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Past environmental change recorded in dune fields

Y. Michaud[1] and C. Bégin[1]

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Abstract : Sand dunes are excellent markers of past eolian activity and paleoenvironmental conditions. In the Mackenzie valley, sand dunes mainly occur in the vicinity of Fort Simpson, in the region of Tulita to Fort Good Hope, and on the northern tip of Tuktoyaktuk Peninsula. The occurrence of both active and stabilized dunes illustrates that paleoenvironmental conditions controlling their development must have changed at least locally during the Holocene. Two generations of dune fields are recognized: old dune fields that were formed during the Late Wisconsinian, and younger dune fields that have been episodically or continuously active in the Holocene. Comparison between dunes morphology, composition, orientation, and age with wind-direction and temperature-moisture records revealed that caution must be exercised in placing a climatic interpretation upon eolian phenomena at regional scale. In many locations, eolian activity may be triggered by ecological and geomorphic factors as well as climatic change.

Résumé : Les dunes de sable sont d'excellents indicateurs de paléoérosion éolienne et de conditions paléoenvironnementales. Dans la vallée du Mackenzie, des dunes de sable se sont formées près de Fort Simpson, dans la région située entre Fort Norman et Fort Good Hope, ainsi qu'à l'extrémité nord de la péninsule de Tuktoyaktuk. La présence de dunes actives et de dunes fixes indique que les conditions environnementales qui prévalaient pendant leur évolution se sont modifiées, du moins localement, durant l'Holocène. On distingue deux générations de champs de dunes : les champs de dunes formés durant le Wisconsinien supérieur et les champs de dunes qui étaient actifs de façon épisodique ou continue durant l'Holocène. La comparaison entre la morphologie, la composition, l'orientation et l'âge des dunes, d'une part, et la direction du vent, la température et l'humidité, d'autre part, incite à dedoubler de prudence lorsqu'on interprète les phénomènes éoliens à l'échelle régionale. En nombre d'endroits, l'activité éolienne peut être due à des facteurs écologiques et géomorphologiques ainsi qu'à un changement climatique.

[1] Geological Survey of Canada, Quebec Geoscience Centre, 2535 Boulevard Laurier, C.P. 7500, Sainte-Foy, Quebec G1V 4C7

INTRODUCTION

Sand dunes are excellent markers of past eolian activity and paleoenvironmental conditions. Dunes may reveal information on vegetation, fire history, temperature-moisture regimes, and wind regimes (David, 1981; Filion, 1984; Thorson and Bender, 1985); however, caution must be exercised in placing a climatic interpretation upon eolian phenomena, in recognition that the direct controls may be ecological or geomorphic factors that may or may not be related to climate. Lake drainage, river-level fluctuations and slope movements are processes that may contribute to sand-dune development by exposing sandy material to wind erosion.

Dune fields occur throughout Canada (David, 1977, 1981), usually in the vicinity of glaciofluvial deltas and outwash plains and glaciolacustrine deposits. Although dune fields have been documented in both subarctic and arctic regions (e.g. Carter, 1981; Filion et al., 1991), very little information has been published about sand dunes in the Mackenzie valley. David (1977) briefly described the dune fields of the Fort Simpson area, while Mackay (1963), Rampton (1988), and Ruz (1993) discussed the occurrence of eolian sediments and foredunes in the Tuktoyaktuk area. This paper provides an overview on the nature, extent, and age of major dune fields in the Mackenzie valley and a brief discussion of the paleoenvironmental changes recorded in dune-field history.

DISTRIBUTION AND AGE OF MAJOR DUNE FIELDS

Dune fields are rare in the Mackenzie valley. They mainly occur in the vicinity of Fort Simpson, and in the region of Tulita (formerly Fort Norman) to Fort Good Hope. A major dune field also lies along the Beaufort Sea coast on the northern Tuktoyaktuk Peninsula (Fig. 1). In the Mackenzie valley, dune fields are mainly composed of parabolic and cliff-top dunes. Most of the dune fields are stabilized with a forest cover, but portions of several dune fields are presently active. The occurrence of both active and stabilized dunes illustrates that conditions controlling their development must have changed at least locally during the Holocene.

Fort Simpson dune fields

Located in the southern Mackenzie valley, the Fort Simpson dune fields consist of three adjacent fields that cover 700 km^2 on both sides of the Mackenzie River near the confluence of Liard and Trail rivers (Fig. 1). They are mainly composed of fossil parabolic dunes and irregular hummocks.

Sand dunes several hundred metres in length and 10–15 m high are widely distributed in this area (Craig, 1965; David, 1977). Field observations along roadcuts on a raised delta of the ancestral Liard River reveal that dunes are composed of fine- to very fine-grained sand and do not contain basal or intercalated organic layers. Figure 1a shows the majority of the dunes that are large enough to be seen on airphotos (J. Aylsworth, pers. comm., 1993). A large number of the dune crests are oriented southeast-northwest, whereas some of them are arcuate towards the west. Other sand ridges oriented southwest-northeast are also present in the area, but considering that they are at least twice as large as the eolian dunes and that many of the ridges show small tails almost perpendicular to their orientation, they are interpreted as alluvial bars associated with the Liard River deltaic formation that have been reworked by eolian activity.

Detailed observation of the southeast-northwest dunes reveals that all of them are asymmetrical parabolic dunes where many show signs of a northwesterly influencing wind and some show evidence of a southeasterly influencing wind. Based on the morphology of all eolian features occurring in the Fort Simpson dune fields, dune-constructing winds were likely coming from the northwest, southeast, and east. Comparison of dune-crest orientations with the wind rose diagram from the Fort Simpson weather station for the interval 1964 to 1990 (Fig. 1) shows that both the southeasterly and the northwesterly winds are still present, whereas easterly winds are rare.

None of the dunes in the Fort Simpson area are presently active. They are heavily forested with the interdune areas being covered by swamps and bogs. Because little buried organic matter occurs within the sand hills, thermoluminescence dating was used to obtain ages on sand grains sampled from easterly and northwesterly oriented dunes. The method known as optically stimulated luminescence (OSL; *see* Aitken and Xie, 1992) was used to determine an age of 8200 ± 1000 years (*see* Appendix 2 for information on this date) for the surface (30 cm depth) of a parabolic dune chain situated on the northwest side of the Liard River and an age of 9000 ± 1000 years (*see* Appendix 2) for sand grains located at 5 m depth in a 15 m high sand ridge situated near Manners Creek.

The morphology, composition, and age of the sand hills indicate that the dune fields were produced in a single phase of eolian activity. The optically stimulated luminescence dates suggest that this eolian period must have started after the drainage of glacial Lake Mackenzie, right after deglaciation (11 500 BP) (Smith, 1992; Lemmen et al., 1994), until approximately 8000 years BP. Drainage of glacial Lake Mackenzie would have exposed the surface of the ancestral Liard River delta to wind erosion eventually leading to the formation of the dune fields. The eolian activity lasted a few thousand years, after which the dunes became stabilized by vegetation. There is no evidence of reworking or reactivation of eolian activity in the Fort Simpson area after this early period of dune formation. This extensive period of eolian activity was characterized by southeasterly, northwesterly, and easterly dune-building winds generated by an anticyclonic air mass centred on both the Laurentide Ice Sheet (David, 1981) and the Cordilleran Ice Sheet, and by an abundance of sand and silt deposits that were exposed as a result of both the retreat of the Laurentide Ice Sheet and the demise of glacial Lake Mackenzie.

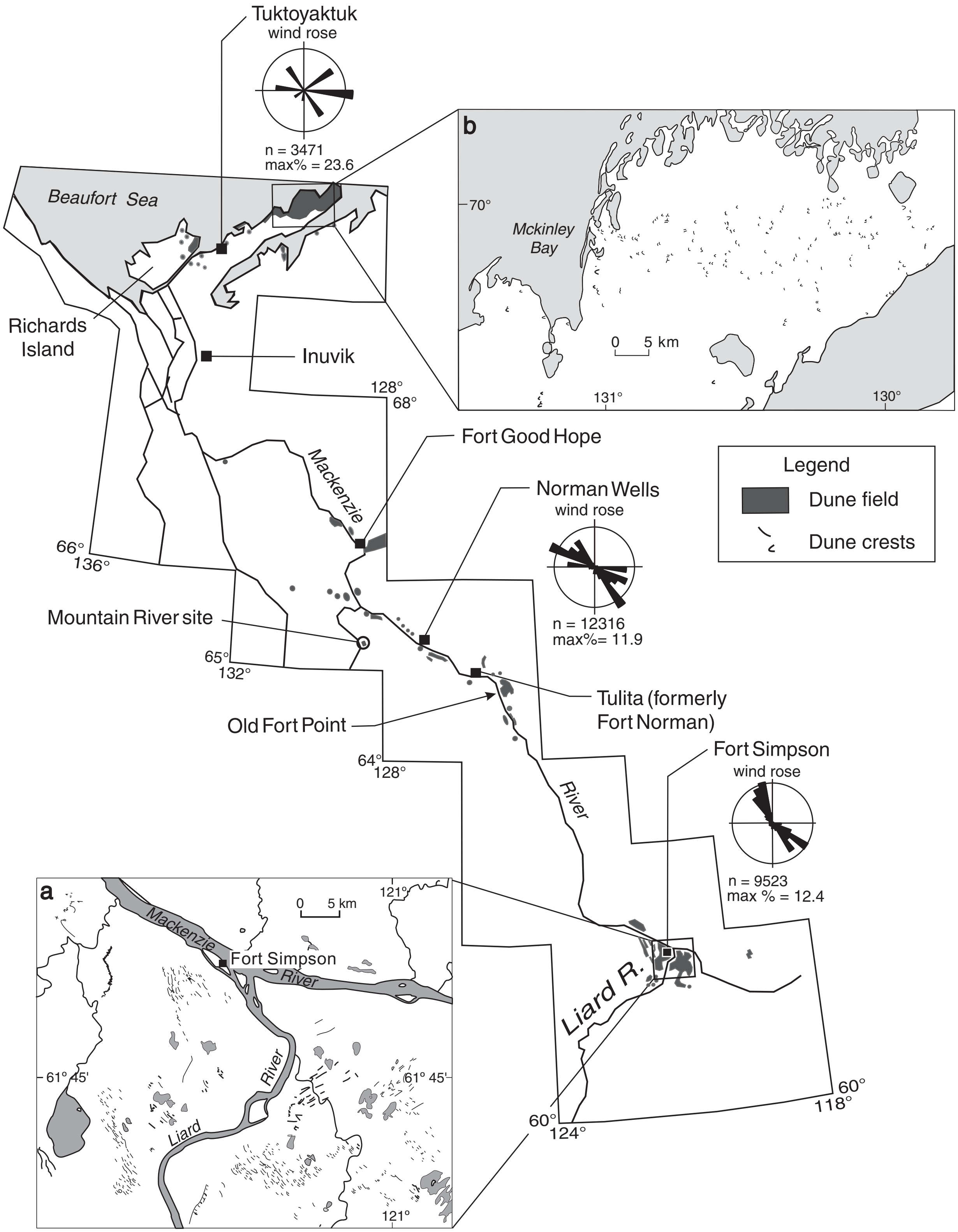

*Figure 1. Location and distribution of dune fields in the Mackenzie valley with enlarged maps of **a**) dune distribution in the Fort Simpson area, and **b**) dune distribution on Tuktoyaktuk Peninsula. Symbols representing parabolic inland dunes on Tuktoyaktuk Peninsula are arcuate in the downwind direction. Bars on the wind rose diagrams indicate the dominance of wind direction in 10° increments.*

Central Mackenzie valley dune fields

Numerous small dune fields or isolated dunes are also present in the central portion of the Mackenzie valley. Most are concentrated along the Mackenzie River between Old Fort Point, near Tulita, and Fort Good Hope, while a few others are distributed sporadically along tributaries. All the dune fields near the Mackenzie River are found on glaciofluvial and glaciolacustrine sediments in the vicinity of glacial Lake Mackenzie (Duk-Rodkin and Hughes, 1992, 1993; Smith, 1992). No dates are available for dune activity at these sites, but considering their location they probably formed immediately after the lake drainage, concomitant with the Fort Simpson dune fields. Individual fields, and even individual dunes, were formed at slightly different times related to the gradual regression of glacial Lake Mackenzie, exposing the former lake bed.

Figure 2. Oblique view of Mountain River cliff-top dune. The winter photograph illustrates the niveo-eolian character of that dune. It also illustrates that the dune is well developed only above a snow- and vegetation-free escarpment. The cliff is 85 m high and the dune is approximately 160 m wide. Photograph by M. Nixon. GSC 2000-029

In the central Mackenzie valley, a cliff-top dune along Mountain River provides an opportunity for paleoenvironmental reconstruction for this area over the last millennia (Bégin et al., 1995). The expansion of this dune towards the north-northeast into a mature white spruce stand along with buried organic horizons and dead trees in growth position, permits an assessment of cliff-top dune dynamics (Fig. 2).

The cliff-top dune, developed on the western edge of a glaciofluvial terrace, covers approximately 11 300 m^2 and consists of a bowl-shaped deflation zone exposing four organic layers, a 13 m high dune crest, and a 3200 m^2 accumulation zone strewn with dead trees buried in vertical position (Fig. 3). Initial cliff-top dune formation occurred between AD 750–860 when sand sprinkling improved the radial growth of trees located within D1-D2 organic horizons. Addition of sand through sand sprinkling modified the D1-D2 forest soils enough to allow trees to produce larger tree rings (Fig. 4). Dune building was actually initiated

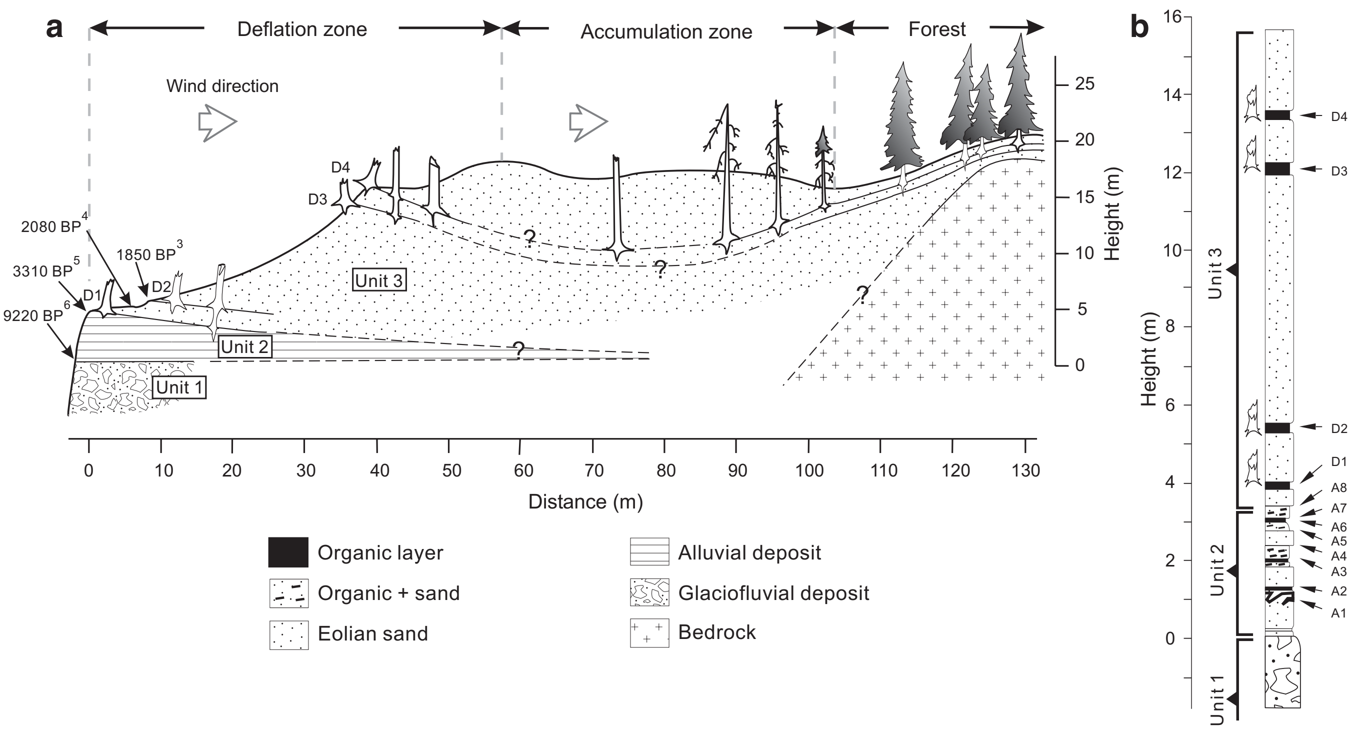

*Figure 3. **a**) Schematic longitudinal section of the Mountain river study site showing the stratigraphic units, the position of the forest paleosols (D1 to D4) and the vegetation types of the cliff-top dune. **b**) Stratigraphic section; A1–A8 refer to organic layers within the alluvial unit.* See *Appendix 2 for list of laboratory numbers for dates given in this figure.*

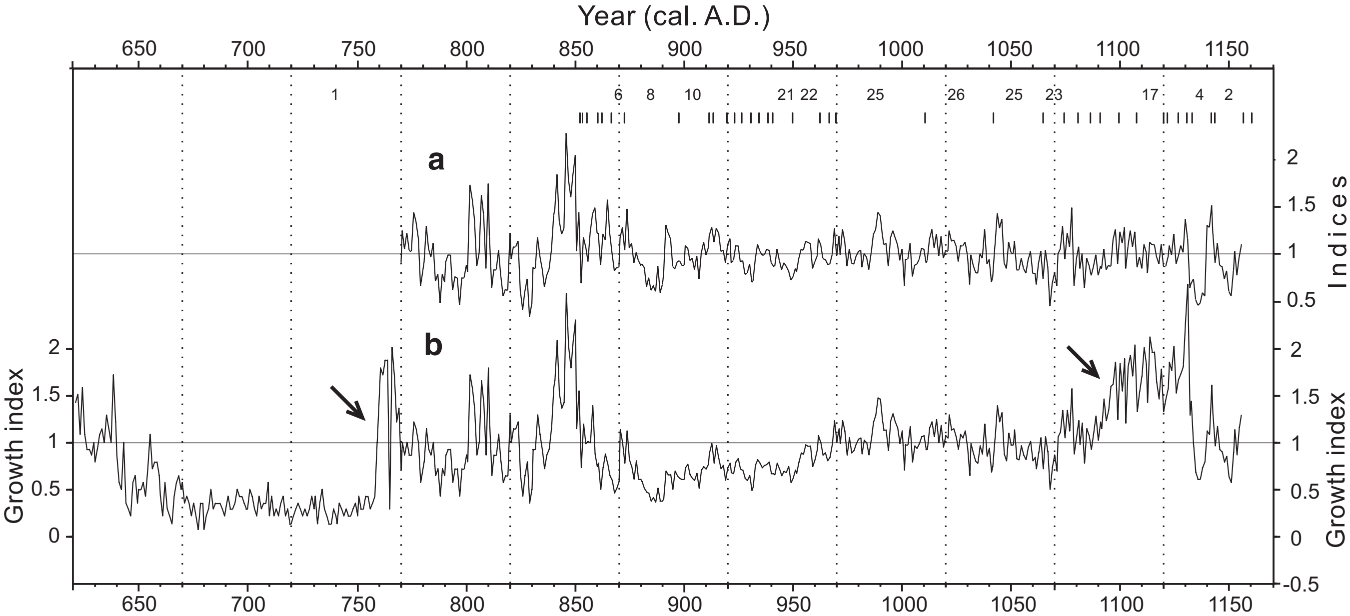

Figure 4. ***a***) *Standardized, and* ***b***) *growth-indexed series from dead trees (n = 26) from D1 and D2 forest paleosols at the Mountain River site. Arrows along the growth-index curve (b) are pointing at periods where tree-ring widths were getting larger than usual in response to slow eolian sedimentation. Numbers at the top refer to the total number of wood samples available. Calendar dates were derived from calibrated radiocarbon dates obtained from subfossil trees.*

around AD 1100, causing the death of several D1-D2 trees and eventually the burial of the forest soils under 7 m of sand. This eolian period lasted about 300 years and was followed by a stabilization phase which is recorded by the arrival of D3-D4 trees around AD 1460. This surface stabilization lasted a few hundred years until AD 1860–1865, when a second episode of eolian activity began.

An average sedimentation rate of 34 cm/year and an accumulation-front displacement of 78 cm/year for the dune were obtained from direct measurements during the summers of 1990 through 1992. Conversely, average erosion rates of 65 cm/year and 60 cm/year were calculated respectively for micro-cliff retreat and surface lowering of the windward zone. Finally, the presence of snow layers interbedded with sand layers and evidence of snow removal in the accumulation zone suggest that winter sand transportation is very important at the site. It appears that much of the dune construction occurs in winter and is the result of niveo-eolian activity.

Tuktoyaktuk area dune fields

The northern tip of the Tuktoyaktuk Peninsula is largely covered by a veneer of eolian sediments (Mackay, 1963; Rampton, 1988). Dune fields run across the peninsula in the vicinity of McKinley Bay and also occur on the eastern shore of Richards Island. Isolated sand dunes occur in the Tuktoyaktuk region between the eastern tip of the peninsula and the eastern end of Richards Island (Fig. 1; Mackay, 1963; Rampton, 1988). The largest dune field lies on the northern tip of the Tuktoyaktuk Peninsula and covers approximately 500 km^2 (Fig. 1b).

The Tuktoyaktuk Peninsula dune field is characterized by the presence of three types of dune that developed in different geomorphic settings and at different times. First, there are the 'inland dunes' which are low-lying parabolic dunes with average lengths varying from 300 m to 600 m and heights ranging from 0.5 m to 3 m. Most of these dunes are arcuate towards the west, thus indicating that they were constructed by easterly winds. These dunes are composed of fine-grained sand (average sand-grain diameter = 0.15 mm (2.85 ϕ)) and developed upon a sandy outwash plain (Rampton, 1988). They are fossilized features that are stabilized by a 25 cm thick humus layer topped by tundra vegetation cover (Fig. 5). An optical date (optically stimulated luminescence) for a fossil parabolic dune produced an age of 8600 ± 1000 years (*see* Appendix 2). This is one of the oldest dates for eolian activity in the Tuktoyaktuk area and is believed to represent the end of dune formation because the dated sand was sampled near the surface.

Second, there are numerous 'lakeshore dunes' located around drained thermokarst lakes. Some are blowout dunes and others are simply elongate ridges developed atop a low scarp surrounding lake edges (Ruz, 1993). Many drained thermokarst lakes have their own group of dunes formed from sand derived from the emerged lake shelves. In general, dunes are located on the eastern, southern, and western sides of partially to completely drained lakes. The development of these dunes depends on the catastrophic drainage of the individual thermokarst lakes, which occurs on the Tuktoyaktuk Peninsula through localized melting of permafrost and coastal retreat due to sea-level rise (Mackay, 1986, 1988; Ruz, 1993). The ages and periods of activity of the lakeshore

Figure 5. Fossil parabolic dune on Tuktoyaktuk Peninsula. This dune is typical of many inland dunes observed near McKinley Bay. The foreground dune is in the order of 400 m in length and 0.5 m in height. Photograph by Y. Michaud. GSC 2000-030

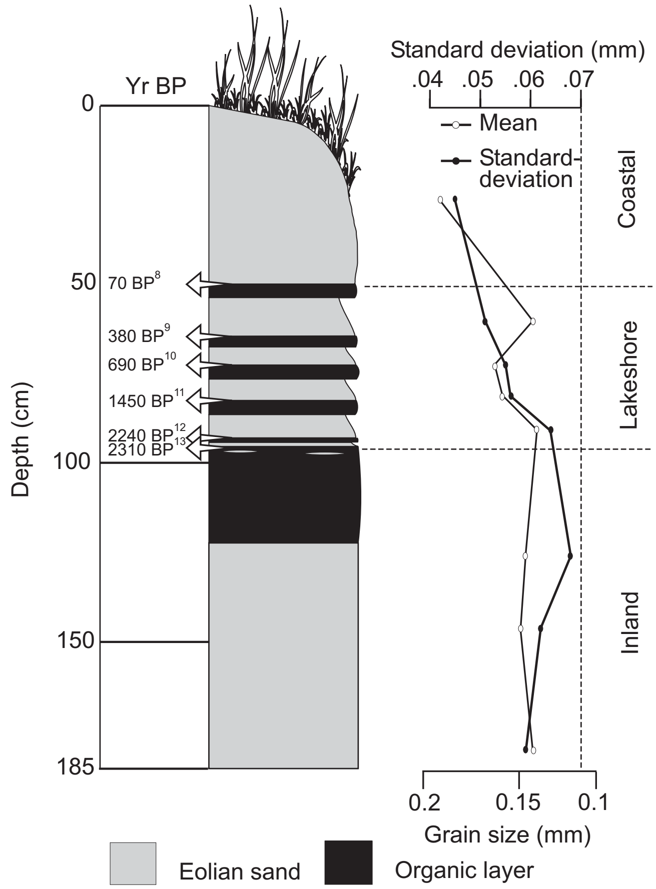

Figure 6. Cross-section showing the detailed chronostratigraphy of a sand bluff along McKinley Bay shoreline. Notice the upward evolution of dune type as coastal retreat progresses towards this location. See *Appendix 2 for list of laboratory numbers for dates given in this figure.*

dunes are variable and dependent upon individual lake drainage, which controls the availability of sand. Detailed dating of organic layers intercalated in lakeshore dune sequences in Atkinson Point (Ruz, 1993) and McKinley Bay (Bégin and Michaud, 1993) suggests periodic activity of these dunes beginning around 3000 years BP (Fig. 6). These organic layers represent several phases of dune stabilization, indicating that these dunes evolved separately in response to drainage of their nearby thermokarst lakes.

Third, there are 'coastal dunes' bordering the Beaufort Sea. These dunes occupy a narrow coastal strip and are widely distributed along Tuktoyaktuk Peninsula and Richards Island (Rampton, 1988; Ruz, 1993). Foredunes are found landward of large beaches along low shorelines, while cliff-top dunes are formed above some of the retreating sand bluffs. These are subjected to both easterly and strong westerly winds usually associated with storms. At present, all coastal dunes are active. Given the context of shoreline erosion caused by the Holocene sea-level rise (Hill et al., 1993), it may be argued that coastal dunes likely formed continuously throughout the Holocene.

PALEOENVIRONMENTAL RECONSTRUCTION ON THE BASIS OF EOLIAN ACTIVITY

Two generations of dune fields are recognized in the Mackenzie valley: 1) old dune fields that were formed during the Late Wisconsinan (prior to 8000 BP), and 2) younger dune fields that have been episodically or continuously active in the Holocene.

Numerous dune fields were developed at the periphery of the Laurentide Ice Sheet shortly after its retreat (Gadd et al., 1971; David, 1981; Filion, 1987; Côté et al., 1990), suggesting the presence of katabatic winds emanating from an anticyclonic air mass centred on the ice sheet (David, 1981). This wind regime seem to have lasted about 2000–2500 years before the temperature-moisture regime of these areas was altered following ice-sheet breakup (David, 1981; Filion, 1987). As shown in Figure 7, the orientation of the old dune fields of the Mackenzie valley indicates that they were formed by bidirectional winds in a large corridor confined between two ice caps. Katabatic winds induced by both the Laurentide and the Cordilleran ice sheets seem to be responsible for the formation of these dune fields during the Late Wisconsinan. Since paleoenvironmental reconstructions for the Mackenzie valley (Spear, 1983; Ritchie, 1984, 1985) revealed that the temperature-moisture regime of the valley had become gradually warmer and more humid by 12 000 BP, they indicate that Fort Simpson and some central Mackenzie valley dune fields likely followed the same pattern of development as the dune fields described in the Prairies and in St. Lawrence Lowlands. As for the Tuktoyaktuk Peninsula inland dunes, the optically stimulated luminescence date suggests that these dunes began forming after the retreat of the Laurentide Ice Sheet, but the orientations of the dunes (Fig. 1b) show that they were built by easterly winds. Therefore, these inland dunes formed under a polar easterly wind regime different from that operating in the Mackenzie valley.

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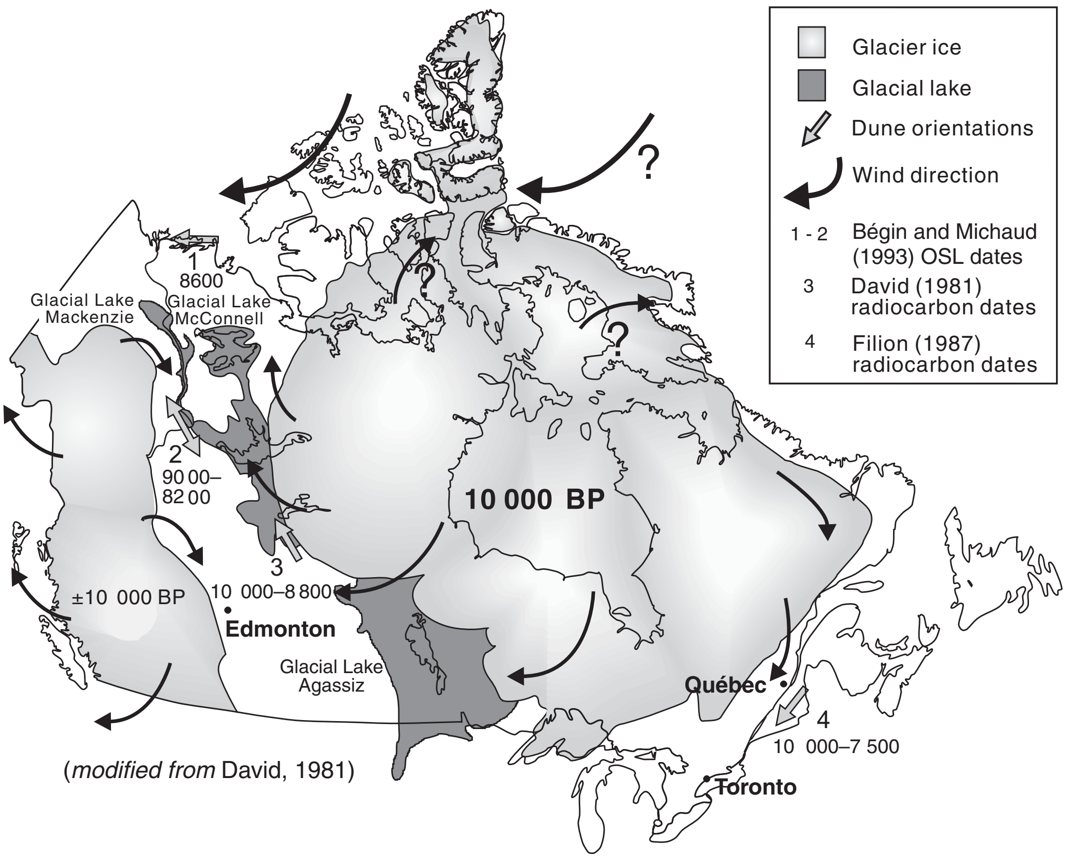

***Figure 7**. Position of some dune fields that were active during the Early Holocene. Most of them were located adjacent to the Laurentide Ice Sheet and were under the influence of anticyclonic air-mass circulation centred over the Laurentide and the Cordilleran ice sheets. Notice that late Wisconsinan inland dunes on the Tuktoyaktuk Peninsula were formed under a polar easterly wind system, which was independent of the wind pattern related to the ice sheets.*

Thus, the late Wisconsinan period seems to have been marked by the presence of two dominant wind systems, namely the anticyclonic air-mass systems centred on both the Laurentide and the Cordilleran ice sheets and the polar easterlies (Fig. 7).

According to wind-direction records from Fort Simpson, Norman Wells, and Tuktoyaktuk (Fig. 1), air masses centred on the ice sheets have been more or less replaced by a wind regime that follows the overall topography of the valley, while the polar easterlies remain active in the Mackenzie Delta. In fact, comparisons between contemporary wind patterns and Holocene eolian activity in the Mackenzie valley, as well as on the Alaskan arctic coastal plain (Carter and Robinson, 1978; Carter, 1981, 1993), indicate that arctic wind regimes have not changed much during the Holocene.

The activity of younger dunes is more difficult to assess regionally, because they are often represented by systems that are active either continuously or episodically, depending upon local factors which control the availability of sand. This seems to be the case for the Mountain River cliff-top dune, where downcutting and slope processes were key triggering mechanisms, and also the case for lakeshore and coastal dunes on the Tuktoyaktuk Peninsula where thermokarst lake drainage and shoreline erosion control the activity; however, by compiling radiocarbon dates for dune initiation in locations in the Arctic, it seems that eolian activity resumed around 4000 years ago resulting from the deterioration of climate in the Arctic (Ritchie and Hare, 1971; Pissart et al., 1977). Dune inception dates of 3790 ± 90 BP and 3460 ± 80 BP from Banks Island (Pissart et al., 1977), 3280 ± 130 BP (Lowdon and Blake, 1978), 2310 ± 70 BP (*see* Appendix 2) (Bégin and Michaud, 1993), and 1530 ± 70 BP (Ruz, 1993) from the Tuktoyaktuk Peninsula, plus many others from northern Alaska (Galloway and Carter, 1992) have been used to interpret the resumption of eolian activity around the Beaufort Sea. On the other hand, the renewal of eolian activity around 4000 BP does not mean that sand dunes were absent in the region prior to that date. Ages of 8430 ± 120 BP (Pissart et al., 1977) and 5800 ± 180 BP (Pissart et al., 1977) were reported from Banks Island, while coastal dunes would likely been active throughout the Holocene.

Obtaining significant regional paleoenvironmental records from younger and smaller dune systems is difficult. It has been shown that many of these dunes are subject to local perturbations controlled by sediment supply. Lakeshore dunes on the Tuktoyaktuk Peninsula and cliff-top dunes along river banks are good examples of such situations. The chronology of lakeshore dunes seems to highlight thermokarst-lake water-level fluctuations (Ruz, 1993) whereas the chronology of the cliff-top dune on Mountain River provides indirect information on river-level fluctuations, slope processes, and katabatic wind regime. Before significant climatic signals can be interpreted from these dune systems, periods and triggers of eolian activity need to be validated by the chronology of other geomorphic processes from the entire Mackenzie valley.

ACKNOWLEDGMENTS

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Appendix 1

Temperate sand-dune nomenclature

A sand dune can be defined simply as a hill or a ridge of sand piled up by the wind (Pye and Tsoar, 1990); it can form under any climatic regime, the key conditions being that bare sand is exposed to wind that is strong enough to entrain sand particles. Deposition of sand at any location is then governed by a combination of factors such as topography, bed-roughness changes, or aerodynamic fluctuations and vegetation. In general, eolian processes are more important in deserts, but they also occur in temperate regions where sand moisture can vary through time and from place to place. In Canada, most, if not all, dunes formed under temperate conditions.

The formation of sand dunes requires the occurrence of three basic elements: 1) a sand-transporting wind (windspeed > 5 m/s), 2) some bare sands available for wind transportation, and 3) some sort of obstacles to trap the sand. Since these requirements are often met, sand dunes are found in many geographic locations, climatic zones, and geographical settings. Sand dunes have been classified and named on the basis of criteria related mainly to morphology and geographical setting.

Morphological aspects

In temperate zones, all dunes are basically **parabolic dunes**. They are curved dunes where sand is removed from the centre of the dune (blowout zone) and carried downwind, leaving two arms pointing upwind. This type of dune is also known as a blowout dune. Depending on the amount of sand available, parabolic dunes may become highly deformed, generating several forms of dunes such as **asymmetrical**, **elongated**, **fish-hook**, **V-shaped**, and **dune ridges**. These are a few of the forms which result from a lack of sand supply.

Geographical settings

Sand dunes are often classified in accordance with the environment or surrounding landscape where they develop. Dunes such as **coastal dunes**, **lake-shore dunes**, and **inland dunes** refer to the general environment where they formed, whereas dunes such as **cliff-top dunes** and **foredunes** refer to a specific topographic context.

Appendix 2

List of laboratory numbers for dates given in text

Number	Age	Standard deviation	Laboratory
1	8200 ± 1000 BP	1	LUX-104gf
2	9000 ± 1000 BP	1	LUX-103gf
3	1850 ± 100 BP	2	GSC-5348 *
4	2080 ± 70 BP	2	GSC-5358 *
5	3310 ± 90 BP	1	BETA-50209
6	9220 ± 170 BP	1	BETA-50210
7	8600 ± 1000 BP	1	LUX-105gf
8	70 ± 80 BP	2	GSC-5573 *
9	380 ± 70 BP	2	GSC-5563 *
10	690 ± 60 BP	2	GSC-5551 *
11	1450 ± 70 BP	2	GSC-5545 *
12	2240 ± 80 BP	2	GSC-5537 *
13	2310 ± 70 BP	2	GSC-5525 *

* $d^{13}C_{PDB}$ = -25‰