Development of a raised bog over 9000 years in Atlantic Canada

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SUMMARY

The chronostratigraphy of a coastal bog was studied in order to distinguish the roles of autogenic and allogenic factors in peatland development. Well-dated stratigraphical sequences from a peat cliff were used. The peatland shows three main vegetation phases: rich fen, poor fen and bog. Peat formation started around 9500 yr BP and the first expansion phase of rich fen occurred between 8550 and 7400 yr BP. The rich fen gradually changed to a poor fen through autogenic processes between 7620 and 5500 yr BP. It then became a bog in two major development phases, possibly in response to climate change, around 5250 yr BP (central part) and 2800 yr BP (margins). Expansion resumed after 5500 yr BP and terminated shortly after 2500 yr BP when the peatland had filled the basin. Although autogenic succession is the dominant process by which the peatland has evolved, climatic variability has also affected peat expansion and vegetation change. The influence of fire was very limited but topography played a major role in peat expansion. One major find is that climate change can trigger simultaneous but various responses in local vegetation, depending upon its position on the bog surface.

KEY WORDS: autogenic, fire, palaeoclimate, peatland processes, Pointe Escuminac, stratigraphy.

INTRODUCTION

Environmental change is a continual process that is well recorded in only a few ecosystems. Amongst these are bogs, which are remarkable archives of long-term natural changes because they document vegetation history within peat that accumulates almost continuously over several millennia (Payette & Rochefort 2001, Charman 2002). The development of bogs is known to be influenced by autogenic processes (peat build-up) and allogenic forcing (climate, disturbance, topography) in more or less complex combinations (Tolonen 1987, Korhola 1992, Kuhry *et al*. 1993, Korhola 1996, Payette & Rochefort 2001, Charman 2002). Understanding how bogs and other wetlands respond to climate change has become increasingly important in recent years for several reasons, the most significant being the possible impacts of global warming on the planetary carbon balance (Moore *et al*. 1998, Limpens *et al*. 2008) as well as on wetland resources and conservation (McCarthy *et al*. 2001).

In previous studies of bog stratigraphy, the use of single or small numbers of cores has contributed to setbacks and controversies (Frenzel 1983, Korhola 1996), primarily because localised effects often cannot be differentiated from total bog response. The best known data have been obtained from cut peat faces, which occur only exceptionally in nature (Tolonen 1987). One example is the impressive peat cliff at Pointe Escuminac, Atlantic Canada. Some paleoecological aspects of this site have been investigated by others (Korpijaako 1976, Tolonen *et al*. 1985, Warner *et al*. 1991 and 1993) on the basis of a few selected profiles. However, its full potential to yield a better understanding of how internal and external factors affect bogs has not previously been realised. Also, information on the stratigraphy of this exceptional site would contribute significantly to knowledge of peatland processes in Atlantic Canada, where few modern studies of peatland development have been completed.

In this paper we use multiple well-dated stratigraphical sequences to provide a detailed understanding of the spatial and temporal development of the Pointe-Escuminac bog, and on this basis present new evidence to distinguish between the autogenic and allogenic factors that regulate the inception and development of ombrotrophic peatland.

METHODS

Study site

Pointe Escuminac (47° 04' 18'' N, 64° 49' 58''W) is a headland on the Gulf of St Lawrence, eastern Canada (Figure 1). It lies at the edge of the New Brunswick lowland, the eastern part of which is characterised by slightly undulating, poorly drained

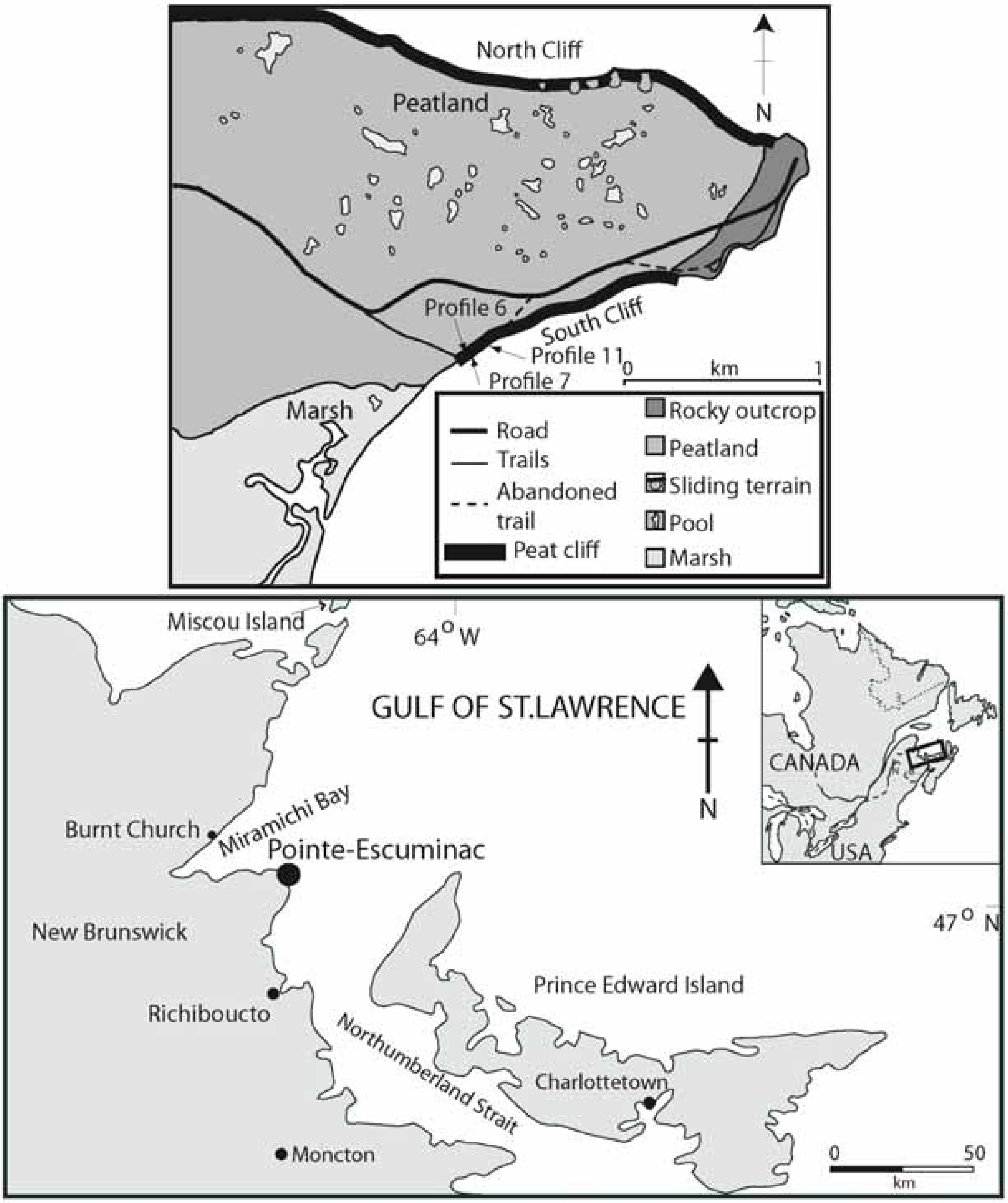

Figure 1. Location of the Pointe-Escuminac peat bog.

terrain which slopes gently towards the coast. The bedrock is Pennsylvanian (Carboniferous) sandstone, and this is covered by a thin layer of glacial sediments which were re-worked by marine processes during the early Holocene coastal regression. The climate is continental and humid with precipitation evenly distributed throughout the year. Annual precipitation is *ca*. 1,000 mm, of which 75–80 % falls as rain, and mean annual temperature is 4.8°C. January and February are the coldest months (monthly mean temperature -9.1°C) and July is the warmest (+19.1°C). The natural vegetation is mixed forest with *Picea mariana*, *Picea rubens* and *Abies balsamea* as the predominant conifers and *Acer rubrum*, *A. saccharum*, *Betula papyrifera* and *B. populifolia* the most common broad-leaved species (Rowe 1972).

The Pointe-Escuminac bog is a plateau raised bog occupying an area of 8.5 km^2. The present vegetation is a mosaic of communities with abundant *Sphagnum* mosses (*Sphagnum rubellum*, *S. fuscum*, *S. magellanicum* and *S. flavicomans*, with *S. cuspidatum* in pools). Lichens are frequent on the plateau. Ericaceaous species are widely distributed, the most abundant being *Kalmia angustifolia*, *Ledum groenlandicum* and *Chamaedaphne calyculata*; but *Rhododendron canadense*, *Gaylussacia baccata*, *G. dumosa*, *Vaccinium* spp., *Andromeda glaucophylla* and others also occur. Some herbaceous species (*Eriophorum spissum*, *Scirpus cespitosus*) are locally abundant. The central plateau is almost treeless except at the eastern fringes of pools, and trees (mostly *Picea mariana* and *Larix laricina*) are poorly represented in general. The slopes surrounding the bog are covered by ericaceous shrubs with scattered trees and an understory of *Sphagnum*.

The Pointe-Escuminac bog was chosen for this work because it has a peat cliff 6 km long, created by marine transgression over the last 7000 years (Kranck 1972). The natural exposures around the headland allow observation of the complete peat profile, from one margin of the bog to the other, and crossing through the central plateau area (Figure 1).

Stratigraphy

The South Cliff is almost 1.1 km long and up to 4.2 m high, exposing the varied peat stratigraphy and a few decimetres of the underlying mineral substrate. A thorough survey of the topography and chronostratigraphy of the cliff was carried out, identifying the major development phases and events according to:

1. peat contacts (mineral/organic, fen/bog *etc*.) and important features (wood layers, humified peat lenses, charcoal layers at the base of the peat and at major peat contacts);
2. expansion of peat over the mineral substrate; and
3. net accumulation rates.

Emphasis was placed on inter-bed contacts, wood and charcoal layers, and stratigraphical correlations and disruptions.

We described 46 profiles along the cliff. The topography of the basal mineral surface, which had been exposed by erosion in most sectors and was dug out if buried by sand, was measured with a theodolite and linked to the Hydrographic Service of Canada datum (the level of the lowest normal tide). The height and thickness of each stratigraphical unit was measured to a precision of ±5 mm. Stratigraphy was correlated along the cliff by inter-bed comparison. Peat humification was estimated following the von Post (1926) method (Damman & French 1987) and determined further from samples returned to the laboratory, mostly on the basis of the state of decay of debris.

Radiocarbon dating

Fifteen representative profiles were used for radiocarbon dating of the base of the peat and major contacts. Radiocarbon dates (n = 42) were obtained for peat, charcoal and wood using a benzene synthesis system and measuring the beta emission in a liquid scintillation counter at the Centre d'études nordiques ^{14}C laboratory, Université Laval. All dates mentioned or extracted from the literature are in conventional ^{14}C years BP. However, calibrated ages (cal yr BP) were calculated using the program CALIB 4.4.2 (Stuiver & Reimer 1993) and used (only) in the calculation of net vertical accumulation rates and lateral expansion rates.

Plant composition

Plant composition was determined for samples taken at the base of the peat, at major stratigraphical contacts, at the centres of major visible layers in the fifteen selected profiles mentioned above, and occasionally in other profiles. The samples were small peat monoliths 1–5 cm thick and roughly 15 cm across. These were placed in plastic bags, returned to the laboratory, then stored in a refrigerator at 2–4°C until analysed. The plant debris was sorted by passing through three sieves of 4.75 mm, 2 mm, and 425 µm mesh. Fragments other than wood and charcoal were identified under a dissecting microscope. The charred material was dried and viewed using a microscope equipped with an episcopic lighting device allowing observation by the reflection of light on the object. Identification was made according to specific anatomical characteristics described previously from a reference collection for each woody species. The relative frequencies (% of total assemblage) and weights (g/total weight) of identified pieces were obtained to infer plant assemblages and help characterise major peat types and general plant distribution for the entire peat sequence. Thus, the major stratigraphic units were described on the basis of a combination of field and laboratory observations, in terms of plant macrofossils, colour and texture, and degree of humification. This allowed the major peat types to be identified. Chronostratigraphical correlation between types was established using the radiocarbon dates and isochrones at 1000 year intervals derived from them by linear interpolation.

Interpretation

The major vegetation phases were inferred from changes in peat humification and the results of macrofossil analysis. Chronological control was provided by the radiocarbon dating, *in situ* correlation between visible stratigraphic features, and a few carefully chosen interpolations within and between peat profiles. Lateral and vertical net accumulation rates were derived from the radiocarbon dates for basal peat and selected stratigraphical contacts. Fire was inferred from the presence of macro-charcoal layers. Finally, we related the major phases of bog development to regional climatic events described in the literature and to recorded fire events, in order to verify potential connections between major vegetation changes and allogenic forcing of bog development.

RESULTS

Radiocarbon dates and calibrated ages are shown in Table 1, net vertical accumulation rates in Tables 2 and 3, and lateral expansion rates in Table 4. The major stratigraphical units are described in Table 5.

From the peat stratigraphy (Figures 2, 3), three major peat types were identified, each representing a major vegetation stage as indicated by the dominant plant taxa and assemblages found in the peat (Table 5). These are described in turn below.

Bottom peat (Type I): rich fen

Type I peat is very dark, compacted and well humified (Table 5), with an average thickness of 30 cm but thinning toward the margins of the bog. In the margins, it is visually indistinct from the overlying Type II peat and apparently non-existent in some profiles (e.g. Profile 7 in Figure 2). Within the central zone, a charcoal horizon at the mineral/peat contact was found at only three locations, and thus represents 10–20% of the contact at most. A few other charcoal layers can be observed within the basal peat of this zone. On the other hand, the charred basal horizon is almost continuous at the bog margins. The top contact with Type II peat is usually distinct.

Table 1. Radiocarbon ages of material from the Pointe-Escuminac southern peat cliff.

Laboratory number	Profile number	Depth (cm)	Description of sample *	Conventional ^{14}C age (years BP)	Calibrated age range at 1 σ of probability (years cal. BP)
UL-1420	1.5	50	Humified basal **peat**.	2640±90	2709–2868
UL-1235	5	85	*Sphagnum* **peat** at base of Type IIIb.	2460±90	2429–2510, 2631–2709
UL-1234	5	86	Humified woody **peat** at top of Type II.	2640±100	2708–2871
UL-1231**	5	135	Wood **charcoal** fragments at base of peat profile.	4020±100	4404–4630
UL-1362	6	92	*Sphagnum* **peat** at stratigraphical contact within Type IIIb.	2460±100	2429–2511, 2630–2709
UL-1379	6	130	Wood **charcoal** (branch) at contact of Types II and IIIb.	2870±70	2918–3078
UL-1363	6	130	Slightly burnt **wood** (branch) at contact of Types II and IIIb.	2940±100	2951–3213
UL-1501	6	170	Well humified basal **peat**.	4780±100	5450–5603
UL-1255	7	129	*Sphagnum* **peat** at base of Type IIIb.	2790±90	2779–2972
UL-1236***	7	130	Humified woody **peat** at top of Type II. Age inversion with sample UL-1255.	2580±90	2488–2653
UL-1673	7	210	Humified basal **peat**.	5090±70	5748–5830
UL-1232	n.a.	315	Humified basal **peat**; sample taken between Profiles 7 and 8.	5230±90	5910–6003
UL-1229	10	145	*Sphagnum* **peat** at base of Type IIIb.	2930±80	2957–3167
UL-1230	10	146	Humified woody **peat** at top of Type II.	2840±80	2852–3074
UL-1408	11	85	Humified **peat** layer within Type IIIb. Thickness of sample: 3 cm.	1110±60	949–1067
UL-1405	11	112	Humified **peat** layer within Type IIIb. Thickness of sample: 2 cm.	2270±70	2178–2266
UL-1415	11	170	*Sphagnum* **peat** at base of Type IIIb.	3080±100	3160–3394
UL-1402	11	265	Humified woody **peat** at base of Type II.	5350±110	5993–6154
UL-1257	14	195	*Sphagnum* **peat**, base of type IIIa.	5250±100	5917–6113

continued overleaf

Table 1 continuation

Laboratory number	Profile number	Depth (cm)	Description of sample *	Conventional ^{14}C age (years BP)	Calibrated age range at 1 σ of probability (years cal. BP)
UL-1256	14	196	Humified woody **peat** at top of Type II.	5240±100	5911–6063
UL-1375	14	260	**Wood** at contact of Types I and II.	7620±90	8339–8480
UL-1233	14	300	Well humified basal **peat**. Thickness of sample: 2 cm.	8550±120	9464–9699
UL-1413	16	243	Humified **peat** at top of Type II. Thickness of sample: 2 cm.	5440±70	6172–6303
UL-1409	16	297	Well humified **peat** at contact of Types I and II. Thickness of sample: 2 cm.	7320±80	8019–8184
UL-1377	19	136	**Wood** (root) below a humified layer within Type IIIa.	3210±70	3356–3478
UL-1403	19	187	*Sphagnum* **peat** below a humified layer within Type IIIa. Thickness of sample: 2 cm.	4210±70	4624–4764
UL-1414	19	237	Humified **peat** 5 cm below the top of Type II. Thickness of sample: 2 cm.	5670±110	6388–6565
UL-1419	19	293	Humified **peat** at base of Type II. Thickness of sample: 2 cm.	7140±80	7918–8026
UL-1376	20.5	300	**Wood** (adventitious root) in upper part of Type II which is a thick wood layer.	5940±80	6665–6807
UL-1499	20.5	335	**Wood** (root) at base of Type II, which is a thick wood layer.	5910±60	6662–6760
UL-1423	20.5	365	Well humified basal **peat**. Thickness of sample: 2 cm.	7720±80	8412–8543
UL-1500	23	250	**Wood** at interface of Types IIIa and IIIb	2770±90	2774–2959
UL-1378	23	385	Slightly burnt **wood** (trunk) 5 cm above base of peat profile.	5410±80	6169–6291
UL-1406	27.5	278	Mixed **peat** (*Sphagnum* above and humified bellow) at the interface of Types II and IIIa. Thickness of sample: 2 cm.	3890±100	4151–4422
UL-1407	27.5	295	Well humified **peat** at top of Type I. Thickness of sample: 2 cm.	4320±100	4813–5048
UL-1465	27.5	316	Well humified basal **peat**. Thickness of sample: 2 cm.	5390±100	6168–6285
UL-1391	31	197	Humified woody **peat** at top of Type II. Thickness of sample: 2 cm.	3000±70	3136–3267
UL-1615	31	270	Humified basal woody **peat**. Thickness of sample: 2 cm.	4540±70	5117–5187, 5051–5112
UL-1410	33	163	Mixed **peat** (*Sphagnum* above and humified bellow) at the interface of Types II and IIIb. Thickness of sample: 2 cm.	1540±90	1349–1521
UL-1392	33	246	Humified basal woody **peat**. Thickness of sample: 2 cm.	3900±100	4220–4439
UL-1393	35.5	95	Mixed **peat** (*Sphagnum* above and humified bellow) at the interface of Types II and IIIb. Thickness of sample: 2 cm.	1010±90	879–989
UL-1380	35.5	143	Slightly burnt **wood** (stump) at base of peat profile.	3130±70	3316–3411

* The peat samples are 1 cm thick unless otherwise stated.
** Sample UL-1231 was contaminated by air during the radiocarbon analysis (due to power failure) and the age may be erroneous. However, the date fits very well within the chronostratigraphy.
*** According to the chronostratigraphy established from the other radiocarbon ages and profile correlation, it is presumed that this date is too young and that UL-1255 indicates the correct age at this level.

The plant composition of Type I peat is highly variable (Table 5). It consists mainly of *Carex* spp., various shrubs (*Myrica pensylvanica*, *Myrica gale*, *Nemopanthus mucronata*, *Viburnum cassinoides*, *Prunus pensylvanica*) and trees (*Pinus strobus, Acer rubrum*, *Betula populifolia*, *Picea* spp., *Larix laricina*, *Salix* spp.). These species are commonly found in rich fen laggs throughout the region.

Basal age varies from 8550 to 2640 yr BP (Figure 2, Profiles 11 and 1.5). The top contact is well dated in the central zone (Figure 3), where it varies from 7620 to 4320 yr BP (Figure 2, Profiles 14 to 27.5). The thickness and duration of Type I peat are highly consistent in the central zone, at around 30–40 cm and 1000 years in most profiles except in the area of the depression (centered on Profile 12), where it is much thicker and longer-lasting (*ca*. 3500 years) (Figure 3). At the margins, it is of shorter duration (< 500 years) and sometimes absent. Mean net accumulation rates vary little and are usually 0.35–0.40 mm year^{-1} (Table 3). Basal dates (Figure 2, Table 1) indicate variations in lateral expansion rate from < 1 m century^{-1} to nearly 30 m and perhaps up to 60 m century^{-1} (Table 4).

Middle peat (Type II): poor fen

The middle layer of peat (Type II) is lighter in colour, a little less compacted and less humified than Type I peat (Table 5). Its thickness ranges from 17 to 79 cm and it is thinnest in the upper-central zone (Figures 2, 3). The contact with the overlying peat (Type III) is very distinct. At this interface, charcoal layers are recorded at only two locations (Profiles 19 and 26.5) in the central zone, and occur intermittently in the north margin. On the other hand, an almost continuous charcoal layer is present at this interface in the south margin (Profiles 1–11). The composition of Type II peat varies less than that of Type I (Table 5), but it is not homogeneous. The distribution of plant macrofossils along the peat section shows that the lower-central zone is composed of *Carex* spp., *Rhyncospora alba*, *Chamaedaphne calyculata* and *Andromeda glaucophylla* at the bottom, and of the same taxa along with *Sphagnum* spp. at the top. At the mire margins and in the upper-central zone, a woody peat is found. This is usually composed of ericaceous shrub remains (*Chamaedaphne calyculata*, *Kalmia angustifolia*, *Ledum groenlandicum*, *Andromeda glaucophylla*, *Gaylussacia dumosa*, *Vaccinium spp*.), but tree fragments (*Picea mariana* and *Larix laricina* only) occur frequently, along with *Carex* remains. *Sphagnum* is common but never abundant.

Type II peat appears to have been formed in a poor fen environment that developed rapidly. It started to expand from the lower-central zone. Its northward expansion is well dated in the central zone (Figure 2): 7620 yr BP (Profile 14), 7320 yr BP (Profile 16), 7140 yr BP (Profile 19), 5940 yr BP (Profile 20.5) and 4320 yr BP (Profile 27.5). It expanded southward over a shorter distance on a steeper slope (Figure 3, Table 4) where contact dates are younger (Figure 2), at 5350 (Profile 11) and around 4250 yr BP (Profile 6) (Figure 2, Table 1). At the top of the poor fen peat, ages are 5400–5250 yr BP in most of the lower- and mid-central zones and 3000–2000 yr BP in the margins (Figure 3). Duration of this poor fen phase is variable (430–2300 years) and shows a tendency to be shorter in the mid-central zone and longer in the margins. Average net accumulation rates range from 0.20 to 0.40 mm year^{-1} (Table 3). In contrast, net accumulation rates are lower in the margins and higher towards the centre.

Table 2. Mean net accumulation rates for profiles with basal dates.

Position in peat cliff	Profile number	Depth (cm)	^{14}C age (years BP)	Mean net accumulation rates (mm year^{-1})
south margin	1.5	50	2640	0.18
south margin	5	135	4020	0.30
south margin	6	170	4780	0.30–0.31
south margin	7	210	5090	0.35–0.36
lower-central zone	14	300	8550	0.31
mid-central zone	20.5	365	7720	0.43
upper-central zone	27.5	316	5390	0.50–0.51
north margin	31	270	4540	0.51–0.53
north margin	33	246	3900	0.56–0.57
north margin	35.5	143	3130	0.42

Table 3. Mean net accumulation rates for peat types I, II and III in different profiles.

Peat type	Profile number	Depth (cm)	Description of peat	^{14}C age (years BP)	Mean net accumulation rates (mm year^{-1})
I	14	300–260	Fine grained humified peat.	8550–7620	0.36
	20.5	365–335	Fine grained humified peat.	7720–5940	*0.39–0.41
	27.5	316–295	Fine grained humified peat.	5390–4320	0.15–0.16
II	5	135–85	Coarse grained humified peat.	4020–2640 4020–2460	0.29–0.30 0.24–0.28
	6	170–130	Coarse grained humified peat.	4780–2940 4780–2870	**0.16–0.17 **0.15–0.16
	7	210–129	Coarse grained humified peat.	5090–2790	0.27–0.28
	11	265–170	Coarse grained humified peat.	5350–3080	0.33–0.35
	16	297–243	Coarse grained humified peat.	7320–5440	0.29–0.31
	19	293–232	Coarse grained humified peat.	7140–5670	0.40–0.41
	27.5	295–278	Coarse grained humified peat.	4320–3890	0.30–0.33
	31	270–197	Coarse grained humified peat.	4540–3000	0.33–0.38
	35.5	143–195	Coarse grained humified peat.	3130–1010	0.20
IIIa	16	243–145	Unhumified peat.	5440–3210	***0.34–0.35
	19	232–136	Unhumified peat.	5670–3210	0.36–0.40
IIIb	5	85–0	Unhumified peat with a thick humified layer.	2640–0 2460–0	0.30 0.32–0.35
	6	130–0	Unhumified peat with a thick humified layer.	2940–0 2870–0	0.41–0.43 0.43
	7	129–0	Unhumified peat with a thick humified layer.	2790–0	0.44–0.45
	10	145–0	Unhumified peat with a thick humified layer.	2840–0 2930–0	0.48–0.49 0.46–0.48
	11	170–0	Essentially unhumified peat.	3080–0	0.50–0.51
	23	250–0	Unhumified peat.	2770–0	0.86
	31	197–0	Unhumified peat.	3000–0	0.61–0.63
	6	130–92	Unhumified peat.	2940–2460 2870–2460	0.49–1.02 0.62–1.16
	11	170–112	Unhumified peat.	3080–2270	0.52–0.61
	6	92–49	Humified peat layer.	2460–[900]	**** [0.23–0.27]
	11	112–85	Mixed peat (humified layers within unhumified peat).	2270–1110	0.20–0.23
	6	49–0	Unhumified peat.	[900]–0	****[0.60]
	11	85–0	Unhumified peat.	1110–0	0.78–0.84
	33	163–0	Unhumified peat.	1540–0	1.12
	35.5	95–0	Unhumified peat.	1010–0	0.98

* Slightly overvalued because the upper date is at the base of Type II and not at the top of Type I.

** Undervalued because at least 5 cm of peat is missing from the profile as indicated by anomalously high content of charcoal and carbonised matter in peat and by stratigraphical correlation with Profile 7. True rates should be near 0.20–0.23 mm year^{-1}.

*** The 3210 yr BP age is from nearby Profile 19.

**** The 900 yr BP age is estimated from stratigraphical correlations with Profile 11.

Top peat (Type III): bog

The topmost peat is yellowish, less compacted and poorly humified (Table 5). We divided it into two subtypes based on differences in humification and stratigraphical position. The lower subtype (IIIa) is slightly more humified (von Post H3–H4) than Subtype IIIb (von Post H2) and occurs in the central zone (Figure 3). Its mean thickness is 90 cm. The top contact is usually delimited by 1) a series of humified peat lenses, 2) a wood layer and/or 3) a clearly visible interface with Subtype IIIb (Figure 3). *Sphagnum* dominates and there are some ericaceous remains (*Chamaedaphne calyculata*, *Andromeda glaucophylla*) with infrequent trees, mostly *Picea mariana* and occasionally *Larix laricina* (Table 5). The tree remains are stumps, sometimes in layers of consistent age, especially *ca*. 4600 yr BP and *ca*. 4100 yr BP (Figures 2, 3). The age of the base ranges from 5400 (central zone) to 3890 yr BP (Profile 27.5), but that of the top apparently only from 2500 to 3000 yr BP (Figures 2, 3). Mean net accumulation rates of this peat range from 0.30 to 0.40 mm year^{-1} (Table 4).

Subtype IIIb is less humified than Subtype IIIa, especially in the central zone. Its margins are slightly more humified and resemble Subtype IIIa in some respects. The thickness of Subtype IIIb ranges from 130 to 250 cm, and this is the thickest layer in most profiles (Figure 3). The unhumified peat is dominated by *Sphagnum* and contains few woody fragments, mostly *Chamaedaphne calyculata* remains, but thick interbedded humified layers are also present, especially in the mire margins (Figures 2, 3). These are more than 5 cm thick, contain less *Sphagnum* and more woody plants - usually *Kalmia angustifolia* along with *Ledum groenlandicum*, *Chamaedaphne calyculata*, *Myrica* spp. and *Picea/Larix* fragments. Subtypes IIIa and IIIb are both typical of a bog environment.

Numerous thinner humified bands (usually less than 1 cm thick), sometimes intertwined and occurring at an average depth interval of 5 cm, are

Table 4. Slopes and estimated expansion rates for selected sections of the peatland.

Zone	Profile interval	Basal ages (yr BP)	Slope (%)	Mean expansion rate (m per 100 years)
south margin	Profiles 12–1.5	*9250–2640	1.80	*1.52
	Profiles 12–8	*9250–5200	2.02	*1.26
	Profiles 8–7	5200–5090	5.43	8.35
	Profiles 7–6	5090–4780	-1.11	3.60
	Profiles 6–5	4780–4020	1.50	0.56
	Profiles 5–1.5	4020–2640	1.55	2.22
central zone and north margin	Profiles 12–35.5	*9250–3130	0.38	*13.73
	Profiles 12–33	*9250–3900	0.24	*15.10
lower-central zone	Profiles 12–14	*9250–8550	0.33	*9.38
	Profiles 14–20.5	8550–7720	0.21	28.33
mid-central zone	Profiles 20.5–22.5	7720–7400**	-0.02	**59.00?
upper-central zone	Profiles 22.5–23	**7400–5410	1.72	**1.30?
	Profiles 23–27.5	5410–5390	0.41	n.a. (very rapid)
	Profiles 27.5–31	5390–4540	-0.11	9.72
north margin	Profiles 31–33	4540–3900	0.21	11.26
	Profiles 33–35.5	3900–3130	2.85	5.38

* estimate assuming a probable basal date of 9250 yr BP for Profile 12.
** estimate assuming a basal date of 7400 yr BP for Profile 22.5.

found throughout Subtype IIIb. According to Tolonen *et al*. (1985), they are composed of lichen-rich communities and represent short dry phases. They are not discussed further in this paper because our methodology was not designed to study such high-frequency phenomena.

In the central zone, charcoal layers are scarce in Type III peat and were observed, along with woody material, only in humified peat layers. Near the mire margins, on the other hand, they are numerous and were found mostly within both thick and thin bands of humified peat, as well as occasionally in unhumified *Sphagnum*-dominated peat.

The basal age of Subtype IIIb is usually around 2800–3000 yr BP (Profiles 6, 7, 10, 11, 23, 31; see Figures 2–3 and Table 1), except at the extreme edges of the bog where it may be younger. The thick humified bands have mean net accumulation rates of 0.25 mm year^{-1}, whereas the unhumified peats have the highest rates recorded, at >0.60 mm year^{-1} or even >1 mm year^{-1} (Table 3). Net accumulation rates may be under-estimated in the upper layers because compaction due to drainage of the cliff margin affects the upper parts of the peat profiles (Landva 1980). Tolonen *et al*. (1985) suggest that actual rates may have been up to 2 mm year^{-1}.

Table 5. Descriptions of the main peat types, including the taxa of the most common plant remains.

Peat type (vegetation stage)	Peat character	Degree of humification (von Post)	Macrofossil content			
			mosses	herbs	shrubs	trees
Type I (rich fen)	very dark brown, compacted and fine grained	very well humified (H7–9)	scarce unidentified brown moss fragments; *Sphagnum* always absent	sometimes dominant, usually abundant; mostly sedges of the genus *Carex*	scarce to common; major taxa are *Myrica pensylvanica*, *Myrica gale*, *Nemopanthus mucronata*, *Viburnum cassinoides*, *Prunus pensylvanica*; ericaceous species occasionally present (mostly *Chamaedaphne calyculata*)	common; wide variety of species (mainly *Pinus strobus*, *Acer rubrum*, *Betula populifolia*, *Picea* spp., *Larix laricina*, *Salix* spp.)
Type II (poor fen)	dark brownish, compacted and coarse grained	well humified (H 5–7)	*Sphagnum* always present, never dominant; species were not determined due to poor preservation (except possible *S. magellanicum*)	common, mostly sedges of the genus *Carex*; also *Rhyncospora alba* (central zone only)	common; mostly Ericaceous (*Chamaedaphne calyculata*, *Kalmia angustifolia*, *Ledum groenlandicum*, *Andromeda glaucophylla*, *Gaylussacia dumosa*, *Vaccinium* spp.)	scarce to common; *Picea mariana* and *Larix laricina*
Type III (bog)	light, yellowish, less compacted and coarse grained	poorly humified (H 2–4) except for humified bands (H 5)	*Sphagnum* abundant and usually dominant; only *S. fuscum* and *S. magellanicum* were identified, but other species occur)	scarce; bog species (*Eriophorum spissum*, *Scirpus cespitosus*)	common, sometimes abundant; mostly ericaceous (*Chamaedaphne calyculata* more common in unhumified peat, *Kalmia angustifolia* and *Ledum groenlandicum* more common in humified bands)	usually scarce; mostly *Picea mariana* and occasionally *Larix laricina*, usually associated with humified bands and peat lenses or in distinct layers

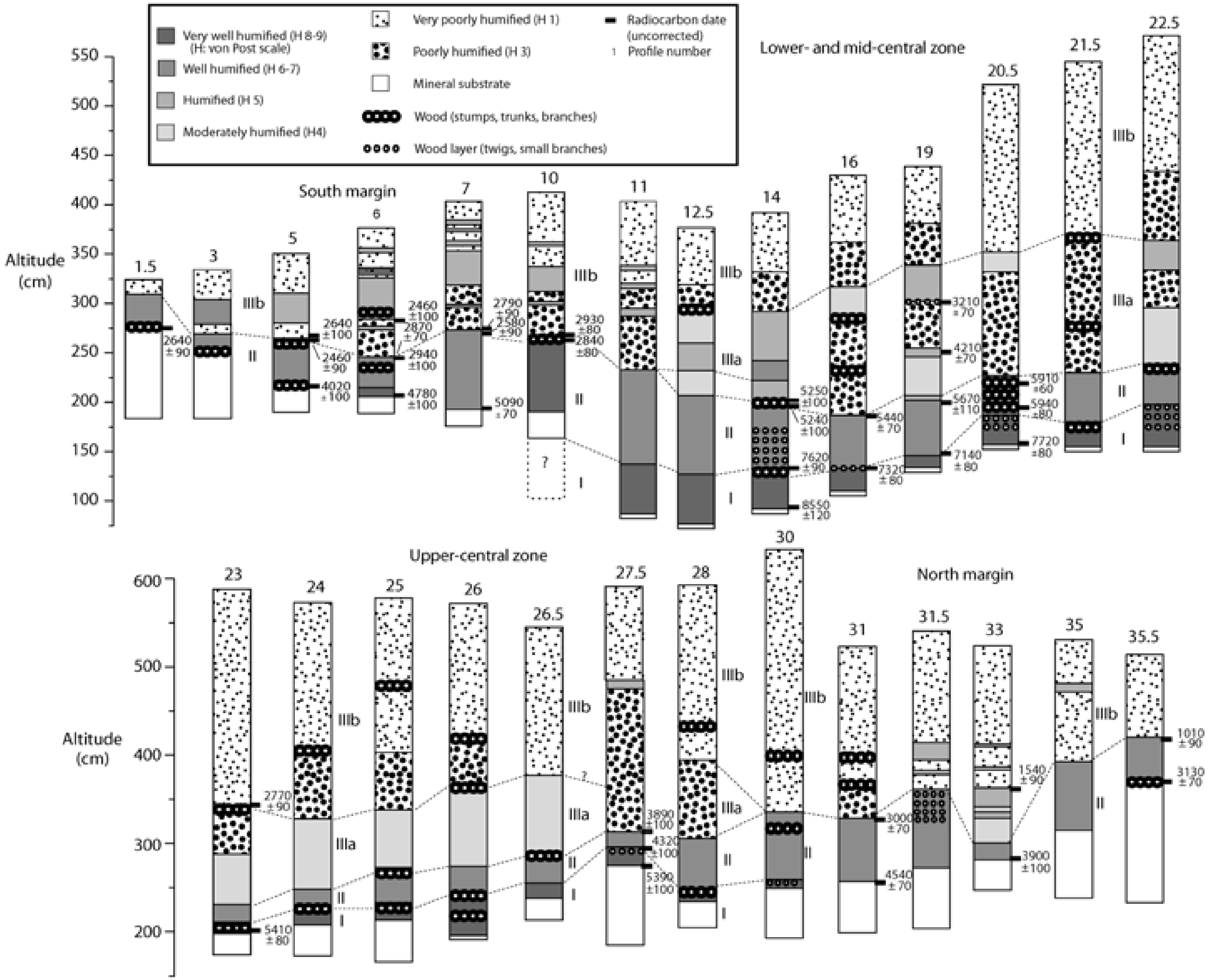

Figure 2. Stratigraphy of selected peat profiles (see Figure 3 for locations), showing degree of humification and the positions of woody remains. The zonation of peat types is indicated by Roman numerals between the profiles and delineated by broken lines. I: rich fen peat; II: poor fen peat; IIIa and IIIb: bog peat. The peat types are described in the text. The altitude datum is the the zero level of the Hydrographic Service of Canada, which corresponds to the lowest normal tide level.

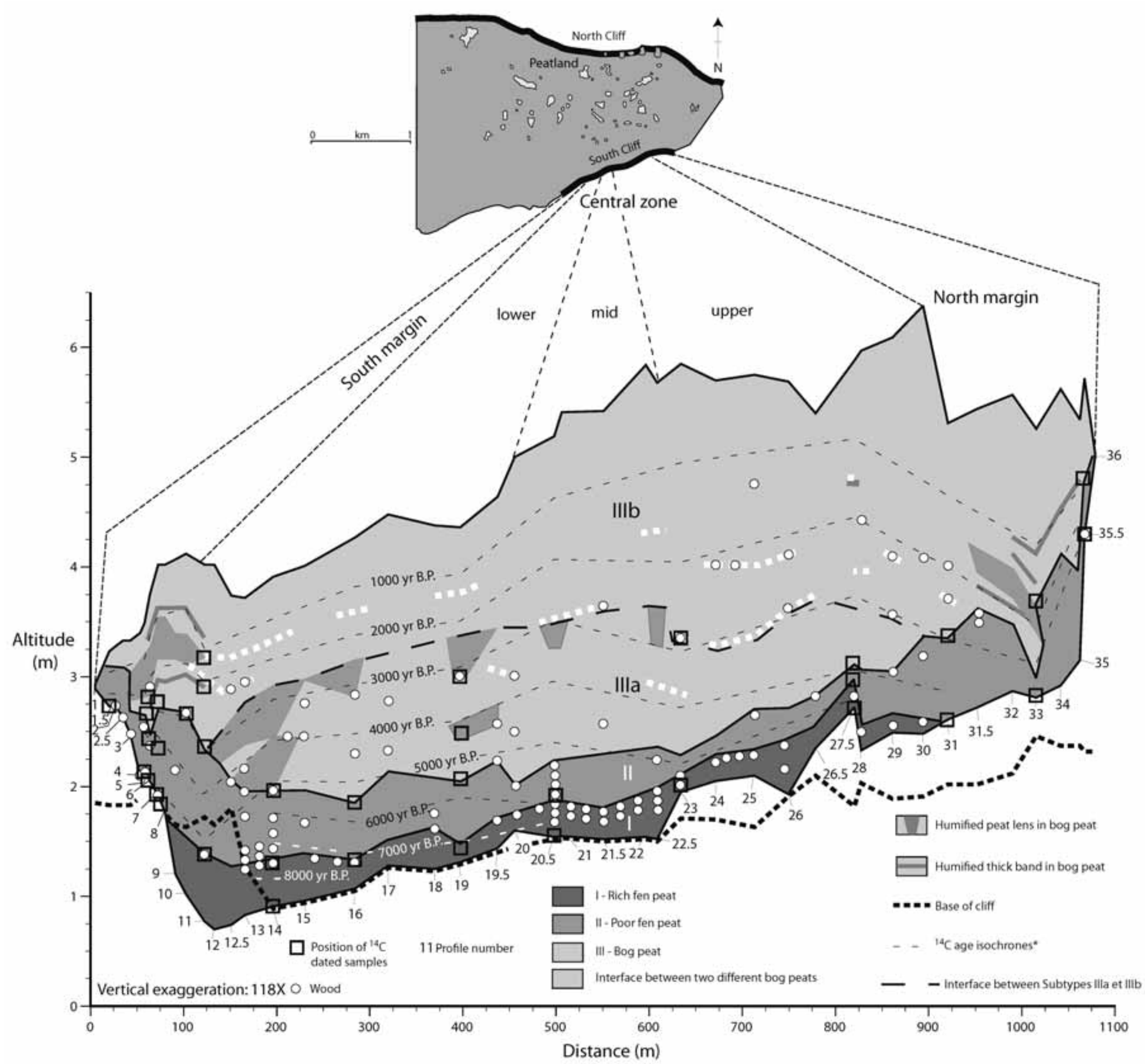

Figure 3. Stratigraphy of the south-eastern peat cliff of the Pointe-Escuminac bog according to the three major peat types identified. The altitude datum is the zero level of the Hydrographic Service of Canada, which corresponds to the lowest normal tide level. The isochrones were calculated by interpolation of radiocarbon dates.

DISCUSSION

Phases of peatland development, climate conditions and fire

Peat initiation and beginning of expansion (9500–7500 yr BP)

Peat formation started around 9500–9000 yr BP at the bottom of a wet depression (Figure 3). Our basal dates are in agreement with those of Tolonen *et al.* (1985) who report basal peat dated at 9500 yr BP overlying an older sediment composed of a mix of highly decomposed organic matter with mineral fines. Warner *et al.* (1991) dated this "silty" peat at 10900 yr BP. From 8550 yr BP, peat expanded laterally northward into adjacent wet areas at rates of 10 to >25 m century^{-1} until 7500–7300 yr BP (Figure 2, Table 4). Southward, the basal slope is much steeper and expansion was very slow (Figure 3, Table 4).

The initial peat accumulation at Pointe-Escuminac is contemporary with the basal ages of the majority of peatlands in New Brunswick, which range from 9000 to 7500 yr BP according to dates taken from Korpijaako (1976), Rampton *et al.* (1984) and Glaser & Janssens (1986). It coincides with a relatively wet and cool climatic episode during post-glacial warming that lasted roughly from 8500 to 8000 yr BP (Anderson & Lewis 1992, MacPherson 1995), suggesting some climatic control (Figure 5). The frequency of fire during this period was low, at one per 500–700 years. Fire seems not to have been a major influence on paludification or peat expansion during this phase as no stratigraphical changes associated with charred layers are noted, and there are fire horizons in only three small sections of the basal peat.

Interruption of lateral expansion and development of a poor fen (7500–5500 yr BP)

During this period, peat expansion almost ceased. The relatively rapid northward paludification halted at Profile 22.5 where the basal slope increases relatively sharply (from -0.02 to 1.7%), and no expansion is detected on the southern side (Figure 3, Table 4). Although the onset of this phase seems to coincide with the brief low-amplitude cooling event of 7500 yr BP (i.e. the 8200 cal yr BP event reported by Spooner *et al.* 2002 and Kurek *et al.* 2004), it would be a mistake to link the two, if only because there is no supporting evidence in the stratigraphy and our data do not allow precise dating for this particular time. However, Hughes *et al.* (2006) found a significant signature of this event in a bog in eastern Newfoundland.

In the meantime, poor fen vegetation started to develop and gradually expand over the rather flat and slightly upward-sloping rich fen surface (Figures 3, 4). For most of this period, the southern and northern mire margins were located near Profiles 10–14 and in the mid-central zone respectively, and were forested. By 5500 yr BP, the surface was almost entirely covered by poor fen communities (Figures 3, 4). Charcoal layers are few within the peat and none correspond to major changes in the stratigraphy. The interruption of expansion is contemporary with a period of warming that eventually culminated in the mid-Holocene hypsithermal at 6500–6000 yr BP. However, it also coincides with the peat expansion reaching a topographical barrier. Perhaps a combination of both unsuitable drier-warmer climate and steeper slopes caused expansion to cease at that time.

Rapid peat expansion and onset of ombrotrophication (5500–5250 yr BP)

Two major events in the history of the peatland occurred during this short period. First, the sudden development of bog peat (*Sphagnum*-dominated vegetation) over poor fen peat in the lower- and mid-central zones around 5400–5250 yr BP (Figures 3, 4) indicates rapid ombrotrophication of large portions of the peatland. Secondly, there was rapid expansion of peat across the entire upper central zone; basal peat layers at the two ends of this zone were aged at 5410 (Profile 23) and 5390 yr BP (Profile 27.5) (Figure 2, Table 1). Peat also started to expand onto the slope rising from the southern end of the depression, the base between Profiles 7 and 8 being dated at 5230 yr BP (Table 1).

Apparently, the warm/dry conditions of the well known Holocene climatic optimum which occurred around 6000 yr BP (Jetté & Mott 1995) shifted to a wetter/cooler climate after 5500 yr BP, as suggested by a peak of *Tsuga* and a decrease of *Pinus* in many pollen diagrams from New Brunswick and adjacent areas (Ritchie 1987, Warner *at al.* 1991, Jetté & Mott 1995). Evidence from eastern North America also indicates a change in climate at this time (Scott & Collins 1996, Bond *et al.* 1997, Schauffler & Jacobson 2002). Therefore, this stage coincides with a significant climatic shift. Warner *et al.* (1991) suggest that a gradual transformation from fen to bog occurred between 6500 and 4700 yr BP at the northern side of the site, although their radiocarbon dates do not allow precise dating of the fen-bog interface. It is unlikely that fires were responsible for these major changes because charcoal horizons are scarce at the mineral/peat interface of the upper-central zone.

Peat doming and wooded phases (5250–3000 yr BP)

After the rapid expansion of 5400 yr BP, peat continued to spread laterally, although at slower rates (Table 4). This expansion was particularly slow (<3 m century^{-1}) where the slope is steep at the southern end of the exposure. The northern edge of the peat moved northward at a rate of *ca*. 10 m century^{-1} from 5390 to 3900 yr BP, then slowed to 5 m century^{-1} from 3900 to 3130 yr BP as it also began to advance onto a steeper slope. The duration of the rich fen phase shortened dramatically (to less than 500 years) after the onset of ombrotrophy at 5500 yr BP (Figures 2, 4). Furthermore, bog vegetation gradually expanded northward over the poor fen and reached Profile 27.5 by 3890 yr BP and Profile 31 by 3000 yr BP (Figure 4). The peatland assumed a domed shape and the apex had located itself over the mid-central zone by 3000 yr BP (Figures 3, 4), perhaps merging slowly with bog expanding from the north-west.

At both margins, charcoal layers are numerous in peat (usually) younger than 5500 yr BP, and there was one fire every 175 years. Relatively slow paludification and frequent fires account for the almost continuous - although diachronic - charcoal layer found at the base of the peat in marginal areas.

Climatic conditions for eastern Canada after 5000 yr BP are difficult to assess from the literature, but regional pollen curves suggest relatively warm conditions (although cooler than during the mid-Holocene climatic optimum) with several

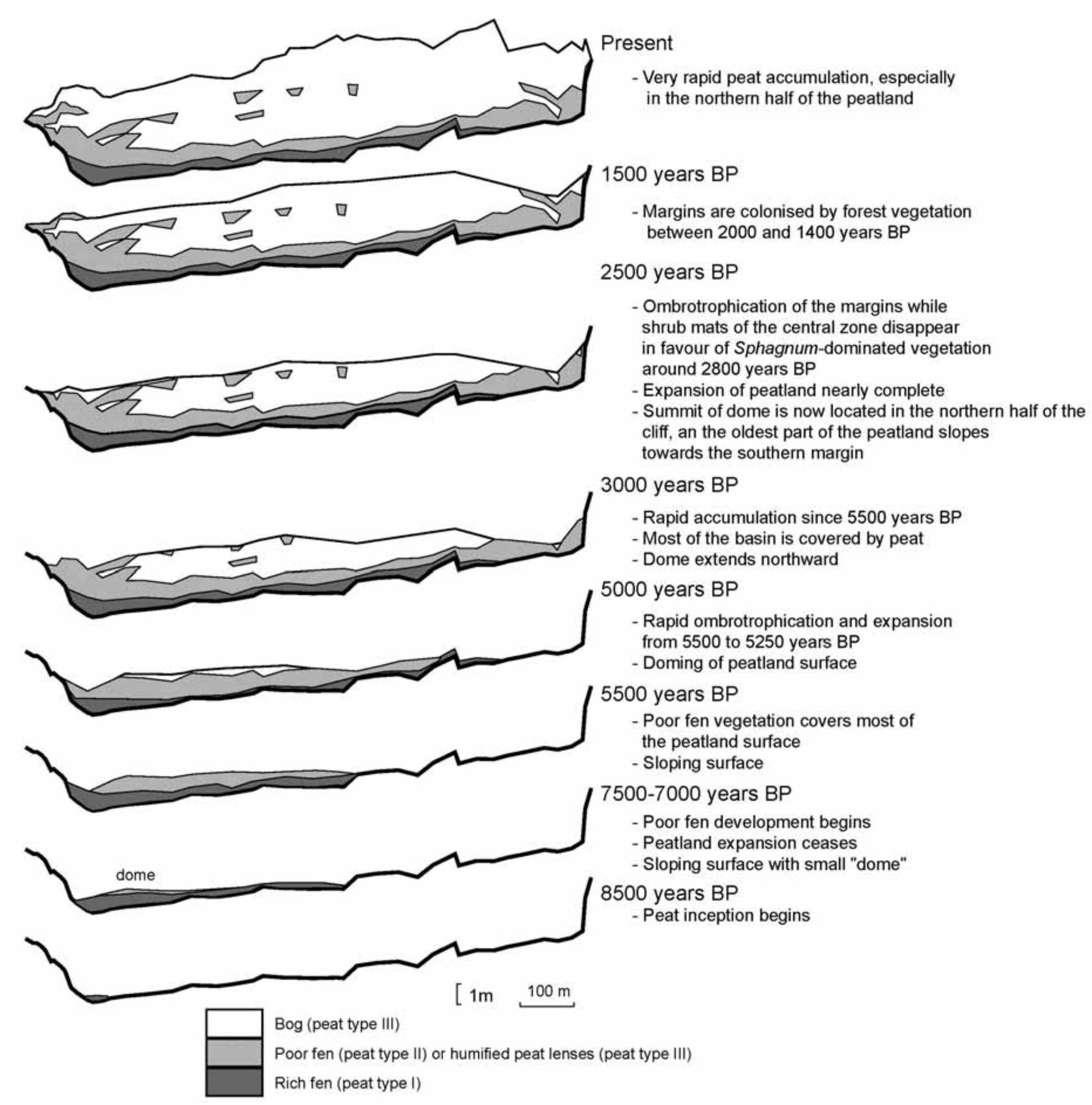

Figure 4. Development stages of the Pointe-Escuminac bog, according to stratigraphy and ^{14}C ages.

fluctuations (Ritchie 1987, Jetté & Mott 1995, Macpherson 1995). The most notable event is the hemlock decline, which may have occurred in two separate episodes according to macrofossil data (Bhiry & Filion 1996) and pollen curves; for example, in New Brunswick it is dated around 4800 yr BP by Jetté & Mott (1995) and near 4300 yr BP by Warner *et al*. (1991). Although most probably caused by pathogens, the decline is also thought to be related to drier conditions which increased the susceptibility of hemlock to pathogen attacks (Bhiry & Filion 1996, Yu *et al*. 1997, Shuman *et al*. 2001).

In any case, the climate supported moderate to slow rates of peat expansion at Pointe-Escuminac. Moreover, possible minor fluctuations may have contributed to vegetation change that favoured colonisation of the bog by trees during two identified periods: wood layers are found in the peat and are concentrated at 4600 and 4100 yr BP (Figure 3). On the nearby eroded beach, Bégin *et al.* (1989) found tree stumps on mineral soil underlying *Sphagnum* peat which were aged between 4880 and 4670 yr BP. Warner *et al.* (1991) suggest a dry peat surface around 4700 yr BP on the basis of an increase of *Empetrum* pollen at that time, and date the hemlock decline in the Pointe-Escuminac pollen curve at around 4300 yr BP. A possible interpretation is that short-duration drier conditions would temporarily favour the development of trees on some parts of the peatland. A return to wetter conditions would allow *Sphagnum* to re-invade these areas and quickly bury the trees, and even to expand onto the surrounding forested mineral soils. Interestingly, Hughes *et al.* (2006) report increased bog surface wetness events during the same period for peat in eastern Newfoundland, which strongly suggest several (climatic) fluctuations in the atmospheric water balance. However, even though some of these events more or less coincide with the Pointe-Escuminac wood layers within dating margin errors, it would be speculative to infer connections between the two regions at this point; first because there are uncertainties about the Newfoundland data between 4400 and 3000 yr BP and secondly because we cannot verify our assumptions about vegetation processes.

Major vegetation changes (3000–2500 yr BP)

Much of the peatland vegetation underwent changes around 3000 yr BP (Figures 3–5), when the mid- and upper-central zones show the shift from Subtype IIIa to Subtype IIIb bog peat. In the lower-central zone, the extensive humified peat lenses (shrub-dominated communities) disappear and are replaced by Subtype IIIb *Sphagnum* peat. Tree remains become less numerous overall. The change from poor fen to bog peat was rapid at the peatland margins and, whilst synchronous at the southern margin (*ca*. 2800 yr BP), occurred asynchronously (3000–2500 yr BP) in the northern section of the cliff (Figures 2, 3).

These events coincide with a major change in climate that occurred over much of the northern hemisphere (Van Geel *et al.* 1996) (Figure 5). The various stratigraphical changes observed at Pointe-Escuminac illustrate the complexity of the bog's response to environmental change, and this in turn reflects the importance of specific local conditions. Thus, the detailed stratigraphy of Pointe-Escuminac shows that different parts of the bog may exhibit simultaneous but different, locally appropriate, responses to a large-scale factor such as climate change.

One local factor that may have played a role is fire. There is an exceptionally long charcoal horizon at the fen/bog boundary in the south margin (Profile 6 to Profile 11), dated around 2800 yr BP. However, many other closely spaced charcoal horizons were found in the peat above and below within the same profiles, without any links to lasting vegetation change (Robichaud 2000). A paper is in preparation about this phenomenon, and this concludes that fire is not solely responsible for ombrotrophication here. We suggest that the onset of a cooler/wetter climate was the main driving force, but that fire accelerated the process by destroying the poor fen vegetation and allowing colonisation by bog plants which were better adapted to the new environmental conditions induced by climate change.

End of expansion, rapid peat accumulation and short dry phases (2800–0 yr BP)

The peatland reached its present boundaries shortly after 2500 yr BP (Figure 4). The highest net accumulation rates were calculated for the most recent period of the peatland's history (0.86 mm year^{-1} over the last 3000 years, Table 3). Rates of more than 1 mm year^{-1} were calculated for the uppermost peat layers at the northern margin, from 1500 yr BP to present (Table 3). Because peat accumulation was faster on its northern than on its southern side, the summit of the bog shifted northward. According to aerial photographs, the mid- and upper-central zones (Profiles 20–32) now lie within the central plateau of the bog, while the southern portion of the cliff is part of the marginal slope (rand). Hence, the oldest part of the peatland (Profile 12) is now paradoxically located along a margin, while the younger basal layers of the upper-central zone lie beneath the thickest peat (Figure 3).

Evidence of obvious changes in the central zone during this period is scarce, except for a major although poorly dated contact around 1500 yr BP at several locations (Figures 2, 3). Conversely, the margins exhibit thick humified bands at 2500, 2200, 1100, 850–750 and 550–460 yr BP (Figures 3, 4). Aaby & Tauber (1974) suggest that the humification degree of ombrogenous peat can reflect local humidity conditions which may be linked to climatic conditions. Lower precipitation and higher temperature create dryer environmental conditions which would lower the water table in raised bogs and promote the formation of humified peat, whilst the opposite conditions would favour the deposition of unhumified peat. More recent studies have reconstructed past climatic conditions from peat humification (Nilssen & Vorren 1991, Mauquoy & Barber 1999), sometimes in combination with other proxies (Hughes *et al.* 2006). In the Pointe-Escuminac bog, four of the five thick humified bands mentioned above seem to correspond to past climatic events. The 2500 and 2270 yr BP humified bands match with drier climatic events reported by Wein *et al.* (1987) in a nearby New Brunswick bog. The 850–750 yr BP event corresponds to the well known Medieval Optimum and the 550–460 yr BP humified peat layer coincides with a short warm episode that occurred within the Little Ice Age (Lamb 1988), which was also detected by dendrochronology in Subarctic Quebec (Payette *et al.* 1989) and is contemporary with a reported recurrence surface in Europe (Tolonen 1987).

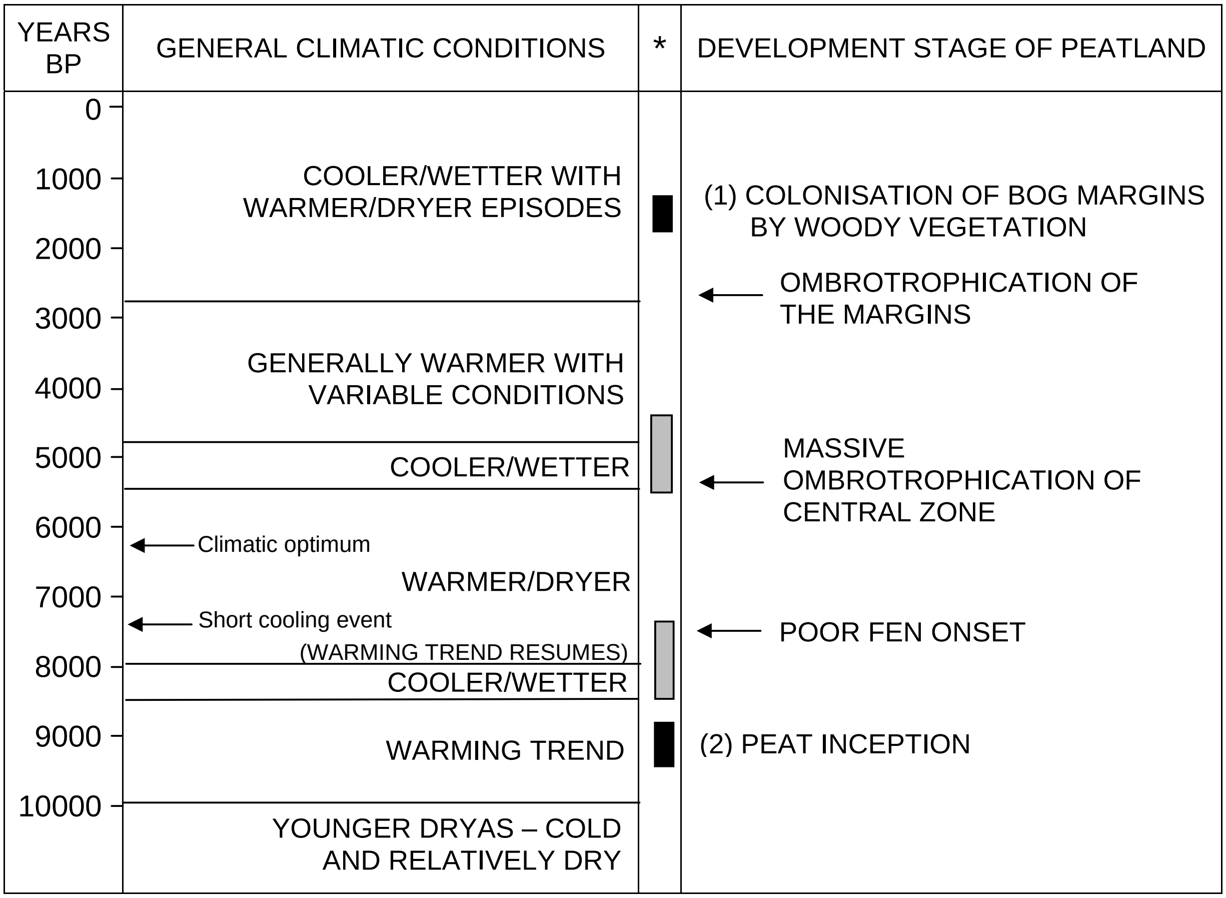

Figure 5. Major stages in development of the Pointe-Escuminac bog in relation to historical climate in eastern New Brunswick. The climate reconstruction is generalised from several studies, which are referenced in the text where appropriate. In the column headed with an asterisk, grey bars indicate episodes of rapid peat expansion onto mineral substrate and black bars represent the durations of Events (1) and (2).

Allogenesis *versus* autogenesis

Interactions between allogenic and autogenic processes are not exceptional in long-term environmental dynamics (White 1979), and such interactions appear to have taken place at Pointe-Escuminac. The succession from fen to bog seems normally to be an autogenic process (Tolonen 1987, Clymo 1991). Why, then, was it influenced by climate change at Pointe-Escuminac? Recent studies of bog hydrology may offer an explanation of the mechanism. Some researchers have observed that upward water flow occurs in fens whereas the flow is downward in bogs, even within the same peatland system (McNamara *et al.* 1992, Podnieski & Leopold 1998). Flow reversals are observed in bogs during contemporary precipitation regime changes (Siegel *et al.* 1995) and palaeo-reversals of groundwater flow have been detected in peatlands by Glaser *et al.* (1996). Therefore, we can reasonably hypothesise that, with substantially more water in the peatland system due to reduced evapotranspiration and higher precipitation during a period of cooler/wetter climate, the upward water flow that normally creates minerotrophic conditions at the vegetated surfaces of fens could be reversed. With flow reversal, minerotrophic water would be unable to reach the surface vegetation, thus initiating ombrotrophic conditions. Hence, it is possible that Pointe-Escuminac's bog phase was initiated by climatically triggered hydrological changes in the peatland.

The Pointe-Escuminac peatland was at a stage when peat thickness was sufficient to allow this process. According to McNamara *et al.* (1992), a slightly convex peat ridge with a water table mound only 10–20 cm high would be sufficient to create a local groundwater recharge system isolating the surface from minerotrophic ground water. It is certain that ombrotrophication would have occurred regardless of climatic conditions as observed in numerous other bogs (e.g. Kuhry *et al.* 1993). In fact, the process did continue at Pointe-Escuminac under drier conditions at other times, although apparently at a slower pace. However, the peatland also responded strongly to a shift in climate, perhaps in part because its "threshold" situation with the central peat surface close to a critical height made it sensitive to changes in the water budget (Janssens *et al.* 1992). A similar situation is shown by Singer *et al.* (1996) in a study on the long-term development of a marsh, where organic sediment accumulation constrained the response of vegetation to climate change.

Bog shape and surface features

Another interesting phenomenon is the series of regularly spaced humified peat lenses in the central zone from 3200 to 2800 yr BP, just before the shift between ombrogenous peat types IIIa and IIIb (Figure 3). Although these could be linked to drier/warmer climate conditions, another hypothesis would invoke ecological processes, driven by the doming of the bog, creating a patterned vegetation mosaic of drier zones alternating with wetter areas on the bog surface. In the "youth" of its bog phase, Pointe-Escuminac possibly had such patterns. Under the cooler/wetter conditions that prevailed after 2800 yr BP, these patterns disappeared as *Sphagnum* spread until it dominated the entire central zone. During this process, the shape of the dome was probably modified, later developing the flat and featureless expanse we observe today on the central plateau. This evolution in bog surface configuration is consistent with the suggestion of Damman (1986) that an increase in moisture surplus would influence peatland morphology; and also with the description by Glaser & Janssens (1986) of a developmental trend in landform patterns and peat stratigraphy, from convex/forested to flat/non-forested with pool formation, under the influence of both climate conditions and autogenic processes.

Autogenic processes and peatland development

Autogenic processes are mediated by the peatland itself and include peat accumulation effects and chemical changes prompted by vegetation change, especially acidification by *Sphagnum* (Kuhry *et al.* 1993, Payette & Rochefort 2001). Several aspects of the chronostratigraphy at Pointe-Escuminac suggest changes controlled mostly by the accumulation and spread of peat.

Transition from rich fen to poor fen

One of the clearest observations in our analysis is that the thickness and duration of the rich fen peat in the central zone varies little. Moreover, the spread of the poor fen peat was gradual during the first phase of its development. This suggests that once a certain peat thickness is exceeded, the rich fen becomes a poor fen regardless of any allogenic changes. The mechanism may lie in peat hydrology, as may be implied from the work of McNamara *et al.* (1992) and Podnieski & Leopold (1998). As peat accumulates during the rich fen phase it is probable that, when a critical peat thickness is reached, new hydrological conditions arise involving a significant slowing of the upward flux of mineralised water from the mineral soil. This will create more weakly minerotrophic conditions which favour poor fen communities and place nutrient-demanding species at a competitive disadvantage. McNamara *et al.* (1992) observed that in a fen environment, the "poor" side (vegetation associated with solute-poor waters) exhibits a slower advection flux of solutes towards the surface vegetation than the "rich" side (vegetation associated with solute-rich waters). Moreover, modelling by Reeves *et al.* (2000) suggests that the presence of a highly permeable mineral substrate beneath the peat, along with the development of a peat dome, can favour the creation of a vertical flow cell that penetrates into the mineral soil, thus favouring ombrotrophy. The mineral substrate below the Pointe-Escuminac peat is mostly comprised of permeable sandy glacio-marine sediments; and the bottom fen peats are fine-grained, well compacted and appear to have low hydraulic conductivity. Only 30–40 cm of fen peat accumulation was necessary for weak minerotrophy to develop at Pointe-Escuminac.

Rich fen duration and peatland stages

Three different spatio-temporal "stages" of the rich fen can be described in terms of time, peat thickness and position in the peatland.

First, there is a small area at or near the depression (Profiles 10–14) where peat formation initially took place and the rich fen peat is relatively thick and has a long duration (≈3500–4000 years). Here, minerotrophic conditions prevailed for a long time because water tended to accumulate in the depression and also because mineralised water would seep into the peat from the adjacent slope. Secondly, northward from the depression, the rich fen phase varies little throughout most of the central zone. This stage started with the first paludification phase, during which the surface vegetation gradually turned into poor fen. Finally, in the third stage, which started shortly after the time when the peatland became a bog, the rich fen phase thinned and shortened to less than 500 years near the mire margins. To explain this we hypothesise that, with rapid vertical peat accumulation in the newly invaded areas, the rich fen lagg was quickly replaced by poor fen communities and then by bog communities following the "normal" autogenic succession. Therefore, as the peatland developed from minerotrophic to ombrotrophic conditions, the initial longer-lived rich fen phase was constrained into a shorter-lived lagg fen in the peripheral paludifying margins; this is also an outcome of autogenic change.

CONCLUSION

The detailed peat stratigraphy of the Pointe-Escuminac bog has shed new light on the roles of allogenic and autogenic factors in peatland development. Autogenic processes arising from peat accumulation and its effect on hydrology and the underpinning nutrient inputs have been the foremost influence on the broad evolution of the peatland, i.e. the rich fen - poor fen - bog succession. Climate change also seems to have significantly affected hydrology at times, with various possible effects on bog development. It appears that large-scale wetter/cooler climatic shifts favoured intense ombrotrophication phases, accelerating expansion and leading to rapid wood burial and dramatic changes in plant assemblages. In some cases, warmer/dryer periods slowed basal expansion and favoured the spread of woody species on the bog surface. Additionally, some localised higher-frequency humification episodes in the ombrotrophic peat may reflect drying events. On the other hand, fire played a very limited role in determining the major development phases, although it may have accelerated some succession processes. Finally, topography exerted some control on peat expansion.

A major conclusion of our study is that ecological responses to climatic shifts varied spatially within the peatland (central zone *versus* margins) and through time (younger *versus* older stage of development). It appears that a single climatic event can trigger different simultaneous reactions in plant communities, according to their locations on the peatland.

ACKNOWLEDGEMENTS

This research benefited from the financial support of Laval University Funds and the Natural Sciences and Engineering Research Council of Canada. We thank Dr Dominique Marguerie (University of Rennes 1 in France), Dr Line Rochefort and Dr Claude Lavoie (both from Laval University) for comments on earlier versions of the PhD thesis that yielded this paper. Field assistance was provided by Laurent Astrade, Simon Boivin and Sylvain Renaudin. The authors are grateful to Guillaume Labrecque for radiocarbon dating.

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Submitted 10 Dec 2007, revision 15 Jan 2009
Editor: Olivia Bragg

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