3 Wetlands of Subarctic Canada

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Wetlands of Subarctic Canada

Subarctic wetland regions extend in a broad belt between the forested Boreal and the treeless Arctic, and cover about 760 000 km² in Canada. This chapter does not include discussion of the Atlantic Subarctic Wetland Region (SA) which is discussed in Chapter 7. Wetlands are common in the Subarctic, constituting about 30% of the land surface, and in some areas they dominate the landscape. Three subarctic wetland regions were delineated on the basis of characteristic wetland development and were divided into High, Low, and Atlantic Subarctic Wetland Regions.

In this chapter the subarctic wetland environments are discussed and the common forms of wetlands described in some detail. Tidal subarctic salt marsh wetlands are considered in Chapter 9.

Environmental Setting

Physiography

The physiography of the subarctic wetland regions varies from nearly level plains to mountainous uplands. Parts of the continental core areas of the Canadian Shield, as well as parts of the Borderlands composed of sedimentary rocks, occur in the Subarctic (Bostock 1970).

The Shield consists of massive crystalline rocks and some local sedimentary belts. The relief is generally typical of a peneplain: low hills of about 100 m in elevation, without prominent peaks. There are innumerable lakes enclosed in bedrock basins, and the rolling hills are thinly covered by sandy moraine. The physiography of the Shield, although generally uniform in geology and topography, has been divided on the basis of geological structure by Bostock (1970).

The Kazan physiographic region lies to the west of Hudson Bay and consists of massive crystalline rocks, forming uplands and plateaus. The plain in the Thelon River area owes its low relief to flat-lying sandstone bedrock. The Whale Lowland, south of Ungava Bay, occurs within the subarctic wetland regions as a broad, drift-covered area with scattered hills. The James region, east of Hudson Bay, has a typical peneplain surface with thin, discontinuous morainal deposits over crystalline bedrock and countless lakes. The Labrador Hills present prominent relief up to 1 000 m high, consisting of folded Precambrian sedimentary and volcanic rocks.

The Hudson physiographic region is composed of flat-lying Paleozoic bedrock over Precambrian basement rocks. The Hudson Bay Lowland is a generally flat plain, covered by glacial drift and thin marine sediments, that slopes gently towards Hudson Bay. Large, well-entrenched rivers cross this area and drain into the Bay.

The Borderlands have a more varied physiography and geology than the Shield. The northwestern portion of the subarctic wetland regions falls within three physiographic regions: the Cordilleran, the Arctic Coastal Plain, and the Interior Plains (Bostock 1970). In the Cordilleran region, subarctic wetlands occur on plateaus and plains between the northern mountain ranges. The Porcupine Plateau is almost entirely unglaciated and consists of a weathered, undulating hilly surface, with a well-entrenched drainage system. The Old Crow Plain is a generally flat lowland of Pleistocene lacustrine sediments. The Eagle Plain has long, even-topped ridges of gently rounded summits typical of unglaciated areas.

Only a small portion of the Arctic Coastal Plain lies within the subarctic wetland regions. This area, the southern part of the Mackenzie Delta, is characterized by a maze of river channels and ponds in a flat alluvial plain.

The northern part of the Interior Plains physiographic region is within the subarctic wetland regions. The Anderson Plain is a gently rolling area of glacial drift over Cretaceous shales and sandstones. The Peel Plain is a low, featureless area, studded with lakes in the western part, and the Peel Plateau rises in three steps of erosional surfaces from the plains to the Mackenzie Mountains. The Mackenzie Plain is a narrow, gently undulating area underlain by Mesozoic and Paleozoic bedrock, while the Great Bear Plain is composed of a rolling surface underlain by Mesozoic strata. The Great Slave Plain is composed of Paleozoic strata that have little relief. The Colville Hills consist of several ridges of Paleozoic strata rising to sinuous ridges some 400 m above the plains.

The drainage characteristics of various areas are influenced by the physiography and by the composition of the materials. In the areas of the Shield with hard, crystalline rock, drainage is poorly organized: chains of lakes interconnected by short stretches of rapid-filled rivers are the typical water courses. In softer bedrock or in drift-covered areas, the rivers tend to be entrenched and have a well-developed tributary system. In such areas poorly drained interfluves are less prominent. Areas of low relief, especially when underlain by dense, fine-textured soil, are likely to have poor drainage and hence will support extensive wetland areas.

Most of the subarctic wetland regions were subjected to repeated glaciation during the Quaternary period. Continental glaciation, radiating from the Hudson Bay area, and mountain glaciers, originating in the Cordilleran region, covered most of the land surface. Glacial action eroded the existing surfaces, depositing debris directly as morainal materials, or in lakes and rivers as sediments. During the waning stages of glaciation, some 7 000–13 000 years ago, the natural drainage to the sea was blocked by the remnant ice sheet and large glacial lakes were formed. In coastal areas the sea invaded the low-lying areas which were depressed as much as 300 m by the weight of the ice. The lake and marine sediments often formed extensive plains which, if poorly drained, were occupied by wetlands.

The northwestern part of the subarctic wetland regions in northern Yukon has never been glaciated. The area is drained by a well-developed river system with tributaries at regular intervals. Wetlands are scarce in this area, but occur where Pleistocene lacustrine sediments are present.

Subarctic Climate and Wetland Regions

The subarctic wetland regions are characterized by very cold winters and short, warm summers. The Subarctic is where the most frequent encounters between arctic and temperate air masses occur (Dolgin 1970). In the summer the average position of the arctic frontal zone is in the Subarctic (Bryson 1966), allowing the incursion of temperate air masses. The winter position of the arctic frontal zone is well to the south, permitting the domination of arctic air masses in the winter. Precipitation is low in the western part of these regions, but increases twofold in the areas around Hudson Bay and eastwards, possibly reflecting the influence of this water body on atmospheric moisture.

In the High Subarctic Wetland Region (SH) (Figure 3–1), the mean annual temperatures are lower in the west than in the east (Table 3–1), possibly due to low winter temperatures. However, the July temperatures are lower in the east,

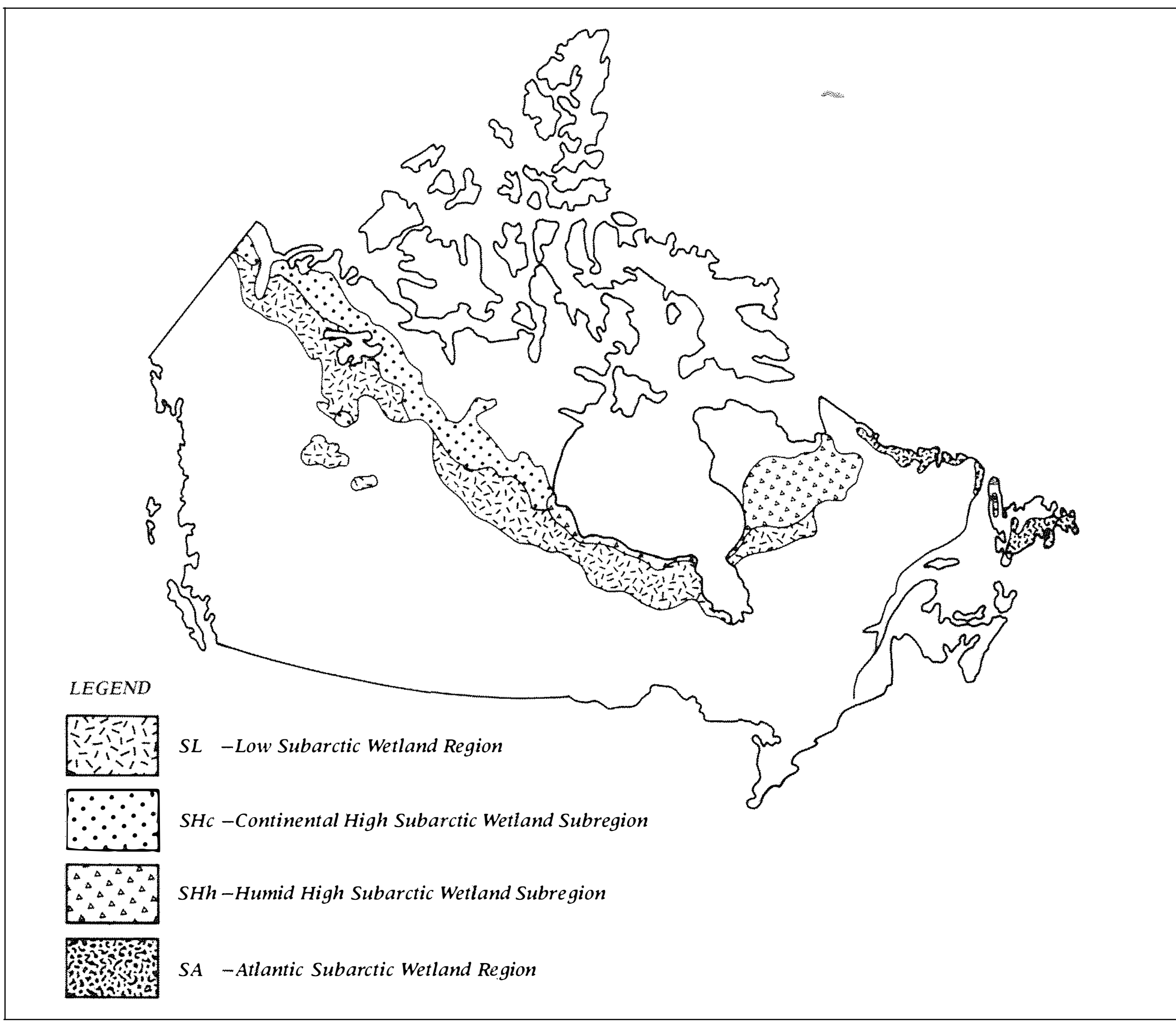


Figure 3–1.
The subarctic wetland regions of Canada.

resulting in lower accumulations of degree-days above 5°C (growing degree-days) in this area. Snowfall and total precipitation are both markedly higher in the east. However, the effects of these climatic differences on wetland development are not pronounced; hence both areas are in the same wetland region, but in different wetland subregions: (i) SHc (Continental) and (ii) SHh (Humid) High Subarctic.

In the Low Subarctic Wetland Region (SL) (Figure 3–1), the mean annual temperature is higher than in the Continental High Subarctic Wetland Subregion (Table 3–1). The mean July temperature is also higher, but the mean January temperatures are virtually the same. This results in a greater number of growing degree-days than in the High Subarctic Wetland Region. Precipitation and snowfall are also somewhat higher in the Low Subarctic Wetland Region.

Table 3–1. Climatic data of the subarctic wetland regions (average values)

Wetland region	*No. of stations*	*Mean annual temp. (°C)*	*Mean daily July temp. (°C)*	*Mean daily January temp. (°C)*	*Mean degree-days above 5°C*	*Mean annual total precip. (mm)*	*Mean annual snowfall (cm)*
SHh	5	−5.4	11.5	−24.1	559.8	622.9	280.8
SHc	5	−9.1	13.4	−30.1	656.4	239.9	127.9
SL	6	−6.6	15.3	−29.6	938.8	330.1	158.8

Source: Atmospheric Environment Service (1982).

Regional Vegetation and Wetlands

The Subarctic lies between the closed-canopied boreal forest in the south and the treeless arctic tundra in the north. It is characterized by open-canopied coniferous forest or by patches of open-canopied forest and tundra. It is included in the transitional forest–tundra (Rowe 1972) and is similar to the "lesotundra" of the Soviet Union (Norin 1961). Permafrost is widespread in subarctic soils. Distinctive wetland forms are produced by the interaction of excess water and severe climate, manifested in the limited growth of some plants and in the development of permafrost.

The vegetation of the high subarctic uplands is characterized by open stands of black or white spruce (*Picea mariana, Picea glauca*), with a conspicuous ground cover of lichen (*Cladina mitis, Cladina rangiferina, Cladina alpestris*). In poorly drained areas *Larix laricina* may also be present. Open tundra patches occupy increasingly larger areas towards the northern limit of the High Subarctic Wetland Region. Such tundra patches consist of low shrubs (*Betula glandulosa, Dryas integrifolia*), sedges, and lichens.

Most wetlands are affected by permafrost in the Continental High Subarctic Wetland Subregion. The common wetlands are peat plateau and polygonal peat plateau bogs, separated by fens. In the Humid High Subarctic Wetland Subregion, in the Hudson Bay Lowland and east of Hudson Bay, unfrozen fens and permafrost-affected palsa and peat plateau bogs, some with ice-wedge polygons, are the characteristic wetland forms.

The low subarctic upland vegetation consists of a spruce–lichen forest, in which open-canopied black and white spruce dominate. There is a patchy lichen cover, consisting of *Cladina* spp., and a layer of heath shrubs. On some hillsides deciduous trees, such as *Populus tremuloides* or *Betula papyrifera*, may occur, and on river floodplains *Populus balsamifera* can be found mixed with *Picea glauca*.

The common and characteristic wetlands are fen and peat plateau–palsa bog complexes. Northern ribbed fens occupy large areas, with incipient permafrost in some of the ridges.

Subarctic Wetland Forms

In this section those wetlands that are characteristic of or abundant in the subarctic wetland regions are described, although not all forms present are included, as other less prominent wetland forms also occur. The discussion of each wetland form in this section consists of two parts: a generalized account followed by a specific example. The most common forms of wetlands in the Subarctic which are highlighted in this section, in order of prominence of occurrence, are:

—peat plateau bogs
—polygonal peat plateau bogs

—palsa bogs
—northern ribbed fens
—channel fens
—veneer bogs/collapse scar fens
—floodplain marshes
—floodplain swamps
—thermokarst shallow waters

Peat Plateau Bogs

Peat plateau bogs are perennially frozen peatlands elevated about 1 m above the water table of the associated wetlands (Zoltai and Tarnocai 1975). They are generally flat, with only minor surface irregularities (Figure 3–2). In the Subarctic they may reach a size of several square kilometres. They resemble the "flat palsas" of the northern Soviet Union (Botch and Masing 1983) or the "palsa plateaus" of northern Norway (Åhman 1977). In Norway, however, they seldom reach 1 km^2 in size. The vegetation consists of scattered, stunted *Picea mariana* with abundant lichen ground cover in the Low Subarctic Wetland Region. In the High Subarctic Wetland Region there is a very open, stunted, scattered spruce woodland with a ground cover of lichen and low heath shrubs. In the Humid High Subarctic Wetland Subregion both treeless (dominated by *Cetraria nivalis*) and treed types are present. The absence of trees may often be the result of fires (Couillard and Payette 1985).

In the subarctic wetland regions, peat plateau bogs generally occupy large portions of wetlands (Figure 3–3), but are usually associated with open or shrubby fens. The fens are not affected by permafrost in the Low Subarctic Wetland Region and in the Humid High Subarctic Wetland Subregion, but usually contain permafrost in the Continental High Subarctic Wetland Subregion (Zoltai and Tarnocai 1975). At the edges of many peat plateau bogs, newly developing peat plateaus can be seen in which a carpet or cushion of *Sphagnum fuscum* contains relatively thin permafrost that does not reach the mineral soil. Such *Sphagnum* carpets or cushions are somewhat elevated (up to 50 cm) above the fen level. If elevated further by the thickening permafrost, the surface becomes dry enough for the establishment of lichens and this developing peat plateau then merges with the main peat plateau body. *Picea mariana* and *Ledum groenlandicum* usually form the upper vegetation layers in these newly developing peat plateaus.

Figure 3–2.
Flat surface of a peat plateau bog with stunted Picea mariana *and abundant ground lichens at Ft. Good Hope, NWT.*

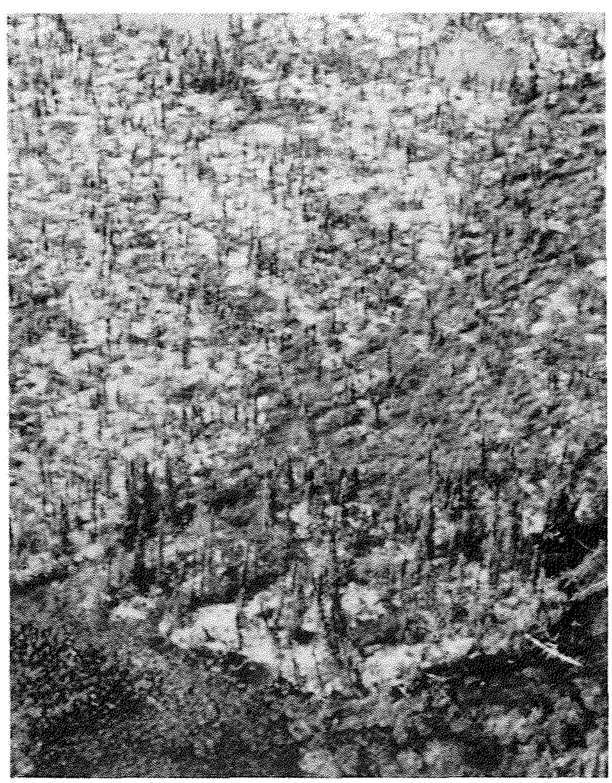


Figure 3–3.
Aerial view of an extensive peat plateau bog with unfrozen fen in foreground near Sans Sault Rapids, NWT.

Although degrading permafrost occurs in the Low Subarctic Wetland Region and in the Humid High Subarctic Wetland Subregion, it is most common in the High Boreal Wetland Region described in the next chapter of this book. If the thermal balance of a portion of a peat plateau bog changes, the permafrost thaws and the surface of the peat plateau subsides into the fen. Such "collapse scar" areas, usually fen wetland forms, are limited in size to a few tens of square metres. They are marked by the presence of dead trees protruding from the fen, and by the bright green colour of *Sphagnum riparium* that grows partially submerged in water in the collapse scar. In the Humid High Subarctic Wetland Subregion *Sphagnum balticum* and *Sphagnum lindbergii* are common in collapse scars (Couillard and Payette 1985).

The thickness of peat deposits is commonly in excess of 2 m and may reach 4 m. In the Mackenzie Valley the peat thickness averaged 217 cm at 83 sites (Zoltai and Tarnocai 1975). Permafrost occurred 30–50 cm below the surface, extending well into the mineral soil (Brown 1970). There is a surface layer (up to 30 cm thick) of moderately to well decomposed forest peat, underlain by *Sphagnum* peat to a depth of 50–60 cm below the surface. Beneath this is moderately decomposed fen peat consisting of sedge and brown moss (mainly *Drepanocladus* spp.) remains. The perennially frozen peat contains ice crystals and small ice veins, but the water content of the peat is about the same as that of unfrozen peat. Ice accumulation may be encountered as 2–10 cm thick layers in the fen peat, or in the upper part of a silty mineral soil.

The vegetation associated with this wetland form is a sparse spruce–lichen woodland, with some shrubs and extensive lichen ground cover. There may be variations in the proportions of these components, but the vegetation is generally uniform. Some variations are caused by fires. In the Humid High Subarctic Wetland Subregion, fires may remove the trees, establishing a seral stage dominated by lichens (*Cetraria nivalis*) and mosses (*Dicranum groenlandicum*). In the Continental High Subarctic Wetland Subregion, the tree cover initially increases and the lichen decreases after a fire, but the open spruce–lichen woodland is re-established within the first generation after a fire. The main shrub species are *Ledum decumbens* in the open woodlands and *Ledum groenlandicum* in the forested areas, as well as *Andromeda polifolia* and *Betula glandulosa*. The distribution and extent of *Vaccinium vitis-idaea* and *Rubus chamaemorus* is sparse but constant. *Sphagnum fuscum* may grow in small, moist depressions, but the main ground cover is provided by *Cladina mitis*, *Cladina stellaris*, *Cladina rangiferina*, and *Cladonia amaurocraea*.

A peat plateau bog near Bonnet Plume River, Yukon Territory (65°37′ N, 134°18′ W), was examined in some detail. A peat plateau complex occupies most of a large depression, where the individual peat plateaus are separated by narrow, wet fen drains. A short transect was made from the central part of the peat plateau to the fen to examine the peat at three sites, describe the vegetation, and conduct levelling to describe the topography (Figure 3–4).

On this peat plateau bog, stunted *Picea mariana* trees cover about 5% of the surface and *Betula glandulosa* shrubs cover about 10% of the area. Dwarf shrubs, mainly *Ledum decumbens* and some *Vaccinium vitis-idaea*, constitute the lowest vascular layer. Lichens cover about 95% of the surface, mainly *Cladina stellaris*, *Cladina rangiferina*, *Cladonia amaurocraea*, and *Cetraria nivalis*.

Along the somewhat protected margin of the peat plateau bog, trees, *Picea mariana*, and some *Larix laricina* form a 15% cover, with a 40% shrub cover composed mainly of *Ledum decumbens* and *Rubus chamaemorus*. The ground cover is nearly continuous, mainly *Sphagnum fuscum* with a few lichens, including *Cladonia amaurocraea* and *Cetraria cucullata*. In the unfrozen fen, *Sphagnum balticum*, *Carex* spp., *Eriophorum* sp., and *Drepanocladus* sp. are found.

The peat was cored 14 m from the edge of the peat plateau bog and at the margin, and it was probed in the adjacent fen. On the peat plateau bog the surface stratum consists of fibric to mesic *Sphagnum* peat (Table 3–2), with the permafrost table at 33 cm. This is underlain by mesic to fibric layers of moss peat and sedge–moss peat. A thin layer of well-humified peat occurs above the mineral soil.

Chemical analyses of the peat (Table 3–2) show that the *Sphagnum* cap within the upper 70 cm is low in calcium (Ca) and magnesium (Mg). At greater depths, in the fen deposits, both the Ca and Mg levels are high.

At the margin core the top layer is composed of *Sphagnum* peat (Table 3–3), with the permafrost table at 25 cm. This is underlain by mesic sedge–moss and fibric *Drepanocladus* moss peat, resting

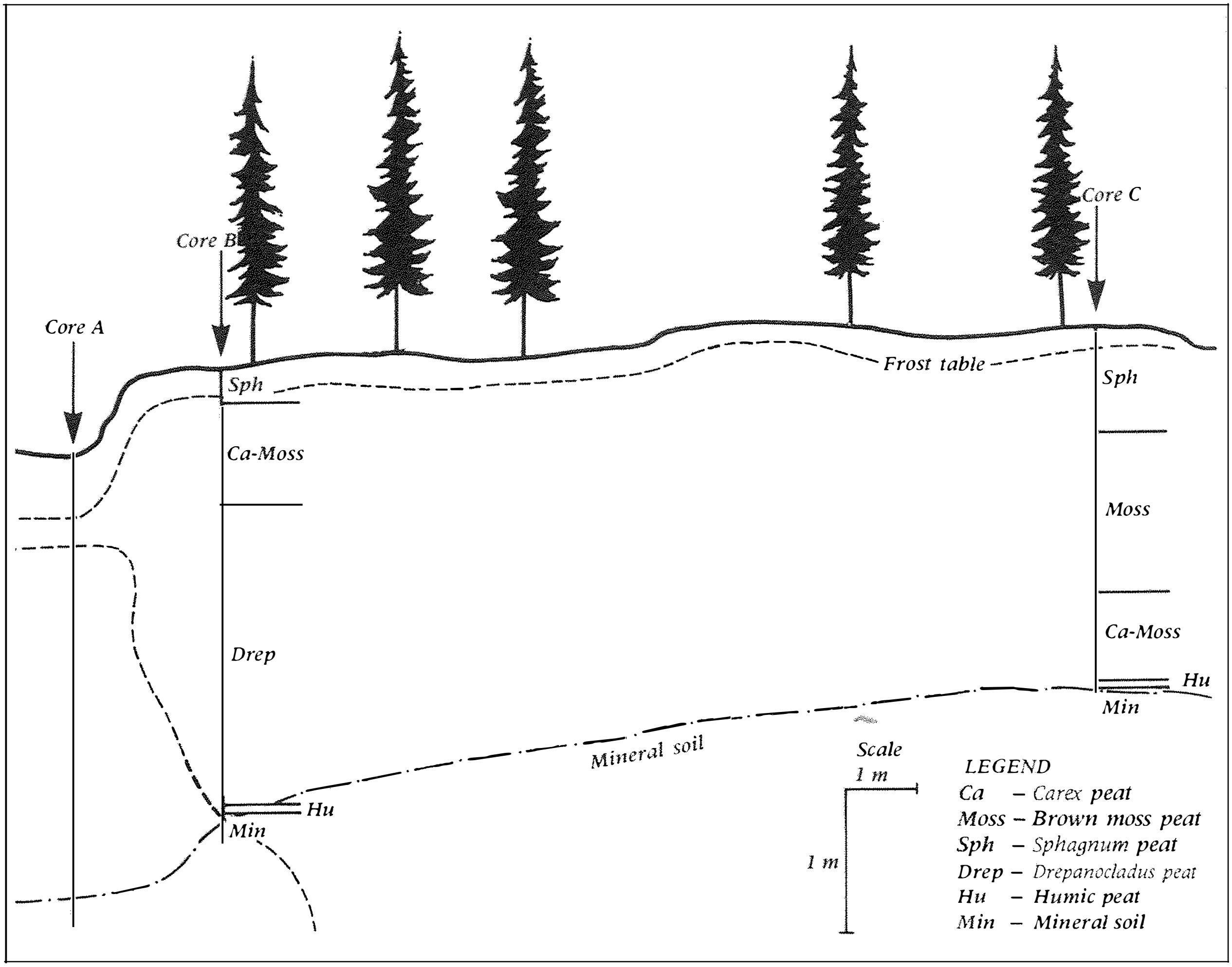


Figure 3–4.
Cross-section showing the stratigraphy at the marginal and central part of a peat plateau bog, Bonnet Plume River, YT.

on a thin layer of aquatic detritus. This is underlain by unfrozen sandy silt.

The analyses (Table 3–3a) show low levels of Ca and Mg in the surface *Sphagnum*, whereas the underlying sedge–moss peat is high in iron (Fe). The Ca and Mg levels are high in the lower fen peat.

In the fen the top 40 cm was unfrozen, composed of fibric *Carex–Sphagnum* peat. Seasonal frost was present (early July) at 40–61 cm in fibric to mesic *Carex–Sphagnum* peat, and beneath this was unfrozen peat. Mineral soil was encountered at 294 cm. The single peat sample from the fen (Table 3–3b) shows moderately high levels of Ca and Mg.

The volumetric water content of the peat and the underlying mineral soil was determined

Table 3–2. Total elemental analysis and other properties of peat from the central part of a peat plateau bog

Depth of sample (cm)	pH	Material	Decomposition (von Post)	Ash (%)	H_2O by volume (%)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)
29	—	*Sphagnum fuscum*	3	3.8	87.9	4 721	518	4 455
41	—	*Sphagnum fuscum*	3	6.0	86.8	3 199	284	7 365
64	—	*Sphagnum fuscum*	5	3.9	71.6	3 141	153	3 914
76	—	Moss	3	4.4	91.1	6 321	435	2 170
99	—	Moss	3	4.1	89.9	9 603	964	1 972
137	—	*Carex*–moss	3	5.9	93.1	6 648	723	1 522
150	—	Moss	5	9.4	94.3	10 074	956	2 180
193	—	*Carex*–moss	5	7.4	91.9	16 854	1 394	3 368
228	6.1	*Carex*–moss	5	14.0	87.6	10 258	1 123	2 637
246	6.1	Mineral	—	77.6	72.5	—	—	—

Table 3–3. Total elemental analysis and other properties of peat from the margin of a peat plateau bog (A) and a fen (B)

Depth of sample (cm)	pH	Material	Decomposition (von Post)	Ash (%)	H_2O by volume (%)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)
A—Peat plateau bog margin								
23	—	*Sphagnum fuscum*	3	2.3	92.2	5 133	564	2 986
31	5.2	*Carex*–moss	5	18.2	70.0	2 259	254	29 714
43	5.2	*Carex*–moss	3	6.9	89.5	4 078	233	10 668
62	5.2	*Carex*–moss	5	7.5	82.9	11 330	377	5 877
86	5.2	*Carex*–moss	5	6.6	82.9	9 196	874	2 204
105	5.2	*Drepanocladus*	3	5.2	94.2	11 393	1 081	2 654
127	6.1	*Drepanocladus*	3	8.2	93.2	13 025	1 139	2 775
149	6.1	*Drepanocladus*	3	6.6	89.6	10 210	892	1 853
183	6.1	*Drepanocladus*	3	4.6	94.4	12 817	1 082	2 537
240	5.8	*Drepanocladus*	3	6.7	95.8	9 263	578	2 152
292	5.8	*Drepanocladus*	3	7.2	93.8	8 563	574	3 523
299	—	Aquatic detritus	7	16.8	59.5	8 815	913	3 516
B—Fen								
45	—	*Sphagnum*	5	20.2	90.4	8 814	1 093	3 571

(Tables 3–2, 3–3). In general, it is found that excess ice is present in the peat samples when the volumetric water content exceeds 93%. In mineral soils, fully saturated clay loam can hold about 45% water by volume (Kohnke 1968). Therefore, moisture values that exceed this limit indicate the presence of excess water occurring as ice. Excess ice occurred at the centre core only in one sample in the peat and in the mineral soil. At the margin site, the lower peat samples had excess ice but the mineral soil showed only slight excess moisture.

The botanical composition of the peat shows that a thin *Sphagnum* cap, composed mainly of *Sphagnum fuscum*, exists over the perennially frozen fen peat of the peat plateau bog. The fibric peat in elevated hummocks is an excellent insulator, delaying thawing during the summer and eventually permitting the development of permafrost. As permafrost develops, the affected area is elevated, and the surface becomes drier, promoting the further development of permafrost. The dry conditions on the surface, however, are not conducive to further *Sphagnum* growth, and peat formation virtually ceases.

The peat is some 60 cm thinner on this peat plateau bog than at the margin or in the fen where peat deposition still continues. This implies that the peat plateau core site was elevated by the permafrost for some time, sufficiently long to allow the addition of 60 cm of peat at the peat plateau margin and in the adjacent fen. Similarly, since the thickness of peat at the margin and in the fen is about the same, the margin was probably affected by permafrost only recently. This is substantiated by the observation that permafrost has not yet reached the mineral soil under the margin (Figure 3–4).

Polygonal Peat Plateau Bogs

These perennially frozen wetland forms resemble peat plateau bogs in many respects: they are elevated about 1 m above the associated fen and their surface lacks relief. The main difference is that they are crisscrossed by trenches that form a polygonal pattern when viewed from above (Zoltai and Tarnocai 1975). Polygonal peat plateau bogs occupy the major portion of the depressions in which they occur, often covering hundreds of hectares. The associated fens are affected by permafrost in the Continental High Subarctic Wetland Subregion, but permafrost may be absent in the Humid High Subarctic Wetland Subregion. The surface of polygonal peat plateau bogs is usually treeless, with dwarf shrubs and a prominent ground lichen layer (Figure 3–5). These plateaus occur chiefly in the Continental High Subarctic Wetland Subregion, although a few have been noted in the Low Subarctic Wetland Region, especially in particularly exposed, windswept localities.

The polygons consist of cells of various sizes and shapes. The average diameter is about 15 m and the shape may vary from rectangles to eight-sided polygons. The pattern is formed by a lineal depression, the trench, flanked on both sides by a slight rise, the shoulders (Figure 3–6). The trench is generally 10–30 cm deeper than the local ground surface, and the shoulders are seldom more than

30 cm higher than the surface. The polygons may, therefore, be slightly concave in cross-section. Examination of eroded peat banks and corings indicates that there is an ice wedge under each polygon trench, extending downwards for 2–4 m. The ice of the wedges is clear, without inclusions, and it often contains bubble trains rising towards the surface in a slightly outward-curving arc (Tarnocai 1973). The peat is cut by the ice wedge, and contorted peat layers have been noted only near the surface where the ice wedge is the widest. The shoulders appear to consist of peat displaced by the developing ice wedges.

The average thickness of peat in polygonal peat plateau bogs is about 2 m (Zoltai and Tarnocai 1975; Dredge 1979). The peat consists of materials deposited in bogs and fens, without any indication of distorted, cryoturbated layers and without any frost-heaved mineral soil inclusions. There are few ice lenses or layers in the peat; when present they are less than 10 cm thick. There may be an ice layer 2–10 cm thick at the peat–mineral soil interface. The thickness of the annually thawed active layer is 25–35 cm, considerably lower than that in adjacent mineral soil (Dredge 1979).

The vegetation of polygonal peat plateau bogs is dominated by the lichen ground cover. *Cladina mitis, Cladina rangiferina, Cetraria cucullata, Cetraria nivalis*, and *Alectoria ochroleuca* are the main species. *Sphagnum fuscum* occurs in some of the wetter trenches. Low shrubs of *Betula glandulosa* and *Ledum decumbens* can also be found in

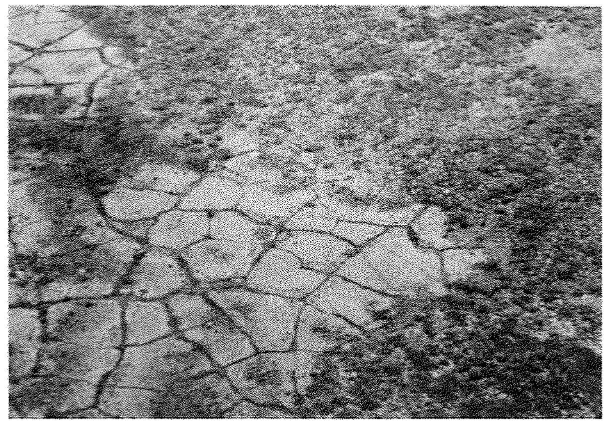


Figure 3–5.
Aerial view of a polygonal peat plateau bog, showing a variety of polygon sizes and shapes, Richardson Mountains, YT.

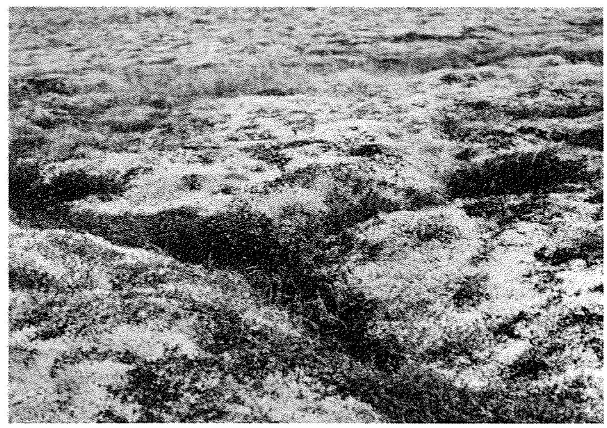


Figure 3–6.
Junction of three polygon trenches on a polygonal peat plateau bog, Richardson Mountains, YT.

Table 3–4. Total elemental analysis and other properties of peat from the shoulder of a peat polygon trough

Depth of sample (cm)	Decomposition (von Post)	Material	Ash (%)	H_2O by volume (%)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	S (mg/kg)
24	3	*Sphagnum*	1.6	71.2	2 156	555	1 332	515
40	3	*Sphagnum*	1.3	94.9	1 925	377	615	445
53	4	*Sphagnum*	6.8	73.5	2 225	342	1 085	808
80	4	*Sphagnum*	2.4	93.2	2 062	419	1 131	529
92	4	*Sphagnum*	3.0	90.8	1 945	392	1 112	737
115	3	*Sphagnum*	1.8	92.8	1 812	356	1 195	528
128	3	*Sphagnum*	1.5	90.8	1 725	400	1 170	410
160	4	*Sphagnum*	2.2	92.0	4 975	480	1 535	349
170	3	*Sphagnum*	3.5	90.1	6 400	552	1 890	456
182	3	*Sphagnum*	3.4	90.7	7 828	549	2 010	620
201	5	*Carex*–moss–wood	8.2	90.1	6 738	309	2 296	1 330
214	5	*Carex*–moss–wood	6.7	87.9	11 375	425	3 938	2 380
225	5	*Carex*–moss–wood	8.9	88.4	19 197	701	6 733	7 020
250	5	*Carex*–moss–wood	8.6	89.0	23 203	830	5 953	12 187
272	5	*Carex*–moss–wood	11.5	88.1	23 250	1 050	4 400	12 525
291	3	*Carex*–moss	8.1	92.1	15 025	850	2 670	9 150
313	3	*Carex*–moss	8.0	76.2	17 187	1 074	3 281	11 925
334	7	*Carex*–aquatic	24.6	76.9	68 000	1 735	4 381	20 100
351	7	*Carex*–aquatic	27.1	85.1	73 750	1 945	4 194	22 500
365	—	●rganic–mineral	53.2	69.2	1 992	2 820	6 250	24 000

the trenches. There may be individual *Picea mariana* present as low, wind-blasted krumholz.

The ice wedges in polygonal peat plateau bogs appear to be identical to the ice wedges that develop in mineral soil. Ice wedges form as thermal contraction cracks are filled with snow, hoarfrost, or water that later turns to ice (Leffingwell 1915). The cracking is caused by low temperatures and rapid cooling (Lachenbruch 1962), and can extend 3 m or more into the ground (Mackay 1974). The cracks cut through the vegetation mat with a sharp, clean cleavage. Examination of ice wedges in polygonal peat plateau bogs has shown that such sharp cuts extended through the peat and initiated the growth of ice wedges in them.

Peat stratigraphy shows that the peat was initially deposited in a non-permafrost environment, in bogs and fens. The macrofossils in a polygonal peat plateau bog in Yukon show a sequence from pond to marsh, then to fen and finally to bog (Ovenden 1982). The peat was later affected by permafrost, as in the peat plateau bogs. In northern areas where winter snowfall is low, or where wind removes much of the snow, the peat surface is subject to cracking by frost. Under such conditions ice wedges have developed, forming polygonal patterns.

A polygonal peat plateau bog at Tundra Lake, Northwest Territories (67°39′ N, 133°38′ W), was investigated. The peatland occupies the lowlands around a large lake and its surface is about 2 m above the level of the lake. The wave action of the lake is eroding the peat, exposing freshly cut banks. The sampling site is located 100 m from the lake where a short transect was run. The vegetation, surface morphology, and depth of thaw were noted along this transect and the peat was cored at three locations: at the centre of a polygon, on the shoulder, and in the middle of a polygon trough (Figure 3–7).

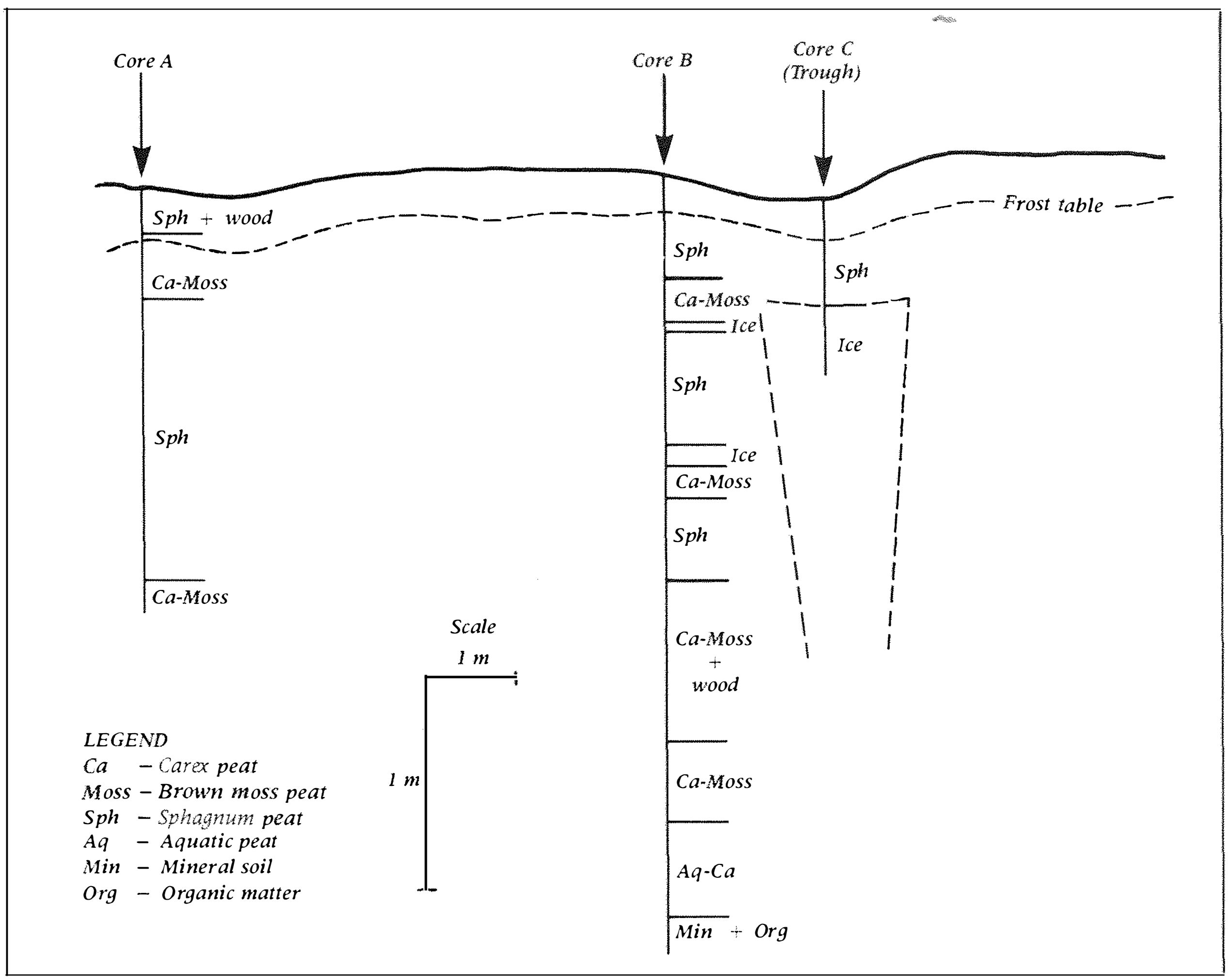


Figure 3–7.
Cross-section along a transect in a polygonal peat plateau bog near Tundra Lake, NWT.

Table 3–5. Total elemental analysis and other properties of peat from the centre of a polygonal peat plateau bog (A) and a polygon trough in a polygonal peat plateau bog (B)

Depth of sample (cm)	Decomposition (von Post)	Material	Ash (%)	H_2O by volume (%)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	S (mg/kg)
A—Centre								
28	4	*Carex*–moss	5.4	82.3	1 775	352	3 037	945
43	5	*Carex*–moss	8.1	83.8	1 185	131	767	325
53	5	*Carex*–moss	4.9	87.2	1 425	207	1 142	532
62	3	*Sphagnum*	1.3	88.2	1 787	335	910	560
76	3	*Sphagnum*	1.6	88.8	1 669	349	712	460
87	3	*Sphagnum*	1.4	94.3	1 875	387	496	414
97	3	*Sphagnum*	2.0	91.6	1 675	295	490	429
110	3	*Sphagnum*	2.5	91.9	1 800	272	525	537
123	4	*Sphagnum*	2.0	89.3	2 475	320	600	486
135	4	*Sphagnum*	2.4	95.7	2 406	310	1 031	667
149	4	*Sphagnum*	2.8	95.5	2 662	315	692	600
160	5	*Sphagnum*	4.5	91.0	5 400	500	1 265	720
170	5	*Sphagnum*	2.5	91.1	5 000	499	1 245	540
183	5	*Sphagnum*	3.3	95.6	5 062	455	1 519	675
196	5	*Carex*–moss	5.4	88.2	7 375	565	1 612	840
B—Trough								
18	2	*Sphagnum*	2.1	90.4	1 992	318	1 947	1 500
27	2	*Sphagnum*	1.9	90.7	1 960	256	1 412	1 331
39	3	*Sphagnum*	2.2	91.0	2 015	364	1 006	787
48	3	*Sphagnum*	1.9	92.9	1 815	432	900	520

Lichen covers about 95% of the surface and is composed of *Cetraria nivalis*, *Cetraria cucullata*, *Cladina mitis*, *Cladina alpestris*, *Cladina rangiferina*, and *Alectoria ochroleuca*. Low *Ledum decumbens* and *Rubus chamaemorus* are occasionally present in the troughs and on shoulders. *Sphagnum fuscum* is present in the troughs.

The peat was cored on the shoulder of a polygon down to the mineral soil, reaching permafrost at 23 cm. The surface material is fibric to mesic *Sphagnum* peat, mostly *Sphagnum fuscum* (Table 3–4). Two narrow (3 and 7 cm thick) ice lenses were encountered. Below this layer, fen peat materials occur over a layer of mixed organic–aquatic detritus and *Carex*. The core ends in a mixture of well-humified organic material and mineral soil.

The chemical analyses (Table 3–4) show that the *Sphagnum* peat is very low in nutrients, especially in Ca and Mg, to a depth of 160 cm. There is a sudden increase in most nutrients in the woody fen peat at 214 cm, while the peat between 160 and 214 cm shows intermediate nutrient levels. The Ca content reaches very high levels, especially in the aquatic detritus, but decreases sharply in the mineral soil. Sulphur (S) levels show a sudden increase in the fen peat (at 201 cm) and continue to increase steadily to high levels at the base. The moisture content of the peat does not show any excessively high levels.

In the polygon trough there is a 60 cm thick *Sphagnum fuscum* peat layer above clear ice (Table 3–5). The ice was penetrated for some 40 cm and then the hole was abandoned. This ice probably represented the ice wedge. The chemical analyses show low values of all nutrients, except for high amounts of sulphur at the surface.

At the centre of the polygon the surface consists of *Sphagnum fuscum* peat that contains twigs. Beneath this is mesic *Carex*–moss (*Drepanocladus*) peat (Table 3–5), which is underlain by *Sphagnum* peat, followed by *Carex*–moss (*Drepanocladus*) peat. The hole was abandoned at 204 cm.

The analyses (Table 3–5, centre) show that the nutrient levels are low until the *Carex*–moss fen peat is reached at 192 cm, where the Ca, Fe, and S levels show a substantial increase. The *Sphagnum* peat immediately above the fen peat (160–192 cm) has somewhat elevated Ca and Fe concentrations. The moisture content of the peat was generally similar to non-permafrost materials, but some excess ice was present in four samples where the water content was higher than 93% by volume. The peat from the trough shows low levels of Ca and Mg (Table 3–5, trough), but high amounts of Fe and S.

An examination of the peat materials shows that, initially, shallow lacustrine and marsh conditions prevailed at the site. These were replaced by an open sedge fen which was later invaded by shrubs, depositing woody sedge–moss peat. The fen was then replaced by a *Sphagnum* bog, depositing nearly 2 m of peat. Permafrost was probably formed in the peat at this time, elevating the peatland into a peat plateau. The development of polygons came later, as the ice wedges cut across both the bog and fen peat.

Palsa Bogs

Palsa bogs are mounds of peat with a permafrost core. They rise 1–7 m above the surrounding wetland and they have a diameter of less than 100 m (Zoltai and Tarnocai 1975). They occur as islands in very wet, unfrozen fens or ponds, or as peninsulas extending into these non-permafrost, wet areas (Figure 3–8). Palsa bogs can occur singly or in groups of several mounds of different sizes (Hamelin and Cailleux 1969). In some wetlands they may coalesce, forming contorted ridges and swales of peat, occupying several hundred hectares.

Small palsa bogs, apparently recently emerged, may occur in the same wetlands as large, deeply fissured peat mounds. Palsa bogs often deteriorate through the thawing of the permafrost core, especially when the core is exposed by cracking of the palsa surface. In such areas permafrost degradation can progress as a result of the collapse and subsidence of the palsa bogs beginning at the margins, and of the thawing of permafrost from below (Kershaw and Gill 1979). In the Subarctic, collapsing palsa bogs occur mainly where the surrounding wetland has become flooded. Aggrading permafrost is frequently encountered, forming a peat plateau margin around the palsa bog, isolating it from the unfrozen wetlands (Figure 3–9).

The internal structure of palsa bogs generally consists of a surface layer of *Sphagnum* peat up to 50 cm thick. The active layer is 30–50 cm thick. The *Sphagnum* cap is underlain by fen peat composed of sedge and brown moss remains. The basal peat may be humified organic matter or aquatic detritus. Permafrost extends well into the

Figure 3–8.
This 3.75 m high palsa bog occurs as a peninsula into a wet fen (foreground), Norman Wells, NWT.

Figure 3–9.
A 2 m high palsa occurring in the centre of a peat plateau bog, Peel River, YT.

mineral soil. Thin (up to 10 cm thick) ice lenses may be encountered in the frozen peat, but large ice accumulations are usually found at the peat–mineral soil interface, especially in the upper mineral soil. The peat in the palsa bogs, as in the peat plateau bogs, is not distorted by cryoturbation, implying that frost has penetrated into the peat from the surface downwards (Seppälä 1980).

The thickness of the peat in palsa bogs is variable. In the Subarctic an average of 267 cm (140–442 cm) has been reported (Zoltai and Tarnocai 1975), but there are also reports of very thin peat cover over palsa bogs: 7 cm in northern British Columbia (Seppälä 1980) and 8–18 cm in the Rocky Mountain foothills in Alberta (Brown 1980).

The vegetation of palsa bogs in the Subarctic resembles that of the peat plateau bogs as described earlier in this chapter. Lichens dominate the ground surface, composed mainly of *Cetraria nivalis, Cetraria cucullata, Cladina rangiferina, Cladina alpestris*, and *Cladina mitis*. Dwarf shrubs of *Ledum decumbens* and *Rubus chamaemorus* may cover up to 20% of the surface. There is a very open *Picea mariana* tree cover, composed of low (less than 5 m tall) trees.

A palsa bog at Eagle River, Yukon Territory (67°07′ N, 137°13′ W), was investigated in some detail. The palsa bog is situated at the edge of a large peat plateau bog, surrounded on three sides by a wet, unfrozen fen. A short transect was run from the fen, across the palsa bog to the peat plateau bog (Figure 3–10). The surface morphology was surveyed by levelling, and the depth of thaw and the vegetation were determined along the transect line.

Trees of low *Picea mariana* form a 5% cover, with an equally sparse shrub layer of *Betula glandulosa*. Dwarf shrubs cover about 70% of the surface, composed mainly of *Ledum decumbens* and some *Rubus chamaemorus* and *Vaccinium vitis-idaea*. Lichens (*Cladina mitis, Cladina alpestris, Cetraria nivalis*) cover about 35% of the surface.

The peat core at the summit of the palsa shows 12 cm of well-decomposed sylvic peat at the surface, made up of humified peat, roots, and needles. This is underlain by mesic *Sphagnum* peat to a depth of 72 cm (Table 3–6). The permafrost table was within this material at 47 cm. The *Sphagnum* layer is underlain by mesic moss peat (*Drepanocladus* sp.) and by peat composed of sedge and moss remains, including layers containing small twigs and wood chips. The mineral soil was reached at 285 cm. The basal peat below 256 cm and the mineral soil contain large amounts of excess ice, as shown by field observations and by the high amounts of volumetric moisture content of these samples. The dominant soil types associated with such palsa bogs are Mesic Organic Cryosols.

The chemical analyses (Table 3–6) show that the surface *Sphagnum* layer is low in nutrients, but the nutrient levels increase in the moss and sedge–moss layers. A sudden increase in all measured nutrient levels takes place at the 183 cm level and thereafter increases with depth.

A second core was taken near the edge of the palsa bog, 3 m from the unfrozen fen. The peat sequence is similar to that at the palsa bog summit (Table 3–7): a 10 cm surface layer of well-decomposed sylvic peat is underlain by a mesic *Sphagnum* peat layer to a depth of 44 cm. The permafrost table was encountered at 36 cm. A fibric moss peat, composed of *Drepanocladus* sp., and a mesic sedge–moss peat occur to a depth of 139 cm where the mineral soil was encountered. Both the peat below a depth of 116 cm and the underlying mineral soil contain large amounts of segregated ice.

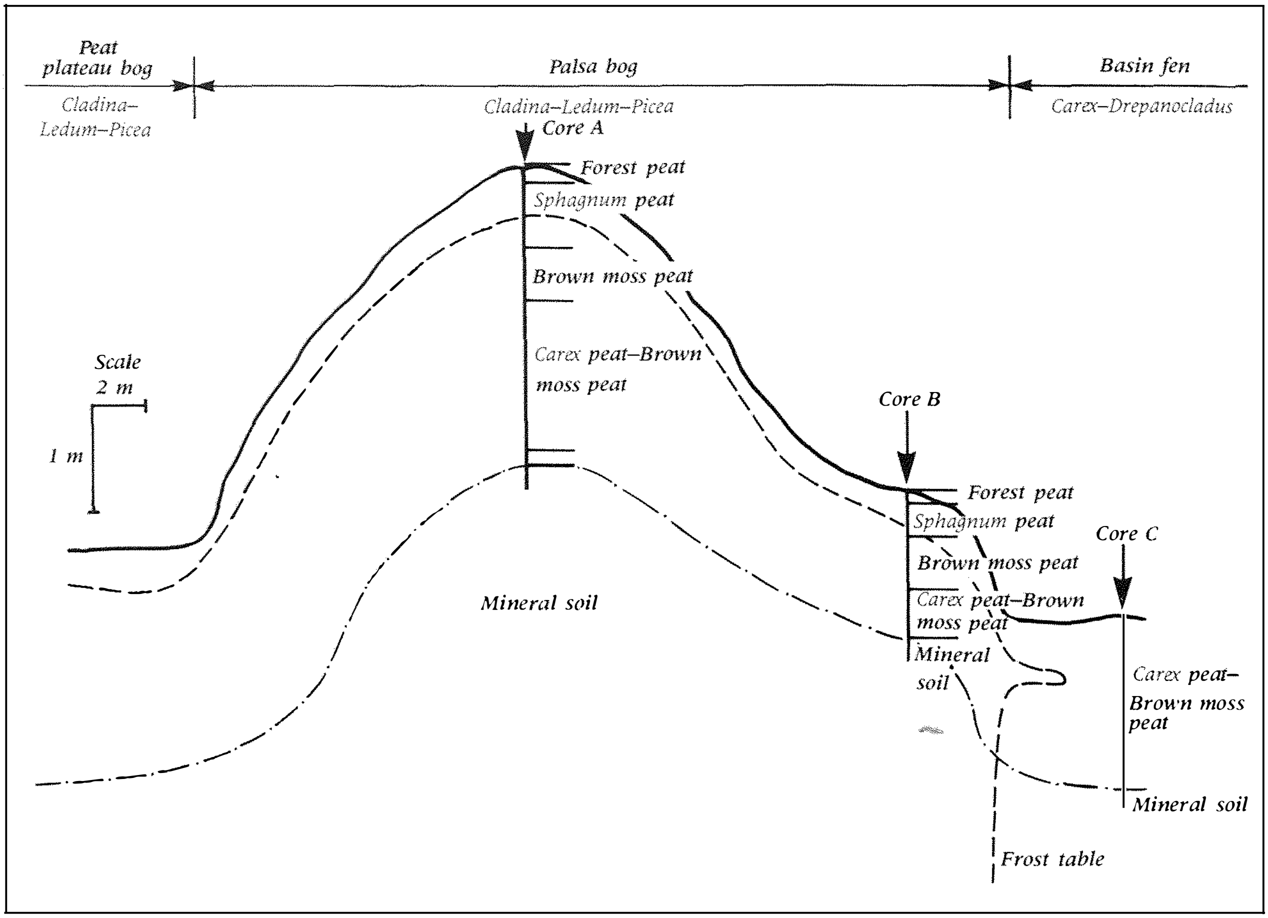


Figure 3–10.
Cross-section showing the internal structure of a palsa bog at Eagle River, YT.

The chemical analyses (Table 3–7) indicate that the surface *Sphagnum* peat is low in all measured nutrients. The nutrient levels, especially magnesium, increase in the moss layer and remain high throughout the rest of the peat profile. The volumetric moisture levels indicate that excess ice was present only in the basal peat and in the mineral soil.

The unfrozen fen was probed about 2.5 m from the edge of the palsa bog. The depth of peat was 163 cm and no permafrost was encountered.

The internal structure of the palsa bog is consistent with that of other permafrost peatlands: a thin *Sphagnum* peat cap covers peat that was deposited in a fen. The general sequence shows an initial deposition of peat in a fen dominated by sedge and moss species (*Drepanocladus*; possibly also *Campylium* sp., *Hypnum* sp.). The fen was later covered by *Sphagnum* spp., mainly *Sphagnum fuscum* or *Sphagnum balticum*. This initiated permafrost development by insulating the surface in the summer. The freezing of water in the peat elevated the surface of the peatland, creating better-drained conditions that effectively terminated *Sphagnum* growth. Lichens and dwarf shrubs became dominant, as shown by the surface sylvic peat. As the permafrost reached the mineral soil, excessive moisture penetrated into the peatland mainly along the peat–mineral soil interface from the fen that surrounds the palsa bog on three sides. As excess ice accumulated in the basal peat and in the mineral soil, the palsa bog was elevated some 3.5 m above the adjoining peat plateau bog and 4.25 m above the fen level.

Northern Ribbed Fens

These wetlands are characterized by low, narrow peat ridges that cut across the fens at right angles to the direction of water movement. The ridges (often called "strings") are spaced from five to several tens of metres apart, forming gentle arcs across the fens. The areas between these ridges are usually very poorly drained in contrast to the ridges, which are somewhat better drained. Although the gradient of the fens is almost always

Table 3–6. Total elemental analysis and other properties of peat from the centre of a palsa

Depth of sample (cm)	Decomposition (von Post)	Material	Ash (%)	H_2O by volume (%)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)
45	4	*Sphagnum*	5.4	58.7	4 646	259	3 423
61	4	*Sphagnum*	3.0	89.2	4 936	533	3 128
72	3	Moss	5.2	88.8	5 499	530	3 282
96	3	Moss	5.1	90.6	6 886	576	3 418
112	4	Moss	4.8	93.6	6 758	564	3 890
132	4	*Carex*–moss	5.5	83.4	7 118	530	3 877
146	5	*Carex*–moss	4.8	90.4	9 324	658	5 272
166	5	*Carex*–moss	5.8	91.0	9 675	639	5 443
183	5	*Carex*–moss	5.8	91.6	14 885	920	7 945
200	6	*Carex*–moss–wood	6.6	97.0	16 515	1 645	9 629
209	6	*Carex*–moss	8.1	92.5	15 942	970	9 437
219	7	*Carex*–moss–wood	12.4	88.9	16 505	1 132	10 001
248	7	*Carex*–moss–wood	10.6	85.9	19 436	1 033	11 541
255	7	*Carex*–moss	8.4	94.5	20 587	1 190	11 554
273	8	Humus–mineral soil	58.7	89.4	—	—	—
285	—	Mineral soil	83.1	74.0	—	—	—

Table 3–7. Total elemental analysis and other properties of peat from the margin of a palsa

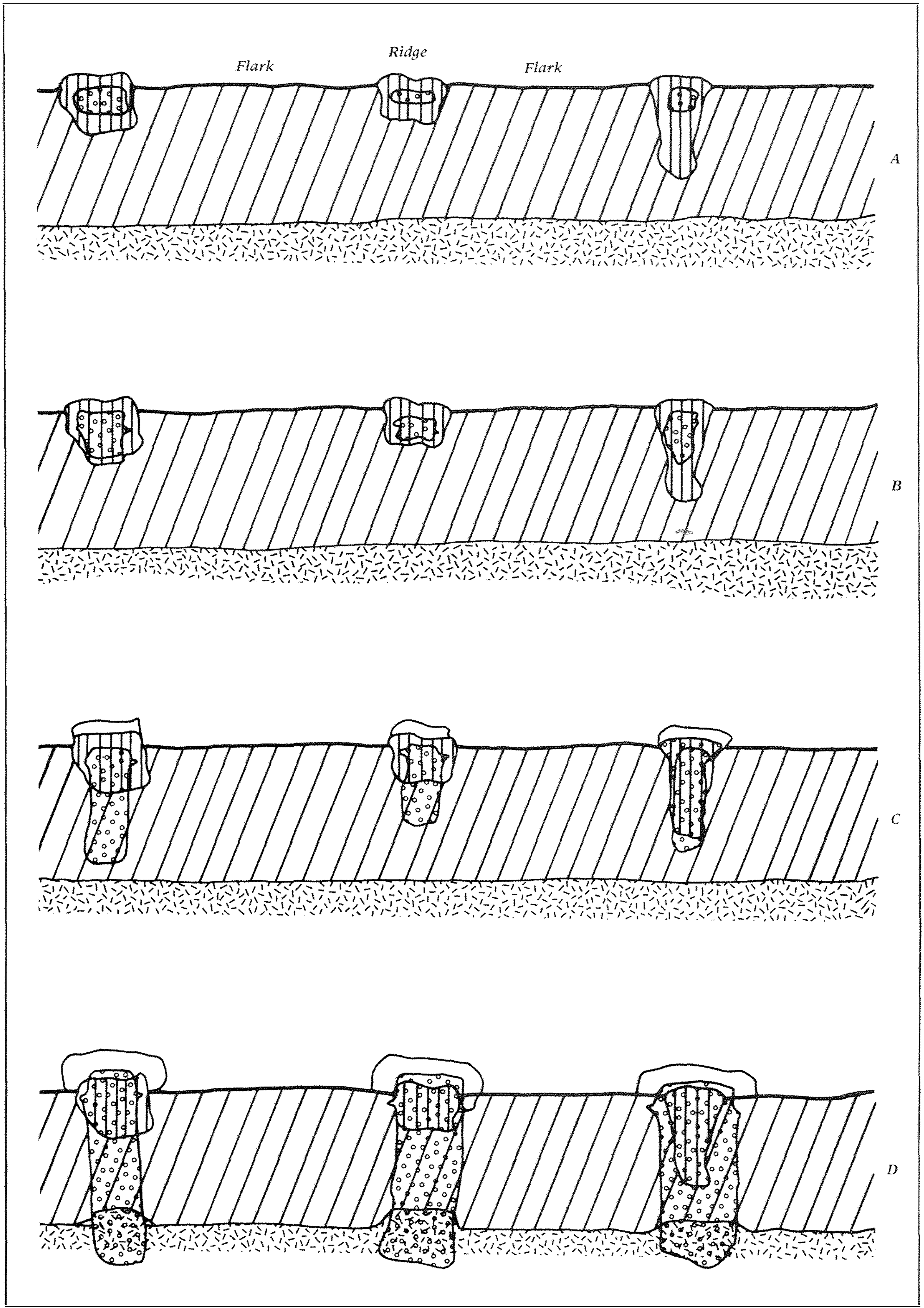
Depth of sample (cm)	Decomposition (von Post)	Material	Ash (%)	H_2O by volume (%)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)
39	3	*Sphagnum*	2.8	90.6	4 498	416	171
77	3	Moss	4.2	88.5	5 162	1 405	2 672
88	3	Moss	4.4	88.2	6 056	773	3 388
96	4	Moss	4.1	87.1	7 507	863	4 731
111	5	*Carex*–moss	6.0	92.8	9 780	885	5 693
120	5	*Carex*–moss	6.1	94.2	11 751	826	7 835
141	—	Mineral	92.4	78.8	—	—	—

less than 1°, the ridges appear to be more closely spaced in fens with higher gradients. Where the gradient is very low, the ridges are not only widely spaced but become more sinuous and interconnected in a net-like pattern. The height of the ridges varies between 10 and 30 cm, and reaches 70 cm or more if affected by permafrost. Northern ribbed fens are common in the Low Subarctic and High Boreal Wetland Regions. The main regional difference is that, in the Low Subarctic Wetland Region, permafrost is often present in the ridges, affecting their morphology and interfering with drainage.

The ridges consist of peat that is somewhat denser and is elevated above the peat in the intervening depressions; these are called "flarks" (Andersson and Hesselman 1907). The flarks may contain wet peat or shallow, peat-bottomed pools, depending on the hydrology of the fen. The ridges act as dams impeding the seepage of water, as shown by the generally wetter conditions on the upslope sides of the ridges. Careful levelling measurements reveal a slight (less than 10 cm) difference in the elevation of the surface of successive flarks.

The ridges present a somewhat drier environment than the main body of the fen. Being slightly higher and periodically drier, the peat acts as an insulator and in the subarctic wetland regions may eventually prevent the complete thawing of seasonal frost. As water is changed into ice, it expands by about 10% of its volume (Pounder 1965), further elevating the surface of the peat. This induces even drier surfaces with better insulating qualities, resulting in the acceleration of permafrost development. This in turn results in the development of small peat plateau bogs on the ridges.

A series of observations in the Low Subarctic Wetland Region revealed a sequence that begins with late-thawing seasonal frost and ends with peat plateau bogs that cover the entire fen (Figure 3–11). Late-thawing frost in the ridges persists long after the seasonal frost has thawed in the fen, but disappears by the end of the summer (Figure 3–11a). However, because frost is present during most of the summer, it impedes the surface


Ridge
Flark
Flark
A
B
C
D

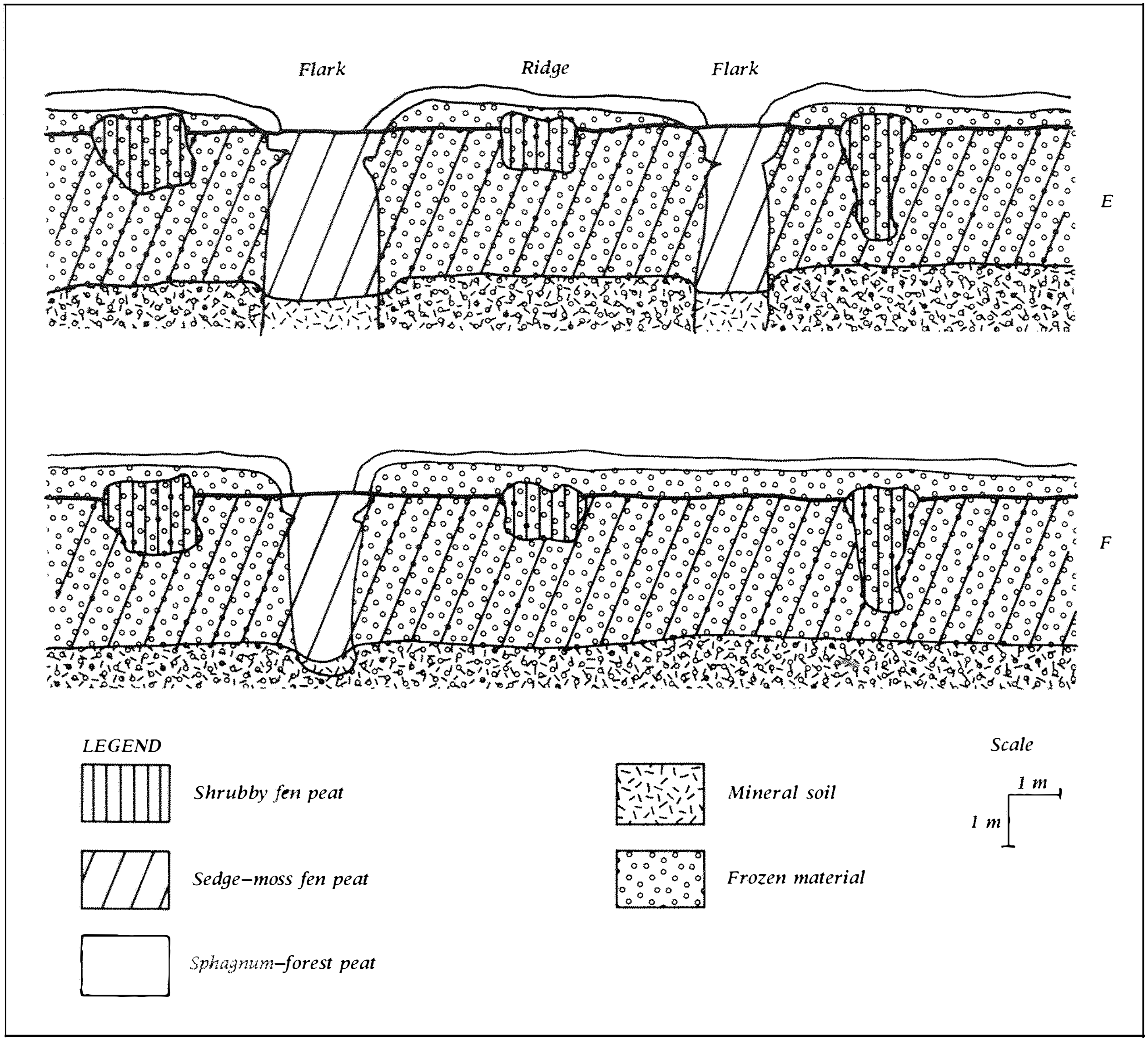


Figure 3–11.
Progress of permafrost development in a northern ribbed fen.
A – Persistent seasonal frost under ridges in mid-summer
B – Small permafrost lenses in peat
C – Large permafrost lenses in peat
D – Permafrost lenses reach mineral soil
E – Permafrost expands
F – Permafrost affects nearly all of the wetland

flow and near-surface water seepage in the fen. Persistent seasonal frost may lead to the establishment of permafrost, where frozen peat remains throughout the year in the upper portion of the ridges (Figure 3–11b); it eventually increases and extends downwards (Figure 3–11c). In many cases such permafrost cores develop first at the nodes where two or more ridges join (Figure 3–12). As the permafrost is blocking only the surface or near-surface water movements, water seepage through the fen is still possible. In time, however, the permafrost lenses may reach the mineral soil (Figure 3–11d), establishing a series of dams across the fen. Observations show that at this stage small creeks are formed on the surface of the fen and provide channels for water flow (Figure 3–13). Consequently, the water quality of the wetland changes, since mineralized water no longer reaches the surface of the wetland. The ridges begin to thicken as permafrost expands into the former flarks (Figure 3–11e). Eventually the flarks disappear, although small, wet depressions may mark their former location (Figure 3–11f). At this stage, permafrost is present under all but the wettest depressions, and the conversion of the patterned fen to a peat plateau bog is completed.

The vegetation of northern ribbed fens is influenced to a large extent by the degree of permafrost development. In those northern ribbed fens where no permafrost is present in the ridges, the vegetation of the flarks consists mainly of *Carex* spp. and *Eriophorum vaginatum*, with mosses such as *Drepanocladus* sp., *Scorpidium* sp. (depending on wetness and nutrient status), *Campylium* sp., and *Pohlia* sp. The ridges usually support shrub vegetation (*Betula glandulosa, Ledum groenlandicum, Chamaedaphne calyculata*) and mosses, such as *Sphagnum fuscum* and *Sphagnum magellanicum*.

In northern ribbed fens where permafrost is already present in the ridges but does not extend to the mineral soil, the vegetation of the flarks is dominated by *Carex* spp. and *Eriophorum vaginatum*. However, *Sphagnum* lawns, composed of *Sphagnum balticum* and *Sphagnum compactum*, may appear on the flark margins. The ridges, if well elevated, support a vegetation of *Ledum decumbens* and lichens (*Cladina mitis, Cladina rangiferina*). Lower ridges tend to have more shrubs (*Betula glandulosa, Kalmia polifolia*) and sedges. When permafrost blocks the drainage in the fen, the *Sphagnum* carpet and *Eriophorum vaginatum* content increase in the flarks. The vegetation of the broad ridges resembles that of peat plateau bogs: scattered *Picea mariana* and *Betula glandulosa* in a dominant lichen ground cover.

Northern ribbed fens in the Subarctic are identical to those in the High Boreal Wetland Region, except for a tendency to develop permafrost in the ridges. The origin of a ridge pattern in fens is subject to debate, as numerous theories have been advanced (Moore 1982). This subject is reviewed more fully in Chapter 4 on the wetlands of the boreal areas of Canada. The only theory that involves permafrost was advanced by Schenk

Figure 3–12.
Northern ribbed fen where permafrost has developed at some ridge nodes, marked by clumps of taller trees, Arctic Red River, NWT.

Figure 3–13.
Extensive permafrost development on former ridges blocked drainage through this fen; drainage now takes place through a series of small creeks, Rengleng River, NWT.

(1963) and was based on observations of permafrost in some ridges in northern Europe and North America. He believed that when a peat-covered permafrost area collapses as a result of thawing from below, the buckled and broken peat blocks form ribs and ditches. However, observations described here indicate that permafrost develops in already existing ridges and there is no evidence of massive collapse under the ribbed fens. Thus, these observations cast doubt on the sequence of events proposed by Schenk (1963).

A northern ribbed fen near Snake River, Yukon Territory (66°55′ N, 133°00′ W), was investigated in some detail. The fen is situated in a broad depression near a major watershed divide. The central part of the fen has a ribbed pattern, but peat plateau bogs occur near the margin of the fen. The ridges are narrow and uneven in height, ranging between 30 and 75 cm even on the same ridge. A short transect was run across two ridges and the intervening flark (Figure 3–14), chosen to intersect a high point on one ridge and the low point on

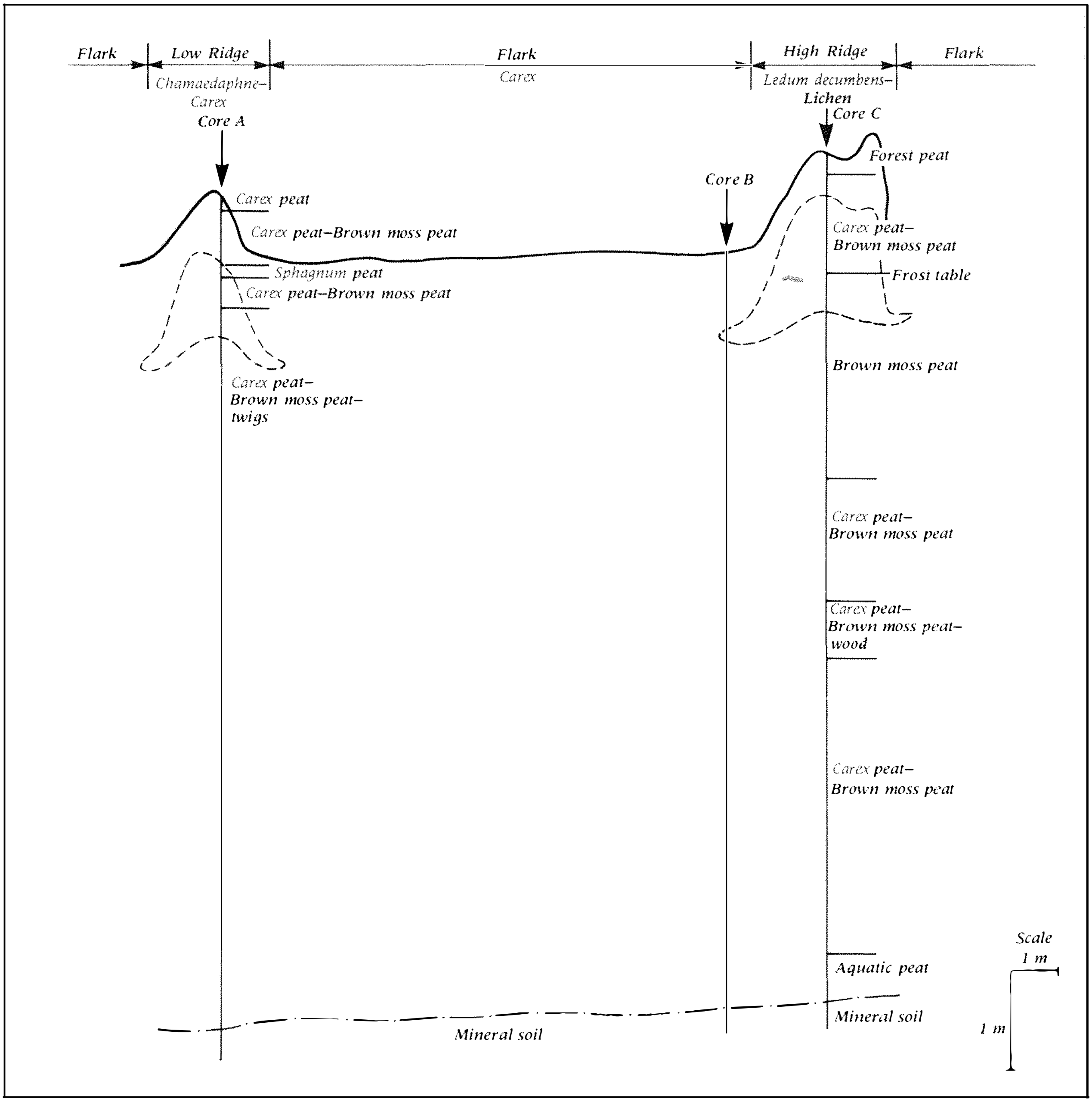


Figure 3–14.
Cross-section with three cores of a northern ribbed fen, with permafrost lenses under the ridges. Permafrost lenses are outlined with broken lines. Snake River, YT.

the neighbouring ridge. Vegetation, depth of thaw, and topography were measured along this transect.

The vegetation on the higher ridge consists of a few low *Picea mariana* trees, forming approximately 10% of the ground cover and associated with some *Ledum groenlandicum*. In the treeless parts, dwarf shrubs (*Ledum decumbens*, *Vaccinium vitis-idaea*, *Rubus chamaemorus*) form about 30% of the ground cover. In the moss layer *Sphagnum fuscum* is dominant, covering about 50% of the surface, and lichens are represented by small patches of *Cladonia sulphurina* and *Cladonia cornuta*. About 20% of the ground is bare of any vegetation.

On the low ridge there are a few *Betula glandulosa* shrubs (5% cover) and some low ericaceous shrubs. The main cover (75%) is provided by various *Carex* spp., but mosses (*Sphagnum warnstorfii*, *Sphagnum magellanicum*) are sparse. The flark is dominated by *Carex* spp. and *Eriophorum vaginatum*, along with *Drepanocladus* mosses.

On the higher ridge the surface layer (0–8 cm) consists of moderately decomposed forest peat made up of root, moss, and lichen remains. This is underlain by fibric woody *Sphagnum* peat (8–28 cm) and by mesic *Carex*–moss (*Drepanocladus*) peat (28–47 cm) (Table 3–8, high ridge). The top of the frost table was in this layer at 22 cm. The underlying peat is composed mainly of fibric *Drepanocladus* moss (47–146 cm), and the base of the frozen lens was reached at 65 cm. Beneath this layer is fibric to mesic *Carex*–moss peat which is underlain by detrital aquatic peat (336–356 cm). The mineral soil was reached at 356 cm.

The chemical analyses (Table 3–8, high ridge) show that the nutrient levels in the upper part of the section are low, generally consistent with nutrient values found in bogs and poor fens. Nutrient levels increase with depth in the unfrozen fen.

On the low ridge (Table 3–8, low ridge) the surface peat (0–8 cm) consists of fibrous *Carex* peat, under which is mesic *Carex*–moss peat (8–24 cm). The frost table occurred at the base of this layer. It is underlain by mesic *Sphagnum*–moss peat (24–36 cm) and by a fibric to mesic *Drepanocladus* and *Carex*–moss peat that contains small twig fragments. This is underlain by unfrozen peat to a depth of 357 cm.

Chemical analyses (Table 3–8, low ridge) show low concentrations of nutrients (especially calcium) in the top part of the section. Nutrient levels generally increase with increasing depth. The single sample from the seasonally frozen fen near the higher peat ridge (Table 3–8, fen) is also low in nutrients, falling within the range of poor fens (Sjörs 1950).

The low levels of nutrients in the top layers of both ridges indicate that they are elevated above the influence of fen waters. Nutrient levels are low

Table 3–8. Total elemental analysis and other properties of peat from three locations on a northern ribbed fen

Depth of sample (cm)	Frozen (F) or non-frozen (NF)	Decomposition (von Post)	Material	Ash (%)	H_2O by volume (%)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)
A—High peat ridge								
29	F	5	*Carex*–moss	5.2	85.6	—	—	—
50	F	3	Moss	4.7	88.5	3 548	234	2 412
62	F	3	Moss	6.0	84.4	3 797	271	1 862
117	NF	3	Moss	8.3	87.7	4 583	286	4 557
135	NF	5	Moss	10.3	83.0	6 216	350	5 448
160	NF	3	*Carex*–moss	6.0	87.0	5 960	340	5 516
173	NF	3	*Carex*–moss	5.0	90.4	6 911	394	6 568
208	NF	6	*Carex*–moss–twiglets	10.4	84.9	9 720	486	8 159
258	NF	4	*Carex*–moss	9.3	91.1	10 124	524	10 033
300	NF	4	*Carex*–moss	12.8	86.9	11 327	534	9 101
345	NF	—	Aquatic detritus	72.2	75.8	—	—	—
358	NF	—	Mineral soil	46.0	93.1	—	—	—
B—Low peat ridge								
27	F	4	*Sphagnum*	4.2	87.5	3 585	350	2 028
49	F	3	Moss	5.6	94.2	4 548	391	3 599
59	F	5	*Carex*–moss–twiglets	6.1	88.5	5 967	376	3 256
C—Seasonally frozen fen								
31	F	3	Moss	7.1	91.5	4 892	367	2 667

even in the fen, indicating that the fen, located near a watershed divide, does not receive large amounts of nutrients from its surroundings.

Thin frozen lenses were encountered under both peat ridges. The time of sampling (mid-August) suggests that these may not thaw completely during the summer and therefore could persist as thin, incipient permafrost bodies.

The peat sections in the ridges show the presence of a shrub fen (*Carex*–moss–small twig peat), indicating a somewhat drier habitat than that in the flark. This may mark the initial formation of the ridges. Under the present conditions in this area, however, permafrost is not expected to occur in shrub fens. Thus the incipient permafrost lenses began to form relatively recently, after the ridges were elevated above the fen level.

Channel Fens

These minerotrophic wetland forms have a generally flat and featureless surface that slopes gently in the direction of drainage. They are confined to narrow, well-defined channels formed by mineral soil uplands, bedrock, or frozen organic landforms. The vegetation is usually uniform, with herbaceous, shrub, and tree species characteristic of nutrient-rich sites fed by minerotrophic waters from the surrounding mineral terrain and from headwater sources. The underlying peat deposit is moderately to well decomposed and ranges in thickness from 40 cm to an average of over 3 m. This wetland form occurs throughout the Subarctic in areas of suitable physiography.

In the Low Subarctic Wetland Region many channel fens occur in complex association with peat plateau and palsa bogs affected by permafrost. The fens are unfrozen and are characterized by flat relief resulting in predominantly poor surface drainage. The associated peat plateau and palsa bog landforms provide local relief within the fens and modify the surface drainage patterns. The boundary between an unfrozen fen and adjacent peat plateau bogs or uplands is strikingly abrupt (Figure 3–15). In the Continental High Subarctic Wetland Subregion the peat in channel fens is often affected by permafrost, without elevating them to peat plateau bogs, and is usually less than 2 m thick.

The structure and composition of the vegetation cover reflect the drainage conditions in the fen: open, stunted forest with poor drainage changes

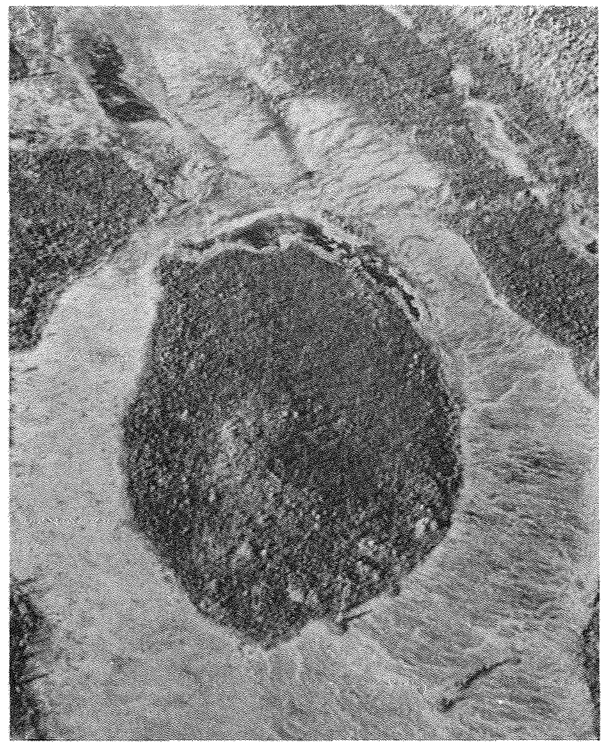


Figure 3–15.
A channel fen with a peaty "island", showing some ridge development, Hume River, NWT.

to fen species growing under the wettest conditions. Treed fens are characterized by an open-canopied forest in which *Larix laricina* is the most common species. Shrubs, usually *Betula glandulosa* (*Betula pumila* in the east), may dominate portions of the fen. In the Continental High Subarctic Wetland Subregion most channel fens are dominated by sedges, and shrubs and trees are usually absent. Shrubs (*Betula glandulosa*) may occur along the margins of the channels where drainage is slightly better.

Open fens with no trees and few shrubs may occupy large portions of the area, usually in association with small pools of water (Sims *et al.* 1982). The dominant vegetation consists of graminoid species (*Scirpus hudsonianus, Scheuchzeria palustris, Rhynchospora alba, Carex limosa*). A few shrubs (*Salix pedicellaris, Myrica gale, Betula pumila*) may be present but are not dominant. They are usually associated with small moss cushions of *Sphagnum fuscum, Tomenthypnum nitens,* and *Pleurozium schreberi.*

The surface 30–60 cm of the peat is usually fibric and scarcely decomposed, consisting of mosses and root masses. This is underlain by moderately to well decomposed peat in which wood chips from trees and shrubs may be present. The basal peat deposits are usually well decomposed. These soils are predominantly Fibric Mesisols.

The waters affecting these fens have been in contact with the mineral soil and have been enriched by the nutrients leached from them. In the James Bay Lowland the pH value of water in graminoid, shrubby, and treed fens averaged between 6 and 6.6. The conductivity averaged 0.091–0.200 mS/cm and the calcium content averaged 16.5–21.9 mg/L (Sims *et al.* 1982).

A treed channel fen in the Hudson Bay Lowland near Pennycutaway River, Manitoba (56°39′ N, 93°03′ W), was investigated in some detail. The fen occupies a relatively narrow (0.3–0.8 km wide) drainage-way extending for some 9 km across the extensive level to depressional landscape of the Lowland, which was formerly affected by marine submergence. The shape of the wetland is largely determined by the peat plateau complexes along the sides of the drainage-way.

The vegetation and peat stratigraphy was examined about 50 m from the edge of the channel fen in the upper reaches of the drainage-way. The treed portion of the fen has a sparse cover of low (3–6 m) *Larix laricina*. Shrubs provide a nearly closed ground cover, dominated by *Betula glandulosa* and *Andromeda polifolia*. The herb layer is composed of *Carex limosa*. A nearly complete moss cover is composed of *Sphagnum warnstorfii* in low ridges and cushions.

Tree cover is absent in more poorly drained areas where the shrubs *Betula glandulosa* and *Andromeda polifolia* are dominant. The herb layer consists mainly of *Carex limosa*, with the common occurrence of *Menyanthes trifoliata*. The moss layer in these wetter sites is dominated by *Aulacomnium palustre* and *Drepanocladus* spp.

The peat thickness was 185 cm, with the water table varying from the surface to 15 cm. The core shows that the surface 45 cm consists of *Sphagnum* peat, grading into mixed *Sphagnum* and sedge peat typical of peat formed under wet, forested conditions. The scarcity of woody inclusions reflects the open and poor quality of the forest cover. Beneath this layer is more decomposed fen peat composed of *Carex* spp., *Drepanocladus* spp., and occasional small twigs (45–120 cm). This is underlain by a mixture of sedge and moss peat grading into a thin layer of well-decomposed peat above the mineral soil. The most common soils associated with channel fens are Typic Mesisols and sphagnic phases of Mesisols.

The chemical analyses (Table 3–9) show that nutrient levels, especially calcium, are high throughout the peat section and increase with depth. The low pH in the upper part of the peat section may reflect a reduced minerotrophy due to the development of permafrost in the headwater area and in the surrounding organic terrain, restricting contact between groundwater and mineral soil.

The stratigraphic sequence observed in the core samples suggests that the wetland was initially a shallow marsh that later became a fen. This was superseded by a shrubby fen with scattered coniferous trees, a wetland that persisted for a long time. During the later stages the *Sphagnum* layer and the tree component increased to form the treed fen that exists at present. Downslope portions of this wetland still have shrub fens and fens with open pools of water, present-day analogues to the suggested early stages at the core site.

Veneer Bogs and Collapse Scar Fens

Veneer bogs are characterized by thin, peaty surface layers on a gently sloping terrain, and by the patchy occurrence of permafrost. The peat varies

Table 3–9. Chemical and physical properties of peat from a horizontal fen

Sampled layer (cm)	pH ($CaCl_2$)	Fibre content (%)		Material	Ash (%)	Organic C (%)	Total N (%)	Exchangeable cations* (me/100 g)				
		Rubbed	Unrubbed					Ca	Mg	Na	K	H
0–45	4.9	56	64	*Sphagnum magellanicum–Carex*	5.0	56.8	2.4	45.9	9.6	1.0	0.6	60.9
45–120	5.0	24	52	Feathermoss–*Sphagnum–Carex*	5.0	57.9	2.6	59.1	11.1	2.6	0.1	59.0
120–185	5.8	20	36	*Carex–Drepanocladus*	7.0	57.3	2.4	86.4	7.6	4.9	0.1	52.5
185+	7.6	—	—	Mineral (silty loam)	—	0.8	—	—	—	—	—	—

*Ammonium acetate extractable bases.

in thickness from about 0.3 to 1.5 m, with the depth of peat usually increasing towards the lower slopes of the bog. Veneer bogs are common on lower and mid-slope positions of gently sloping terrain throughout the northern part of the High Boreal Wetland Region and the southern part of the Low Subarctic Wetland Region. When viewed from the air, these slopes are characterized by distinctive patterns of parallel lineations. These lineations or "runnels" vary in spacing, but they are always oriented downslope, suggesting drainage patterns (Zoltai and Pettapiece 1973). Although the topography associated with runnels is often poorly expressed, differences in vegetation between the runnel and interrunnel areas help to locate them on the ground (Figure 3–16). The border of each runnel is marked by taller trees (up to 10 m high), compared with tree heights of 3–7 m between runnels (Mills *et al.* 1978). In addition, species variety in the vegetation is much greater in the runnels. Mixtures of *Picea mariana*, *Larix laricina*, and occasional *Betula papyrifera* occur with shrubs (*Betula glandulosa*, *Alnus rugosa* or *Alnus crispa*, and *Salix* spp.), sedges, and some mosses. In the boreal wetland regions, small upland shrubs and herbs, such as *Cornus canadensis* and *Fragaria vesca*, also occur. The enhanced tree growth and rich assemblage of minor species along the runnels reflect the flow of drainage waters, which create swamp-like conditions.

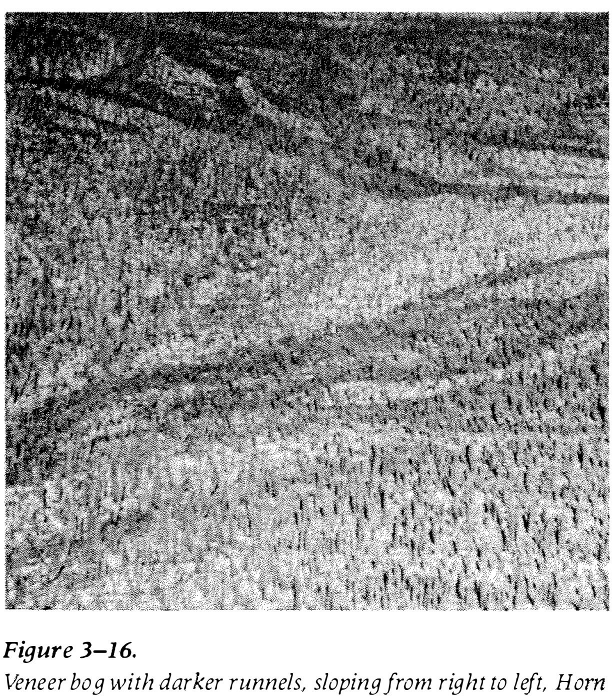


Figure 3–16.
Veneer bog with darker runnels, sloping from right to left, Horn Plateau, NWT.

In the boreal wetland regions the areas between runnels are characterized, depending on the thickness of the peat, by forest cover typical of poorly drained organic soils developed from forest or *Sphagnum* peat and imperfectly drained mineral soils. Therefore, the forest cover varies from patchy, closed stands of black spruce to fairly open forests of black spruce. In the Low Subarctic Wetland Region, the forest cover primarily consists of open stands of stunted black spruce regardless of the depth of peat. The shrub layer consists predominantly of *Ledum groenlandicum* (*Ledum decumbens* in the Subarctic), with lesser amounts of *Chamaedaphne calyculata*, *Rubus chamaemorus*, and shrub-sized *Picea mariana*. Other low shrubs and herbs include *Vaccinium myrtilloides*, *Vaccinium vitis-idaea*, *Oxycoccus microcarpus*, *Eriophorum* spp., and *Carex* spp. The shrub layer is sparse or absent in the more densely treed areas. Ground cover consists of feathermosses, such as *Pleurozium schreberi* and *Hylocomium splendens*, interspersed with large hummocks of *Sphagnum fuscum*. Lichens (mainly *Cladina* spp.) occur in patches on locally drier feathermoss sites. The lichen ground cover is more abundant in the subarctic wetland regions where the tree cover is much more sparse.

The permafrost in veneer bogs is discontinuous; its occurrence is more widespread in the subarctic than in the boreal wetland regions. Variations in active layer thickness range from 60 cm to more than 150 cm, but the variations decrease in the subarctic and northern portions of the boreal wetland regions.

Veneer bogs are often the dominant wetland component in gently undulating, rolling, or ridged terrain and may extend continuously over areas of several square kilometres. The boundaries of veneer bogs are not well defined, merging gradually to well-drained uplands along the upper slopes and to fens or peat plateau complexes along the lower slopes.

A veneer bog with collapse scar fens (Figure 3–17) near Thompson, Manitoba (55°55′ N, 97°43′ W), was studied in detail (Mills *et al.* 1985). It occupies the very gently sloping middle and lower north-facing slopes on a lacustrine clay deposit. Several transects were made downslope across the veneer bog, and topography, vegetation, soil types, thickness of peat veneer, and depth to permafrost table were noted.

The elevation difference of the bog surface is 2.5 m over a distance of 175 m from the upland to

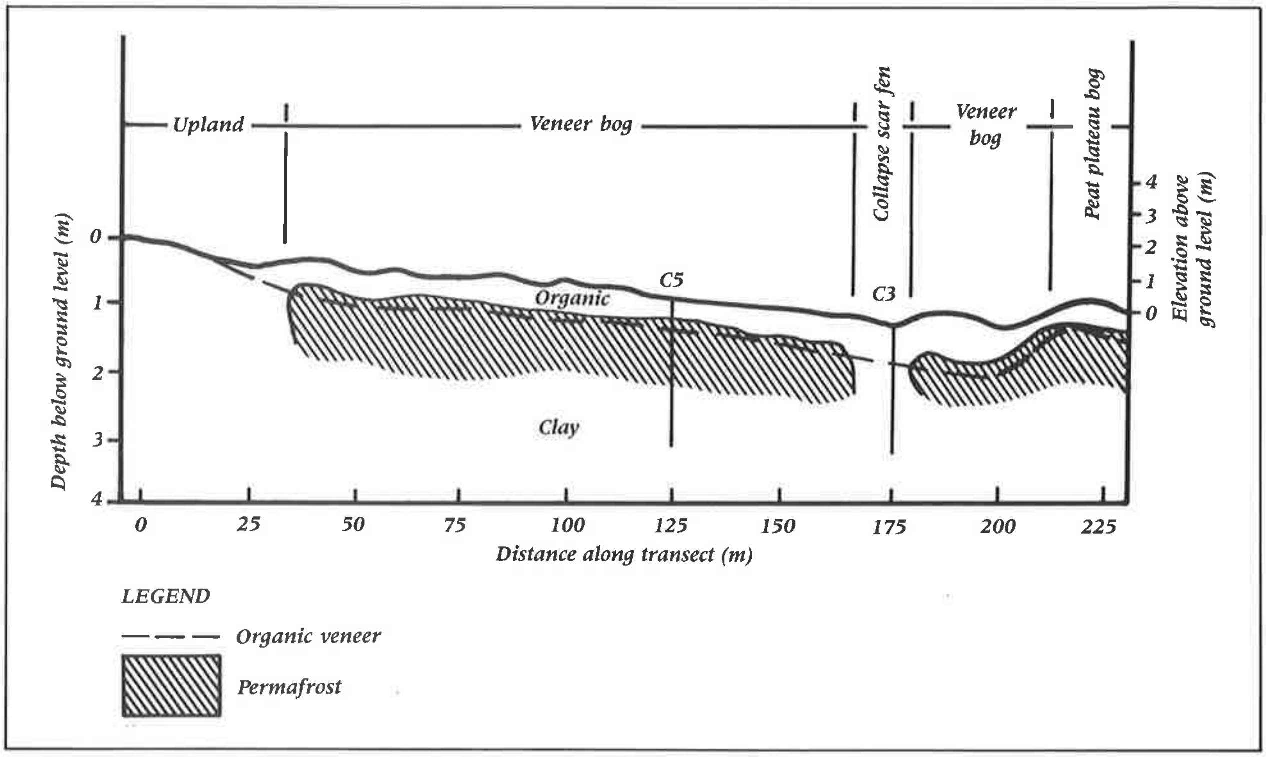


Figure 3–17.
Cross-section of a veneer bog on a gently sloping, deep lacustrine clay deposit near Thompson, Manitoba.

a peat plateau bog at the toe of the slope. The surface of the bog is microhummocky with gently sloping drainage-ways and level to depressional collapse areas.

The veneer bog is treed with unevenly aged black spruce forest typical of northern portions of the boreal wetland regions. The trees cover about 40% of the surface, growing in fairly open stands with frequent small openings. The trees vary from 3 to 5 m in height, with shrub-sized spruce (less than 1 m high) growing in association with *Ledum groenlandicum* and *Vaccinium myrtilloides* in open areas. A herb layer consisting of species such as *Vaccinium vitis-idaea* and *Rubus chamaemorus* is common in openings. Under more dense spruce the feathermosses *Pleurozium schreberi* and *Hylocomium splendens* form a hummocky surface. Lichens (*Cladina* spp.) occupy the apices of drier hummocks. *Sphagnum* spp. form both carpets and hummocks or cushions in association with mixed feathermosses and cover about 75% of the surface in broad drainage-ways and wetter depressions.

The bog is characterized by shallow Organic Cryosols associated with Brunisolic Static Cryosols and Gleyed Brunisols where the organic veneer is thin. Permafrost usually occurs within 2 m of the surface, but runnels may have a deeper active layer or permafrost may be lacking. Collapse scar fen areas occur in the veneer bog where the permafrost has thawed; the soils there are Terric Fibrisol or Rego Gleysols (peaty phase).

The organic layer on the veneer bog varies from 27 to 70 cm in thickness and averages 46 cm. Two sites were cored and sampled in detail (C5 and C3 in Figure 3–17). Site C5 is located at approximately the mid-point in the veneer bog and is characterized by an organic layer 72 cm thick. It is composed of 58 cm of fibric *Sphagnum* peat underlain by 12 cm of humic sedge–reed peat with woody inclusions. The underlying mineral soil is clay with a weakly developed Bm horizon occurring above the frost table. The active layer ranged from 85 to 120 cm thick at the time of sampling and the thickness of organic veneer varied from 30 to 75 cm. The soil is classified as a Terric Fibric Organic Cryosol.

The upper 30 cm of the peat is low in available nutrients and extremely acid (Table 3–10). Nutrient levels increase slightly in the next layer and are highest in the humified basal layer. These analyses indicate that the living moss vegetation is largely dependent on rainfall for nutrients, but some of the deeper-rooted vegetation on the bog may obtain nutrients from the well-decomposed peat and the upper layers of the mineral soil.

Site C3 (Figure 3–17) was cored in a small, irregularly shaped collapse scar fen ranging in diameter from 25 to 75 m and located 50 m downslope from site C5. This collapse scar fen is on the lower slope of the veneer bog and hence receives both surface runoff and seepage from the upper slopes of the bog. The collapse scar fen is very poorly drained and treeless. In the centre the dominant vegetation is *Carex* spp. and *Drepanocladus* spp. The slightly better-drained edges of the collapse scar fen also support low shrubs, such as *Salix* spp., *Chamaedaphne calyculata, Betula glandulosa, Vaccinium myrtilloides*, and a few scattered shrub-sized *Picea mariana*. The ground cover under the shrubs consists of *Carex* spp. and *Drepanocladus* spp., with patches of *Sphagnum* spp. and feathermosses.

The peat thickness at this site was 55 cm. The peat sequence indicates a relatively uniform accumulation of fibric *Carex–Drepanocladus* peat. This shallow organic soil is classified as a Terric Fibrisol. The chemical analyses (Table 3–10) show that the nutrient levels of the peat are very similar to those from the treed portion of the veneer bog, differing mainly in pH and exchangeable hydrogen (H) concentration. The surface peat of the treed portions of the veneer bog is thus not as strongly influenced by groundwater as that in the collapse scar fen.

The thickness of the active layer at the same locations across the veneer bog varied between 60 and 150 cm over a five-year period. Such fluctuation in the depth of the active layer from year to year and from site to site is an indication of the condition of fragile equilibrium in which frost persists in these wetlands. Indications are that particular sequences of weather conditions can increase or decrease the extent of permafrost and the thickness of the active layer. Warm summers, cold winters, lack of snow, or unusually thick snow can induce substantial annual variations. Fire in dry seasons may completely remove the organic veneer, usually resulting in the complete degradation of the permafrost.

The drainage of the veneer bog also influences wetland development and the distribution of permafrost. The morphology of the runnels indicates that they serve as runoff channels which carry the largest amounts of water in the spring and seepage flow during the rest of the thermal season as the seasonal frost melts. Probings show that the active layer is deeper or that the permafrost is absent under the runnels and seepage channels, whereas in the better-drained portions (between runnels or under slightly raised ridges along the sides of runnels) the depth of annual thaw is usually less. The channeling of most runoff waters improves the surface drainage in the interrunnel areas and results in the persistence of permafrost on the veneer bog.

Table 3–10. Chemical and physical properties of soils from two sites in a veneer bog

Soil horizon	Sampled layer (cm)	pH ($CaCl_2$)	Fibre content (%)		Material	Ash (%)	Organic C (%)	Total N (%)	Exchangeable cations* (me/100 g)				
			Rubbed	Unrubbed					Ca	Mg	Na	K	H
A—Veneer bog													
Of1	0–30	3.6	86	96	*Sphagnum*	6.2	56.5	0.7	24.9	8.8	3.4	3.9	79.6
Of2	30–58	5.2	64	88	*Sphagnum*	7.6	56.3	1.1	64.5	15.1	0.7	1.5	49.1
Oh	58–70	5.6	8	16	*Carex*–wood	50.4	27.7	1.0	74.9	18.0	2.9	1.3	41.4
Ah	70–73	5.9	—	—	Silty loam	—	7.4	0.3	31.0	6.9	0.2	0.5	12.6
AB	73–80	6.0	—	—	Clay	—	2.5	—	21.8	6.0	0.2	0.6	6.7
Bm	80–95	7.3	—	—	Clay	—	0.5	—	22.9	5.1	0.2	0.6	4.1
BC	95–115	7.5	—	—	Clay	—	0.4	—	31.8	1.6	0.2	0.6	—
Ck**	115–120	7.5	—	—	Clay	—	—	—	32.2	4.7	0.2	0.7	—
Ckz	120–150	7.5	—	—	Clay	—	—	—	33.2	5.4	0.2	0.7	—
B—Collapse scar fen													
Of1	0–30	5.3	—	78	*Carex–Drepanocladus*	13.8	50.8	1.6	20.4	9.0	0.4	2.5	47.4
Of2	30–55	5.1	—	76	*Carex–Drepanocladus*	19.9	48.2	1.3	30.3	10.8	1.6	1.3	54.4
Ahg	55–70	5.1	—	—	Silty clay	—	11.3	0.4	29.1	3.1	1.3	0.1	35.1
ACg	70–80	5.3	—	—	Clay	—	4.7	0.2	21.3	1.0	0.4	0.3	15.6
Cg1	80–100	5.5	—	—	Clay	—	—	—	17.2	0.3	0.2	0.3	9.0
Cg2	100–150	6.2	—	—	Clay	—	—	—	19.2	7.5	0.1	0.6	7.5
Ckg1	150–200	7.3	—	—	Clay	—	—	—	31.8	6.8	0.1	0.5	—

*Ammonium acetate extractable bases.
**Frost table at 120 cm.

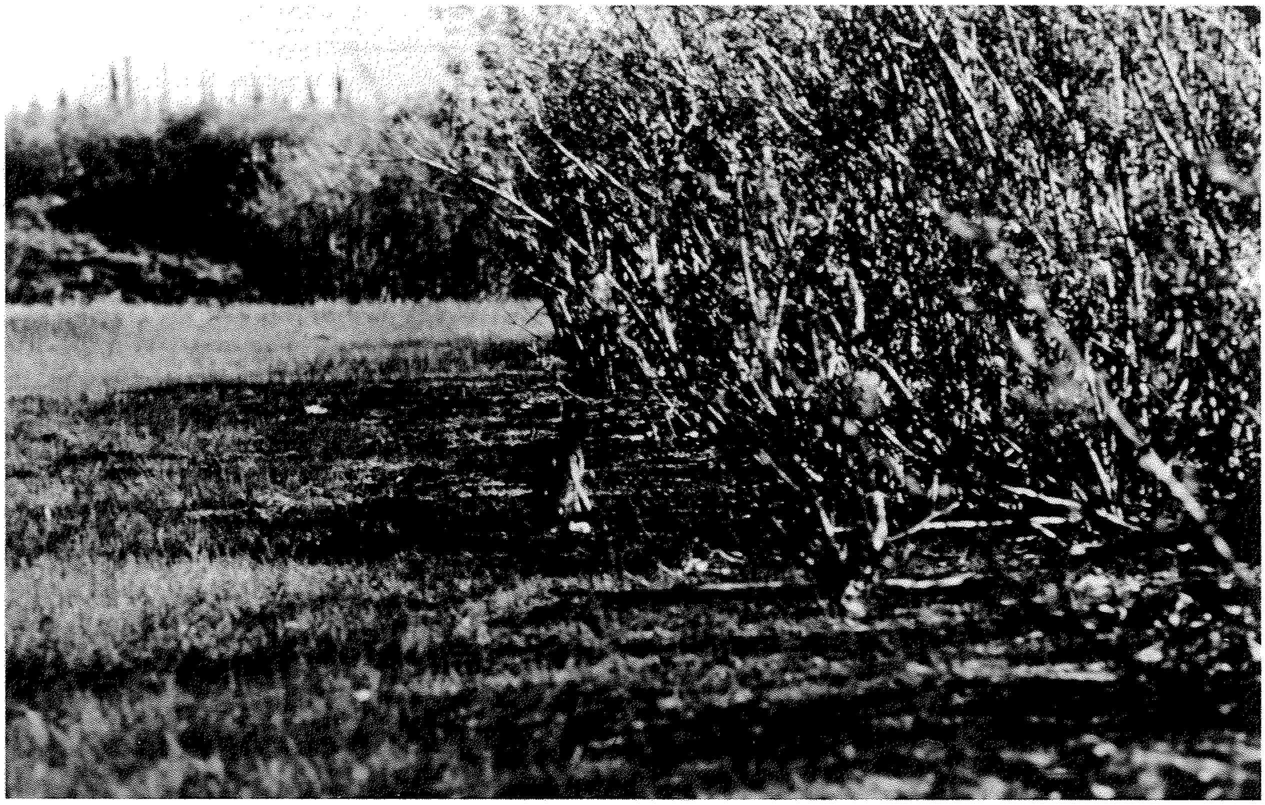


Figure 3–18.
Abrupt boundary between floodplain marsh (left) and floodplain swamp (right), Mackenzie Delta, NWT.

Peat stratigraphy, vegetation, drainage, and permafrost relationships associated with veneer bogs indicate a possible path of development. Peat macrofossils from the lower slopes of the veneer bog show that this portion of the bog probably evolved from a wet moss–sedge–shrub meadow, developing gradually into a *Sphagnum*–feathermoss–black spruce forest. On the moderately well-drained mid-slope positions, upland forests dominated by *Pinus banksiana*, *Picea glauca*, and *Populus tremuloides* developed on Brunisolic soils. However, such slopes were gradually paludified as spruce forest, dominated by a mixed moss ground cover, advanced up the slope. In the subarctic wetland regions the open black spruce–lichen forest growing on mid-slope positions was gradually altered as mosses became more prevalent through the encroachment of the mixed moss cover.

As the peaty surface advanced up the slopes, it retained much of the moisture falling on the area and also intercepted much of the runoff from upslope positions. Expansion of the peat veneer combined with the insulation provided by the peat and the shade provided by the associated forest to initiate permafrost development. The distribution of permafrost was initially sporadic, but it became more widespread as the peat veneer advanced and peat depths increased.

Floodplain Marshes and Swamps

Most larger rivers have an active floodplain that becomes flooded during high-water stages in the spring. A distinctive vegetation zonation occurs, reflecting the ground surface levels below flood levels, the duration of flooding, and the frequency of flooding (Gill 1971). In the Mackenzie Delta, the vegetation zone nearest the river channel consists of an *Equisetum* community, followed by *Salix*–*Equisetum*, *Populus*, decadent *Populus*, and finally by *Picea* communities farthest from the river (Gill 1973). Of these communities the *Equisetum* community is a marsh, as it is annually submerged for a long period (Figure 3–18). The somewhat less frequently flooded *Salix–Equisetum* community represents a floodplain swamp, but the treed communities (*Populus* sp., *Picea* sp.), which are flooded very infrequently, have a water table below the rooting zone and are not wetlands. A similar zonation is found along some of the floodplains associated with the Big Spruce and Seal rivers in northern Manitoba (Ritchie 1959).

In the floodplain marsh the dominant vegetation consists of *Equisetum fluviatile* with some *Salix alaxensis* and the moss *Leptobryum pyriforme* (Gill 1971, 1973). The soil shows no profile development and is classed as a Rego Gleysol (Veldhuis 1980). In the summer the water table is slightly above the water level in the nearby river channel. Permafrost is usually absent (Figure 3–19) (Heginbottom and Tarnocai 1983).

(Veldhuis 1980). A Gleyed Cumulic Regosol underlies the leading edge of the willows in a strip parallel to the channel. In this area the accumulation of drifted snow is usually the deepest and its insulating effect the strongest, possibly preventing the formation of permafrost. The soil in the remainder of the willow zone is a Gleyed Cumulic Regosol, cryic phase, and contains permafrost at a depth of about 100–120 cm.

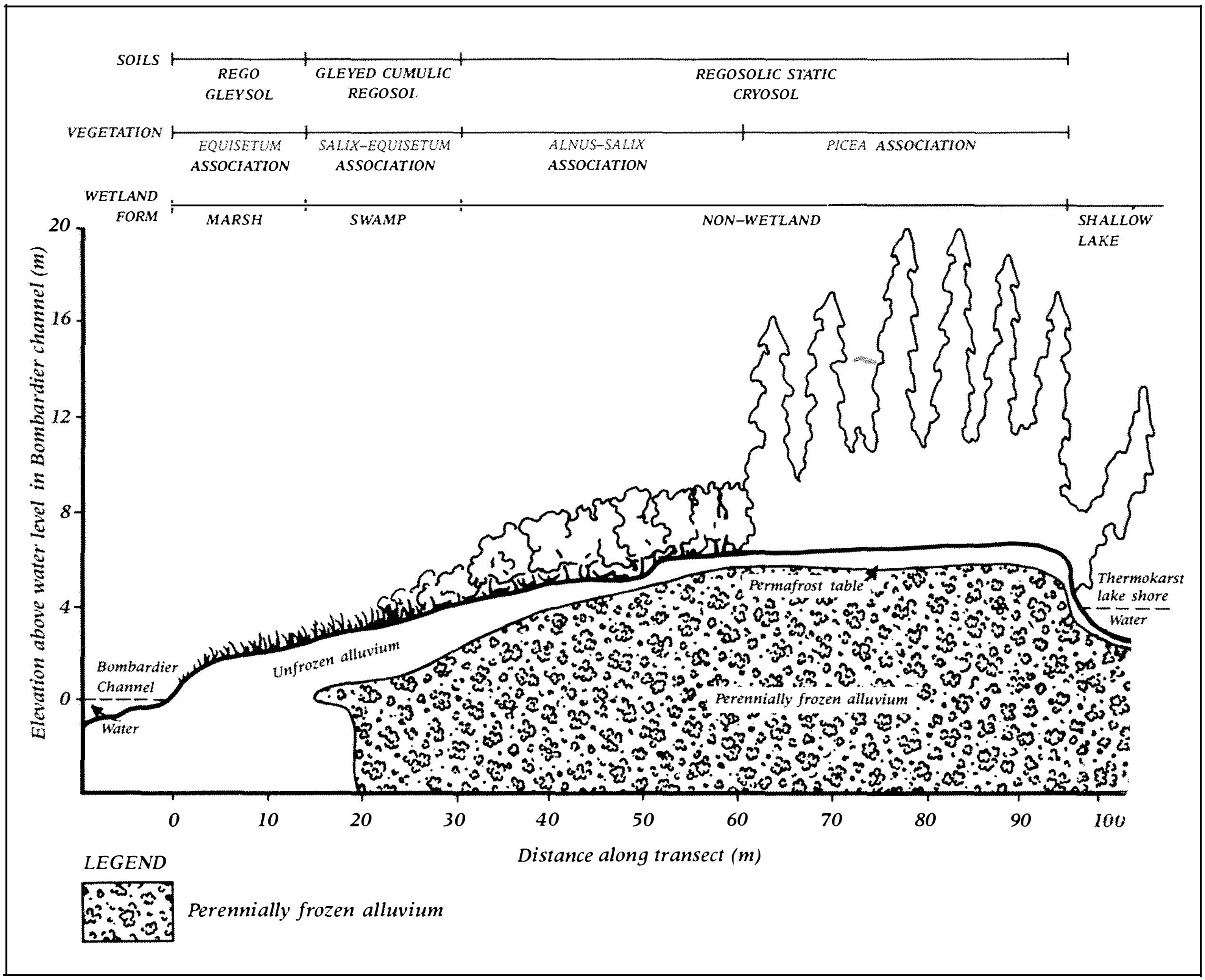


Figure 3–19.
Cross-section showing vegetation, soil, and permafrost conditions on a floodplain, Mackenzie Delta, NWT.

The next level of the vegetation zone is a swamp, consisting of *Salix alaxensis* growing to a height of 3–4 m, and a nearly complete ground cover of *Equisetum arvense*. Other species include *Hedysarum alpinum, Aster sibiricus, Campylium stellatum,* and *Leptobryum pyriforme* (Gill 1971). The soils in the willow (*Salix* sp.) zone are of two kinds

Thermokarst Shallow Waters

Lakes situated in shallow basins on ice-rich soils have unstable shorelines. Thermal and wave erosion cut into the shorelines, constantly thawing and eroding them. The basin under the newly submerged shore deepens as the ice in the degrading permafrost thaws and the ground subsides (thermokarst process). In some instances this process can erode the outlet of a lake, resulting in the partial or complete drainage of the lake (Figure 3–20). Permafrost develops on the exposed lakebed, elevating it as the groundwater freezes. Second-generation lakes are often formed in the lower parts of the old lakebed, renewing the cycle of lake formation and erosion.

Large subarctic concentrations of such shallow lakes occur on the older part of the modern Mackenzie Delta, on the peat-covered lacustrine basin at Old Crow, and on the peaty marine sediments on the coastal Hudson Bay Lowland. They are also a prominent feature on the Great Plain of the Koukdjuak on Baffin Island.

In the Hudson Bay Lowland, thermokarst lakes are common in peatland environments characterized by high- and low-centre polygons. The lakes are elongated (longer than 1 km) but fairly shallow (less than 3 m in depth) and flat-bottomed. One hypothesis for the development of these lakes is based on predicted change in the thermal characteristics of the peat with changing moisture content (Dredge and Nixon 1979). These shallow water bodies appear to be part of the development sequence of low- and high-centre polygons. Initially, small pools develop as some polygon troughs deepen. The pools may expand and coalesce into larger thermokarst lakes which, if drained, may begin peatland development again.

The lakes vary in size from a few to several hundred hectares. Many are without outlets, but others may be interconnected by small streams.

Figure 3–20.
Shallow lakes and lakebeds recently exposed by drainage of the lakes, Old Crow Flats, YT.

The average depth of 11 lakes on the Old Crow Flats was 1.4 m (Ruttan 1974a). Similarly, the maximum depth in an experimental lake in the Mackenzie Delta was 2.25 m (Snow and Rosenberg 1975a). The mean ice thickness during March ranged between 75 and 90 cm in the Old Crow Flats (Ruttan 1974a), leaving unfrozen water in the deeper parts of the lakes.

The pH values in two shallow lakes in the Mackenzie Delta ranged from 7.2 to 8.75, and the specific conductivity was 0.15–0.31 mS/cm (Snow and Rosenberg 1975b). In general, lakes that have inlet channels or are periodically flooded by river overflow have higher nutrient levels than lakes without inflow.

Macrophyte distribution is influenced by the depth of water. In stable shoreline shallows *Carex aquatilis* and *Juncus* spp. are common. The floating plant *Lemna trisulca* often occurs in large numbers in these areas. In shallow waters *Equisetum fluviatile*, *Menyanthes trifoliata*, *Hippuris vulgaris*, *Potamogeton foliosus*, and *Myriophyllum* sp. occur. In deep water (approximately 0.9–1.8 m), *Potamogeton foliosus* and *Potamogeton richardsonii* are found, along with *Nuphar polysepalum* (Ruttan 1974a).

It was found that, among the phytoplankton in the Mackenzie Delta area, *Chrysophyta* completely dominated a turbid lake. They were also very common in clear lakes, but diatoms such as *Chlorophyta* spp., *Pyrrhophyta* spp., and *Cryptophyta* spp. were also present in significant amounts (Snow and Rosenberg 1975a, 1975b).

Regional Wetland Development

Nutrient Status

The nutrient status of wetlands is influenced by the chemical composition of the associated groundwater and the atmospheric moisture that falls on the area. Elemental contaminants deposited from the atmosphere are generally similar in various parts of northern Canada and, indeed, in northern Europe (Glooschenko and Capobianco 1978). The main differences in nutrient status among subarctic wetlands can be attributed to the quality of groundwater that has been in contact with mineral soil and has been enriched by it. However, regional differences in geology and geochemistry influence the amounts of nutrients contained in the groundwater. Thus, fen peat from carbonate-rich regions (Silcox site, Table 3–11) has a much higher pH value and Ca content than fen peat from low carbonate regions (sites 27C, 35A, and 28A in Table 3–11).

Wetlands in which the surface is not affected by groundwater are nourished by atmospheric enrichment only (and are called "ombrotrophic"); hence they are lower in pH and nutrients than fens. Tarnocai (1973) found that the electrical conductivity of groundwater from fens ranged between 0.20 and 0.55 mS/cm and in bog water it averaged 0.05 mS/cm. The Ca content in the water from fens was 18.6–83.8 mg/kg and the Mg was 2.8–28.8 mg/kg. In bog water the Ca content was 1.4–2.8 mg/kg and the Mg 0.12–0.73 mg/kg. In a generally nutrient-poor area the electrical conductivity was higher in the mineral-enriched groundwaters (0.04–0.06 mS/cm) than in the ombrotrophic bog waters (0.02–0.03 mS/cm) (Jasieniuk and Johnson 1982).

Nutrient levels are far lower in surface *Sphagnum* peat of the active layer of bogs than in underlying perennially frozen fen peat (Table 3–10). Levels of Ca are more than 10 times higher in fen peat, and Mg shows a consistent, but less pronounced, increase. The pH increases and hydrogen ion (H) concentration decreases in fen peat.

Perennially frozen peats are able to take up Ca selectively by exchanging H (Tarnocai 1972). Thus perennially frozen *Sphagnum* peat contains more Ca and less H than the covering unfrozen *Sphagnum* peat (Table 3–11). This tends to increase the

Table 3–11. Chemical analyses from active layer, perennially frozen Sphagnum *cap, and fen peat from permafrost bogs*

Bog form and site no.	pH*			Ca**			Mg			H		
	Active layer peat	Frozen *Sphagnum* cap peat	Frozen fen peat	Active layer peat	Frozen *Sphagnum* cap peat	Frozen fen peat	Active layer peat	Frozen *Sphagnum* cap peat	Frozen fen peat	Active layer peat	Frozen *Sphagnum* cap peat	Frozen fen peat
Polygonal peat plateau												
Site 27C (Tarnocai 1973)	2.5	3.6	4.7	8.08	30.80	73.73	3.03	3.66	11.86	85.95	71.50	44.50
Site 35A (Tarnocai 1973)	2.7	3.6	4.4	5.05	34.59	56.30	4.04	4.80	10.35	73.35	60.38	43.65
Peat plateau												
Site 28A (Tarnocai 1973)	2.5	3.3	4.4	4.04	32.06	69.94	5.05	8.83	9.85	83.92	71.55	47.25
Silcox site (Tarnocai 1972)	3.0	4.0	6.3	8.65	35.60	98.90	8.44	12.40	22.90	103.5	44.7	5.1

*pH in KCl.
**Nutrients as me/100 g of ammonium acetate extractable bases.

nutrient (mainly Ca) content of the perennially frozen *Sphagnum* cap that covers the fen peat in many permafrost peatlands. In a comparison of the total elemental composition of the perennially frozen *Sphagnum* cap with that of the frozen fen peat, it was found that in 14 out of 26 permafrost-affected peatlands the Ca and Mg content of the *Sphagnum* cap was as high or higher than that in the fen peat below. At 11 of the 26 sites Fe was higher in the frozen *Sphagnum* peat than in the frozen fen peat, while S was higher at only 3 of the 11 measured sites. This shows that translocation of elements in the perennially frozen peats tends to equalize the mineral constituents in peats of different origin, regardless of the nutrient content at the time of deposition. The exception is sulphur, which appears to increase with depth.

Wetland Dynamics

In the Subarctic, wetlands develop in depressional areas, generally going through a series of developmental stages from fens to bogs to permafrost forms. A wetland may originate as a pond which is gradually filled in with lacustrine organic debris and then invaded by fen species ("hydrosere"). Equally important is the "primary mire formation" process (Sjörs 1980) in which wetland development begins on moist soil where the water table is close to the surface. "Paludification", a process of wetland development in previously upland environments, occurs in the Subarctic as the water table rises in an accreting peatland, expanding its margins onto the adjacent lower slopes.

In the Subarctic the basal deposit in most wetlands is a thin (1–15 cm), well-humified peat that may be mixed with mineral soil. Such deposits currently occur under some wet meadows, dominated by *Carex* spp. and *Eriophorum* spp. Next to the basal layer is fen peat, with various proportions of *Carex* spp., *Drepanocladus* spp., and the remains of associated fen species. In some cases the fen peat rests on detrital, organic lacustrine deposits, indicating the infilling of a pond and a subsequent invasion by a fen. The fens may proceed to a shrub and treed stage, but repeated reversions to open fens are sometimes indicated by the peat stratigraphy. In fens of low nutrient regime a carpet of *Sphagnum* moss may become established.

The development of a peat plateau bog complex in northern Quebec has been documented by the examination of peat macrofossils and by radiocarbon dating (Couillard and Payette 1985). It was found that at first a minerotrophic herbaceous vegetation had colonized the depression, but peat plateau bogs began forming about 1 000 years after the establishment of the wetland. In many cases treed fens and sedge fens preceded the peat plateau bogs which are invariably found in an ombrotrophic environment, dominated by *Sphagnum nemoreum*, *Sphagnum fuscum*, and *Sphagnum russowii*, as well as *Picea mariana*. Peat plateau bogs expanded as ombrotrophic conditions developed, although several fires swept over them. Palsa bogs appeared only relatively recently, within about the last 700 years.

The internal structure of perennially frozen peatlands suggests that permafrost developed in them at a later stage. The majority of such wetland forms (peat plateau, palsa, and polygonal peat plateau bogs) shows at least a thin *Sphagnum fuscum* cap covering the fen peat. In the Mackenzie Valley it was found that in 96 out of 116 cored peatlands the *Sphagnum* cap averaged 33–42 cm in thickness (Table 3–12). Thick *Sphagnum* peat (thicker than 1 m) was present at 8 sites, and *Sphagnum* peat was absent at only 12 sites. The surface peat was strongly oxidized at many of the 12 sites and the recognizable macrofossils at a depth of 20–30 cm were those of fen species. Fen species were also identified in the surface peat materials of two palsas.

Permafrost is formed when heat loss (cooling) exceeds heat influx (warming) on a perennial basis. It has been shown that dry peat has low thermal conductivity (about 0.00017 g cal/sec/cm^2/°C), but that it greatly increases when saturated (0.0011 g cal/sec/cm^2/°C) (Brown 1966). Dry *Sphagnum* peat also has low thermal conductivity (Tikhomirov 1952). It has been found that in central Saskatchewan seasonal frost thaws much later (57 days) in *Sphagnum* hummocks than in fens (FitzGibbon 1981).

The presence of a thin *Sphagnum fuscum* cap indicates that *Sphagnum* spp. play a role in the establishment of permafrost in many peatlands. This may take the form of small *Sphagnum fuscum* cushions occurring randomly in fens, or as somewhat elevated ridges in patterned fens. In the summer the dry surface *Sphagnum* moss insulates the underlying seasonal frost, and in the fall the wet *Sphagnum* allows heat loss from the peat (Railton and Sparling 1973). This results in late-thawing,

Table 3–12. Thickness of Sphagnum fuscum cap over fen peat in permafrost bogs in the Mackenzie Valley

Bog form	*Sphagnum fuscum* cap				Thick *Sphagnum*	Sites where *Sphagnum* not present
		Thickness (cm)				
	No. of sites	Mean	Maximum	Minimum	No. of sites	No. of sites
Peat plateau	63	41.4	80	18	6	8
Palsa	11	33.4	68	15	0	2
Polygonal peat plateau	22	42.4	87	12	2	2

seasonal frost that may eventually become a small permafrost lens. The freezing of water in the peat elevates the mound, encouraging further *Sphagnum* growth and more permafrost development. Small *Picea mariana* trees may become established on the mounds, decreasing the depth of snow there, and thus reducing insulation still more in the winter (Zoltai and Tarnocai 1971). Eventually the small mounds may coalesce to form large peat plateau bogs. Such a developmental sequence has been observed in various parts of the Subarctic (Zoltai and Tarnocai 1975; Payette *et al.* 1976).

If plentiful moisture is available, the mounds may become palsa bogs. As most palsa bogs occur as islands or peninsulas in wet fens, abundant moisture is available along most of their periphery. As moisture moves from the warm side (fen) to the cold side (palsa) (Hoekstra 1966), ice accumulation takes place in the palsa bog, mostly at the mineral–peat interface which is often more permeable by water. In peat plateau bogs only a small portion of their area is close to the periphery, and the influx of water into the frozen peat is limited to the fen margin.

Another form of permafrost development has been observed in areas of thin fen peat or shallow ponds. Here low mounds of peat are created by intensive frost action in the winter (Brown 1970). In some cases the exposed peat may dry out, especially if swept free of snow by the wind, and may provide sufficient insulation to prevent its thawing during the summer. Once initiated, mosses, lichens, and trees will colonize the small permafrost mound, and it can develop into a peat plateau or palsa bog.

In the High Subarctic Wetland Region and in exposed areas in the Low Subarctic Wetland Region, the intense winter cold creates cracks in the frozen peat and ice-wedge development takes place. Nevertheless, in polygonal peat plateau bogs, as in peat plateau and palsa bogs, frost penetration takes place from above, that is, permafrost is established in peat deposited in a non-permafrost environment. This contrasts with the development of lowland polygons (both low- and high-centre) in the Arctic which develop under permafrost conditions.

The time of permafrost development in peatlands is not known in sufficient detail to relate it to climatic events or changes. However, in northern Quebec the expansion of peat plateau bogs in a minerotrophic fen has been related to cooling periods 2 700, 1 400, 1 100, 700, and 150 years before the present (BP) (Couillard and Payette 1985). This interpretation is based on nine radiocarbon dates taken at the ombrotrophic–minerotrophic contact and thus relates the change to ombrotrophic conditions. Development of permafrost probably followed some time after that.

In the continental climate of the Subarctic, peat accumulation virtually ceases after permafrost elevates the peatland, which consequently becomes dry at the surface. Available dates from such peatlands show a great age for near-surface peat. Peat from a level of 5.5–8.5 cm in a polygonal peat plateau bog was dated 1 145 ± 65 years BP (Ovenden 1982), and peat from a level of 35 cm in another polygonal peat plateau bog was dated 2 710 ± 60 years BP (Zoltai and Tarnocai 1975). The age of peat from a depth of 30 cm at Natla River, Northwest Territories, was 3 000 ± 50 years BP (MacDonald 1983). However, these samples give only minimum dates for permafrost development in these peatlands.

In the absence of information one can only speculate on the time of permafrost formation in the peatlands. Some permafrost peatlands may be several thousand years old, as suggested by the humified upper soil horizon; others are still in the process of formation. Virtually all initial peat deposition was in unfrozen fens and often several metres of fen peat were formed before permafrost affected the peat. It is possible that widespread permafrost formation took place after a general cooling of the climate some 5 000 years ago (Ritchie *et al.* 1983).

The surface of elevated permafrost wetland forms is dry, except for small moist depressions. Under such conditions peat-forming vegetation does not grow and therefore these wetland forms are no longer functioning as wetlands. Although the peat is saturated with water beneath the active layer, the water is present in a relatively inert, frozen form and this too throws their wetland status into question. However, as a result of severe disturbance the permafrost may thaw in these peatlands and they may collapse into the fen. Similarly, new peat plateau and palsa bogs are currently forming under *Sphagnum* hummocks. Because of the occurrence of these potential and actual changes, and because of the development of these wetland forms from a saturated environment, they may be regarded as wetlands.

The development of wetlands in the Subarctic is dictated by the hydrology and climate of the area as manifested by permafrost dynamics (Sjörs 1980). The evolution of wetlands is from a fen (established on pond deposits, wet meadows, or paludified lowlands) to a fen with an ombrotrophic cap, and finally to peat plateau and palsa bogs (Figure 3–21). This succession proceeds at a different pace at different locations, due to such factors as hydrology, water quality, history, and local climate. In some areas it may stall for a long time; in other areas setbacks may occur due to short-term environmental changes. In addition, some of the earlier stages in the developmental sequence may remain in equilibrium with environmental factors, such as physiography and hydrology, and may not always proceed to the next stage in the succession. The completion of the developmental sequence appears to be the development of peat plateau bogs. However, because the time that has elapsed since glaciation and the establishment of wetlands is relatively short, this apparent final point may not represent the true end in the development of wetlands.

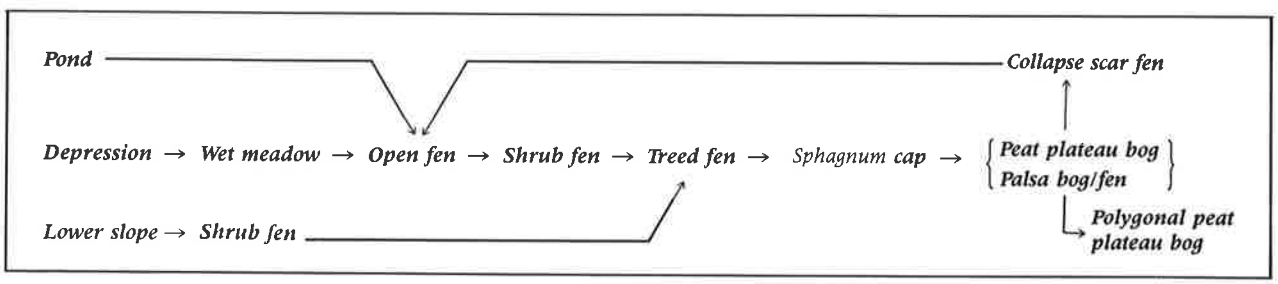


Figure 3–21.
Developmental trends of wetlands in the subarctic wetland regions.

Stability of Wetlands

Wetlands are dynamic ecosystems that are subject to long-term developmental changes and to short-term changes in response to catastrophic events such as drought, fire, or flood, or to anthropogenic activities. Given the slow rate of change because of the developmental process, wetlands are relatively stable and tend to recover from catastrophic events.

Fires are frequent on peat plateaus with their open-canopied *Picea mariana*, erect woody shrub, and dry lichen cover. Fire kills only the dry surface vegetation but does not destroy the peat to any depth (Jasieniuk and Johnson 1982). Many rhizomes, rhizoids, and gemmae remain alive and regenerate rapidly after a fire. Other species are slow in reoccupying the burned surface, but the original vegetation once again becomes prevalent within about 100 years after a fire.

Permafrost occurring in veneer bogs is particularly susceptible to disturbance by fire. Fire often sweeps across veneer bogs, starting from the adjacent better-drained mineral soils. Removal of the vegetation cover and the thin peat veneer by fire often alters the thermal regime of the veneer bog sufficiently to induce the complete degradation of permafrost. Permafrost often remains absent from a recently burned veneer bog until the moss cover encroaches up the slope from adjacent poorly drained terrain. The resulting cooler and wetter conditions permit the regeneration of permafrost.

Permafrost peatlands are also subject to degradation through thawing of the permafrost. When such thawing occurs, the peatland surface subsides to the level of the surrounding fen and fen vegetation invades the collapse scar fens. Dead trees and bright green *Sphagnum riparium* patches mark the recently collapsed permafrost margins. In some cases new permafrost development has been observed in such collapse scar fens (Tarnocai 1973).

When palsa bogs reach a senescent stage, they are subject to erosion by rain and runoff, and large blocks can be detached ("calved") from them (Railton and Sparling 1973). Ultimately the palsas may disappear completely (Kershaw and Gill 1979). The cracking of palsas may be due to their expansion as ice accumulates in their core. It has been noted that palsas which are sealed off from the wet fen stage by peat plateau development do not show intensive crack development, possibly because they are no longer growing.

Thermal degradation has been observed on polygonal peat plateau bogs in the Hudson Bay area (Dredge and Nixon 1979). Here some ice wedges may begin to thaw, becoming water-filled depressions. The accumulated water may saturate the surface peat in the centres of the polygons, causing deeper summer thaw. This may create shallow pools in the polygons. Once the depth of water exceeds 25 cm, the pools become heat sinks and thawing is accelerated, eventually resulting in expansion of the pools to form shallow lakes.

In the Subarctic, thermal degradation of permafrost peatlands does not occur on a large scale. Disturbances such as fires rarely set off extensive thawing except in areas where the peat is so thin that fires can completely consume it. Most collapses are triggered by persistent raising of the water table caused by linear construction activity, such as the building of roads or pipelines. Direct damage to the frozen peat surface caused by activities such as bulldozing or deep rutting can also initiate thermal subsidence.

Rate of Peat Accumulation

Peat is composed of the preserved remnants of plants that grew on a peatland. Peat accumulation takes place at the surface where the remnants of plants (both above and below the surface portions) are preserved. Decay and decomposition tend to reduce the volume of plant materials and only the surplus remains as peat. The thickness of peat can be further reduced by compaction, and can be increased by freezing as water changes to ice. Thus the rate of peat accumulation is only a very crude approximation of the productivity of a wetland.

The rate of peat accumulation near the surface of a number of sites in the Mackenzie Valley was indicated by the thickness of peat over a thin but widespread layer of volcanic ash. This ash, the White River ash, was deposited about 1 250 years BP by a volcanic eruption west of the area (Lerbekmo *et al.* 1975). The thickness of peat deposited in various environments, as determined by Tarnocai (1973), is shown in Table 3–13. A few additional measurements are included.

It is evident that the least peat accumulation took place in the lichen–forest environment, found on peat plateaus and palsas. This can be attributed to the generally dry conditions that persist on these well-elevated landforms where more decomposition than deposition of peat takes place. Lichen contains no fibres and leaves little residue. The *Picea*–ericaceous shrub forest is

Table 3–13. Peat accumulation in different environments, as indicated by peat thickness above White River volcanic ash layer in the Mackenzie Valley

Peat material	*No. of sites*	*Range of depth to ash (cm)*	*Mean depth (cm)*	*Accumulation (cm/100 yr)*
Cladina ***forest peat***	3	2–5	3.6	0.29
Feathermoss forest peat	10	23–40	36.6	2.93
Ericaceous–woody forest peat	1	—	13.0	1.04
Sphagnum fuscum ***peat***	9	20–61	38.8	3.10
Sphagnum riparium ***peat***	1	—	104.0	8.32
Carex ***fen peat***	8	19–67	33.2	2.66

Source: Tarnocai (1973).

somewhat higher in peat production, but still much below other wetland environments. The feathermoss forests, the wet *Sphagnum* bogs, and the sedge fens produced peat at about the same average rate. The fastest rate of peat development was found on level sites with wet *Sphagnum* spp.

Longer-term average accumulation rates can be obtained from radiocarbon-dated peat sections (Table 3–14). All four sections show at least one period of a high rate of accumulation occurring in their lower halves. All peatlands display a marked reduction in the accumulation rate at the top of the peat sections. The accumulation rates are similar to the very low rates found in the lichen–forest environment occurring on peatlands in the Mackenzie Valley that are currently affected by permafrost. The onset of the very slow rate of accumulation may well signal the establishment of surface-dry peatlands elevated by permafrost.

***Table 3–14.** Peat accumulation in radiocarbon-dated peat sections from subarctic wetland regions*

Depth of sample (cm)	*Radiocarbon age (yr BP)*	*Radiocarbon lab. no.*	*Rate of peat accumulation (cm/100 yr)*
A—Ennadai Lake (61°10′ N, 100°55′ W) (Nichols 1967)			
4	630±70	WIS–133	0.63*
20	1 510±80	WIS–88	1.82
55	2 670±105	WIS–93	3.02
72	3 140±105	WIS–139	3.62
90	3 650±100	WIS–80	3.53
110	4 800±90	WIS–166	1.74
132	5 570±100	—	2.86
150	5 780±110	WIS–67	8.57
B—Colville Lake (67°06′ N, 125°47′ W) (Nichols 1974)			
35	1 810±60	WIS–297	1.93*
44	3 160±65	WIS–314	0.67
69	3 980±65	WIS–295	3.05
90	4 130±55	WIS–294	14.00
124	5 730±75	WIS–296	2.12
174	6 630±85	WIS–299	5.56
206	6 790±75	WIS–275	20.00
C—Old Crow (67°49′ N, 139°50′ W) (Ovenden 1982)			
7	1 145±65	S–1864	0.61*
23	3 025±85	S–1865	0.85
27	3 250±85	S–1866	1.78
39	3 865±80	S–1867	1.95
66	5 285±115	S–1868	1.87
90	5 750±130	S–1869	5.16
122	7 575±170	S–1870	1.75
146	7 975±110	S–1778	6.00
150	8 200±180	S–1906	1.78
176	10 080±340	S–1871	1.44
215	11 435±270	S–1779	2.88
D—Natla River (63°00′ N, 129°05′ W) (MacDonald 1983)			
10	1 250	White River ash	0.80*
30	3 000±50	GSC–3176	1.14
90	5 460±70	GSC–3171	2.44
150	7 750±90	GSC–3169	2.69
220	8 420±80	GSC–3383	10.45
230	8 640±160	GSC–3097	4.54

**Accumulation rate based on assuming present date for the surface (0 cm).*

Long-term average peat accumulation rates of between 2.15 and 5.08 cm/100 yr were obtained for peatlands where at least two radiocarbon dates were available (Table 3–15). These permafrost peatlands also show a severe reduction in peat accumulation rates near the surface.

A number of radiocarbon dates are available from basal peat samples (Table 3–16). The peat accumulation rates were calculated on the assumption that they were uniform until the present. However, in the permafrost peatlands these rates are probably somewhat low because of the slow accumulation rates near the surface, as found in other permafrost peatlands. The data in Table 3–16 confirm this; the accumulation rates in non-frozen peatlands are higher than those in frozen peatlands.

Age of Wetlands

The ultimate determinant of the age of the wetlands in the Subarctic is the time of deglaciation and the disappearance of glacial lakes. Most of the Subarctic was glaciated during the Wisconsin glaciation with the exception of northwestern Yukon Territory, parts of which were never glaciated. Eventually, as the glaciers waned, the land was exposed, beginning about 13 000 years BP in the west, with the ice completely disappearing from the area by about 7 000 years BP (Prest 1970). In the unglaciated area, large areas such as Old Crow, Bell, and Whitefish basins were occupied by lakes fed by glacial meltwaters; hence they too were available for wetland development only after the glaciers disappeared.

The ages of basal peat samples (Table 3–16) indicate that peat started accumulating at least 1 000–2 000 years after glaciers vacated the land, and in some areas development began considerably later. Radiocarbon dates of organic lacustrine sediments overlain by peat are available mainly from the unglaciated–glaciated boundary in Yukon Territory (Table 3–17). The dates show that deposition of organic debris in small ponds began almost immediately after the disappearance of glacial ice. The dates from the Northwest Territories show the usual delay of 1 000–2 000 years after glaciation.

Table 3–15. Radiocarbon dates of surface and deeper peat deposits in subarctic wetland regions

Location	Bog wetland form	Depth of sample (cm)	Radiocarbon age (yr BP)	Radiocarbon lab. no.	Source	Rate of peat accumulation (cm/100 yr)
58°13′ N, 71°59′ W, Que.	Peat plateau	7	1 040±80	QU–977	Couillard and Payette (1985)	0.67*
	Peat plateau	95	3 640±100	QU–790	Couillard and Payette (1985)	3.38
63°00′ N, 129°05′ W, NWT	Peat plateau	30	3 000±50	GSC–3176	MacDonald (1983)	1.00*
	Peat plateau	230	8 640±160	GSC–3097	MacDonald (1983)	3.55
61°10′ N, 100°55′ W, NWT	Peat plateau**	4	630±70	WIS–133	Nichols (1967)	0.63*
	Peat plateau**	150	5 780±110	WIS–67	Nichols (1967)	2.83
67°06′ N, 125°47′ W, NWT	Peat plateau**	34	1 810±60	WIS–297	Nichols (1974)	1.88*
	Peat plateau**	206	6 790±75	WIS–275	Nichols (1974)	3.45
67°41′ N, 132°05′ W, NWT	Polygonal peat plateau	35	2 710±60	BGS–147	Zoltai and Tarnocai (1975)	1.29*
	Polygonal peat plateau	229	7 200±60	BGS–149	Zoltai and Tarnocai (1975)	4.32
67°49′ N, 139°50′ W, YT	Polygonal peat plateau	23	3 025±85	S–1865	Ovenden (1982)	0.76*
	Polygonal peat plateau	175	10 080±340	S–1871	Ovenden (1982)	2.15
55°34′ N, 84°38′ W, Ont.	Palsa	5	243±55	BGS–5	Railton and Sparling (1973)	2.06*
	Palsa	89	1 897±63	BGS–6	Railton and Sparling (1973)	5.08

**Accumulation rate based on assuming present date for the surface (0 cm).*
***Inferred, wetland form not precisely identified in original reference.*

Table 3–16. Radiocarbon dates of basal peat deposits from subarctic wetland regions

Location	Depth of sample (cm)	Frozen (F) or non-frozen (NF)	Radiocarbon age (yr BP)	Radiocarbon lab. no.	Source	Rate of peat accumulation (cm/100 yr)
68°22′ N, 132°44′ W, NWT	366	F	8 200±300	GSC–25	Dyck and Fyles (1963)	4.46
69°12′ N, 132°27′ W, NWT	213	F	7 400±200	GSC–16	Dyck and Fyles (1963)	2.88
64°52′ N, 138°19′ W, YT	162	F	9 620±150	GSC–310	Dyck *et al.* (1966)	1.68
68°04′ N, 139°50′ W, YT	183	F	6 430±140	GSC–372	Dyck *et al.* (1966)	2.85
68°45′ N, 133°16′ W, YT	213	F	7 120±140	GSC–371	Dyck *et al.* (1966)	2.99
64°36′ N, 138°20′ W, YT	162	F	6 840±150	GSC–415	Lowdon and Blake (1968)	2.37
64°36′ N, 138°22′ W, YT	140	F	3 100±130	GSC–416	Lowdon and Blake (1968)	4.52
64°36′ N, 138°22′ W, YT	126	F	3 180±130	GSC–469	Lowdon and Blake (1968)	3.96
68°22′ N, 133°44′ W, YT	330	F	11 500±160	GSC–1514	Lowdon and Blake (1973)	2.87
56°52′ N, 95°47′ W, Man.	170	F	6 490±170	GSC–1738	Lowdon *et al.* (1977)	2.62
65°34′ N, 135°30′ W, YT	300	F	8 980±90	GSC–2341	Hughes *et al.* (1981)	3.34
65°15′ N, 126°42′ W, NWT	170	F	3 960±50	—	Korpijaakko *et al.* (1972)	4.29
65°59′ N, 135°03′ W, YT	372	F	10 470±80	BGS–144	Zoltai and Tarnocai (1975)	3.55
66°10′ N, 134°18′ W, YT	255	F	5 910±60	BGS–140	Zoltai and Tarnocai (1975)	4.31
67°08′ N, 137°25′ W, YT	438	F	9 530±170	GSC–1829	Lowdon *et al.* (1977)	4.60
54°34′ N, 84°40′ W, Ont.	290	NF	5 580±150	GSC–247	Dyck *et al.* (1965)	5.20
55°00′ N, 82°20′ W, Ont.	122	NF	1 210±130	GSC–231	Dyck *et al.* (1965)	10.01

Table 3–17. Radiocarbon dates of organic lacustrine sediments overlain by peat in subarctic wetland regions

Location	Radiocarbon age (yr BP)	Radiocarbon lab. no.	Source
64°34′ N, 138°15′ W, YT	7 510±100	GSC–50	Dyck and Fyles (1963)
67°28′ N, 139°54′ W, YT	10 740±180	GSC–121	Dyck and Fyles (1964)
65°28′ N, 139°42′ W, YT	12 550±190	GSC–128	Dyck and Fyles (1964)
63°30′ N, 135°24′ W, YT	10 840±150	GSC–150	Dyck *et al.* (1966)
64°52′ N, 138°19′ W, YT	13 870±180	GSC–296	Dyck *et al.* (1966)
64°38′ N, 138°24′ W, YT	13 740±190	GSC–515	Lowdon and Blake (1968)
65°29′ N, 126°34′ W, NWT	8 880±150	GSC–1099	Lowdon *et al.* (1971)
67°54′ N, 139°26′ W, YT	6 020±140	GSC–2225	Lowdon *et al.* (1977)
68°19′ N, 133°25′ W, NWT	7 230±130	Beta–6600	This paper

Some indication of the sequence and time involved in wetland development is given by a study of the present Hudson Bay shoreline. At present this shoreline is receding about 6 cm a year in the York Factory area of northern Manitoba, as a result of post-glacial crustal rebound and sedimentation (Tarnocai 1982). This permits the study of wetland development as the land emerges from the sea and slowly becomes elevated. The initial low tidal marshes give way to high marshes that emerged from the sea 500–700 years ago. Some peat development begins during this stage about 600 years after emergence. These marshes are succeeded by horizontal fens with small palsas, inundated periodically by flood waters that maintain their minerotrophic character. Peat is actively formed during this fen phase. The land finally rises sufficiently to elevate it above even the highest floods; bogs with peat plateaus and palsas develop, beginning about 2 000 years after emergence from the sea. In areas not subject to flooding, ombrotrophic conditions are reached much earlier, some 1 000 years after emergence.

This sequence shows that under climatic conditions favourable for peat formation, peat deposition began some 600 years after the establishment of wetlands. The greater delay (over 2 000 years) in many wetlands, indicated by radiocarbon dating, implies that conditions were not optimal for peat formation immediately after glaciation. Conditions such as combinations of climate, plant migration, or other environmental factors may account for the delay in peat development.

Subarctic Wetland Values

Wetlands occupy the most moisture-rich habitats that constitute the landscape, contributing to the biotic diversity of any area. The intrinsic value of wetlands in an undisturbed landscape has already been determined by their invaluable contribution to the organisms that occupy them. Therefore the value of wetlands is best considered from a human-centred viewpoint.

Wetlands can be regarded both as places of biological production and as suppliers of resources. Although some uses may be totally non-consumptive and non-disruptive (such as viewing), most uses involve the removal of some wetland products (such as pelts or peat). These different intensities of use cause variations in the magnitude of disruptions resulting from human use.

Wetlands possess exploitable values, including production of waterfowl, fur-bearers, and ungulates, and a potential for peat harvesting and for land development for uses such as agriculture and water management. However, the remoteness of most subarctic wetlands makes the use of some of these resources unprofitable at present. This does not reduce the intrinsic value of the wetlands; their use is a matter of accessibility and economics.

There are enormous peat resources in the Subarctic. The estimated amount of peat in the Northwest Territories is 577 553 million m^3 (Tarnocai 1984). However, as most of the peat occurs in the Subarctic, a large portion is perennially frozen and development for uses such as mining would be dependent on special extraction techniques.

The biologically most active wetlands are the marsh–shallow lake complexes where both waterfowl and fur-bearing animals abound. Such areas are common in the Mackenzie Delta, in the Old Crow Flats, and the coastal areas of Hudson Bay, characterized by flat, poorly drained terrain with abundant peatlands and many shallow thermokarst lakes. In the Old Crow Flats ducks are common, although they are scarce everywhere else in the region (Schweinsburg 1974). Nine species were found, with the American Widgeon (*Anas americana*) and White-winged Scoter (*Melanitta fusca*) being the most common. Furthermore, the Old Crow Flats and the Mackenzie Delta are extremely important as staging areas during the migration of geese, ducks, and swans (Schweinsburg 1974), as is the Hudson Bay coastal zone (Wellein and Lumsden 1964).

Both the Old Crow Flats and the Mackenzie Delta are very important for muskrat (*Ondatra zibethicus*) breeding and, in the Old Crow Flats, the shallow lakes and their marshy margins provide excellent habitat for muskrat (Ruttan 1974a). Muskrat are trapped in great numbers, with annual harvests averaging 14 800 pelts (Stager 1974). Muskrat meat is an important food resource for the trapper families. In 1973, 10% of the meat harvested by the Old Crow community was muskrat (Stager 1973).

Beaver (*Castor canadensis*) are basically aquatic animals that derive most of their food from the neighbouring lands. They are common in small lakes and streams in flat, boggy areas (Wooley 1974). Their main food sources are the stems and branches of various *Salix* spp., abundant in such areas.

Moose (*Alces alces*) are heavily concentrated during the summer in the Old Crow Flats and in the southern Mackenzie Delta (Ruttan 1974b). Wetland complexes, composed of flat, marshy areas with ponds, provide very important moose habitats (Watson *et al.* 1973), especially if there is a significant deciduous shrub component. These areas are especially important for the winter survival of moose.

Caribou, both woodland (*Rangifer tarandus caribou*) and barren-ground subspecies (*Rangifer tarandus tarandus*), winter in the widespread subarctic *Picea mariana*–lichen woodlands (Jakimchuk *et al.* 1974), including the treed peat plateau bogs. It has been found that areas without significant *Picea mariana*–lichen components are avoided by wintering caribou (Watson *et al.* 1973).

The most important value of wetlands at present appears to be their utilization for waterfowl and other wildlife production. The most important wetlands in this respect are the shallow lake–marsh–fen complexes. Peatlands (bogs and fens) are far less important for wildlife, with the exception of caribou. However, peatlands do represent a potential resource for peat production for various commercial uses.

At present, the remoteness of subarctic wetlands offers some measure of protection from intensive exploitation and disruption. However, pressure on these wetlands is already evident. Increased accessibility by new roads affects the wetlands and their use. Pipeline routings may avoid highly concentrated wetland areas, but they will have an impact on smaller wetlands. Nevertheless, there is still time to plan for the protection and conservation of both unique and representative wetlands throughout the Subarctic to ensure their continued existence.

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References

ÅHMAN, R. 1977. Palsar i Nordnorge. The Royal University of Lund, Sweden. Department of Geography Series. Avhandlingar No. 78. 165 p.

ANDERSSON, G., AND H. HESSELMAN. 1907. Vegetation och flora i Hamra kronopark. (Vegetation and flora in the state forest of "Hamra Kronopark".) Meddelelser Statens Skogsförsöksanst. 4:35–102.

ATMOSPHERIC ENVIRONMENT SERVICE. 1982. Canadian climate normals, 1951–1980. Volume 2: Temperature; Volume 3: Precipitation; Volume 4: Degree-days. Environment Canada. Downsview, Ontario.

BOSTOCK, H.S. 1970. Physiographic subdivisions of Canada. *In* Geology and economic minerals of Canada. R.J.W. Douglas, editor. Geological Survey of Canada. Economic Geology Report No. 1. 5th edition. Ottawa, Ontario. pp. 9–30.

BOTCH, M.S., AND V.V. MASING. 1983. Mire ecosystems in the USSR. *In* Ecosystems of the world. Volume 4B. Mires: swamp, bog, fen and moor. A.J.P. Gore, editor. Elsevier Scientific Publishing Company. Amsterdam, The Netherlands. pp. 95–152.

BROWN, G. 1980. Palsas and other permafrost features in the lower Rock Creek valley, west-central Alberta. Arctic and Alpine Research 12:31–40.

BROWN, R.J.E. 1966. Influence of vegetation on permafrost. *In* Proceedings, 1st International Permafrost Conference. National Academy of Science–National Research Council. Publication No. 1287. Washington, DC. pp. 20–25.

BROWN, R.J.E. 1970. Occurrence of permafrost in Canadian peatlands. *In* Proceedings, 3rd International Peat Congress. National Research Council of Canada. pp. 174–181.

BRYSON, R.A. 1966. Air masses, streamlines, and the boreal forest. Geographical Bulletin 8:228–269.

COUILLARD, L., AND S. PAYETTE. 1985. Evolution holocène d'une tourbière à pérgélisol (Québec nordique). Canadian Journal of Botany 63:1104–1121.

DOLGIN, I.M. 1970. Subarctic meteorology. *In* Ecology of the subarctic regions. Ecology and Conservation, UNESCO. Report No. 1. pp. 41–61.

DREDGE, L.A. 1979. Thaw depths and permafrost in polygonal peat terrain, Hudson Bay Lowland, Manitoba. Geological Survey of Canada. Paper 79-1C. Ottawa, Ontario. pp. 27–30.

DREDGE, L.A., AND F.M. NIXON. 1979. Thermal sensitivity and the development of tundra ponds and thermokarst lakes in the Manitoba portion of the Hudson Bay Lowland. Geological Survey of Canada. Paper 79-1C. Ottawa, Ontario. pp. 23–26.

DYCK, W., AND J.G. FYLES. 1963. Geological Survey of Canada radiocarbon dates, I and II. Geological Survey of Canada. Paper 63-21. Ottawa, Ontario. 31 p.

DYCK, W., AND J.G. FYLES. 1964. Geological Survey of Canada radiocarbon dates, III. Geological Survey of Canada. Paper 64-40. Ottawa, Ontario. 15 p.

DYCK, W., J.G. FYLES, AND W. BLAKE, JR. 1965. Geological Survey of Canada radiocarbon dates, IV. Geological Survey of Canada. Paper 65-4. Ottawa, Ontario. 23 p.

DYCK, W., J.A. LOWDON, J.G. FYLES, AND W. BLAKE, JR. 1966. Geological Survey of Canada radiocarbon dates, V. Geological Survey of Canada. Paper 66-48. Ottawa, Ontario. 32 p.

FITZGIBBON, J.E. 1981. Thawing of seasonally frozen ground in organic terrain in central Saskatchewan. Canadian Journal of Earth Sciences 18:1492–1496.

GILL, D. 1971. Vegetation and environment in the Mackenzie River Delta, Northwest Territories—a study in subarctic ecology. Ph.D. thesis, Department of Geography, University of British Columbia, Vancouver, British Columbia. 694 p.

GILL, D. 1973. Floristics of a plant succession sequence in the Mackenzie Delta, Northwest Territories. Polarforschung 43:55–65.

GLOOSCHENKO, W.A., AND J.A. CAPOBIANCO. 1978. Metal content of *Sphagnum* mosses from two northern Canadian bog ecosystems. Water, Air and Soil Pollution 10:215–220.

HAMELIN, L.E., AND A. CAILLEUX. 1969. Les palses dans le bassin de la Grande Rivière de la Baleine. Revue géographique de Montréal 23:329–337.

HEGINBOTTOM, J.A., AND C. TARNOCAI. 1983. Mackenzie Delta and Inuvik. *In* Northern Yukon Territory and Mackenzie Delta, Canada. H.M. French and J.A. Heginbottom, editors. Guidebook to Permafrost and Related Features. International Conference on Permafrost, Guidebook No. 3. pp. 113–146.

HOEKSTRA, P. 1966. Moisture movements in soils under temperature gradients with the cold-side temperature below freezing. Water Resources Research 2:241–250.

HUGHES, O.L., C.R. HARINGTON, J.A. JANSSENS, J.V. MATTHEWS, JR., R.E. MORLAN, N.R. RUTTER, AND C.E. SCHWEGER. 1981. Upper Pleistocene stratigraphy, paleoecology, and archaeology of the northern Yukon interior, Eastern Beringia. I. Bonnet Plume Basin. Arctic 34:329–365.

JAKIMCHUK, R.D., E.A. DEBOCK, H.J. RUSSELL, AND G.P. SEMENCHUK. 1974. A study of the Porcupine Caribou Herd, 1971. Canadian Arctic Gas Study Ltd. Biological Report Series. Volume 4, Chapter 1. 111 p.

JASIENIUK, M.A., AND E.A. JOHNSON. 1982. Peatland vegetation organization and dynamics in the western subarctic, Northwest Territories, Canada. Canadian Journal of Botany 60:2581–2593.

KERSHAW, G.P., AND D. GILL. 1979. Growth and decay of palsas and peat plateaus in the Macmillan Pass–Tsichu River area, Northwest Territories, Canada. Canadian Journal of Earth Sciences 16:1362–1374.

KOHNKE, H. 1968. Soil physics. McGraw-Hill Book Company. New York, New York. 224 p.

KORPIJAAKKO, M., M.L. KORPIJAAKKO, AND N.W. RADFORTH. 1972. Ice-biotic relationship in frozen peat. *In* Proceedings, 14th Muskeg Research Conference. 1971. Associate Committee on Geotechnical Research, National Research Council of Canada. Technical Memorandum No. 102. pp. 111–120.

LACHENBRUCH, A.H. 1962. Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Geological Society of America. Special Paper No. 70. 69 p.

LEFFINGWELL, E. DE K. 1915. Ground-ice wedges: the dominant form of ground-ice on the north coast of Alaska. Journal of Geology 23:635–654.

LERBEKMO, J.F., J.A. WESTGATE, D.G.W. SMITH, AND G.H. DENTON. 1975. New data on the character and history of the White River volcanic eruption, Alaska. *In* Quaternary Studies. R.P. Suggate and M.M. Cresswell, editors. Royal Society of New Zealand. Wellington, New Zealand. pp. 203–209.

LOWDON, J.A., AND W. BLAKE, JR. 1968. Geological Survey of Canada radiocarbon dates, VII. Geological Survey of Canada. Paper 68-2, Part B. Ottawa, Ontario. pp. 207–245.

LOWDON, J.A., AND W. BLAKE, JR. 1973. Geological Survey of Canada radiocarbon dates, XIII. Geological Survey of Canada. Paper 73-7. Ottawa, Ontario. 61 p.

LOWDON, J.A., I.M. ROBERTSON, AND W. BLAKE, JR. 1971. Geological Survey of Canada radiocarbon dates, XI. Geological Survey of Canada. Paper 71-1. Ottawa, Ontario. pp. 255–324.

LOWDON, J.A., I.M. ROBERTSON, AND W. BLAKE, JR. 1977. Geological Survey of Canada radiocarbon dates, XVII. Geological Survey of Canada. Paper 77-7. Ottawa, Ontario. 25 p.

MACDONALD, G.M. 1983. Holocene vegetation history of the upper Natla River area, Northwest Territories, Canada. Arctic and Alpine Research 15:169–180.

MACKAY, J.R. 1974. Ice-wedge cracks, Garry Island, Northwest Territories. Canadian Journal of Earth Sciences 11:1366–1383.

MILLS, G.F., D.B. FORRESTER, AND H. VELDHUIS. 1978. A guide to biophysical land classification, Knee Lake, 53M. Manitoba Department of Renewable Resources and Transportation Services. Technical Report No. 78-2. Winnipeg, Manitoba.

MILLS, G.F., H. VELDHUIS, AND R.G. EILERS. 1985. Preliminary results of soil climate and hydrology studies in the discontinuous permafrost zone near Thompson, Manitoba. *In* 28th Annual Meeting, Canadian Society of Soil Science. January 9 and 10, 1985. Winnipeg, Manitoba. pp. 179–200.

MOORE, P.D. 1982. Pool and ridge patterns in peat mires. Nature 300:110.

NICHOLS, H. 1967. The post-glacial history of vegetation and climate at Ennadai Lake, Keewatin, and Lynn Lake, Manitoba, Canada. Eiszeitalter und Gegenwart 18:176–197.

NICHOLS, H. 1974. Arctic North American palaeoecology: the recent history of vegetation and climate deduced from pollen analysis. *In* Arctic and alpine environments. J.D. Ives and R.G. Barry, editors. Methuen and Company, Ltd. London, UK. pp. 637–667.

NORIN, B.N. 1961. Chto takoe lesotundra? (What is the lesotundra?) Botanicheskij Zhurnal 46(1).

OVENDEN, L. 1982. Vegetation history of a polygonal peatland, northern Yukon (Canada). Boreas 11:209–224.

PAYETTE, S., H. SAMSON, AND D. LAGAREC. 1976. The evolution of permafrost in the taiga and in the forest-tundra, western Quebec–Labrador Peninsula. Canadian Journal of Forest Research 6:203–220.

POUNDER, E.R. 1965. The physics of ice. Pergamon Press. Oxford, UK.

PREST, V.K. 1970. Quaternary geology of Canada. *In* Geology and economic minerals of Canada. R.J.W. Douglas, editor. Geological Survey of Canada. Economic Geology Report No. 1. 5th edition. Ottawa, Ontario. pp. 675–764.

RAILTON, J.B., AND J.H. SPARLING. 1973. Preliminary studies on the ecology of palsa mounds in northern Ontario. Canadian Journal of Botany 51:1037–1044.

RITCHIE, J.C. 1959. The vegetation of northern Manitoba. III. Studies in the Subarctic. Arctic Institute of North America. Technical Paper No. 3. 56 p.

RITCHIE, J.C., L.C. CWYNAR, AND R.W. SPEAR. 1983. Evidence from north–west Canada for an early Holocene Milankovitch thermal maximum. Nature 305:126–128.

ROWE, J.S. 1972. Forest regions of Canada. Canadian Forestry Service, Environment Canada. Publication No. 1300. Ottawa, Ontario. 172 p.

RUTTAN, R.A. 1974a. Muskrat studies on Old Crow Flats, Yukon Territory, 1972. Chapter IV. *In* Studies of furbearers associated with proposed pipeline routes in the Yukon and Northwest Territories. R.A. Ruttan and D.R. Wooley, editors. Canadian Arctic Gas Study Ltd. Biological Report Series. Volume 9. 104 p.

RUTTAN, R.A. 1974b. Observations of moose in the northern Yukon Territory and Mackenzie River valley, 1972. Chapter VI. *In* Studies of furbearers associated with proposed pipeline routes in the Yukon and Northwest Territories. R.A. Ruttan and D.R. Wooley, editors. Canadian Arctic Gas Study Ltd. Biological Report Series. Volume 9. 45 p.

SCHENK, E. 1963. Origin of string bogs. *In* Proceedings, 1st International Permafrost Conference. National Academy of Science–National Research Council. Publication No. 1287. Washington, DC. pp. 155–159.

SCHWEINSBURG, R.E. 1974. An ornithological study of proposed gas pipeline routes in Alaska, Yukon Territory, and the Northwest Territories, 1971. Canadian Arctic Gas Study Ltd. Biological Report Series. Volume 10. 215 p.

SEPPÄLÄ, M. 1980. Stratigraphy of a silt-cored palsa, Atlin region, British Columbia, Canada. Arctic 33:357–365.

SIMS, R.A., D.W. COWELL, AND G.M. WICKWARE. 1982. Classification of fens near southern James Bay, Ontario, using vegetational physiognomy. Canadian Journal of Botany 60:2608–2623.

SJÖRS, H. 1950. On the relation between vegetation and electrolytes in north Swedish mire waters. Oikos 2:241–258.

SJÖRS, H. 1980. An arrangement of changes along gradients, with examples from successions in boreal peatland. Vegetatio 43:1–4.

SNOW, N.B., AND D.M. ROSENBERG. 1975a. Experimental oil spills on Mackenzie Delta lakes. I. Effect of Norman Wells crude oil on Lake 4. Fisheries and Marine Service, Environment Canada. Technical Report No. 548. 44 p.

SNOW, N.B., AND D.M. ROSENBERG. 1975b. Experimental oil spills on Mackenzie Delta lakes. II. Effect of two types of crude oil on Lakes 4C and 8. Fisheries and Marine Service, Environment Canada. Technical Report No. 549. 19 p.

STAGER, J.K. 1974. Old Crow, YT. and the proposed northern gas pipeline. Environmental–Social Committee, Northern Pipelines. Task Force on Northern Oil Development. Report No. 74-21. 233 p.

TARNOCAI, C. 1972. Some characteristics of cryic organic soils in northern Manitoba. Canadian Journal of Soil Science 52:485–496.

TARNOCAI, C. 1973. Soils of the Mackenzie River area. Environmental–Social Committee, Northern Pipelines. Task Force on Northern Oil Development. Report No. 73-26. 136 p.

TARNOCAI, C. 1982. Soil and terrain development on the York Factory Peninsula, Hudson Bay Lowland. Naturaliste canadien 109:511–522.

TARNOCAI, C. 1984. Peat resources of Canada. National Research Council of Canada. Publication No. 24140. Ottawa, Ontario. 17 p.

TIKHOMIROV, B.A. 1952. The importance of moss cover in the vegetation of the far north. Botanicheskiy Zhur. Sept. 629–638.

VELDHUIS, H. 1980. Soil and vegetation sequences in the Mackenzie Delta, NWT. *In* 24th Annual Meeting, Canadian Society of Soil Science. Winnipeg, Manitoba. pp. 12–21.

WATSON, G.H., W.H. PRESCOTT, E.A. DE BOCK, J.W. NOLAN, M.C. DENNINGTON, H.J. POSTON, AND I.G. STIRLING. 1973. An inventory of wildlife habitat of the Mackenzie Valley and the northern Yukon. Environmental–Social Committee, Northern Pipelines. Task Force on Northern Oil Development. Report No. 73-27. 152 p.

WELLEIN, E.G., AND H.G. LUMSDEN. 1964. Northern forests and tundra. *In* Waterfowl tomorrow. J.P. Linduska, editor. Bureau of Sport Fishing and Wildlife, Fish and Wildlife Service, United States Department of the Interior. pp. 67–76.

WOOLEY, D.R. 1974. Beaver (*Castor canadensis*) studies in the Mackenzie Valley, 1972. Chapter II. *In* Studies of furbearers associated with proposed pipeline routes in the Yukon and Northwest Territories. R.A. Ruttan and D.R. Wooley, editors. Canadian Arctic Gas Study Ltd. Biological Report Series. Volume 9. 52 p.

ZOLTAI, S.C., AND W.W. PETTAPIECE. 1973. Terrain, vegetation, and permafrost relationships in the northern part of the Mackenzie Valley and northern Yukon. Environmental–Social Committee, Northern Pipelines. Task Force on Northern Oil Development. Report No. 73-4. 105 p.

ZOLTAI, S.C., AND C. TARNOCAI. 1971. Properties of a wooded palsa in northern Manitoba. Arctic and Alpine Research 3:115–129.

ZOLTAI, S.C., AND C. TARNOCAI. 1975. Perennially frozen peatlands in the western Arctic and Subarctic of Canada. Canadian Journal of Earth Sciences 12:28–43.

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