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2002

Natural Resources Canada
Ressources naturelles Canada
Canada

Catalogue No. M44-2002/B3E-IN
ISBN 0-662-31670-3

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Wolfe, S.A., Ollerhead, J., Huntley, D.J., and Campbell, C., 2002: Late Holocene dune activity in the Duchess dune field, Alberta; Geological Survey of Canada, Current Research 2002-B3, 8 p.

Abstract: The geomorphology and stratigraphy of the Duchess dune field, in southeastern Alberta, provides a proxy record of the relationship between late Holocene paleoenvironmental conditions and eolian activity. Optical ages of eolian deposits show activity ca. 4500 to 2900 years ago and ca. 400 to 230 years ago, whereas combined radiocarbon and optical ages from sheet sand and paleosol sequences indicate dune stability ca. 980 to 400 years ago. Episodes of dune activity and stability were contemporaneous with periods of increased aridity and increased moisture availability, respectively. Unlike the Great Sand Hills of southwestern Saskatchewan, there is no evidence of significant dune activity in the last 200 years, possibly due to the predominance of northwesterly winds providing greater moisture to this area.

Résumé : La géomorphologie et la stratigraphie du champ dunaire de Duchess dans le sud-est de l’Alberta nous procurent un compte rendu indirect des relations qui existaient entre les conditions environnementales et l’activité éolienne à l’Holocène tardif. Les âges des dépôts éoliens déterminés par des méthodes optiques témoignent de périodes d’activité il y a de cela 4 500 à 2 900 ans environ et de 400 à 230 ans environ. Par ailleurs, les âges radiocarbone combinés aux âges déterminés par des méthodes optiques de nappes de sable et de séquences de paléosol indiquent une stabilité des dunes il y a de cela 980 à 400 ans environ. Les épisodes d’activité dunaire coïncident avec des périodes d’accroissement de l’aridité, alors qu’un accroissement de l’humidité entraînent des épisodes de stabilité des dunes. Contrairement à la situation des collines Great Sand dans le sud-ouest de la Saskatchewan, il n’y a pas d’indices significatifs d’activité dunaire au cours des 200 dernières années, probablement en raison des vents dominants du nord-ouest qui procurent une plus grande humidité à cette région.

INTRODUCTION

Inactive and partially active sand dunes occur across much of the Great Plains of Canada and the United States. Chronologies of past dune activity (Forman et al., 2001) have been constructed from radiocarbon dates on paleosols and luminescence ages on sand deposits (Forman et al., 1992; Madole, 1994; Holliday, 1995; Muhs and Holliday, 1995; Wolfe et al., 1995, 2000, 2001; Muhs et al., 1997a, 1997b; Muhs and Wolfe, 1999). Paleoclimatic proxy records show close associations between regional aridity and eolian activity, and regional moisture and paleosol development (Fritz et al., 1994; Case and MacDonald, 1995; Laird et al., 1996; Vance and Wolfe, 1996; Vance et al., 1997; Sauchyn and Beaudoin, 1998). Modelling studies reveal that even a modest increase in aridity can reactivate sand dunes across much of the North American Great Plains (Muhs and Maat, 1993; Wolfe, 1997).

In the southern Canadian prairies, sand dunes are widespread, but mostly inactive. Radiocarbon dating can be of limited use for determining chronologies in this area, as paleosols and/or organic matter are rare in many dune exposures. However, using optical dating, the time since sediment was last exposed to sunlight can be used to develop chronologies of eolian activity (e.g. Wolfe et al., 2001). Optical dating studies suggest that the most recent period of widespread dune activity across this region occurred within the last 200 years (Wolfe et al., 1995). Subsequent work confirmed that sand dunes in the Great Sand Hills region of Saskatchewan reactivated approximately 200 years ago, in association with drought conditions in the late 1700s (Wolfe et al., 2001). Accelerator mass spectrometry (AMS) and conventional radiocarbon age determinations on organic matter from paleosols in the Brandon Sand Hills area of southern Manitoba indicate recurrent intervals of eolian activity in the past 5000 years (Wolfe et al., 2000). Although precise regional correlations are precluded by dating uncertainties, periods of most notable paleosol development occurred at about 2300 to 2000, 1400 to 1000, and 600 to 500 cal. BP. Eolian activity is inferred to have occurred before and after each of these periods, most notably prior to 6000 and 3000 cal. BP, and between 2000 and 1600, 1000 and 800, and 500 and 200 cal. BP.

Here we present optical ages of sand dunes in the Duchess dune field in southeastern Alberta, extending the spatial and temporal record of dune activity to the southwestern Canadian prairies.

BACKGROUND AND STUDY AREA

The Duchess dune field is located approximately 160 km east-southeast of Calgary, Alberta (Fig. 1) in the Mixed Grassland Ecoregion of the Prairie Ecozone. The area has a mid-latitude, continental climate with long, cold winters and short, warm summers (Environment Canada, 1993). At Brooks, Alberta, approximately 40 km south of the study site, mean January (coldest month) and July (warmest month) temperatures are -12.5°C and 18.4°C, respectively. Mean potential evapotranspiration exceeds precipitation by about 200 mm·a^{-1} (Environment Canada, 1993), but approaches 300 to 350 mm·a^{-1} in drought years, such as in 1987–1988. Historically, the area has experienced recurrent droughts associated with the development of stable high-pressure ridges that displace cyclonic tracks, moist air masses, and fronts (Dey and Chakravarti, 1976). Although the area experiences dry subhumid conditions on average (as per the United Nations Environment Programme (1992) classification of aridity), it may experience semi-arid climatic conditions during times of drought. Similar drought conditions are observed throughout the southern prairies that, when prolonged, may result in dune reactivation (Wolfe, 1997; Wolfe et al., 2001).

The dominant eolian sediment source for the Duchess dune field is associated with the ancestral Red River delta (Shetsen, 1987), which formed when Glacial Lake Drumheller decanted into Glacial Lake Bassano during the Late Wisconsinan. The dunes have formed since deglaciation ca. 12 600 BP (Bryan et al., 1987) on the downwind distal limits of the deltaic deposits (Campbell, 1997). The dune field consists of two distinct sections, divided by a linear region of wetlands with small areas of open water, running along a north-south axis (Fig. 1). This interdune corridor predominantly consists of ice-contact glaciolacustrine and glaciofluvial deposits up to 25 m thick (Shetsen, 1987).

The dune field lies to the north of Matzhiwin Creek, and is bounded by agricultural lands to the south and west, and the Red Deer River to the north and east. The dominant dune form consists of large tongues with border ridges (terminology of David, 1998) oriented to the east-southeast, extending to the Red Deer River valley at its easternmost extent (Fig. 1). This orientation is similar to that of other dune fields north and east of Calgary, indicative of dune-forming winds predominantly from the northwest. Individual dunes are small (1–7 m high), partially filled parabolic dunes (classification as per David, 1998), although the area exhibits extensive secondary modification by blowout activity, disrupting the majority of the larger dune forms (Fig. 2). The dunes are predominantly vegetated and inactive.

The study site is in the eastern portion of the dune field, directly south and west of the Red Deer River (Fig. 1). The dunes here range from 1 to 6 m high and are constructed of well sorted to moderately well sorted fine sand. On average, less than 1% of the sediment is silt and clay. All the dunes show signs of reworking and some of the larger ones contain buried soils.

OPTICAL DATING

Sampling

Six samples from blowout exposures within dunes were collected for optical dating (Fig. 1). The samples were taken from shallow pits dug horizontally into natural exposures (Fig. 3 and 4), and stored in light-tight steel cans. Because of the palimpsest nature of eolian deposits (cf. David, 1998), samples were collected only from dunes with recognized morphology and internal structure, so that the geological relevance of the optical ages was known. Dunes selected for

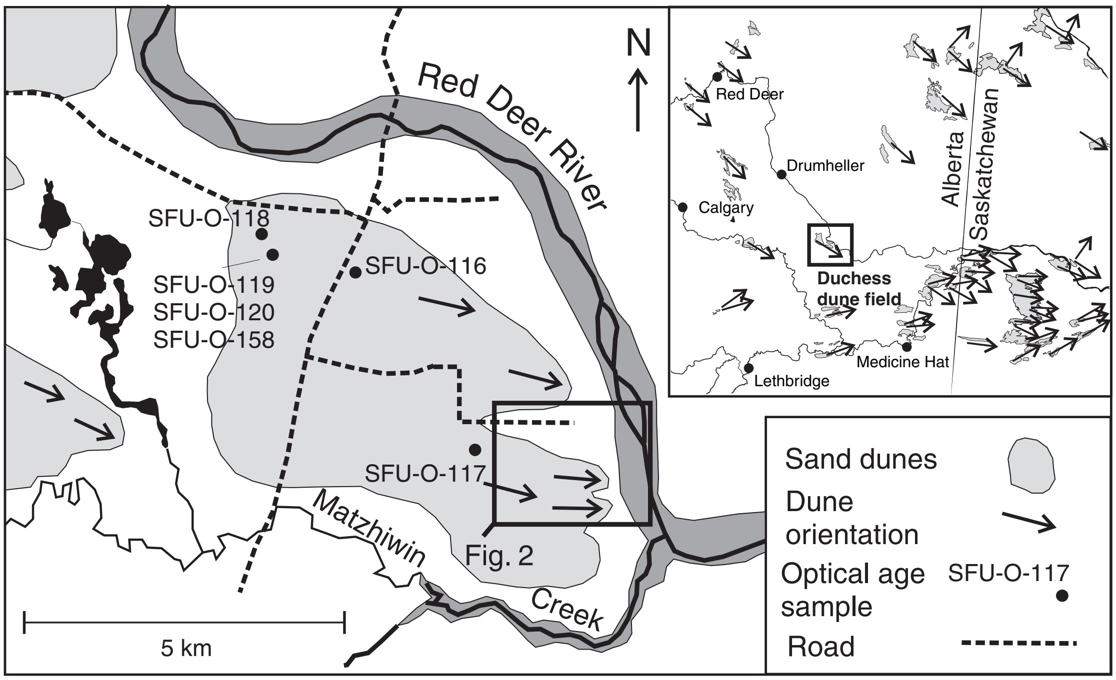

Figure 1. Location of the Duchess dune field with dune orientations and locations of samples taken for optical dating.

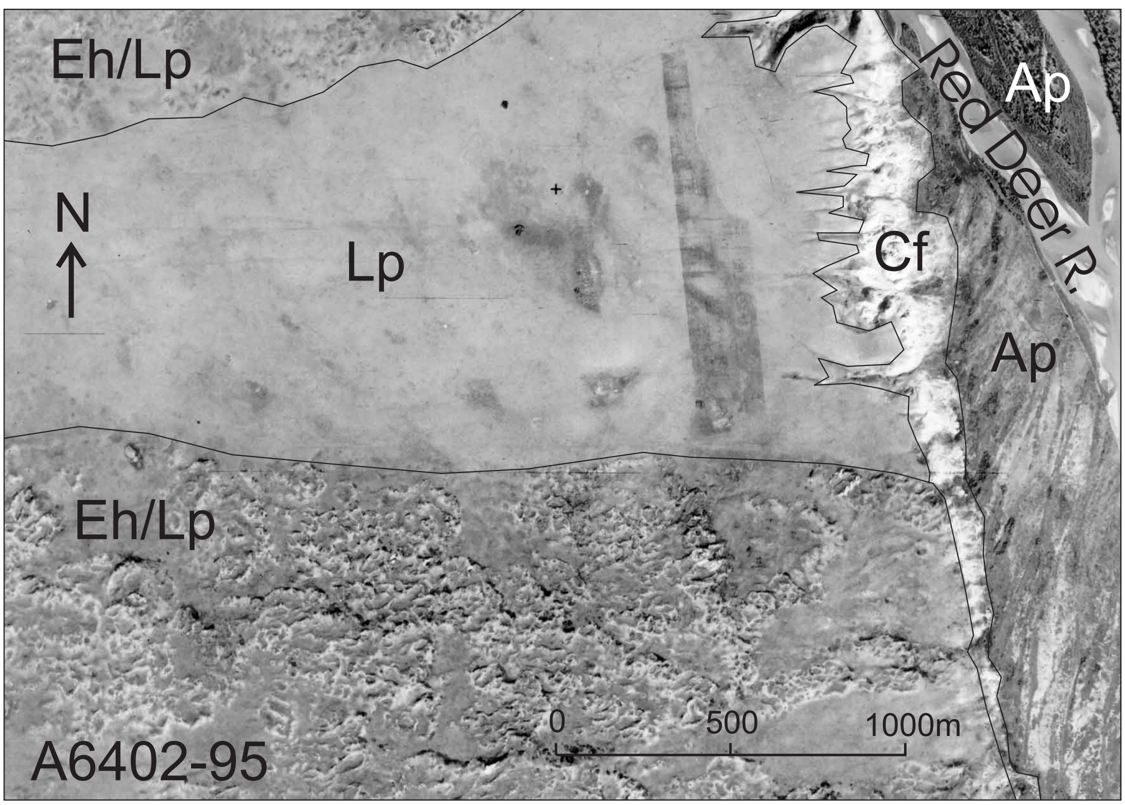

Figure 2. Aerial photograph depicting the southeast portion of the study area (NAPL A-6402-95, 1938; scale ~ 1:19 000). Note the chaotic and hummocky appearance of the dune field in the southern part of the photograph, indicative of extensive blowout activity. Eh - hummocky eolian terrain; Lp - lacustrine plain; Cf - colluvial fan; Ap - modern alluvial plain

sampling were considered morphologically representative of surrounding dunes. The stratigraphy and sedimentology of each site was studied and described to establish the origin and geomorphic significance of the deposits, and to avoid bioturbated sites.

Optical dating

Optical dating measures time elapsed since selected mineral grains were last exposed to sunlight. General descriptions of available techniques are found in the journal *Radiation Measurements* (vol. 27, no. 5/6, 1997), Aitken (1998), and Huntley and Lian (1999). This study used sand-sized K-feldspar grains with 1.4 eV (infrared) excitation and measurement of the 3.1 eV (violet) emission. An additive-dose procedure was used to obtain an equivalent dose (D_{eq}) for each sample. A detailed description of the apparatus and methods used can be found in Ollerhead et al. (1994) and Huntley and Clague (1996).

The stratigraphic contexts of the six samples dated are described in Table 1. Dose rates for the samples were determined using the data in Table 2 along with the conversion factors of Nambi and Aitken (1986), as updated by Adamiec and Aitken (1998), and the β attenuation factors of Mejdahl (1979). Optical ages were calculated by taking the equivalent dose for a sample and dividing it by its calculated dose rate (Table 3). The ages were corrected for anomalous fading, which is ubiquitous in K-feldspar samples, as described by Huntley and Lamothe (2001). A fading rate of 3.8 ± 0.4% a decade (a decade being a factor of ten in time since irradiation) was determined for sample SFU-O-120. This value was also applied to the remaining samples, under the assumption that the mineralogy of the samples, which are derived from the same glaciolacustrine and glaciofluvial source sediments, is sufficiently similar. The corrected ages are given in Table 3.

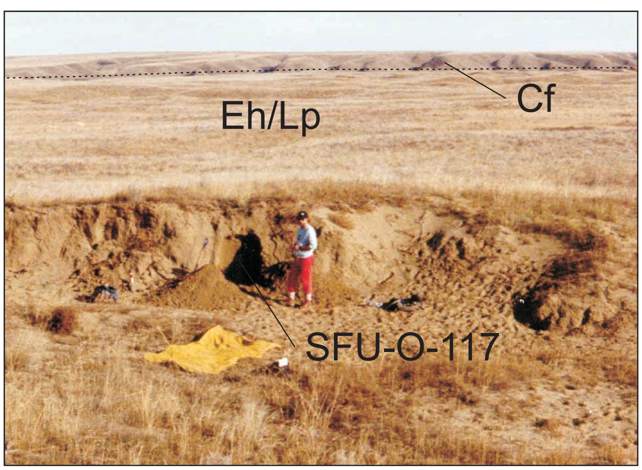

Figure 3. Small blowout in the southeast portion of the study area. Sample SFU-O-117 was collected here. Note gullies leading to the Red River channel in the background. Eh - hummocky eolian terrain; Lp - lacustrine plain; Cf - colluvial fan. Photograph by S.A. Wolfe

RESULTS

Optical ages obtained from the Duchess dune field range from about 4500 years to 230 years. The oldest age of 4540 ± 420 years (SFU-O-118) was obtained from a large blowout exposure in the northern part of the dune field, which contained multiple buried soils. Sand from this section was well indurated by carbonate cementing, which was likely caused by long-term drying of the south-facing exposure. In support of this hypothesis, the as-collected moisture content of this sample was the driest, with only 2% by mass (Table 2). A blowout exposure south of this section consisted of a lower unit of crossbedded sands dated at 2940 ± 200 years (SFU-O-119) with an overlying unit of horizontally stratified sand containing two buried soils, and an upper unit of dune sand with a basal age of 260 ± 26 years (SFU-O-120) at 3 m depth. In a west-facing exposure adjacent to this section, an optical age of 403 ± 27 years (SFU-O-158) was obtained above the fifth buried soil, in a section containing at least eleven buried soils. A ^{14}C age of 669 to 910 cal. BP (TO-5478; standard error at 1-sigma) was obtained from a bison cervical vertebra collected by Ian D. Campbell from the same location (Campbell, 1997).

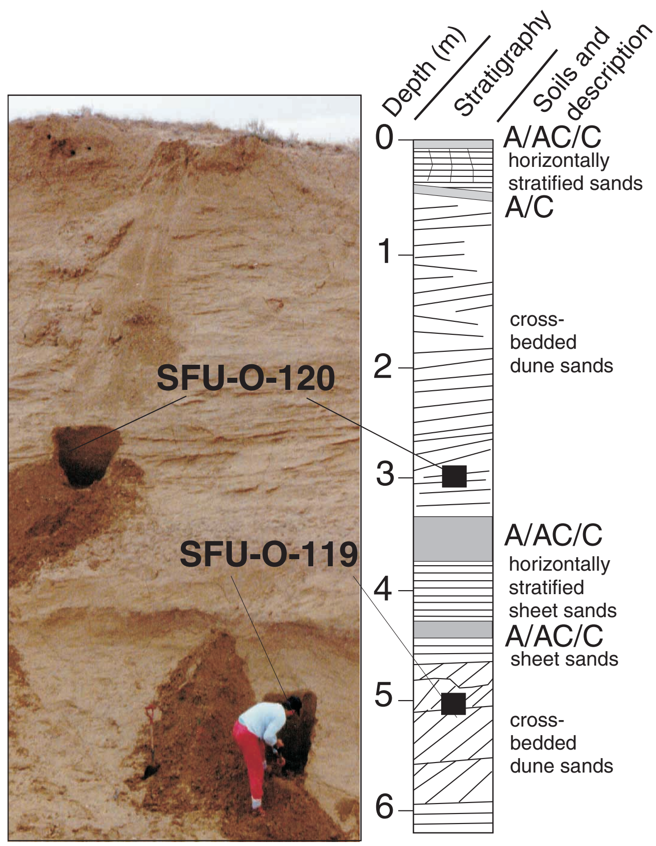

Figure 4. Collection site for samples SFU-O-119 and SFU-O-120 in large blowout in the northwest portion of the study area. Photograph by S.A. Wolfe

Table 1. List of samples collected, depth of collection in section, and a brief description of each site.

Field sample	Lab. number	Depth (m)	Description
IC2-01	SFU-O-116	1.5	Small blowout near several compound blowouts. Massively bedded medium to fine sand (no apparent structure). Buried A-horizons at about 120, 130, and 180 cm.
IC3-01	SFU-O-117	1.5	Small, west-facing blowout. Low-angled (8° to 19°) stratified fine sand overlying horizontally stratified sands, indicative of sheet-sand deposits. No buried soils.
IC4-01	SFU-O-118	2	Large, mostly stabilized blowout. Section is south-facing. Highly indurated, massively bedded fine sand, with multiple organic layers (weak A-horizons).
IC5-01	SFU-O-119	5	Large, active blowout. Section is north-facing. Lower unit of crossbedded sands beneath upper unit of dune sands (*see* SFU-O-120), two buried A-horizons, and horizontally stratified sand (Fig. 4).
IC5-02	SFU-O-120	3	Large, active blowout (same as SFU-O-119). Lower portion of high-angled crossbedded sands indicative of bottomset of dune deposit (Fig. 4).
SAW94-88	SFU-O-158	1.5	High, west-facing blowout, near SFU-O-119 and SFU-O-120. Section has multiple buried soils. Sample is from above the fourth prominent buried soil, collected from same location as a bison cervical vertebra (TO-5478).

Table 2. Analytical data used for calculating dose rates.

Lab number	K whole sample (%) [a]	K surroundings (%)	U (µg/g) [b]	Th (µg/g) [c]	H_20 (g/g) [d]	Grain size (µm)
SFU-O-116	1.26	1.31	0.90 ± 0.04	2.8 ± 0.03	0.05	180–250
SFU-O-117	1.43	1.30	0.99 ± 0.04	(3.0)	0.05	180–250
SFU-O-118	1.46	1.41	1.20 ± 0.04	(3.6)	0.02	180–250
SFU-O-119	1.46	1.49	1.22 ± 0.04	(3.6)	0.06	90–125
SFU-O-120	1.43	1.42	1.02 ± 0.04	(3.0)	0.08	180–250
SFU-O-158	1.47	1.44	1.39 ± 0.08	(4.2)	0.03	180–250

[a] K contents are from atomic absorption analyses.
[b] U contents are from delayed neutron analyses.
[c] Th contents are from neutron activation analyses. Values in parentheses are calculated on the basis of a constant Th/U ratio for the sands.
[d] water content = water mass/dry mass.

Table 3. Final dose rate, equivalent dose (D_{eq}), optical age, and optical age corrected for anomalous fading for each sample.

Lab number	Dose rate [a] (Gy/ka ± 0.13)	Equivalent dose (Gy)	Uncorrected age (years before AD 1994)	Delay[b] (days)	Corrected age[c] (years before AD 1994)
SFU-O-116	2.59	2.14 ± 0.06	826 ± 47	17	980 ± 60
SFU-O-117	2.76	0.56 ± 0.04	203 ± 17	44	229 ± 20
SFU-O-118	2.92	10.8 ± 0.8	3700 ± 320	11	4540 ± 420
SFU-O-119	2.54	6.1 ± 0.2	2400 ± 150	7	2940 ± 200
SFU-O-120	2.70	0.62 ± 0.05	230 ± 22	46	260 ± 26
SFU-O-158	3.02	1.04 ± 0.05	344 ± 22	10	403 ± 27

[a] K and Rb contents of the K-feldspar grains were assumed to be 12.5% and 350 µg/g respectively, and the dose rate due to alphas emitted by U and Th within the grains was assumed to be 0.06 Gy/ka.
[b] This is the time delay between irradiation and measurement in the equivalent dose determination.
[c] The correction for anomalous fading was made as described by Huntley and Lamothe (2001), using a value of 3.8 ± 0.4%/decade, where a decade is a factor of 10 in time since irradiation, measured for sample SFU-O-120.

The remaining optical ages are for samples collected from blowout exposures to the east and southeast of the previous samples. An age of 980 ± 60 years (SFU-O-116) was obtained from massively bedded sands in an exposure in a small blowout. Two buried soils occurred above the sample, at depths of about 120 and 130 cm, with a third buried soil at a depth of 180 cm. The massive appearance of the sands in this section is probably due to sand deposited onto vegetation (i.e. grasses and other forbs). A final optical age of 229 ± 20 years (SFU-O-117) was obtained from a small blowout in the southeast portion of the dune field, from low-angled stratified sands lacking any overlying buried soils.

DISCUSSION AND CONCLUSIONS

Optical ages from the Duchess dune field indicate that eolian deposits in this area have been repeatedly active during the last 4500 years. Dune activity may correspond to periods of drought, during which the landscape experiences dry surface soils, reduced vegetation cover, and increased susceptibility to erosion. Correlation of dune stratigraphy is commonly made difficult because of erosion and reworking of older eolian deposits. However, all the sections observed can be correlated by age and stratigraphy to the section described in Figure 4. A composite stratigraphic section, based on multiple sites in the Duchess dune field, indicates three major episodes of eolian activity in the late Holocene (Fig. 5). Massive and crossbedded sands observed at depths varying from 2 to 5 m indicate episodes of dune activity ca. 4500 and 2900 years ago. Overlying sheet sand deposits and multiple paleosols interbedded with eolian sands up to 2 m thick indicate increased vegetation cover and generally reduced eolian activity between 980 and 400 years ago. Dune and/or blowout deposits, ranging in thickness from 1.5 to 3 m and dating to about 260 to 230 years ago, indicate renewed eolian activity resulting from a combination of drought and/or natural disturbance (e.g. fire, grazing, human occupation).

It is significant that all the optical ages postdate the mid-Holocene warm period of about 8000 to 5500 cal. BP (Hypsithermal). This suggests that, as in other parts of the Great Plains (Stokes and Gaylord, 1993; Muhs et al., 1997a, 1997b; Stokes and Swinehart, 1997; Wolfe et al., 2000), environmental conditions in the Duchess dune field were sufficiently arid in the late Holocene to maintain dune activity, in particular 4500 and 2900 years ago. In addition, there is evidence for a period of soil development occurring between 980 and 400 years ago (AD 1020 to AD 1600). This period corresponds to the Little Ice Age, which began in the Canadian Rockies about AD 1150 (Luckman, 1995) and continued until about AD 1850 (Vance et al., 1997).

In the Duchess dune field, multiple paleosols and bison bones found in association with this sequence suggest that vegetation cover was abundant, but that the terrain was frequently disturbed by bison activity. Stability may have persisted until about AD 1700, after which renewed, but localized, dune activity occurred as recorded by sand-dune and/or blowout deposits dating to ca. 260 to 230 years ago. This activity may have resulted from droughts in the early to mid-1700s, the driest century on the prairies in the last 500 years (Case and MacDonald, 1995; Wolfe et al., 2000). Unlike the Great Sand Hills of southwest Saskatchewan, the Duchess dune field does not appear to have experienced widespread dune activity in the last 200 years. This suggests that either drought conditions in the Duchess dune field were less severe, or local soil, topographic, or vegetation conditions inhibited widespread dune activity during that time.

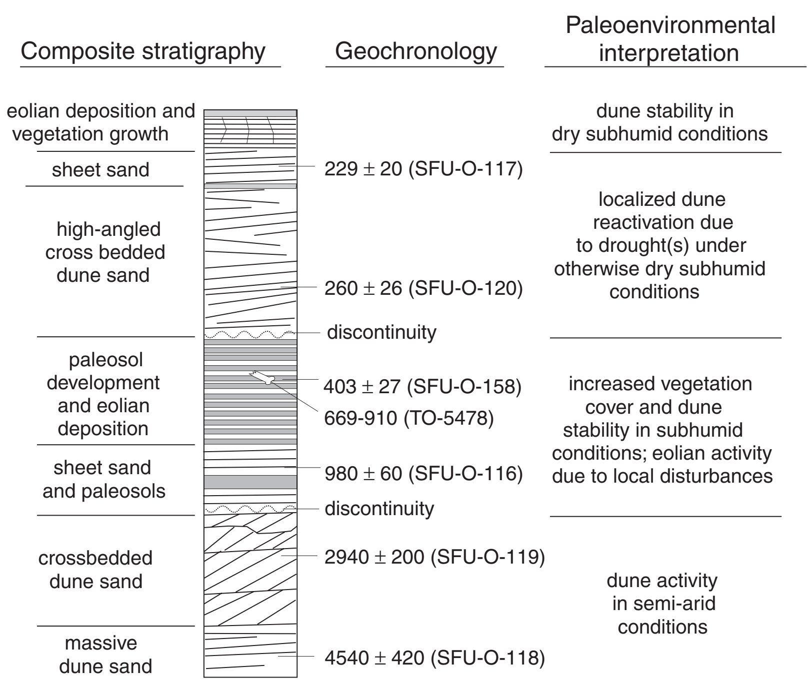

Figure 5.

Composite stratigraphy, geochronology, and paleoenvironmental interpretation of eolian deposits in the Duchess dune field. Note that because of erosional or nondepositional discontinuities, the stratigraphy shown does not correspond to any one individual section, but is a composite of multiple sections used for the purpose of paleoenvironmental interpretation. For this reason no scale is shown, although the total depth of a representative section containing all units could be between 5 and 7 m thick. Soil and paleosols are shown as grey units.

Additional evidence suggests that the Duchess dune field could be less affected by drought, whereas the Great Sand Hills area could be more severely affected. Historical climate records show that drought does not affect the southern prairies uniformly. During the 1987–1988 drought, moisture conditions in the Duchess dune field area were subhumid whereas those in the Great Sand Hills region were predominantly semi-arid (Wolfe, 1997). In addition, southwesterly airflow, which affects the southern prairie region, appears to have a minimal effect in the Duchess dune field as dunes in the Duchess area are oriented with winds from the northwest, in line with the dunes to the north (Fig. 1).

In addition to the stratigraphic and geochronological evidence of dune activity, the chaotic surface geomorphology of the present-day landscape is indicative of repeated, but localized, dune reactivation. As all the eolian deposits and paleosols observed in this study date to the late Holocene, eolian activity has likely reworked most of, if not all, the dune field in this period.

ACKNOWLEDGMENTS

Ian A. Campbell (IAC) is thanked for helping collect the optical dating samples, George Morariu is thanked for preparing, treating, and measuring them, and B.W.-L. Ong is thanked for making the anomalous fading measurements. Zoe Pfeiffer is thanked for helping to prepare this paper. Financial support from the Natural Sciences and Engineering Research Council (grants to JO, DJH, and IAC), the Geological Survey of Canada (grants to SAW and IAC), and Canada's Green Plan (grant to IAC) are gratefully acknowledged. This paper benefited from critical review by Alain Plouffe.

REFERENCES

Adamiec, G. and Aitken, M.J.
1998: Dose-rate conversion factors: update; Ancient TL, v. 16, p. 37–50.

Aitken, M.J.
1985: Thermoluminescence dating; Academic Press, London, United Kingdom, 359 p.
1998: An introduction to optical dating; Oxford University Press, Oxford, United Kingdom, 267 p.

Bryan, R.B., Campbell, I.A., and Yair, A.
1987: Postglacial geomorphic development of the Dinosaur Provincial Park badlands, Alberta; Canadian Journal of Earth Sciences, v. 24, p. 135–146.

Campbell, C.
1997: Postglacial geomorphic response and environmental change in southeastern Alberta, Canada; Ph.D. thesis, University of Alberta, Edmonton, Alberta, 187 p.

Case, R.A. and MacDonald, G.M.
1995: A dendroclimatic reconstruction of annual precipitation on the western Canadian Prairies since A.D. 1505 from *Pinus flexilis* James; Quaternary Research, v. 44, p. 267–275.

David, P.P.
1998: Eolian processes and landforms; *in* Geomorphic Systems of the Palliser Triangle, Southern Canadian Prairies: Description and Response to Changing Climate; Geological Survey of Canada, Bulletin 521, p. 25–39.

Dey, B. and Chakravarti, A.K.
1976: A synoptic climatology analysis of summer dry spells in the Canadian Prairies; Great Plains-Rocky Mountain Geographical Journal, v. 5, p. 30–46.

Environment Canada
1993: Canadian climate normals, 1961-1990: Prairie Provinces; Minister of Supply and Services, Ottawa, Ontario.

Forman, S.L., Goetz, A.F.H., and Yuhas, R.H.
1992: Large-scale stabilized dunes on the High Plains of Colorado: understanding the landscape response to Holocene climates with aid of images from space; Geology, v. 20, p. 145–148.

Forman, S.L., Oglesby, R., and Webb, R.S.
2001: Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links; Global and Planetary Change, v. 29, p. 1–29.

Fritz, S.C., Engstrom, D.R., and Haskell, B.J.
1994: 'Little Ice Age' aridity in the North American Great Plains: a high-resolution reconstruction of salinity fluctuations from Devils Lake, North Dakota, USA; The Holocene, v. 4, p. 69–73.

Holliday, V.T.
1995: Late Quaternary stratigraphy of the Southern High Plains; *in* Ancient Peoples and Landscapes, (ed.) E. Johnson; Museum of Texas Tech University, Lubbock, Texas, p. 289–313.

Huntley, D.J. and Clague, J.J.
1996: Optical dating of tsunami-laid sands; Quaternary Research, v. 46, p. 127–140.

Huntley, D.J. and Lamothe, M.
2001: Ubiquity of anomalous fading in K-feldspars, and the measurement and correction for it in optical dating; Canadian Journal of Earth Sciences, v. 38, p. 1093–1106.

Huntley, D.J. and Lian, O.B.
1999: Using optical dating to determine when a sediment was last exposed to sunlight; *in* Holocene Climate and Environmental Change in the Palliser Triangle, (ed.) D.S. Lemmen and R.E. Vance; Geological Survey of Canada, Bulletin 534, p. 211–222.

Laird, K.R., Fritz, S.C., Maasch, K.A., and Cumming, B.F.
1996: Greater drought intensity and frequency before AD 1200 in the northern Great Plains, USA; Nature, v. 384, p. 552–554.

Luckman, B.H.
1995: Calendar-dated, early 'Little Ice Age' glacier advance at Robson Glacier, British Columbia, Canada; The Holocene, v. 5, p. 149–155.

Madole, R.F.
1994: Stratigraphic evidence of desertification in the west-central Great Plains within the past 1000 yr; Geology, v. 22, p. 483–486.

Mejdahl, V.
1979: Thermoluminescence dating: beta-dose attenuation in quartz grains; Archaeometry, v. 21, p. 61-72.

Muhs, D.R. and Holliday, V.T.
1995: Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers; Quaternary Research, v. 43, p. 232–237.

Muhs, D.R. and Maat, P.B.
1993: The potential response of eolian sands to greenhouse warming and precipitation reduction on the Great Plains of the U.S.A.; Journal of Arid Environments, v. 25, p. 351–361.

Muhs, D.R. and Wolfe, S.A.
1999: Sand dunes of the northern Great Plains of Canada and the United States; *in* Holocene Climate and Environmental Change in the Palliser Triangle, (ed.) D.S. Lemmen and R.E. Vance; Geological Survey of Canada, Bulletin 534, p. 183–197.

Muhs, D.R., Stafford, T.W., Jr., Swinehart, J.B., Cowherd, S.C., Mahan, S.A., Bush, C.A., Madole, R.F., and Maat, P.B.
1997a: Late Holocene eolian activity in the mineralogically mature Nebraska Sand Hills; Quaternary Research, v. 48, p. 162–176.

Muhs, D.R., Stafford, T.W., Jr., Been, J., Mahan, S.A., Burdett, J., Skipp, G., and Rowland, Z.
1997b: Holocene eolian activity in the Minot dune field, North Dakota; Canadian Journal of Earth Sciences, v. 34, p. 1442–1459.

Nambi, K.S.V. and Aitken, M.J.
1986: Annual dose conversion factors for TL and ESR dating; Archaeometry, v. 28, p. 202–205.

Ollerhead, J., Huntley, D.J., and Berger, G.W.
1994: Luminescence dating of sediments from Buctouche Spit, New Brunswick; Canadian Journal of Earth Sciences, v. 31, p. 523–531.

Sauchyn, D.J. and Beaudoin, A.B.
1998: Recent environmental change in the southern Canadian prairies; Canadian Geographer, v. 42, p. 337–353.

Shetsen, I.
1987: Quaternary geology of southern Alberta; Alberta Research Council Map, Edmonton, Alberta, scale 1:500 000.

Stokes, S. and Gaylord, D.R.
1993: Optical dating of Holocene dune sands in the Ferris Dune Field, Wyoming; Quaternary Research, v. 39, p. 274–281.

Stokes, S. and Swinehart, J.B.
1997: Middle and late Holocene dune reactivation in the Nebraska Sand Hills; The Holocene, v. 7, p. 263–272.

United Nations Environment Programme
1992: World Atlas of Desertification; Edward Arnold, Sevenoaks, United Kingdom.

Vance, R.E. and Wolfe, S.A.
1996: Geological indicators of water resources in semi-arid environments: southwestern interior of Canada; *in* Geoindicators: Assessing Rapid Environmental Changes in Earth Systems, (ed.) A.R. Berger and W.J. Iams; A.A. Balkema, Rotterdam, Netherlands, p. 251–263.

Vance, R.E., Last, W.M., and Smith, A.J.
1997: Hydrologic and climatic implications of a multidisciplinary study of late Holocene sediment from Kenosee Lake, southeastern Saskatchewan; Canada Journal of Paleolimnology, v. 18, p. 365–393.

Wolfe, S.A.
1997: Impact of increased aridity on sand dune activity in the Canadian Prairies; Journal of Arid Environments, v. 36, p. 421–432.

Wolfe, S.A., Huntley, D.J., and Ollerhead, J.
1995: Recent and late Holocene sand dune activity in southwestern Saskatchewan; *in* Current Research 1995-B; Geological Survey of Canada, p. 131–140.

Wolfe, S.A., Huntley, D.J., David, P.P., Ollerhead, J., Sauchyn, D.J., and MacDonald, G.M.
2001: Late 18th century drought-induced sand dune activity, Great Sand Hills, Saskatchewan; Canadian Journal of Earth Sciences, v. 38, no. 1, p. 105–117.

Wolfe, S.A., Muhs, D.R., David, P.P., and McGeehin, J.P.
2000: Chronology and geochemistry of late Holocene eolian deposits in the Brandon Sand Hills, Manitoba, Canada; Quaternary International, v. 67, p. 61–74.

Geological Survey of Canada Project PS-1023