A paleoecological analysis of a southern permafrost peatland, Charlevoix, Quebec

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Abstract: The southernmost site where permafrost has been located in the Quebec–Labrador peninsula is in a peatland on the subalpine summit of Lac des Cygnes Mountain (47°41′N, 70°36′W). Because of the thickness of its peat deposit, this site contains rich ecological information about the history of the peatland and its surrounding subalpine environment. We conducted a detailed macrofossil analysis to reconstruct the 6000-year history of the peatland. In general, the development of the Lac des Cygnes Mountain peatland has followed the classic succession of rich fen – poor fen – bog found in other peatlands in subarctic, boreal, and temperate environments. An abrupt decline in all tree macrofossils ca. 4000 BP suggests that a major deforestation event occurred on the summit of Lac des Cygnes Mountain. The exact cause of this deforestation event is unknown, but fire is a possible factor. The lack of absolute chronological resolution near the top of the macrofossil record precludes proper dating of permafrost inception, but the balance of evidence appears to indicate that the permafrost is modern.

Résumé : Le site avec pergélisol le plus méridional de la péninsule du Québec–Labrador (à ce jour) est localisé dans une tourbière au sommet subalpin du mont du Lac des Cygnes (47°41′N, 70°36′O). En raison de son dépôt tourbeux épais, la tourbière contient un grand nombre d’informations de nature écologique sur l’histoire de la tourbière et de son environnement subalpin immédiat. Nous avons réalisé une analyse macrofossile détaillée pour reconstituer l’histoire de la tourbière sur une période de près de 6000 ans. En général, le développement de la tourbière du mont du Lac des Cygnes suit la succession classique fen riche – fen pauvre – bog observée dans d’autres tourbières des régions subarctiques, boréales ou tempérées. La disparition abrupte des macrofossiles des essences arborescentes vers 4000 ans avant le Présent suggère que le plateau sommital du mont du Lac des Cygnes a subi une déforestation de grande importance à cette époque. La cause exacte de cette déforestation est inconnue, mais il est possible qu’un feu soit à l’origine du phénomène. La faible résolution chronologique de l’analyse macrofossile ne permet pas de dater de façon précise le début de la formation du pergélisol dans la tourbière, mais plusieurs indices laissent croire que ce pergélisol est d’origine récente.

Introduction

Permafrost covers approximately one third of the Quebec–Labrador peninsula. In the northern part of the peninsula (north of 58°N), cold climatic conditions are responsible for the formation of a continuous, thick (~150 m) permafrost zone (Fig. 1). South of 56°N, permafrost is widespread, but mainly located in peatlands (Allard and Seguin 1987). Peat is a good insulating material, and prevents frozen soils from thawing during the summer season (Brown 1970). South of 52°N, permafrost islands are scarce, and to date, the southernmost are located on mountains in the Charlevoix and Gaspésie regions (Gray and Brown 1979; Dionne 1984; Payette 1984).

The southernmost site with permafrost identified in the Quebec–Labrador peninsula is located on the summit of Lac des Cygnes Mountain, in Charlevoix (47°41′N, 70°36′W), and was discovered by S. Payette in 1982 (Payette 1984). The 2-m thick frozen soil is restricted to a small (0.3 ha) peat bog surrounded by subalpine vegetation. The permafrost likely remains at temperatures very close to the freezing point for most of the year (Allard and Fortier 1990). From an analysis of the peat stratigraphy, Payette (1984) has suggested that permafrost development was initiated during the Little Ice Age (ca. AD 1570–1880).

The occurrence of permafrost in such a southern and low-altitude site (<1000 m) is an interesting periglacial phenomenon, since it is not clear whether cold climatic conditions alone or a combination of climatological and ecological factors (Arseneault and Payette 1997) led to its formation. Furthermore, the peatland itself is ecologically significant, since its peat deposit would have recorded environmental changes in the surrounding area during the late-Holocene epoch. Lac des Cygnes Mountain is covered

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Fig. 1. Spatial distribution of permafrost in the Quebec–Labrador peninsula (Allard and Seguin 1987; Dionne 1984; Payette 1984), and location of the study area.

by large patches of subalpine–alpine vegetation dominated by lichens. This vegetation is similar to that found 700 km further north in the forest-tundra of the Quebec–Labrador peninsula (Payette 1983). Such open vegetation is unusual in the Charlevoix region: most mountains at a similar altitude are covered by dense spruce forests. Bussières et al. (1996) and Lavoie (2001) reconstructed the recent evolution of the vegetation in the area using macroscopic charcoal and fossil insects. They concluded that subalpine and alpine belts found in the Charlevoix region developed after 4000 BP, and resulted from reduced postfire tree regeneration, which likely occurred in relation to cold climatic conditions. It has also been suggested that the progressive opening up of the forest cover in the study area may have resulted from the cumulative impact of insect outbreaks, cold climatic conditions, and fires (Payette et al. 2000). However, a long, continuous record of environmental changes has not yet been developed for the alpine–subalpine summits in the Charlevoix area. Furthermore, it has not been possible to precisely date the beginning of the deforestation period and to make conclusions regarding the exact cause of this deforestation.

The Lac des Cygnes Mountain appears to be very sensitive to ecological disturbances, and the reconstruction of its vegetation history during the Holocene epoch may provide rich information about past environmental conditions. The vegetation history of the mountain can be reconstructed using the peat deposit of the permafrost peatland located near the summit, where environmental changes are expected to be more important (Lavoie 2001). We conducted a detailed macrofossil analysis (vascular plant, moss, lichen, cladoceran, and charcoal remains) using a peat core extracted from this peatland. The objectives of this study were to (1) reconstruct the history of the peatland and its surrounding environment and (2) determine when the deforestation event of Lac des Cygnes Mountain occurred and the possible causes underlying this deforestation.

Study area

The Lac des Cygnes site (Fig. 1) is a part of Grands-Jardins Provincial Park and one of several mid-altitude (700–1000 m) mountains in the Charlevoix area that form a high plateau subdivided by many deep valleys. In 1986–1987, temperatures were recorded on the summit of Lac des Cygnes Mountain at the exact location of the permafrost peatland. Between May 1986 and April 1987, the annual mean temperature was –1.3°C, the mean temperature for the coldest month (February) was –15°C, and that of the warmest month (July) was 10°C (Allard and Fortier 1990). Vegetation was established after deglaciation, ca. 9200 BP. Pollen analyses indicate that a forest cover composed of balsam fir (*Abies balsamea*), white birch (*Betula papyrifera*), and black spruce (*Picea mariana*) became established about 8000–7400 BP on the plateau, although these tree species were probably present in the study area from 8700 BP (Bussières 1992). Today, on mesic sites, balsam fir is the main tree species, but it is replaced in wet depressions and on high-altitude (>800 m) sites by black spruce. Fir and spruce forests are mainly disturbed by spruce budworm (*Choristoneura fumiferana*) outbreaks. Three spruce budworm outbreaks were recorded in the study area during the 20th century, between AD 1909–1921, 1948–1954, and 1974–1987 (Perron 1994). Fire is also a common disturbance in the Charlevoix region. The most recent fires that burned Lac des Cygnes Mountain were reported in AD 1915 and 1991. The 1991 fire did not disturb the permafrost peatland and its surrounding environment. Another, earlier fire occurred on Lac des Cygnes Mountain about AD 1807 (Dion 1986).

The permafrost peatland is located at an altitude of 960 m. Tree cover in the surrounding well-drained sites is low (<30%) and characterized by the presence of scattered black spruce individuals with eroded growth forms, which are typical of environments with harsh winter conditions (Lavoie and Payette 1992). The main part of the bog is occupied by a peat plateau, slightly raised (50–100 cm) above the water level. On the plateau, vegetation is sparse and dominated by lichens (mainly *Cladina rangiferina*) and ericaceous shrubs. Tree cover is very low (<1%); only stunted balsam fir, black spruce, mountain paper birch (*Betula cordifolia*), and tamarack (*Larix laricina*) individuals are present. During the sampling period (May 1998), the maximum thickness of the thawed surface layer was 10 cm. The frozen layer extended to the underlying rock surface and was at least 217 cm thick.

Methods

In spring 1998 (15 May), a 227 cm-long peat core (diameter: 6 cm) was extracted from the center of the permafrost peatland using a power auger. In the laboratory, peat sections were kept frozen before processing to prevent fungal contamination (Wohlfarth et al. 1998). Subsamples of 150 cm^3 were taken each 5 cm along the peat core. Subsamples were washed through a series of screens (2, 1, and 0.5 mm meshes), and the remaining fractions were air-dried, again to prevent fungal contamination (Wohlfarth et al. 1998). Macroscopic remains (vascular plant, moss, lichen, cladoceran, and charcoal pieces) were sorted under a low-power (50×) binocular microscope. Identified specimens were mounted on micropaleontological slides with gum tragacanth. When macrofossil remains of a particular taxon were too numerous in a subsample to be easily counted (n > 200), 0.5 g of the subsample was extracted; fossil pieces were then counted, and the real number of pieces was estimated for the total weight of the subsample (Lavoie and Payette 1995). Macrofossil diagrams were constructed using the total number of pieces for each taxon that were detected, and macrofossil zones were then delimited according to the changes observed in the relative abundance of taxa and the species composition through the peat profile.

Past fires in the peat profile were detected by extracting 10 cm^3 from the 1- and 0.5-mm fractions of each subsample and counting the charcoal pieces under a binocular microscope. Charcoal pieces from the 2-mm fractions were not considered, because they differed too much in size to be compared, but their presence was nevertheless noted. Charcoal number was adjusted for a total volume of 150 cm^3 of peat (Pellerin and Lavoie 2000). Finally, plant remains were extracted from the subsamples for conventional (5–10, 45–50, 100–105, 150–155 cm) or accelerator mass spectrometry (225–227 cm) radiocarbon dating. Radiocarbon dates were calibrated (Stuiver and Reimer 1993) and used to calculate the peat accumulation rate. This rate is essential for determining the macrofossil influx, or the number of macrofossil pieces that were deposited per cm^2 per year (Birks and Birks 1980).

Nomenclature follows (1) Scoggan (1978–1979) for vascular plants, except Farrar (1996) for trees, (2) Ireland et al. (1987) for mosses, (3) Esslinger and Egan (1995) for lichens, and (4) Thorp and Covich (1991) for cladocerans.

Results

Peat accumulation rate

Peat accumulation (Table 1; Fig. 2) extended over a period of 6600 years, i.e. from ca. 4650 BC to present (ca. 5800 BP to present). A high peat accumulation rate (0.56 mm/year) was recorded in the basal peat deposit (5800–4820 BP). Between 4820 and 3130 BP, the peat accumulation rate decreased strongly (0.23 mm/year), but then increased slightly (0.33 mm/year) between 3130 and 1720 BP. The accumulation rate was low after 1720 BP (0.24 mm/year).

Macrofossils

According to changes observed in the relative abundance of taxa and the species composition throughout the peat profile (Figs. 3, 4), six zones can be delimited to reconstruct the history of the peatland and its surrounding environment.

Zone I: 227–195 cm (ca. 5800–5380 BP)

This zone corresponds to the beginning of peat accumulation in the depression. The peat formed during this period was composed mainly of moss (*Drepanocladus* spp.) fragments. The dominant sedge species identified was *Carex lasiocarpa*. Tree remains (*Abies balsamea*, *Betula cordifolia* and (or) *papyrifera*, *Larix laricina*, *Picea mariana*) were very numerous. Some fossil pieces from shrub species were recovered (*Chamaedaphne calyculata, Ledum groenlandicum*). Seeds of an aquatic species, *Menyanthes trifoliata*, were also extracted from the peat samples. Ephippia of *Daphnia* spp. were particularly numerous in the basal peat subsample (227–225 cm). A few charcoal pieces were recovered between 227 and 225 cm, and 220 and 215 cm.

Zone II: 195–150 cm (ca. 5380–4820 BP)

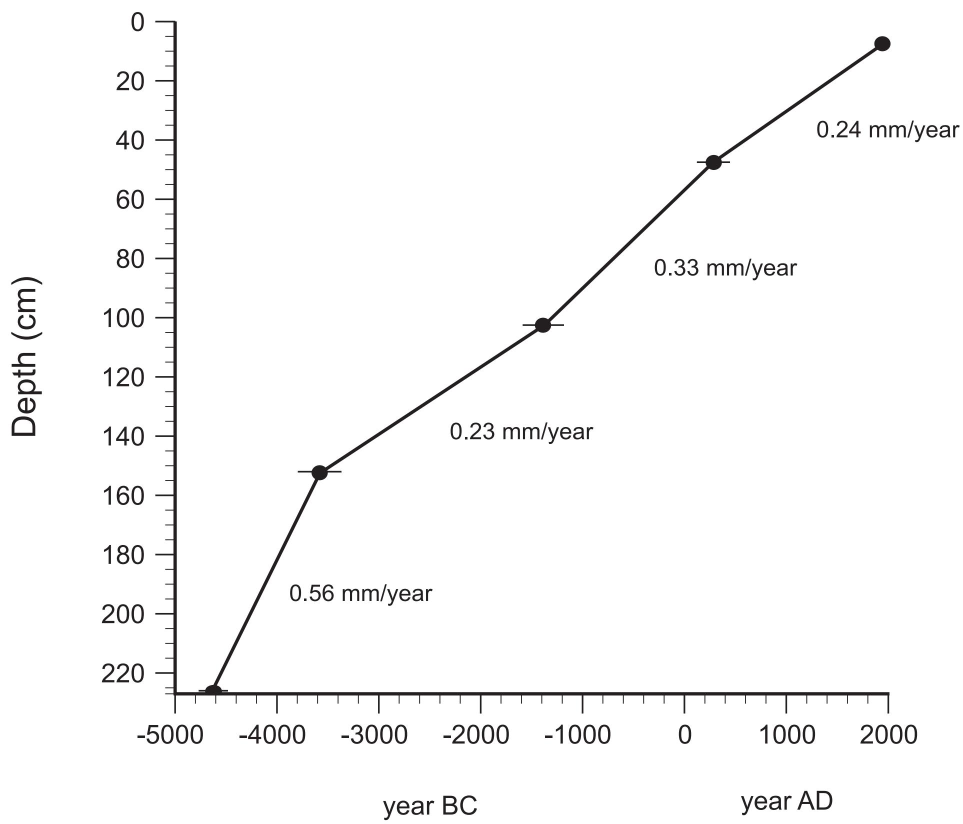
This zone is characterized by the almost complete disappearance of *Drepanocladus* fragments. Remains of the sedge

Table 1. Radiocarbon ages from the Lac des Cygnes Mountain peatland.

Laboratory No.	Core depth (cm)	Radiocarbon age (years BP ± σ)	Calibrated age (years AD or BC)[a]	Dated material
UL-1954	5–10	Modern	AD 1950	Peat, wood
UL-1900	45–50	1720 ± 70	AD 283	Peat
UL-1955	100–105	3130 ± 100	1375 BC	Peat, wood
UL-1956	150–155	4820 ± 100	3578 BC	Peat, wood
TO-7604	225–227	5800 ± 60	4630 BC	Peat

[a]Mean from the standard deviation.

Fig. 2. Peat accumulation rate for the permafrost peatland of Lac des Cygnes Mountain, Quebec. Horizontal bar: ± 1 standard error.



species *Carex lasiocarpa* were also progressively replaced by those of *C. trisperma*. Tree remains decreased in abundance during this period. Between 180 and 150 cm, numerous charcoal pieces were recovered, particularly between 160 and 155 cm. Charcoal was composed of wood fragments and charred needles of fir, tamarack, and spruce trees.

Zone III: 150–130 cm (ca. 4820–4060 BP)

The peat in this zone was composed of numerous *Sphagnum* and sedge or cotton-grass (*Carex limosa*, *Eriophorum vaginatum* ssp. *spissum*) remains. Fossil pieces from tree species and from two ericaceous shrub species (*Chamaedaphne calyculata*, *Ledum groenlandicum*) were also abundant.

Zone IV: 130–50 cm (ca. 4060–1720 BP)

Very few remains of tree species were recovered in the peat samples corresponding to Zone IV, which contrasts strongly with Zone III. Throughout this period, the tree macrofossil influx was close to zero. Two tree species disappeared almost completely from the record (fir, birch). Few remains of spruce and tamarack were detected. The most abundant remains of shrub species were *Andromeda glaucophylla*, *Chamaedaphne calyculata*, and *Ledum groenlandicum.* Some cotton-grass pieces were identified. *Sphagnum* fragments were the most abundant moss remains recovered, but they were not very numerous. Three abundance peaks of charcoal (120–110, 105–95, 75–55 cm) suggest fire events. The first two charcoal assemblages contained very few identifiable remains. However, the charcoal assemblage located between 75 and 55 cm was composed of several spruce and ericaceous shrub remains.

Zone V: 50–10 cm (ca. 1720 to recent)

The peat in this zone was mainly composed of *Sphagnum* fragments. Spruce remains were more abundant in Zone V than in Zone IV. Cyperaceae remains were dominated by

Carex trisperma and *Eriophorum vaginatum* ssp. *spissum*. Numerous charcoal pieces (spruce and shrub charred remains) were recovered between 25 and 15 cm.

Zone VI: 10–0 cm (present)

Between 10 and 5 cm, a rise in both the number of tree (fir, tamarack, spruce) macrofossil pieces and the tree macrofossil influx was observed. However, very few tree remains were recovered from the surface peat sample (5–0 cm). Throughout Zone VI, there was an increase in the quantity and diversity of ericaceous shrub remains (*Chamaedaphne calyculata*, *Kalmia angustifolia*, *Ledum groenlandicum*, *Vaccinium angustifolium/myrtilloides*, *V. oxycoccus*, *V. uliginosum*). Lichens and some moss species (*Dicranum* spp., *Pleurozium schreberi*) were also particularly abundant, and contributed to form sylvic peat. A major abundance peak of charcoal was detected between 10 and 5 cm.

Vegetation reconstruction

Zone I: rich and humid treed fen (ca. 5800–5380 BP)

Peat accumulation began ca. 5800 BP, and contributed to the formation of a rich and humid treed fen (Fig. 5). Moss and sedge species were dominated by taxa such as *Drepanocladus* spp. and *Carex lasiocarpa*, that proliferate in minerotrophic environments when the water table is close to the soil surface and water pH values are high (Jeglum 1971; Kuhry et al. 1992; Jasinski et al. 1998; Camill 1999; Garneau 1999). The presence of small shallow ponds is indicated by *Menyanthes trifoliata* and *Daphnia* spp. (Jeglum 1971; Couillard and Grondin 1986; Lavoie 1998; Peteet et al. 1998). The high tree macrofossil influx (birch, fir, spruce, tamarack) indicates that the peatland and its surrounding environment were characterized by a dense boreal forest cover. However, birch and fir individuals were probably located only on the mesic sites surrounding the peatland, since these trees are not wetland species (Richard 1975; Lavoie 1998). Some of their plant structures (seeds, needles) are easily dispersed by wind, which could explain their presence in the macrofossil assemblage. In the fen, the tree cover was probably composed of black spruce and tamarack, which are typical peatland species (Montague and Givnish 1996).

Zone II: transition: rich fen – poor fen (ca. 5380–4820 BP)

About 5400 BP, a transition occurred in the trophic regime: the rich fen progressively developed into a poor fen. *Drepanocladus* spp. mosses disappeared rapidly, and *Carex lasiocarpa* was replaced by *C. limosa* and *C. trisperma*, sedge species that colonize more acid oligotrophic wetlands (Jeglum 1971; Couillard and Grondin 1986). The presence of seeds of *Menyanthes trifoliata* suggests that some shallow ponds were still present. During this period, the tree macrofossil influx decreased and reached a minimum during a fire event occurring ca. 4900 BP. This fire disturbed not only the mesic sites surrounding the peatland, but also the peatland itself, as suggested by the decrease in the number of macrofossil pieces of all tree species, including black spruce and tamarack.

Zone III: poor and humid treed fen (ca. 4820–4060 BP)

For a period of ca. 880 years, the site was characterized by a poor and humid treed fen. The peatland was colonized by black spruce, tamarack, and several ericaceous shrub, sedge, and *Sphagnum* species. Numerous remains of cotton-grass (*Eriophorum vaginatum* spp. *spissum*) were recovered, suggesting more ombrotrophic conditions (Couillard and Grondin 1986). The high tree macrofossil influx indicates a dense tree cover. The surrounding mesic sites were still covered by fir and birch populations.

Zone IV: open bog with ericaceous shrubs (ca. 4060–1720 BP)

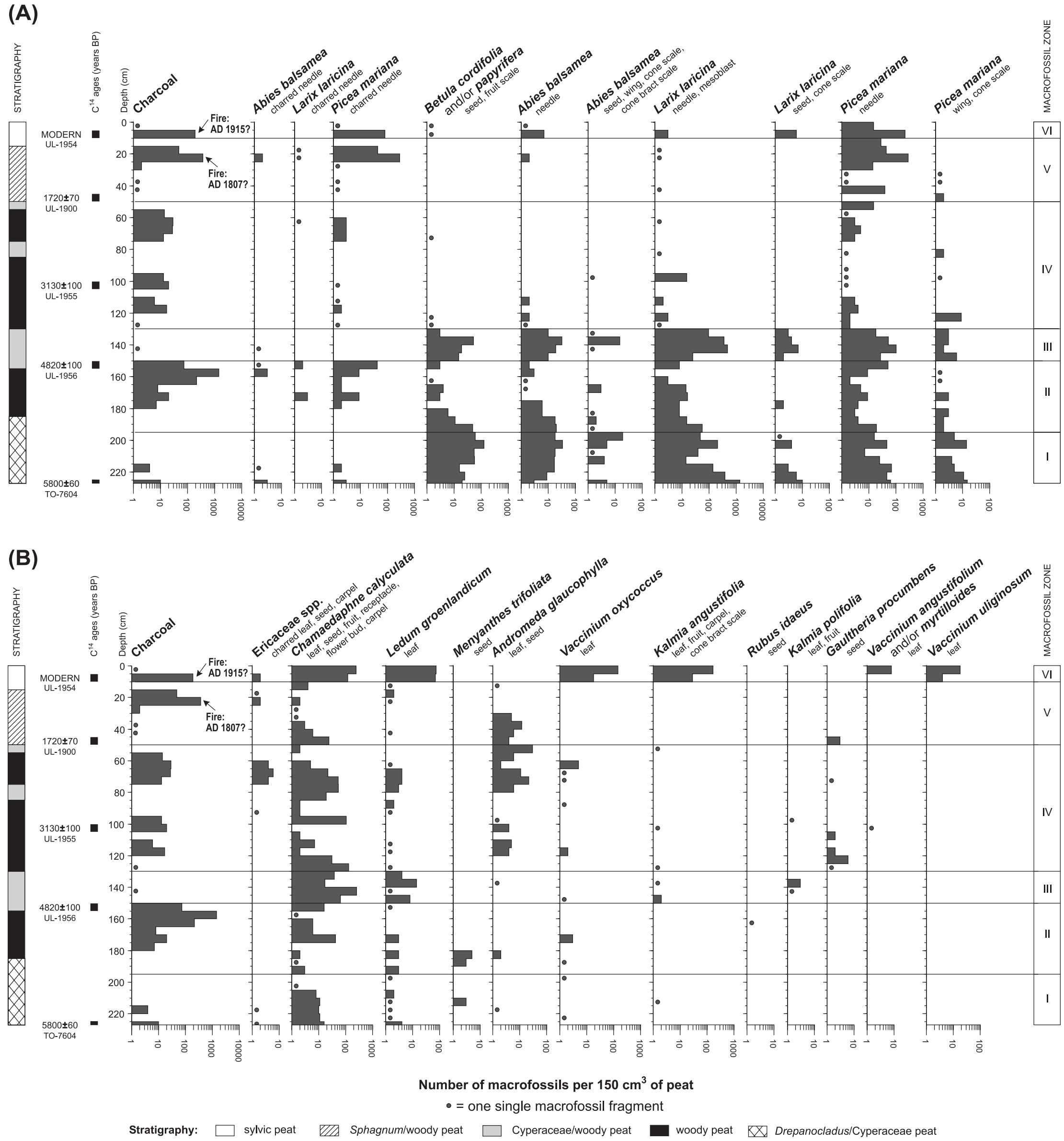
About 4000 BP, the tree cover of the peatland and its surrounding environment drastically declined. The peatland was also more ombrotrophic. Remains of *Andromeda glaucophylla*, a typical bog plant species (Comtois 1982), were numerous. Macrofossil pieces of *Carex limosa*, a fen species (Camill 1999), disappeared during this period. Fluctuations in the relative abundance of *Sphagnum*, lichen, ericaceous shrub, and cotton-grass remains could be related to vegetation changes associated with microrelief modifications through time (Ikonen 1993). Of the three charcoal assemblages detected in Zone IV (ca. 3600, 3100, and between 2500–2000 BP), only the fire, which occurred between 2500–2000 BP, disturbed the peatland, since charred remains of black spruce and ericaceous shrubs were recovered.

A change in the trophic regime of the peatland could partially explain the decline of black spruce and tamarack. However, it does not explain the simultaneous decline of tree species colonizing mesic sites (birch, fir). It is unlikely that an insect outbreak was the main cause of this decline since all tree species (broad-leaved and coniferous species) disappeared during this period. Furthermore, the decline does not seem to coincide with a fire event. Consequently, there are two possible explanations for this phenomenon. First, tree decline may have been related to a fire event that was not detected in the macrofossil analysis. This fire would likely have occurred during cold climatic conditions, reducing postfire tree regeneration (Payette and Gagnon 1985; Bussières et al. 1996; Arseneault and Payette 1997). Second, an abrupt (no more than several decades long) and major (several degrees Celcius) climate cooling event may have occurred, strongly reducing the forest cover on the summit of Lac des Cygnes Mountain. However, the latter hypothesis is not preferred, since no major climatic cooling episode has been reported for southern Quebec ca. 4000 BP (Richard 1994; Lavoie 1998).

Zone V: open *Sphagnum* bog (ca. 1720 to recent)

For most of the last 1700 years, the peatland was characterized by an open bog dominated by *Sphagnum*, ericaceous shrub, and cotton-grass species. Few black spruce individuals were present, but the tree macrofossil influx increased at the end of Zone V, suggesting a closing in of the tree cover in the peatland and (or) the surrounding mesic sites. The quasi-absence of fir and birch remains suggests that these tree species have never recolonized mesic sites. A major charcoal assemblage (25–15 cm) suggests that a fire disturbed the bog and mesic sites. Dion (1986) estimated that a fire occurred on Lac des Cygnes Mountain ca. AD 1807; it

Fig. 3. Macrofossil diagram for the permafrost peatland of Lac des Cygnes Mountain, Quebec: (A) Betulaceae and Pinaceae, (B) Ericaceae, Menyanthaceae, and Rosaceae, (C) Cyperaceae and (D) Bryophyta, Lichenes, and Cladocera.



is likely that the charcoal assemblage located between 25 and 15 cm was produced by this fire.

Zone VI: open permafrost bog (present)

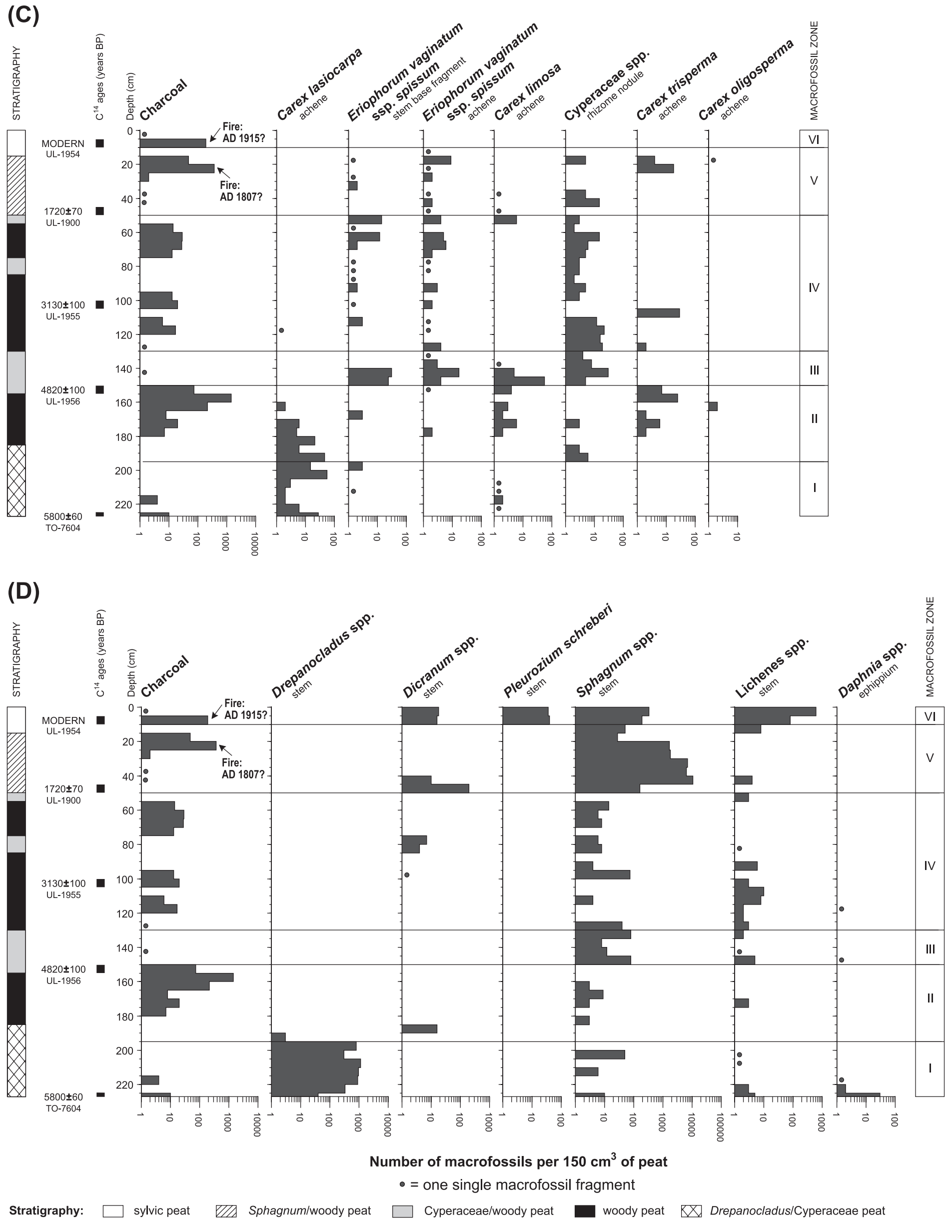
Today, a treeless permafrost peat plateau characterizes the site. The growth of ice lenses in the soil has raised the bog surface above the water table. This has caused the soil surface to dry out, and favored the establishment of lichens and the formation of sylvic peat. Two species appear here for the first time in the macrofossil record: *Pleurozium schreberi* and *Vaccinium uliginosum*. Remains of ericaceous shrub species were also particularly abundant in Zone VI, suggesting a drying of the environment (Zoltai 1993). A charcoal assemblage (10–5 cm) suggests that a fire recently burned the peatland and the surrounding environment. This assemblage probably corresponds to the AD 1915 fire (Dion 1986). This fire also favored the establishment of ericaceous shrubs on the bog (Zoltai and Tarnocai 1975; Morneau and Payette 1989).

Discussion

Development of the peatland of Lac des Cygnes Mountain: autogenic and allogenic processes

In the period following deglaciation of the Charlevoix region and up until 6000 BP, cold climatic conditions probably persisted in the mountainous areas of southern Quebec. After 6000 BP, the climate of southern Quebec was warmer and wetter (Richard 1995), which probably contributed to initiating peat accumulation on Lac des Cygnes Mountain (about 5800 BP). After this event, peatland development was mainly influenced by autogenic processes. This study shows that the progressive thickening of the peat deposit favored the establishment of ombrotrophic species (e.g., *Sphagnum*

Fig.3 (*concluded*)



spp.) at the expense of minerotrophic species (e.g. *Carex* spp.). In general, and for most of its existence, the development of the Lac des Cygnes Mountain peatland followed the classic succession of rich fen to poor fen to bog found in other subarctic (Jasinski et al. 1998; Vardy et al. 1998), boreal (Kuhry et al. 1992, 1993; 1997; Lavoie 1998) and temperate peatlands (Lavoie et al. 1995; Lavoie 1998; Robichaud 2000).

Deforestation of Lac des Cygnes Mountain

The macrofossil analysis of the Lac des Cygnes Mountain peatland gives information not only about the development of the bog, but also about the forest cover in the surrounding environment. An abrupt decline in all tree species ca. 4000 BP suggests that a major deforestation event occurred on the summit of Lac des Cygnes Mountain. The summit has been partially reforested with black spruce during the last 1000 years, but fir and birch tree species have never recolonized the site. Today, balsam fir is rarely seen on Lac des Cygnes Mountain above an altitude of 800 m (Dion 1986). The exact cause of this deforestation is still unknown, but the fact that balsam fir has a low postfire regeneration potential (Payette 1992; Sirois 1997) suggests that fire was a possible factor in this decline.

Initiation of permafrost in the peatland of Lac des Cygnes Mountain

Autogenic or allogenic factors may be responsible for the aggradation and degradation of permafrost in peatlands. Seppälä (1982) has shown that a thin snow cover is a major factor favoring the formation of permafrost in subarctic peatlands, since a larger quantity of snow insulates the ground surface

Fig. 4. Macrofossil concentration and influx diagram for the permafrost peatland of Lac des Cygnes Mountain, Quebec.

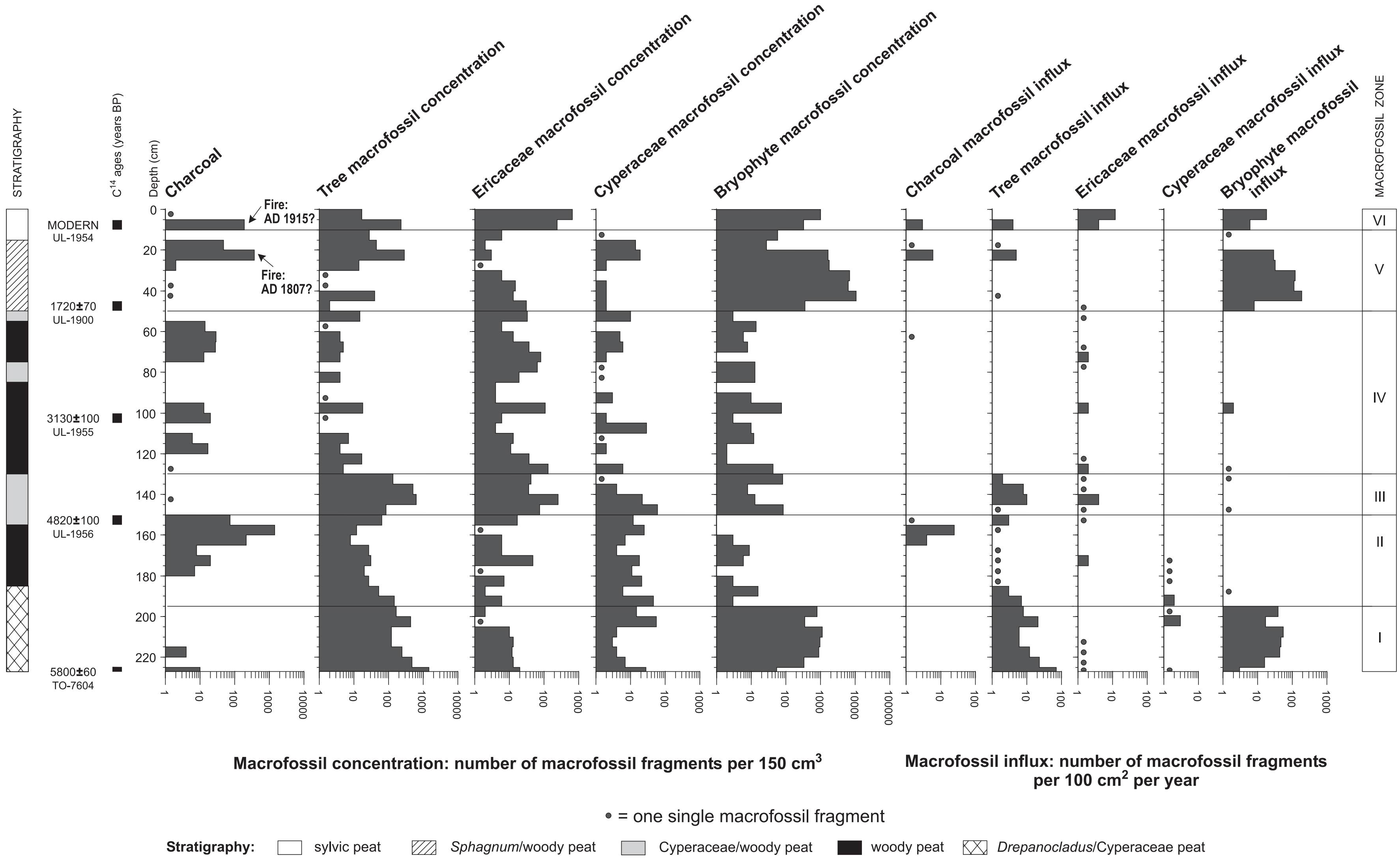
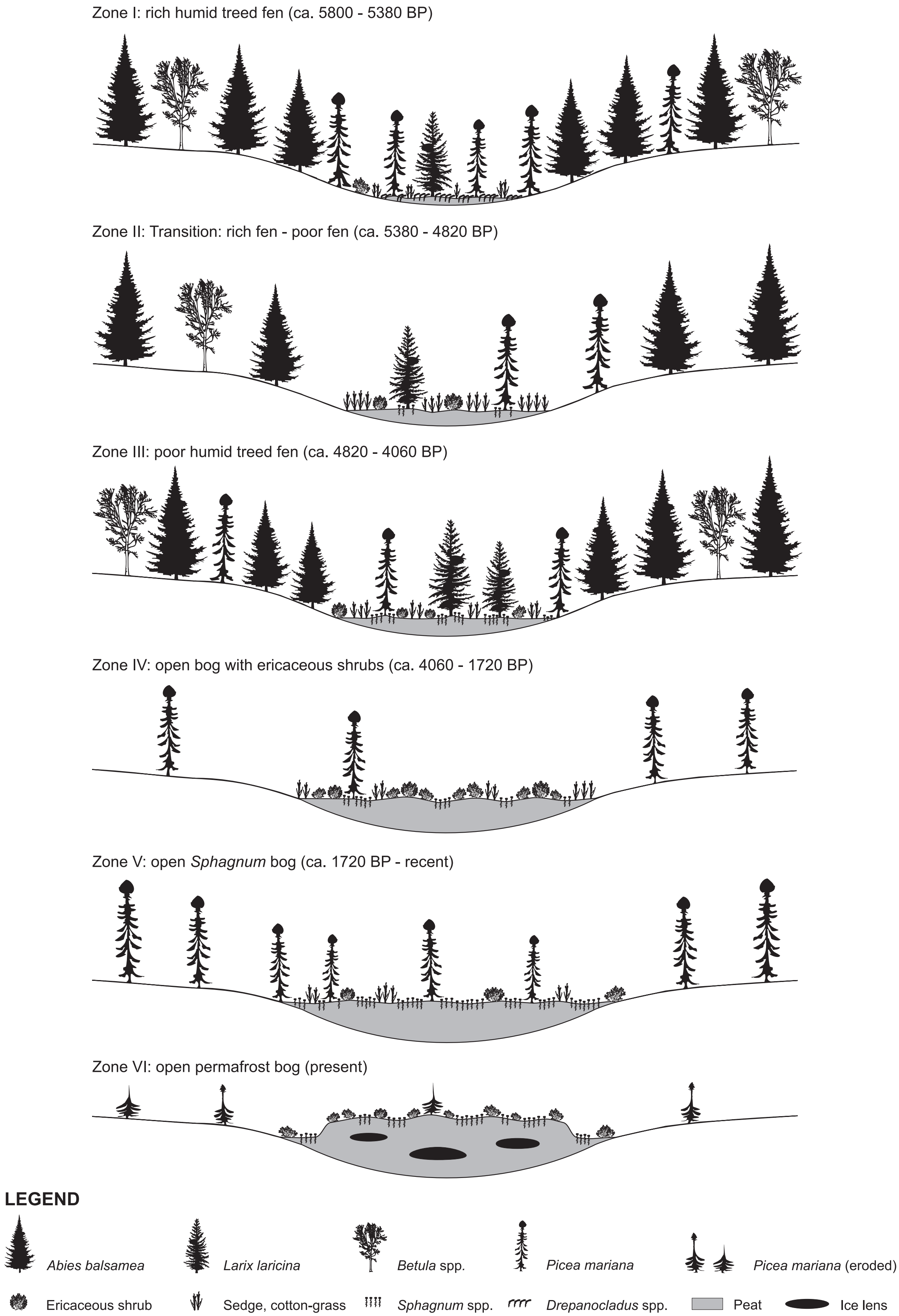


Fig. 5. Schematic representation of the history of the permafrost peatland of Lac des Cygnes Mountain, Quebec, and its surrounding environment.



from frost. Using macrofossil analyses, Zoltai (1993) proposed that the presence of a thin layer (40–70 cm) of *Sphagnum fuscum* in the bogs of northwestern Alberta (Canada) allows the surface to become dry during summer and increases the insulation value of the peat, thus preventing complete thawing of the frozen soil. The aggrading permafrost elevates the peat surface above the water table, creating a dry habitat favoring the establishment of trees, ericaceous shrubs, feathermosses, and lichens, as well as the formation of sylvic peat. This elevation of the soil surface strongly reduces the peat accumulation rate, but does not completely prevent peat formation (Robinson and Moore 1999, 2000). Fires may consume vegetation and dry peat in the active layer and initiate widespread permafrost degradation, but this is not necessarily the case for all fire events (Zoltai 1993).

The peatland environment of the summit of Lac des Cygnes Mountain was open as early as 4000 BP and the low tree cover between 4000 and 1700 BP probably did not favor snow accumulation (Allard and Fortier 1990). However, there is no indication in the vegetation record of permafrost development during this period, such as the formation of sylvic peat (sensu Zoltai 1993, 1995). In fact, this peat is present only in the surface (10–0 cm) peat layer, and just above a thick (50 cm) layer of *Sphagnum* spp. It is thus possible that climatic conditions were not cold enough between 4000 and 1700 BP to initiate the formation of permafrost in the peatland. An alternative hypothesis would be that because of the absence of a thick *Sphagnum* layer in zone IV, the insulation value of the peat was not great enough to prevent thawing of the frozen soil, particularly at such a southern and low-altitude site as Lac des Cygnes Mountain.

The lack of absolute chronological resolution near the top of the record precludes proper dating of permafrost inception. However, the balance of evidence appears to indicate that the permafrost is modern. The presence of sylvic peat near the surface suggests permafrost during deposition, but the permafrost likely started to form in the latter stages of *Sphagnum* accumulation (Robinson and Moore 2000), i.e. at the end of Zone V. As previously suggested by Payette (1984), the Little Ice Age seems to be the best candidate for the time when environmental conditions would permit inception, within resolution of the chronology. This would be another indication that this global climatic event had impacts not only in subarctic environments (Payette et al. 1985), but also at the southern fringe of the boreal forest in northeastern North America.

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