

Relict Late Wisconsinan Dune Fields of the Northern Great Plains, Canada

Champs de dunes reliques du Wisconsinien tardif dans les Grandes Plaines septentrionales du Canada

Stephen A. Wolfe, David J. Huntley et Jeff Ollerhead

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Résumé de l'article

Les auteurs étudient l'activité dunaire au Wisconsinien tardif dans la forêt boréale et la prairie-parc actuelles des Grandes Plaines septentrionales du Canada, afin d'approfondir les connaissances sur l'évolution spatiotemporelle de l'activité éolienne. Les âges optiques mesurés sur des dunes de sable stabilisées permettent de reconstituer la chronologie de l'activité passée. Les âges de l'activité éolienne s'échelonnent entre 16 ka dans le centre-ouest de l'Alberta et 9 ka dans le nord-ouest de la Saskatchewan. Entre 16 et 13 ka, l'activité dunaire dans le centre de l'Alberta a eu lieu dans un environnement de toundra juxtaglacière le long des marges des inlandsis laurentidien et cordillérien. Les vents efficaces prédominants soufflaient de l'ouest et du nord-ouest. L'activité dunaire s'est poursuivie dans cette région entre 13 et 11 ka dans des environnements de prairie-parc et de prairie herbageuse, avec le recul de l'Inlandsis laurentidien vers le nord-est. Les vents ont continué de souffler de l'ouest et du nord-ouest, et le climat a probablement été influencé par une masse d'air du Pacifique de plus en plus dominante. Également au début de 13 ka, les vents efficaces le long des marges de l'Inlandsis laurentidien en recul ont été influencées par des vents anticycloniques du sud-ouest, qui ont duré jusqu'à 9 ka. Avec le retrait de l'Inlandsis laurentidien, ces vents ont été successivement remplacés par des vents du nord-ouest associés à la masse d'air du Pacifique. L'activité dunaire dans la région s'est terminée de façon diachrone à partir du sud-ouest, vers 11 ka, jusqu'au nord-est, vers 9 ka, par l'établissement d'une végétation forestière boréale et la diminution de la force des vents.

RELICT LATE WISCONSINAN DUNE FIELDS OF THE NORTHERN GREAT PLAINS, CANADA*

Stephen A. WOLFE**, David J. HUNTLEY and Jeff OLLERHEAD, respectively: Geological Survey of Canada, Natural Resources Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8; Department of Physics, Simon Fraser University, Burnaby, British Columbia V5A 1S6; Department of Geography, Mount Allison University, 144 Main Street, Sackville, New Brunswick E4L 1A7.

ABSTRACT Late Wisconsinan dune activity is investigated within the present-day boreal forest and parkland regions of the northern Great Plains, Canada, to extend the understanding of the spatial and temporal eolian record. Optical ages from stabilized sand dunes document the timing of past activity. Eolian activity ranges from about 16 ka in west-central Alberta to 9 ka in northwestern Saskatchewan. Between about 16 and 13 ka, dune activity in central Alberta occurred in an ice-proximal tundra setting along the margins of the Laurentide and Cordilleran ice sheets. Predominant dune-forming winds were from the west and northwest. Dune activity continued in this area between about 13 and 11 ka within parkland and grassland settings as the Laurentide Ice Sheet retreated to the northeast. Winds continued to blow from the west and northwest, and the climate was likely influenced by an increasingly dominant Pacific air mass. Also beginning at about 13 ka, dune-forming winds along the margins of the retreating Laurentide Ice Sheet were influenced by anticyclonic winds from the southeast that were maintained until about 9 ka. As the Laurentide Ice Sheet retreated, these southeasterly anticyclonic winds were successively replaced by winds from the northwest associated with the Pacific air mass. Dune activity across the region terminated in a time-transgressive manner from the southwest, at about 11 ka, to the northeast, at about 9 ka, with the establishment of boreal forest vegetation and reduced wind strength.

RÉSUMÉ *Champs de dunes reliques du Wisconsinien tardif dans les Grandes Plaines septentrionales du Canada.* Les auteurs étudient l'activité dunaire au Wisconsinien tardif dans la forêt boréale et la prairie-parc actuelles des Grandes Plaines septentrionales du Canada, afin d'approfondir les connaissances sur l'évolution spatiotemporelle de l'activité éolienne. Les âges optiques mesurés sur des dunes de sable stabilisées permettent de reconstituer la chronologie de l'activité passée. Les âges de l'activité éolienne s'échelonnent entre 16 ka dans le centre-ouest de l'Alberta et 9 ka dans le nord-ouest de la Saskatchewan. Entre 16 et 13 ka, l'activité dunaire dans le centre de l'Alberta a eu lieu dans un environnement de toundra juxtaglaciaire le long des marges des inlandsis laurentidien et cordillérien. Les vents efficaces prédominants soufflaient de l'ouest et du nord-ouest. L'activité dunaire s'est poursuivie dans cette région entre 13 et 11 ka dans des environnements de prairie-parc et de prairie herbageuse, avec le recul de l'Inlandsis laurentidien vers le nord-est. Les vents ont continué de souffler de l'ouest et du nord-ouest, et le climat a probablement été influencé par une masse d'air du Pacifique de plus en plus dominante. Également au début de 13 ka, les vents efficaces le long des marges de l'Inlandsis laurentidien en recul ont été influencées par des vents anticycloniques du sud-ouest, qui ont duré jusqu'à 9 ka. Avec le retrait de l'Inlandsis laurentidien, ces vents ont été successivement remplacés par des vents du nord-ouest associés à la masse d'air du Pacifique. L'activité dunaire dans la région s'est terminée de façon diachrone à partir du sud-ouest, vers 11 ka, jusqu'au nord-est, vers 9 ka, par l'établissement d'une végétation forestière boréale et la diminution de la force des vents.

INTRODUCTION

Eolian deposits in the form of loess, sand sheets and dunes serve as important records of paleoclimate. In addition to placing potential limits on moisture balance at the time of formation and acting as sensitive indicators of vegetation cover, they record evidence of past wind regimes (Muhs and Bettis, 2000; Muhs and Zárate, 2001). Across the North American Great Plains, stratigraphic, geomorphic and chronologic studies of dune fields provide insights into eolian activity and stability in relation to Holocene climatic variability (Forman *et al.*, 2001). However, due to extensive late Holocene reworking, Late Wisconsinan and earlier Holocene dune deposits are difficult to find (Muhs and Zárate, 2001), thereby limiting the applicability of older paleoclimate records.

In the past, geological evidence of former wind directions from eolian features was used in an attempt to validate atmospheric general circulation model (AGCM) simulated patterns of Late Wisconsinan and Holocene paleoclimatic parameters in North America (Kutzbach and Wright, 1985; COHMAP Members, 1988). However, evidence from mid-continental dune fields and loess deposits (Flemal *et al.*, 1972; Warren, 1976; Wells, 1983 and others) showed that winds south of the glacial limit were from the west and northwest during full glacial conditions, although model outputs indicated that anticyclonic (easterly) winds prevailed.

However, a major obstacle to using evidence from eolian deposits at that time was an absence of age control (Kutzbach and Wright, 1985). Most paleowind evidence was derived from eolian features that were speculated to be Late Pleistocene in age, but that lacked sufficient dating of these deposits. Ahlbrandt *et al.* (1983) provided the first radiocarbon ages showing that most dune fields south of the Late Wisconsinan glacial limit, thought to have formed in the Late Pleistocene, record mostly mid- to late Holocene episodes of activity. Since then, numerous studies on the North American Great Plains have used radiocarbon, thermoluminescence and optical dating techniques to document episodes of Holocene dune activity (Madole, 1994; Muhs *et al.*, 1997; Stokes and Swinehart, 1997; Forman *et al.*, 2001; Wolfe *et al.*, 2002a, 2002b, 2002c; Goble *et al.*, 2004). Thus, reconstructing paleoclimatic parameters from dune fields in North America has remained an outstanding issue with respect to understanding late glacial climates and circulation patterns, and in verifying paleoclimatic simulations.

In this study, we extend investigations of the spatial and temporal record of dune activity of the northern Great Plains into the boreal forest regions of western Canada (Fig. 1). Geochronological data, together with glacial ice and paleovegetation distributions (Dyke *et al.*, 2003, 2004), are used to develop a chronology of Late Wisconsinan dune activity, wind regimes, and paleoclimate in this northernmost extent of the Great Plains.

DUNE FIELDS ON THE NORTHERN GREAT PLAINS

ORIGINS

With the exception of a few ice-free uplands, the northern Great Plains region was covered by glacial ice during the Late

Wisconsinan (Fig. 1). As a result, source deposits for dune fields within the glacial limit are typically sandy glaciolacustrine or glaciofluvial outwash deposits (David, 1977; Muhs and Wolfe, 1999) associated with meltwaters of the Laurentide and Cordilleran ice sheets. Consequently, the maximum limiting ages of these dune fields are a function of the timing of deglaciation and subsequent drainage of proglacial lakes and rivers (Wolfe *et al.*, 2006). In Canada, the chronology of maximum limiting age follows the trend of the receding Laurentide Ice Sheet, with oldest dune fields in the southwest and progressively younger dune fields towards the northeast (Fig. 2A).

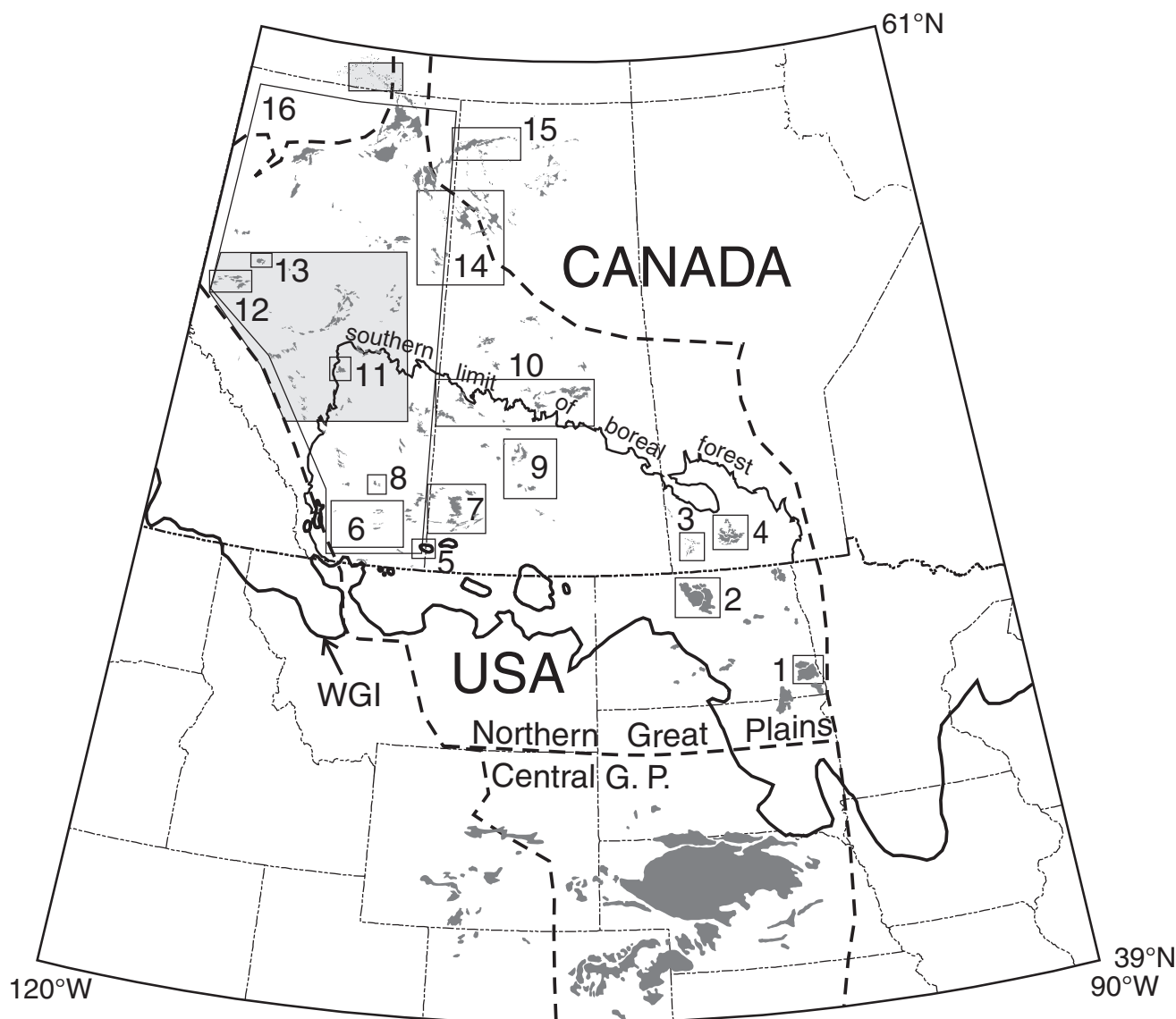
More than 130 dune fields on the northern Great Plains collectively occupy over 40 000 km² (Fig. 1). These dune fields are small in comparison to the central Great Plains dune fields located south of the Wisconsin glacial limit. This difference is due to the fact that glacial outwash, from which most northern Great Plains dune fields are derived, was limited in spatial extent by short-lived intervals of deposition during recession of the Laurentide Ice Sheet. In addition, these northern Great Plains dune fields have not migrated far from their original source (Muhs and Wolfe, 1999).

Today, the mostly-stabilized dune fields of the northern Great Plains contain primarily parabolic, and occasionally transverse, dunes (Fig. 3A-B). Most parabolic dunes on the prairies, south of the present-day limit of the boreal forest (Fig. 1), are superimposed by stabilized or active blowouts that commonly destroy the primary dune morphology (Fig. 3C). Despite this secondary erosion, many dunes nevertheless contain buried soils, indicative of multiple periods of activity and stability (Wolfe *et al.*, 2002b). Given the glacial history of the region, the dune fields in the prairies could potentially date to the Late Wisconsinan. Nevertheless, most dune fields yield ages related to the late Holocene (Fig. 1, #1-10) and, more rarely, mid-Holocene (Fig. 1, #3, 9, 10). In contrast, most stabilized dune fields in the boreal forest are well preserved with few superimposed blowouts (Fig. 3A, B, E), though some show evidence of multiple wind directions (Fig. 3F). This suggests that a single episode of eolian activity, though with varying net sediment transport directions, was succeeded by stabilization. This apparent lack of reworking further suggests that these more northerly Great Plains dune fields may contain older eolian records than those to the south, since much of this northern region has been vegetated by boreal forest since ca. 10 to 9 cal ka BP¹ (Dyke *et al.*, 2004).

PREVIOUS WORK

Eolian deposits in the Canadian portion of the northern Great Plains were extensively mapped and described by David (1977), providing a basis for the regional interpretation of sand dunes. Past detailed chronologic investigations have been restricted to the prairie ecozone (Fig. 1, #1-10), whereas studies in the boreal forest document eolian deposits in the context of surficial mapping, timing of post-glacial events, paleowind

1. "cal ka BP" designates calibrated radiocarbon ages, whereas "ka BP" designates uncalibrated radiocarbon ages; "ka" is used herein to designate ages derived from optical dating.



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|--|---|
| 1. Sheyenne Delta dunes (Hopkins and Running, 2000) | 10. Central Saskatchewan (Wolfe <i>et al.</i> , 2006) |
| 2. Minot SH (Muhs <i>et al.</i> , 1997) | 11. Stony Plain SH (Westgate, 1970) |
| 3. Glacial Lake Hind Basin (Running <i>et al.</i> , 2002; Wallace, 2002) | 12. Grande Prairie dune field (Halsey <i>et al.</i> , 1990; Halsey and Catto, 1994) |
| 4. Brandon SH (David, 1977; Wolfe <i>et al.</i> , 2000; 2002a) | 13. Watino SH (Henderson, 1959) |
| 5. Cypress Hills (Catto, 1983) | 14. Cree Lake moraine region (Tremblay, 1961; David, 1981a; Fisher, 1996) |
| 6. Southwestern Alberta (Beaty, 1975) | 15. Athabasca Sand Dunes (Carson and Maclean, 1986; David, 1981b; Raup and Argus, 1982) |
| 7. Great SH region (Wolfe <i>et al.</i> , 2001) | 16. Alberta (Odynsky, 1958) |
| 8. Duchess dune field (Wolfe <i>et al.</i> , 2002c) | |
| 9. south-central Saskatchewan (Wolfe <i>et al.</i> , 2002b) | |

FIGURE 1. The northern Great Plains, showing dune fields (after Muhs and Wolfe, 1999; Muhs and Zárate, 2001 and Wolfe, 2001), extent of Wisconsin glacial ice (WGI) at ca. 21.4 ka (after Dyke *et al.*, 2003), and relevant eolian studies. Shaded areas in boxes show regions where optical dating was used in the present study (SH = Sand Hills).

Les Grandes Plaines septentrionales, où la carte montre les champs de dunes (d'après Muhs et Wolfe, 1999; Muhs et Zárate, 2001 et Wolfe, 2001), l'étendue de la glaciation Wisconsinienne aux alentours de 21,4 ka cal. (d'après Dyke *et al.*, 2003), et des études éoliennes pertinentes. Les surfaces grisées montrent les régions où l'on a eu recours à la datation optique pour cette étude (SH = Sand Hills).

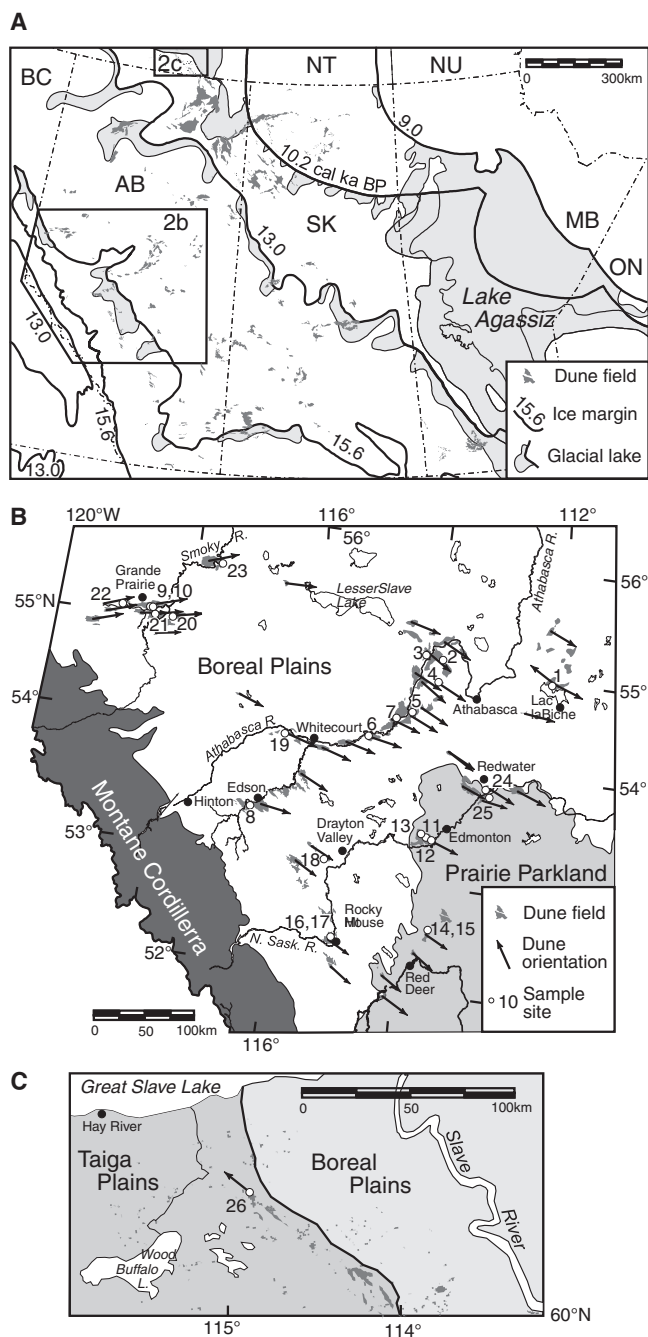


FIGURE 2. Study area and surrounding region. (A) Glacial limits and pro-glacial lakes at 15.6, 13.0, 10.2 and 9.0 cal ka BP (after Dyke *et al.*, 2003) and distribution of dune fields (after Wolfe, 2001). (B) Location of optical-dating samples collected from central Alberta. Dune orientations derived from Pfeiffer and Wolfe (2002) and this study. (C) Location of optical-dating sample collected from stabilized dune at Sandy Lake, NWT.

La région à l'étude et ses environs. (A) Limites glaciaires, lacs pro-glaciaires à 15,6, 13,0, 10,2 et 9,0 k cal. BP (d'après Dyke *et al.*, 2003) et répartition des champs de dunes (d'après Wolfe, 2001). (B) Lieu de prélèvement des échantillons soumis à une datation optique dans le centre de l'Alberta. Orientations des dunes dérivées de Pfeiffer et Wolfe (2002) et de la présente étude. (C) Lieu de prélèvement d'un échantillon pour datation optique provenant d'une dune stabilisée à Sandy Lake, dans les Territoires du Nord-Ouest.

regimes, and stratigraphy (Fig. 1, #11-16). These latter studies suffered from a lack of absolute dating control, with the relative timing of eolian activity inferred by deglacial and post-glacial events.

Previous studies of dune fields in Alberta suggest differing chronologies. Stabilized parabolic dunes indicating westerly to southwesterly winds were investigated by Halsey *et al.* (1990), in the vicinity of Grande Prairie, Alberta (Fig. 1, #12). The authors speculated that the dunes formed after deglaciation, and were of early to mid-Holocene age. Dune deposits derived from glaciolacustrine sediments in the vicinity of Watino (Fig. 1, #13), northeast of Grande Prairie, indicate paleowinds from the west (Henderson, 1959). Here, Henderson (1959) interpreted dune formation under the influence of periglacial winds, post-dating drainage of glacial lakes north of Grande Prairie. In contrast, eolian sands in the Stony Plain sand hills southwest of Edmonton contain a paleosol with Mazama Ash (Fig. 1, #11), indicating eolian activity post-dating about 7.7 cal ka BP (Westgate, 1970).

Effective wind directions throughout Alberta have been derived from dune orientations (Fig. 1, #16; Odyinsky, 1958). In central Alberta, the effective dune building winds were generally from the northwest, whereas in southern Alberta, they were from the southwest, similar to the average pattern of the direction of modern-day strong winds. In southern Alberta, coulee alignment with the present-day strongest Chinook winds from the southwest was also noted (Fig. 1, #6; Beaty, 1975). In contrast, ventifacts and wind-eroded grooves on bedrock surfaces, north and west of Fort McMurray, Alberta, record effective winds that differ from present-day northeasterly winds (Fig. 1, #14; Tremblay, 1961). From these features, Tremblay (1961) concluded that strong winds in this area had blown from southeast ($\sim 145^\circ$) soon after deglaciation.

In the Cree Lake region of northern Saskatchewan, David (1981a) interpreted southeasterly paleowinds as responsible for the formation of elongate parabolic dunes (Fig. 1, #14). He suggested that these dunes were probably active from about 10 to 8.8 ka BP, based on the timing of the local ice front position (Prest, 1969), and were rapidly stabilized by vegetation due to a change in local climate when the ice retreated further. David (1981a) speculated that the southeasterly dune-forming winds were derived from anticyclonic winds originating from a stationary high-pressure centre over the ice sheet, as proposed by Bryson and Wendland (1967). This interpretation supported AGCM simulations, which modeled a weakened but persistent anticyclonic circulation around the Laurentide Ice Sheet between 12 and 9 ka BP (Kutzbach and Wright, 1985). With further retreat of the ice front, wind directions in the region changed and winds blew from the north and northwest, causing local deformation of dunes prior to stabilization (Fig. 3F). Fisher (1996) also investigated paleowind directions derived from ventifacts and sand dunes in the Cree Lake area, relying on regional radiocarbon ages and deglacial events for dating control. He suggested that eolian and periglacial processes were dominant from ca. 11 to 10.5 ka BP under local katabatic and regional anticyclonic winds, with eolian processes continuing as late as 9.9 ka BP.

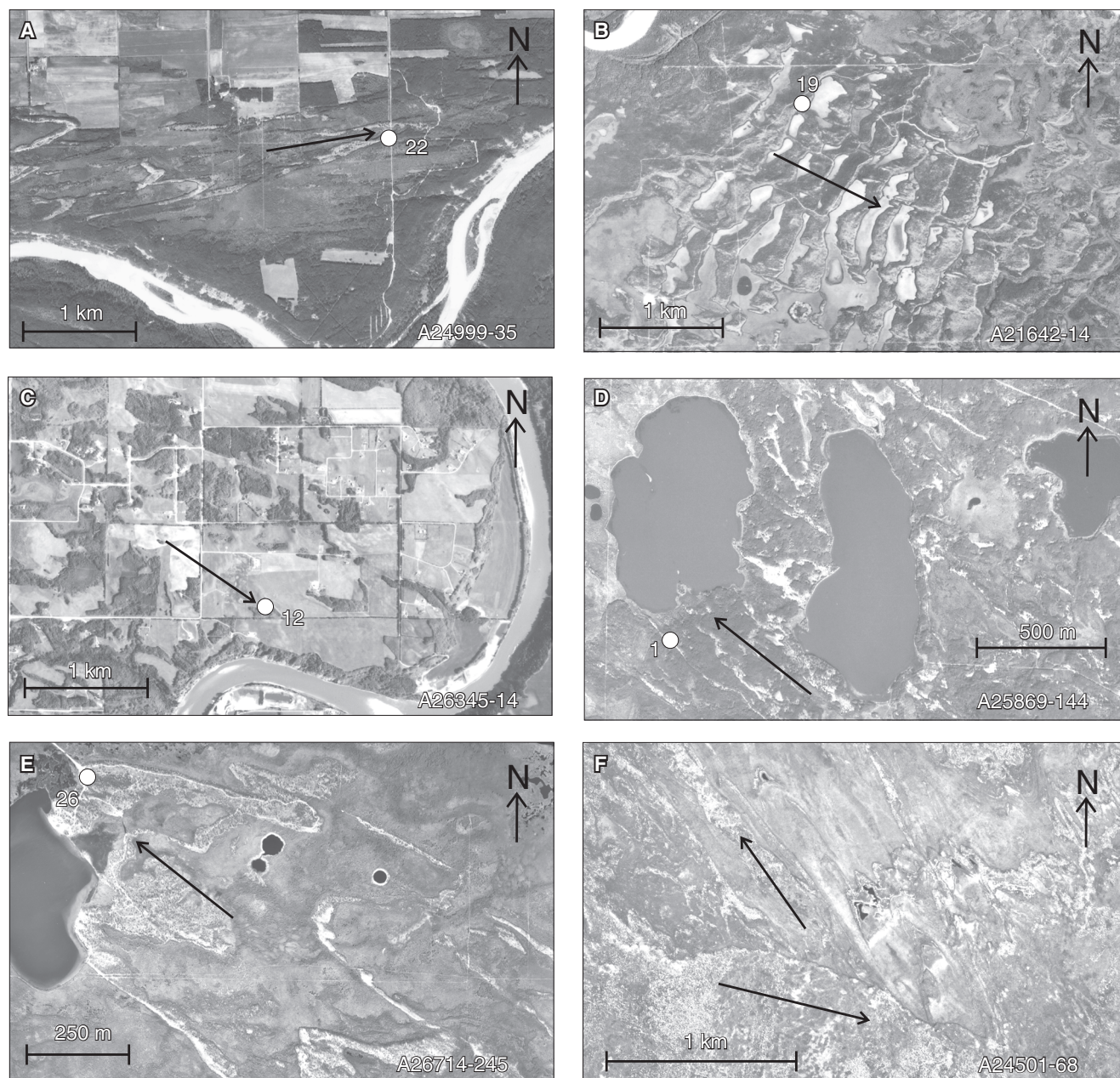


FIGURE 3. Characteristic dune fields of the Canadian northern Great Plains with optical dating sample locations (where relevant) and primary transporting wind directions (indicated by arrows) as derived from dune orientations. (A) Stabilized parabolic dunes, Pipestone Sand Hills near Grande Prairie. (B) Stabilized transverse dunes, Holmes Crossing Sand Hills near Whitecourt. (C) Stabilized parabolic dunes and blowouts, Stony Plain Sand Hills near Edmonton. (D) Stabilized parabolic dunes, Lac la Biche Sand Hills. (E) Stabilized parabolic dunes, Wood Buffalo Sand Hills near Hay River. (F) Stabilized parabolic dunes in northwestern Alberta indicating older transporting winds from the southeast and more recent transporting winds from the west-northwest.

Champs de dunes caractéristiques des Grandes Plaines septentrionales du Canada, avec les lieux de prélèvement des échantillons pour la datation optique, de même que les principales directions des vents efficaces établies à partir de l'orientation des dunes. (A) Dunes paraboliques stabilisées, Pipestone près de Grande Prairie. (B) Dunes transversales stabilisées, Holmes Crossing près de Whitecourt. (C) Dunes paraboliques stabilisées et creux de déflation, Stony Plain près d'Edmonton. (D) Dunes paraboliques stabilisées, Lac la Biche. (E) Dunes paraboliques stabilisées, Wood Buffalo Sand Hills près de la rivière Hay. (F) Dunes paraboliques stabilisées dans le nord-ouest de l'Alberta qui indique les vents efficaces du sud-est, plus anciens, et des vents efficaces de l'ouest-nord-ouest, plus récents.

David (1981a) emphasized that dune activity across this most northerly region of the Great Plains should not be considered synchronous, nor should it be considered to have lasted the same length of time everywhere. It probably began earlier farther west, as soon as the ice sheet disappeared, than it did in the east. He suggested that it apparently lasted for only a short period of time in the westernmost dune areas, whereas it may have lasted longest in the Wood Buffalo Sand Hills of Alberta.

Despite studies documenting the occurrence, stratigraphy and relative timing of dune activity in the Canadian portion of the northern Great Plains, a regional picture of past dune activity is still lacking. In addition, given the apparent complexities in the relative timing of eolian events, it is important that detailed chronologic investigations be conducted to determine the timing of eolian activity relative to deglacial and Holocene events.

This study focuses on the northwestern extent of the northern Great Plains (Figs. 1, 2A), in central Alberta from Red Deer to Lesser Slave Lake and eastward from Grande Prairie to Lac la Biche (Fig. 2B). The majority of the area is in the boreal plains except for the southeast portion, which is in the aspen parkland region of the prairies. An additional site located southeast of Hay River, in the Northwest Territories, was investigated (Fig. 2C).

METHODS

To compare the timing of dune field activity, sampling strategy for optical dating focused on determining the most recent episode of dune activity. Twenty-six samples were obtained from the heads or arms of stabilized parabolic and transverse dunes (Table I) that were typically easily recognizable on air-photos (Fig. 3). Most samples were collected from a depth of at least one metre, in shallow pits excavated into roadcuts or the surface of stabilized dunes to avoid potential mixing of the parent dune sands with overlying pedogenically-altered sediment. Stratigraphy was described at each sample site, noting depth of pedogenesis, orientation of bedding planes within eolian sediments, and the occurrence of buried soils. Dune orientations, reflecting the dominant wind directions in which the dunes formed, were determined in the field. The morphology and orientation of stabilized dunes across the entire region were also derived from aerial photographs (Pfeiffer and Wolfe, 2002). Among the dune fields sampled were those investigated by Henderson (1959), Halsey *et al.* (1990) and Westgate (1970); thus providing a chronology for these areas (Fig. 1, #11, 12, 13).

Optical dating measures the time elapsed since mineral grains were last exposed to sunlight, which usually corresponds to the time since the grains were buried. Wintle (1997), Aitken (1998), Huntley and Lian (1999), and Lian and Huntley (2001) describe techniques, and Lian *et al.* (2002) provide methodological details applied to this study. Sand sized K-feldspar grains (180–250 μm diameter) were dated by excitation with near-infrared (1.4 eV, ~ 880 nm) photons and measuring the violet (3.1 eV, 400 nm) photons emitted in response. The multiple-aliquote additive-dose with thermal transfer correction

method was used to determine the equivalent dose and this, together with a measure of the environmental dose rate and a correction for anomalous fading, was used to calculate the ages (Tables II and III). This technique has been used successfully elsewhere on sand dunes in the Canadian Great Plains (Wolfe *et al.*, 2001, 2002a, 2002b, 2006), with ages that are in agreement with radiocarbon ages (Wolfe *et al.*, 2002a) and an optical age derived from quartz (Huntley and Lamothe, 2001).

The average analytical uncertainty in the optical ages at 1σ is about 7% of the reported age, but a few (SFU-O-269, 274 and 275) are about 10% or greater. About half of this uncertainty is derived from uncertainty in the fading rates.

RESULTS AND DISCUSSION

STRATIGRAPHY AND OPTICAL AGES

Most soils on stabilized dunes contain some expression of O/Ah/B/C horizons. Ah-horizons were about 10 to 20 cm thick. Between 20 and 80 cm depth, iron-oxidation, mottling and increased firmness of the sand were indicative of developing Bfm-horizons, though the degree of expression of these may be insufficient to fully meet this criteria. Iron-oxidation and/or calcareous tree-root casts extending to a depth of 50 to 80 cm frequently obscured eolian stratigraphy in this portion of the sample pits. Where stratigraphy was noted, it was commonly continuous, sub-horizontal bedding with individual layers 0.5 to 3 cm thick, representing grain deposition by saltation. Almost without exception, the eolian sands were medium-to-fine grained and well sorted.

With the exception of the Stony Plain sand hills, none of the dune fields sampled contained buried soils in the upper few metres of the sections. Although it is possible that paleosols may have been eroded during dune reactivation, the lack of buried soils suggests that most dune fields underwent a sustained period of activity, followed by stabilization. This speculation is further confirmed by the ages of the dunes (Table III). With the exception of one mid-Holocene age (*ca.* 6.2 ka) from the Stony Plain sand hills obtained below two buried soils, optical ages range between *ca.* 15.3 and 10.5 ka. These ages are significantly older than those derived from dunes on the prairies, and indicate that the most recent episode of dune activity throughout much of this region was during the Late Wisconsinan.

The optical ages conform well to earlier speculation regarding the timing of dune activity, but provide several useful refinements regarding the timing and length of activity. In Grande Prairie, Halsey *et al.* (1990) speculated that the dunes were of early to middle Holocene age. However, our optical age of 14.0 ± 0.8 ka (SFU-O-264) from section 5 of Halsey *et al.* (1990), indicates that these dunes are of Late Wisconsinan age. Activity may have occurred for a few thousand years, terminating as late as 11.8 ± 0.8 ka (SFU-O-276) east of Grande Prairie. In the Watino area, Henderson (1959) speculated that the dunes post-dated drainage of glacial lakes, and may have occurred in a periglacial setting. An age of 12.9 ± 0.8 ka (SFU-O-279), is consistent with the deglacial chronology (Fig. 4A–B), but suggests that dune activity may have continued into a period when parkland vegetation had replaced

TABLE I
Sample locations and dune descriptions

No.	Sand Hill	Latitude	Longitude	Elevation asl (m)	Dune Type	Location	Orientation
1	Lac la Biche	54° 58' 23"	112° 06' 35"	564	Parabolic	Head	301°
2	Hondo	55° 02' 18"	114° 02' 58"	609	Parabolic	Head	124°
3	Decrene	55° 06' 47"	114° 09' 12"	594	Parabolic	Head	130°
4	Chisholm	54° 50' 50"	114° 10' 36"	609	Parabolic	Head	125°
5	Nelson Lake	54° 29' 07"	114° 17' 07"	648	Parabolic	Head	118°
6	Holmes Crossing	54° 17' 55"	114° 51' 23"	686	Transverse	Head	112°
7	Fort Assiniboine	54° 25' 33"	114° 29' 15"	609	Transverse	Head	126°
8	Edson	53° 29' 31"	116° 37' 30"	960	Parabolic	Head	111°
9	Bear River	55° 05' 20"	118° 48' 09"	655	Parabolic	Head	86°
10	Bear River	55° 05' 16"	118° 48' 35"	655	Parabolic	Arm	86°
11	Stony Plain	53° 24' 09"	113° 45' 04"	705	Parabolic	Head	—
12	Stony Plain	53° 23' 25"	113° 40' 53"	705	Parabolic	Head	124°
13	Stony Plain	53° 26' 48"	113° 48' 20"	705	Parabolic	Arm	127°
14	Battle River	52° 34' 47"	113° 37' 02"	853	Parabolic	Arm	124°
15	Battle River	52° 34' 47"	113° 37' 02"	853	Parabolic	Arm	124°
16	Rocky Mt. House	52° 22' 17"	115° 00' 30"	1006	Parabolic	Head	127°
17	Rocky Mt. House	52° 22' 17"	115° 00' 30"	1006	Parabolic	Head	127°
18	Lodgepole	53° 06' 54"	115° 14' 39"	884	Parabolic	Arm	128°
19	Windfall	54° 11' 56"	116° 08' 00"	808	Parabolic	Head	113°
20	Economy Creek	55° 03' 54"	118° 12' 50"	640	Parabolic	Arm	84°
21	Grovedale	55° 02' 57"	118° 44' 37"	655	Parabolic	Arm	86°
22	Pipestone	55° 03' 16"	119° 13' 16"	686	Parabolic	Arm	78°
23	Watino	55° 43' 24"	117° 32' 12"	564	Parabolic	Arm	75°
24	Redwater	53° 56' 24"	112° 57' 05"	640	Parabolic	Head	117°
25	Beaverhill Creek	53° 51' 35"	112° 54' 05"	617	Parabolic	Head	109°
26	Sandy Lake	60° 31' 50"	114° 33' 54"	265	Parabolic	Head	304°

shrub tundra (Dyke *et al.*, 2004). Lastly, the observation by Westgate (1970) that eolian deposits overlay Mazama Ash in the Stony Plain area is consistent with an optical age of 6.2 ± 0.6 ka (SFU-O-269) obtained from a stabilized dune in that area, though earlier activity is also noted at about 12.0 and 13.4 ka (SFU-O-267, 268).

Dune orientations across central Alberta indicate that dune-forming winds in this area were primarily from the west or northwest (Figs. 2B, 3A-C). An exception is Lac la Biche, where dune orientations indicate dominant transporting winds from the southeast (Fig. 3D). Dune orientations in the Hay River area also indicate transporting winds from the southeast (Figs. 2C, 3E). Orientations across much of remaining northern Alberta and Saskatchewan indicate transporting winds were from the northwest or southeast, and commonly both (Fig. 4B).

LATE WISCONSINAN AND EARLY HOLOCENE DUNE ACTIVITY

The glacial chronology of western Canada has been a topic of considerable debate, with much discussion around the issue of the maximum extent of the Cordilleran and Laurentide ice

sheets during the last glacial maximum and the timing of glacial recession (Dyke and Prest, 1987; Catto and Mandryk, 1990; Levson and Rutter, 1996). Differing views of glacial history were due largely to the relatively few pre-Holocene radiocarbon ages, and uncertainty in radiocarbon ages obtained from non-woody organics because of contamination by old carbonate or reworked organics (Macdonald *et al.*, 1987; Levson and Rutter, 1996). Today there is less debate over the maximum glacial extent and relative timing of deglacial events, though there is still some uncertainty in the details of the chronology. The most recent deglacial chronology for Canada was developed by Dyke *et al.* (2003) for 21.4 cal ka BP to present, with approximately 500-year BP time-steps since 17.4 cal ka BP.

The present chronology and orientations of northern Great Plains dune fields are placed into context with the Late Wisconsinan deglacial chronology depicted by Dyke *et al.* (2003). In doing so, the analytical uncertainty in the optical ages (averaging about ± 850 years at 1σ) is considered. Thus, the results focus on several large time intervals, between about 15.6 and 9.0 cal ka BP in western Canada (Fig. 4). All of the optical ages are consistent with the deglacial chronology when the uncertainties of the ages are considered. The

TABLE II

Locations, sample depths, K, Th and U concentrations used for dosimetry, and water contents of sample

No.	Sand Hill	Lab. No.	Depth ^a (cm)	K (% $\pm 5\%$)		Th ^c ($\mu\text{g g}^{-1}$) ± 0.1	U ^d ($\mu\text{g g}^{-1}$) ± 0.1	Water content ^e (%)
				Sample	Surr. ^b			
1	Lac la Biche	SFU-O-257	80	0.73	0.72	2.7	0.92	4.1 \pm 0.3
2	Hondo	SFU-O-258	100	0.91	0.87	3.1	1.05	3.4 \pm 1.0
3	Decrene	SFU-O-259	100	0.90	0.91	3.0	0.90	4.1 \pm 0.3
4	Chisholm	SFU-O-260	100	0.79	0.87	4.0	1.35	4.3 \pm 0.9
5	Nelson Lake	SFU-O-261	100	0.97	0.96	3.7	1.30	4.3 \pm 0.3
6	Holmes Crossing	SFU-O-262	100	0.80	0.83	2.4	0.89	2.3 \pm 0.2
7	Fort Assiniboine	SFU-O-263	250	0.81	0.83	3.2	1.02	3.7 \pm 0.3
8	Edson	SFU-O-264	150	1.33	1.38	3.6	1.34	6.2 \pm 0.5
9	Bear River	SFU-O-265	100	0.75	0.71	2.4	1.21	3.4 \pm 0.3
10	Bear River	SFU-O-266	500	0.76	0.71	2.4	0.99	4.3 \pm 0.7
11	Stony Plain	SFU-O-267	100	1.23	1.10	3.5	1.33	3.8 \pm 0.3
12	Stony Plain	SFU-O-268	100	1.34	1.31	3.8	1.50	8.0 \pm 3.6
13	Stony Plain	SFU-O-269	115	1.27	1.23	2.9	1.11	5.4 \pm 0.9
14	Battle River	SFU-O-270	100	1.13	1.24	3.4	1.22	9.7 \pm 2.0
15	Battle River	SFU-O-271	400	1.09	1.13	3.2	0.96	3.5 \pm 0.6
16	Rocky Mt. House	SFU-O-272	110	0.99	0.98	2.8	1.22	5.1 \pm 1.6
17	Rocky Mt. House	SFU-O-273	600	0.88	0.93	2.7	1.26	6.9 \pm 3.2
18	Lodgepole	SFU-O-274	300	1.40	1.41	3.7	1.50	6.9 \pm 2.0
19	Windfall	SFU-O-275	170	0.73	0.77	2.5	0.81	4.9 \pm 1.7
20	Economy Creek	SFU-O-276	130	0.71	0.72	2.5	1.21	2.6 \pm 0.7
21	Grovedale	SFU-O-277	130	0.66	0.76	2.4	1.08	2.7 \pm 0.3
22	Pipestone	SFU-O-278	110	0.81	0.87	2.8	1.34	3.6 \pm 0.4
23	Watino	SFU-O-279	120	0.76	0.87	3.3	1.19	3.6 \pm 0.5
24	Redwater	SFU-O-280	115	0.95	0.99	2.0	0.61	3.0 \pm 0.5
25	Beaverhill Creek	SFU-O-281	100	0.70	0.83	3.2	0.84	4.0 \pm 0.1
26	Sandy Lake	SFU-O-159	150	0.80	0.85	2.0	0.45	3.0 \pm 0.1

a. Sample depth beneath the ground surface used for calculation of the cosmic-ray dose rate.

b. K contents are from atomic absorption analyses. Average of K content of samples in surroundings collected 30 cm below and above the main sample.

c. Th contents are from neutron activation analyses.

d. U contents are from delayed neutron analyses.

e. Water content = (mass water)/(dry mineral mass); water content is the as-collected value expressed as a percentage, and is the mean of three samples.

Note: Rb contents were in the range of 15-40 $\mu\text{g g}^{-1}$.

ages indicate that the earliest dune activity likely occurred in close proximity with the retreating Laurentide Ice Sheet, beginning about 15.6 cal ka BP (Fig. 4A).

15.6 to 13.0 cal ka BP

By about 15.6 cal ka BP, a narrow deglaciated plain existed in west-central Alberta between the Laurentide and Cordilleran ice sheets (Fig. 4A). Only a few dune fields likely existed at this time, owing to the relatively small area of deglaciated land and source outwash deposits. Dune fields were active in a proglacial setting in the vicinity of glacial Lake Drayton Valley (ca. 15.7 ka) and along the margins of the retreating Laurentide Ice Sheet (ca. 15.3 ka). The orientations of these

dunes indicate that dominant transporting winds were from the northwest.

By about 13.5 cal ka BP, the newly deglaciated plain extended northward and eastward (Fig. 4A). Several large proglacial lakes existed along the western edge of the Laurentide Ice Sheet (St-Onge, 1972), including glacial lakes Peace and Leduc. Many dune fields were active in central Alberta at about this time, as evidenced by optical ages that are the same within analytical uncertainties. Sand dunes in the Grande Prairie area were probably active soon after drainage of glacial Lake Peace (ca. 14.9, 14.2, 13.7 and 13.5 ka), and the dominant transporting winds were from the west. Dune fields in the vicinity of glacial Lake Leduc were also active in this interval (ca. 14.8, 14.9, 14.5, 14.5 and

TABLE III
Total dose rate (\dot{D}), equivalent doses (D_e), and optical ages

No.	Lab. No.	\dot{D} (Gy/ka) ^a ± 0.07	D_e (Gy)	Uncorrected optical age ^b (ka)	Fading rate ^c (%/decade)	Delay days ^d	Corrected optical age ^e (ka)
1	SFU-O-257	2.15	18.0 \pm 0.4	8.36 \pm 0.33	6.29 \pm 0.29*	14	12.6 \pm 0.6
2	SFU-O-258	2.36	23.3 \pm 0.4	9.86 \pm 0.37	5.70 \pm 0.27*	14	14.2 \pm 0.7
3	SFU-O-259	2.32	23.0 \pm 0.7	9.91 \pm 0.46	6.11 \pm 0.41*	17	14.8 \pm 0.9
4	SFU-O-260	2.39	25.2 \pm 0.7	10.52 \pm 0.46	5.70 \pm 0.27	13	15.3 \pm 0.8
5	SFU-O-261	2.52	24.6 \pm 0.8	9.77 \pm 0.44	5.98 \pm 0.48	13	14.5 \pm 0.9
6	SFU-O-262	2.19	22.1 \pm 0.7	10.09 \pm 0.49	5.98 \pm 0.48*	17	14.9 \pm 1.0
7	SFU-O-263	2.25	22.1 \pm 0.8	9.84 \pm 0.47	"	16	14.5 \pm 1.0
8	SFU-O-264	2.84	25.5 \pm 0.7	8.97 \pm 0.40	6.62 \pm 0.37	16	14.0 \pm 0.8
9	SFU-O-265	2.20	20.9 \pm 0.6	9.50 \pm 0.41	5.75 \pm 0.62*	16	13.7 \pm 1.0
10	SFU-O-266	2.09	19.6 \pm 0.7	9.36 \pm 0.43	"	17	13.5 \pm 1.0
11	SFU-O-267	2.70	23.6 \pm 0.8	8.75 \pm 0.37	5.47 \pm 0.32*	36	12.0 \pm 0.6
12	SFU-O-268	2.87	28.2 \pm 1.3	9.82 \pm 0.51	"	61	13.4 \pm 0.8
13	SFU-O-269	2.65	12.3 \pm 1.0	4.65 \pm 0.40	"	61	6.2 \pm 0.6
14	SFU-O-270	2.60	26.4 \pm 0.8	10.14 \pm 0.41	4.25 \pm 0.30*	36	12.8 \pm 0.6
15	SFU-O-271	2.44	21.8 \pm 0.4	8.95 \pm 0.37	"	37	11.3 \pm 0.5
16	SFU-O-272	2.42	21.7 \pm 1.2	8.99 \pm 0.56	4.64 \pm 0.43*	46	<11.6 \pm 0.8 ^f
17	SFU-O-273	2.27	21.8 \pm 0.9	9.62 \pm 0.50	"	47	12.4 \pm 0.8
18	SFU-O-274	2.89	30.3 \pm 1.2	10.49 \pm 0.49	5.2 \pm 1.5	56	14.1 \pm 1.8
19	SFU-O-275	2.07	23.5 \pm 1.1	11.35 \pm 0.66	5.5 \pm 1.0	47	15.7 \pm 1.6
20	SFU-O-276	2.15	20.0 \pm 1.0	9.31 \pm 0.56	4.46 \pm 0.23	62	11.8 \pm 0.8
21	SFU-O-277	2.08	22.0 \pm 0.6	10.60 \pm 0.46	5.75 \pm 0.62	43	14.9 \pm 1.0
22	SFU-O-278	2.33	23.6 \pm 0.7	10.15 \pm 0.43	"	58	14.2 \pm 0.9
23	SFU-O-279	2.26	23.0 \pm 1.1	10.18 \pm 0.58	4.40 \pm 0.29*	61	12.9 \pm 0.8
24	SFU-O-280	2.21	19.0 \pm 0.6	8.61 \pm 0.39	5.49 \pm 0.30*	62	11.7 \pm 0.6
25	SFU-O-281	2.13	19.4 \pm 0.7	9.11 \pm 0.45	5.65 \pm 0.27*	62	12.5 \pm 0.7
26	SFU-O-159	2.10	17.9 \pm 0.3	8.50 \pm 0.40	4.80 \pm 0.30	212	10.5 \pm 0.5

a Total $\dot{D} = \dot{D}_c + \dot{D}_{\alpha, \beta, \gamma}$, where $\dot{D}_{\alpha, \beta, \gamma}$ is the dose rate due to α , β , γ radiation and \dot{D}_c is the cosmic-ray dose rate.

b Optical ages, not corrected for anomalous fading.

c Fading rates calculated from data collected between 1.6 and 813 days (SFU-O-257 to 266), 223 days (SFU-O-267 to 281), or 346 days (SFU-O-159) after laboratory irradiation as described for method 'b' in Huntley and Lamothe (2001). An asterisk (*) after the value indicates the fading rate was measured for this sample; otherwise the fading rate used is assumed, based on value in this column for other samples from the same site with mineralogy expected to be similar.

d Delay is the time between laboratory irradiation and equivalent dose measurements.

e Optical ages, corrected for anomalous fading using the data listed in the previous two columns.

f The nature of the scatter in the normalized dose-response data suggests that this sample contains grains that were not exposed to sufficient sunlight, and hence its age must be interpreted as an upper limit.

Notes: Past water content was assumed to be $5.0 \pm 3.0\%$ (95 % confidence) for all samples. Aliquots used for thermal transfer correction were given a red-infrared laboratory bleach.

14.2 ka), and transporting winds here were also predominantly from the northwest. Dune fields were active farther south around Rocky Mountain House (ca. 14.1, 14.0 and 13.4 ka), also with predominant transporting winds from the northwest.

13.0 to 9.0 cal ka BP

By about 13.0 cal ka BP, the Laurentide and Cordilleran ice sheets were well separated. At about this time, dunes

active in the vicinity of Lac la Biche (ca. 12.6 ka) were formed by transporting winds from the southeast. This is the earliest documented evidence of anticyclonic winds in western Canada. Subsequent to about 13.0 ka, other dune fields residing along the margins of the retreating Laurentide Ice Sheet also were affected by winds from the southeast. As the Laurentide Ice Sheet retreated, these southeasterly winds were replaced by winds from the northwest (Fig. 4B). By about

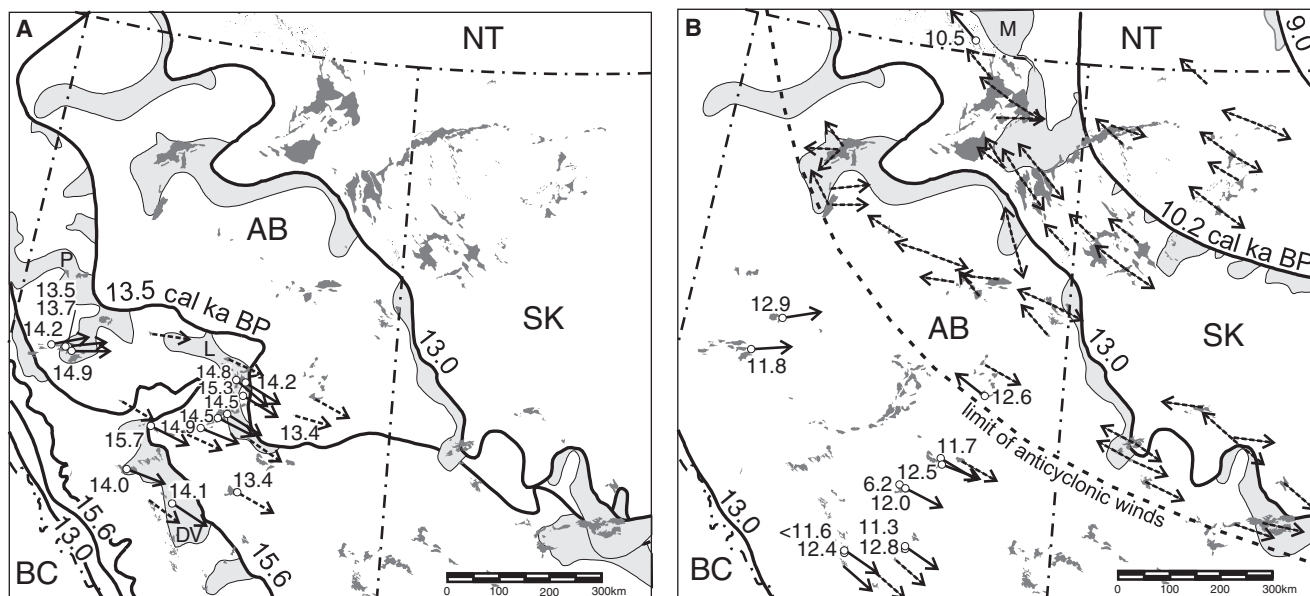


FIGURE 4. Dune activity and wind directions in relation to glacial limits and pro-glacial lakes (after Dyke *et al.*, 2003) for (A) between 15.6 and 13.0 cal ka BP and (B) between 13.0 and 9.0 cal ka BP. Uncertainty in optical ages is about 7% at 1σ (see Table III for values). Solid arrows indicate dune-forming wind directions (derived from dune field orientations) with age control, and dashed arrows indicate orientations with inferred timing. Also labeled are glacial lakes Peace (P), Leduc (L), Drayton Valley (DV) and McConnell (M). Dashed line in Figure 4B denotes the southern and western limit of anticyclonic winds.

Activité dunaire et direction des vents en relation avec les limites glaciaires et les lacs proglaciaires (d'après Dyke et al., 2003) pour (A) la période entre 15,6 et 13,0 ka cal. BP et (B) la période entre 13,0 et 9,0 ka cal. BP. La marge d'incertitude des âges optiques est de l'ordre de 7% à 1σ (voir les valeurs au Tableau III). Les flèches pleines indiquent la direction des vents efficaces (dérivée de l'orientation des champs de dunes) avec des âges obtenus par datation et les flèches tiretées représentent l'orientation des vents avec les âges inférés. L'emplacement des lacs glaciaires Peace (P), Leduc (L), Drayton Valley (DV) et McConnell (M) sont aussi montrés. La ligne tiretée de la figure 4B représente la limite méridionale et occidentale des vents anticycloniques.

10.2 cal ka BP, the southwest margin of the Laurentide Ice Sheet had retreated into northern Saskatchewan. In the southern Northwest Territories, dunes were active (ca. 10.5 ka) soon after drainage of glacial Lake McConnell (Lemmen *et al.*, 1994). These dunes are oriented towards the northeast, indicating transporting winds from the southwest and a continuation of anticyclonic circulation along the margins of the retreating ice sheet. By about 9.0 cal ka BP, the southwest margin of the Laurentide Ice Sheet had retreated into northeastern Saskatchewan. Dune field orientations indicate that anticyclonic winds continued along the margins of the retreating ice sheet, and were subsequently replaced by winds from the northwest.

Outside the limit of anticyclonic winds, dune-forming winds continued to originate from the west and northwest. Dune activity occurred in the Grande Prairie area (ca. 12.9 and 11.8 ka) and in the south (ca. 12.8, 12.5, 12.4, 12.0, 11.7, <11.6 and 11.3 ka), but dunes were fully stabilized by about 11 ka. The only exception is the Stony Plain area, southwest of Edmonton, where dune reactivation occurred at about 6.2 ka.

DUNE ACTIVITY IN RELATION TO LATE WISCONSINAN PALEOCLIMATE

As with the glacial chronology, the post-glacial sequence of paleoenvironmental change in western Canada has been a

topic of some debate, due to the uneven distribution of study sites, limited early deglacial records and unreliable radiocarbon ages derived from non-woody organics, such as peat and gyttja (Beaudoin, 1993). Most paleoenvironmental interpretations from western Canada are derived from pollen or diatom records of lake cores (*e.g.* Hickman and Schweger, 1993, 1996; MacDonald, 1989; Vance, 1986), with additional data from macrofossil, peatland and vertebrate localities (Beaudoin *et al.*, 1996; Wilson, 1996; Halsey *et al.*, 1998). Dyke *et al.* (2004) describe and map the vegetation history of glaciated North America for 21.4 cal ka BP to present, and include 1000-year BP time steps since 17.4 cal ka BP, based on an extensive compilation of published pollen, macrofossil and macrofaunal assemblages. The chronology of dune activity presented herein is discussed in context with this interpretation of paleo-vegetation distribution, for the interval between 15.6 and 9.0 cal ka BP.

15.6 to 13.0 cal ka BP

Between about 15.6 and 13.5 cal ka BP, the newly deglaciated terrain in western Canada must have been cold and intensely windy. Dunes dating to this period indicate that winds were from the northwest. Therefore, winds blowing off both the Cordilleran and Laurentide ice sheets were apparently funneled southward through this corridor, as ice blocked flow to the north. Katabatic winds carrying dry air probably

created a cold-tundra periglacial environment, as reflected by the predominantly herb tundra vegetation at this time (Dyke *et al.*, 2004). Cold-climate eolian processes were likely dominant at this time, in addition to possible stagnant ice and permafrost (Mandryk, 1996). It appears that glacial anticyclonic circulation, evident after 13.0 cal ka BP, was not present and may have been inhibited by winds blowing southward along the margins of the Laurentide and Cordilleran ice sheets.

As the Laurentide Ice Sheet retreated eastward between 13.5 and 13.0 cal ka BP, much of central Alberta previously occupied by tundra vegetation was replaced by parkland in the north and grassland in the south (Dyke *et al.*, 2004). Continued dune activity in this area indicates that transporting winds were still strong and vegetation was, at least locally, sparse.

13.0 to 9.0 cal ka BP

By about 13.0 cal ka BP, dune fields in eastern Alberta were influenced by transporting winds from the southeast, which we infer were generated by glacial anticyclonic circulation. The limit of anticyclonic winds, as suggested by dune field orientations, is depicted in Figure 4B. Based on this interpretation, the influence of anticyclonic winds probably extended 200 km or less beyond the Laurentide Ice Sheet. Southwest of this limit, winds in central Alberta were from the west and northwest. Central Alberta was covered by parkland vegetation between 13.0 and 11.5 cal ka BP (Dyke *et al.*, 2004), probably reflecting the moderating influence of a relatively warm Pacific air mass. Subsequent stabilization of sand dunes across most of this area appears to be coincident with the replacement of parkland vegetation by boreal forest after 11.5 cal ka BP (Dyke *et al.*, 2004).

As the Laurentide Ice Sheet receded, anticyclonic circulation around the ice sheet receded with it. Dunes, active between 13.0 and 9.0 cal ka BP under anticyclonic winds, were influenced by cold off-ice winds and formed in shrub tundra to forest-tundra environments (Dyke *et al.*, 2004). These anticyclonic winds were replaced, time transgressively, by winds probably associated with the eastward-migrating influence of the more moderate Pacific air mass. Sand dunes were modified by winds from the northwest, and boreal forest replaced tundra vegetation. Stabilization probably occurred as a result of reduced winds and increased vegetation cover.

Dune reactivation in the Stony Plain area at ca. 6.2 ka is consistent with eolian deposition inferred by Westgate (1970) for the Stony Plain area. It is also synchronous with other dune activity along the grassland-parkland boundary in central Saskatchewan, which may have occurred in response to increased aridity and reduced vegetation cover during the mid-Holocene (Wolfe *et al.*, 2006).

LATE WISCONSINAN CIRCULATION

The concept of a cold-core anticyclone centred over the Laurentide Ice Sheet was conceptually proposed by Bryson and Wendland (1967), and subsequently modeled using AGCMs in the 1980s (Manabe and Broccoli, 1985; COHMAP

Members, 1988). Anticyclonic circulation around the perimeter of the ice sheet was generated by the Coriolis force, which causes air flowing away from a high pressure centre to be deflected in a clockwise direction in the northern hemisphere. Although support for an anticyclonic circulation pattern has been found from eolian features, evidence is mostly constrained to eastern North America (Thorson and Schile, 1995; French and Demitroff, 2001), and for later glacial positions (David, 1981a, 1988; Fillion, 1987; Krist and Schaetzl, 2001). In contrast, evidence from loess deposits in the midcontinent indicates that winds south of the Laurentide Ice Sheet were predominantly northwesterly and westerly during full glacial conditions (Muhs and Bettis, 2000; Bettis *et al.*, 2003).

This study provides a time constraint on glacial anticyclonic circulation in western Canada. Dune field orientations indicate that anticyclonic circulation is first noted at about 13.0 cal ka BP (Fig. 4B). This circulation may have extended no more than about 200 km from the Laurentide Ice Sheet, as dunes west of this limit show no evidence of transporting winds from the southeast. Although it is possible that morphological evidence of anticyclonic winds was destroyed by later westerly or northwesterly winds, this appears unlikely as many dune fields to the northeast clearly retain records of multiple wind directions prior to stabilization (Fig. 4B; David, 1981a). In addition, dunes dating before and after ca. 13.0 ka in central Alberta record paleowinds only from the west or northwest (Fig. 4A-B). These winds appear to have originated from air parcels funneled southward between the Cordilleran and Laurentide ice sheets.

Although AGCMs simulate a persistent glacial anticyclone between ca. 21 and 10 cal ka BP, surface winds were relatively weak along the southeastern margin of the ice sheet (Kutzbach *et al.*, 1998). Kutzbach and Wright (1985) suggest that south of the ice sheet at ca. 21 cal ka BP the strong winds from the northwest (interpreted from the eolian geological record) may have been enhanced by the existence of a "sag" at the Rocky Mountain front at the junction of the Cordilleran and Laurentide ice sheets. This topographic low may have allowed the escape of cold Arctic air accumulating to the north (Bryson and Wendland, 1967), thus inhibiting the westward flow of anticyclonic winds. The ice was thin where the Laurentide and Cordilleran glaciers met (Little *et al.*, 2001), and ice surface elevations in southwestern Alberta during the last glacial maximum were probably less than 1 500 m compared to greater than 3 000 m in the Rocky Mountains. Evidence from sand dunes for paleowinds from the northwest during early deglacial conditions (ca. 15.6 to 13.5 cal ka BP) in central Alberta lends further support to the hypothesis that winds during full-glacial conditions along the foothills may have been from the northwest.

The southwesterly limit of anticyclonic winds (Fig. 4B) also closely parallels the present-day mean frontal position of the mild Pacific air mass in western Canada (Bryson, 1966), suggesting that the limit may be defined by the eastern extent of excursions of the Pacific air mass into western Canada at ca. 13.0 cal ka BP. The suggestion that the influence of Pacific air could extend nearly as far eastward during the Late Wisconsinan as it does today is certainly plausible. Pacific air must have entered the Cordillera during full-glacial conditions, as this would be the primary source of moisture-laden air

responsible for snow and ice accumulation to form the Cordilleran Ice Sheet. In continuing eastward, moisture would be lost in the Cordillera and dry air would subsequently descend and warm, as it does today, providing little precipitation east of the Rockies. Consequently, ice at the confluence of the Laurentide and Cordilleran ice sheet was relatively thin. As the Laurentide Ice Sheet retreated, the frontal position of Pacific air mass would also extend eastward, until reaching its easternmost limit. Thus, glacial anticyclonic winds were not effectively generated in western Canada, and possibly western North America, until the Laurentide Ice Sheet was sufficiently east of the influence of westerly wind associated with the Pacific air mass (Fig. 4B).

As the Laurentide Ice Sheet retreated after ca. 13.0 cal ka BP, the extent of anticyclonic circulation retreated with it. This circulation probably extended farther from the ice sheet, and was stronger in winter than in summer as the polar front extending off the ice sheet was more dominant in winter (Bryson and Wendland, 1967; Kutzbach and Wright, 1985). The termination of anticyclonic circulation is probably closely connected in time with the collapse of the Laurentide Ice Sheet subsequent to 9.0 cal ka BP (Dyke *et al.*, 2003).

CONCLUSIONS

This study provides the first dating control on dune activity within the most northerly portion of the northern Great Plains. Unlike those in other parts of the Great Plains, these stabilized dune fields are mostly relict phenomena of a Late Wisconsinan deglacial environment.

The key conclusions of this study are:

- 1) Dune activity in central Alberta occurred in an ice-proximal tundra setting along the deglacial margins of the Cordilleran and Laurentide ice sheets between ca. 15.6 and 13.5 cal ka BP. Transporting winds were predominantly from the northwest, with katabatic winds funneled along the ice margins. Winds were probably also influenced, in part, by easterly incursions of Pacific air.
- 2) Anticyclonic circulation with transporting winds from the southeast influenced dune activity starting at about 13.0 cal ka BP, after the Laurentide Ice Sheet had retreated sufficiently east of the influence of the Pacific air mass. Anticyclonic circulation likely extended no more than 200 km from the Laurentide Ice Sheet.
- 3) As the Laurentide Ice Sheet retreated northeastward, between 13.0 and 9.0 cal ka BP, the anticyclonic circulation retreated with it. Transporting winds from the southeast were successively replaced by winds from the west and northwest as Pacific air migrated eastward to its approximate present-day limit.
- 4) Dune fields across the region probably stabilized in a time-transgressive manner from central Alberta to northeastern Saskatchewan, between about 13.0 and 9.0 cal ka BP, as boreal forest covered the region.
- 5) Dunes in the Stony Plain area, southwest of Edmonton, reactivated during the mid-Holocene along with other dune fields in the present-day prairie parkland ecozone of western Canada (Wolfe *et al.*, 2006).

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