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Datación óptica de las dunas de las arenas modernas y del Holoceno superior en la región de Brandon Sand Hills al sudoeste de Manitoba, Canadá

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Résumé de l'article

En datation optique, on doit tenir compte de deux aspects : les échantillons d'âge zéro livrent-ils bien un âge optique de zéro ? Les âges optiques correspondent-ils aux autres données d'ordres stratigraphique et chronologique ? Un test a été réalisé sur des échantillons d'âge zéro provenant d'une dune de sable active. Les résultats obtenus sur trois échantillons de surface ont démontré qu'en soumettant des feldspaths potassiques à un rayonnement infrarouge de 1,4 eV, la dose équivalente nécessaire, et par conséquent l'âge, dépendait du type de transfert de correction thermique, radiation infrarouge/rouge ou solaire, ce qui entraînait une marge d'erreur possible de ±40 ans. Les âges optiques des échantillons situés à 50 cm sous ces derniers, calculés en fonction de ceux-ci, étaient de 8 ± 8, 1 ± 7, et 38 ± 7 ans, peu importe le type de remise à zéro. Ces âges correspondent aux valeurs attendues dans tous les cas. Les âges optiques de sables dunaires de l'Holocène supérieur obtenus à la coupe de Brookdale Road correspondaient aux âges au radiocarbone de la matière organique dans les sols enfouis. La série des âges optiques et au radiocarbone obtenus dans les Brandon Sand Hills révèle l'existence de périodes d'activité et de stabilité des dunes dans la région et indique l'existence probable de périodes d'activité éolienne vers 2 ka, de 3,1 à 4,0 ka et avant 5,2 ka BP.

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OPTICAL DATING OF MODERN AND LATE HOLOCENE DUNE SANDS IN THE BRANDON SAND HILLS, SOUTHWESTERN MANITOBA*

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ABSTRACT For any suite of optical dating samples two issues that must be considered are: do zero-age samples yield an optical age of zero, and are the optical ages consistent with independent stratigraphic and chronologic information? A test of the zero-age of dune sands was performed by dating samples from the crest, lee slope and stoss slope of an active dune in southwestern Manitoba. Three surface samples showed that, using 1.4 eV (infrared) excitation of K-feldspars, the equivalent dose, and hence “age”, depended on whether the bleach used for the thermal transfer correction was infrared/red or sunlight, leading to an age uncertainty of about ±40 years. Optical ages for samples 50 cm below these, and calculated relative to them, were 8 ± 8, 1 ± 7, and 38 ± 7 years, independent of the bleach used. These ages are consistent with expectations for the crest, lee slope and stoss slope, respectively. Optical ages of late Holocene dune sand units at the Brookdale Road section, southwestern Manitoba, were consistent with radiocarbon ages from organic matter within intervening buried soils. The suite of optical and radiocarbon ages from the Brandon Sand Hills provides a record of dune activity and stability for the region, and tentatively identifies periods of eolian activity at about 2 ka, 3.1 to 4.0 ka, and prior to 5.2 ka.

RÉSUMÉ *Datation optique de dunes de sable modernes et de l’Holocène supérieur dans les Brandon Sand Hills, au sud-ouest du Manitoba.* En datation optique, on doit tenir compte de deux aspects : les échantillons d’âge zéro livrent-ils bien un âge optique de zéro ? Les âges optiques correspondent-ils aux autres données d’ordres stratigraphique et chronologique ? Un test a été réalisé sur des échantillons d’âge zéro provenant d’une dune de sable active. Les résultats obtenus sur trois échantillons de surface ont démontré qu’en soumettant des feldspaths potassiques à un rayonnement infrarouge de 1,4 eV, la dose équivalente nécessaire, et par conséquent l’âge, dépendait du type de transfert de correction thermique, radiation infrarouge/rouge ou solaire, ce qui entraînait une marge d’erreur possible de ±40 ans. Les âges optiques des échantillons situés à 50 cm sous ces derniers, calculés en fonction de ceux-ci, étaient de 8 ± 8, 1 ± 7, et 38 ± 7 ans, peu importe le type de remise à zéro. Ces âges correspondent aux valeurs attendues dans tous les cas. Les âges optiques de sables dunaires de l’Holocène supérieur obtenus à la coupe de Brookdale Road correspondaient aux âges au radiocarbone de la matière organique dans les sols enfouis. La série des âges optiques et au radiocarbone obtenus dans les Brandon Sand Hills révèle l’existence de périodes d’activité et de stabilité des dunes dans la région et indique l’existence probable de périodes d’activité éolienne vers 2 ka, de 3,1 à 4,0 ka et avant 5,2 ka BP.

RESUMEN *Datación óptica de las dunas de las arenas modernas y del Holoceno superior en la región de Brandon Sand Hills al sudoeste de Manitoba, Canadá.* A fin de establecer la edad óptica de una muestra dos aspectos necesitan ser considerados: primero saber si muestras estimadas a una edad cero llevan a obtener una edad óptica cero y segundo si la edad óptica coincide con la información obtenida a partir de datos estratigráficos y cronológicos independientes. Durante el presente estudio una prueba de edad-cero de las dunas de arena fue realizada a partir de muestras provenientes de la cima, y de las laderas a sotavento y a barlovento de una duna activa situada al sudoeste de Manitoba. Tres muestras superficiales mostraron que usando un rango de excitación infrarrojo de 1,4 eV sobre feldespato potásico, la dosis equivalente y por lo tanto la “edad” depende de si el excitante empleado para obtener la corrección de transferencia térmica se sitúa en la región del rojo/infrarrojo o de la luz solar y proporciona un margen de error de ±40 años. La edad óptica de muestras de 50 cm situadas por debajo se estimaron respecto a las anteriores. Los resultados obtenidos las sitúan entre 8 ± 8, 1 ± 7, y 38 ± 7 años, independientemente del excitante empleado. Estas edades concuerdan con lo que se esperaba para la cima y las laderas a sotavento y a barlovento, respectivamente. La edad óptica correspondiente a dunas de arena datando del Holoceno superior en la sección de Brookdale Road al sudoeste de Manitoba coincidió con la edad estimada con carbono radioactivo obtenida a partir de la materia orgánica en diversos suelos sepultados. Los datos correspondientes a la edad óptica y la estimada con radiocarbono en la zona de Brandon Sand Hills proporcionan un registro de la actividad de las dunas e igualmente de la estabilidad de la región. Podemos además suponer que identifican periodos de actividad eólica que los sitúan entre 2000, 3100 a 4000 y 5200 años anteriores al presente, respectivamente.

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INTRODUCTION

Increasingly, optical dating is used to develop records of dune chronologies on the Great Plains of North America, and elsewhere (Stokes and Gaylord, 1993; Stokes and Swinehart, 1997; Wolfe *et al.*, 2001; Arbogast *et al.*, 2002; Thomas and Shaw, 2002). Whereas radiocarbon dating is still a commonly used technique for determining Holocene chronologies in these and other paleoenvironments, the suitability of eolian sediments for optical dating and the absence of organic material suitable for reliable radiocarbon dating in dune sands, has led to the common use of optical dating of these sediments. Despite the acceptance of optical dating, there is still a need for rigorous testing of the technique as applied to these and other environments.

The primary objective of this study was to improve the present chronology for the timing of eolian activity in the Brandon Sand Hills, southwestern Manitoba, using optical dating of dune sands. In achieving this objective, we also tested the ability of optical dating to provide zero and modern ages for an active sand dune, and compared optical ages of dune sands with radiocarbon ages of organic matter within intervening paleosols.

The Brandon Sand Hills are located approximately 19 km east of Brandon, Manitoba (Fig. 1), and are comprised of a number of separate dune fields with a total area of 1 400 km^2 including a main dune area of 960 km^2. This is the easternmost dune occurrence on the southern Canadian prairies, residing within the aspen parkland ecoregion of the prairie ecozone. Most of the sand dunes in the area are presently stabilized by parkland and forest vegetation. Exposed sections within the stabilized dunes typically reveal several metres of sandy eolian deposits, separated by buried soil horizons, representing periods of past eolian activity and stability, respectively. Accelerator mass spectrometry (AMS) and radiometric age determinations have been obtained from organic matter contained within these

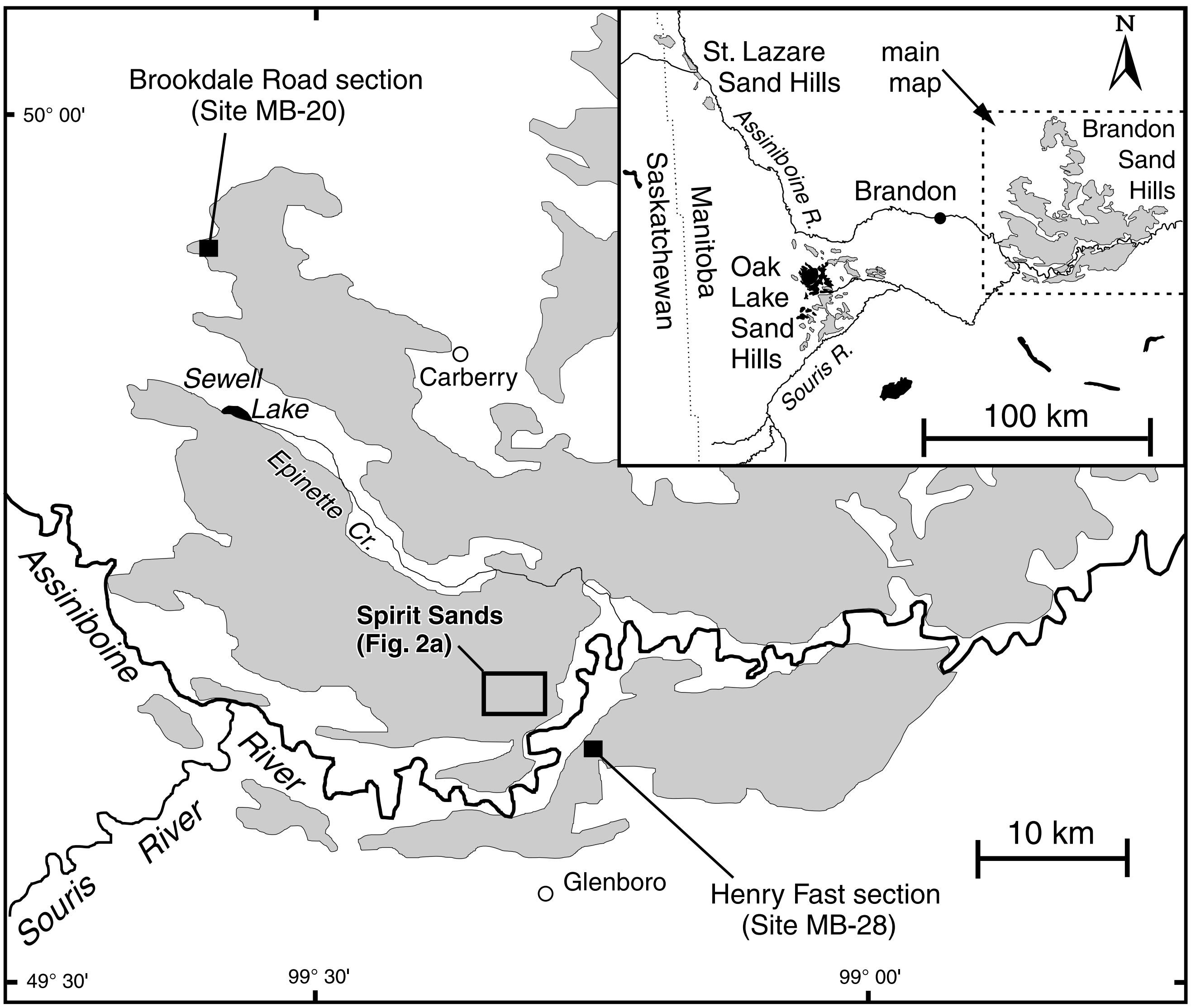

FIGURE 1. Location map of the Brandon Sand Hills and site locations.

Localisation des Brandon Sand Hills et des sites d'échantillonnage.

buried soils (David, 1971; Wolfe *et al*., 2000). Numerous uncertainties are associated with age estimates derived from radiocarbon analyses of organic matter in buried soils, in part because organic matter within a soil is derived from a variety of sources accumulated over the soil residence time. Thus, a conservative approach to interpreting radiocarbon ages of buried soils is to consider them as maximum limiting ages for any overlying deposits (David, 1971) and as minimum limiting ages for the parent eolian sand and any underlying deposits (Muhs *et al*., 1997). Radiocarbon dating of soil organic matter in the Brandon Sand Hills indicates recurrent intervals of eolian stability and activity in the past 5000 years. Although precise regional correlations are precluded by dating uncertainties, periods of most notable paleosol development are interpreted at 0.5 to 0.6, 1.0 to 1.4 and 2.0 to 2.3 cal ka BP (Wolfe *et al*., 2001). Eolian activity is inferred to have occurred during the intervening periods, possibly corresponding to periods of drought. As eolian activity was inferred by the absence of paleosols in these previous studies, the main objective of this study was to apply optical dating techniques to intervening dune sands to improve the chronology of dune activity in this area.

On the Canadian prairies, optical dating has also been used as a means of determining the timing of the most recent eolian activity, typically by collecting samples 50 to 100 cm below the surface of stabilized dunes (David *et al*., 1999; Wolfe *et al*., 2001, 2002a). In these circumstances, it is assumed that samples collected close to the surface will give an adequate estimate of the time of last activity, because of the relatively rapid rate of deposition of dune sands and subsequent stabilization by surface vegetation. Using modern, partially active sand dunes on the Canadian prairies as analogues for older stabilized dunes, it has been noted that the last portion of the dune to stabilize is typically the head, between the crest and the brink of the dune (Fig. 2b). Therefore, samples for optical dating have been collected from the head of stabilized dunes to determine the timing of most recent activity (Wolfe *et al.,* 2001).

One finding from these studies is that many stabilized sand dunes on the Canadian prairies have been active within the last few hundred years, with many optical ages reported being between 70 and 300 years old (Wolfe *et al*., 2001). For such relatively young ages, the accuracy of the optical age can be affected by a zero-age error. This error represents the difference between the actual equivalent dose of the sample at the time of deposition, and the expected value of zero for a sample that has been fully bleached by sunlight. This error may arise from variation in the duration and spectrum of sunlight exposure of the mineral grains prior to burial. In Wolfe *et al.* (2001), surface samples were collected to test that sands of a similar composition were adequately zeroed under modern conditions. These samples revealed equivalent doses of 0.052 ± 0.014 Gy and -0.01 ± 0.02 Gy, leading to 17 ± 5 and -4 ± 7 years, respectively. Other researchers have reported similar non-zero equivalent doses and ages for modern samples (*e.g.*, Ollerhead *et al*., 1994). As part of the present study, we compared the ages of samples collected at the surface, and at 50 cm depth, from the lee slope, crest and stoss slope of an active dune in order to evaluate the zero-age error and the resolution in ages derived from different parts of the dune.

FIELD METHODS

Eleven samples were collected in the summer of 1997 from the surface of the active dune, from shallow pits dug into the active dune, and from two sections within stabilized sand dunes. Field and laboratory reference numbers, sample depths and locations are recorded in Table I.

ACTIVE DUNE

A dune field, known locally as the Spirit Sands (and the Bald Head Hills), is one of a few areas of presently active sand dunes in the Brandon Sand Hills (Fig. 1 and 2a). The active dunes appear transitional between transverse and parabolic dunes. In historical times the area of active dunes has diminished from about 400 ha in 1950 to about 175 ha in 1990 (Wolfe *et al*., 2000) and the active dunes have taken on a more parabolic form, with blowouts occurring between intervening vegetated areas. A sand dune at the easternmost edge of this complex (Fig. 2a) was chosen for the modern analog tests, as it occurs along the advancing front of the dune field, and has been active throughout historical times. Comparison of successive aerial photographs of the dune indicates that it has migrated approximately 6 m between 1970 and 1990, for an average rate of about 0.3 m•a^{-1}. Shay *et al.* (2000) reported short-term migration of a nearby dune slipface on the order of 0.15 to 0.2 m between 1975 and 1976, consistent with these longer-term observations. Additional measurements of erosion and deposition from May to October in each year, indicated net erosion on the stoss slope of the dune, deposition in the crestal area, and deposition on the lee slope (Shay *et al.,* 2000). These findings are similar to a 16-month study by Wolfe and Lemmen (1999) in the Great Sand Hills, which found erosion on the upper and lower stoss slopes of a parabolic dune, deposition between the crest and the brink of the dune, and deposition on the lee slope.

Six samples were collected from the active dune in the Spirit Sands (Fig. 2a and b). Three surface samples were collected from the lee slope, crest and stoss slope of the dune to act as zero-age test samples. These samples were collected by removing approximately the upper 3 mm of sand grains from the surface of the active dune and placing them in light-tight one-litre containers. Samples were collected on a sunny day. Three sub-surface samples were also collected in order to compare the relative ages of the buried samples to the zero-age test samples on the lee slope, crest and stoss slope of the active dune. These samples were collected by digging pits and inserting a light-tight sampling tube into the section at a depth of 50 cm. Additional samples were collected 30 cm above and below the sub-surface samples for dosimetry analyses.

STRATIGRAPHIC SECTIONS

Samples were collected from the Brookdale Road section (site MB-20) that had been previously radiocarbon dated. The site is a roadcut through the north wing (arm) of a stabilized easterly-trending parabolic dune in the northwestern portion of the Brandon Sand Hills (Fig. 1). The section contains a series of buried soils separated by beds of humus-free dune sands, that overly deltaic deposits. The section was first dated by

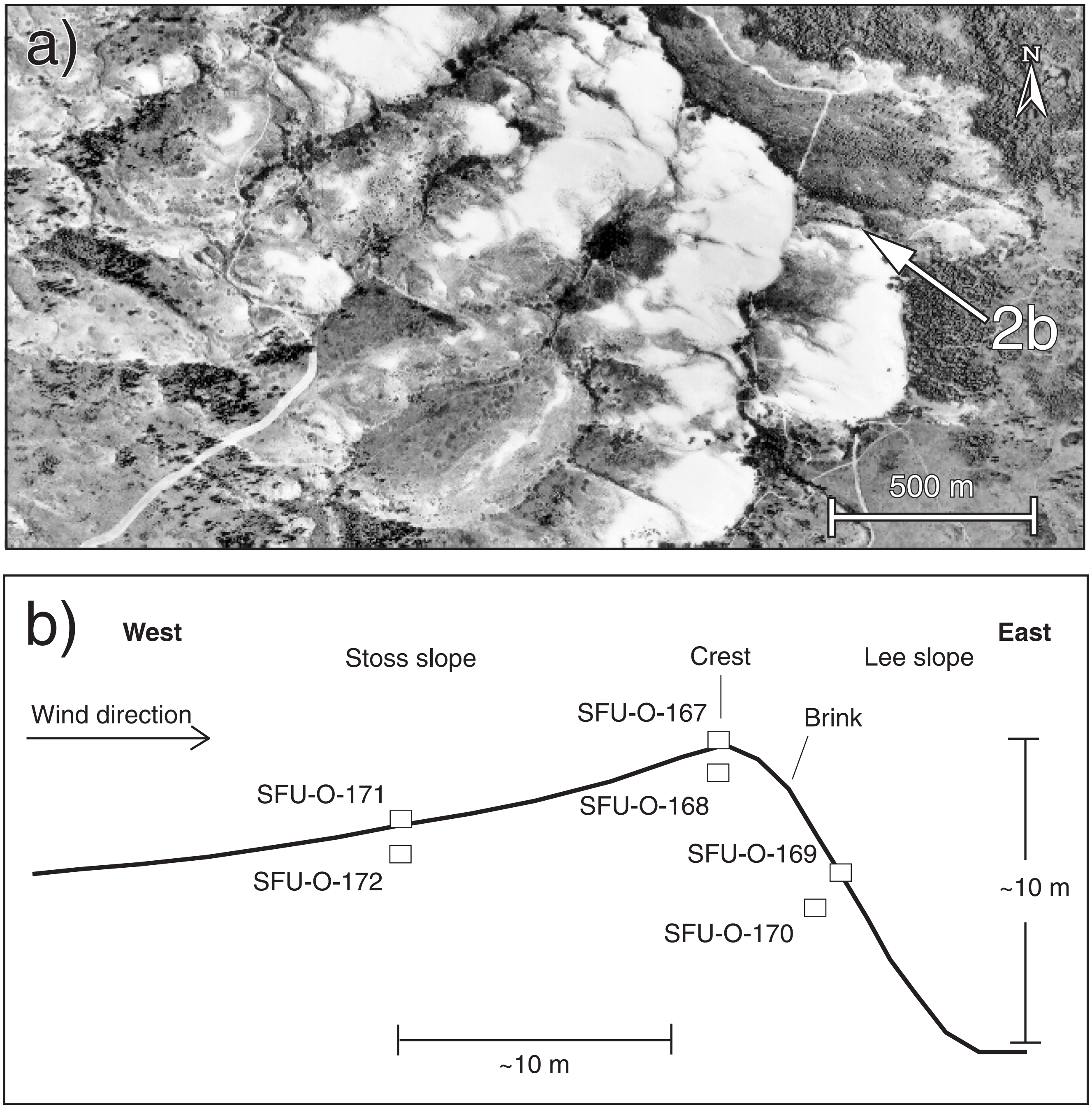

FIGURE 2. a) Airphoto of the Spirit Sands; b) cross-section of active sand dune marked in (a) and locations of samples collected for optical dating.

a) Photographie aérienne des Spirit Sands ; b) dune de sable active localisée en a) vue en coupe et sites d'échantillonnage pour la datation optique.

David (1971) using radiometric dating of organic matter extracts from four organic-rich paleosol A-horizons in eolian sands. Samples were collected from the upper few centimetres of the paleosols, except for the lowest sample (GSC-949) which was collected from the central portion of the paleosol richest in organic matter. These buried soils were subsequently re-sampled for dating by Wolfe *et al.* (2000), using AMS dating. In dating these, Wolfe *et al.* (2000) used humic acid extractions from the organic matter in the buried soils, as described by Abbott and Stafford (1996). Only two of the four sampled paleosols were dateable, due to insufficient humic acids in the other soil horizons. It was found that the radiometric ages were comparable to those obtained from AMS dating, but that the former may be too young by a few hundred years. This age difference could be attributed to differences in sampling locations, or to the incorporation of younger mobile carbon leached from paleosols higher in the profile into the lower paleosol used in the radiometric dating. As noted by Wolfe *et*

TABLE I

Sample numbers, depths and locations

Field sample	Lab Number	Depth (cm)	Location
97SAW-01	SFU-O-167	0	Spirit Sands, dune crest, surface
97SAW-02	SFU-O-168	50	Spirit Sands, dune crest, sub-surface
97SAW-04	SFU-O-169	0	Spirit Sands, dune lee slope, surface
97SAW-05	SFU-O-170	50	Spirit Sands, dune lee slope, sub-surface
97SAW-07	SFU-O-171	0	Spirit Sands, dune stoss slope, surface
97SAW-08	SFU-O-172	50	Spirit Sands, dune stoss slope, sub-surface
97SAW-10	SFU-O-173	257	Site MB-20, Brookdale Road section
97SAW-11	SFU-O-174	217	Site MB-20, Brookdale Road section
97SAW-12	SFU-O-175	157	Site MB-20, Brookdale Road section
97SAW-13	SFU-O-176	197	Site MB-28, Henry Fast section
97SAW-14	SFU-O-177	95	Site MB-28, Henry Fast section

al. (2000), whereas the humic acid extraction method minimizes the inclusion of recycled and mobile carbon, the dating of total soil humus may include these additional materials. Indeed, detailed studies by Abbott and Stafford (1996) indicate that humic acid extractions minimize both contamination by younger organic acids and recycling of older organic matter, and show that humic acid extractions give radiocarbon ages closest to radiocarbon ages of plant macrofossils.

With these uncertainties in mind, three sediment samples were collected from dune sands in this section in order to determine the timing of dune sand deposition, and to compare the optical ages of dune sands to the radiocarbon ages of the organic horizons. Samples were collected beneath a tarpaulin to exclude light exposure, and by inserting a light-tight sampling tube into the pits dug horizontally in the section at the desired depth. Additional samples were collected 30 cm above and below the optical dating samples for dosimetry analyses.

A second exposure in a stabilized parabolic dune from the Henry Fast section (site MB-28) was sampled for optical dating of dune sands. Three buried soils within this section were previously sampled for AMS dating, but contained insufficient organic carbon for reliable ages. Two samples were collected to determine the timing of dune sand deposition in lieu of any radiocarbon chronology.

These five optical ages are compared to the suite of radiocarbon ages from the Brandon Sand Hills (Wolfe *et al.*, 2000) in order to provide a better chronology of dune activity and stability in this area.

SAMPLE PREPARATION AND MEASUREMENTS

Optical dating measures the time elapsed since mineral grains were last exposed to sunlight. General descriptions of available techniques are found in *Radiation Measurements* (27: 5/6, 1997), Aitken (1998), and Huntley and Lian (1999). Sand-sized (180 to 250 µm diameter) K-feldspar grains were separated; equivalent doses were determined using 1.4 eV (infrared) excitation and measurement of the 3.1 eV (violet) emission, and an additive dose procedure. The preheat was 16 h at 120 °C. The thermal transfer correction was made using an infrared/red bleach or, where noted, a sunlight bleach. A detailed description of the apparatus and methods used can be found in Ollerhead *et al.* (1994) and Huntley and Clague (1996).

Environmental beta and gamma dose rates were calculated from measured or assumed K, U, Th, Rb and moisture contents (Table II), using the conversion factors of Nambi and Aitken (1986), as updated by Adamiec and Aitken (1998), and the beta attenuation factors of Mejdahl (1979). Cosmic-ray dose rates were estimated according to the prescription of Prescott and Hutton (1988). Internal dose rates were calculated as per footnotes to Table II, and the total dose rates for the active dune and section samples were calculated. Apparent optical ages were determined by taking the equivalent dose for a sample obtained using an infrared/red bleach for the thermal transfer correction, and dividing it by its calculated dose rate (Tables III and IV). For the section samples, the apparent ages were corrected for anomalous fading using the approach described by Huntley and Lamothe (2001). The corrected optical ages for these samples are shown in Table IV. All analytical uncertainties shown are at ±1σ.

RESULTS

ACTIVE DUNE

For each of the modern dune samples, equivalent doses and apparent ages were obtained using the standard infrared/red bleach and using a sunlight bleach for the thermal transfer correction (Table III). For all of the surface samples, the equivalent doses from the infrared/red bleaches are significantly non-zero, and the apparent optical ages calculated using them range from 27 to 43 years. The equivalent doses from the infrared/red bleaches for the 50 cm-depth samples were also all significantly non-zero. For two of these (SFU-O-168 and 170), the apparent optical ages were within the range of those calculated for the surface samples, and cannot be differentiated from them. The 50 cm-depth sample (SFU-O-172) collected from the stoss slope of the dune is the only sample to have an equivalent dose that is significantly greater than the other samples. The apparent age, calculated

TABLE II

Analytical data for calculating dose rates

Lab number	K (%) [a]			U ($\mu g \cdot g^{-1}$) [b]			Th ($\mu g \cdot g^{-1}$) [c]			H_2O ($g \cdot g^{-1}$)[d]
	U	M	L	U	M	L	U	M	L	
SFU-O-168	0.96	0.97	0.96	1.10	0.61	1.01	3.9 ± 0.2	2.0 ± 0.1	5.8 ± 0.3	0.02
SFU-O-170	0.99	1.05	1.02	0.94	0.68	0.80	3.3 ± 0.2	1.9 ± 0.1	3.6 ± 0.2	0.03
SFU-O-172	1.05	1.01	1.02	0.78	0.95	0.77	4.2 ± 0.2	2.5 ± 0.1	2.8 ± 0.1	0.04
SFU-O-173	1.19	1.15	1.12	0.63	0.63	0.72	2.55 ± 0.1	2.2 ± 0.1	2.5 ± 0.1	0.05
SFU-O-174	1.15	1.17	1.20	0.68	0.71	0.75	2.8 ± 0.1	2.55 ± 0.1	2.6 ± 0.1	0.04
SFU-O-175	1.16	1.17	1.17	0.80	0.68	0.74	2.1 ± 0.1	2.3 ± 0.1	2.8 ± 0.1	0.03
SFU-O-176	1.20	n.m.	1.20	1.22	n.m.	1.08	4.1 ± 0.2	n.m.	4.2 ± 0.2	0.04
SFU-O-177	1.23	n.m.	1.21	0.83	n.m.	0.99	3.85 ± 0.2	n.m	3.7 ± 0.2	0.07

[a] K contents are from atomic absorption analyses, with ±5 % relative error.

[b] U contents are from delayed neutron analyses, and are ±0.06 $\mu g \cdot g^{-1}$.

[c] Th contents are from neutron activation analyses.

[d] Measured water content = water mass ÷ dry mass. Water contents used for dose rate calculations were 0.03 ± 0.01 for samples SFU-O-168, 170, 172 and 0.05 ± 0.02 for samples SFU-O-173 to 177.

Notes

U, M, and L are upper, middle and lower dosimetry samples taken from 30 cm above the sample location, from the sample location itself, and from 30 cm below it. "n.m." is no measurement.
The K content within the grains was assumed to be 12.5 ± 0.5 % (Huntley and Baril, 1997).
The Rb content within the grains was assumed to be 400 ± 100 $\mu g \cdot g$ (Huntley and Hancock, 2001).
The effective dose rate from alpha particles emitted by U and Th within the grains was assumed to be 0.08 $Gy \cdot ka^{-1}$ (following Huntley and Lian, 1999).
A condition of secular equilibrium is assumed for both the uranium and thorium decay chains.

TABLE III

Dose rates, equivalent doses (D_e) *and apparent ages for surface and near- surface samples*

Lab number	Location	Dose rate ($Gy \cdot ka^{-1}$ ±0.07)[a]	D_e (Gy) infrared/red bleach[b]	D_e (Gy) sunlight bleach[b]	Apparent age before AD 1999 (years ±1σ)	
					Infrared /red bleach[b]	Sunlight bleach[b]
Surface samples						
SFU-O-167	crest	(2.65)	+0.070 ± 0.015	- 0.08 ± 0.02	27 ± 6	-30 ± 8
SFU-O-169	lee	(2.72)	+0.100 ± 0.015	- 0.053 ± 0.017	37 ± 6	-20 ± 6
SFU-O-171	stoss	(2.75)	+0.117 ± 0.018	+0.000 ± 0.015	43 ± 7	0 ± 5
Samples at 50 cm depth						
SFU-O-168	crest	2.65	+0.082 ± 0.018	- 0.046 ± 0.013	31 ± 7	-17 ± 5
SFU-O-170	lee	2.72	+0.076 ± 0.025	- 0.023 ± 0.015	28 ± 9	-8 ± 6
SFU-O-172	stoss	2.75	+0.217 ± 0.015	+0.110 ± 0.021	80 ± 6	40 ± 8

[a] For a surface sample, where only the upper 3 mm of surface grains was collected, the dose rate used was that determined for the corresponding sample collected 50 cm below the surface, and is shown in brackets.

[b] Bleach used for thermal transfer correction.

TABLE IV

Dose rates, equivalent doses (D_e) *and ages (uncorrected, and corrected for anomalous fading) for section samples*

Lab number	Dose rate ($Gy{\cdot}ka^{-1}$ ± 0.07)	D_e (Gy) infrared/red bleach[a]	Apparent age (years before AD 1999 ±1σ)	Delay (days)[b]	Anomalous fading rate (% per decade)[c]	Corrected age before AD 1999 (years ±1σ)
SFU-O-173	2.7	10.8 ± 0.3	4000 ± 160	74	(6.4 ± 0.4)	5600 ± 270
SFU-O-174	2.76	8.1 ± 0.1	2930 ± 80	74	(6.4 ± 0.4)	4040 ± 150
SFU-O-175	2.75	4.2 ± 0.2	1530 ± 80	72	6.4 ± 0.4	2050 ± 120
SFU-O-176	2.98	7.4 ± 0.2	2480 ± 90	73	6.6 ± 0.3	3440 ± 150
SFU-O-177	2.95	6.5 ± 0.2	2200 ± 90	73	(6.6 ± 0.3)	3040 ± 150

[a] Bleach used for thermal transfer correction.

[b] The delay is the time between laboratory irradiation and equivalent dose measurement.

[c] Anomalous fading rate is expressed in percent per decade where a decade is a factor of 10 in time since irradiation, for a starting point 2 days after irradiation. Figures in brackets are assumed, based on figures for other samples from the same site with mineralogy expected to be similar. Details of the measurements are in Huntley and Lamothe (2001).

using the infrared/red bleach, is approximately 37 years older than that of the corresponding surface sample (SFU-O-171).

The non-zero equivalent doses for the surface samples are attributed to the sunlight exposure at deposition having put electrons into the traps being sampled for optical dating as well as evicting them, there thus being a dynamic equilibrium. The equivalent dose measurements were therefore repeated using a sunlight bleach instead of the infrared/red bleach for the thermal transfer correction. The resulting equivalent doses and corresponding ages (Table III, columns 5 and 7) are all smaller, as expected.

With the assumption that each 50 cm-depth sample at burial was in the same state as its corresponding surface sample was at collection, it is possible to calculate ages for them that should be correct. This has been done first by taking the equivalent dose for the 50 cm-depth sample, and subtracting the equivalent dose for the corresponding surface sample; the results are shown in Table V. Since the resulting values obtained using the two different bleaches were consistent, they were averaged and divided by the dose rates to obtain the ages. This approach yielded ages of 8 ± 8 years for the crest, 1 ± 7 years for the lee slope, and 38 ± 7 years for the stoss slope.

STRATIGRAPHIC SECTIONS

Figure 3 compares optical ages at Brookdale Road section (site MB-20) to calibrated radiocarbon ages derived from ages reported by David (1971) and Wolfe *et al.* (2000). For consistency with the radiocarbon ages, the optical ages are shown as years before AD 1950 with uncertainties at ±2σ (*i.e.* 95 % confidence level). The lower three eolian deposits in the section are optically dated to about 2.0, 4.0 and 5.6 ka, respectively.

The first notable observation is that the optical ages are in the correct chronologic sequence, both in relation to their stratigraphic positions and to the radiocarbon ages. The second observation is that, when accounting for the uncertainty in the optical and radiocarbon ages, each optical age is closer in age to the underlying paleosol than to the overlying one, even where the optical dating sample was obtained within a few centimetres of the overlying paleosol. As discussed earlier, this may be due to the radiometric ages being too young due to the incorporation of younger (mobile) carbon leached down from higher in the profile. Indeed, this could be true for the lowermost radiometric age (4255-3725 cal BP), which is a few hundred years younger than the corresponding AMS age (4865-4450 cal BP). This observation is also consistent, however, with the assertion made by David (1971) that the radiocarbon ages derived from the paleosols should be considered maximum limiting ages for the time of burial of soils. If organic matter in these soils was alive when they were buried by eolian sands, then it is reasonable to assume that the age of the overlying sand unit could more closely approximate the age of the buried soil.

Figure 4 shows the chronostratigraphic profile for the optical ages obtained at the Henry Fast section (site MB-28). As stated earlier, three samples for AMS dating were previously collected from this site, but contained insufficient humic acids for reliable ages. Thus the optical ages represent the only chronology available at this site. The age of the lower sample is about 3.4 ka and that of the upper sample is about 3.0 ka. Although the range in uncertainties at ±2σ includes the possibility that the ages differ by as much as 1000 years, it also includes a possible overlap in ages by 200 years. Thus, the time interval for soil organic accumulation between the two eolian deposits could, in fact, have been quite short. This may explain why there was insufficient organic material in the intervening soil horizon for radiocarbon dating.

DISCUSSION

ACTIVE DUNE

Based on field observations at the time of sampling, it is expected that the three surface samples (SFU-O-167, 169, 171) should have been well-exposed to sunlight, and should all have returned ages that were similarly close to zero. However, the equivalent doses and apparent optical ages obtained from those samples given an infrared/red bleach for the thermal

TABLE V

Equivalent doses for the 50 cm-depth samples less the equivalent doses for the corresponding surface samples, obtained using the infrared/red bleach (column 3) and using the sunlight bleach (column 4) for the thermal transfer correction. Since these were not distinguishable they were averaged to calculate the ages (column 5)

Lab number	Location	D_e (Gy) infrared/red bleach	D_e (Gy) sunlight bleach	Apparent age before AD 1999 (years ±1σ)
SFU-O-168	crest	0.012 ± 0.023	0.034 ± 0.024	8 ± 8
SFU-O-170	lee	-0.024 ± 0.029	0.030 ± 0.023	1 ± 7
SFU-O-172	stoss	0.100 ± 0.023	0.110 ± 0.026	38 ± 7

Note: the grains are expected to have received up to 0.03 Gy from the K within them during the 3 years since the grains were separated. No allowance was made for this.

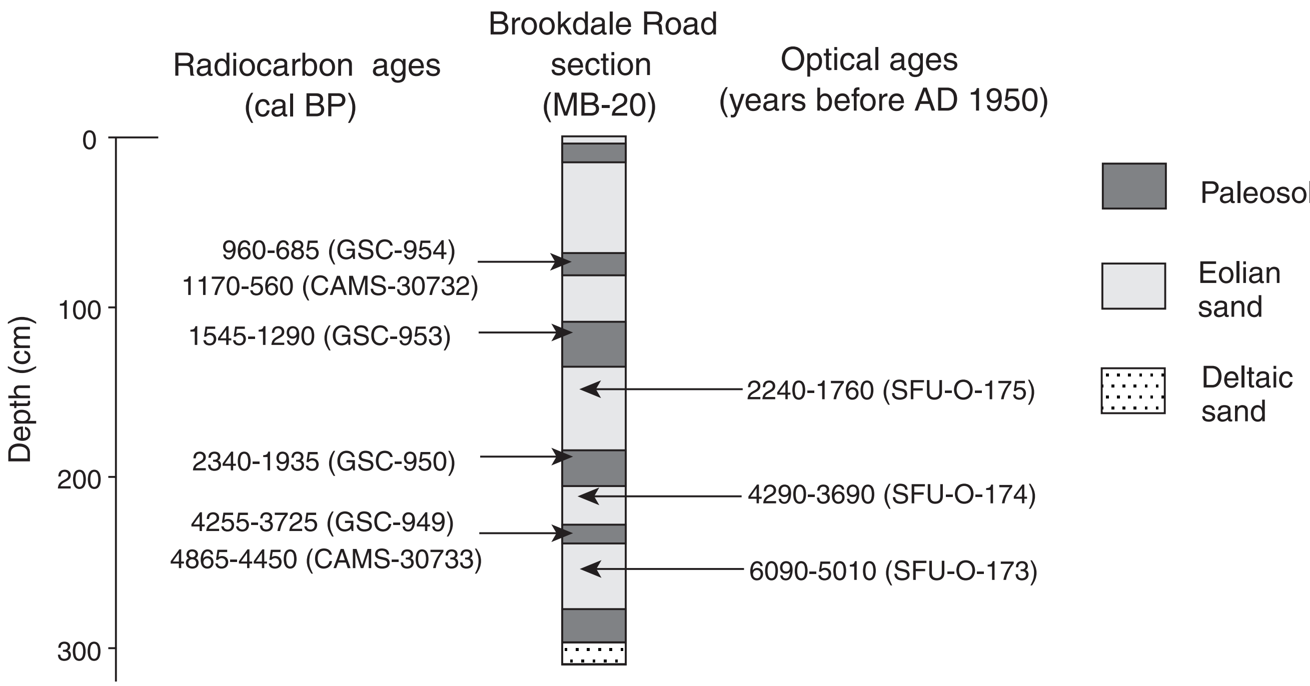

FIGURE 3. Chronostratigraphic profile of the Brookdale Road section (MB-20) showing calibrated radiocarbon ages of David (1971) and Wolfe *et al.* (2000), and optical ages from this study. Uncertainties in the ages are shown at ±2σ.

Chronostratigraphie de la coupe de Brookdale Road (MB-20) montrant les dates au radiocarbone étalonnées de David (1971) et de Wolfe et al. *(2000), ainsi que les âges optiques obtenus de la présente étude. La marge d'erreur est à ±2σ.*

transfer correction were significantly non-zero. The sunlight bleach used for the thermal transfer correction reduced the equivalent dose values (Table III), but the fact that two of the three values are negative indicates that the bleach left more electrons in the traps being measured than did the natural sunlight bleach at deposition. This could occur if the spectra of the two sunlight exposures were different. It is also apparent from the different equivalent doses obtained for the three surface samples using the two different bleaches (Table III) that there is uncertainty as to what technique should be used to obtain the correct equivalent dose of zero. This problem is not resolved here, and one can simply state that there is a zero-error of about ± 0.1 Gy, corresponding to ± 40 years.

Based on the historical migration rates, the 50 cm-depth sample from the lee slope of the dune (SFU-O-170) is expected to have been buried for about 2 to 5 years. The 50 cm-depth sample from the crest of the dune (SFU-O-168) is expected to have been buried for a similar length of time, since sand deposition is observed between the crest and brink of similarly active dunes (Wolfe and Lemmen, 1999; Shay *et al.*, 2000). The 50 cm-depth sample from the stoss slope of the dune (SFU-O-172) is expected to be older than either of the other two sub-surface samples, since sand is typically eroded from this portion of active dunes (Wolfe and Lemmen, 1999; Shay *et al.*, 2000), exposing older deposits. Based on an estimated migration rate for the dune of between 0.15 and 0.3 $m \cdot a^{-1}$, the maximum age of the 50 cm-depth sample on the stoss slope could be 50

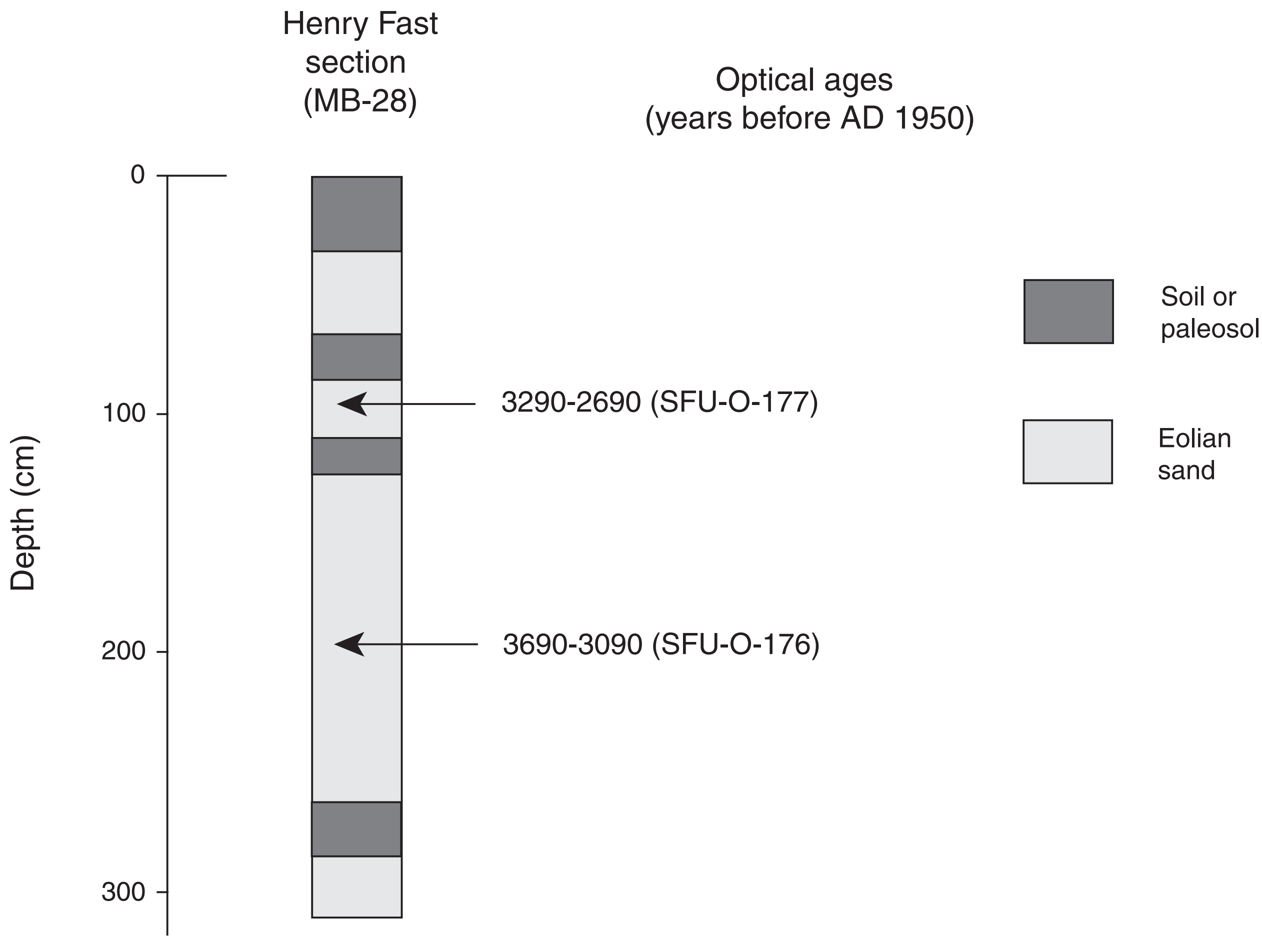

FIGURE 4. Chronostratigraphic profile of the Henry Fast section (MB-28). Uncertainties in the ages are shown at ±2σ.

Chronostratigraphie de la coupe de Henry Fast (MB-28). La marge d'erreur est à ±2σ.

to 100 years, if the sample represented slipface deposits that were originally deposited on the lee slope of the dune. The age could also be younger than this, if the near-surface sediments are comprised of top-set beds, derived from migrating secondary bedforms that commonly form near the crest of the dune.

The ages derived from the 50 cm-depth samples are consistent with the above expectations; notably, that the ages of the crest and lee slope are a few years old and are similar in age, and that the stoss slope sample is significantly older than the other two. The apparent ages of 1 ± 7 years and 8 ± 8 years for the lee slope and the crest (Table V), respectively, are consistent with expected high rates of sand deposition on the crest and lee slope of the dune, but indicate that a significant difference in age cannot be resolved for these samples. An age of 38 ± 7 years for the stoss slope is also consistent with expectations that the stoss slope is an area of net erosion, and that it represents former slipface or top-set deposits. Given the estimated rates of dune migration, the age obtained is more consistent with sediment derived from top-sets deposited near the crest of the dune, than with slipface deposits derived from the lee slope of the dune.

With respect to sampling of stabilized dunes for optical dating (*e.g.* Wolfe *et al.*, 2001), these results indicate that near-surface samples collected from the head of stabilized dunes (between the crest and the brink) may be appropriate to determine the timing of most recent activity. In contrast to this, near-surface samples collected from the stoss slope of the dune are more likely to result in ages that are several decades older, as this is an area of net erosion.

STRATIGRAPHIC SECTIONS

Optical ages derived from the stratigraphic sections provide direct ages of eolian activity. As noted above, all ages are in correct chronologic sequence, both in relation to their stratigraphic positions and to the radiocarbon ages derived from organic matter in buried soils, thus providing support for their reliability. In order to compare the age estimates from the two methods, a "radial" plot (Galbraith, 1988), depicting the radiocarbon and optical ages, was constructed (Fig. 5). Suggested times of eolian activity, corresponding to the optical ages and excluding radiocarbon ages, are shown as stippled regions, and periods corresponding to paleosol development (*i.e.*

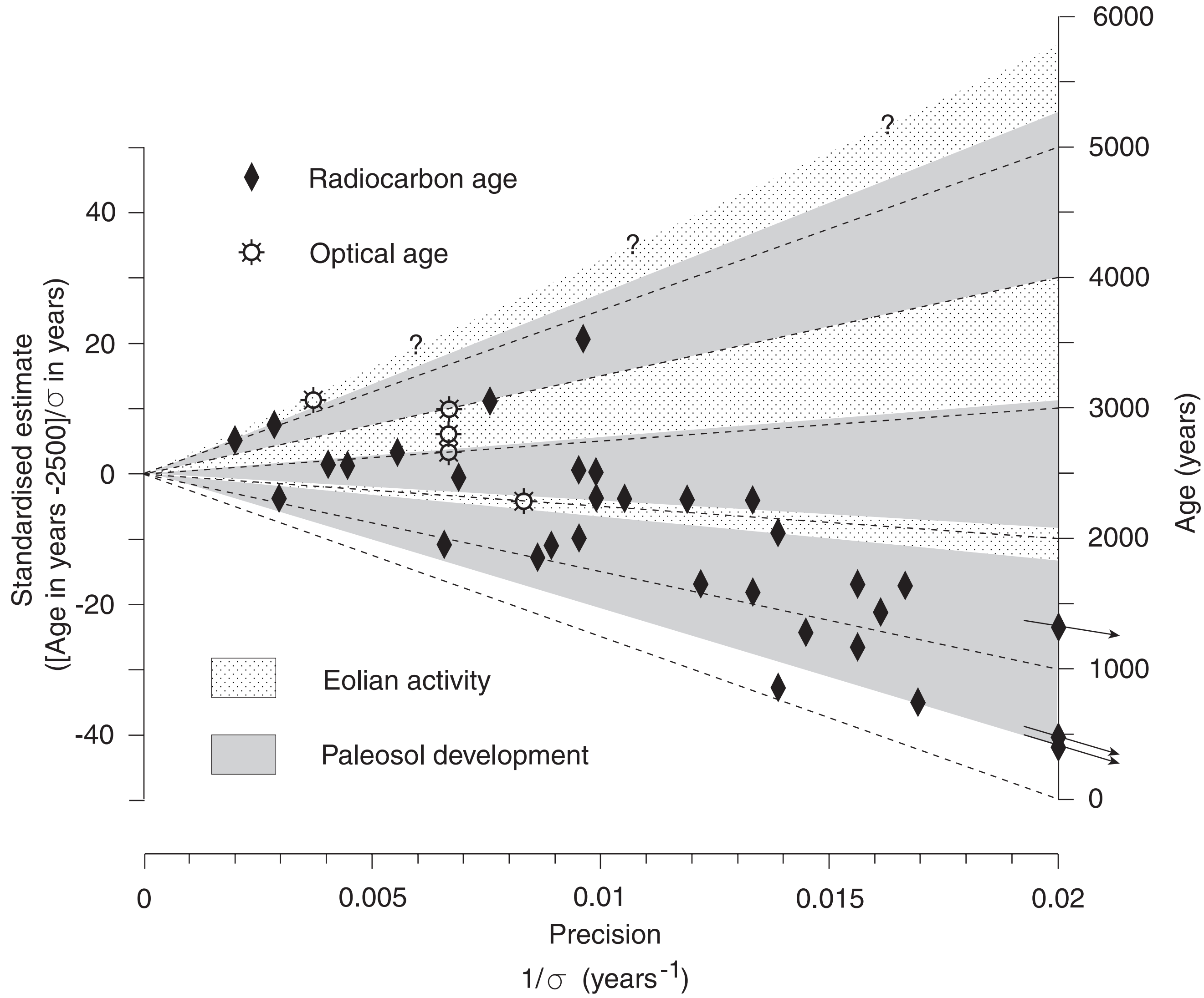

FIGURE 5. "Radial" graph (Galbraith, 1988) showing the calibrated radiocarbon and optical ages. All ages shown herein are before AD 1950. The radiocarbon ages are those listed in Table I of Wolfe *et al.* (2000), excluding those listed as modern. An age for any point is read by extending a straight line from the origin of the left-hand (standardized estimate) axis, through the point, to the age on the right-hand axis. The 95 % confidence limits are represented by the vertical extent for all points; that is, if a line is drawn from the origin of the left-hand axis through the top of a point, and another is drawn from the origin through the bottom of the same point, then the corresponding 2σ ages for this point may be read off the right-hand axis. On such a plot, the most precise points fall to the right and the least precise to the left. The three most precise points are off to the right hand side of the graph and their locations are indicated by the arrows. The pie-shaped stippled areas are drawn to include optical ages, and exclude radiocarbon ages, and it is suggested that these indicate periods of eolian activity. The pie-shaped shaded areas are drawn to include radiocarbon ages and exclude optical ages and it is suggested that they indicate periods of dune stability. Uncertainty about the validity of the radiocarbon ages is described in the text and should be noted.

Graphique « radial » (Galbraith, 1988) illustrant les dates au radiocarbone étalonnées et les âges optiques. Tous les âges datent d'avant 1950. Les âges au radiocarbone sont tirés du tableau I de Wolfe et al. *(2000), sauf ceux considérés comme étant modernes. Un âge, à un point donné, est identifié en projetant une ligne droite à partir du début à gauche (estimation standardisée), en passant par le point choisi, jusqu'à l'âge indiqué sur l'axe donné à droite. L'intervalle de confiance à 95 % est représenté par le prolongement vertical de chacun des points. C'est dire que si une ligne est tracée à partir du début, à gauche, jusqu'au sommet d'un point et qu'une autre ligne est tracée à partir du début jusqu'à la base de ce point, l'âge correspondant à 2σ pour ce point peut être identifié sur l'axe de droite. Dans un tel graphique, les points les plus précis tendent vers la droite et les moins précis, vers la gauche. Les trois points les plus précis sont situés au-delà de l'axe de droite et leur localisation est donnée par les flèches. Les pointes tramées en pointillé comprennent les âges optiques et excluent les âges au radiocarbone ; on croit qu'elles correspondent à des périodes d'activité éolienne. Les pointes tramées en gris comprennent les âges au radiocarbone et excluent les âges optiques ; on croit qu'elles correspondent à des périodes de stabilité. Les incertitudes quant à la validité des dates au radiocarbone sont expliquées dans le texte et devraient être retenues.*

stability) are shown as shaded regions. The three periods of eolian activity are approximately 1.9 to 2.1 ka, 3.1 to 4.0 ka, and prior to 5.2 ka. Whereas other periods of potential eolian activity, as inferred by a lack of paleosols, may also exist, only those corresponding to the optical ages are shown. The time periods younger than 4.0 ka and 2.1 ka were previously suggested by David (1971) as corresponding to intervals of drought. The most significant of these appears to be that between 4.0 and 3.1 ka (Fig. 5). This time period also correlates well with a period of high salinity between about 4.6 and 3.2 cal ka BP at Kenosee Lake, Saskatchewan, about 200 km west of Brandon (Vance *et al.,* 1997), suggesting that this was a period of greater aridity. Other evidence from the Lauder Sand Hills, about 100 km west of Brandon, suggests that the period between 4.6 and 3.5 cal ka BP may have been one of increasing landscape stability, but that eolian activity also occurred there during this interval (Boyd, 2000). Evidence for eolian activity occurring at about 5.2 ka is also noted in other areas of the southern prairies, and has been interpreted as representing the latter phases of mid-Holocene dune activity, prior to regional stabilization (Wolfe *et al.*, this volume). The absence of any eolian sediments or paleosols with ages older than this in the Brandon Sand Hills is consistent with observations in many other areas of the southern Canadian prairies.

CONCLUSIONS

The results of this study are summarized as follows:

1. Using 1.4 eV (infrared) excitation and an infrared/red or a sunlight bleach for the thermal transfer correction, a test of the zero-age of dune sands from the lee slope, crest and stoss slope of an active dune gave an uncertainty of about ±0.1 Gy, corresponding to ±40 years.

2. Ages for 50 cm-depth samples, calculated after subtracting the equivalent doses measured for the corresponding surface samples, are consistent with expectations: ages from the crest and the lee slope are young, but undifferentiable (approximately 8 ± 8 and 1 ± 7 years, respectively); an age from the stoss slope of about 38 ± 7 years is consistent with expectations that this sample of sand is derived from an area of net erosion, and probably represents top-sets that were deposited near the crest of the dune.

3. Based on the above, near-surface samples collected from the head of stabilized dunes should be appropriate for determining the timing of most recent activity.

4. Optical ages derived from eolian deposits in stratigraphic sections are in correct chronologic sequence, both in relation to their stratigraphic positions and to the radiocarbon ages derived from organic matter in buried soils.

5. Based on the optical ages from stratigraphic sections, periods of eolian activity occurred at about 2.0 ka, 3.1 to 4.0 ka, and prior to 5.2 ka. These periods are consistent with earlier inferences of dune activity in the Brandon Sand Hills, and with interpretations of periods of drought and dune activity elsewhere in the southern Canadian prairies.

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