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# Evolution of Holocene Eolian Landscapes in the Glacial Lake Hind Basin, Manitoba
# Évolution des paysages éoliens dans le bassin du Lac glaciaire Hind (Manitoba), à l’Holocène
# Evolución del paisaje eólico de la cuenca del Lake glaciar Hind en Manitoba, Canadá

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Article abstract

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# EVOLUTION OF HOLOCENE EOLIAN LANDSCAPES IN THE GLACIAL LAKE HIND BASIN, MANITOBA

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ABSTRACT Stratigraphic investigations into dune fields in Glacial Lake Hind basin reveal three lithologic units: a lake basin unit, a lower eolian unit, and an upper eolian unit. The lake basin unit contains gleyed silty clays representing a low energy lake environment, and coarse sands and black shale gravels representing higher energy depositional environments. The lower eolian unit contains sedimentary and organic laminations and no buried soils. The upper eolian unit does not have laminations, but contains multiple buried soil profiles. Preservation of organic laminations and presence of redoximorphic colouring in the lower eolian unit suggest that it has been preserved by groundwater. The upper eolian unit contains four soil profile types that appear in sequence with an interdunal profile at the bottom and a dune profile at the top. Radiocarbon ages of soils in the upper eolian unit (2350 ± 50 and 1100 ± 40 BP) indicate regional synchronicity with soil forming periods across the northeastern Great Plains. However, the morphology of a buried soil profile depended on the site's location on the paleolandscape during development.

RÉSUMÉ *Évolution des paysages éoliens dans le bassin du Lac glaciaire Hind (Manitoba), à l'Holocène.* Les recherches stratigraphiques menées dans les champs de dunes du bassin du Lac glaciaire Hind ont permis d'identifier trois unités lithologiques : une unité lacustre, une unité éolienne inférieure et une unité éolienne supérieure. L'unité lacustre est composée d'argiles silteuses gleyifiées, témoignant d'un milieu lacustre de faible énergie, et de sables grossiers ainsi que de graviers de schiste noir, témoignant de milieux de sédimentation de plus grande énergie. L'unité éolienne inférieure contient des feuillets sédimentaires et organiques, mais pas de sol enfoui. L'unité éolienne supérieure ne comprend pas de stratification fine, mais contient plusieurs profils de sol enfoui. La conservation des feuillets organiques et la présence d'une coloration attribuable à l'oxydo-réduction dans l'unité inférieure indiquent qu'elle a été préservée par l'eau souterraine. L'unité supérieure comprend quatre types de profils de sol qui semblent se présenter en séquence, un profil interdunaire étant à la base et un profil dunaire, au sommet. Les âges au radiocarbone de sols de l'unité supérieure (2350 ± 50 et 1100 ± 40 BP) reflète un synchronisme régional quant aux périodes de formation des sols à travers les Grandes Plaines du nord-est. Toutefois, la morphologie d'un profil de sol enfoui dépend de la localisation du site par rapport aux paysages anciens durant leur formation.

RESUMEN *Evolución del paisaje eólico de la cuenca del Lake glaciar Hind en Manitoba, Canadá.* Los estudios estratigráficos de las dunas de la cuenca del Lake glaciar Hind revelan tres unidades litológicas: una unidad lacustre situada entre dos unidades eólicas una en la parte superior y la otra en la parte inferior. La unidad estratigráfica de la cuenca esta compuesta por arcillas de tipo fangoso que reflejan un ambiente lacustre de baja energía y también por arenas gruesas y pizarras negras típicas de ambientes sedimentarios de alta energía. La unidad eólica inferior contiene capas laminares orgánicas y sedimentarias pero no suelos expuestos. La unidad eólica superior no contiene capas laminares pero contiene perfiles múltiples de suelos sepultados. La conservación de las capas laminares orgánicas y la presencia de coloraciones de reacciones redox en la unidad eólica inferior sugiere que ésta ha sido preservada gracias al agua subterránea. La capa superior contiene cuatro tipos de perfiles de suelo que se alternan con un perfil interdunar en la base y otro en el tope. La datación con radiocarbono de los suelos situados en la unidad eólica superior los sitúan hace 2350 ± 50 y 1100 ± 40 años e indica una sincronía regional con formación de suelos a través de las grandes praderas del noreste. Sin embargo, la morfología de los perfiles de los suelos sepultados depende de la localización del sitio en el paisaje antiguo durante su desarrollo.

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## INTRODUCTION

Hamilton and Nicholson (1999) have correlated the settlement patterns of pre-contact native peoples to soil and vegetation patterns in sand dune-dominated landscapes of the Glacial Lake Hind basin (GLHB) of southwestern Manitoba. They propose that greater ecological complexity provides pre-contact hunter-gatherers and horticulturalists with a more diverse set of resources, thus making those areas more attractive for occupation (Hamilton and Nicholson, 1999). If there is a relation between prehistoric land use and landscape, understanding the evolution of these landscapes is critical to understanding the evolution of their use. Because humans continue to occupy these landscapes, understanding of how they evolved is also applicable to modern land use problems.

Prior to the last quarter century, many researchers thought that dune formation in the northern Great Plains was related to anticyclonic winds off the Laurentide Ice Sheet (Kutzbach and Wright, 1985) and that the dunes have been stable throughout most of the Holocene (Watts and Wright, 1966; Wright, 1970; Warren, 1976; Sarnthein, 1978; Wells, 1983; Kutzbach and Wright, 1985). Over the past two decades, however, stratigraphic, geomorphic, and historical evidence of multiple cycles of dune activity and periods of stability have become increasingly well documented (Jorgensen, 1992; Muhs and Maat, 1993; Muhs and Holliday, 1995; Muhs *et al.*, 1997; Wolfe, 1997; Muhs and Wolfe, 1999; Wolfe *et al.*, 2000; Forman *et al.*, 2001; Hopkins and Running, 2000; Wolfe *et al.*, 2001; Running *et al.*, this volume). Although most of the dune fields are now stable, many have been active in past thousand years (Muhs and Wolfe, 1999) and reactivation could occur in the future with only a minor change in climate (Muhs and Maat, 1993; Wolfe, 1997).

Periods of dune activity result in erosion and sedimentation, while periods of stability result in soil formation. Historically, eolian activity on the Great Plains is linked to drought (Muhs and Holliday, 1995). Conversely, soil formation is linked to periods of increased moisture availability (Muhs and Holliday, 1995; Wolfe, 1997) and colonization of bare sand by vegetation (Hopkins and Running, 2000). Radiocarbon dating can be used to date periods of soil formation and optically stimulated luminescence (OSL) can be used to date periods of eolian activity. The application of these complimentary methods over the past two decades has yielded many detailed chronologies (see review in Forman *et al.*, 2001). Throughout much of the northern Great Plains, these chronologies are restricted to the last 2000 years due to suspected «cannibalization» of older dune sediment by late Holocene eolian activity (Muhs and Wolfe, 1999; Forman *et al.*, 2001). However, in dune fields such as the Lauder Sand Hills, located in the GLHB (Boyd, 2000; Running *et al.*, this volume), and Brandon Sand Hills of Manitoba (Wolfe *et al.*, 2000), and the Sheyenne Delta of North Dakota (Hopkins and Running, 2000), all near the more humid northeastern boundary of the Great Plains, evidence of earlier cycles of eolian activity are preserved.

Although Sun and Teller (1997) described the late Pleistocene/early Holocene evolution of the GLHB, the continued evolution of the basin after the final drainage of Glacial Lake Hind has not previously been fully documented. The modern geomorphology of the youngest stabilized dunes in the basin is reported in several sources (David, 1977; Ollendick *et al.*, 2001; Wolfe, 2002; Pfeiffer and Wolfe, 2002; Wallace, 2002). While morphology is important in interpreting the most recent phase of dune evolution prior to stabilization, more information about the time period between the final drainage of Glacial Lake Hind and the present may be contained within the stratigraphy of the dunes. Prior investigations into dune stratigraphy within the GLHB have been limited to a few sites near the southeastern edge of the Lauder Sand Hills (Boyd, 2000; Bergstrom *et al.,* 2002; Havholm *et al.*, 2003; Running *et al.*, this volume). One of the Lauder Sand Hills sites, Flintstone Hill, contains a nearly complete Holocene stratigraphic record, which has been examined in detail (Running *et al.*, this volume). However, little was known about the eolian stratigraphy elsewhere in the basin. The purpose of this paper is to present a comparison of the stratigraphy and dune orientations from seven sites across the basin and provide a general model for how the landscape of the GLHB evolved during the Holocene.

## SETTING AND BACKGROUND

The GLHB is situated in a northeast-trending bedrock valley approximately 80 km southwest of Brandon, Manitoba (Fig. 1). During the late Pleistocene, the basin housed Glacial Lake Hind. Glacial Lake Hind was a proglacial lake connected to a system of proglacial lakes and spillways covering much of the northern Great Plains (including parts of Saskatchewan, Manitoba, North Dakota, and Minnesota) that ultimately emptied into Glacial Lake Agassiz (Sun and Teller, 1997). Catastrophic drainage of one lake in the system typically led to a rapid filling of downstream lakes, which, in turn, incised their outlets, and drained in succession. During high stands of Glacial Lake Hind, up to 25 m of clay-rich silt accumulated in the basin. Catastrophic floods deposited an additional 20 m of coarsely textured glaciofluvial and glaciodeltaic sediments on top of the silt (Sun and Teller, 1997).

The present climate of the GLHB is sub-humid continental (Thorpe *et al.*, 2001). While prone to droughts like the rest of the northern Great Plains, the basin is located close to the present prairie/boreal forest ecotone and therefore has a slightly more humid climate than other portions of the northern Great Plains located to the west and south. The basin experiences an obtuse bimodal wind regime of high energy and intermediate directional variability (based on measurements from the Brandon Airport located 80 km north-east; Wolfe and Ponomarenko, 2001). Winds are typically out of the northwest, but vary from more northerly during the early spring to more westerly during the summer and winter (Wolfe and Ponomarenko, 2001). Numerical values for climate parameters are shown in Table I.

Vegetation patterns in the dune fields are strongly influenced by topography. Oak-aspen savanna typically covers north-facing slopes, while xeric grasslands cover south-facing slopes. Shallow wetland and open grassland communities exist in the interdunal areas (Boyd, 2000). Whereas reports from the

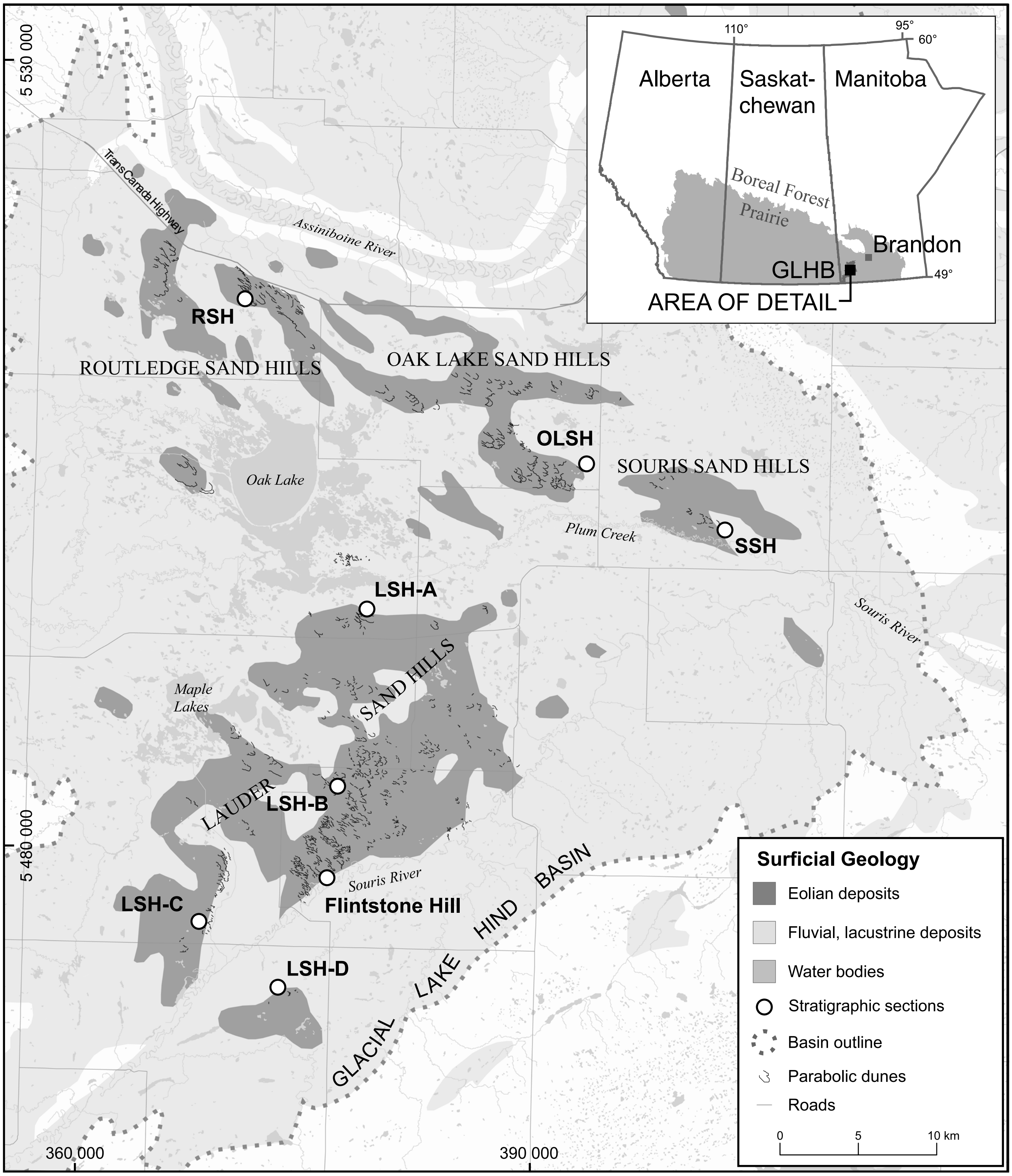


FIGURE 1. Eolian deposits (Fullerton *et al.*, 2000), their designations (Wolfe, 2002), parabolic dune ridges (Wallace, 2002), Flintstone Hill (Running *et al.*, this volume) and locations of stratigraphic sections described in this study. The inset map shows the location of the Glacial Lake Hind basin in relation to Brandon, Manitoba, the prairie/boreal forest ecotone, and the prairie provinces of Canada.

*Les dépôts éoliens (Fullerton* et al.*, 2000) et leurs désignations (Wolfe, 2002), les dunes paraboliques (Wallace, 2002), Flinstone Hill (Running* et al.*, présent numéro) et la localisation des coupes stratigraphiques étudiées. Le carton montre la localisation du bassin du Lac glaciaire Hind, par rapport à Brandon, au Manitoba, et l'écotone Prairies/Forêt boréale.*

TABLE I

*Values of climate parameters mentioned in text*

| | |
|---|---|
| Annual precipitation/potential evapotranspiration (P/PE)[1] | 0.75 |
| Annual drift potential (DP)[2] | 582 |
| Annual resultant drift potential (RDP)[2] | 240 |
| Annual steadiness (DP/RDP)[2] | 0.41 |
| Annual resultant drift direction (RDD)[2] | 125° |
| March RDD[2] | 160° |
| July RDD[2] | 96° |
| January RDD[2] | 110° |

1 Penman-Montieth method, Thorpe *et al.*, 2001.
2 Wolfe and Ponomarenko, 2001.

earliest phase of Euro-Canadian settlement suggest that patches of forest were relatively isolated, there has been a significant southward shift of the aspen-oak parkland (savanna) border so that aspen forest is now the dominant vegetation type in the basin (Hamilton and Nicholson, 1999). Shallow wetlands are found in the interdunal areas of the basin and adjacent to Oak, Maple and Plum Lakes. Attempts to reclaim land for agriculture in 1969 led to the construction of the Maple Lakes drainage canal (Hamilton and Nicholson, 1999). The canal initiated the demise of many localized interdunal wetlands and humid meadows, which changed the local vegetation pattern.

Eolian sand now covers approximately 460 km$^2$ (Fullerton *et al.*, 2000) of the 3 600 km$^2$ basin. Most of the basin is still covered in glaciofluvial and glaciolacustrine sediments (Sun and Teller, 1997; Fullerton *et al.*, 2000), but eolian deposits are more concentrated where the basin is elongated west to east (Fig. 1). David (1977) divides the dunes in the basin into 18 dune fields, which are referred to collectively as the Oak Lake Sand Hills. Wolfe (2002) groups these fields into four sets: the Routledge, Oak Lake, Souris, and Lauder Sand Hills (Fig. 1). These dune fields contain border ridges and elongate sand ridges, along with blowout hollows and heavily vegetated blowout dunes. Dunes occur in successional, superimposed, or en echelon arrangements. Composite dune ridges can extend for more than 2 km, but most single parabolic dune arms are less than 0.5 km long and up to 10 m high (Wallace, 2002). Eroded parabolic dunes, sand sheets, and undifferentiated eolian deposits have also been identified (David, 1977; Pfeiffer and Wolfe, 2002). Dune activity in the basin is mostly limited to areas disturbed by agriculture and municipal activity (*e.g.*, roads, borrow pits).

## METHODS

Seven stratigraphic sections were examined: one each in the Routledge (RSH), Oak Lake (OLSH), and Souris Sand Hills (SSH), and four in the Lauder Sand Hills (LSH-A, LSH-B, LSH-C, LSH-D) (Fig. 2). Where possible, the stratigraphic section was described in two parts. The upper part was described and sampled from a profile excavated into the slope of a dune, and the lower part was described and sampled from a core taken adjacent to the foot of the profile. All cores were extracted with a truck-mounted Geoprobe using 7 cm diameter core barrels. Three samples of soil organic material were submitted to Beta Analytic, Inc. for radiocarbon dating (Table II). All samples were sent to the University of Calgary geoarchaeology laboratory for Malvern Mastersizer grain size analysis and preparation for radiocarbon analysis. Hand sample descriptions (Wallace, 2002) and grain size analysis from each section were compared and classified into lithologic units and soil types.

Dune ridges were identified from aerial photography (Province of Manitoba, 1992-1994) and then traced over digital orthophotography in ArcView 3.2. Criteria used to interpret dune ridges included the following: 1) positive vertical relief when viewed stereoscopically; 2) strongly contrasted vegetation between north and south slope (*e.g.*, woodland on the north side, prairie on the south); 3) presence of bare sand; 4) obvious dune morphology (arcuate ridges, slope steeper on the downwind side). It is assumed that the dunes formed in a glacial lake basin of low initial relief, and positive relief visible in the modern landscape is due to eolian processes or human activity (fluvial processes result in down-cutting, and therefore negative relief). Although some arcuate channel scars are visible, they are typically related to a modern stream channel and are of significantly lower relief than dune ridges as to be easily distinguishable. Where dunes are severely eroded, no attempt was made to interpret the eroded portions that do not meet the above criteria. Dune orientations were determined by inferring the bisecting line between north and south arms of dunes interpreted to be from the same dune. The bisecting line was then digitized in ArcView and the orientation was determined by calculating the angle of the line with respect to the map's coordinate system.

## RESULTS

Figure 2 is an illustration of the occurrence of lithologies and soil types in each stratigraphic section. Where they occur together in a section, the units occur in the order they are presented below from base to surface. The lithologic units and soil types are described below in detail.

### LAKE BASIN UNIT

The lake basin unit is located at the base of the sections (Fig. 2) and is composed of carbonate-rich, medium to coarse-grained sands with localized horizons of gleyed silty clay, clayey rip-up clasts, dolomite pebbles, and/or very coarse black shale fragments increasing with depth. The silty clay and coarse black shale fragments appear to represent two end member facies (a low energy and a high energy facies, respectively). The silty clay can be found interbedded with the sands, but the coarse black shale fragments are typically found at the base of the unit. Redoximorphic colouring (oxidized in the upper part; gleyed at the base) may extend down into this unit from upper units.

### LOWER EOLIAN UNIT

The lower eolian unit contains fine to medium-grained sands and loamy sands up to 3.25 m thick, with well-expressed

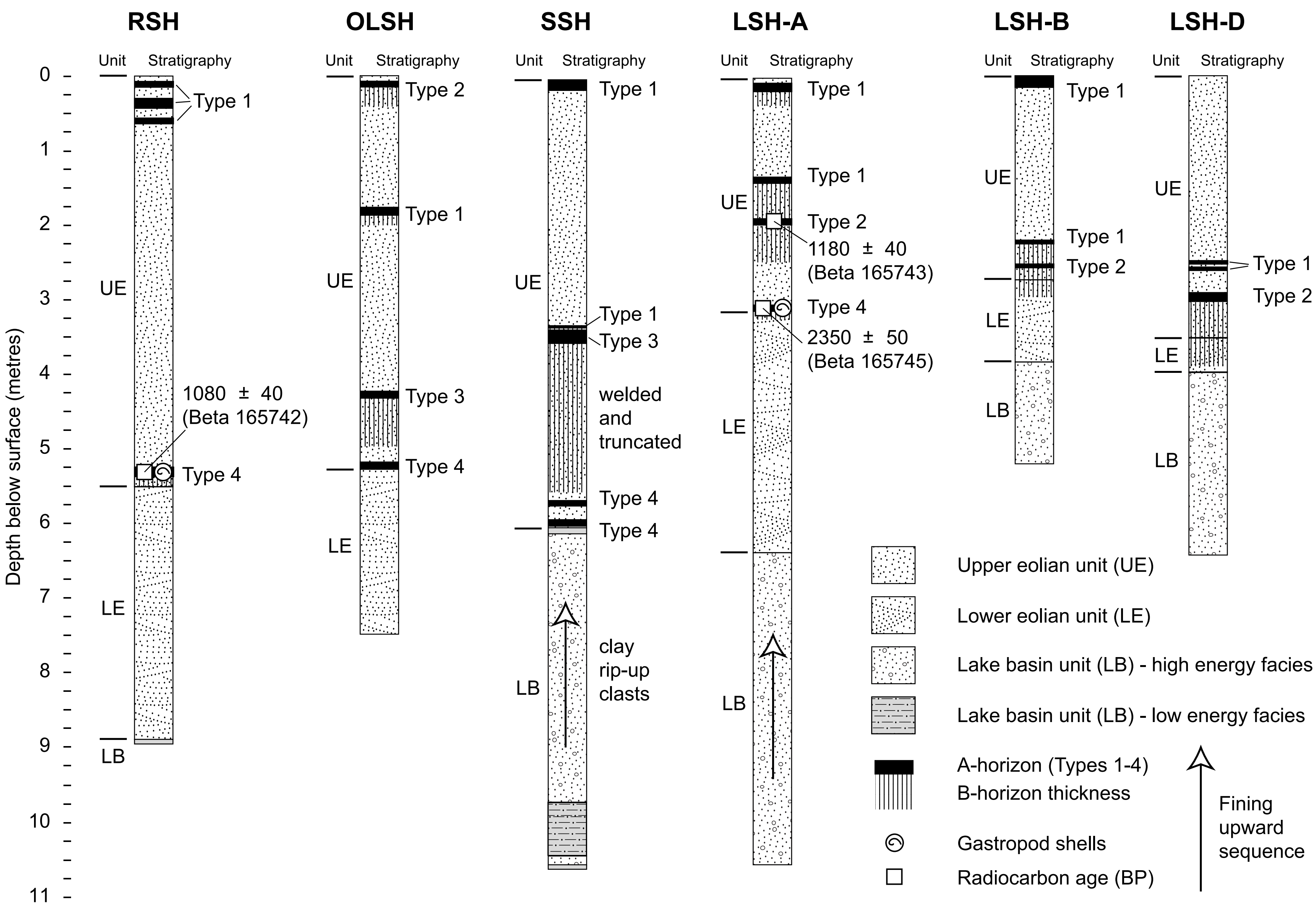


FIGURE 2. Litho and pedo-stratigraphy of six sites in the Glacial Lake Hind basin (locations shown in Figure 1). Units and soil types are described in text.

*Lithostratigraphie et pédostratigraphie de six sites dans le bassin du Lac glaciaire Hind. Les unités et les types de sols sont décrits dans le texte.*

TABLE II

*Radiocarbon samples, preparations, and ages*

| Location (soil) | Lab number | Material (type, pre-treatment) | Age (BP) | Calibrated age (cal BP)* |
|---|---|---|---|---|
| LSH-A (Ab3) | Beta 165742 | Organic sediment (AMS, acid washes) | 1180 ± 40 | 1180 to 980 |
| LSH-A (Ab4) | Beta 165743 | Organic sediment (AMS, acid washes) | 2350 ± 50 | 2470 to 2320 |
| RSH (Ab6) | Beta 165745 | Organic sediment (bulk low carbon analysis, acid washes) | 1080 ± 40 | 1050 to 930 |

*Calibrated ages according to Stuvier *et al.* (1998a,b). The calibrated range contains probable dates within two standard deviations (2$\sigma$) from the mean.

laminations of finely disseminated organic matter and local occurrences of charcoal and plant macrofossils along bedding planes (also described by Running *et al.*, this volume). Organic-rich laminations and organic fragments are associated with an increase in silt content (+2 to 5 % silt). Redoximorphic features (oxidized in the upper part; gleyed at the base) are common in this unit. This unit is found in five sections (Fig. 2). No soils appear to have formed within this unit, but some soil profiles that originated in the upper eolian unit cut lithologic boundaries and extend into this unit.

### UPPER EOLIAN UNIT

The upper eolian unit contains friable, massive to weakly bedded, fine to medium-grained sands and loamy sand. Where it is present, the only suggestion of bedding is a slight change to a higher Munsell colour value rather than organic laminations as in the lower eolian unit (*i.e.* a decrease in Munsell colour value). However, the colour change in this unit may also be a diagenic effect.

This unit contains the majority of buried soil profiles found in the basin. The profiles take four forms (Fig. 2). Where present in the same section they follow a distinct pattern (except at OLSH) where the weakest developed profiles occur near the top of the unit and better-developed profiles are found lower in the unit (Fig. 2). The uppermost profiles have low organic matter contents, silt accumulation in the A-horizon and no B-horizon development (type 1 soil). Type 2 profiles, commonly found near the tops of sections, are similar to type 1 profiles but have silt accumulations in the B-horizon. The type 3 profiles are similar to type 2 profiles except they exhibit clay accumulation in the B-horizon. Type 3 profiles are welded soils in some sections (Fig. 2). Type 4 profiles are thin with an organic-rich A-horizon and local occurrences of gastropods. Units immediately below type 4 profiles are often enriched in carbonates or exhibit the oxidized to gleyed redoximorphic colouring seen in the lower eolian unit and the lake basin unit. Radiocarbon ages were determined for three soils in this unit (Table II). Soil organic matter in a horizon (“Ab6” of Wallace, 2002) at RSH yielded an age of 1080 ± 40 BP, while ages of two horizons (“Ab3” and “Ab4” of Wallace, 2002) at LSH-A are 1180 ± 40 BP and 2350 ± 50 BP, respectively (Fig. 2).

### DUNE ORIENTATIONS

Over 900 dune ridges were identified from aerial photographs and mapped (Fig. 1). The ridges mapped are the erosional remnants of elongated, often compound, parabolic dunes. As a result of erosion, typically only one arm remains. Only dunes where a bisecting line could be interpreted between dune ridges were used in determining the orientation (Fig. 1 and Table III). Identification of dune types from aerial photographs was successful for the large (>5 m of relief) parabolic dunes since their relief usually exceeds that of the covering vegetation. However, aerial photographs were not very useful for identifying low (<5 m of relief) conical, irregular, or sinuous mound dunes, which are often present in association with the parabolic dunes and obscured by forest cover. Therefore, maps of dune fields made solely from aerial photographs are more accurately maps of parabolic dune fields. This explains the absence of identifiable parabolic dune ridges in some areas classified as dune fields by previous researchers (*e.g.* David, 1977). Orientations were found to be consistent with prior studies by Pfeiffer and Wolfe (2002) and Ollendick *et al.* (2001) (see Table III for comparison) and the modern wind direction (Table I).

## DISCUSSION

### LAKE BASIN UNIT

The lake basin unit is interpreted to represent depositional environments that predate the initiation of eolian activity. A high-energy facies that contains coarse sand to gravel-sized grains of black shale, and a low-energy facies of gleyed silty clay are identified. The sizes of the black shale grains (up to 2 cm in diameter) suggest that they were transported by a medium other than wind. Because the lake basin unit occurs in a sequence that fines upward into medium to fine grained sand, it is interpreted to represent a glaciofluvial or fluvial environment consistent with the Glacial Lake Agassiz spillway system. The gleyed silty clay is interpreted to represent high stands in the lake or subsequent smaller lakes that formed after drainage. The presence of clayey rip-up clasts in a sand unit between two clay beds at SSH indicates that, during the early period of its history, the location may have alternated between offshore lacustrine and nearshore lacustrine or fluvial environments.

TABLE III

*A comparison of dune orientations by study and dune field*

| | Pfeiffer and Wolfe (2002) | | Ollendick *et al.* (2001) | | Wallace (2002) | |
|---|---|---|---|---|---|---|
| Dune fields | Orientations | n | Orientation | n | Orientations | n |
| Routledge | 118 | 10 | 118.13 | 22 | 118.25 | 16 |
| Oak Lake | 121 | 8 | 108.3 | 8 | 118.45 | 21 |
| Souris | 97.5 | 8 | 99.13 | 8 | 105.55 | 8 |
| Lauder | 112 | 8 | 113.22 | 71 | 121.8 | 31 |

The lake basin unit appears to correlate to a similar deposit at Flintstone Hill (unit "A" of Running *et al.*, this volume). Although Running *et al.* (this volume) were able to divide their unit "A" into two subunits that represent glacial lake and post-glacial lake depositional environments based on the presence of a thick peat layer, no such marker was identified in this study.

## LOWER EOLIAN UNIT

The lower eolian unit is differentiated from the upper eolian unit by organic-rich laminations and localized plant macrofossils along bedding planes. The organic laminations may be the result of organic debris on the dune surface being incorporated into the dune, but prevented from decay due to a reducing environment. Because redoximorphic colouring is often associated with this unit, it is interpreted that a subsequent rise in water table inundated this unit and preserved bedding and organic material.

A similar lower eolian unit (unit "B" of Running *et al.*, this volume) was identified at Flintstone Hill, where it appears to have migrated from the southwest (Bergstrom *et al.*, 2002) prior to 5350 ± 50 BP (Boyd, 2000; Running *et al.*, this volume). The drift direction of these earliest dunes, as determined by Bergstom *et al.* (2002), differs from the modern resultant drift direction for southwestern Manitoba (Wolfe and Ponomarenko, 2001), but is consistent with wind regimes present in drier parts of northern Great Plains (Wolfe, 2002). Therefore, it is likely that the climate was drier during the period of the Holocene when this unit was forming at Flintstone Hill. This unit may have formed at a similar time in the rest of the basin, because the sequence of dune units appears to be similar throughout the basin, but better age control on stratigraphy across the basin is required.

## UPPER EOLIAN UNIT

Unlike the lower eolian unit, this unit typically lacks identifiable bedding planes or organic-rich laminations. Therefore, this unit appears to have, for the most part, remained above the water table.

Soil profiles in the upper eolian unit can be divided into two soil-forming facies on the basis of landscape position, as reflected in the morphology of each soil type. Type 4 profiles are interpreted to be wetland soils and appear to represent a landscape position at or adjacent to the water table at the time of formation. Therefore, they may have formed in an environment equivalent to the modern interdunal environment.

The remaining types of soil profiles (1-3) appear to have formed in more elevated landscape positions (*e.g.* on the dunes themselves). Interdunal soil profiles are typically found at the base of this unit. Dunal soil profiles, which are typically found in sequence where they occur together, appear to represent soil forming environments at progressively higher landscape positions. This would indicate that dunes accrete upward from an interdunal environment and become progressively higher (topographically) as the dune crest migrates over the location. Such a process may have been interrupted by multiple soil forming intervals and periods of erosion, producing welded or truncated soils at some locations.

The modern landscape of the GLHB is a mosaic of different soil forming environments. Therefore, it is not surprising that radiocarbon ages of buried soils indicate that wetland (interdunal) and dune soils formed simultaneously at different locations in the basin (RSH and LSH-A, Fig. 2) for at least the past 2300 radiocarbon years. Furthermore, radiocarbon ages from Flintstone Hill of 4090 ± 70 and 5350 ± 50 BP on soils that correlate to Type 4 soil profiles in this study (unit "C" of Running *et al.*, this volume), may extend the time period for which the above soil-landscape model is applicable back another 3000 radiocarbon years.

## DUNE ORIENTATIONS

Based on orientations of the youngest dunes, those present on the modern landscape, there appears to be a net migration to the southeast (105°-122°), which is similar to orientations proposed by Ollendick *et al.* (2001) and Pfeiffer and Wolfe (2002) (Table III). Pfeiffer and Wolfe reported the greatest range (98°-121°). The resultant drift direction (RDD) calculated from 30-year climate normals indicates that the RDD of sand transport should be between 96° to 120° during the dry, hot summer months (June-September), whereas it would be 156°-160° during the wetter spring months (March-May) (Wolfe and Ponomarenko, 2001). Because the dominant wind direction is related to atmospheric circulation patterns that influence other climate factors, such as mean annual precipitation and mean annual temperature (Bryson, 1966), the orientation of the dunes should indicate which circulation pattern was dominant prior to their last stabilization. Several authors have suggested that dunes in the northern Great Plains are near the threshold of dune activity under the modern climate (Muhs and Maat, 1993; Muhs and Holiday, 1995; Wolfe, 1997; Muhs and Wolfe, 1999; Wolfe *et al.*, 2001). Based on the orientations determined in this study, it appears that the dunes formed when the climate of the GLHB was dominated by a regime similar to that experienced during the summer months today. The more westerly winds present in such a climate regime (maximum orientation = 122°) suggest that the region may have experienced slightly more zonal circulation on average in the recent past compared to the present (annual RDD = 125°). The degree of modification of original dune morphology in the GLHB is also significant. In more western dune fields in the northern Great Plains and in some of the dune fields in the Brandon Sand Hills, the dunes retain much of their original form. However, GLHB dunes, in addition to other dunes in the Minot Dune Field, ND (Muhs *et al.*, 1997) and the Brandon Sand Hills (Wolfe *et al.*, 2001), are commonly missing an arm or a head. The degree of erosion suggests that complete reactivation, which might reform the dune morphology, has not occurred for a significantly longer time than in other dune fields. Whether or not most of the dunes in the basin were active at the same time is unknown, but might be answered with sufficient luminescence (OSL, TSL) ages, or by comparing soil profile development at similar landscape positions across the GLHB.

### LANDSCAPE EVOLUTION SCENARIO

After the drainage of Glacial Lake Hind, the basin was relatively flat and at a low elevation, both because of scouring by spillway processes and isostatic depression (Sun and Teller, 1997). The water table was probably near the basin surface. The basin was likely a mosaic of wetlands and lakes with wide, shallow rivers, which were not competent enough to incise spillway gravel deposits. Gravels were deposited during glaciofluvial and fluvial episodes and the silty clays were deposited when deeper lakes were present at those locations.

Cross-strata from the basal eolian unit at Flintstone Hill (unit «B» of Running *et al.*, this volume), which correlates to the lower eolian unit in this study, suggests that, in the GLHB, eolian activity may have been initiated as warmer/drier climatic conditions associated with a more zonal wind regime than present set in during the middle Holocene (Running *et al.*, this volume). Redoximorphic colouring in the lower eolian unit and lake basin unit indicates that a rise in water table occurred subsequent to the deposition of those units. It is possible that the elevated water table contributed to the preservation of the bases of the dunes while the upper portions were eroded away by continued eolian activity.

As climate fluctuated, landscape stability and soil formation occurred. Of the soils formed during the earliest periods of landscape stability, only interdunal wetland soils were preserved. In the GLHB, the oldest such interdunal wetland soil profiles are found at Flintstone Hill because they formed at a low elevation, adjacent to the Souris River. There, they would have been protected by the topography and their proximity to the water table. Wetland soils were probably more resistant to wind erosion than upland soils because they have the advantage of being located low on the landscape, where they are protected from stronger winds, and tend to have a firmer consistency. These interdunal soils formed the base of the modern landscape. As more eolian sediment accumulated in the dune fields, and dunes migrated (to the east-southeast) the wetland, soils were gradually buried.

During subsequent soil forming periods, soils gradually formed on progressively higher landscape positions. Erosion undoubtedly truncated some soils. Those that accumulated some clay in the B-horizon resisted erosion and, in some instances, outlasted the period of eolian activity. The next soil formed on top of the truncated soil, creating a welded soil. Eventually, further accumulation of sediment raised the height of the dune above the water table enough that only weakly developed soils could form. These soils are more easily eroded by wind. Thus, the number of weakly to moderately developed buried soil profiles (types 1 and 2) varies from section to section. These dunes built with an orientation that suggests that they formed in a climate with a wind regime similar to the modern in which zonal circulation was slightly more dominant.

## CONCLUSIONS

Three lithologic units are identified in seven stratigraphic sections located in dune fields across the Glacial Lake Hind basin. The units record lacustrine, fluvial, and eolian environments. Four types of soil profiles are identified and used in conjunction with lithostratigraphy to interpret how the modern eolian landscape in the basin evolved from an early Holocene glaciolacustrine plain. The lithologic units appear to correlate well with units in Flintstone Hill (as described in Running *et al.*, this volume), indicating that Flintstone Hill could be used as a type section for GLHB stratigraphy. While Flintstone Hill has been studied more intensively, the results of this study show how paleoenvironmental interpretations derived therefrom may be applied across the basin. Furthermore, this study demonstrates a component of spatial variation among soils of the same age from which it is deduced that the modern relation between dunes and interdunal wetlands was present back to at least 2300 BP and probably as far back as 5300 BP. The radiocarbon ages of soils presented in this research are broadly consistent with ages determined by others working in the GLHB (Boyd, 2000; Running *et al.*, this volume) and the northeastern Great Plains (Muhs *et al.*, 1997; Muhs and Wolfe, 1999; Wolfe et al, 2000; Hopkins and Running, 2000). Because soils appear to be of similar ages at a regional scale, it is inferred that climate is the dominant control on the timing of soil-forming periods vs. periods of dune activity. However, landscape position is the controlling factor affecting soil morphology in dune fields of the GLHB because different soil types formed at the same time (presumably under the same regional climate). Therefore, with good age control, future workers in the GLHB should be able to interpret topographic position from buried soil profiles, and paleoclimatic interpretations of buried soil profile morphology must be made in the context of past landscape positions.

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