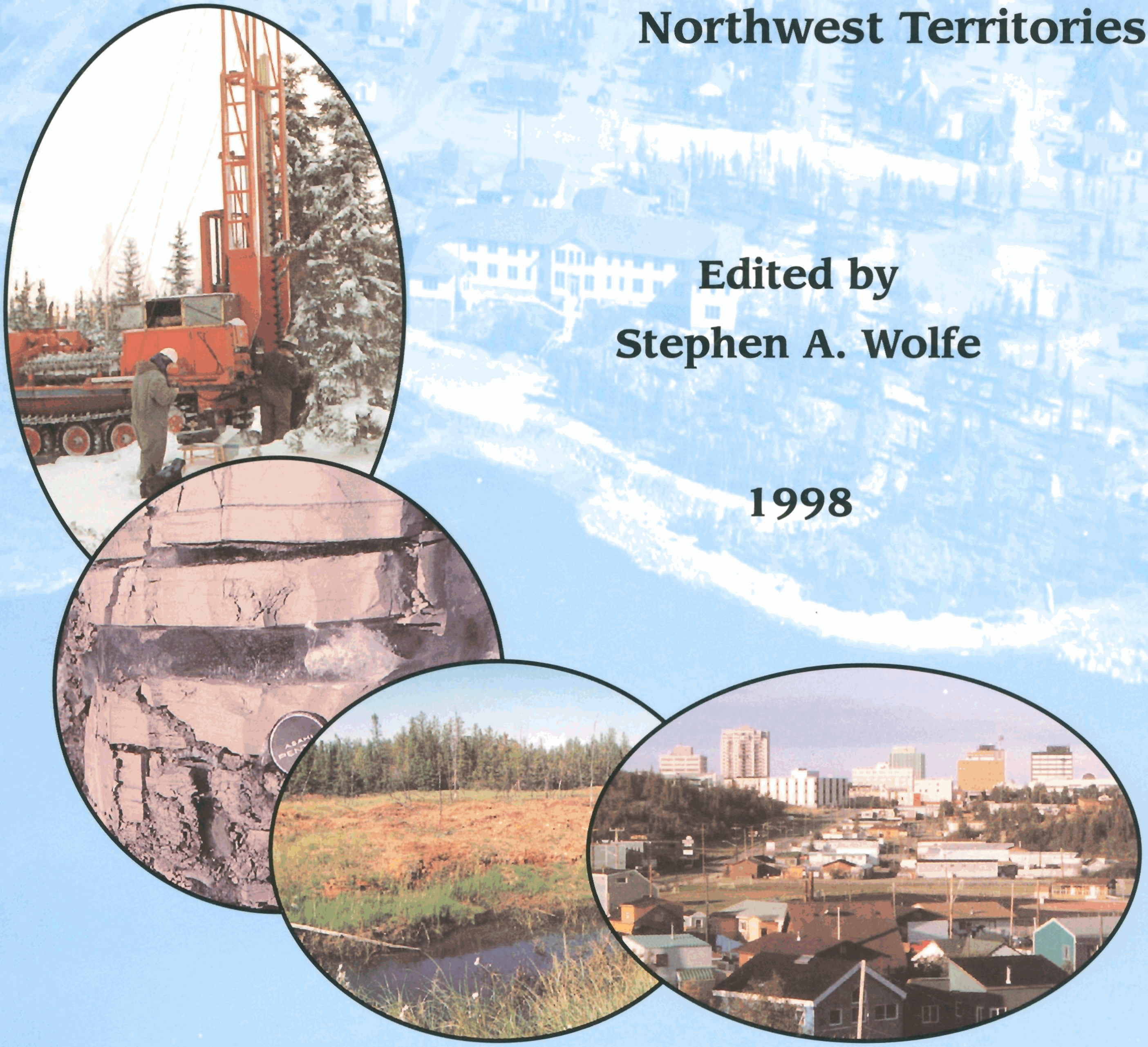
Geological Survey of Canada
Miscellaneous Report 64

LIVING WITH FROZEN GROUND

A field guide to permafrost in Yellowknife, Northwest Territories



Edited by
Stephen A. Wolfe

1998

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Stephen A. Wolfe

Contributions by

Stephen A. Wolfe
Sharon Smith
T. Edward Hoeve
Jamie Bastedo
Philip D. Keddie

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Cover illustration

Front cover:
Background: The 'New Town' area of Yellowknife as it appeared in July 1951 (NAPL REA-640-3). Insets, from top left: **a)** drilling and sampling of permafrost soils in the Niven Lake area before construction of a housing development, December 1992. 1998-006 SS; **b)** ice lenses up to 5 cm thick formed in silty clay sediments (photo by Larry Aspler, October, 1977); **c)** peat plateau and thermokarst ponds formed in permafrost-affected soils, July 1996. 1998-006 UU; **d)** view of downtown Yellowknife from Willow Flats, August 1997. 1998-006 VV

Back cover:
Background: The 'New Town' area of Yellowknife as it appeared in July 1951 (NAPL REA-640-3). Inset: Yellowknife City Hall. 1998-006 TT

Critical reviewers

B.R. Pelletier
M.M. Burgess

Author's address

Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

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CONTENTS

LIVING WITH FROZEN GROUND

A field guide to permafrost in Yellowknife, Northwest Territories

Abstract

This guidebook describes some of the challenges to development that permafrost, or frozen ground, presents to the City of Yellowknife. Part I of the guide provides an overview of the geological events, subarctic environment and recent human developments that have shaped this city. Part II describes permafrost occurrence in Yellowknife, the impacts of permafrost on development, and potential changes to permafrost under conditions of possible climate warming. Part III presents two walking tours of Yellowknife, illustrating where the effects of permafrost can be seen throughout the city. The tours illustrate the occurrence of permafrost prior to development, changes that have occurred over the last 50 years, and the impacts that these and other processes related to frozen ground have had on buildings, roadways, and the people of Yellowknife. Part IV describes the Niven Lake trail, highlighting the general ecology and discontinuous permafrost environment of the subarctic Canadian Shield.

Résumé

Ce livret-guide décrit quelques-uns des défis au développement que le pergélisol, ou sol gelé, présente à la ville de Yellowknife. La Partie I du guide fournit un aperçu des événements géologiques, de l'environnement subarctique et des développements humains qui ont influencés la ville. La Partie II décrit la distribution du pergélisol à Yellowknife, les impacts du pergélisol sur le développement et les changements au pergélisol qui pourraient survenir par suite d'un éventuel réchauffement climatique. La Partie III présente deux promenades à pied à Yellowknife, au cours desquelles on peut voir les effets du pergélisol dans la ville. Les promenades démontrent la distribution du pergélisol avant le développement urbain, les changements survenus au cours des 50 dernières années et les impacts que ces processus et d'autres associés aux sols gelés ont eu sur les édifices, les routes et les habitants de Yellowknife. La Partie IV décrit le sentier du lac Niven, y compris l'écologie générale et le milieu du pergélisol discontinu du Bouclier canadien subarctique.

ACKNOWLEDGMENTS

In preparing this field guide, considerable support was received from several contributors, namely, Jamie Bastedo, Cygnus Environmental Consulting; Ed Hoeve, EBA Engineering Limited; Philip Keddie, Department of Geography, University of Guelph; and Sharon Smith. In addition, this guide could not have been written without the experience and efforts of numerous geologists and engineers including Larry Aspler, Adrian Bader, Bob Boon, Don Hayley, Neil Jamieson, Gary Koop, Rob LaChance, Tahrana Lovlin, Laura Prentice, and Walter Orr. Additional assistance was provided by John Anderson, Melissa Daoust, Ron Daoust, Dave Hill, Grant Hinchey, John Jardine, Dave Lovell, Norm Muffitt, Peter Pagonis, and Sam Yurkiw. This guide was produced with the assistance of Marie-France Dufour, Judy Kingsley, Debby Busby, Krista Lamer, Helen Dumych, Jill Coulthart, and Rachelle Lacroix. The guide benefitted from reviews by Bernard Pelletier, Philip Keddie, Jackie Wolfe, Chris Burn, Don Hayley, Margo Burgess, Alan Heginbottom, John Jardine, Adrian Bader, and Gino Pin.

Production of this guide was directed by the Geological Survey of Canada for the 7th International Conference on Permafrost, held in Yellowknife June 23-27, 1998. However, it is for all those interested in permafrost and Yellowknife – visitors and residents alike.

WELCOME TO YELLOWKNIFE

Situated on the north shore of Great Slave Lake at a latitude of 62°29'N, the City of Yellowknife is unique in many ways. With a population in 1997 of more than 17 000, it is the largest community in the Northwest Territories and historically one of the fastest growing cities in Canada (Fig. 1). It is the capital of the Northwest Territories but owes its existence to mining. It is a youthful city, rich in history. Yellowknife also lies within the discontinuous permafrost zone that forms a broad band across northern Canada that separates northern regions where permafrost is continuous from southern regions where permafrost is localized or absent (Fig. 2).

Figure 1. *Yellowknife from the air. The city is home to more than 17 000 residents, but appears much larger. GSC 1998-006 A*

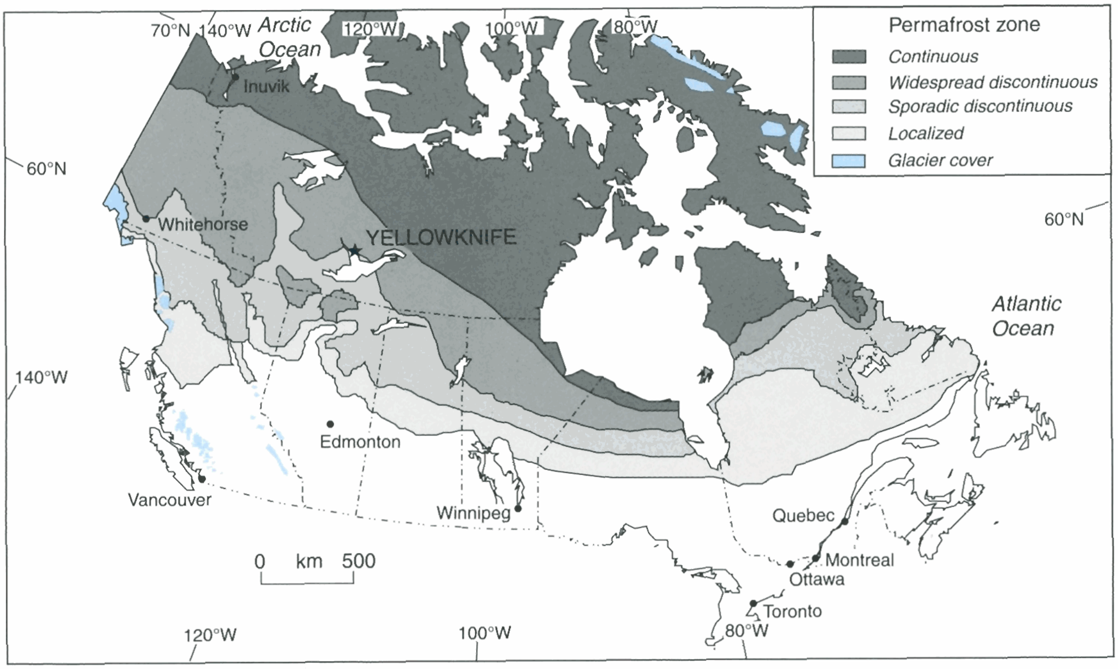


Figure 2. *Distribution of permafrost in Canada (modified from Kettles et al.,1997, based on Heginbottom et al., 1995, and Zoltai, 1995). Yellowknife lies in the discontinuous permafrost zone, near the boundary between widespread and sporadic permafrost.*

Strictly speaking, permafrost is ground that remains below 0°C for two summers and an intervening winter. In practical terms, however, permafrost may be thought of as frozen ground, because it is the ice in the ground that creates most of the challenges associated with permafrost. In many ways permafrost defines the North – it is the ground on which plants and animals must survive. It has also determined the way people live in the North; buildings, roadways, and other facilities must handle the distinct conditions associated with "frozen ground".

The geology and history of the Yellowknife area are summarized in this guide, with an emphasis on permafrost. Several areas are described within Yellowknife where examples of the effects of permafrost may be observed. These include elevated peat plateaus and thermokarst terrain, buildings designed to cope with frozen ground (and others that were not!), thermosyphons used to prevent the ground from thawing, and various impacts of thawing permafrost and frost heave on roadways and buildings. Because the terms used in this guide may be new to many readers, a glossary is provided at the end of the guide. When a word found in the glossary appears for the first time in the guide, it is shown in ***bold italics*** for easy reference.

The guide also includes several tours of the Yellowknife area. The first is a short tour around the Capital Site, which begins and ends at the Visitors Centre. Following this, you may continue on a second tour through the heart of the city. The final tour is the Niven Lake trail, a subarctic oasis adjacent to downtown Yellowknife.

PART I: THE LANDSCAPE AND THE PEOPLE

Stephen A. Wolfe, Philip D. Keddie, and Sharon Smith

The landscape of the Yellowknife region reflects the long-term interaction of geology and climate and, more recently, the influence of people. Rock-forming processes have been active over billions of years, and successive ***glaciations*** have eroded the resistive ***Precambrian*** bedrock leaving a landscape of lakes, rock, and surficial deposits. In the last 8000 years a ***subarctic*** climate has created a setting with stunted vegetation and pockets of frozen ground. Native people have lived in the region for more than 7500 years but Yellowknife, as recognized in the modern context, has existed since only 1934.

Geological evolution of the landscape

Situated on the ***Canadian Shield*** on the north shore of Great Slave Lake, Yellowknife lies at an elevation about 180 m above sea level. The difference in elevation across the city is less than 40 m. The present day terrain consists mainly of bare rocky outcrops with glacial, river, and lake sediments scattered across the area. ***Marshes, fens, peat bogs***, and small lakes occupy many of the basins and valleys.

Bedrock geology

The bedrock of the Yellowknife region constitutes part of the Canadian Shield, the stable ***cratonic*** core that underlies almost two thirds of Canada. Yellowknife lies on the southern tip of the ***Slave Structural Province*** near the eastern limit of the ***Interior Plains*** (Fig. 3). Within this region, the world's oldest rocks, the Acasta gneiss, which are nearly 4 billion years old, have been discovered.

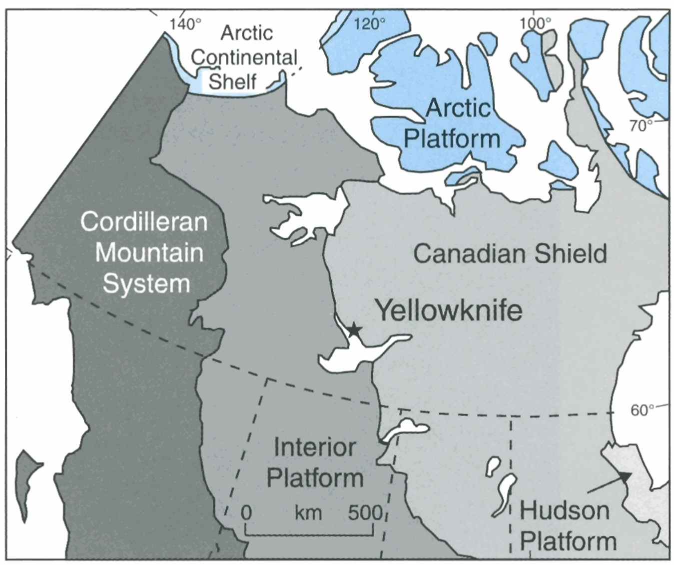


Figure 3. *Main geological structural units of northwestern Canada (modified from Trenhaile, 1990). Yellowknife is located on the Canadian Shield.*

Yellowknife straddles two main bedrock types generally referred to as ***granitic*** and ***volcanic***. These rocks date back to the ***Archean Eon*** of the Precambrian (Fig. 4), and are about 2.5 to 2.7 billion years old. Massive ***granite*** deposits lie to the north and west and, along Yellowknife Bay, volcanic rocks comprising massive ***basalts*** and ***metamorphosed sedimentary rocks*** called ***greenstones*** occur. Several major fault lines divide the granitic rocks from the older volcanic rocks, including the Kam Lake Fault and West Bay Fault that run through Yellowknife. Throughout the area, younger igneous rocks have intruded along weaker planes in both main bedrock types.

Millions of years ago	EON	ERA	PERIOD
Present	Phanerozoic	Cenozoic	Quaternary
1.8			Tertiary
65		Mesozoic	Cretaceous Jurassic Triassic
250		Paleozoic	Permian Carboniferous Devonian Silurian Ordovician Cambrian
570	Proterozoic	Precambrian	
2500	Archean		
4000 +			

Figure 4. Geological time scale, with ages in millions of years. Most rocks in the Yellowknife region date back to the Archean Eon.

Bedrock and structural features have played a significant role in Yellowknife's history. Gold was first discovered in 1898 along the mouth of the Yellowknife River. The Yellowknife volcanic rocks host the gold mined at both the Con and Giant mines (Fig. 5). West of Kam Lake, the bedrock contains joints and fractures that provide good crushed rock for construction material. In addition, the natural drainage around Yellowknife has been influenced by the bedrock structure. Elongated lakes have formed where weaker rocks have been eroded along fault lines, while hills and valleys have formed due to different rates of weathering.

Several informative field guides providing further details about the bedrock geology of the Yellowknife area have been written. These and other field guides are listed at the back of this guide.

Figure 5. *The Con mine, as it looked in 1949. NAPL REA 578-11*

Surficial geology

The region has been subjected to numerous periods of glaciation that have shaped the bedrock surface. During the most recent glaciation, the ***Laurentide Ice Sheet*** advanced to the southwest and retreated to the northeast. This period of glaciation reached a maximum approximately 20 000 years ago during the ***Late Wisconsinan*** when most of Canada was covered by ice.

Glacial deposits, although common in the region, are rare in the Yellowknife area. Although ***till*** deposits occur north of the city near the Giant mine, they are not exposed in the downtown area. Glacial scouring and postglacial erosion resulted in the general absence of till in this area. Excellent examples of the glacial scouring of bedrock are visible throughout the city. ***Striations*** (Fig. 6), polished surfaces, grooves, and ***whalebacks*** are seen on many rock surfaces. These features indicate that the general direction of ice movement was from the northeast.

Figure 6. *Striations, or scratches on the rock surface, are produced when fragments carried beneath glacial ice scrape the underlying bedrock. These striations indicate that the direction of ice movement in the Yellowknife area was roughly from northeast to southwest. GSC 1998-006 B*

During glaciation, the weight of glacial ice depressed the land surface in this region by as much as 130 m. Later, as the ice receded, the newly exposed land to the west rose due to release from the ice load while the area to the east remained depressed. Near the end of the last glaciation, about 10 000 years ago, ***meltwater*** was released in enormous quantities from the melting ice sheets, and watercourses surged through the area. Sand and gravel deposits were laid down by energetic rivers. A large delta formed north of the city near the present-day airport while a second sandy delta was deposited in downtown Yellowknife.

At the same time as these sandy plains were deposited, a large lake was beginning to form that would remain until about 8500 years ago. This lake originated in the Great Bear Lake basin and was dammed to the east by the edge of the retreating Laurentide Ice Sheet. As the ice retreated to the northeast, the lake filled the basins now occupied by Great Bear, Great Slave, and Athabasca lakes (Fig. 7). This lake, referred to as ***glacial Lake McConnell***, is named after the geologist R.G. McConnell who, in 1890, was the first to recognize evidence for it along Great Bear Lake. ***Erratics*** (Fig. 8), visible today on bare rock surfaces around the Yellowknife area, probably represent the remnants of the glacial till that was subsequently washed away by wave action during the rise and fall of glacial Lake McConnell.

With the rise of glacial Lake McConnell, the entire Yellowknife area was flooded to an elevation of what is now about 280 m above sea level, a height more than 100 m above the present-day elevation. During this submergence, lake ***silts*** and ***clays*** were deposited in topographic lows that formed deep-water basins. These deposits are found in many areas around Yellowknife, including School Draw, Willow

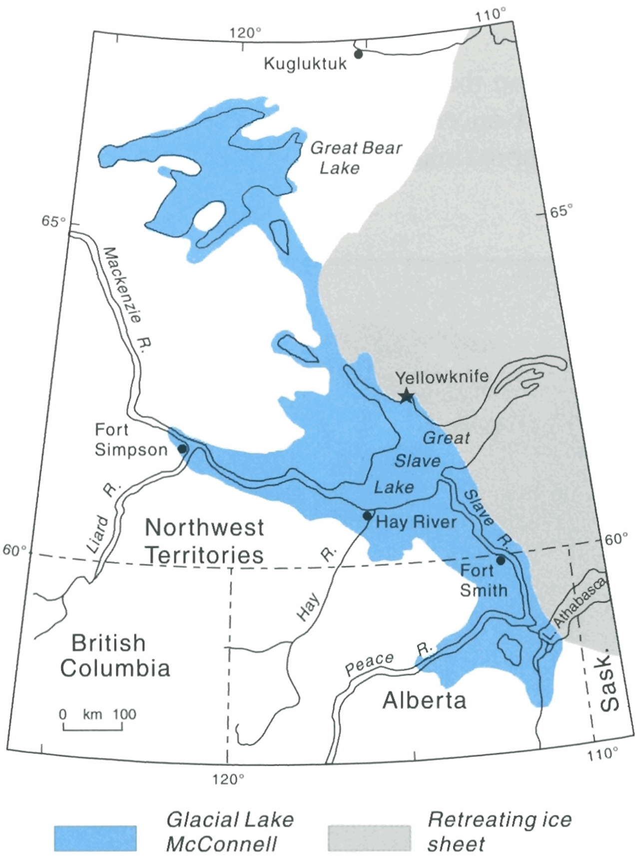


Figure 7. The area covered by glacial Lake McConnell (shaded) about 10 000 years ago (modified from Lemmen, 1990).

Flats, the Capital Site, and Frame Lake South. It is these sediments, deposited by glacial Lake McConnell, that pose some of the greatest construction difficulties associated with buildings, utilities, and roadways in Yellowknife.

Climate and vegetation

Yellowknife is presently in an area affected by a continental subarctic climate, dominated by ***Arctic air masses*** in winter and spring. The Arctic air mass originates over the pack ice of the Arctic Ocean and spreads out over a large area, keeping warmer air out of the Yellowknife area in winter. In summer and fall, the cold Arctic air is replaced by westerly air flows originating from the Pacific Ocean. The mean annual air temperature at Yellowknife is -5.2°C, compared to -3.4°C at Hay River on the southern shore of Great Slave Lake. Monthly average temperatures in Yellowknife range from a high of 16.5°C in July to a low of -27.9°C in January. The coldest temperature ever recorded in Yellowknife was -51.2°C. Precipitation averages about 270 mm, with just more than half falling as rain. Prevailing winds are from the east and northeast during most of the year, but primarily

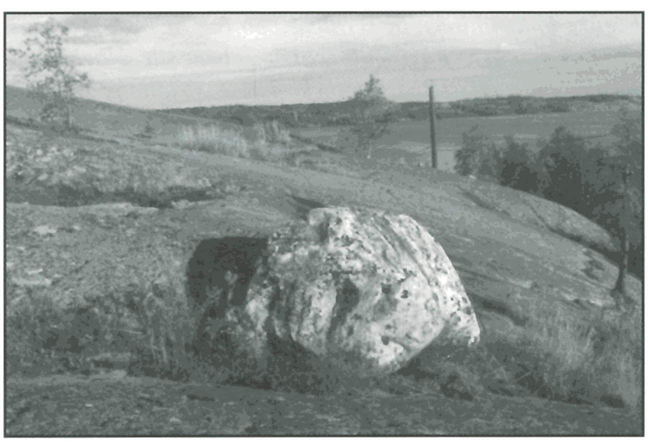


Figure 8. Large erratic resting on bedrock surface in Old Town. Much of the bedrock in the Yellowknife area has been scoured by ice and washed by glacial Lake McConnell, leaving bare and polished surfaces. GSC 1998-006 C

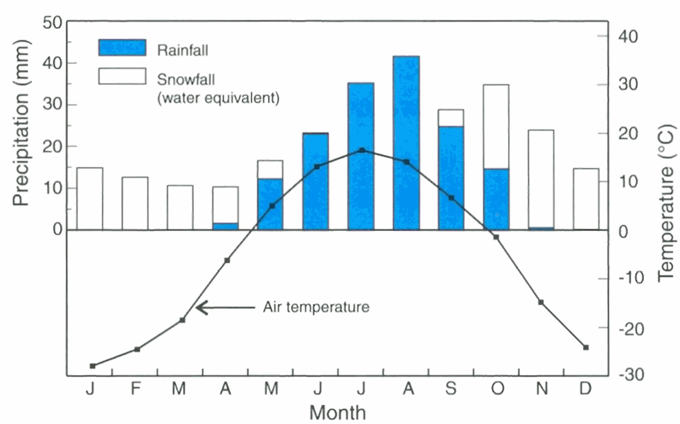


Figure 9. Monthly climate summary for Yellowknife (data for 1961-1990 normals from Environment Canada, 1997). The average air temperature in Yellowknife is -5.2°C.

from the south in summer. By the last week of September, the daily average temperature falls below freezing and, typically, does not rise above 0°C again until the third week of April. The monthly climatic averages for Yellowknife are shown in Figure 9.

The Yellowknife area lies within the ***Taiga*** Shield ***Ecozone*** (Fig. 10), a "land of little sticks". This landscape represents the combined effects of many interacting factors such as the cool climate, the shallow soils, the short growing season, and the geology, specifically of the Canadian Shield. The vegetation is typical of the taiga forest. It is characterized by open forests of stunted black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) mixed with bogs and other wetlands in low-lying areas, all found on granitic and volcanic bedrock (Fig. 11). Other common tree species include trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*), while ***sphagnum*** and ***sedges*** cover ***peatlands***.

The northeastern boundary of the taiga is marked by the so-called ***treeline***, where scattered miniature trees give way to the sedge-dominated landscape of the ***tundra***. The present-day boundary between the treeline and the tundra is about 250 km northeast of Yellowknife (Fig. 10).

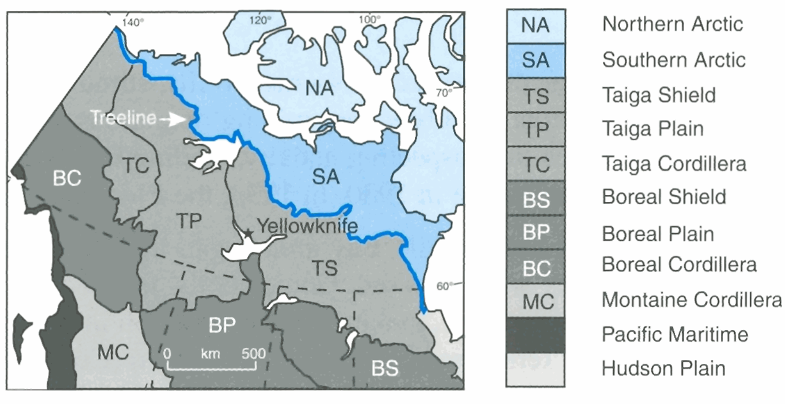


Figure 10.

Ecozones of northwestern Canada (modified from Wiken et al., 1996). Yellowknife is on the Taiga Shield, where the taiga forest and the Canadian Shield are combined.

Figure 11.

The taiga forest of the Yellowknife region. Black spruce and open peatlands surround wetland areas (centre), and scattered jack pine and paper birch find footholds on bedrock outcrops. GSC 1998-006 D

History of Yellowknife

From gold to government

The Great Slave Lake region was the traditional home area of the Yellowknife River Dene and the Yellowknives Dene Band for thousands of years. The first European, Samuel Hearne, arrived in the area in 1771. Much like later prospectors in search of gold, Hearne was charged with finding the source of copper from which the tools of the "Yellowknives" Dene were made. Hearne's travels took him more than 500 km north of Yellowknife, to the mouth of the Coppermine River. Other European explorers, including Alexander Mackenzie and Sir John Franklin, also passed through the region en route to more northerly destinations. By the 1870s numerous fur trading posts had been established in the Mackenzie and Great Slave Lake regions.

The first known gold discoveries in the Yellowknife area were made by prospectors heading to the Yukon, who explored for minerals near the mouth of the Yellowknife River. In 1898 samples were submitted to the Geological Survey of Canada for assay. The attraction of the Klondike, however, surpassed the considerable quantities of gold and silver found in the Yellowknife samples and the find went relatively unnoticed.

In 1914 oil was discovered at Norman Wells, stimulating prospecting activities and contributing to a reduction in the cost of subsequent mining operations. By the late 1920s, Great Bear and Great Slave lakes were centres of prospecting activity, leading to the discovery of silver and pitchblende at LaBine Point on Great Bear Lake in 1930. In 1933, the Eldorado mine (Port Radium) went into production.

Staking in the Yellowknife Bay area began in 1933, after the results of a mapping program by the Geological Survey were released. Coincidently, in 1934 the United States raised the price of gold from \$20.67 to \$35.00 an ounce, making gold production in the area economically viable. The first gold brick in the Northwest Territories was poured at the Con (Consolidated Mining and Smelting Company) mine in 1938. By the early 1940s, Yellowknife was an established mining camp with six producing mines and several others undergoing active exploration. The population of Yellowknife increased from 1000 in 1939 to 1410 in 1941. In the early years, the population of Yellowknife was subject to extreme fluctuations.

Boom-and-bust was a significant feature of the early years. Shortages of labour, materials, and markets during the war led to a decline in prospecting and mining such that, by 1944 and 1945, all gold production had ceased. At virtually the same time, however, Frobisher Exploration was undertaking an extensive drilling program on its Giant property. Spectacular results by Frobisher initiated a prospecting

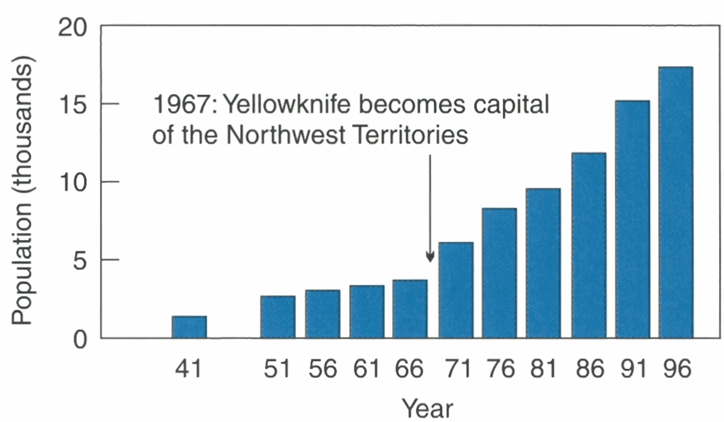


Figure 12.

Change in the population of Yellowknife from 1951 to 1991 (data from Bourne, 1963, and various Statistics Canada census publications). Yellowknife has grown from a small mining town to a major government centre.

rush with 8851 mineral claims staked in the Yellowknife Mining District in 1945 alone. Mines that closed earlier were reopened and new producers entered the area. Yellowknife's population, which had declined in the early 1940s, reached about 3000 in 1945. Subsequently, the population declined to 2724 in 1951, followed by slow growth in the following decade (Fig. 12). During this period, the initiation of milling at Giant Yellowknife Mines in May 1948 and the pouring of the first gold brick in June were the most significant developments.

The importance of mining to the economic base of Yellowknife in 1951 and 1962 is clearly indicated by the employment numbers at that time (Fig. 13). In 1951 about 56% of the employed labour force of 1438 was engaged in mining. In 1962, although mining employment had declined, it still accounted for about 44% of employment and about 68% of Yellowknife's basic activities. At the same time, government services contributed about 16% to the employment profile and was one of the more rapidly growing employment sectors (Fig. 13).

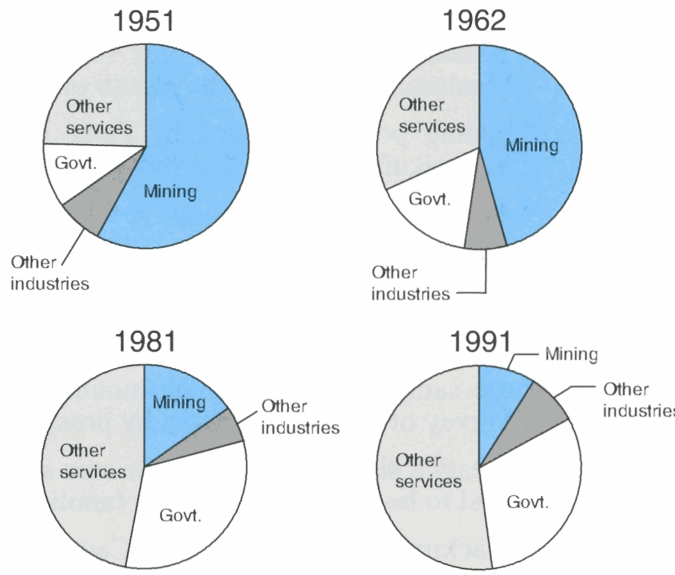


Figure 13. *Change in employment by sector in Yellowknife (data from Bourne, 1963, and Statistics Canada, 1984, 1994). Yellowknife's economic base has changed from mining to government services in the last 30 years.*

The progressive transition of Yellowknife from a small mining town, with a population of 3245 in 1961, to its current status as a major government centre with a population of 17 775 in 1996, is shown in Figure 12. In 1967 Yellowknife was designated the capital of the Northwest Territories. While growth was substantial in subsequent years, the highest rate of growth (63.6%) occurred between 1966 and 1971. Yellowknife's share of the territorial population has also steadily increased from 13% in 1966 to nearly 27% in 1996.

Figure 13 shows the impact of this transition on the town's employment structure. Mining dominated employment (44%) in 1962, but was reduced to just under 15% by 1981 although the number of people in the mining category was larger in 1981 than in 1962. By 1991, mining accounted for just under 9% of employment, and was virtually unchanged in absolute numbers from 1981. While mining-related employment has declined, the transition from mining town to administrative capital and regional centre has resulted in a substantial increase in government and social services between 1962 and 1991.

In just a few decades, Yellowknife has grown from a small mining camp to a major urban centre with full amenities. Although mining employment still constitutes a part of Yellowknife's basic employment, it has been displaced in importance as the underpinning of the city's economy, largely by government employment and related regional services.

Significant events

	➠ traditional home area of the Yellowknife River Dene and the Yellowknives Dene Band
1771	➠ Samuel Hearne travelled past Yellowknife Bay from Fort Prince of Wales (now Churchill, Manitoba) en route to the mouth of the Coppermine River
1786	➠ trading post established by Peter Pond approximately 20 km southeast of present-day Yellowknife – referred to today as "Old Fort Providence"
1789	➠ Alexander Mackenzie stops at Old Fort Providence en route to the Arctic Ocean
1820	➠ John Franklin explores the region to the north
1870s	➠ numerous fur trading posts exist in the Mackenzie-Great Slave region including Fort Franklin, Fort Smith, Fort Resolution, and Fort Rae
1898	➠ ore samples from near the mouth of the Yellowknife River submitted to the Geological Survey of Canada for assay by prospectors en route to the Yukon
1890	➠ Treaty 8 signed by Dene in the area south of Tucho (Great Slave Lake) – provision made for land to be reserved for Indian families, but no lands set aside
1921	➠ Mackintosh Bell and Charles Camsell of the Geological Survey of Canada conduct the first geological mapping of the Yellowknife River area
1921-22	➠ Treaty 11 signed by Dene in places west of Tucho – terms include reserve of one square mile for each family of five but no formal reserves established
1928	➠ influenza epidemic kills an estimated 10-15% of the Aboriginal population
1934	➠ gold discovered by Johnny Baker, Major Burwash, and Huey Muir in the Yellowknife Bay area – the region's first mine is built
1934	➠ the United States raises the price of gold from $20.67 to $35.00 an ounce – large-scale gold mining becomes economically viable in Yellowknife
1935	➠ Norman Jennejohn and Fred Jolliffe discover gold on the west side of Yellowknife Bay
1937	➠ mining camps grow among Dene settlements near the mouth of the Yellowknife River
1938	➠ the first gold brick in the Northwest Territories is poured at the Consolidated Mining and Smelting Company mine
1944	➠ Frobisher Exploration embarks on an extensive drilling program on their Giant property and the spectacular results initiate an unprecedented rush to stake, restake, and prospect throughout the Yellowknife area
1945	➠ grid street pattern for the New Town surveyed on a sand plain about 3 km inland from and west of the site of the Old Town

- 1948 ➠ initiation of milling at Giant Yellowknife Mines
- 1948-49 ➠ houses constructed, and water and sewer lines installed in New Town site
- 1953 ➠ Yellowknife becomes a municipal district
- 1960 ➠ completion of a road connection with Hay River and the "South"
- 1963 ➠ Yellowknife incorporated as a town
- 1967 ➠ Yellowknife named capital of the Northwest Territories
- 1968-69 ➠ new subdivisions surveyed in the School Draw area to accommodate rapidly growing population – southern construction styles still widely used
- 1973 ➠ water and sewer lines installed east of City centre in Forrest Drive area
- 1990 ➠ water and sewer upgrades on Franklin Avenue toward Old Town
- 1992 ➠ diamonds discovered in the Lac de Gras area 300 km northeast of Yellowknife
- 1993 ➠ Legislative Assembly building officially opened
- 1996-97 ➠ water and sewer upgrades on School Draw and Forrest Drive
- 1999 ➠ division of the Northwest Territories into Nunavut in the east and Northwest Territories in the west

PART II: LIVING WITH FROZEN GROUND

Stephen A. Wolfe, T. Edward Hoeve, and Sharon Smith

Permafrost

Permafrost is defined on the basis of temperature, as soil or rock that remains below 0°C throughout the year, and forms when the ground cools sufficiently in winter to produce a layer of frozen ground that persists throughout the following summer. An example of typical ground temperatures within permafrost in the Yellowknife region is shown in Figure 14. The annual range in ground temperatures is shown by the warmest and coolest temperatures occurring at depth. With increasing depth in the ground, the seasonal difference in temperature decreases. The point at which there is no discernable change in temperature is termed the "depth of zero annual amplitude". In Yellowknife, this depth occurs at about 15 m. Below this depth, temperatures change very little during the year.

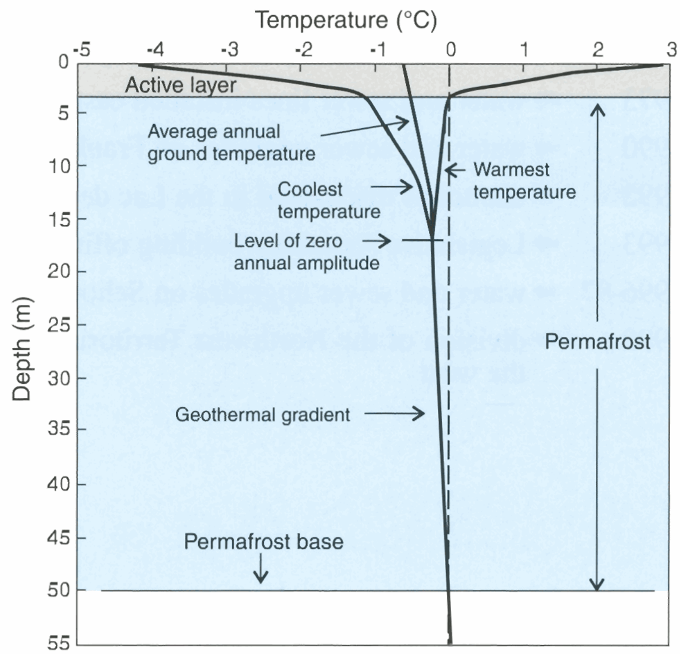


Figure 14. *An illustration of the range in temperatures at different depths in the ground during the year. The active layer (shown in grey) thaws each summer and freezes each winter, while the permafrost layer below remains below 0°C.*

Each year a portion of the ground at the surface rises above 0°C during the summer. This part of the ground, termed the ***active layer***, freezes and thaws with the changing seasons. The thickness of both permafrost and the active layer depends on local climatic conditions, vegetation cover, and soil properties. The thickness of permafrost can be altered by changes in the climate or disturbance of the surface. Permafrost cools and thickens if there is a decrease in surface temperature resulting in cooling of the ground below the surface. The active layer increases in thickness and permafrost thins when ground temperatures increase.

Regional distribution

Permafrost underlies more than 50% of the ground surface of Canada. The two major divisions of permafrost are ***continuous permafrost*** and ***discontinuous permafrost*** (Fig. 2). In the continuous permafrost zone, permafrost occurs everywhere beneath the ground surface. The discontinuous permafrost zone is broken into other divisions: the ***widespread permafrost*** zone, where permafrost underlies 50% to 90% of the land area, and the ***sporadic permafrost*** zone, where permafrost underlies 10% to 50% of the land area. Permafrost can also occur in localized areas, where it is found in small isolated lenses in ***peat*** and affects less than 10% of the land area. Yellowknife lies at the boundary between widespread and sporadic permafrost in the discontinuous zone.

About 300 km northeast of Yellowknife, in the diamond-rich region of Lac de Gras, permafrost is continuous and is found everywhere except beneath lakes and river beds (Fig. 15). In these areas, it reaches thicknesses of more than 200 m. Over the same distance southward across Great Slave Lake to Hay River, permafrost is restricted primarily to peatlands and is classified as sporadic discontinuous permafrost.

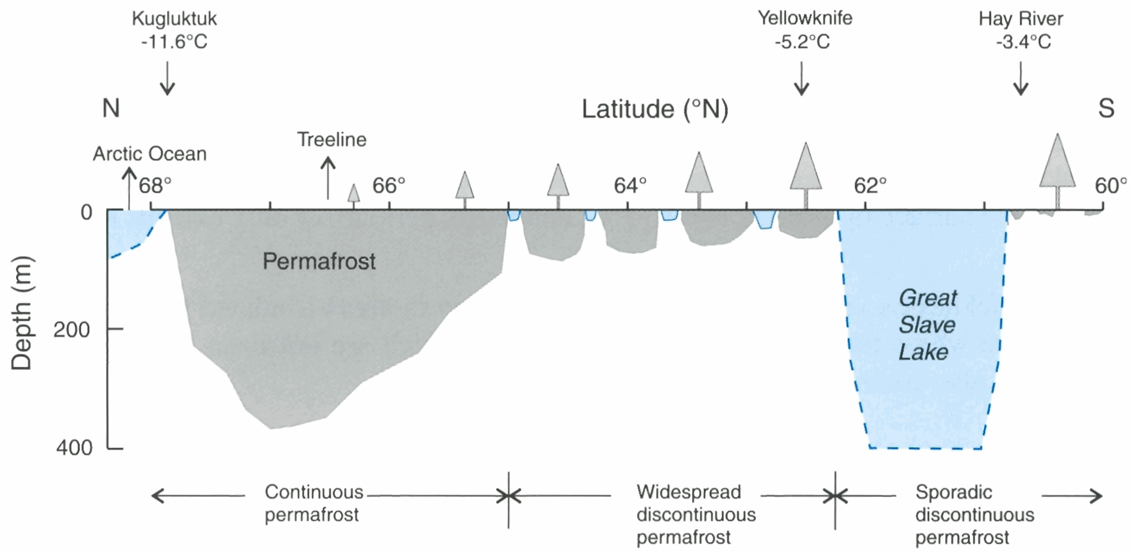


Figure 15. *Thickness and distribution of permafrost along a north-south transect from Hay River to Kugluktuk (formerly Coppermine). Average annual air temperatures for specific locations are also shown (adapted from Brown, 1970).*

Permafrost occurrence in Yellowknife

Permafrost occurrence in the Yellowknife area is highly variable. It is commonly found as "islands" or "pockets" in ground that is otherwise unfrozen. Permafrost occurrence is affected by climate, topography, vegetation cover, winter snow accumulation, hydrological conditions, and subsurface geology. Variations in these factors result in abrupt transitions from frozen to unfrozen ground over short distances.

Permafrost in Yellowknife is comparatively "warm". It is found mostly in peat bogs where accumulations of organic material contribute to forming and preserving permafrost. The mean annual ground temperatures of permafrost in these areas is typically in the range of 0°C to -1°C (Fig. 16). Permafrost does not occur in exposed bedrock, in which the average annual temperatures at a depth of 15 m may be between +1°C and +2°C. Similarly, permafrost is generally absent where the underlying sediments are coarse and vegetation cover is thin. For example, in unfrozen sandy sediments with a dense stand of birch, jackpine, alder, and willow, and with an organic cover of about 3 cm, the mean annual ground temperature at 10 m depth is about +0.8°C.

	Sedge peat Temperature (°C)			Spruce peat Temperature (°C)			Beach ridge Temperature (°C)			Till Temperature (°C)			Black rock Temperature (°C)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Surface	-4.2	2.9	-0.6	-9.2	3.7	-2.1	-4.2	5.8	0	-7.5	14	2.2	-10.8	14.6	1.0
5 m depth	-0.8	0	-0.4	-1.6	-0.7	-0.9	0.8	1.7	0.6	0	2.5	1.3	-4.2	6.7	0.9
10 m depth	-0.2	-0.2	-0.2	-0.8	-0.4	-0.6	0	1.2	0.8	0.8	1.7	1.2	0	2.1	1.1
Active layer thickness	68 cm			30 cm			---			---			---		
Permafrost thickness	30 m			50 m			No permafrost			No permafrost			No permafrost		

Figure 16. *Annual ground temperatures, active layer thicknesses, and permafrost thicknesses under different terrain conditions in Yellowknife (data from Brown, 1966a, 1973).*

Permafrost thickness is also a function of a number of factors, including the temperature at the ground surface and the rate of temperature increase with depth. Because rock deep beneath the Earth's crust is hot and molten, the temperature beneath the Earth's surface increases with depth. This change of temperature is known as the ***geothermal gradient*** (Fig. 14), and ranges between 12°C/km and 16°C/km in the Yellowknife area. Because of effects of the geothermal gradient and relatively warm temperatures of the ground at the surface (a mean of about -1°C, annually), permafrost only extends to depths of 50 to 85 m.

Active layer thicknesses vary in depth from less than 1 m in areas insulated by organic material, to about 3 m or more where there is little insulation. ***Taliks***, which are unfrozen zones within otherwise frozen ground, are also common.

Significance of peat

Peat is partly decomposed plant material formed under oxygen-deprived, waterlogged conditions. A major constituent of peat is sphagnum moss, which grows and accumulates in this environment. Peat also acts as a natural form of insulation. Seasonal changes in moisture conditions and the associated differences in the thermal properties of peat are the primary factors controlling the existence of permafrost in peatlands within the discontinuous permafrost zone. Dry peat acts as a barrier to heat penetration due to its low ***thermal conductivity***. Drying of peat at the surface occurs in summer due to evaporation and the resulting dry surface layer restricts the flow of heat to the underlying soil. Gradually, the lower peat layers thaw during summer and become wet as the ice melts. In the fall, the moisture content in the surface peat tends to increase with increasing rainfall and decreased evaporation. As freezing occurs, the thermal conductivity of this layer increases dramatically. Because of these unique properties of peat, the average ground temperature beneath a peat soil is commonly colder than in adjacent areas without peat.

Peat plateaus are flat, elevated peatlands that have a perennially frozen core. They are elevated about 1 m above the lowland water table, and occur as islands, a few metres to several kilometres in size, in unfrozen bogs. The vegetation cover around the bogs may consist of black spruce, lichen, and Labrador tea. In more southerly regions, permafrost does not usually reach to the depth of the underlying soil. Around several small lakes in Yellowknife, peat thickness averages more than 1.0 m and permafrost is present in the underlying sediments.

Peat plateaus initially appear as low mounds protruding above the water level in the middle of shallow ponds less than 1 m deep (Fig. 17). These shallow ponds often freeze to the bottom in winter, causing the underlying peat to dome up as it freezes. During the summer this elevated peat layer becomes dry.

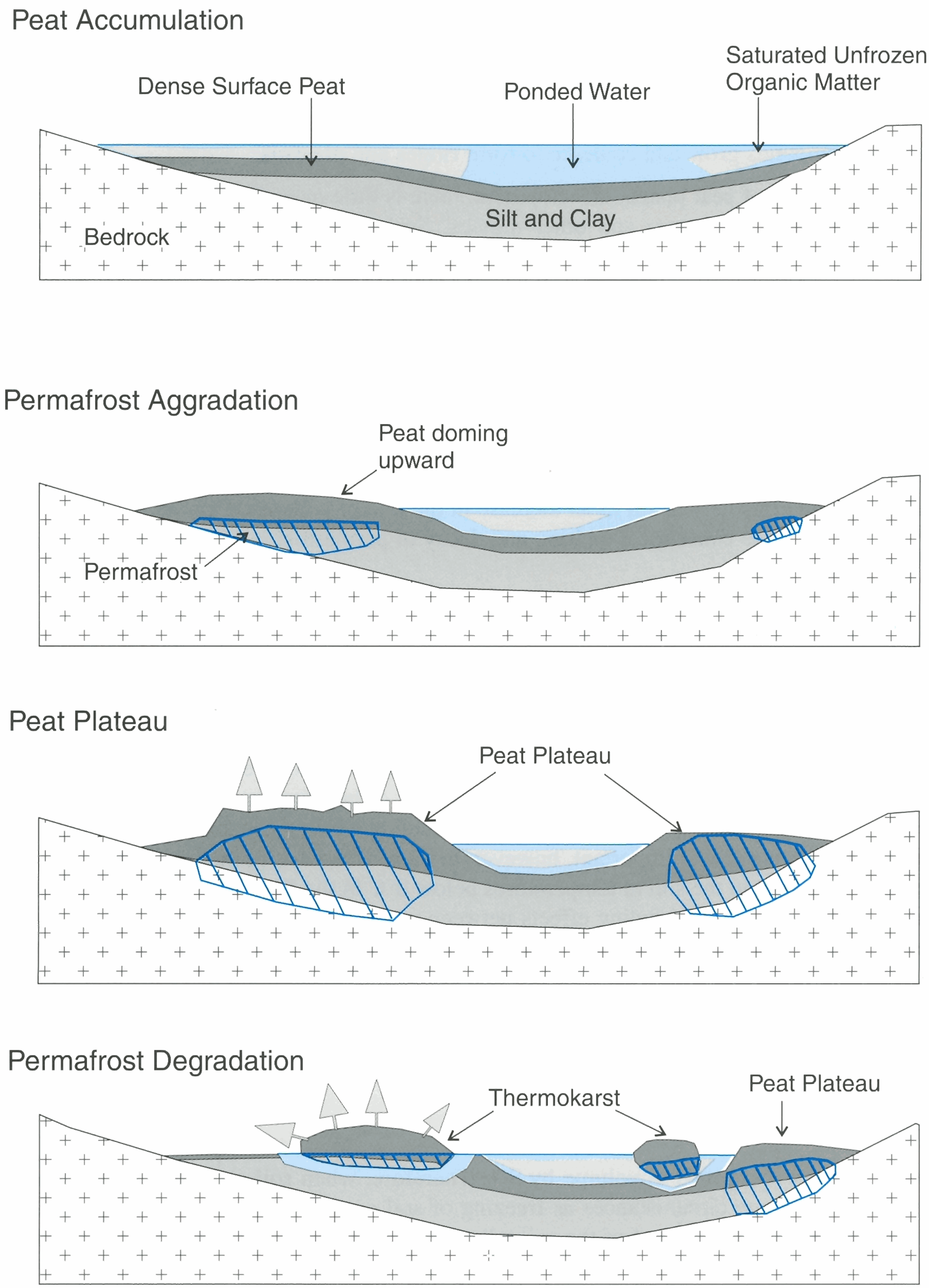


Figure 17. *The formation and decay of a peat plateau in permafrost.*

The dry peat acts as insulation, preventing the frozen core from thawing, and thus initiating permafrost. The elevation of the flat peat surface above the surrounding ground level results in exposure of the surface to wind, and the removal of the snow cover in winter. This results in a greater penetration of winter frost than in the surrounding areas, thus promoting permafrost growth. As the permafrost thickness increases each winter, the mounds grow and coalesce to form ridges and plateaus.

In the initial stages of peat plateau development, there is little or no living vegetation on the peat surface. During maturity, sphagnum and other mosses, lichen, Labrador tea, and black spruce become established.

After the plateau reaches the maximum degree of development permitted by climatic and local conditions, the permafrost may degenerate. This is thought to occur as a result of some disturbance to the water table, vegetation, insulating cover, or climate. The thawing of permafrost is marked by collapse of the edges, and the formation of depressions known as ***thermokarst***. Collapse also appears to be a part of the peat plateau life cycle and does not necessarily indicate a warming of the climate. Degradation may begin when the insulating ground cover ruptures due to biological oxidation. This process results in thawing of the underlying frozen core. During the years when snowfall is heavy, seasonal frost may not reach the permafrost table and this may result in an increase in the rate of collapse. Uprooting of trees by wind or removal by fire may also cause local melting and decay of permafrost in peat plateaus.

Significance of moisture

The definition of permafrost as ground with temperatures below 0°C is irrespective of the type of material (soil, peat, or bedrock), moisture, or ice content. However, material type and ice content are the primary influences on earthworks and engineered structures in permafrost regions as they define the ***geotechnical properties*** associated with permafrost. As stated earlier, permafrost may be thought of in practical terms as “frozen ground”. Indeed, for all aspects of building foundations, roadways, and utilities it is the physical change from unfrozen ground containing water, to frozen ground containing ice, that is of greatest significance. It is important, however, to understand that permafrost need not be “frozen”, because water can exist in the soil at temperatures below 0°C in the form of a liquid. This water remains liquid as a result of the strong binding effects between it and the fine-grained silt and clay soils, but is progressively replaced by ice at colder temperatures. Where permafrost temperatures are warm, say in the range of 0°C and -1°C, and where the soils are fine grained, as is common in Yellowknife, partly frozen permafrost can occur. The presence of ice and water in the ground results in differences in the strength of the soil depending upon the temperature.

Ice lenses

When water freezes it expands in volume by 9%. Therefore, when soil saturated with water freezes, it will expand. Under some circumstances as freezing of soil occurs, water from the unfrozen part of the soil migrates toward the colder part of the soil where it freezes and accumulates to form ***ice lenses***. The formation of ice lenses results in further expansion of the soil and uplift of the surface, thus creating ***frost heave***. The size of ice lenses is often much greater in fine-grained silt and clay than in coarse-grained sand (Fig. 18). In Yellowknife, ice lenses can reach thicknesses of more than 20 cm, although they are seldom more than a few millimetres thick.

Figure 18. Ice lenses formed in silty clay sediments deposited by glacial Lake McConnell. The ice lenses grew in the soil as the sediments froze, creating layers of ice up to 5 cm thick. (Photo by Larry Aspler, October, 1977)

Thaw stable and thaw unstable ground

Frozen ground can be considered ***thaw stable*** or ***thaw unstable*** depending on the type of frozen material and the moisture content of the permafrost. Frozen ground that experiences minimal settlement upon thawing is considered thaw stable, and occurs in ground that does not contain ice lenses or ***excess ice***. In Yellowknife, clean sands and gravels or rock do not normally contain excess ice. Frozen ground that could undergo excessive settlement if allowed to thaw is considered thaw unstable. In Yellowknife, silts and clays containing ice lenses are generally thaw unstable. Thaw unstable conditions can pose problems for roadways and buildings. Several examples of these are shown in the tour portion of the guide.

Thaw settlement

Thaw settlement results from the melting of ice within thaw unstable ground and can have two components. First, there can be relatively quick settlement following the melting of ice in the soil, if the water has an opportunity to drain rapidly. Second, ***thaw consolidation*** can occur when water drains more slowly and the soil compresses under its own weight or the weight of an additional load, such as a building. Thaw consolidation can occur over many years, particularly in fine-grained soil such as clay.

Frost heave

Frost heave has just as harmful an effect on structures such as buildings as thaw settlement. It may occur during seasonal freezing of soil and causes uplift forces to act on structures within the active layer if moisture is available and if frost-susceptible soils such as silt and clay are present. These forces can be strong enough to heave structures above their originally built elevation. In addition, heaved ground exhibits a loss of strength when it thaws. On roadways, thaw settlement often results in potholes and dips in springtime. Repeated cycles of frost heave can progressively lift foundation elements such as ***piles***, a phenomenon known as ***frost jacking*** (Fig. 19). Several examples of frost jacking can be seen around Yellowknife (Fig. 20).

Development

Where permafrost is comparatively warm (close to 0°C), construction can bring about changes to the ground temperature regime that often result in partial or complete thawing of permafrost. Such changes are commonly caused by terrain-altering factors including removal of vegetation, alterations

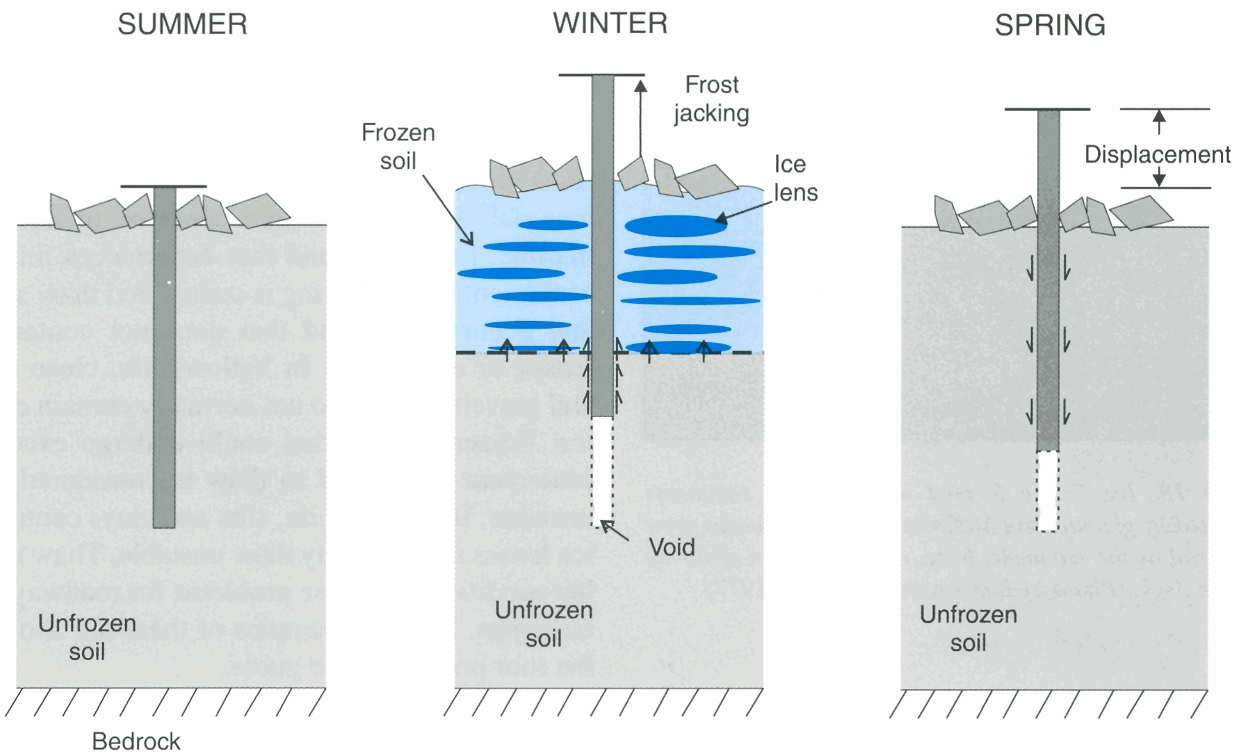


Figure 19. *Illustration of seasonal frost jacking. The freezing of the soils causes pile foundations to be lifted in winter. In the spring, the lifted piles often do not settle back to their original position.*

Figure 20. *An example of frost jacking. The corner of this abandoned concrete foundation has been cracked and lifted more than 30 cm by frost jacking of a supporting pile. GSC 1998-006 E*

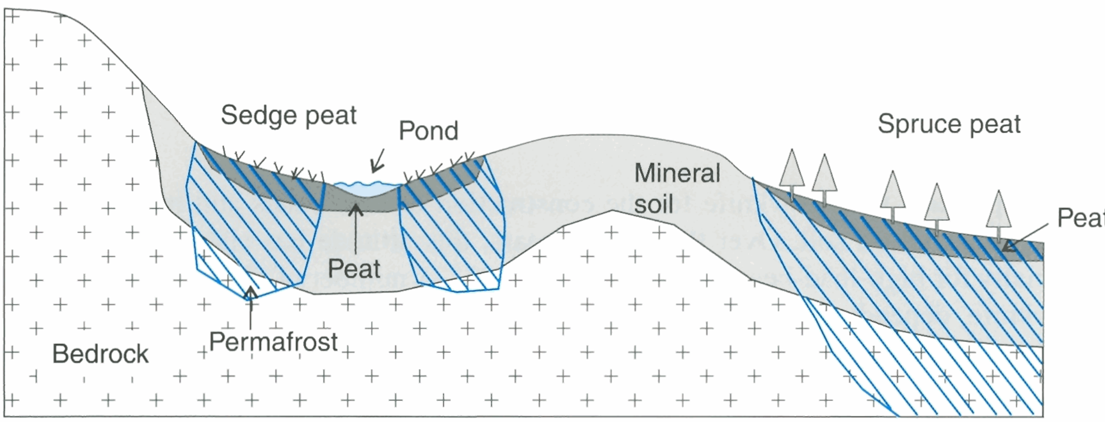
to the natural drainage patterns, or the introduction of heat into the ground, such as from buildings.

During early development in the North, little attention was paid to the frozen ground beneath the surface. Even in the 1960s, houses were built using traditional southern-based designs without regard for the possible effects on the underlying permafrost. In cases where the ground was thaw unstable, this resulted in differential settling of buildings (Fig. 21).

In recent decades, engineering practices have emphasized the importance of minimizing disturbance to permafrost. This can be a considerable challenge in the Yellowknife area where permafrost is discontinuous and the terrain is highly variable. Here, average ground temperatures are often only slightly below freezing, and seldom colder than -2°C. Under these relatively warm conditions, permafrost can be highly sensitive to disturbance (Fig. 22). Today, engineers attempt to predict the consequences of such disturbances and design structures to accommodate them.

Figure 21.

Known locally as Slant 6, this building on Bretzlaff Drive is among the earliest of Yellowknife's original buildings. The underlying permafrost has thawed over time resulting in differential settlement beneath the building. GSC 1998-006 F



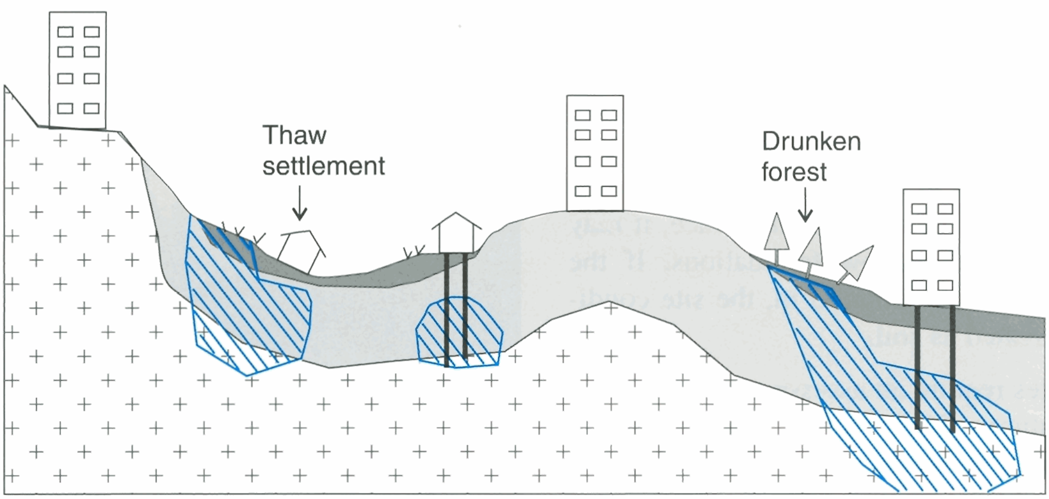


Figure 22. *Impact of development on permafrost. Thawing of permafrost can cause differential settlement of buildings and the ground surface. Many buildings located on permafrost are built on piles that are anchored to the bedrock to prevent the building from settling. Other buildings are situated on bedrock, or on unfrozen soil, and do not require piles.*

In thaw stable soils, permafrost conditions are not a constraint, and conventional foundations and construction methods can often be applied. In thaw unstable soils, such as silts and clays, permafrost becomes a constraint that must be considered when developing the area.

All constructions have an ***allowable displacement***. Generally, roads have the greatest allowance followed by utility corridors, with building foundations being the least flexible. In the end, a decision must be made as to whether to allow permafrost to thaw or to attempt to preserve it. Because permafrost in the Yellowknife area is warm, conventional practice has generally resulted in the thawing of permafrost. This practice differs from that in continuous permafrost, further north, where it is normal to attempt to preserve permafrost. Recently, however, there have been some trial projects in Yellowknife that attempt to preserve permafrost using ***thermosyphons***. Development practices in Yellowknife, including the use of thermosyphons, are described below.

All developments are unique. Thermal regimes, drainage conditions, and underlying geology can vary along with the allowable settlement, budget, and long-term purpose of the development. In Yellowknife, some methods are used more frequently than others. Next, we examine how these various methods have been used.

Buildings

In the past, the approach in Yellowknife for the construction of both roads and buildings was to avoid bedrock and to construct on soil. Over the last 30 years, this attitude has changed to one of targeting bedrock, especially for high-load-bearing buildings (Fig. 23). A number of different foundation types are used in Yellowknife, depending upon local terrain conditions and specifications of building designs.

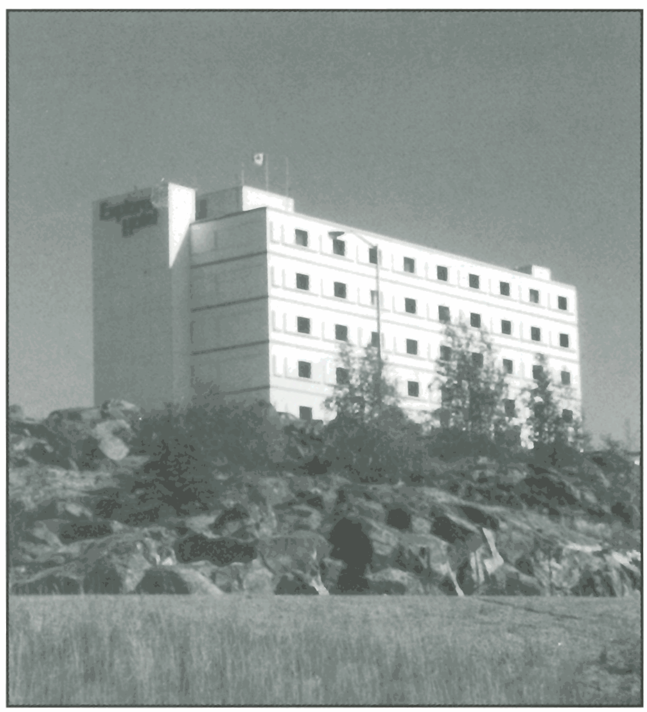


Figure 23. *The Explorer Hotel is situated on a bedrock outcrop in downtown Yellowknife. GSC 1998-006 G*

Where bedrock outcrops or is close to the surface, a shallow foundation is often appropriate. The foundation construction is similar to southern designs. Cost is a potential constraint, especially if the foundation is formed to the bedrock topography or if blasting is required. Seasonal frost action in rock is not a major concern in the area, but may occur in the fissures in the rock. Even if bedrock is within about 3 m of the ground surface, it may be practical to use shallow foundations. If the bedrock is deeper than about 3 m, the site condition is often treated as soil.

All soil sites require an assessment of the presence and nature of permafrost and depths to bedrock in order to select an appropriate foundation. In Yellowknife, buildings built on steel piles anchored into bedrock are used extensively in thaw unstable ground and on soils where poor foundation conditions exist (see stops 7 and 10 of the Capital Tour). In general, concrete ***slab-on-grade*** foundations and basements are not feasible in this type of terrain. Instead, the floor must be supported by the piles.

The piles must be designed to resist frost-heaving forces, otherwise frost jacking can occur (Fig. 24). Only a pile embedded an appropriate distance and properly anchored into rock can be assured of having this resistance. Often the piles are anchored to the rock using a cement ***grout***. However, water seepage or collapsing soil often make proper grouting difficult. Specialized drilling systems are available to ensure that holes are properly sealed from moisture and soil during drilling. These techniques, which increase the cost of construction, can be used for structures with high loads. Such piles have been used on some building foundations in Yellowknife and the bridge to Latham Island in Old Town (Fig. 25). Other techniques such as greasing, heating, or wrapping piles in a sleeve can be used to reduce forces associated with frost heave, but with varied results. A less costly alternative is to protect the soil in the active layer from freezing by burying horizontal insulation around the perimeter of the building. This can be used for low-rise residential, commercial, and light industrial projects.

Figure 24. *Frost jacking has lifted the right-hand corner of this building. GSC 1998-006 H*

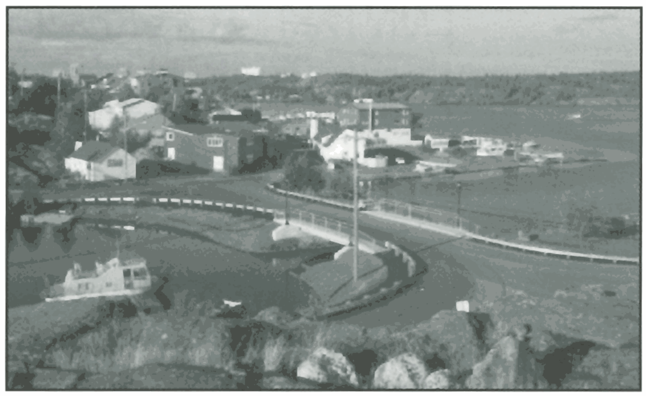


Figure 25. *The Latham Island bridge was rebuilt in 1996. Piles, anchored to bedrock, were used to prevent frost heaving. GSC 1998-006 I*

Southern construction techniques including shallow foundations bearing directly on the soil may be used where permafrost is absent or thaw stable. Slab-on-grade floors and basements are generally feasible on this type of terrain. Shallow foundations, however, should be protected with insulation against ***seasonal frost action***. Thick perimeter slab-on-grade, with insulation laid horizontally around the outside of the foundation, is a common type of shallow foundation used in this area. This approach is used when a slab-on-grade floor without a basement is desired, as this avoids having to excavate and install the foundation below the relatively deep level of seasonal frost penetration. The Boston Pizza and Taco Time buildings are examples of this type of construction (see Stop 16 of the City Tour).

Small, light structures are sometimes built on wood or concrete pads on the ground surface. This foundation type can be used on any terrain type, and the support structure moves with the ground. Seasonal movements are to be expected so this type of foundation is only appropriate for buildings that can tolerate differential movement, and a means of leveling the building is recommended. In the past, this foundation type was used extensively for trailer homes, but current use is generally confined to garages and sheds.

Roads

The greatest challenge in constructing roads in Yellowknife is to achieve good performance in areas of seasonal frost action or thaw unstable ground. These conditions occur in all areas of Yellowknife where silt and clay soils were originally overlain by peat. By comparison, road construction on bedrock and on sand and gravel may be carried out using methods similar to those in the south.

Gravel roads in Yellowknife typically are not paved until a few years after construction, to allow for settlement of the subsurface. Many Yellowknife drivers have experienced the bumps associated with thaw settlement beneath roads (Fig. 26). One area where large differential settlement has occurred is 49 Avenue at the intersection with 49 Street, another is on Franklin Avenue down the hill to Old Town.

Several roads in Yellowknife have had problems with seasonal frost heaving (see Stop 18 of the City Tour). The method currently used to reduce movement is to remove 1 m to 1.5 m of the ***frost susceptible*** soil and replace it with gravel. Insulation beneath the road bed has been used to reduce movement in other cities that have had problems with frost heave, but has not been applied widely in Yellowknife.

Figure 26. *Courtesy of Norm Muffitt, Northern News Services Ltd.*

The road surface itself, whether asphalt or gravel, can generally tolerate movement resulting from ***seasonal frost heave*** or thaw settlement. An undulating surface may result, producing a poor driving surface and impeding proper drainage. Concrete curbs and sidewalks cannot tolerate much differential movement and often crack (see stops 11 and 12 of the City Tour).

Methods can be employed to reduce the likelihood of differential settlement. Most require a higher initial cost but can result in less maintenance and future remediation. They include removing the ice-rich soil and backfilling with gravel, increasing the road gravel thickness, placing insulation between the road gravel and the underlying soil, or using thermosyphons to keep the ground frozen. Some of these methods have been used in Yellowknife and are highlighted in several field stops in the Capital and City tours.

Utilities

Buried utilities such as water and sewer pipes are generally installed below roads and have been placed within most local terrain types in Yellowknife (Fig. 27). They can, in general, tolerate slightly less settlement than roads. Thaw unstable terrain is particularly challenging for their construction.

Over the years, water and sewer utilities have changed in Yellowknife as technology changed and as demands on the system increased. Pipes have been replaced as old ones corroded and as larger diameter ones were required to meet rapidly growing demand.

Figure 27. *Underground utilities being replaced in sandy sediments beneath Forrest Drive during water and sewer upgrades in August 1997. GSC 1998-006 J*

In 1945, a grid street pattern for the new town was surveyed on a sandy plain about 2 km inland from and west of Old Town. At that time, the decision was made to incorporate conventional underground piped water and sewer into all new developments. For the most part, the original designs for the underground systems were typical of southern practices at that time. One major exception was the use of peat to insulate the pipes. The effectiveness of peat for insulating buildings was well known at the time, and peat was the most widely available form of insulation in the area. Unfortunately, the properties of peat are such that it is a good insulator when dry, but not very effective when wet or frozen.

Following installation of the underground piping systems in the 1950s and the late 1960s, it became apparent that problems existed. Dramatic local settling appeared in many areas, accompanied by the pulling apart of the water mains at the joints and regular freezing in winter. By the 1970s, manufactured insulated pipes were generally available and in use. Heating cables were also used in residential and business hook-ups to the main lines to prevent the uninsulated water lines from freezing. However, the only reliable way to prevent the lines from freezing was to install ***bleeders***, which allowed a small amount of water to run through the pipes at all times. In the end, even the City installed bleeders from the water mains and sewers to keep sections of the buried systems from freezing. The situation continued until the mid 1980s, when the high cost of maintenance and the need for greater water capacity meant replacing the entire system. Today, city water lines and residential hook-ups are covered by about 2.5 to 5 cm of insulation to prevent the lines from freezing. In addition, water is constantly circulated through the entire system in a manner that ensures that the lines remain open.

The main geotechnical problems with buried utilities in Yellowknife are thaw settlement and the erosion of soil by groundwater flow into utility trenches. Although attempts have been made to use additional insulation in thaw unstable ground, it is generally not possible to eliminate thaw settlement. Utility trenches can also become routes for groundwater flow. Flow of groundwater over ***ice-rich permafrost*** can accelerate thawing. This may have happened on the hill on Franklin Avenue leading down to Old Town (see Stop 27 in the City Tour).

Local ***lacustrine*** soil, particularly silt and fine-grained sand, is prone to washing into the voids of the coarse granular backfill that is normally used in utility trenches. One solution is to use as much native soil as possible for filling in trenches. However, this is not practical where the soils are a silty clay. Over time, a number of material types have been used to backfill trenches, as the material became available. In the 1960s, clay soils were returned to the utility trenches but they were often difficult to compact properly. From the 1970s to the late 1980s, locally available sand was used; subsequently, crushed quarry rock was used to backfill trenches. The high void space of the crushed rock created problems with settlement as the surrounding soils filtered into open spaces in the gravel. Today, crushed rock is still used, but it is blended with finer grained natural soils and compacted to create a tightly packed fill.

Seasonal frost-heave is also a problem in some areas because utilities are generally buried within, or just below, the depth of seasonal freezing. In addition, vaults, manholes, and fire hydrants must extend to the surface, through seasonally frozen ground. Seasonal frost action on these structures is dealt with by installing materials, such as plastics, to act as bond breakers on the outside of the structures; backfilling with non-frost-susceptible gravel fill is also carried out.

Thermosyphons

Thermosyphons act like refrigerators. They extract heat from the ground and dissipate it into the air. They can be used to preserve permafrost and to prevent settlement associated with permafrost degradation. They can lower the ground temperature in areas close to 0°C, and decrease the time required for the ground to refreeze after disturbance. Thermosyphons have been used since the late 1950s. Their modern design has found widespread application in Canada where the maintenance or creation of frozen ground is considered an advantage (Fig. 28). Applications include the use of thermosyphons for stabilizing building foundations, roadways, and dams. Unlike refrigerators, however, thermosyphons do not require an external source of power to operate.

The thermosyphons in Yellowknife use circulating carbon dioxide (CO_2) to cool the ground. Enhanced cooling of the soil by the thermosyphons occurs when the air temperature is colder than the soil. The evaporation of carbon dioxide from a liquid to a gas within buried tubes causes heat to be extracted from the surrounding soil, resulting in cooling of the soil (Fig. 29). From the tubes in the soil, the gas then circulates up the thermosyphons into ***condensors***, where cold air causes the gas to condense into a liquid and release the heat extracted from the ground. The liquid is then returned to the buried tubes to continue the process. The thermosyphons do not operate in summer because warm air temperatures prevent the carbon dioxide from recondensing, and this causes the circulating process to stop. However, only a small difference in temperature between the soil and the air will restart the process.

Thermosyphons have been used in Yellowknife to stabilize parking lots, roadways, and building foundations. Several examples of their use in Yellowknife are shown in the Capital and City tours.

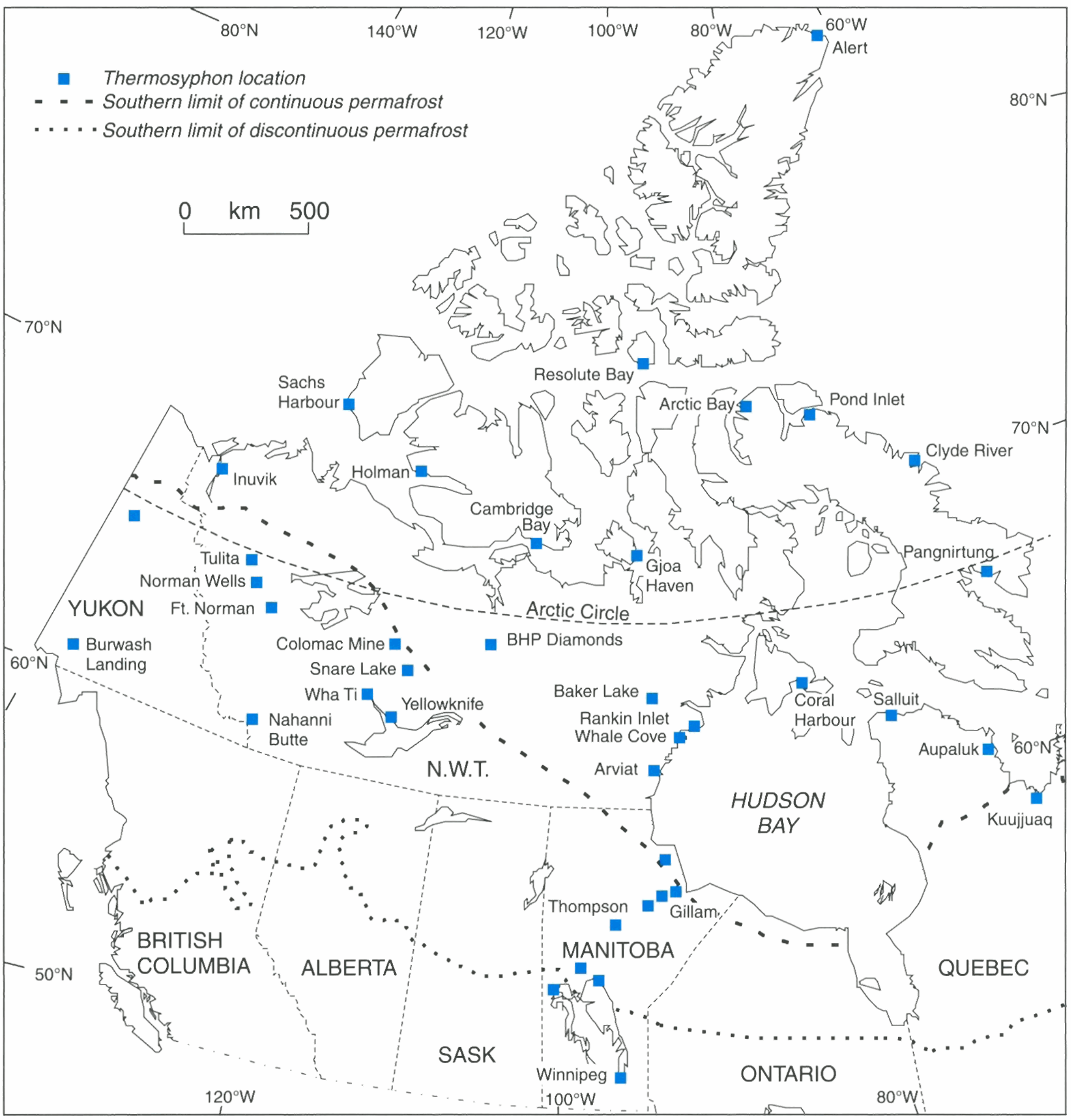


Figure 28. Thermosyphon use in Canada (Arctic Foundations of Canada, Inc). Thermosyphons have been used as far north as Alert and as far south as Winnipeg.

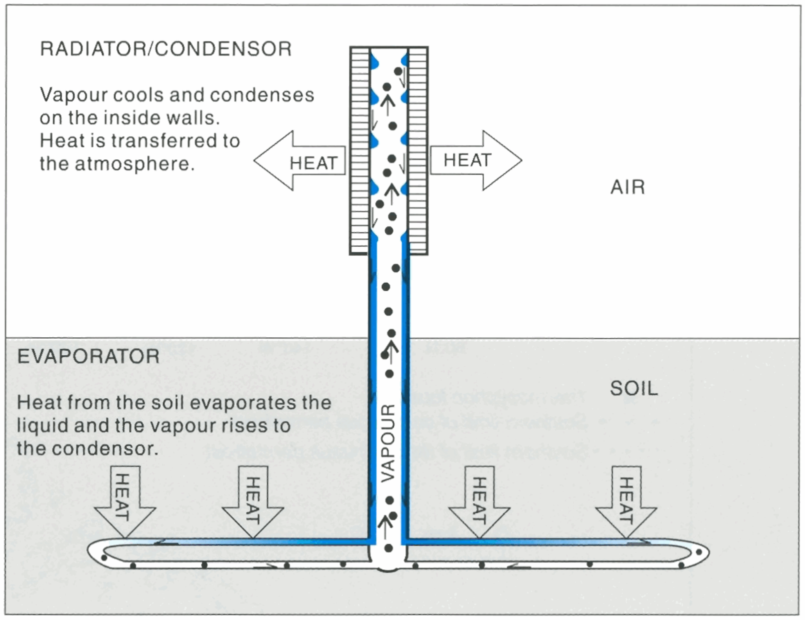


Figure 29.

Thermosyphon design presently used in Yellowknife (published with permission of Arctic Foundations of Canada, Inc.). Thermosyphons operate when the air temperature is colder than the ground temperature (usually in winter).

Climate change – an uncertain future for permafrost

Climate and permafrost history

Following the draining of glacial Lake McConnell, colonization by plants was probably rapid. The emergence of new land coincided with a period of warmer temperatures that the local climate has not reached since. This was the ***Hypsithermal (warm) Period***, which lasted until about 6000 years ago. During this period, summer temperatures were significantly warmer than today, and it is very likely that permafrost did not exist in the Yellowknife area for the first few thousand years after the lake receded. With this comparatively warm climate, the treeline was much farther north than its present-day limit. The first humans are known to have arrived in the area about 7600 years ago.

We do not know exactly when permafrost first began to form in the ground around Yellowknife, but it was probably somewhere between 6000 and 3500 years ago. The first major cold interval since the disappearance of the glaciers had begun by about 3500 years ago. During this, the ***Sub-Boreal Period***, the treeline shifted south as the tundra expanded. With a thick organic cover well established in many areas due to the previous warm climate, permafrost likely formed in most areas around Yellowknife where it occurs today.

It is difficult to say whether, and when, permafrost disappeared or reappeared in the area in response to more recent changes in climatic conditions. Other shorter periods of warming and cooling have followed the Sub-Boreal Period. It is unlikely that permafrost ever disappeared completely from the area, although its thickness and pattern of distribution have likely changed over the last 3500 years and will continue to change.

Air temperature trends over the last century

Over the last century, the Mackenzie District, which includes Yellowknife, has experienced the greatest overall warming in the country, with an increase of 1.7°C (Fig. 30). An examination of air temperature data for Yellowknife suggests that a warming of about 1.0°C occurred over the last 40 years, with significant warming from the 1960s to the end of the 1980s. Warming in western Canada has been more pronounced during the winter and spring than in the summer and fall. In Yellowknife, the monthly average temperature for January has increased by about 3.7°C, while July temperatures have only increased by about 0.7°C over the last 40 years.

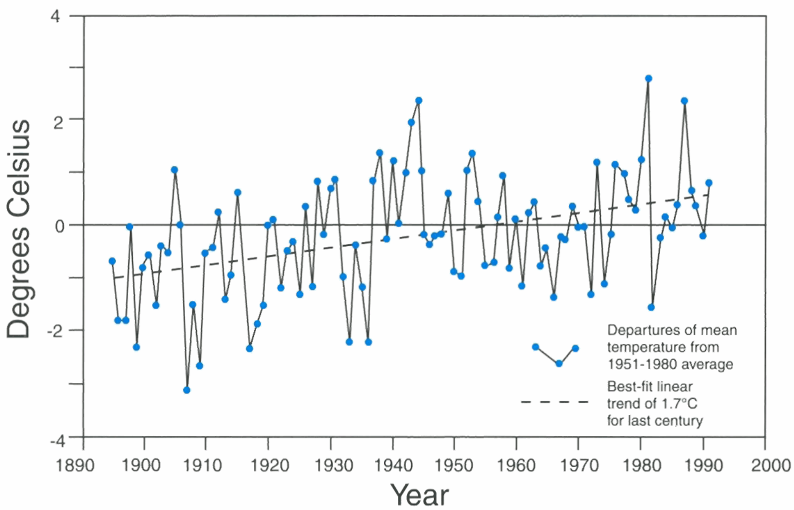


Figure 30.

Departures of mean annual temperatures from the 1951-1980 average for the Mackenzie District (including Yellowknife). The figure shows a trend toward increased annual temperatures over the last century. (From Gullet and Skinner, 1992)

Response of air temperatures to doubling of greenhouse gases

The possible temperature change for the Yellowknife area, under conditions of a doubling of greenhouse gases predicted by Canadian climate models, is between 4°C and 5°C by the latter half of the twenty-first century, with most warming occurring in winter and spring. This doubling of greenhouse gases is expected to occur in the first half of the next century, but the predicted changes in air temperatures are not expected for several more decades. The mean annual air temperature in Yellowknife under this scenario would be about -1°C in the latter half of the next century, compared to the present-day temperature of about -5°C.

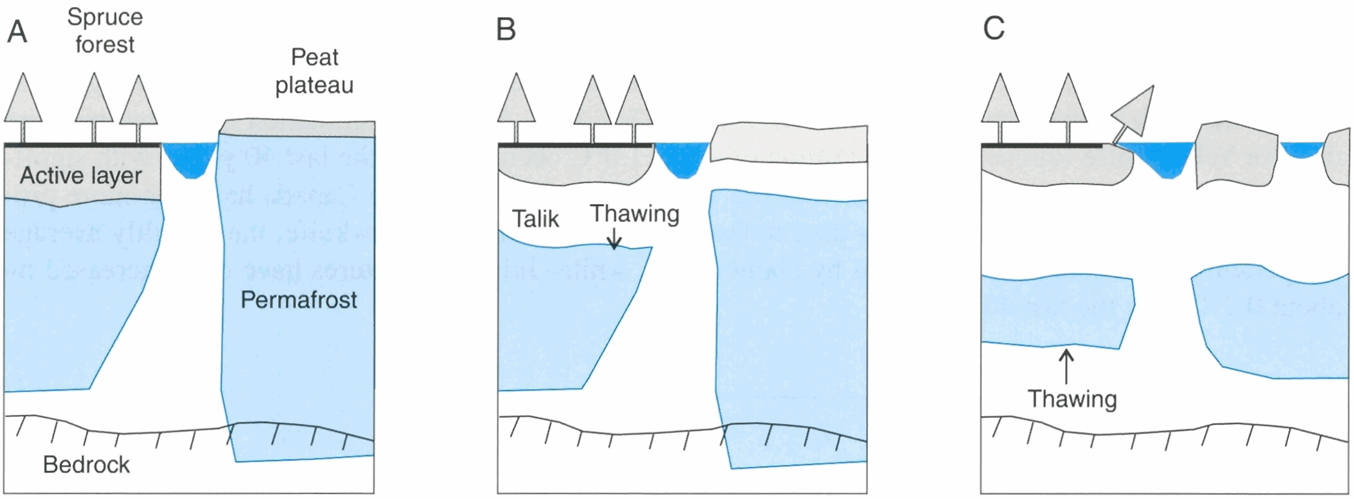


Figure 31. *The possible impact of climate warming on permafrost in the Yellowknife area.* ***A)*** *Present-day conditions;* ***B)*** *ground warming resulting in thawing of permafrost and creation of taliks;* ***C)*** *further thawing of permafrost causing thaw settlement and thermokarst.*

Effect of climate warming on permafrost in Yellowknife

In general, average annual ground surface temperatures are about 4.5°C warmer than average annual air temperatures in discontinuous permafrost areas in Canada. In Yellowknife, average ground surface temperatures are about 3°C to 7°C warmer than the average annual air temperature of -5.2°C (see Fig. 16) and range from about -2°C to +2°C. This is due to a variety of factors, as discussed earlier.

If the increase in ground temperatures following a doubling of greenhouse gases is similar to that for air temperature (assuming all other factors remain constant), the average ground surface temperature in Yellowknife would increase to about +3°C to +4°C. Permafrost in this region, therefore, would be expected to disappear over time and the southern limit of permafrost could eventually be located north of Yellowknife.

Changes in ground temperatures lag behind changes in air temperatures, and deeper ground temperatures would not rise above 0°C for several decades or longer. The time required for permafrost to disappear completely depends on the soil's thermal properties and the ice content in the ground. Ground temperatures near the surface would increase in response to climate warming, and a talik would develop below the seasonally frozen layer. This talik would deepen as the permafrost degraded (Fig. 31). The complete disappearance of permafrost would probably take decades or centuries. Permafrost would likely disappear from soils with low ice content before disappearing from soils with high ice content, because the former require less heat to thaw. The presence of thick peat layers, which occur in the Yellowknife area, could delay the initiation and rate of permafrost degradation.

Impacts of climate warming

Since most permafrost in the Yellowknife area is warmer than -2°C, significant melting of permafrost would be expected in response to a warming of 4°C to 5°C. Melting of ice-rich permafrost can lead to thaw subsidence and ground instability (Fig. 31). In areas where a thick layer of ice-rich peat is present or where the organic layer is underlain by ice-rich silts or clays, thawing of permafrost could result in the formation of thermokarst ponds. Changes in the microclimate induced by human activity have resulted in the formation of ponds 1.5 m deep in organic terrain (see Stop 1 of the Capital Tour). Similar conditions might be expected to occur in response to climate warming.

Frost heave associated with seasonal freeze-thaw cycles could remain an important process in this region, even if permafrost were to degrade.

PART III: GUIDE TO FIELD STOPS

Stephen A. Wolfe

Introduction

The following guide provides you with a tour through the heart of downtown Yellowknife. Several areas in Yellowknife where examples of the effects of permafrost may be observed are described. These include elevated peat plateaus and thermokarst terrain, buildings designed to cope with frozen ground (and some that were not), thermosyphons used to freeze back thawing ground, and various examples of the effects of thaw settlement and frost heaving on roadways and buildings. Because the tour takes you through the streets and avenues of downtown Yellowknife, it can be followed on foot, by bicycle, or by car.

As shown in Figure 32 three tours are available.

If you don't have much time, you may wish to take the ***Capital Tour***, which takes about 40 minutes and begins and ends at the Visitors Centre. It is best done as a walking tour. To take this short tour, complete stops 1 to 10 and return to the Visitors Centre. The more ambitious can continue on the ***City Tour***, which requires from 2 to 3 hours if walking, and about 1.5 hours if driving or bicycling.

The end of the City Tour takes you to Niven Lake. You can follow the ***Niven Lake Trail*** (presented in Part IV of this guide) or save this for another day. Note that Stop 29 takes you toward Niven Lake along a smooth and steep trail where cars cannot be used. You can leave your car in the parking lot near the baseball diamond at the bottom of the hill, or drive to Niven Lake via the access road.

The Capital Tour – Capital Site to Bowling Green building

The field tour begins west of the Visitors Centre, at the Legislative Assembly access road, near the intersection with Highway 3 (Fig. 33). This area is called the Capital Site, and a road loop links the Visitors Centre, Legislative Assembly, and Prince of Wales Heritage Centre.

Stop 1. The Capital Site – a profusion of peat

Yellowknife lies within the discontinuous permafrost zone, meaning that frozen ground occurs as "islands" or "pockets". Due to the lack of organic cover, the exposed bedrock outcrop next to the highway does not contain permafrost. Most permafrost in the area is found below a ground cover of 30 cm or more of insulating organic material. The permafrost itself can extend into the soil and bedrock for a depth of over 50 m.

In the centre of the road loop is a large peat plateau where the organic material is over 1 m thick (Fig. 34). This peat plateau is about 250 m long and 150 m wide and is ringed by bedrock to the north, west, and south. The peat area is underlain by frozen ground. Beneath the peat is an ice-rich silty clay that is underlain by a sandy silt containing little or no ice. These sediments were deposited by glacial Lake McConnell about 10 000 years ago.

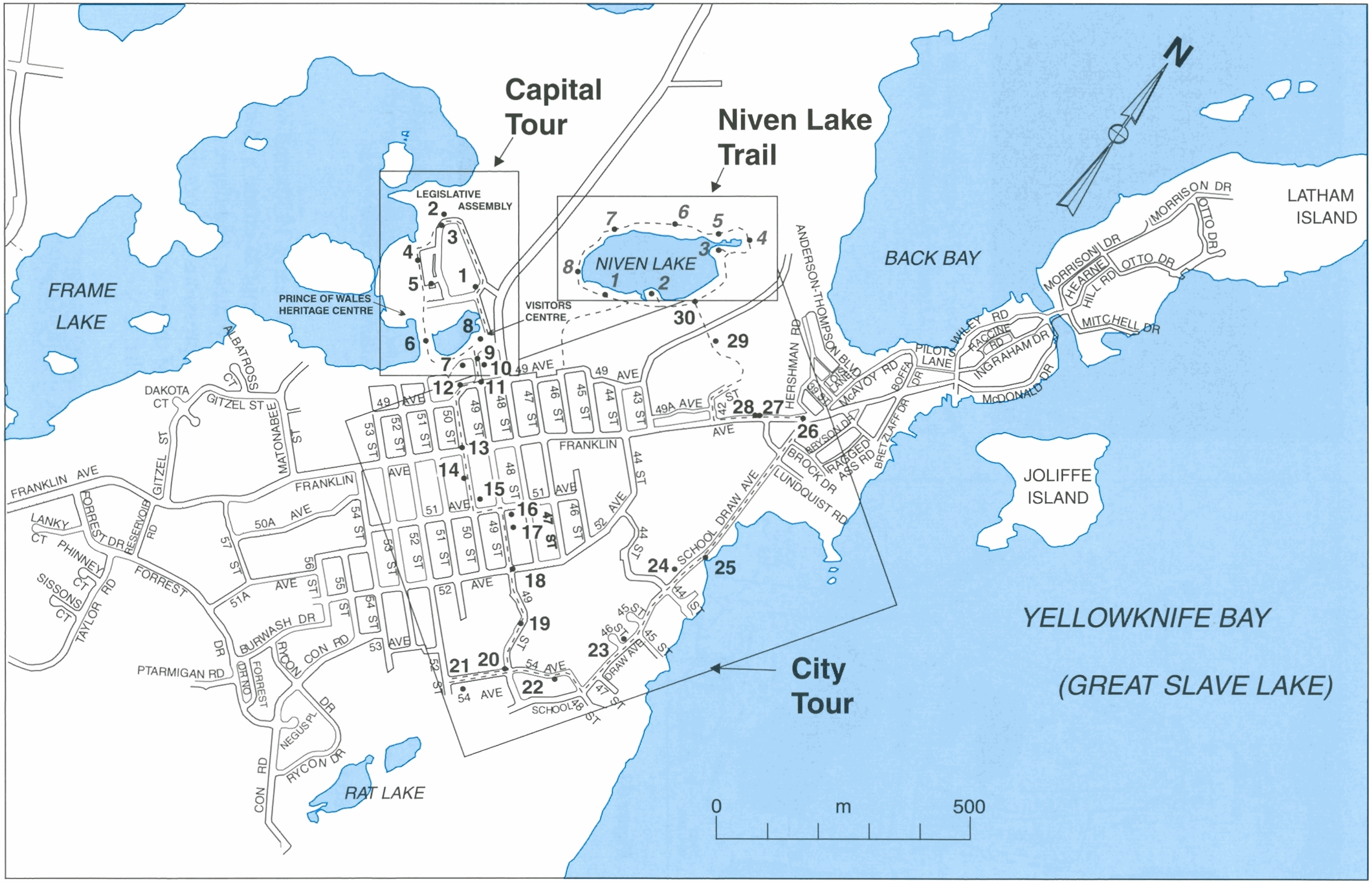


Figure 32. The three field tours of Yellowknife: Capital, City, and Niven Lake Trail.

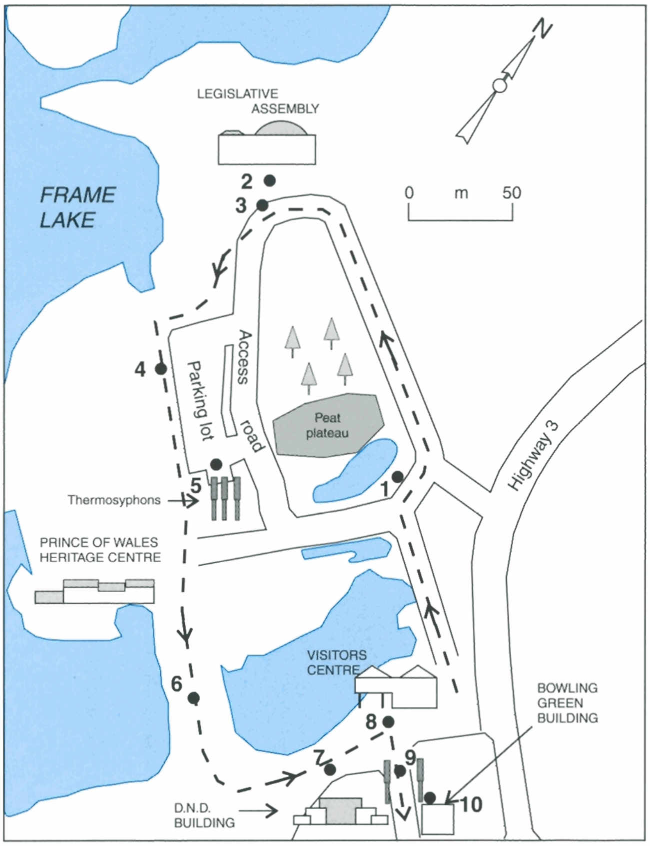


Figure 33. The Capital Tour.

Figure 34. *Stop 1 – The large peat plateau in front of the Legislative Assembly is underlain by permafrost. GSC 1998-006 K*

Figure 35. *The ponds and depressions next to the peat plateau are the result of permafrost melting and are known as thermokarst. GSC 1998-006 L*

The peat plateau grew as sphagnum moss accumulated in the damp, acidic environment. As the peat layer thickened, it acted as an insulating layer, causing frozen ground to form beneath the surface. As the ground froze, ice lenses grew within the soil and peat causing the entire surface to rise.

In summer, the upper part of the peat thaws only to a depth of about 50 cm. Much of the southwest portion of the plateau was stripped of the upper layer of peat in the early 1950s and now lacks any vegetation cover. The vegetation was stripped in an unsuccessful attempt to create a market garden on the peat. A series of ponds up to 1.5 m deep occur next to the peat plateau, and depressions can be seen as you walk toward the Legislative Assembly (Fig. 35). These depressions and ponds are the result of permafrost degradation, or thermokarst, caused by disturbance of the peat surface. The peat plateau gradually collapses as the ice-rich permafrost beneath it slowly melts.

Proceed along the road toward the front court of the Legislative Assembly.

Stop 2. Legislative Assembly – design with nature

Construction of the Legislative Assembly building took three years. The building was opened in 1993 to house the elected members of the Territorial Government and their staff (Fig. 36). Prior to its construction, sessions were held at the Yellowknife Inn, and before that at the Explorer Hotel and throughout the Northwest Territories. The building is constructed on bedrock because of the shallow soil in the local area, and it was designed to take advantage of the natural setting, preserving as much of the original vegetation and lake shoreline as possible.

In front of the Legislative Assembly building is a large concrete sidewalk that was constructed by removing the ice-rich permafrost down to the bedrock and replacing this with a stable crushed rock fill. The sidewalk rests directly on this fill.

Figure 36. *Stops 2 and 3 – The Legislative Assembly. Permafrost exists beneath the gravel road in front of the Legislative Assembly building. The roadway was paved in 1997, with precautions taken to preserve the permafrost. GSC 1998-006 M*

From the Legislative Assembly, turn and look at the access road.

Stop 3. Legislative Assembly roadway – perils of paving peat

Construction of the roadway first began in the 1980s to access the Prince of Wales Heritage Centre. A gravel road and parking lot were completed in 1993 with the opening of the Legislative Assembly (Fig. 36). This road is built directly over the peat terrain and permafrost. Originally, the gravel roadway was laid down with a geotextile fabric placed on top of the peat to prevent gravel from penetrating into the underlying organic material. In August 1996, boreholes drilled beneath the roadway confirmed that permafrost still existed to a depth of more than 10 m. The temperature of the permafrost was warm, ranging from -0.1°C to -0.7°C at the bottom of the holes. In addition, the base of the peat was frozen and no significant settlement had occurred along the roadway.

In the summer of 1997 the roadway was paved. Because of the possibility of thawing the permafrost beneath the road, several preventative measures were taken. Stop 5 provides additional details on what was done to preserve the permafrost.

From the Legislative Assembly, proceed along the walking path to the far end of the Legislative Assembly parking lot, observing as you go.

Stop 4. Walking path – tipping trails

The walkway to the Legislative Assembly was built in 1994. In 1996 and 1997, cracks up to 20 cm wide were visible between the parking lot and the pedestrian trail, indicating that thaw settlement was occurring as the underlying permafrost melted. Differential settlement was noticeable at several locations along the pedestrian trail (Fig. 37) with dips up to 50 cm along the path. Repairs to the walkway were made in August 1997, but more settlement can be expected as the permafrost continues to thaw.

Proceed from the walkway up the slope onto the parking lot. Proceed to the east end of the sidewalk where large poles are sticking out of the ground.

Figure 37. Stop 4 – Settlement of the walking trail between the Legislative Assembly and Prince of Wales Heritage Centre, caused by thawing of the underlying permafrost. GSC 1998-006 N

Stop 5. Legislative Assembly parking lot – preserving permafrost

In the summer of 1997, the access road and parking lot were paved. However, due to the occurrence of underlying peat and ice-rich clay, the subsurface conditions around the Legislative Assembly access road and parking lot were considered poor for supporting an asphalt pavement. Thermal calculations predicted that, if the road were covered with asphalt, thaw would penetrate approximately 1.0 m below the peat, causing the road to settle.

Preparations prior to paving represented a sort of three-part experiment. Insulation on the one hand, and thermosyphons on the other, were used in different locations in order to compare how well each method prevented thawing of the underlying permafrost (Fig. 38). Calculations showed that the addition of insulation could restrict the seasonal thawing in most areas to within the peat layer for 10 to 15 years, thus preventing the underlying ice-rich clays from melting. Prior to paving, part of the gravel surface was temporarily removed and rigid styrofoam insulation was laid within the gravel bed above the peat (Fig. 39). This was done under most of the road, except for the southwest portion between the parking lot and the Heritage Centre. Along this section of the road, thermosyphon tubes were placed within the peat beneath the gravel bed. The thermosyphons act to remove heat from the ground and dissipate it into the air, thereby cooling the ground to create or maintain frozen ground (Fig. 40). Finally the south end of the parking lot and the section of the access road beside the lot were insulated, and thermosyphon tubes were laid down below the insulation. To learn more about thermosyphons, refer to the section on Development in Part II.

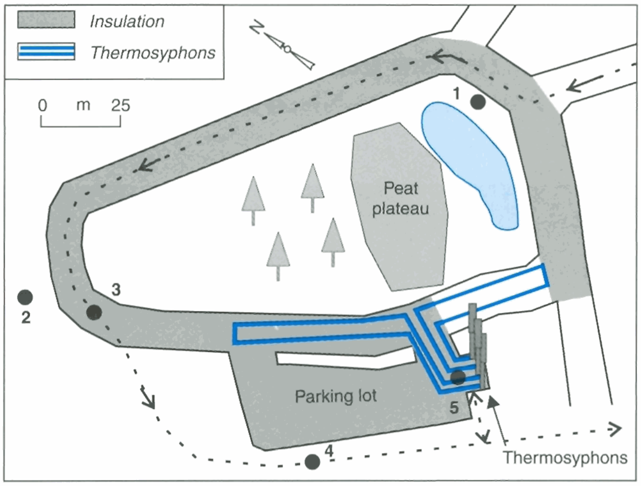


Figure 38. Plan of the access road to the Legislative Assembly showing where two methods were used to prevent thawing of the underlying permafrost.

Figure 39. Insulation was placed beneath the road in order to preserve the permafrost. GSC 1998-006 O

Figure 40. Stop 5 – Thermosyphons at the Legislative Assembly parking lot being charged with carbon dioxide (CO_2) gas. GSC 1998-006 P

From the west end of the parking lot, return to the pathway and follow it past the Miner's Monument and the Prince of Wales Heritage Centre to the causeway beside the lake.

Stop 6. Frame Lake – Yellowknife's aquatic centrepiece

The large lake beside the Heritage Centre is Frame Lake (Fig. 41). The pond on the left was once part of the lake until the causeway was constructed in 1975 to access the Heritage Centre. Prior to development, the natural water drainage through here was northward from Frame Lake to Niven Lake and into Back Bay. Water levels on Frame Lake have dropped since the 1950s, and the drop may be attributed, in part, to storm sewers that channel runoff away from the lake. Along the edges of the lake you will notice cattails and sedges, many of which have grown in recent years as the water level has dropped.

Figure 41. *Stop 6 – Frame Lake and the Prince of Wales Heritage Centre. Willows, cattails, and sedges surround the shoreline at this end of the lake. GSC 1998-006 Q*

From the causeway, proceed along the walking path to the large concrete circle and turn left. Continue along the walkway past the large building on the right.

Stop 7. National Defence building – seeking solid ground

The Department of National Defence building was constructed in 1993 and demonstrates some of the challenges facing construction in the Yellowknife area (Fig. 42). The soils beneath the building are mostly silts and clays that cannot withstand the load of such a large building. In addition, the depth to bedrock changes considerably beneath the building. On the south side, the bedrock is very near the surface. On the north side (the side closest to the Explorer Hotel), the bedrock is more than 30 m below the surface. Like many buildings in Yellowknife, the National Defence building is constructed on steel piles anchored in bedrock.

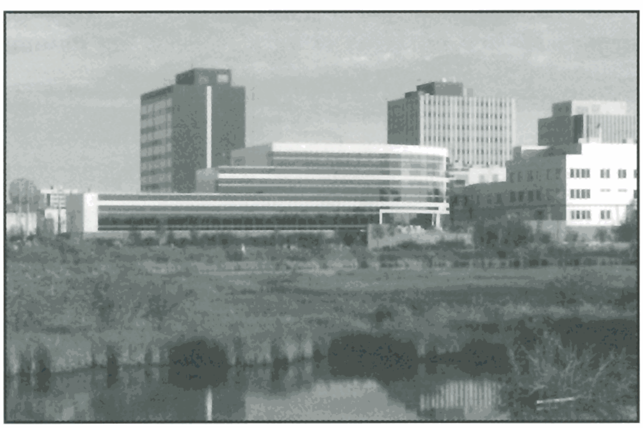


Figure 42. *Stop 7 – The Department of National Defence building (centre of photo). Piles driven over 30 m deep support the building on one side (right) while the other half rests soundly on bedrock. GSC 1998-006 R*

Continue along the walkway to the intersection with the road (49 Street). Stop here and look northeast, toward the Visitors Centre.

Stop 8. Visitors Centre – rocking and rolling

In its original state, the site of the Visitors Centre was low-lying organic terrain with low bushes, likely similar to the undisturbed terrain surrounding the adjacent pond today. Beneath the surface is a fine-grained silty clay underlain by silt deposited by glacial Lake McConnell. The steeply sloping bedrock outcrop on which the Explorer Hotel now stands is indicative of the sloping rock surface beneath the ground. In the vicinity of the Visitors Centre, the depth to bedrock is over 30 m. Although permafrost is widespread in the immediate area, it is generally absent close to the pond. It is not known exactly where the boundary between the frozen and unfrozen ground occurs, but it is most likely within or near the site of the Visitors Centre (Fig. 43). The clay soils are weak where they are unfrozen.

Figure 43. *Stop 8 – Part of the Visitors Centre rests on piles. GSC 1998-006 S*

Construction of the Visitors Centre began in 1991. The centre is supported by piles driven into the underlying sediment. Installation of the support piles involved driving the piles into the ground to the point where they met strong resistance, indicating contact with bedrock.

The problem with the building is that it is subject to frost jacking (Fig. 19). Each winter, the water in the shallow pond freezes to the bottom and the underlying soils also freeze. In the fine-grained soil, ice lenses form as the soils freeze. This causes the soil to expand upward. Freezing also causes the soil to adhere to the supporting piles, and the piles subsequently heave upward with the growing ice. At the bottom, voids can be created by the rising piles. In the spring when the pond and the soil melt, the piles do not return to their original position because of friction between them and the soil; instead, they remain elevated, which causes part of the building to lift. Each year this process (referred to as frost jacking) is repeated. By the spring of 1997, the building had lifted in places by more than 15 cm.

To repair the effects of frost jacking, pieces of the raised piles were cut out to lower the building. Unfortunately, this does not prevent frost jacking from occurring again the following year. To further reduce the effect of frost jacking, the piles are now heated in the winter to prevent the soil from freezing to the piles and lifting them.

From the same location, look down 49 Street in the opposite direction at the two tall poles standing on either side of the street near the sidewalks.

Stop 9. 49 Street thermosyphons – keeping it cool

Prior to development along 49 Street, this area was dominated by a spruce forest with an underlying layer of peat and permafrost. The underlying sediment was predominantly frozen clay. It is generally thick, and bedrock occurs between 3.5 m and 35 m beneath the surface.

The roadway was built in the 1960s. Prior to 1995, thaw settlement had occurred on 49 Street resulting in the displacement of paving stones, cracking of the paved road surface, settling of the parking area adjacent to the Bowling Green building (Fig. 44), and formation of a dip in the entrance to the National Defence parking lot across the street. By 1995, it was believed that most of the permafrost adjacent to and beneath the Bowling Green building had degraded (see Stop 10), although permafrost still existed beneath the roadbed.

Figure 44. Settlement beside the Bowling Green building on 49 Street. (Photo by Larry Aspler, October 1977)

In August 1995, thermosyphons were installed along 49 Street to counter the potential problems posed by the thawing of permafrost beneath the road (Fig. 45). The design uses two thermosyphons on each side of the road. Each thermosyphon has an ***evaporator*** tube buried beneath the road for a distance of about 45 m (Fig. 46). The total length of the roadway affected by the thermosyphons is about 90 m. The thermosyphon poles stand almost 9 m tall and are comprised mostly of radiator fins that permit heat to dissipate into the air. This was the first use of thermosyphons in Yellowknife for roadway construction.

Figure 45.

Stop 9 – View down 49 Street. The Bowling Green building is on the left (Stop 10), thermosyphons stand beside the sidewalks on both sides of the street (Stop 9). GSC 1998-006 T

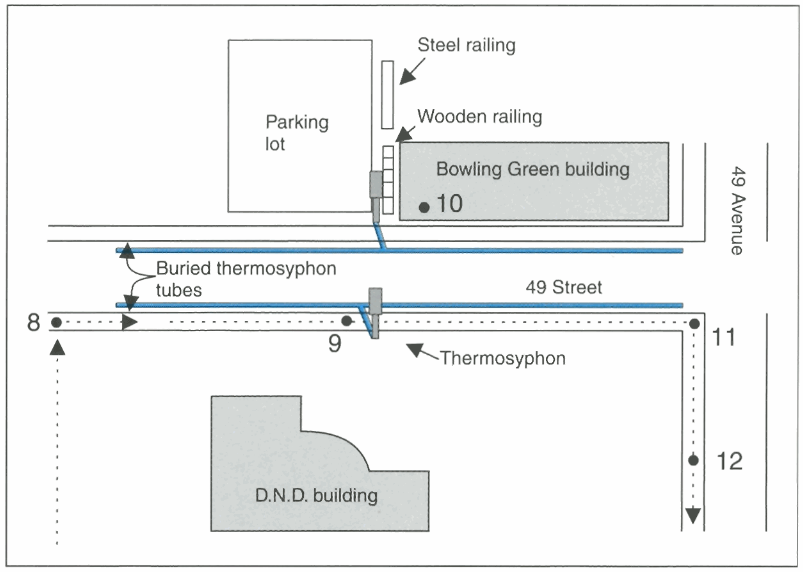


Figure 46.

Plan of the thermosyphon layout along 49 Street. The numbers refer to the stops along the tour.

Proceed along 49 Street to the thermosyphons.

Stop 10. Bowling Green building – swallowing sidewalks

The Bowling Green building was constructed in 1973 and opened in 1974 (Fig. 45). It is built on piles driven to bedrock. On the east side, the piles extend down about 3.5 m; on the west side, they extend more than 35 m. Because thaw unstable conditions were known to exist, nearly twice the number of piles were installed than would normally be necessary to support the building, and to ensure that the foundation remained stable. Indeed, in the last 25 years, the building itself has moved very little.

However, although about 1 m of insulation was laid down on top of the bare soil beneath the building, between 1973 and 1980 the space between the flooring and the ground was heated. Within about five years, thaw settlement occurred beneath the building as the underlying permafrost thawed. Thawing of the permafrost was probably due in part to heat conduction into the soil through the steel piles. By 1995, the soil level had dropped by more than 2 m.

As the soil beneath the building settled, soil around the building collapsed into the developing hole (Fig. 44). This caused the surrounding sidewalk, guard rails, and even the roadway to slope toward the building. As a countermeasure, the perimeter of the building was filled back with crushed rock, and a wooden boardwalk replaced the lost sidewalk.

In 1995, 49 Street was repaved and the thermosyphons were installed beneath the roadbed as described. At that time, the perimeter of the building was levelled again with gravel fill, and a new side-walk installed along the road. Since then, the soil beneath the Bowling Green building appears to have stabilized, perhaps because most of the ice-rich permafrost beneath the building is now thawed.

Along the western side of the building you will notice a wooden guard railing that slopes toward the building. This sloping was caused by soil slowly collapsing into the hole beneath the building. If you look beyond the wooden railings you will notice a metal railing supported by metal piles. At the far end, the

Figure 47. Stop 10 – Steel railing beside the northern corner of the Bowling Green building. The railing has been "swallowed" by the ground as the soil around the building has settled. A black wooden railing was put up beside the building after the steel railing had sunk into the ground. The wooden railing is now leaning towards the building because of the shifting soils. GSC 1998-006 U

railing is about 50 cm high, but it soon disappears into the ground as it approaches the building. This steel railing actually extends across to the south side of the building but disappears below wooden piles – it has sunk completely beneath the ground (Fig. 47).

If you are not continuing on the City Tour, return to the Visitors Centre.

The City Tour - 49 Avenue to Niven Lake

Continue along 49 Street to the intersection.

The City Tour begins at the intersection of 49 Street and 49 Avenue across from the Bowling Green building. From here, you will proceed through downtown Yellowknife to School Draw and Yellowknife Bay, ending at Niven Lake. A map of the City Tour is shown in Figure 48 to assist you in following the route.

Stop 11. 49 and 49 intersection – rolling roadways

At the intersection of 49 Avenue and 49 Street, you will notice that the road dips on each corner of the intersection and along 49 Avenue away from the intersection (Fig. 49). These dips are caused by the thawing of ice-rich sediments beneath the road. The roadway along 49 Avenue was excavated in the summer of 1985 as a part of the city's water and sewer replacement program. During excavations at least 1 m of highly compacted peat was removed from beneath the road and replaced with fill. Almost immediately after construction, the roadway settled again. In 1988, the roadway was rebuilt again, utilizing insulation across the entire roadway to slow down permafrost thawing. Undoubtedly the road will soon require further repairs.

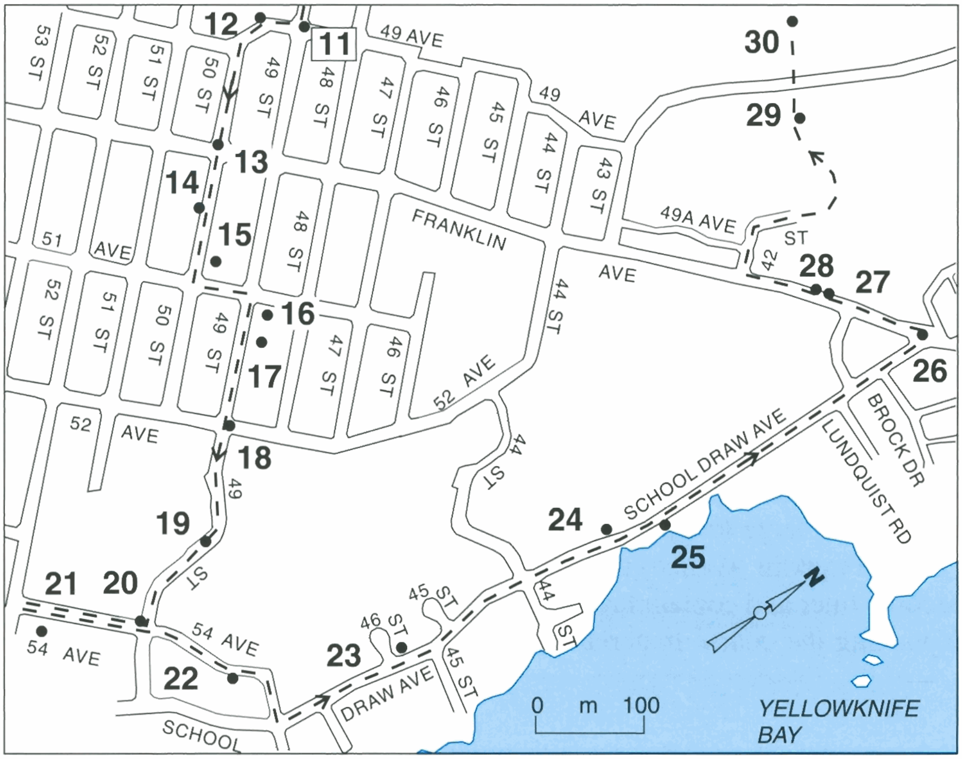


Figure 48. The City Tour.

Figure 49. Stops 11 and 12 – View of 49 Avenue from Stop 12, looking back at the Bowling Green building. GSC 1998-006 V

Proceed south along 49 Avenue to the intersection with 50 Street. Note the sidewalk on the way.

Stop 12. 49 Avenue – sagging sidewalks

As you walk along 49 Avenue toward 50 Street you will notice that the sidewalk is constructed of interlocking bricks, rather than concrete (Fig. 49). When the roadway was repaved in 1985, it was recognized that thaw settlement was a problem in this area and that a concrete sidewalk would not remain intact for long. Interlocking bricks were used instead as they would more readily conform to the undulating surface that developed over time. This is one example of how city engineers are coping with the problem of thaw settlement.

As you approach the 50 Street intersection you will note that road and sidewalk conditions improve. The bedrock is very close to the surface at this location, as is indicated by the outcrop on the west side of the intersection.

From the intersection, head east along 50 Street to Franklin Avenue.

Stop 13. Downtown Yellowknife – safe on sand

As you walk toward Franklin Avenue, there are changes in the geology and in the original permafrost conditions beneath your feet. The underlying sediments change from lake-deposited silts and clays to ***outwash***-deposited sands and gravels (Fig. 50). These sandy sediments were deposited during a highly energetic period of glacial melting about 10 000 years ago, before the lake was fully formed. The glacial meltwater brought with it large amounts of sediment, deposited as a sandy plain across the downtown area. Eastward down Franklin Avenue, the underlying sediments contain more gravel. In the opposite direction they become finer and contain layers of silt. This indicates that the water flowed from northeast to southwest, depositing the coarse material near the source of the water and the finer material farther away.

Figure 50.

Surficial geology of downtown Yellowknife, showing areas covered by the sandy plain and the silty clay sediments. The numbers refer to the stops along the tour. (Modified from Aspler, 1979)

In 1945, this sandy plain was considered an ideal spot to locate the "New Town" of Yellowknife (Fig. 51). It was flat, easy to build on, and contained only a few patches of frozen ground. Prior to the development of New Town, the area supported scattered black and white spruce, jackpine, birch, and poplar. The organic ground cover was only about 30 cm thick and did not provide enough insulation for the growth and preservation of permafrost.

Figure 51. *Downtown Yellowknife as it appeared in August, 1949 (NAPL REA 578-14). The intersection in the centre of photograph is 50 Street and 50 Avenue (Franklin Avenue); view toward the north.*

In most places where permafrost was present, it has now thawed near the surface. The eastern corner of the intersection of 50 Street and Franklin Avenue was the site of the old Miner's Mess, a popular coffee shop built in the 1950s (Fig. 52). When it was torn down in the early 1990s, permafrost still existed at a depth of 5.5 m.

From the intersection, continue east along 50 Street toward 51 Avenue.

Figure 52.

Stop 13 – View from corner of 50 Street and 50 Avenue (Franklin Avenue), looking toward the Yellowknife Inn and the location of the former Miner's Mess. This portion of the city rests on a broad sandy plain. GSC 1998-006 RR

Stop 14. Gold Range Hotel – making things work

Although many buildings in downtown Yellowknife are as modern as in any city in southern Canada, the Gold Range Hotel stands as an icon of old-fashioned ingenuity (Fig. 53). The Gold Range, built in 1946, was owned and operated by Jacob (Jack) Glick. First called the Veterans Cafe, it was originally constructed from two prefabricated U.S. Army Dallas huts – relics of the ***Canol pipeline***, which he skidded up from Old Town. Later he built a new ground floor and used two bunkhouses from the nearby Negus mine to construct the hotel's second story. The hotel was built on top of his root cellar which served as the hotel's cold storage for supplies that were shipped in yearly by barge. Since 1977, the Gold Range Hotel has been owned by Sam Yurkiw. The cellar still exists, but it is shored up with concrete. This is a lasting example of what can be done when the underlying sediments are sandy – do not attempt this on ice-rich clay!

Figure 53.

Stop 14 – The Gold Range Hotel. GSC 1998-006 W

From the Gold Range Hotel continue along 50 Street to 51 Avenue.

Stop 15. Centre Square Mall – stemming shifting sands

In contrast to the Gold Range Hotel, the Centre Square Mall is built on concrete-reinforced steel piles socketed 1 m into bedrock – a far cry from a soil root cellar. During construction, builders had to deal with loose wet sand and highly irregular bedrock surfaces with slopes of up to 45 degrees. Although permafrost did not exist in the sands beneath the building, the bedrock-secured piles were needed to carry the very heavy load of this concrete building (Fig. 54).

From the intersection turn left and proceed along 51 Avenue to the next intersection.

Figure 54. *Stop 15 – The Centre Square Mall, built on reinforced piles secured to bedrock. GSC 1998-006 X*

Stop 16. Boston Pizza – fast food on a slab

There are many examples of different construction styles in Yellowknife. Some are similar to those used in the south, but with a northern touch. The Boston Pizza and the former Taco Time buildings are examples of these (Fig. 55). They are thickened perimeter slab-on-grade buildings. In simpler terms, they have a concrete slab foundation that is reinforced around the edges. To cope with northern conditions, flat-lying rigid insulation is laid down around the edge of the building beneath the ground. This prevents seasonal frost from freezing around the building and lifting or damaging the foundation. This method is also used in southern Canada where the risk of seasonal frost heaving around buildings might be a problem.

Figure 55.

Stop 16 – The Boston Pizza building on the corner of 48 Street and 51 Avenue. Although the building is similar in appearance to southern-style buildings, the edges of the foundation are thickened and insulation has been placed below the ground around the building to prevent possible damage due to frost heaving. GSC 1998-006 Y

From the intersection turn right and proceed along 49 Street. Note the houses on the left side of the road.

Stop 17. Royal Oak Mines Inc. houses – half a century later

After the New Town area was surveyed in 1945, Royal Oak Mines Inc. bought a block of land and constructed houses. The three houses across from the liquor store were built in the late 1940s to house miners and their families (Fig. 56). They were constructed using standard southern designs and included basements. Because the underlying soils were sandy and stable, they have fared surprisingly well over the last half century.

Figure 56. Stop 17 – House built in the late 1940s to accommodate workers at the Giant mine. GSC 1998-006 Z

As you continue along 49 Street the underlying geology changes again. By the time you have reached the intersection, the soil has changed from sands to finer silts and clays. This transition to finer sediments provides a new challenge (described at the next stop).

Continue along 49 Street to the intersection with 52 Avenue. From the corner of 49 Street and 52 Avenue look left (north) down 52 Avenue.

Stop 18. 52 Avenue – up, up, and ... away

This area is underlain by silts and clays, rather than by sandy sediments like those downtown. Here, the soils beneath 52 Avenue are susceptible to frost heaving. Each winter, as the surface beneath the road freezes, ice lenses grow within the natural soils and raise the surface of the road. In the summer the road settles back again, but not always to its original position. The result is a cracked and bulging road (Fig. 57).

To eliminate the problem, the original frost-susceptible soils were removed to a depth of 1.5 m beneath the road in the summer of 1997. Additional wedges of native material were removed along utility trenches to minimize the

Figure 57. Frost heaving of silty soils beneath 52 Avenue caused the road to crack and bulge. GSC 1998-006 AA

effect of any future frost heave. This native material was replaced with a mixture of compacted crushed rock and sand. The road was repaved in the summer of 1997 (Fig. 58). How does it look today?

Figure 58. Stop 18 – The corner of 49 Street and 52 Avenue. The problem soils beneath 52 Avenue were removed and the road was repaved in the summer of 1997. How does it look now? GSC 1998-006 BB

From the intersection, continue along 49 Street, down the hill toward 54 Avenue.

Stop 19. 49 Street hill – leaving good ground

In the Yellowknife area, fine-grained clayey sediments generally overlie slightly coarser grained silts that were deposited by glacial Lake McConnell (Fig. 7). Sands and gravels are found in some of the deepest locations beneath these silts. As the glacial ice receded, the energy associated with the meltwaters in this area lessened. Finer grained sediments were then deposited in basins: first silts and then clays. This explains why most areas have a layer of silt underneath a surface layer of clay. In some areas the silts and clays are mixed and interfingered.

As you continue along 49 Street down the hill toward the School Draw subdivision, a substantial change in the underlying sediments and permafrost occurs. The sandy plain of the New Town area is gone and in its place is a bedrock basin, filled with fine-grained silts and clays (Fig. 50).

Turn right at the intersection of 49 Street and 54 Avenue.

Stop 20. 54 Avenue – frozen dangers underfoot

Much of the soil beneath this area is a silty clay, laid down originally as lake-bottom sediments in glacial Lake McConnell. Following drainage of the lake about 8500 years ago to a level similar to that of Great Slave Lake, permafrost formed in these sediments. Because the sediments are fine grained, ice lenses formed in them. Ice-rich layers over 1 m thick have been found in some areas beneath the road. Even in 1994, approximately 25 years after the road was constructed, ice-rich permafrost still existed from about 2 m below the surface. In other sections the permafrost has thawed, leaving only a very soft, moist clay. Even where there is ice-rich permafrost, the temperature is between 0°C and -0.2°C. It is permafrost, but just barely.

Proceed up 54 Avenue toward 52 Street and the Rockcliffe Apartments (on the left).

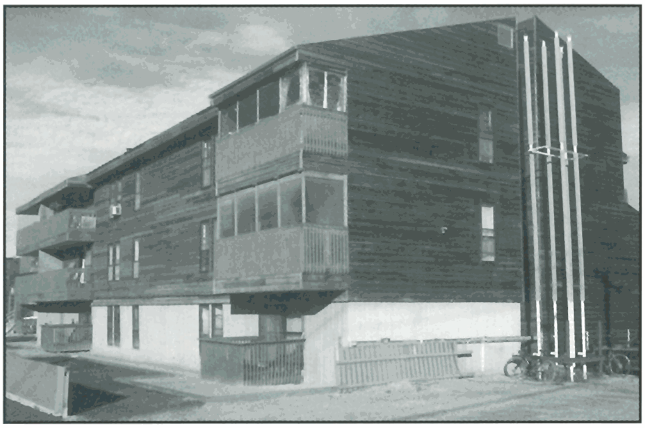


Figure 59. Stop 21 – Rockcliffe Apartments and thermosyphons used to stabilize the thawing of permafrost beneath the building. GSC 1998-006 CC

Stop 21. Rockcliffe Apartments – creeping crawl space

The Rockcliffe Apartments were built in 1974 (Fig. 59). The building's foundation consists of piles drilled through the soil to underlying rock at a depth of 20 m. A heated crawl space under the main floor was originally 1 m deep. Permafrost degradation under the building resulted in thaw settlement, so that over time the crawl space deepened to over 3 m in the centre of the building (Fig. 60). Fill around the building exerted pressure on the piles as it moved to fill the space beneath the building. The stress on the piles resulted in movement of the building itself.

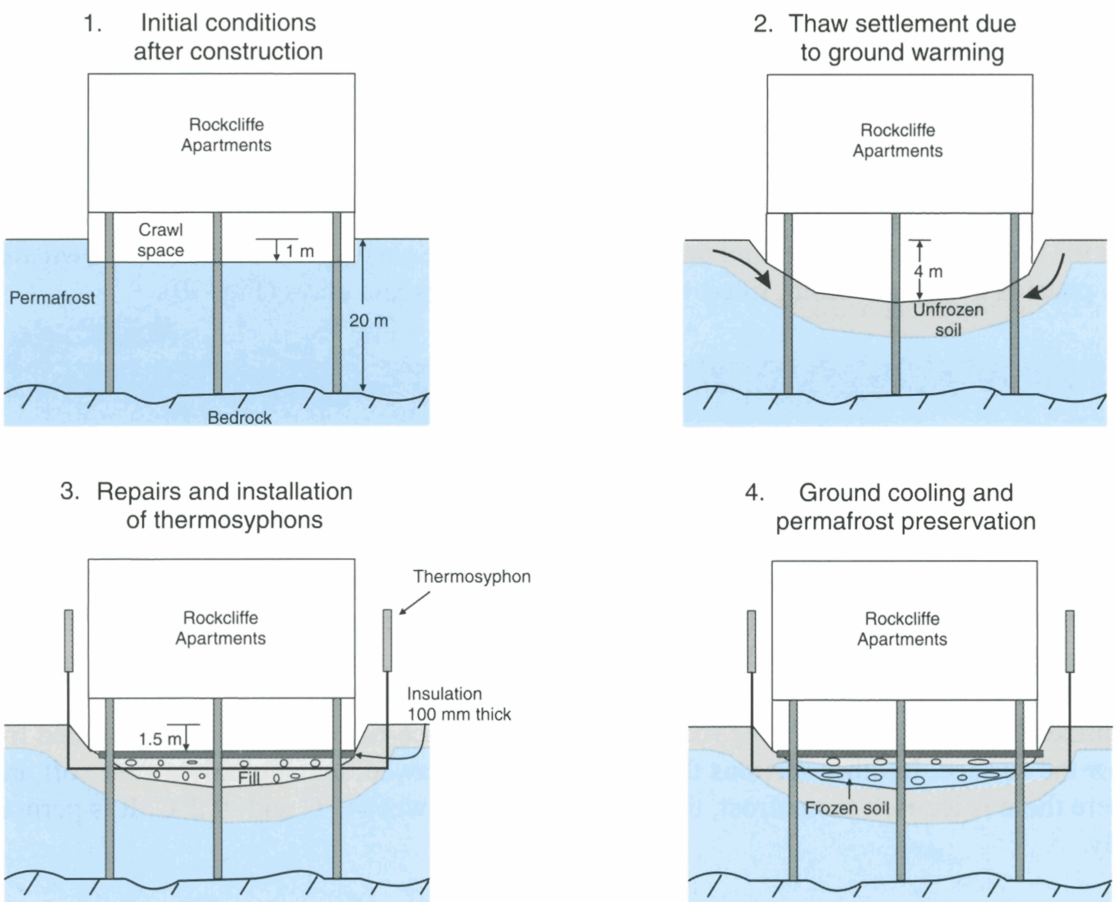


Figure 60. The effects of ground warming and the installation of thermosyphons beneath the Rockcliffe Apartments.

In October 1994, the expanded space beneath the building was filled in with soil; thermosyphon tubes were installed and covered with fill and insulation to return the crawl space to a depth of about 1.5 m. The thermosyphons are being used to cool the soil and arrest the thawing beneath the building. In the summer of 1997, the soil beneath the centre of the building had cooled to temperatures below 0°C, indicating that the thermosyphons were working.

From the Rockcliffe Apartments, return down 54 Avenue past the intersection with 49 Street. Continue down 54 Avenue and observe the houses on the right.

Stop 22. School Draw subdivision – houses on the move

After it was named capital of the Northwest Territories, Yellowknife grew rapidly. To accommodate this expansion, new subdivisions were planned to the south and west of the existing New Town (Fig. 61). By 1968, nearly 150 residential lots were surveyed in the School Draw area. Lots for single family dwellings sold for slightly over $3000. The subdivision was advertised as having all the conveniences of the South – sanitary and partial storm sewers, municipal water, fire hydrants, street lighting, electricity, telephone lines, and gravelled roads.

Prior to development of the School Draw area, permafrost was widespread in the underlying soils. Soils were predominantly ice-rich silty clays that, when thawed, are unstable. Bedrock outcrops also existed in the area. Although bedrock does not pose a significant hazard to construction, removing the rock by blasting makes construction more expensive. At that time, the development philosophy was to stay on the soils and avoid bedrock as much as possible. In 1968, it was known that challenging foundation and soil conditions existed in the School Draw area. Advertisements for the lots included a statement that "*soil conditions throughout the subdivision are not, in all cases, suitable to the use of conventional foundation systems. The purchaser must bear this in mind when investigating and selecting his lot.*" The extent of the problem surrounding local permafrost and soil conditions would not be fully recognized until a few years later.

Figure 61. *Stop 22 – School Draw subdivision. Because of settling caused by the thawing of permafrost, most of the houses in School Draw had to be removed from their foundations and the foundations rebuilt using piles anchored to bedrock. GSC 1998-006 DD*

Many of the original foundations in the School Draw subdivision were built to southern standards and designs. Houses built on concrete footings with basements were common. Other homes were built on steel piles, but the piles were commonly not driven to bedrock or not secured, and began to shift. Within three to four years it was apparent that many of buildings were settling due to thawing of the underlying ice-rich sediments.

The houses along 54 Avenue on the south side of the road were originally owned by the Territorial Government and were built on concrete footings with basements. As the permafrost thawed, the foundations began to settle. Less than ten years after construction it was decided that the foundations had to be changed. Some of the houses were systematically picked up from their original locations, the basement foundations removed, and steel piles driven to the underlying bedrock and secured. The houses were then placed on the piles, each one in a new location. Since then most of these houses have remained stable.

In addition to relocating houses on new foundations, nearly 25 of the original houses were moved out of the School Draw subdivision into other areas. In their place, newer houses with more secure foundations have been built, most of them on piles or on bedrock.

Proceed down 54 Avenue to School Draw Avenue. Turn left on School Draw Avenue and proceed to the School Draw Park on the left.

Stop 23. School Draw Park – from basements to basketballs

School Draw Park is on unstable ground (Fig. 62). Prior to establishment of the park, a house was situated on this lot. Like many other homes, it had a standard concrete footing foundation and basement. Because of thaw settlement of the underlying soil, the house was moved across the street to number 4503. It now sits on a concrete foundation directly on bedrock and again has a basement. The original foundation was removed, the hole filled in, and an asphalt basketball court built in its place.

Figure 62. *Stop 23 – School Draw Park is located on the site of a former home. The house was built on unstable ground and was moved across the street (on School Draw Avenue). GSC 1998-006 EE*

Proceed down School Draw Avenue to the large rock outcrop on the left side of the road.

Stop 24. Rock outcrop – on the shores of glacial Lake McConnell

The large rock outcrop on the left side of the road is part of the West Bay Fault (Fig. 63), which extends northward from Yellowknife Bay and along the western edge of Back Bay. You will also notice that the rock appears sculpted, and is smooth and polished. This is due to glacial erosion. Look closely at the rock and you will see long linear scratches on it. These are striations that formed as the glacial ice dragged

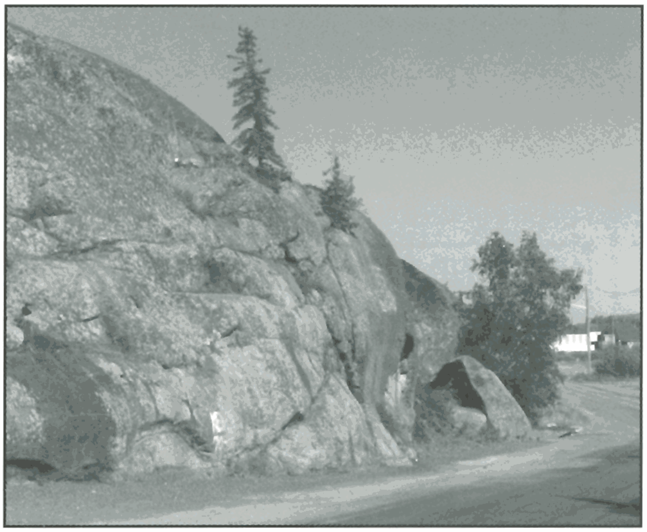


Figure 63. *Stop 24 – This rock outcrop once lay more than 100 m underwater when glacial Lake McConnell covered the Yellowknife area. If you look closely at it you will also see striations indicating the direction in which the glaciers moved when they covered the area. GSC 1998-006 FF*

loose rocks over the surface of the bedrock. The striations indicate that the direction of ice movement was from the northeast to the southwest.

As you stand at the base of this enormous wall of rock, imagine yourself at the bottom of a huge lake. When the glaciers receded, glacial Lake McConnell took their place. At its greatest extent, this lake was larger than any freshwater lake in existence today, and was more than 1000 km long. At this location about 10 000 years ago, you would have been be under more than 100 m of water.

From the rock outcrop continue along School Draw Avenue and look right toward Yellowknife Bay.

Stop 25. Detah ice road – crystal highway

South of Yellowknife is the aboriginal community of Detah. In the summer, a road past the Giant mine connects Detah and Yellowknife. The road is about 25 km long. In winter a much shorter route is taken directly across Yellowknife Bay. This shortcut is an ice road (Fig. 64, 65).

Ice roads are very common in northern Canada, as they are often the only land route to get large supplies into remote communities and mining camps. For example, much of the supplies for diamond mining in the Lac de Gras area, about 300 km northeast of Yellowknife, are trucked in over the ice and tundra in winter.

From here, continue along School Draw Avenue to the intersection with Franklin Avenue.

Figure 64. *Stop 25 – The Detah ice road. GSC 1998-006 GG*

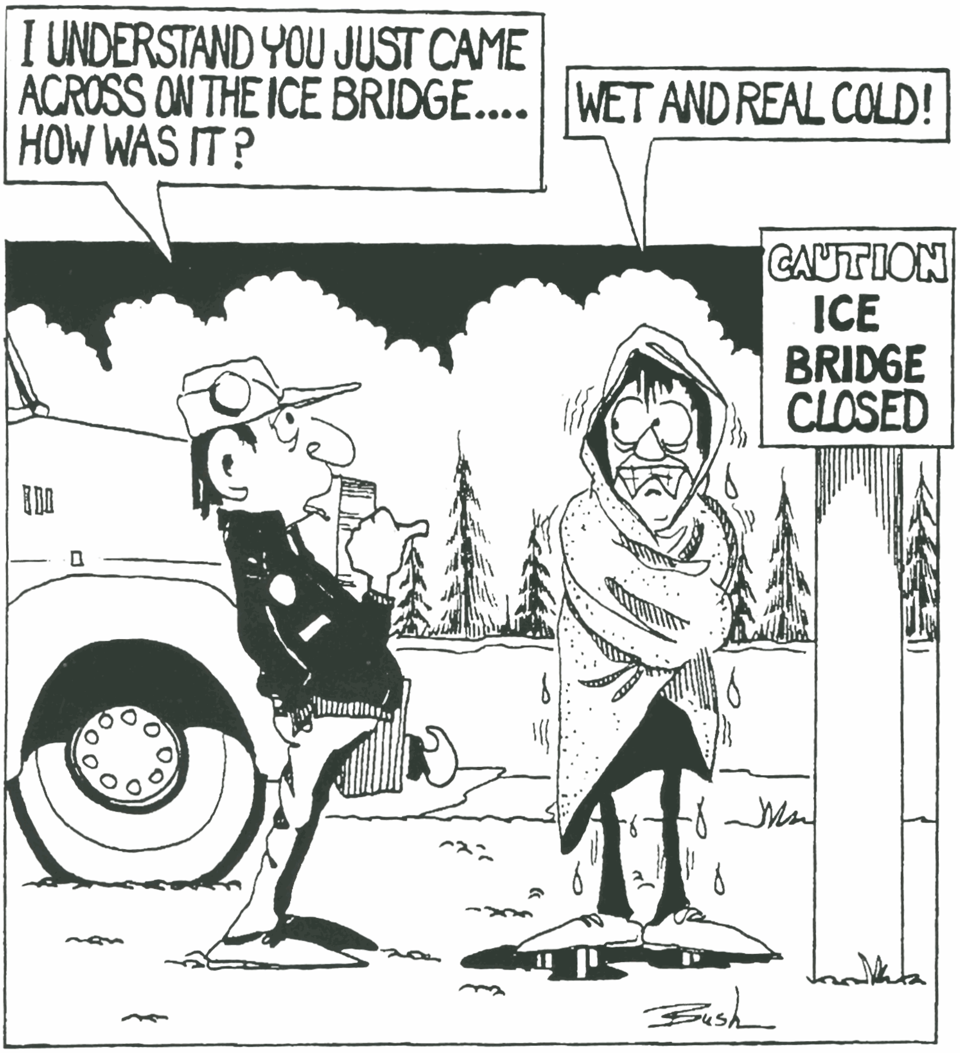


Figure 65. *Courtesy of Norm Muffitt, Northern News Services Ltd.*

Stop 26. Old Town – doing things the old-fashioned way

Until the late 1940s Yellowknife existed entirely on the flat land and rocky peninsula extending into Yellowknife Bay, in the area referred to today as Old Town. At that time, outhouses were used and water supplies were hand-carried from the bay. Today, even though above-ground water and sewer utilities are used in the Old Town area in the summer, water and sewage are trucked in and out in the winter to prevent pipes from freezing (Fig. 66).

From the corner of Franklin and School Draw avenues, head toward downtown along Franklin Avenue, stopping at the baseball diamond (Fritz Theil Park) on the right.

Figure 66. *Residents of the Old Town area have sewage trucked out because of the difficulty of placing sewer lines in the rocky terrain. Water is piped into homes in the summer, and trucked in in the winter. GSC 1998-006 HH*

Stop 27. Franklin Avenue – whither frozen ground?

In 1990, the deteriorating water and sewer system extending along Franklin Avenue toward Old Town was replaced. The underlying sediments change predominantly from sands near the downtown centre at the top of the hill, to silts and clays near the base of the hill (Fig. 67). Boreholes drilled in the area exposed sediments that were ice-rich in some areas, especially between 42 Street and School Draw

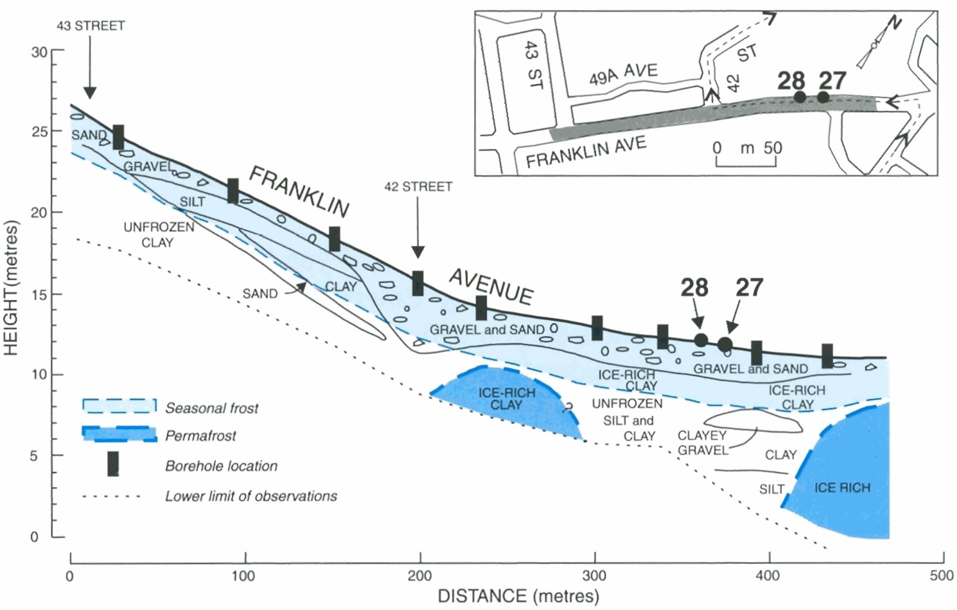


Figure 67.

Cross-section along Franklin Avenue showing geology and permafrost conditions prior to reconstruction of the sewer lines (published with permission of Stanley Associates Engineering Ltd.).

Avenue at the base of the hill. In addition, the permafrost in the area was very warm, being only about -0.3°C at depth of 7 m. Thaw settlement and frost heaving were considered serious problems in several places.

Surveys of the road and sewer system in 1990 found a discrepancy of as much as 2 m between the original designs and existing conditions. During installation of the new water and sewer system, it was found that substantial thaw settlement had occurred on the east side of the road due to thawing of the permafrost up to 6 m away from the original uninsulated pipes. At least two older asphalt surfaces were found beneath the existing road surface, indicating that as the road settled, it had been filled in several times. On the west side of the road, however, permafrost still existed. Because the existing pipes were on the east side, the new pipes were placed on the west side, on top of the permafrost and outside of the original thawed area.

Figure 68. Excavations along Franklin Avenue in 1990 revealed a substantial amount of ice in the form of ice lenses. The man in the photo is measuring ice lenses, which look like white layers in the soil. (Photo by Walter Orr)

Near the base of the hill on Franklin Avenue, ice lenses were found in the clayey sediments. In an attempt to remove this ice-rich material, the ground was excavated to a depth of almost 5 m below the ground surface. The amount of ice lensing, however, increased with depth and some ice lenses were more than 20 cm thick (Fig. 68). During installation of the new water and sewer system, it was found that this ice-rich permafrost extended under much of Franklin Avenue on the west side of the road

To overcome the problems with the sensitive ice-rich permafrost, insulation was placed below the water and sewer lines to minimize thawing beneath the pipes. To do this, a trench was excavated to the top of the frozen ground and insulation was placed on top of the permafrost. Since 1990, settlement has occurred beneath the west side of the road, and the surface has been filled several times (Fig. 69).

From this location, if you look across the street at the Two-Way Enterprises building (large blue Quonset) you will notice that it also has undergone considerable settlement. This is evident by the sagging roof top (Fig. 70).

From Fritz Theil Park on Franklin Avenue, turn right and walk down the road toward the Racquet Club.

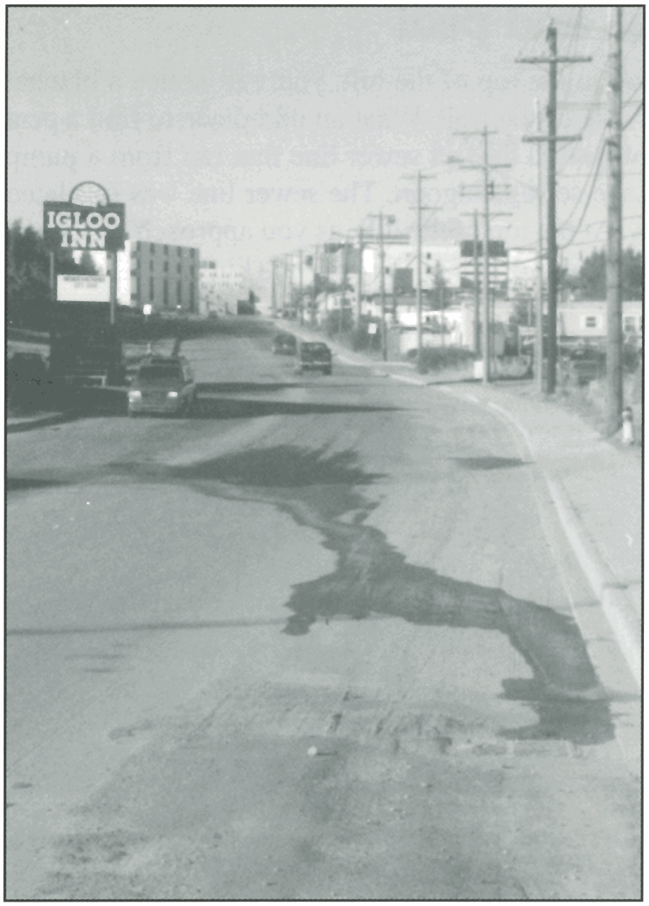


Figure 69. Stop 27 – View up Franklin Avenue. The road surface has been patched several times since 1990 in an attempt to "take out the bumps" (west is on the right). GSC 1998-006 II

Figure 70. The Two-Way Enterprises building across from Fritz-Theil Park has undergone differential settlement due to thawing of permafrost. GSC 1998-006 JJ

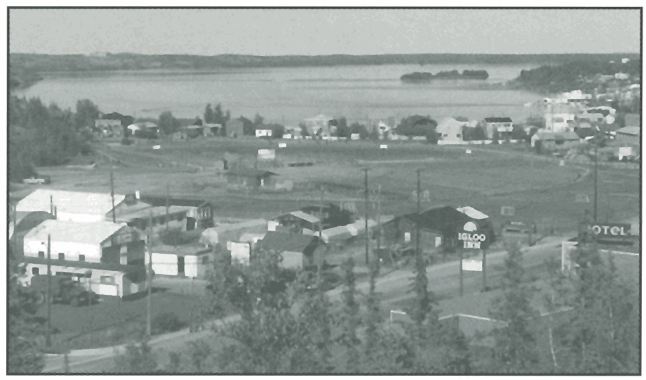


Figure 71. View across Back Bay with Fritz Theil Park (Stop 28) in centre. GSC 1998-006 KK

Stop 28. Fritz Theil Park – from dump to diamond

As you walk toward the Racquet Club, you will notice the two large baseball diamonds on the right. Originally this flat area was a large pond at about the same level as Great Slave Lake. From the mid 1930s to the 1950s the area was used as the main dump site for Old Town. Later, it was used as a trailer park until the site was cleared for the ball diamonds (Fig. 71).

Continue to the Racquet Club and walk around it to the path leading up the hill. Follow the path to the top, looking carefully along the right-hand side as you go.

Stop 29. Old sewage line – pipes and peat

As you walk up the gravel path behind the Racquet Club to the top of the hill, you will notice a blanket of peat and thick vegetation cover along the right-hand side of the trail. What an odd place to find a peat mound! No, its not natural. Buried beneath this layer of peat is the old sewer line that ran from a pump house at the bottom of Franklin Avenue to the Niven Lake sewage lagoon. The sewer line was insulated and protected by peat and seems to be well hidden today. At the top of the hill, as you approach the Niven Lake access road, some of the old pipes can still be seen sticking out of the ground (Fig. 72).

From the intersection of the trail and the access road, cross the road and proceed along the trail on the other side.

Figure 72. The old sewage line running to Niven Lake is still visible in a few places. GSC 1998-006 LL

Stop 30. Niven Lake – a subarctic oasis

For over 30 years, Niven Lake was the sewage lagoon for the City of Yellowknife (Fig. 73). It was closed in 1981 and has since become an attraction for over 50 species of waterbirds each spring - and for people all year round. As part of the Niven Lake Subdivision Plan, interpretive signposts have been set up around the lake to inform Yellowknife residents and tourists about this unique environment and its diverse habitat.

The permafrost field tour ends here. If you wish, you can proceed around Niven Lake from either the eastern or western route and enjoy the interpretive sites along the way. A path south of the wooden walkway nearest the highway will lead you behind the Explorer Hotel. From there you can return to the Visitors Centre.

Figure 73. Niven Lake, formerly a sewage lagoon and now a habitat for birds, beaver, muskrat and more! GSC 1998-006 MM

PART IV: THE NIVEN LAKE TRAIL

Jamie Bastedo

Introduction

Welcome to Niven Lake! It's time to enjoy a leisurely stroll along the Niven Lake Trail (Fig. 74). If you have arrived from Stop 30 of the City Tour then you are now between stops 1 and 2 of the trail. By following the trail to the right, you will encounter a peat plateau, see boreal forest vegetation, and step onto rocks more than 2.7 billion years old. If you are an avid bird-watcher, then you will certainly enjoy this area. You may catch a close-up look at some of the over 125 species of birds that make Yellowknife their home each summer. As you proceed around the Niven Lake Trail, you will encounter eight interpretive signposts. The material presented at each stop is reprinted in this guide for your convenience.

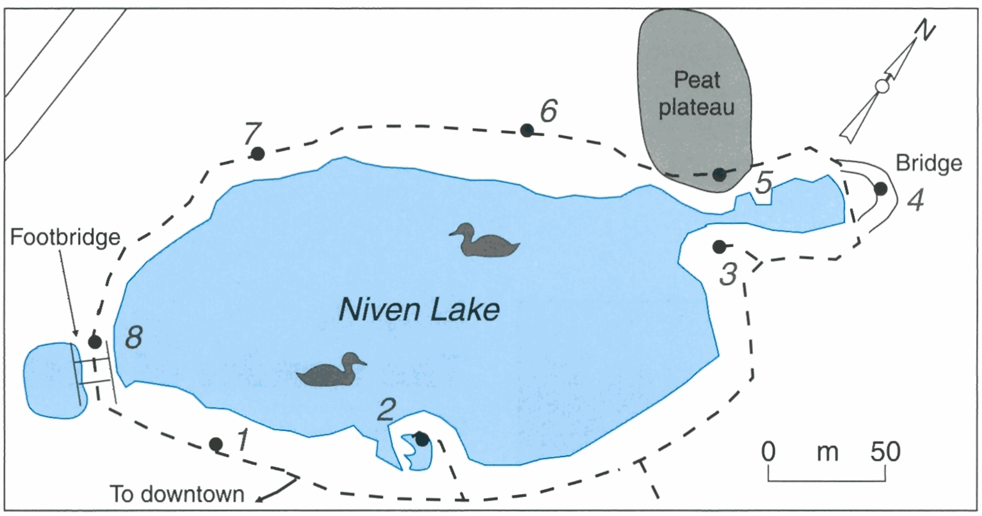


Figure 74. The Niven Lake Trail.

Stop 1. A biological magnet for waterbirds

Niven Lake's greatest claim to wildlife fame is its role as a staging area for migrating waterbirds in the spring. Because it is so shallow, this lake often thaws sooner than nearby bigger lakes. As well, its lush wetlands are a nursery for aquatic plants, insects, snails, and other foods attractive to travel-weary birds.

In May and June you may see hundreds of waterbirds at one time, including ducks, grebes, gulls, terns, and shorebirds. Some species, like the horned grebe, mallard, and green-winged teal stay all summer, finding good spots for nesting and hiding among the dense marsh plants. Others, like oldsquaw ducks and Canada geese, only stop here briefly to rest and feed before continuing on their way to Arctic nesting grounds far to the north.

Stop 2. The land of little sticks

Here, in Canada's northernmost forests, you can count the number of tree species on two hands – with a couple fingers to spare! Cool temperatures, a short growing season, frequent forest fires, and thin, acidic soils underlain by permafrost are among the many challenges faced by trees in this region (Fig. 75). The open, stunted forests around you are dominated by a few highly adaptable tree species such as black spruce, white spruce, paper birch, trembling aspen, and jack pine – the official territorial tree.

Permafrost is a major influence on tree growth in low soggy ground near the lakeshore. The shallow active layer above the permafrost offers little rooting support for trees. Trees growing in these ever-shifting soils are often tipped in random directions.

Figure 75. *Jack pine, birch, and spruce have adapted to the hardships of winter, permafrost, and poor soils. GSC 1998-006 NN*

Figure 76. *Cattails line the shores of Niven Lake. GSC 1998-006 OO*

Stop 3. The wonder of wetlands

Welcome to the wetland fringe of Niven Lake. This cattail marsh, like other wetlands, acts as a giant sponge, soaking up rain and snowmelt, then slowly releasing much needed water to drier habitats around it. Like kidneys, these plants act as filters that absorb or break down pollutants in the water and lake bottom.

The relatively warm, shallow waters of wetlands and their rich supply of decaying organic matter support the highest biological productivity of any northern ecosystem. For instance, in less than two months, the cattails before you can produce a dense stand of sturdy reeds 2 m high. Such luxuriant growth in turn supports complex aquatic food chains and offers essential food and cover for muskrats, beavers, ducks, and songbirds (Fig. 76).

Stop 4. Niven Lake – urban oasis for wildlife

Throughout the northern boreal forest, there are thousands of small shallow lakes like this one, most of them nameless. What makes Niven Lake special? One reason is the great variety of wildlife it supports so close to downtown. Also, this lake is enriched biologically because of its past role as a sewage lagoon.

Named after John McNiven, Yellowknife's first mayor, the lake received more than 30 years of sewage, which fertilized the entire ecosystem. Since its closure as a lagoon in 1981, the lake has returned to a remarkably natural state. It now attracts more than 50 species of waterbirds each spring. It is also a year-round home to many aquatic mammals including muskrat, beaver, and ermine.

Stop 5. Peat, beautiful peat

Still or gently flowing water in most wetlands holds little oxygen. Starved for oxygen, bacteria and other soil organisms have a tough time breaking down each year's crop of plants and other biological debris. When things pile up faster than they can be decomposed, the result is peat – cold, soggy, smelly, squishy peat – that marvelous mire underlying most wetlands.

You are standing on a large peat plateau. This flat expanse of peat rises more than 1 m above the lake (Fig. 77). Several metres below you are pollen and other well preserved bits of plants that lived here thousands of years ago. Beneath the surface are large, ancient lenses of ice that do not melt even during the hottest days of summer thanks to the insulating effect of so much peat – remnants of the last ice age perhaps![1]

To protect this insulating blanket of peat and the sensitive plants that grow on it, please avoid disturbing its surface by staying on the trail.

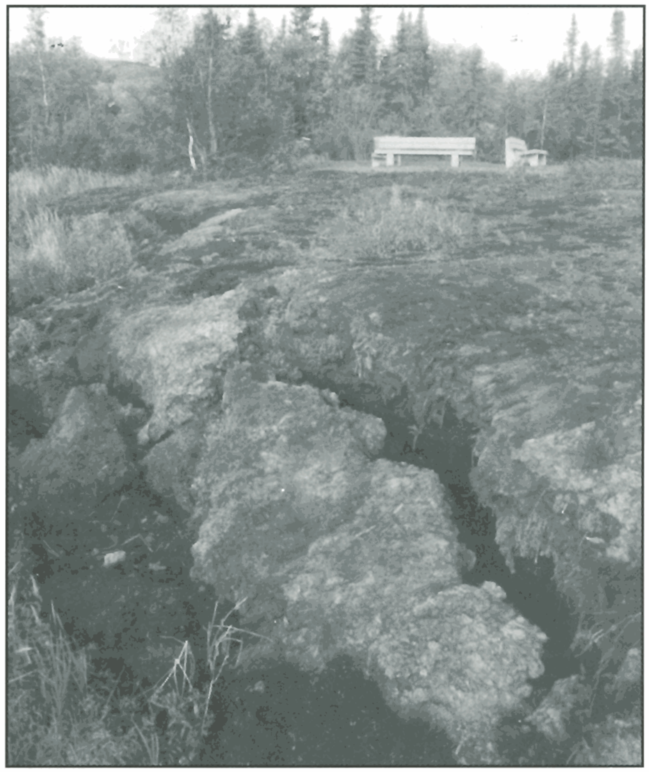


Figure 77. *The peat plateau is underlain by permafrost. The edges of the peat are slowly degrading to form thermokarst. GSC 1998-006 PP*

Stop 6. Honolulu north?

What do Honolulu and Yellowknife have in common? Not much weatherwise, but geologically they share a lot. The Hawaiian Islands rose out of a great sea and are dominated by one kind of rock: lava. Active volcanoes continue to make new land both above and below the sea. That is exactly what this region looked like when the rocks below your feet were formed about 2.7 billion years ago.

[1]The ice in the peat is not from the last glaciation, but could be up to 8000 years old.

Figure 78. Looking as though they have just cooled, these volcanic rocks are more than two billion years old. They have been grooved and polished by glaciers, giving them a fresh appearance. GSC 1998-006 QQ

These volcanic rocks, on which much of Yellowknife is built, testify to the earliest eruptions of lava that once engulfed this land. Now only slivers or "belts" of volcanic rock remain, testimony to the awesome power of billions of years of erosion (Fig. 78).

In summer, close inspection of such seemingly bare rock outcrops reveals a colourful array of lichens, wildflowers, and ground-hugging shrubs.

Stop 7. Home sweet home – all year round

About 125 species of birds make the Yellowknife area their summer home. Many warblers and terns come here from as far away as South America. As the leaves begin to fall and the lake freezes over, most birds migrate south to warmer climes. Only a handful of hardy species stays behind through the long subarctic winter.

The most obvious of our winter residents is the raven, known the world over for its cleverness. Besides scavenging caribou kills and garbage, the raven hides food for the winter throughout the forest. Its cousin, the gray jay, is another food hoarder. It uses saliva to stick berries, bugs, and meat to tree branches or under bark. This trick helps these birds survive the frigid winter and gives them a head start on nesting before most other species return in the spring.

Stop 8. Those mud-slinging, bug-poking shorebirds

Who-who-who-who-who. What was that ghostly noise way up above the lake? It's a passionate common snipe performing for his mate hiding in the grass. Tew-tew-tew. Who is that scolding from the top of a spruce tree? It's an alarmed lesser yellowlegs protecting his territory. There are over 15 species of shorebirds that add much character to the bird life of Niven Lake.

Shorebirds can be found searching for insects and worms along the muddy edges of the lake. Each species has different table manners depending on the size and shape of its beak. Some have long beaks to probe deeply into the mud while others with short stubby beaks peck for food near the surface. Curved beaks are good for swishing through mud and shallow water. *Bon appétit*!

GLOSSARY OF TERMS

Active layer. The top layer of the ground that is subjected to annual thawing and freezing in areas underlain by permafrost.

Allowable displacement. The maximum amount of movement permitted for a given type of structure.

Archean Eon. A division of geological time preceding about 2.5 billion years ago, during which the oldest rocks were formed.

Arctic air mass. A high pressure cell of very cold, dry and stable air, positioned over the Arctic region of North America.

Basalt. Fine-grained, dark-coloured igneous rock formed by rapid cooling of lava.

Bleeders. A system that allows a small amount of heated water to flow constantly through pipes in order to prevent freezing.

Canadian Shield. Shield-like outline of bedrock (also known as the Precambrian Shield) underlying nearly two-thirds of Canada, which formed during the Archean or Proterozoic eons. Most of the rock is granite or granitic gneiss with elongated belts of greenstone consisting of metamorphosed sedimentary and volcanic rocks.

Canol pipeline. During the Second World War, the Canol pipeline was constructed to carry oil from Norman Wells to Whitehorse, and on to Fairbanks, Alaska. The pipeline was about 1000 km long and some 25 000 people were involved in its construction.

Clay. Particles of soil less than 0.004 mm in size.

Condensor. The upper part (above ground) of a ***thermosyphon*** where cold CO_2 gas flowing from below the ground surface is cooled and condenses into a liquid (see ***evaporator***).

Continuous permafrost. Permafrost that occurs everywhere beneath the exposed land surface.

Craton(ic). That portion of a continent that is composed of very ancient crystalline rocks and that has remained tectonically stable for several hundred million years.

Discontinuous permafrost. Permafrost occurring in some areas beneath the exposed land surface. Discontinuous permafrost is widespread near its northern boundary, whereas it occurs in isolated patches or islands and is commonly referred to as “sporadic permafrost” near its southern boundary.

Ecozone. An area of the Earth’s surface, at the top of the ecological hierarchy, having similar biotic and nonbiotic characteristics including climate, vegetation, soil, geology, and physiographic features.

Erratic. A rock fragment or boulder that has been carried by glacial ice from its place of origin and deposited in an area with a different type of bedrock.

Evaporator. The underground part of a ***thermosyphon*** in which liquid CO_2 gas evaporates by extracting heat from the surrounding soil.

Excess ice. The volume of ice in the ground that exceeds the total volume that the ground would have under natural, unfrozen conditions.

Fen. A peat-covered or peat-filled wetland with a high water table that is usually at, or above, the surface. The water is mainly nutrient-rich. The dominant peat materials are shallow to deep, well to moderately decomposed fen peat. The vegetation consists of sedges, grasses, reeds, and brown mosses with some shrub cover and locally, scanty tree cover.

Frost heave. The upward or outward movement of the ground surface (or of objects on or in the ground) caused by the formation of ice in the soil.

Frost jacking. Progressive uplift of objects due to repeated cycles of frost heave.

Frost susceptible. Said of ground (soil or rock) in which segregated ice will form (causing frost heave) under the required conditions of moisture supply and temperature.

Geotechnical properties. Thermal and mechanical properties of soils that are relevant to engineering problems.

Geothermal gradient. The increase in temperature with depth below the maximum depth of annual variation. The gradual increase in temperature is due to the heat of the Earth's interior.

Glaciation. Alteration of the Earth's surface through erosion and deposition by glacial ice.

Glacial Lake McConnell. A large ***proglacial lake*** that joined the basins of Lake Athabasca, Great Slave Lake, and Great Bear Lake about 10 000 years ago. Its final demise is thought to have come 8700 years ago with a catastrophic flood that overtopped the Liard River Delta.

Granite. A coarse-grained, ***igneous***, intrusive rock.

Greenstones. Slightly metamorphosed igneous rocks that have been altered from their original structure by relatively low temperatures and pressures. They are commonly greenish in colour due to the presence of chlorite, hornblende, and epidote.

Grout. Cement-like material used to anchor piles to rock.

Holocene. The most recent epoch of geological time, covering approximately the last 10 000 years.

Hypsithermal (warm) Period. The period of pronounced warmth that marked the end of the ***Pleistocene Epoch***. Although it lasted from approximately 10 000 to 6000 years ago, the period of greatest warmth varied in different regions depending on latitude and the location of retreating glaciers.

Ice lens. A predominantly horizontal lens-shaped body of ice.

Ice-rich permafrost. Permafrost containing excess ice.

Igneous. Formed by solidification from a molten or partially molten state.

Interior Plain. The surface of the Interior Platform that forms the mainland of Canada between the Canadian Shield and the Cordillera.

Lacustrine. Pertaining to lakes.

Late Wisconsinan. The last stage of the Wisconsin Glaciation that started about 25 000 years ago and ended about 10 000 years ago (start of the ***Holocene***).

Laurentide Ice Sheet. The large ice sheet that formed during the last glacial stage (Wisconsinan) and covered most of Canada between the eastern margins of the Rockies, the Parry Channel in the Arctic, and the eastern seaboard of Nova Scotia. It attained its maximum dimensions about 18 000 years ago (Late Wisconsinan).

Marsh. A mineral or peat-filled wetland that is periodically inundated by standing or slowly moving waters. Surface water levels may fluctuate seasonally, with declining levels exposing downdrawn zones of matted vegetation or mud flats. The waters are nutrient rich and the substratum usually consists of mineral material, although some marshes are associated with peat deposits. Vegetation comprises grass and sedge sods, and emergent nonwoody plants such as rushes, reeds, and sedges may be found around the edges of the marsh. Submerged and floating aquatic plants are found in open-water areas.

Meltwater. Water flowing from a glacier as glacial ice melts. Large amounts of water flow in streams or sheets on the surface of warm glaciers and through tunnels or conduits within the ice. Meltwater flows away from the ice margins in rivers or, if the terminus is standing in water, into ice-dammed lakes or the sea.

Metamorphosed. Said of igneous or sedimentary rocks that were subjected to great changes in temperature, pressure, and/or chemical environment, and thus were transformed into metamorphic rocks.

Outwash. Sediments that are deposited by streams flowing away from melting glacial ice.

Peat. A dark brown mass of partially decomposed plant material formed under oxygen-poor conditions in a waterlogged environment.

Peatlands. Areas where peat thickness exceeds 40 cm. In northern wetlands, peatlands can cover vast areas of land and be tens of metres deep.

Peat bog. A peat-covered or peat-filled wetland, generally with a high water table that is at or near the surface. The bog surface is often raised, or is level with the surrounding wetlands, and is unaffected by the nutrient-rich groundwater from the surrounding mineral soil. The groundwater of a bog is therefore generally acidic and low in nutrients. Dominant peat materials are sphagnum and forest peat, which may be underlain by fen peat. Bogs may be forested or treeless and are usually covered with sphagnum moss, feathermosses, and ericaceous shrubs.

Peat plateau. A generally flat-topped expanse of peat, elevated above the general surface of a peatland, and containing segregated ice that may or may not extend downward into the underlying mineral soil.

Permafrost. Ground (soil or rock) that remains at or below 0°C for at least two winters and an intervening summer.

Piles. Posts made of wood or steel and driven into the ground to provide support for buildings.

Pleistocene Epoch. The earlier of the two time divisions in the Quaternary Period, formerly called the "Ice Age".

Precambrian. Period spanning from 4 billion to 590 million years ago. It comprises the Archean (4 billion to 2.5 billion years ago) and Proterozoic (2.5 billion to 590 million years ago) eons.

Proglacial lake. A lake in a basin in front of a glacier and often in direct contact with the ice.

Seasonal frost action. Geomorphological or weathering process dependent on the seasonal freezing of soil or rock.

Seasonal frost heave. The upward or outward movement of the ground surface that occurs in response to seasonal freezing of the ground

Sedimentary rocks. Rocks formed from the accumulation of sediments including fragments of other rock, precipitated salts, or organic material.

Sedge. A coarse grass-like plant that grows in wet areas and is a dominant component of sedge peat.

Silt. Soil particles with a diameter of 0.002 to 0.05 mm.

Slab-on-grade. Concrete slab formed on the ground to provide the foundation for a building.

Sphagnum. A type of moss that is the dominant component of sphagnum peat.

Slave Structural Province. A province of the Canadian Shield located north of Great Slave Lake. It is underlain mainly by granitic rocks, gneisses, and metamorphosed sedimentary rocks.

Sporadic permafrost. Permafrost occurring in isolated patches or islands near the southern boundary of ***discontinuous permafrost***.

Striations. Small scratches on bedrock usually less than 1 m in length, oriented parallel to the direction of ice movement. They are produced when rock debris in moving glacial ice scratches the underlying bedrock.

Subarctic. The region north of the boreal forest consisting of open-canopied conifer woodlands with tundra patches. The mean annual air temperature in this region ranges from -2°C to -10°C and the total annual precipitation averages 250 to 800 mm.

Sub-Boreal Period. A time of pronounced cooling that began 3500 years ago and that forced the treeline to retreat.

Taiga. A term generally used to refer to the northern part of the boreal forest that stretches across the entire circumpolar world and that is characterized by open lichen woodland and the "land of little sticks". Also referred to as the "tundra-boreal transition".

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

Thaw consolidation. Time-dependent compression resulting from thawing of frozen ground and subsequent drainage of pore water.

Thaw stable permafrost. Perennially frozen ground that will not experience either significant thaw settlement or loss of strength upon thawing.

Thaw settlement. Lowering of the ground surface and structures caused by the melting of ice within thaw unstable ground.

Thaw unstable permafrost. Perennially frozen ground that will experience either significant thaw settlement or loss of strength upon thawing.

Thermal conductivity. The ability of a material to transmit heat.

Thermokarst. Process by which troughs and depressions form as a result of thawing of ice-rich permafrost.

Thermosyphon. A passive heat transfer device installed to remove heat from the ground (see ***condensor*** and ***evaporator***).

Till. Unsorted and unstratified material carried and laid down by glacial ice.

Treeline. An imaginary line (or a line drawn on a map but not distinguishable on the ground) north of which trees, other than ground-hugging dwarf forms, are no longer found even in favoured, less exposed, sites.

Tundra. Vegetation zone of lichen, mosses, sedges, and dwarf trees in high latitudes.

Volcanic rocks. Rocks that formed by the extrusion of lava onto the Earth's surface.

Whaleback. A large, smooth, glacially sculptured bedrock knob that is shaped like the back of a whale.

Widespread permafrost. Permafrost occurring near the northern boundary of ***discontinuous permafrost***.

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