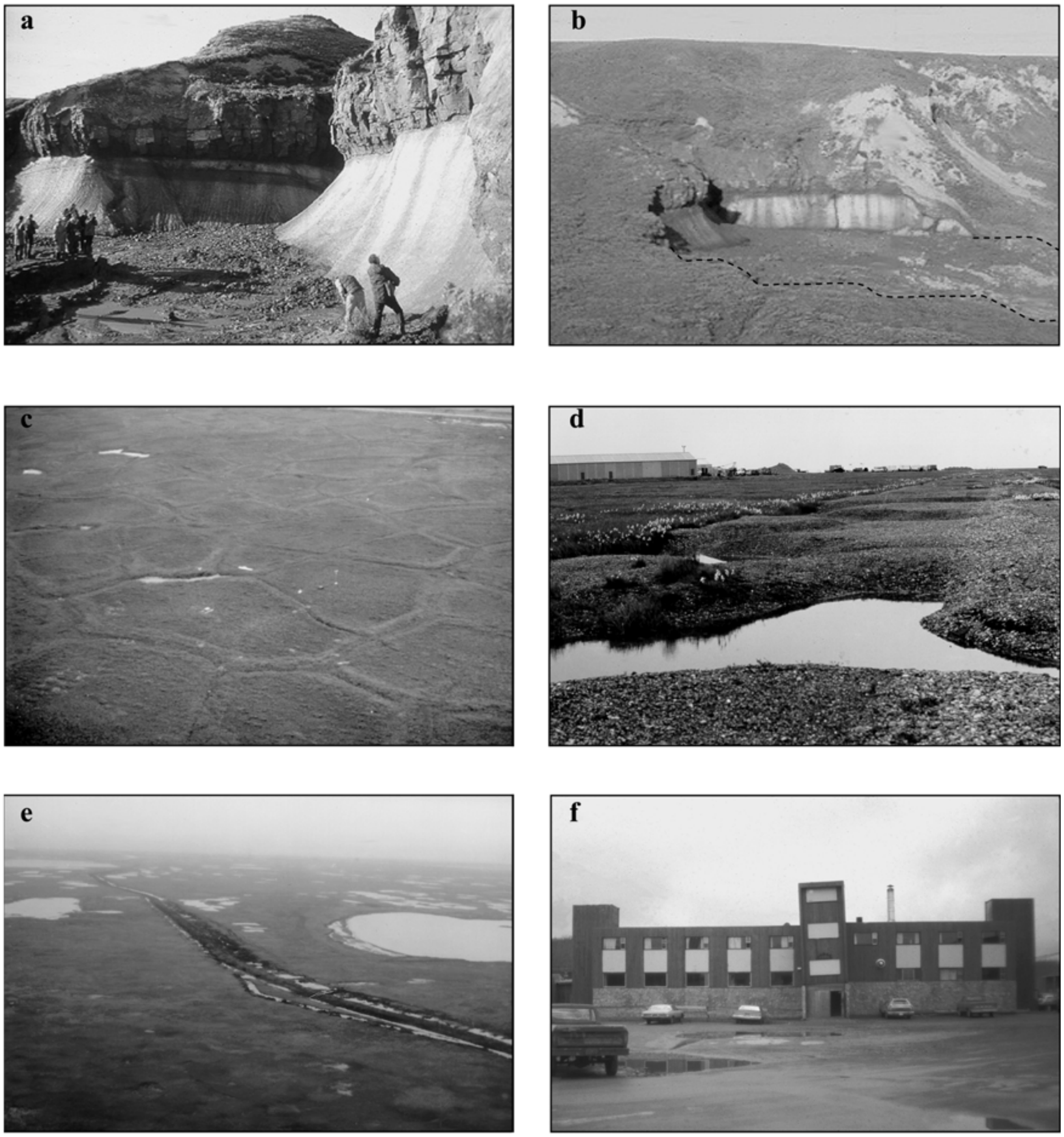


Figure 8. Effects of thermokarst processes on natural landscapes and engineered works. (a) Massive ground ice in the Yamal Peninsula, western Siberia; (b) Active-layer detachment slide, delineated below the headwall with dashed lines. The slide is associated with the presence of massive ground ice and developed in response to a particularly warm summer in the late 1980s; (c) Network of ice-wedge polygons near Prudhoe Bay; (d) Thermokarst that developed in terrain underlain by ice wedges near Prudhoe Bay, resulting from an inadequate amount of gravel fill in road construction; (e) Severe thermokarst developed over one decade in a winter road near Prudhoe Bay; the road was constructed by stripping the organics and stacking the mats in the intervening area; (f) Building in Faro, Yukon, undergoing differential settlement because of thawing of ice-rich permafrost. [From Nelson et al., 2002.]

move downward as much as 6.7 m over a 26-year period, simply by removing the insulating layer of vegetation (Linell, 1973). Even trampling can trigger thermokarst (Mackay, 1970), so agencies regulating tourism in the Arctic (Johnston, 1997) will have to thoroughly assess the relative merits of developing concentrated traffic through systems of foot trails or encouraging more diffuse patterns of use. Developmental encroachment on lands traditionally used to support herbivores may increase herd densities to such an extent that overgrazing could induce widespread thaw settlement (Forbes, 1999). Brown (1997) provided a comprehensive review of a wide range of anthropogenic disturbances affecting permafrost terrain.

1.3 Effects on Civil Infrastructure

Thermokarst can have severe effects on engineered structures, in many cases rendering them unusable. Because of its potential for settlement, thawing of ice-rich permafrost constitutes a significant environmental hazard in high-latitude regions, particularly in the context of climatic change. Although hazards related to permafrost have been discussed in specialist literature and textbooks (e.g., Brown and Grave, 1979; Péwé, 1983b; Williams, 1986; Woo et al., 1992; Andersland and Ladanyi, 1994; Koster and Judge, 1994; Yershov, 1998; Dyke and Brooks, 2000; Davis, 2001), they are given scant attention in most English-language texts focused on natural hazards (e.g., Bryant, 1991; Coch, 1995). Much of the literature treating social science and policy issues in the polar regions (e.g., Peterson and Johnson, 1995; Brun et al., 1997) also fails to adequately consider issues related to permafrost.

Although the permafrost regions are not densely populated, their economic importance has increased substantially in recent decades because of the abundant natural resources in the north circumpolar region and improved methods of extraction and transportation to population centers. Economic development has brought expansion of the human infrastructure: hydrocarbon extraction facilities, transportation networks, communication lines, industrial projects, civil facilities, and engineering maintenance systems have all increased substantially in recent decades. Rapid and extensive development has had large costs, however, in both environmental and human terms (e.g., Williams, 1986; Smith and McCarter, 1997), and these could be aggravated severely by the effects of global warming on permafrost.

Construction in permafrost regions requires special techniques at locations where the terrain contains ice in excess of that within soil pores. Prior to about 1970, many projects in northern Alaska and elsewhere disturbed the surface significantly, triggering thermokarst processes and resulting in severe subsidence of the ground surface, disruption of local drainage patterns, and in some cases destruction of the engineered works themselves. The linear scar in Figure 8e marks the route of a winter road constructed in 1968-69 by bulldozing the tundra vegetation and a thin layer of soil (Anonymous, 1970). This disturbance altered the energy regime at the ground surface, leading to thaw of the underlying ice-rich permafrost and subsidence of up to 2 m along the road (Nelson and Outcalt, 1982), which became unusable several years after construction.

Environmental restrictions in North America, based on scientific knowledge about permafrost, now regulate construction activities to minimize their impacts on terrain containing excess ice. The Trans-Alaska Pipeline, which traverses 1300 km from Prudhoe Bay on the Arctic coastal plain to Valdez on Prince William Sound near the Gulf of Alaska, carries oil at temperatures above 60°C. To prevent the development of thermokarst and severe damage to the pipe, the line is elevated where surveys indicated the presence of excess ice. To counteract conduction of heat into the ground, many of the pipeline's vertical supports are equipped with heat pipes that cool the permafrost in winter, lowering the mean annual ground temperature and preventing thawing during summer. In several short sections of ice-rich terrain where local above-ground conditions required burial of the line, the pipe is enclosed in thick insulation and refrigerated.

Other unusual engineering techniques devised for ice-rich permafrost include constructing heated buildings on piles, which allows air to circulate beneath the structures and prevents conduction of heat to the subsurface. Roads, airfields, and building complexes are frequently situated atop thick gravel pads or other insulating materials. In relatively large settlements such as Barrow, water and sewage are transported in insulated, elevated pipes known as "utilidors" (Fig. 9).

Figure 9. Utilidor in Barrow, Alaska.