Holocene dune activity and environmental change in the prairie parkland and boreal forest, central Saskatchewan, Canada

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Abstract:

Past eolian activity was reconstructed at four dune fields in the prairie parkland and boreal forest of central Saskatchewan to elucidate landscape response to environmental change. Optical ages from stabilized dunes in the boreal transition ecoregion indicate two episodes of activity. The first, between about 12.8 and 8.4 ka, corresponds to a period of early Holocene parkland and grassland cover following deglaciation and drainage after about 13.0 ka, and brief establishment of boreal forest. The second, between about 7.5 and 4.5 ka, corresponds to a period of mid-Holocene parkland-grassland cover. Optical ages from sand hills in the prairie parkland primarily record mid-Holocene activity, between about 7.5 and 4.7 ka, corresponding to a period of grassland cover, with some reworking continuing into the late Holocene. Although this area was deglaciated by about 13.5 ka, there is no evidence of early Holocene dune activity, suggesting that mid-Holocene activity may have reworked earlier deposits here. Consequently, much of the morphology and stratigraphy observed in these dune fields are associated with mid-Holocene activity, likely associated with increased aridity, and reduced vegetation cover at that time. This study provides the most northerly evidence of mid-Holocene dune reactivation on the Great Plains, lending support to the assertion that eolian activity was widespread at that time.

Keywords: sand dunes, northern Great Plains, mid-Holocene, paleoenvironments, optical dating

Introduction

Dune fields on the Great Plains of North America provide widespread evidence of past landscape response to environmental change (Muhs and Zárate, 2001). Radiocarbon and luminescence ages (Forman *et al.*, 1992; Madole, 1994; Muhs and Holliday, 1995; Wolfe *et al.*, 1995, 2000, 2001, 2002a, 2002b, 2002c; Muhs *et al.*, 1997a, 1997b; Stokes and Swinehart, 1997; Muhs and Wolfe, 1999; Hopkins and Running, 2000; Mason *et al*., 2004) have been used to develop chronologies of past dune activity and stability during the Holocene (*e.g.*, Dean *et al*., 1996; Forman *et al.*, 2001). Dune fields over a much of the Great Plains were active in the late Holocene, with multiple periods of eolian activity likely linked to repeated severe droughts (Forman *et al.*, 2001; Mason *et al*., 2004). Although mid-Holocene eolian stratigraphic records are more limited, they indicate activity at that time (Forman and Maat, 1990; Forman *et al*., 1995; Grigal *et al*., 1976 and Holliday, 1995) in response to heightened aridity in midcontinental North America (Dean *et al*., 1996). Although eolian sands were likely active over much of the Great Plains during the mid-Holocene the spatial extent is uncertain, as extensive eolian activity in the late Holocene may have removed much of the record (Muhs and Zárate (2001).

Muhs and Zárate (2001) hypothesize that sub-humid areas around the margins of the Great Plains may have a better record of mid-Holocene eolian activity because these areas were likely affected by mid-Holocene aridity but, unlike the drier Great Plains, were unaffected by reworking during the late Holocene. They further suggest that it would be worthwhile to conduct stratigraphic and geochronologic studies in these areas to see if the last period of eolian activity dates to the mid-Holocene.

More than 50 dune fields in the Canadian prairie ecozone collectively occupy over 9000 km^2 (Fig. 1). Many dune fields on the southern Canadian prairies, including Dundurn, Pike Lake, Elbow, Lauder and Brandon sand hills were repeatedly active during the last 5600 years (Wolfe *et al.*, 2002c). In the more southerly parts of the prairies, dune fields including Duchess, Elbow, Bigstick, Seward and Great sand hills, were active in the past few hundred years. Evidence of early Holocene activity, prior to about 8.5 cal ka BP, is found in the Dundurn and Pike Lake areas of south-central Saskatchewan. Evidence of mid-Holocene activity, however, is mostly absent. Given that the mid-Holocene was likely the most persistently arid period on the prairies since deglaciation (Ritchie and Harrison, 1993; Vance *et al.*, 1995), it is reasonable to expect that dunes were active at that time. At present, however, mid-Holocene dune activity on the Canadian prairies is only in the Lauder sand hills of southwestern Manitoba (Running *et al.*, 2002).

Wolfe *et al.* (2002c) suggest mid-Holocene eolian deposits may be preserved in stabilized dune fields in the prairie parkland and boreal forest transition ecoregions (Fig. 1). Both the grassland and parkland boundaries were north of their present-day limits during the mid-Holocene (Vance *et al.*, 1995). It follows that, with increased aridity and reduced vegetation cover, dune fields along the present-day northern limit of the grassland may have been active in the mid-Holocene. Because most of these dune fields are partly or completely stabilized, they may retain stratigraphic records from that time. In this study, we develop a chronology of Holocene dune activity in central Saskatchewan (Fig. 1) and discuss it in relation to past environmental change.

Methods

Dune stratigraphy was examined in roadcuts and pits and, in the case of one site, from 7-cm diameter Geoprobe core samples. Sediment samples were collected to determine soil Munsell colour, grain size and organic carbon content. Organic carbon content was determined on pulverized whole sample splits using a LECO CR-412 carbon analyzer, based on carbon released at a combustion temperature of 840°C. Geochemical and mineralogical analyses used pulverized (63-500 µm diameter) sediment splits following the methodology of Muhs *et al.* (1995).

Fourteen samples were collected for optical dating. 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 exciting them with near-infrared (1.4 eV, ~880 nm) photons and measuring the violet (3.1 eV, 400 nm) photons emitted in response. The multiple-aliquot 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 1 and 2).

A literature search was conducted for radiocarbon ages from paleosols, charcoal or detrital organic samples in association with eolian deposits of interest to this study. The quantity and character of organic matter in paleosols may provide age estimates for soil development between episodes of eolian activity. Organic matter in paleosols at the interface between eolian deposits and non-eolian sediment substrates may provide limiting ages for eolian deposition. Eleven relevant radiocarbon ages (Table 3) are reported in Morlan *et al.* (2001), with supporting details found in Christiansen (1970) and Mott (1973).

Climatic variables were derived from data obtained from Environment Canada (1985a, 1985b, 1993). Modern vegetation zonations are discussed in the context of ecozones and ecoregions as defined by the Ecological Stratification Working Group (1996; Fig. 1).

Post-glacial and Holocene environmental change

Deglaciation

The northern Great Plains were ice covered during the late Wisconsin glacial maximum with the exception of a few ice-free upland regions in the southernmost parts of Alberta and Saskatchewan (Fig. 1 inset, and Dyke *et al.*, 2003). As a result, source deposits for sand dunes within the glacial limit are mainly glaciolacustrine or glaciofluvial outwash sediments, particularly sandy deltas (David, 1977). In addition, the timing of deglaciation and subsequent drainage of proglacial lakes and rivers provides maximum limiting ages for dune fields (Fig. 2).

The Laurentide Ice Sheet retreated northeastward, such that the maximum limiting ages of source-sediment deposits diminish in that direction. The Manito and North Battleford areas were deglaciated between about 14.1 and 13.5 cal ka BP. The Nisbet area was deglaciated at about 13.5 cal ka BP, but was still inundated by water until about 13.0 cal ka BP. Similarly, most of Fort à la Corne remained inundated until about 12.7 cal ka BP, when the western shoreline of glacial Lake Agassiz was positioned east of this area (Dyke *et al.*, 2003).

Holocene environmental change

The few paleoenvironmental proxy sites in the study area lack strong chronological control. Nevertheless, paleolimnological studies in the prairie ecozone provide a broad view of Holocene climate change. The vegetation history within glaciated North America based on macrofossil, mammal and pollen sites (Dyke *et al.*, 2004) also provides regional context in the form of biome maps at 1000-year time intervals since the Last Glacial Maximum (ca. 21.4 cal ka BP).

Pollen stratigraphy of a core from Coubeaux Lake (Lake A; Mott, 1973) in the Nisbet sand hills suggests that a spruce (*Picea*)-dominated boreal forest followed the retreating ice. A basal age of 15.0 to 12.8 cal ka BP (11,560 ± 640 yr BP; GSC-648) is in keeping with the regional timing of deglacation (Fig. 2) and does not appear to be anomalously old, though it may be affected by dead carbon derived from calcareous sediments (Mott, 1973 and pers. comm., 2004). Pollen assemblages indicate a decline in boreal forest following invasion by grassland, with a brief interval of birch (*Betula*). Grassland pollen assemblages are comparable to those found in modern treeless grassland and, with the possible exception of aspen (*Populus*), the Prince Albert area was probably open grassland (Mott, 1973). Grassland was followed by a steady increase in mixed forest, culminating in a dominance of jack pine (*Pinus banksiana*).

According to Dyke *et al* . (2004), the receding ice sheet may initially have been replaced by a grassland biome along its southern boundary in the northern Great Plains, between 21.4 and 15.6 cal ka BP (Fig. 2). Southern Saskatchewan may have been occupied by grassland at about 15.6 cal ka BP. However, a northwestward migrating boreal forest biome may have initially colonized much of the deglaciated terrain in southern and central Saskatchewan between about 15.6 and 13.0 cal ka BP, including most of the study area (Fig. 2). Post glacial conditions on the prairies are considered to have been cooler and moister than present, as indicated by regional evidence of open spruce woodland (Yansa and Basinger, 1999) and full-basin, freshwater conditions of presently-saline prairie lakes (Lemmen and Vance, 1999). An abrupt change from freshwater to saline conditions marks the transition to an arid prairie climate in the early Holocene. Between about 13.0 and 10.2 cal ka BP, the boreal forest biomes across central Saskatchewan were replaced by parkland, and subsequently by grassland (Dyke *et al.*, 2004). This transition was followed by a period of peak aridity in the mid-Holocene, which was marked by saline and dry lakes in the prairie ecozone (Lemmen and Vance, 1999). The mid-Holocene was evidently an interval of severe aridity across the southern Canadian prairies, with regional water-level reductions (Remenda and Birks, 1999), frequent and severe droughts (Vance *et al*., 1992) and a northward advance of grassland (Vance *et al.*, 1995). The grassland biome was at its northern maximum extent as early as 9 cal ka BP, covering most of central and southern Saskatchewan (Dyke *et al.,* 2004). At this time, the Manito and North Battleford sand hills existed within the grassland biome, while the Nisbet and Fort à la Corne sand hills resided on the northern grassland and parkland margins.

Cooler climatic conditions occurred after the mid-Holocene. However, cooling appears to have been time transgressive across the prairies, occurring earlier in southern Alberta (about 7 to 5.5 cal ka BP) than in southern Manitoba (about 4.5 to 3 cal ka BP). In southern Saskatchewan, moister conditions are evident between about 6.3 and 4.4 cal ka BP (Vance *et al.*, 1995). A local signal of late Holocene climate is derived from Redberry Lake (van Stempvoort *et al.*, 1993), approximately midway between North Battleford and Prince Albert. A relatively dry and/or warm period occurred between 2400 and 1400 cal BP, with comparatively humid and/or cooler conditions thereafter, but with warmer and/or drier conditions occurring from about 900 to 800 and in the last 500 cal BP. Multi-proxy lake records from the southern Canadian prairies and the northern and central Great Plains of the United States suggest that even the last 1000 years have been interspersed by droughts that were more frequent and of greater magnitude than those in historic times (Lemmen and Vance, 1999; Fritz *et al.*, 2000; Yu *et al.*, 2002; Mason *et al*., 2004).

Modern ecoregions and climate

The four dune fields studied occur along a 450 km-long west-to-east transect at a latitude of about 53° N (Fig. 1). The two westernmost dune fields reside in a narrow strip of aspen parkland. The Manito sand hills lie close to the northern limit of the grassland boundary and the North Battleford sand hills lie close to the southern limit of the boreal forest. In comparison, the Nisbet and Fort à la Corne areas reside in the boreal transition ecoregion of the boreal forest. Hogg (1994, 1997) has found a strong correlation between vegetation and climate along this grassland - forest boundary of western Canada. Present-day boundaries closely correspond to climatic moisture regimes, in particular with annual precipitation minus potential evapotranspiration, using the Jensen-Haise method of calculating potential evapotranspiration (Jensen *et al.*, 1990). The southern boreal forest - parkland boundary closely correlates with the zero isoline of P-PE, and the southern parkland - grassland boundary closely correlates with the -150 mm isoline (Hogg and Hurdle, 1995). This relation also holds well within the study area.

Climatic characteristics for the city of North Battleford provide suitable indications of conditions in the Manito and North Battleford sand hills. The area has a humid moisture regime (ratio of precipitation (P) to potential evapotranspiration (PE) = 0.77) though nearly sub-humid (P/PE < 0.75). The climate of Prince Albert is representative of the Nisbet and Fort à la Corne sand hills, and has a humid moisture regime (P/PE = 0.91) with a slight moisture deficit (P-PE = -41 mm). Notable differences in the climate of these two localities include cooler seasonal and annual air temperatures and higher annual precipitation at Prince Albert, resulting in a shorter growing season and greater available moisture than in North Battleford. Although record droughts were encountered 2001-02, these areas are less prone to droughts of the southern Canadian prairies. Much of the area northeast of Prince Albert was settled in the 1930s by farmers migrating from the drought-ridden prairies.

Geomorphology and vegetation

Manito and North Battleford sand hills

The Manito sand hills lie at the western edge of the study area and cover 480 km^2 (Fig. 3a). They are elongate sand ridges with blowout hollows and windpits, similar to the Minot (Muhs *et al.*, 1997a). Dune activity is confined to drier south-facing slopes of some elongate ridges. Source sediments are glaciolacustrine deposits (David, 1977). Most of the flora are grassland species, except for 29 species normally associated with boreal forest (approximately 100 km to the north) and 17 species normally associated with drier grasslands (Thorpe and Godwin, 1993). Stands of trembling aspen *(Populus tremuloides)* occur on stabilized dunes, particularly on north-facing and lower slopes (Thorpe and Godwin, 1993). Balsam poplar (*Populus balsamifera*) and river birch (*Betula occidentalis*) occur on moist lowland sites typically together with a few stands of white birch *(Betula papyrifera*). Creeping juniper (*Juniperus horizontalis*) is a dominant prostrate shrub on lower stabilized slopes.

The North Battleford sand hills consist of several discrete zones along the Battle River that together comprise 480 km^2 (Fig. 3a). Here, too, the dunes are elongate sand ridges marked with blowout hollows (David, 1977). Eolian activity is restricted to the south-facing slopes of ridges and blowouts. The dune sands were derived from sandy glaciolacustrine deposits (Craig, 1952). The flora in the North Battleford sand hills are also similar to those of the Manito area, being comprised of grassland and parkland species. Trembling aspen is the dominant tree, with river birch and balsam poplar occurring in moist areas (Houston, 1997). Creeping juniper is common on lower slopes of stabilized dunes. Although boreal conifers are absent in the sand hills, white spruce (*Picea glauca)* is present on north-facing slopes of the North Saskatchewan River valley (T. Hogg, pers. comm., 2004).

David (1977) suggests that the dune ridges at Manito and North Battleford were derived from reworked heads and arms of elongate parabolic dunes, such that only parts of the arms remain. This interpretation is significant, as it implies an initial period of dune formation followed by intervals of partial reactiviation. The orientations of the elongate ridges range between 112° and 125° SE (Fig. 3a), similar to those of other dune fields in the area (Pfeiffer and Wolfe, 2002) and indicative of dune-forming winds from the northwest. The sand-rose for North Battleford, constructed using the method of Fryberger and Dean (1979) indicates a high wind energy with high directional variability and a bimodal-to-complex directional wind regime. This complex wind regime may be attributed, in part, to the location of the meteorological station within the North Saskatchewan River valley, where the presence of topographically steered winds result in winds from the northeast and southwest being under represented.

As noted above, the Manito and North Battleford dune fields are mostly stabilized except for some south-facing slopes of elongate ridges and isolated blowouts. Under the present-day wind regime and moisture availability at North Battleford, dunes were modelled as inactive using the Lancaster mobility index (Lancaster, 1988), and this is true as well of most drought years (Wolfe, 1999). In general, dune fields in the grasslands are modelled as having active crests, whereas those in parkland and boreal regions are modelled as inactive. Wolfe and Lemmen (1999) suggest that, in the grasslands, aspect plays an important role in maintaining differences in morphology between north-facing and south-facing slopes on active blowouts, because south-facing slopes are drier and less steep than north-facing slopes. Similarly, aspect coupled with disturbance by grazing probably plays an important role in maintaining activity on south-facing slopes for some dunes within the parkland.

Nisbet and Fort à la Corne sand hills

The Nisbet sand hills reside along the north side of the North Saskatchewan River valley, north of Prince Albert, and cover 130 km^2. The surrounding terrain is level to gently sloping. The landscape is comprised of plains and some hummocky upland, underlain by till, glaciolacustrine and glaciofluvial sands (Saskatchewan Research Council, 1987a). Source sediments for the dunes are sandy glaciolacustrine deltas (David, 1977). The Nisbet sand hills are comprised of transverse dune ridges with wavelengths of about 1 km, superimposed by parabolic dunes trending 108° ESE (Fig. 3b). The dunes are stabilized by boreal and parkland vegetation (Rowe, 1959). In order of abundance, trees include trembling aspen, jack pine, balsam poplar, black spruce (*Picea mariana*), white spruce, tamarck (*Larix laricina*), white birch and balsam fir (*Abies balsamea*). Many parts of the dunefield have been logged and replanted with white spruce and jack pine.

The Fort à la Corne sand hills are the largest and easternmost dunefield, covering 1210 km^2 (Fig. 3b). The dunes were derived from a large glaciolacustrine delta (Saskatchewan Research Council, 1987b). Stabilized parabolic dunes trending 100° ESE occur over a series of north-south trending ridges that are separated by deeply incised stream valleys terminating at the North Saskatchewan River. Although similar in morphology to transverse dunes, the ridges probably originate from fluvial channels that eroded into the deltaic surface and drained southward into the North Saskatchewan River basin (Saskatchewan Research Council, 1987b).

The forest cover in the Fort à la Corne area is dominated by jack pine, trembling aspen and white spruce. The area is susceptible to forest fire, and nearly half of it has been burned since 1967, although there is no evidence of fire-induced dune reactivation.

Parabolic dune orientations in the Prince Albert area range between 117° and 100° SE

(Fig. 3b) and become less southerly toward the east. The sand-rose for Prince Albert indicates a high energy unimodal wind regime with a resultant drift direction of 138° SE, which is similar to, but more southerly than, the dune orientations. The dune fields are modelled as inactive under the present-day wind and moisture regimes, which is consistent with present observations.

Stratigraphy and chronology

Manito sand hills

A road cut through a northwest-southeast trending dune ridge exposes sand in the arm of an elongate parabolic dune (site 50a; Fig. 4a) with blowouts on the south-facing slope. The ridge is about 18 m high and 150 m wide. Sampling was conducted by excavating the exposed upper 12 m of the section and also by augering below the exposed section and along the southern slope of the dune away from the road cut.

The section exposed olive brown to light olive brown (2.5Y 5/4 to 6/4 moist) eolian sands with two poorly developed dark greyish brown (10YR 4/2 moist) Ah/AC/C buried soil profiles in the top two metres (Fig. 4a). The eolian sands observed here, and at all sites, are mostly massive, sub-angular to rounded, fine- to medium grained sands with low-angle wind-ripple cross-strata preserved locally. The sands are nearly devoid of organic carbon, but the lowermost paleosol recorded only a slight increase (0.2 %) in organic carbon. Calcium contents were also uniformly low (Fig. 4a). In the lower portion of the section, the sands show wavy, horizontal stratification. Olive brown (2.5Y 4/4 moist) sand layers, 1 to 2 cm thick, are separated by olive coloured (5Y 5/4 moist) sand layers about 3 to 5 cm thick. The olive brown layers are slightly finer (6.4 % < 63 μm) than the other layers (4.2 % < 63 μm), but the layers are otherwise similar in geochemistry and mineralogy. These layers appear to be akin to pedogenic or pedo-petrogenic lamellae, as reviewed by Rawling (2000) and as observed elsewhere on the Canadian prairies (Coen *et al*., 1966 and Running *et al*., 2002) in addition to more southerly portions of the Great Plains.

Optical ages of three samples between 15 and 7 m depth in the dune ridge indicate that most of the sand was deposited and buried between about 7 to 5 ka (SFU-O-219, 220, 221; Fig. 4a). A fourth sample from the uppermost paleosol dates to about 2.6 ka (SFU-O-218). A final sample, collected mid-way downslope on the southern slope of the ridge at a depth of 4.5 m, was undatable (SFU-O-222) as it was found to contain grains that had been inadequately exposed to sunlight prior to burial. Sand at 3 m depth in the auger hole contains more fines (13.7% < 63 μm) and more feldspar minerals than sands higher in the section. The inadequate exposure to sunlight and change in sedimentology indicates that the lower sand is probably glaciofluvial or glaciolacustrine sediment.

North Battleford sand hills

The exposure in the North Battleford sand hills is in a road cut through an elongate dune ridge (site 46; Fig. 4b). The ridge is 5 m high and 15 m wide. Most of the section is composed of light olive brown (2.5Y 5/4 moist) sand, although multiple paleosols similar to those found at the Manito site occur in the upper 2 m. Wavy, horizontally stratified sand layers interpreted as lamellae, were observed below 5 m depth. Two sediment samples were nearly devoid of organic carbon, and calcium contents were similarly low (Fig. 4b). Sand at 6 m depth returned an optical age of about 6.5 ka (SFU-O-216) and a sample from a paleosol at 1.2 m depth returned an age of about 5.6 ka (SFU-O-217).

Nisbet sand hills

The sample site in the Nisbet sand hills is a northwest-southeast trending, stabilized parabolic dune, 8 m high and 100 m in circumference, superimposed on a larger northeast-southwest trending transverse dune ridge. Stratigraphic interpretation and sampling were conducted at a 3-m deep pit in the head of the dune and a 5-m deep auger hole in the deflation hollow (Fig. 4c). An optical age from the head of the dune is expected to provide the most recent time of dune activity, whereas one from the deflation hollow may provide an earlier age of activity. This sampling strategy has been successful in bracketing the timing of past dune activity elsewhere on the Canadian prairies (Wolfe *et al.*, 2001).

Neither of the sites contained buried soils, although humic layers were thicker than the parkland sites and B-horizons were present (15 and 60 cm thick, respectively), possibly indicating longer periods of stability. Sand in the dune head is well-sorted, and contains less than 5 % fines. The upper 1.5 m is olive yellow (2.5Y 6/6 moist) and mottled by oxidization, whereas the underlying sand is olive brown (2.5Y 4/4 moist) and less oxidized. By comparison, sands from the deflation hollow contain slightly more fines (6 to 7 % < 63 μm). These sands are also somewhat oxidized, though darker in colour at depth. The organic carbon and calcium contents are uniformly low at both sites (Fig. 4c).

As expected, the age of sand deposition at the dune head is younger than in the deflation hollow; the sample from 1.2 m depth in the dune head returned an age of about 5.2 ka (SFU-O-214), whereas the age from the sample collected at 3.0 m depth in the deflation depression is about 11.8 ka (SFU-O-215).

Fort à la Corne sand hills

Three sample sites in the Fort à la Corne sand hills were located on the summit of a large (20 to 30 m high) north-south trending ridge containing numerous stabilized parabolic dunes on the western side (Fig. 4d). The eastern side of the ridge is steeply sloping, and an incised stream occurs along the base. The first site (site 5a) was a 3-m deep pit on the summit of the ridge in the head of a stabilized parabolic dune; the second site (FAC01-13) was a 16-m deep Geoprobe core in a small swale behind the head; and the third (site 5b) was a 6-m deep auger hole in the deflation hollow. The forested ridge was burned in 1995, and was subsequently cleared and replanted with spruce and jack pine. Tilling and tree planting have heavily disturbed or removed the surface soil.

The stratigraphy here differs from that at the other dune fields, as paleosols containing B-horizons were encountered at about 4 m depth in the deflation hollow and in the intermediate swale. Sediment grain size is similar to that at other sites, with 3 to 9 % of sediment < 63 μm in diameter. Moist sands are predominantly olive brown to light olive brown (2.5Y 4/4 to 5/6) and, in places, are light yellowish brown (10YR 6/4). High-angled cross-beds, underlain by sub-horizontally laminated sands, occur between 6 and 13 m depth. In addition, LOI analyses identified higher organic carbon contents (between 0.5 and 0.8 %) in the lower strata, due to detrital lignite. Calcium content ranges between 2 and 4%, and is generally higher in sands below 6 m depth.

These observations indicate that the upper sands at Fort à la Corne are eolian, but the lower sands may be deltaic. Optical ages confirm this interpretation. A sample from 2 m depth in the dune head returned an age of about 6.8 ka (SFU-O-212), whereas a sample at 3.2 m depth in the deflation hollow, just above the buried soil, retuned a similar age of about 6.6 ka (SFU-O-240). A sample below the buried soil at 5.5 m depth returned an age of about 9.8 ka (SFU-O-

213). Two samples from 9 and 16 m depth in the intermediate swale were undatable (SFU-O-241 and 242) because not all the sample grains had been exposed to adequate sunlight prior to burial.

Discussion

Regional eolian chronology

Optical ages obtained from the Manito and North Battleford sand hills indicate dune activity primarily in the mid-Holocene (7 to 5 ka) in the parkland ecoregion. Ages from the Nisbet and Fort à la Corne sand hills indicate activity in the early and late Holocene (12 to 10 ka and 7 to 5 ka) in the boreal transition ecoregion. Additional insight into the eolian chronology and paleoenvironments may be derived from published radiocarbon ages (Table 3) and paleo biome distributions (Dyke *et al.*, 2004). Most of the radiocarbon ages are from bulk organic matter in paleosols, which may be conservatively interpreted as providing maximum limiting ages for the overlying eolian sands and minimum limiting ages for the parent eolian sand and any underlying deposits (Muhs *et al.*, 1997).

Figure 5 summarizes eolian chronology and paleoenvironments in the study area. There are no radiocarbon-dated deposits in the Manito and North Battleford area, and thus the eolian chronology is derived only from our optical ages. One major phase of dune activity is identified between about 7.6 to 4.7 ka (at 2σ analytical uncertainty), coinciding with the mid-Holocene period of grassland cover in the region. Dune construction appears to be associated primarily with this phase, forming the parabolic dunes observed in the area today. Much of the sand in both dune fields dates to this period (Fig. 5a). This is followed by a period of increasing stability in the late Holocene, occurring in a parkland-dominated biome. Sporadic eolian activity in the late Holocene resulted in local reworking of mid-Holocene dunes. At both sites, reworking appears to be confined to the top few metres of the sands (Fig. 4 a and b).

There is presently no evidence of eolian activity or stability before 7.6 ka in the western part of the study area. However, the deglacial and biome reconstructions indicate that eolian activity could have occurred following deglaciation, at about 13.5 ka. It is uncertain whether any dunes that formed at that time would have stabilized prior to mid-Holocene dune construction or remained active throughout the early Holocene.

Two active and two stable phases are identified in the Nisbet and Fort à la Corne regions (Fig. 5b). An initial phase of early Holocene dune activity occurred between about 12.8 and 8.4 ka (at 2σ analytical uncertainty), during a transition from boreal to parkland-grassland dominated biomes. This activity post-dates deglaciation and drainage of the area by several thousand years (Fig. 2), and occurs when the shoreline of glacial Lake Agassiz was east of the sand hills. The optical ages probably record times of dune activity closer to the termination of eolian activity than to the onset. Dune activity may have been initiated by strong off-ice winds, resulting from a high pressure centre over the Laurentide Ice Sheet (David, 1981). The absence of optical ages in the Nisbet and Fort à la Corne sand hills, and the abundance of radiocarbon ages elsewhere in the region, signifies the first stable phase between 9.5 and 7.5 ka. A stable phase is further inferred from the paleosol at Fort à la Corne dating sometime between 9.8 and 6.7 ka (Fig. 4d). The onset of dune stabilization may be coincident with the drainage of glacial Lake Agassiz, but stability may have been relatively short-lived as the period between 9 and 7 ka coincides with maximum aridity and the northernmost extent of grassland advance in the region. Optical ages identify a second phase of eolian activity between 7.5 and 4.8 ka. Again, these ages are probably closer to the termination of dune activity in the mid-Holocene, than they are to the onset, due to continued reworking of sand during dune migration. Dune activity in the Nisbet area probably terminated later than at Fort à la Corne, due to longer persistence of the drier grassland-parkland conditions there.

The onset of a final stable phase by about 5 ka in the Nisbet and Fort à la Corne regions appears to have been synchronous with the development of parkland-boreal vegetation and less arid conditions in the late Holocene. Paleosols dating to this interval suggest that dunes were mostly stable between 5 and 4 ka, but became locally active again thereafter. Localized eolian activity probably resulted from forest fires, which may have occurred frequently in the jack pine dominated forests common to the region. Late Holocene charcoal from the Holbein sand hills, west of Prince Albert (Figs. 3b and 5b), suggests that fire may have initiated local eolian activity there.

Implications for past environmental conditions

With the recognition that the most recent phase of eolian activity in the Nisbet and Fort à la Corne sand hills occurred between 7.5 and 4.8 ka, the dunes of this area are considered to be relict, mid-Holocene features. Dune orientations, between 117° and 100° SW, record mid-Holocene transporting winds. These transport directions are similar to, but slightly more easterly, than those of modern winds at Prince Albert (138° SW). The orientations of parabolic dunes in the Manito and North Battleford areas likely also record mid-Holocene wind directions, although there is evidence of late Holocene and present-day reworking of these dunes. The orientations range between 112° and 125° SW (Fig. 4), indicating a more southerly component to the mid-Holocene transporting winds than of modern winds in the eastern part of the study area. In addition, David (1977) indicates that reworking has resulted in a northeastward displacement of the dunes, suggesting that late Holocene winds in this area were more easterly than were the mid-Holocene winds. These differences in wind directions may be due to an increased influence of the Pacific airstream over the northern Great Plains during the mid-Holocene (Dean *et al*., 1996)

Evidence of dune activity between 7.5 and 4.8 ka across central Saskatchewan lends support to the interpretation that the mid-Holocene climate was significantly more arid than the present climate, resulting in dune reactivation across much of the Great Plains (Dean *et al*., 1996; Forman *et al*., 2001). The Nisbet and Fort à la Corne areas presently reside in the boreal transition ecoregion under a humid climate (P/PE = 0.91 and P-PE = -41 mm). According to Dyke *et al.* (2004) these areas were near the parkland-grassland boundary during the mid-Holocene, although Mott (1973) suggests that the Nisbet Sand Hills may have been dominated by grassland. A change in ecoregions from boreal transition to the grassland-parkland boundary suggests a reduction in available annual moisture of at least 100 mm during the mid-Holocene (from P-PE = -41 in Prince Albert to -150 mm along the parkland-grassland boundary) accompanied by sub-humid climate conditions ($0.65 \leq P/PE < 0.75$). By comparison, mid-Holocene dune activity in the Manito and North Battleford areas occurred in association with grassland cover (Fig. 5a), whereas these areas presently reside in a grassland-parkland transitional zone. This change would have been accompanied by a reduction in available moisture of at least 50 mm (from a present P-PE = -109 mm in North Battleford today to -150 mm or lower within the grassland ecoregion), corresponding to sub-humid ($0.65 \leq P/PE < 0.75$) or dry sub-humid ($0.50 \leq P/PE < 0.65$) conditions. Mid-Holocene dune activity may have also reworked earlier deposits, implying that the dunes were fully active during that time. Fully active dunes on the North American Great Plains today occur where annual P/PE values are below 0.35

(Muhs and Holliday, 1995). Thus, dune fields in this area were likely subjected to frequent and severe droughts in the mid-Holocene, resulting in semi-arid conditions comparable to those presently experienced during the most severe drought years in the southern Canadian prairies (Wolfe, 1997).

Conclusions

This study provides the most-northerly evidence of mid-Holocene dune reactivation on the Great Plains of North America, confirming earlier hypotheses that dune fields on the margins of the Great Plains may retain eolian records from this time (Muhs and Zárate, 2001; Wolfe *et al*., 2002c). This study further lends support to the assertion that dune fields across much of Great Plains during were active during the mid-Holocene (Dean *et al*., 1996; Forman *et al*., 2001).

Key conclusions of this study are:

1. Optical ages from stabilized sand dunes in the Nisbet and Fort à la Corne sand hills within the southern boreal forest, indicate two distinct periods of past dune activity. The first was in the early Holocene (ca. 12.8 to 8.4 ka) and the second was in the mid-Holocene (ca. 7.5 to 4.5 ka). Both periods are associated, at least in part, with parkland-grassland vegetation cover.
2. Optical ages from partly active sand dunes in the Manito and North Battleford sand hills indicate mid-Holocene dune activity (7.6 to 4.7 ka) associated with a period of grassland cover, as well as late Holocene reworking of dunes under a parkland cover.
3. Mid-Holocene dune activity in central Saskatchewan was likely related to a period of

increased aridity, and associated reduction in vegetation cover via a northward migration of grassland and parkland biomes.

4. Given that early Holocene deposits are found in the Nisbet and Fort à la Corne sand hills, failure to uncover comparable deposits in the nearby Manito and North Battleford sand hills suggests that mid-Holocene dune activity may have reworked older deposits there.

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Figures

Fig. 1. Location of dune fields in the study area and the surrounding region. Sand hills referred to in text are labeled in the figure. The inset map depicts the study area (boxed) and the northern Great Plains (shaded) in relation to the North American Great Plains. Also shown in the inset is the late Wisconsin glacial ice limit (WGL) at ca. 21.4 cal ka BP (after Dyke *et al.*, 2003).

Fig. 2. Glacial limits and positions of pro-glacial lakes during retreat of the Laurentide Ice Sheet in southern and central Saskatchewan (from Dyke *et al.*, 2003). Distribution of dune fields is also shown.

Fig. 3. Optical dating sample locations for A) North Battleford and Manito sand hills and B) Nisbet and Fort à la Corne sand hills. Also shown are stabilized parabolic dune orientations (from Pfeiffer and Wolfe, 2002), locations of dunes with active ridges on south-facing slopes and the modern sand roses.

Fig. 4. Stratigraphy and optical ages of sand dunes for A) North Battleford, B) Manito, C) Nisbet and D) Fort à la Corne sand hills.

Fig. 5. Chronology of dune activity and stability for A) North Battleford and Manito sand hills and B) Nisbet and Fort à la Corne sand hills and surrounding region. Analytical uncertainty in the optical and calibrated radiocarbon ages are shown at 2σ. Time scales of "ka" for optical ages (before ~ 2000 AD) and "cal ka BP" for radiocarbon ages (before 1950 AD) are used, with the

assumption that the ~ 50 year difference between reference points is not significant. The time bars representing dune activity and stability in the chrono-stratigraphy are placed at the mid-points of the derived ages, although they could potentially occur anywhere within the 2σ uncertainty age ranges. The paleoenvironments are derived from the paleo-biome interpretations of Dyke *et al.* (2004). The eolian phases represent the dominant state of dune activity in the area at that time, although shorter periods of dune activity or stability have occurred within them.

Table 1. Site name, laboratory number, sample depth, concentrations of radioisotopes used for dosimetry calculations, and water content for each sample.

Site	Lab Number	Depth (m)	K (%), ± 5%		Th ($\mu g.g^{-1}$)[c]	U ($\mu g.g^{-1}$)[d]	Water Content
			sample	surroundings[b]			
Nisbet							
ST-6b	SFU-O-214	1.30	1.24	1.20	3.1	0.94	0.040 ± 0.004
ST-6a	SFU-O-215	3.00	1.24	1.20	3.8	0.90	0.061 ± 0.004
Fort à la Corne							
ST-5a	SFU-O-212	2.00	1.11	1.09	4.9	1.00	0.037 ± 0.003
ST-5b	SFU-O-213	5.40	1.15	1.09	4.0	0.95	0.059 ± 0.015
ST-5b	SFU-O-240	3.25	1.14	1.07	1.6	0.71	0.052 ± 0.018
FAC01-13	SFU-O-241	15.85	—	—	—	—	0.077 ± 0.031
FAC01-13	SFU-O-242	8.80	—	—	—	—	0.061 ± 0.050
North Battleford							
ST-46	SFU-O-216	5.85	1.20	1.18	2.3	0.90	0.059 ± 0.005
ST-46	SFU-O-217	1.25	1.27	1.16	3.0	0.90	0.044 ± 0.004
Manito Lake							
ST-50a	SFU-O-218	1.80	1.31	1.26	3.3	0.90	0.045 ± 0.005
ST-50a	SFU-O-219	7.00	1.33	1.31	3.6	0.88	0.056 ± 0.010
ST-50a	SFU-O-220	10.00	1.34	1.26	3.5	0.91	0.056 ± 0.008
ST-50a	SFU-O-221	14.45	1.29	1.21	2.9	0.82	0.048 ± 0.003
ST-50a	SFU-O-222	4.40	1.47	—	4.6	1.31	0.245 ± 0.030

[a]Sample depth beneath ground surface.
[b]Average K content for samples collected 30 cm below and above the main sample. That these are systematically lower than those for the main samples reflects on the consistency of the analyzing laboratory.
[c]Th contents from neutron activation analyses.
[d]U contents from delayed neutron analyses.
[e]Water content = (mass water)/(dry mineral mass); water contents are the as-collected values and are an average of three samples.

Note: Rb contents were approximately 40 $\mu g.g^{-1}$.

Table 2. Cosmic ray dose rate ($\dot{D}_c$), total dose rate ($\dot{D}_T$), equivalent dose ($\dot{D}_e$), and optical age for each sample.

	$\dot{D}_c$ Gy/ka[a]	$\dot{D}_T$ Gy/ka[b]	$\dot{D}_e$ Gy	Uncorrected Optical age ka[c]	Fading rate %/decade[d]	Delay days[e]	Corrected Optical age ka[f]
Nisbet							
SFU-O-214	0.18	2.64	11.2 ± 0.4	4.24 ± 0.19	(4.15 ± 0.27)	34	5.23 ± 0.25
SFU-O-215	0.14	2.64	24.9 ± 0.6	9.42 ± 0.34	4.15 ± 0.27	38	11.8 ± 0.5
Fort à la Corne							
SFU-O-212	0.16	2.64	14.6 ± 0.4	5.53 ± 0.21	(3.99 ± 0.32)	30	6.81 ± 0.30
SFU-O-213	0.10	2.55	20.1 ± 0.52	7.89 ± 0.52	3.99 ± 0.32	38	9.75 ± 0.69
SFU-O-240	0.14	2.36	12.5 ± 0.22	5.30 ± 0.22	(3.99 ± 0.32)	13	6.62 ± 0.31
SFU-O-241	—	—	—	—	—	—	—
SFU-O-242	—	—	—	—	—	—	—
North Battleford							
SFU-O-216	0.10	2.47	12.8 ± 0.3	5.18 ± 0.19	4.33 ± 0.32	30	6.51 ± 0.28
SFU-O-217	0.18	2.65	11.8 ± 0.4	4.46 ± 0.19	(4.33 ± 0.32)	30	5.58 ± 0.27
Manito Lake							
SFU-O-218	0.16	2.70	5.60 ± 0.41	2.08 ± 0.16	(4.44 ± 0.29)	44	2.55 ± 0.21
SFU-O-219	0.09	2.66	10.6 ± 0.2	3.99 ± 0.13	(4.44 ± 0.29)	49	4.96 ± 0.19
SFU-O-220	0.06	2.64	12.8 ± 0.5	4.86 ± 0.23	(4.44 ± 0.29)	49	6.07 ± 0.31
SFU-O-221	0.04	2.51	13.9 ± 0.4	5.54 ± 0.22	4.44 ± 0.29	51	6.94 ± 0.31
SFU-O-222	—	—	—	—	—	—	—

[a]Dose rate from cosmic ray radiation calculated using present burial depth.
[b]Total dose rate: $\dot{D}_T = \dot{D}_c + \dot{D}_{\alpha,ß,\gamma}$ is the dose rate due to α, ß, and γ radiation.
[c]Optical ages *not* corrected for anomalous fading.
[d]Fading rates calculated from data collected between 1.7 and 641 days after laboratory irradiation as described by Huntley and Lamothe (2001) method 'b'. Figures in brackets are assumed based on values for other samples from the same site with similar expected mineralogy.
[e]Delay is the time between laboratory irradiation and equivalent dose measurement.

[f]Optical ages, corrected for anomalous fading using the data listed in the previous two columns, are relative to ~ 2000 AD.

Notes: past water content was assumed to be 4.5 ± 1.5% for all samples. Aliquots used for thermal transfer correction were given a natural sunlight bleach.

Table 3. Applicable radiocarbon ages in the study area (compiled from Morlan *et al*., 2001; Christiansen, 1970; Mott, 1973).

No.	Lab. Number	Series	Depth (m)	Age (^{14}C BP)[a]	Age (cal BP)[b]	Description
1	S-455	South Sask. River I	1.5	7070 ± 115	8000 - 7750	A-horizon in eolian sand
2	S-234	South Sask. River II	——	8100 ± 120	9260 - 8780	A-horizon under eolian sand & over fluvial sand
3	S-233	South Sask. River III	7.1	>32 000	——	Charcoal in fluvial sand under eolian sand
4	S-164	Prince Albert	——	1800 ± 80	1820 - 1610	Charcoal in eolian sand
5	GSC-648	Prince Albert	0.59	11 560 ± 640	15 010 - 12 840[c]	Organics beneath gytta underlain by (eolian) sand
6	S-2167	Nipawin A I	9.5	9240 ± 525	11 170 - 9730	A-horizon in dune sand
7	S-2166	Nipawin A II	10.0	10 265 ± 585	12 900 - 11 220	Paleosol over fluviolacustraine seds. & under eolian sand
8	S-2156	Nipawin	0.6	3600 ± 90	4080 - 3730	Paleosol under eolian sand
9	S-235	Nipawin B I	1.5	6610 ± 95	7570 - 7430	A-horizon in dune sand
10	S-2289	Nipawin B II	——	7725 ± 165	8930 - 8350	Organic silt overlain & underlain by eolian sand
11	S-634	Strong Pine River	2.1	4140 ± 105	4820 - 4530	A-horizon in dune sand

[a] Radiocarbon ages uncorrected for $\delta^{13}C$ values; ages reported with an error of ± 1σ, except for GSC-648 which is reported at ± 2σ.
[b] Calibrated age range shown with an error of ± 1σ, except for GSC-648 which is reported at ± 2σ.
[c] Although this age was considered reliable when published (Mott, 1973), it is now consider to be affected by dead carbon, rendering it too old (R. Mott. Pers. Comm..).

Fig. 1. Wolfe, Ollerhead, Lian and Huntley

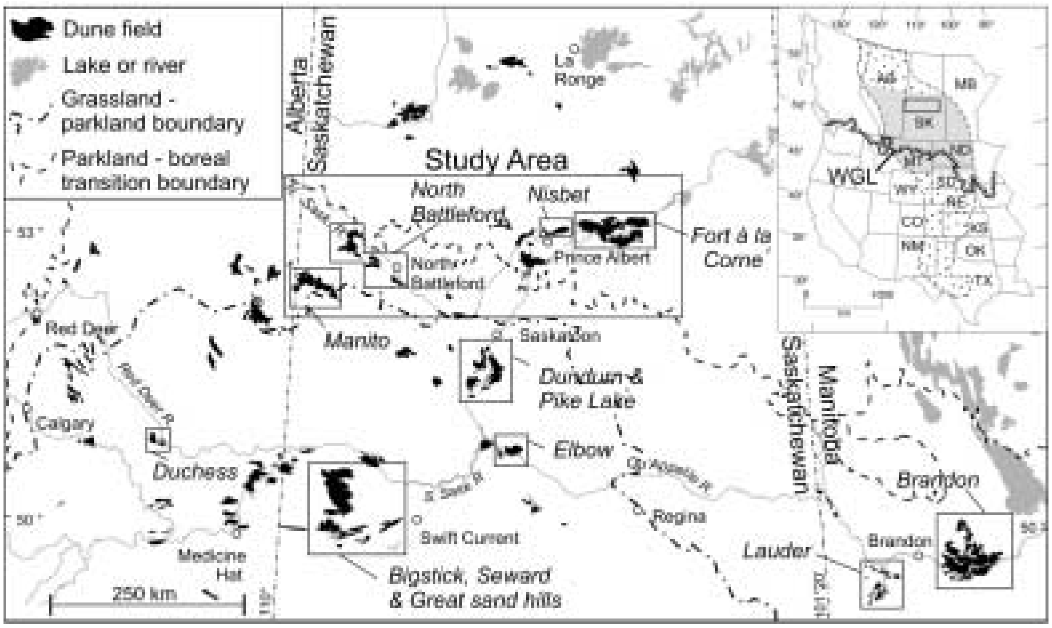

Fig. 2. Wolfe, Ollerhead, Lian and Huntley

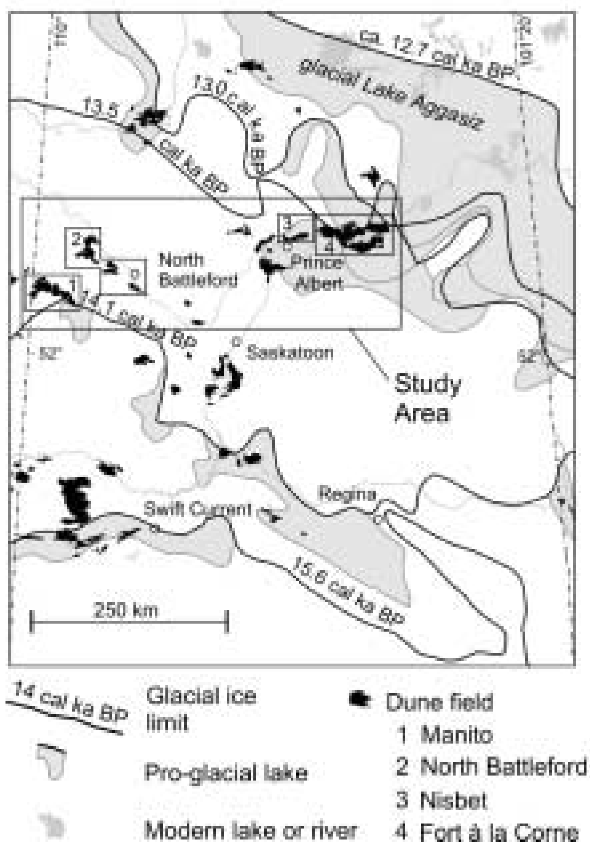

Fig. 3. Wolfe, Ollerhead, Lian and Huntley

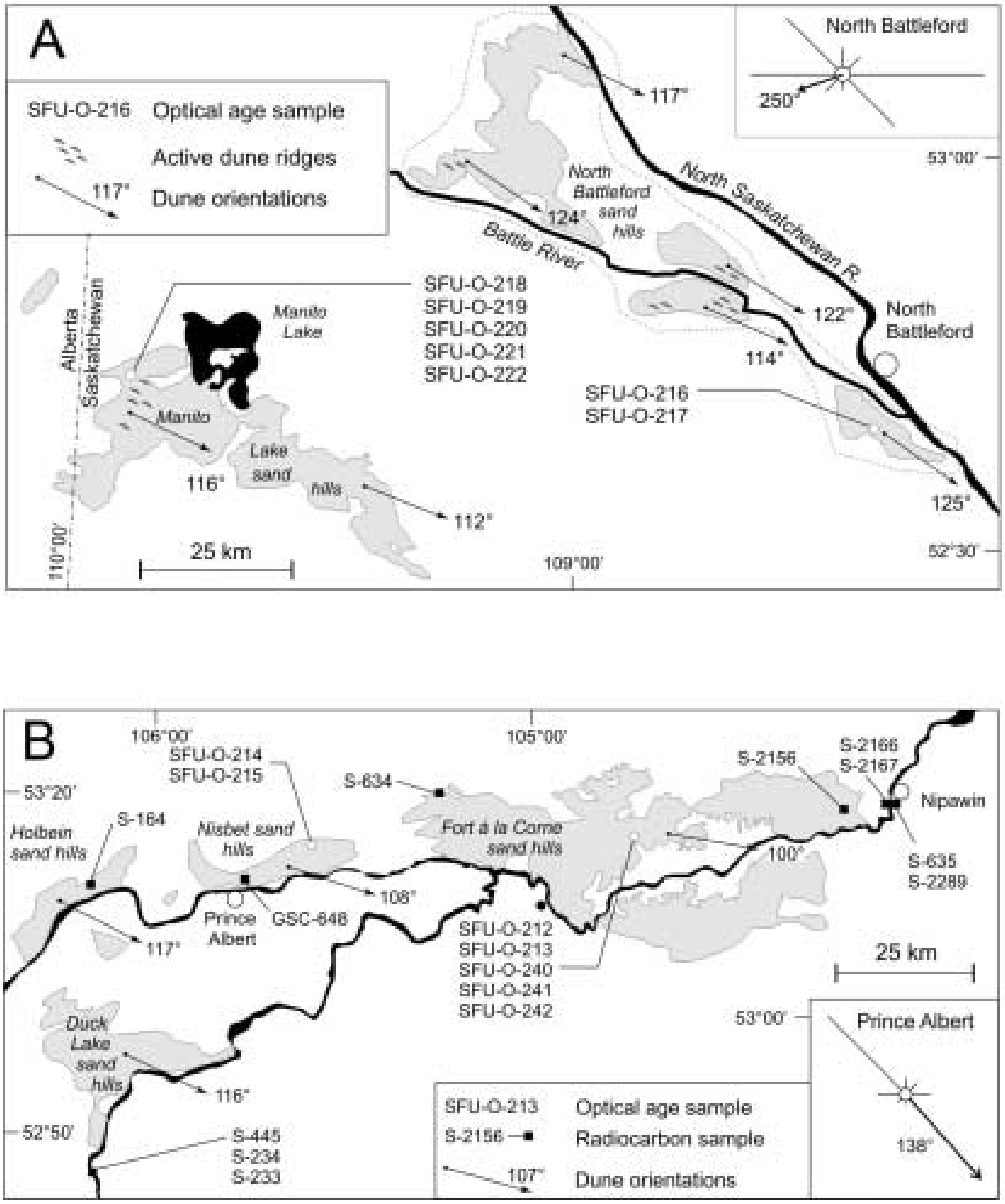

Fig. 4. Wolfe, Ollerhead, Lian and Huntley

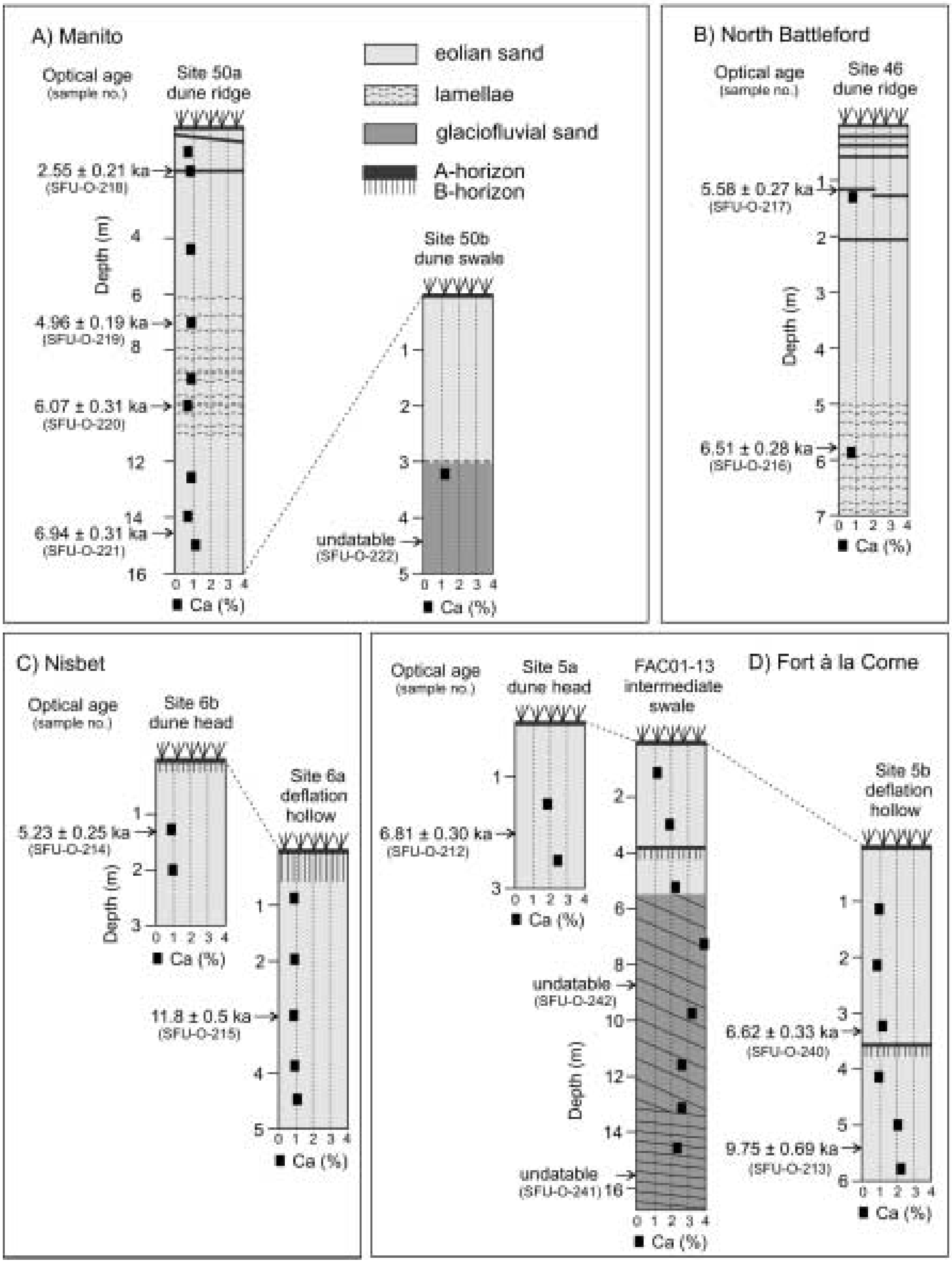

Fig. 5. Wolfe, Ollerhead, Lian and Huntley