GUIDEBOOK 3

GUIDEBOOK TO PERMAFROST AND RELATED FEATURES OF THE NORTHERN YUKON TERRITORY AND MACKENZIE DELTA, CANADA

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CONTENTS

Page

CONTENTS (cont.)

FIGURES

CONTENTS (cont.)

Page

CONTENTS (cont.)

CONTENTS (cont.)

Page

CONTENTS (cont.)

TABLES

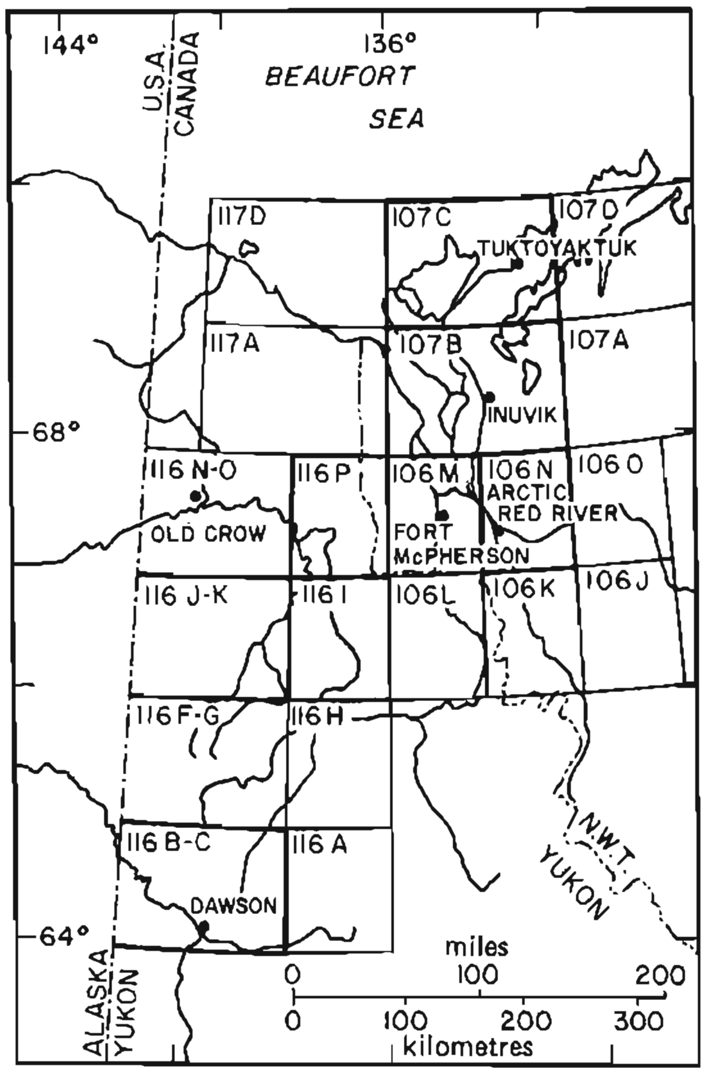
PREFACE

The primary objective of this guide is to illustrate permafrost conditions and associated geomorphic phenomena existing in the northern interior Yukon and Mackenzie Delta regions of northwestern Canada. Completion of the Dempster Highway makes it possible to undertake an integrated transect through this vast region, commencing in the Klondike district of the Yukon at latitude 64°N. and finishing at the shore of the Arctic Ocean at Tuktoyaktuk, N.W.T. (latitude 69°30'N.). The transect is of particular interest because it a) encompasses the zones of sporadic, discontinuous and continuous permafrost, b) traverses alpine, intermontane, and lowland area, c) includes both glaciated and unglaciated terrain, and d) passes from the northern boreal forest through both alpine timberline and northern tree line to arctic tundra.

Although prepared specifically for participants in Excursion B-3 of the Fourth International Conference on Permafrost, Fairbanks, Alaska, July 18-23, 1983, the volume is intended to be of use to anyone interested in the natural landscape of this part of arctic Canada. As far as possible, the guide has been written so that it will not become outdated too quickly. On the other hand, certain site descriptions will undoubtedly change in future years, and the variable pace of economic development, especially in the Mackenzie Delta, may affect the reliability of the latter sections of the guide in the future.

The guide and excursion were also prepared on behalf of the Commission on the Significance of Periglacial Phenomena of the International Geographical Union (Chairman, H.M. French). The basic aim of the Commission is to understand the nature, extent, and previous existence of periglacial conditions. Permafrost is central to such an aim. Viewed in this context, this guide, by demonstrating the nature of present-day permafrost conditions and landforms, may aid interpreting and reconstructing paleogeographic conditions of those temperate latitudes that experienced cold, nonglacial conditions during the Pleistocene.

A final objective relates to the increasing importance of northern regions, both in North America and elsewhere, in terms of man's quest for natural resources. Permafrost presents unusual and distinct geotechnical problems for virtually all aspects of economic development. Deliberately,



Index map to the 1:250,000-scale topographic maps along and adjacent to the excursion route.

therefore, the guide includes discussion of such topics as oil and gas exploration; road, bridge, and airport construction; townsite development; permafrost hydrology; placer mining; and environmental concerns. It can be demonstrated that successful economic development of permafrost regions can be accomplished only if the particularities of permafrost terrain are fully appreciated.

The organization of the guide follows in general outline the itinerary of the excursion. The first chapter presents a background summary of the climate, terrain, permafrost, vegetation, and Quaternary history of this part of northwestern Canada. The next chapter describes the permafrost conditions in the Klondike District of west-central Yukon, an area of great importance to the history of Canada---the site of the Klondike Gold Rush of 1896-98. The third and fourth chapters constitute an integrated road log of the 760-km-long Dempster Highway, which links the Klondike Highway with Inuvik, one of the largest Canadian settlements in the continuous permafrost zone. The surrounding Mackenzie Delta region are the subjects of the fifth chapter. The final chapter illustrates the permafrost conditions, geomorphic processes, and landforms in the Tuktoyaktuk area north of tree line on the arctic coast.

As editors of the guidebook, we are very conscious of the help which numerous individuals and organizations have provided. Although the major authors are listed at the beginning of each chapter, additional material has been supplied by J.C. Anderson (Inland Waters Directorate, Environment Canada, Ottawa), G.D. Hobson (Polar Continental Shelf Project, Energy, Mines and Resources, Ottawa), J.A. Hunter (Geological Survey of Canada, Ottawa), G.H. Johnston (Division of Building Research, National Research Council of Canada, Ottawa, and A.S. Judge (Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa). In places we have relied heavily on material prepared for previous conference excursions in the region, notably the 11th Congress of the International Society of Soil Sciences, held in Edmonton in June 1978, and the Third International Conference on Permafrost, held in Edmonton in July 1978. We are particularly grateful to the Geological Survey of Canada, which provided support for reconnaissance fieldwork in the summer of 1982 and cartographic, secretarial and other logistical support in Ottawa, through the Terrain Sciences Division.

Also, we ask the readers to bear with us regarding spelling of certain terms. The text was edited and typed by the Alaska Division of Geological and Geophysical Surveys to be consistent with the other guidebooks published for the Fourth Permafrost Conference; the camera-ready artwork was prepared by several Canadian agencies. Hence, you'll find variances in common (but not confusing) terms such as metre (meter), harbour (harbor), and so forth.

We are also pleased to acknowledge the logistical support given to the Excursion B-3 by the Scientific Resource Centre, DIAND, at Inuvik (Manager - D. Sherstone), and the Polar Continental Shelf Project station at Tuktoyaktuk (Director - G.D. Hobson). Much of the fieldwork expenses of the leaders are being met by grants from the Natural Sciences and Engineering Research Council of Canada. The participation of all government employees is being borne directly by the agencies concerned.

Finally, we would like to express our gratitude to the many, many people who assisted with the excursion, including guide and leaders, pilots, and all those who provided transportation, meals, accommodation, hospitality, and entertainment.

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REGIONAL SETTING - PHYSIOGRAPHY AND GEOLOGY

By
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The physiography and geology of Canada consists, at the macroscale, of a core of Precambrian crystalline rocks surrounded by a crescent of younger, mainly sedimentary rocks. The latter form many regions and subregions, the two most obvious being the Interior Plains, which are underlain by generally flat sedimentary rocks, and the Cordillera, an area of discontinuous fold mountains and plateaus (fig. 1). This guidebook includes parts of these regions as well as the Mackenzie Delta portion of the Arctic Coastal Plain.

The Interior Plains are underlain by flat Paleozoic, Mesozoic, and Tertiary strata. The terrain consists of a series of lowlands, hills, and plateaus that rise gradually southward from the Arctic coast, reaching elevations of 1,000 m in central Alberta.

The Cordillera can be divided into a) an eastern system, composed almost entirely of folded sedimentary strata (Richardson Mountains, Porcupine Plateau, and Mackenzie Mountains), b) an interior system, composed of folded sedimentary, metamorphic, and volcanic strata, together with some flat volcanic rocks (British Mountains, Ogilvie Mountains, Yukon Plateau, and Selwyn Mountains), and c) a western system, possessing plutonic rocks and containing Canada's highest mountains, the St. Elias Range, culminating in Mt. Logan (6,050 m). Several east-west trending belts of relatively low terrain (the Yukon and Porcupine Plateaus) separate the major mountain ranges.

The Arctic Coastal Plain is represented on the mainland of northwestern Canada by the Mackenzie Delta and the Yukon Coastal Plain. The former includes both the Holocene and Pleistocene deltas. The Holocene delta is remarkable for its intricate pattern of channels and lakes, whereas the Pleistocene delta possesses numerous pingos, many of which form outstanding features of the landscape. West of the Mackenzie Delta is the Yukon Coastal Plain, a gently sloping erosional surface cut in bedrock and mantled with a veneer of surficial sediments. The plain is characterized by lakes, lagoons, deltas, and alluvial fans formed by streams flowing from the nearby Richardson and British Mountains.

QUATERNARY GEOLOGY

A diverse Quaternary history characterizes the area of northwestern Canada treated in this guidebook. Parts of the area were glaciated by the northern Cordilleran ice sheet; other parts supported extensive montane glacial systems or were glaciated by the Laurentide ice sheet. Finally, large areas were never glaciated and, instead, display a wide range of Quaternary deposits and periglacial landforms.

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For convenience of description, the Yukon and adjacent parts of western District of Mackenzie can be divided into six regions (figs. 1 and 2): a) An area in southern and central Yukon, comprising the western slopes of Selwyn Mountains, all of Yukon Plateau, except for an elongate belt adjacent to the Alaska border, plus the Coast Mountains. This large area was subject to repeated advances of the Cordilleran ice sheet. b) An area comprising the northeastern slope of the St. Elias Mountains, the adjacent Shakwak Trench, and a small part of Yukon Plateau northeast of Shakwak Trench. The area was subject to repeated advances of montane glaciers originating in the St. Elias Mountains. c) The Wernecke Mountains and southern Ogilvie Ranges. These mountains were repeatedly affected by advances of montane glaciers that were independent of Cordilleran ice (although outlet glaciers of the latter may have spilled northward across the lowest passes in the Wernecke Mountains). d) The Mackenzie Mountains. Virtually all of the major valleys of Mackenzie Mountains were occupied repeatedly by glaciers that flowed eastward and northward, locally extending as piedmont glaciers beyond the mountain front. e) The Interior Plains and adjoining areas to the west, including the lower slopes of Mackenzie Mountains, Peel Plateau, Bonnet Plume Basin, the lower slopes of Richardson Mountains, and Yukon Coastal Plain. These areas lie within the maximum limit of Laurentide glaciation and, depending on location, were glaciated one or more times. f) Unglaciated western and northern Yukon, comprising part of Yukon Plateau, northern Ogilvie Mountains, the Porcupine Plain and Plateau region, Richardson Mountains, and the Arctic Ranges. This region is the eastern extremity of Beringia, a vast, generally unglaciated region extending westward through Alaska that is the largest unglaciated area in Canada.

The field-trip route begins in the unglaciated part of the Yukon Plateau, then follows the Dempster Highway northward through the glaciated southern Ogilvie Ranges and across the southern part of the unglaciated Porcupine Plain and Plateau region. It then crosses the mainly unglaciated Richardson Mountains. Finally, on the eastern flanks of the Richardson Mountains, the route enters the area of Laurentide glaciation.

Cordilleran Ice Sheet

Bostock (1966) inferred four advances of the Cordilleran ice sheet: Nansen (oldest), Klaza, Reid, and McConnell, each successive advance being less extensive than the previous advance. Few glacial features remain from the Nansen and Klaza advances, and detailed ground studies are required outside the area mapped by Bostock to define precisely the limits of those advances. Ice-marginal features marking the limits of the Reid advance are moderately well preserved and those of the McConnell advance very well preserved, permitting airphoto interpretation of their limits across much of the central Yukon (fig. 2; Hughes and others, 1969, Map 6-1968). Deposits of the respective glaciations are further distinguished by conspicuous differences in soil development (Hughes and others, 1972, p. 40-56; Foscolos and others, 1977). Soils developed at well-drained sites on pre-Reid drift are typically truncated Brunisols with relatively thick Bt horizons; soils on Reid drift are truncated Brunisols with relatively thick Bm horizons; and soils on McConnell drift are Brunisols with relatively thin Bm horizons.

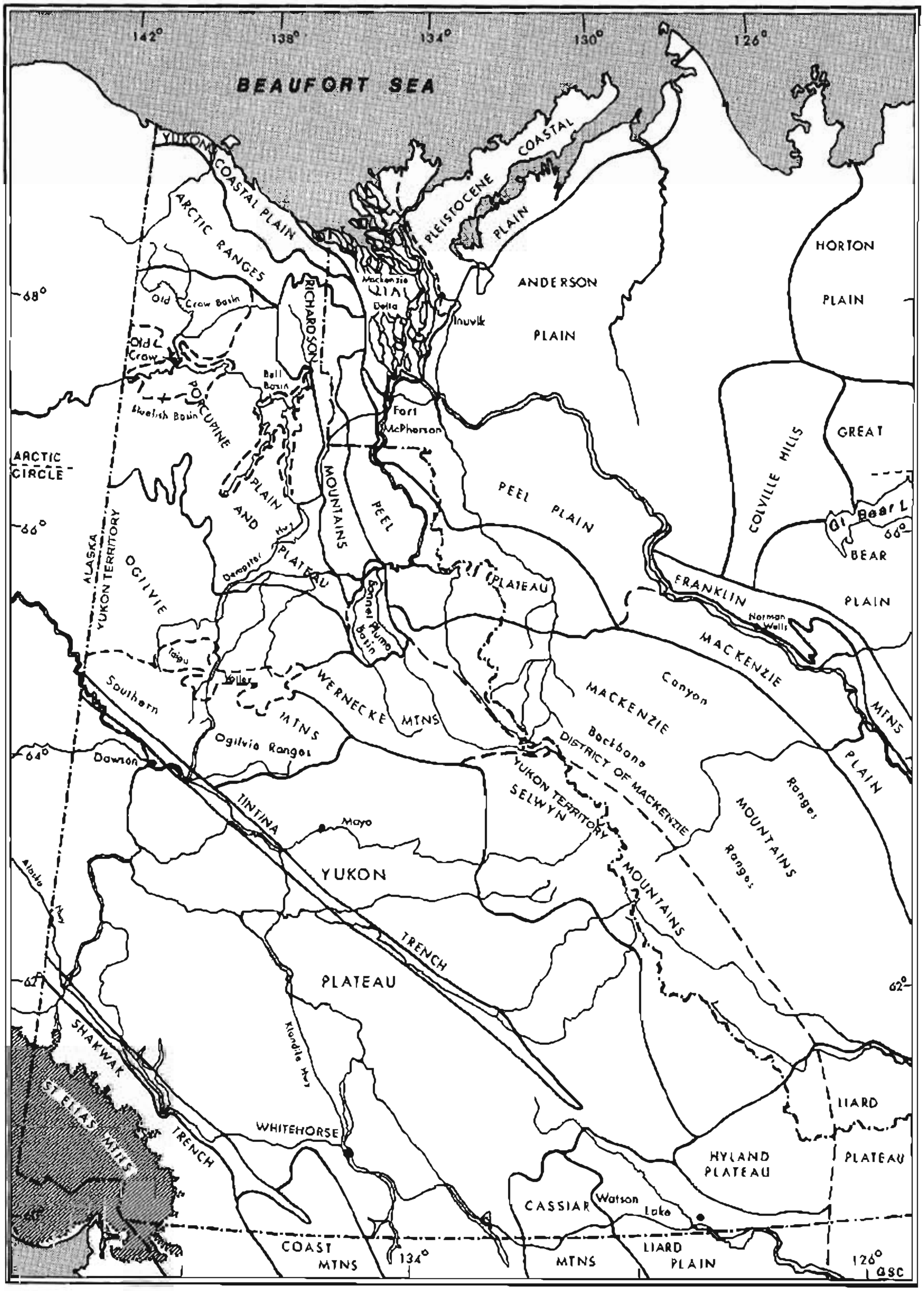

Figure 1. Physiography of Yukon and western District of Mackenzie, N.W.T. (after Bostock, 1948, 1961, 1970).

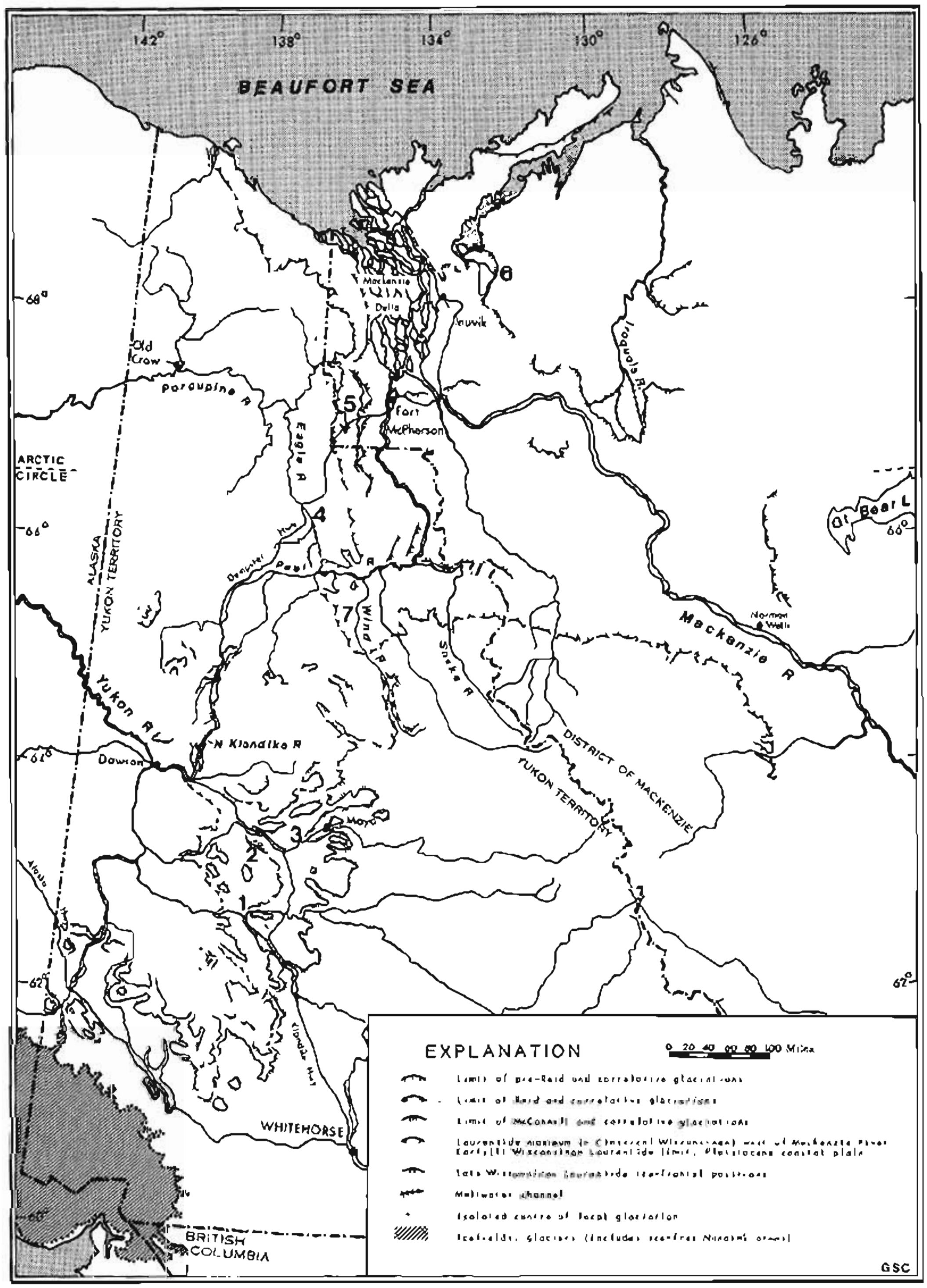

Figure 2. Glacial limits in Yukon and western District of Mackenzie, N.W.T. (after Bostock, 1966; Hughes and others, 1969, 1974; Hughes, 1972; Rampton, 1971, 1979; and Ricker, 1968). Numbered localities, referred to in text: 1) Fort Selkirk tephra locality, 2) type locality of Reid Glaciation, 3) type locality of McConnell Glaciation, 4) Eagle River discharge channel, 5) McDougall Pass, 6) Sitidgi Lake moraine, 7) type section of Hungry Creek till.

During successive advances of the Cordilleran ice sheet, ice moved generally westward and northwestward. The topography of the deeply dissected Yukon Plateau controlled local patterns of ice movement to produce highly irregular ice margins. Near the limits of successive glaciations, numerous peaks and plateaus were isolated as nunataks.

Montane glaciers of Southern Ogilvie Ranges. At least three glaciations, termed simply 'old,' 'intermediate,' and 'last' (Vernon and Hughes, 1966), have been distinguished in the Southern Ogilvie Ranges. During one or possibly more old glaciations, montane glaciers extended northward and southward from the axis of the ranges, reaching Taiga Valley in the north and Tintina Trench in the south. Montane glaciers had a similar pattern during the intermediate glaciation, but fell short of the early advance. The last glaciation was very restricted, with glaciers for the most part occupying tributary valleys and only locally extending into and along major north- or south-draining valleys.

In the Tintina Trench east of Dawson, the Flat Creek beds (McConnell, 1905) comprise lacustrine sediments, outwash gravel, and till 200 m or more thick. To the west of the trench, outwash gravel, the Klondike River gravels, or Klondike gravels of McConnell (1907, p. 1 and 29) lie on bedrock terraces along the lower reaches of the Klondike River. These gravels are thought to be the product of one or more old advances of montane glaciers in the Southern Ogilvie Ranges that extended to and across the trench.

Deposition of the old drift was followed by incision of the Klondike River and the lower reaches of tributaries, such as the North Klondike River, to near present levels, some 200 m below the surface of the early drift. Consequently, moraines and other terminal features of the next (intermediate) advance, which in North Klondike Valley reached the east margin of the Tintina Trench, are inset below the surface of the old drift. There, ice of the intermediate glaciation appears to have reached its maximum extent, then retreated upvalley. In the north-draining Blackstone Valley, two moraines of intermediate age (Ricker, 1968) suggest a halt or a readvance following retreat from the maximum position.

In terms of the degree of preservation of primary morphology, drift of the intermediate and last glaciations corresponds closely to Reid and McConnell drift of the Cordilleran ice sheet. Drift of the old glaciation(s) (Flat Creek beds) resembles pre-Reid drift of the Cordilleran ice sheet with respect to a lack of readily discernible glacial features and the development of Brunisolic soils with thick Bt horizons.

Correlation and chronology. Near Fort Selkirk at the confluence of Pelly and Yukon Rivers (fig. 2, loc. 1), a cemented till is overlain in upward succession by gravel and sand, silt (loess?) containing 20 cm of Fort Selkirk tephra, basaltic lapilli containing charred remains of tree trunks and, at the top, over 90 m of basalt of the Selkirk Group (Tempelman-Kluit, 1974, p. 54) in which as many as 10 cooling units are distinguishable. The tephra has yielded glass-fission-track ages of 0.84 ± 0.13 m.y. and 0.86 ± 0.18 m.y. and a zircon fission-track age of 0.94 ± 0.40 m.y. (Naeser and others, 1982). A sample of basalt from immediately above the lapilli yielded a K-Ar age of 1.08 ± 0.05 m.y. (M.L. Silberman, personal commun. to J.V. Matthews, 1981).

Bostock (1966, p. 6) considered the till to be referrable to the Nansen or a still older advance, and glacial striae on the upper surface of the basalt to be related to the Klaza advance. The age of about 1 m.y. by fission-track and K-Ar dating should be minimum for the Nansen advance and maximum for the Klaza advance.

Mosquito Gulch tephra, from a terrace of Bonanza Creek near Dawson, has a fission-track age of 1.22 m.y. (Naeser and others, 1982). The terrace was formed after the Klondike River and tributaries such as Bonanza Creek began to incise through the Klondike gravels; hence the date is minimum for the old glaciation(s) of Southern Ogilvie Ranges. The dates from Fort Selkirk and that of the Mosquito Gulch tephra indicate at least comparable antiquity for the Nansen advance of the Cordilleran ice sheet and the old glaciation(s) of the Southern Ogilvie Ranges.

There are no dates directly relevant to the end of the Klaza advance or to the beginning of the Reid advance. Organic silt on the valley floor of Hunker Creek, a tributary of Klondike River upstream from Bonanza Creek, has been radiocarbon dated as greater than 53,900 yr B.P. (GSC-527, GSC VIII). Because of poor counting characteristics, the fission-track age of Dawson tephra from within the organic silt could be stated only as probably younger than 120,000 yr B.P. (Naeser and others, 1982). These ages are minima for the incision of the Klondike drainage system, which preceded the intermediate glaciation of Southern Ogilvie Ranges. Incision may have been much earlier.

The Cordilleran ice sheet began retreating from the Reid limit (fig. 2, loc. 2) more than 42,900 yr ago (GSC-524, GSC VII). This age is from wood in the Steward tephra near the base of organic silt lying above Reid drift (Hughes and others, 1969). Wood from beneath till of McConnell age (fig. 2, loc. 3), dated as greater than 46,580 yr old, is probably also of post-Reid age (Hughes and others, 1969, p. 6-7).

Laurentide Glaciation

The maximum extent of Laurentide ice can be traced by the presence of discontinuous moraines, ice-marginal channels, and erratics of Shield origin. The limit lies at 1,525 m against the Canyon Ranges of the Mackenzie Mountains near Keele River. It then descends along the Mackenzie Mountains and, near the south end of the Eagle River discharge channel (fig. 2, loc. 4), lies at slightly above 380 m. The limit is at about 975 m at the south end of Richardson Mountains and declines to sea level west of Herschel Island.

Around the periphery of the Bonnet Plume Basin, moraines, meltwater channels, and associated features appear fresher than along the east flank of the Richardson Mountains, where few features are preserved. Meltwater channels and glaciofluvial deposits are moderately well preserved along the inner margin of the Yukon Coastal Plain, but moraines are subdued or lacking. Differences in topographic setting and drift texture, together with regional variations in weathering intensity, may be the cause. Hughes and others (1981) suggested that the Laurentide maximum represents a single advance; the possibility that different parts of the limit are of different ages, however, cannot be totally dismissed.

Within the maximum Laurentide limit, moraines and other ice-marginal features mark subsequent readvances of the ice. For example, a major ice-marginal channel occurs on the Peel Plateau to the east of McDougall Pass (fig. 2, loc. 5). The channel is partly incised into bedrock and partly impounded by moraine. Several streams that cross the plateau are diverted northward for short distances along the channel, which is conspicuous where it is crossed by the Dempster Highway.

A morainal system traceable along the western margin and across the southern part of the Anderson Plain records a readvance of Laurentide ice in the Mackenzie Valley after all the Anderson Plain and probably also the Horton Plain had become ice free. A second moraine around the east and north sides of Sitidgi Lake (fig. 2, loc. 6) and a lobate form in the upper Anderson River may be correlative features. However, the major meltwater channel on the Peel Plateau is too high to be correlated with the moraine on the western margin of the Anderson Plain. At the same time, there is no continuous ice-marginal feature at a lower elevation. A moraine belt that extends eastward from Fort McPherson may mark the limit of a later readvance, whereas a moraine system east of Norman Wells probably marks the limit of the last readvance of Laurentide ice in the Mackenzie Valley.

The Hungry Creek till is the only till recognized in the Bonnet Plume Basin. It was deposited during the Hungry Creek Glaciation, when Laurentide ice advanced to its maximum in the interior northern Yukon. At this time, drainage from the Mackenzie and Wernecke Mountains, together with the Peel River, was diverted northward across a low divide into the Eagle River. A wide, canyonlike channel was incised down to an elevation of about 360 m. The field-trip route crosses the northern end of this channel at the Eagle River crossing.

The type section for Hungry Creek till is near the confluence of Hungry Creek and Wind River (fig. 2, loc. 7) (Hughes and others, 1981, table 1). The lowest unit comprises dark-gray gravel with lenses of organic silt. Pollen, plant megafossils, and fossil arthropods indicate relatively cold tundra conditions. Glaciolacustrine sediments, which include dropstones, lie above and indicate the proximity of an advancing Laurentide ice sheet that impounded a glacial lake in the Bonnet Plume Basin but did not override it. These deposits grade into mainly fluvial sediments.

A date of 36,900 ± 300 yr B.P. (GSC-2422) is maximum for the Hungry Creek Glaciation (Hughes and others, 1981). However, the maximum advance, which diverted the Peel River, also reversed drainage of the Porcupine River and initiated glacial lakes in the Bell, Bluefish, and Old Crow Basins. These lakes drained westward into the Yukon River. The glacial lake stage began about 30,000 yr ago (Hughes and others, 1981, p. 359). Laurentide ice had retreated from its maximum by 16,000 yr ago (Hughes and others, 1981, p. 358). According to Rampton (personal commun., 1982), a date of 12,900 ± 150 yr B.P. (GSC-1784-2) for grass and/or sedge in outwash beyond the Sitidgi Lake moraine (fig. 2, loc. 6) establishes the timing of the readvance to the moraine or closely postdates it. The only date relevant to the possibly correlative readvance marked by moraines on the west margin of Anderson Plain is for spruce wood from outwash associated with the moraines. One date (greater than 42,000 yr B.P.; GSC-2765) suggests that the wood was reworked from older deposits. Minimum dates for final deglaciation on the Peel Plateau and Mackenzie Plain include 11,800 ± 170 yr B.P. (GSC-2745) from Snake River east of the Bonnet Plume Basin and 11,530 ± 170 yr B.P. (I-3734) from near Fort Good Hope (Mackay and Matthews, 1973).

The assignment of an age of about 30,000 yr B.P. to the maximum Laurentide advance against the northern Richardson Mountains conflicts with several older dates from sites in the Pleistocene Mackenzie Delta that must have been overridden by that extensive advance (Hughes and others, 1981, p. 359). Rampton (1979) assigned an early(?) Wisconsin age to the same limit. Although a farther glacial limit cuts diagonally across the Tuktoyaktuk Peninsula (fig. 2) (Rampton, 1979), there is no evident limit to the south that might define the extent of a glaciation comparable in age to the Hungry Creek Glaciation. Convincing correlation between the Bonnet Plume Basin and the Mackenzie Delta region obviously requires considerable new data.

CLIMATE AND PERMAFROST

Quaternary Climate

The oldest climatic evidence from the Yukon consists of ice-wedge pseudomorphs found in the upper part of the White Channel gravels of Bonanza Creek near Dawson. These gravels interfinger with Klondike gravels and hence are correlative with the old glaciation(s) of the Southern Ogilvie Ranges (Hughes and others, 1972). The development of ice wedges implies a climate colder than the present mean annual temperature of about -4°C. According to Mackay (1974), ice-wedge cracking is infrequent at Inuvik (mean annual temperature -9.6°C) but common at Garry Island, N.W.T., where the mean annual temperature is -11.2°C. Thus the ice-wedge pseudomorphs imply temperatures 5.6°C to 7°C or more colder than at present during the old glaciation(s) (that is, Nansen and Klaza, undivided, of the Cordilleran ice-sheet chronology) of the Southern Ogilvie Ranges. Because Nansen and Klaza drifts have not been differentiated at localities where soils have been studied, climates of the Nansen-Klaza and Klaza-Reid nonglacial intervals, as inferred from soils, cannot be differentiated. Luvisolic soils on pre-Reid drift indicate a warm, subhumid climate, however, followed by a more moderate humid climate during one or both of the intervals (Foscolos and others, 1977; Rutter and others, 1978).

In areas of pre-Reid drift, further study is required to differentiate periglacial features (sand wedges, ice-wedge pseudomorphs, cryoturbation) referrable to the McConnell Glaciation. Sand wedges appear restricted to pre-Reid drift, however, indicating a prolonged interval with extremely cold and arid conditions.

Brunisols developed on Reid drift indicate a cool, subhumid climate during the Reid-McConnell nonglacial interval. Boreal forest conditions prevailed earlier than 42,900 yr ago, but by 37,700 yr ago conditions were colder than present (Denton and Stuiver, 1967, fig. 7; Schweger and Janssens, 1980).

Brunisols on Reid drift are penetrated by relatively narrow sand wedges, ice-wedge pseudomorphs, and composite features gradational between the two.

These features indicate cold conditions during the McConnell Glaciation, as do abundant ventifacts found at the contact between loess of McConnell age and the tops of paleosols developed on Reid and pre-Reid drift.

Paleoclimatic data are lacking for pre-Wisconsin time in the region affected by Laurentide ice. Late Wisconsin climate has been summarized by Heginbottom (1978, p. 28):

> Sketchy paleoecological data indicate that the climate was very cold and probably dry during the late Wisconsin. The climate approached conditions similar to today's around 11,500 B.P. but was significantly warmer by 8,000 B.P. Because of this warming, the active layer thickened, ground ice melted, and the development of thermokarst basins reached a maximum between 10,000 and 9,000 B.P. and the expansion of thermokarst basins slowed. Today, many of these basins are being drained and permafrost is being reestablished.

Present Climate

Detailed annual meteorological data for six stations in northwestern Canada are given in table 1 and the regional distribution of temperature and precipitation are presented in figure 3.

In summary, the climate of Yukon Territory and the western part of the District of Mackenzie is continental, with long, very cold winters and short summers. In the north, summers are cooler and shorter than in the south, but winter temperatures do not vary significantly. The interior Yukon and the Mackenzie Valley have exceptionally warm summers in contrast to comparable latitudes elsewhere in Canada. Most of the area is forested and falls within the humid microthermal (Dfc) of the Koppen System, with a tundra climate (ET) occurring beyond the regional tree line, in the interior, and along the Beaufort Sea coastal area.

Within the forested area, there are significant changes in climatic parameters, as can be seen in a comparison of ecological regions (table 2). In general, the northern boreal region has mean annual temperatures warmer than -5°C, with the subarctic regions between -5°C and -10°C and the low arctic regions below -10°C. Mean July temperature ranges exceed 15°C in the boreal and southern subarctic regions, dropping to around 10°C beyond the regional tree line (fig. 3). Accumulated heat units (degree-days) greater than 5°C exceed 900 in the boreal regions but drop to 250 at Tuktoyaktuk in the low arctic region, with subarctic regions having between 500 and 850 degree-days.

Moisture is quite variable although generally low, ranging from 200 to 350 mm mean annual precipitation in the forested areas to about 130 mm in the low arctic tundra (fig. 3). Of the total, between 40 and 45 percent falls as rain during the summer. There are more than 200 days with a snow cover.

On the Yukon Plateau, the cold air of winter dissipates fairly quickly, with mean May temperatures above 5°C (Kendrew and Kerr, 1955). Mean temperatures for June, July, and August are all above 10°C with mean maxima

Table 1. Meteorological data for six selected stations in northwestern Canada (Burns, 1973).

Station		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Dawson City	Temperature (°C)													
	Mean	-28.6	-23.0	-14.1	- 1.8	7.8	13.9	15.5	12.7	6.4	- 3.2	-16.5	-25.3	- 4.7
	Maximum	-24.9	-17.9	- 7.1	5.2	14.7	21.0	22.2	19.0	11.7	0.2	-13.3	-21.8	0.7
elevation 324 m	Minimum	-32.7	-27.6	-21.1	- 8.8	0.9	6.7	8.8	6.3	1.2	- 6.8	-19.8	-28.9	- 10.1
	Precipitation													
	Total (mm)	19	16	13	9	22	37	53	51	28	27	26	27	328
	Snow (cm)	19	16	13	7	2	-	-	1	2	20	26	27	132
Mayo A	Temperature (°C)													
	Mean	-26.7	-19.6	-11.3	- 0.8	7.7	13.3	14.7	12.1	6.4	- 2.1	-15.7	-23.3	- 3.8
	Maximum	-21.5	-13.4	- 3.9	5.7	14.4	20.6	21.9	16.8	12.3	2.3	-11.3	-18.3	2.3
elevation 495 m	Minimum	-31.9	-25.8	-18.9	- 7.4	0.9	6.1	7.6	5.1	0.6	- 6.6	-20.2	-28.3	- 9.9
	Precipitation													
	Total (mm)	22	15	10	8	19	32	44	42	29	25	25	23	294
	Snow (cm)	22	15	10	7	2	-	-	-	2	18	25	23	123
Old Crow	Temperature (°C)													
	Mean	-31.7	-30.0	-23.3	-11.7	- 1.1	10.6	14.4	8.9	2.2	- 8.3	-21.7	-30.6	- 10.0
	Maximum	-27.8	-25.6	-17.8	- 5.6	3.9	17.2	21.1	15.0	6.7	- 3.9	-17.8	-26.7	- 5.0
elevation 244 m	Minimum	-36.1	-34.4	-28.3	-18.3	- 6.7	3.3	8.3	3.3	- 2.8	-12.8	-26.1	-33.9	- 15.6
	Precipitation													
	Total (mm)	8	5	8	10	13	25	33	38	20	20	13	10	203
	Snow (cm)	8	5	8	10	5	T	T	T	3	20	13	10	81
Fort Good Hope	Temperature (°C)													
	Mean	-31.0	-28.8	-20.5	- 9.4	3.8	13.2	15.9	12.7	5.1	- 5.4	-20.2	-27.3	- 7.7
	Maximum	-26.9	-24.3	-14.4	- 2.6	9.8	19.6	22.3	18.9	10.2	- 1.6	-16.4	-23.2	- 2.4
elevation 53 m	Minimum	-34.9	-33.1	-26.6	-16.2	- 2.2	6.7	9.6	6.4	0.0	- 9.2	-24.1	-31.3	- 12.9
	Precipitation													
	Total (mm)	16	11	11	11	14	33	41	48	32	26	22	19	284
	Snow (cm)	16	11	11	9	7	0.5	0	T	6	23	22	19	124
Inuvik	Temperature (°C)													
	Mean	-29.0	-29.2	-23.6	-14.4	- 0.8	9.7	13.2	10.2	2.7	- 7.2	-20.4	-26.8	- 9.6
	Maximum	-24.1	-23.9	-17.7	- 7.9	3.9	16.0	19.2	15.5	6.8	- 3.8	-16.5	-22.1	- 4.6
elevation 60 m	Minimum	-34.5	-35.0	-30.0	-21.2	- 5.7	3.7	7.4	5.0	- 1.3	-10.7	-24.7	-32.1	- 14.9
	Precipitation													
	Total (mm)	20	10	17	14	18	13	34	46	21	34	15	19	260
	Snow (cm)	22	12	18	15	14	2	T	4	11	35	19	22	174
Tuktoyaktuk	Temperature (°C)													
	Mean	-27.2	-29.2	-24.9	-16.9	- 4.6	- 4.7	10.3	8.7	2.3	- 6.9	-19.3	-25.2	- 10.7
	Maximum	-23.6	-25.6	-21.5	-12.7	- 1.1	9.1	14.9	12.2	4.6	- 4.5	-16.2	-21.8	- 7.2
elevation 18 m	Minimum	-30.8	-32.7	-28.2	-21.1	- 8.2	0.2	5.8	5.2	0.0	- 9.4	-22.4	-28.5	- 14.2
	Precipitation													
	Total (mm)	5	5	4	5	7	13	22	29	14	13	5	8	130
	Snow (cm)	5	5	4	5	4	3	T	0.5	4	12	5	8	56

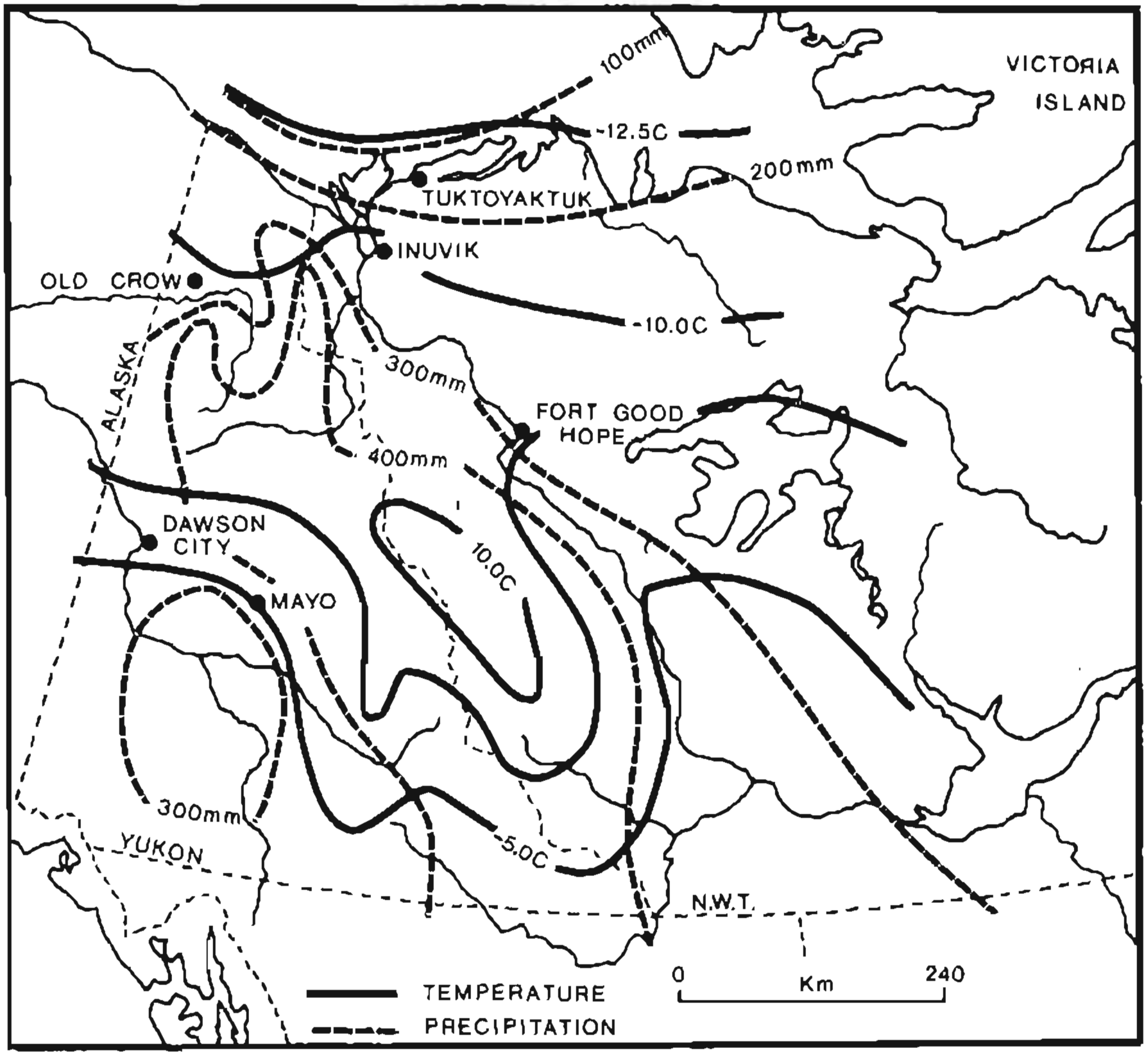

Figure 3. Distribution of mean annual air temperature and precipitation in northwestern Canada (Burns, 1973).

for June and July greater than 20°C and extreme maxima up to 35°C. By October, the mean temperature is again below 0°C. Temperature variation is quite extreme and frost may occur in any month. Temperature inversions are common in the winter, with the cold air tending to collect and be trapped by the surrounding mountains. The coldest recorded temperatures in Canada are from the Yukon Plateau (-63°C, at Snag, Y.T., February 3, 1947).

The Inuvik area has a continental climate but does not have the temperature extremes typical of inland sites (cf. Fort Good Hope). Whereas the three summer months have mean temperatures near or above 10°C, the total heat accumulation is low and frost can occur in all months (Burns, 1973). The extreme maximum and minimum temperatures recorded at Inuvik are 31°C and -57°C, respectively.

Tuktoyaktuk on the coast has a more maritime climate, with slightly warmer winters and cooler summers. Although 80 km beyond the tree line, the mean July temperature there is about 10°C. The temperature extremes recorded at Tuktoyaktuk are 28°C and -50°C. Precipitation in the north is low.

Table 2. Climatic summary for six selected stations in northwestern Canada (Burns, 1973).

Physiographic region	Cordilleran			Interior Plains		
	Dawson City	Mayo	Old Crow	Fort Good Hope	Inuvik	Tuktoyaktuk
Ecological region	Northern boreal	Boreal - subalpine	Northern subarctic	Southern subarctic	Northern subarctic	Low arctic
Elevation (m)	325	495	245	53	60	18
Mean temperatures (°C):						
. Annual	- 4.7	- 3.8	-10.0	- 7.7	- 9.6	-10.7
. January	-28.6	-26.7	-31.7	-31.0	-29.0	-27.2
. July	15.5	14.7	14.4	15.9	13.2	10.3
Average frost-free period (1941-70), days	92	66	<30	66	45	55
Degree-days over 5°C	910	850	540	850	530	250
Average precipitation:						
. Annual (mm)	328	294	203	284	260	130
. June-August (mm)	141	118	96	122	93	64
. Snowfall (cm)	132	123	81	124	174	56

Nature and Extent of Permafrost

A broad relationship exists between permafrost and climate in Canada (Brown, 1978; fig. 4; table 3). In northwestern Canada the relationship is complicated by the Cordillera and the variability of mountain and intermontane climatic conditions.

The permafrost regions of northwestern Canada are divided into two broad zones: a) continuous in the north and b) discontinuous in the south. In the continuous zone, permafrost exists everywhere beneath the land surface and varies in thickness from about 100 m at the southern limit to over 350 m in the Mackenzie Delta. The active layer---the zone near the surface subject to seasonal thaw---usually extends down to the permafrost. Most of the central Yukon lies in the discontinuous zone. There, some areas have permafrost beneath the land surface and other areas are free of permafrost. The distribution ranges from widespread in the northern Yukon, where permafrost areas predominate, to scattered in the southern Yukon, where permafrost occurs in 'islands' in generally unfrozen terrain. It varies in thickness from a few meters or so at the southern limit to about 100 m at the boundary with the continuous zone. Where relict (that is, Pleistocene) permafrost is present, suprapermafrost taliks may exist.

Permafrost in the Cordillera of western Canada comprises a continuous zone at higher elevations and, below that, a discontinuous zone extending down to the lower altitudinal limit of permafrost. At the northern limit of the Cordilleran alpine permafrost in the central Yukon, permafrost occurs in valley bottoms and at elevations of less than 1,200 m. North of the continuous-permafrost boundary, the distinction between continuous and alpine permafrost assumes little significance.

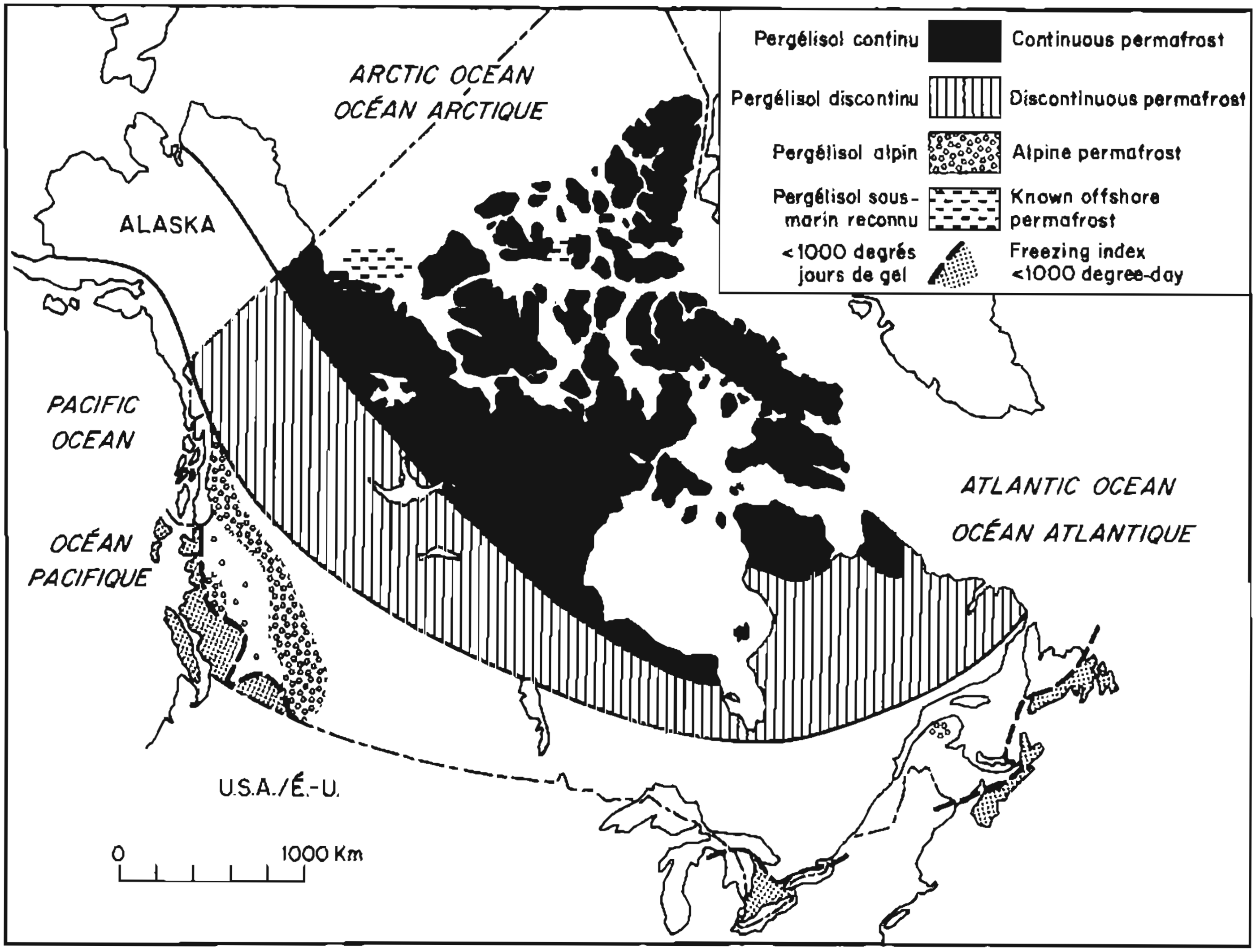

Figure 4. Distribution of permafrost in Canada (Brown, 1978).

In general, the overall distribution of permafrost is related to air temperature. The temperature of permafrost is between 1 and 5.5°C (average 3.3°C) warmer than the average annual air temperature at a given locality (table 3). However, relict permafrost complicates the pattern. Permafrost temperatures range from -8°C to -9°C in the Pleistocene Mackenzie Delta to -1°C to -2°C in the Dawson City area of the Yukon. The boundary between the continuous and discontinuous permafrost zones corresponds to a mean annual air temperature of -8.3°C (Brown, 1978) and the southern limit of permafrost to about -1°C. The lower altitudinal limit of Cordilleran permafrost coincides approximately with the -1°C average annual air isotherm.

Because the nature and controls over permafrost distribution are central to the following chapters, a more detailed outline of permafrost conditions is not presented here.

Table 3. Representative thicknesses and permafrost temperatures in the Yukon and Northwest Territories (Brown, 1978; Taylor and Judge, 1974).

Locality	Thickness of permafrost (m)	Ground temperature (°C)	Mean annual air temperature (°C)
YUKON TERRITORY			
Dawson City	20	- 2.0	- 4.7
Eagle River bridge, Dempster Highway	90	- 2.5	unknown
United Keno Hill Mines Ltd.	135	- 1.5	- 4.0 (Elsa)
NORTHWEST TERRITORIES			
Fort Simpson	0-15	unk.	- 3.8
Yellowknife	60	- 2.0	- 5.5
Norman Wells	45-76	- 2.5	- 6.5
Inuvik	360	- 4.0	- 9.7
Rankin Inlet	350	- 7.0	-11.6 (Chesterfield Inlet)
Storkerson Bay A-15 wellsite, Banks Island	430	-12.0	-13.7 (Sachs Harbour)
Resolute Bay	400-600	-13.0	-16.4

PERMAFROST HYDROLOGY

According to van Everdingen (1976), permafrost (ground with a temperature perennially below 0°C) may contain neither ice nor water (dry permafrost); it may contain water exclusively, if the freezing point of the water is depressed sufficiently by mineralization (wet or nonfrozen permafrost); it may contain both water and ice (partially frozen permafrost); or it may only contain ice (permafrost and ice-rich permafrost). The hydraulic conductivity in partially frozen, frozen, and ice-rich permafrost is normally one or more orders of magnitude lower than in dry and nonfrozen permafrost.

Hydrology

The presence of permafrost and of a seasonally frozen active layer usually restricts infiltration of water and its recharge to ground-water systems. Hence, a very high percentage of rainfall and snowmelt tends to contribute to surface runoff. This condition in turn leads to extreme differences between seasonal maximum and minimum streamflow rates in areas with permafrost. The occurrence of ground water in permafrost regions is summarized in figure 5.

Winter baseflow in rivers (sustained exclusively by discharge of ground water in basins without significant lake storage) generally ranges from 1 to 5 $l/s\text{-}km^2$ in the zone of discontinuous permafrost. It approaches zero with increasing latitude, because a rapidly increasing percentage of the discharge is stored as icings. These icings provide seasonal redistribution of surface-water resources; melting of seasonal icings produces additional runoff during spring and summer at rates that may be from 1.5 to 4 times higher than the rates of ground-water discharge that contributed to the formation of the icings.

Recharge and discharge of ground water are concentrated in smaller areas and at fewer points where more highly permeable conditions (for example, in coarse-grained unconsolidated deposits, fractured bedrock, or karst) allow concentrated flow of water to maintain unfrozen conditions. As a result, high-rate inflow into sinkholes (greater than 1 m^3/s) and high-rate discharge from springs (greater than 10 m^3/s) occur in permafrost areas.

Ground-water movement in permafrost areas is limited to unfrozen zones or taliks, including:

a) Suprapermafrost aquifers in the active layer (seasonal, water temperature above 0°C) and in closed taliks below river and lake beds (may be perennial, water temperature above 0°C).

b) Intrapermafrost aquifers in lateral and open (hydrothermal and sometimes hydrochemical) taliks in or through permafrost (perennial, water temperature usually above 0°C, but sometimes below 0°C).

c) Subpermafrost aquifers below the permafrost (perennial, water temperature above 0°C).

Hydrochemistry

The chemistry of ground water is affected more by the low temperatures generally prevailing in permafrost regions than by the presence of permafrost. Lower temperatures lead to lower dissolution rates; this effect may be canceled out, however, by slower movement and longer residence times of ground water. The solubilities of carbonate minerals (calcite and dolomite) increase at low temperatures because of increased solubility of carbon dioxide.

River-water chemistry often shows extreme seasonal variations because of the great differences between seasonal maximum and minimum flow rates in individual rivers in permafrost regions. Dissolved-solids concentrations, which may be as low as 25 mg/l during high-rate snowmelt runoff, rise during the summer due to increasing contributions from active-layer aquifers. These concentrations may reach values over 500 mg/l in the same rivers during the winter, when most or all of the limited runoff is supplied by discharge of more mineralized water from intrapermafrost or subpermafrost aquifers.

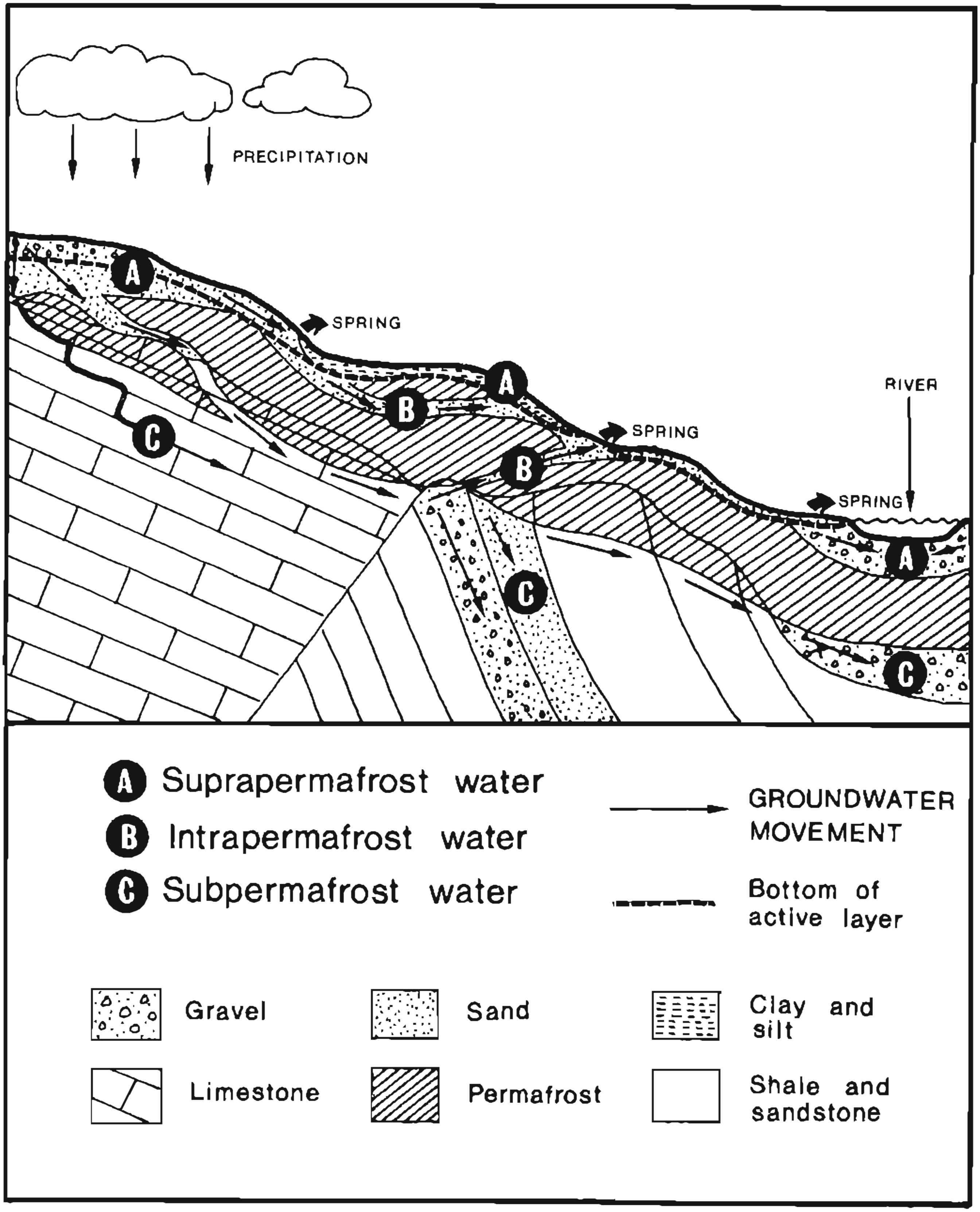

Figure 5. Occurrence of ground water in permafrost areas.

Variations in dissolved-solids concentration are usually accompanied by significant changes in ionic composition of the river water (which reflects the different ionic composition of snowmelt and rainfall), of active-layer discharge, and of waters from intrapermafrost or subpermafrost sources.

Related Phenomena

Discontinuities in permafrost that are either induced or maintained by hydrologic causes fall into two categories: a) those where permafrost distribution is in equilibrium with the present hydrologic regime, and b) those in which the ground-temperature regime has not yet adjusted fully to a new equilibrium after a recent change in hydrology.

The first category includes closed lake-bed and river-bed taliks (suprapermafrost) and open hydrothermal taliks (intrapermafrost, maintained through convective heat transport by ground-water flow). Examples of the latter include a number of spring areas along the Dempster Highway, at least one of which is characterized by the annual formation of seasonal frost mounds (Hughes and van Everdingen, 1978).

In the second category are recently drained ponds and lakes and recently abandoned segments of stream channels, where invasion of unfrozen bed materials by permafrost may produce closed-system pingos. Examples of these pingos are found in the valley of the Blackstone River and in the Mackenzie Delta.

Seasonal and perennial frost mounds (frost blisters, open-system pingos) can develop in ground-water discharge areas, where freezing of the active layer restricts perennial discharge from intrapermafrost or subpermafrost aquifers (van Everdingen, 1978). Gradual buildup of hydraulic potential in these discharge areas leads to lifting of seasonally frozen ground (and any overlying ice or snow) by a growing, water-filled 'blister.' Part or all of the injected water will freeze gradually from the top downward. Such frost blisters may be completely destroyed by thawing and slumping of the active layer and melting of the ice during the first summer after their formation, or they may be preserved through one or more summers, depending on the insulating quality of their soil cover. Examples are found in a spring area along the Dempster Highway in the North Fork Pass area. Continued development of frost mounds in the past produced true (perennial) open-system pingos. An example of an open-system pingo is located on the old Dawson Road near Bear Creek.

SOILS AND VEGETATION

All soils of northern Canada are characterized by a cold soil climate and, in most cases, by the presence of permafrost. Cryosolic soils dominate throughout northwestern Canada and are associated with Brunisolic and Organic soils in the southern part of the area (fig. 6). Some Luvisolic soils occur in the upper Mackenzie River-Liard River area and in the southern Yukon Territory. The classification of these soils is according to 'The Canadian System of Soil Classification' (Canada Soil Survey Committee, 1978).

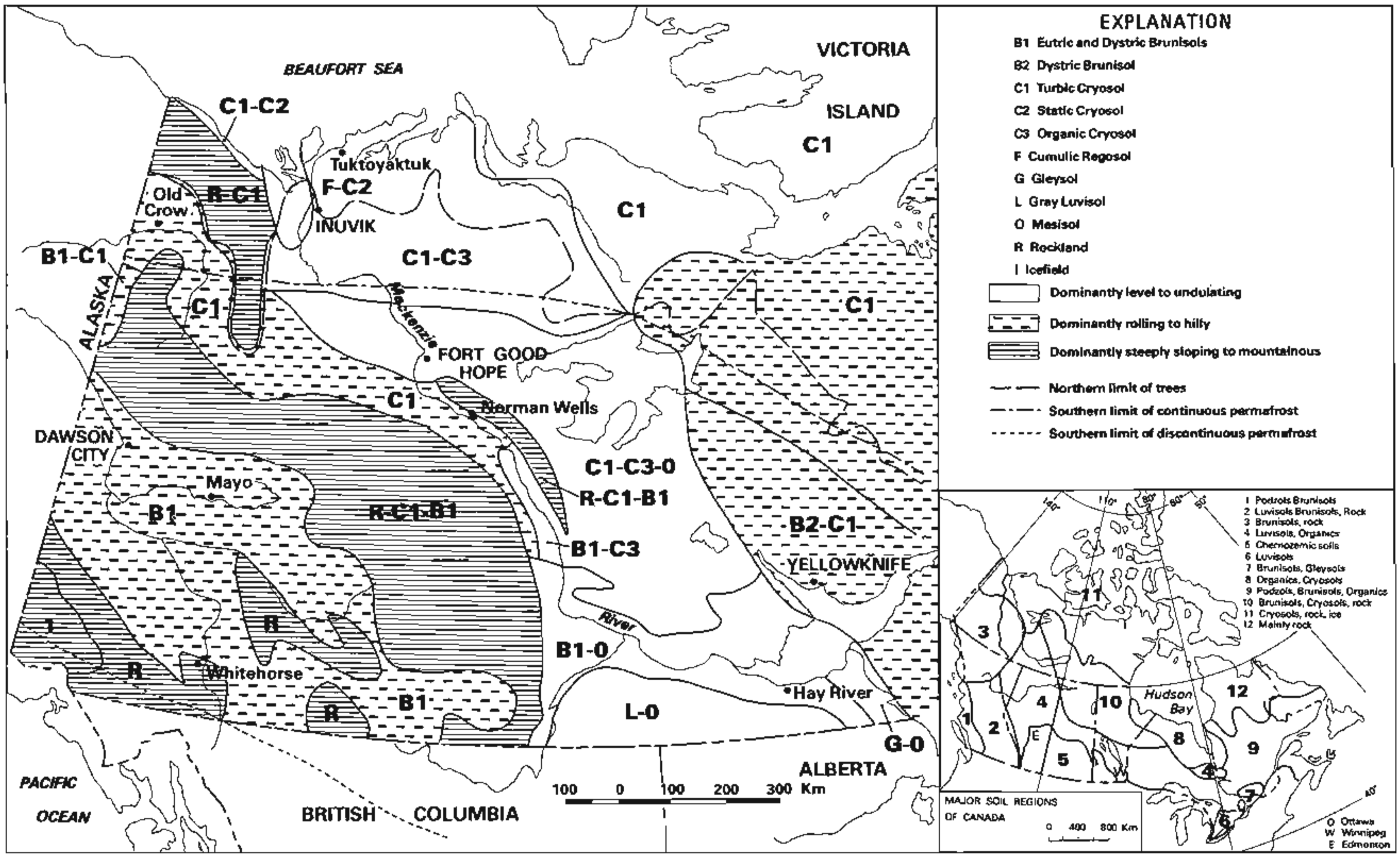

Figure 6. Distribution of soils in northwestern Canada.

Distribution of Soils

In the southern part of the discontinuous permafrost zone, Cryosols are mainly associated with peat deposits (Organic Cryosols). Organic soils (Mesisols), which are very common in this area, are found mainly on fen peatlands. The mineral soils are dominantly Brunisols with Eutric Brunisols in the west and Dystric Brunisols in the Canadian Shield area in the east.

In the rest of the discontinuous permafrost zone, Cryosols are the common soils on both mineral and organic materials. On medium- and fine-textured materials, permafrost is near the surface and the soils are affected by cryoturbation (Turbic Cryosols). On coarse-textured materials (sand and gravels) Eutric and Dystric Brunisols still occur.

The continuous permafrost zone is dominated by Cryosolic soils. Minor amounts of Brunisols may occur in coarse-textured materials in the extreme south, but elsewhere only Cryosolic soils are found. Turbic Cryosols are the dominant soils in fine-textured and loamy materials where they are associated with strong cryoturbation and various types of patterned ground. Static Cryosols occur mainly in coarse-textured materials, whereas Organic Cryosols are associated with peatlands.

The Yukon Plateau is dominated by Brunisols and Cryosols. Because much of this area was not glaciated, the more stable upland surfaces often have soils with deeply weathered, well-developed Bt horizons. Most of these old Luvisols are capped with postglacial loess on which Brunisolic soils have developed. Because of the strongly dissected nature of the plateau, there are marked microclimatic variations, depending on aspect. Steep, north-facing slopes support an open black-spruce forest and have Cryosolic soils, often with a significant thickness of surface peat. Profile development is very weak and most of these soils represent Regosolic and Gleysolic subgroups.

Areas above tree line are dominated by Brunisolic soils and bedrock. Some of the soils are associated with well-developed patterned ground, but these features do not appear to be presently active and are probably relict features from a cooler past. Thick organic accumulations are extremely rare in the unglaciated area because of the well-developed drainage systems. They occur only on some of the younger flood plains, usually in association with alluvial silts. The associated soils are commonly Mesisols on fens and Organic Cryosols on peat plateaus.

The Ogilvie and Richardson Mountains are dominated by Cryosols. Some Brunisolic soils are found on well-drained, coarse-textured materials. On calcareous colluvium, especially on south-facing slopes of the Ogilvie Mountains, Regosolic soils are found in association with minor Brunisols. Various patterned-ground types are common in these areas.

The Eagle Plain is dominated by Cryosolic soils, with Turbic and Organic Cryosols being the most common. Most of the Turbic Cryosols are associated with earth hummocks. Organic Cryosols are associated mainly with peat plateaus and occasionally with polygonal peat plateaus.

The lower Mackenzie River valley and the Pleistocene coastlands are dominated by Turbic Cryosols. The topography of these areas is irregular in the Arctic Red River and Inuvik areas, gradually becoming flatter northeastward to the coast.

Microrelief of mineral terrain is dominated by earth hummocks (fig. 7A), which cover about 80 percent of the landscape south of the arctic tree line and approximately 95 percent north of this tree line (Zoltai and Tarnocai, 1974). Most of the soils in the forested region are associated with various thick- nesses of surface peat; in the arctic region, surface peat is found mainly in the interhummock depressions. Mineral horizons are rich in organic material, which occurs either dispersed or as smears and intrusions. Organic-rich subsurface mineral horizons or subsurface peaty layers commonly occur near the permafrost table. Some of these soils have a granular-structured B horizon and most show evidence of gleying, even on better drained sites. All of these soils are associated with high ice contents in the perennially frozen layer (fig. 7B).

Coarse-textured deposits, especially along the arctic coast, are associated with Static Cryosols. South of Inuvik in the forested region, these deposits are associated mainly with Brunisols.

Organic soils developed from peat materials are common in the Mackenzie Valley. The term 'organic soils' refers to all soils that include more than 40 cm of peat; they may be classified in the organic order or as Organic Cryosols, depending on the presence or absence of perennially frozen conditions within 1 m of the surface. South of the arctic tree line in the lower Mackenzie River valley, these soils are associated with peat plateaus and a palsa type of peatland. These features develop mainly from moderately decomposed woody peat or woody peat underlain by fen peat. North of the arctic tree line, Organic Cryosols occur only in association with tundra polygons (fig. 7C), of both high- and low-center types, and are composed mainly of sedge peat with some Sphagnum peat.

Soils in the Mackenzie Delta are Static Cryosols, Gleysols and Regosols, all of which have developed on recent alluvium. Specific soil types are related to elevation above the distributary channels. The sequence of soils, permafrost, and vegetation from the river channel to the higher portion of the delta follows a regular pattern. Low areas adjacent to the river channels are unfrozen and are associated with Gleysols and an Equisetum type of vegetation (Gill, 1972). This association is succeeded by a slightly higher and better drained area that is associated with regosols and a Salix-Equisetum type of vegetation. Both areas are subject to annual spring flooding. Above the main flood plain, soils are perennially frozen Regosolic Static Cryosols associated with Alnus-Salix and Picea types of vegetation. The latter occurs only south of the arctic tree line.

Soil Properties

Most of the soil textures in the Yukon are loamy with various amounts of coarse fragments. Soils in the Mackenzie Valley are dominantly silt loam, silty clay, and clay. Soils associated with the Mackenzie Delta are silt loam

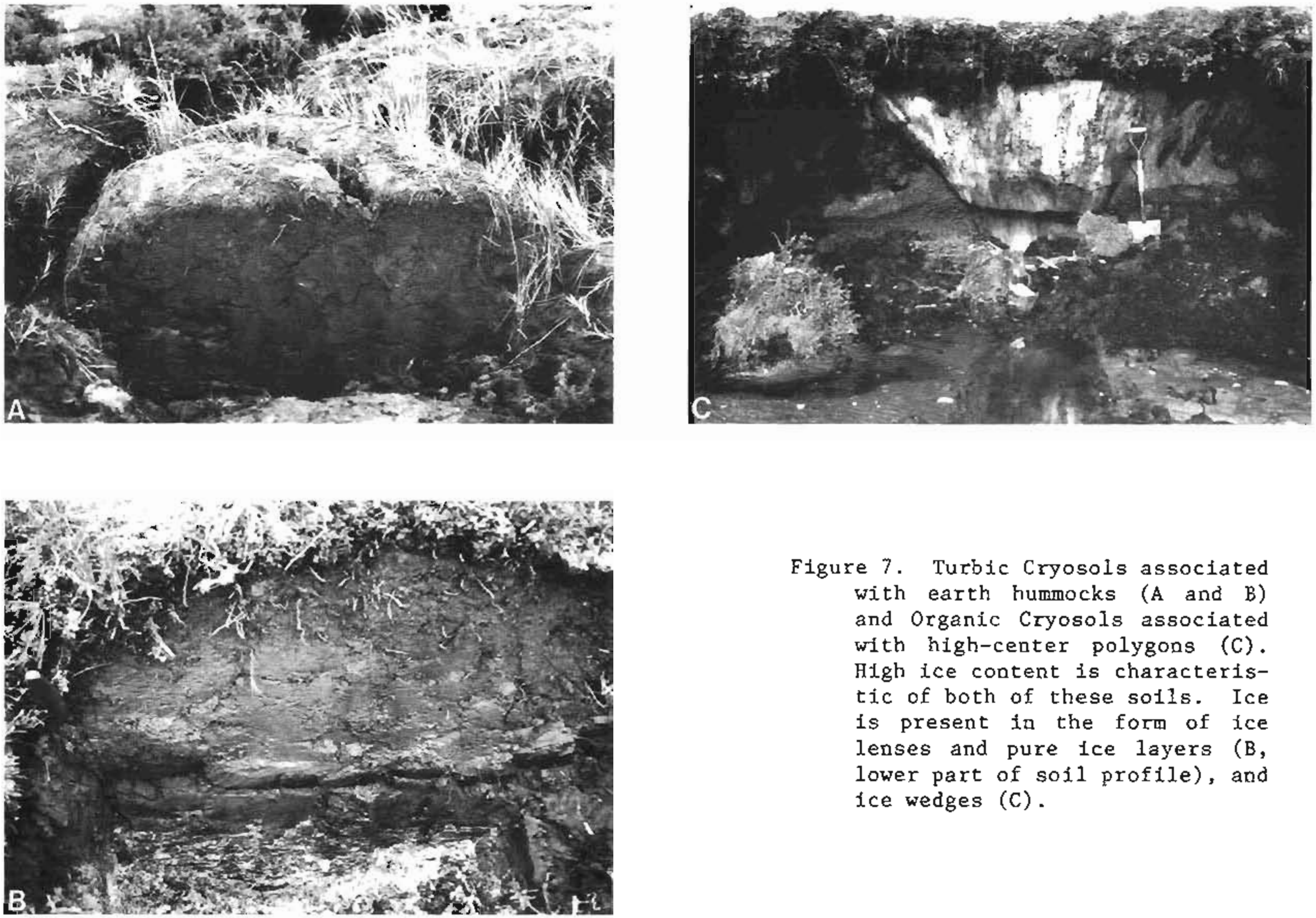

Figure 7. Turbic Cryosols associated with earth hummocks (A and B) and Organic Cryosols associated with high-center polygons (C). High ice content is characteristic of both of these soils. Ice is present in the form of ice lenses and pure ice layers (B, lower part of soil profile), and ice wedges (C).

and loam. Organic soils are associated with moderately decomposed forest and fen peat and undecomposed fibric *Sphagnum* peat.

Moisture and ice content. Texture is one of the main factors controlling moisture and ice content. Fine-textured Cryosols generally have higher moisture and ice content than coarse-textured soils. The relationship between texture and ice and moisture content is shown on a volume basis in figure 8. Coarse-textured soils (for example, DC6, fig. 8) have a relatively small increase in moisture content (30 percent) with depth; thus the moisture and ice-content curve is nearly vertical. Medium- and fine-textured soils, on the other hand, have a slightly greater surface moisture content than do coarse-textured soils. In medium- and fine-textured soils, moisture content increases close to the permafrost table and increases rapidly below the permafrost table. In these soils the difference between the moisture content of the active layer and the ice content of the near-surface permafrost can be as much as 80 percent. Pure ice layers are common in fine-textured Cryosols, especially in near-surface permafrost. Although coarse-textured soils have relatively low ice contents, they are often associated with ice-wedge polygons.

Organic Cryosols associated with palsas and peat plateaus have ice contents between 60 and 90 percent on a volume basis (Tarnocai, 1972, 1973; Zoltai and Tarnocai, 1971, 1975). Ice occurs mainly in the form of crystals, layers, and lenses. Organic Cryosols associated with polygonal peat plateaus and lowland polygons may also contain large amounts of wedge ice. The ice content of these soils ranges from 60 to 100 percent (Tarnocai, 1973; Zoltai and Tarnocai, 1975).

Soil temperatures. According to the Soil Climate of Canada map (Clayton and others, 1977), the mean annual soil temperature at the 50-cm depth in the subarctic region ranges between -7°C and 2°C, whereas in the arctic region, it is lower than -7°C. Most subarctic soils are associated with permafrost, and all soils in the arctic are perennially frozen.

The Soil Climate of Canada map uses temperature at a depth of 50 cm for characterization of the soil thermal regime. Typical data at this depth in the Inuvik-Arctic Red River area are presented in table 4. At the 50-cm depth the Cryosols have a mean annual soil temperature (MAST) between -3.3°C and -2.1°C and a mean summer soil temperature (MSST) between -0.7°C and 0.6°C; the number of frost-free days ranges from 87 to 108 days. Brunisols, on the other hand, have a MAST value of -1.7°C, a MSST value of 1.8°C, and 140 frost-free days. Cryosols associated with the Mackenzie River Delta are the coldest soils in the Inuvik area. The rooting zone generally occurs within 20 cm of the surface, and soil temperatures at this depth show a slight increase compared to temperatures at the 50-cm depth. The increase is especially noticeable in the mean summer soil temperatures and the number of days above 5°C (table 4).

Topographic position, vegetation cover, and thickness of the surface organic layer affect the temperature regimes of these perennially frozen subarctic soils. Soil moisture affects not only the rate of thawing and freezing but also the depth of the active layer. Soil texture and materials have little effect on temperatures.

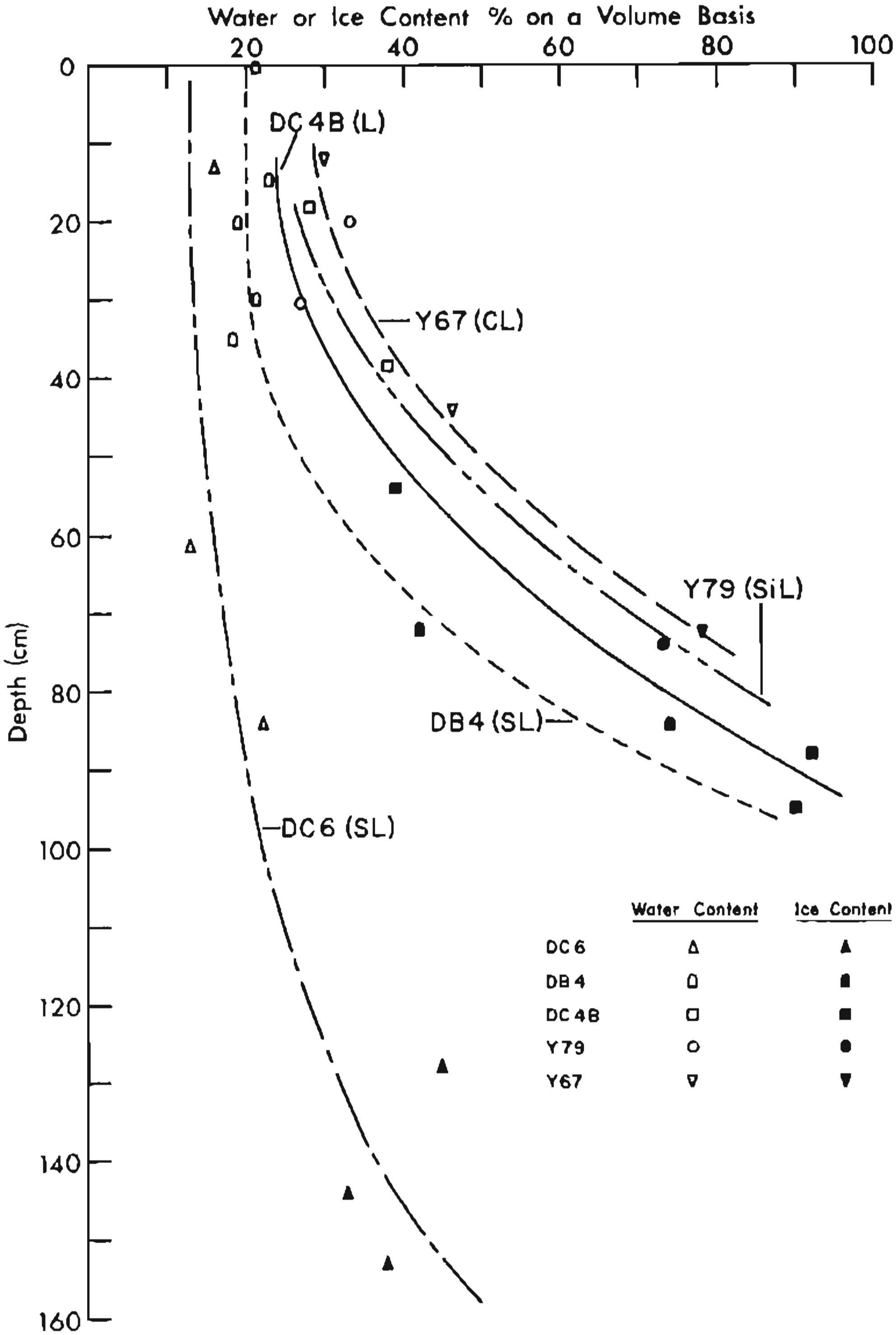

Figure 8. Moisture and ice content of some soils in the Canadian north. Locations and corresponding textures are as follows: DC6 sandy loam (lat. 70°10'N., long. 94°37'N.); DB4 sandy loam (lat. 75°40'N., long. 97°41'W.); DC4B loam (lat. 68°38'N., long. 92°52'W.); Y79 silt loam (lat. 69°35'N., long. 131°48'W.); Y67 clay loam (lat. 68°44'N., long. 134°03'W.).

Table 4. Soil temperatures in the Inuvik-Arctic Red River areas at depths of 20 and 50 cm. Mean temperature values are in parentheses.

Soil subgroup	Materials	Mean annual soil temperature (°C)		Mean summer soil temperature (°C)		Number of frost-free days		Number of days above 5°C	
		20 cm	50 cm	20 cm	50 cm	20 cm	50 cm	20 cm	50 cm
Brunisolic Turbic Cryosol and Orthic Turbic Cryosol	Fine-textured materials associated with earth hummocks	-0.9 to -2.9 (-2.0)	-2.1 to -3.4 (-2.8)	1.9 to 5.1 (3.2)	0.1 to 1.6 (3.2)	110 to 136 (123)	91 to 108 (100)	27 to 71 (43)	0 to 25 (8)
Regosolic Static Cryosol	Loamy material associated with Mackenzie Delta alluvium	-3.1 to -3.2 (-3.1)	-3.2 to -3.5 (-3.3)	-0.6 to 2.4 (0.9)	-0.6 to 0.1 (-0.2)	87 to 113 (100)	87 to 88 (87)	0 to 45 (22)	0
Eluviated Dystric Brunisol	Sandy outwash alluvium	-1.3	-1.7	3.5	1.8	125	140	56	21
Mesic Organic Cryosol	Peat materials associated with peat plateaus and polygonal peat plateaus	-1.1 to -2.5 (-1.8)	-1.4 to -2.9 (-2.1)	1.8 to 3.2 (2.5)	-0.7 (-0.7)	98 to 112 (105)	84 to 133 (108)	31 to 42 (36)	0

The correlation between patterned ground type and soil temperature is not always obvious. Mineral soils associated with earth hummocks have various soil-temperature regimes, but organic soils associated with peat plateaus possessing a polygonal network of troughs have lower soil temperatures than organic soils associated with peat plateaus without these troughs.

Micromorphology. Soil matrices of mineral Cryosols have a distinct micromorphology due to cryogenic processes. Microscale upward movement and sorting of the skeleton grains produces circular and elliptical patterns and distinct horizontal units. The resulting fabric types can be characterized following the terminology of Brewer and Pawluk (1975), Pawluk and Brewer (1975), and Fox and Protz (1981).

Two of the microstructures associated with freezing and thawing are illustrated in figures 9A and 9B. Freezing also produces movement of soil materials and/or cracking, which lead to the downward displacement of mineral and organic material from surface soil horizons. Within the soil, these materials are subject to ice lensing, resulting in a conglomeric fabric (fig. 9C). Finally, the formation of ice lenses and veins under freeze-thaw conditions results in a banded fabric (fig. 9D).

Cryoturbation. Most northern Canadian soils are subject to cryoturbation. This process makes soil surfaces unstable when soil materials are mixed internally and soil horizons are disrupted and displaced. Cryoturbation phenomena are associated with Turbic Cryosols and with those Brunisols and Gleysols in the northern coniferous forest zone or above tree line in mountainous areas.

Recent studies (Zoltai and Tarnocai, 1974; Zoltai and others, 1978) indicate that cryoturbation has been active in arctic areas since deglaciation, but it was probably initially absent from the subarctic forest region. When climatic conditions became cooler about 4,500 yr ago, cryoturbation became widespread throughout northern Canada, including the subarctic forest region. Dendrochronological data (Zoltai, 1975) from the Mackenzie Valley have shown that during the last 200 yr there have been alternating active and dormant periods of cryoturbation. There has been a dormant period since 1967.

Distribution of Vegetation

The vegetation of northern Canada strongly reflects latitudinal and altitudinal temperature gradients.

Northern Canada is dominated by four broad vegetation zones (fig. 10). The arctic and alpine tundra zones occur north of the arctic (northern) tree line and at high elevations above timberline (alpine tree line). The subarctic forest zone, occurring south of the arctic tree line, generally supports an open coniferous forest. The boreal forest zone in the southern areas of northwestern Canada is covered by closed coniferous and mixed coniferous forests. Within these four broad zones, local differences occur because of variations in soil, moisture, aspect, elevation, and fire history.

The Yukon Plateau, especially in the area of Dawson City, is covered by boreal forest. White and black spruce (*Picea glauca* and *P. mariana*) are found

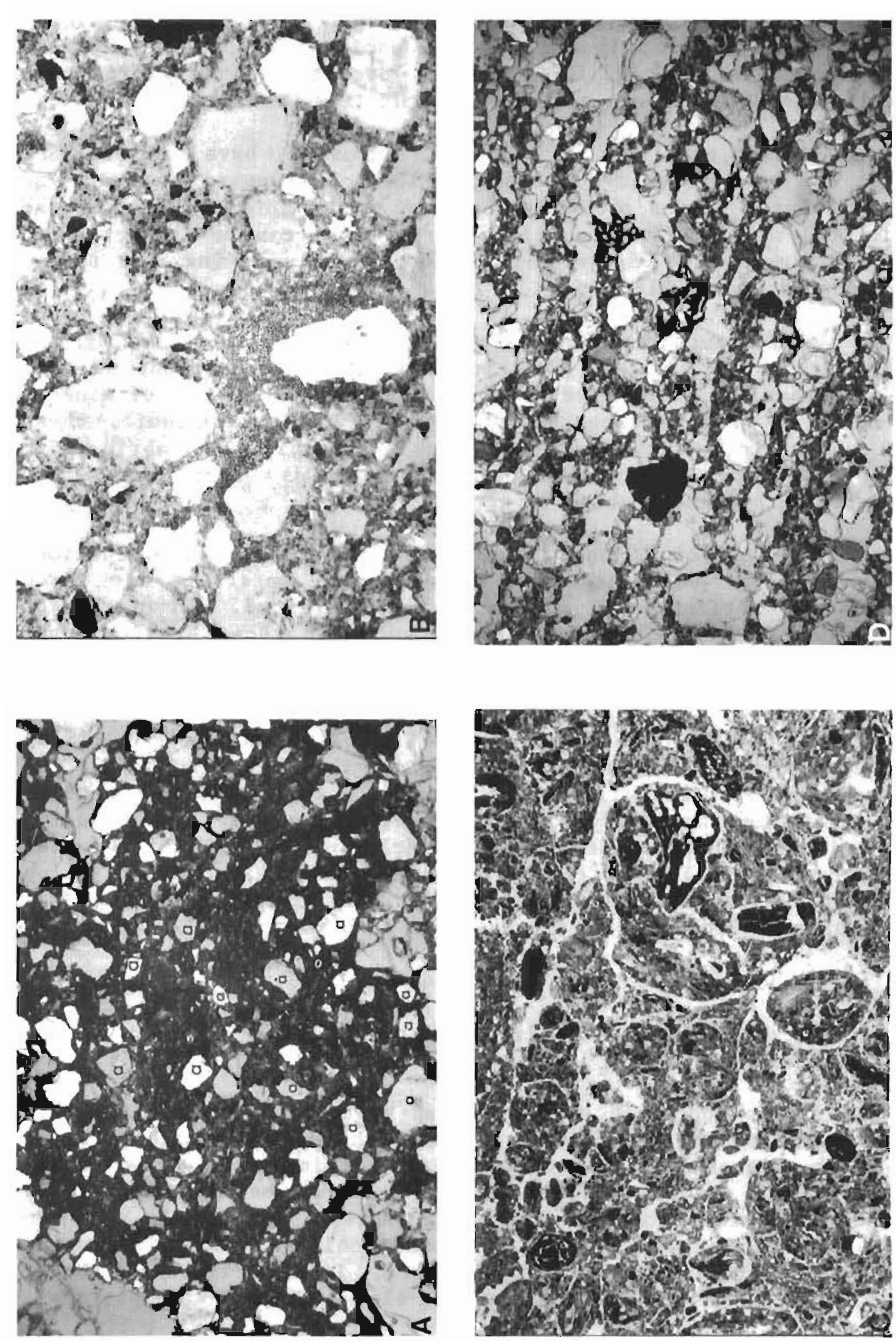

Figure 9. Micromorphology of Cryosolic soils. (A) Ombiculic fabric--a circular or ellipsoidal arrangement of skeleton grains (identified as 'a' on photo); (B) suscitic fabric---vertically aligned skeleton grains with accumulation of finer materials at the base; (C) conglomeric fabric---skeleton grains and organic fragments are enclosed by a dense groundmass of fine material; (D) banded fabric---skeleton grains are sorted in a nearly horizontal direction.

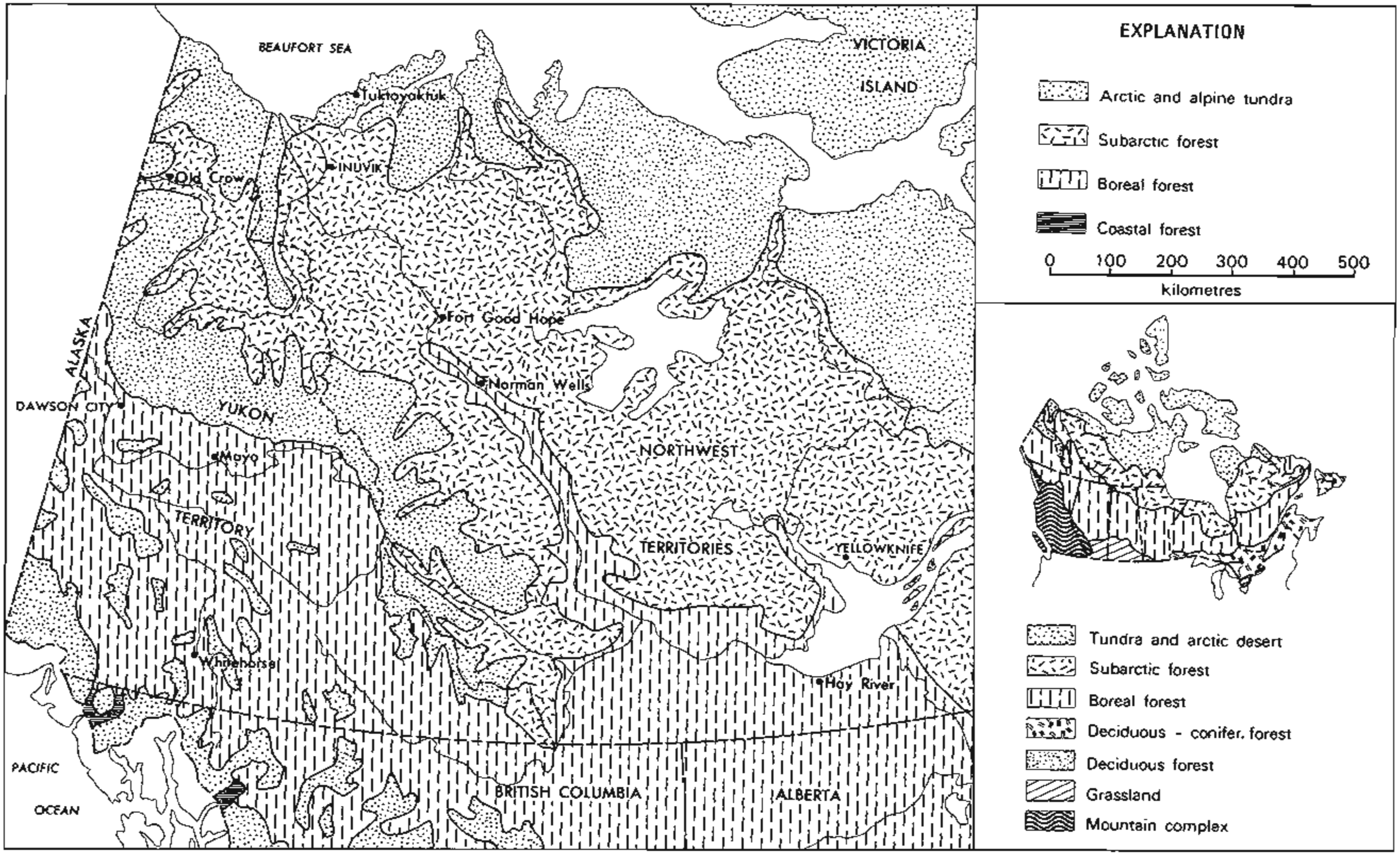

Figure 10. Distribution of vegetation in northwestern Canada.

in pure stands or mixed with aspen (Populus tremuloides), balsam poplar (P. balsamifera), and white birch (Betula papyrifera ssp. humilis).

In the Dawson City area, the northern character of the forest is reflected by the absence of common boreal species such as tamarack (Larix laricina) and pine (Pinus spp.). South-facing slopes are generally covered with aspen and/or white spruce. On north-facing slopes, which are associated with permafrost, black spruce is the dominant tree.

The perennially frozen peatlands (peat plateaus and palsas) are also dominated by black spruce, whereas fens are dominated by sedges (Carex spp.).

On mineral soils, disturbance and fire create a situation that initially favors the growth of hardwoods. As these trees mature, however, spruce invades until it forms a significant portion of the forest.

At higher elevations in the Yukon Plateau, poplar and white birch are absent. These subalpine sites are covered by open stands of white and black spruce with a dense shrub growth of resin birch (Betula glandulosa). Subalpine forests may vary from nearly closed-canopy spruce stands at lower elevations on south-facing slopes to a scattering of dwarfed, wind-sculptured trees (krummholtz) at higher elevations. Fires are common in areas of resin birch, and it may take a long time for conifers to become reestablished (Rowe and Scotter, 1973).

In the Yukon Plateau and in the Ogilvie and Richardson Mountains, the dominant vegetation above tree line is low shrub, consisting of dwarf birch (Betula nana), Labrador tea (Ledum palustre ssp. decumbens) and other ericaceous (heath) shrubs, along with lichens (Cetraria spp. and Cladonia spp.), mosses (Polytrichum spp.) and some herbs. In rocky areas, the cover is much reduced, being confined mainly to sheltered spots. Crustose lichens grow on boulders and rock outcrops, but the specific species depends on the type of rock.

In the Ogilvie Mountains, the valleys below timberline are covered with an open spruce forest with a dense shrub layer.

The most common vegetation in the Eagle Plain area is a spruce-tussock forest, which covers large areas on poorly to imperfectly drained silty soils. The tree cover consists of stunted black spruce with some tamarack. Although the trees are small (less than 4 m tall), they may be over 200 yr old. The sparse shrub layer consists mainly of willow (Salix spp.) and resin birch (Betula glandulosa), with some ericaceous shrubs. Tussocks, composed mainly of sedge (Carex bigelowii), occur on low earth hummocks. White spruce commonly occurs on well-drained sites with white birch and black spruce.

The uplands around Inuvik support subarctic forests of open, stunted stands of black spruce with some willow; lichen (Cladonia spp.) and moss provide ground cover. Where black spruce grow on severely cryoturbated soils, they are usually tilted (fig. 11A) by frost heaving of the ground. After fires (especially on south- and west-facing slopes), white birch forms the pioneer vegetation. Later, both white and black spruce invade the birch stands.

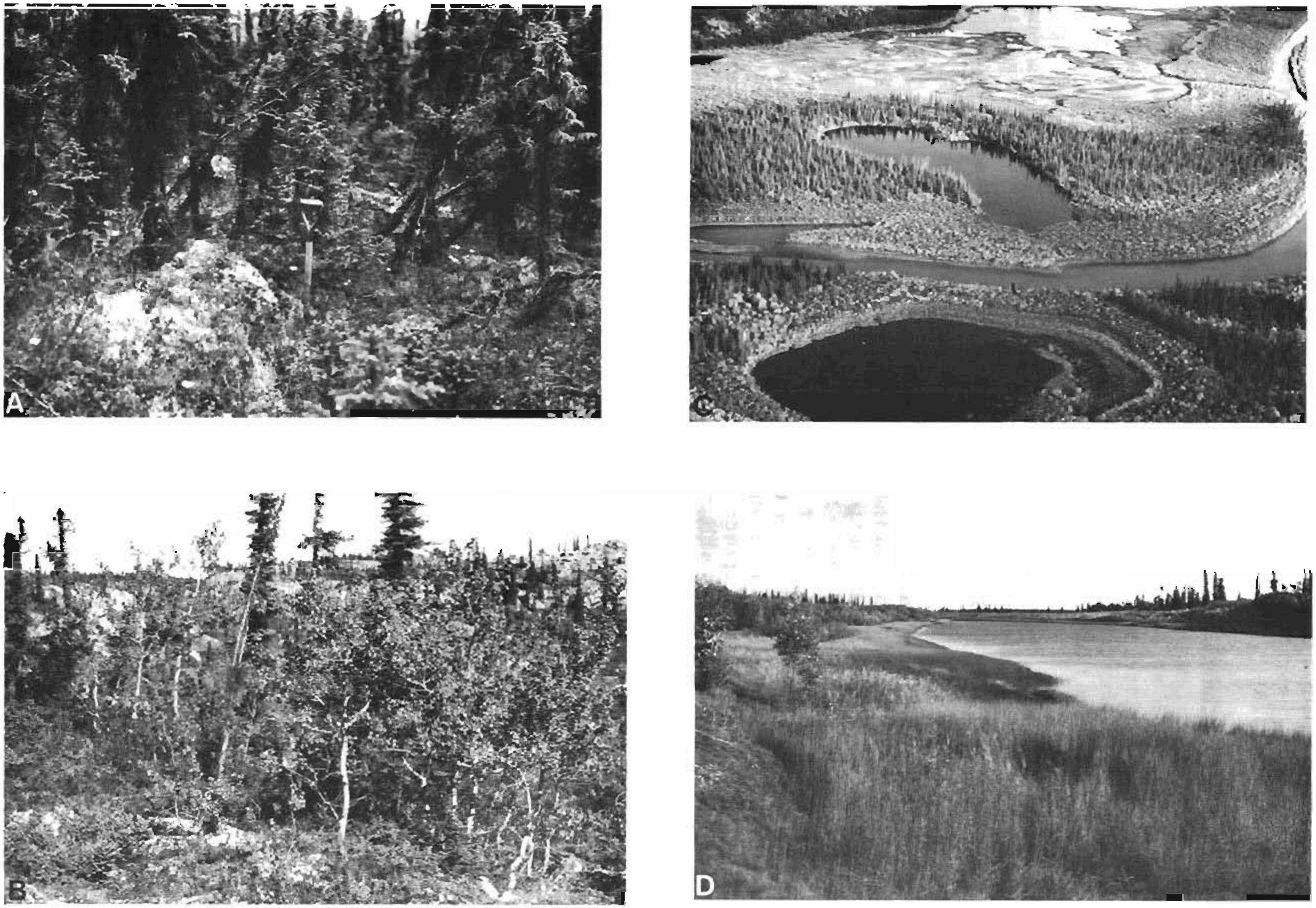

Figure 11. Typical vegetation assemblages of the Mackenzie Delta region. (A) Tilted black spruce on hummocky terrain; (B) northern limit of quaking aspen on the rocky upland at Campbell Lake; (C) sequence of vegetation communities on the Mackenzie Delta; (D) Equisetum community occurring adjacent to the channel, followed by Salix-Equisetum community and then by white-spruce forest on the highest part of the delta.

As a point of interest, tamarack reaches its northern limit at the Inuvik airport, and the most northerly quaking aspen are seen on the rocky upland at Campbell Lake (fig. 11B).

Northward from Inuvik on the uplands, the subarctic forests gradually become restricted to small clumps of white or black spruce growing in sheltered locations in an increasingly dominant tundra setting. Forest fires in the arctic-tree-line zone kill the trees, and it may be several hundred years before they are reestablished (Nichols, 1976). In this area, it is common to find these fire-induced tundras.

The arctic tundra in the Tuktoyaktuk area consists of low shrub-cottongrass-moss-lichen assemblages in the better drained sites. Poorly drained areas are characterized by sedges, mosses, and cottongrass (Eriophorum vaginatum).

The vegetation of the Mackenzie Delta contrasts with the flora of the till uplands in the area. The southern and central parts of the delta are covered by white spruce, which often forms a closed-canopy forest. The absence of forest fires allows white spruce to attain a great age, with some individuals reaching more than 500 yr (Gill, 1971). Over this long period, a considerable thickness of alluvium is deposited, and the rising ground surface is followed by a corresponding rise in the permafrost table. In adjusting to the rising permafrost, white spruce send out adventitious roots from the buried stem section into the new alluvium.

There is a well-developed sequence of vegetation communities from the river channels to the higher and older portion of the flood plain (Gill, 1971; Veldhuis, 1980) (fig. 11C). An Equisetum association dominated by Equisetum fluviatile occurs adjacent to the channels (fig. 11D). This shade-intolerant species withstands flooding and high rates of sedimentation and thus is adapted to the exposed lower slopes, where it forms nearly pure communities. The Salix-Equisetum association is dominated by feltleaf willow (Salix alaxensis) (fig. 11D). This species is especially capable of placing adventitious roots, an adaption necessary for colonizing sites that alluviate rapidly. The herb layer is dominated by Equisetum arvense, another species capable of withstanding extended flooding and sedimentation. The third community in the sequence, the Populus association, is normally dominated by Populus balsamifera, which grows as high as 6 m. The dominant shrub is Salix alaxensis. This association is followed, just above the mean flood level, by the Alnus-Salix association, whose main species are Alnus crispa, Salix arbusculoides, S. glauca and S. barclayi. The ground cover consists of Arctostaphylos rubra, A. alpina, Pyrola grandiflora, Picea glauca seedlings, and mosses. The Picea association represents the climax stage. Relatively open white-spruce stands occupy the highest level areas, which are rarely flooded and are subjected to infrequent sedimentation. The trees are 10 to 20 m tall, with diameters up to 25 cm. Associated shrubs are Alnus crispa, Salix glauca, and S. arbusculoides. The ground vegetation consists of Hedysarum alpinum, Arctostaphylos rubra, A. alpina, and mosses.

The northern delta is covered by arctic tundra. Along river channels, the vegetation sequence is essentially the same as in the southern and central part with the exception of the Picea association, which is absent. Large, low areas are dominated by sedge wetlands.

THE KLONDIKE AND DAWSON

By
H.M. French,[1] S.A. Harris,[2] and R.O. van Everdingen[3]

KLONDIKE GOLDFIELDS

The Klondike district is important to studies of the Quaternary history of the Yukon Territory because many environmental changes are represented in the landscape and surficial deposits. Throughout Quaternary time, the area remained unglaciated (see fig. 2) and relict permafrost is widespread. Numerous faunal remains preserved within the permafrost indicate that it was part of the southeastern Bering refugium. In addition, the presence of extensive auriferous gravels of late Tertiary or Quaternary age or both prompted an important historic event in the development and settlement of northern Canada---the Klondike Gold Rush of 1896-1898.

Relief and Surficial Geology

The Klondike (Yukon) Plateau is an intermontane upland, deeply dissected by valleys with an average depth of 200 m (fig. 12). The plateau is developed mainly on Paleozoic metamorphic rocks, but there are extensive areas of basalt, shale, sandstone, and conglomerate of Tertiary age. Valleys possess a characteristic V-shaped cross profile (fig. 13), often with a high-level bench or terrace, which suggests a history of multicyclic valley development. Intervening ridges have uniform elevations and are presumed to be remnants of an old, uplifted erosion surface (Tempelman-Kluit, 1980). Ridges converge into domes or groups of relatively smooth-sloped mountains. Two prominent domes occur in the Klondike: Midnight Dome, near Dawson, and King Solomon Dome, about 25 km to the southeast.

Rivers that fashioned the upland surface are represented today by extensive, high-level gravels, probably of Pliocene age. Evidence of changes in drainage is the various levels of bedrock terraces beneath these gravels. They indicate that the Proto-Yukon River, from the vicinity of modern Dawson City to Fort Selkirk, may have flowed southward as late as Pliocene time. The old bedrock terraces slope southeast, opposite to the gradient of present streams (Tempelman-Kluit, 1980). Present patterns of the Sixtymile and Indian Rivers also suggest that these streams were once tributaries to a south-flowing Proto-Yukon River.

In detail, the drainage of the Klondike district is dendritic (fig. 14). The most important gold-bearing creeks flow from King Solomon Dome and the ridges extending northwest. Bonanza, Hunker, and Allgold Creeks drain northward into the Klondike River, whereas Quartz, Dominion, and Sulphur Creeks drain southward into Indian River. All of these streams, as well as the Yukon River and its other major tributaries, flow in narrow inner valleys that are

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Figure 12. General view of the dissected Klondike Plateau, Y.T.

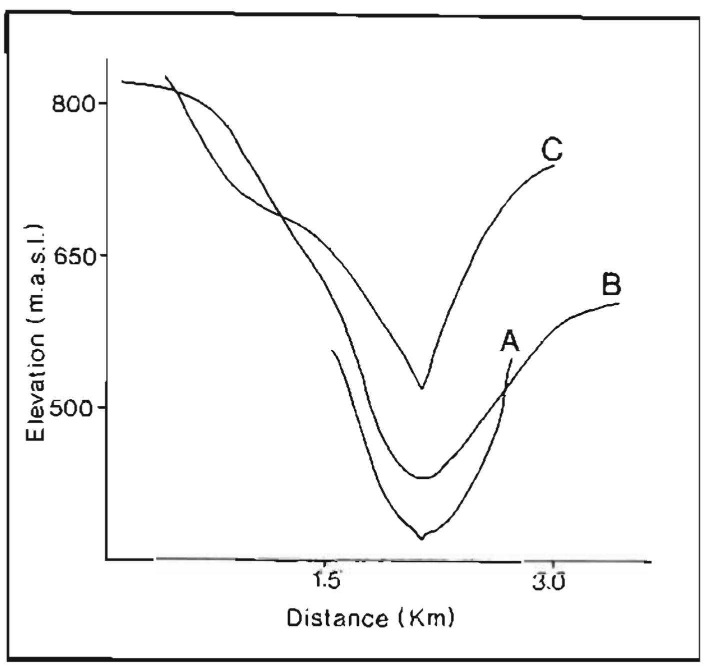

Figure 13. Cross-profiles of Bonanza (A), Hunker (B) and Gold Bottom (C) Creeks. Vertical exaggeration is 10X. Note the similarity of Hunker and Bonanza Creeks and the youthful nature of Gold Bottom Creek (Naldrett, 1982).

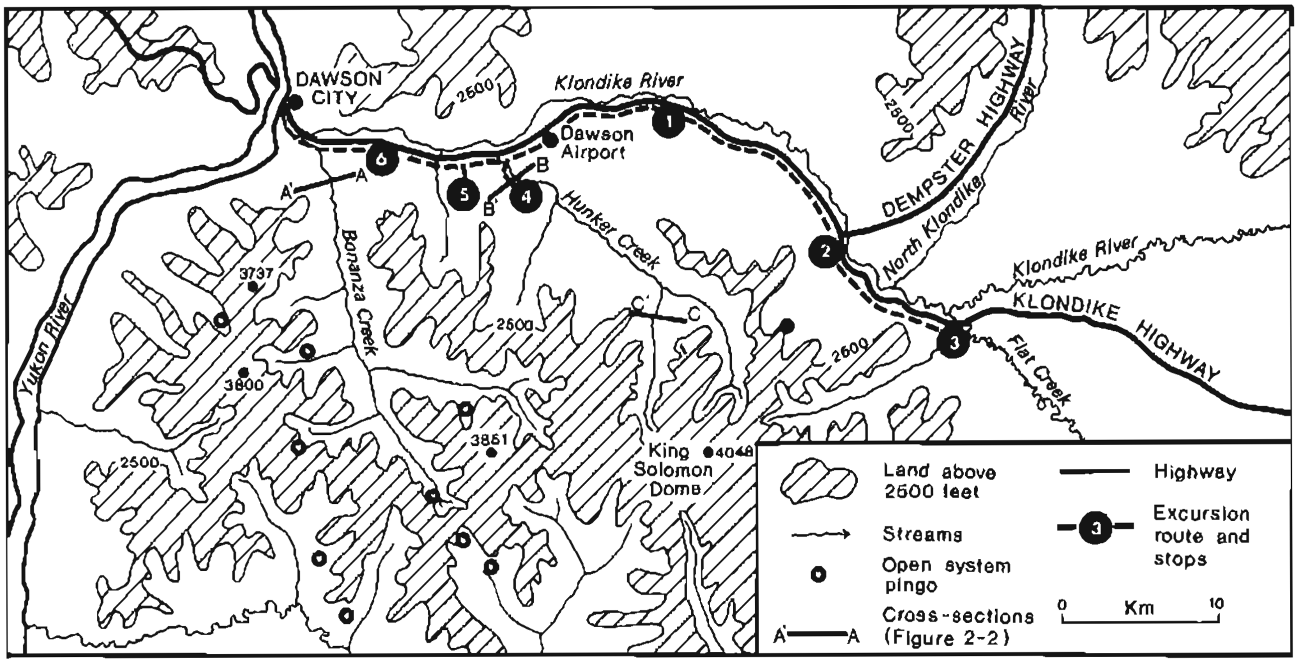

Figure 14. Topographic map of the Klondike goldfields, showing excursion route and stops for Day 1.

incised into much broader, high-level valleys, which in turn are deeply eroded into the Yukon Plateau.

Apart from its placer-mining areas, the surficial deposits of the Klondike have been largely neglected. The only systematic study is by Vernon and Hughes (1966), who mapped the surficial geology of the Dawson, Nash Creek, and Larsen Creek areas. In contrast, gravels in the region have long attracted attention because of their auriferous nature (McConnell, 1905). They can be divided into valley and creek gravels and terrace gravels. The terrace gravels can be subdivided into White Channel Gravel (oldest), Yellow Gravel, and Klondike Gravel (youngest).

Although the Klondike remained unglaciated throughout Quaternary time, pre-Reid glaciations provided source material for the Klondike Gravels and for windblown silt that later became incorporated into the ice-rich muck deposits covering the valley and creek gravels. Because the interior northern Yukon was not glaciated during Pleistocene time, the main valleys were repeatedly infilled by clastic sediments that varied in amounts and physical characteristics with climatic cycles. Because of the cold climate prevailing at the time, permafrost aggraded into these sediments and massive ice bodies formed, especially ice wedges. These sediments are usually silty, having originated as lacustrine silt or silty windblown deposits and colluvium.

A typical association of slopes and surficial deposits in the Klondike is shown in figure 15. In some places, the ice-rich silty alluvium contains abundant mammal remains (table 5). These sediments frequently overlie auriferous gravels of late Tertiary or early Quaternary age and require removal

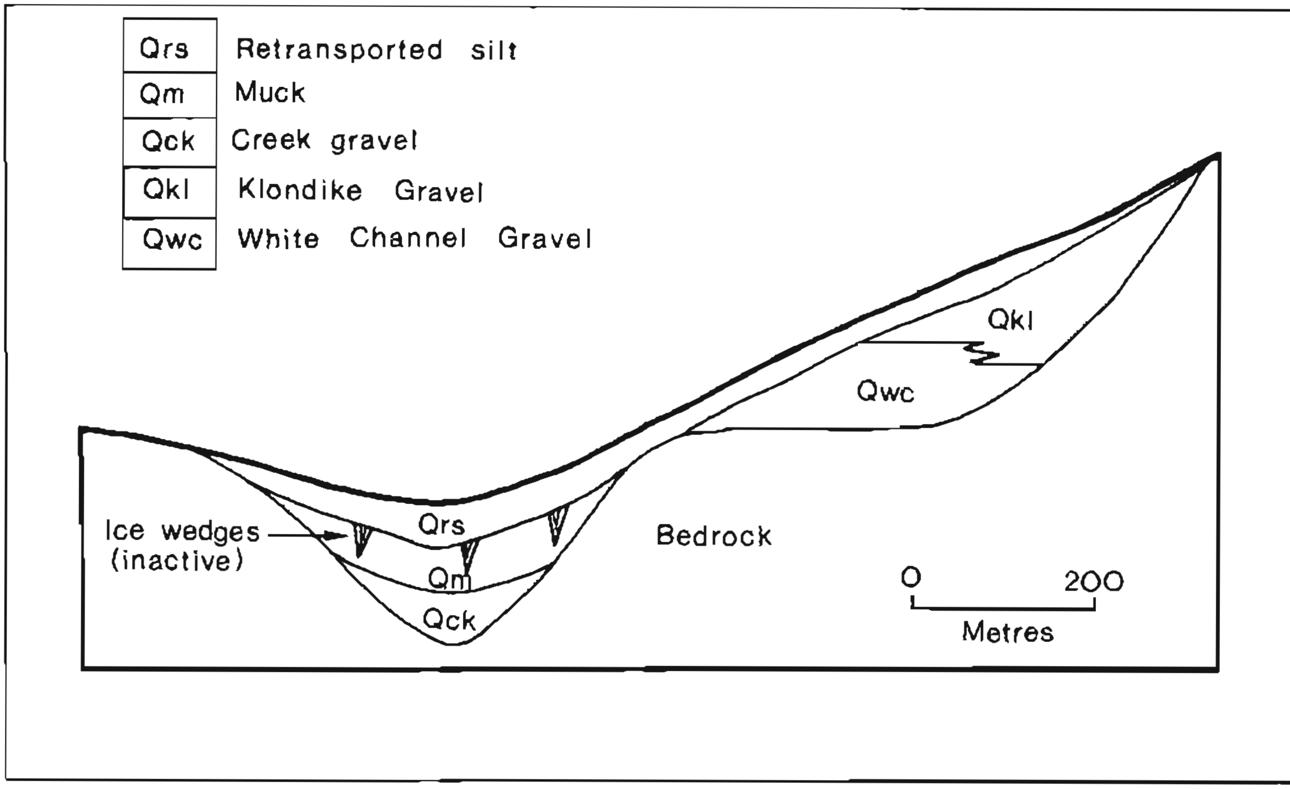

Figure 15. Typical distribution of valley, creek, and terrace gravels in the Klondike area. Terrace gravels occupy upper benches; valley and creek gravels occupy the lower, smaller valleys (Naldrett, 1982).

before modern placer operations are possible. A similar erosional history of downcutting in late Tertiary-early Quaternary time is found in interior central Alaska (Péwé, 1975; 1977). The lower Yukon and Tanana Valleys, particularly in the Fairbanks area, have terrain and surficial deposits that are similar to those of the central interior Yukon. Like the Klondike region, much of central Alaska escaped Quaternary glaciation, and analogous valley cross profiles and deposits of gold-bearing gravels are present.

Climate

The climate of the Klondike area is subarctic continental, with short summers, long winters with periods of intense cold, infrequent winds, and little snowfall. The drainage of cold air into lowland sites such as Mayo and Dawson is common in January. The temperature and precipitation range of the area (as recorded at the Dawson airport over a 30-yr period) is illustrated in figure 16. Weather stations in the Yukon Territory are sparse and almost all are situated in valley bottoms. Thus, climatic data for Dawson are not necessarily characteristic of all the Klondike.

Orographic effects modify both rainfall and snowfall. Mountain areas receive more snow, especially on western slopes. In contrast, precipitation

Table 5. Quaternary mammal remains, Klondike region (Harington, 1977, 1978).

Linnean name	Common name	Age (yr B.P.)
	GOLD RUN CREEK	
Canis lupis	wolf	
Arctodus simus yukonensis	Yukon short-faced bear	
Taxidea taxus	American badger	
Panthera (leo) atrox	American lion	
Mammut americanum	American mastadon	
Mammuthus primigenius	woolly mammoth	32,250 ± 1,750 (I-4226)
Equus (Asinus) lambei	Yukon wild ass	
Equus (Asinus) cf. *kiang*	Kiang-like wild ass	
Alces alces	moose	
Rangifer tarandus	tundra caribou	
Bison alaskensis	Alaskan bison	>39,900 (I-5404)
Bison crassicornis	large-horned bison	22,200 ± 1,400 (I-3570)
Bootherium sp.	extinct muskox	
	DOMINION CREEK	
Spermophilos undulatus	ground squirrel	
Mammuthus primigenius	woolly mammoth	
Equus sp.	small horse	14,870 ± 260
Alces alces	moose	
Rangifer tarandus	tundra caribou	
Bison crassicornis	large-horned bison	
Panthera (leo) atrox	American lion	22,680 ± 300
	QUARTZ CREEK	
Canis sp.	wolf	
Mammuthus primigenius	woolly mammoth	
Equus sp.	small horse	
Rangifer tarandus	tundra caribou	
Bison crassicornis	large-horned bison	30,300 ± 1,850

at Dawson is approximately 10 percent higher than at Elsa (see table 1), even though the latter is at a higher elevation. Another important factor determining local climatic conditions is temperature range. Both freezing and thawing indices decrease with increasing elevation, causing the temperature lapse rate to be reversed below 650 m elevation and to be unusually gentle above it.

Plots of freezing and thawing indices for class A weather stations against latitude show that the indices are basically similar between the St. Elias Range in the south and Old Crow in the north. Closer to the Arctic Ocean, amelioration of the indices occurs, probably because of the influence of the sea. In winter, areas beyond tree line have higher freezing indices than areas with forest, probably due to differences in albedo. Thus, oro-

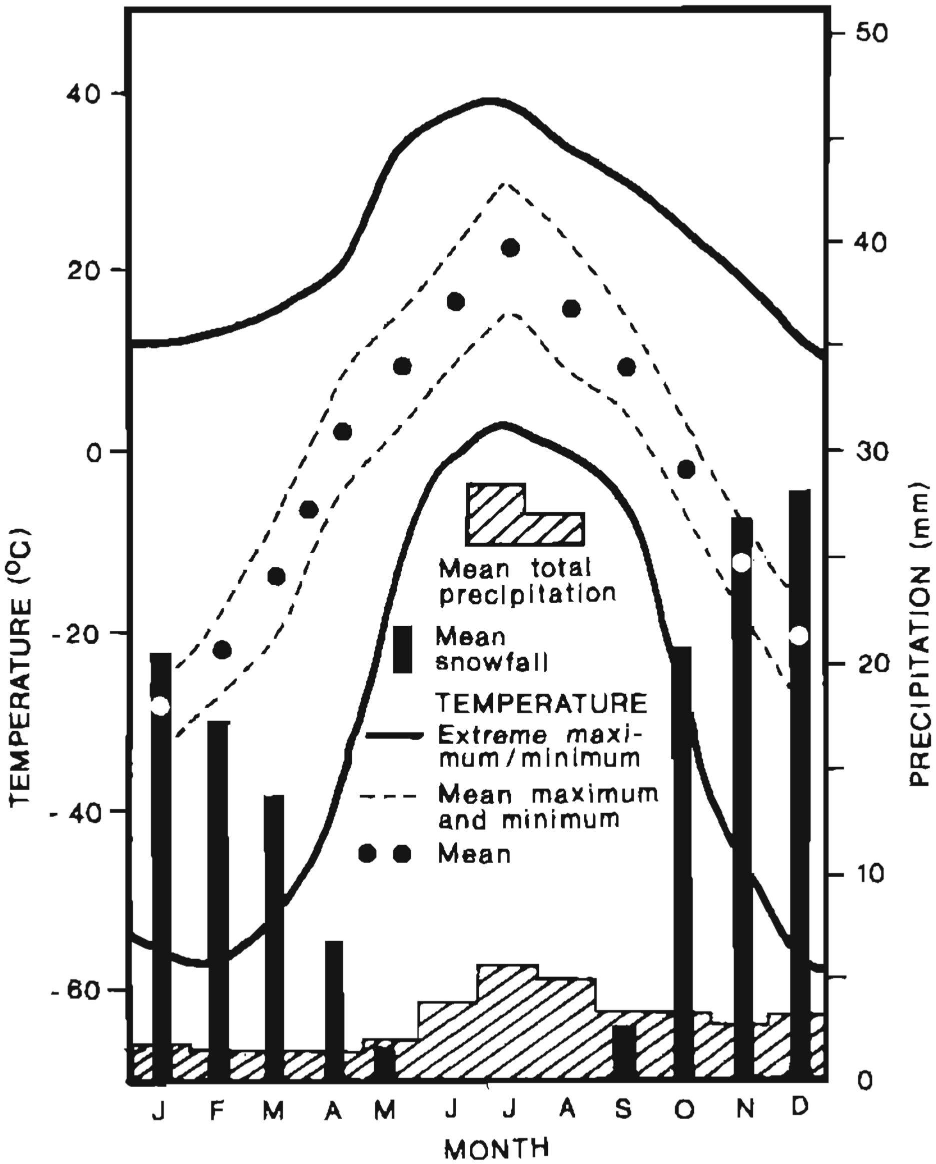

Figure 16. Climatic data for Dawson airport, Y.T., 1941-1971 (Atmospheric Environment Service, Department of Environment).

graphic effects, cold-air drainage, and aspect are major controls of climate and, indirectly, permafrost distribution in the area.

Permafrost Conditions

Although mapped by Brown (1978) as an area of discontinuous permafrost, it now appears that continuous permafrost is widespread at higher elevations throughout west-central Yukon Territory. In addition, cold-air drainage in interior basins and valleys in winter causes the distribution to be more complicated than would normally be predicted based on freeze-thaw indices. Furthermore, the presence of relict permafrost greatly complicates the situation. In general, permafrost is thickest under north-facing slopes and often absent beneath south-facing slopes. Thicknesses are highly variable, depending on the host materials, slope configuration, aspect, and vegetation. The depth of permafrost in the Dawson area is reported to be about 60 m (EBA Engineering, 1977, 1978). Ground temperatures vary from between -2° and -1°C in areas of discontinuous permafrost to between -6° and -4°C in areas of higher elevation and continuous permafrost.

Relationship to surficial materials and vegetation. In areas of discontinuous permafrost, there is often a close relationship between permafrost, surficial materials, and vegetation cover. Vegetation influences ground-surface temperatures and, therefore, the presence or absence of permafrost. Aspect is also important in hilly areas, because south-facing slopes tend to be warmer than north-facing slopes. The distribution of many plants is affected primarily by water availability, which is only partly related to the presence or absence of shallow perennially frozen ground. Thus, relationships are all complex.

Vegetation usually reflects differences in environment. In areas of poor drainage and (often) of permafrost, the primary association is black spruce (*Picea mariana*), resin birch (*Betula glandulosa*), a shrub layer, and a ground cover of lichen, feather mosses, and *Sphagnum* mosses. In areas of good drainage or of little or no permafrost, white birch (*Betula papyrifera*), poplar (*Populus* spp.), and alder (*Alnus rubra*) are present. However, caution needs to be used in forest-permafrost relationships. For example, well-drained, dry permafrost ridges on the Sixtymile Highway support a mixed forest normally associated with no permafrost.

In the Dawson area, it is particularly important to note that the present vegetation assemblage is a result of regrowth since gold-rush time. During the period 1896-1903, nearly all the forest in the Klondike area was cut for lumber and fuel and, although the species distribution was not significantly affected, a stable community has still not developed.

An even more important factor influencing general vegetation distribution is fire, which destroys trees, thickens the active layer, and produces a fire-climax vegetation that may have cycles as short as 300 yr (Zoltai and Pettapiece, 1973, p. 16). The most notable change is from black spruce to white spruce (*Picea glauca*). On the upland areas, fire changes forest to a tundra-tussock community (for example, on Swede Dome). The thickening of the active layer and sudden release of water also causes significant debris-flow activity, adding large volumes of colluvium to the valley fill, thus increasing permafrost thicknesses in the valley floors by burying frozen sediments.

Permafrost hydrology. The presence of discontinuous and relict permafrost gives rise to a number of important hydrologic problems and characteristics. Permafrost presents a relatively impermeable barrier as long as the ground remains frozen. Where topographic gradients are encountered, it is possible for substantial hydrostatic heads to develop. Moreover, in placer operations in areas of relict permafrost, the flow of water in the suprapermafrost talik may be responsible for ground-water icings.

In the Klondike area, the unusual nature of ground-water flow is shown by disrupted drainage in the Dawson townsite, numerous icings along the Dempster

Highway, and the presence of several open-system pingos in the Klondike goldfields. The latter are some of several hundred pingos known in the central Yukon and interior Alaska (Hughes, 1969; Washburn, 1980, p. 188).

Road Log and Site Descriptions

The day starts at Dawson airport and finishes in Dawson. General relief, drainage, and permafrost conditions of the Klondike area are examined at a number of localities along the Klondike Highway as far east as the junction with the Dempster Highway. Permafrost and ground-ice conditions can be observed in modern placer-mining operations along Hunker and Bonanza Creeks. The historic tailings piles along lower Klondike Valley and an open-system pingo are examined. The excursion route and stops are indicated in figure 14.

From Dawson airport proceed east on the Klondike Highway for 5.9 km.

KM 159.6 (Klondike Highway). STOP 1. HAY FARM. The Hay Farm has been functioning more or less continuously since the early 1900s, primarily to produce hay for pack horses. The outline of the original cleared and cultivated area cannot be determined precisely because of an overgrowth of willows. There has been progressive abandonment of cultivated land, however, as indicated by polygonal networks of ice wedges that have melted out, leaving hummocky 'cemetery mound' topography that cannot be worked by farm machinery. The mounds and associated network of trenches are best developed in thick silt around the periphery of an alluvial fan west of the presently cultivated fields. Local relief is 1 to 2 m and small angular ponds are common where trenches intersect. Polygons range in diameter from 12 to 25 m. Farther from the apex of the fan, where fan silts are thinner, former ice wedges are expressed as sharp, straight trenches, 1 to 1.5 m wide and about 0.5 m deep, which divide the surface into flat polygonal areas comparable in size to the higher cemetery mounds. In parts of the presently cultivated area, where alluvial gravel is overlain by 0.4 to 1 m of silt, polygons are visible on airphotos and slight depressions are discernible on the ground, but local relief is not sufficient to impede machinery. Evidently the volume of ice in the former ice wedges was roughly proportional (up to a limit) to the thicknesses of the silt in which they developed. This condition is in accord with observations along fresh river banks where ice wedges are best developed in thick peat and/or silt, whereas wedges narrow abruptly where they penetrate gravel at shallow depths.

Continue east on the Klondike Highway for 17 km to the junction with the Dempster Highway.

KM 176.5 (Klondike Highway). STOP 2. PEAT PLATEAU AND FENLAND. This site is located south of the highway, immediately past the junction with the Dempster Highway. It consists of a small peatland complex (fig. 17) comprising a black spruce-moss association, which forms a 'peat plateau' underlain by permafrost in the middle of a fen. The peat plateau is 50 to 100 cm above the fen and better drained. The fen is fed by nutrient-rich seepage waters, supports mainly sedges and shrubs, and contains no permafrost. The depth of peat is about 80 cm in the plateau and 140 cm in the fen. In terms of the Canadian Soil Classification System, the soil on the peat plateau is a Terric Mesic Organic Cryosol and that in the fen is Terric Mesisol.

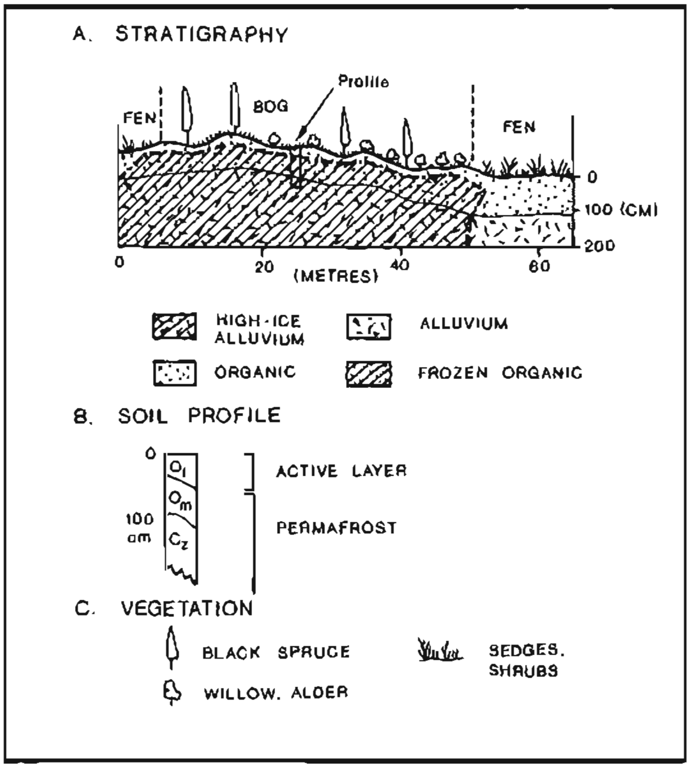

Figure 17. Section through peat plateau and fenland in discontinuous permafrost terrain, Klondike Highway (Pettapiece and others, 1978).

In the discontinuous permafrost zone, wet fens are not affected by permafrost because the peat is completely saturated with water and readily conducts heat. As the fen matures and peat accumulates, small cushions of *Sphagnum* may become established on the fen. *Sphagnum* (especially *S. fuscum* and *S. rubellum*) is an excellent insulator, particularly when dry in the summer. Seasonal frost under these cushions persists late into the summer and may eventually remain into the fall, becoming permafrost. As water freezes in the peat, it expands, raising the small peat mound farther above the level of the fen. The improved drainage permits the growth of black spruce. These small trees shade the ground in summer and keep the snow cover thin in winter. The combined effects of tree and *Sphagnum* growth initiate and preserve permafrost in the peat. The small frozen mound (a peat plateau) expands farther into the fen as *Sphagnum* and trees invade the fen. Disturbances such as forest fires tend to destroy the insulating cover, often inducing thawing and the subsequent collapse of the peat plateau.

Continue south on the Klondike Highway for 4 km.

KM 180.5 (Klondike Highway). STOP 3 (OPTIONAL). VEGETATION-PERMAFROST RELATIONS, TOO MUCH GOLD CREEK. Too Much Gold Creek drains the northeast flank of King Solomon Dome and flows into the Klondike Valley. It illustrates the differences in soils and vegetation caused by differences in slope aspect (fig. 18).

The southeast-facing slope is warm and freely drained. Vegetation there is a white birch forest with minor white spruce and aspen, scattered shrubs, and a herb layer. The main pedological process is oxidation of the parent material associated with some hydrolysis and the release of iron.

The northwest-facing slope is cool and moist. The soil has permafrost within 30 cm of the surface. The vegetation is a typical subarctic community consisting of an open black-spruce forest with a continuous moss and lichen ground cover. This condition is in marked contrast to the opposing slope and indicates a much cooler, moister microclimate. The possible distribution of permafrost in this valley is presented in figure 18.

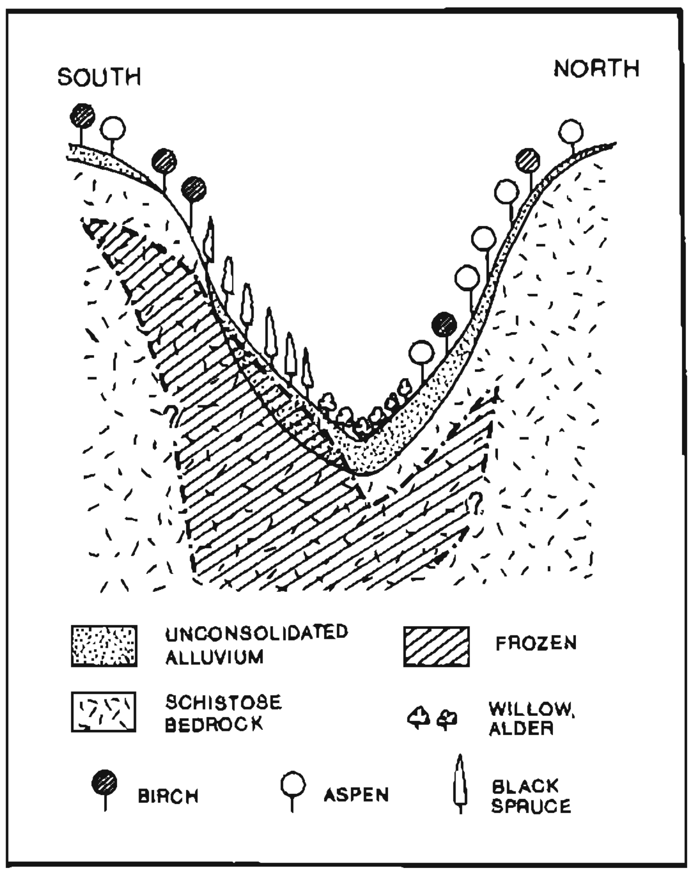

Figure 18. Schematic cross section of Too Much Gold Creek showing assumed permafrost distribution and present vegetation (modified from Pettapiece and others, 1978).

Retrace the route along the Klondike Highway toward Dawson City. Continue past the airport for 2.4 km and turn south on Hunker Creek Road for 1.7 km.

STOP 4. PLACER MINING, HUNKER CREEK.

Modern gold placer-mining operations. Since dredging ceased in the Klondike District in 1966, placer mining has been conducted mainly by two methods. The most common method, 'cat' mining using bulldozers, is generally used in low-level gravels. Areas to be mined must first be stripped of perennially frozen peat and silt ('muck' in local terminology). The gravel is allowed to thaw by solar heat for one or two summers, depending on its thickness. To mine the gravel, sluice boxes are set on an inclined earth ramp and water, pumped from the creek, is supplied to the head of the sluice box. The gravel is then bulldozed into the head of the sluice box and washed through it by the force of the water. The gold is retained in various types of riffles on the bottom of the sluice box.

The second method, 'hydraulicking,' is used to mine high terrace deposits. It is a system virtually unchanged since it evolved in California about 125 yr ago. Water is supplied at high pressure to 'monitors,' either by pump or gravity. The stream of water issuing from the monitor dislodges gravel from a steep working face and washes it to the head of a large sluice box, from which it discharges near the edge of the terrace. As with cat mining, the gold is retained in riffles in the sluice box. The high-level White Channel Gravel is mostly perennially frozen. Because the moisture content of these gravels is relatively low, they thaw rapidly and permafrost is not a hindrance to mining. This condition is particularly true where the working face is broad and high, exposing a large area to solar heat.

The only modern innovations seen in hydraulic mining in the Klondike district are the use of diesel pumps to supply water to the monitors and the use of bulldozers to move the coarsest material to the head of the sluice box.

Mayes Claim, Hunker Creek. The Mayes Claim, which is worked on Hunker Creek by the Colin Mayes family, is typical of a small cat-mining operation. Gold-bearing gravels are situated on a low bedrock terrace that lies against a rather steep valley wall on the left limit of Hunker Creek. These gravels are overlain by a wedge of muck that attains a thickness of 15 m or more at the junction of the terrace and the valley wall.

The muck is currently stripped by hydraulicking to expose the gravel for subsequent mining by bulldozer. Water is pumped from Hunker Creek at the upstream end of the property and carried about 1,000 m by a pipe to the upper edge of the workings. Lateral pipes distribute water to monitors that are operated in rotation to remove the muck as it thaws by solar heat.

The deposit has been mined extensively by underground hand mining. Remains of old shafts, filled with ice and perfectly preserved timbers, are being exhumed in the course of stripping. Tailings from the hand-mining operations are widely distributed at the surface. Whereas the thawed muck is readily flushed away, the coarser tailings tend to lag behind, slowing the stripping operation and adding to mining costs.

Stripping frequently exposes large mammal bones throughout the muck. Bones of small mammals and birds are no doubt present but escape notice. Preliminary identifications by C.R. Harington (Curator of Quaternary Zoology, Museum of Natural Sciences, Ottawa) indicate the following taxa from the area of the Mayes operations: Alopex lagopus (arctic fox), Taxidea taxus (American badger), Panthera (leo) atrox (American lion), Mammuthus primigenius (woolly mammoth), Equus (Asinus) lambei (Yukon wild ass), Alces sp. (moose), Bison crassicornis (large-horned bison), Rangifer tarandus (caribou), Ovis cf. dalli (large mountain sheep) and Ovibovinae (muskox subfamily).

A large permafrost exposure occurs at the downstream end of the Mayes claim. Part of this section was first observed in June 1978 by Hughes and van Everdingen. An exposure, observed in 1980, is illustrated in figure 19. About 2 m of silty sandy colluvium overlies 5 to 10 m of ice-rich muck. Nearer the creek bed, the muck grades into ice with silt inclusions.

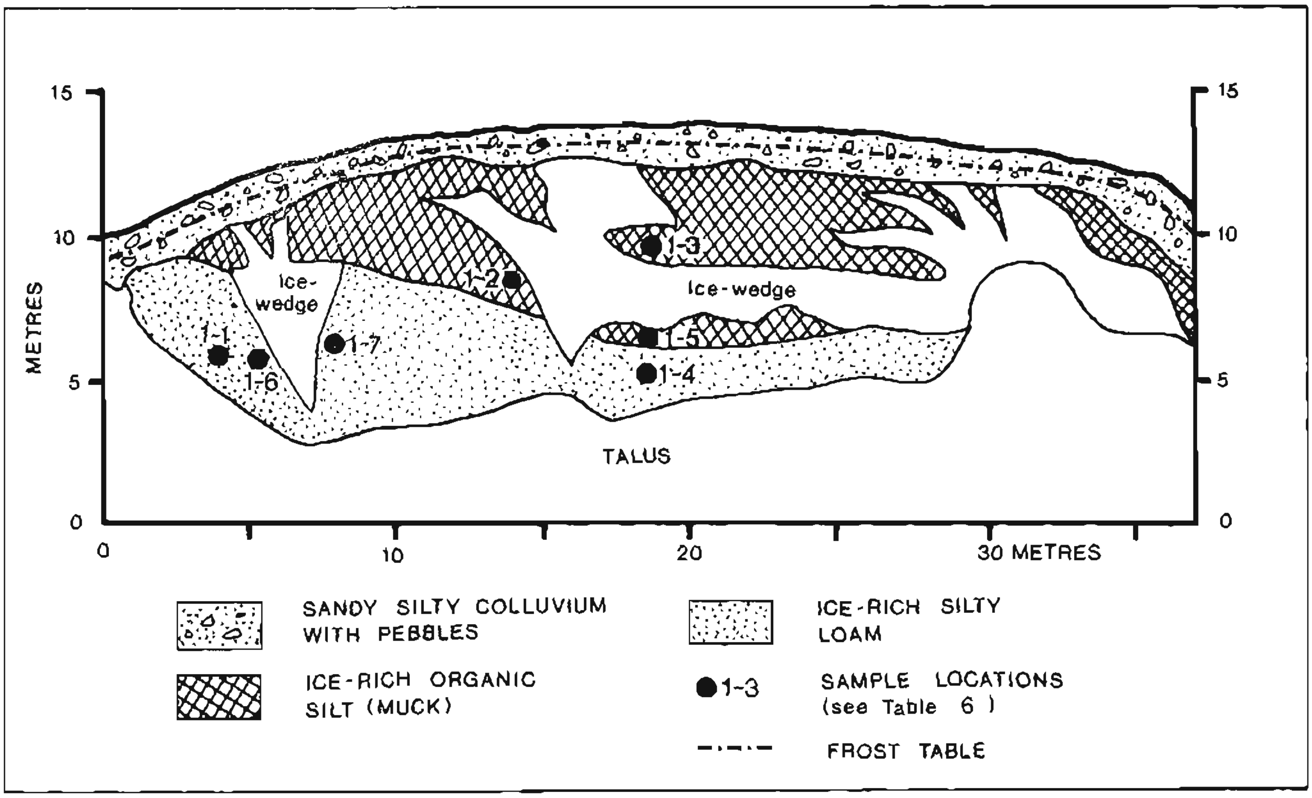

Figure 19. Diagram showing permafrost section exposed in Mayes operation, Hunker Creek, August 30, 1980 (Naldrett, 1982).

The ice content and cryotextures of these muck and ice-rich silts are documented in table 6. Massive ice in the form of large, inactive wedges comprises 40 to 50 percent of the exposed face. The proportion of ice to organic silt is exaggerated by the orientation of the face relative to the geometry of ice wedges because most wedges are seen obliquely in both natural and artificial sections. Moreover, many wedges are not simple and vertical in plan, but curve and branch into smaller veins.

Because the active layer does not exceed 50 to 70 cm in thickness and the upper ends of the ice wedges lie at depths of 150 to 170 cm below the surface, the wedges are thought to be inactive. Frozen silt lies between the base of the active layer and the tops of the wedges. The tops of the wedges probably reflect a thaw unconformity related to the postglacial climatic optimum;

Table 6. Ice content and cryotextures in permafrost section exposed in Mayes operation, Hunker Creek, August 1980 (Naldrett, 1982). (See figure 19 for sample locations.)

Sample	Excess ice content (%)	Cryotexture[a]
Ice-rich silty loam		
1-1	6	Medium silt, Vr[b] ice; medium-coarse sand, Vr ice; silt clay, Nbe[c] ice.
1-4	38	Silt with Vs[d] ice, some ice with soil inclusions.
1-6	14	Silt in Vr lenses 2-3 cm thick, randomly oriented sand and grit inclusions.
1-7	43	Wedge ice, horizontal bubble trains.
Ice-rich organic and silty sediments		
1-2	29	Wedge ice, oblique bubble trains, ice with silt inclusions.
1-3	22	Interbedded organic silt and clay, Vs-Vr ice.
1-5	23	Interbedded organics and silt, Nbe ice.

[a]Ground-ice terminology according to Pihlainen and Johnston (1963).
[b]Random visible ice.
[c]Stratified visible ice.
[d]Well-bonded excess ice.

alternatively, the wedges may have become inactive because of burial by silt and other colluvium at a later date.

Stutter operation (Hunker Creek, 2 km south of Klondike Claim). The name Dago Hill is applied to the high terrace of White Channel Gravel on the left limit of Hunker Creek between Last Chance Creek and Henry Gulch. The gravels are currently being mined by hydraulicking. Like all the White Channel deposits, those at Dago Hill were mined extensively during the early decades of the Klondike gold rush. However, the high cost of hand mining and the relatively low gold values of the deposit made mining uneconomical until recently, when the price of gold increased considerably.

In this operation, water is supplied to monitors from Hunker Creek by a diesel-powered pump. Water and tailings are discharged over the edge of the terrace upstream of the pump station, allowing recycling of the limited water supply. Hydraulic mining is relatively cheap for those parts of the deposit close to the edge of the terrace. However, as mining progresses back from the edge of the terrace, it becomes increasingly difficult to maintain an adequate gradient on the sluice box carrying gravel from the working face to the terrace margin. The operators are considering the use of heavy earth-moving equipment to replace hydraulicking.

From the Stutter operation, the route is retraced along Hunker Creek to the Klondike Highway. Proceed toward Dawson City 3 km and turn west on Bear Road for a distance of 0.8 km. Park and walk along the unused track for 0.8 km.

STOP 5. OPEN-SYSTEM PINGO (2 km east of Bear Creek). This pingo, one of 461 pingos identified in central Yukon by Hughes (1969), is situated at the transition between the steep south wall of the Klondike River valley and the valley floor. The pingo contains a small crater enclosed on the north (downhill) side by a high, rather steep-sided rim and on the south side by the valley wall. Vegetation on the north-facing slope above the pingo consists of black spruce, white birch, and resin birch, with a ground cover of lichen, feather mosses, and *Sphagnum*. This association, growing on an active layer 15 to 25 cm thick over permafrost, contrasts markedly with the flora on the south-facing slopes of Midnight Dome.

A small pond, measuring about 30 by 45 m with a maximum depth of 7 m, occupies the crater. The crater rim is breached on the east side near where it abuts the valley wall. This breach carries overflow from the pond during snowmelt and after heavy rains in the summer. During periods of no overflow, the water level in the pond recedes at the same rate as the level in a floating evaporation pan. On July 20, 1972, the pond water had a temperature of 20.1°C and dissolved-solids content of only 89 mg/l.

A small spring (45 l/min) issues from the outside slope below the breach in the crater rim, about 15 m from the edge of the pond. On July 20, 1972, the spring water temperature was 0.9°C, and the dissolved-solids content was 577 mg/l.

Recent isotope analyses of pond water, spring water, and average snowpack from this site are listed in table 7. Values of $\delta^{18}O$ and $\delta^{2}H$ are plotted in

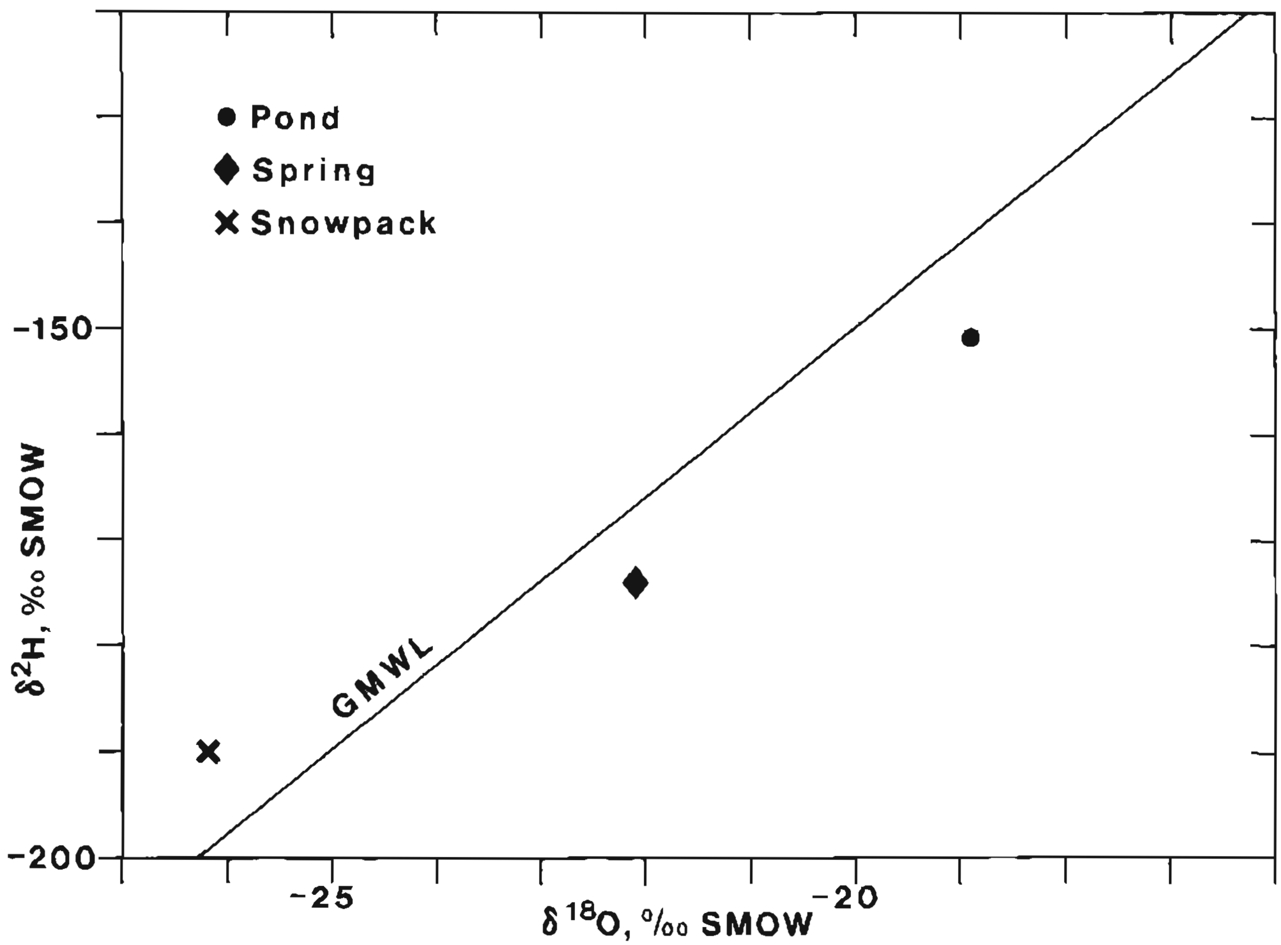

Figure 20. δ^2H vs $\delta^{18}O$ for water samples from the pond and the spring at the open-system pingo on the old Dawson road, 2 km east of Bear Creek, Y.T., and for average snowpack sample from the area. GMWL - global meteoric water line. SMOW - standard mean ocean water. (Craig, 1961).

figure 20 for comparison with the global meteoric water line (GMWL) (Craig, 1961). Both the pond water and the spring water are enriched in ^{18}O, which may be the result of isotope fractionation during evaporation (or sublimation).

From these data, it is inferred that the pond in this pingo is fed directly by snowmelt and rainfall runoff, whereas a major portion of the spring water is derived from a subpermafrost source that is recharged primarily by snowmelt.

Although the pingo is in an advanced state of decay, recent slumping and cracking along the inside of the rim indicate continuing subsidence, presumably due to further melting of pingo ice. The slumping has exposed coarse gravel around a smaller pond low on the northeast margin of the pingo.

Return via Bear Road to Klondike Highway and proceed toward Dawson City.

Table 7. Isotope data, Bear Creek Pingo near Dawson, Y.T. (analyses by F.A. Michel, University of Waterloo, Ontario).

Source	$\delta^{18}O$, ‰ SMOW[a]	$\delta^{2}H$, ‰ SMOW	^{3}H, TU[b]
Pond water 9/20/80[c]	-18.9	-151	41
Spring water 9/20/80	-22.1	-174	40
Snow pack 3/31/81	-26.2	-190	31;59

[a]Standard mean ocean water.
[b]Tritium units (1 atom ^{3}H in 10^{18} atoms ^{2}H); all values ± 10 TU.
[c]Date collected.

KM 204.3 (Klondike Highway). STOP 6. KLONDIKE VALLEY DREDGE TAILINGS. Tailings in Klondike Valley are the product of dredging that began in 1905 and continued until 1952. The highly irregular pattern of the tailings resulted mainly from both the irregular distribution of permafrost and from the evolution of techniques for preparing perennially frozen ground for mining. Early dredging was concentrated on unfrozen ground beneath the active flood plains of Klondike River and Bonanza Creek. Although both steam and later cold water were used for thawing the frozen ground, these techniques were expensive in the Klondike Valley, where the depth to bedrock was greater than in tributary creeks and the gravel had many large quartzite boulders that impeded thaw points. As early as 1906, spring runoff was used to remove the surface layer to promote thawing. Diverting water from the Klondike River by canals for the same purpose was an established practice by 1934. At about the same time, there was considerable use for large dredges to rework tailings left by smaller dredges, and to dredge patches of virgin ground that had been bypassed in following the unfrozen ground.

The settlement of Bear Creek, now under restoration by Parks Canada, was the former operation headquarters of the Yukon Consolidated Gold Corporation. Here, a span across the former course of the Klondike River carries the last segment of the Klondike Ditch, which consisted of a series of ditches, flumes, and wooden and steel siphons that carried water from the Little Twelve Mile River in the Ogilvie Mountains to hydraulic workings along Bonanza Creek. When first built, the system had a capacity of 5,000 'miner's inches' (3,500 l/sec) and cost about $3 million. The system was abandoned in 1933.

Bonanza Creek was the site of the first gold discoveries in the Klondike that led to the Klondike Gold Rush of 1896-1898. The city of Dawson grew up to service the gold-mining operations and at one time had more than 30,000 inhabitants, second only to San Francisco in western North America. Today, the population of Dawson fluctuates from 500 in winter to about 1,000 inhabitants in summer.

DAWSON CITY

Dawson is located on a restricted area of the flood plain of the Yukon River just north of the Klondike River confluence (64°03'N., 139°25'W.). The town is now protected from flooding by a dike that also supports a ring road. This dike did not prevent flooding in 1980, however, when a number of houses were damaged by exceptionally high spring floodwaters.

Surficial Geology

The flood plain is underlain by 2 to 4 m of silt over alluvial gravel. At the confluence of the Klondike River, fine sands and silts lie over the alluvial gravel. Borehole data verify a contact between the base of Klondike delta sediments and the Yukon River alluvial gravels (fig. 21). Thus, the south end of the townsite occupies a portion of the Klondike River delta where coarse-grained sediments built up contemporaneously with sediments deposited by the Yukon River. In contrast, the remainder of the townsite is underlain by silty sediments of the Yukon River. Former channels on the flood plain contain fillings of organic silt and peat and, locally, of artificial fill. A transition zone between the flood plain and the steep slope bounding the city on the east is underlain by a wedge of slopewash silt, colluvium, and organic deposits.

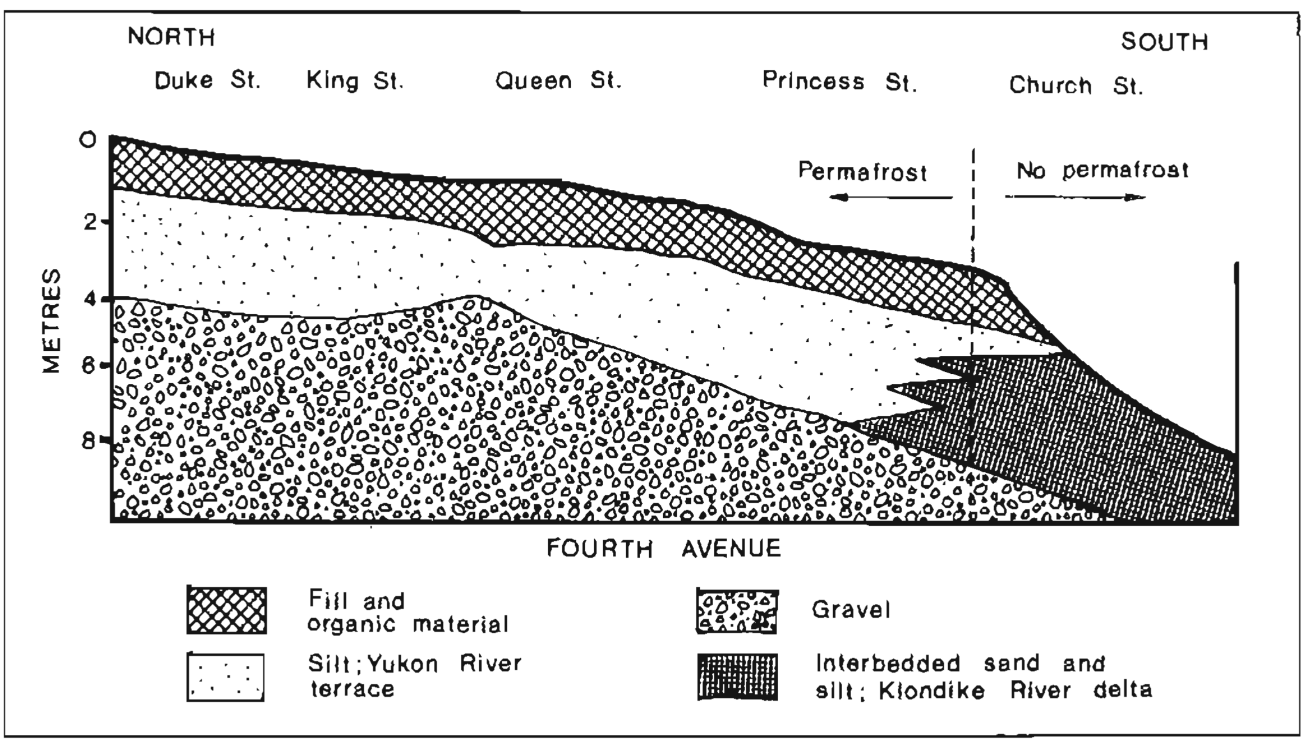

Figure 21. Generalized surficial geology along Fourth Avenue, Dawson (EBA Engineering, Limited, 1977).

Permafrost Conditions

Despite over 50 yr of occupation, much of the soil underlying Dawson retains permafrost and ground ice, and is subject to thaw settlement. A slough separates the main areas of frozen and unfrozen ground in the townsite (fig. 22). This boundary is inferred from borehole data and roughly coincides

Figure 22. Air photograph (A23905-58) showing townsite of Dawson, August 1974. Slough location is indicated; frozen ground is to the northeast and unfrozen ground to the southwest.

with the boundary between the deltaic sediments of the Klondike River and fine-grained silts and terrace sediments of the Yukon River. Figure 23 illustrates thermal conditions of the ground in unfrozen and frozen areas of the townsite. The permafrost is warm (between -3° and -1°C) and thought to be modern (that is, related to present climatic conditions). It is about 20 m deep. The active layer varies in thickness between 1 and 2 m; where muck accumulations are present, the active layer is thinner. In unfrozen zones, the depth of seasonal frost ranges from 2 to 4 m with an average frost penetration of 3 m.

Sections exposed in sewer excavations in May 1980 indicate that frozen sediments are ice rich (fig. 24). Segregated ice is present in the organic-rich silts and occurs as well-stratified or randomly oriented lenses approximately 4 to 5 cm thick. In places, the segregated ice gives a layered appearance, termed 'ice gneiss' (Mackay and Black, 1973). These sediments commonly have excess ice contents of 30 to 90 percent by volume. In addition to segre-

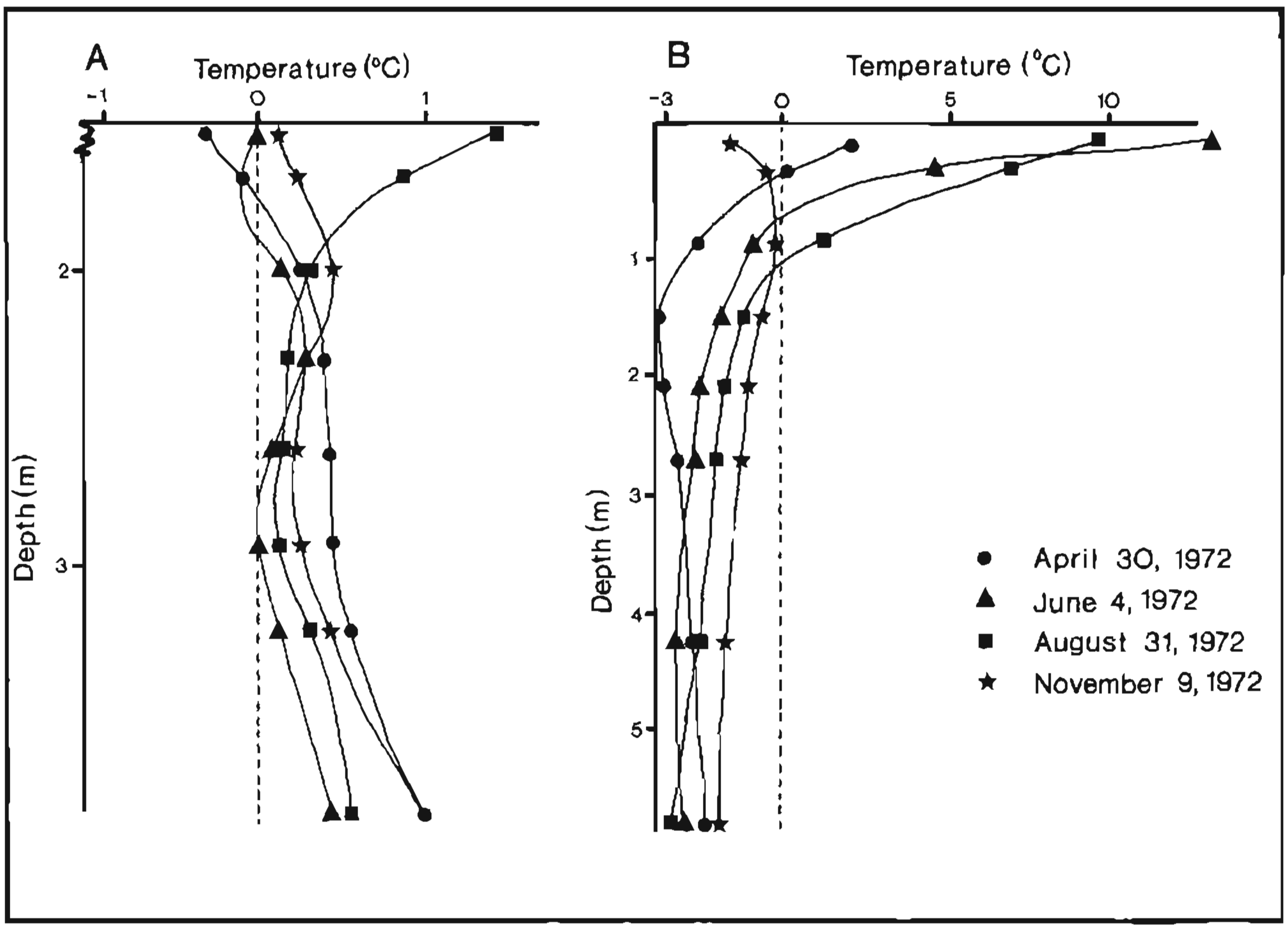

Figure 23. Ground-temperature profiles, Dawson townsite. (A) Commissioner's residence in unfrozen zone (BH 72-9); (B) Red Feather Saloon in frozen zone (BH 72-5). (EBA Engineering, Limited, 1977).

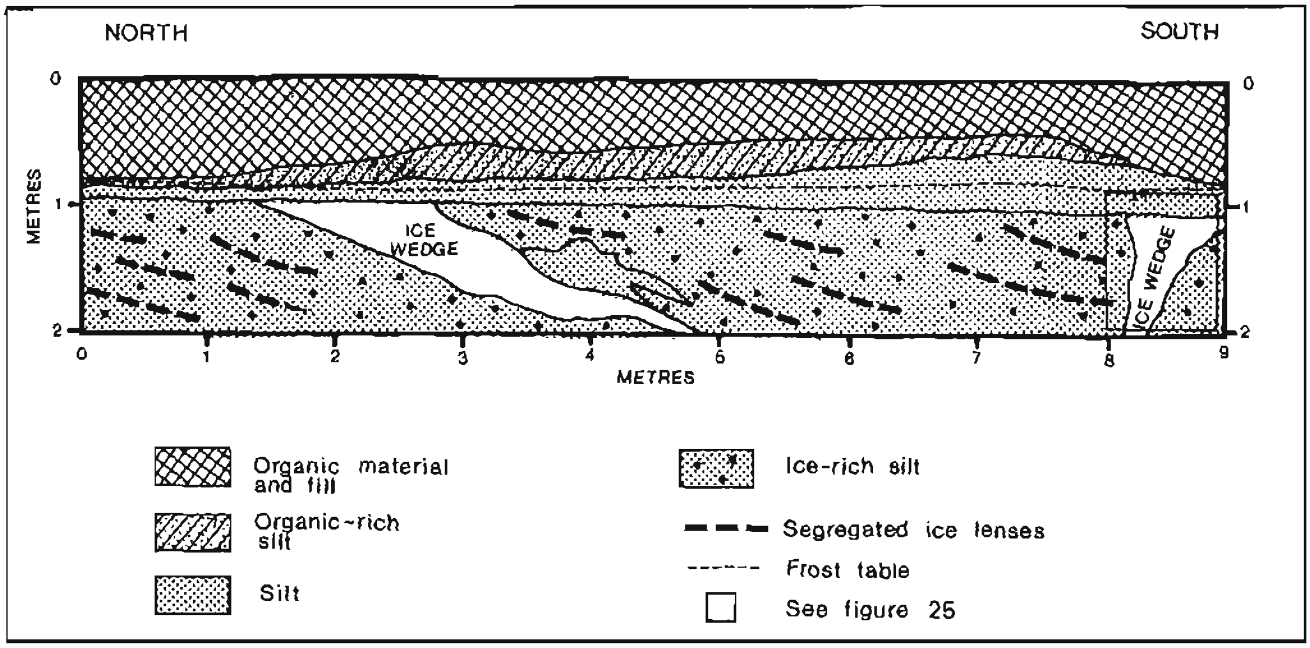

Figure 24. Generalized stratigraphy of surficial sediments exposed in sewer excavations near Robert Service School, May 19, 1980.

gated ice lenses, ice wedges are common in the silts. These wedges are all of the same general size and age; they range in width from 50 to 70 cm at the top and in depth from 1 to 2 m (fig. 25).

Building Practices

The earliest buildings in Dawson were log structures, with the lower course of logs resting on the ground. Frame buildings constructed shortly after were based on 'mud sills,' large squared timbers laid at or near the surface under the perimeter of the building. Large buildings have additional mud sills from which floors were supported by posts or cribbing. Virtually all older buildings differentially settled to some degree, necessitating periodic jacking and leveling with additional cribbing or blocking and, eventually, the replacement of sunken or rotted mud sills.

Today, several of these old buildings still illustrate the problems of construction on permafrost without adequate precautions. These structures include St. Andrews Church, built in 1901 and now abandoned (fig. 26), and the Canadian Imperial Bank of Commerce buildings on the waterfront.

Since the early 1960s, all major new buildings have been constructed on wooden piles. These buildings include the Federal Building and post office, the schools, and the Palace Grand Theatre, which was completely rebuilt from new material on the original site. Small buildings, such as private residences, are now constructed on thick gravel pads. One of the most recent buildings is the Downtown Hotel, a modern complex of over 40 rooms.

Figure 25. Ice wedge exposed in sewer excavations, Dawson, May 20, 1980.

The Historic Sites Branch of Parks Canada is engaged in a long-term restoration program in Dawson. A number of buildings have been completely restored, including the Yukon Hotel, Ruby's Place, and several others in the vicinity of the Downtown and Eldorado Hotels.

In restoring the historic buildings, Parks Canada tries to maintain the original levels of the buildings with respect to the streets, ruling out replacement of thick gravel pads above surface level. Elevation of the buildings on piles is ruled out for the same reason (as well as by high cost). In

Figure 26. St. Andrews Church, Dawson, built in 1901, is now abandoned and has suffered subsidence because of the thawing of underlying ice-rich sediments. (Photo: June 1981).

current practice, thawed soil beneath a building to be restored is excavated to permafrost and replaced by granular material. The operation is conducted as rapidly as possible to minimize permafrost degradation. If the condition of the building permits and if adjacent space is available, the building is first moved to facilitate excavation and backfilling, and is then replaced. The building is supported by short adjustable jacks placed on treated timbers.

Municipal Services

Dawson uses water from infiltration wells situated near the bank of the Klondike River. In May 1980, a new municipal water and sewage system was installed. Previously, the city water distribution and sewage systems were constructed in 1904 and consisted of woodstave pipes laid in gravel in the active layer. The water system was laid 1.2 m deep, although in some places it was as shallow as 15 cm; the sewage system was never shallower than 1.2 m. In winter, the water was heated by electricity to +5.5°C and enough flow was maintained to prevent freezing by bleeding into each house and bleeding from the dead ends of the main. At the end of the circulation system, the water temperature was about 1.1°C.

These water and sewage systems required frequent repairs as a result of seasonal frost heave, settlement due to melting of permafrost, and frost deterioration of the pipes. During the winter and spring of 1980, a new system of underground services was installed in trenches that were excavated to a minimum depth of 2 m and backfilled with coarse (frost-stable) gravel fill (EBA Engineering, 1977).

Walking Tour

A walking tour of the downtown area of Dawson City is highly recommended, not only to examine geotechnical problems of construction but also to appreciate some of the colorful and interesting history of Dawson City.

SIXTYMILE HIGHWAY

The Sixtymile Highway is a gravel road that traverses the upland divides of the Klondike Plateau (fig. 27). This is a totally unglaciated region of subalpine and tundra vegetation on which a range of periglacial landforms has developed. The plateau ranges in elevation from 1,000 to 1,300 m and is deeply dissected by V-shaped valleys. The road, linked to Dawson by a ferry across the Yukon River, is open only between late May and early October. Except for the mining operations at Clinton Creek and Sixtymile, there are no permanent settlements in this area.

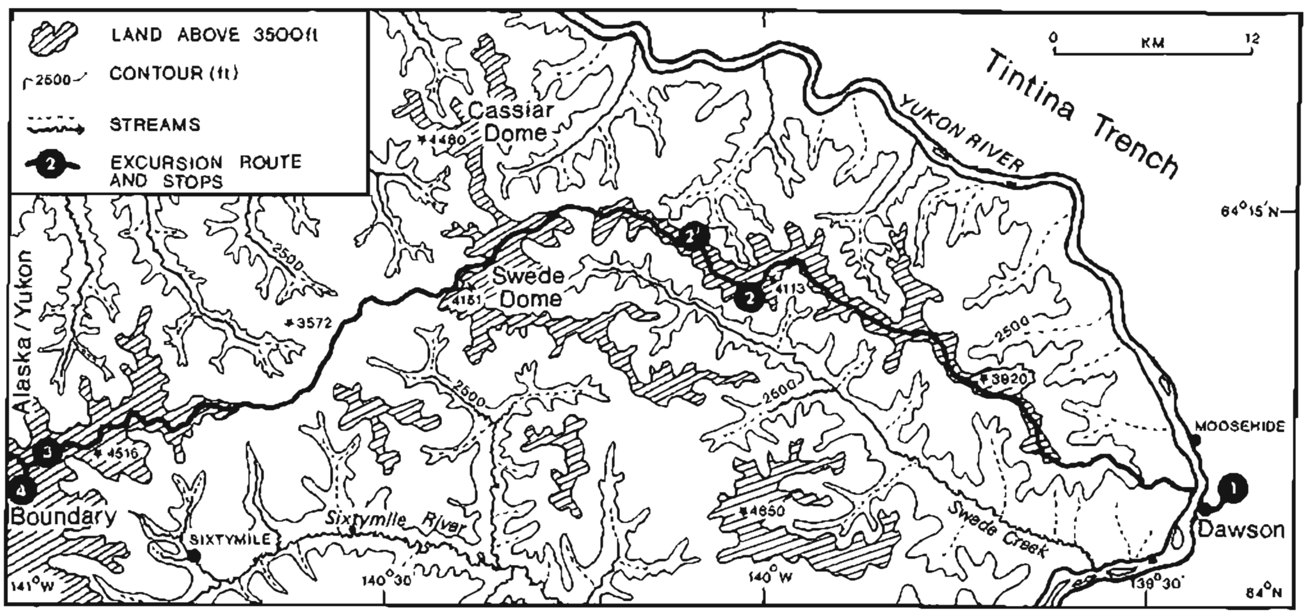

Figure 27. Topographic map of the Sixtymile Highway showing location of excursion stops.

Relatively little is known of the geology, permafrost conditions, and landforms of this part of the Yukon. The bedrock geology is complex and consists of extremely old quartzites, schists, and shales, with igneous intrusions. Extensive surficial deposits are lacking. Climatic data are also lacking, except at Boundary near the Alaska-Yukon border, and at Clinton Creek, and there are no instrumented boreholes to confirm the presence of permafrost. However, evidence along the Dempster Highway and data from mining operations indicate that permafrost is continuous and, in the absence of reliable ground-ice indicators, is assumed to be dry and thaw stable.

Road Log and Site Descriptions

Weather and road conditions permitting, the day starts with a 7.6-km ascent to the summit of Midnight Dome. From there one has a superb panoramic view of Dawson City and the adjacent Klondike goldfields.

STOP 1. MIDNIGHT DOME VIEWPOINT (7.6 km by side road from Dawson). The road up to Midnight Dome rises across remnant terraces of glaciofluvial gravel (see below) and then onto steeply sloping, deeply weathered bedrock.

The view from the lookout displays the major geomorphic features of the Klondike district. These include the general aspect of the unglaciated Klondike Plateau, with deeply entrenched streams and intervening ridges from 'domes' that rise above the plateau level, and the high terrace system of the Yukon and Klondike Rivers and Bonanza Creek. A bedrock terrace is visible immediately south from the mouth of the Klondike River (Lousetown Bench) and in Jackson Cut upstream from the mouth of Bonanza Creek. It can be traced in a series of hydraulic workings up Bonanza Creek. The bedrock bench in the Klondike Valley is overlain by a thick gravel fill considered to be glacial outwash of early Pleistocene age derived from valley glaciers in the Ogilvie Mountains that were independent of the main Cordilleran ice sheet. The upper limit of fill can be seen in a roadcut on the west side of the Yukon River and as prominent terraces downstream along the Yukon River and upstream along the Klondike River. At Jackson Cut, the bedrock bench is overlain by 40 m of nonglacial quartzose (White Channel) gravel and 45 m of glaciofluvial gravel. The latter thins rapidly up Bonanza Creek and is absent on Cripple Hill, 1.9 km from the Jackson Cut.

KM 0 (Sixtymile Highway). Return to Dawson City and take the ferry across the Yukon River. From the river, the route proceeds westward, climbing up to the level of the plateau, which is deeply dissected with local relief commonly in excess of 400 m.

KM 30-107 (Sixtymile Highway). In the subalpine region of the well-drained, unglaciated Yukon Plateau, soils exist as a thin, silty veneer overlying deeply weathered schistose bedrock. The vegetation is dominated by a shrub layer composed mainly of resin birch (<u>Betula glandulosa</u>) and some willow (<u>Salix</u> spp.). There are a few scattered white spruce (<u>Picea glauca</u>), many with a krummholtz form. The ground cover consists of several ericaceous species, including <u>Cassiope</u>, lichens, and mosses. Aspect is an important control on the elevation of the tree line. Another influence is the fire history and the stage of vegetation succession.

KM 53 (Sixtymile Highway). STOP 2. TORS ON KLONDIKE PLATEAU. Tors occur widely in the unglaciated portion of the Klondike Plateau (Hughes and others, 1972). They are developed mainly on gneisses and quartzites, especially of the Nasina Series, but examples occur on all rock types except sediments of Tertiary age.

The feature at KM 53 is formed in a quartz-mica-schist complex of the Nasina Series. It occurs on an interfluve with other tors at lower elevations on the same ridge to the south. Variations in tor morphology and distribution are illustrated by tors at KM 54 and KM 57. The latter is a large castellated tor (fig. 28) over 20 m high and 200 m long; the former is a simple valleyside

Figure 28. Castellated tor, unglaciated Klondike Plateau, KM 57, Sixtymile Highway.

tor, the outline of which is closely controlled by joint sets in the quartzite (fig. 29). The growth of lichens on the rock surfaces of all the tors examined, the absence of freshly weathered rock debris, and the stable vegetation growth around the features suggest that they are relict Pleistocene phenomena and are not forming under today's climate.

Tors are commonly associated with cryoplanation (altiplanation) terraces and are considered to be the product of parallel retreat of slopes under periglacial conditions (French, 1976, p. 154-155; Washburn, 1980, p. 78-79). Some tors on the Klondike Plateau are probably the final stages in the reduction of larger masses that have been removed by cryoplanation. Three factors suggest a different origin for many of the tors: a) the common occurrence of tors without immediate association with cryoplanation terraces, b) their occurrence on the western Klondike Plateau at a mean elevation some 150 m lower than the terraces, and c) their occurrence in glaciated areas where recognizable terraces are lacking. One possible process is downwasting by solifluction (rather than scarp retreat). Under this hypothesis, tors would be left where the rock was more resistant to weathering. Some rows of tors on sloping ridges appear to be interrupted outcrops of resistant quartzite. Individual tors may be rock masses in which jointing is more widely spaced than in surrounding rock, or rock that is locally more resistant by reason of secondary alteration, for example silicification.

Figure 29. Valleyside tor, unglaciated Klondike Plateau, KM 54, Sixtymile Highway.

KM 64.7 (Sixtymile Highway). Swede Dome, elevation 1,265 m. Part of this elevation relates to the presence of low- to medium-grade metamorphic rocks.

KM 101.5 (Sixtymile Highway). STOP 3. SOLIFLUCTION LOBES AND SOIL STRIPES. In the lower alpine and subalpine zones, solifluction lobes are generally limited to sites with a moderately fine soil matrix, excess moisture due to seepage, and slopes greater than 12°. Stripes occur on lower slope gradients and are not dependent on excess moisture conditions. The alpine vegetation on the north-facing slope has a high proportion of mosses and ericaceous shrubs, with some sedges and herbs.

KM 107 (Sixtymile Highway). STOP 4. CRYOPLANATION TERRACES AT THE CANADA-UNITED STATES BOUNDARY. The site is a ridge located 1.2 km east of the Yukon-Alaska International Boundary, and about 150 m west of the old Sixtymile Highway. The maximum elevation is 1,315 m and relative relief in the general area is 585 m.

A series of well-defined, gently sloping bedrock surfaces occur, in a steplike manner, on the west-facing interfluve (figs. 30 and 31). They are separated by steep bedrock scarps. On the basis of morphology and the widespread occurrence of lichens on the rock rubble surface, Reger (1975;

Reger and Péwé, 1976) interprets these features as inactive cryoplanation terraces.

Figure 30. Cryoplanation terraces 1.2 km east of the Yukon-Alaska boundary, Klondike Plateau, Sixtymile Highway.

The ridge summit is above timberline and the vegetation consists of a herbaceous-lichen alpine tundra. In the valley immediately to the west, spruce reaches an average elevation of about 818 m on northwest-facing slopes, and in wetter, more favorable sites, extends to an elevation of about 1,120 m. On southeast-facing slopes, spruce extends to an average elevation of about 1,030 m and a maximum altitude of 1,090 m. Subalpine shrub tundra (birch and willow) has an upper elevation limit of about 1,150 m on the southeastern flank of Davis Dome, a hill rising to 1,250 m elevation farther to the west.

A short but nearly complete climatic record was obtained from the Boundary landing strip, located 6.2 km to the west at an elevation of 890 m. According to this record, between 1948 and 1957 the average annual temperature at Boundary was -5.5°C and the average summer temperature was 11.4°C (table 8). From June through August, the average total precipitation was 19.4 cm; the annual average precipitation was 33.8 cm.

The local bedrock is dominantly metamorphic and includes carbonaceous quartz schist, quartz-sericite and quartz-muscovite schist, and gray micaceous quartzite. An increase of metamorphic grade to the west is indicated by the

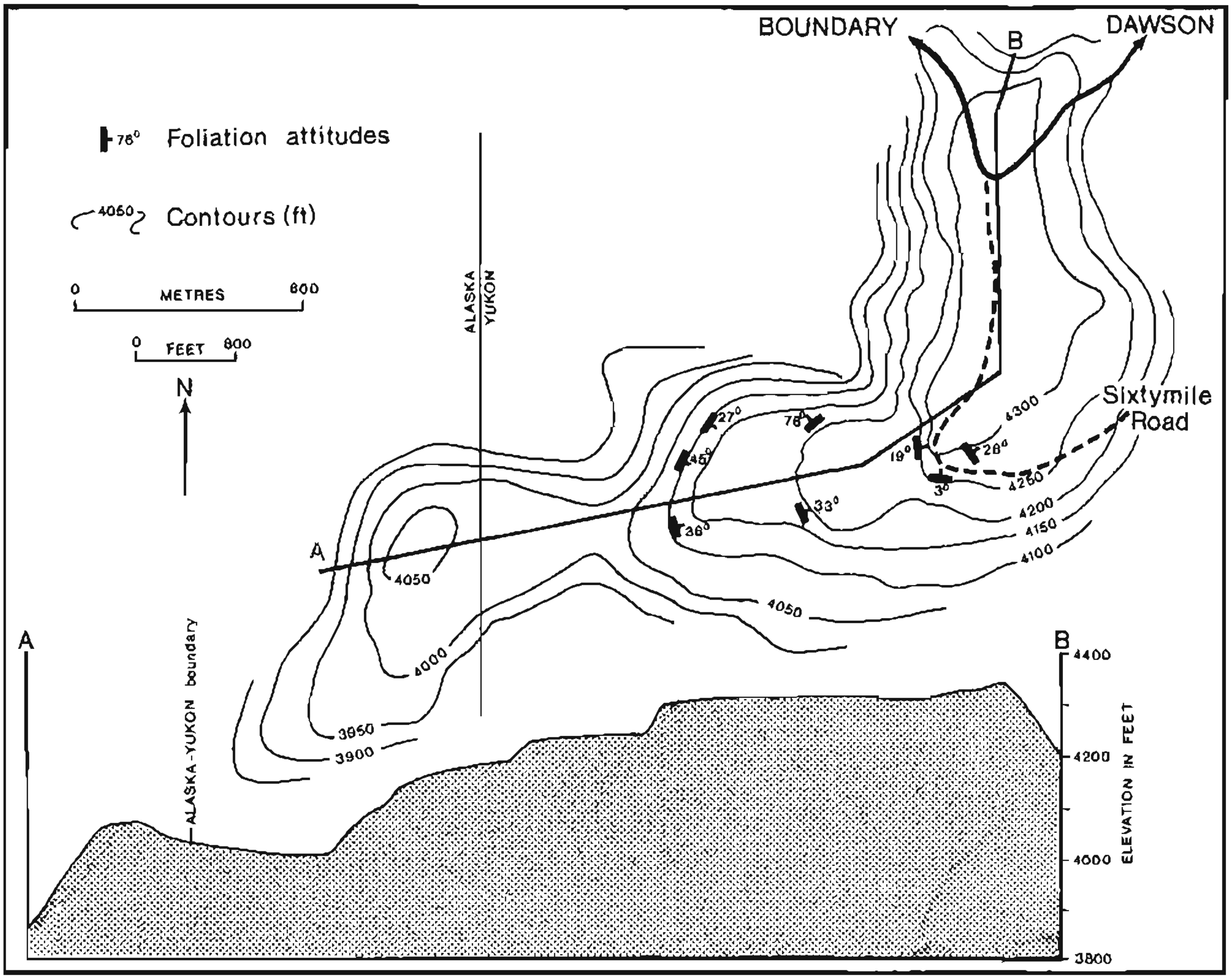

Figure 31. Topographic map of cryoplanation terraces near Yukon-Alaska boundary, Klondike Plateau, Sixtymile Highway, showing typical attitudes of foliation in bedrock of cryoplanation scarps (Reger, 1975).

common occurrence of gneissic rocks and the presence of garnetiferous schists and amphibolites.

Typical attitudes of foliation in the bedrock of the cryoplanation scarps are illustrated in figure 31. Because dip directions and attitudes bear no resemblance to the surface morphology, it must be concluded that the terraces are erosional features. Although there is local evidence of frost shattering of bedrock along the scarps, the occurrence of crustose lichens on the terrace surfaces suggests that the terraces are not being formed in the modern periglacial climate. The age of their formation is unclear.

During the stop, an opportunity exists to examine the nature of these striking terrace features. Large, inactive, nonsorted polygons formed in angular bedrock fragments and smaller nonsorted patterns formed in fine-

Table 8. Summary of climatological data for Boundary, Alaska (1948-1957) (64°04'N., 141°07'W.; elevation 890 m) (Reger, 1975).

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Ann.
Avg monthly temp (°C)	-24.4	-21.3	-12.2	-4.5	4.7	10.9	12.6	10.8	4.5	-6.2	-16.2	-24.4	- 5.5
Yr recorded	9	9	9	9	9	6	8	9	8	9	9	7	--
Avg monthly precipitation (cm)	1.1	0.9	0.8	0.6	3.3	5.9	6.7	6.8	2.5	2.0	1.2	2.0	33.8
Yr recorded	8	9	8	6	9	6	8	9	8	7	9	7	--

grained material occur widely over the surfaces. The existence of the terraces is unquestionable; the processes responsible for their formation and age are debatable.

Return to Dawson City.

THE DEMPSTER HIGHWAY - DAWSON TO EAGLE PLAIN

By
S.A. Harris,[1] R.O. van Everdingen,[2] and W.H. Pollard[3]

The Dempster Highway, linking Dawson City and Inuvik, is one of the most scenic wilderness roads in the world. The only visitor facilities are at Eagle Plain Hotel, some 363 km after leaving the Klondike Highway at Klondike Lodge. This situation limits the possibilities for stops along the route and those noted in the guide have been chosen to provide a sample of the range of permafrost features and associated landforms along the route.

HISTORY OF THE DEMPSTER HIGHWAY

The highway follows an old route used to travel through the mountains from the Yukon Plateau to the Arctic Ocean. This route was usually traversed in winter because major rivers are frozen and become gently sloping 'highways.'

During the Klondike Gold Rush, large numbers of people arrived in the vicinity of Dawson City. The Northwest Mounted Police (the forerunners of the Royal Canadian Mounted Police---the 'Mounties') followed them to maintain law and order. When the main gold rush subsided, some adventurers followed the rivers into other parts of the mountains to continue their search for gold. As the work of the Mounted Police stabilized in Dawson City, a detachment was given the task of traveling overland to the old whaling station of Herschel Island, off the Arctic coast of the Yukon, and also to the fur-trading post of Fort McPherson. This responsibility gave them the opportunity to police the mountains of northern Yukon, to keep an eye on the activities of the trappers, and to deliver mail.

Between 1904 and 1921, the trip from Dawson City was made twice a year over the frozen rivers with dog teams. Intermittent patrols were made in this way until 1945. One of these patrols, upon leaving Fort McPherson in December 1910, became lost by taking the wrong tributary of the Peel River in its attempt to go to Dawson City. The trip normally took about 50 days, and when they had not been seen in 60 days, a second patrol under the command of an enthusiastic and tough Corporal Dempster left Dawson City on February 28, 1911, to look for them. Dempster traveled the usual route---up the north fork of the Klondike River, down the Blackstone River, over Engineer Creek Pass into the Ogilvie River drainage, and finally across the Richardson Mountains and into the Peel River drainage. He found the remains of the 'lost patrol' some 50 km south of Fort McPherson and brought them into that town, where they were buried. His trip took about 45 days. Dempster went on to become a superintendent and had a major influence on Mounted Police activities in the area.

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After World War I, aircraft took over the distribution of mail in northern Canada, and the need for the police patrols supported by dog teams declined. It was obvious, however, that significant mineral resources were likely to be found in northern Yukon Territory. Indeed, since 1935 tracked vehicles have been used in groups---'cat trains'---to haul supplies to the few hunting, fishing, and mining camps on the eastern portion of Eagle Plain and Peel Plateau. In the 1950s the Canadian government decided that northern Canada should be opened by road development.

In 1954, the first oil well (Chance No. 1) was drilled and the utility of a road through the region became apparent. Accordingly, between 1958 and 1964, the first section of the road was constructed as far as Chapman Lake. This segment traversed discontinuous-permafrost terrain to North Fork Pass and then descended part of the way down the valley of the Blackstone River over continuous permafrost. Cat trains hauled supplies to more distant localities in winter.

Road construction stopped at Chapman Lake because of a change in priorities of the government of the time. Oil and gas exploration continued, however, and, in 1975, the second stage of highway construction began. By late 1976, the road was completed across the Yukon Territory except for the crossing of Eagle River. The Eagle River bridge was constructed during the next winter and the Eagle Plain Hotel was added in 1978 before the official opening of the road in 1979. The hotel provides accommodations, garage, and repair facilities about 363 km along the route.

The last section of the road to be completed was between the Yukon border and Fort McPherson. This area has steep grades over siltstone bedrock, which weathers to silt by frost action, producing a surface that is slippery when wet. In one place the road follows a stream bed through a gorge, where there are considerable icing problems in winter. The weather on the east side of the Richardson Mountains divide is much wetter, and snow falls in any month of the year; this section remains the most difficult part of the highway to negotiate.

The highway has made a significant impact on the transfer of goods to the Mackenzie Delta region. Barge traffic on the Mackenzie River can only operate for about 3 months each year and winter roads can only be used for about 4 months each year. The Dempster Highway, by contrast, provides an almost year-round---albeit adventurous---route for hauling goods. Recently, much of the equipment and supplies for oil and gas exploration in the Beaufort Sea moved along it. Barge traffic on the Mackenzie River has decreased considerably.

PERMAFROST AND TERRAIN CONDITIONS

The Dempster Highway transects through 4½ degrees of latitude from the Yukon Plateau to a point where continuous permafrost occurs at sea level beyond the northern fringes of the northern boreal forest (taiga). Along the way, it passes through the Ogilvie and Richardson Mountains and the intermontane plateau of the Eagle Plain. It descends to the Mackenzie Valley just south of the Mackenzie Delta and continues along the eastern margin of the delta to Inuvik.

Timberline descends from near 1,219 m elevation at Dawson City to 750 m at Eagle Plain Lodge and to about 100 m at Inuvik. Thus the road covers the transition from northern alpine permafrost to lowland arctic permafrost. This road transect is unique in Canada.

Discontinuous permafrost occurs from the vicinity of Dawson City through the valley of the North Klondike River as far as North Fork Pass. Thereafter the entire route lies within the zone of continuous permafrost, as demonstrated by data from thermistors installed in boreholes drilled along the route of the proposed Dempster Lateral Gas Pipeline.

The route also passes through glaciated terrain in the Southern Ogilvie Mountains (due to local mountain glaciation), areas of Laurentide glaciation in the Mackenzie Valley, and large areas of unglaciated terrain between the Ogilvie Range and the east side of the Richardson Mountains.

Highway Construction

Major considerations in road building in northern Canada include preservation of permafrost along the right-of-way, selection of road-building materials, and the design of river-crossing facilities. With regard to the first concern, experience has shown that disruption of the insulating surface vegetation cover may induce thawing of permafrost, leading to thermokarst development and possible erosion wherever ground-ice amounts are high. Consequently, modern construction techniques avoid stripping of the surface vegetation mat except where roadcuts are essential. Normally, right-of-way preparations simply consist of cutting down trees by hand. The roadbed is then laid over the relatively undisturbed surface vegetation by progressive end dumping.

Once in place, the road can destabilize thermal regimes because road-building materials commonly have different thermal properties than the underlying materials. Usually, the roadbed has a higher thermal conductivity and a lower moisture content than the neighboring terrain (bedrock exposures excluded). Hence, the road is a poorer insulator than natural ground and greater heat flux occurs through the road than through adjacent terrain. In summer, the thaw front penetrates to greater depths under the road surface than under natural conditions. If the depth of fill in the roadbed is insufficient, thaw can proceed beyond the preconstruction permafrost table and thermokarst subsidence may follow if the ground-ice content is high. Good gravel deposits for road construction along the Dempster Highway right-of-way are limited because much of the region is unglaciated. Thus, the most common material used has been bedrock, particularly shale, obtained from quarries along the route. With gravel in such short supply and because of the need for a thick roadbed to maintain permafrost stability, experiments have been undertaken to study the use of insulating layers within the fill. Three test sections have been built along the highway, one near the Eagle River crossing and two south of Inuvik, where insulation has been incorporated and its effects monitored.

At river crossings along the Dempster Highway, culverts or bridges were installed or ferries are used, depending on the size of the crossing. With regard to culverts, a number of important design criteria were developed. It was suggested, for example, that culverts not be used at sites where the upstream drainage area exceeds 100 km^2. However, because of the great number of stream and river crossings involved and the high cost of bridge construction, culverts have been installed on basins that may exceed 1,000 km^2 in area. Various culvert diameters are chosen to accommodate expected peak flood discharges with recurrence intervals of 50 yr. A major difficulty in culvert design has been the lack of available hydrologic data for small drainage basins throughout the northern Yukon and Mackenzie valleys. As a result, discharges were estimated by indirect techniques such as the rational formula and the slope-area method. In addition, culverts are installed with their bases at or below the natural stream-bed elevation to discourage the formation of upstream ponds and downstream plunge pools.

The higher and sustained water velocities that occur within culverts may block fish migration in the upstream direction. Several important fish species have an upstream spawning run during the spring snowmelt flood, when water velocities are already high under natural conditions. Studies of fish swimming performance show that mean cross-sectional water velocities in excess of 0.9 m/s over the length of these highway culverts are detrimental to fish passage. Therefore, mean water velocities within culverts do not exceed 0.9 m/s except for a maximum allowable period of 3 days during the mean annual flood and 7 days during the 50-yr-design flood.

In addition to flood-discharge prediction, the occurrence of river-channel icings in winter is an important design consideration. Culvert interiors, shielded from direct solar radiation, are preferred locations for icing development. In some instances where the chosen culvert diameter is inappropriate, icings completely block culverts during winter and pose an obstruction to spring flood. Remedial measures include steaming, the installation of larger culverts, and the improvement of drainage ditches. Important icing localities along the Dempster Highway are indicated in the road log.

Although roadcuts were avoided as much as possible, a number were necessary, especially north of the Eagle River crossing. Some cuts exposed ice-rich permafrost and degradation of the cuts resulted. Others fill with snow in winter and seasonal bypasses had to be constructed. Localities where these problems exist are also indicated in the road log.

ROAD LOG AND SITE DESCRIPTIONS

Leave Dawson and proceed about 41 km east on the Klondike Highway to Klondike Lodge, at the southern terminus of the Dempster Highway. (All distances on the Dempster Highway are measured from Klondike Lodge.)

KM 0-129. Klondike Lodge to Chapman Lake. Turn northeast on the Dempster Highway. The Dempster Highway follows the Klondike River valley through the Ogilvie Mountains. Continuous permafrost exists at higher elevations, and there is discontinuous permafrost in the valleys. In the first 15 km, permafrost occurs only in valley bottoms and on lower slopes; no permafrost occurs on higher, well-drained terrain. After 45 km, permafrost becomes almost continuous except in areas of tall willows on the valley floor.

There, snow accumulates to the level of the tops of the willows in winter and spring, providing ground insulation.

At a distance of about 30 km, the highway enters glaciated terrain of the Ogilvie Mountains. Low, forested ridges on either side of the road are moraines related to the oldest glaciation of the Ogilvie Mountains (Vernon and Hughes, 1966; fig. 32). Evidence of at least three glaciations is present in the Ogilvie Mountains in the form of lateral or end moraines, numerous cirques, oversteepened headwalls, and broad, U-shaped valleys (for example, Tombstone Valley).

KM 34. STOP 1 (OPTIONAL). ICING SITE. A perennial discharge of water from intrapermafrost or subpermafrost flow systems in mixed alluvial and talus fans west of the highway feeds small streams that can cause severe highway icing problems in winter. At this locality, the small stream discharges only about 25 l/s, with a water temperature of 3°C and dissolved-solids content of 97 mg/l. The icing it produces in winter blocks the culvert and fills the upslope drainage ditch; in some winters, the icing covers the roadway north of the stream crossing over a distance of more than 400 m. Channel improvements to provide a straight, narrow channel from the discharge area to the culvert will eliminate much of the icing problem at this site.

KM 68. STOP 2 (PHOTO STOP). OLD ROCK-DEBRIS FAN OR ROCK GLACIER. Rock glaciers or rock-debris fans are common in the Ogilvie Mountains (Vernon and Hughes, 1966) (fig. 32). Typically, they are in north-facing cirques at elevations above 1,400 m. The dominant rock at this locality is Keno Quartzite; the feature faces west, heads at 1,460 m, and extends down to 975 m. The outer ramparts resemble a rock glacier, whereas the younger, inner material appears to be formed of debris-flow deposits (fig. 33).

Tracks of both cliff and gully avalanches are numerous in the vicinity. These paths are marked by low shrubs forming vertical stripes down the hillsides. Snow avalanches cause an unusually low tree line in the area. Farther along the highway, at KM 105, the road passes through a forested area that is free of avalanche danger. Tombstone Campground is deliberately located in an area of minimal snow-avalanche danger.

KM 76. STOP 3. PANORAMIC VIEW UP NORTH KLONDIKE VALLEY TO TOMBSTONE MOUNTAIN (elevation 1,189 m). Tombstone Mountain, the most distinctive peak in the Ogilvie Mountains, was used as a landmark by early trappers, Mounted Police patrols, and aircraft. It is composed of syenite (Tempelman-Kluit, 1970). The U-shaped glacial valley is obvious (fig. 34).

Just visible from this stop is a wide, braided section of the flood plain of North Klondike River. This braided reach is the area of a large icing, about 1.3 km long and up to 240 m wide, which forms each year. The icing area shows evidence of lateral erosion by meltwater channeling along the edges of the icing during the spring melt. Most of the ice is usually gone by mid-July. Water is supplied to the icing by ground water discharging into North Klondike River farther upstream. The discharge area is characterized by well-developed willows and poplars. This is one of the last areas of discontinuous permafrost before ascending North Fork Pass.

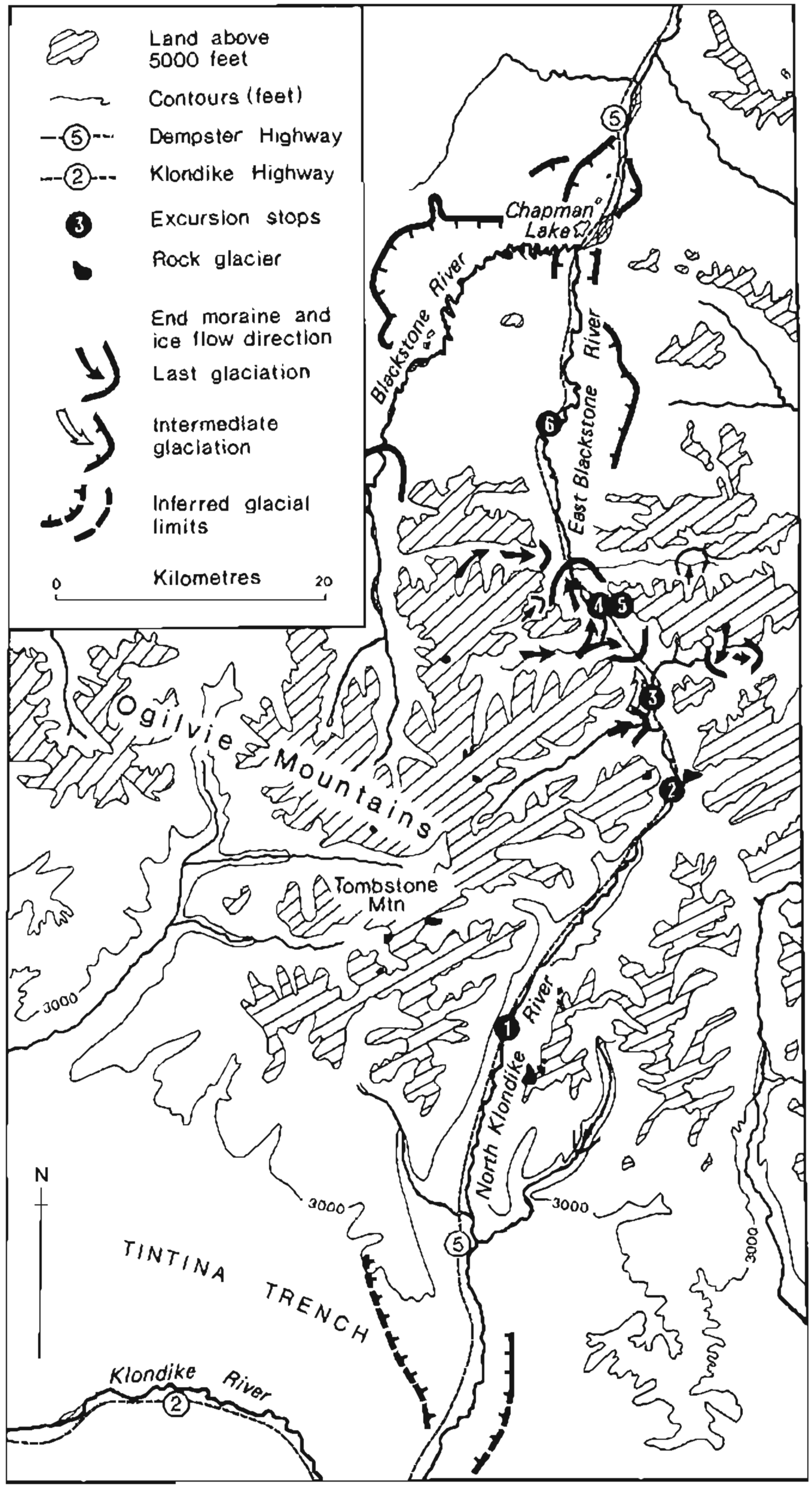

Figure 32. Map of landforms and surficial geology of the North Klondike and East Blackstone valleys to Chapman Lake (Vernon and Hughes, 1966).

Figure 33. Stabilized rock glacier (debris flow), North Klondike valley, KM 68, Dempster Highway.

About 5 km ahead is the prominent North Fork Pass moraine of the McConnell Glaciation. The glacier originated in the East Blackstone River valley (fig. 32). The ridge has a sharp crest and is hummocky, in sharp contrast to older moraine systems in the Ogilvie Mountains. The East Blackstone River valley is U shaped in cross section; the glacier moved both north and south in North Fork Pass, forming a distinct 'hammerhead' moraine.

Ground-temperature measurements in the North Fork Pass area indicate continuous permafrost with temperatures between -8° and -2°C below a 3-m-thick active layer. The elevation of the pass is 1,370 m.

KM 86. STOP 4: SEASONAL FROST MOUNDS. An area of gently sloping, wet alpine tundra situated in the valley floor downslope from the highway is a location where, each winter, several groups of small, seasonal frost mounds develop. Cold, mineralized perennial springs discharge from the base of a till-alluvial-fan talus slope. The location of the outlets and the amount of seepage vary seasonally. Low concentrations of dissolved solids indicate that the springs discharge from local flow systems that presumably receive their recharge at higher elevations in the mountains directly above the highway (maximum elevation approximately 2,000 m). The results of isotope analysis of spring and snowpack samples show that oxygen (^{18}O) and deuterium (^{2}H) values correlate reasonably well with the global meteoric water line (GMWL), indicat-

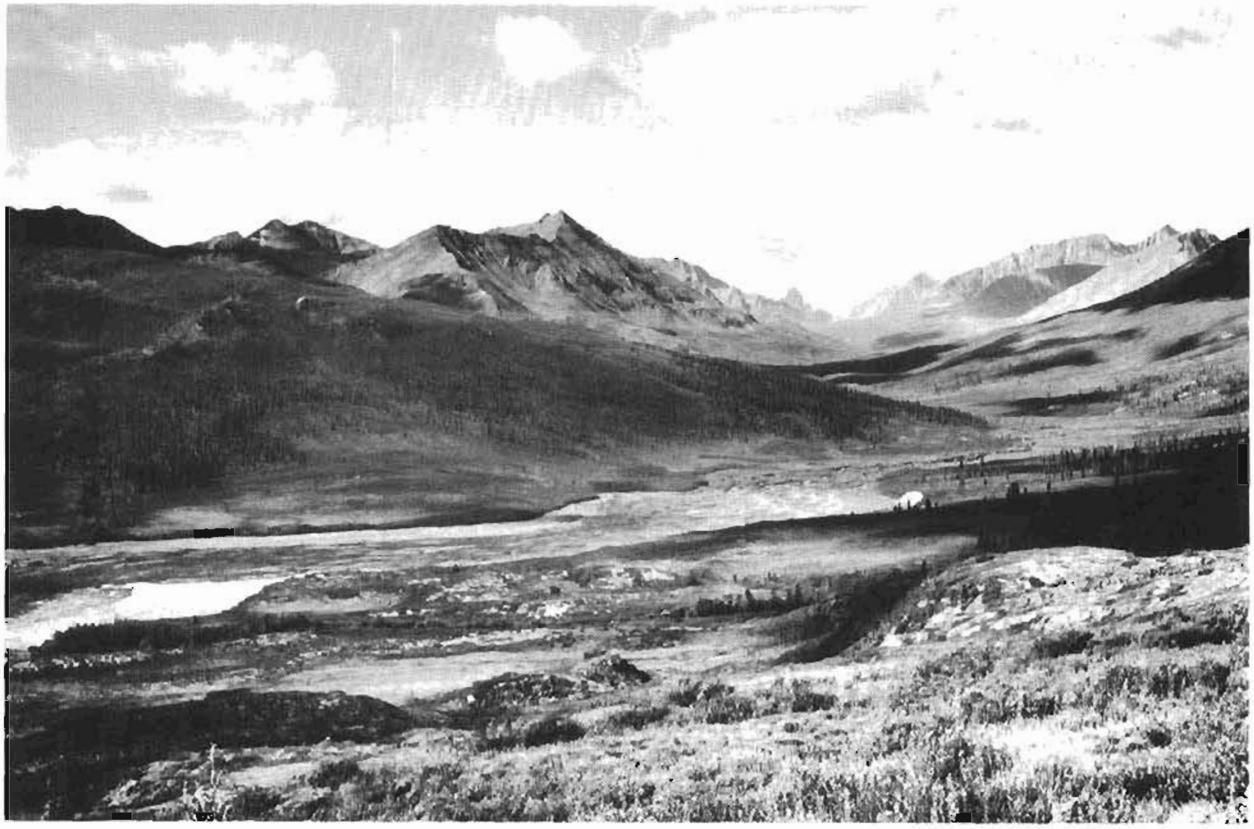

Figure 34. View of upper part of North Klondike valley showing Tombstone Mountain in background and U-shaped valley, KM 76, Dempster Highway.

ing that unaltered precipitation probably provides water for the spring discharges.

Seasonal frost mounds occurring in this setting are a ground-water-discharge phenomenon resulting from hydraulic pressures developed in suprapermafrost ground water flowing through or trapped within a residual section of the active layer during winter freezeback. The formation of seasonal frost mounds requires low-temperature, perennial spring discharge, long, cold winters characterized by deep frost penetration, and suitable stratigraphic conditions where a relatively thin aquifer is underlain by a low-permeability aquitard. The perennially frozen mineral soil overlain by peat and fine-grained sand and silt at this location provide a suitable stratigraphic setting. A hydraulic gradient with enough hydraulic potential to deform and displace overlying materials is also a requirement.

In the North American literature, seasonal frost mounds were first defined by Muller (1947), who distinguished between frost blisters, icing mounds, and icing blisters. All three types occur in the North Fork Pass area. Icing mounds and icing blisters differ from frost blisters in that they are composed entirely of ice and frequently form part of an icing accumulation. As such, they may be associated with river icings as well as ground-water (seepage) icings.

A simple model of frost-blister formation was first presented by Muller (1947, p. 61). A detailed model showing the evolution of both frost and icing blisters and a surface icing through a complete cycle of development is illustrated in figure 35.

Seasonal frost mounds are common in this part of the East Blackstone River valley. At least six other similar locations are known. Between 1980 and 1982, more than 30 seasonal frost mounds were noted at this particular site (figs. 36A-D). They occur frequently in groups of two or three. Some low, structurally intact features have existed for almost 3 yr and in at least three instances there appears to have been some reactivation of a mound. In one case, a frost blister was surveyed in 1980; although partially collapsed, its height was 1.2 m. In 1981, the same mound had a height of 2.3 m and displayed a larger and distinctly different shape. In other cases, the changes observed were not as dramatic.

During the period of observation, the largest mound attained a height of 2.4 m and a long-axis basal diameter of 37 m. A large number of small features less than 1 m high were observed, but most were between 1.2 and 1.5 m high and 15 to 25 m in diameter. On the other side of the valley, frost blisters have reached heights of 3.5 m and displayed long-axis basal diameters of 57 m; these large features have occurred as single features.

The structure of frost blisters has been examined by excavating partially collapsed features and by coring whole ones. The typical internal stratigraphy consists of a layer of 30 to 50 cm of peat and organic-rich silt overlying 50 to 120 cm of clear, layered ice, domed up over a cavity 20 to 40 cm high and containing water. On a number of occasions, the cavity was not present, and the ice covered a fine-grained mineral soil. Where the mound had ruptured, the water cavity was empty.

In March 1982, several frost blisters and icing blisters 1 to 2 m high were drilled and instrumented with antifreeze-filled piezometers to measure hydraulic potential. A number of mounds were obviously inactive as a solid ice core was encountered; in six cases, however, water under pressure was encountered inside the frost mound. Measurements made on four of these features displayed hydraulic potentials which ranged from 25 to 70 kPa. In some cases, pressure did not redevelop once it had been released. On one occasion water discharged for more than 5 hours, and the height of the mound decreased from 1.3 to 1.1 m.

Tension cracks frequently develop in surface ice and peat layers during frost-mound formation. Radial cracking patterns have been observed for conical mounds, whereas elongated mounds display a longitudinal crack pattern. Although tension cracks up to 30 cm wide have been seen, they tend to close as the mound collapses or subsides. In some cases the crack penetrates deep into the ice core.

KM 86. STOP 5 (OPTIONAL). LIMITS OF MOUNTAIN GLACIATION. At this locality, the end moraine of the last (McConnell) glaciation can be seen. The contrast between the freshly glaciated valley of the East Blackstone River and the unglaciated uplands and mountains in the distance to the north is apparent.

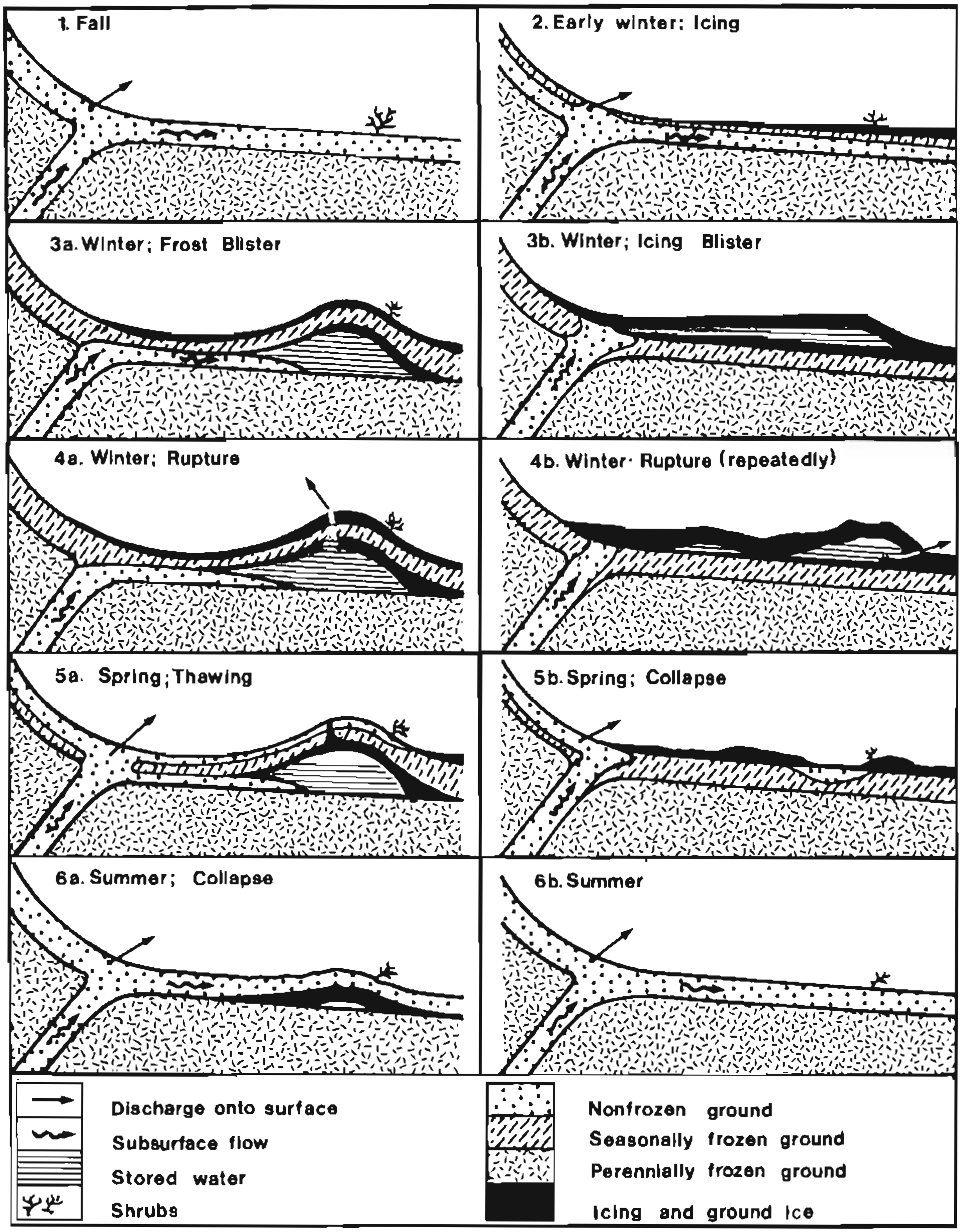

Figure 35. Schematic drawing of the sequence of events in the formation of frost blisters and icing blisters (van Everdingen, 1978).

At KM 107, the terminal moraine of the most extensive (Reid) glaciation is passed (fig. 32).

KM 98. STOP 6. ROAD-CONSTRUCTION PROBLEMS AND MAN-INDUCED THERMOKARST. One of the early techniques used in building the Dempster Highway consisted of scraping off the surface organic layer and then laying a gravel pad. At this particular locality in 1961, a 400-m-long section of the proposed road was left without a gravel pad until the following year. By the following spring, a long, narrow thermokarst lake had formed where the road alignment crossed ice-rich permafrost. The original alignment was abandoned. In subsequent years, a hummocky microrelief, typical of man-induced thermokarst topography, developed with a local relief in excess of 2 m. Investigations of ice content in adjacent terrain indicate that ice may constitute as much as 70-80 percent by weight of the mineral soil. Ground temperatures of -5°C at 2.7 m depth have been measured. In addition, an inactive system of ice wedges is present, as indicated by shallow depressions marking the polygons.

To prevent the ponding of surface water, which would lead to thawing of the permafrost, a series of drainage realignments was made adjacent to the present road.

KM 129-198. Chapman Lake to Ogilvie River. North of Chapman Lake, the route of the highway continues through the valley of the Blackstone River for about 30 km. It then crosses over into the main valley of the Ogilvie River via the valley of Engineer Creek.

KM 165. STOP 7 (OPTIONAL). ENGINEER CREEK PASS (elevation 1,067 m). The limestone in these unglaciated mountains has been frost shattered to an extent that the valley walls consist of block (scree) slopes close to the maximum angle of repose. Typically, upper hillslopes are convex and debris-flow aprons are common at the foot of the gullies. There are few trees or shrubs on east-facing slopes, but a reasonable cover exists on west-facing slopes. Solifluction processes are widespread. Tors appear as cliff remnants with increasing frequency downvalley. North of Engineer Creek airstrip, the limestone bedrock is replaced by shale, which supports more vegetation on all slopes.

KM 172. STOP 8 (OPTIONAL). IRON-RICH DISCHARGE AND SULFUROUS SPRINGS, ENGINEER CREEK. At this point, the highway crosses a small stream of brownish ground-water discharge that has a temperature of about 9°C and a dissolved-solids content of about 1,080 mg/l. Chemical analyses (table 9) indicate a high sulfate content and a relatively low iron content. Iron also occurs in the stream as suspended iron hydroxide, giving the brownish tinge to the water; in addition, the stream bed upstream and downstream from the bridge is covered with brown iron hydroxide, indicating that a portion of the original dissolved iron is lost by deposition. The significant iron and sulfate contents are presumed to be derived from oxidation of iron sulfides.

About 200 m beyond the bridge, a group of sulfurous springs discharge below an outcrop of black shale of the Cambro-Ordovician Road River Formation. The spring water has a temperature of 6°C and a dissolved-solids content of 1,454 mg/l. The smell of hydrogen sulfide pervades the air near the springs. Chemical analysis of the water (table 9) shows high calcium, magnesium,

Figure 36. Seasonal frost mound, North Fork Pass. (A) Frost blister 3.5 m high on west side of North Fork Pass, March 15, 1982; (B) icing blister, 200 m downslope from KM 86, North Fork Pass, March 13, 1982. Blister is 1.7 m high; associated icings extend to the nearest tributary of the East

Figure 36 (cont.)

Blackstone River; (C) section through frost blister at North Fork Pass showing ice core and internal stratigraphy, September 25, 1980; and (D) frost blisters at locality B, July 26, 1982.

Table 9. Ground-water (A-D) and surface-water (1-7) chemistry along Engineer Creek (EC) and Ogilvie River (OR), Y.T. (see fig. 37).

	A Iron-rich discharge A (Km 172)	B Sulfur springs (Km 172)	C Iron-rich discharge C (Km 178)	1 EC below discharge C	2 EC above acidic discharge	D Acidic discharge (Km 184)	3 EC below acidic discharge	4 EC above confluence with OR	5 OR above confluence with EC	6 OR below confluence with EC	E Castles Hill springs	7 OR below Castles Hill springs
Parameters												
Temperature (°C)	8.9	3.0-7.0	7.7	0-13.0	9.8	6.0	--	0.5-13.0	0-15.0	0-16.0	4.0-6.0	0-13.0
pH units	7.3	7.4-7.5	7.9	7.6-8.2	7.9	2.8	4.0	7.4-8.2	7.4-8.2	7.4-8.3	7.6	7.4-8.3
Conductivity (µS/cm)	1200	1700-1800	600	256-789	773	5620	1580	176-703	137-575	124-561	438-460	134-450
Constituents (mg/l)	(c)	(a), (c)	(c)	(a)	(c)	(b)	(b)	(a)	(a)	(a)	(a), (c)	(a)
Calcium	202	151-159	108	35.9-115	129	174	118	25.0-105	21.7-73.4	20.0-75.8	63.6-68.8	22.3-60.3
Magnesium	59	51.2-89	20.5	8.6-37.5	31.7	577	123	5.6-24.7	2.2-23.0	1.6-22.0	15.1-16.0	2.0-15.2
Sodium	19	121-125	1.4	1.6-15.4	9.6	--	--	1.6-12.6	2.1-14.8	3.4-12.6	6.1-7.7	3.0-12.3
Potassium	1.8	4.4-4.5	0.5	0.3-1.2	0.9	--	--	0.3-1.0	0.2-0.8	0.3-0.7	0.4-0.5	0.3-0.8
Iron	13.5	0.01-0.12	3.3	0.12-2.2	0.78	190	40	0.34-1.8	0.11-0.31	0.18-0.37	0.02-0.18	0.15-0.32
Bicarbonate	152	323-562	140	68.8-317	214	--	--	53.8-228	54.2-255	48.0-250	211-218	54.2-185
Sulfate	620	320-410	192	51.0-230	236	4400	1270	30.0-223	16.7-89.5	20.0-90.0	56-68	20.0-92.0
Chloride	17	140-155	0.4	1.7-19.3	9.8	--	--	1.7-14.7	1.3-13.6	1.0-11.9	3.7-5.0	1.4-4.2
Silicate	4.7	10-11	3.9	2.5-5.1	4.9	14.4	6.5	2.1-4.3	2.1-3.7	2.0-4.2	3.5-3.6	2.0-3.4

From analyses by Water Quality Branch, Environment Canada, Calgary (Alberta) and Vancouver (British Columbia).

(a) Samples collected by H. Schreier, October 1977 - August 1978.
(b) Samples collected by H. Schreier, August 1978.
(c) Samples collected by R.O. van Everdingen, July 1982.

bicarbonate, and sulfate concentrations, as well as significant sodium and chlorine contents, which indicate carbonate rocks and evaporite gypsum and halite as sources for the minerals in the water. Microbiological reduction of sulfates to sulfide is responsible for the high hydrogen sulfide content (26 mg/l) of the water. Oxidation of the dissolved sulfide produces extremely fine particulate sulfur, giving a bluish milky color to the water.

The discharge of both the iron-rich and sulfurous waters is perennial and is most likely derived, via open hydrothermal taliks, from subpermafrost flow systems. The same conclusion applies to several other springs described below.

KM 172-198. For the next 26 km the highway parallels Engineer Creek. Over the first 6 km, the creek water gradually loses some of its brownish color. Near KM 178, a second stream of iron-rich water discharges into Engineer Creek, which slightly enhances its brownish color.

Over the next 6 km, the creek water loses most of its remaining iron and color until a third stream of iron-rich water discharges into it near KM 184. In addition to an extremely high iron content (190 mg/l; table 9), the water from this source is acidic; pH values as low as 2.8 have been measured by Schreier (1978).

Where the brown-colored acidic water comes into contact with the relatively clear creek water, a white plume develops that is visible for a long distance downstream. Analyses (table 9) indicate that the plume consists of an extremely fine-grained precipitate of calcium sulfate. The water of Engineer Creek is almost clear again by the time it reaches the confluence with Ogilvie River.

The geochemistry of the ground water and associated variations in the composition of Engineer Creek are illustrated in figure 37.

KM 217. STOP 9 (OPTIONAL). CASTLES HILL. Striking scree slopes and castellated cliffs occur in limestone along the Ogilvie River gorge (fig. 38). The mountains are rounded with convex upper slopes (fig. 39), whereas valleys are V shaped. The area is unglaciated. Thermistor readings indicate the ground beside the Ogilvie River is unfrozen, whereas the rest of the landscape is underlain by permafrost.

At this point, several large culverts have been installed beneath the highway to accommodate large fresh-water springs that emerge from mixed alluvium and talus at the base of Castles Hill, about 600 m southwest of the highway. Fresh water is discharged at a rate of 1.4 m^3/s. Discharge is perennial; the water has a temperature of 4°C and a dissolved-solids content of 362 mg/l (table 9). During winter, the discharge forms icings in Ogilvie River beginning about 1 km downstream.

From October to March, the chemical composition of Ogilvie River from 3 km above to about 30 km below the confluence of Engineer Creek is similar to the composition of the water discharged at Castles Hill. The chemical composition of the ground-water discharge shows little variation throughout the

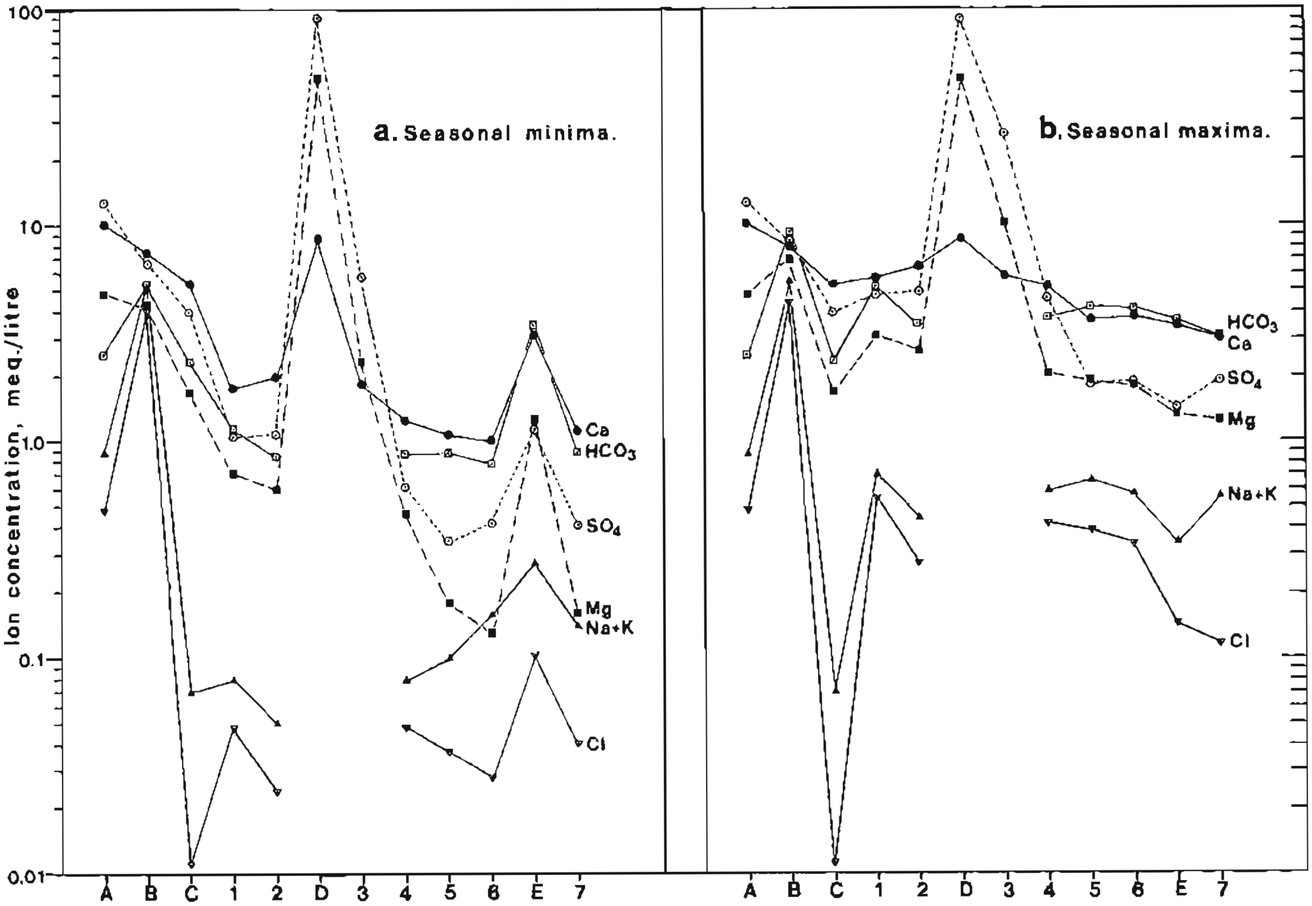

Figure 37. Chemical composition of ground-water discharge (A-D) and surface waters (1-7) along the courses of Engineer Creek and Ogilvie River (letters and numbers refer to table 9). (A) Minimum measured values, May 1978; (B) maximum measured values, October 1977 to August 1978.

the year. Thus, the discharge at Castles Hill apparently represents the dominant type of ground water in this part of the Ogilvie River basin.

KM 198-363. Ogilvie River to Eagle Plain Hotel. At Seven Mile Hill (KM 237), the Dempster Highway leaves the flood plain of the Ogilvie River and ascends the southern escarpment of Eagle Plain. The highway trends northeast and follows well-drained drainage divides where icy permafrost is least common. In addition, by reducing the number of stream crossings, the problems of icings are minimized.

Eagle Plain is an extensive (about 17,500 km^2) intermontane plateau between 65° and 67°N. It is bordered on the west and south by the northern and central Ogilvie Mountains, respectively, to the east by the southern Richardson Mountains, and to the north by Bell Basin (see fig. 1). The plateau is an upland surface, between 650 and 800 m in elevation, dissected by broad, shallow valleys (fig. 40) that drain northward and westward into the Yukon River via the Eagle, Bell, and Porcupine Rivers. The southern edge of the plateau is delineated by a prominent escarpment (fig. 41) formed by a resistant member of the Eagle Plain Formation, a sandstone of Cretaceous age

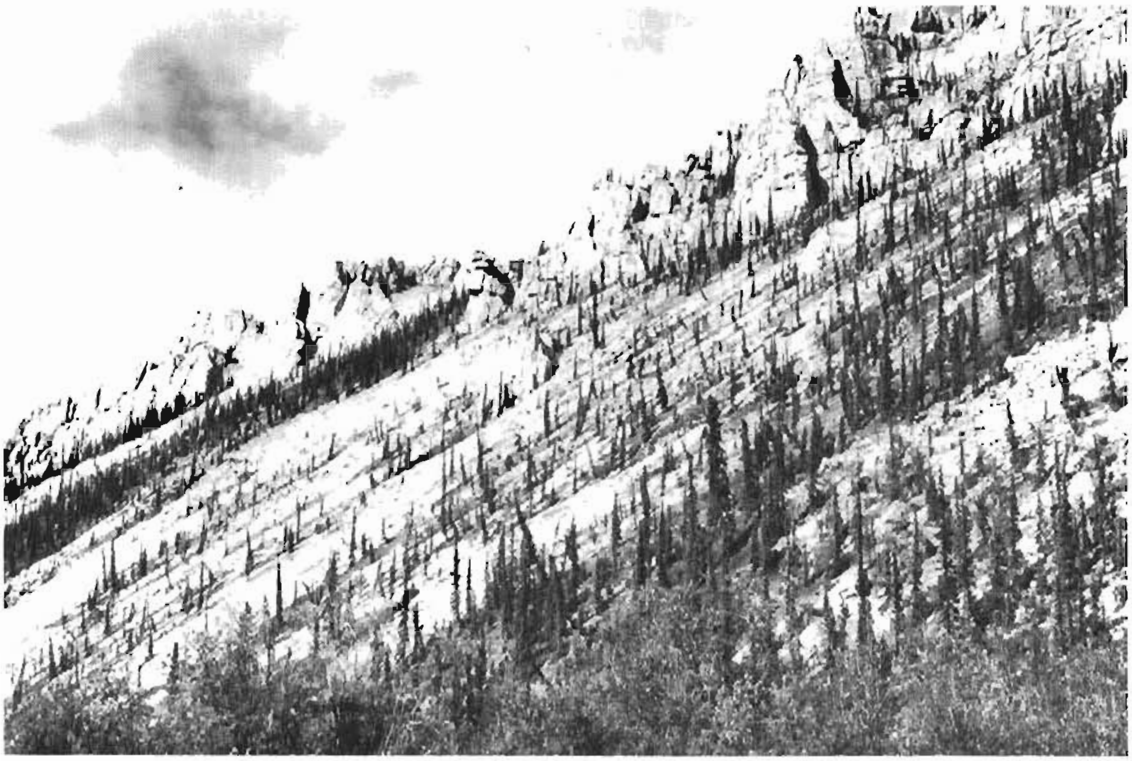

Figure 38. Scree and castellated tors developed in limestone along Ogilvie River gorge, KM 217, Dempster Highway.

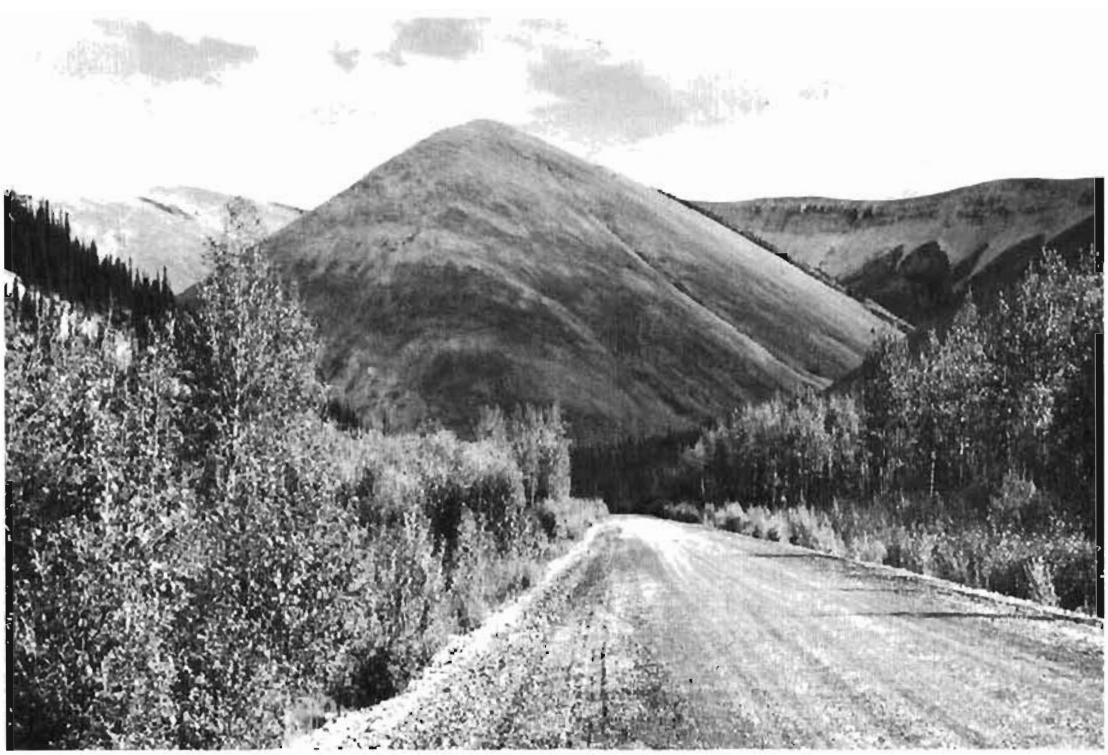

Figure 39. Convex, debris-covered scree slopes in Ogilvie Mountains, KM 219, Dempster Highway.

Figure 40. General view of the upland surface of the Eagle Plain. Vegetation consists of an open black-spruce woodland and shrub tundra. Lat 66°16'N., long 137°10'W. (French, 1981).

Figure 41. View west along the main Eagle Plain escarpment. Note shrub tundra on upland surface and assemblage of birch, poplar, alder, and white spruce on warm, well-drained south exposures. Lat 65°55'N., long 136°50'W. (French, 1981).

that underlies most of the plateau (Norris and others, 1963). Older Carboniferous and Devonian shales, limestones, and conglomerates surround Eagle Plain. Vegetation consists of a stunted and open boreal forest that changes to shrub tundra at higher elevations. Timberline decreases northward from about 850 m in the south to 600 m in the north.

Hughes (1969) identified the western limit of Laurentide (Wisconsin) ice as being east of Eagle Plain Plateau where the Richardson Mountains form an imposing topographic barrier (see fig. 1). Likewise, in the south and west, although the Ogilvie and Wernecke Mountains nourished small alpine glaciers, these ice streams never extended very far northward and were confined to the middle and upper reaches of larger valleys such as Blackstone Valley. As a result, a long and uninterrupted period of very intense periglacial conditions produced an extensive, frost-shattered veneer of rock rubble (felsenmeer) that mantles the interfluves and upper surfaces of Eagle Plain. Often, this angular regolith has been reworked by frost sorting. Lower valley walls are covered by silty colluvium and peaty organic sediments are restricted to depressions. Fluvial deposits up to 30 m thick, together with ice-rich glaciolacustrine silts, are found along the major river valleys (Hughes, 1969; Johnston, 1980). These deposits were formed when Laurentide ice blocked drainage from the central Yukon to the Mackenzie Delta area. During Quaternary time, meltwater streams flowed across Eagle Plain away from the various ice fronts to the east. In places, ponding produced proglacial lakes of short duration.

Surficial deposits are absent from large areas of Eagle Plain, and unconsolidated, fine-grained and ice-rich sediments are restricted to lower valley walls and bottoms. Moreover, the near-continuous forest cover, the relatively poor airphoto coverage of the area, and the apparent absence of certain terrain features diagnostic of highly sensitive terrain in other parts of northern Canada (for example, pingos, low-center ice-wedge polygons, palsas) make permafrost mapping difficult. Within Eagle Plain, however, there are a number of locally important ground-ice indicators, including a) areas of thermal-contraction cracks that form immature polygonal networks in valley bottoms where fine-grained alluvial and/or colluvial sediments are present (fig. 42C), b) beaded drainage patterns in some of the smaller valleys (fig. 42A), and c) ice-expanded joints in bedrock, which are commonly exposed in the floors of borrow pits located along the Dempster Highway (fig. 42B).

KM 243. STOP 10 (OPTIONAL PHOTO STOP). PANORAMIC VIEW SOUTHEAST AND FOREST-SHRUB TUNDRA TRANSITION. At this locality, an excellent view is obtained southeast across the Ogilvie River valley to the Mackenzie Mountains.

The forest-tundra boundary is at 853 to 914 m on south-facing slopes and at 762 m on north-facing slopes. Black spruce (*Picea mariana*) is a dominant species below timberline, together with scattered balsam poplar (*Populus balsamifera*), birch (*Betula* spp.), and willow (*Salix* spp.). In better drained sites, white spruce (*Picea glauca*), tamarack (*Larix laricina*), and alder (*Alnus* spp.) are present.

KM 298. STOP 11 (OPTIONAL). FROST-SHATTERED BEDROCK AND EXPANDED JOINTS. The surface of the Eagle Plain consists of a 2- to 3-m-thick regolith of shattered bedrock as exposed in borrow pits. In many places, sorted

Figure 42. Terrain characteristics of the Eagle Plain area (French, 1981). (A) Oblique aerial view of small tributary stream of Chance Creek, which drains part of the southern Eagle Plain. Note the beaded drainage. Lat 66°15'N., long 137°25'W. (B) Frost-widened joints in shale bedrock exposed in borrow pit at KM 366. Dempster Highway, Eagle Plain. (C) Thermal-contraction cracks and peat polygons on the flood-plain deposits of the Peel River. Note also the area of ribbed fen. Lat 65° 51'N., long 136° 50'W.

patterned ground occurs along ridge crests, but elsewhere or in siltier regoliths there are nonsorted circles (mudboils). Many borrow pits expose expanded joints in the bedrock that were formed by the freezing of downward percolating water.

KM 324. STOP 12 (OPTIONAL). RECENT FOREST FIRE. The northern boreal forest is often regarded as a fire-climax vegetation because forest fires, started primarily by lightning, are frequent. In this burn, notice the distinct hummocks that have been exposed by the removal of the vegetation cover.

KM 334 and 338. STOPS 13 AND 14 (OPTIONAL). BEDROCK EXPOSURES ON EAGLE PLAIN. At Stop 13, a roadcut provides a good opportunity to examine the Eagle Plain Sandstone, a massive, well-jointed and free-draining sandstone of Cretaceous age. It provides excellent material for the subgrade of the highway.

At Stop 14, there is an exposure of a black shale unit interbedded with sandstone lying stratigraphically below the Eagle Plain Sandstone. This mixed unit is used as a surfacing material for the highway to provide a smooth travel surface and reduce wear on tires. From here to Eagle Plain Hotel, the highway is well made, with a smooth surface, an adequate thickness of fill, and good drainage.

KM 363. Eagle Plain Hotel. The hotel was constructed in 1978 on an outcrop of Eagle Plain Sandstone in a small patch of shrub tundra on the north side of the crest of the ridge beside the highway. The sandstone and overlying regolith provide a relatively frost-stable base for the buildings and parking lot, and the open area reduced the necessary destruction of forest. The pad was extended over the upper slopes of the hill by dumping sandstone blocks onto existing surfaces in a layer thick enough to prevent thawing of the permafrost. Two localized areas with icy permafrost were excavated and the material removed, to be replaced with shale. Then a 10-cm-thick layer of polystyrene foam insulation was placed on the ground. A 75-cm-high crawl space was installed but is sealed and heated and remains dry.

Heat and light are supplied by diesel engines, and water is trucked from the Eagle River. Sewage drains in insulated and electrically heated pipes that are sloped to provide gravity flow to a settling pond at the head of a small creek on the north side of the building.

A short walk in the vicinity of the Eagle Plain Hotel offers a good opportunity to examine the terrain and micromorphology of the Eagle Plain Plateau. Typical relict sorted polygons and stripes occur adjacent to the highway about 0.3 km from the hotel in the Inuvik direction. Patterns are formed in at least 2.5 m of frost-shattered sandstone of the Eagle Plain Formation. Individual boulders are lichen-covered, but active frost boils can occur in the vegetated centers that contain finer material. Polygons grade into stripes at slope angles of about 10 degrees.

Lichen-covered stones in polygons are common in areas of alpine permafrost in Canada. This plant cover indicates a cessation of frost-churning activity once sorting is complete or the beginning of unsuitable microclimatic conditions. At Plateau Mountain, Alberta, churning has occurred after man-induced mixing of the material, but no churning and sorting are apparent in disturbed regolith at Eagle Plain Hotel. Thus, the present climate is apparently unsuitable for formation of sorted polygons, even though the area is well within the zone of continuous permafrost.

By crossing the highway and walking through the forest northwest of the cuesta, a number of well-developed earth hummocks can be examined. They occur on the finer-grained interbedded shales and sandstones below the Eagle Plain Sandstone. These patterns are common on fine-grained surficial material in this part of the Yukon. A good view can also be obtained northeast toward Eagle River with the Richardson Mountains in the distance.

You can return to the hotel complex by walking southwest along the cuesta to the parking area behind the hotel. There, the bedrock pad and the sewage facilities can be seen.

THE DEMPSTER HIGHWAY - EAGLE PLAIN TO INUVIK

By
S.A. Harris,[1] J.A. Heginbottom,[2] C. Tarnocai,[3] and
R.O. van Everdingen[4]

After crossing the Eagle River, the Dempster Highway follows upland drainage divides of the Eagle Plain and the western footslopes of the Richardson Mountains. It then crosses the Richardson Mountains and descends into Mackenzie Valley. Ferries across the Peel and Mackenzie Rivers operate for limited periods each day and the loss of 1 hr on crossing the Yukon-Northwest Territories boundary limits field time.

KM 372. EAGLE RIVER CROSSING. The bridge over Eagle River was the last link of the Dempster Highway to be completed. The river had to be crossed in a single 100-m-long span, with the footings on the north side placed on ice-rich permafrost. The bridge was constructed by the Canadian Armed Forces between August 1976 and June 1977.

REGIONAL SETTING

Eagle River is a major tributary of Porcupine River. It drains the western slopes of the southern Richardson Mountains and the southeastern Eagle Plain. Porcupine River subsequently drains through Old Crow Basin to eventually join the Yukon River at Fort Yukon, Alaska, about 220 km northeast of Fairbanks.

During late Wisconsin time, ice from the Laurentide ice sheet occupied the Bonnet Plume Basin at the junction of the Bonnet Plume and Peel Rivers. This ice effectively blocked drainage from the central Yukon to the Mackenzie Delta area, diverting upper Peel River into the Porcupine River drainage system via Eagle and Bell Rivers. The significance of this diversion is the potential for high discharges through the Eagle River system during late Pleistocene time. High-level terraces on both sides of the valley relate to either greater river discharge or the impoundment of glacial-lake waters in the Bonnet Plume Basin. Stratigraphic information obtained from a number of borings made prior to construction along the highway alignment as it crosses the high-level terrace on the southwest side of the Eagle River valley favors the latter interpretation (fig. 43). Between KM 368 and 379, the terrace is underlain by ice-rich organic silt and clay that contain massive ice lenses.

During construction of the highway at this point in 1976 to 1977, great care was taken to ensure minimal disturbance to the thermal regime of the underlying permafrost. The road was placed on a thick (3 to 4 m) gravel pad. Thermistors installed in the subgrade and in boreholes are measured periodically. On July 29, 1982, for example, temperatures at the base of the

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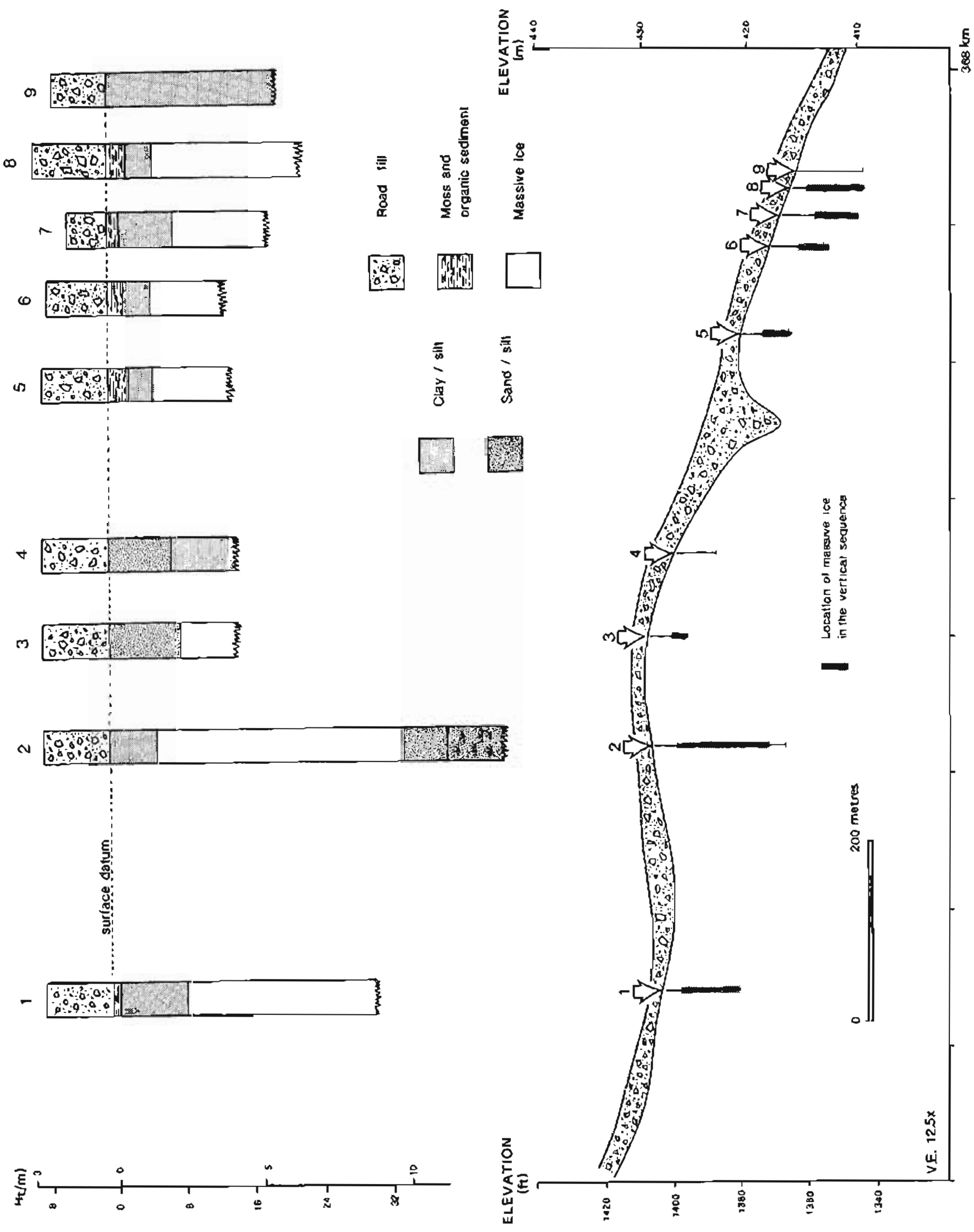

Figure 43. Surficial deposits underlying Dempster Highway, KM 368-370, near Eagle River bridge. (Source: G.H. Johnston, Division of Building Research, National Research Council of Canada, Ottawa.)

subgrade were between -3.4° and -3.3°C, indicating that the active layer associated with the road surface is totally within the fill, thus protecting the ice-rich permafrost from melting.

The Eagle River flood plain ranges from 900 to 1,000 m in width and is characterized by numerous meander scars, oxbow lakes, infilled channels, and low fluvial terraces (fig. 44). An irregular microrelief consisting of ubiquitous earth hummocks up to 70 cm high and 50 cm in diameter retards surface drainage and results in a saturated active layer. Following construction of the highway, the natural drainage pattern was modified. The roadbed effectively stops downslope active-layer throughflow, and the placement of culverts artificially channelizes flow. A number of springs occur at various locations near the base and partway up the north side of the valley. Discharge from these springs produces saturated soil conditions, and the slope may become unstable and fail, as illustrated by numerous slump and flow scars in this area.

STRATIGRAPHY AND PERMAFROST CONDITIONS

There is reasonably good documentation of the stratigraphy of the flood-plain sediments in the vicinity of the Eagle River bridge and the Dempster Highway (Johnston, 1980). During highway and bridge construction, 20 test holes were drilled, 14 to depths of between 4.5 and 30 m. Two 30-m-long multiple thermistor cables were installed at the proposed abutment locations. The data obtained indicate a wide range of soil and permafrost conditions.

The generalized stratigraphy is illustrated in figure 45. From 0 to 3 m depth is a layer of ice-rich silty clay. This clay is underlain by 12 to 13 m of stratified silt, sand, and gravel and 15 to 18 m of sandy silt and silty clay. Compacted silt, sand, and gravel were encountered at the bottom of the sequence. A glacial origin for the basal unit has been suggested, based on the lack of sorting, its dense nature, and the wide range of rock material not commonly found in the area (Johnston, 1980). Because the crossing site is about 60 km downstream from the maximum extent of Laurentide ice, as mapped by Hughes (1972), more work is needed to resolve this apparent conflict. The overlying sediments are thought to be valley-fill alluvium. Closely spaced lenses of segregated ice, 1 to 2 cm thick, were common in the fine-grained materials, whereas visible crystals and coatings of ice on individual soil particles were common in coarser materials.

Beneath Eagle River flood plain, permafrost distribution is modified by the presence of the river channel and its migration, which is estimated to be about 1 to 1.5 m/yr. Some of the larger oxbow lakes may also modify the underlying permafrost.

Borings prior to bridge construction indicated permafrost was present in the north bank, where it is probably as thick as 90 m, based on a recorded ground temperature of -3°C and a geothermal gradient of 26 mK/m. A deep, near-isothermal talik existed beneath the main river channel and in adjacent alluvium, including the south shore. Near the proposed south bridge abutment, however, permafrost had aggraded to depths of almost 8 to 9 m and was marginal in temperature (-0.4°C). In all probability, the shape of the thaw basin reflects the lateral migration of the river as described in other permafrost

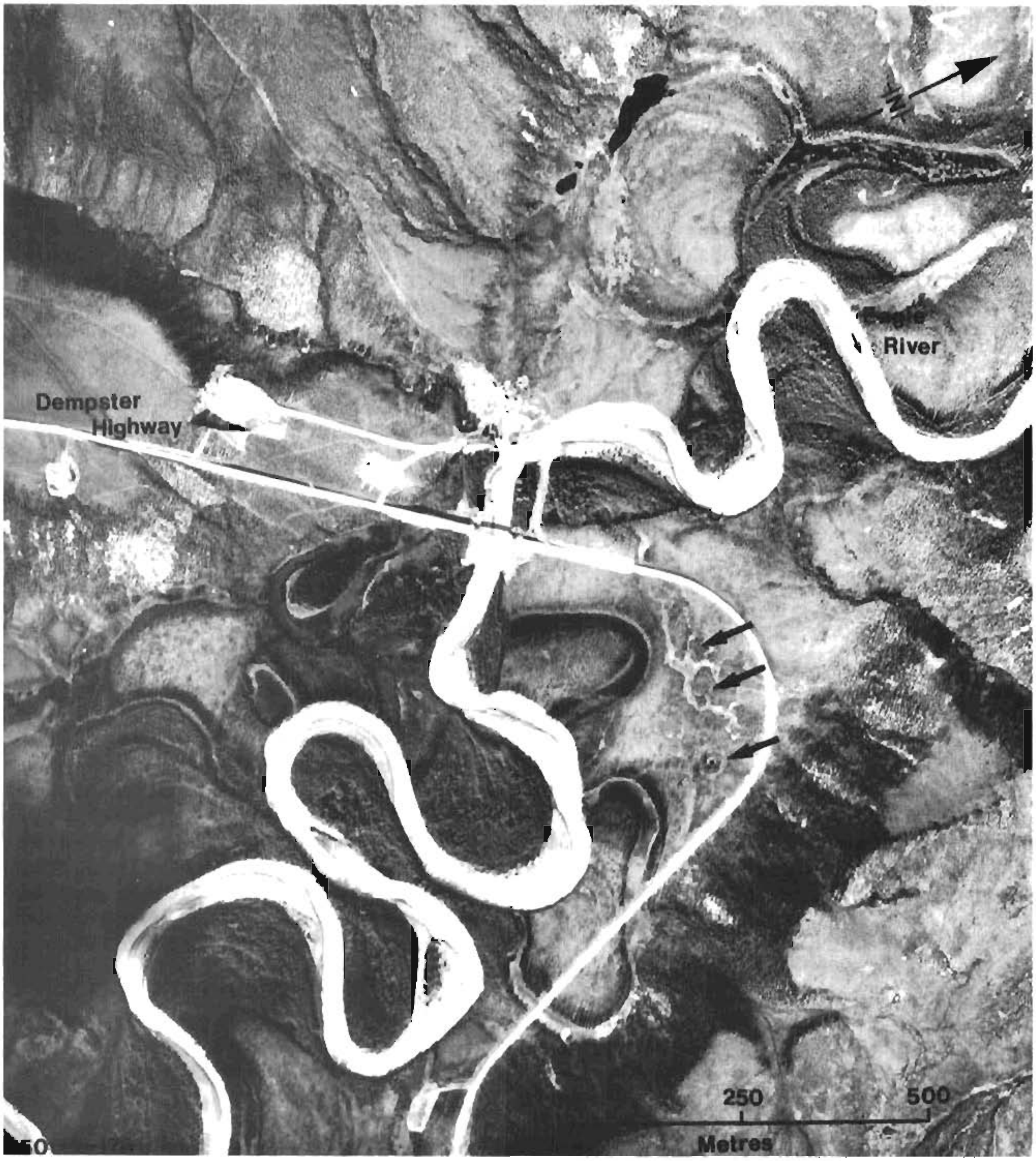

Figure 44. Aerial photograph of Eagle River and flood plain near Eagle River bridge. Arrows indicate occurrence of spring activity and possible seasonal frost mound (airphoto A25005-176, EMR).

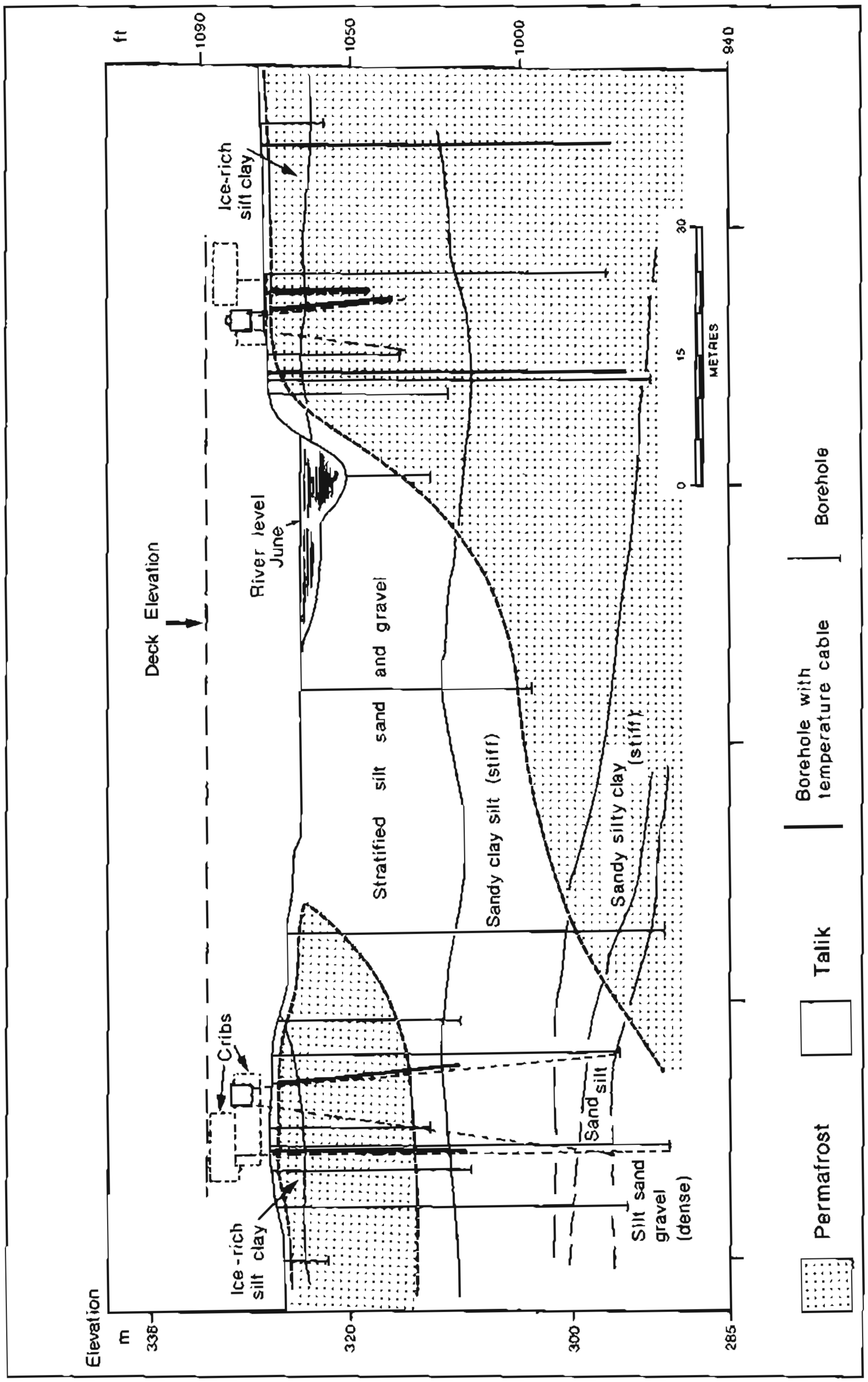

Figure 45. Plan and profile at Eagle River bridge site with stratigraphic and permafrost information determined by drilling (Johnston, 1980).

regions (Smith and Hwang, 1973). As the river migrated northward, former channels on the south side were infilled. As they became exposed to cold subaerial temperatures, permafrost began to aggrade into unfrozen sediments.

ENGINEERING DESIGN AND CONSTRUCTION

Eagle River Bridge

Fifteen steel piles were used for bridge foundations in each abutment. Because of the marginal permafrost conditions in the south abutment, no support could be derived from the perennially frozen ground. The installation procedure followed, therefore, was to auger 45-cm-diameter holes to the bottom of the 8- to 10-m-thick layer of newly formed, warm (less than -0.4°C) permafrost, place the piles in the holes, and backfill the cylindrical void around the piles with fine to medium sand. The piles were then driven to refusal in the dense silt, sand, and gravel layer at a depth of about 30 m.

In the north abutment, where the mean annual ground temperature is -2°C, the piles were placed in 45-cm-diameter auger holes and backfilled with a sand slurry. Adfreeze strength dictated that an embedment depth of about 5 m was required for each pile. As a precaution against both short- and long-term effects on the ground thermal regime (for example, due to construction activity, pile emplacement, and lateral shift of the river), north abutment piles were installed in holes augered to a depth of about 12 m below the original ground surface. Furthermore, a moist sand was placed in the bottom 5 m of the hole and the piles were driven through it into the underlying permafrost to gain immediate load-bearing capacity from shaft friction. The holes were subsequently filled with a sand slurry.

To measure the performance of the piles in following years, thermistor cables were installed on two of the piles and in the approach fill at each abutment during construction. Measurements to date (G.H. Johnston, personal commun., September 1981) indicate good performance. Temperatures in the south abutment indicate a slow but general cooling with temperatures at or just below 0°C to a depth of at least 30 m. Freezeback of the piles in the north abutment was accomplished very quickly in the early winter of 1977, and by September 1979 the ground around the piles had cooled further.

In addition to measures designed to maintain natural permafrost conditions, other important design criteria included the construction of earth dikes covered with rock-filled gabions to stabilize both riverbanks. A subsequent problem has been a tendency for flood waters to accumulate behind the gabion on the north bank, causing some thermokarst subsidence there.

Insulated Roadbed

A 250-m-long section of the highway just north of the Eagle River bridge on the Eagle River flood plain is being used to monitor the effectiveness of urethane insulation in reducing ground thermal fluctuations beneath the roadbed. An insulated section and a control section are separated by a transition zone. A series of multithermistor cables was installed to monitor ground thermal regimes. The study is not yet complete and results have not been reported.

ROAD LOG AND SITE DESCRIPTIONS

KM 371-538. Eagle River Crossing to Peel River, N.W.T.

KM 409. STOP 1 (OPTIONAL). MUDBOILS AND TIMBERLINE. North of Eagle River, timberline progressively drops in elevation from 790 to 750 m near the Arctic Circle. At Eagle Plain airstrip, relict sorted polygons occur on the regolith overlying the Eagle Plain Sandstone. Alpine larch (Larix yallia) becomes a conspicuous part of the subalpine forest together with black spruce (Picea mariana).

Nonsorted circles (mudboils) are a common part of the landscape above timberline wherever a silty regolith is present.

KM 414. STOP 2. PHOTO STOP. ARCTIC CIRCLE (lat 66°66'N, elevation 750 m). At this stop, one can examine nonsorted circles (mudboils) formed in silty regolith; note the influence of wind and snow on vegetation in tundra regions, and observe a panoramic view of the western slope of the Richardson Mountains.

Typical nonsorted circles (mudboils) are 80 to 180 cm in diameter and have a microrelief of 10 to 40 cm. In addition to forming in silty, frost-sensitive materials, their occurrence is closely related to exposed localities where the winter snow cover is thin. In hollows between mudboils, white spruce (Picea glauca) exhibit marked krummholtz form. Labrador tea (Ledum spp.), birch (Betula spp.), prickly rose (Rosa acicularis), blueberry (Vaccinium spp.), and willow (Salix spp.) are also present.

In lee positions, where snow accumulates, small white spruce, alder (Alnus spp.), and resin birch (Betula glandulosa) form a shrub layer up to 1.3 m high. A few white spruce that are taller are stunted. In winter, snow accumulates to the top of the shrub layer.

KM 441. STOP 3 (OPTIONAL). ICING AREA IN ROCK RIVER. Extensive seasonal icings develop in Rock River and several of its tributaries. These icings are fed by the perennial discharge of ground water along the Richardson Mountains. The discharge has temperatures up to 6°C and a dissolved-solids content near 225 mg/l. The icing area in Rock River extends from 0.75 km upstream of the highway to about 2 km downstream. Four high-arch culverts have been installed at this crossing to accommodate the icing. One culvert is equipped with a steamline to facilitate steam thawing just before the snowmelt after winters of excessive ice buildup. Similar provisions have been made at other crossings along the highway.

KM 462-465. Winter trails. The number of roadcuts was minimized during construction of the highway to avoid melt and degradation of ice-rich permafrost. At some localities where thaw-sensitive permafrost was not present, roadcuts were excavated. Although satisfactory in summer, these roadcuts fill with snow in winter. To avoid delay and expense in snow plowing, winter 'bypasses' have been used at these locations; these alternate routes can be seen along the highway at several points.

KM 465-480. Richardson Mountains. The Richardson Mountains form an impressive north-south barrier between the lowlands of the Arctic Coast and Mackenzie Delta and the intermontane plateau of the northern interior Yukon. They rise to elevations in excess of 1,700 m. At this latitude (67°N.), timberline is below 650 m. The mountains are unglaciated because the Laurentide ice extended only to the eastern foothills. The Dempster Highway crosses the main divide of the Richardson Mountains via a pass with an elevation of 949 m.

Climatic conditions in the mountains are highly variable and may differ significantly on the west and east sides. In particular, eastern slopes have higher precipitation and greater snowfall. The mixing of relatively warm, moist air from the Arctic Coastal Plain with cold, dry air from the interior Yukon produces frequent fog and drizzle, especially in summer. As a consequence, the highway through the mountains is often slippery and treacherous, with poor visibility.

KM 470. STOP 4. CREST OF THE RICHARDSON MOUNTAINS. Well-developed and active solifluction lobes, terraces, and stripes are common in the Richardson Mountains, especially east of the crest and at high elevations. Terracettes and turf-banked lobes, 1 to 3 m high, occur at lower elevations on the eastern flanks. At higher elevations, sorted stone nets and stripes are developed in frost-shattered and often highly metamorphosed shale and sandstone. Between the Yukon Government Campground (KM 465) and the N.W.T. Highway Maintenance Camp (KM 479), numerous examples of these periglacial phenomena can be seen adjacent to the highway (fig. 46).

KM 480. STOP 5. VITTREKWA GORGE AND ICING AREA. About 1 km past the N.W.T. Highway Maintenance Camp, the Dempster Highway crosses a major 5-km-long icing area related to a tributary of the Vittrekwa River. The icing that forms in this area is fed by perennial discharge of ground water between 1.5 and 6 km upstream from the highway. The discharge area is characterized by well-developed willows and poplars. The discharge is cold (about 4°C) and fresh (dissolved-solids content 125 mg/l). The problem is compounded because at this locality the highway closely follows the Vittrekwa River, which flows through a narrow, sinuous, and deeply incised gorge. Large, steep slopes of siltstone scree are an additional maintenance problem.

The use of high-arch culverts has so far prevented serious icing problems for the highway, although constant maintenance is required.

KM 490-538. Eastern foothills of Richardson Mountains. At the exit of the Vittrekwa Gorge, the highway leaves the Richardson Mountains and descends through the foothills toward Peel River. Tundra conditions are replaced by northern boreal forest-tundra transition vegetation. Stunted black spruce appear at elevations of 450 to 700 m. These trees are replaced by mixed stands of black spruce and larch at about 400 m elevation, with willow and birch in more open areas. At elevations below 300 m, there is a northern boreal forest typical of the interior northern Mackenzie Valley.

The highway also passes into areas glaciated by Laurentide (Wisconsin) ice. Ice-rich deposits consisting of till or lacustrine sediments are indicated by kettle lakes and thermokarst ponds (for example, at KM 521 and KM

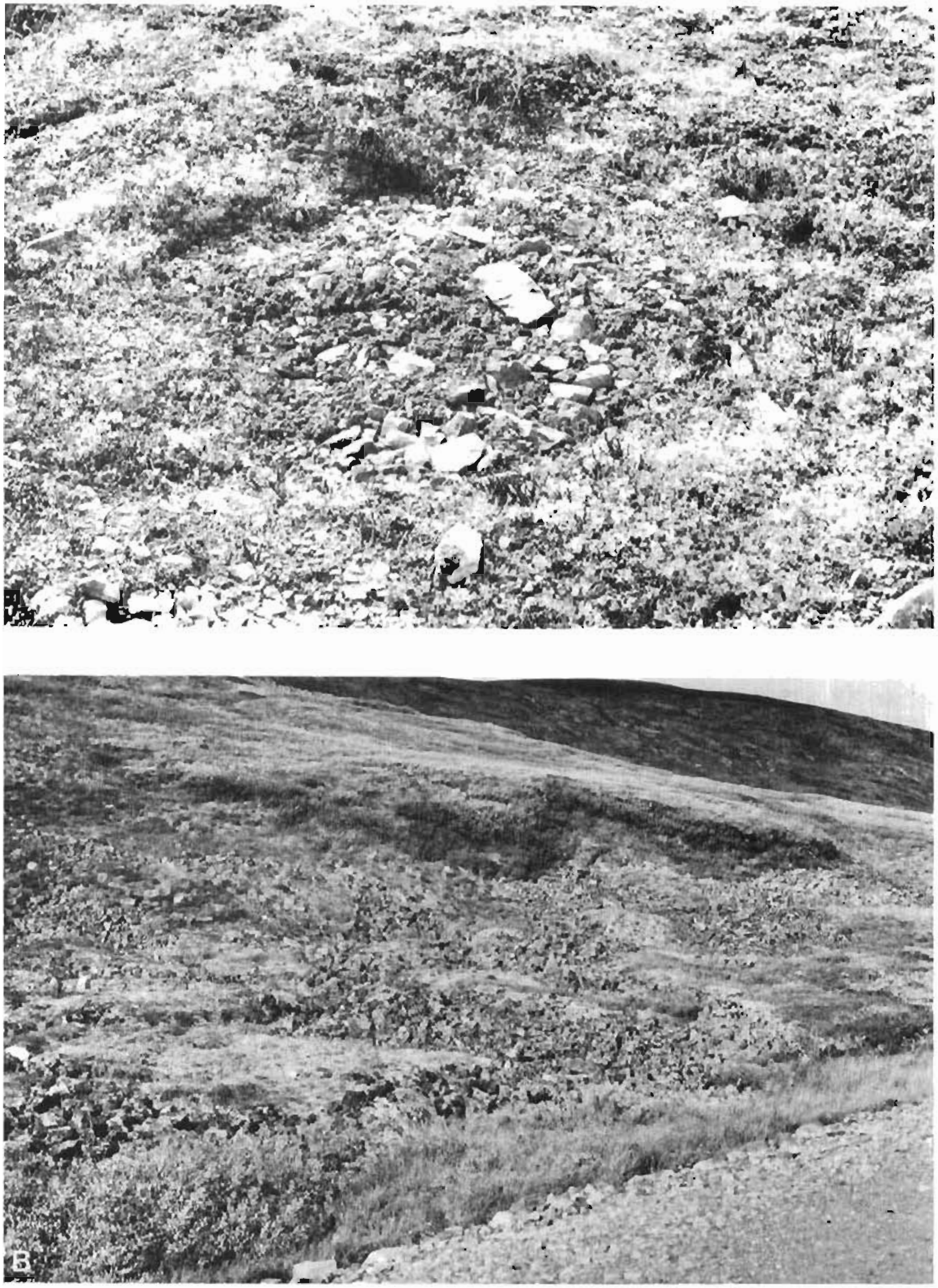

Figure 46. Periglacial features in the Rat Pass area of the Richardson Mountains. (A) Sorted circle developed in silty coarse regolith; (B) solifluction lobe and sorted stone nets beneath.

Figure 46 (cont.). (C) Stone stripes.

531). At KM 535 (elevation approximately 80 m), lowland (swamp) larch appears with tilted black spruce in poorly drained areas. Tall (6 to 10 m) white spruce grow in slightly better drained areas adjacent to water bodies, where the active layer is thicker.

Peel River Crossing to Inuvik

KM 538. STOP 6. PEEL RIVER CROSSING. Dempster Highway crosses Peel River about 12 km upstream from Fort McPherson by a ferry in the summer and over an ice bridge in winter. The crossing is closed to traffic for a short period during freezeup and breakup. The spring flood, caused by snowmelt, normally occurs in late May or early June (Henoch, 1960). At the crossing site, the river is 400 to 450 m wide, depending on the stage. Bed and bank material are fine grained and little bed scour or bank erosion occur.

KM 548. Fort McPherson (1981 population, 618). Situated on the east bank of the Peel River (fig. 47), about 40 km south of the Mackenzie Delta, Fort McPherson was founded as a fur-trading post in 1840. The settlement was built on a flat-topped hill, about 30 m above the river. Each spring, the surrounding alluvial plain is flooded, leaving the settlement an island for a few weeks.

Water for the settlement is pumped all year from a nearby lake to a treatment and storage center situated in the school hostel. A plywood utilidor system supplies water to part of the community and a tank truck supplies the rest. Waste passes via the utilidor to a lagoon that floods each spring and can contaminate the water supply. Power is supplied by a diesel

Figure 47. Site and plan of Fort McPherson, 1979 (airphotos A25224-166, 167, EMR).

generating plant. There is a small wharf about 1.6 km downriver, and a new airfield has recently been completed.

KM 551-635. Peel Plain. The Peel Plain is a level, poorly drained glaciated area. A morainal belt near Frog Creek is the only noticeable relief in the area. The underlying bedrock, flat Devonian shale and sandstone, is not exposed, but is covered by a variable thickness of morainal and organic deposits. Fairly thick (100 to 200 m) continuous permafrost underlies the area, and there are numerous thermokarst lakes. Permafrost temperature is about -1°C at the 3- to 5-m depth; ground-ice contents are commonly medium to high. Vegetation is characteristically an open forest of black spruce with a closed ground cover of lichens. The forest cover is broken by fens around lakes.

KM 556 STOP 7 (OPTIONAL). ICING AREA WITH FROST BLISTERS. At this point the highway crosses a shallow depression that carries drainage from Dark Water Lake, about 2 km southeast of the highway. During the first winter after construction of the highway embankment at this site, differential uplift affected an area more than 100 m wide along the highway and extended over 200 m upstream. Subsurface drainage from Dark Water Lake was impeded by compaction of water-bearing materials under the weight of the embankment and by aggradation of permafrost below the embankment. The increase in hydraulic potential due to freezing of the active layer caused uplift of parts of the affected area, followed by repeated rupture of seasonally frozen materials and buildup of an icing that eventually extended across the highway.

As a remedial measure, a second (dummy) embankment of similar dimensions was built across the shallow drainage depression some distance upstream to duplicate the effects of the highway embankment on subsurface flow and to induce formation of the icing farther upstream. A narrow gap was left in the dummy embankment to pass surface runoff. This solution has been effective.

KM 616. STOP 8 (OPTIONAL). ROADCUT NEAR FROG CREEK. During construction of this section of the Dempster Highway, the morainal belt referred to in the previous section was used as a source of construction materials. An otherwise unnecessarily deep and wide cut was excavated, and the highway was constructed through its center. When the cut was first opened, the slopes failed because of the melting of massive ground-ice bodies and icy sediments (fig. 48). Fortunately, the ice bodies were neither large nor extensive, and the cutslopes are now generally stable.

KM 635. Mackenzie River. Mackenzie River is one of the great river systems of the world. It is the twelfth largest in drainage area and eleventh largest in mean annual discharge. It is the largest north-flowing river in North America. The catchment includes three major lakes and two significant fresh-water deltas.

The Mackenzie River catchment is the largest in Canada, draining an area of about 1.8×10^6 km^2. From its most distant point at the head of Finlay River, B.C., the river is over 4,200 km long; the mean discharge at its mouth is estimated at between 10,500 and 11,000 m^3/s. The three largest lakes in the basin, Great Bear Lake, Great Slave Lake, and Lake Athabasca, are all in the east along the boundary between the Interior Plains and the Canadian

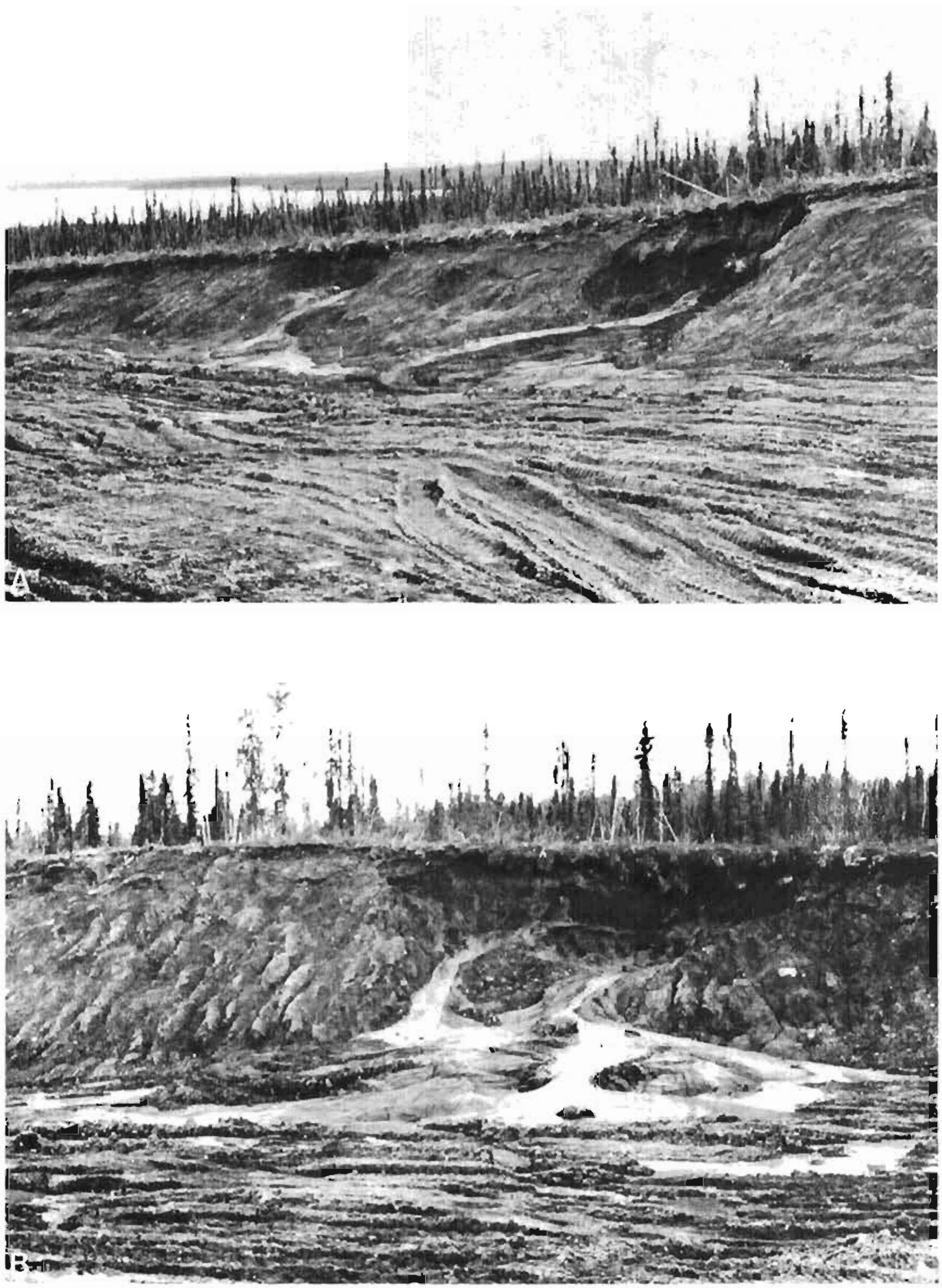

Figure 48. Frost Creek roadcut, KM 616, Dempster Highway, during construction in 1972 (GSC photos 202095-A, -B).

Figure 48 (cont.). GSC photo 202095-C.

Shield. The Mackenzie River proper begins in Great Slave Lake and flows over 1,600 km northwest to the Beaufort Sea. The largest tributaries, the Peace, Liard, and Athabasca Rivers, flow generally northeastward from headwaters in the Cordillera.

KM 636. STOP 9. MACKENZIE RIVER CROSSING AT ARCTIC RED RIVER. Dempster Highway crosses the Mackenzie River at its confluence with the Arctic Red River. The settlement of Arctic Red River (1981 population, 117) is situated on the interfluve (fig. 49). In summer, a single ferry serves both sections of the highway and the settlement, and in winter an ice bridge is constructed. These connections are interrupted during annual freezeup and breakup.

Arctic Red River is one of the smallest settlements in the Mackenzie Valley and originated as a missionary settlement of the Roman Catholic Church in 1868. Fur trading soon followed. There is no formal community organization, and there is no wharf or airstrip. Planes land on the river (on floats in summer and on skis in winter). Water is taken from the river in winter and from a nearby lake in summer and trucked to a central distribution station. Sewage collection is primitive, and waste washwater is dumped directly on the ground.

KM 636-736. Anderson Plain between Arctic Red River and Campbell Lake. This slightly irregular, dissected, drift-covered plain with elevations of 30 to 150 m, is underlain by Upper Devonian sandstone and shale, with a discontinuous cover of morainal deposits and extensive organic deposits. Anderson Plain is characterized by thick, continuous permafrost, generally with medium to high ice content and with ground temperatures near -1°C at 3

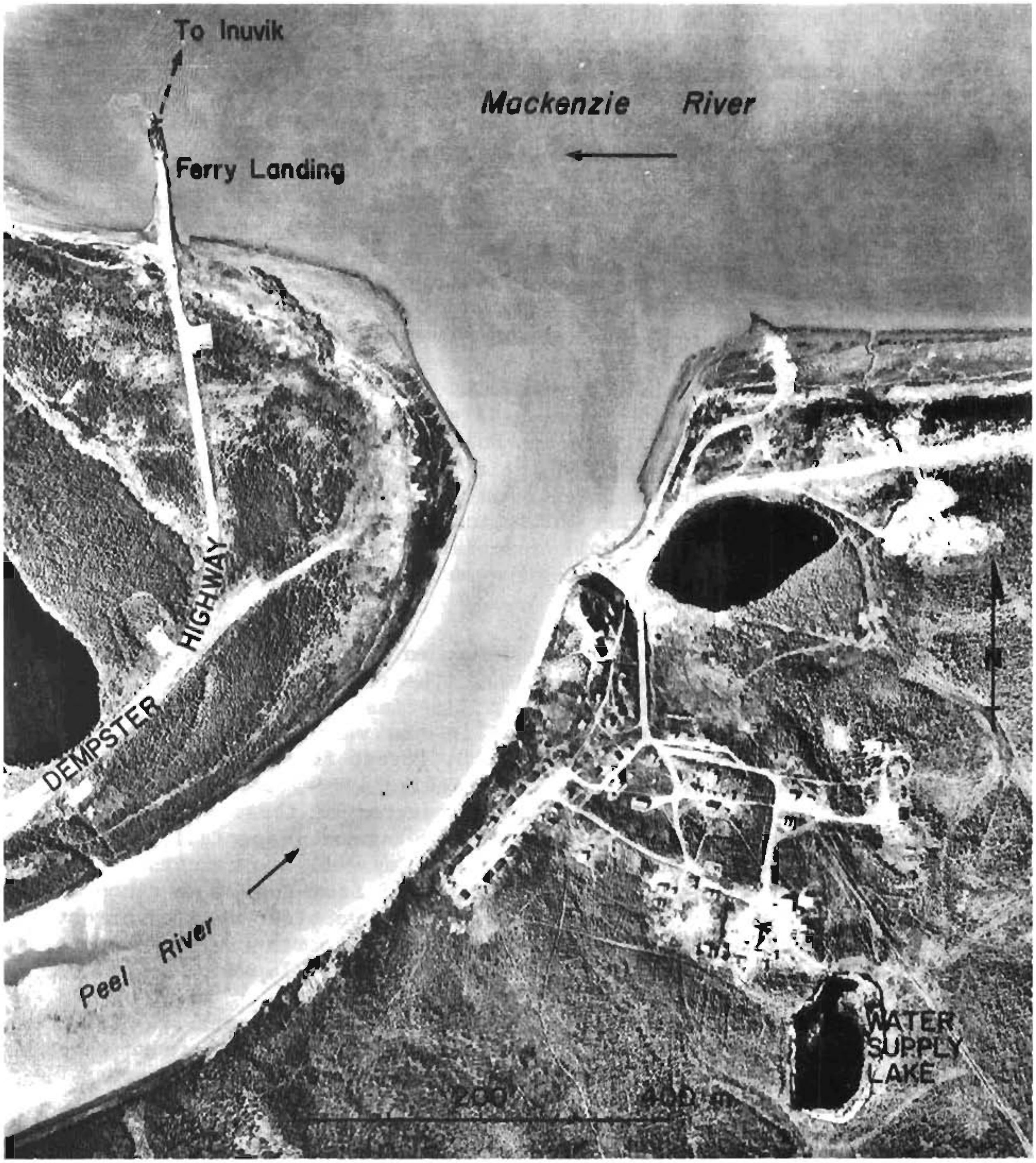

Figure 49. Site and plan of Arctic Red River, 1979 (airphoto A25224-155, EMR).

to 5 m below the surface. The vegetation is similar to vegetation of the Peel Plain between Fort McPherson and Arctic Red River.

KM 669. STOP 10 (OPTIONAL). RENGLING RIVER. One of the larger streams draining this part of the Anderson Plain is the Rengling River, which flows in an incised valley over an alluvial bed. The normal width of the river is about 12 m; the discharge can range from less than 1 m^3/s in the winter to over 800 m^3/s during the annual spring flood in June. The highway crosses the river by means of a large embankment pierced by five large culvert pipes. Both approaches to the crossing are through substantial roadcuts, which provided most of the fill for construction of the embankment.

KM 698. Mackenzie-Dempster Highway Junction. The last 60 km of highway going to Inuvik are officially part of the Mackenzie Highway. The Mackenzie Highway is proposed to run the length of the Mackenzie Valley, from Inuvik to Fort Simpson, and southward to connect in Alberta with the highway system of southern Canada. At present the highway is only open from the Alberta boundary to Fort Simpson (480 km) and for 60 km south of Inuvik.

KM 711. STOP 11. EARTH HUMMOCKS AND VEGETATION IN CONTINUOUS PERMAFROST. Earth hummocks are widely distributed in arctic and subarctic Canada (Tarnocai and Zoltai, 1978; Zoltai and Tarnocai, 1974). Their diameters vary from 60 to 80 cm and their heights range between 40 and 60 cm (see fig. 7). Earth hummocks develop on materials having 58 to 99 percent total clay and silt and either high ice content or pure ice layers in near-surface permafrost. The soil associated with this site is an Orthic Turbic Cryosol, peaty phase (table 10). A cross section of the hummock is given in figure 50.

Vegetation is a mature black spruce-lichen forest characteristic of this part of the northern subarctic (table 10). The trees lean in all directions, indicating ground movement during their lifetime. The soil is typical of those Turbic Cryosols that are situated in the vast subarctic area of the Mackenzie Valley and have been unaffected by forest fires for a long time. A continuous peaty surface layer, a shallow active layer, and high ice content in the near-surface permafrost are common features of these subarctic soils. In addition, intrusions of organic matter are common (especially in the BCy horizons), and a discontinuous subsurface Omy horizon occurs near the permafrost table. Radiocarbon dating of material from the Omy horizon yields an age of 4,690 ± 100 yr B.P. (BGS-320), which is an older date than most for organic material from earth hummocks in the Canadian north (Zoltai and others, 1978) and could mark the beginning of earth-hummock development in the area.

The soil is silty loam and there is negligible textural difference between the mineral horizons. Some coarse rock fragments are found close to the interhummock depressions, and orientations of long axes may be noted.

Peaty surface organic horizons are moderately moist. The Bm horizon has the lowest moisture content, and the moisture increases with increasing depth. The Cyz horizon contains up to 99 percent ice, mainly in the form of lenses and veins. The BCy horizon is typical of those horizons affected by cryoturbation and has the highest bulk density (1.68 mg/m^3), with very little void space and an irregular distribution of organic materials. The active layer of these soils is typically acidic. The perennially frozen material may, however, be mildly alkaline and weakly calcareous.

KM 722. STOP 12 (OPTIONAL). CAMPBELL LAKE OVERLOOK. During the last glaciation, Laurentide ice approached the Inuvik area from the southeast.

Table 10. Site description (fig. 50) and associated soils and vegetation in the continuous permafrost zone, northern Mackenzie Valley (Pettapiece and others, 1978).

A. Site description

Location:	68°08'N. lat, 133°27'W. long
Elevation:	30 m
Landform:	Slightly irregular morainal plain
Slope:	3% to the southwest, site is mid-slope
Drainage:	Internal-moderately well to poor; external-imperfect to poor
Vegetation:	Subarctic forest of black spruce-lichen
Soil temperature:	10 cm = 2°C, 50 cm = 0°C, 100 cm = -1°C (September 13, 1975)
Parent material:	Fine silty till
Patterned ground:	Earth hummocks (average diameter 135 cm, average height 45 cm)
Soil classification:	Canada - Orthic Turbic Cryosol, peaty phase U.S.A. - Pergelic Ruptic Cryaquept F.A.O. - Gelic Cambisol

B. Soil description

Horizon	Depth (cm)	Description
Of	6-3	Very dusty red (2.5 YR 2.5/2 m), fibric feathermoss forest peat; loose to matted; abundant medium to large horizontal roots, extremely acidic; clear, wavy boundary; found mainly in interhummock depression, 0 to 20 cm thick.
Oh	3-0	Black (5 YR 2.5/1 m), moderately well decomposed, feathermoss forest peat; matted; plentiful medium to fine random roots, few medium horizontal roots; slightly acidic; clear, wavy boundary; 2 to 10 cm thick.
Bm	0-10	Dark-brown (10 YR 4/3 m), silt loam; strong, fine to medium granular; sticky and plastic; friable; plentiful fine random roots, few medium horizontal roots; very strongly acidic; clear, wavy boundary; found on apex of hummock, 0 to 10 cm thick.
Bmy	10-35	Very dark grayish-brown (10 YR 3/2 m), silt loam; moderate, fine to medium granular; sticky and plastic; friable; few fine random roots; slightly acidic; gradual, wavy boundary; discontinuous, 0 to 30 cm thick.

Table 10 (cont'd)

Horizon	Depth (cm)	Description
BCy	35-65	Dark-brown to very dark gray (10 YR 3/3 to 3/1 m) silty clay; strongly cryoturbated with intrusions of organic matter; structureless, massive; sticky and plastic; firm; very few vertical roots; stones up to 10 cm in diameter in interhummock depressions; neutral; abrupt, wavy boundary; discontinuous, 0 to 3 cm thick.
Ahyz		Black (2.5 Y 2.5/0), frozen, well-decomposed organic matter; neutral; ice lenses up to 5 mm thick; 0 to 5 cm thick.
Cyz	65-110+	Dark-grayish-brown (2.5 Y 4/2), frozen silty clay; 65% segregated ice crystals and lenses up to 10 mm thick; intrusions of organic matter; structureless, massive; mildly alkaline.

C. Vegetation description

Tree ages *Picea mariana* 232 yr
129 yr
108 yr
59 yr
50 yr

(1) On hummock tops

Trees 5%
100% *Picea mariana*

Tall shrubs 20%
80% *Alnus crispa* ssp. *crispa*
20% *Salix alaxensis*

Low shrubs 35%
60% *Vaccinium uliginosum*
30% *Ledum palustre* ssp. *groenlandicum*
10% *Ledum palustre* ssp. *decumbens*

Dwarf shrubs 35%
55% *Vaccinium vitis-idaea*
40% *Arctostaphylos rubra*
5% *Empetrum nigrum*

(2) In interhummock troughs

Trees 20%
100% *Picea mariana*

Tall shrubs 30%
75% *Salix alaxensis*
25% *Alnus crispa* ssp. *crispa*

Low shrubs 40%
40% *Ledum palustre* ssp. *groenlandicum*
35% *Vaccinium uliginosum*
25% *Ledum palustre* ssp. *decumbens*

Dwarf shrubs 45%
50% *Vaccinium vitis-idaea*
25% *Empetrum nigrum*
25% *Arctostaphylos rubra*

Table 10 (cont'd)

(1) On hummock tops	(2) In interhummock troughs
Herbs 1%	Herbs 1%
100% *Saussurea angustifolia*	100% *Equisetum scirpoides*
Grasses 1%	Grasses 1%
100% *Arctagrostis latifolia*	80% *Arctagrostis latifolia*
	20% *Carex lugens*
Mosses - lichens 90%	Mosses - lichens 80%
45% *Cladina mitis*	25% *Dicranum fuscescens*
30% *Cladina alpestris*	25% *Hypnum crista-castrensis*
15% *Cladina rangiferina*	20% *Cladina mitis*
5% *Cladonia amaurocrea*	20% *Dicranum acutifolium*
5% *Cetraria nivalis*	10% *Ptilidium ciliare*

East of Campbell Lake there was a divergence in flow, with one stream moving northward toward Sitidgi Lake and the other moving northwestward across the Campbell Lake Hills. The latter ice tongue was diverted to a westerly flow direction north of Dolomite (Airport) Lake and produced an area of drumlinoid ridges and fluted terrain around Inuvik airport. The ridges are rock cored with only a thin cover of till and organic soil. The till is clayey silt with a low stone content and overlies the southern part of the Caribou Hills. Southeast of Inuvik, the Campbell Lake Hills have only a patchy cover of till over dolomite of Devonian age. This dolomite exhibits numerous karst features, which are considered to be postglacial in age. From the overlook, the outlet of Campbell Lake can be seen. Campbell River drains from the lake to East Channel. During the annual spring flood, the high water levels in the Mackenzie Delta cause the flow of the Campbell River to reverse, and flood waters flow into the lake. This inward flow has built the large, birdfoot delta visible from the overlook.

KM 736. STOP 13 (OPTIONAL). CAMPBELL CREEK. The Mackenzie Highway from near Caribou Creek skirts the eastern side of a broad valley---the Campbell Lake-Sitidgi Lake lowland. Mackay (1963, p. 144-145) interpreted this trough as part of the old course of a Pleistocene(?) river:

> Glacial deposits, including kames and recessional moraines, occur on both the lowland flats and the slopes. As the deposits show no evidence of recent erosion, there was probably no appreciable postglacial flow through the lowland.

At the north end of Campbell Lake, the highway swings west toward Inuvik and crosses the creek by an embankment, which is pierced by a pair of culverts, each 2.5 m in diameter.

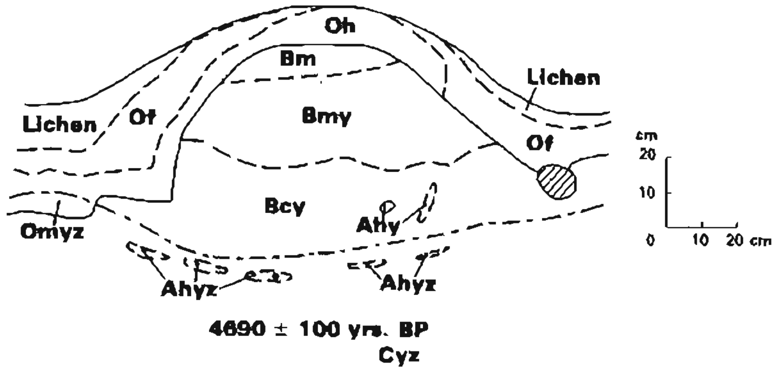

Figure 50. Cross section of an earth hummock with Canadian Soil Classification terminology (Pettapiece and others, 1978).

The Campbell Lake-Sitidgi Lake lowland has long been used as a portage route to the Eskimo Lakes and Anderson River. Although the portage trail is nearly overgrown by vegetation, there are stretches with crosslogs still preserved, as in a corduroy road, over which heavy whaleboats and canoes used to be dragged. The route was frequently used to reach Anderson River, in preference to the more exposed coastal route. Today, the highway crossing is a favorite fishing hole for local residents (jackfish or pike) and a boat-launching site for access to Campbell Lake.

KM 737. STOP 14. INSULATED ROAD EMBANKMENT, MACKENZIE HIGHWAY. An experiment to determine the effects of incorporating a layer of insulation in an embankment to prevent or control thawing of permafrost and reduce the quantity of fill required was begun at this site in 1972 by the Division of Building Research, National Research Council of Canada in cooperation with Public Works Canada. An initial overlay (pioneer) fill, from 60 to 90 cm thick, was placed across the site in late November 1971 (fig. 51). Four insulated and two uninsulated (control) test sections were constructed in 1972. The 'winter test site' was installed in April and the 'summer test site' in September of 1972. The insulation used was extruded polystyrene plastic foamboards (Styrofoam HI-60) laid down in 5-, 9-, and 11.5-cm thicknesses and covered with 60 to 75 cm of fill. The total thickness of the insulated and uninsulated embankment test sections varied from 120 to 135 cm.

Thermocouple cables were installed to measure ground temperatures in undisturbed areas off the right-of-way, in the control sections, and above and below the insulation to depths of at least 6 m. Settlement plates installed in the fill and cross-section surveys were used to determine the amount of settlement of the roadbed.

Ground temperatures were measured at regular intervals from 1972 to the fall of 1978. In undisturbed terrain adjacent to the road, the natural maximum depth of thaw varied from 90 to 120 cm. At the uninsulated control sections, the maximum depth of thaw below the centerline of the road surface increased from about 1.8 m in the summer of 1972 to nearly 2.5 m in 1978. In the insulated sections, the maximum depths of thaw observed beneath the centerline were as follows:

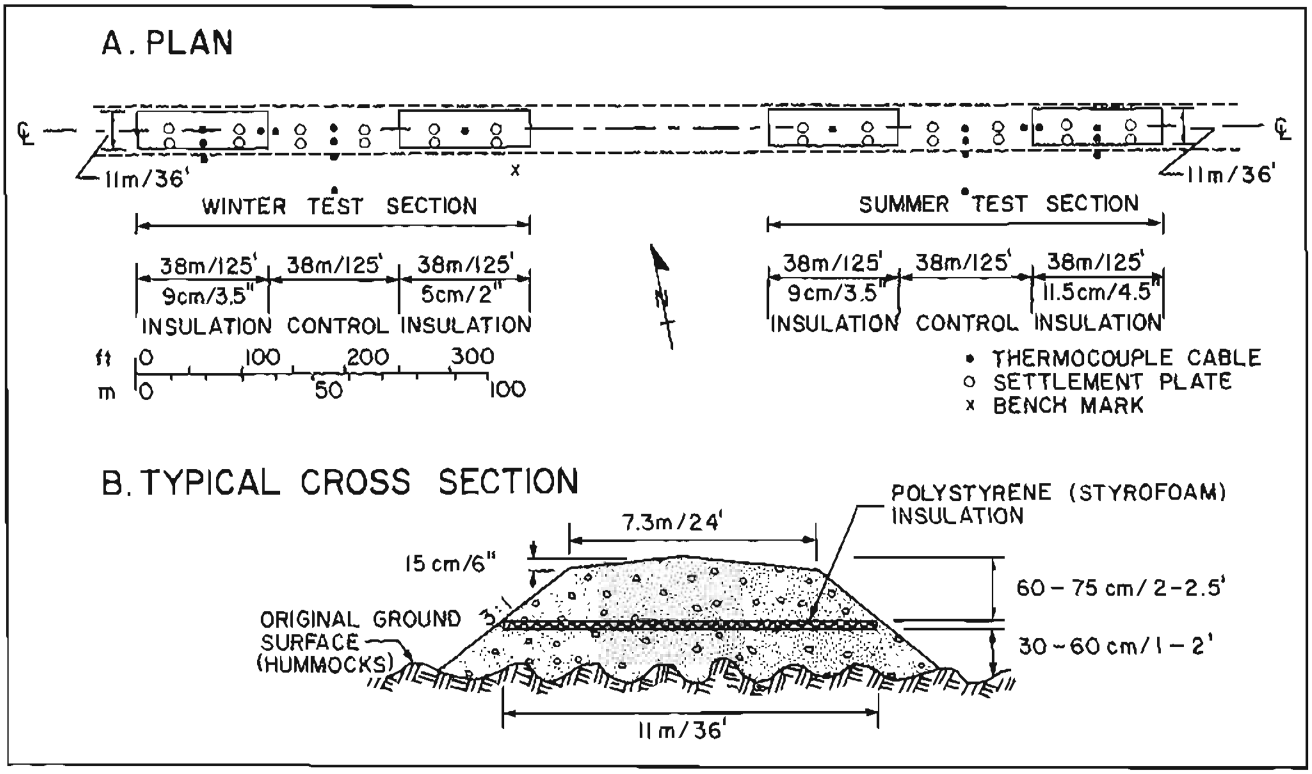

Figure 51. Plan showing the general layout and typical cross section of the insulated roadbed test site at Stop 14, 21 km east of Inuvik (from information supplied by G.H. Johnston, 1982).

Insulation thickness (cm)	Maximum depth of thaw (cm)	Site
5	121	Winter
9	96	Winter
9	114	Summer
11.5	80	Summer

Beneath the control sections, the permafrost table was lowered by 30 to 60 cm. Beneath the insulated sections, the permafrost table rose to the original ground surface under the 5-cm insulation. With the thicker insulation (9 and 11.5 cm), the permafrost table was contained within the embankment.

Considerable settlement of the uninsulated control sections occurred by October 1978---more than 30 cm at both test sites. About 30 cm of settlement occurred in the test section with 5 cm of insulation. In contrast, settlement of the section with 11.5 cm of insulation was negligible, and in the two sections with 9 cm of insulation, settlement varied from negligible to about 10 cm. In all cases, deeper thawing and greater settlement accompanied by cracking and slumping occurred under the embankment sideslopes, where there was less fill and no insulation.

KM 744. STOP 15. POLYGONAL PEAT PLATEAU. Polygonal peat plateaus (Zoltai and Tarnocai, 1975) resemble peat plateaus, but are crisscrossed by trenches that form a polygonal pattern. The usual diameter of the polygons is about 15 m. A wedge of pure ice extends downward from each trench for 2 to 4 m. Polygonal peat plateaus are perennially frozen, with the permafrost extending into the mineral soil beneath the peat. The surface morphology of polygonal peat plateaus is dominated by the polygonal trench and the adjacent mound. The center of the polygon is level or slightly concave.

A description of this site and the pedon with a cross section of the polygonal peat plateau is given in figure 52 and table 11. The soil has developed mainly from moderately decomposed fen peat ranging in rubbed fiber content from 20 to 40 percent. A thin Sphagnum peat layer is present, but only adjacent to the polygonal trench. The moister environment in the polygonal trench provides a favorable condition for Sphagnum peat development.

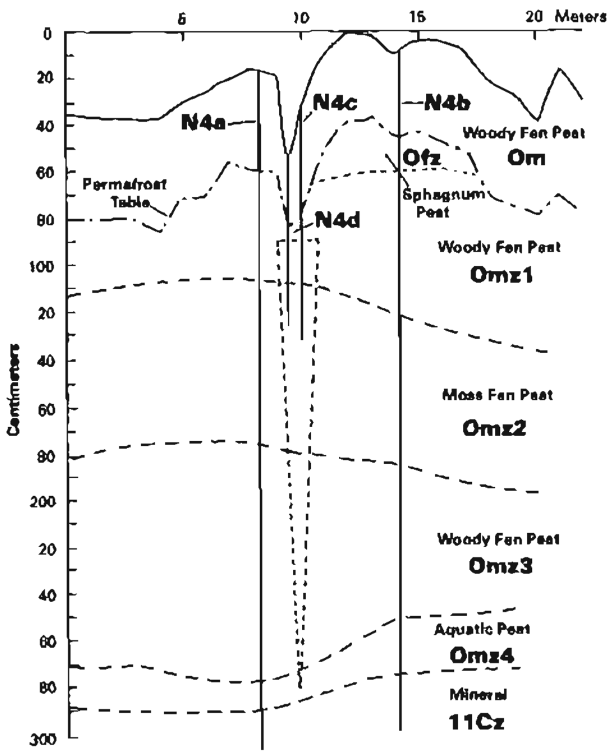

Figure 52. Cross section of polygonal peat plateau, Mackenzie Highway near Inuvik. Locations of auger holes are indicated by N4a to N4d (Pettapiece and others, 1978).

Table 11. Site description and associated soils and vegetation on a polygonal peat plateau, Mackenzie Highway near Inuvik (Pettapiece and others, 1978).

A. Site description

Location	68°19'N. lat, 133°25'W. long
Elevation	100 m
Landform	Polygonal peat plateau
Slope	Level
Drainage	Poor to imperfect in the rooting zone
Vegetation	Tundra of dwarf shrubs, lichens, and mosses
Soil temperature	10 cm = 4°C, 50 cm = 0°C, 100 cm = -1°C (September 14, 1975)
Parent material	Mesic fen peat
Patterned ground	Large polygonal pattern (approximate diameter 10 m, up to 50-cm relief along trenches)
Soil classification:	Canada - Mesic Organic Cryosol U.S.A. - Pergelic Cryohemist F.A.O. - Gelic Histosol

B. Soil description

Horizon	Depth (cm)	Description
Om	0-35	Black (2.5 YR 2.5 m), moderately decomposed, woody fen peat composed dominantly of sedges, birch, and brown mosses; loose, friable; very strongly acidic; smooth boundary.
Ofz	35-39	Dark-brown (7.5 YR 4/4 m), frozen, undecomposed *Sphagnum* peat composed dominantly of *Sphagnum* mosses, minor amounts of birch branches; segregated ice crystals; very strongly acidic.
Omz1	59-110	Dark-reddish-brown (5 YR 3/3 m), frozen, moderately decomposed, woody-moss fen peat composed dominantly of sedges, brown mosses, and woody remains; segregated ice crystals; medium acidic.
Omz2	110-175	Dark-reddish-brown (5 YR 2.5/2 m), frozen, moderately decomposed, moss fen peat composed dominantly of brown mosses and sedges; segregated ice crystals; medium acidic.
Omz3	175-240	Black (10 YR 2/1 m), frozen, woody fen peat composed dominantly of sedges, woody remains, and mosses; segregated ice crystals; very strongly acidic.

Table 11 (cont'd)

Horizon	Depth (cm)	Description
Omz4	240-265	Black (10 YR 2/1 m), frozen aquatic peat; charcoal particles; segregated ice crystals and lenses; very strongly acidic.
Cz	265-300	Frozen silt loam; segregated ice crystals and lenses; extremely acidic.

C. Vegetation description

(1) Central part

Tall shrubs 5%
- 80% Betula glandulosa
- 10% Salix sp.
- 10% Alnus crispa ssp. crispa

Low shrubs 20%
- 75% Ledum palustre spp. groenlandicum
- 25% Vaccinium uliginosum

Dwarf shrubs 20%
- 75% Vaccinium vitis-idaea
- 25% Andromeda polifolia

Herbs 1%
- 100% Tofieldia pusilla

Grasses 10%
- 100% Arctagrostis latifolia

Mosses - lichens 95%
- 50% Cladina rangiferina
- 45% Cetraria nivalis
- 5% Cladina alpestris

(2) In polygonal trench

Low shrubs 15%
- 60% Vaccinium uliginosum
- 40% Chamaedaphne calyculata

Dwarf shrubs 5%
- 100% Rubus chamaemorus

Grasses 50%
- 100% Eriophorum sp.

Mosses - lichens 70%
- 70% Sphagnum fuscum
- 30% Hylocomium splendens

The fen-peat material in this soil has a pH between 4.8 and 5.6. Its exchangeable calcium and magnesium levels are relatively high. These values are characteristic of fen peat deposited in a minerotrophic environment.

The vegetation on this peatland consists mainly of lichens, mosses, and ericaceous shrubs with some stunted black spruce, shrub birch, and alder near the edge of the peatland (table 11). The central part of the peatland is virtually treeless except for some occasional stunted black spruce.

As with other organic soils associated with polygonal peat plateaus, no basal mixing of organic and mineral soil occurs, which indicates that the peat was deposited in a permafrost-free environment (Zoltai and Tarnocai, 1975). In fact, the peat layers are often contorted near ice wedges, demonstrating that the wedges developed after the peat was deposited. The floristic composition of the peat also indicates permafrost-free deposition. Thus, both the internal structure and the floristic composition suggest that these organic soils first developed in a permafrost-free environment (Typic Mesisol) and later, as the climate deteriorated, became frozen and elevated into peat plateaus with subsequent ice-wedge development and the formation of the Mesic Organic Cryosol.

KM 758. Inuvik.

MACKENZIE DELTA AND INUVIK

By
J.A. Heginbottom[1] and C. Tarnocai[2]

MACKENZIE DELTA REGION

The Mackenzie Delta region comprises the northeastern flank of the Richardson Mountains and Arctic Ranges, the modern Mackenzie Delta, the coastal plain of Pleistocene age east of the modern delta, and the northwestern edge of the Anderson Plain (fig. 53). The Pleistocene coastal plain continues offshore as a shallow continental shelf for 100 to 200 km.

Physiography and Geology

Sedimentary rocks in the area range in age from Proterozoic to Holocene. Thick Mesozoic and Cenozoic strata underlie the central part of the Beaufort-Mackenzie basin, which is bounded on the southeast by the rolling plateau country of the Interior Platform and on the west by the mountain ranges of Cordillera (Young, 1978). The geology of the continental shelf portion of the coastal plain is not well known. A generalized cross section showing the relationship between physiography, bedrock geology, and Quaternary deposits is illustrated in figure 54.

Richardson Mountains. Much of the present topography of the Richardson Mountains can be attributed to structures resulting from tectonic deformation of pre-Paleozoic and Mesozoic strata during late Cretaceous and early Tertiary time. Opposite Inuvik, the Richardson Mountains are rugged, containing sharp ridges with steep, rocky slopes and spurs separated by deep, V-shaped valleys. The boundary between the mountains and the delta is a straight, steep escarpment that may be a fault-line scarp. Large coalescing alluvial fans formed at the base of the scarp during postglacial time (Legget and others, 1966).

Mackenzie Delta. The Mackenzie Delta constitutes an elongate north-northeast-trending lowland, the surface of which is a complex network of lakes and anastomosing channels. Mackay (1963) described the morphology and origin of most features on the delta. The large number of thermokarst lakes differentiates it from deltas formed in more temperate latitudes. Mackay believed that most lakes are of a fluvial rather than thermokarst origin; on the other hand, lakes are most abundant in the southern part of the delta where permafrost, vegetation, and drainage conditions favor thermoerosion and thaw subsidence.

Little is known of the stratigraphy directly beneath the surface of the modern Mackenzie Delta. A hole drilled beneath a lake 8 km southwest of Inuvik penetrated 69 m of unconsolidated material before encountering bedrock (Johnston and Brown, 1965). The upper 54 m consisted of organic-rich sand and

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[1] Terrain Sciences Division, Geological Survey of Canada.
[2] Land Resource Institute, Agriculture Canada.

Figure 53. An uncontrolled satellite photomosaic of the Mackenzie Delta taken in 1973 (Energy, Mines and Resources, Canada, MG-1224).

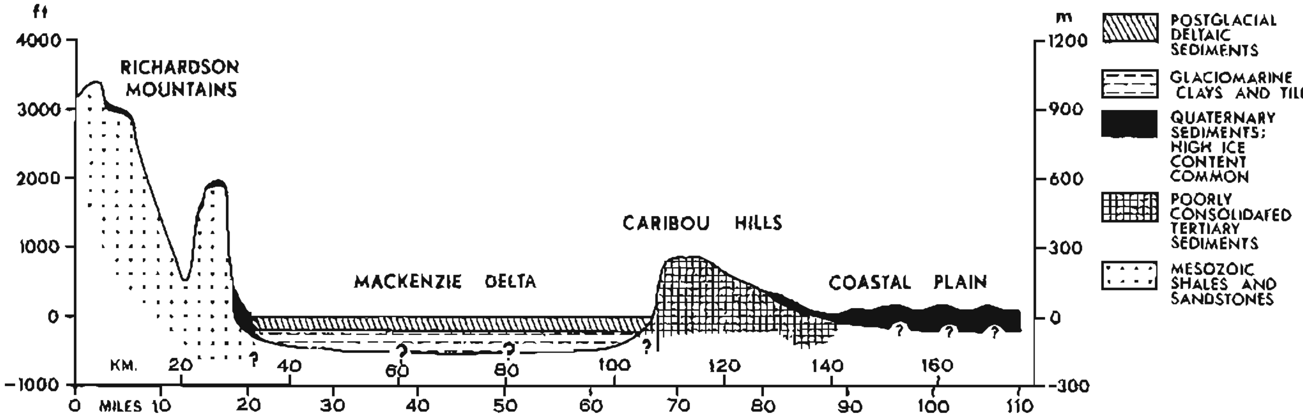

Figure 54. Generalized cross section of the Mackenzie Delta north of Inuvik, showing relationship between physiographic units, bedrock geology, and Quaternary deposits (Fyles and others, 1972).

silt believed to be of a deltaic fresh-water origin. These sediments were underlain by 8 m of dense, silty clay of possible glaciomarine origin. The bottom 7 m of unconsolidated material consisted of pebbly clay of probable glacial (till) origin. Permafrost was absent in this hole but was present in adjacent holes drilled on land. Near the seaward limit of the delta, other boreholes indicate at least 150 m of surficial material.

Caribou Hills. The Caribou Hills form an irregular upland well above the surrounding Mackenzie Delta and the Pleistocene coastal plain. Quaternary materials, generally very thin, cap Tertiary gravel, sand, silt, and coal in the northern part of the hills and Cretaceous shale in the southern part.

Coastal Plains. An extensive coastal plain of Pleistocene age borders the eastern edge of the Mackenzie Delta and Caribou Hills. It is described by Mackay (1963, p. 136) as follows:

> The coastlands . . . consist mainly of Pleistocene fluvial and deltaic deposits. The southern limit is about 10 to 20 miles south of the Eskimo Lakes. Most of the area lies below an altitude of 200 feet with about 50% below 100 feet. . . . the highest altitudes are in southern Richards Island, the areas adjacent to the Caribou Hills, and in an irregular belt on the north side of the Eskimo Lakes between Parsons Lake and Campbell Island.

West of the Mackenzie Delta is the Yukon Coastal Plain, a gently sloping erosion surface completely covered by unconsolidated sediments on its coastal edge (Rampton, 1982). The Yukon Coastal Plain forms a narrow foothill zone between the British and northern Richardson Mountains and the Beaufort Sea.

The coastal plains continue offshore to form the Beaufort Sea continental shelf. Both the emerged and submerged portions of the plain are mantled by surficial deposits.

Anderson Plain. The boundary between Anderson Plain and the coastal plain coincides with the southern limit of thick Quaternary deposits. Cretaceous shales are exposed in many river cuts; toward Inuvik, Paleozoic rocks directly underlie Quaternary materials. Except for some areas of till, unconsolidated materials are relatively thin.

Quaternary History

Most of the lower Mackenzie region and adjacent area was glaciated during early Wisconsin ice expansions (fig. 55). West of the Mackenzie Delta, the limit of this glaciation decreases from an elevation of 90 m in the Richardson Mountains west of Aklavik to present sea level near Herschel (Hughes, 1972; Rampton, 1982). East of Mackenzie Delta, the limit of glaciation can be traced across the Tuktoyaktuk Peninsula and along the western edge of the uplands east of the Anderson River (Mackay and others, 1972). Many islands (for example, Herschel, Garry, and Peily) and coastal promontories such as Nicholson Peninsula and the Kay Point-King Point ridge are results of thrusting by glacial ice during this glaciation. Permafrost was already present in the lower Mackenzie region by this time because ground ice, contained within sediments deformed by this glaciation, is similarly deformed (Mackay, 1956; Mackay and Stager, 1966).

East of the Mackenzie Delta throughout Richards Islands, Tuktoyaktuk Peninsula, and adjacent to Liverpool Bay, till of probable early Wisconsin age is underlain by glaciofluvial sediments, marine clay, sand, and deltaic sand. This sequence indicates a history of aggradation in which a marine environment was superseded by fluvial (probably glaciofluvial) and deltaic environments.

Late Wisconsin glaciers apparently were confined mainly to the trench underlying the modern Mackenzie Delta and adjacent lowlands. West of Aklavik, the late Wisconsin ice limit is at about 90 m. Much of the continental shelf was exposed during late Wisconsin and earlier glaciations, allowing permafrost to develop there.

Sketchy paleoecological data indicate that the climate was very cold and probably dry during late Wisconsin time. The climate approached conditions similar to those of today around 11,500 yr ago, but was significantly warmer by 8,000 yr ago. Because of this warming, the active layer thickened, ground ice melted, and development of thermokarst basins reached a maximum between 10,000 and 9,000 yr ago (Rampton, 1974). The climate cooled between 5,000 and 4,000 yr ago, and the expansion of thermokarst basins slowed (Ritchie and Hare, 1971). Today, many of these basins are being drained and permafrost is aggrading.

The modern Mackenzie Delta has formed since the retreat of late Wisconsin ice. Silt and clay is being deposited in Mackenzie Canyon and other glacially eroded channels that traverse the continental shelf. Today, shoreline erosion and retreat predominate along the coast.

Permafrost Conditions

Permafrost conditions vary greatly between the modern (Holocene) Mackenzie Delta and the Pleistocene delta and the Arctic Coastal Plain to the

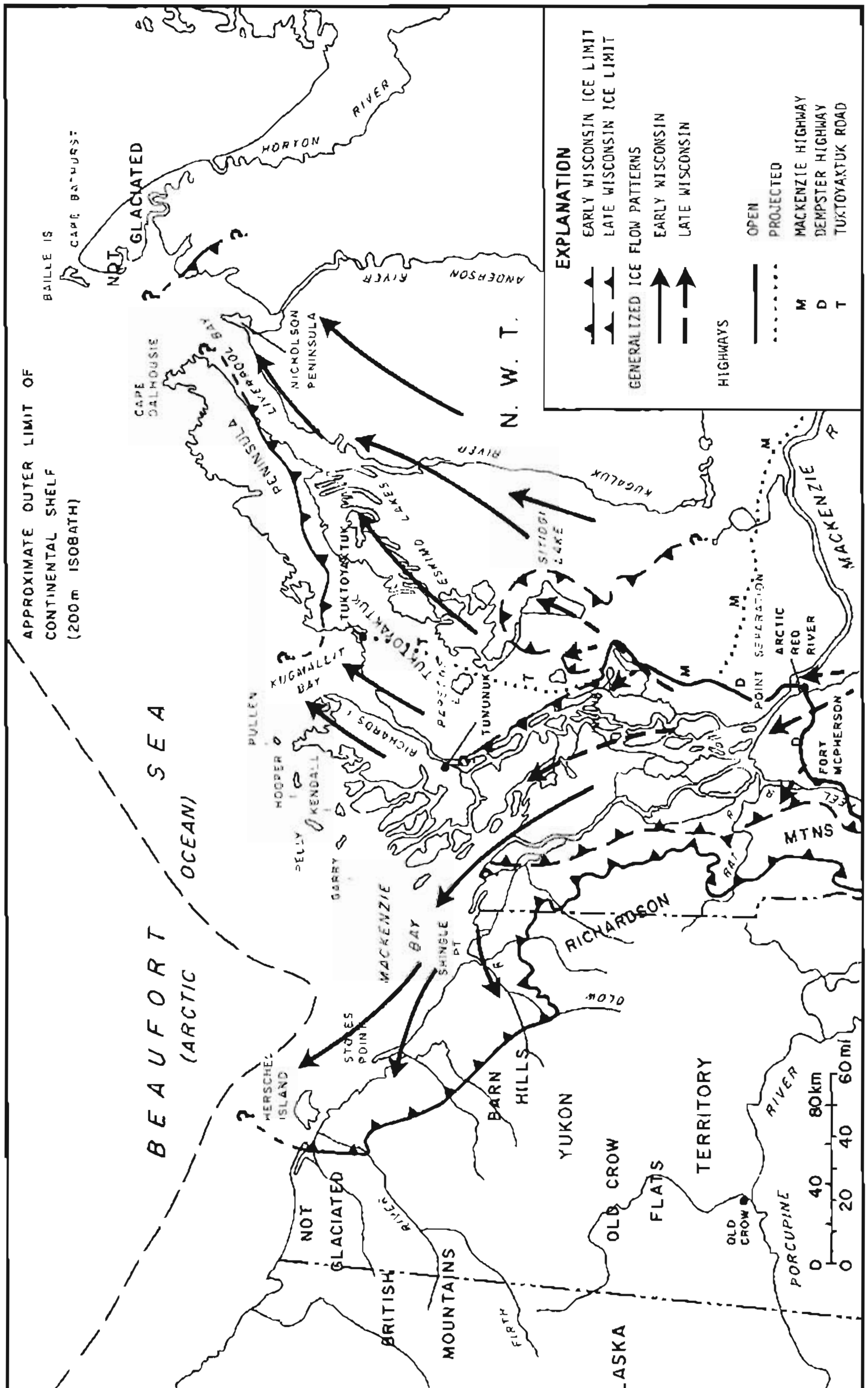

Figure 55. Map showing limits of glaciation and generalized ice-flow patterns, Mackenzie Delta and Arctic Coastal Plain (Heginbottom, 1978).

east and west, respectively. All of the modern delta is susceptible to flooding, with 15 to 50 percent of the total surface area in lakes and channels, and the terrain undergoes continuous geomorphic and vegetational changes. Consequently, the three-dimensional permafrost distribution is extremely complex. Most land surfaces are underlain by permafrost, except for many taliks, which may be closed or connected, beneath the numerous lakes and shifting channels (Smith, 1976). In the southern part of the delta, mean annual ground temperatures are about -3° to -4°C, and permafrost can exceed a thickness of 100 m. In the northern part of the delta, where the land is barely above sea level, ground temperatures are about -2° to -3°C, and permafrost is between 50 and 150 m thick. At the distal end of the delta, where shoals are being built into islands, permafrost is now aggrading for the first time. Permafrost features in the delta are not conspicuous, except for thermokarst lakes, a few ice-wedge polygons, and tilted trees around retreating lake shores. Syngenetic ice wedges are present throughout most of the delta, but they rarely exceed 1 m in width. About 80 pingos occur in the northern portion of the delta; the majority are beyond the limit of trees. Some pingos have grown as ridges up to 600 m long in river channels, rather than as circular features in shallow lakes (Mackay, 1963). The modern delta lacks the massive beds of segregated ice that are abundant in some parts of the Pleistocene delta and Arctic Coastal Plain.

The Arctic Coastal Plain and Pleistocene delta have permafrost that is much older, colder, and thicker than permafrost in the modern delta. Mean annual ground temperatures are in the -6° to -10°C range. Permafrost thickness, except near water bodies, is generally in the 400- to 700-m range (Taylor and Judge,. 1977). Syngenetic ice wedges in glacially disturbed sediments at Hooper Island, about 150 km north of Inuvik, show that the permafrost is very old. Hooper Island is beyond the limit of late Wisconsin glaciation, and the syngenetic ice wedges there grew in sediments of inferred interglacial age.

The sediments of the Pleistocene delta consist primarily of coarse sand and gravel of fluvial, deltaic, and estuarine origin (Fyles and others, 1972). The few areas of higher elevation are commonly underlain by massive bodies of tabular ice, often exceeding 20 to 30 m in thickness (Mackay, 1971, p.397-410; Rampton and Mackay, 1971, p. 11-14; Rampton and Walcott, 1974) and sometimes occurring at depths in excess of 50 m (Rampton and Mackay, 1971, p. 3). Although there is always the possibility that some buried glacier ice may be present, the stratigraphy, ice petrofabrics, and water-quality analyses suggest a segregation origin.

Using data from the Mackenzie Valley Geotechnical Data Bank (Lawrence and Proudfoot, 1977), Pollard and French (1980) estimated that ice represents 47.5 percent of the total volume of earth material in the upper 10 m of Richards Island. This area is thought to be typical of conditions in the Pleistocene delta. By compiling a typical ground ice-vs-depth curve (fig. 56), pore and segregated ice are calculated to comprise over 80 percent of the total ice volume. It was also concluded that 14.3 percent by volume of the upper 9.5 cm of permafrost is excess ice. It follows, therefore, that thawing of the top 10 m of Richards Island would cause a general thermokarst subsidence of 1.4 m.

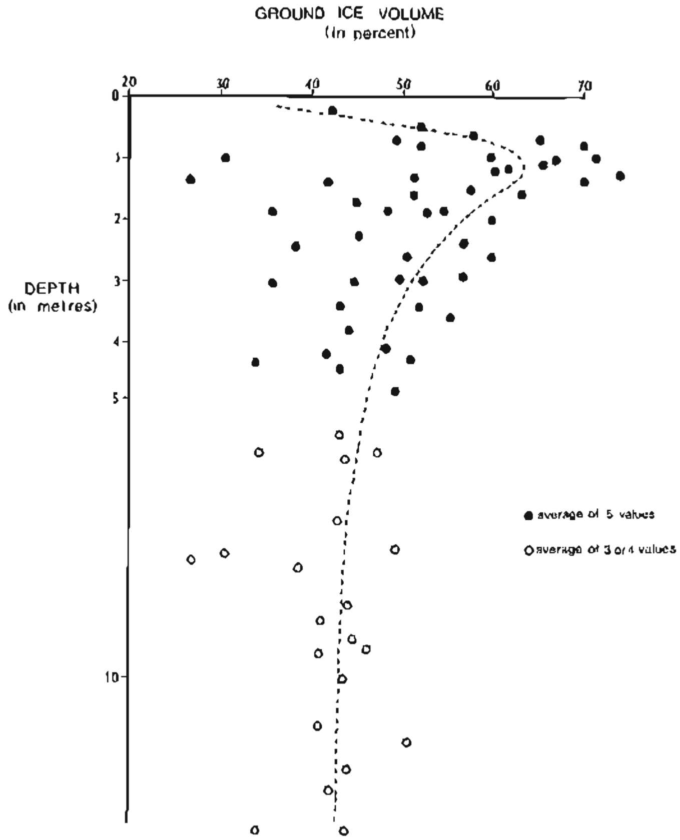

Figure 56. Curve of ground ice vs depth, Richards Island, N.W.T., Canada. Source: Mackenzie Valley Geotechnical Data Bank (Lawrence and Proudfoot, 1977). Note: Curve is a visual best fit and is not calculated (Pollard and French, 1980).

Both massive ice bodies and ice wedges are important types of ground ice in the Pleistocene delta. Pollard and French (1980) concluded that wedge ice constitutes 12 to 16 percent of total ice volume in the upper 4.5 m on Richards Island and may exceed 50 percent in the upper 1 to 2 m.

On Garry Island, ice-wedge cracking rarely occurs before January or after April (Mackay, 1974), and very few ice wedges crack each year. Most of the ice wedges probably postdate the Hypsithermal, although the lower half of relict ice wedges, truncated by Hypsithermal thawing, show that ice wedges were active prior to 10,000 yr ago.

Hydrology and Ice Conditions

The Mackenzie Delta is the largest modern delta in Canada. It extends about 200 km from Point Separation in the south to the Beaufort Sea in the north, and 65 km from the Richardson Mountains in the west to the Caribou Hills and Pleistocene delta islands in the east and northeast. It is an estaurine deposit, built from sediments delivered primarily by the Mackenzie and Peel Rivers. The delta surface is covered by an intricate network of channels of various types (distributary, river, network, lake, reversing, and tidal) and a multitude of lakes of different types and origin (abandoned channel, arcuate, flood plain, thermokarst, and dammed). Surface water covers more than 25 percent of the area and much more during floods. Levee heights, referenced to late-summer low-water elevations, range from about 9 m in the south to about 6 m in the middle and 3 m or less north of a line joining southern Shallow Bay to a point about 15 km south of Tununuk. Interlevee basins are progressively shallower with increasing distance downstream.

Mackenzie and Peel Rivers contribute by far the greatest water and sediment to the delta. Numerous smaller rivers also enter the delta perimeter, among them Rat and Rengling Rivers and Caribou and Frog Creeks. All rivers have their annual discharge maxima during either spring or summer, with the spring flood of late May or early June usually being the greatest hydrologic event (approximately 30,000 m^3/s in Mackenzie River). Flow minima occur in March and April.

Within the delta, the greatest proportion of incoming discharge is carried by the Middle Channel. Below Horseshoe Bend (opposite Aklavik), the Middle Channel transports 80 to 95 percent of total delta inflow, the lower percentages occurring during the summer high-water season. About 10 km southwest of Tununuk, the flow divides in three directions: a) west to Shallow Bay via Reindeer Channel, b) northwest by way of the Middle Channel to Mackenzie Bay, and c) and northeast via the East Channel to Kugmallit Bay.

The Peel Channel at Aklavik is second to the Middle Channel in volume of flow. From 2 to 7 percent of all delta discharge was observed to pass through it during a 1-yr study period.

Data are scarce with respect to suspended-sediment concentrations entering and within delta channels and lakes. However, Mackenzie and Peel Rivers are clearly the most important sediment sources. For the Mackenzie River above Arctic Red River, measured concentrations in the summer are mostly in the 100- to 1,000-mg/l range. On August 12, 1974, a daily extreme of 9,640 mg/l was recorded, with the river discharge at 28,000 m^3/s, which gave a daily suspended sediment load of 2.33×10^7 tons. Concentrations decline below 100 mg/l by the end of September and remain low until the next spring flood. In Peel River upstream from Fort McPherson, concentrations for the period July 1 to August 31, 1973, ranged from 200 to 1,900 mg/l, the maximum occurring during a flood discharge of 2,830 m^3/s to produce a daily suspended sediment load of 4.65 x 10 tons.

In winter, ice forms on lakes and channels. Channels are usually ice covered from late October through mid-May. Maximum ice thicknesses of 0.9 to 1.6 m occur in March or April. Ice development is highly dependent on winter air temperature and snowfall regimes as well as latitudinal position within the delta (Mackay, 1969).

Spring floods of the Mackenzie and Peel Rivers normally peak in late May, but ice starts to move in delta channels about a week before (Mackay, 1965). By the time of peak flooding, much ice has been flushed from the channels. Ice jams can occur, especially at sharp bends or in shallow reaches. Spring floodwaters may rise as high as 7 m above winter ice levels in East Channel at Inuvik, but more commonly are within the range of 3 to 6 m. Consequently, flooding is more severe in the outer delta, where levee heights are lower. Delta lakes also flood during high-water conditions. Breakup of lakes is accelerated as a result, and the ice disappears 1 or 2 wk after channel ice moves out.

Delta water temperatures rise rapidly after spring breakup because of heat input from major southern tributaries, especially the Liard River (Davies, 1975). In addition, there is a high absorption of solar radiation by the sediment-laden waters of Mackenzie River. For example, in 1974, the Mackenzie River reached its spring maximum discharge on May 30 above Arctic Red River and shortly after in the delta. Water temperatures in the East Channel at Inuvik remained close to 0°C until June 6, but rose swiftly afterward to 1.5°, 5.5°, 9.5°, and 12.5°C on June 7, 12, 14, and 26, respectively. On average, channel water temperatures in the delta reach a maximum of 16°C in late July.

The unique spring flood and heat balance in the Mackenzie Delta results in lakes becoming ice free up to a month earlier than lakes immediately to the east in the Caribou Hills. Also, the northward extension of tree line within the modern delta is evidence of the warmth offered by Mackenzie River waters. Finally, the larger, deeper channels and lakes insulate the ground beneath, and taliks can occur in or through the permafrost.

Geomorphology and Vegetation

A distinctive feature of many levees in the delta is their near-vertical erosional bank caused by channel shifting and the presence of permafrost. Although channel migration is not pronounced, cutbanks undergo rapid recession in some locations (Smith, 1976). The greatest levee retreat is caused by the development of thermoerosional niches, which form principally along northwest-oriented distributaries where the prevailing northwest storm winds are opposed to the direction of river flow. High-energy waves that occur along such channels are the principal erosional agents in niche formation. The time of greatest undercutting is mid-July, when water temperatures may reach 20°C. The efficiency of thermal erosion by this water is greatly increased by wave action, which rapidly removes thawed sediments; during periods of high wind, a niche may penetrate 5 m into a frozen levee in less than 48 hr. At this time, large blocks of frozen alluvium fall into the channel, where they are soon removed by thermal and fluvial erosion. At one location, thermoerosional niches have caused levee retreat of 10 m/yr in the past 25 yr.

Delta soils are formed from alluvium derived principally from Cretaceous shales and other sedimentary rocks that underlie the western and central Mackenzie Basin. The soils are uniformly fine grained, ranging from silty loam on upper levees to silty clay in interlevee depressions. Such fine material, together with organic material and the underlying permafrost, maintain high soil moisture and low soil temperature.

Terrestrial vegetation of the delta can be divided into three zones that grade from south to north without distinct boundaries: a) southern forest, b) central forest-shrub, and c) northern tundra (Lambert, 1972).

The southern forested zone is dominated by white spruce (Picea glauca), that often forms closed-crown stands on higher levee surfaces. Because forest fires are absent, trees may be as old as 500 yr. During their growth, a considerable thickness of alluvium will be deposited, and the rising ground surface leads to a corresponding rise in the permafrost table. Long-lived species such as white spruce adjust to aggrading permafrost by extending adventitious roots from the buried stem section into the new alluvium. Spruce stems, with ladderlike horizontal extensions, are exposed along many cutbanks. The only other important tree species is balsam poplar (Populus balsamifera).

The central forest-shrub zone is similar to the forest zone to the south, but the levees are lower and flooding is more extensive. Willows (Salix spp.) and alders (Alnus spp.) become more important, with horsetails (Equisetum) as a pioneer species. The northern tundra zone is dominated by wet sedge meadows, with low growths of willow in better drained areas.

In lakes connected to distributary channels of the delta, aquatic vegetation is dominated by horsetails, sedges, and semiaquatic grasses. These lakes receive an influx of sediment-laden water each spring, forming a miniature delta at the channel entrance. This channel transmits water draining out of the lake later in the season. Thus, there is reversal of flow each year. Lakes not directly connected to distributaries receive nutrient-rich floodwaters over low points in the levees. Because sediment influx is reduced and the lakes are less turbid, they support considerably more aquatic vegetation.

A final group of lakes comprises those bounded by levees that are high enough to prevent overtopping during most floods. They do not undergo the normal process of infilling by alluvium. Moreover, if these lakes are more than 2 m deep, they do not freeze to their bottoms during winter, and the mean annual water temperature is high enough to thaw their ice-rich, perennially frozen banks (Mackay, 1963). Shoreline retreat makes colonization impossible for normal littoral plant successions, and these lakes are bordered consequently by upper-levee vegetation, especially spruce stands. The nearshore trees show evidence of bank retreat (leaning over the lake at various angles).

KM 758. INUVIK. Inuvik (lat 68°21'N., long 133°44'W.) is the main government administrative center and distribution point for Mackenzie Delta and the western Arctic. It is also a major base for petroleum exploration and a business and commercial center. Apart from southern-based companies, there are several locally owned enterprises.

The population of Inuvik has declined in recent years from a peak of over 4,000 a decade ago to 2,065 in 1981. Of these inhabitants, a little over half are white Canadians of southern origin. The remainder is predominantly Inuit, with small numbers of Dene and Metis. Inuvik is the most racially mixed community in the Mackenzie Valley. Most of the native people in Inuvik are dependent on wage employment; some also hunt and fish for food and recreation.

The facilities of the town include general stores, hotel, schools, a 100-bed hospital, police detachment, radio station, banks, liquor store, post office, churches, court house, recreation facilities, and service industries. There is a large wharf with adjacent warehouse, and the town has road connections to Arctic Red River and Fort McPherson via the Mackenzie and Dempster Highways. Apart from the main airport, located 12 km southeast of town, there is a gravel airstrip near the wharf; float planes use the East Channel and a nearby lake. An alignment for extending the Mackenzie Highway to Tuktoyaktuk has been laid out, but construction is not expected to start for several years. Ice roads are built along the frozen delta channels each winter to Aklavik and Tuktoyaktuk.

Townsite Selection

In the early 1950s, the Canadian government decided to establish a major administration, medical, education, transportation, and communication center to serve the growing needs of the western Canadian Arctic. The townsite of Aklavik in the Mackenzie Delta was not suitable because it is situated in the flat, low delta and is subject to flooding each spring. Moreover, drainage is bad, bank erosion would be costly to control, room for expansion is restricted, and water supply and sewage disposal would be major problems. To compound these problems, the nearest sources for granular materials are more than 20 km away in the mountains on the western edge of the delta, and the town is underlain by silty, ice-rich permafrost. Subsurface investigations conducted in 1953 showed that 60 percent by volume of the frozen fine-grained soils is ice. It was decided, therefore, to conduct a detailed survey of the surrounding area to find a more suitable site.

An extensive field investigation was carried out during the late winter, spring, and summer of 1954. Essential requirements for a new site were that it should be a) economically and socially acceptable, b) suitable for installation of permanent water and sewer systems, building foundations, and roads, c) adjacent or close to a navigable river channel, d) convenient to the site of a major airfield, and e) capable of having an adequate water supply. Other considerations, such as convenient disposal of sewage and a good supply of gravel and sand, were listed as 'highly desirable.'

On the basis of airphoto studies during the winter of 1953-54, 12 potential sites along the east and west sides of the delta were selected for detailed field study. Following initial field investigations, eight of these sites were quickly eliminated as unsuitable. Terrain studies, river-breakup observations, topographic and hydrographic surveys, and soils investigations were conducted at the other four sites. By midsummer, a preliminary appraisal indicated one site, on the edge of the delta, 56 km east of Aklavik, was the most favorable. Accordingly, more detailed investigations were carried out at this site in the late summer and early fall of 1954 with emphasis on a potential townsite layout, water supply, airfield, wharf facility, and subsurface conditions (Pritchard, 1962). The site was ultimately confirmed by the Government of Canada in November 1954 as the location for the 'New Aklavik.' In 1958 it was officially named Inuvik (Inuttitut for 'The Place of Man').

Permafrost and Construction

The Inuvik site was selected because it was a well-drained, relatively flat area suitable for the intended size of the town with room for future expansion if necessary. There were large deposits of granular material for use as fill, and a suitable area for a major airport was located nearby. In addition, the East Channel provided good access by water, and acceptable water supply and sewage disposal facilities could be developed (Pihlainen, 1962).

During the summer of 1955, further detailed investigations of site and permafrost conditions, including measurement of ground temperatures, were conducted for the planning of land use, utilities, roads, and an airport. Construction materials were stockpiled, borrow pits opened, roads started, the first construction-camp buildings erected, and several hectares were cleared of brush. The major construction period lasted from 1956-61. During those years, a large school, two large hostels, a powerhouse, a water-treatment plant, several kilometers of utilidors, the airstrip, and several other major buildings plus many housing units were completed. Large-scale petroleum exploration began in the delta area in the late 1960s and early 1970s and spurred a second boom period.

Permafrost underlies the townsite and adjacent areas to depths of more than 200 m. Although granular materials are widespread, soils vary from site to site. In many places, all soil types contain considerable quantities of ice in a variety of forms, including lenses and layers, wedges, coatings on particles, and large, massive bodies several meters thick (Johnston, 1966). Examples of these ice bodies can be seen in most excavations in the area and are often seen in the gravel pits south of Boot Gully. In areas of undisturbed terrain, about 30 to 35 percent of the volume of the ground in the top 3 m is made up of ice (Heginbottom, 1975). Gravimetric moisture contents of soils range from 20 percent to several hundred percent.

Certain basic decisions were made regarding design and construction practices. Every effort was made to avoid disturbance of the existing ground thermal regime and thus preserve the permafrost. Clearing of small trees and brush was done by hand methods, and destruction of the surface organic layer was avoided. All work areas were protected by a gravel layer placed directly on the ground surface. Construction vehicles and equipment were not permitted to operate off the gravel pads, no cuts were permitted, and drainage was carefully assessed, with culverts installed if required. These procedures are still followed today.

Wooden piles were the preferred type of foundation for buildings and other facilities (Johnston, 1966). Initially they were placed in steam-thawed holes. Today, all new piles are placed in augered, slurry-filled holes. A clear air space of 0.1 to 1 m is left between the floor of the structure and the ground surface.

Although piles are widely used, structures are also supported by various other foundations. These foundations range from mud sills and footings on gravel pads for lightweight buildings (houses and small utilidors) to duct-ventilated pads for structures such as maintenance garages, workshops, large heated oil tanks, and aircraft hangars.

The Northern Canada Power Commission (NCPC) operates a generating plant to supply electric power not only to Inuvik, but also to Tuktoyaktuk and Aklavik by overhead transmission lines. NCPC also supplies heat, water, and sewage services to most of the buildings within the town of Inuvik. Water, sewer, and hot-water heating lines are contained in above-ground utilidors. In some parts of the town, water is distributed and sewage and garbage are collected by truck. Sewage flows by gravity to a lagoon north of the town; effluent from the lagoon discharges into the East Channel downstream of Inuvik.

Points of Interest

This section comprises notes on selected buildings or points of interest within the town of Inuvik, keyed to the maps in figures 57 and 58.

Town monument (fig. 59). The three arms of this sculpture in the center of the town represent the three races of people involved in Inuvik: Inuit, Dene (Indian), and Caucasian. The monument was unveiled at the official opening ceremony at Inuvik by the Right Honorable John G. Diefenbaker, P.C., M.P., the first Prime Minister to visit any part of Canada north of the Arctic Circle, who did so on July 21, 1961.

Roman Catholic Church (fig. 60). The Church of our Lady of Victory in Inuvik is also known as the Igloo Church because of its shape. The resemblance to an igloo was intentional. The church was designed and built by the Oblate Fathers---missionaries to northern Canada. It is one of the few heated buildings in Inuvik that is not on a pile-ventilated foundation. Instead, the foundation consists of a circular pad of reinforced concrete, about 30 cm thick, laid on a pad of gravel some 2 m thick that in turn was built up on a layer of brushwood and the undisturbed, natural vegetation. The church is of timber-arch construction 23 m in diameter and 21 m high; it seats 350.

Scientific Resource Centre (fig. 61). This scientific laboratory is operated by the Department of Indian and Northern Affairs. The purpose of this center is to support arctic research by universities, government, and industry by providing well-equipped facilities; it serves as a base from which field studies can be undertaken. The Centre contains laboratories, photographic darkroom, library, offices, seminar rooms, and workshop and storage facilities.

Power station and tank farm. Electrical power and heating water are supplied from a powerhouse complex near the East Channel. The original powerhouse was constructed in 1958 with a concrete mat floor supported above the ground by 9-m-long wooden piles driven into permafrost. Under this floor is an insulated crawl space that encloses the underfloor piping and has an air space of 0.6 to 2.5 m. This arrangement was designed to prevent thawing of permafrost around the piles. The soils at this site are very stony, and during pile installation a combination of steaming and drilling had to be employed. There was concern that too much steaming was done at several locations. To check on this situation, seven thermocouple cables were installed in drilled holes adjacent to selected piles, and ground-temperature readings were taken at 2-wk intervals for several years. These observations show no adverse effects on the ground thermal regime.

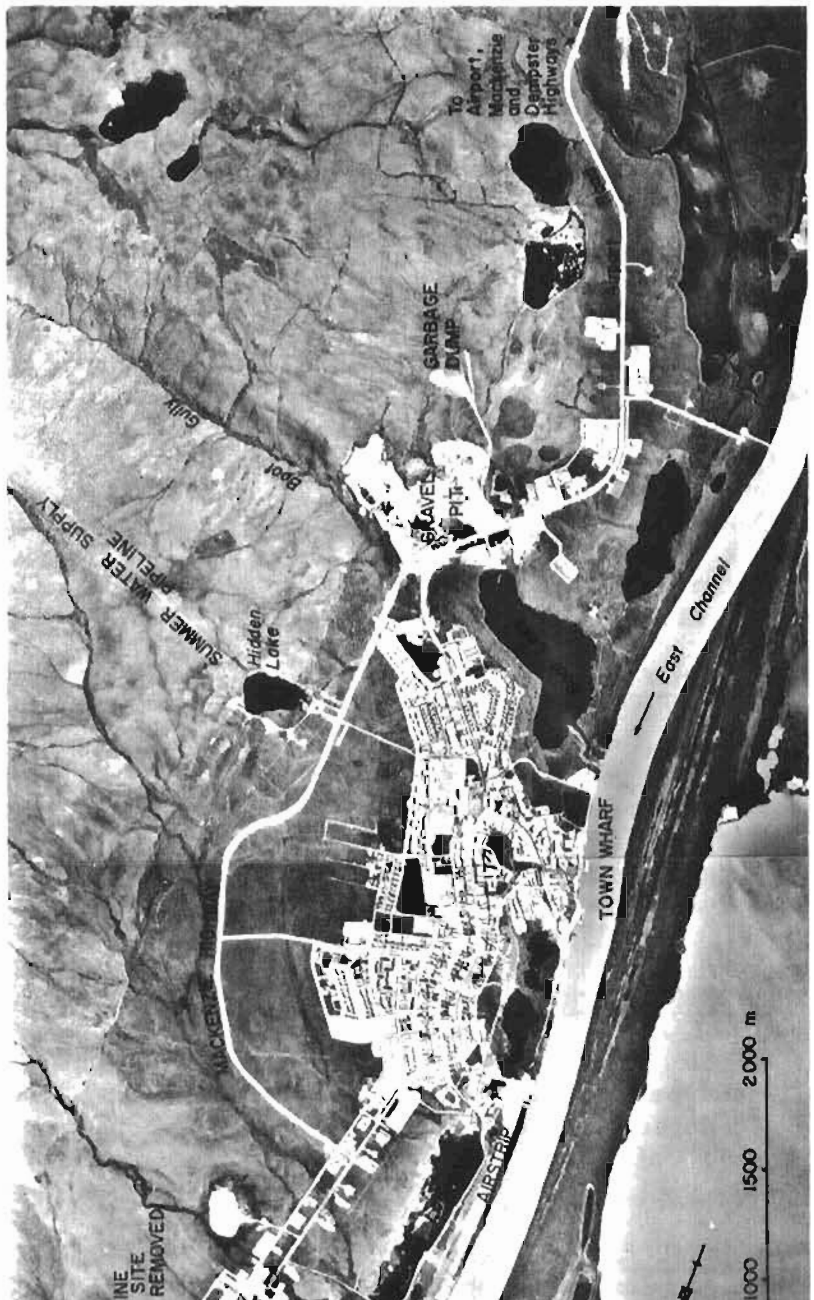

Figure 57. Annotated airphoto mosaic of Inuvik and vicinity.

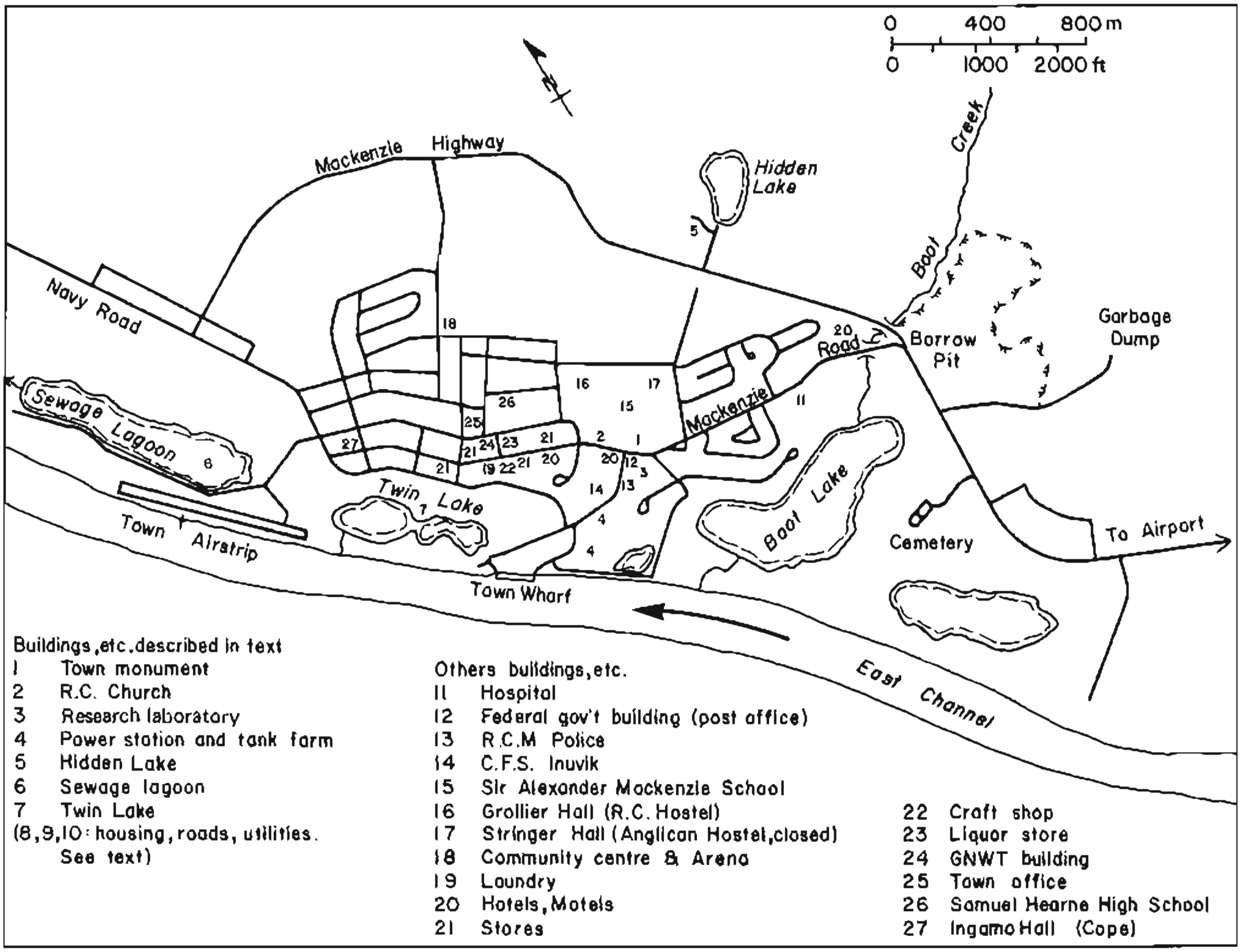

Figure 58. Town plan of Inuvik with buildings and points of interest indicated.

Rapid growth of Inuvik necessitated an addition to the powerhouse in 1967. A very different foundation design was selected (fig. 62). The main feature of the foundation is the duct system buried in the base of the fill and joined by headers at each end, through which cold air is circulated during winter months. Ground-temperature conditions beneath this extension were also monitored by thermocouples installed during construction.

Continued growth led to the construction of a second powerhouse in 1970, which contains one large generator. This powerhouse was built on piles which had been installed many years earlier. The generator block is supported separately from the main floor and the superstructure of the building.

The fuel-oil tanks at Inuvik have been constructed on a variety of different foundations. A number of the tanks are heated during winter. Most tanks are built on circular pads of gravel or crushed rock with ventilation ducts of steel culvert pipe. Typically the ducts are 45 or 60 cm in diameter

Figure 59. The Inuvik town monument (Photo: July 1982).

and spaced 1.2 or 1.4 m apart (center to center). Where possible, the ducts are oriented (108 degrees true azimuth) so that the prevailing wind blows directly through. There is a thickness of 0.1 to 3.6 m of gravel below the ducts and 1 to 1.2 m above them. Some of the pads also include one or more layers of urethane foam insulation, 5 to 15 cm thick. Only one tank is on a pile foundation. This tank is built on a circular concrete pad, 25.6 m in diameter by 38 cm thick, supported on 282 wooden piles (each 10 m long); it has an air space not less than 75 cm high. The piles are arranged in a series of concentric circles, with an average spacing of about 1.4 m. The foundations of all the tanks appear to have performed satisfactorily, with no more than ordinary maintenance required.

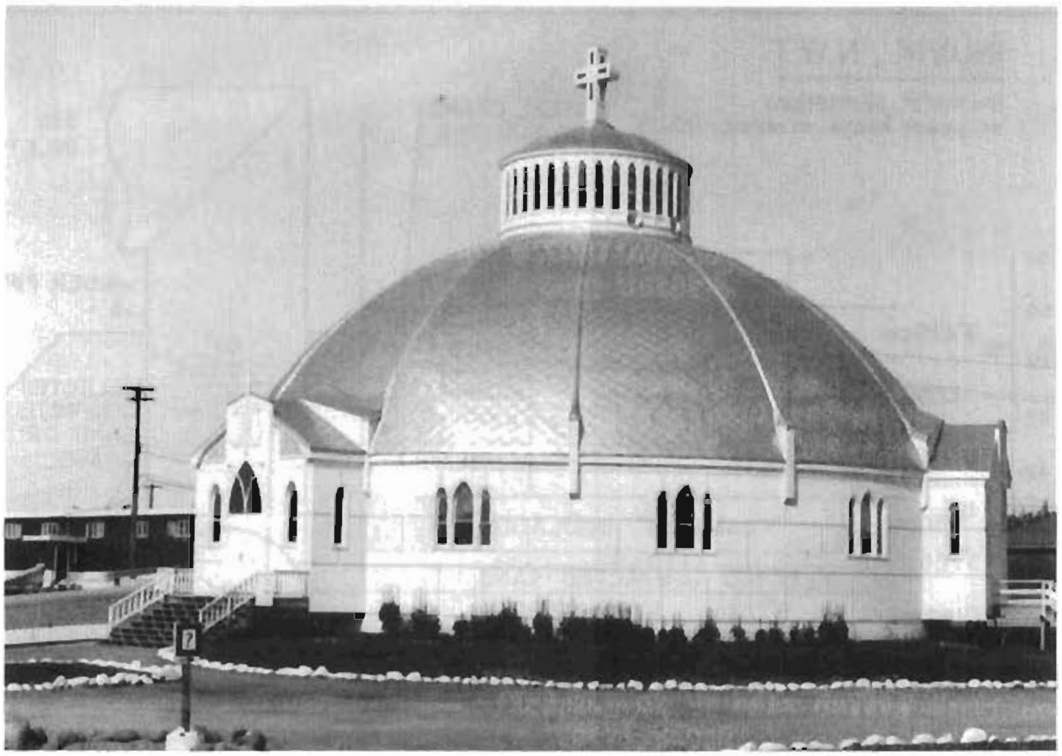

Figure 60. Roman Catholic Church, Inuvik (Photo: July 1982).

Figure 61. The Scientific Research Centre, Department of Indian and Northern Affairs, Inuvik (Photo: July 1982).

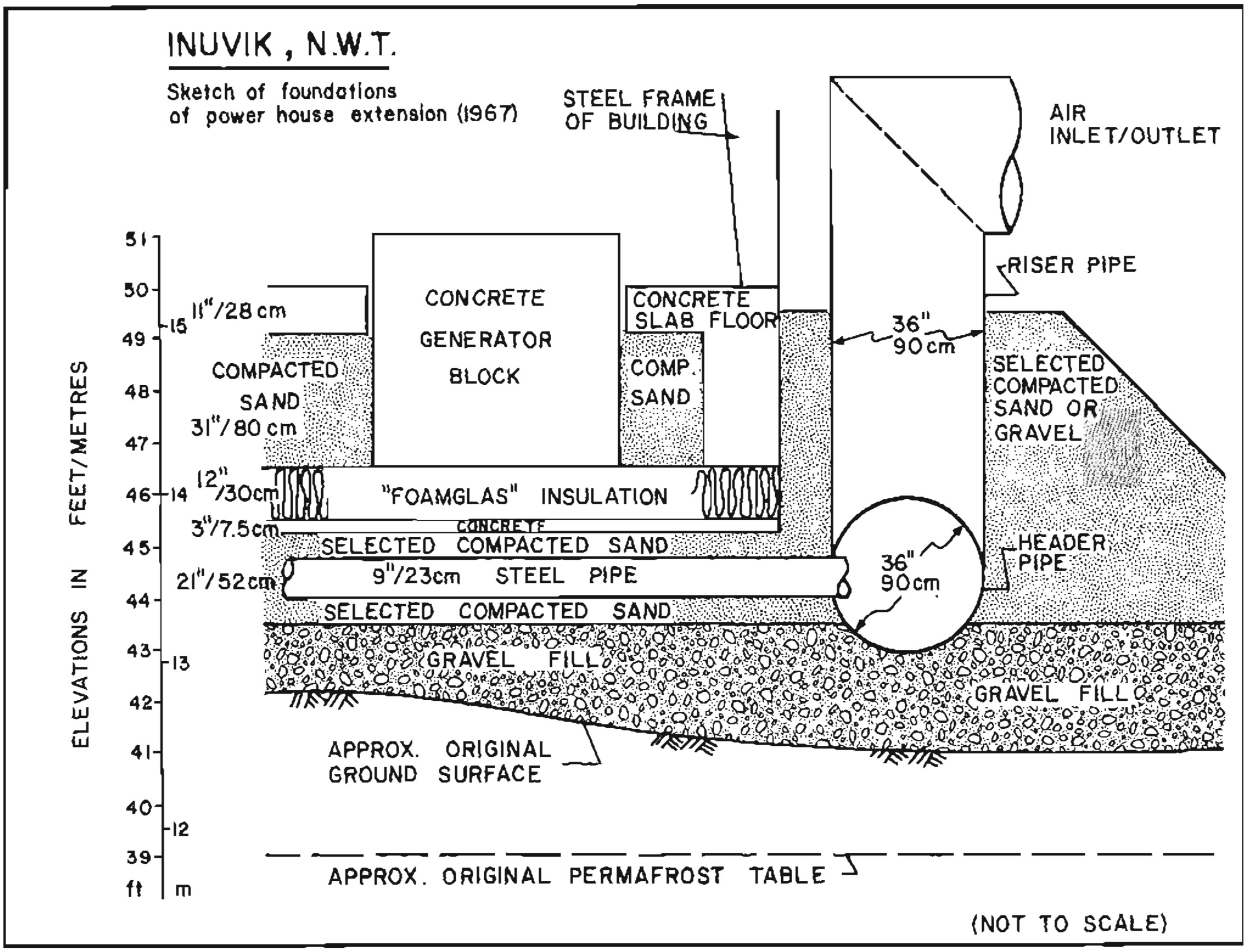

Figure 62. Diagrammatic sketch of the ducted foundation for the 1967 extension to the Inuvik powerhouse (Johnston, 1982).

Hidden Lake. This small lake immediately behind the town was the original drinking-water supply for Inuvik. Water for the town is now drawn from the East Channel and from another lake about 5 km to the east. The lake basin probably originated as a thermokarst depression.

The antenna dish above the town receives television and commercial communications signals from southern Canada via satellite. There is a good view across the town and Mackenzie Delta from near the antenna structure.

Sewage lagoon. All sewage piped from the town system flows through the utilidor system and is discharged into this lagoon, which was formed by damming a natural depression and raising a berm adjacent to the East Channel. Some vegetation was stripped off the bottom of the lagoon to provide a greater depth by thawing the permafrost. The purpose of the lagoon is to store sewage for discharge into East Channel during those times of the year when there is no danger of contaminating the water supply. Discharge from the lagoon is via a sluice at the north end. The lagoon was reconstructed in 1982.

Sewage from the unserviced parts of the town is collected by tank trucks, which also discharge into the lagoon but at the north end near the outfall. In winter, a partial ice cover forms on the surface of the lake. The warm effluent inflow keeps a large area of water open all winter at the south end of the lake. This pool attracts early migrant birds, and even tempts some species to winter here.

Twin Lakes. The lakes, which are really a single lake, are considered to be kettle holes. A thick deposit of peat in the northeast bank has been described by Mackay (1963, p. 41), Mackay and Terasmae (1963), and Kuc (in Fyles and others, 1972, fig. 5). The peat is 340 cm thick and overlies about 15 m of glaciofluvial gravel and till. Six radiocarbon dates provide ages ranging from 11,500 ± 160 yr B.P. (GSC-1514) at the base of the peat to 5,420 ± 70 yr B.P. (WIS-279) at 30 to 40 cm from the top. The macrofossil sequence identified by Kuc records the change from an aquatic environment through swamp to forest and agrees with sequences proposed by Mackay and Terasmae (1963) and Ritchie and Hare (1971).

Housing. Housing in Inuvik includes a mixture of government-, company-, and privately owned houses and apartments.

The original government housing included apartments for single staff members and either four-unit row houses or single-family dwellings for married staff. Each type of dwelling was provided with complete water, heat, and sewage services by means of utilidors. Each building contains its own heat-exchange unit. Apartments have a living room with kitchenette, bedroom, and bathroom; a common laundry room is provided within the building. The row houses each have three bedrooms and a bathroom upstairs, with a large living room and a kitchen downstairs. Each is equipped with a refrigerator, washing machine, and clothes dryer. The single-family houses include another bedroom and a separate dining room.

Private houses and apartments include a wide variety of styles and designs. Most are built on pile foundations, and most use the utilidor for water supply and sewage. A few also use the heating water from the utilidor, but many have their own oil furnaces for space heating.

Roads and sidewalks. As in most communities in northern Canada, the roads of Inuvik were all gravel surfaced until 1979. Although satisfactory in winter, they were either dusty or muddy in summer. The original sidewalks were boardwalks.

In 1979, the main street was asphalted as an experiment. The section in the town center, which receives the most traffic, broke up within 2 yr and was repaired in 1981 using chip seal, a mixture of oil and sand spread out, compacted, and covered with a layer of rock chippings. Chip seal was also used on the road to the airport, where it has worn better than in the center of town.

The concrete sidewalks were laid in the summer of 1980 and appear to be holding up well.

Utilities. There are at least eight utilidor designs in service in the townsite. Utilidors distribute drinking and hot water and collect waste water and effluent. The original utilidors were constructed with a 1- by 1-m steel frame, clad with aluminum and insulated with 7.5 cm of fiberglass (fig. 63). The system was supported on wooden piles driven into the permafrost at least 6 m. Connections to dwellings were by smaller 'utilidettes' containing smaller pipes. Some housing units (rows) were later built astride the main utilidor.

Several other utilidor designs have since been developed. They include insulated sections of metal or insulated plywood boxes. Most utilidors are supported on piles, but some sections use timber sleepers laid on a gravel pad and others use gravel-filled oil drums. One problem that results from the use of above-ground utilidors is the difficulty of arranging road crossings (fig. 64). This problem has resulted in the construction of several bridges where roads go over utilidors. There is also one underpass, which was constructed after the utilidor was in place.

Electric power is distributed around the town by normal overhead lines. The supporting poles are strapped to piles driven deep into the permafrost, and most piles are stable. The powerlines to Tuktoyaktuk and Aklavik are supported in the same manner.

ROAD LOG AND SITE DESCRIPTIONS

The site descriptions are arranged in order from southeast to northwest, following the progression of the sites along the main Dempster and Mackenzie Highways. The distances continue to be related to the southern terminus of the Dempster Highway at Klondike Lodge.

KM 748-760. Airport Road sites. The original concept for Inuvik placed the airport immediately north of the town, where the present Mackenzie Highway bypasses the town (fig. 58). Fortunately, the present site, 11 km east of the town, was chosen instead, thus sparing the townsite the noise associated with a busy airport. In recent years, a number of industrial and commercial enterprises have been established along Airport Road (fig. 57).

KM 748. STOP 1. INUVIK AIRPORT. The Inuvik airfield was constructed between 1956 and 1958 on a site underlain by frozen fine-grained soils containing considerable ice. Its design and performance were therefore of considerable concern. The airfield consists of a rock-fill embankment constructed on the undisturbed ground surface in a thickness sufficient to prevent (or minimize) thawing of the frozen subgrade soils (from 2.5 to 4.2 m, and averaging about 3 m) (fig. 65). The airfield was paved with asphaltic concrete in 1969. From 1958 to 1974 ground temperatures were measured at several locations in the subgrade and in the embankment (Johnston, 1982). All temperature observations showed that the permafrost table moved up at least 0.6 m into the fill after construction was completed in 1958 and remained at about the same level in subsequent years, even after paving. The airstrip has performed extremely well and has required little maintenance work.

In addition to the runway, taxiways, and apron, the airport includes a number of buildings with different foundation designs. The control tower and terminal are founded on piles installed between 1956 and 1958. Hangars with

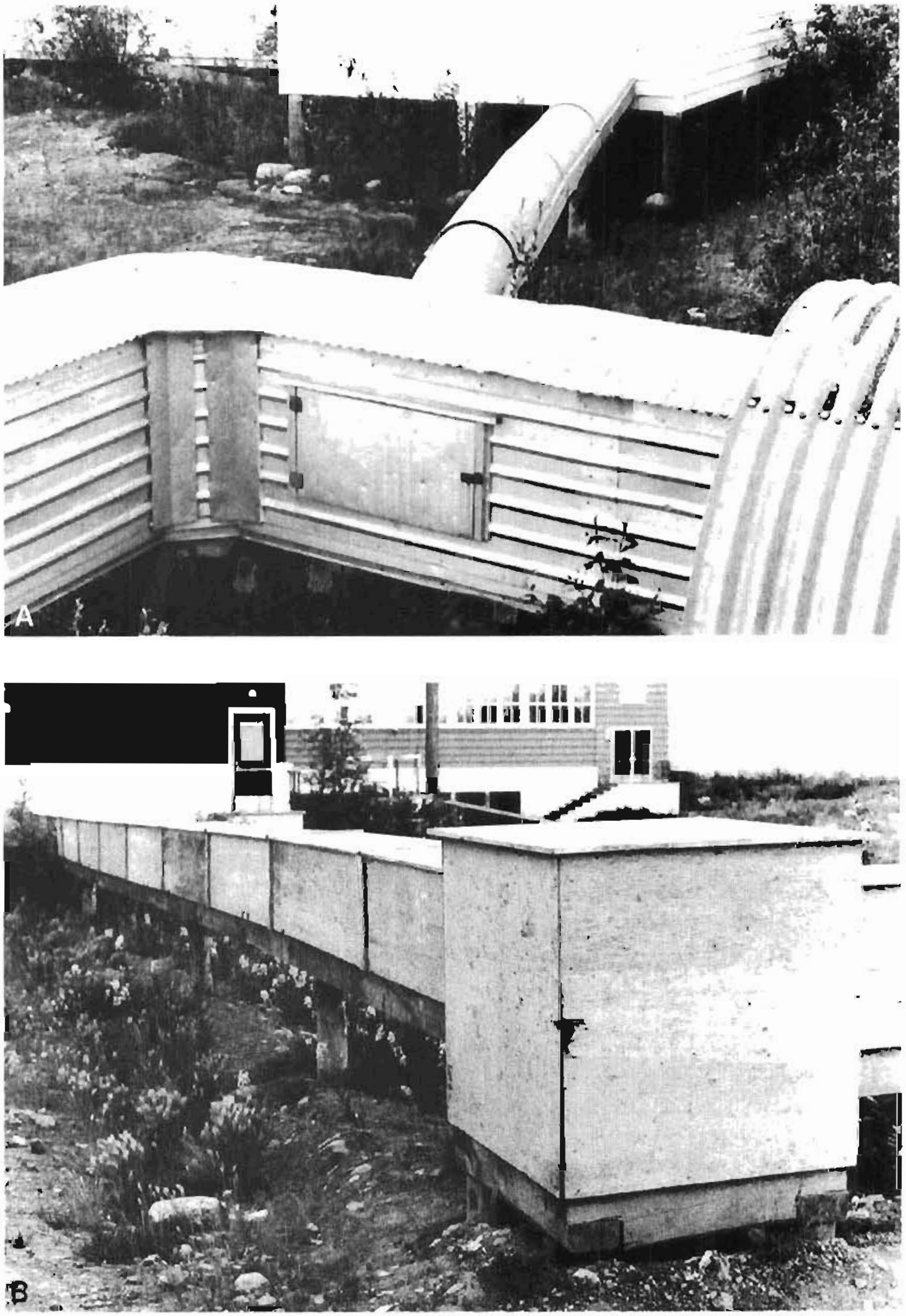

Figure 63. Original utilidors in Inuvik townsite, 1982. (A) Original metal-clad utilidor and 'utilidette' house connection; (B) wooden box on piling utilidor.

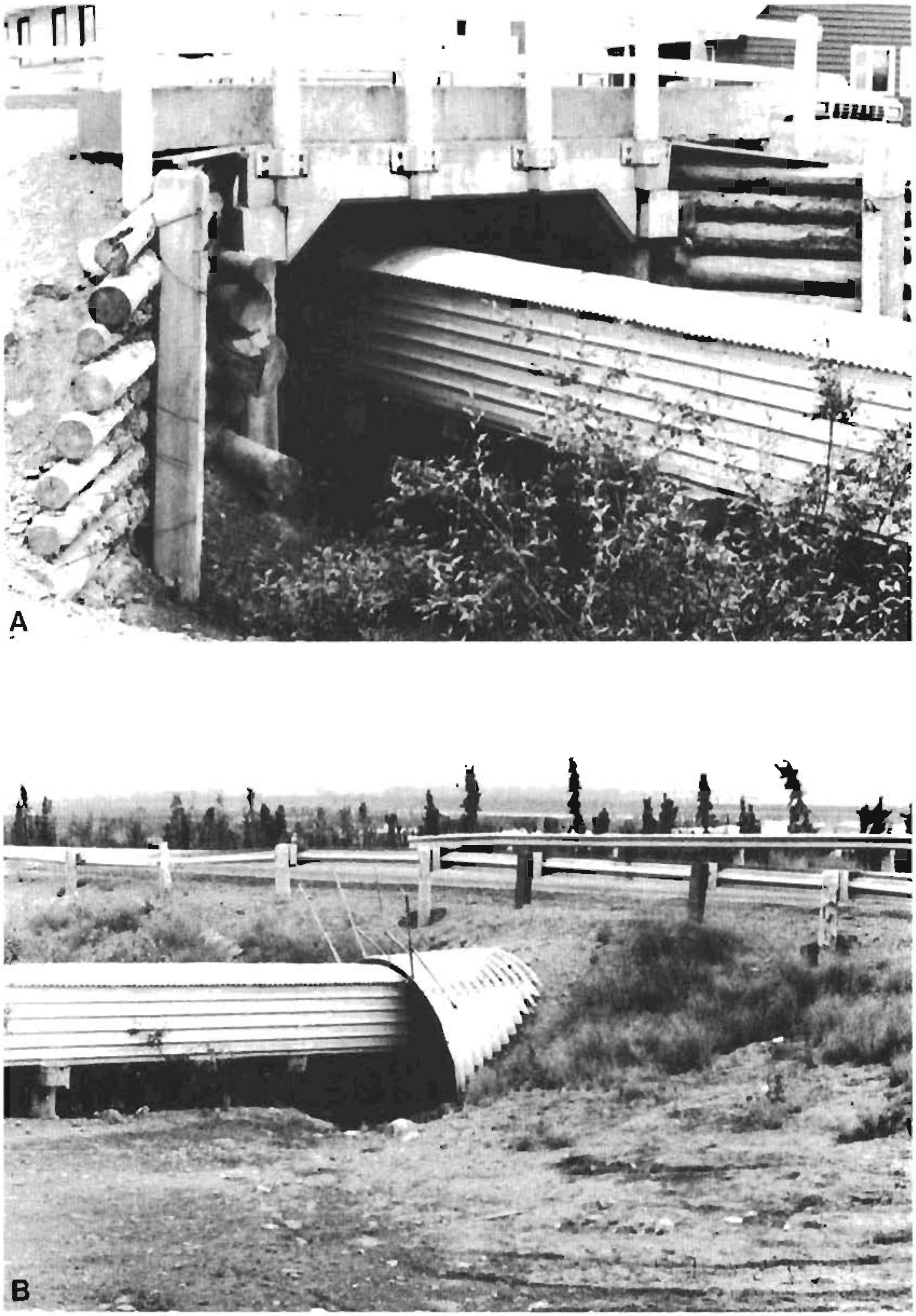

Figure 64. Road crossings of utilidor, Inuvik townsite: (A) original pattern concrete bridge; (B) current metal culvert.

duct-ventilated foundations were built for Imperial Oil Company, Ltd. (Nixon, 1978) and Okanagan Helicopters in 1959 and 1972, respectively; both seem to be performing satisfactorily.

KM 749. STOP 2. SNOW-ROAD TEST SITE. (Note: this site is on airport property and the permission of the airport manager is required prior to any visit.)

Snow-road construction and performance studies were undertaken in this area during the winter of 1973-74 (Adam, 1978). The test site consisted of a lane 520 m long and a loop of about 625 m for a total length of about 1,150 m. Site preparation consisted of clearing trees by hand methods (although willows and alders were left in place). After the snow road was constructed, trafficability was tested with various vehicles having gross loads up to 36 tons and conducting as many as 1,600 vehicle passes. When the site was examined the following summer, there had been a reduction in the shrub vegetation, but there were no significant changes to the mosses and lichens, root systems of shrubs, ground-surface elevation, organic layer, or active-layer thickness (Younkin and Heltinger, 1978).

KM 754. STOP 3 (OPTIONAL). GAYNOR LAKE. In 1967, Imperial Oil Ltd. ('Esso') installed one of the first 'test' pipelines at this location. The 30-cm-diameter line was about 600 m long. Most of the pipeline was buried beneath the ground. One 80-m-long sector was laid beneath 'Gaynor Lake,' and part was laid on the ground and covered with a low berm. A section was also laid beneath the roadbed. The line and the ground along the right-of-way were monitored for a few years. Originally it was planned to circulate crude oil through the pipeline. Today, it is heavily overgrown with willows, alders, and fireweed.

<u>1968 forest fire</u>. A serious forest and tundra fire burned around Inuvik from 8 to 18 August 1968 and destroyed many tens of square kilometers of lichen-rich tundra and forest-tundra. As a direct result, some bare hillslopes became gullied, sediment was transported into otherwise clear lakes, ice-rich permafrost degraded, flow slides developed, bulldozed firebreaks subsided, and the active layer thickened over most regions. The fire started between Gaynor Lake and 'Tower Lake' and spread to the north and east. Studies of the effects of this fire and of the fire-fighting activities were started in 1969. Surveys show that the depth of the active layer, where the vegetation had been burned, increased rapidly from 1968 to 1972, but more slowly since then (fig. 66). Beneath the bulldozed firebreaks the response was even more rapid.

KM 759. STOP 4. 'BOOT GULLY' AND TOWN BORROW PIT. Boot Gully served as a meltwater channel during deglaciation. The valley connects the Campbell Lake-Sitidgi Lake lowland and the Mackenzie Delta. At the west end of the gully is a 10-m-thick deposit of outwash gravel about 1 km^2 in extent. This gravel overlies gray clayey silt. Most of the gravel has now been removed for use as general fill during construction of the town and for road building. Several masses of ground ice, including large lenses and wedges, were found in the gravel during borrow operations (fig. 67). At times, their presence led to considerable slumping and thermokarst, which hampered use of the borrow pit.

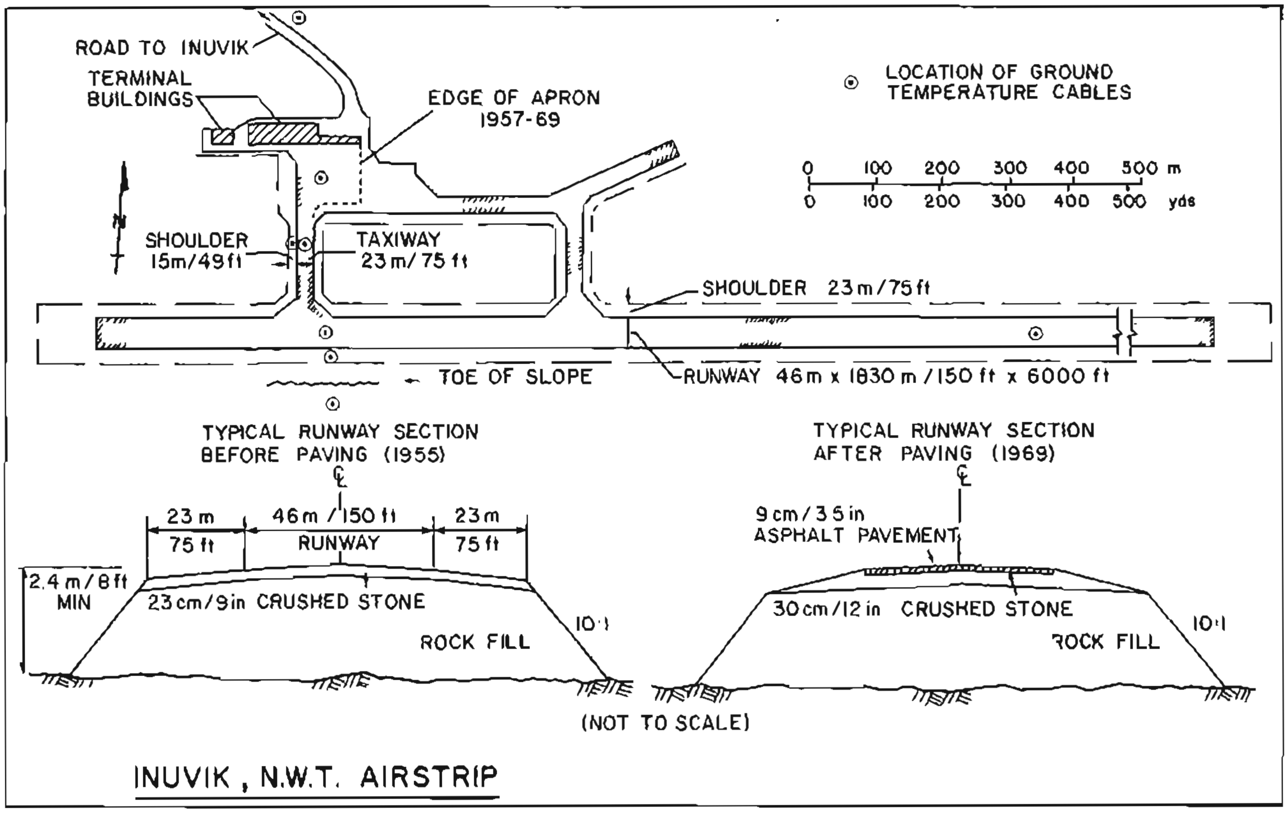

Figure 65. Plan showing the general layout of the Inuvik airstrip and typical sections of the runway before and after paving (Johnston, 1982).

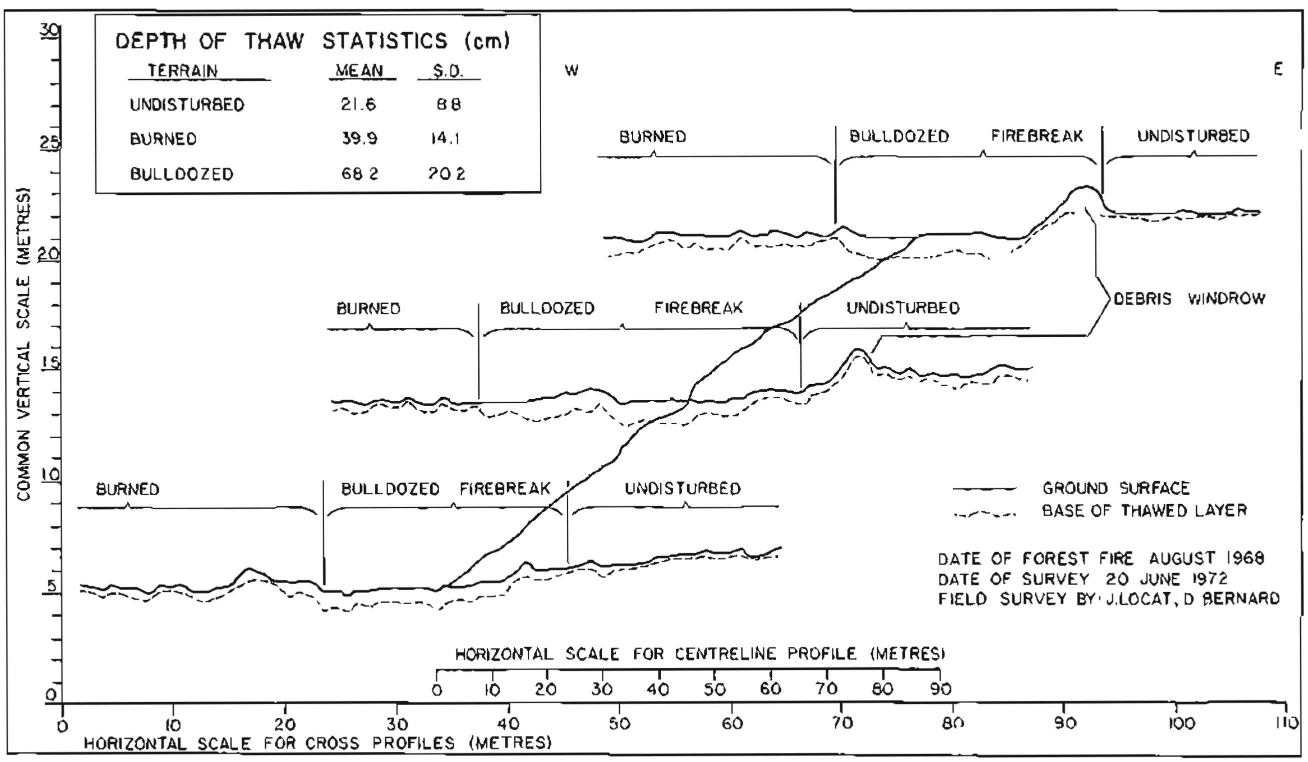

Figure 66. Profiles of ground-surface elevation (arbitrary datum) and depth of thaw across the firebreak north of Inuvik.

Figure 67. Small ice wedge in gravels at 'Boot Gully' borrow pit, 1971.

Navy Road Sites

North of Inuvik is an industrial area, which includes the main wharf and warehouse of Northern Transportation Company Ltd. and the Imperial Oil Company tank farm beside the river.

KM 760-764. Navy road to CFS Inuvik. For 12 km north of Inuvik, there is a bench about 1,500 m wide between the delta and the hills. This bench is covered by low-angle fans of clayey silts that extend from gullies in the hills. Under these fans, gravel occurs in several places, generally at a depth of 1.5 m or more. These gravel occurrences are interpreted as kame-terrace deposits laid down between the hills and a late glacial ice lobe in the Mackenzie Delta. Excess ice is found in both the silty clay and the gravel, with up to 90 percent ice by volume in some horizons. The active layer is typically 15 to 100 cm deep. In winter, the uppermost meter of the ground contains an average of 30 percent excess ice by volume. The underlying meter of soil typically includes an average of 50 percent excess ice throughout the year. Any ground-surface disturbance, whether by fire or bulldozing, leads to a virtual disappearance of excess ice in the top meter and a significant decrease in the second meter (fig. 68).

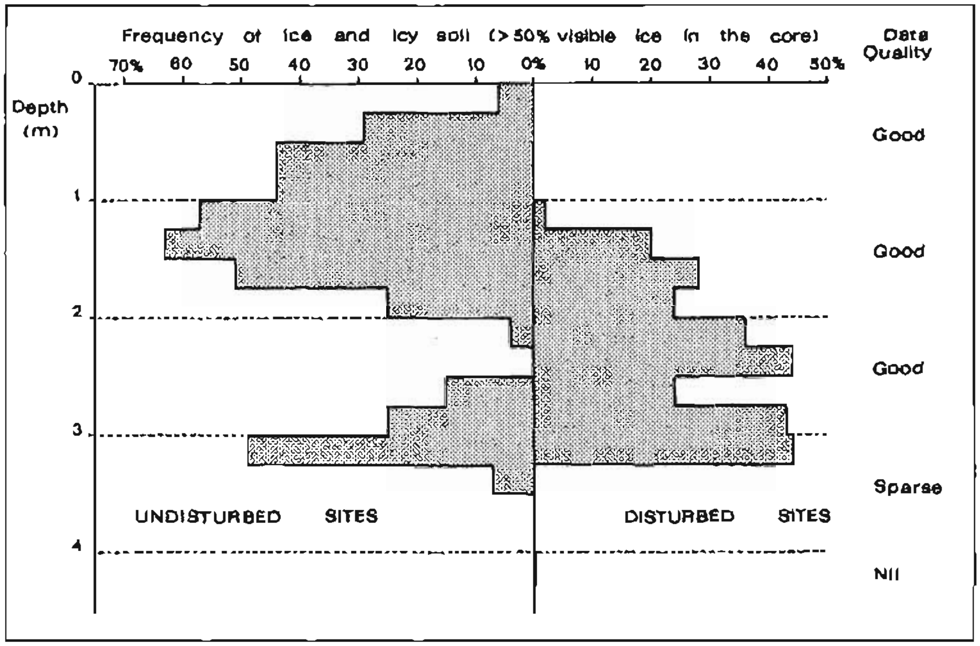

Figure 68. Effects of surface disturbance on ground-ice content and distribution in the upper 3 m of the ground near Inuvik (Heginbottom, 1975).

KM 761. STOP 5 (OPTIONAL). PIPELINE TEST SITE. A hot-oil pipeline test facility was constructed in 1969 by Mackenzie Valley Pipeline Research Ltd., a consortium of 16 oil and pipeline companies. The facility consists of a 610-m-long closed loop of 1.22-m-diameter pipe containing crude oil from Norman Wells. Half of the pipeline was supported above ground on piles and the other half was laid on a gravel pad and covered with a gravel berm. Various types and thicknesses of insulation were installed on different segments of the pipeline and heated oil was circulated around the loop. The site was chosen to simulate the severe climatic and permafrost conditions that would be encountered by an arctic pipeline system. Soils at the site consisted of 2 m of ice-rich silt containing ice lenses, overlying 4.5 m of well-drained sandy gravel, over frozen or plastic clay of low-moisture content. The test facility was operated from February 1970 until late 1972. It has since been dismantled and removed except for the gravel pads.

KM 762. STOP 6. HUMMOCK FROST-HEAVE SITE. In 1975, J.R. Mackay and others started a field program at this site to determine if volume changes (frost heave) could be detected in the active layer after the entire active layer had cooled below 0°C and frozen through to permafrost. Three different methods were used to measure frost heave: a) a 'bedstead' arrangement, b) heavemeters, and c) wooden stakes leveled with reference to three invar rod benchmarks, which were the supports for the bedstead. The elevations of these various devices were measured to an accuracy of 1 mm or less. The results (fig. 69) show that frost heave can occur in fine-grained soils from January to late spring, after the entire active layer is at a temperature below 0°C (Mackay and others, 1979). The cumulative results show that ground-surface heave of 1 to 2 cm occurs after January with some heave continuing until May. There is some evidence that the amount of heave relates directly to the thickness of the active layer.

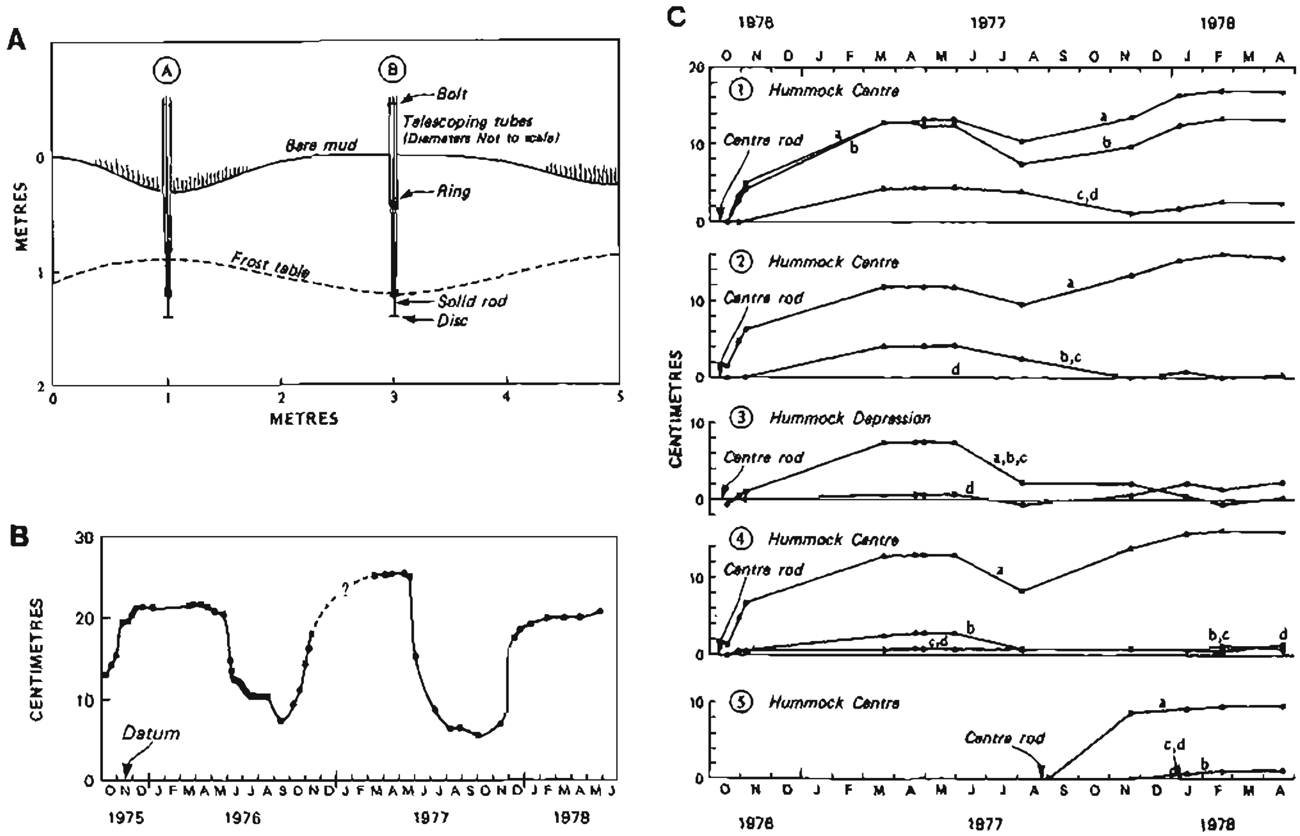

Figure 69. Winter frost heave at mud hummocks (Stop 6), Inuvik, N.W.T. (A) Schematic diagram of telescoping tubes with one set installed in an inter-hummock depression, the other in the hummock center. The bolts serve to keep the tubes in position during insertion. (B) Graph showing the amount of heave of one of the six invar spindles (No. 2) that rested on the surface of a mud hummock. (C) Graph showing the amount of heave of the five sets of telescoping (tubes a, b, c, d) heavemeters referenced to their datum center rods.

Hummocks (nonsorted circles) occur widely in the arctic and subarctic regions of northwestern Canada. At Inuvik, the hummocks are composed of fine-grained frost-sensitive soils. The late-summer frost table is bowl shaped and the hummocks grade from those that are completely vegetated (earth hummocks) to those with bare centers (mud hummocks). Mound form is usually attributed to an upward displacement of material resulting from cryostatic (freezeback) pressures generated in a confined, wet, unfrozen pocket of the active layer. Theoretically, cryostatic pressure should not develop in a frost-sensitive hummock soil because ice lensing at the top or bottom of the active layer will desiccate the last unfrozen pocket so that the pore water is under tension, not under pressure.

Field observations by Mackay (1979a, 1980) on Garry Island and at Inuvik provide no evidence for the cryostatic theory. Instead, they suggest that an equilibrium model of hummock growth is more appropriate (fig. 70). The upward displacement of material is believed caused by the freeze and thaw of ice lenses at the top and bottom of the active layer with a gravity induced, cell-like movement, because the top and bottom freeze-thaw zones have opposite curvatures. The cell-like circulation is evident from the grain-size distribution of the hummock soils and from upward-moving tongues of saturated soil observable in late summer. The most active period is late summer.

KM 764. STOP 7 (OPTIONAL). BRUNISOLIC TURBIC CRYOSOL. This site is located on strongly cryoturbated, fine-textured colluvium at the edge of the 1968 forest fire. The soil is classified as a Brunisolic Turbic Cryosol. The vegetation is mainly sedges and cottongrass, but in an adjacent unburned area there is a typical black spruce-lichen subarctic forest. The earth hummocks here are much larger than average, but, because of the' deep active layer resulting from the burn, they are good for illustrative purposes (fig. 7A). Note in particular the intrusions of peaty materials and the subsurface organic horizon (Ohy) near the frost table. Analytical data for the soil profile at this site are presented in table 12.

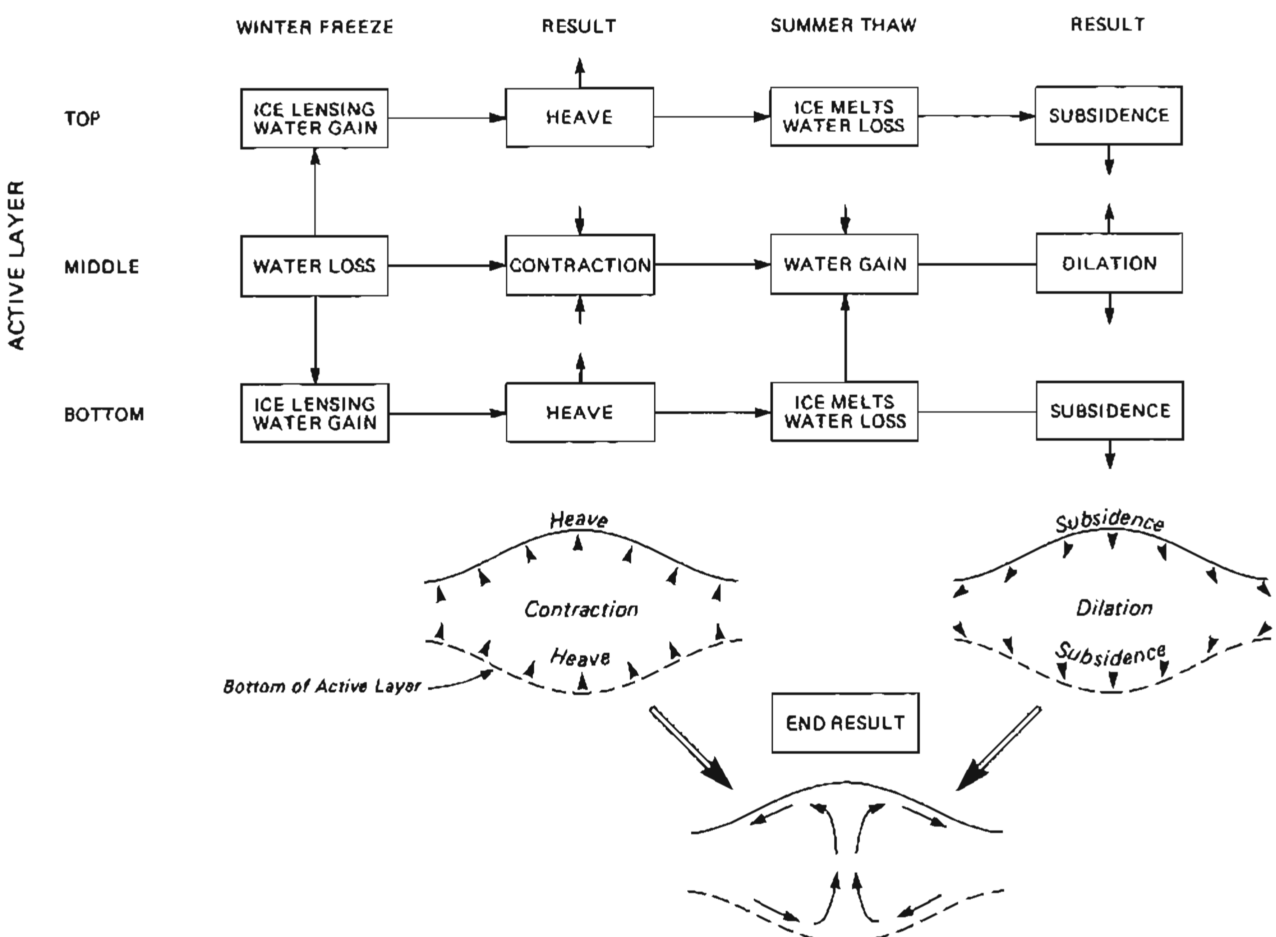

Figure 70. The equilibrium model for hummock growth (Mackay, 1980).

Table 12. Analytical data for the Brunisolic Turbic Cryosol at Stop 7, Navy Road, near Inuvik (Pettapiece and others, 1978).

Horizon	pH H_2O	pH $CaCl_2$	Total C%	Total N%	C/N	Exchangeable cations (me/100 g): Neutral salt extraction K	Ca	Mg	Al	Total	Buffered NH_4OAc (pH7) Total	Ca	Mg	Na	K
Bm	4.3	3.8	2.0	0.17	12	0.5	0.1	0.2	8.0	8.7	26.9	0.1	0.2	0.1	0.3
BCy1	4.2	3.7	1.2	0.09	13	0.5	0.2	0.2	7.0	7.9	25.4	0.2	0.3	0.1	0.5
BCy2	4.2	3.7	2.3	0.17	13	0.5	0.7	0.3	6.1	7.6	26.9	0.6	0.5	0.1	0.6
Ohy	4.4	4.1	17.4	0.76	23	0.7	3.4	1.2	5.7	10.9	78.0	2.4	1.3	0.2	0.5
Cg	3.8	3.7	2.7	0.26	11	0.9	7.0	3.2	2.2	13.2	25.7	6.8	3.8	1.2	0.7

Horizon	Sesquioxides (%): Dithionite Fe	Al	Mn	Oxalate Fe	Al	Pyrophosphate Fe	Al
Bm	3.15	0.30	0	1.67	0.27	0.74	0.29
BCy1	3.17	0.34	0	1.66	0.29	0.66	0.26
BCy2	3.06	0.27	0	1.58	0.29	0.72	0.27
Ohy	1.93	0.64	0	1.84	0.45	1.46	0.56
Cg	2.76	0.14	0.01	0.91	0.07	0.29	0.11

Horizon	Available nutrients (ppm) N	P-Bray	K	S	Organic matter: Extracted %C	%N	Cha/Cfa	FA E4/E6	HA E4/E6	Mineralogy (<2 μ clay)[a] Mica	Chlor.	Koalin	Smect.	Verm.	Quartz	Felds.
Bm	1	0	101	41	33	53	0.43	7.6	3.6	tr	--	tr	1	tr	2	tr
BCy1	1	0	138	50	41	41	0.40	5.0	3.4	1	tr	tr	1	1	4	tr
BCy2	--	--	--	--	--	--	--	--	--	1	--	tr	1	1	2	--
Ohy	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Cg	--	--	--	--	--	--	--	--	--	1	tr	tr	1	1	4	tr

Horizon	Physical: Fiber content Unrub %	Rub %	Particle size distribution - % <2 mm Sand	Silt	Clay	F-Clay	Moisture % 1/3 atm	15 atm	Atterberg PL	LL	Classification Unified	USDA
Bm	--	--	3	49	48	17	35	24	--	--	--	C
BCy1	--	--	2	45	53	20	--	--	28	44	--	C
BCy2	--	--	3	47	50	17	--	--	29	43	--	C
Ohy	50	5	--	--	--	--	--	--	--	--	--	--
Cg	--	--	2	48	50	14	--	--	--	--	--	C

[a]Amount estimated from X-ray diffractograms: tr = trace, 1 = 2-20%, 2 = 20-40%, 3 = 40-60%, 4 = 60-80%, 5 = 80-100%.

There is a uniform particle-size distribution throughout the profile. However, marked differences in structure and bulk density are characteristic. The surface horizon (Bm) has a loose granular structure and a low bulk density (0.89 Mg/m^3), whereas the transition horizons (BCy1 and BCy2) have high bulk densities (1.46 Mg/m^3 and 1.42 Mg/m^3, respectively) and massive structure.

The Bm horizon at the top of the hummock is always better drained than the other horizons during the warm part of the year. The combination of drying during the summer and freezing in the fall and winter is responsible for the development of a characteristic granular (shotty), loosely packed structure in the Bm horizon. The central portion of the earth hummock has a higher moisture content in summer than in winter. During winter, high bulk densities and massive, structureless and closely packed microstructures develop as a result of desiccation.

The soil is extremely acidic and contains very small amounts of exchangeable calcium and magnesium. The pyrophosphate-extractable iron and aluminum, on the other hand, are high, especially in those horizons (Bm, BCy2, and Ohy) that are associated with more organic material. The total organic carbon is high in all horizons. Most of the organic carbon is mixed into mineral horizons as a result of cryoturbation, often as an accumulation near the permafrost table, which forms an organic horizon (Ohy). The subsurface organic horizon is composed of porous mineral and organic material in alternating but distorted layers. The large amounts of pore space are likely the result of ice lensing. Radiocarbon dating of material from the Ohy horizon yields a date of 1,660 ± 90 yr B.P. (BGS-321). Organic-matter fractionation indicates that acid is the major soluble component, although over half of the total organic carbon was found to be insoluble, residual, humic material (table 12). Qualitative clay-mineral analysis indicates the presence of all major species of phyllosilicates, but mica, kaolinite, and vermiculite tend to dominate. There is usually some degradation of mica in very acidic surface horizons and often some increase in expanding-layer clays, but this phenomenon has not been studied in detail.

North of here, the forest fire of 1968 crossed the road and extended to the river. The effects of the fire were quite severe in this area.

Mackenzie Delta Ecosystems

A short boat excursion is taken into the Mackenzie Delta to demonstrate the vegetation, soil, and permafrost relationships at a site 8 km down East Channel.

STOP 8. BOMBARDIER CHANNEL SITE. Four major ecosystems are encountered at this site, each having distinct vegetation, soil, drainage, and permafrost components (fig. 71). A brief description of the four ecosystems, named according to their vegetation association, and beginning at the water's edge, is as follows:

a) _Equisetum_. This ecosystem covers a 14-m-wide strip along the Bombardier Channel. The highest part is about 2 m above the water level, as measured on August 28, 1980. The vegetation consists of 90 percent _Equisetum fluviatile_. Minor species are a moss (_Leptobryum pyriforme_) that gives a

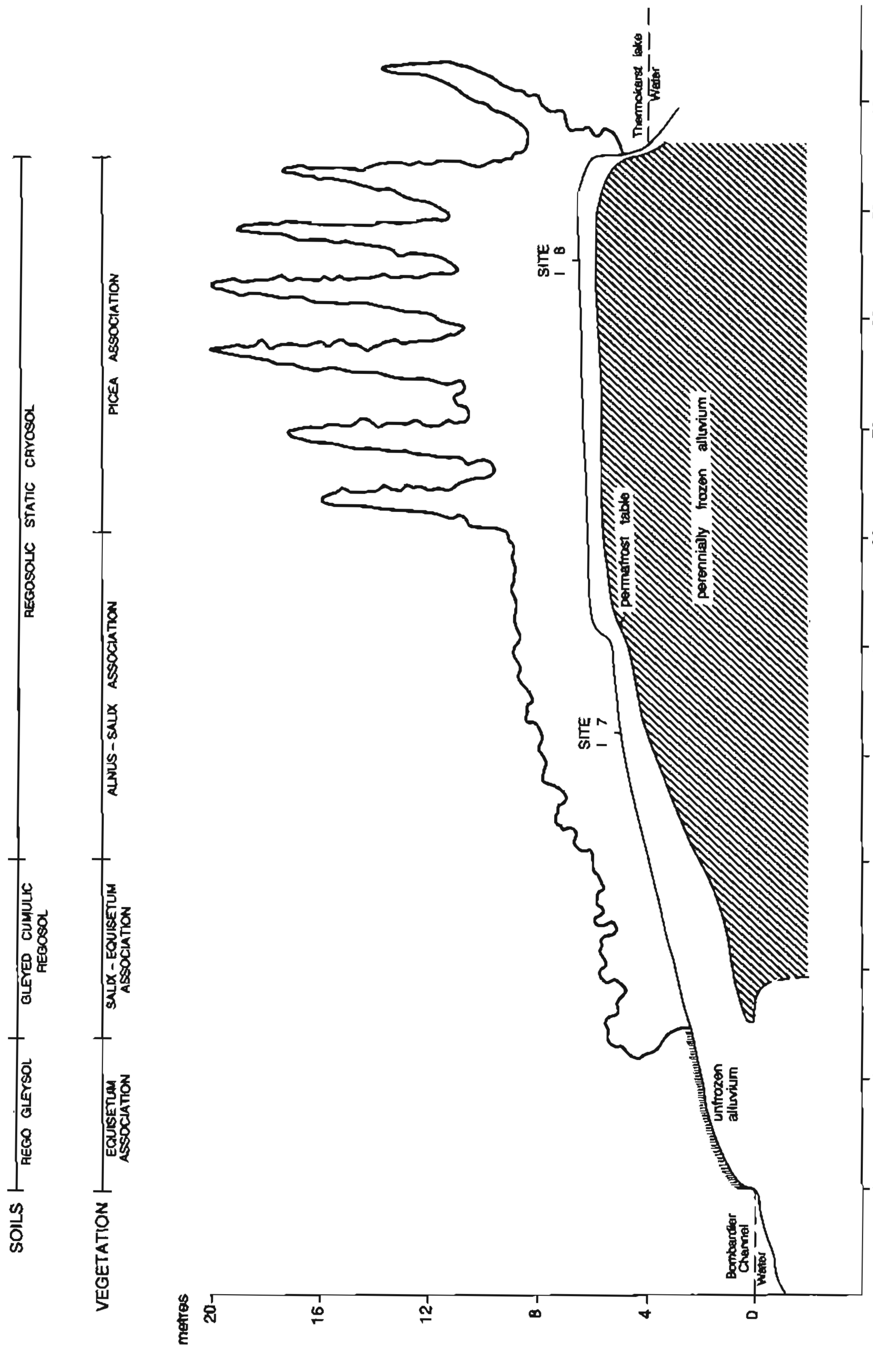

Figure 71. Cross section showing vegetation, soil, and permafrost conditions for an ecosystem sequence at the Bombardier Channel in the Mackenzie River Delta.

greenish appearance to the soil surface, Salix alaxensis, Potentilla egedii, and some Carex spp.

The soil in the ecosystem is a poorly drained Rego Gleysol with a silt loam texture. No permafrost is encountered within a depth of 4 m.

b) Salix-Equisetum. This ecosystem occurs above the Equisetum zone and covers a strip about 17 m wide and 2 to 4 m above the water level. The shrub layer consists mainly of Salix alaxensis, which grows to a height of 3 to 4 m and covers about 80 percent of the area. The herb layer is dominated by Equisetum arvense, which covers about 40 percent of the area.

The soil in this ecosystem is an imperfectly drained gleyed Cumulic Regosol with a silt-loam texture. Permafrost was encountered at a depth of 110 cm.

c) Alnus-Salix. This ecosystem occurs above the Salix-Equisetum zone and covers a band about 30 m wide and 4 to 6 m above the water level. The ecosystem lies just above the average flood level, which is marked by a thick band of driftwood that is usually lodged at the foot of this (Alnus-Salix) zone. The dominant species of the ecosystem are alder (Alnus crispa) and willows (Salix arbusculoides, S. glauca and S. alaxensis). These shrub species range in height from 0.5 to 3.5 m. The low-shrub and herb layers consist of Arctostaphylos rubra and A. alpina, Hedysarum alpinum, Pyrola grandiflora, Picea glauca seedlings, and mosses.

There is a well-developed litter layer (L and F horizons) associated with soils in this zone. Permafrost is encountered at a depth of 70 cm, and the soil is a well-drained Regosolic Static Cryosol with a silt-loam texture and medium ice content.

Soil temperatures measured in this ecosystem at site 17 (fig. 71) were found to be colder in winter and warmer in summer than temperatures at site 18, located in the Picea zone (table 13).

d) Picea. This ecosystem represents the climax stage on the delta south of the arctic tree line. It is situated just above the Alnus-Salix zone, 6 to 6.3 m above the water level of the Bombardier Channel and drops about 4 m down to the level of a thermokarst lake.

The vegetation is dominated by an open stand of white spruce (Picea glauca), which are distinctly spire shaped. The white-spruce trees are 10 to 12 m tall with trunk diameters up to 25 cm. Associated high shrubs are Alnus crispa, Salix glauca and S. arbusculoides. The low shrub and herb layers consist of Arctostaphylos rubra and A. alpina, and Hedysarum alpinum. There is also a well-developed moss layer.

The soil is a well-drained Regosolic Static Cryosol with a silt-loam texture, medium to high ice content, and a well-developed litter layer (L and F horizons). These soils have a better developed granular and weak blocky structure than do soils in the previous association. Permafrost is encountered at 35 cm depth.

Table 13. Soil-temperature regimes, Bombardier Channel site, Mackenzie Delta.

Site	Depth (cm)	MAST[a] (°C)	MSST[b] (°C)	Number of frost-free days	Date of 0°C		Minimum temp.		Maximum temp.		Date of 5°C		Days above 5°C
					Spring	Fall	°C	Date	°C	Date	Spring	Fall	
17	2.5	-2.2	5.9	130	5/26	10/3	-16.3	3/16	13.6	8/17	6/29	9/7	70
	5	-2.1	5.2	128	5/28	10/3	-16.1	3/16	11.8	8/17	7/5	9/7	64
	10	-2.5	3.9	123	6/4	10/5	-15.6	3/16	9.1	8/17	7/6	9/12	68
	20	-3.1	2.4	113	6/15	10/6	-15.3	3/16	7.0	8/17	7/15	8/29	45
	50	-3.5	0.1	88	7/9	10/5	-13.3	3/16	2.9	8/17	--	--	0
	100	-3.3	-1.4	0	--	--	-11.1	3/23	-0.3	--	--	--	0
18	2.5	-1.7	6.3	134	5/22	10/3	-14.2	3/16	12.0	8/10	6/24	9/7	75
	5	-2.4	5.1	126	5/30	10/3	-13.8	3/16	10.1	8/10	7/6	9/7	63
	10	-3.2	1.1	110	6/24	10/3	-11.1	3/22	4.1	8/17	--	--	0
	50	-3.2	-0.6	87	7/10	10/5	-10.0	3/16	0.2	9/1	--	--	0
	100	-3.1	-1.2	0	--	--	- 8.6	3/22	-0.4	--	--	--	0

[a]Mean annual soil temperature.
[b]Mean summer soil temperature.

The Picea ecosystem usually occupies the highest areas in the delta and, as a result, is only infrequently flooded. Even though white spruce is able to grow adventitious roots into newly deposited sediments, it can only do this after reaching a certain age. For this reason, white spruce is not encountered in areas that are flooded on a regular basis.

Soil temperatures measured at site 18 (fig. 71) on this ecosystem are presented in table 13. Although the soil temperature of the rooting zone (0 to 30 cm) at this site was the lowest of the soils monitored in the Inuvik area, its forest productivity is probably the highest, suggesting that forest growth is controlled to a greater extent by the nutrient status of the soil than by soil temperature. The higher nutritive and pH values result from periodic inundation by the Mackenzie River. A similar phenomenon was found on disturbed sites in Alaska by Chapin and Shaver (1981).

TUKTOYAKTUK

By
J.R. Mackay,[1] H.M. French,[2] and J.A. Heginbottom[3]

Tuktoyaktuk is the main Inuit community in the western Arctic. It is situated on a narrow, low peninsula jutting into Kugmallit Bay (fig. 72). The settlement was founded in 1934 by the Hudson's Bay Company, with the opening of a fur-trading post. This initial development was followed a few years later by Anglican and Roman Catholic missions. Inuit from villages and camps along the coast were attracted to Tuktoyaktuk by the possibilities of employment. The settlement is continuing to grow; the population increased from 590 in 1976 to 752 in 1981.

The topography of the area is low, with numerous lakes and thermokarst depressions. Except for pingos, the maximum relief is less than 50 m. Surficial materials in the area consist mainly of till, colluvium derived from till, glaciofluvial sand and gravel, lacustrine sediments, and peat (fig. 73). Thick deposits of sand of probable glaciofluvial origin underlie this surface complex.

PERMAFROST CONDITIONS AND GEOMORPHIC PROCESSES

The Tuktoyaktuk area has a variety of features of permafrost interest, the most important being pingos, thick beds of massive ice, and ice-wedge polygons. Although these features occur in abundance, ice exposures are infrequent except along fresh coastal slumps and wave-eroded bluffs. The slightly irregular tundra surface is composed mostly of vegetation-covered hummocks. The active layer is a mirror image of the ground surface, being deepest beneath the mounds and shallowest beneath the peaty, interhummock depressions. Depth to the frost table in the peaty, interhummock depressions may be so slight, even in late summer, that it can often be probed with a pencil. Freezeback of the active layer usually begins in September. Freezeback is two sided: downward from the ground surface and upward from the late-summer frost table.

Recent studies by Mackay (1981a) have involved measuring active-layer movement on hillslopes with numerous vegetation-covered hummocks. It can be demonstrated that there is a very slow downslope movement of the active layer, the average rate being probably less than 1 cm/yr (table 14). Contrary to most field studies of mass-wasting processes, which indicate movement decreases with depth (Washburn, 1980, p. 200-213), measurements on Garry Island between 1964 and 1980 indicate that the vertical-velocity profile on hillslopes with clayey hummocks is convex downslope (fig. 74). In addition, the movement is pluglike and occurs in late summer. This movement progres-

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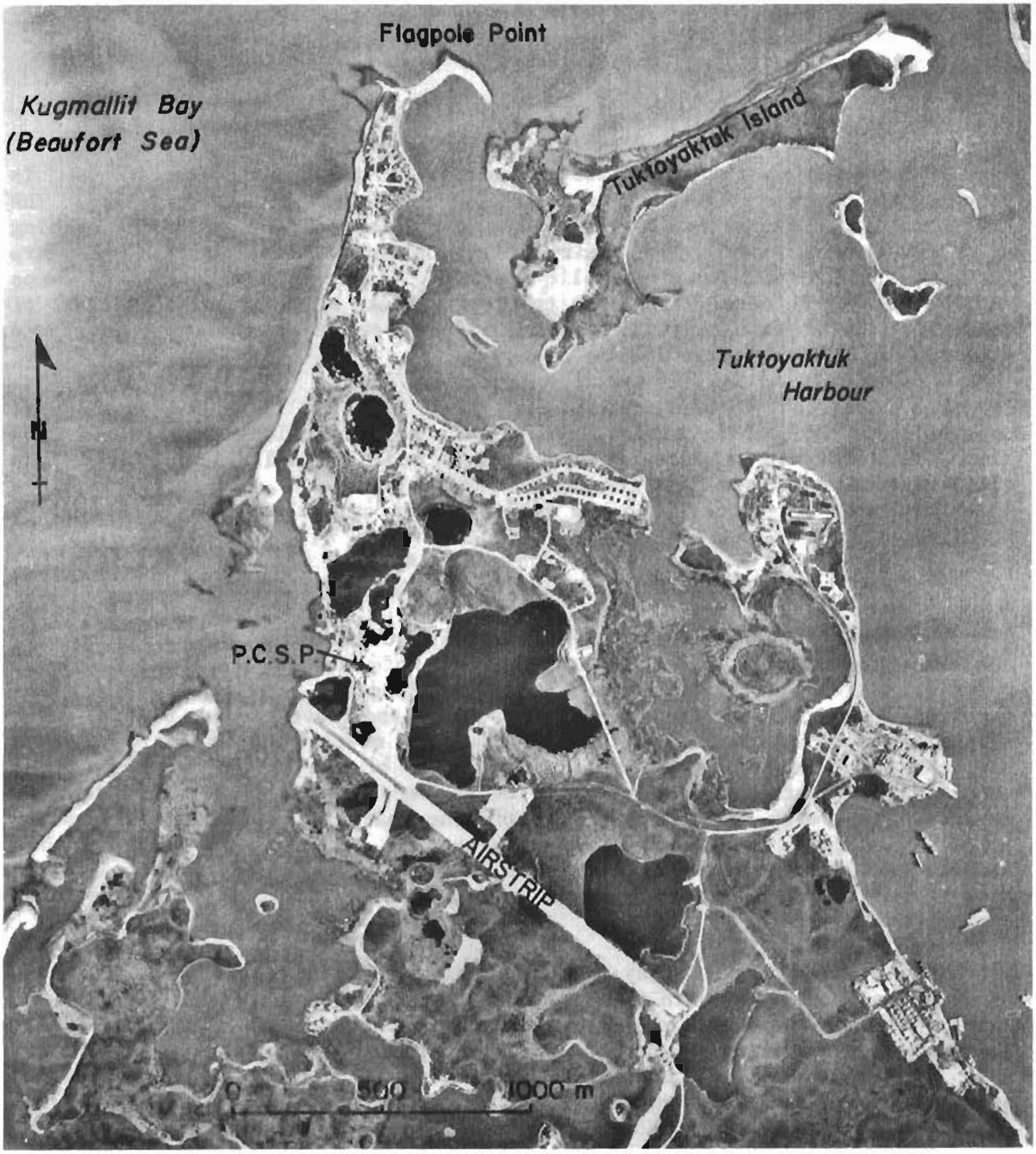

Figure 72. Plan of Tuktoyaktuk, 1979 (NAPL A25223-5).

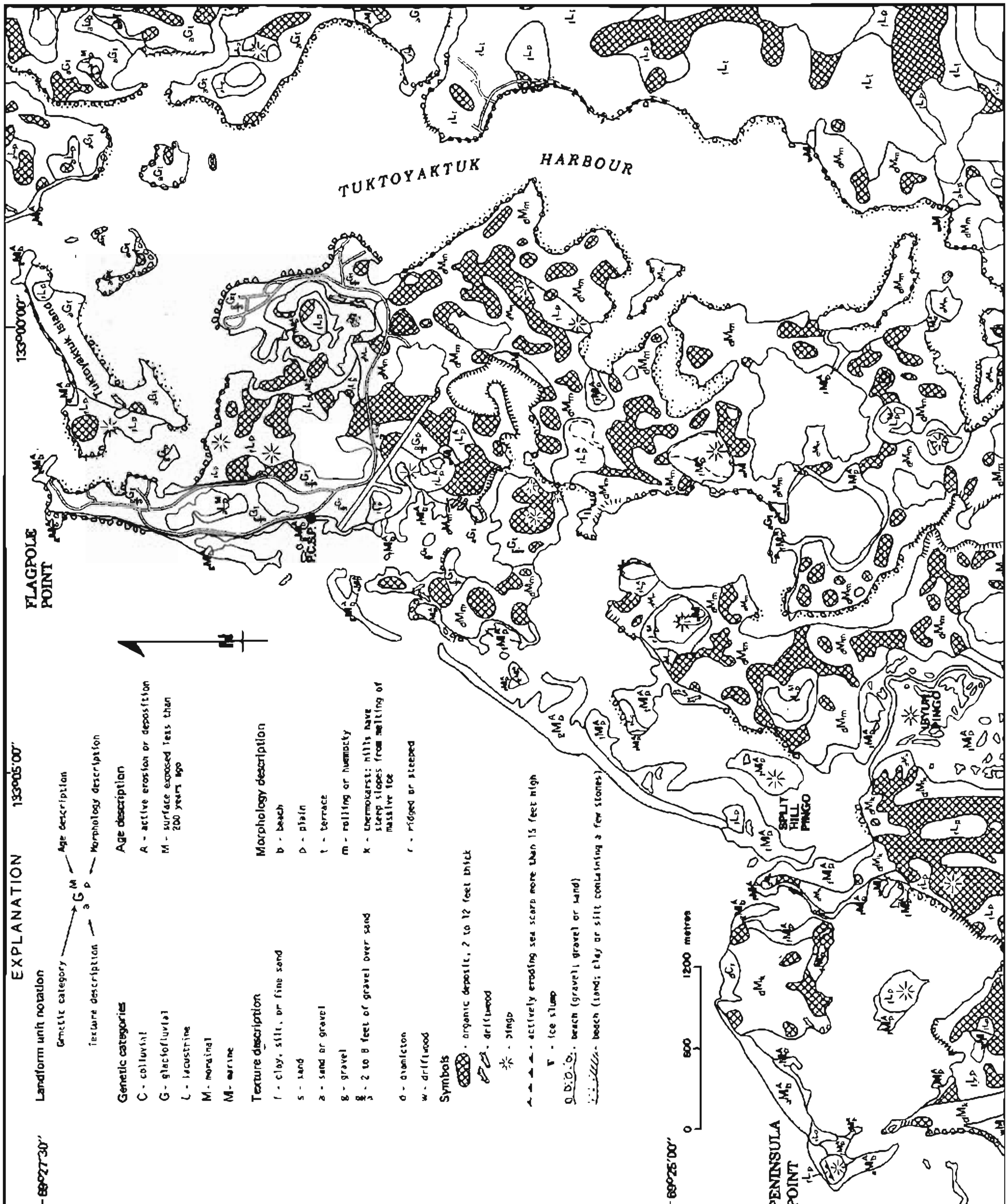

Figure 73. Map of surficial deposits and landforms near Tuktoyaktuk (Rampton and Bouchard, 1975).

Table 14. Data for movement of earth hummocks, Garry Island, N.W.T. (Mackay, 1981a).

Site	Measurement period	Slope	Surface movement (cm/yr)	Heave for frost creep (cm/yr)	Active-layer thickness (cm)	Volumetric transport (cm^3/cm/yr)
Site 1						
1	1964-1977	3	0.40	8	75	20
2	1964-1977	5	0.80	9	55	31
3	1964-1977	7	0.60	6	55	23
4	1964-1977	7	1.00	8	55	38
Site 2						
8	1965-1976	3	0.20	4	50	7
9	1965-1977	1	0.20	11	45	--
10	1965-1976	3	0.30	6	60	13
11	1965-1977	7	1.00	8	75	52
12	1965-1977	1	0.25	14	40	--

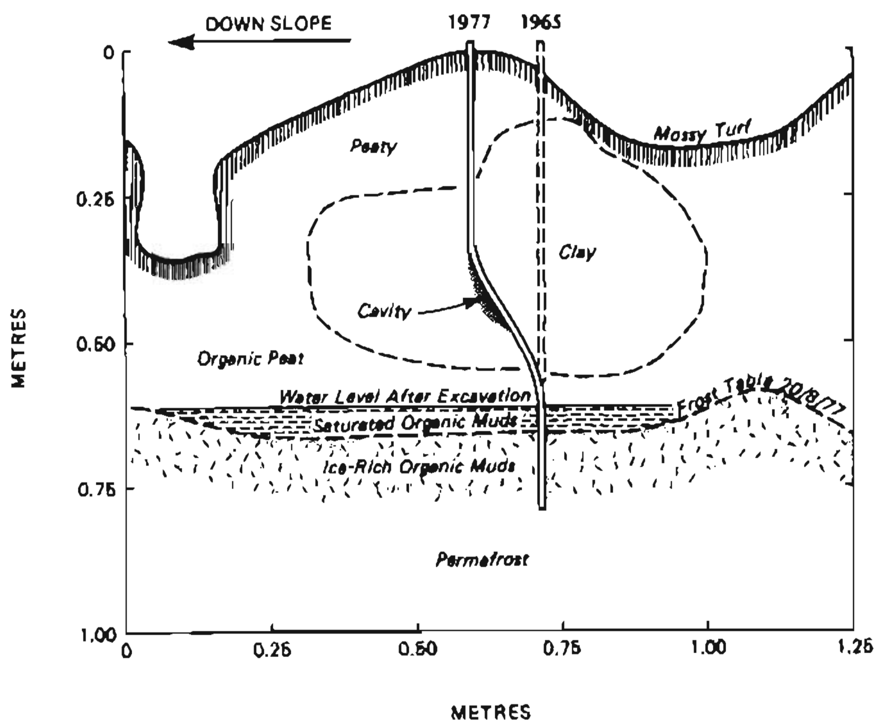

Figure 74. Diagrammatic cross section of an earth hummock following excavation in August 1977 (Mackay, 1981a).

sively buries the interhummock peat to form a buried organic layer. Most of the movement can be attributed to frost creep by thaw of an ice-rich layer at the bottom of the active layer. The latter forms by upfreezing in winter, and the ice content may be augmented by ice lensing in the summer thaw period. This ice-rich organic zone at the bottom of the active layer and above permafrost is often seen along coastal exposures.

Well-developed gelifluction (solifluction) lobes are uncommon. The Tuktoyaktuk area, unlike many other arctic regions, generally lacks sorted forms of patterned ground.

Ice slumps, or retrogressive-thaw-flow slides, occur along coasts or along shores of larger lakes where direct wave erosion either exposes massive ground ice or causes slope failure with subsequent exposure of ice-rich permafrost. Once exposed, the ice and overburden thaw rapidly. Supersaturated debris flows from the base of the face until loss of water causes it to stabilize at a low angle of repose. Active scarps generally retreat at rates of between 2 and 5 m/yr.

Tuktoyaktuk Settlement Area

Thick sands, probably of glaciofluvial origin, underlie most of the area around the settlement of Tuktoyaktuk (Rampton and Bouchard, 1975). The glaciofluvial sands in turn are usually overlain by a fine-grained diamicton consisting of till or colluvium derived from till. Unless protected, the west side of the peninsula on which the settlement is located is subject to rapid coastal retreat during intense autumn storms. The road from the airstrip to the settlement can be flooded during a severe storm. Driftwood is common on the inland (east) side of the road. Protected scarps, such as those in Tuktoyaktuk Harbour, and the edges of intertidal flats are generally fairly stable. Figure 75, based on airphoto interpretation, shows the extent of coastal retreat in the vicinity of Tuktoyaktuk.

Elsewhere in the region, spits are the most rapidly changing part of the shoreline, especially where they are attached to a rapidly retreating coastal scarp. For example, the spit at the eastern side of the ice slump 5.5 km southwest of Tuktoyaktuk has extended 170 m in the period 1950-71, an average of 8 m/yr.

Pingos

Pingos are ice-cored hills that can only grow and be preserved in a permafrost environment. The 'type' pingo, from which pingos derive their name, is 'Pingorssarajuk' (the poor thing that is getting to be a pingo), located 65 km southwest of Tuktoyaktuk (Mackay, 1981b). The term 'pingo' is commonly used to describe a conical hill. The equivalent term in Soviet literature is 'bulganniakh.'

The Pleistocene coastal plain, where Tuktoyaktuk is situated, has about 1,350 pingos. In addition, there are about 80 more pingos on the low seaward islands of the Mackenzie Delta. Elsewhere in the western Arctic, pingos occur in northern Alaska (Brown and Péwé, 1973; Washburn, 1980, p. 188) and in the western Arctic islands (Fyles, 1963, p. 33; Pissart and French, 1976; Wash-

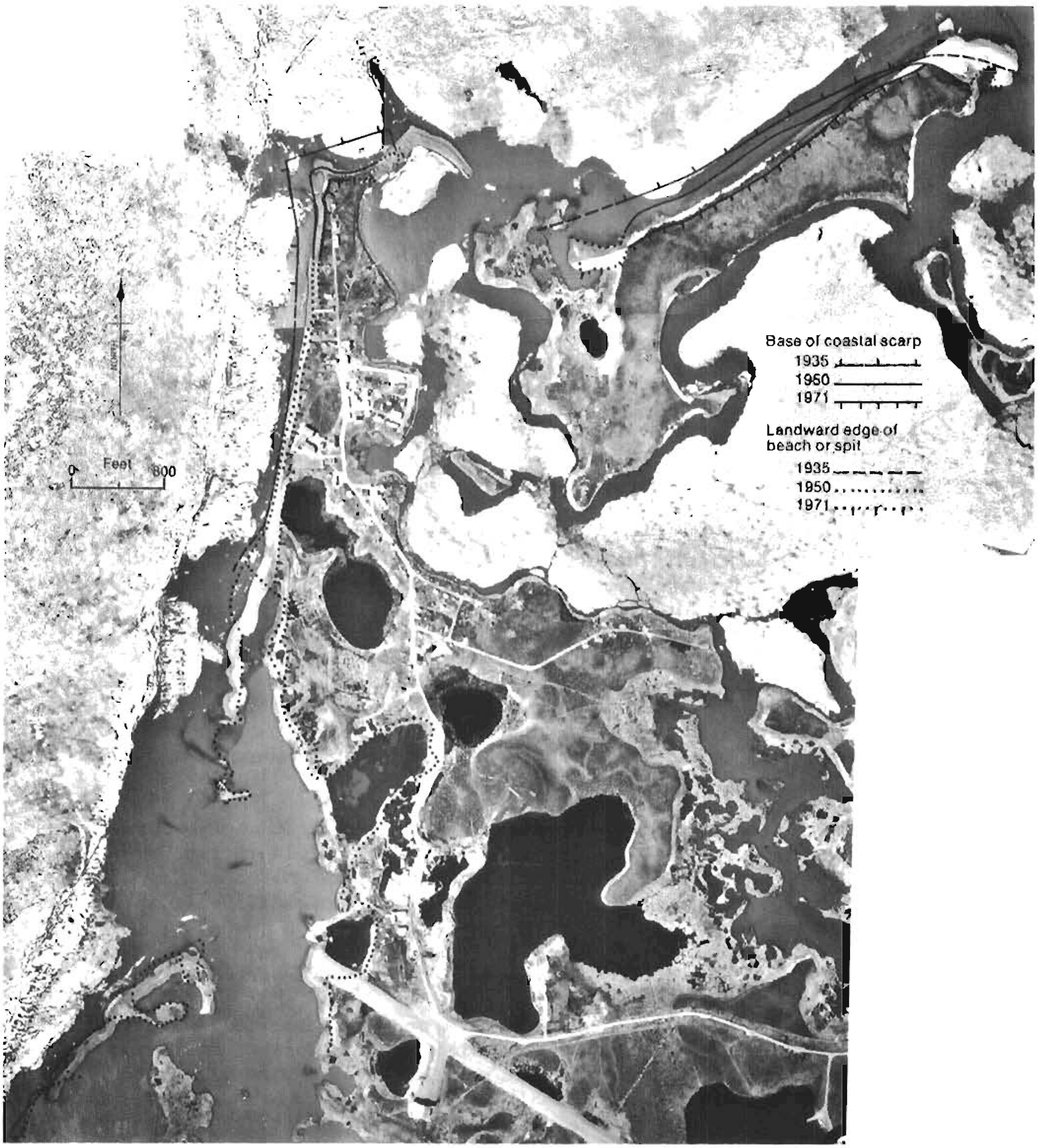

Figure 75. Airphoto mosaic showing position of shoreline in 1935, 1950, 1969, and 1971 near Tuktoyaktuk (EMR airphotos A21019 40, 46). Plot is on 1969 photos (Rampton and Bouchard, 1975).

burn, 1950, p. 43). The site of pingo growth in the Tuktoyaktuk area, with very few exceptions, is a shallow residual pond left by rapid lake drainage, which can take place within 1 day. A substantial proportion of the drained lakes in which pingos have grown are thermokarst in origin. Sublake bottom sediments are usually sands. When permafrost aggrades downward in a drained-lake bottom, the heat of a residual pond may retard permafrost growth relative to the area surrounding the pond. Therefore, pingo growth tends to be focused where permafrost is thinnest, that is, beneath a residual pond (fig. 76). The subpermafrost water pressure, which helps to dome up a pingo, is derived from pore water expelled by downward permafrost growth in the saturated lake-bottom sands. For this reason, the Tuktoyaktuk pingos are of the hydrostatic (closed-system) type in contrast to the hydraulic (open-system) type, which derives its water pressure by gravity flow from an upslope source (Mackay, 1979b).

In general, the diameter of a pingo is less than that of the residual pond in which it grows. Precise surveys for the 1969-82 period show that pingos reach their maximum diameters in early youth and afterwards grow higher but not much wider (fig. 77). If a pingo grows solely from the freezing of segregated ice at the bottom of the ice core, the growth rate will be fairly regular and will decrease with time. However, if a pingo is underlain by a subpingo water lens, the growth rate will be erratic. If the inflow to the water lens constantly exceeds the rate of freezing, the pingo must eventually rupture, but if the inflow is less than the rate of freezing, the water lens must eventually freeze. Drilling has shown that some subpingo water lenses exceed 2 m in depth and the piezometric surface is commonly above the top of the pingo (fig. 78). The freezing of a water lens forms clear 'injection ice,' that is, the ice freezes from injected water (fig. 79).

Most large pingos have a crater at the summit. This crater is usually not a sign of pingo collapse but a sign of dilational failure in the overburden above the growing ice core. Most overburden stretching is relieved by rupture at the summit and not uniformly over the pingo so the diameter of the crater approximates the amount of overburden stretching. When a pingo does collapse, it tends to form a donut-shaped ring that encloses a lake.

Offshore Permafrost

As a result of worldwide sea-level lowering in the late Pleistocene, the shelf area of the Beaufort Sea was exposed to mean annual air temperatures thought to be similar to those existing today.

Sea-bottom and drillhole temperature measurements as well as compressional-seismic-velocity measurements have established that permafrost is widespread on the Beaufort Shelf (fig. 80). Beyond the warming influence of the Mackenzie River outflow, sea-bottom temperatures are negative (-1° to -1.8°C). Where pore-water salinity is low, ice bonding occurs and is occasionally found within 1 m of the sea bottom. Largely marginal and in thermal disequilibrium, the permafrost has temperatures between 0° and -3°C and is discontinuous both laterally and vertically. In shallow water (less than 20 m), the permafrost is degrading from both the top and bottom, whereas in deeper water (more than 20 m) it is degrading at depth but may be aggrading at the sea bottom. Preliminary drilling results suggest that the base of permafrost occurs as deep

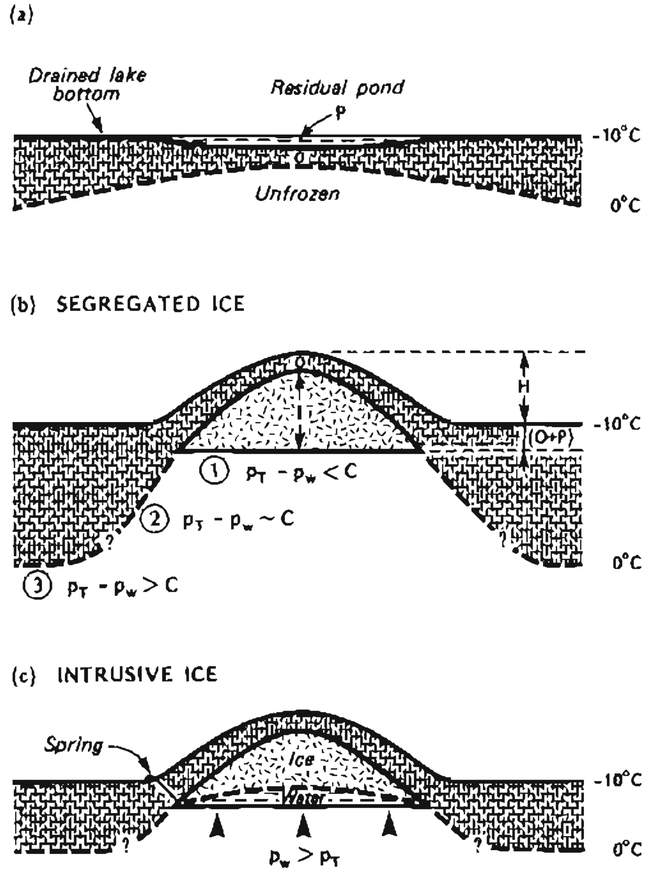

Figure 76. Diagram to illustrate the growth of a pingo in the residual pond of a drained lake. a) The residual pond has a depth of P in the center, the overburden thickness of permafrost is 0, and the permafrost is thinnest beneath the center of the residual pond; b) shows the growth of segregated ice. P_t is the total resistance to heaving and includes lithostatic pressure and resistance to bending of the overburden, P_w is the pore-water pressure, and C is the soil constant. Ice lensing is favored at site 1, ice lenses and pore ice at site 2, and pore-water expulsion at site 3. The values of P_t and P_w change from site 1 to site 3; c) as the pore-water pressure exceeds P_t (the total resistance to uplift), a subpingo water lens accumulates and intrusive ice forms by freezing of bulk water. Peripheral failure may result in spring flow (Mackay, 1979b).

as 670 m below sea bottom, and the upper boundary is at depths between sea bottom and more than 60 m below the bottom. In general, ice-bonded materials are found east of lat 134°W. and beneath water depths of less than 60 m.

From seismic profiling, two layers of ice-bonded permafrost have been defined: an upper discontinuous zone with a thickness of 100 m or less and a deeper continuous zone with an upper boundary at a depth of 150 to 250 m. Shallow natural gas has been found in several locations offshore, and gas hydrates have been detected in wells in both the onshore (Mackenzie Delta) and the offshore (Beaufort Sea) areas. The lower ice-bonded boundary may in part be the result of formation of gas hydrates.

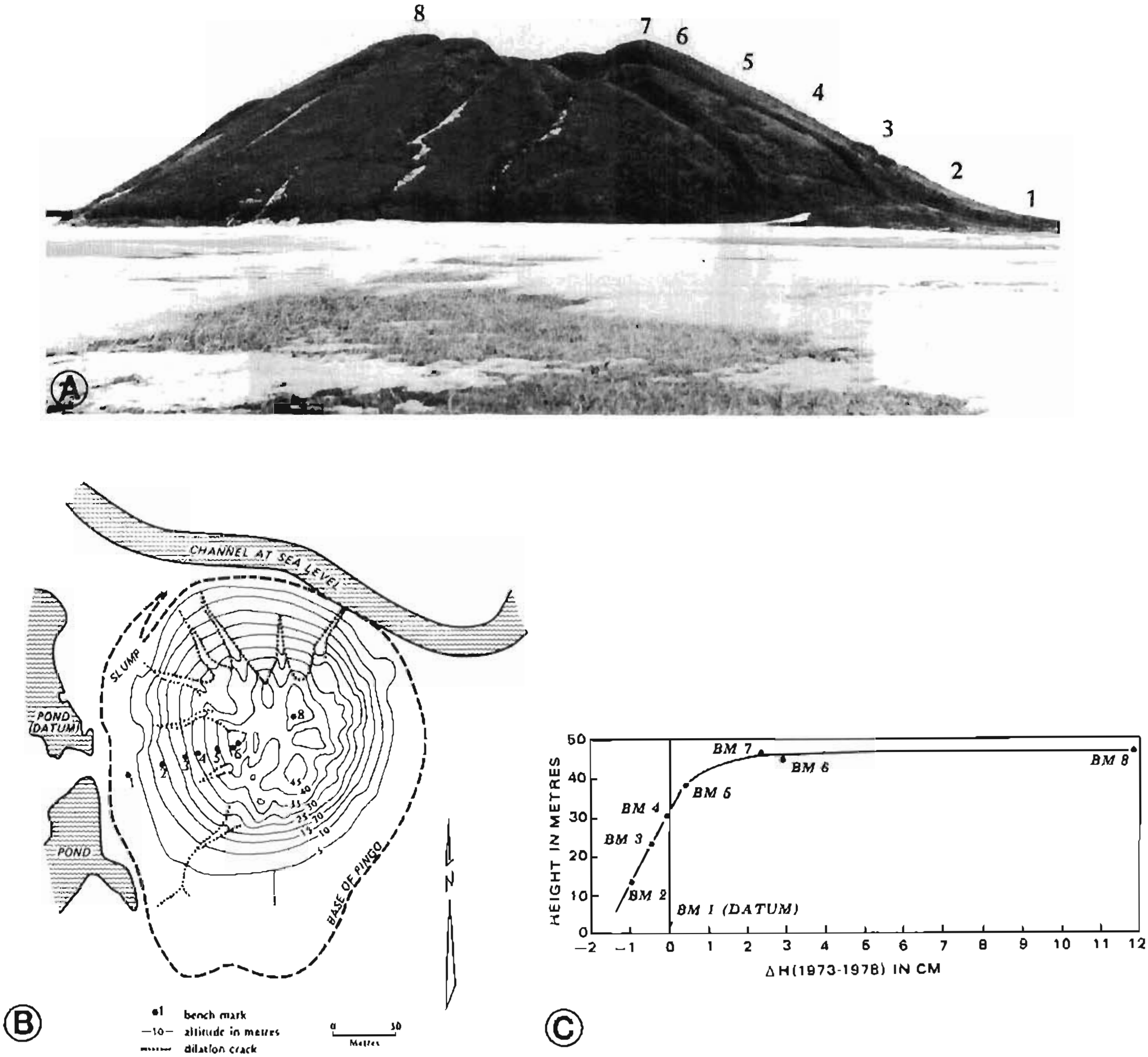

Figure 77. Ibyuk Pingo. (A) As viewed from the northwest showing location of benchmarks 1 to 8; (B) topographic map; (C) changes in height of benchmarks referenced to benchmark 1 plotted against elevation of benchmarks above the lake flats for 1973-78 (Mackay, 1979b).

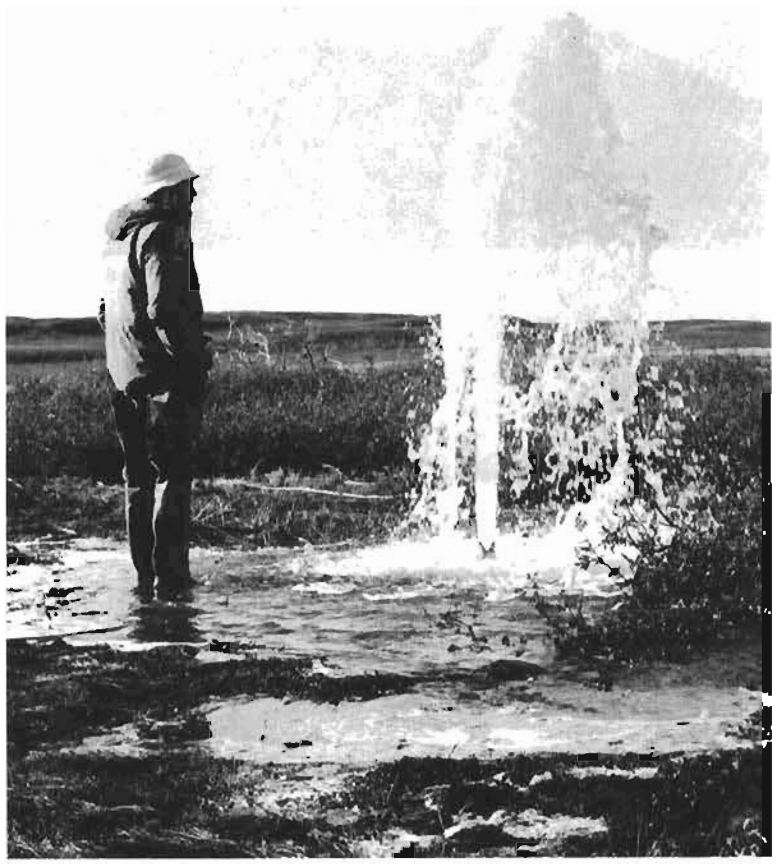

Figure 78. Water flow from a drillhole in a pingo, Tuktoyaktuk Peninsula. The water came from a depth of 22 m and jetted up 2.6 m high from a 7.5-cm-diameter hole. The clear water was mineralized and cold; the orifice water temperature ranged from -0.05°C to -0.10°C.

PERMAFROST CONDITIONS AND OIL AND GAS DEVELOPMENT

Exploration for hydrocarbons in the Mackenzie Delta-Beaufort Sea region began in the mid-1960s. In 1970, the first oil discovery was made by Imperial Oil Company Ltd. at Atkinson Point, and in 1972 the first natural-gas discovery was made by Gulf-Mobil at Parsons Lake. Other discoveries, predominantly of natural gas, have since been made in the Delta-Beaufort region.

By the end of 1981, 84 wells had been drilled onshore in the Mackenzie Delta and 34 in the offshore area. Of these 118 holes, 67 were dry and have been abandoned; 44 are considered to be producing wells, of which 10 are

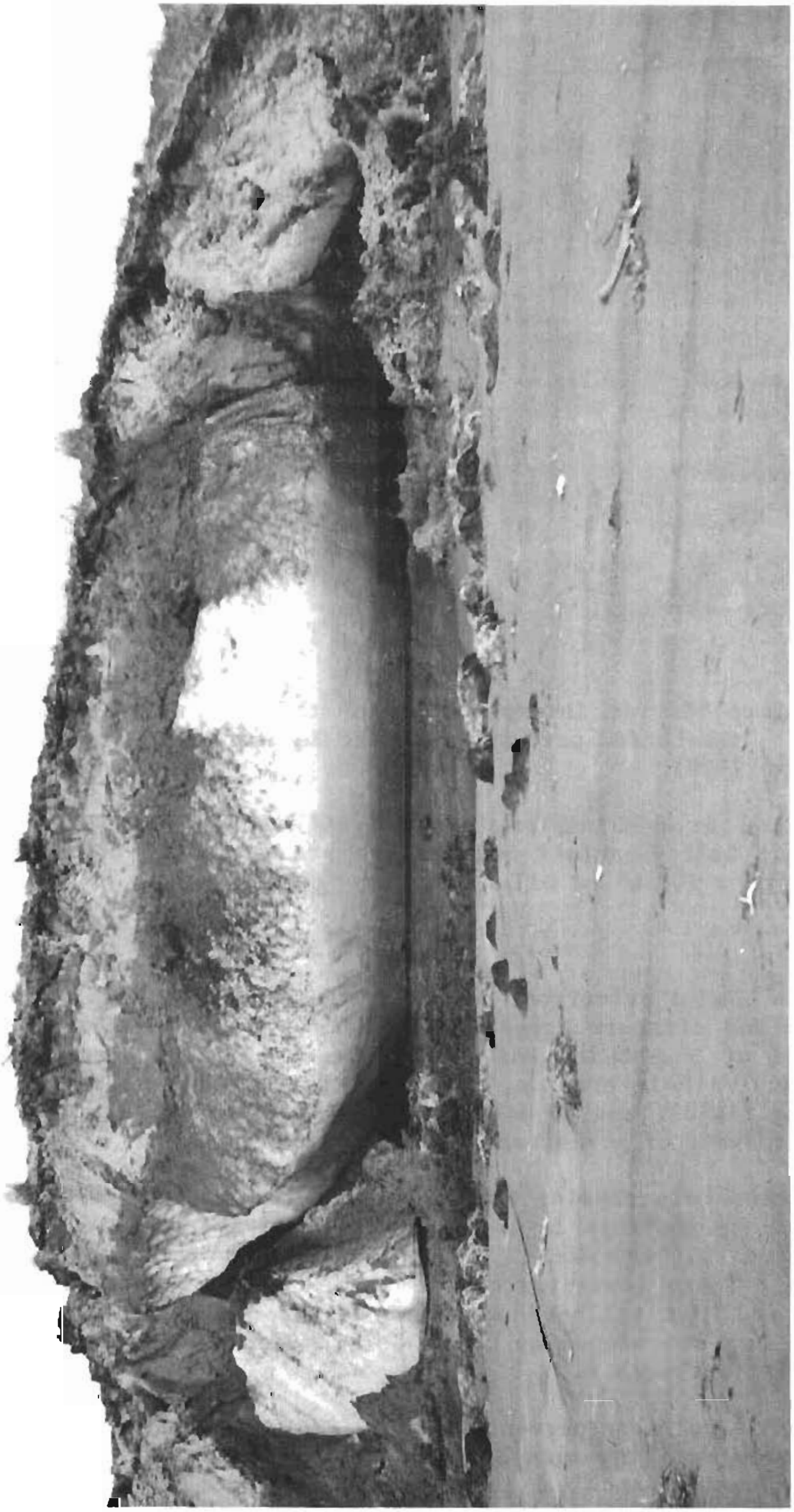

Figure 79. Wave-cut pingo, 100 km northeast of Tuktoyaktuk. Photo by J.R. Mackay, 1954.

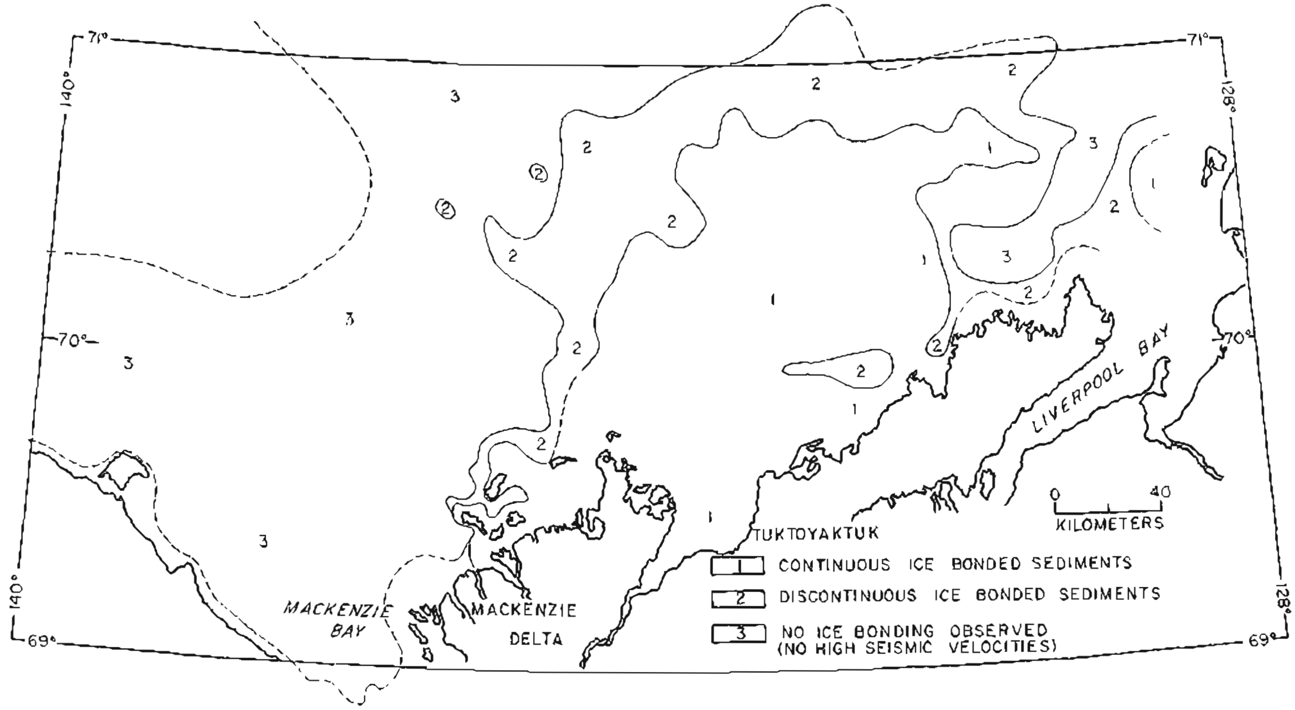

Figure 80. An interpretation of the occurrence of sub-seabottom ice-bonded permafrost in the Beaufort Sea (Hunter and others, 1978).

mainly oil or combination (gas and oil) producers. Proven reserves in the Mackenzie Delta-Beaufort Sea regions are estimated at about 150 x 10^6 m^3 of gas and 65 x 10^6 m^3 of oil.

Ice-bonded Permafrost

Ice-bonded permafrost has been encountered in exploratory wells in both onshore and offshore areas of the Mackenzie Delta-Beaufort Sea region. The presence of ice-bonded soils complicates drilling operations in three ways: a) excessive hole erosion, b) casing failure due to freezing of water-based drilling fluids, and c) excessive downdrag load on the surface casing string due to thawing of permafrost.

Excess hole erosion occurs because the presence of pore ice renders the ice-bonded permafrost layer impermeable and the drilling mud does not form a protective 'filter cake.' Erosion can be very severe and can create problems for the primary cementing operation. In one instance, the primary cementing failed and the wellhead subsided because of lack of axial support. The problem can be reduced by using cold, viscous drilling mud to drill through permafrost sections.

Casing collapse prevents reentry into a suspended well and arises because water-based drilling muds are used in arctic regions. As the mud in the casing and casing annulus freezes after cessation of drilling, the resulting cryostatic pressure collapses the casing string. In most of the earlier exploratory wells drilled on land, the casing strings have now collapsed. Casing collapse can largely be prevented by adding chemicals to the mud (usually potassium chloride) to depress the freezing point and so prevent the mud from freezing during a period of well suspension. There is also some additional pressure exerted on the surface casing by the refreezing of thawed permafrost around the well. This added pressure is counteracted by using stronger surface casing.

The thawing and subsidence of unconsolidated permafrost around a well leads to downward forces developing on the surface casing, normally referred to as downdrag load. The magnitude of this load depends on the lithology, the degree of consolidation, and the ice content of the near-surface strata. The load can change from tension to compression as the lithology changes from sand to clay. For normally consolidated soils, this load can be successfully resisted by using stronger casing.

Gas Hydrates and Offshore Permafrost

Gas hydrates have been encountered extensively in wells drilled offshore in the Beaufort Sea (Judge, 1982; Weaver and Steward, 1982). Their presence presents additional problems for drilling. For example, the decomposition of hydrates around a well bore results in both a loss of strength of sediments and the discharge of large volumes of gas, creating a thaw-subsidence problem in the presence of high gas concentrations. The presence of gas also presents problems in the cementing of wells during the initial completion. Reformation of hydrate through freezeback of a well during shut-in periods may induce high pressures on the casing. Finally, the extensive occurrences of shallow gas and high water pressure offshore are believed to result from the natural decomposition of hydrates.

Offshore permafrost can considerably influence the design of facilities used in northern waters. Frozen soil in thermal equilibrium provides an excellent foundation. If ice-rich, however, it will, when thawed, tend to subside differentially with reduced bearing strength. The presence and properties of permafrost and gas hydrates must be fully considered in the design of structures and wells founded on the bottom or subbottom. Dredging operations may be far more difficult in the presence of permafrost because dredging equipment is usually not designed to handle ice-bonded materials. A misinterpretation of deep structures by exploratory seismic-reflection methods can result from a discontinuous lateral distribution of high-seismic-velocity ice-bonded permafrost; such errors in interpretation can result in the drilling of costly dry holes.

Artificial Islands and Drillships

The most efficient platform for exploratory drilling in shallow waters of the Beaufort Sea has proved to be an artificial island. To date, 20 islands have been constructed in water depths less than 25 m. They are designed as temporary structures to provide a stable drilling platform for the exploration phase only, that is, to withstand ice pressures and wave action for the drilling season only. Several designs have been instituted, depending on such local conditions as availability of fill, wave height, water depth, and soil condition. Most islands provide for a 100-m-diameter work area composed of silt or gravel, although sunken barges have also been used. Island slopes, designed for protection against waves and ice, are constructed of wire netting, sand bags, gabions, and sand-filled plastic tubes. The most recent island, in 25 m of water, consists of a sand-filled caisson support on a berm constructed on the seabed.

The design of the islands takes into consideration the aggradation of permafrost on the surface as well as degradation and consolidation around the drill holes. At one island, Unark L-24, where the fill material is gravel, very little consolidation and settlement were observed, and the permafrost table, which was initially immediately below sea bottom, has been raised. The design of islands for production wells will undoubtedly require detailed knowledge of the permafrost configuration beneath the sea bottom and its long-term thermal response to the well bore as well as the growth rate and geotechnical properties of permafrost aggrading in the fill.

In areas of deeper water, exploratory drilling has been conducted from specially designed drillships operating during the short open-water season. Drilling begins each year as soon as ice conditions permit, usually in late July or early August, and ends in October or early November.

So far only one company is involved in this deep-water drilling---Dome Petroleum. Operation of drillships is done by a subsidiary company, Canadian Marine Drilling Ltd. (CanMar).

The effects of permafrost on offshore subsea drilling are different from those effects onshore only in the greater relative warmth and increased thaw sensitivity of the offshore permafrost. Apart from this difference, all other aspects of drilling are made more difficult because of the need to work from a ship. The real difficulties are caused by sea ice. The Beaufort Sea is infested by heavy, moving pack ice. This ice creates problems in keeping drillships on location and maintaining reasonable rates of drilling and safety. Closer to shore, the ice impinges on and severely scours the sea bed. Thus, major problems will be encountered in laying pipelines to bring oil or gas onshore. Finally, should an oil spill or blowout occur, containment and cleanup will be an extremely difficult---if not impossible---task.

Terrain and Environmental Problems

Environmental concerns associated with land-based oil and gas exploration in the Mackenzie Delta have centered around a) the melting of ice-rich permafrost terrain due to the removal of vegetation along seismic lines and at wellsites, b) the movement of vehicles and heavy equipment in the summer, when the ground surface is soft, c) the onshore disposal of toxic and other waste-drilling effluent, and d) the search for suitable aggregate for road and pad fill (Kerfoot, 1974; French, 1978a,b; 1980).

In an attempt to minimize such concerns and realizing that considerable damage was caused by summer seismic programs authorized in the early and middle 1960s, the Canadian government passed The Territorial Arctic Land-Use Act and Regulations in 1971. Under these regulations, companies are required to obtain land-use permits that stipulate various restrictions. As far as possible, the movement of heavy equipment, seismic programs, and drilling operations are restricted to the winter months. In addition, drilling fluids must be contained within below-ground sumps, and site-rehabilitation measures are required prior to final abandonment of the site. Since that time, severe thermokarst associated with vehicle movement has been rare; most problems have been related to sump construction in ice-rich permafrost terrain, meltout along ice wedges in terrain immediately adjacent to the well site (fig. 81A), and the excavation of gravel aggregate (fig. 81B). The containment of drilling fluids in below-ground sumps has not always proved satisfactory (French, 1980), and fluids have escaped into adjacent water bodies.

Despite these problems, land-based oil- and gas-exploration activity in the Mackenzie Delta have not been accompanied by the same degree of environmental damage that was sometimes associated with exploration activity in the Mackenzie Valley and interior Yukon in the 1960s. This difference can be attributed to a) the effectiveness of the Territorial Arctic Land-Use Act and Regulations, and b) improved operating procedures and awareness by the companies concerned.

SITE DESCRIPTIONS

Many of the more interesting and informative sites in the vicinity of Tuktoyaktuk are accessible only by helicopter or by boat during summer. Thus, this section comprises a series of site descriptions.

Tuktoyaktuk Ice Cellar

The most accessible site in Tuktoyaktuk for viewing ground ice is in the village ice cellar, which was excavated to serve as a refrigerated storage unit (Rampton and Mackay, 1971). The cellar is entered by ladder in a vertical shaft, and caution should be used in entering and leaving. A flashlight is desirable and a flash is necessary for photography. Layers of sand 5 to 20 cm thick separated by layers of ice up to 25 cm thick are exposed in the walls of the ice cellar. A sample taken in one wall over a vertical extent of 2 m contained excess ice amounting to 80 percent of the total volume. The icy sands have been deformed into horizontal overturned folds, probably as a result of overriding by glacial ice (fig. 82). If this inference is correct, then the age of the ice predates the late Wisconsin glaciation because the Tuktoyaktuk area is north of the limit of the last glaciation (see fig. 55). Segregated ice is rare in sands, so this exposure is of considerable scientific interest.

Pingo Tunnel

For more than a decade, one of the more interesting tourist attractions at Tuktoyaktuk was 'Pingo Tunnel,' which was excavated into the side of a pingo. The tunnel opened into a large room sited beneath the pingo summit.

The internal stratigraphy of the pingo was first described by Rampton and Mackay (1971). The core consists of interlayered sand and ice lenses up to 12 cm thick. In addition, thin ice lenses in fine-grained silts, ice wedges, and the faultlike contact between the icy core of the pingo and the overlying sediments are visible in the wall of the tunnel.

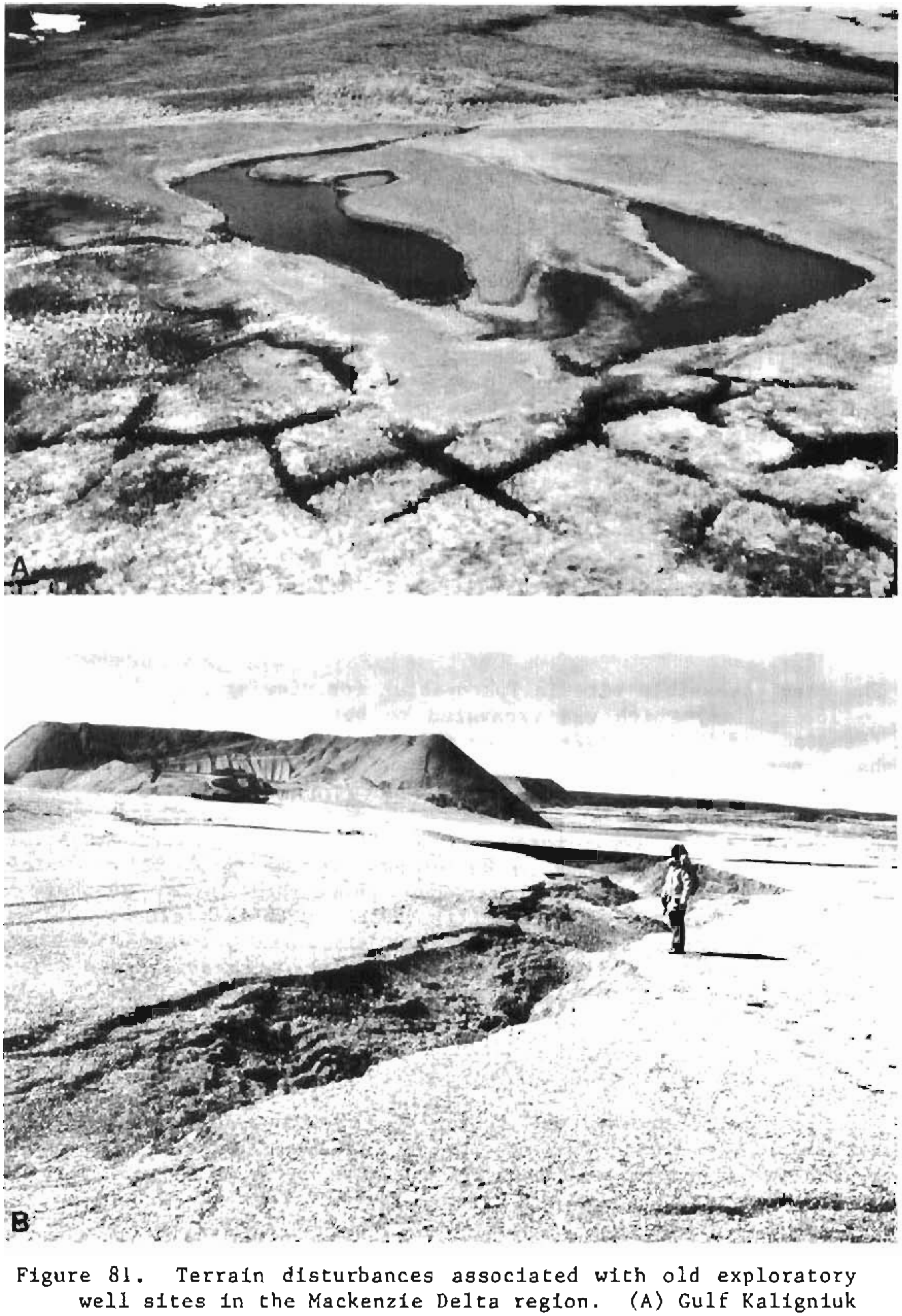

Figure 81. Terrain disturbances associated with old exploratory well sites in the Mackenzie Delta region. (A) Gulf Kaligniuk F-48 well site; (B) Ya Ya gravel pits with subsidence along ice wedges.

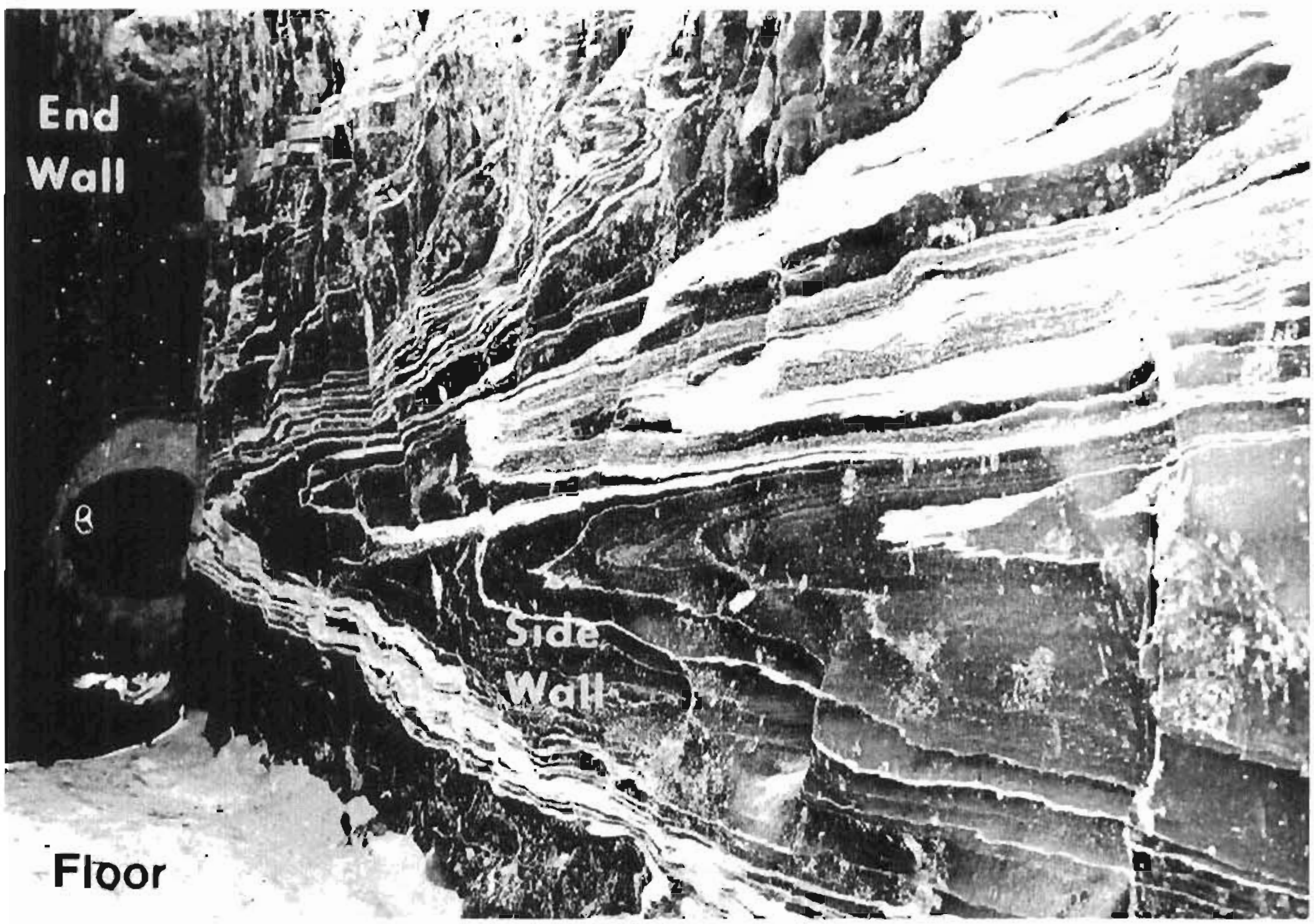

Figure 82. Deformed icy sands in Tuktoyaktuk ice cellar.

Unfortunately, in July 1979 the tunnel collapsed near the entrance because of thermal erosion along an ice wedge. The pingo can be recognized by a large log house built on the west side. A good view of the settlement can be obtained from the top of the pingo. A new tunnel may someday replace the old one.

Ibyuk Pingo

Ibyuk Pingo, 48 m high, is the prominent pingo 10 km to the south-southwest of Tuktoyaktuk (fig. 83). Split Hill Pingo, 37 m high, is to the north (seaward) of Ibyuk Pingo. Both Ibyuk and Split Hill Pingos are accessible from Tuktoyaktuk by small boat, but care should be taken because of shoal water offshore. An energetic person can walk to Ibyuk Pingo in a day, but the route is deceptively tortuous so the hiker should possess a good map or aerial photograph. The bare east-facing slope of Ibyuk Pingo is very unstable and should not be traversed under any circumstance to avoid any further damage to the pingo.

The overburden of Ibyuk Pingo is 15 m thick (Muller, 1959). The volume of ice required to dome Ibyuk Pingo is slightly greater than the total volume

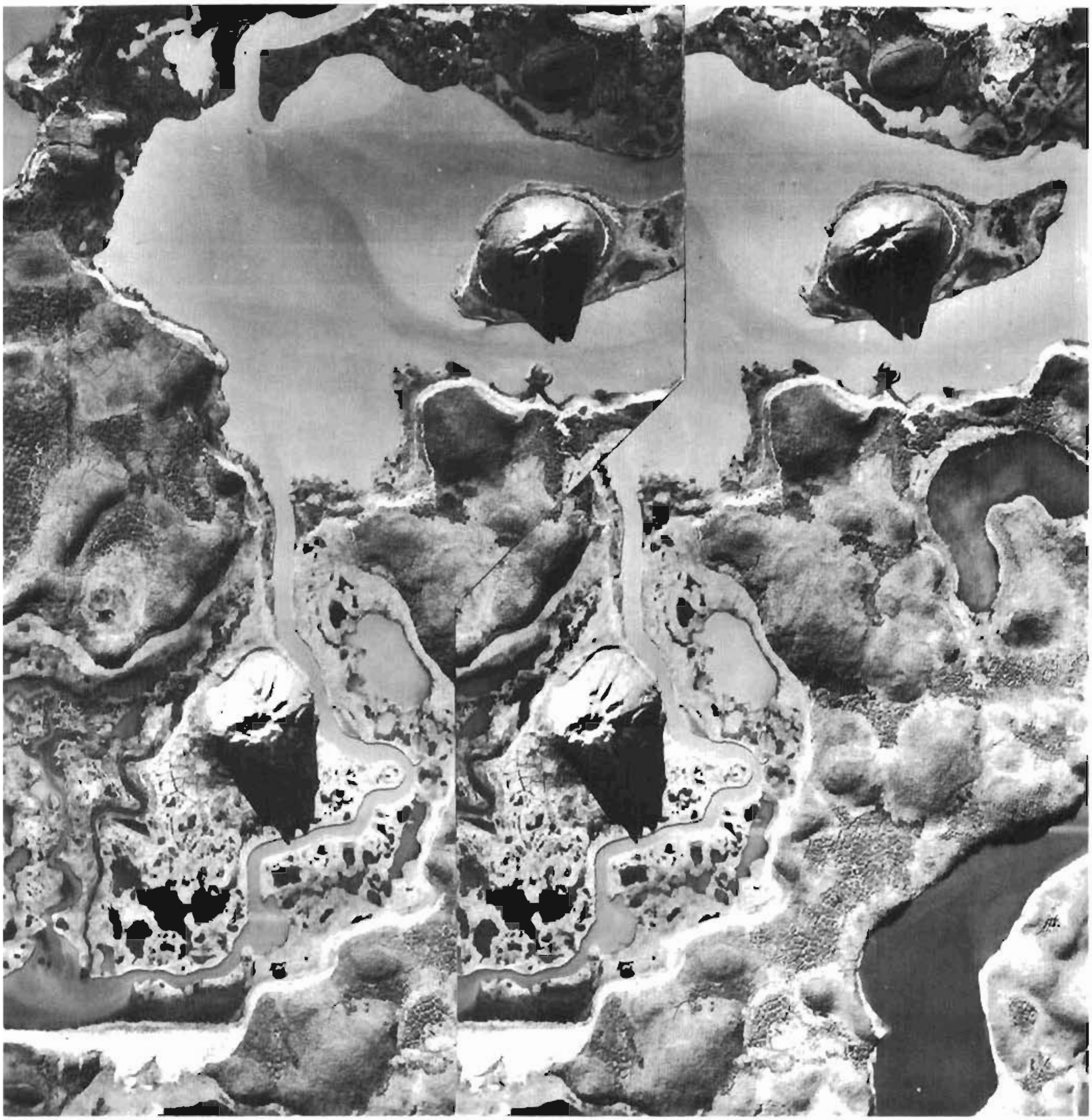

Figure 83. Airphoto stereopair of Ibyuk and Split Hill Pingos near Tuktoyaktuk, Mackenzie Delta. Split Hill is the upper one in the photograph; the pingos are about 1 km apart (see fig. 73)(NAPL A22535-60, 61).

of the pingo above the surrounding lake flat. Numerous radiocarbon dates for the overburden of Ibyuk Pingo confirm that the Tuktoyaktuk area lay beyond the limit of late Wisconsin glaciation. The former lake basin in which Ibyuk Pingo has grown was in existence at least 10,000 yr ago, and the lake probably drained no more than several thousand years ago. Evidence for the age of the former lake is the age of lacustrine deposits in the overburden, which are dated at 12,000 ± 300 yr B.P. (S-69), 8,855 ± 205 yr B.P. (GX-7014), and 8,624 ± 210 yr B.P. (GX-7013).

Ibyuk Pingo is still growing and has a youthful appearance, as shown by the grassy slopes, lack of turf mat, and slope instability. The pingo has a peculiar growth pattern (fig. 77C). For the 1973-79 period, precise surveys were carried out on eight benchmarks installed on the pingo and referenced to benchmarks in stable land far from the pingo. The results show that the upper third of the pingo was growing, the midportion showed little change, and the lower third was losing height, presumably from a glacierlike creep. The top (benchmark 8, fig. 77A) grew at a maximum rate of about 2.5 cm/yr.

Peninsula Point Pingo

The pingo at Peninsula Point, 7 km southwest of Tuktoyaktuk, is accessible from Tuktoyaktuk only by water or air. The pingo has been sectioned by wave action and has retreated at an average rate of about 0.5 m/yr since 1935 (fig. 79). The extent and freshness of the exposures vary from year to year. Dilation-crack ice and ice-wedge ice are at times exposed at the very top; this ice should not be confused with pingo-core ice. A veneer of lacustrine deposits, which includes a) 1.2 to 1.8 m of stony clay with pieces of wood and pockets of peat and b) up to 6 m of laminated organic silts, overlies more than 18 m of sand. Peat from the base of the stony clay has been dated at 12,800 ± 180 yr B.P. (GSC-1214). The interpretation of the sequence here is very similar to that at Ibyuk Pingo.

About 5.5 km southwest of Tuktoyaktuk, a flattish ice-cored hill is being eroded by waves (fig. 84), and horizontally banded massive ice is periodically exposed by slumping (Mackay, 1971; Rampton and Mackay, 1971). The ice face has retreated at an average rate of about 5 m/yr since 1935. The massive ice is at least 10 m thick (fig. 85). Horizontal bands in the ice are dirt layers, that is, concentrations of scattered pellets of silty clay with a few pebbles and even some glacial boulders in the ice. Arching in the ice may be seen directly below some ice wedges and beneath some fresh slumps, which suggests that the arching is due to uplift from pressure release because of a lowered overburden beneath ice wedges and slumps.

The ice is generally capped by 4.5 to 6 m of stony clay that contains vertical ice veins up to 10 cm thick. Melting of the ice veins gives the pebbly clay a vertically jointed appearance. In some exposures, laminated clay containing lenses of peat dating back to the Holocene warm period (8,500 to 5,500 yr ago) attest to the former existence of shallow ponds on the hill. The mudflow debris below the melting ice face may show ribbing that may sometimes correspond to annual summer thaw. (Note: all fresh mudflows and overhangs should be avoided. Even apparently firm mud can be surprisingly soft at depth.)

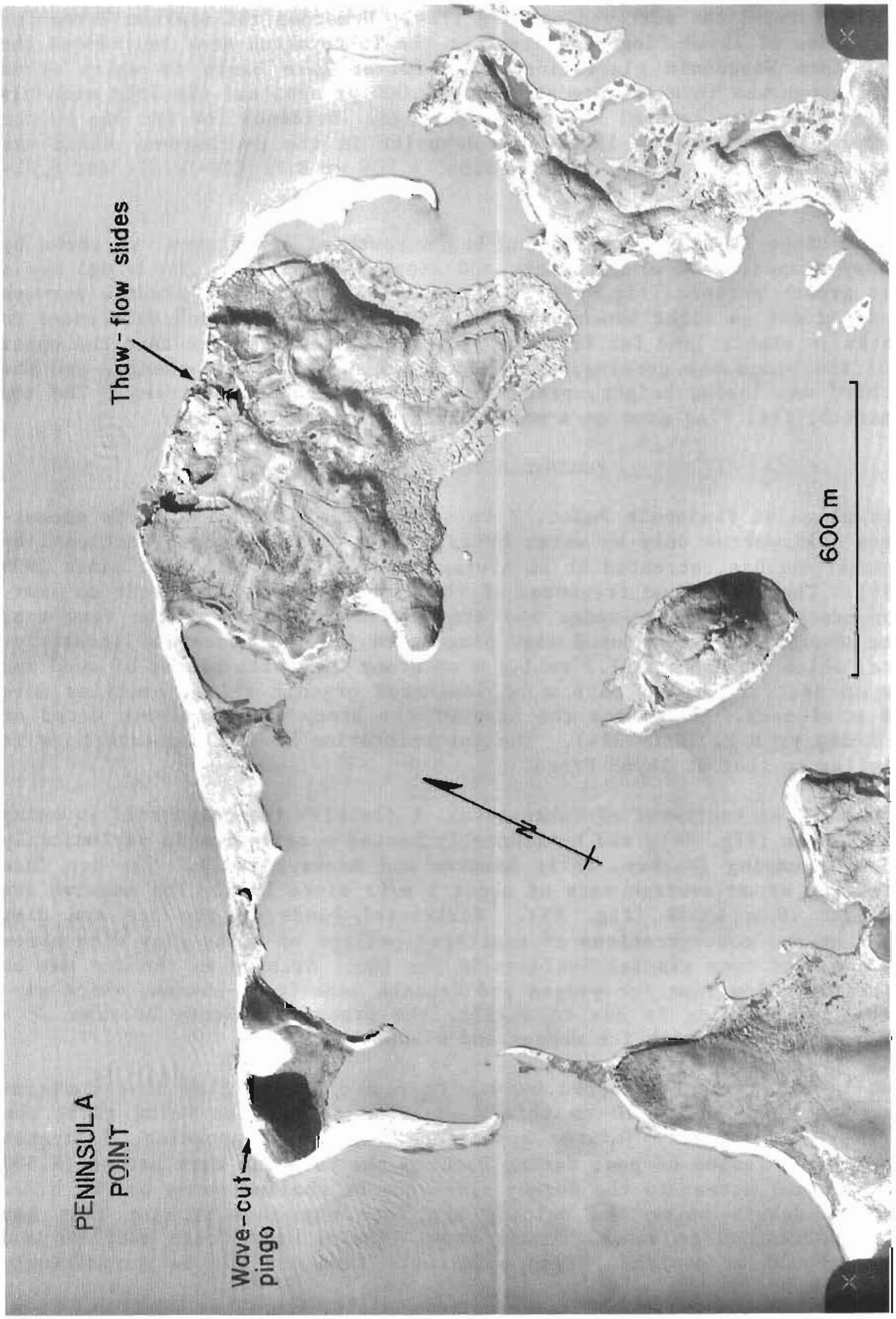

Figure 84. Airphoto of Peninsula Point Pingo and ice slump 5 km southwest of Tuktoyaktuk. Both are affected by active coastal erosion and retreat (NAPL A22535-66).

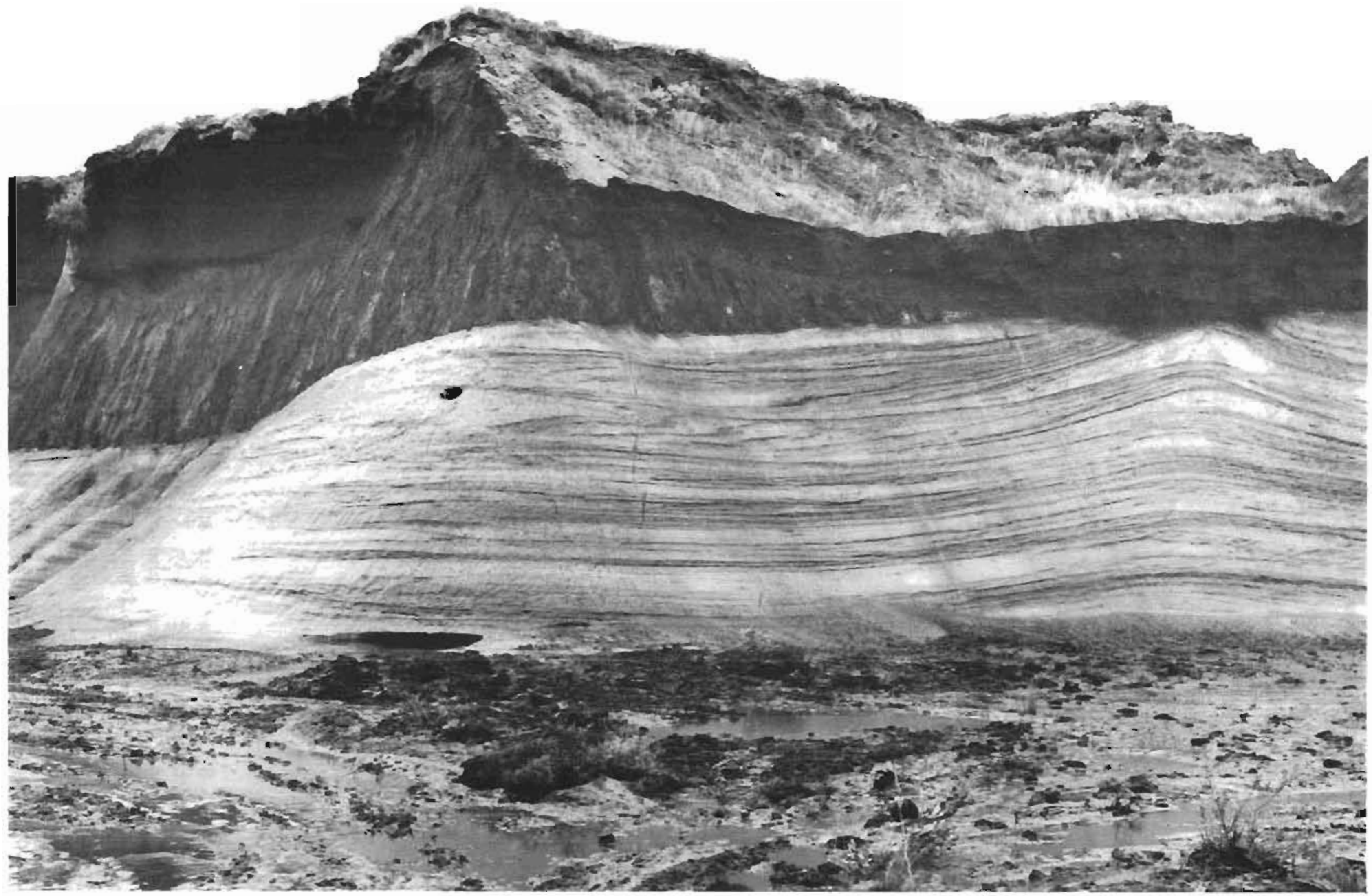

Figure 85. Massive ground ice exposed at Peninsula Point ice slump 5 km southwest of Tuktoyaktuk.

Oxygen-isotope analyses of the massive ice indicate a very cold water source (^{18}O about $-30^{o}/_{oo}$) such as glacier ice. Detailed ice petrofabric analyses suggest that the ice is segregated ice and not buried glacier ice (Gell, 1976), but the evidence is not conclusive.

Involuted Hill Area

Numerous flat-topped and relatively steep-sided hills in the Tuktoyaktuk area are underlain by as much as 20 m of massive ice---similar to ice in the slump just discussed. The ice, in turn, is underlain by sand. The hills, when viewed from the air (fig. 86) or examined on aerial photographs (fig. 87), show a peculiar ridged or involuted pattern. Some ridges are associated with the outlines of gigantic ice-wedge polygons. Gravity profiling, the identification of Bouguer anomalies, conventional drilling techniques, and water-quality determinations have established the stratigraphy of these involuted hills.

Figure 86. Oblique aerial view of an involuted hill near Tuktoyaktuk. Mackay (1963, p. 138) described the surface appearance on air photographs as resembling the wrinkled skin of a well-dried prune (see fig. 87).

At Involuted Hill, 15 km east of Tuktoyaktuk, excess ice accounts for 70 percent of the surface relief, and drill holes reveal the ice to be 22 m thick at the crest of the hill (Rampton and Walcott, 1974). According to Rampton (1974), 4 to 5 m of reworked clay or diamicton overlies the massive ice.

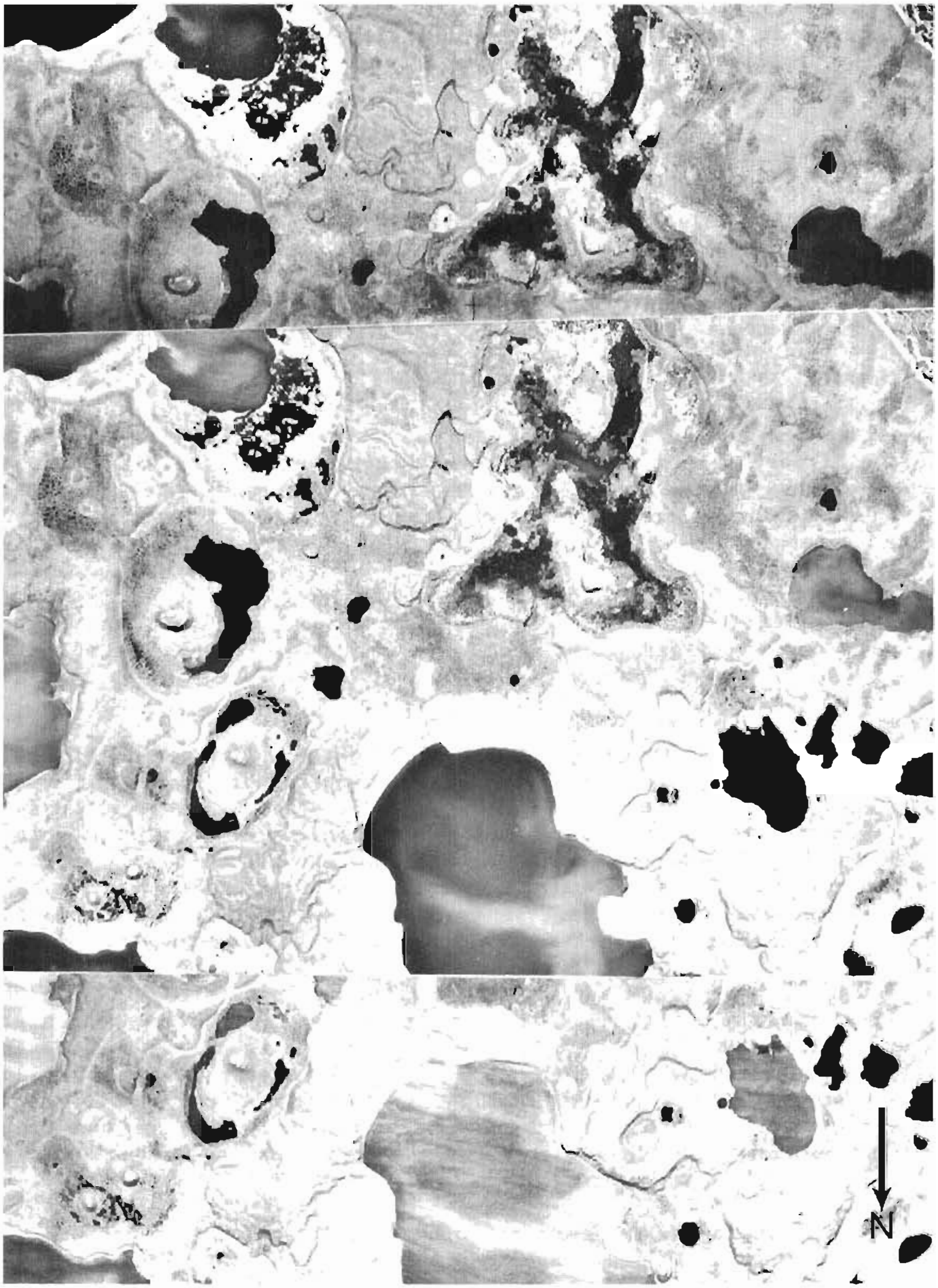

Figure 87. Stereotriplet of involuted terrain northeast of Tuktoyaktuk centered at lat 69°32'N., long 130°50'W. Several pingos can also be recognized (NAPL A12902-120/122).

Oxygen-isotope ratios, which are similar to those of ice in the slump southwest of Tuktoyaktuk, indicate a very cold water (glacier?) source. Because there is no discontinuity in either the oxygen-isotope or water-quality profiles in passing from the massive ice to the underlying sand, a common water source is implied.

The former large lake (which can be seen immediately south of Involuted Hill) drained before 1890 A.D. (age from willows). The drained lake is about 1 km wide and 6.5 km long. Permafrost beneath the lake bottom is about 40 ± 5 m thick. All drill holes that have penetrated the permafrost have produced artesian flow. Three large (12-m-high) pingos have developed on the lake bottom. One of the pingos periodically ruptures near the base, water escapes as spring flow, and the top of the pingo subsides; then pressure rebuilds and the cycle is repeated.

Ice-wedge Polygons

Ice-wedge polygons at Tuktoyaktuk can be seen along the east side of the road to the airport and in flats near the southwest end of the airstrip. The ice-wedge polygons in the Tuktoyaktuk area vary greatly in age, from those that are just beginning to grow in the bottoms of recently drained lakes to ice wedges several thousand years old (fig. 88). During the Holocene warm period (8,500 to 5,500 yr ago), the Tuktoyaktuk Peninsula area was warmer than now (Ritchie and Hare, 1971). Consequently, the active layer thickened and the tops of preexisting ice wedges were truncated. In the ensuing cold period, new ice wedges grew. In some coastal exposures such as at Garry, Pelly, and Hooper Islands, the 'roots' of the old ice wedges can be seen at a depth of several meters.

Ice wedges grow by thermal-contraction cracking. The period of active ice-wedge cracking at Garry Island (and presumably at Tuktoyaktuk) is concentrated between mid-January and mid-March (Mackay, 1974). Winter cracks average about 1 cm across at the surface and taper downward to a maximum depth of about 5 to 6 m. The wedges crack preferentially near the center. The cracks tend to close partially before water can enter, so the annual growth rate is less than the annual crack width. In early summer, it is often possible to find the preceding winter's crack in the *Sphagnum* of the ice-wedge troughs.

Ice wedges do not crack every year. On the average, probably less than half of the wedges in any given area crack annually. As the ice wedges grow wider, peaty ridges usually develop parallel to the troughs. If so, the initial polygon profile resembles that of a polygonal saucer (that is, a low-center polygon). The ice wedges in low-center polygons are usually active (that is, the wedges still crack). However, many polygons are bun shaped (high-center polygons) and in these features cracking of the wedges is infrequent.

Ice-wedge cracking is closely associated with snow depth because snow acts as an insulator. Indeed, experiments have shown that the addition of even 1 m of snow may prevent ice-wedge cracking.

Ice-wedge polygons play a number of different geomorphic roles in the Tuktoyaktuk area. Many of the lakes owe their existence to ponding and to the

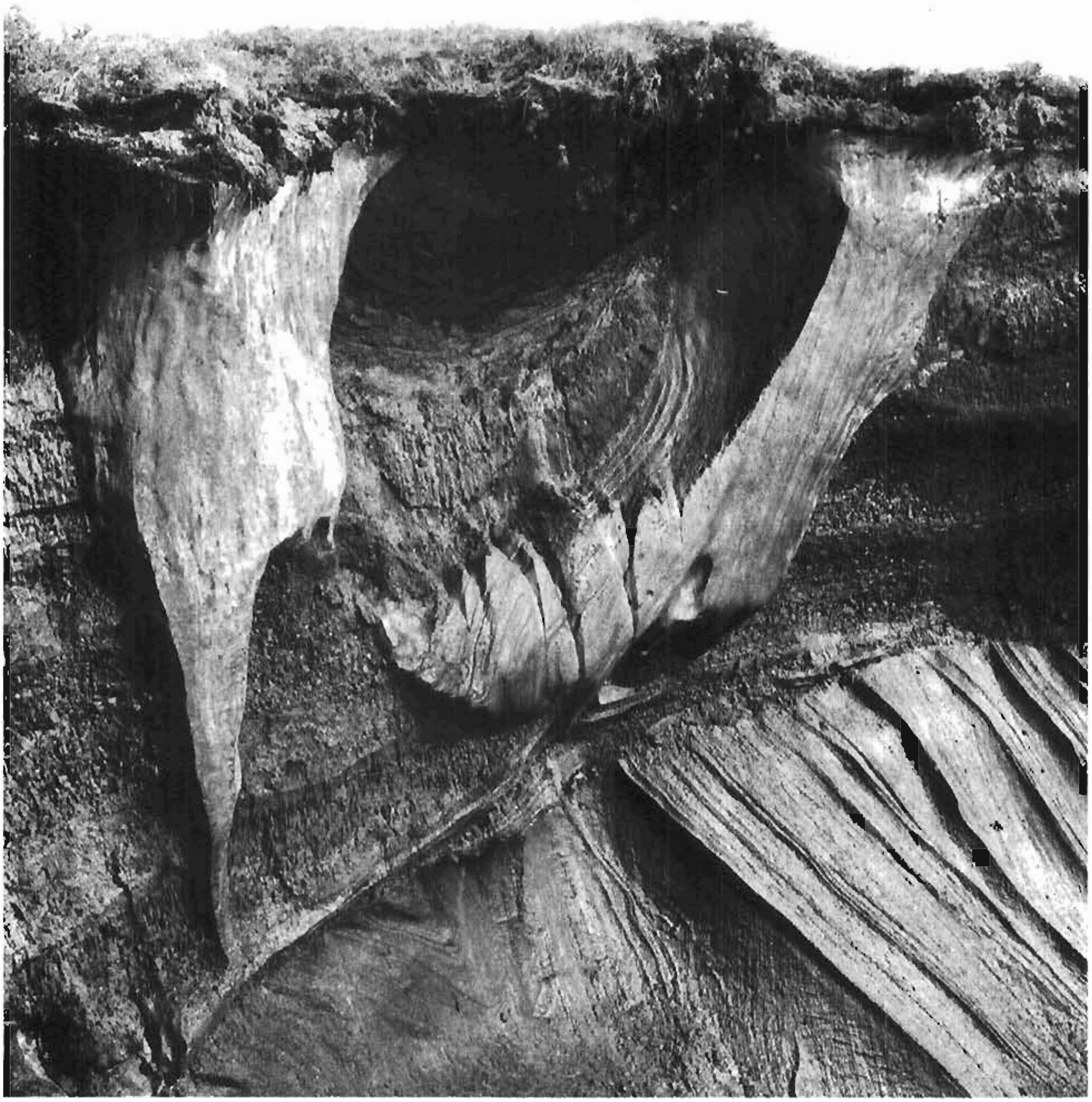

Figure 88. Ice wedges at Garry Island, Mackenzie Delta. The ice wedge at the left is 4.5 m wide at the top. Note the absence of a surface depression above the ice wedge. At the center right, another ice wedge is seen in transverse section.

growth of ice-wedge polygons, which can raise the surface of the ground 1 to 2 m by the addition of ground ice and the growth of peat. Conversely, about once a year, a large lake somewhere in the Tuktoyaktuk Peninsula area drains suddenly due to the erosion of ice wedges at its outlet. Where polygons form in the coastal zone, erosion can be remarkably rapid. There is an excellent example 20 km southwest of Tuktoyaktuk. Between 1935 and 1982, the shoreline eroded back more than 500 m in an area with many low-center ice-wedge polygons. A favorite location for the excavation of ice cellars in the days before mechanical refrigerators were available was at the intersection of two ice wedges.

Organic Deposits

Significant areas in the Tuktoyaktuk region are covered by organic (peat) deposits between 1 and 2 m thick that grade downward into underlying material (fig. 73). Peat is especially common in areas of lacustrine and intertidal deposits.

Peat has a high ice content and commonly will yield up to 60 percent free water when thawed uncompressed. When frozen, ice contents are generally between 200 and 500 percent, but may exceed 2,000 percent, depending on the number and thickness of the ice lenses.

Most organic deposits have a surface pattern; most common are high-center peat polygons (baydzherakh); less common are low-center polygons (fig. 89). Generally, high-center peat polygons have smaller diameters (average, 10 m) than low-center ones (15-20 m). Usually, there is standing water in trenches that outline polygons.

An oddity of the Tuktoyaktuk area is the occurrence of 'pitted' peat (Rampton and Bouchard, 1975). This terrain occurs in the intertidal zone where holes 1 to 2 m deep and 2 to 4 m wide penetrate the surface organic layer. Good examples occur in the settlement area south of the Arena (fig. 89), near Ibyuk Pingo, and elsewhere along the coast. This terrain is probably a form of thermokarst and results from the thawing of ice in peat that is inundated regularly by brackish waters. Some of the pits appear to be distributed in a linear fashion, probably along ice wedges; others are irregular in distribution. The fibrous, cohesive nature of the peat, tidal scour, and high-ice content of the materials are apparently important factors controlling the formation of this terrain.

WALKING TOUR OF TUKTOYAKTUK SETTLEMENT AREA

A representative idea of the permafrost conditions, geomorphology, and geotechnical problems associated with economic activity in the Tuktoyaktuk area can be obtained in the morning or afternoon, even in poor weather. The tour begins and ends at the Polar Continental Shelf Project Station. About 3 to 4 hours are required.

Some general comments are followed by an itinerary and a route map (fig. 90).

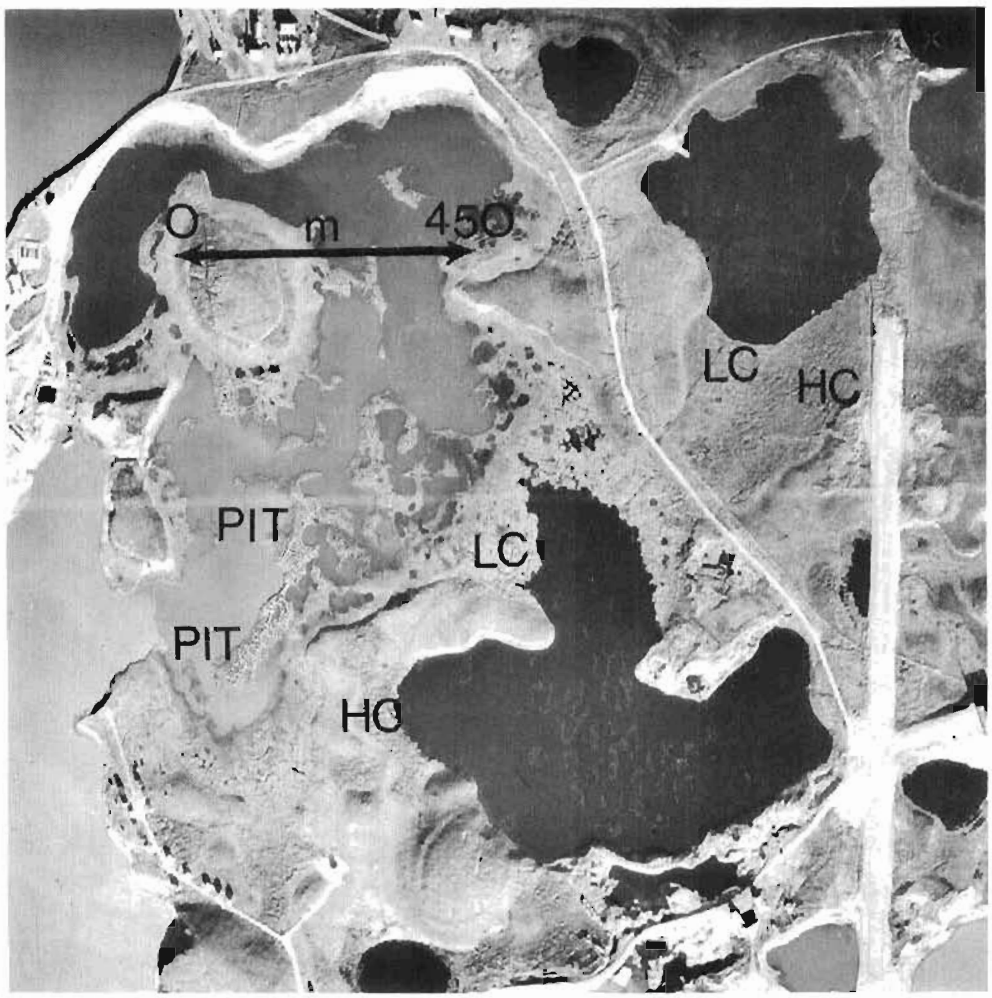

Figure 89. Airphoto taken in 1972 of area immediately south of Tuktoyaktuk settlement showing different types of patterned ground developed in organic terrain. LC - low-center polygons, HC - high-center polygons, PIT - 'pitted' peat areas. Much of this area is now built on by recent expansion of the Tuktoyaktuk settlement (NAPL A22535-56.

General Background

Development at Tuktoyaktuk has proceeded despite special constraints imposed by coastal erosion, permafrost, and ground ice. Although hunting and fishing are still undertaken by local Inuit, the major employment is related to freight transshipment, for Tuktoyaktuk Harbour is strategically located near the exit of the Mackenzie River. At Tuktoyaktuk, Mackenzie River barges from Hay River are unloaded and ocean-going barges and vessels are loaded to take freight as far west as Point Barrow, Alaska, and as far east as Spence Bay---a distance of 2,400 km.

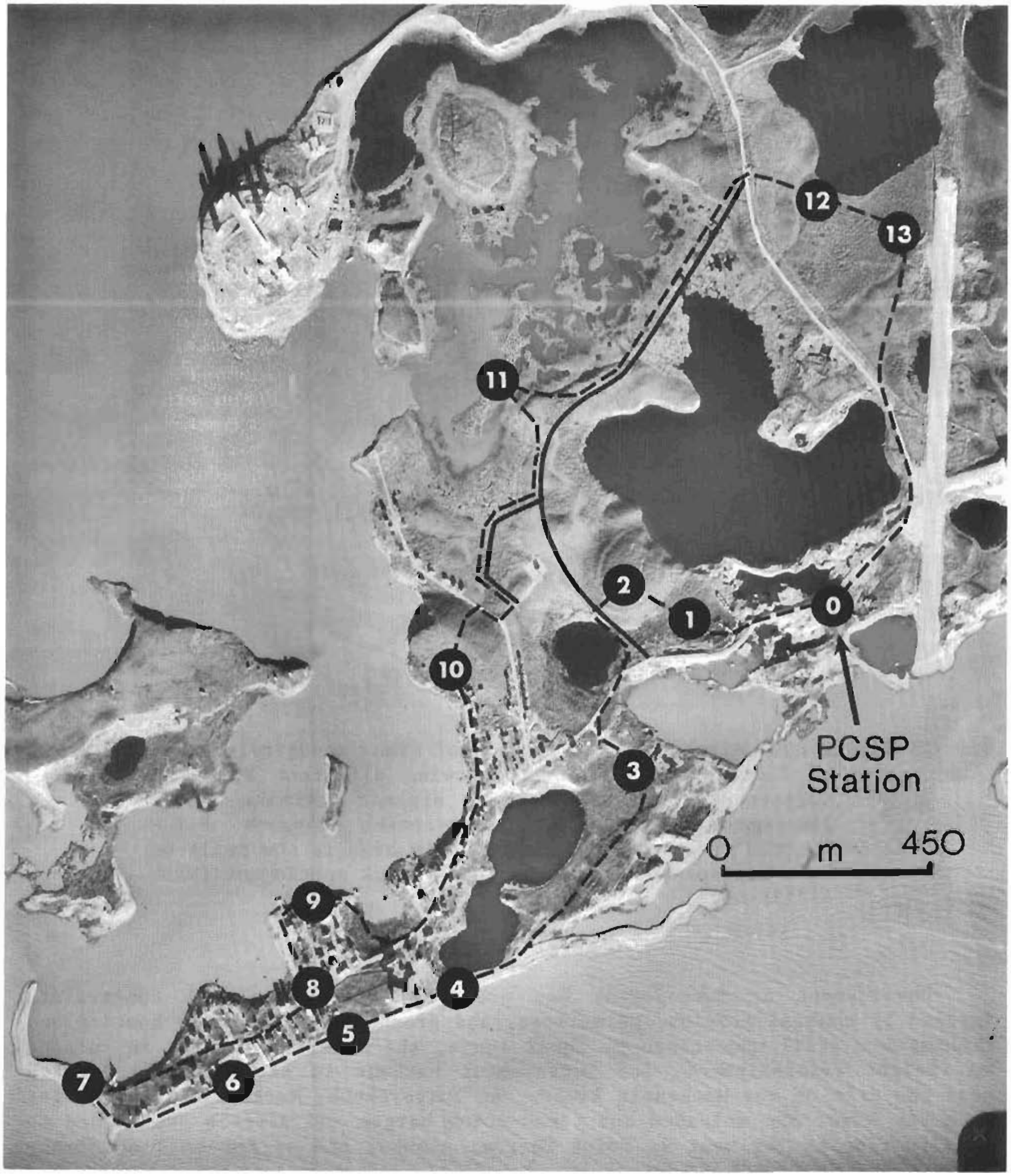

Figure 90. Walking-tour itinerary and route map, Tuktoyaktuk.
Stops 1 to 12 (NAPL A22535-56).

The economy of the area was reinforced by the construction of the DEW line radar station between 1955 and 1957. In the late 1960s, petroleum exploration in the Mackenzie Delta by Canadian subsidiaries of the large multinational oil companies (ESSO, Gulf, Shell) brought further activity to the settlement. In 1969, the federal Department of Energy, Mines and Resources established a research-base facility in Tuktoyaktuk as part of the Polar Continental Shelf Project. There was a decline in land-based drilling in the mid-1970s, but recently, offshore petroleum exploration in the Beaufort Sea---especially by Dome Petroleum and its subsidiary, CanMar Ltd.---has brought renewed growth to the settlement. Today, harbor facilities include a floating dry dock, extensive fuel-storage farms, and modern loading equipment. The airstrip has been extended and upgraded to accommodate large modern jets and Hercules aircraft.

Because of the presence of ice-rich sediments at shallow depths, all development is designed to prevent thawing of the ground as much as possible. Most structures have been placed on gravel pads, piles, or similar foundations to prevent permafrost degradation. In many places, however, the gravel thickness in pads and fill under roads has been insufficient and subsidence has occurred. The proposed road alignment between Tuktoyaktuk and Inuvik avoids steep slopes because erosion may expose massive ice or icy sediment and result in retrogressive-thaw-flow slides.

Obtaining granular material has been a problem at Tuktoyaktuk because of a general scarceness of material and the expense of stripping and thawing icy overburden. There is some granular material (now inaccessible) beneath the developed part of the settlement. Spits have also served as the main supply of granular material. Granular material is now drawn from sources in the southern Tuktoyaktuk Peninsula or dredged from the harbor or sea bottom.

Itinerary

Start: Polar Continental Shelf Project Station.

STOP 1. Tundra terrain immediately east of the road leading from airstrip to settlement, about 200 m from the station buildings.

A vegetation assemblage representative of low arctic tundra in the Pleistocene Mackenzie Delta is present. Dominant species include willow (*Salix alaxensis*), resin birch (*Betula glandulosa*), lupine (*Lupinus arcticus*), entire-leaved mountain avens (*Dryas integrifolia*), white heather (*Cassiope tetragona*), lousewort (*Pedicularis* spp.) and Labrador tea (*Ledum* spp.).

STOP 2. Proceed to top of adjacent hill (pingo) on which a radio antenna is located.

Vegetation-covered hummocks, 1 to 2 m in diameter, cover the tundra surface. Interhummock depressions are infilled with peat. Thickness of the active layer varies from 5 to 15 cm in the interhummock depression to 30 to 40 cm beneath the hummocks.

STOP 3. Retrace path to road, proceed 200 m toward settlement and turn left through an area of new housing past Reindeer Cafe.

Many of these buildings have been erected since 1980. Wood piles, driven into the permafrost, are used as foundations.

STOP 4. Beach adjacent to settlement school.

About 120 m of the shore near this point have been covered with wave-attenuation devices to reduce wave energy during storms and prevent subsequent erosion due to thawing of icy sediments. The devices consist of a network of sand-filled plastic tubes, 1 m in diameter, laid on the beach (Shah, 1978). They are known as the Longard System and were manufactured in Denmark.

STOPS 5 and 6. Cliff sections immediately west of the settlement.

Stratigraphy. Between 1 and 2 m of pebbly clay diamicton is exposed. These sediments overlie glaciofluvial sands, which are occasionally exposed at the base of the section. The pebbly clay is interpreted as a pre-Wisconsin till that has been considerably reworked by ablation, frost churning, and slumping. In places, an ice-rich organic zone can be seen at the bottom of the active layer and above the permafrost table. This layer formed by downslope movement of the hummocky active layer.

STOP 7. Flagpole Point (northern tip of the peninsula).

Aerial photographs taken between 1935 and 1971 indicate that the coast eroded about 135 m, an average rate of about 3.75 m/yr. Note the curling rink, which has been undermined by coastal retreat.

STOP 8. Retrace steps through settlement past the RCM Police building and the mission ship, 'Our Mary of Lourdes,' to the main intersection.

Note the older buildings, some of which have subsided. The ice cellar (small, red wooden hut) is just off the main intersection. Permission is required from settlement authorities to examine it.

STOP 9. The Hudson's Bay Store.

The protected, leeward side of the peninsula on which Tuktoyaktuk settlement is located can be appreciated by contrasting it with the opposite (eroded) side (STOPS 4 to 6).

STOP 10. Proceed back through settlement, past Igloo Inn Cafe and A&W Hardware. Turn left toward E. Gruben Transport Ltd. and the pingo (hill) on which the wooden house is located.

The former entrance to the pingo tunnel is located on the north side of the hill. The top of the hill is a good vantage point for photography of the settlement. Note the tundra vegetation and hummocks on the hill.

STOP 11. Proceed past newer subdivisions in the settlement to the Post Office and Arena. Walk toward the tidal-mud flats in the bay between the DEW line station and Arena.

A good example of pitted peat (fig. 89) can be examined here.

STOPS 12 and 13. Proceed past settlement water reservoir (constructed in 1981 at a cost of $3 million). Cross main road leading to the harbor facilities and Dome Petroleum camp. Proceed across tundra toward the airstrip. Both high- and low-center peat polygons are present in this area.

Retrace steps to the road. Proceed to Polar Continental Shelf Project Station via Dome airstrip terminal and side road.

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