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Cliff-Top Eolian Sedimentation Reflecting Mid- to Late-Holocene Environmental Changes at Anticosti Island, Gulf of St. Lawrence, Eastern Canada

Daniel Germain[†]*, Martin Lavoie[‡], and Louise Filion[‡]**

[†]Université de Moncton, Campus de Shippagan
Shippagan, Nouveau-Brunswick
Canada E8S 1P6

[‡]Centre d'études nordiques and Département de Géographie
Université Laval
Québec, Québec
Canada G1K 7P4
martin.lavoie@cen.ulaval.ca

ABSTRACT

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The study site (Cape Sandtop) consists of a 15 m high marine terrace exposed to strong easterly winds, at the eastern end of Anticosti Island in the Gulf of St. Lawrence (Québec, Canada), where eolian sedimentation occurred. Sections at the terrace edge exposed thick, well-humified, buried organic deposits with many wood fragments. Sedimentological and plant-macrofossil analyses were conducted from four sections to provide a chronology of eolian activity and to evaluate the causal factors for the development of treeless plant communities. Plant remains indicate that Cape Sandtop was forested between 6520 and *ca.* 4740 cal YBP. After *ca.* 4740 cal YBP, the terrace experienced a rapid change from coastal conifer forests and treed fen to marshes. Sustained erosional activity by easterly winds along the upper limestone cliff and the terrace edge started 1560 cal YBP and caused peat burial. The key factors responsible for cliff-top eolian sedimentation were relative sea level changes, increased exposure to easterly winds associated with higher elevation (15 m asl) of the marine terrace and sediment availability. In spite of its limited extent, this coastal site appeared as a system that was sensitive to environmental changes during the Mid- to Late-Holocene.

ADDITIONAL INDEX WORDS: *Climatic changes, marshes, paleoenvironments, plant macrofossils, relative sea level changes.*

INTRODUCTION

Cold-climate eolian processes and landforms are sensitive to environmental changes and are used extensively for paleoenvironmental reconstruction (*e.g.,* Björck and Clemmensen, 2004; Filion, 1984, 1987; Käyhkö *et al.,* 1999; Wiles *et al.,* 2003; Willemse *et al.,* 2003; Wolfe and Nickling, 1997).

Several studies have shown the importance of climatic conditions in the initiation of eolian sedimentation, especially in cold areas where low temperature, high wind velocity, surface dryness, and sediment availability are of paramount importance for niveo-eolian activity (Bélanger and Filion, 1991; Koster, 1995; McKenna Neuman, 1993; Mountney and Russell, 2004; Seppälä, 2004). Because deflation is primarily controlled by seasonal variations in surface moisture, sand transportation can occur when maximum dryness is reached under low winter temperatures that coincide with strong winds (Ballantyne and Whittington, 1987; McKenna Neuman, 1990). Recent studies conducted in North America (Bégin, Michaud, and Filion, 1995; Hétu, 1992; Lauriol *et al.,* 2002; Rawling, Fredlund, and Mahan, 2003) and northern Europe (Ballantyne, 1998; Wilson, 1989) have demonstrated the significant contribution of niveo-eolian deposition in cliff-top eolian dynamics.

On the east coast of Anticosti Island, in the Gulf of St. Lawrence (Figure 1a), cliff-top eolian sedimentation occurred at Cape Sandtop on a low-elevated marine terrace [15 m about sea level (asl)], where a subboreal climate and a strong maritime influence prevail. Morphometric measurements on detrital material at this site indicate that eolian processes were efficient in transporting particles of various sizes on the terrace edge, from fine-to coarse-grained sediments, with granule ripples up to 23 cm in height, to large disk-shaped fragments up to 19 cm in length and 197 g in weight (Germain and Filion, 2002). Sections at the edge of the terrace above the cliff exposed thick, well-humified organic deposits with tree logs and many wood fragments underlying eolian deposits, which indicated that this terrace was once forested. Although coastal dunes can form in almost any climatic zone (Carter, Nordstrom, and Psuty, 1990), Cape Sandtop provided an excellent opportunity to study the initiation of cliff-top eolian sedimentation and related changes in plant communities in relation to Holocene environmental and climatic changes.

The objectives of this study were: (1) to provide a chronol-

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* Corresponding author.
** Present address: Université du Québec à Montréal, Départment de Géographie, C.P. 8888, Succursale Centre-Ville, Montréal, QC H3C 3P8, Canada.

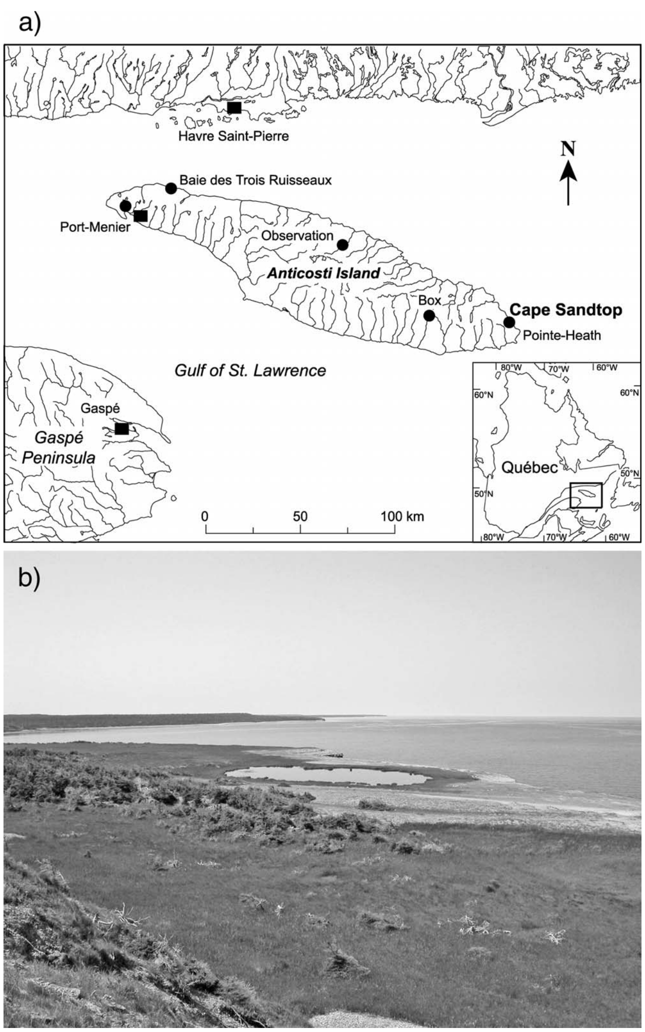

Figure 1. (a) Location of Anticosti Island and the study site (Cape Sandtop). Four peatlands (●) studied by Lavoie and Filion (2001) for pollen analysis are also indicated. (■) Location of modern settlements. (b) A general view (north direction) of the site showing cliff-top eolian deposits, marshes, and forests.

ogy of eolian activity based on ^{14}C dating on the edge of a low-elevated marine terrace located at the eastern end of Anticosti Island, (2) to reconstruct changes in local vegetation communities using plant-macrofossil assemblages, and (3) to evaluate the regional and local factors responsible for increased eolian sedimentation and the development of a treeless environment at Cape Sandtop.

STUDY AREA

Located in the northwestern sector of the Gulf of St. Lawrence, Anticosti Island covers an area of 7953 km^2 (Figure 1a). A series of low-elevated cuestas that dip to the SSW form the relief of the island, made of sedimentary rocks consisting of thinly bedded limestones with occasional shale layers. The island can be divided in two distinct physiographic units: a large central plateau, which reaches 150–313 m in elevation and coastal lowlands $<$150 m asl. The north shore is bounded by sea cliffs up to 100 m asl. During the late Wisconsinan, the central part of the island was occupied by an ice cap shortly after the retreat of the Laurentian Ice Sheet (Painchaud, Dubois, and Gwyn, 1984). Between ~13,000 and 10,600 ^{14}C YBP [~15,500 and 12,700 calibrated (cal) YBP], the Goldthwait Sea waters submerged the south and north shores to maximum elevations of 60 and 70 m, respectively (Grant, 1989). Glacio-isostatic rebound was estimated at ~2 cm y^{-1} between ~11,000 and 9000 ^{14}C YBP (~12,900 and 10,200 cal YBP). After 9000 ^{14}C YBP (10,200 cal YBP), marine terraces were formed 15, 10, and 8 m asl (Painchaud, Dubois, and Gwyn, 1984).

A detailed description of the biogeographical setting of the island was given by Desloges and Émond (1975), Chouinard and Filion (2005), and Lavoie and Filion (2001). The dominant tree species are balsam fir (*Abies balsamea* [L.] Mill.), white spruce (*Picea glauca* [Moench] Voss.], black spruce (*Picea mariana* [Mill.] BSP.), and paper birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) as secondary companion species in disturbed sites. Along the coast, white spruce clearly predominates, exhibiting several growth forms (especially the flag type) in response to wind exposure. In the eastern part of the island, large peatlands developed inland on poorly drained soils. The climate is subboreal and largely influenced by the Labrador Current. The mean annual temperature is 2.0°C. Monthly minimum and maximum temperatures are −11.8°C (February) and 16.2°C (July), respectively (Port-Menier Weather Station; Figure 1a). Annual precipitation totals 924 mm and the mean annual snowfall is about 400 cm (Environment Canada, 2007). On the east coast, meteorological data from Pointe-Heath Weather Station (1901–1931) (Figure 1a), where records are available for this 30-year period only, air temperatures and precipitations were similar to those from Port-Menier. Prevailing winds blow from the northeast in summer and the southwest in winter. However, cyclonic depressions from the Atlantic result in strong easterly winter winds with gales exceeding 130 km h^{-1} (Desloges and Émond, 1975), exacerbated by an extensive fetch, *i.e.,* the Gulf of St. Lawrence. Therefore, cliffs above the north and northeast shores receive a continuous supply of spin drift until a seasonal ice cover is formed, which lasts from January to April (Canadian Ice Service, 2000).

The study site (Cape Sandtop) at the eastern end of the island (Figure 1a) consists of a marine terrace 15 m high, which is a former shore platform subsequently cut into the Ordovician limestone (Figure 1b). It is overlain by raised beaches of gravels and pebbles, and eolian deposits (Figure 2). The maximum extent of eolian sediments is within ~100 m from the cliff (Germain and Filion, 2002). Local exposure to easterly winds decreases inland from the cliff, and from the southern to the northern sector of the terrace (Figure 2).

This south–north gradient in wind exposure is evidenced by large wind-deflated, rugged surfaces with a sparse vegetation cover in the southern sector (*Plantago maritima* ssp. *juncoides, Festuca rubra, Gentianopsis nesophila*), and a forest-fringed northern sector where the SN shoreline direction changes to the WNW and white spruce with flag-type growth forms colonize

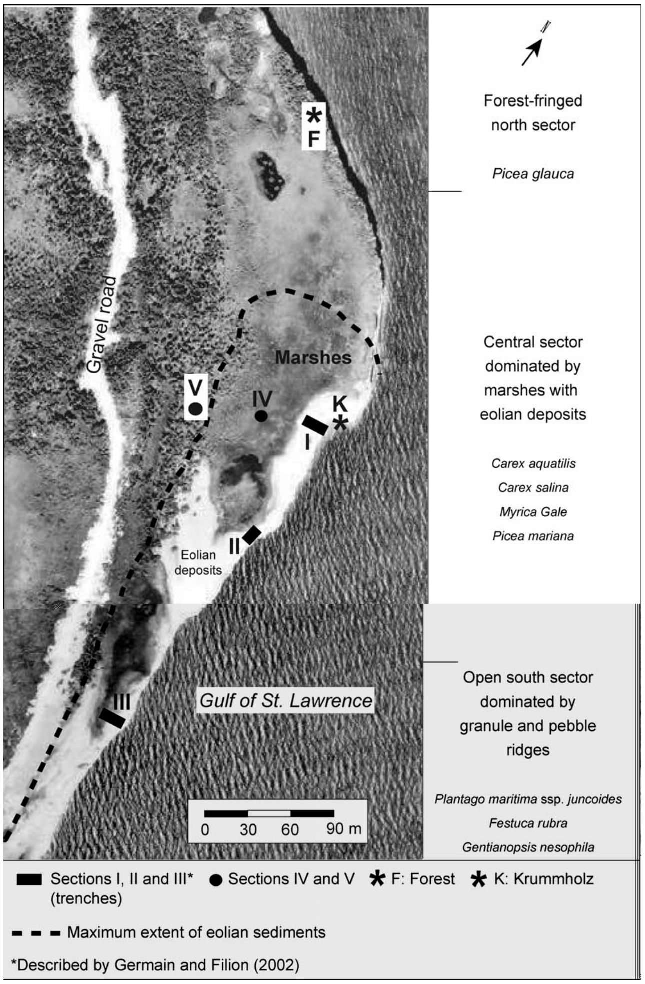

Figure 2. Aerial photograph (1987: Q87867–55) showing Cape Sandtop and the location of the studied sections (I, II, IV, V). A description of Section III is given by Germain and Filion (2002). ^{14}C dates were also obtained from a white spruce forest basal humus in the forest-fringed north sector (F) and a dead krummholz at the terrace edge in the central sector (K). Dominant plant species in each sector of the terrace are also indicated.

the terrace edge. The central sector is a complex of eolian deposits and marshes with many exposed wood fragments (Figure 2). Thus, wind activity and eolian sedimentation still contribute to landscape development at this coastal site.

METHODS

Sampling

Four stratigraphic sections (I, II, IV, and V) were excavated in the central sector (Figure 2). Their location corresponds to a decrease in wind exposure, from Sections I and II close to the terrace edge (eolian deposits) to Sections IV (marshes) and V (white spruce forest) inland. Section III excavated through granule ripples in the south sector (Germain and Filion, 2002) was not used in this study.

Sections I and II were analyzed along 10 and 2 m long soil trenches along a small gully perpendicular to the cliff and from a detachment crack parallel to the cliff, respectively. The organic material was extracted by cutting lengthwise 20 × 20 × 10 cm monoliths. Additional organic material from these two sections was collected in metal boxes (10 × 10 × 10 cm) for micromorphological analysis. In Section I, two logs and several wood fragments were collected for conventional ^{14}C dating. In Section II, mineral sedimentary units were sampled for grain-size and quartz-grain surface-roundness analysis. Section IV was sampled within a marsh in the central sector (Figure 2), using a 5-cm hand-driven side-wall peat corer (Jowsey, 1966), with four replicates collected within a very short distance to provide additional material for radiocarbon dating. Section V consists of a 20 × 20 × 30 cm organic monolith collected under a white spruce forest west of Sections I and IV (Figure 2). Monoliths and cores were wrapped in plastic and aluminum foil for transportation to the laboratory, where they were stored at 5°C until analysis.

Laboratory Methods

The Wentworth (1922) classification system and Powers (1953) roundness scale were used for the grain-size and quartz-grain surface-roundness analysis, respectively. The grain-size distribution for the ≥63-μm fraction was determined by dry sieving at quarter-phi intervals using a mechanical shaker. The silt and clay fractions (<63 μm) were removed by wet sieving and analyzed with a Sedigraph. The cumulative grain-size frequency curves were plotted graphically and the statistical parameters were calculated based on the procedures of Folk and Ward (1957). Thin sections (10 cm × 10 cm × 25 μm) were prepared based on the guidelines of Caillier *et al.* (1987). Contiguous sections were examined under a stereomicroscope at 40× magnification to determine the first sand occurrence within the buried peat.

Sections I, II, IV, and V were analyzed for plant macrofossils. Monoliths collected from Sections I, II, and V were cut into 1 cm thick slices, and intervals for analysis were 2 or 4 cm, depending on the abundance of plant remains. Cores collected from Section IV were cut into 5 cm thick slices and analyzed as contiguous samples. Sample volumes ranged from 50 to 100 cm^3. Macrofossils were separated from the organic matrix by boiling the material for about three minutes in a weak 5% KOH solution. The material was then wet screened through a series of sieves of 0.850-, 0.425-, and 0.180-mm mesh (Bhiry and Filion, 2001). Macrofossils were picked out, identified, and counted under a stereomicroscope at 40× magnification. The number of macrofossils in each sample was converted to frequency per 100 cm^3. References used in identifying plant remains were Lévesque, Dinel, and Larouche (1988), Montgomery (1977), and the plant-macrofossil reference collection of the Centre d'études nordiques (Université Laval). Botanical nomenclature follows Marie-Victorin (2002). Macrofossil zones were labeled alphanumerically, *i.e.,* with roman numerals corresponding to the sections analyzed (I, II, IV, and V), and letters (A to D) to the zones defined from macrofossil assemblages. The macrofossil diagrams were constructed using the Palaeo Data Plotter 1.0 software (Juggins, 2002).

Table 1. *List of radiocarbon dates.*

Sections and Depth (cm)	Sedimentary Units	Laboratory Sample No.	Material Dated	^{14}C Age (Conventional YBP)	Calibrated Age Median Probability (cal YBP)
Section I					
15–17	5	UL-1521	Organic matter	3230 ± 90	3450
25–27	5	UL-1514	Wood	3030 ± 60	3220
31–33	5	UL-1524	Wood	2750 ± 90	2900
33–35	4	UL-1527	Organic matter	1670 ± 70[a]	1560[a]
51–53	4	UL-1515	Wood	3750 ± 60	4110
54–56	4	UL-1516	Wood	3120 ± 60	3340
56–58	4	UL-1613	Organic matter	3080 ± 90	3260
70–71	4	UL-2208	Organic matter	4100 ± 70	4660
82–84	4	UL-1525	Organic matter	4270 ± 60	4880
89–91	4	UL-1614	Organic matter	4680 ± 100	5430
92–94	4	UL-1526	Organic matter	4790 ± 80	5550
92–95	[b]	UL-1557	Wood	5090 ± 80	5820
92–95	[b]	UL-1534	Wood	5370 ± 80	6140
106–108	3	UL-1522	Organic matter	5700 ± 120[a]	6520[a]
Section II					
37–39	4	UL-1539	Organic matter	980 ± 90[a]	880[a]
41–43	3	UL-1538	Organic matter	1390 ± 80[a]	1290[a]
73–75	3	UL-1523	Organic matter	2710 ± 90[a]	2890[a]
Section IV					
43–46		UL-2180	Organic matter	1660 ± 80	1560
68–71		UL-2182	Organic matter	4140 ± 80	4680
94–97		UL-2183	Organic matter	4750 ± 80	5460
Section V					
25–30		UL-2181	Organic matter	360 ± 80	410
Krummholz					
56–58		UL-1517	Wood	3060 ± 70	3240
Forest					
80–83		UL-1518	Organic matter	5500 ± 70	6310

[a] Radiocarbon dates from Germain and Filion (2002).
[b] Logs found at the contact of Units 2 and 4, 5 m west of Section I where Unit 3 was absent (see Figure 3 for location along the trench).

A total of 23 ^{14}C dates were used in this study (Table 1): 16 samples from Sections I, IV, and V, which were radiocarbon dated at Université Laval's ^{14}C laboratory; 5 ^{14}C dates from Sections I and II from Germain and Filion (2002); and 2 additional ^{14}C dates from the bottom of a 80 cm thick forest humus (F: Forest) in the forest-fringed north sector of the terrace, and from a conifer stump (K: Krummholz) found in live position close to Section I (Figure 2). All samples were pretreated in the laboratory prior to dating to remove carbonates and avoid old carbon reservoir effects (Olsson, 1986). Radiocarbon ages (^{14}C YBP) were calibrated (cal YBP) using the CALIB 5.0.1 program (Stuiver and Reimer, 1993; Reimer *et al.,* 2004). Calibrated dates were rounded to the nearest 10 years using 2-sigma cal age range. A present-day age was assigned to the top (0 cm) of Sections IV and V. Interpolated ages were obtained by linear interpolation. Results are expressed as cal YBP.

RESULTS

Section I

In Section I, five sedimentary units (1 to 5) were defined based on stratigraphy (Figure 3). Unit 1 is composed of very poorly sorted ($1.59ø < S_o < 2.30ø$) fine to coarse sand and silt ($1.86ø < M_z < 1.88ø$), light to dark gray in color. The coarse fraction (>2 mm) accounted for 30–35% of the total sediment weight. Unit 2 consists of a 5- to 25-cm layer of dark gray, thinly stratified, poorly sorted ($S_o = 1.16ø$) fine to coarse sand and silt ($M_z = 1.99ø$). The upper half of Unit 2 was slightly bioturbated and contained abundant root remains. Units 1 and 2 included several dropstones. Based on these sedimentary characteristics, they were identified as shallow-water regression deposits corresponding to tidal-flat (Unit 1) and low-marsh (Unit 2) sediments.

Unit 3 is a fibric peat layer 6 to 10 cm thick. Unit 4 is composed of well-humified, dark peat material with many wood fragments. The organic matrix of both Units 3 and 4 consists of a mixture of herbaceous remains and brown mosses. The basal peat (Unit 3; 106–108 cm) was dated 6520 cal YBP and the top (Unit 4; 33–35 cm) 1560 cal YBP (Germain and Filion, 2002). The change from fibric to well-humified peat (92–94 cm) was dated 5550 cal YBP (Figure 3 and Table 1). Two logs 15 cm in diameter overlying Unit 2, 95 cm from the surface and 5 m from Section I in the trench, were dated 6140 and 5820 cal YBP (Figure 3 and Table 1). In upper Unit 4, two wood fragments 3 to 5 cm in diameter were dated 4110 (51–53 cm) and 3340 cal YBP (54–56 cm) (Figure 3 and Table

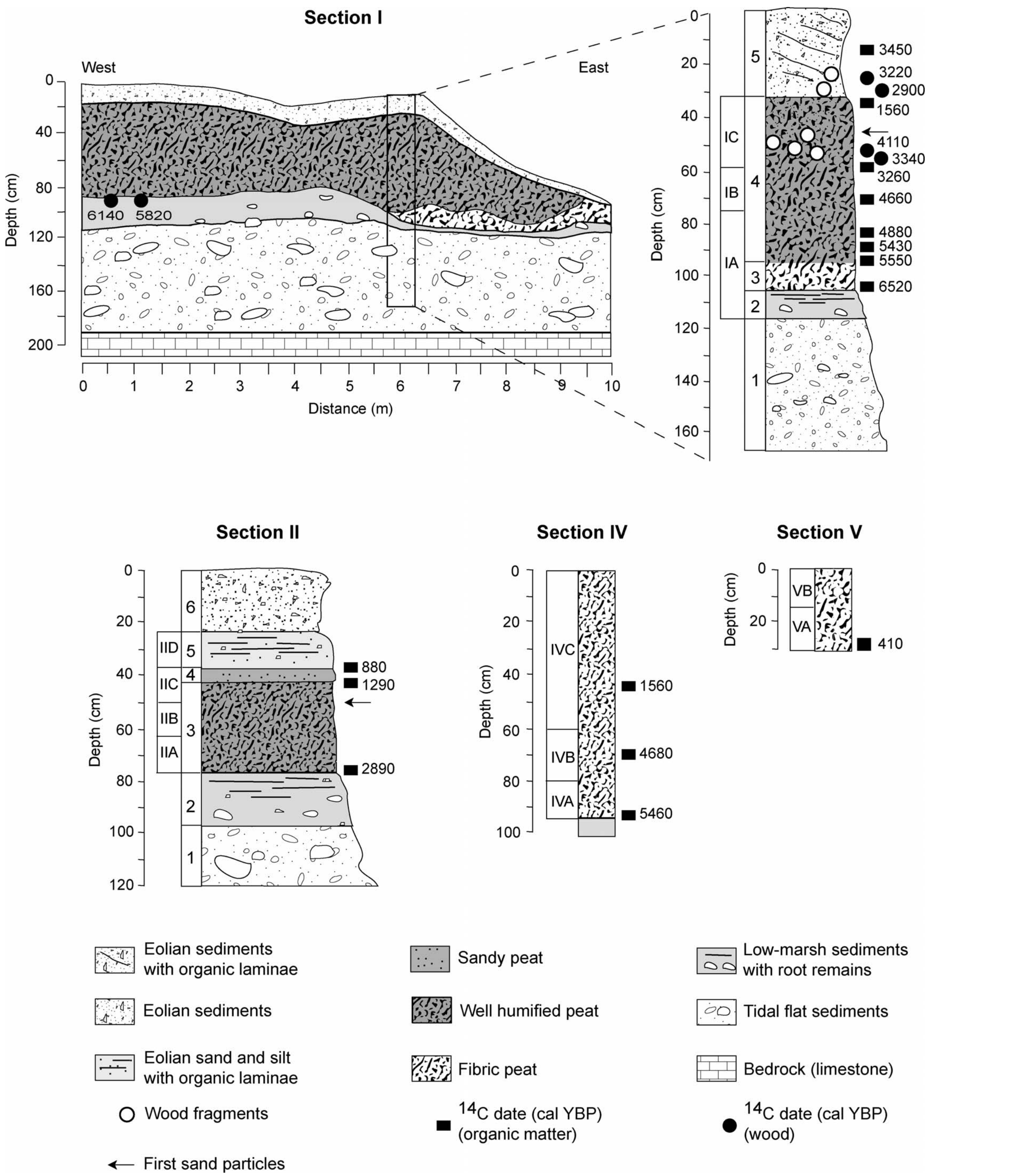

Figure 3. Stratigraphy and ^{14}C dates (cal YBP) of Sections I, II, IV, and V. 1 to 5 (Section I) and 1 to 6 (Section II): sedimentary units; IA to IC (Section I), IIA to IID (Section II), IVA to IVC (Section IV), and VA and VB (Section V): plant macrofossil zones.

1). These two dates were inverted chronologically with respect to those from the *in situ* organic matter above (1560 cal YBP) and below (3260 cal YBP) this wood layer.

The first sand particles in thin sections were found in upper Unit 4, from material collected at 45 cm (*ca.* 2375 cal YBP). Based on stratigraphic correlation, the stump found in live position 10 m away from the trench near the cliff (Figure 2, K: Krummholz), with exposed root collar 56–58 cm from the ground surface, and dated 3240 cal YBP (Table 1), is associated with the woody layer in Section I.

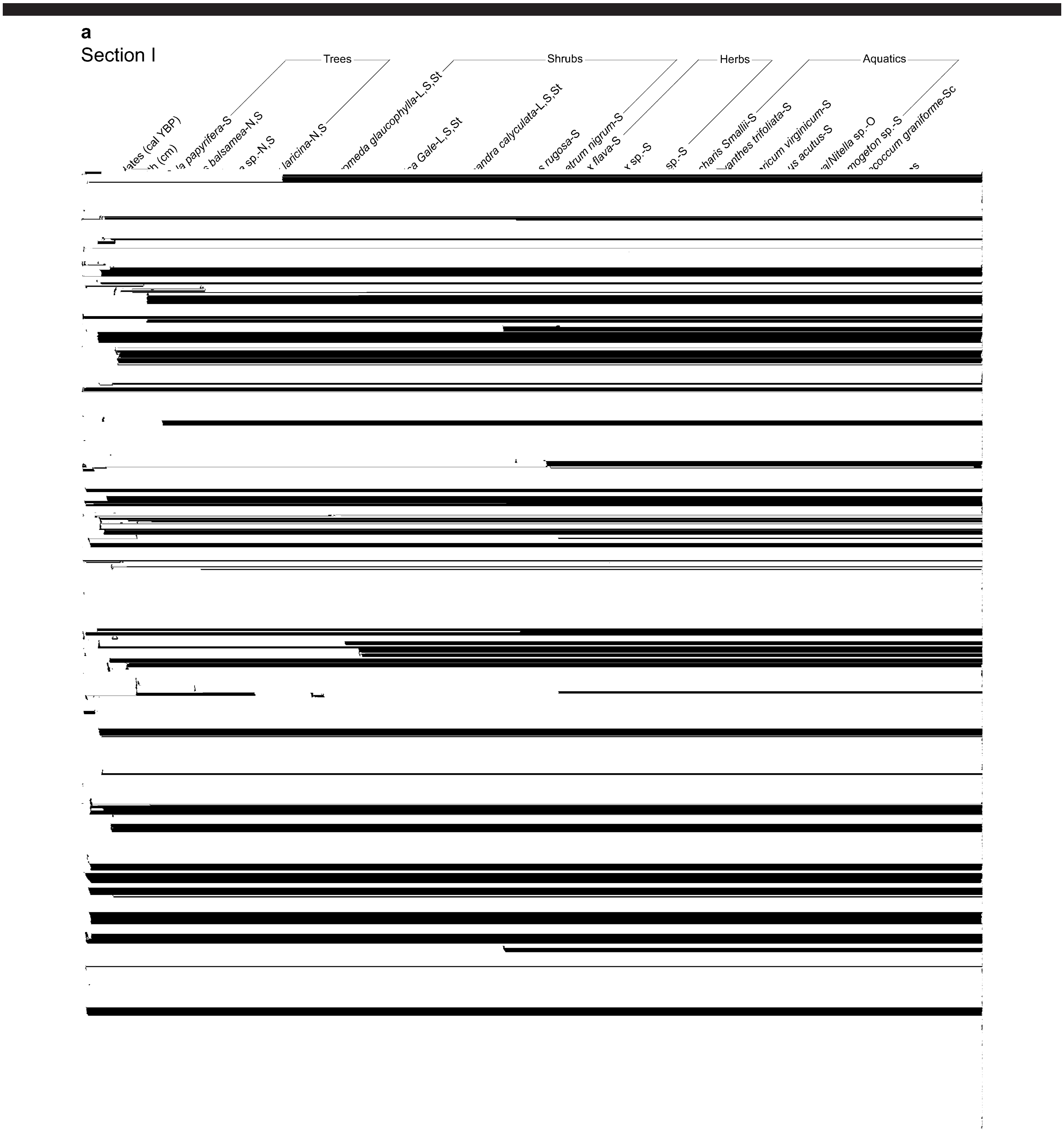

Figure 4. Plant-macrofossil diagrams from (a) Section I and (b) Section II. Results are expressed as number of macrofossils per 100 cm³ of sediment. Plant-macrofossil zones and sedimentary units (see Figure 3) are indicated on the right.

Unit 5 consists of stratified fine to very fine eolian sand (M_z = 2.28ø; S_o = 1.21ø) up to 30 cm in thickness, with organic laminae a few millimeters thick. The thickest (1 cm) organic laminae and two small wood fragments were dated 3450, 3220, and 2900 cal YBP, respectively (Figure 3 and Table 1), three dates inverted chronologically with respect to the uppermost buried peat dated 1560 cal YBP.

Based on plant remains and assemblages of Units 2 (eolian sand and silt), 3 (fibric peat), and 4 (well-humified peat), three biostratigraphic zones (IA to IC) were defined (Figure

4a). In Zone IA (115–75 cm), needles and seeds from balsam fir (*Abies balsamea*), spruce (*Picea* sp.), eastern larch (*Larix laricina*), and paper birch (*Betula papyrifera*) indicate that several tree species were established on the terrace shortly before 6520 cal YBP (contact of Units 2 and 3) until *ca.* 4740 cal YBP. Remains from shrubs (*Andromeda glaucophylla, Myrica Gale, Cassandra calyculata, Alnus rugosa, Empetrum nigrum*) and sedges (*Carex* sp.) were also abundant. High soil moisture was deduced from seeds of *Menyanthes trifoliata* and *Eleocharis Smallii* (Lavoie, 1984).

An abrupt change in plant assemblages occurred around 4740 cal YBP. Thereafter no tree or shrub remains were found in the macrofossil record of Section I. Zone IB (75–58 cm; *ca.* 4740 to *ca.* 3365 cal YBP) is clearly dominated by sedges, *Scirpus acutus* and *Viola* sp. Sclerotia from a mycorrhizal fungus, *Cenococcum graniforme,* were also abundant. In Zone IC (58–32 cm; *ca.* 3365 to 1560 cal YBP or shortly after), corresponding to upper Unit 4, plant macrofossils were much less abundant, and assemblages were dominated by sedges (*Carex* sp., *Carex flava*). Remains of *Potamogeton* sp. and *Chara/Nitella* sp. were also identified. Seeds of *Scirpus acutus* were much less abundant than previously, and no seeds of *Viola* sp. were found.

Section II

In Section II, six sedimentary units (1 to 6) were defined (Figure 3). Units 1 and 2 are similar to those in Section I identified as tidal flat and low-marsh sediments, respectively. Unit 3 is a well-humified peat 34 cm thick with an organic matrix composed of herbaceous plant remains and brown mosses. It was dated 2890 cal YBP at the base (73–75 cm) and 1290 cal YBP at the top (41–43 cm), *i.e.,* at the contact with Unit 4, a 5 cm thick brownish sandy peat (Figure 3 and Table 1). The first sand particles on thin sections were found within Unit 3 at 50 cm (*ca.* 1690 cal YBP). Fine but very poorly sorted sand (M_z = 2.27ø; S_o = 2.41ø) was distributed throughout Unit 4. Unit 5 overlying the sandy peat consists of a 15-cm layer of poorly sorted sand and silt (S_o = 2.01ø, M_z = 2.66ø) interstratified with thin organic laminae. Unit 6 is composed of brownish fine to medium sands (2.09ø < M_z < 2.61ø; 2.04ø < S_o < 2.32ø), deposited within a grass- and forb-dominated cover. The deposit was not stratified but heavily bioturbated, and included coarse angular limestone gravels and pebbles. An inverse grading was apparent, small to coarse pebbles being abundant near the soil surface.

Textural characteristics of littoral and eolian deposits contrasted sharply (Figure 5a). Whereas most quartz grains in littoral deposits (Units 1 and 2) were rounded, those found in eolian deposits (Units 5 and 6) were angular. Grains found in the sandy peat (Unit 4) had surface roundness similar to that of eolian sands. Furthermore, textural characteristics showed a clear difference in the two types of deposits (Figures 5b and 5c), with low mean size indices (<2ø), high variability in sorting indices, and a large sand:silt ratio (>8) for littoral deposits, and high mean size indices (>2ø), low variability in sorting indices, and a low sand:silt ratio (<7) for eolian deposits and sandy peat.

Units 3, 4, and 5 were analyzed for plant remains, and four macrofossil zones (IIA to IID) were defined (Figure 4b). In Zone IIA (75–62 cm; 2890 to *ca.* 2290 cal YBP), sedges (*Carex* sp.) dominated in the macrofossil record, although conifer needles (*Picea* sp. and *Abies balsamea*) were also found. Seeds of *Potamogeton* sp. indicated that shallow ponds were also present. In Zone IIB (62–50 cm; *ca.* 2290 to *ca.* 1690 cal YBP), shrub (*Andromeda glaucophylla, Myrica Gale, Cassandra calyculata* and *Alnus rugosa*) and sedge (*Carex* sp.) remains were abundant. In Zone IIC (50–36 cm; *ca.* 1690 to <880 cal YBP), which corresponds to the top of Unit 3, Unit 4, and the bottom of Unit 5, the macrofossil record was characterized by aquatic taxa (*Potamogeton* sp., *Myriophyllum* sp., *Eleocharis Smallii, Chara/Nitella* sp.), indicating high soil moisture (Marie-Victorin, 2002). Remains of shrub and herb species were

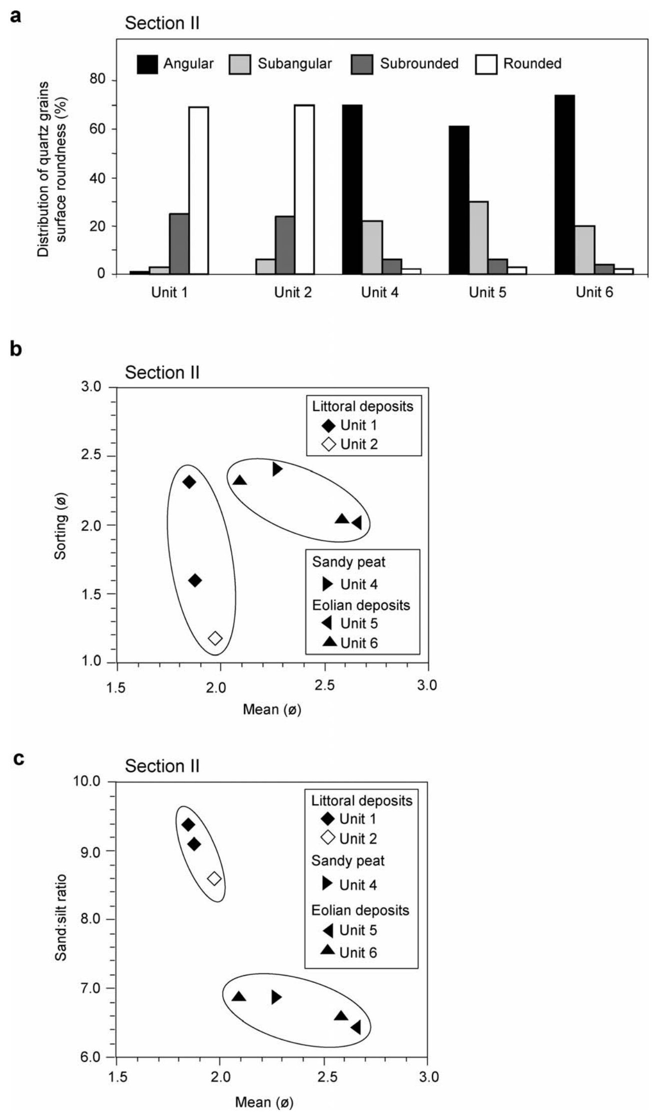

Figure 5. Textural characteristics of sedimentary Units 1 and 2, 5 and 6 from Section II, corresponding to littoral and eolian deposits, respectively, and Unit 4, a transitional sandy peat: (a) Distribution of quartz grain surface roundness; (b) mean *vs.* sorting; (c) mean *vs.* sand : silt ratio.

also identified (*M. Gale, Empetrum nigrum, Viola* sp.). Very few macrofossils were found in Zone IID, which corresponds to sedimentary Unit 5, composed of eolian sand and silt.

Section IV

Section IV, which was sampled in the marsh (Figure 2), is composed of a 97 cm layer of well-humified herbaceous peat dated 5460 cal YBP at the base (Figure 3 and Table 1). Three macrofossil zones (IVA to IVC) were defined based on plant assemblages (Figure 6a). In Zone IVA (97–80 cm; 5460 to *ca.* 5000 cal YBP), only seeds from sedges and *Comandra Richardsiana,* and sclerotia of *Cenococcum graniforme* were found. In Zone IVB (80–60 cm; *ca.* 5000 to *ca.* 3500 cal YBP), remains from *Larix laricina* and shrubs (*Andromeda glaucophylla, Myrica Gale,* and *Alnus rugosa*) and sedges dominated the record. Abundant seeds from *Menyanthes trifoliata* were also found. In Zone IVC (60–0 cm; *ca.* 3500 cal YBP to present), plant macrofossils included two needles from *Picea* sp., seeds from *C. Richardsiana,* and shrub remains (*M. Gale, Vaccinium Vitis-Idaea, Empetrum nigrum*). Remains from herb and aquatic plants included *Viola* sp., *Juncus* sp., *Utricularia* sp., and *Chara/Nitella* sp. No mineral matter (sand or silt) was found near the soil surface.

Section V

Section V is a 30-cm layer of fibric, herbaceous peat, which was sampled under a white spruce forest (Figure 2) and dated 410 cal YBP at the bottom (Figure 3 and Table 1). Two macrofossil zones were defined (Figure 6b). In Zone VA (30–15 cm; 410 to *ca.* 225 cal YBP), plant remains were very scarce, but sclerotia from *Cenococcum graniforme* were abundant. In Zone VB (*ca.* 225 cal YBP to present), tree remains, especially from *Picea* sp., were found at all levels analyzed. Several shrubs (*Myrica Gale, Andromeda glaucophylla, Cassandra calyculata*), *Viola* sp., and sedges were also identified. No mineral matter was found.

DISCUSSION

Forest fragmentation, development of treeless plant communities, and cliff-top eolian sedimentation at the Cape Sandtop terrace edge thus reflect drastic, Mid- to Late-Holocene environmental changes at the eastern end of Anticosti Island.

Relative Sea Level Changes

On Anticosti Island, paleogeography over the last 11,000–10,000 ^{14}C YBP (12,900–11,500 cal YBP) is still poorly documented. The few ^{14}C dates available (Bigras and Dubois, 1987; Gratton, Gwyn, and Dubois, 1984; Painchaud, Dubois, and Gwyn, 1984) indicate that the main events pertaining to relative sea level (RSL) changes were similar to those documented for Atlantic Canada, the Gulf of St. Lawrence, and the St. Lawrence estuary (Dionne, 1988; 2001; Scott and Collins, 1996; Shaw, Garneau, and Courtney, 2002). In the St. Lawrence estuary, the main events were as follows: (1) Between 9000 and 8000 ^{14}C YBP (10,200 and 8800 cal YBP), the RSL was slightly higher than the present RSL, *i.e.,* 15 m (Dionne, 1988, 2001). (2) After a low RSL stand between 8000 and 6400 ^{14}C YBP (8800 and 7350 cal YBP), land submergence occurred during the Laurentian transgression between 6400 and 4400 ^{14}C YBP (7350 and 4900 cal YBP), which was interpreted as a response to isostatic adjustment and possibly the northward migration of the postglacial forebulge (Bhiry, Garneau, and Filion, 2000; Dionne, 1988) (Figure 7). (3) A second but minor RSL rise occurred between 2500 and 1500 ^{14}C YBP (2550 and 1380 cal YBP), which was interpreted as a response to local tectonic events, *i.e.,* neotectonic faulting or seismicity (Dionne, 1996; Dyke and Peltier, 2000). On Anticosti Island, ^{14}C dates indicate that the maximum sea level was reached around 11,500 ^{14}C YBP (13,300 cal YBP) and 10,600 ^{14}C YBP (12,700 cal YBP) on the west (Gratton, Gwyn, and Dubois, 1984) and the north coast (Painchaud, Dubois, and Gwyn, 1984), respectively. At Cape Sandtop, no shells from the tidal flat and low-marsh sediments were found at the bottom of Sections I and II (Units 1 and 2, respectively). Even though the emergence of the rock platform could not be dated, we presumed that exposure to easterly winds increased with higher elevation (15 m asl).

Peat Inception and Shift from Forest to Treeless Plant Communities

Peat started to accumulate between 6520 (Section I) and 6310 cal YBP (F: Forest) on the Cape Sandtop terrace (Figure 7). The ^{14}C dates from basal peat buried by eolian sediments are close to those from three peatlands (Baie des Trois Ruisseaux, Port-Menier, and Box; Figure 1a), *i.e.,* 7260, 6860, and 6280 cal YBP, respectively (Lavoie and Filion, 2001). They support the interpretation for a wet, mid-Holocene climate, which was conducive to paludification of terrestrial sites. Increased paludification was also reported for southern Labrador (Lamb, 1980), Newfoundland (Davis, 1984), and the St. Lawrence lowlands (Filion, 1987). The much younger date for peat inception at Section II (2890 cal YBP) may be a result of local factors associated with distribution and thickness of littoral sediments and/or differential wind exposure and shore erosion in relation to changes in shoreline direction.

Abundant tree macrofossils in the buried peat in Section I (Figure 4a), as well as tree logs (Figure 3), indicate that Cape Sandtop was forested between *ca.* 6520 and *ca.* 4740 cal YBP. The local vegetation formed a mosaic of treed fen (*Larix laricina,* sedges, *Menyanthes trifoliata*) and spruce–balsam fir–paper birch forests (Figure 7) similar to conifer forests currently found in the north sector of the study site (Figure 2) and inland (Chouinard and Filion, 2005).

Whether the two logs (dated 6140 and 5820 cal YBP) found at the top of low-marsh sediments in Section I (Figure 3) can be associated with the rise in RSL after 7300 cal YBP in the St. Lawrence estuary (Laurentian transgression) remains uncertain. However, their horizontal rather than vertical position and the absence of roots suggest that they may be driftwood associated with the Laurentian transgression (Dionne 1988, 2001).

At the present terrace edge (Section I), the decrease of trees and shrubs in the macrofossil record occurred abruptly, around 4740 cal YBP (Figure 4a), *i.e.,* after the Laurentian transgression (4900 cal YBP) in the St. Lawrence estuary. Bigras and

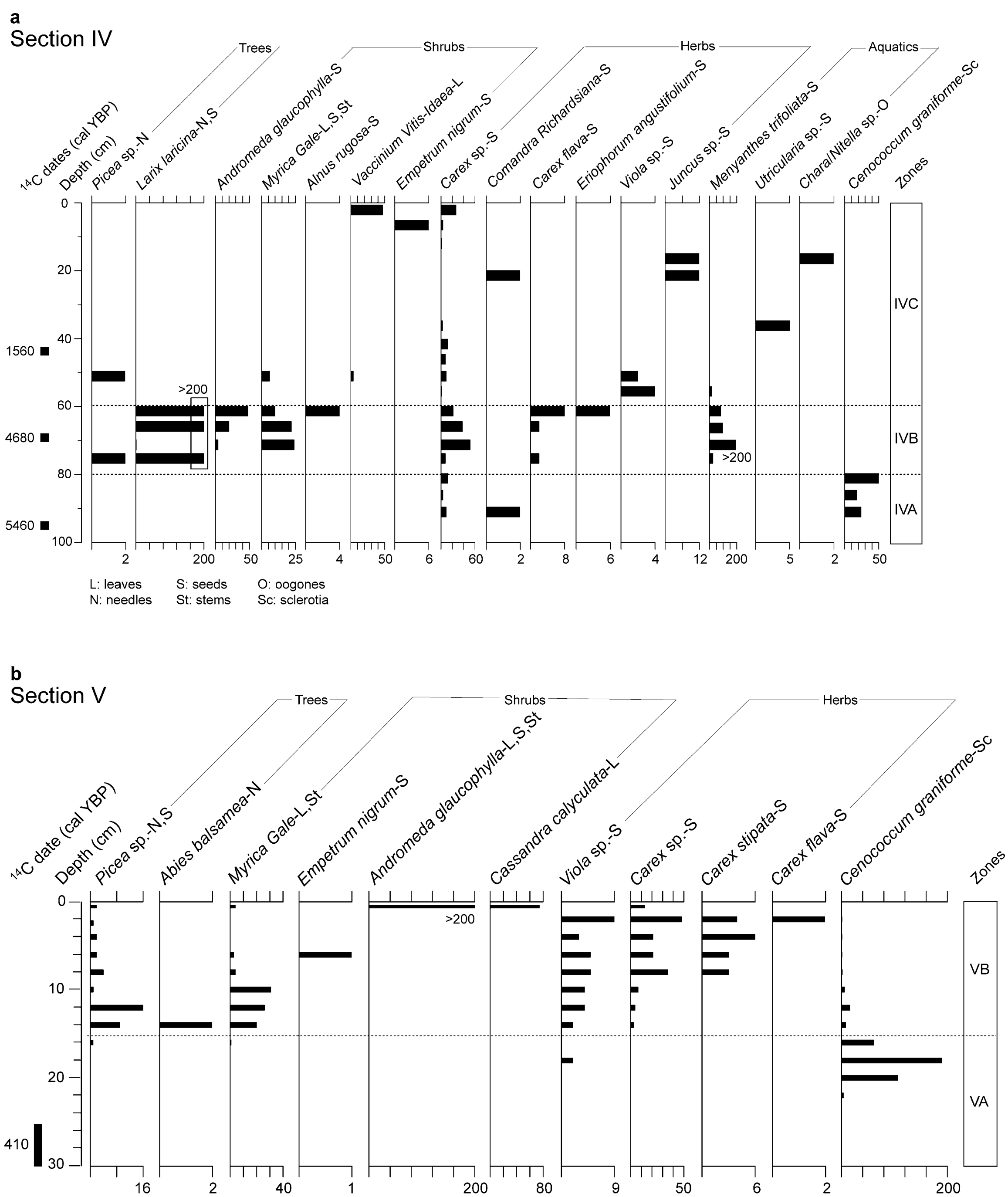

Figure 6. Plant-macrofossil diagrams from (a) Section IV and (b) Section V. Results are expressed as number of macrofossils per 100 cm³ of sediment. Plant-macrofossil zones are indicated on the right.

Dubois (1987) found evidence for a RSL 5 to 8 m higher than present about 4000 ^{14}C YBP (4500 cal YBP) in the western part of the island. The decrease in woody plants was followed by an increase in sedges and aquatic plants. *Scirpus acutus,* a species adapted to coastal windy environments (Marie-Victorin, 2002), was abundant at that time. About 30 m west of Section I, remains of *Larix laricina* and *Picea* sp. and sedges (Section IV; Zone IVB) indicate that the treed fen migrated inland and persisted until *ca.* 3500 cal YBP (Figure 6a). After 4740 cal YBP, the Cape Sandtop terrace thus experienced a change from coast-

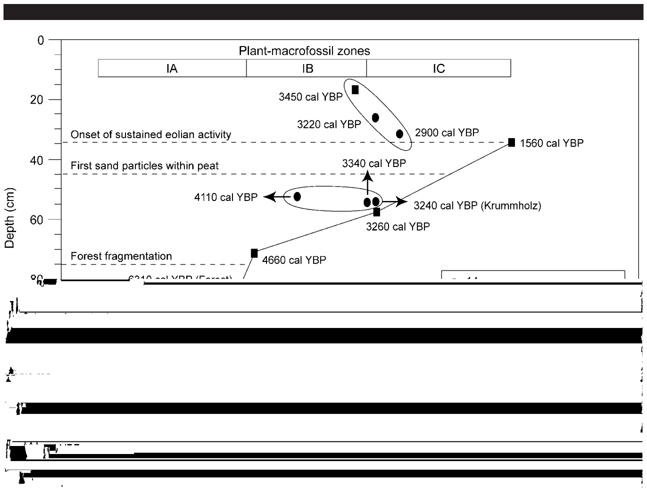

Figure 7. Age-depth peat accumulation model from Section I and chronology of local events on the Cape Sandtop marine terrace. Plant-macrofossil zones (IA to IC) and RSL changes in the St. Lawrence estuary (Dionne, 1988, 2001) were also indicated at the top and bottom, respectively.

al conifer forests and treed fen to marshes. This rapid shift in plant communities occurred during a period of forest densification inland, and development of closed balsam fir–spruce forests throughout the island, as deduced from arboreal pollen concentration and influx (Lavoie and Filion, 2001). Forest fires were not likely involved in forest fragmentation at the study site because no charcoal was found in the buried peat at any level analyzed.

Causal Factors for Cliff-Top Eolian Sedimentation

Occurrence of the first sand particles in thin sections from buried peat were dated *ca.* 2375 and *ca.* 1690 cal YBP in Sections I and II, respectively (Figure 3). These two interpolated ages correspond to the onset of erosional activity along the upper limestone cliff and the terrace edge (Bowen and Lindley, 1977). Sustained activity by easterly winds was evidenced by a subsequent burial of the peat after 1560 (Section I) and 1290 cal YBP (Section II) (Figure 3). Increased wind velocity and transport capacity was evidenced by large-sized, disk-shaped fragments, granule ripples, and coarse-grained detrital covers deposited over the terrace (Germain and Filion, 2002). In Section II, interstratified sand, silt, and organic matter with small flakes (Unit 5) overlying the sandy peat may be related to impeded drainage caused by silt-derived eolian sediments that were trapped by marsh plants during summer (Ballantyne, 1998; Germain and Filion, 2002; Wilson, 1989). In Section I, the four wood fragments dated between 4110 and 2900 cal YBP from the upper buried peat and eolian sediments, which caused chronological inversion (Figures 3 and 7), were found as wind-transported fragments. They likely originated from dead trees and/or krummholz located windward on the terrace edge, where a subfossil stump found in live position was dated 3240 cal YBP (Figures 2 and 7).

Whether wind erosion at Cape Sandtop occurred during the snow-free or the snow season remains uncertain in absence of direct field observations or measurements, the easternmost part of the island being inaccessible after October. However, cliff-top eolian activity at this site is more likely to occur during winter, when low air and soil surface temperatures and high wind velocity create conditions conducive to niveo-eolian activity (Germain and Filion, 2002; Mountney and Russell, 2004). In addition, sea waters surrounding Anticosti Island currently experience seasonal shore ice from January to April (Canadian Ice Service, 2000), a period with increased surface dryness (upper rock wall and sediments). Conditions during summer, with heavy fog, frequent rainfalls, and continuous supply of spin drift seem less propitious to wind activity. Cliff-top eolian deposition was attributed to winter activity at similar wind-exposed sites in the northern Gaspé Peninsula, Québec (Hétu, 1992), in the Northwest Territories, Canada (Bégin, Michaud, and Filion, 1995), and in Ireland (Wilson, 1989).

Sustained eolian activity after *ca.* 1600 cal YBP also resulted from a cooler climate during the Late Holocene as documented elsewhere in eastern Canada. In the northern Gaspé Peninsula (Figure 1a), the increase in balsam fir and green alder (*Alnus crispa*) pollen after 2550 cal YBP was attributed to cooler conditions (Marcoux and Richard, 1995). In the alpine and subalpine belts of the Chic-Choc Mountains (Gaspé Peninsula), conifers regressed after 2270 cal YBP (Payette and Boudreau, 1984). After 1960 cal YBP, on the north shore of the Gulf of St. Lawrence, eastward from Havre Saint-Pierre (Figure 1a) to Blanc-Sablon (close to southern Labrador), dry ombrotrophic peat blankets developed over well-drained soils in response to cooler and wetter conditions (Dionne, 1983; Dubois, 1980).

CONCLUSION

In spite of their limited extent, cliff-top eolian systems can provide useful information on the development of coastal (*e.g.,* Hétu, 1992) or terrestrial (*e.g.,* Bégin, Michaud, and Filion, 1995) sites during the Holocene. The coastal site studied thus appeared as a system that was sensitive to mid- to late-Holocene environmental changes that have resulted from the combined influence of regional and local factors. One of the key factors was the change in RSL, especially the sea level high stand *ca.* 4500 cal YBP, possibly at the end of the Laurentian transgression (7350 and 4900 cal YBP) identified in the St. Lawrence estuary. One or a series of catastrophic events, *i.e.,* floods resulting from major storms similar to those currently occurring along the Atlantic coast in eastern Canada and the United States (Elsner and Kara, 1999; Miller, 2004), may also have played a key role in the fragmentation of coastal forests. Local factors include increased exposure to easterly winds (after 1560 cal YBP) associated with higher elevation (15 m asl) of the marine terrace and sediment availability, which contributed to deposition of mineral particles of all sizes from the cliff onto the terrace.

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