COMPARISON OF SAND DUNE CHRONOLOGIES IN THE GREAT PLAINS AND EASTERN LAKE MICHIGAN COASTAL ZONE

By

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ABSTRACT

COMPARISON OF SAND DUNE CHRONOLOGIES IN THE GREAT PLAINS AND EASTERN LAKE MICHIGAN COASTAL ZONE

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Extensive deposits of eolian sand occur throughout the Great Plains region as well as along the eastern coastal zone of Lake Michigan. Numerous studies have been conducted on dunes in the Great Plains and along the Lake Michigan coast. Recent research suggests that dunes in both regions were active contemporaneously during the Medieval Warm Period (MWP). This finding is interesting because it suggests that broad regional climate patterns may have influenced dunes in both systems.

Given the apparent synchroneity in dune systems within the Great Plains and Great Lakes regions during the MWP, this research further compares the chronology of sand dune evolution in both regions during the Holocene. To test this relationship, published literature from both regions was reviewed and all published radiocarbon and luminescence ages reported were logged, including 348 ages from the Great Plains and 246 ages from the Great Lakes region. Ages were used to construct probability density distributions, inform Principal Components Analysis (PCA), and construct time-slice maps to compare and contrast dune evolution events over the past 7000 years. Based upon interpretation of the results of this study, similar dune activation events have likely been taking place in both regions from ~4400 years ago to the present.

ACKNOWLEDGEMENTS

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Chapter 1: Introduction

Sand dunes are common in the central part of the United States (e.g. Thorp and Smith, 1952; Arbogast et al., 2009; Halfen and Johnson, 2013). They occur in environments that range from the semiarid/sub-humid Great Plains to the humid continental climate of the Great Lakes region. In the Great Plains (Figure 1.1), large dune fields are present in Manitoba, North Dakota, South Dakota, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas (e.g., Holliday, 1989; Arbogast, 1996; Muhs et al., 1997a; Havholm and Running, 2005; Lepper and Scott, 2005; Halfen et al., 2012). Dunes in the Great Lakes region (Figure 1.2) range from interior dunes in Michigan (e.g., Arbogast et al., 1997) to coastal dunes along the lakes (Peterson and Dersch, 1981; Snyder, 1986; Arbogast and Loope, 1999; Blumer et al., 2012; Lovis et al., 2012). The best developed of these dunes are those along the eastern coastal zone of Lake Michigan. These dunes may collectively represent the largest body of freshwater coastal dunes in the world (Peterson and Dersch, 1981).

Dunes throughout the Great Plains region have been studied extensively since the late 19^{th} century. Early studies (e.g., Hay, 1893; Haworth, 1897; Moore, 1920; Lugn, 1935; Smith, 1937, 1939, 1940; Melton, 1940; Simonett, 1960; Ogden and Kay, 1965; Smith, 1965; David, 1968) were mostly qualitative in nature and sought to determine sources of dune sand, as well as to construct late Pleistocene and Holocene dune activity through relative dating methods, utilizing stratigraphic research of dunes and associated soils.

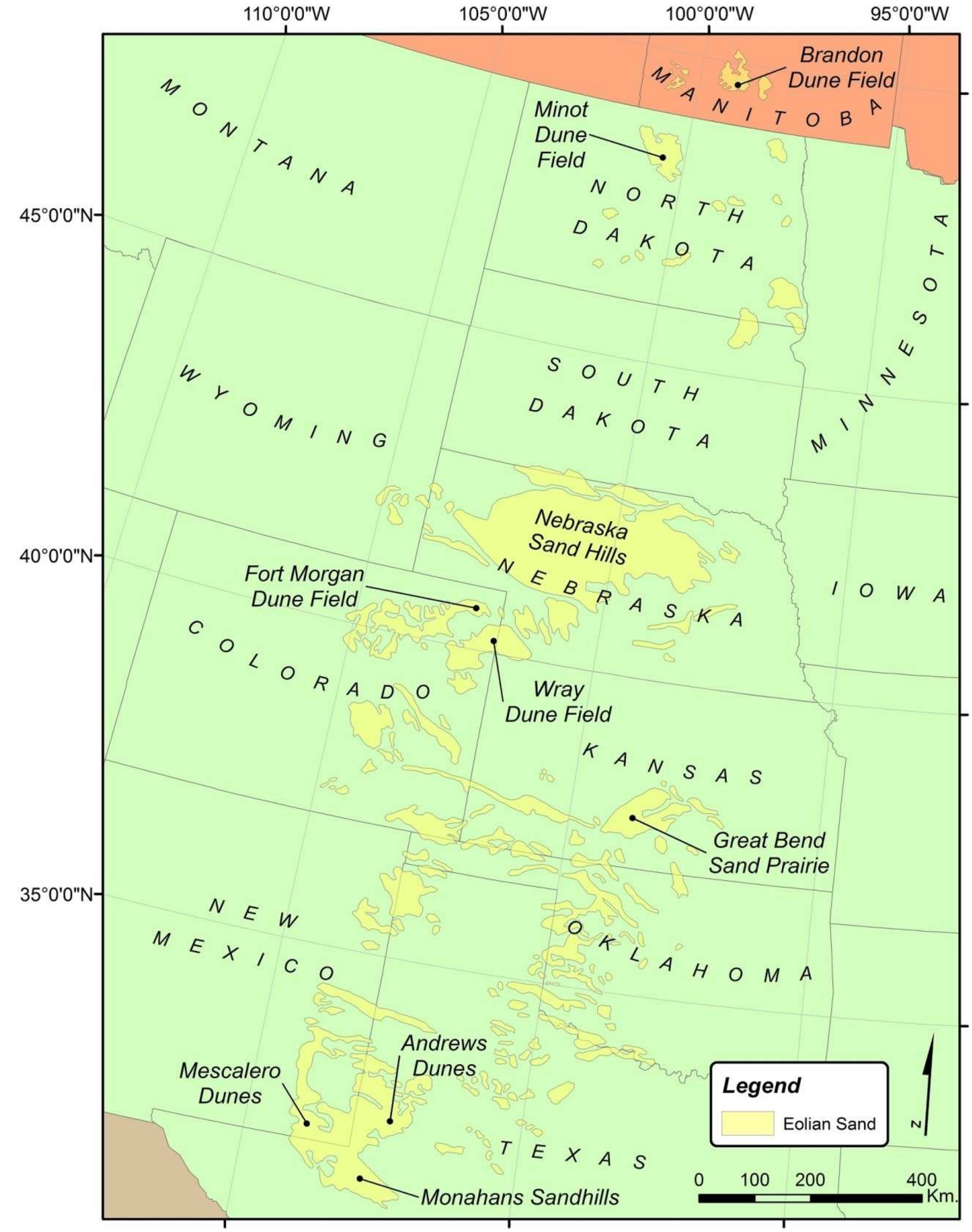


Figure 1.1: Dune field locations in the Great Plains (modified from Muhs et al., 1997b).

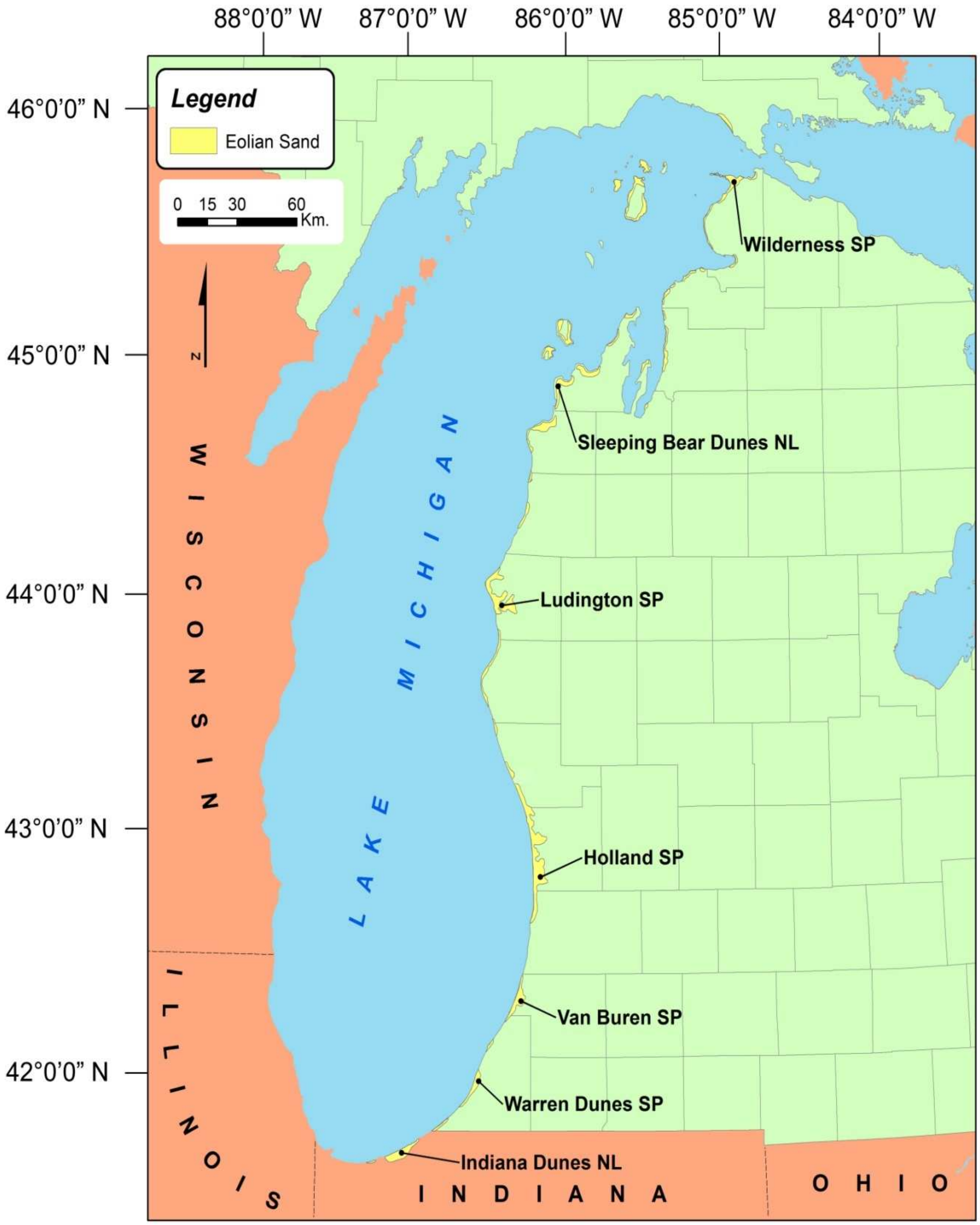


Figure 1.2: Dune locations along the eastern shore of Lake Michigan (modified from Van Oort et al., 2001; Arbogast et al., 2004).

The first published radiocarbon dates in the Great Plains were from David (1971) as part of a study from the Brandon Sand Hills in Manitoba. Similar studies were conducted from the late 1970s to the present (e.g., Warren, 1976; David, 1977, 1979; Gile, 1979; Ahlbrandt and Fryberger, 1980; Ahlbrandt et al., 1983; Wright et al., 1985; Brady, 1989; Holliday, 1989; Swineheart, 1990; Ponte et al., 1994; Loope et al., 1995; Mason et al., 1995; Muhs et al., 1995; Olson et al., 1995; Arbogast, 1996; Arbogast and Johnson, 1998; Arbogast and Muhs, 2000; Forman et al., 2001; Holliday, 2001; Muhs and Holliday, 2001; Olson and Porter, 2002; Feathers, 2003; Miao et al., 2005; Miao et al., 2007; Forman et al., 2008; Hanson et al., 2009; Rich and Stokes, 2011; Werner et al., 2011; Halfen et al., 2012; Halfen and Johnson, 2013). These studies collectively suggest that dune activation and stabilization has occurred in the Great Plains several times over the past 7000 years, and that mobilization of eolian sand is related to enhanced drought conditions and reduced vegetative cover.

Geomorphic studies in the Great Lakes region also began in the late 19th century, with the most attention focusing on the coastal dunes along the eastern coast of Lake Michigan. Early coastal dune studies were qualitative in nature; for example, Cowles (1899) focused on dune vegetation and how differing plant species can contribute to differences in dune evolution. Dow (1937) investigated the formation of “perched” dunes on high bluffs north of Manistee, and possible sources of eolian sand. Scott (1942) observed the differences in dune formation north and south of the isostatic “hinge line” proposed by Goldthwait (1908). Other qualitative studies (i.e., Tague, 1946; Olson, 1958a, 1958b, 1958c; Dorr and

Eschman, 1970; Buckler, 1979) contributed to the general understanding of coastal dunes in the Great Lakes region.

Snyder (1985) reported the first radiocarbon dates from the region at Sleeping Bear Dunes National Lakeshore. Since that time, an abundance of geomorphic studies have contributed to the chronology of dune activation and stabilization events in the Great Lakes region from the mid-1990s to the present (Arbogast and Loope, 1999; Loope and Arbogast, 2000; Van Oort et al., 2001; Arbogast et al., 2002; Hansen et al., 2002; Arbogast et al., 2004; Lepczyk and Arbogast, 2005; Hansen et al., 2010; Blumer et al., 2012; Lovis et al., 2012). These studies also suggested several episodes of dune activation and stabilization along the eastern Lake Michigan coastal zone over the past 7000 years and have largely attributed eolian sand mobilization to periods of high lake level.

To date, radiocarbon dating has been the most widely used method to reconstruct dune chronology in the Great Plains and along the eastern coast of Lake Michigan (e.g. Arbogast and Loope, 1999; Loope and Arbogast, 2000; Van Oort et al., 2001; Madole, 1994; 1995; Arbogast, 1996; Stokes and Swineheart, 1997; Holliday, 2001; Olson and Porter, 2002; Goble, 2004), with most ages derived from charcoal and wood fragments within buried paleosols. More recently, luminescence dating techniques (i.e. optically-stimulated luminescence, thermoluminescence, infrared-stimulated luminescence) have allowed researchers to sample buried sands from various depths in the profile and directly estimate the timing of past dune activation events (e.g. Hansen et al., 2002; Hanson et al., 2009; Hansen et al. 2010; Rich and Stokes, 2011; Werner et al., 2011; Blumer et al., 2012; Halfen et al., 2012; Lovis et al., 2012).

1.1: Statement of Problem

This research compares and contrasts dune chronologies in the Great Plains and along the eastern shore of Lake Michigan for the past 7000 years. It is motivated by a recent study conducted by Arbogast et al. (2011), which suggested that dune activation occurred in both the Great Plains and along the eastern coastal zone of Lake Michigan during the Medieval Warm Period (MWP) about 1000 years ago. Their finding is interesting because the regions are in different climate zones: the Great Plains in a semi-arid to arid climate zone, and the Great Lakes region in a humid climate zone. Past research in both regions has demonstrated very different drivers of dune activation in each respective region. In the Great Lakes region, high lake levels as a result of heavy precipitation and cold winters have generally correlated with dune building activity (Loope and Arbogast, 2000; Van Oort et al., 2001; Arbogast et al., 2002; Fisher and Loope, 2005), while drought conditions have corresponded with periods of dune activation in the Great Plains (Holliday, 1989; Muhs et al., 1997a; Wolfe et al., 2000; Werner et al., 2011). Given the simultaneous activity in both regions during the MWP, it is possible that broad climate patterns may influence dunes in both regions at other similar times during the Holocene.

Comparison of dune chronologies in both regions will be conducted through collection of published radiocarbon and luminescence data for both regions. Probability density distributions (PDDs) will then be constructed using the data, with peaks in the OSL distributions used to infer periods of activation, and peaks in radiocarbon distributions used to infer stabilization events or the onset of activation events through the Late Holocene. Principal components analysis (PCA) will then be utilized to determine if there are any multiregional similarities from an exclusively numerical standpoint. Lastly, time-slice maps are displayed to demonstrate the spatial patterns of sand dune activity in 200-year intervals. This research will contribute (1) the first known collection of published dates from both regions, (2) the first known utilization of PCA in dune chronology research, (3) PDDs that display peaks in luminescence curves during stages of activation and peaks in radiocarbon curves during periods of stabilization in both regions, (4) time-slice maps of dune activity and stabilization for both regions in 200-year increments, and (5) a discussion of potential forcing variables relating to activation and stability events in both regions.

Chapter 2: Literature Review

Abundant research has been conducted on sand dunes and dune chronologies in the Great Plains and Great Lakes regions. The evaluation of this literature is organized into four sections. The first section is a broad review of eolian processes as they relate to the mobilization of wind-blown sand. The second section is a discussion of the types of dunes associated with the study regions. The third section is a survey of dating methods used in the reconstruction of dune chronologies in both regions. The fourth section is a review of previous studies and dates obtained from sand dunes in the Great Plains and eastern coastal zone of Lake Michigan.

2.1: Eolian Processes and Landforms

2.1.1: Eolian Processes

Given the scope of this study it is important to have an understanding of how flowing air can shape sandy terrain. Bagnold (1941) was the first to study the physics of wind-blown sand through a series of wind tunnel experiments, showing a relationship between wind velocity and movement of sand grains. Sand grains are relocated in eolian environments mainly as contact load via saltation and creep (Figure 2.1). Saltation describes grains that reflect across a sand dune, and creep occurs when grains roll or slide across a sand dune (Bagnold, 1941; Ritter, 1986; Bloom, 1991).

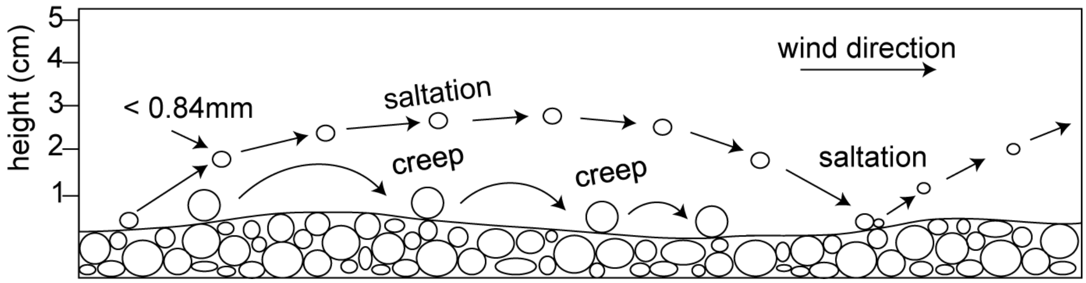


Figure 2.1: Illustration of the saltation and creep processes (modified from Ritter, 1986).

The predominant variable for both saltation and creep is wind velocity. For example, erosion by wind in dune fields occurs largely via deflation, which is the effect of volatile air mobilizing loose sand. According to Ritter (1986), the minimum velocity for desert sand mobilization is 16 km/hr, but specific values are contingent upon density, shape, soil moisture, surface irregularities, mineralogy, and sorting (Bagnold, 1941; Belly, 1964; Williams, 1964; Woodruff and Siddoway, 1965; Gerety and Slingerland, 1983; Greeley et al., 1983).

The main factor dictating minimum velocity of wind is the diameter of sand particles, with 0.84 mm the apparent upper limit for unassisted eolian transport (Bagnold, 1941). Larger particles are kept in place by saltating grains bouncing across the surface. Once a sand grain becomes airborne, wind transport carries it on an irregular, short path within 3 cm of the surface (Bagnold, 1941). As the grains return/descend to the surface, their impact can entrain other small particles on the landscape, propelling them into the air. Although sand grains are initially moved by other smaller particles, the grains are ultimately propelled forward because of wind moving above the surface; wind speed is close to zero nearer to the surface, but increases dramatically as elevation from the surface increases (Bagnold, 1941). Sand grains larger than 0.84 mm do not enter the airstream above the surface, and move along the surface via creep, which is the result of saltating grains propelling larger sand grains forward without pushing them upward (Bagnold, 1941).

2.1.2: Landforms Associated with Eolian Sand

A variety of landforms can develop from the accumulation of eolian sand, the largest being sand sheets and sand seas. Sand sheets are broad areas of sand that exhibit little to no surface relief, while sand seas develop in massive deserts (e.g. Sahara) where tremendous amounts of sand develop a multitude of sand sheets and dune forms (McKee, 1979). Within the complex of eolian landscapes, sand dunes have been the focus of the most geomorphic study (Ritter, 1986).

Dune forms develop as a result of the interaction of three factors: vegetation, prevailing winds, and sand supply (Olson, 1958a). When grains of sand begin moving, they will continue to do so until wind speed drops below a critical velocity. As this happens sand grains begin to fall out of suspension and be dropped onto the surface. At microscale this usually happens when obstacles are present, such as vegetation, which cause wind speed to decrease minimally (Olson, 1958a). In the early stages of dune formation, a small mass of sand will begin to accumulate.

As sand deposition continues, the sand mass starts to develop a profile typically associated with sand dunes. These profiles consist of three separate elements: an erosional surface or backslope, crest, and a depositional surface or slip face (Figure 2.2). The typical backslope angle is ~8-15°, with the slip face angle positioned between 30-35°, which is near the angle of repose (Livingstone and Warren, 1996; Pye and Tsoar, 2009).

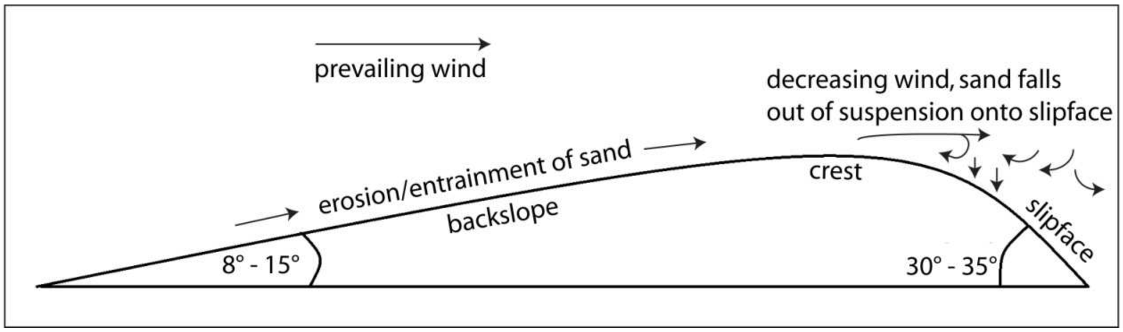


Figure 2.2: Cross-section of a typical sand dune (modified from Ritter, 1986).

Differences in wind direction and velocity, particle size, and vegetation, for example, can result in very distinctive characteristics in many dunes (Ritter, 1986). In spite of the complexity of dune formations, several attempts have been made in the literature to classify sand dunes based upon appearance (e.g. Bagnold, 1941; Hack, 1941; McKee, 1966, 1979). Classification relies mostly on any of a number of distinctive traits including shape, direction in which “arms” are oriented, evolution, and wind direction. Figure 2.3 illustrates how certain types of dunes might develop based upon sand supply, wind, and vegetation.

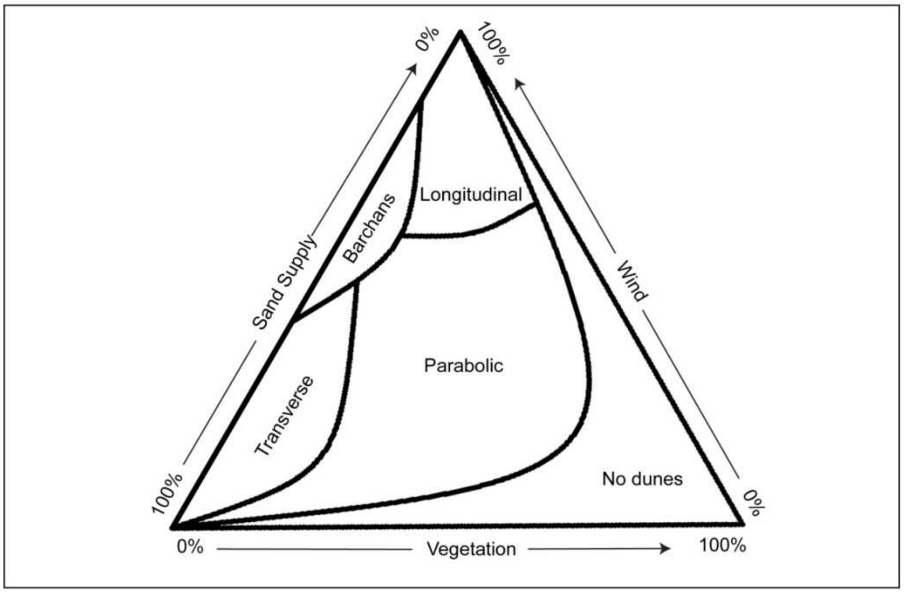


Figure 2.3: Illustration of dune form in response to sand supply, vegetation, and wind power. Constant wind direction is inferred (modified from Hack, 1941).

2.2: Dune Types

According to McKee (1979), nine classes of dune forms are recognized (Figure 2.4) that can, in turn, be divided into two groups: those that form in the presence of vegetation, and those that form in extremely arid environments where plants are absent. The two dune forms that develop in the presence of vegetation are parabolic dunes and blowout dunes. Parabolic dunes are noted for their crests bowing downwind, with elongated arms following the dune (Figure 2.4). The elongated arms are fixed by vegetation, while most of the sand in the dune moves forward downwind (Ritter, 1986). Blowout dunes are common in what was once the backslope of an existing parabolic dune (Figure 2.4), but can also be the initial landform in development of parabolic dunes. Blowouts form as a result of reduced vegetation, which allows wind to move sediments forward, leaving a bowl-shaped depression.

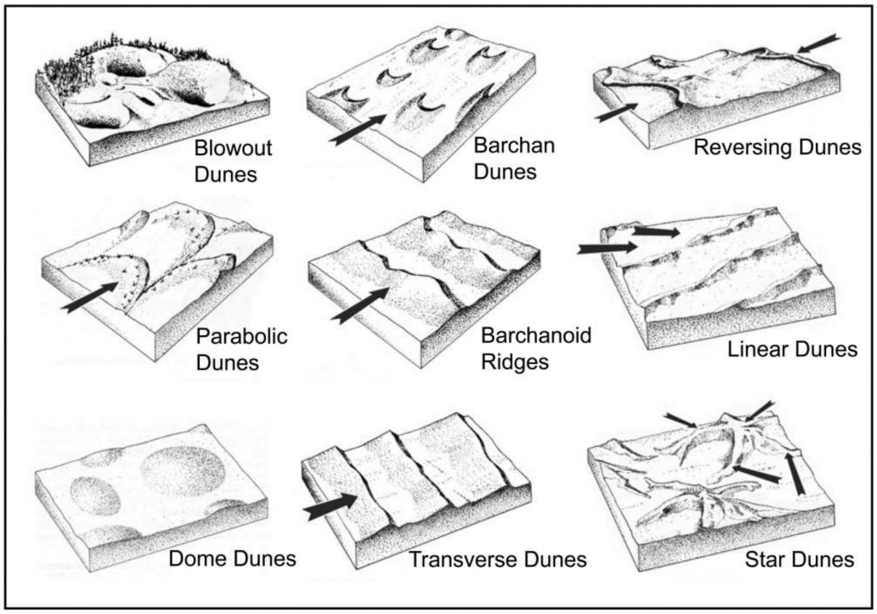


Figure 2.4: Basic dune forms. Arrows indicate wind direction (modified from McKee, 1979).

Compound parabolic dunes also occur in many places where several dunes are superimposed, or often as part of a complex dune field where more than one type of dune has formed (Breed and Grow, 1979). Parabolic and blowout dunes both typically form when sand supply is high and in areas of strong wind.

The remaining dune types in Figure 2.4 typically form without the presence of dense vegetation. Barchan (or cresentic) dunes, barchanoid ridges, and transverse dunes (Figure 2.4) are genetically similar and are the typical dune forms in sandy terrain (McKee, 1979). Barchan dunes have a shape opposite to that of parabolic dunes, with arms extended downwind, and typically form where sand supply is limited but where strong winds are present. Several joined barchan dunes can form barchanoid ridges, which are asymmetrical dunes that form at right angles to the prevailing wind direction, with the barchan dunes themselves forming a wave-like feature in the ridge (McKee, 1979). These ridges form in areas where sand supply is not limited, and weak winds prevail (Bloom, 1991).

If consistently strong winds are present, or multi-directional winds continue, the crest of a barchan dune may be reduced and the backslope flattened, resulting in coppice (or dome) dunes (Figure 2.4). Coppice dunes are a common landform in sand plains and desert areas, where blowing sand and small shrubs are abundant. These dunes typically form around small bushes, and are varying in size based upon sand supply.

Transverse and linear dunes (Figure 2.4) are both ridge-like features that form in environments without vegetation and/or moisture. Transverse dunes typically develop perpendicular to wind direction, whereas linear dunes normally form parallel to the prevailing wind direction, with some seasonal shifts in prevailing wind direction occurring (McKee, 1979). Reversing dunes (Figure 2.4) typically take on any of the forms mentioned previously, and occur in regions where wind direction reverses periodically. Reversing dunes often possess major and minor slipfaces oriented in different directions (McKee, 1979).

The last dune form to discuss is the star dune (Figure 2.4). Star dunes are predominantly found in sand seas and deserts, and develop as a result of multidirectional winds, an abundance of sand, and no vegetation. These dunes are pyramidal mounds of sand, with slipfaces on three or more arms that radiate outward from the center of the mound (McKee, 1979).

2.3: Dating Methods

Researchers have attempted to construct dune chronologies since the late 19th century (e.g. Hay, 1893; Haworth, 1897; Cowles, 1899), with early studies mostly qualitative in nature, utilizing stratigraphic interpretation and soil development as relative proxies for chronology. More recently, researchers have been able to quantitatively construct dune chronologies globally through the use of two primary methods: radiocarbon and luminescence dating (Pye and Tsoar, 2009). The following is a discussion of both methods.

2.3.1: Radiocarbon Dating

Radiocarbon dating has been widely utilized for reconstruction of dune chronologies. Developed by Arnold and Libby (1949), this method is based upon the nature of the carbon cycle and the relationship among three carbon isotopes, specifically ^{12}C , ^{13}C , and ^{14}C. The first pair are stable isotopes, whereas ^{14}C is radioactive and thus unstable.

In order to clearly understand the radiocarbon dating process, a discussion about the carbon cycle (Figure 2.5) is necessary. Carbon-14 (^{14}C)

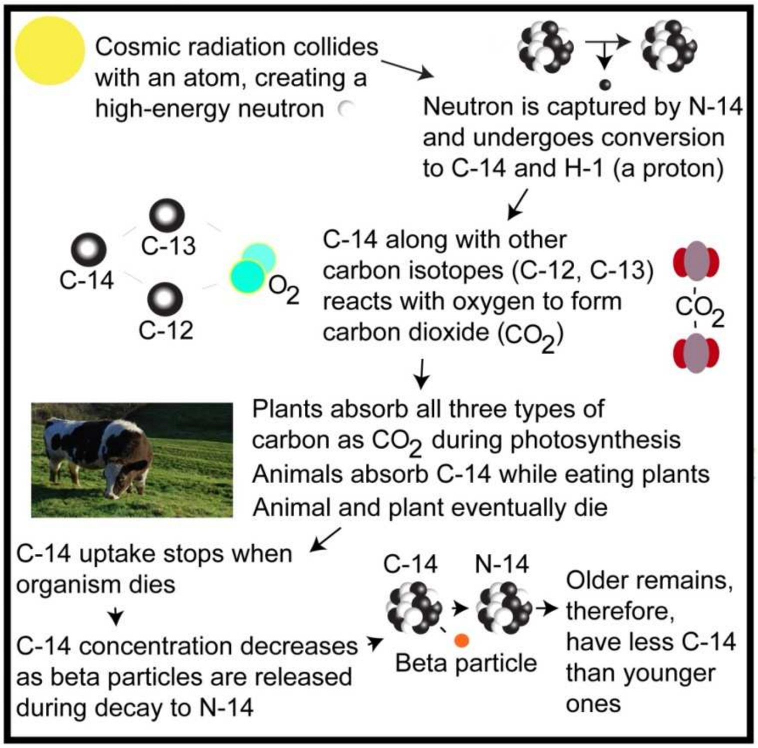


Figure 2.5: Illustration of the carbon cycle.

production is a result of a collision of high-energy neutrons produced by cosmic rays and nitrogen ($^{14}N_2$) gas. The ^{14}C isotope is rapidly changed to $^{14}CO_2$ and is absorbed by plants through photosynthesis and is incorporated into an animal's biomass through herbivory (Schaetzl and Anderson, 2005). While the plant or animal is alive, it continues to absorb ^{14}C. Uptake of ^{14}C stops upon death, at which time ^{14}C begins to decay logarithmically at the known half-life of 5730±400 years (Arnold and Libby, 1949) (Figure 2.6). Materials used to produce a radiocarbon date must have been living at some period. These materials include wood fragments, organic matter from decaying plants and animals, shells, bone, ceramics, and bulk soil humates (Holliday, 1989).

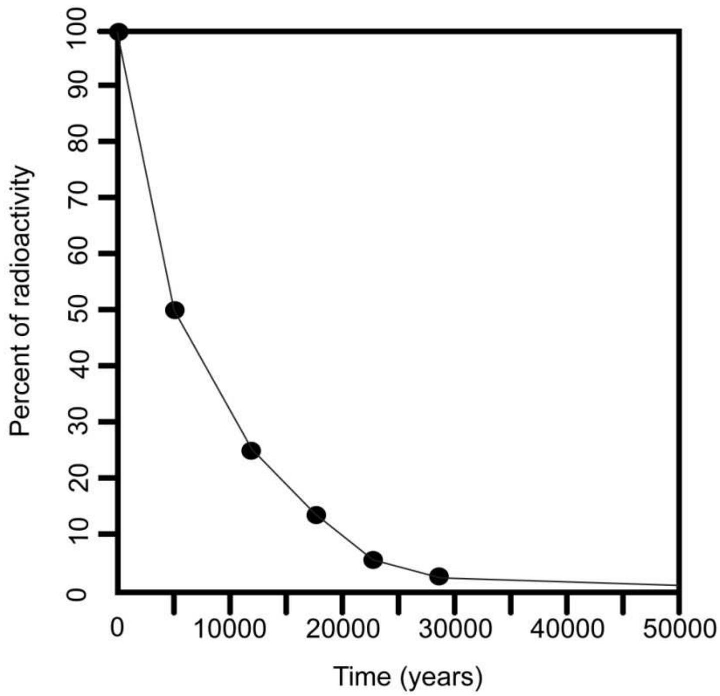


Figure 2.6: Radiocarbon half-life curve (modified from Arnold and Libby, 1949).

2.3.2: Age Considerations

Given the multitude of applications with radiocarbon dating, there are many considerations to take into account with respect to dune-chronology research. The first is the interpretation of the age obtained via sampling. Laboratory ages are typically reported with a mean date plus or minus two standard deviations. Therefore, a date provides a statistical statement – not an exact period of time – and should only be viewed in context of probability.

Additional considerations are presented within the research design. For instance, given the half-life of ^{14}C, radiocarbon dating can only be utilized for samples ranging from ~50,000 years ago to the present (Kolstrup, 2007). Another consideration to take into account is that radiocarbon dates on a buried paleosol may only provide a maximum or minimum limiting date for a dune-building event, and do not provide information about sand movement over shorter periods of time, most notably when paleosols are unable to develop (Rich and Stokes, 2011). Thus, solely utilizing radiocarbon dating for chronologies of buried soils in dunes may not show all periods of dune stabilization and activation throughout the period sampled.

2.3.3: Sources of Error within the Radiocarbon Dating Method

Many potential sources of error are possible within the radiocarbon dating method. One potential source of error exists with the type of material used to produce a radiocarbon date. For example, shells often exchange carbon with soils or water surrounding them, altering their radiocarbon age and making them appear older (Bowman, 1990). The marine reservoir effect can also impact the accuracy of radiocarbon dates. According to Stuiver and Braziunas (1993), sample materials that obtain carbon from an alternative source (reservoir) than atmospheric carbon could potentially yield what are termed “apparent ages.” For example, the average difference between a terrestrial sample and marine sample of the same age is about 400 radiocarbon years. The apparent age of the marine sample is influenced by two possible causes: 1) a delay in exchange rates between atmospheric CO_2 and ocean bicarbonate, and 2) a dilution effect caused by mixing of surface waters with upwelled deep waters that are very old (Mangerud, 1972). For example, a shellfish that is presently alive in a marine environment within a limestone catchment will likely yield a radiocarbon date that is much older than the true age of the shellfish. This occurs because the limestone, which is weathered and eventually dissolved into bicarbonate, has no radioactive carbon. Through dilution, the radioactivity of the lake is depleted in comparison to radiocarbon activity elsewhere. Therefore, marine dates often require correction to account for this issue (Stuiver and Braziunas, 1993).

Fluctuations in atmospheric ^{14}C levels through time (secular variation) caused by alterations in the earth's magnetic field, as well as changes in sunspot activity, pose a potential issue as far as accuracy (Kigoshi and Hasegawa, 1966; Bowman, 1990) is concerned. Additionally, increased levels of atmospheric ^{14}C post-1950 were detected after nuclear bomb testing and subsequent radiation fallout (de Vries, 1958). According to Taylor (1987), bomb testing may have as much as doubled the amount of ^{14}C in terrestrial carbon-bearing materials. To correct for these variations through time, radiocarbon dates are often calibrated. The most popular calibration method has been by dendrochronology (tree-ring curves).

The first extensive tree ring correction curve was compiled by Suess (1967), who examined ^{14}C levels in tree rings extracted from trees alive prior to 1950. Many calibration curves have been utilized in the years that followed as a result of more robust data sets, duplicate sampling, and improved radiocarbon dating methods. The current tree ring correction curve utilized by researchers is that developed by Reimer et al. (2004), and is shown in Figure 2.7. Convention dictates that calibrated radiocarbon dates are reported as “cal yrs BP” in the literature to differentiate them from uncalibrated dates. The base year used for

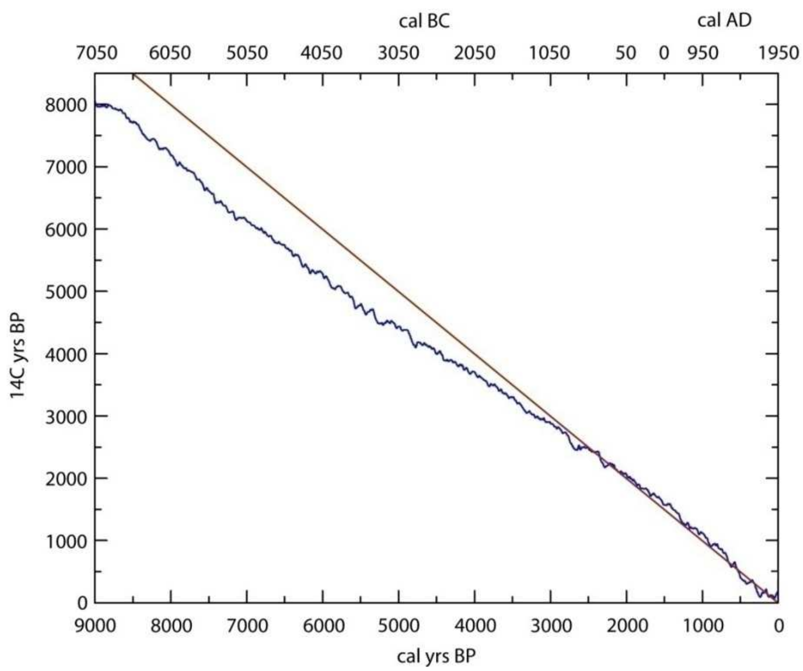


Figure 2.7: IntCal04 tree-ring calibration curve. Red line indicates linear time, with the blue line indicative of secular variation (modified from Reimer et al., 2004).

measurements of how old a sample is via ^{14}C methods is A.D. 1950, reported as “yrs BP.” The year 1950 is used for no particular reason other than to recognize the publication of the first radiocarbon dates calculated in December of 1949 (Taylor, 1987).

2.3.4: Luminescence Dating

In addition to radiocarbon dating, luminescence dating can also be used to reconstruct dune chronologies. This method is broadly based on the premise that the emission of luminescence in sand samples is the measure of time since the last light exposure during transport (e.g. saltation, creep), deposition, and burial of the host deposit (Aitken, 1998; Clarke et al., 1999). Developed by Huntley et al. (1985), luminescence dating is best utilized on samples dating from ~200,000 years old to modern (Schaetzl and Anderson, 2005), but has been shown to accurately date materials up to 780,000 years old (Watanuki et al., 2005; Wang et al., 2006). A discussion of the geoscientific applications of luminescence dating is presented here, but will not address the physics of the technique. Details about the physics of the technique can be found in the literature (e.g. Aitken, 1998; Berger, 1994; Forman, 1989; Wintle, 1993; Duller, 1996) and the references found within those articles.

A luminescence date is obtained by measuring the amount of stored radiation trapped within defects in a quartz grain, also called “crystal lattice” defects (Keizars et al., 2008). Radiation within the crystal lattice comes from alpha, beta, and gamma radiation emitted during the decay of ^{235}U, ^{238}U, ^{232}Th, ^{40}K, and ^{87}Rb, as well as their daughter products, both within the mineral grain and in their surroundings (Lian, 2007), and is “trapped” within the crystal lattice defects. When excited by heat or light, the radiation stored within the traps is capable of escaping (Figure 2.8). A date is determined by measuring the amount of electrons released from the crystal lattice through stimulation by heat or light, depending upon the luminescence method used (Stokes, 1999). A luminescence date, or age, is determined by the following equation:

$$AGE = D_E / D_R$$

with AGE estimating the date of burial, D_E representative of the absorbed dose or equivalent dose (total amount of radiation absorbed within the sediment traps, using the conventional unit of “gray” (Gy)), and D_R representing the dose rate, or dose of radiation that the sand grain can store. The dose rate is determined in

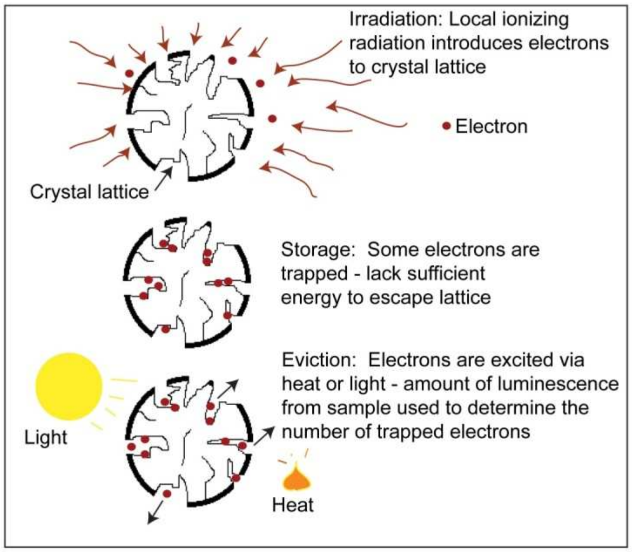


Figure 2.8: Illustration of the methods used to obtain a luminescence date (modified from Aitken, 1998).

the lab from a separate sample collected at the same site as the luminescence sample (Rhodes, 2011).

Three luminescence dating methods are commonly used (Figure 2.9): specifically, thermoluminescence (TL), infrared stimulated luminescence (IRSL), and optically stimulated luminescence (OSL), with OSL being the most widely used method. Luminescence dating has been shown to produce consistent age estimates on sand dunes on both the Great Plains and the eastern Lake Michigan coastal zone (e.g. Wolfe et al., 2002; Rich and Stokes, 2011; Halfen et al., 2012; Lovis et al., 2012). For example, Wolfe et al. (2002) collected samples from the crest, lee slope, and stoss slope of an active dune in the Brandon Sand Hills of Manitoba to determine the accuracy of IRSL dating with modern dune activity. Samples conveyed dates of 1 ya from the lee slope, 8 ya from the crest, and 38 ya from the stoss slope. The dates were found to be consistent with expected high rates of sand deposition on the crest and lee slope of a dune, as well as expected net erosion of the stoss slopes of dunes (Wolfe et al., 2002). In addition, Wolfe et al. (2002) obtained IRSL samples from a dune roadcut and radiocarbon samples from intervening paleosols in the dune. The IRSL ages collected from eolian deposits in stratigraphic sections were found to be in the correct chronological sequence, both in terms of stratigraphic position and to radiocarbon ages obtained from organic matter in the buried soils, suggesting that activation events occurred at ~5600, 4000-3100, and ~2000 years ago (Wolfe et al., 2002). Convention dictates that luminescence dates are reported as “ya” (years ago) in the literature to differentiate them from radiocarbon dates.

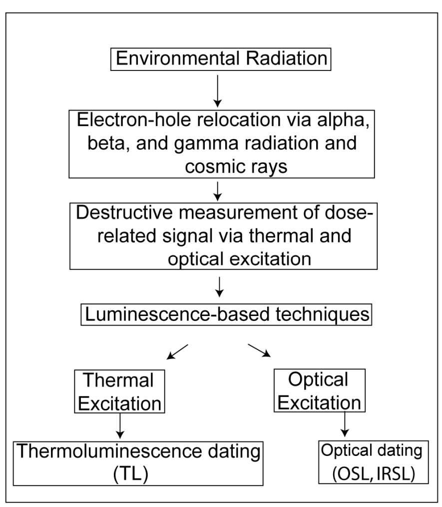


Figure 2.9: Review of dating methods relating to environmental radiation and process (modified from Stokes, 1999).

2.3.5: Sources of Error within Luminescence Dating Method

There are several potential sources of error with luminescence dating that may yield inaccurate ages. In particular, the OSL dating method assumes that the sand grains were sufficiently exposed to sunlight before burial, effectively "zeroing out" any radiation being held within the sand grain. If the sand grain was only partially bleached when it was buried, it can potentially yield a date older than burial (Schaetzl and Anderson, 2005). OSL can also yield a date younger than burial if sand grains are partially bleached by post-depositional disturbance. For example, Bateman et al. (2003) demonstrated that bioturbation could affect the accuracy of OSL dating in pocket gopher burrows in the Great Plains due to exposure and subsequent reburial as a result of excavation. Dose rates can also differ based upon the sample and geographic location (H. Wang, personal communication).

2.4: Northern Great Plains Dune Fields

2.4.1: Manitoba

Several dune fields occur in the northern Great Plains. The Brandon Sand Hills (BSH) and Lauder Sand Hills (LSH) are located in southwestern Manitoba (Figure 2.10). The BSH cover an area of ~1400 km^2 and are derived from sandy deposits of the Assiniboine delta of Glacial Lake Agassiz (Elson 1960). The Sand Hills consist of southeast-trending, stabilized parabolic dunes and some stabilized blowouts.

Early studies in the area were conducted by David (1968, 1971), who sought to determine the chronology of dune activation. Twelve radiocarbon dates obtained by David (1971) as well as an additional radiocarbon date from Lowdon and Blake (1975) suggested a short period of dune stability prior until ~3700 yrs BP, and ensuing activity around 2100, 1500, 900, and 400 yrs BP. Periods of dune activity were assumed to be the result of regional drought events. Additional research by David (1977, 1979) involved study of time-lapse aerial photographs from the mid-20th century, with results showing more recent stabilization trends throughout the region.

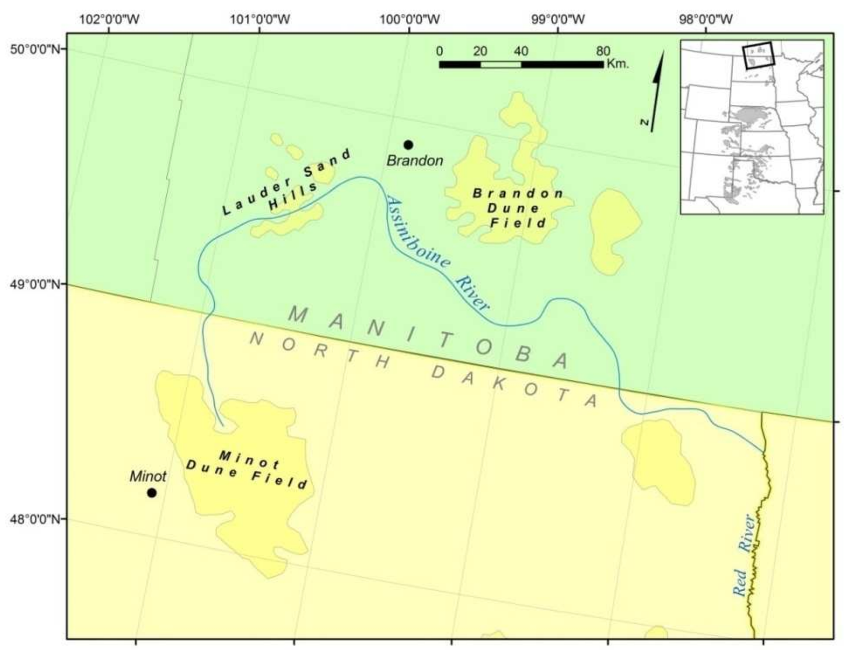


Figure 2.10: Dune fields in the Northern Great Plains.

Following the work by David (1968, 1971, 1977, 1979) and Lowdon and Blake (1975), Wolfe et al. (2000) published 25 radiocarbon dates as part of a study that assessed activation events in the region. Results suggested periods of dune stability at ~2150, 1200, and 550 yrs BP, with dune activity occurring between the periods of stability. Periods of activity were thought to correspond with episodes of regional drought previously recorded in northern Great Plains lakes (Fritz et al., 1991). The most recent study conducted on dunes in the BSH was by Wolfe et al. (2002) that produced results suggesting activation events at ~5600, 4000-3100, and ~2000 years ago, using infrared stimulated luminescence (IRSL) dates.

The LSH are located in southwestern Manitoba (Figure 2.10) and cover an area of ~70 km^2. The Sand Hills consist of southeast-trending parabolic dunes with long, northwest-oriented arms. The first study of the LSH was conducted by Running et al. (2002), who examined the Holocene history of the area. Their research, based on radiocarbon dates, suggested that parabolic dune migration took place from 6700-5400 yrs BP, and again at least six times from 3250 yrs BP to the present. Havholm and Running (2005) conducted the most recent research in the LSH, which examines dune stratigraphy and sedimentology using four radiocarbon dates and previously published (e.g. Forman et al., 1995; Mason et al., 1997; Stokes and Swineheart, 1997; Wolfe et al., 2002) radiocarbon and luminescence dates. Data suggest that dune mobilization occurred ~6100 years ago, and was likely tied to broader-scale drought events in the Great Plains (Havholm and Running, 2005).

2.4.2: North Dakota

A small number of dune fields also occur in North Dakota. The largest is the Minot dune field, which is located in the north-central part of North Dakota

(Figure 2.10), and covers an area of ~1500 km^2. The dunes in the area consist of southeast-trending stabilized parabolic dunes with limbs oriented to the northwest (Muhs et al., 1997a). Early studies in the Minot area involved extensive soil mapping (e.g. Knobel et al., 1926; DesLauriers, 1990) and sand mapping (e.g. Clayton et al., 1980; Bluemle, 1982; 1985; and Lord, 1988).

The only quantitative study on the Minot dune field was conducted by Muhs et al. (1997a). Ten radiocarbon dates were reported on paleosols, and results indicated that there were at least two episodes of dune activity in the past 1200 years, with the earliest event represented by a radiocarbon age of 1260 yrs BP. The authors attributed dune activation to a lack of vegetative cover and drought (Muhs et al., 1997a).

2.5: Central Great Plains Dune Fields

2.5.1: Nebraska

Several dune fields occur within the central Great Plains, ranging from Nebraska to central Colorado (Figure 2.11). The largest dune field in the region is the Nebraska Sand Hills (NSH), which covers an area of about 57,000 km^2 and is the largest sand sea in the western hemisphere (Smith, 1965; Ahlbrandt and Fryberger, 1979). The NSH are bordered by the Niobrara River to the north and the North Platte and Platte Rivers to the south (Figure 2.11). Through early geomorphic investigation, the NSH were thought to be no younger than late Pleistocene in age, based upon the description of sediments below the dunes and loess adjoining the area (Lugn, 1935; Smith, 1965). The source has been debated through other studies (e.g. Reed and Dreeszen, 1965; Stanley and Wayne, 1972), with the most commonly agreed upon origin for NSH sands suggesting the upper Tertiary Ogallala Formation as their source (Lugn, 1960; 1962; Swineheart, 1990).

Dunes in the region consist of parabolic dunes, compound parabolic dunes, barchan dunes, barchanoid dune ridges, and longitudinal dunes (Loope and Swineheart, 2000; Mason et al., 2011). “Megabarchans” are also present in the Sand Hills area, with some more than 100 meters high and several kilometers long (Mason et al., 2011).

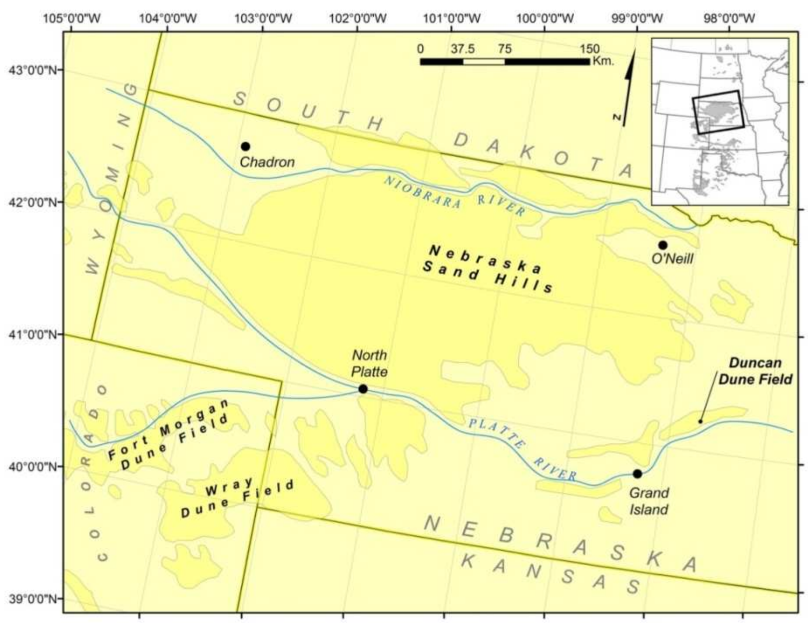


Figure 2.11: Dune fields in Nebraska and north-eastern Colorado.

Previous studies in Nebraska focused on dune morphology and texture of the dune sand (Lugn, 1935; Smith, 1965; 1968; Warren, 1968; Warren, 1976; Ahlbrandt and Fryberger, 1980). Ahlbrandt and Fryberger (1983) were the first to report radiocarbon dates from dunes in Nebraska. Their dates, ranging from

5150-860 yrs BP, suggested for the first time that the NSH were much younger than the late Pleistocene timeframe previously thought (Lugn, 1935; Smith, 1965).

Muhs et al. (1995b, 1997b) reported 19 radiocarbon dates from the NSH. The dates range from 4330-220 yrs BP and suggested that sand deposition occurred at least twice in the last 4000 years. Stokes and Swineheart (1997) reported 16 dates from the NSH, with eight radiocarbon dates ranging from 5300-270 yrs BP and eight OSL dates ranging from 5730-210 ya. These dates suggested that dune activation events took place at least twice during the mid-Holocene. Goble et al. (2004) collected six radiocarbon dates ranging from 4150-modern yrs BP and 35 OSL dates ranging from 6180-150 ya, suggesting five different dune activation events in the mid-to-late Holocene in the NSH. Mason et al. (2004) collected seven radiocarbon dates ranging from 4150-modern yrs BP and 10 OSL sample dates ranging from 3900-180 ya, and suggested the youngest reactivation event likely took place between 1000-700 years ago during an extended period of drought.

More recent studies in Nebraska have focused on the collection of OSL dates from previously-studied dune fields, as well as unstudied fields. In a study conducted in the western NSH and Wray dune field, Forman et al. (2005) collected 32 OSL samples, with dates ranging from 1490-40 ya, and suggested that six different dune activation events took place in western Nebraska in the past 1500 years. Hanson et al. (2009b) collected 18 OSL dates as part of their study of the Duncan dune field, the easternmost dune field in Nebraska. Dates ranged from 5070-490 ya, suggesting that the Duncan dune field was active at least twice in the past ~5000 years, between ~4400-3400 years ago and again during the MWP. According to Hanson et al. (2009b), the dune field was likely active as a result of regional megadrought in each case. The most recent study on dunes in Nebraska was conducted by Mason et al. (2011). Their study contributed 12 mid-to-late Holocene OSL dates, ranging from 7500-490 ya, with their findings suggesting several periods of dune activation in the past 7000 years.

2.5.2: Northeastern Colorado

Several dune fields occur in northeastern Colorado, with the largest fields being the Wray, Sterling, Fort Morgan, and Greeley dune fields with a combined area of 4,700 km^2 (Figure 2.11). Derived from South Platte River sediments, dunes in the region are mostly parabolic in form with southeast-trending crests and arms oriented to the northwest (Muhs, 1985, 2000). Early studies in northeastern Colorado were conducted mostly for geologic mapping purposes (Thorp and Smith, 1952; Hill and Tompkin, 1953; Colton, 1978; Scott, 1978; Trimble and Machette, 1979; Bryant et al., 1981).

The first effort to determine the age of dunes in northeastern Colorado was conducted by Muhs (1985) through the use of soil-stratigraphic methods. Dates of 3000-1500 yrs BP were estimated based upon previous studies dating paleosols from the southern High Plains (e.g. Gile, 1979). Forman and Maat (1990) estimated that dunes most recently stabilized about 3000 years ago near

Hudson, Colorado, based upon the morphology of surface soils. Jorgensen (1992) estimated that young, high relief dunes in the Fort Morgan Dune Field formed about 1500 years ago based upon a regional comparison of soil properties.

Madole (1994) reported the first radiocarbon dates from northeastern Colorado. Eight radiocarbon dates were obtained and ranged from 1380-810 yrs BP. These dates suggested periods of stability in the southern Platte River area. Madole (1995) also reported 10 radiocarbon dates from paleosols in northeastern Colorado that show episodic periods of stability from 5640-810 yrs BP. Forman et al. (1995) obtained four radiocarbon dates from paleosols within dunes on the south side of the South Platte River, reporting dates ranging from 5520-920 yrs BP. Muhs et al. (1996) reported radiocarbon dates from the Fort Morgan and Wray dune fields, reflecting episodic dune reactivation during the Late Holocene, with the youngest date falling within 1500-1000 yrs BP. In the most recent study of dunes in Colorado, Clarke and Rendell (2003) collected eight samples from the Fort Morgan dune field, with reported infrared stimulated luminescence (IRSL) dates ranging from 4850-370 ya. These dates suggested that dunes in northeastern Colorado were also episodically active during the late Holocene megadrought events in the region.

2.5.3: Kansas

A variety of dune fields exist throughout central and southwestern Kansas (Figure 2.12). The largest dune fields in the region are the Great Bend Sand

Prairie, Hutchinson, Abilene, and Arkansas River dune fields, with a combined area of ~5400 km^2. Derived from late Wisconsin deposits, reworked eolian sands, and deflated alluvium from the Arkansas River (Simonett, 1960; Arbogast, 1996; Arbogast and Muhs, 2000; Halfen et al., 2012), dunes in Kansas are mostly parabolic and crescentic in shape, with arms oriented in the direction of northwesterly prevailing winds through time. Transverse dunes, sand sheets, barchanoid ridges, and blowouts are also present throughout Kansas (Smith, 1940; Forman et al., 2008; Hanson et al., 2009a; Werner et al., 2011; Halfen et al., 2012).

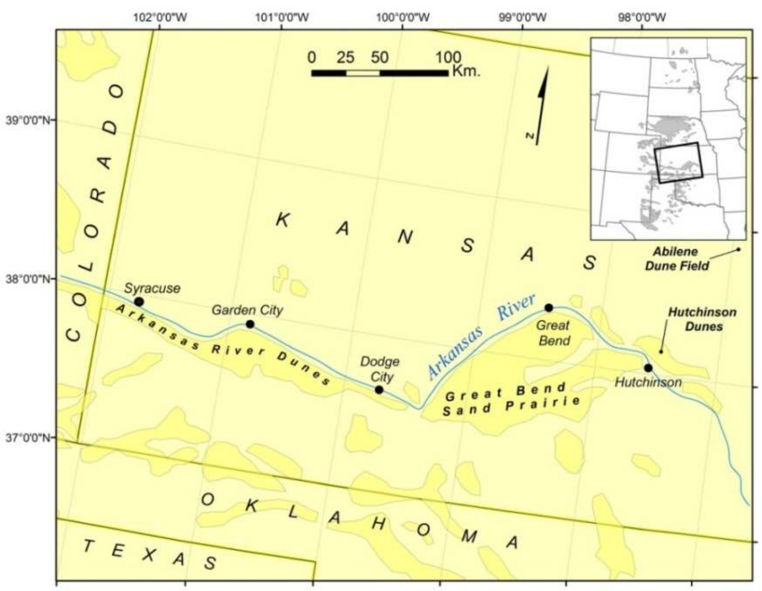


Figure 2.12: Dune fields in central and south-western Kansas.

Early dune studies in Kansas were qualitative in nature and focused on the Arkansas River valley. Studies conducted by Hay (1893) and Haworth (1897) sought to determine the source of sand for dunes along the Arkansas River, suggesting the local Ogallala Formation as a source (Hay 1893), as well as nearby valley sands (Haworth, 1897).

The first study using paleowind direction to infer a source for dune sand was conducted by Moore (1920). He suggested that the source of sand for the Arkansas Valley dunes was the Arkansas River floodplain, based upon assumed northwesterly paleowinds. Smith (1937) noted three separate soil sections in a blowout near the Hutchinson dune field, and suggested that there were three different periods of activation and stabilization in recent history. Strike and dip measurements in a basal dune also led Smith (1937) to suggest that northeasterly paleowinds formed the dune. Smith (1939, 1940) was the first to discuss vegetation as a factor in dune morphology in Kansas. Given the prevalence of parabolic dunes in the region, he suggested that some vegetation had always been present during the course of dune formation.

Simonett (1960) sought to further determine the age and origin of dunes in Kansas. Working along the Arkansas River near Syracuse, he obtained cores across the area. The presence of Peoria loess in the cores showed a more northerly source for the dune sand, as the loess section was thinner in the southerly cores. In the same study, Simonett (1960) was also able to show that more recent southerly winds had reworked dunes in the Syracuse area, based upon the location and orientation of blowouts.

A study by Porter et al. (1994) in the Cimarron River valley indicated that dune ages could be estimated based upon the morphology of soils. For example, they found that older dunes possessed surface soils with A/Bt/2Bk horizonation and younger dunes had a less developed A/C profile (Porter et al., 1994). In a review of the accounts of early surveyors in the Arkansas River valley, Muhs and Holliday (1995) cited evidence for active sand in the Great Bend Sand Prairie (GBSP). Areas of active and inactive dunes extended west along the Arkansas River into Colorado, suggesting that sand movement along the stream valley varied extensively depending on location.

The first quantitative studies were conducted in the GBSP in the mid-1990s. Arbogast (1996) reported 23 radiocarbon dates from the GBSP, ranging from 6050 yrs BP-modern. The dates indicated that at least five different periods of soil formation had occurred in the region at ~2300, 1400, 1100-900, 700-500, and 300 years ago, and compared well with other late Holocene studies in the Great Plains (e.g. Ahlbrandt et al., 1983; Muhs, 1985). A study by Arbogast and Johnson (1998) indicated that dunes in the GBSP typically contain one to two weakly developed soils, indicating dune activation periods in the late Holocene. Additionally, the authors suggested that dunes could be easily reactivated if vegetation is minimized, based on the poor development of surface soils (Arbogast and Johnson, 1998). Arbogast and Muhs (2000) utilized mineralogy and trace element concentrations to determine the source of dune sands in the GBSP. This study indicated that dunes in the region are chemically similar to sands in the Arkansas River valley, and also suggested that paleowinds were northwesterly during early sand deposition in the GBSP (Arbogast and Muhs, 2000).

Following the GBSP studies, three radiocarbon dates were collected in the Cimarron Bend area of southwestern Kansas by Olson and Porter (2002), ranging from 5770-1450 yrs BP. Based upon their findings, the authors suggested that two periods of dune activation and stability took place during the mid-to-late Holocene. In the first study to use OSL dates in Kansas, Forman et al. (2008) collected 23 OSL dates ranging from 6280 ya-present from dunes south of the Arkansas River. This study suggested that the dates obtained were reflective of dune activation during previously recorded continental-wide periods of drought in the tree-ring record.

Hanson et al. (2009a) were the first to construct a chronology of the Abilene dune field in eastern Kansas (Figure 2.12). They reported 15 late Holocene OSL dates ranging from 1060-460 ya. The peak activity appears to have occurred during the Medieval Warm Period (MWP). This interval correlates with dune activation in other regions of the Great Plains (e.g., Muhs et al., 1996; Mason et al., 2004; Forman et al., 2005; Hanson et al., 2009b) and suggested that the MWP impacted areas further east than originally thought (Hanson et al., 2009a). As part of a study in southwestern Kansas and northwestern Oklahoma by Werner et al. (2011), eight OSL samples were collected south of the Cimarron River near Liberal. Dates ranged from 6440-520 ya and suggested at least three dune activation events occurred during the mid-to-late Holocene: ~6500-5700, ~3600-2600, and ~800-500 years ago (Werner et al., 2011).

In the most recent dune study in Kansas, Halfen et al. (2012) collected 60 OSL dates from the Hutchinson dune field in central Kansas (Figure 2.12). Dates ranged from 2080-80 ya, and indicated that three major episodes of dune activation took place over the past 2100 years: ~2100-1800, ~1000-900, and after 600 years ago. According to Halfen et al. (2012), the period of activation at ~1000 years ago appears to be coincident with regional-scale dune activity in the NSH (Miao et al., 2007), Duncan Dune Field (Hanson et al., 2009), and Abilene Dune Field (Hanson et al., 2010) during the MWP.

2.6: Southern Great Plains Dune Fields

2.6.1: Oklahoma

Although a number of dune fields exist in northwestern Oklahoma (Figure 2.13), the dunes in the region remain some of the least-studied in the Great Plains. Dune fields in the region are complex, consisting of mostly transverse dunes and barchanoid ridges, with single and compound parabolic dunes also present (Brady, 1989). Few quantitative studies have been conducted on dunes in Oklahoma, with the first study conducted by Brady (1989) in Alfalfa and Major Counties in northwest Oklahoma. He produced two radiocarbon dates from paleosols within dunes, one at 6385 yrs BP and the other 1200 yrs BP. The next quantitative study was conducted by Lepper and Scott (2005) in the Cimarron River valley in southeast Major and northwest Kingfisher counties in northern Oklahoma. Nine late Holocene OSL dates, ranging from 3330-770 ya, were collected, as well as two late Holocene radiocarbon dates, ranging from 1630-1120 yrs BP.

The most recent dune study in Oklahoma was conducted by Werner et al. (2011). Six late Holocene OSL dates were obtained, ranging from 810-460 ya. According to Werner et al. (2011), these dates likely reflect one period of dune activation during the late Holocene.

2.6.2: Eastern New Mexico and Northwestern Texas

Several dune fields are present in the Southern High Plains (SHP) of eastern New Mexico and northwestern Texas (Figure 2.13). The largest dune fields in the region are the Muleshoe, Mescalero, Lea-Yoakum, Andrews, and Monahans dune fields, with a combined area of ~8750 km^2. Dunes in the region are mostly stable except for an area of about 300 km^2 in the Monahans dune field that is still active. Dune forms in the region include parabolic dunes with blowouts, barchan dunes, barchanoid ridges, and coppice dunes (Rich and Stokes, 2011).

Early studies were conducted to study the geology and soils of the region (e.g. Melton, 1940; Wendorf et al., 1955; Green, 1961; Frye and Leonard, 1964; Reeves, 1976; Gile, 1981). The dunes overlie the Blackwater Draw Formation, a late Quaternary eolian deposit thought to be derived from two sources: the Pliocene-Miocene Ogallala Formation (Lugn, 1968), and sediments from the Pecos River Valley (Holliday, 1989). The source of dune sands in the SHP has also been previously attributed to two different sources, the first being the Pecos River Valley (e.g. Huffington and Albritton, 1941; Green, 1961; Hawley et al., 1976; Carlisle and Marrs, 1982). However, geochemical and mineralogical analysis conducted by Muhs and Holliday (2001) indicates a source more like that of the Blackwater Draw Formation.

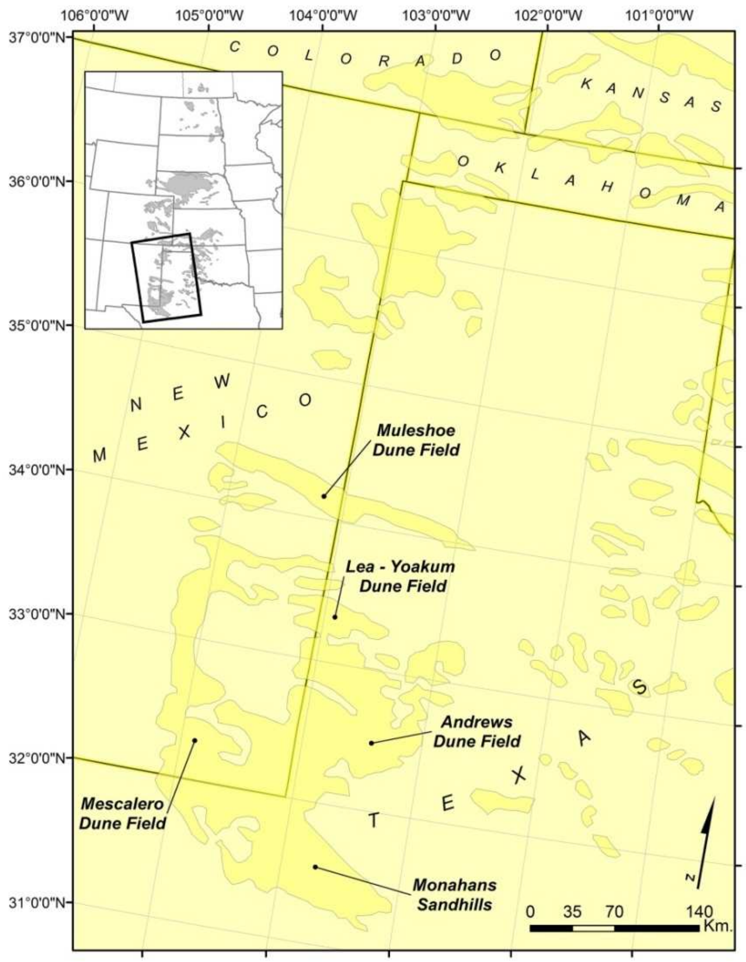


Figure 2.13: Dune fields in the Southern Great Plains.

The first detailed study of Holocene dune activation in this region was conducted by Holliday (1989). Based upon geomorphological, paleontological, and archaeological evidence, he suggested that widespread dune activation occurred across the SHP between 5500 and 4500 years ago, which appeared to correspond with activation events across the broader Great Plains region (Holliday, 1989). As part of a study on the geochronology and stratigraphy of the

Southern High Plains sand, Holliday (2001) collected 19 radiocarbon dates from the Andrews/Monahans, Lea-Yoakum, and Muleshoe dune fields, ranging from 6130 yrs BP-modern. According to Holliday (2001), the Muleshoe dunes were active at least five times during the past 1400 years, and the Andrews/Monahans dunes were active at least twice during the past 2300 years (Holliday, 2001). Feathers (2003) contributed five mid-to-late Holocene OSL dates as part of a study to determine the accuracy of OSL dating on a variety of sediments in the SHP. Dates ranged from 6500-950 ya, indicating that several periods of activation likely took place through the mid-to-late Holocene.

The most recent study in the region was conducted by Rich and Stokes (2011). As part of a broad study of the Muleshoe, Lea-Yoakum, Mescalero, and Monahans/Andrews dune fields (Figure 2.13), 19 OSL samples were collected, with dates ranging from 5100-70 ya. The authors found that all of the dune fields sampled were active at multiple times in the mid-to-late Holocene, as well as during the "Dust Bowl" event in the 1930s.

2.7: Eastern Lake Michigan Coastal Zone

One of the largest systems of freshwater coastal dunes in the world occurs along the eastern coast of Lake Michigan (Peterson and Dersch, 1981) (Figure 2.14). Dunes in this part of the Great Lakes Region have been studied since the late 19th century, with early studies being mostly qualitative in nature. The first of these studies was conducted by Cowles (1899), who studied dune vegetation and evolution of dune forms as related to plant species. The next research was by Dow (1937), who studied the formation of “perched” dunes north of Manistee. Subsequent qualitative dune research continued until the end of the 1970s (i.e. Scott, 1942; Tague, 1946; Olson, 1958a, 1958b, 1958c; Dorr and Eschman, 1970; Buckler, 1979). These studies as a whole provided much of the background for future qualitative and quantitative research.

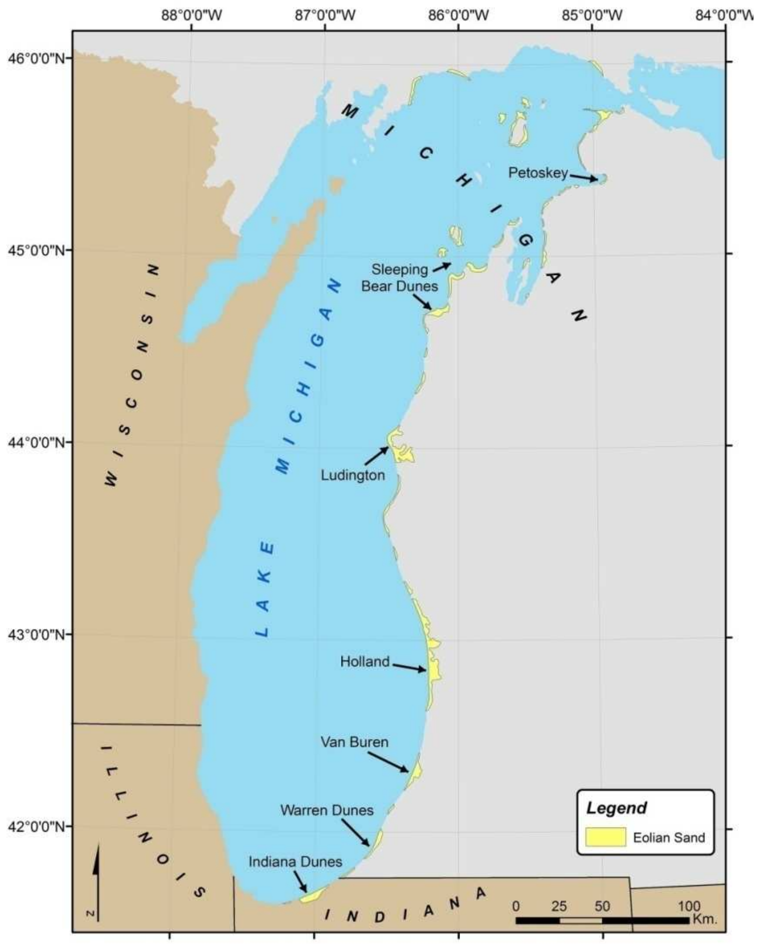


Figure 2.14: Major dune fields along the eastern Lake Michigan coastal zone.

Snyder (1985) was the first to report radiocarbon dates from dunes along the eastern coastal zone as part of a study at Sleeping Bear Dunes National Lakeshore (Figure 2.14). Three radiocarbon dates were collected from paleosols that were exposed as a result of bluff erosion. The stratigraphically lowest soil within the dune produced a date of about 4600 yrs BP, with the middle and upper soils producing dates of about 2800 and 700 yrs BP, respectively. Snyder (1985) interpreted the older date as being from a soil that developed when the lakeshore was far to the west during the Chippewa low phase, with the other two sites representing periods of dune stabilization in the late Holocene.

Following the Snyder (1985) study, radiocarbon dating was utilized extensively in the late 1990s to construct dune chronologies along the eastern Lake Michigan coastal zone. The first of these studies was conducted by Arbogast and Loope (1999) who presented five radiocarbon dates from the Nordhouse dunes, Nugent and Jackson quarries, and the Rosy Mound Natural Area. A sample date of about 4030 yrs BP from the Nordhouse dunes, dates of 3720 and 3730 yrs BP from the Nugent and Jackson quarries, and dates of 2920 and 2890 yrs BP from the Rosy Mound site suggested that dunes formed during the Nipissing high lake phase at the Nordhouse site, and at the other two sites (to the south) the dunes formed sometime later (Arbogast and Loope, 1999).

Following the Arbogast and Loope (1999) study, Loope and Arbogast (2000) collected 75 radiocarbon samples from paleosol outcrops at 32 different locations along Lake Michigan's eastern shore, with dates ranging from 5330 yrs BP to modern. The authors constructed a probability density distribution and compared it with a late Holocene lake level curve created by Thompson and Baedke (1999). The authors found that peaks in soil development coincided with ~150 year high lake-level periods over the past ~1500 years, suggesting cyclical periods of stability (Loope and Arbogast, 2000). In a similar study, Van Oort et al. (2001) collected 16 samples from paleosol outcrops at Van Buren State Park along the southeastern coast of Lake Michigan. Dates ranged from 5160 yrs BP to modern, indicating several periods of dune activation and stability during the mid-to-late Holocene.

As part of a study on dunes along the central part of the eastern coastal zone of Lake Michigan, Arbogast et al. (2002) collected 16 radiocarbon dates from four dunes south of Holland, ranging from 4840-35 yrs BP. Based on the dates, they found that dune activation likely began during the Nipissing high lake stage, with a period of dune stability until about 4000 years ago. Dates suggested that activation occurred around 4000 years ago, with later periods of dune growth at about 3200, 2400, and 900 years ago (Arbogast et al., 2002). The dune activation periods in the late Holocene appeared to coincide with high lake level stages (Baedke and Thompson, 2000). As part of a study on backdune activity near Holland, Hansen et al. (2002) collected four OSL samples from three separate dunes, with dates ranging from 4990-3720 ya. The dates were all within one standard deviation of each another, suggesting that deposition likely occurred in a single activation event (Hansen et al., 2002). The authors attributed this period of dune growth to sands supplied after the Nipissing high lake phase, when sand supply was likely plentiful (Hansen et al., 2002).

In association with these studies, a relatively well-developed paleosol, informally named the “Holland Paleosol,” was recognized in the upper part of the stratigraphic sequence in dunes along the southeastern Lake Michigan coastal zone. Arbogast et al. (2004) collected seven radiocarbon samples from dunes from Montague south to the Indiana Dunes National Lakeshore, with dates ranging from 3090-50 yrs BP. The soil varies in development from weakly developed Spodosols with A-E-Bs-Bw-BC-C profiles, to Entisols with A-Bw-BC-C profiles. As paleosols in dunes typically have weakly-developed A-C horizonation, the development of the soils suggested a long period of dune stability occurred in the region. This Holland Paleosol would probably qualify as a formal pedostratigraphic unit if it were covered by an overlying formal lithographic or allostratigraphic unit (Arbogast et al., 2004).

Following the Arbogast et al. (2004) study, Lepczyk and Arbogast (2005) collected 12 radiocarbon samples from dunes in Petoskey State Park (Figure 2.14), with dates ranging from 4620 yrs BP-modern. The authors found that several episodes of dune activation and stability have occurred over the past 5000 years.

Hansen et al. (2010) published a study conducted at P.J. Hoffmaster and Warren Dunes State Parks that sought to further explain dune chronology in southwestern Michigan. Twenty mid-to-late Holocene OSL dates were reported, ranging from 4360-710 ya. Fourteen radiocarbon dates were also reported, ranging from 2970-180 yrs BP. The authors broadly identified six stages of dune development in southwestern Michigan: a series of dune activation and stabilization stages after deglaciation until ~5700 years ago, activation during the Nipissing phase from ~5700-3800 years ago, a period of stability from ~3800-3300 years ago, dune activation and stabilization as a result of the Algoma phase

~3300-1600 years ago, dune stabilization ~1600-500 years ago, and stages of activation and stabilization in the last 500 years (Hansen et al., 2010).

Following the Hansen et al. (2010) study, Blumer et al. (2012) conducted a study on perched dunes at the Arcadia dune field in northwest lower Michigan using OSL dating to evaluate the chronology of perched dune growth. A total of 12 OSL dates were collected from three separate exposures, ranging from 4500-320 ya. Through pedostratigraphic analysis and analysis of OSL dates, the authors identified four distinct periods of dune activation: ~4500 ya (during the Nipissing phase), ~3500 ya during the post-Nipissing phase, ~1700 ya, and between 1000-500 ya (Blumer et al., 2012). Through comparison of their OSL dates with previous dune chronologies that utilized uncalibrated radiocarbon dates for their analysis (e.g. Snyder, 1985; Anderton and Loope, 1995), Blumer et al. (2012) provided a model for comparisons between uncalibrated radiocarbon and OSL chronologies in dune systems.

The most recent study conducted on dunes along the eastern shore of Lake Michigan was by Lovis et al. (2012). As part of a geoarchaeological study on dune activation, the authors collected 30 mid-to-late Holocene radiocarbon dates ranging from 6550-150 yrs BP, and 28 mid-to-late Holocene OSL dates ranging from 5150-540 ya, suggesting that several periods of dune stability and activation occurred during the mid-to-late Holocene along the eastern Lake Michigan coastline.

2.8: Summary of Past Dune Chronology Research

In summary, the study of dune chronology in both the Great Plains and eastern Lake Michigan coastal zone is a cumulative product of more than a century of early qualitative and more recent quantitative dune research in both areas. Chronological studies in the early 1980s explored the variability of dune activation and stabilization events in each region. A study by Arbogast et al. (2011) drew attention to a similar period of dune activation in the Great Plains and eastern Lake Michigan coastal zone during the Medieval Warm Period, but was limited to data from three sites in the Great Plains and one Lake Michigan site. This research provides an analysis of all radiocarbon and luminescence dates in the literature for both regions, and utilizes probability density distributions (PDDs) and Principal Components Analysis (PCA) along with regional time-slice maps to compare and contrast dune chronologies in both areas.

Chapter 3: Methods

In order to compare the dune chronologies of the Great Plains and eastern Lake Michigan coastal zone over the past 7,000 years, chronological data from published literature for both areas were collected. The methodologies used in this research to compare and contrast dune chronologies are based on the interpretation of peaks in probability density distributions (PDDs), interpretation of dimensions using Principal Components Analysis (PCA), and the analysis of 200-year time-slice maps**.** The use of PDDs has been well documented in previous studies in both the Great Plains and eastern Lake Michigan coastal zone (Forman et al., 2008; Hanson et al., 2009; Blumer et al., 2012; Lovis et al., 2012). No previous record of the utilization of PCA for dune chronology research has been found. Time-slice maps have been used more recently to display regional activation and stability events during the late Holocene in 100-year “slices” of time in the Great Plains (Halfen and Johnson, 2013). These techniques provide different ways to compare and contrast dune chronologies graphically.

3.1: Data Collection

Data for this study were collected as part of the literature review process. The collection procedure was based on three criteria: sites with a mean date between 7000 ya-modern for luminescence dates, and an uncalibrated mean date between 7000 yrs BP-modern for radiocarbon dates, the sample must have been obtained from within a sand dune, and, if applicable, the sample was noted as “reliable” by the author.

Data meeting all of the above requirements were entered into an Excel spreadsheet, and were sorted by location, lab number, author, mean date, standard deviation, and date type (radiocarbon or luminescence). Dates were then separated by region (Great Plains or eastern Lake Michigan coastal zone) into two separate spreadsheets (see Appendix A). Great Plains data were divided further into three subregions for comparative analysis: Northern Great Plains (Manitoba and North Dakota), Central Great Plains (northeastern Colorado, Nebraska, and Kansas), and Southern Great Plains (Oklahoma, eastern New Mexico, and northwestern Texas).

3.2: Probability Density Distributions (PDDs)

The most widely used method to present dune chronologies in the Great Plains and eastern Lake Michigan coastal zone has been through the use of probability density distributions (PDDs) of radiocarbon and luminescence ages (e.g. Hanson et al., 2009a; Blumer et al., 2012; Lovis et al., 2012; Halfen and Johnson, 2013). PDDs display the varying likelihood of probable ages through time (on the x-axis) and normalize the function to unity; in the scope of this research, unity is represented by a value of one (1) on the y-axis. However, the y-axis does not infer actual probability similar to that of a normal curve. Rather, the y-axis in a PDD shows that some dates are more likely than others, and when taken together, have higher density distribution values and appear as peaks in the PDD curve (Lovis et al., 2012). Alternatively, if a particular date does not occur (for example, 500 years ago), the density value would be zero, and no peak would be displayed on the plot (see Figure 3.1).

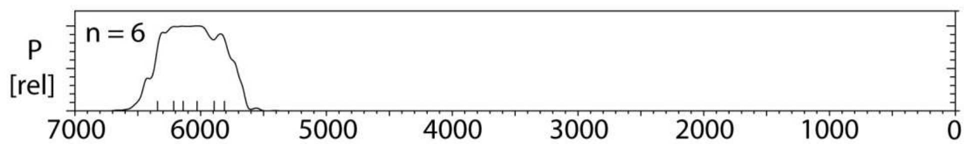


Figure 3.1: Hypothetical example of a probability density distribution (PDD).

For this research, PDDs were generated by incorporating mean dates and their error (one standard deviation in this study, or 1σ) over the past 7,000 years of dune activity, as published in the literature. Data were entered into CalPal (v.2013) calibration software, and all radiocarbon dates were calibrated as part of the PDD creation process. PDDs were also generated in CalPal, utilizing a Gaussian kernel density function over a dataset with an unknown bandwidth (see Figure 3.1). The generated PDDs were saved as .eps (Encapsulated PostScript) files, and Adobe Illustrator was utilized to color and fill the PDDs. The PDD plots were then stacked for comparative purposes when necessary.

3.3: Principal Components Analysis (PCA)

Aside from PDDs, the use of other statistical methods in dune chronology research is not well documented. There are methods, however, that can be utilized to better develop our understanding of dune evolution with respect to time and location. Principal Components Analysis (PCA) is one such method that is most often used for data summarization or data reduction. PCA is commonly applied to sizable datasets that display evidence of collinearity, with the intent of finding the least amount of independent variables that best represent the variation of the total number of independent variables in the dataset. In the context of this research, PCA is utilized to potentially uncover patterns or interrelationships at a local scale, and allows for further analysis of data structure (Jolliffe, 2002). As a result, geographical patterns can emerge from the dataset, offering a useful tool in the comparison of interregional chronological studies of dunes.

Radiocarbon and luminescence dates were entered into SYSTAT 13 statistical software, and a PCA was run for both datasets. Based upon generation of eigenvalues greater than one, as well as factor loadings and percentage of variance explained, factors were extracted and rotated using a VARIMAX standard. This rotation allows for variance maximization of loadings on a designated dimension, which can assist in the interpretation and explanation of all dimensions (B. Pigozzi, personal communication).

3.4: Time-Slice Maps

Although the use of PDDs has been and will likely continue to be a common method to construct sand dune chronologies, they do not show spatial patterns. Although typically not an issue with chronologies at a local scale, the lack of location data can be troublesome when comparing and contrasting sand dune activity on a interregional scale.

As a result of this shortfall, time-slice maps have recently been utilized to display spatial patterns of sand dune activity (e.g. Halfen and Johnson, 2013). These maps display a specific study area, with points placed in locations of dune activity for a particular period of time. As part of a review of Great Plains dune chronologies, Halfen and Johnson (2013) used time-slice maps to display location and timing of dune activity and stability through the late Pleistocene and Holocene. However, maps of this sort have not yet been utilized for interregional dune chronologies. In this study, regional maps were generated using ArcMap 10.1 and saved as .jpg (JPEG) files. Adobe Illustrator was then utilized to combine the two regional maps into a single figure, with luminescence and radiocarbon data plotted through the interpretation of locational data from previous literature. To demonstrate how time-slice maps are constructed, a map displaying the geographic location of all radiocarbon and luminescence samples collected from both regions is shown in Figure 3.2. The map illustrates the spatial distribution of the samples collected through decades of dune research in each region, as well as displaying locations that have yet to be studied. Red squares represent dune activity supported by luminescence dates, while green circles represent dune stability supported by radiocarbon dates. Differing shapes were utilized for interpretation of figures if color is not available.

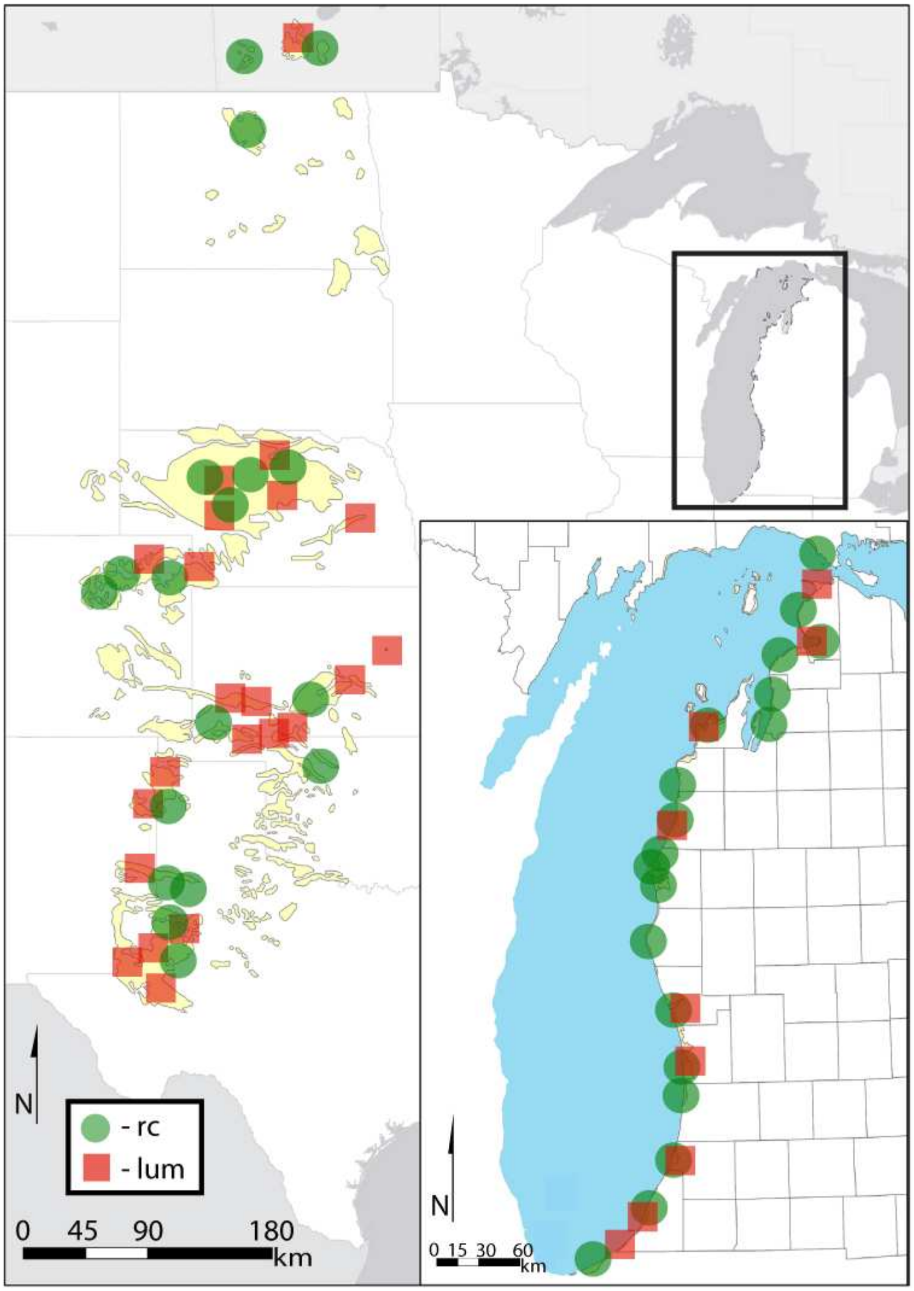


Figure 3.2: Example of regional maps utilized in construction of time-slice maps, displaying the spatial distribution of all samples collected from both regions.

Chapter 4: Results and Discussion

This chapter is organized into five main sections. First, PDD results are organized by region for comparison purposes, beginning with Great Plains radiocarbon and luminescence plots. Radiocarbon and luminescence PDDs are first shown separately, and then graphically stacked to compare regional chronologies in a single illustration. Next, Great Plains and eastern Lake Michigan coastal zone radiocarbon and luminescence plots are overlain into two separate plots for comparison purposes. This comprehensive comparison of the generated PDDs provides an understanding of chronological trends, and in addition, can enlighten the discussion of issues associated with using PDDs to assess the chronology of sand dune evolution.

The second part of the chapter is a discussion of Principal Components Analysis (PCA) in this dune chronology research. PCA is most commonly applied to large collinear datasets as part of a data reduction process. The typical objective of such analysis is to find the least amount of independent variables that best represent the variation of the entirety of independent variables in the data set. The primary reason for utilizing PCA in this study is to investigate possible underlying patterns of interrelationships within the data set, and thus develop local or regional groupings based upon similar dune activity.

The third part of the chapter describes the development and interpretation of comparative “time-slice” maps. These maps are designed to visually compare the geographic distribution of luminescence and radiocarbon ages between the two regions in 200-year "slices" of time over the past 7000 years. Similar to the PDDs, the time-slice maps provide a technique to compare and contrast activation and stabilization events in both regions through the mid-to-late Holocene. The fourth part of the chapter is a discussion of the applications of the methods used as part of this chronology research, and provides a deeper analysis of potential drivers for dune activity and stability in both regions. The fifth and final part of the chapter incorporates both the conclusions as well as suggestions for future research.

4.1: PDD Results

4.1.1: Analysis of Great Plains PDDs

A total of 125 radiocarbon ages were acquired from samples taken within Great Plains dune fields. Prior to constructing the PDD, dates were calibrated using CalPal calibration software (v.2013, developed by Weininger et al., 2013) to provide a similar time scale for comparison of radiocarbon and luminescence dates. The PDD of radiocarbon dates from the Great Plains suggests that nine main periods of dune stability and soil development have occurred during the past 7000 years (Figure 4.1). Notable peaks in the probability of radiocarbon dates occur ~6800-6400, ~6200-5600, ~4900-4600, ~4500-4100, ~3200-2900, ~2800-2500, ~2400-2000, ~1600-1300, and ~1100-500 years ago.

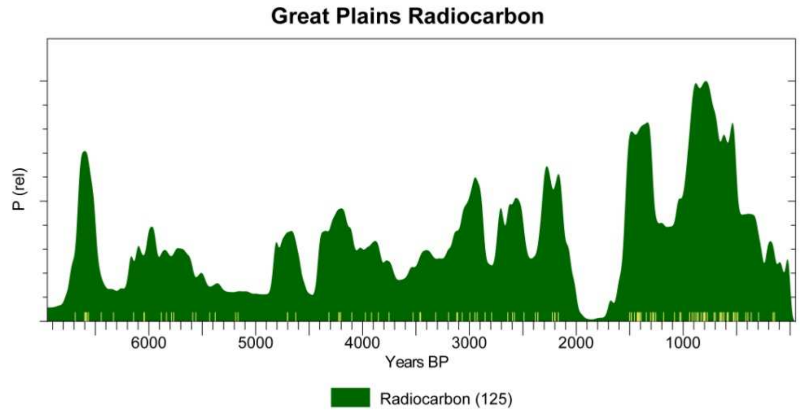


Figure 4.1: PDD showing peaks in radiocarbon dates in the Great Plains.

A total of 223 luminescence dates were acquired from samples recovered from Great Plains dune fields. The Great Plains luminescence PDD (Figure 4.2) suggests that four potential activation events occurred over the past 7000 years, most notably ~1000-600, ~500-300, ~200-100, and ~50 years ago.

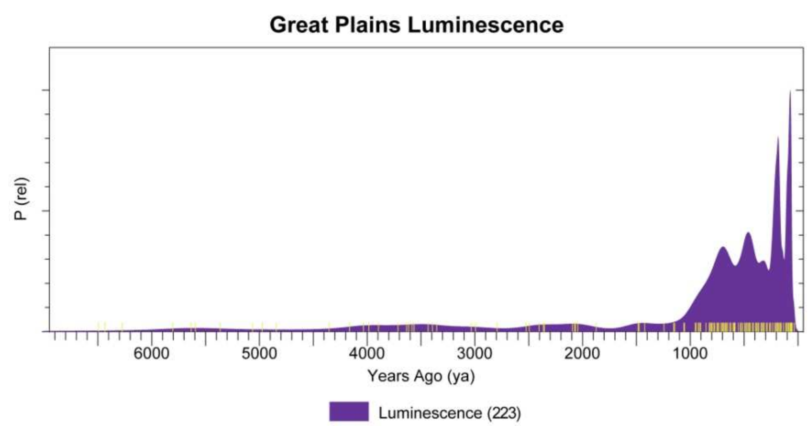


Figure 4.2: PDD showing peaks in luminescence dates in the Great Plains.

In order to more closely compare the probability of stabilization and activation events in the Great Plains, radiocarbon and luminescence PDDs were stacked in a single illustration (Figure 4.3). The plots suggest that both stabilization and activation periods have occurred over the past 1500 years. A spike in the radiocarbon peak ~400 years ago corresponds with a gradual decrease in the luminescence PDD, suggesting ~1000 years of dune stability in the region. Elevated luminescence peaks in the last ~300 years appear to correspond with a small peak in the radiocarbon PDD, suggesting that many dunes have recently been active.

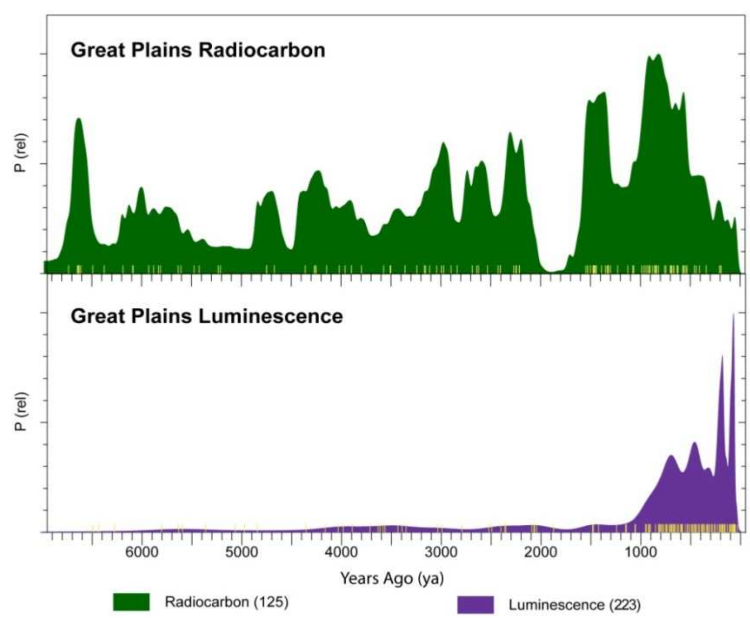


Figure 4.3: Stacked PDD showing peaks in radiocarbon and luminescence dates in the Great Plains.

The abundance of luminescence dates younger than 1000 years is noteworthy. At face value, a high number of younger dates suggests that sand dunes in the Great Plains are very young. However, the prevalence of younger luminescence dates may be explained in part by the Great Plains being in a semiarid/sub-humid environment. Low precipitation inhibits vegetation growth, which allows dunes to reactivate on a more frequent basis. As a consequence, reworked sands, especially common in the upper parts of dunes, would often return much younger luminescence dates (e.g., Wolfe et al., 2002).

4.1.2: Analysis of Eastern Lake Michigan Coastal Zone PDDs

A total of 166 radiocarbon dates were analyzed from sand dunes along the eastern Lake Michigan coastal zone. The PDD generated from these data suggests that five periods of dune stability and soil development occurred during the past 7000 years (Figure 4.4). The highest probability of dune stabilization occurs from ~4300-4000, ~3500-2900, ~2200-2000, ~1000-700, and ~500 years ago to the present.

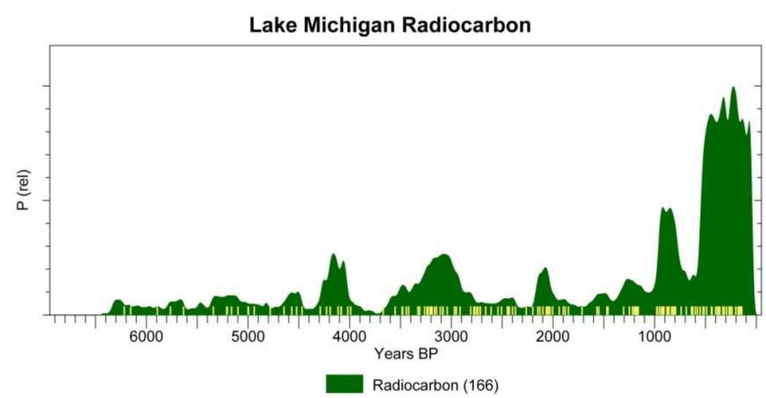


Figure 4.4: PDD showing peaks in radiocarbon dates obtained along the eastern Lake Michigan coastal zone.

Compared to the radiocarbon PDD in Figure 4.4, the luminescence PDD data were less variable, and suggested that six dune activation events occurred over the past 7000 years (Figure 4.5). Notable peaks occur from ~2900-2600, ~2300-1600, ~1000-700, and ~400-200 years ago. The subdued nature of the peak from ~4600-3100 years ago is difficult to interpret.

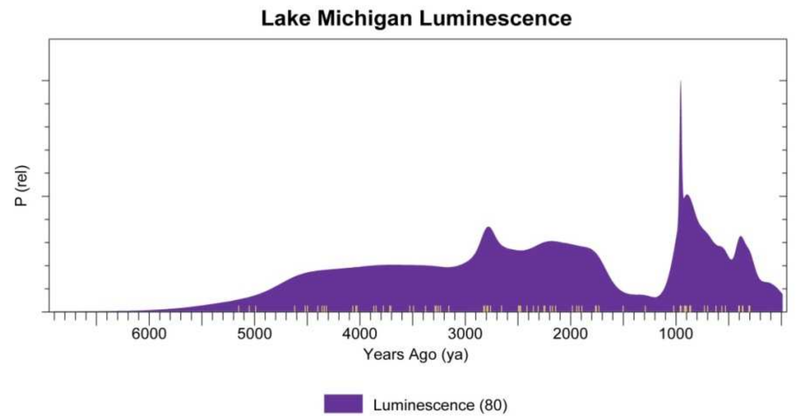


Figure 4.5: PDD showing peaks in luminescence dates obtained along the eastern Lake Michigan coastal zone.

As previously demonstrated with the Great Plains radiocarbon and luminescence PDDs (Figure 4.3), stacking the two plots provides an opportunity to closely compare and contrast the probability of dune stabilization and activation events. Stacking the eastern Lake Michigan coastal zone radiocarbon and luminescence PDDs within a single illustration (Figure 4.6) supports the hypothesis that five main periods of stabilization and activation have likely occurred over the past 4000 years. A vertical variation in the radiocarbon peak from ~3600-2900 years ago implies a short period of dune stability during that time, followed by a period of dune activation from ~2900-1700 years ago. A notable peak in the radiocarbon PDD from ~1900-1100 indicates that a period of dune stability likely occurred at this time, subsequent to an interval of activation between ~1000-800 years ago. The presence of notable radiocarbon and luminescence peaks in the last 500 years suggests that similar dune stabilization and activation events may have occurred at a local level.

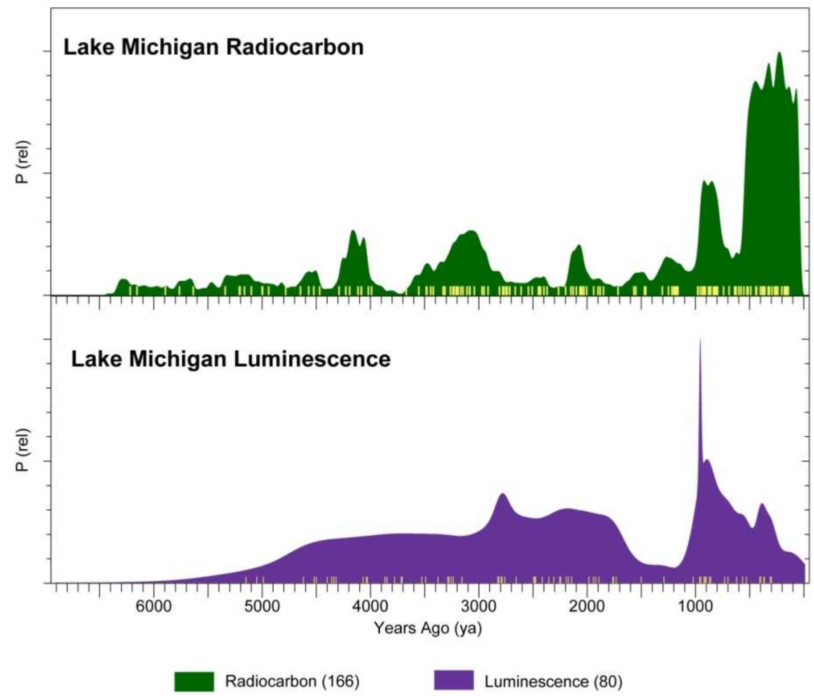


Figure 4.6: Stacked PDD illustration displaying peaks in radiocarbon and luminescence dates along the eastern Lake Michigan coastal zone.

4.1.3: Comparison of Great Plains and Eastern Lake Michigan Coastal Zone PDDs

The primary goal of this study is to compare and contrast dune stabilization and activity in the Great Plains and eastern Lake Michigan coastal zone over the past 7000 years. A useful tool for multiregional comparison of dune evolution is the graphical stacking of radiocarbon and luminescence PDDs from each respective region. Stacking radiocarbon PDDs from the Great Plains and eastern Lake Michigan coastal zone into a single illustration provides for comparison of dune stabilization events in both regions over the past 7000 years (Figure 4.7). The stacked PDDs suggest that six similar periods of dune stability have occurred over this interval of time in the two regions. The oldest synchronous interval of stability appears to have transpired from ~5800-5600 years ago, with subsequent periods of stability occurring from ~4300-4100, ~3600-3400, ~3100-2900, ~1000-750, and ~500 years ago to the present. In addition to displaying synchronous dune stabilization events, asynchronous events for the past 7000 years are also displayed in Figure 4.7. For example,

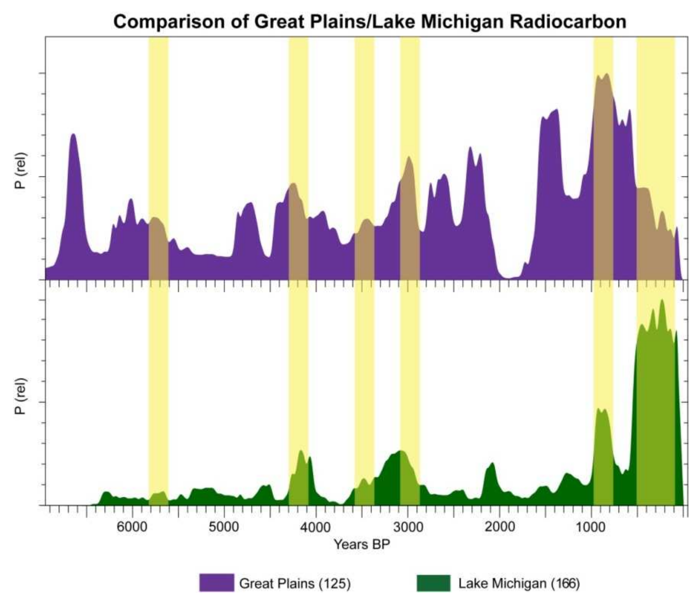


Figure 4.7: Stacked PDD illustration displaying peaks in radiocarbon dates for dunes in the Great Plains and near the eastern Lake Michigan coastal zone. Similar periods of stability are highlighted.

notable peaks in the Great Plains from ~6700-6500, ~2800-2500, and ~2400-2100 suggest dunes were likely stable in the Great Plains during these periods of time.

Similar to the stacked radiocarbon PDDs for both regions shown in Figure 4.7, stacked luminescence PDDs from the Great Plains and eastern Lake Michigan coastal zone allow for comparison of dune activation events in both regions (Figure 4.8). The illustration suggests that two main periods of similar dune activation likely occurred in both locations in the past 1000 years. The oldest appears to have taken place from ~1000-600 years ago, followed by a period of activation from ~500-300 years ago.

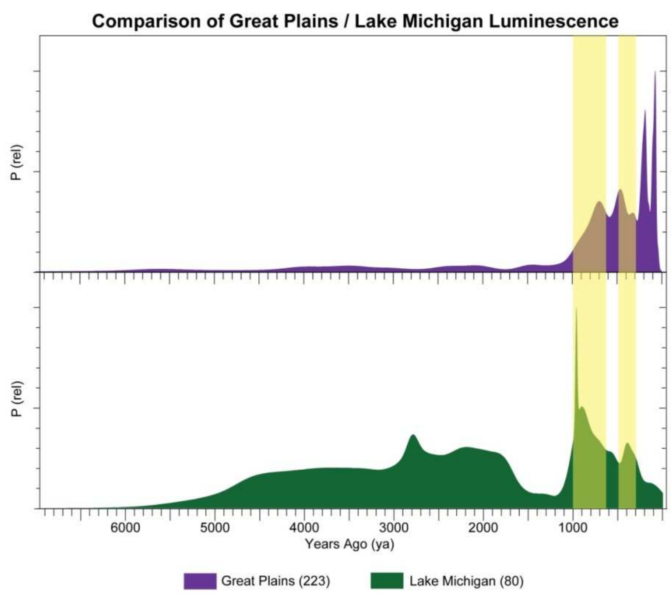


Figure 4.8: Stacked PDD illustration display-Ing luminescence dates for dunes in the Great Plains and near the eastern Lake Michigan coastal zone. Similar periods of activation are highlighted.

Similar to the stability events shown in Figure 4.7, many asynchronous activation events are also displayed in Figure 4.8. Two such events appear to have occurred over the past 5000 years, the first from ~4800-1600 years ago along the eastern Lake Michigan coastal zone, while relatively limited activity was displayed on the Great Plains luminescence PDD during the same time interval. Two notable peaks occur from ~400-100 years ago in the Great Plains, which correspond with a decline in the Lake Michigan luminescence peak.

In summary, visual analysis of the radiocarbon PDDs (Figures. 4.1, 4.4, and 4.7) suggests that several simultaneous periods of dune stability occurred in both regions over the past 7000 years. The luminescence PDDs (Figures 4.2, 4.5, and 4.8) suggest that only two similar activation events likely occurred over the past 7000 years in both regions, but provide limited information about comparable dune activity prior to 1000 years ago in the Great Plains.

4.1.4: Considerations Associated with Utilizing PDDs for Sand Dune Chronological Research

Although PDDs are commonly used to illustrate the chronology of sand dune evolution (e.g. Hanson et al., 2009a; Blumer et al., 2012; Lovis et al., 2012; Halfen and Johnson, 2013), several conceptual issues regarding this method at a regional level have recently surfaced. According to Halfen and Johnson (2013), this method may be problematic for a number of reasons. For example, PDDs used for regional dune chronologies often lack an important geographical component of where individual samples were collected. While typically not an issue when presenting subregional data (e.g., the Minot dune field), locational data are critical for interregional analysis, as when comparing distributions of dune evolution among several locations (Halfen and Johnson, 2013). Additionally, PDDs are particularly sensitive to clustering within datasets. An abundance of radiocarbon dates for a certain time period (e.g., 1000-800 years ago) may reflect a false high probability for that period, while disregarding other potentially significant intervals of stability due to a smaller sample size for those usually earlier time intervals. This section discusses the issues presented when using PDDs for this research.

Although the absence of a geographical component undeniably impacted the way PDDs displayed dune chronologies in Figures 4.1-4.8, the most noteworthy issue with regard to PDDs as used in this research is potential sample bias, particularly as regarding sample age. An excellent example of this type of bias can be seen when analyzing the luminescence PDD from the Great Plains (Figure 4.2). In this case, an abundance of dates younger than 1000 years old (n=161, ~72% of data set) has significantly skewed the PDD, resulting in fewer notable curves prior to 1000 years ago, even though several samples are present. This is likely due to the fact that samples nearer to the surface are often easier to collect, and have been potentially reworked through periods of subsequent activation or bioturbation. In an effort to demonstrate how bias affects the results of the PDD, a separate PDD of luminescence dates for the Great Plains is presented in Figure 4.9 which removes dates younger than 1000 ya. Thus, the PDD values for older periods are proportionately increased.

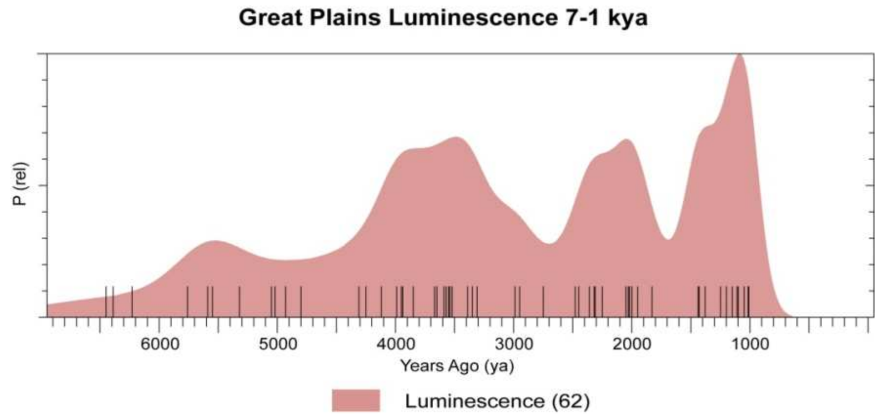


Figure 4.9: PDD of Great Plains luminescence mean dates from 7000-1000 years ago, with the last 1000 years removed.

The Great Plains luminescence PDD in Figure 4.9 is noticeably different than the Great Plains luminescence PDD shown in Figure 4.2. Because of the removal of dates younger than 1000 years old, substantial peaks are now visible from ~6000-5100, ~4300-2700, ~2500-1800, and ~1500-700 years ago. The overlap in the plot, i.e., its "tail," appears younger than 1000 ya due to the standard deviations of younger dates being factored into the PDD. To further illustrate how sample bias can affect peaks in a PDD, Figure 4.10 shows four Great Plains luminescence PDDs in a single illustration, with four subregions displayed.

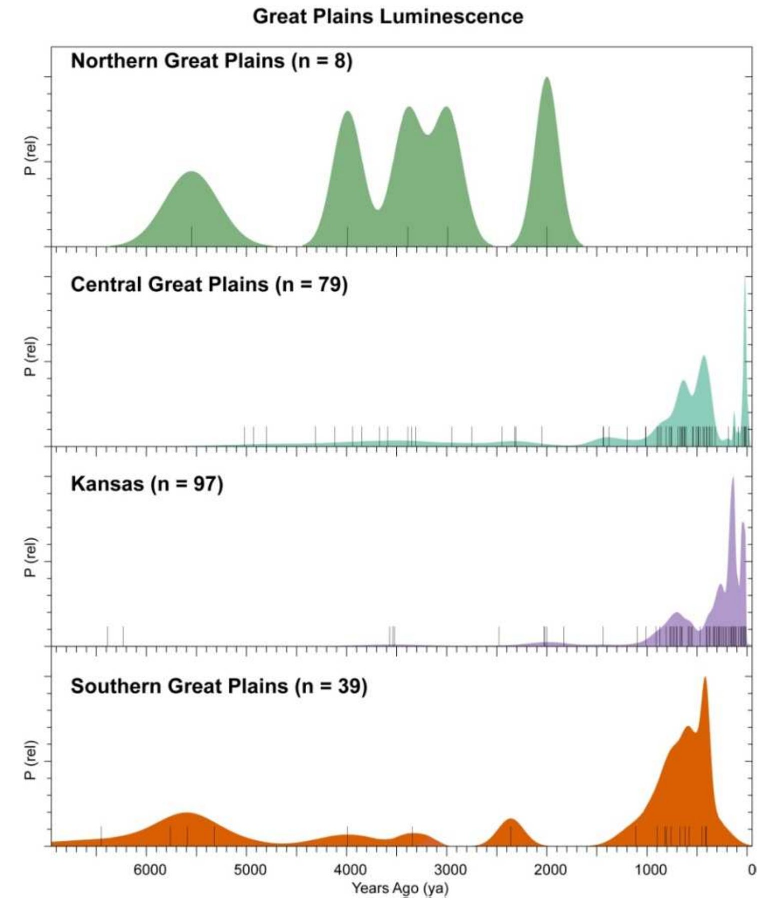


Figure 4.10: Great Plains luminescence PDDs arranged by subregion.

The plots in Figure 4.10 display how PDDs are affected by sample size and sample distribution for four subregions in the Great Plains. For example, the PDD for the Northern Great Plains is influenced by the paucity of dates (n = 8). The peaks show where the five dates OSL dates are present (three of eight samples are modern dates and therefore not shown on the PDD). A younger date with a smaller standard deviation results in a taller, thinner peak, as shown from ~2300-1700 ya. Older ages typically have a larger standard deviation, with a shorter, wider peak, as displayed from 6300-4900 ya. Additionally, the Central

Great Plains and Kansas luminescence PDDs (Figure 4.10) are skewed to the late Holocene given the high number of ages younger than 1000 years. The Southern Great Plains luminescence PDD data (Figure 4.10) show similar trends in sample distribution to the Central Great Plains and Kansas, with peaks skewed to the late Holocene as a result of a large quantity of younger dates. However, with a smaller luminescence sample size (n=39) in the Southern Great Plains, single older dates show as individual curves, whereas older dates in the Central Great Plains and Kansas PDDs cluster and show only amalgamated curves due to the increased sample size and clustering from 1000 years ago to the present.

4.2: PCA Results

PCA is a statistical method typically utilized for data reduction or summarization. Although I could find no indication that PCA has been used in dune chronology studies, the method does have application to this type of research. This section demonstrates how the application of PCA to radiocarbon and luminescence data offers the opportunity to evaluate large datasets using a few factors, based upon factor values with an absolute value > 0.40. Based upon the grouping of the locations into the factors, it may be possible to interpret spatial relationships within those variables.

The objective of utilizing PCA in this study was to determine if interregional similarity was present through time in the radiocarbon and luminescence datasets. To do this, both radiocarbon and luminescence datasets were separated into localized groupings in Excel. Depending upon available data, in some cases specific dune fields were assigned their own column. When locations with no data were encountered, they were removed from the dataset to prevent correlation with other sites that had low probability of activity, as a zero in the dataset could mean low probability in one particular location, and no data in another.

In order to compare the subregions as accurately as possible, 100-year intervals were used to interpolate probability, resulting in 71 time intervals for each location. Data were divided by locality and PDDs were constructed using CalPal (v.2013). Probabilities were interpolated at the 100-year interval for each location, and values were noted at each of the 71 time intervals in the Excel spreadsheet. Radiocarbon data were divided into nine subregions, while luminescence data were separated into ten subregions (Figure 4.11).

Table 4.1: Subregions and their abbreviations used in the PCA.

Subregions for Radiocarbon PCA

NLM	Northern Lake Michigan
CLM	Central Lake Michigan
SLM	Southern Lake Michigan
MANITOBA	Brandon and Lauder Sand Hills, Manitoba
MINOT	Minot Dune Field, ND
NSHNECO	Nebraska Sand Hills / NE Colorado
GBSP	Great Bend Sand Prairie, KS
OKSWKS	Oklahoma / SW Kansas
TEXASNM	W Texas / E New Mexico

Subregions for Luminescence PCA

NLM	Northern Lake Michigan
CLM	Central Lake Michigan
SLM	Southern Lake Michigan
MANITOBA	Brandon and Lauder Sand Hills, Manitoba
NSHNECO	Nebraska Sand Hills / NE Colorado
DUNCAN	Duncan Dune Field, NE
HUTCH	Hutchinson Dune Field, KS
ABILENE	Abilene Dune Field, KS
OKSWKS	Oklahoma / SW Kansas
TEXASNM	W Texas / E New Mexico

4.2.1: Radiocarbon PCA

A total of nine subregions were used for the radiocarbon PCA. The minimum eigenvalue was set to 0.01 with unlimited factors (Table 4.2). After examination of eigenvalues and component loadings, and based upon dimensions one and two having multiple high loadings (> |0.70|), extraction of three dimensions may potentially draw "MANITOBA" and "OKSWKS" into the third dimension. As shown in Table 4.3, extraction of three dimensions pulled

Table 4.2: PCA results from SYSTAT 13 for radiocarbon data. Highest loadings are highlighted.

Latent Roots (Eigenvalues)								
1	2	3	4	5	6	7	8	9
3.146	1.745	1.103	1.008	0.843	0.430	0.384	0.181	0.159

Component Loadings									
	1	2	3	4	5	6	7	8	9
SLM	0.837	-0.377	-0.091	0.145	0.111	0.091	0.042	0.199	-0.255
CLM	0.797	0.173	-0.164	0.098	0.244	-0.119	0.454	-0.084	0.104
NLM	0.797	-0.247	0.154	0.146	0.127	0.409	-0.202	-0.141	0.125
MINOT	0.777	-0.302	0.093	-0.209	-0.302	-0.287	-0.145	0.160	0.183
GBSP	0.713	0.506	0.114	-0.152	-0.272	-0.174	-0.132	-0.218	-0.174
TEXASNM	0.188	0.789	-0.173	-0.256	-0.325	0.326	0.087	0.157	0.041
NSHNECO	0.140	0.660	0.320	0.005	0.616	-0.111	-0.188	0.118	0.022
MANITOBA	-0.073	0.094	0.812	0.460	-0.289	0.023	0.168	0.045	-0.003
OKSWKS	-0.046	-0.310	0.480	-0.782	0.148	0.095	0.160	-0.024	-0.042

"MANITOBA" and "OKSWKS" into the third dimension, indicating that substantial similarity exists over time between the two subregions. Closer analysis shows that "OKSWKS," the microregion having the lowest of the high factor scores, is in fact most unlike the other subregions with regard to the chronology of dune

Table 4.3: Rotated loading matrix from SYSTAT 13 for radiocarbon data. Highest loadings are highlighted, and indicate three groupings are present in the data set.

Rotated Loading Matrix (VARIMAX, Gamma = 1.000000)			
	1	2	3
SLM	0.910	-0.122	-0.093
NLM	0.838	0.032	0.130
MINOT	0.834	-0.037	0.081
CLM	0.702	0.369	-0.251
GBSP	0.527	0.706	-0.025
TEXASNM	-0.066	0.766	-0.313
NSHNECO	-0.060	0.718	0.197
MANITOBA	-0.079	0.212	0.789
OKSWKS	0.063	-0.219	0.526

stabilization through time. For example, relatively low probability of stabilization in the microregion is not reflected in the data set until 1800 years ago. The same could be said for the “MINOT” data, but higher probability with younger dates in the dataset aligns well with the other locations conveying high loadings (e.g., SLM, NLM).

The importance of the high loadings in the first factor of the rotated matrix (Table 4.3) grouping into three dimensions indicates that similarity in dune stabilization occurred across several dune fields at various times throughout the Holocene. Given these groupings, I named the first factor “Northern US” due to the grouping of the Great Lakes regions and North Dakota, the second factor “Central/Southern Plains” due to the similarity and grouping of those subregions, and the third factor “Limited” due to the minimal amount of data from Manitoba, Oklahoma, and southwestern Kansas. The factor scores were saved and displayed on scatterplots (Figures 4.11-4.13) for comparison.

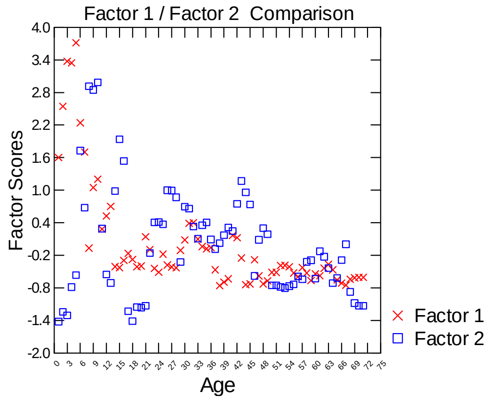


Figure 4.11: Scatterplot of scores for Factors 1 (Northern US) and 2 (Central/Southern Plains) of the radiocarbon data set.

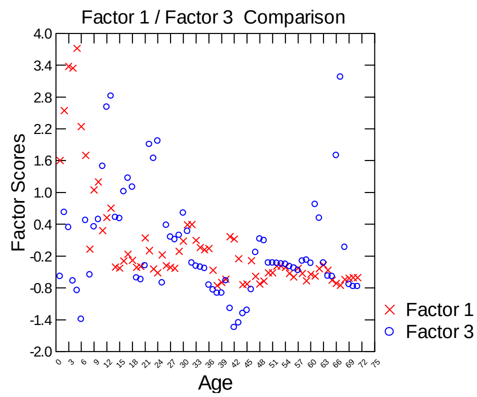


Figure 4.12: Scatterplot of scores for Factors 1 (Northern US) and 3 (Limited) of the radiocarbon data set.

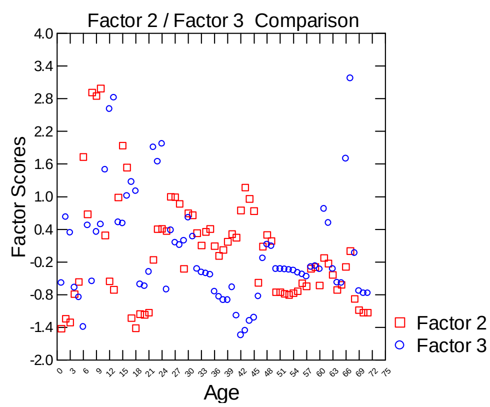


Figure 4.13: Scatterplot of scores for Factors 2 (Central/Southern Plains) and 3 (Limited) of the radiocarbon data set.

Interpretation of the scatterplots of factor scores suggests that the most similar period of stability between the subregions occurred during the early Holocene. Most notably, however, the plots indicate that for the most part, the subregions contrasted greatly with regard to intervals of stability through the Holocene.

4.2.2: Luminescence PCA

A total of 10 subregions were used for the luminescence PCA. The minimum eigenvalue was set to 0.01, with unlimited factors (Table 4.4).

Table 4.4: PCA results from SYSTAT 13 for luminescence data. Highest loadings are highlighted.

Latent Roots (Eigenvalues)									
1	2	3	4	5	6	7	8	9	10
3.460	2.086	1.471	1.098	0.873	0.324	0.284	0.237	0.122	0.046

Component Loadings										
	1	2	3	4	5	6	7	8	9	10
NSHNECO	0.920	-0.145	0.046	0.051	0.033	-0.254	0.165	-0.123	-0.055	-0.128
OKSWKS	0.788	-0.329	-0.149	0.214	-0.392	-0.083	0.147	-0.010	-0.028	0.141
NLM	0.680	0.410	0.321	0.146	-0.294	0.158	-0.282	-0.230	0.042	-0.010
ABILENE	0.678	0.414	-0.437	-0.181	0.196	-0.030	-0.209	0.155	-0.197	0.017
HUTCH	0.600	-0.589	0.329	0.205	-0.066	0.153	-0.083	0.320	0.057	-0.051
DUNCAN	0.512	0.279	-0.759	0.038	0.147	0.064	0.044	0.016	0.233	-0.014
CLM	0.165	0.822	0.241	0.281	0.050	0.244	0.297	0.071	-0.067	-0.006
SLM	0.261	0.585	0.527	-0.456	-0.058	-0.256	0.011	0.141	0.121	0.036
MANITOBA	-0.372	0.322	0.007	0.812	0.079	-0.270	-0.122	0.071	0.022	0.005
TEXASNM	0.464	-0.266	0.364	0.086	0.745	0.031	-0.008	-0.108	0.026	0.072

After examining the eigenvalues and loadings, and based upon the outcomes of the radiocarbon data set, two dimensions were extracted and VARIMAX rotation was utilized to determine if the single high loadings in dimensions 3-5 could potentially load into the second dimension (Table 4.5).

Table 4.5: Rotated loading matrix from SYSTAT 13 for luminescence data. Highest loadings are highlighted, and indicate two groupings are present in the data set.

Rotated Loading Matrix (VARIMAX, Gamma = 1.000000)		
	1	2
HUTCH	0.834	-0.106
OKSWKS	0.827	0.214
NSHNECO	0.821	0.440
TEXASNM	0.531	0.069
CLM	-0.366	0.754
ABILENE	0.290	0.739
NLM	0.294	0.737
SLM	-0.146	0.624
DUNCAN	0.239	0.532
MANITOBA	-0.491	0.032

As shown in Table 4.5, all of the subregions had medium to high loadings (> |0.40-0.99|) on the first two factors; notably, the first three subregions (HUTCH, OKSWKS, NSHNECO). However, in the first factor of the luminescence rotation, one negative loading appears in the first dimension for “MANITOBA.” Upon closer analysis of the data set, “MANITOBA” has a high probability of activity in the early-to-mid Holocene, and had a probability of zero in the last 1500 years. This was almost the exact opposite of the other subregions, and thus “MANITOBA” is similar in magnitude to the top four loadings in the first dimension, but in an opposite manner, which is represented by the negative loading.

Based upon the groupings, I named the first factor “Western Plains,” due to its similarity in late Holocene dune activity to the westernmost dune fields in the Great Plains. The second factor was named “Eastern Plains/Great Lakes” due to the similarity in mid-to-late Holocene dune activity on the easternmost fringes of the Great Plains and along the eastern coast of Lake Michigan. The factor scores were saved and displayed on a scatterplot for interpretation (Figure 4.14).

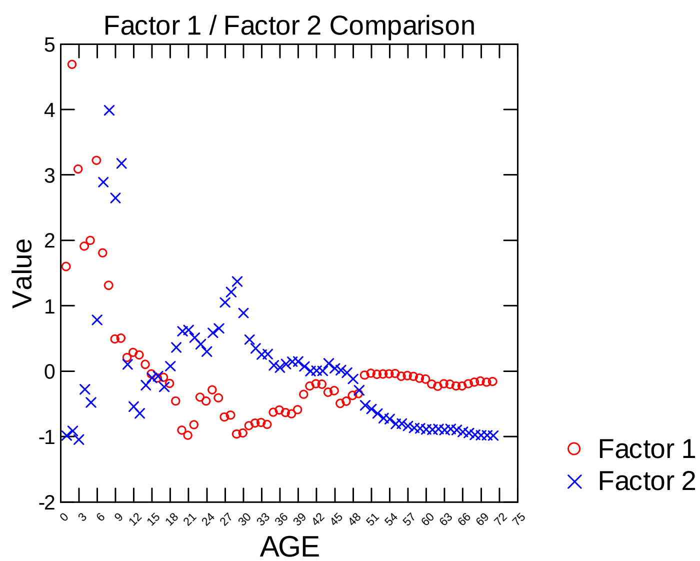


Figure 4.14: Scatterplot of scores for Factors 1 (Western Plains) and 2 (Eastern Plains/Great Lakes) of the luminescence data set.

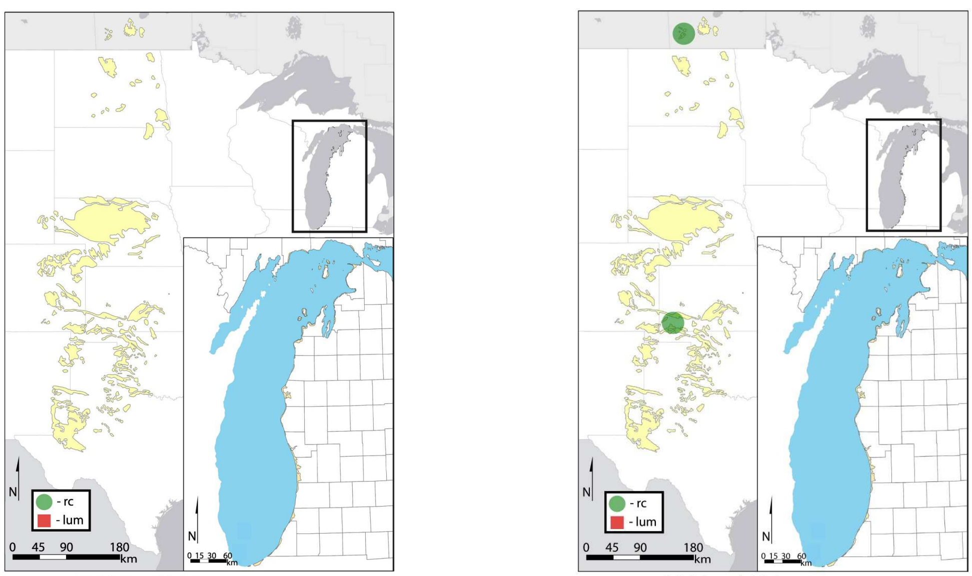
Interpretation of the scatterplots of factor scores in Figures 4.11-4.13 suggests that a period of similar stability occurred between the Western Plains and Eastern Plains/Great Lakes during the late Holocene. Most notably, however, the plots indicate that for the most part the subregions contrasted greatly with regard to intervals of stability throughout most of the Holocene. The high amount of variance in the late Holocene is most likely an example of how the abundance of younger luminescence dates, as a result of reworked sands, influences PCA when utilized in chronology studies. For example, both factors peak late in the Holocene, and progressively flatten as time regresses into the early Holocene (Figure 4.14). Factor 2 (Eastern Plains/Great Lakes), which includes the eastern Lake Michigan coastal region and the easternmost Great Plains sites (Duncan and Abilene Dune Fields), shows a period of prolonged activity into the mid-Holocene which is also demonstrated by the luminescence PDD from Lake Michigan (Figure 4.8).

In summary, utilizing PCA and a rotated loadings matrix (Tables 4.2-4.5) for the radiocarbon and luminescence data sets broadly suggests that, to some extent, subregions were both stable and active during similar intervals of time in both regions. Further, plotting radiocarbon and luminescence factor scores (Figures 4.11-4.14) suggests that dune stability and activity are not limited to regional-scale events, but may be influenced by contrasting drivers at the microregional level, as indicated in Figure 4.14.

4.3: Time-Slice Map Results

As previously discussed, many PDDs used in regional dune chronology research often lack a spatial component. PCA allows for interpretation of factor groupings on an interregional scale over time, but may still lack data for certain areas. In an effort to display chronological data by location, Halfen and Johnson (2013) developed 100-year time-slice maps to present radiocarbon and luminescence dates for the Great Plains dunes for the past 1200 years. However, time-slice maps have not yet been utilized to display geographic patterns in dune evolution across multiple regions. This section displays time-slice maps for both the Great Plains and eastern Lake Michigan coastal zone, beginning at 7000 years ago. As demonstrated in Figures 4.15-4.32, presenting chronological data in a sequence of time-slice maps provides a tool to visualize the spatial chronology of dune evolution within and between regions.

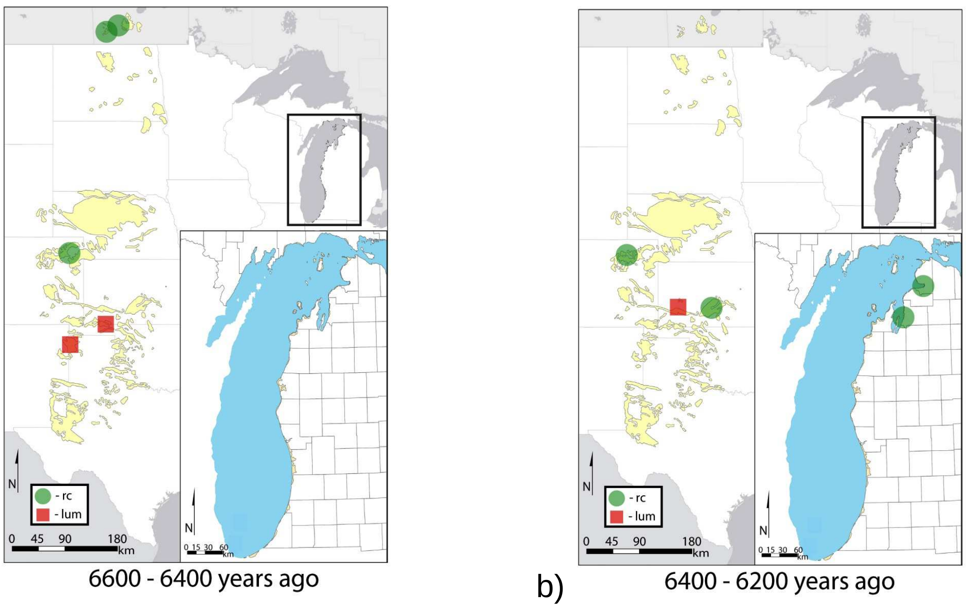
For this study, a 200-year interval was chosen for two reasons, the first being similarity in how data are presented. Between a 100-year and 200-year interval the maps looked almost identical, and as a result the 200-year interval was chosen in an effort to be more conservative as far as probability is concerned. The second reason chosen for using a 200-year interval was to reduce the total number of maps from 70 to 35. In the maps, luminescence dates are indicated by red squares, whereas radiocarbon dates are indicated by green circles.



a) 7000 - 6800 years ago b) 6800 - 6600 years ago

Figure 4.15: Time-slice maps for the Great Plains (GP) and eastern Lake Michigan (LM) regions. a): map showing distribution of ages between 7000-6800 years ago; b): map showing distribution of ages between 6800-6600 years ago.

Due to a lack of data for the two intervals of time, the time-slice maps in Figure 4.15 present a limited amount of information about stabilization and activation events in both regions. Figure 4.15a displays no information about dune evolution in either region, while Figure 4.15b suggests that at least some of the dunes in the central and northern Great Plains were stable. However, neither of the maps display any information for dunes in the Great Lakes region.



a) b)

Figure 4.16: Time-slice maps for the GP and LM regions. a): distribution of ages between 6600-6400 years ago; b): distribution of ages between 6400-6200 years ago.

The map in Figure 4.16a suggests that dunes in Manitoba and northeastern Colorado were stable from 6600-6400 years ago, while at least some dunes in southwestern Kansas and northern Texas were active. Figure 4.16b indicates that dunes in northeastern Colorado and central Kansas were likely stable, while dunes in southwestern Kansas may have been active.

Radiocarbon data from northern Lake Michigan suggests that dunes were stable in that part of the region from 6400-6200 years ago.

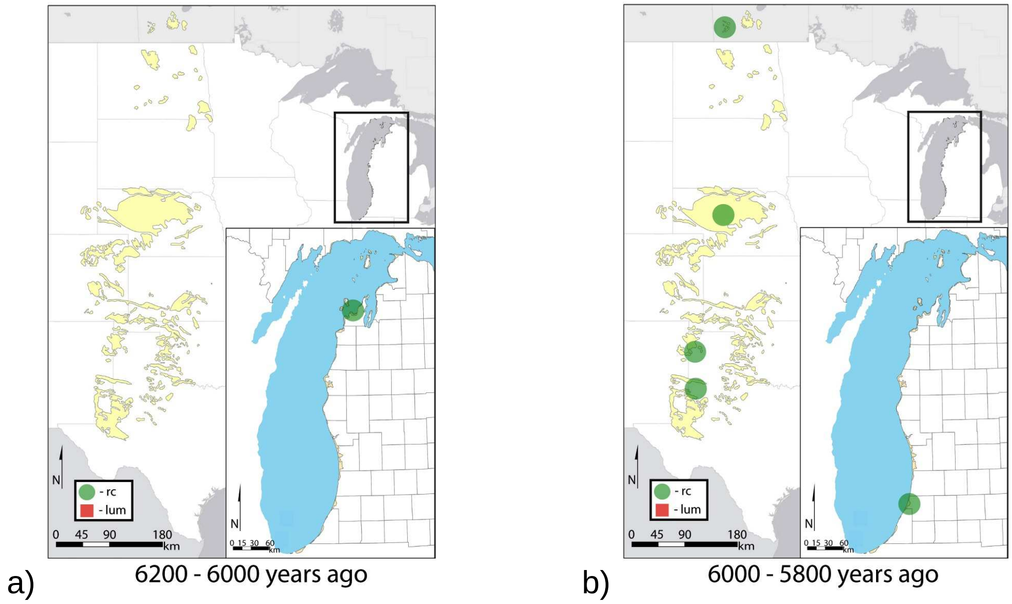


Figure 4.17: Time-slice maps for the GP and LM regions. a): distribution of ages between 6200-6000 years ago; b): distribution of ages between 6000-5800 years ago.

Data displayed in Figure 4.17a, with one radiocarbon date from northern Lake Michigan, suggest that a period of stability occurred from 6200-6000 years ago. Figure 4.17b indicates that dune fields throughout much of the Great Plains region were likely stable from 6000-5800 years ago, as well as in the southern Lake Michigan region.

Figure 4.18a suggests that dunes were largely stable in the central and southern Great Plains, as well as the southern Lake Michigan region. Luminescence data from northern Texas indicates that dune activity may have occurred from 5800-5600 years ago in this part of the Plains. In Figure 4.18b, radiocarbon data from northeastern Colorado and the southern Lake Michigan region indicate that both areas were likely stable from 5600-5400 years ago. A luminescence date from the Brandon Dune Field in Manitoba suggests that dune activity occurred there during the same time interval.

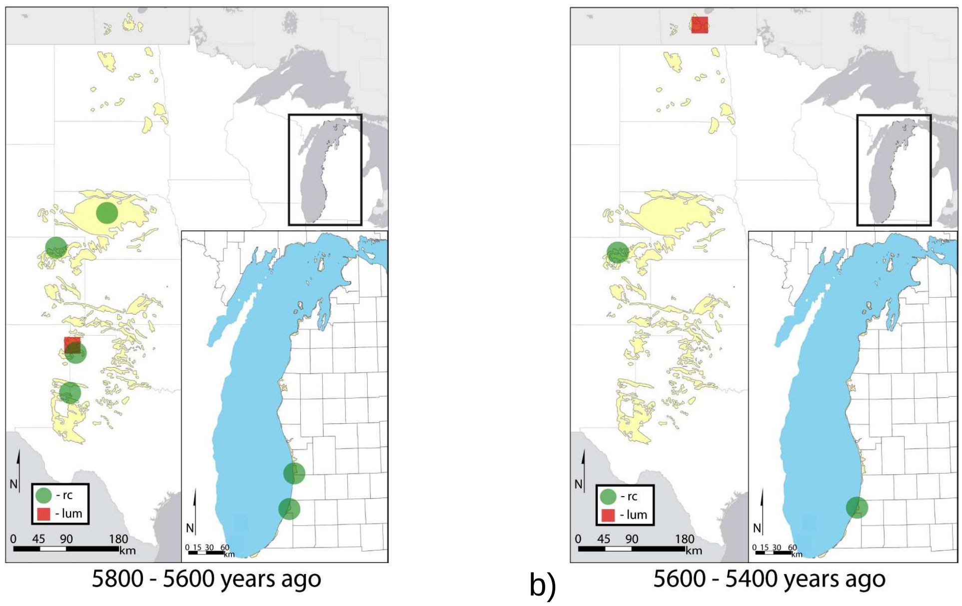
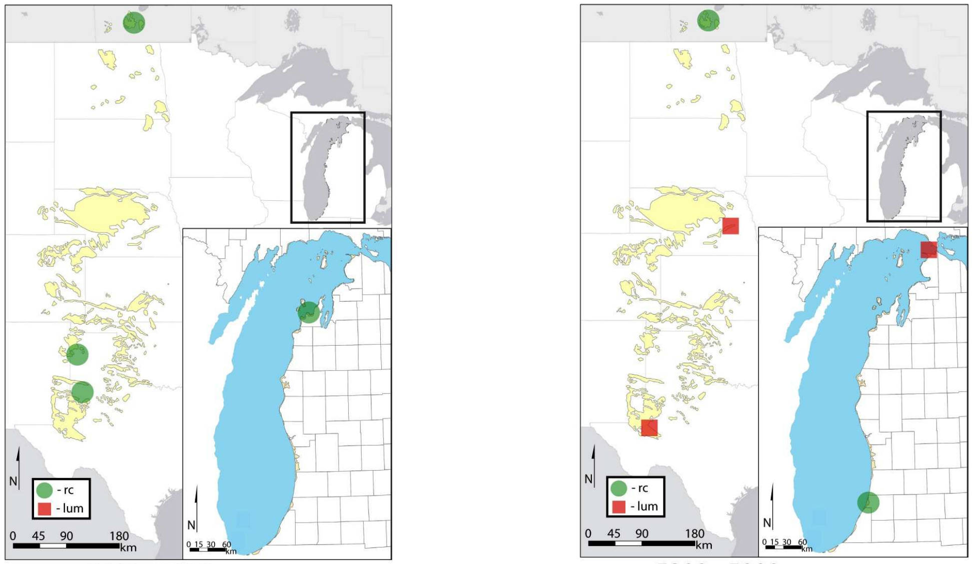


Figure 4.18: Time-slice maps for the GP and LM regions. a): distribution of ages between 5800-5600 years ago; b): distribution of ages between 5600-5400 years ago.

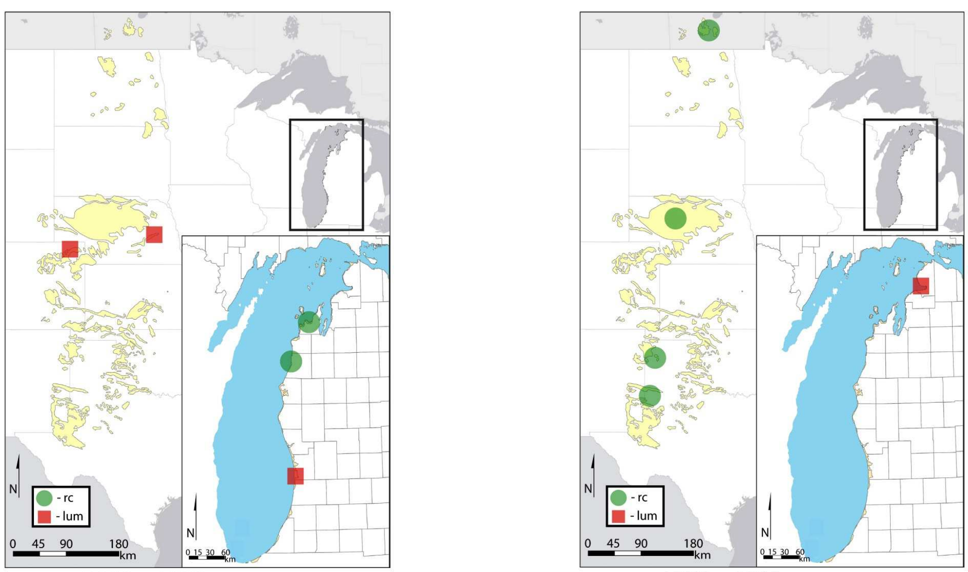
The map in Figure 4.19a displays radiocarbon data from both regions, which suggests a similar period of stabilization occurred in those areas from 5400-5200 years ago. In Figure 4.19b, luminescence data from the central and southern Great Plains indicate that dunes may have been active there, whereas radiocarbon data from Manitoba suggest an interval of stability occurred in the northern part of the Plains at the same time. Radiocarbon data from southern Lake Michigan indicates that a period of stability likely took place from 5200-5000 years ago, while local activation may have been occurring in the northern part of the Lake Michigan region.



a) 5400 - 5200 years ago b) 5200 - 5000 years ago

Figure 4.19: Time-slice maps for the GP and LM regions. a): distribution of ages between 5400-5200 years ago; b): distribution of ages between 5200-5000 years ago.

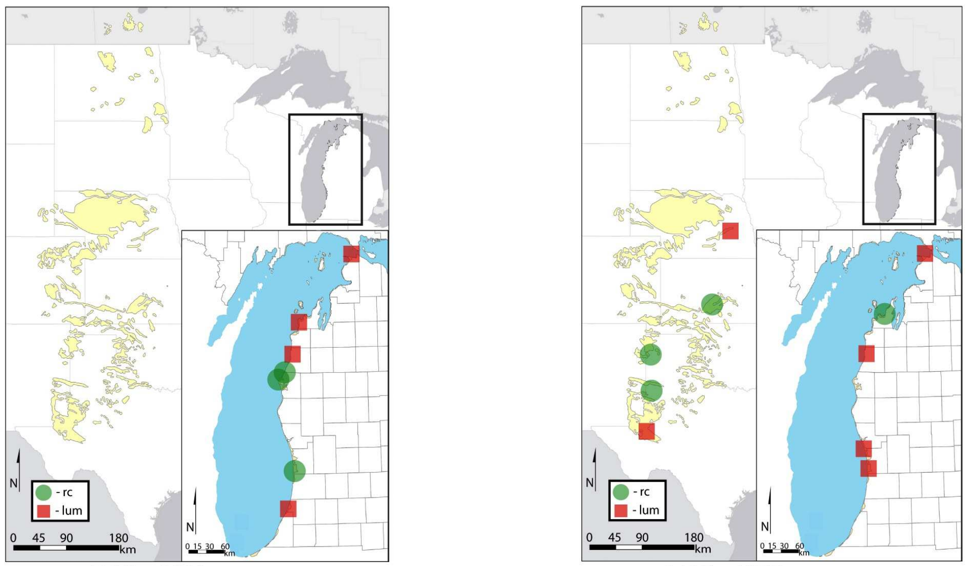
Figure 4.20a suggests that dunes in the central Great Plains and central Lake Michigan areas were largely active from 5000-4800 years ago, whereas



a) 5000 - 4800 years ago b) 4800 - 4600 years ago

Figure 4.20: Time-slice maps for the GP and LM regions. a): distribution of ages between 5000-4800 years ago; b): distribution of ages between 4800-4600 years ago.

radiocarbon data from northern Lake Michigan indicate that a period of local stability occurred. Figure 4.20b suggests that dunes were largely stable in the Great Plains region from 4800-4600 years ago, whereas dunes were likely active in the northern part of the Lake Michigan region.



a) 4600 - 4400 years ago　　b) 4400 - 4200 years ago

Figure 4.21: Time-slice maps for the GP and LM regions. a): distribution of ages between 4600-4400 years ago; b): distribution of ages between 4400-4200 years ago.

The map in Figure 4.21a displays limited information about dune evolution in the Great Plains. However, luminescence data from northern and southern Lake Michigan suggest that dunes were active in those areas from 4600-4400 years ago. Radiocarbon data from central Lake Michigan indicate that a period of stability likely occurred there during that same time. Figure 4.21b shows that dunes were widely stable in the central Great Plains from 4400-4200 years ago, with localized dune activity in the Duncan Dune Field and western Texas. Dunes along the central and northern parts of the eastern Lake Michigan coastal zone were likely active, with a radiocarbon date from northern Lake Michigan reflecting a period of localized stability.

The map in Figure 4.22a suggests that the dunes in central and southern Great Plains were largely stable from 4200-4000 years ago, with localized activation in Manitoba, eastern Nebraska, and northern Texas. Activity likely occurred in northern and southern Lake Michigan, with stability occurring in the central part of the region.

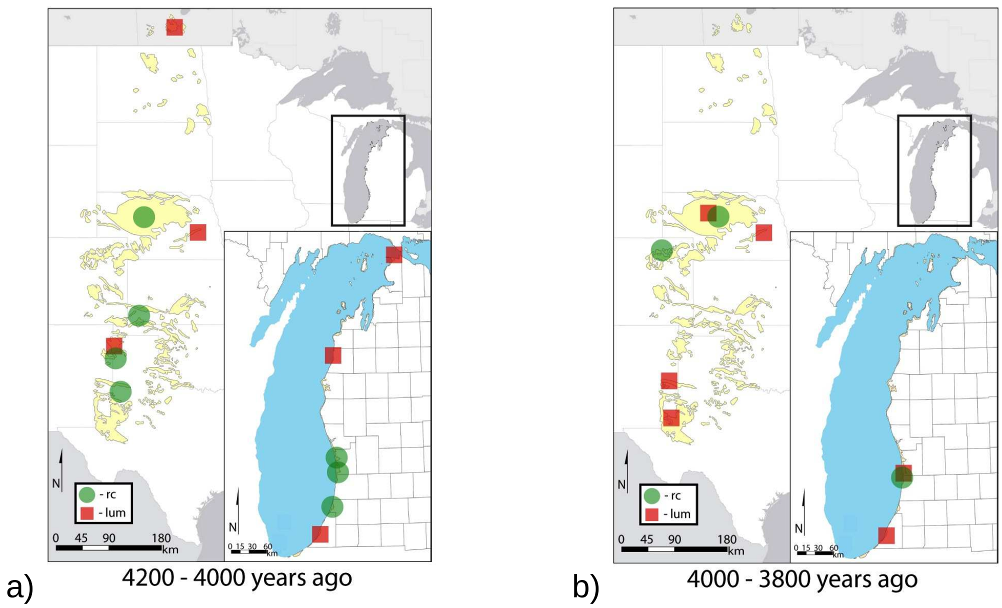
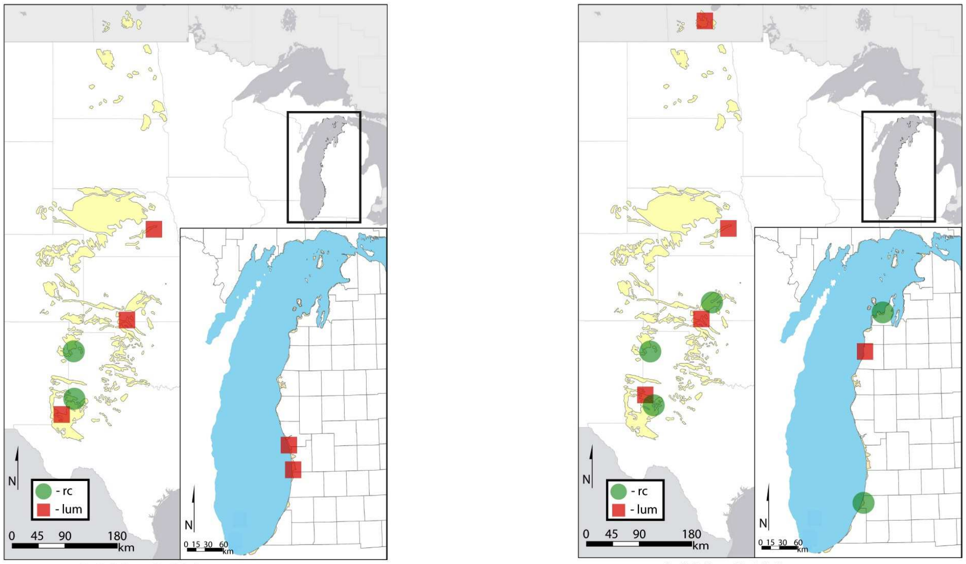


Figure 4.22: Time-slice maps for the GP and LM regions. a): distribution of ages between 4200-4000 years ago; b): distribution of ages between 4000-3800 years ago.

In Figure 4.22b, the maps indicate that the central and southern Great Plains were largely active with localized dune stability in the Nebraska Sand Hills and northeastern Colorado. Dune activity likely occurred in the central and southern Lake Michigan from 4000-3800, whereas localized stability probably took place in central Lake Michigan.

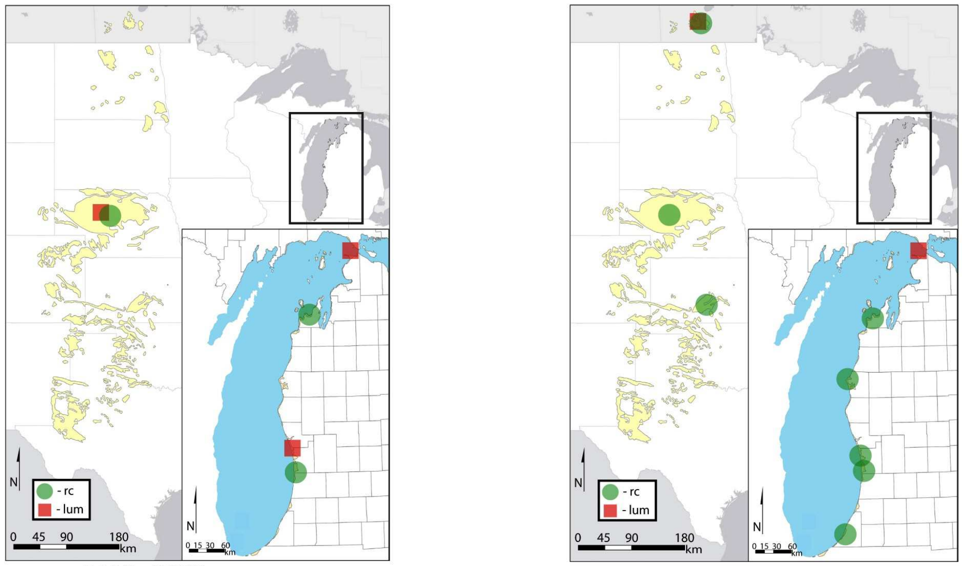


a) 3800 - 3600 years ago b) 3600 - 3400 years ago

Figure 4.23: **Time-slice maps for the GP and LM regions. a): distribution of ages between 3800-3600 years ago; b): distribution of ages between 3600-3400 years ago.**

The map in Figure 4.23a suggests that dunes in central Lake Michigan as well as the central and southern Great Plains were active from 3800-3600 years ago. Radiocarbon data from northern Texas may indicate localized dune stability during that same time period. Figure 4.23b indicates that dunes were largely active throughout most of the Great Plains region, with localized stability in central Kansas and northern Texas. The northern and southern subregions of Lake Michigan were likely stable from 3600-3400 years ago, with localized activity likely occurring in the northern part of the Lake Michigan region.

Figure 4.24a suggests that localized stability and activation events occurred in the Nebraska Sand Hills from 3400-3200 years ago. Localized stability likely occurred in the northern and central subregions of Lake Michigan, with localized dune activation occurring in the same subregions. Figure 4.24b



a) 3400 - 3200 years ago b) 3200 - 3000 years ago

Figure 4.24: Time-slice maps for the GP and LM regions. a): distribution of ages between 3400-3200 years ago; b): distribution of ages between 3200-3000 years ago.

is the only map that truly suggests that dunes in the Great Lakes and Great Plains were mostly stable at the same time, with localized dune activation probably occurring in Manitoba. Radiocarbon data from the Great Lakes region largely indicates that dunes were stable, with localized dune activation in the northern part of the region.

The map in Figure 4.25a shows that dunes were likely stable in the northern and central Great Plains from 3000-2800 years ago, with localized activity occurring in the Nebraska Sand Hills. Northern Lake Michigan was probably stable during the same time interval, with dune activity occurring in the central and southern parts of the region. Figure 4.25b suggests that dune stability was occurring in northeastern Colorado whereas dunes were active in the Nebraska Sand Hills. Localized stability and activation was likely occurring in the northern part of the Great Lakes region from 2800-2600 years ago, with simultaneous activity occurring in the central part of the region.

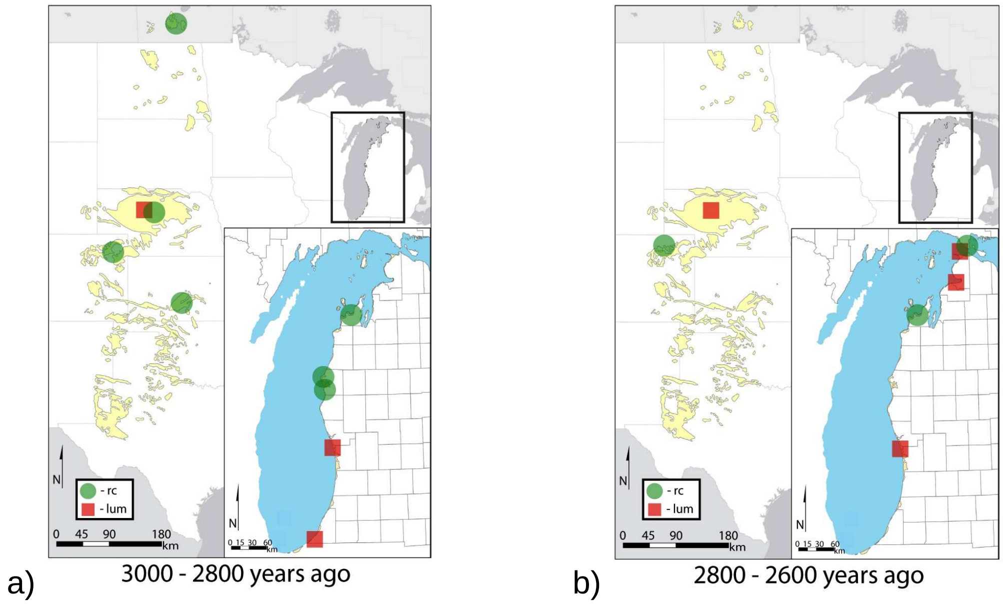


Figure 4.25: Time-slice maps for the GP and LM regions. a): distribution of ages between 3000-2800 years ago; b): distribution of ages between 2800-2600 years ago.

In Figure 4.26a, the map shows that dunes across much of the Great Plains were likely stable with some localized activation in the central part of the region. In the Great Lakes, dunes appear to have been active in the northern and southern subregions, with stability occurring in the central part of the region, as well as localized stability in the northern part of the Great Lakes region. Figure 4.26b suggests that dunes were largely stable across the Great Plains from 2400-2200 years ago, with localized activation in the central Plains. Dunes were likely active along most of the Lake Michigan coastal zone, with some localized stability in the northern part of the region.

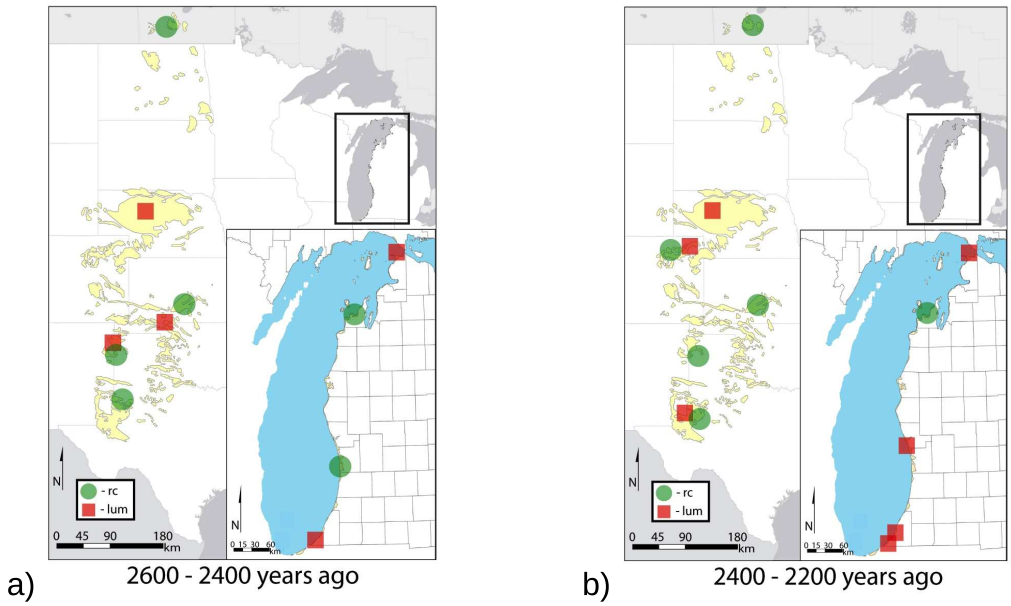


Figure 4.26: Time-slice maps for the GP and LM regions. a): distribution of ages between 2600-2400 years ago; b): distribution of ages between 2400-2200 years ago.

The map in Figure 4.27a suggests that dunes were largely stable in the northern and central Great Plains, with localized activity in the Nebraska Sand

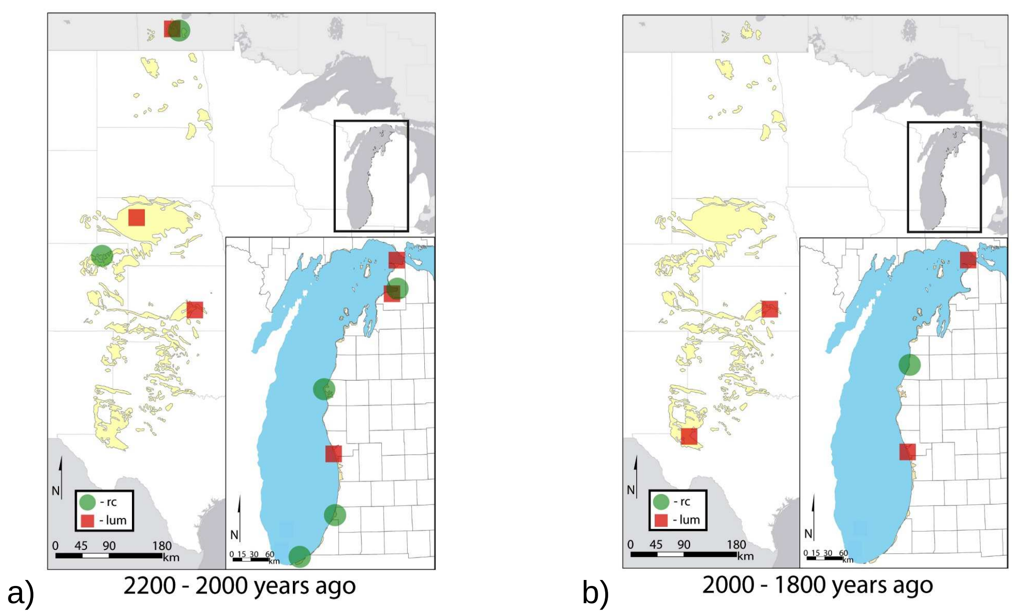


Figure 4.27: Time-slice maps for the GP and LM regions. a): distribution of ages between 2200-2000 years ago; b): distribution of ages between 2000-1800 years ago.

Hills and central Kansas. Dunes along the eastern Lake Michigan coastal zone were largely stable, with localized activity occurring in the central and northern parts of the region from 2200-2000 years ago. Figure 4.27b shows that dunes were likely active in both regions, with localized stability in the northern part of the Great Lakes region from 2000-1800 years ago.

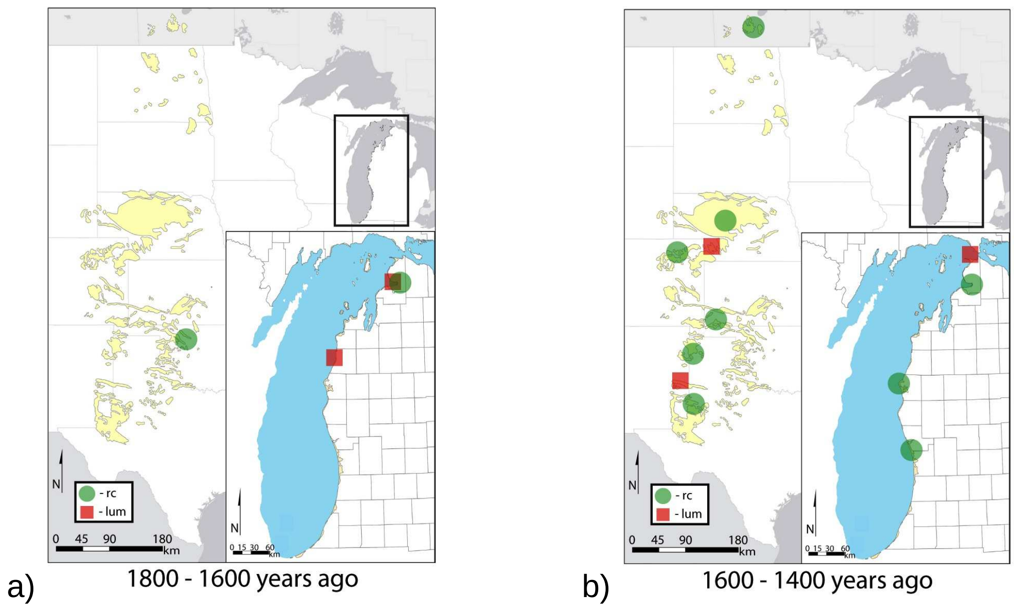
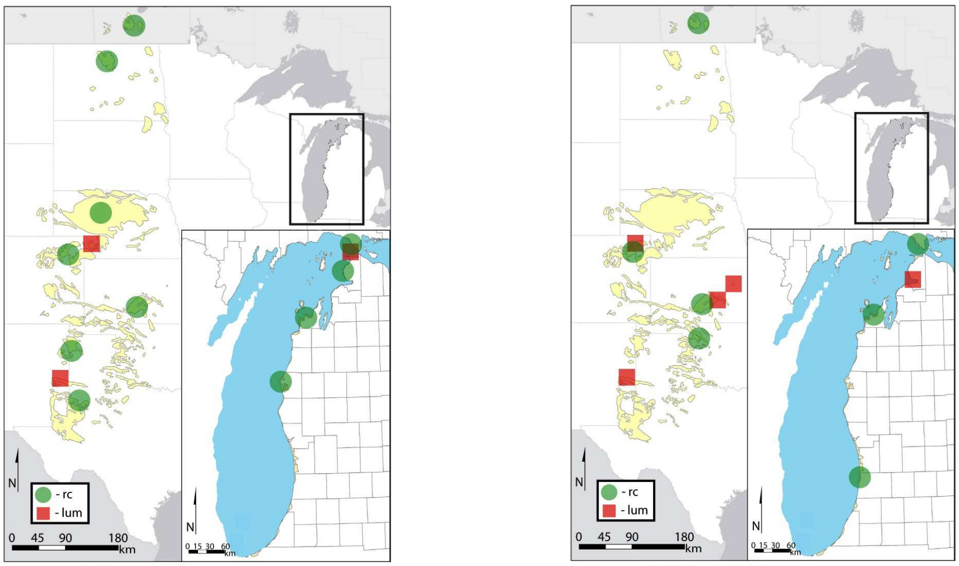


Figure 4.28: Time-slice maps for the GP and LM regions. a): distribution of ages between 1800-1600 years ago; b): distribution of ages between 1600-1400 years ago.

Limited data in Figure 4.28a suggest that dunes were stable from 1800-1600 years ago in the southern Great Plains, as well as the northern part of the Great Lakes region. However, localized activity appears to have also occurred in the northern part of the Great Lakes coastal zone. Figure 4.28b indicates that dunes in both regions were largely stable from 1600-1400 years ago, with some isolated dune activity. This time interval represents the core of the "Holland

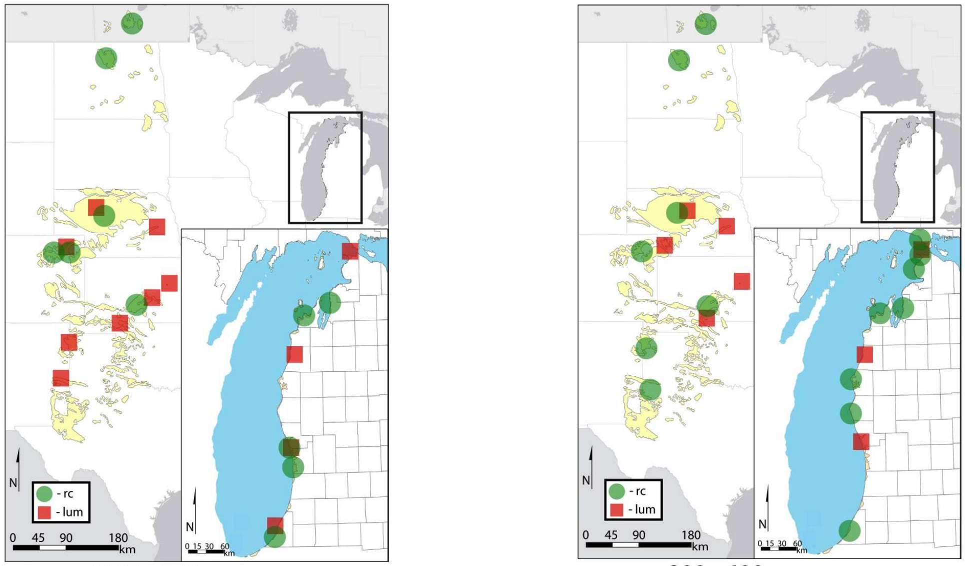
Paleosol” interval – a time of regional, widespread dune stability in the Great Lakes region (Arbogast et al., 2004).



a) 1400 - 1200 years ago b) 1200 - 1000 years ago

Figure 4.29: Time-slice maps for the GP and LM regions. a): distribution of ages between 1400-1200 years ago; b): distribution of ages between 1200-1000 years ago.

The map in Figure 4.29a suggests that dunes in both regions were largely stable from 1400-1200 years ago. Some localized dune activity likely occurred in the central and southern Great Plains, as well as in the northern part of the Great Lakes region. Figure 4.29b shows that dunes were mostly stable throughout the Great Plains, with localized activation in the central and southern subregions of the Great Plains from 1200-1000 years ago. Dunes were likely stable throughout most of the Great Lakes region, with localized activity in the northern part of the region.



a) 1000 - 800 years ago b) 800 - 600 years ago

Figure 4.30: Time-slice maps for the GP and LM regions. a): distribution of ages between 1000-800 years ago. b): distribution of ages between 800-600 years ago.

In Figure 4.30a, the map suggests that dunes were stable in the northern and central Great Plains, with localized activity occurring throughout most of the central and southern parts of the region. Dunes appear to have been stable throughout the entirety of the Great Lakes region, with dune activity occurring at a local level along the eastern Lake Michigan coastal zone from 1000-800 years ago. Similar dune evolution is displayed in Figure 4.30b, with dune stability likely occurring across the entirety of both regions. Similar dune activity is revealed in the central Great Plains and central Great Lakes subregions from 800-600 years ago. Additionally, the data in Figure 4.30 suggest that the MWP may not have been an interval of widespread dune activation across both regions, but does allude to the likelihood of similar dune activity in the eastern Great Plains and northern Lake Michigan as previously suggested by Arbogast et al. (2011).

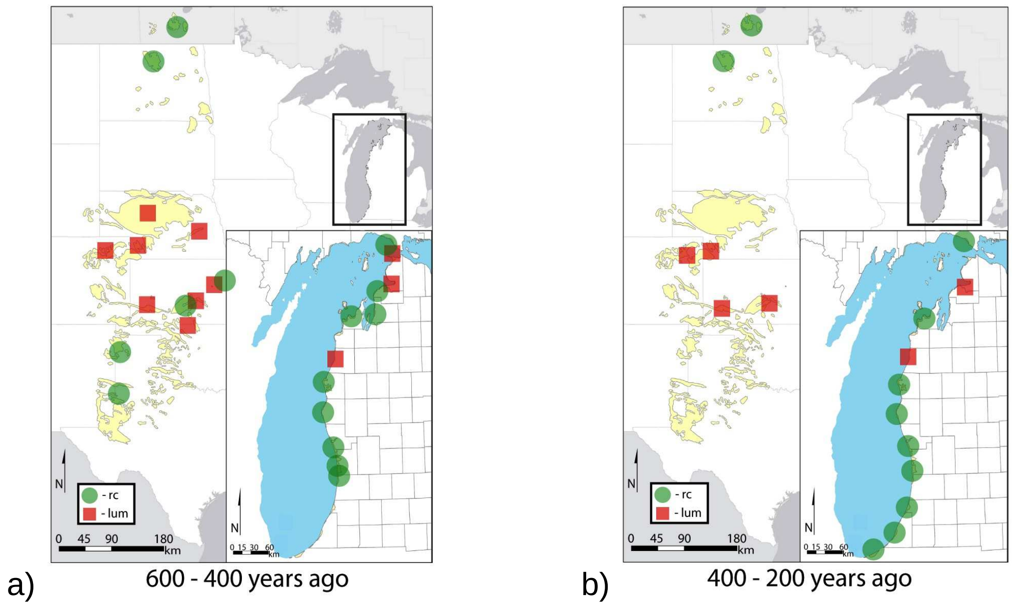


Figure 4.31: Time-slice maps for the GP and LM regions. a): distribution of ages between 600-400 years ago; b): distribution of ages between 400-200 years ago.

The map in Figure 4.31a indicates that dunes were largely stable across both regions, with an abundance of activity in the central Great Plains and northern Lake Michigan from 600-400 years ago. Figure 4.31b suggests that dunes were stable in the northern Great Plains and across most of the Great Lakes region from 400-200 years ago. However, similar dune activation appears to have occurred in the central Great Plains and in the northern Lake Michigan region during that time interval.

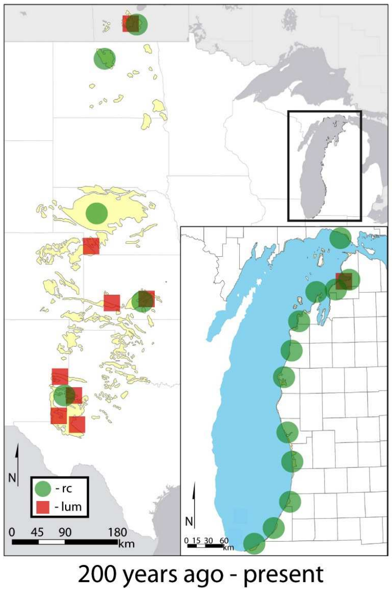


Figure 4.32: Time-slice map for the GP and LM regions, displaying the distribution of ages between 200 years ago and the present.

In Figure 4.32, dunes in the Great Plains appear to have been largely active across the region from 200 years ago to the present, with some localized stability. The Great Lakes region appears to have been stabilized with localized activity in the northern part of the region from 200 years ago to the present.

4.3.1: Analysis of Time-Slice Maps

Through analysis of the time-slice maps, it appears that several activation events occurred from 5200-4800 years ago, and from 4400-1800 years ago in both the Great Plains and Great Lakes regions. The spatial variability in dune activity has differed extensively throughout the past 7000 years in both regions, and further suggests that dune activity was normally not constrained to a single dune field, but that activity was spread across both regions. Similar to the abundance of activation events shown in the time-slice maps for both regions, the maps also display several stabilization events over the past 7000 years in both regions. In order to easily compare the time-slice map results, Figure 4.33 displays dune evolution through time in both regions, based upon sample size for each time interval. Individual rectangles represent a period of time in a particular

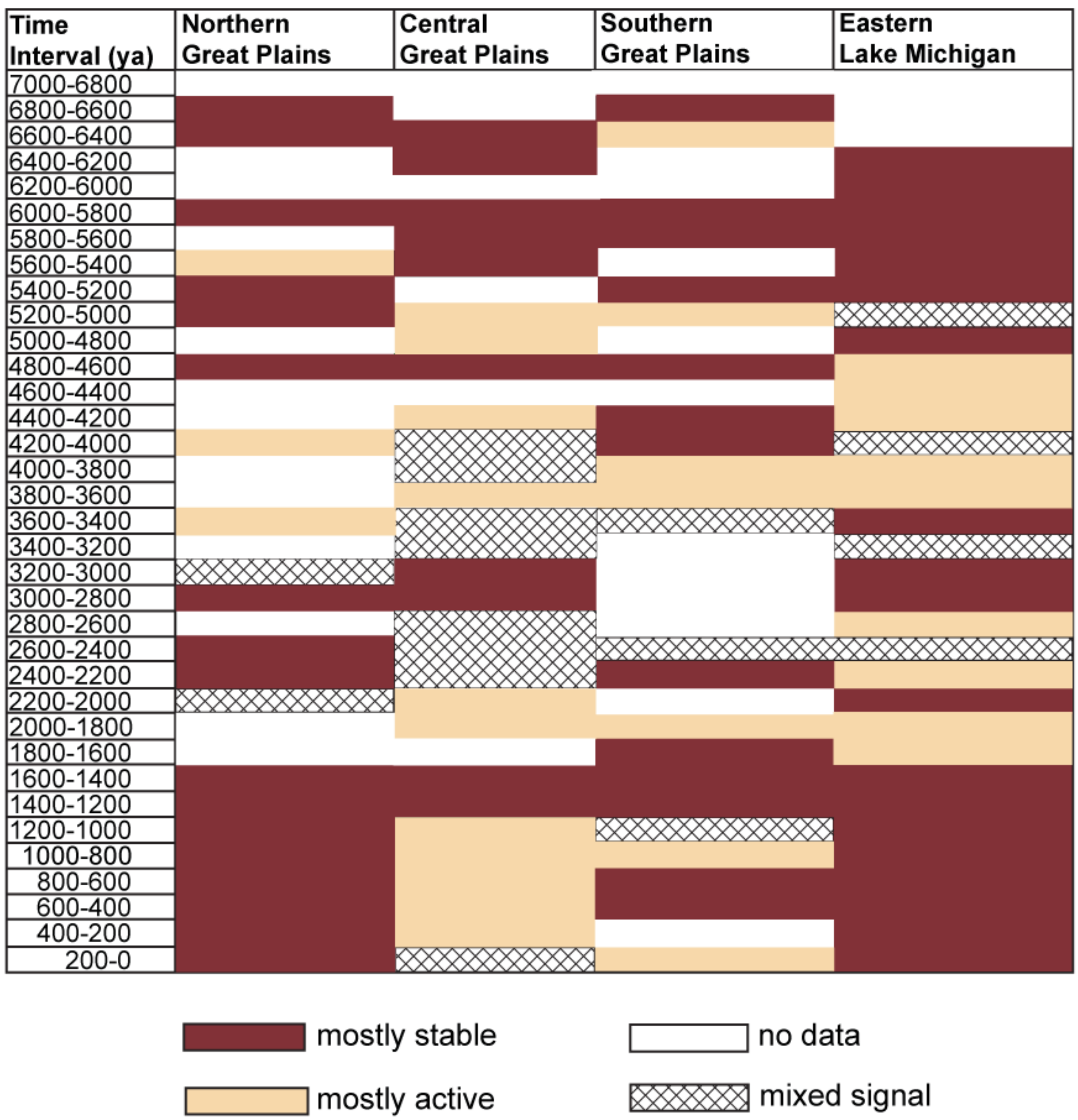


Figure 4.33: Summary of time-slice maps, derived from data shown in Figures 4.15-4.32.

location, with color indicating if the subregion or region was mostly active or mostly stable. If the same number of luminescence and radiocarbon dates appeared during a particular time interval, then the rectangle was filled with a wide crosshatch pattern, indicating a mixed signal. If a subregion or region had no data for a particular time interval, the rectangle was left blank.

Similar to the time-slice maps (Figures 4.15-4.32), Figure 4.33 suggests that whereas some similarity in dune evolution existed between the two regions, dune activity and stability mostly contrasted among regions throughout the Holocene. For example, there are only three intervals of time when both regions were largely stable: from 6000-5800 years ago, 1600-1400 years ago, and 1400-1200 years ago. Whereas dune activity occurred subregionally in the Great Plains and at similar times to dune activity in the Great Lakes, no similar interval of activity is present across the entirety of both regions.

Figure 4.33 also provides information on the variety of mixed and missing data from both regions. For example, although there are no samples from the early Lake Michigan record, a consistent record of dune evolution exists from 6400 years ago to the present. Alternatively, the dune evolution record in the northern and southern Great Plains is intermittent, with more consistency in younger dates in the entirety of the region.

4.4: Discussion

4.4.1: Advantages to Utilizing Time-Slice Maps in Dune Chronology

Through utilization of time-slice maps and PDDs, dune chronologies in the Great Plains and eastern Lake Michigan coastal zone have been constructed. In the context of this research, the most notable advantage of using the time-slice maps as opposed to PDDs is in the display of dates prior to 1000 years ago. For example, the luminescence PDD from the Great Plains (Figure 4.2) suggests little to no dune activity occurred prior to 1000 years ago. However, when analyzing the time-slice maps (Figures 4.15-4.32), it is evident that significant dune activation occurred in the Great Plains prior to 1000 years ago. By using the time-slice maps for both areas in 200-year spans, older dates are equally represented and not subject to the bias of an abundance of younger dates, as occurs with the PDDs.

Additionally, the use of time-slice maps allows for the identification of gaps in spatial data and temporal bias (Halfen and Johnson, 2013). For example, of the 35 200-year time periods presented in Figures 4.15-4.32, eight periods of time occur where data are missing for one or both regions: (1) from 7000-6800 years ago in both regions, (2,3) from 6800-6400 years ago (two periods) along eastern Lake Michigan, (4) from 6200-6000 years ago in the Great Plains, (5) from 5000-4800 years ago in the Great Plains, (6) from 4800-4600 years ago along eastern Lake Michigan, (7) from 4600-4400 years ago in the Great Plains, and (8) 3800-3600 years ago along eastern Lake Michigan. Because activation or stabilization events must be occurring at any given time in either location, the lack of luminescence or radiocarbon dates suggests that samples bracketed by the previously mentioned time periods have not yet been collected as part of any study in one or both respective locations.

In addition, throughout the course of geomorphic study in both regions, certain dune fields have attracted more research interest than others (e.g. Nebraska Sand Hills, Great Bend Sand Prairie, Sleeping Bear Dunes), and thus an inadvertent research bias has developed. In much of the previous dune chronology literature from both regions, an abundance of dates from a particular area has led researchers to suggest a higher likelihood for activation/stabilization events, when in fact this may not actually be the case. For this reason, sample sizes were left off of the maps shown in Figures 4.15-4.32. Until equal amounts of chronological data are collected for each dune field in both regions, an abundance of dates for a particular area only lends weight to increased interest in a particular area. In this regard, the time-slice maps are helpful in that they provide geomorphologists the opportunity to visualize where data are missing for particular time periods in different areas, and the opportunity for possible development of a research design for obtaining dates from the areas where data are absent on the maps.

4.4.2: Potential Catalysts for Dune Activation and Stabilization in the Great Plains and Eastern Lake Michigan Coastal Zone

Interpretation of PDDs (Figures 4.1-4.8) and time-slice maps shown in Figures 4.15-4.32 show that several periods of similar dune activation and stabilization have taken place in the Great Plains and along the eastern Lake

Michigan coastal zone over the past 7000 years. This history suggests that dunes in both regions may have responded to both similar and different forcing variables. Previous dune chronology research in both regions has focused primarily on specific dune fields (e.g. Ahlbrandt and Fryberger, 1980; Arbogast, 1996; Forman et al., 2001; Holliday, 2001; Arbogast et al., 2002; Hugenholtz and Wolfe, 2005; Hanson et al., 2009b; Blumer et al., 2012), and has associated sporadic dune activity in the Great Plains with periods of drought through the Holocene (e.g. Mason et al., 2004; Cook et al., 2004; Miao et al., 2007). Prior research conducted in eastern Lake Michigan dune fields has commonly associated periods of dune activation with high lake levels (e.g. Loope and Arbogast, 2000; Arbogast et al., 2002; Hansen et al., 2010). These conclusions suggest that contrasting conditions trigger dune activation events in these regions. However, a study by Arbogast et al. (2011) showed a similar period of dune activation occurred in both regions during the Medieval Warm Period (MWP), which was a period of warmer climate, lower lake levels, and associated drought from ~1100-800 years ago in North America (Laird et al., 1996; Grissino-Mayer, 1996; Schmeider et al., 2011).

Although the Arbogast et al. (2011) study suggests that broad climate patterns may have concurrently affected dunes in both regions, it has been shown with the time-slice maps in Figures 4.15-4.32 that the MWP may have been a geographically isolated dune activation event, as dune fields on the eastern fringes of the Great Plains (Duncan and Abilene) were concurrently active with dunes on the eastern Lake Michigan coastal zone during that time.

Dune activity during the MWP may have been widespread in the Great Plains, but it is possible that reworking of sands may have potentially altered the activation record. Thus, the MWP appears to have been only one of several intervals of similar dune activation across both regions during the past 7000 years.

Although the MWP is noteworthy because of the severity of drought and its great extent in the midcontinent, additional work has also been done to determine when other periods of Holocene drought occurred in the region. Wetherald et al. (1999) argued that mid-continental warming can lead to increased evaporation and decreased soil moisture. Forman et al. (2001) and Booth et al. (2005) suggested that periods of drought might be associated with a La Niña-influenced climate, and proposed that cool sea surface temperatures (SST) in the eastern tropical Pacific Ocean, tropical Atlantic Ocean, and Gulf of Mexico can significantly weaken cyclogenesis over central North America, initiating both micro and macro scale drought (Booth et al., 2005; Forman et al., 2008). Feng et al. (2008) proposed that SSTs in the North Atlantic Ocean might also have an effect on the initiation of drought episodes in the central and southern Great Plains. Other research has also suggested that drought in the Great Plains and potentially North America as a whole may be linked to variations in the Atlantic Multidecadal Oscillation (e.g. Knight et al., 2006), or to the Pacific Decadal Oscillation (e.g. McCabe et al., 2004).

Significantly less research has been conducted within the Great Lakes region pertaining to Holocene drought. Booth et al. (2006) examined one peat core from the thumb in Lower Michigan and one from northern Minnesota. The authors hypothesized that SST anomalies in the North Pacific, Tropical Pacific, and North Atlantic likely had a combined impact on North American climate over the past 1000 years (Booth et al., 2006). More recently, Arbogast et al. (personal communication) found that dune activation and stabilization events in the Great Lakes may correlate with the 7000-year El Niño record from Peru obtained by Moy et al. (2002). In order to test this hypothesis and incorporate the lake level data discussed in previous studies (e.g., Arbogast et al., 2002; Hansen et al., 2010), Great Lakes OSL and radiocarbon PDDs from Figure 4.6 were placed above a 4700-year lake level curve from Lake Michigan and the El Niño record for the past 7000 years (Figure 4.34).

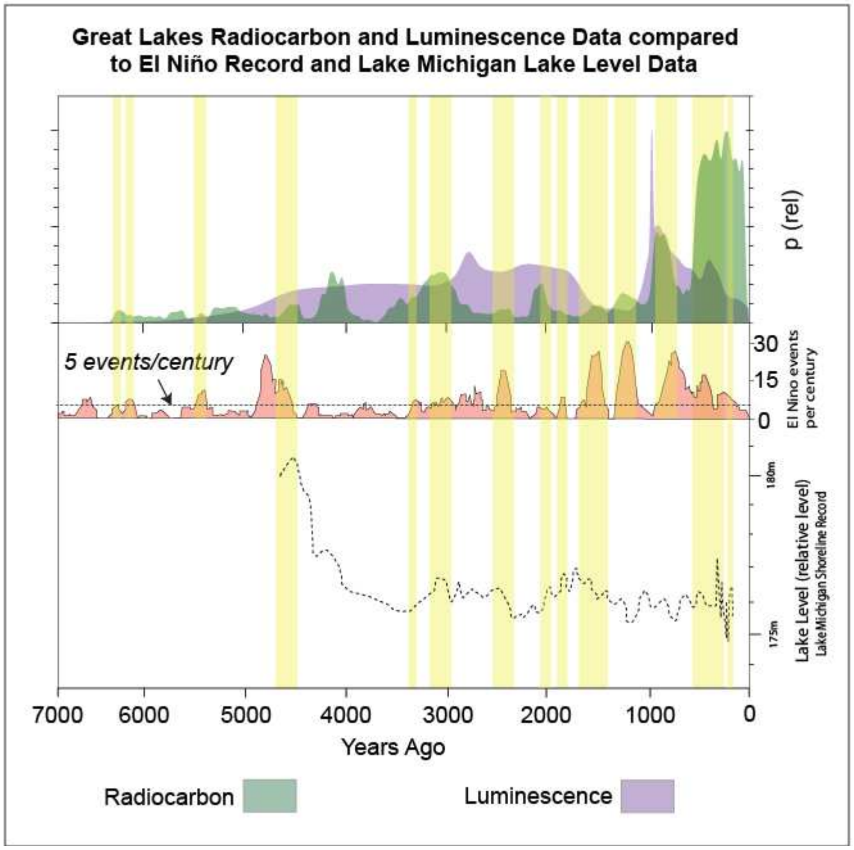


Figure 4.34: Great Lakes radiocarbon and luminescence PDDs combined with El Niño record and Lake Michigan lake level data (modified from Moy et al., 2002; Baedke and Thompson, 2000; Arbogast et al., unpublished data). Yellow bars highlight similar intervals of high lake level, El Niño occurrence, and dune stability.

As shown in Figure 4.34, dune stabilization appears to have occurred mostly when both lake levels and the number of El Niño events per century were high (>5). Conversely, activation events appear to have transpired when both lake levels and the number of El Niño events per century were low (<5). This finding assumes that La Niña events were occurring when El Niño events were not, and that the La Niña events may have caused increased storminess, leading to landscape instability and associated dune activation (Arbogast et al., personal communication).

Given the findings in the Great Lakes region, a similar figure (Figure 4.35) was created to compare how stabilization events correlated with El Niño events and the C_4 plant carbon record from buried soils (Nordt et al., 2008) in the Great Plains. The C_4 plant carbon record was utilized because C_4 plants thrive in a semi-arid environment and respond positively to increases in temperature, thus serving as a climate proxy (von Fischer et al., 2008). Based upon interpretation of Figure 4.35, correlation between frequent El Niño events and periods of dune stability in the Great Plains appears to be similar to that of the Great Lakes. However, the C_4 plant carbon record appears to correlate with both periods of dune stability and activation in the Great Plains, which may be a result of C_4 plants responding positively to a variety of climate conditions, including intervals of time between drought events (Nordt et al., 2008).

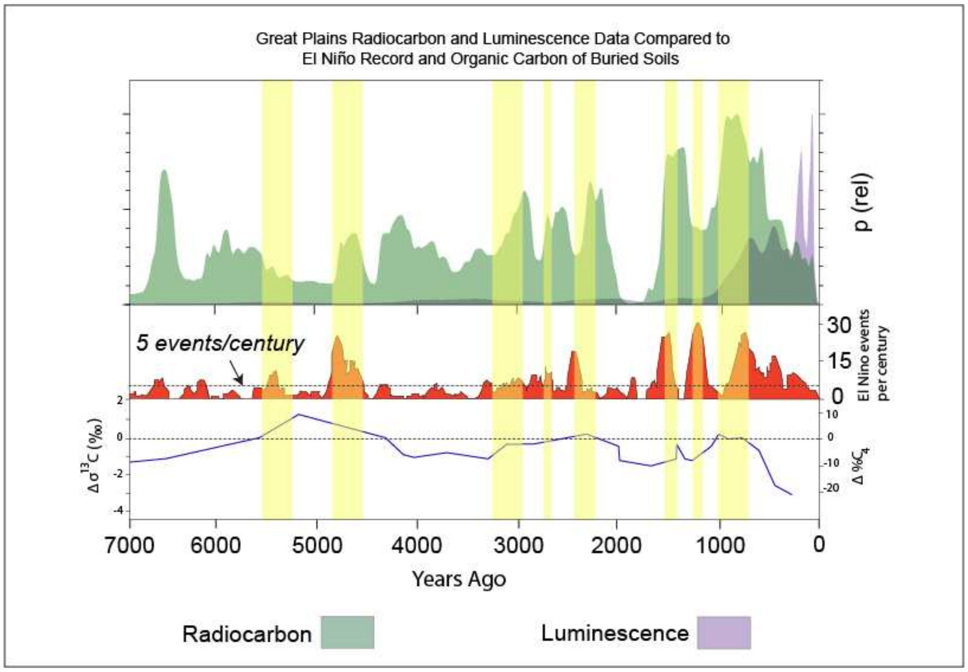


Figure 4.35: Great Plains radiocarbon and luminescence PDD combined with El Niño event and buried soil organic carbon data (modified from Moy et al., 2002; Nordt et al., 2008; Arbogast et al., unpublished data).

Nevertheless, an association between frequent El Niño events and dune stabilization events in both the Great Plains and Great Lakes regions appears to exist, and suggests that broad climate patterns likely affect dune systems in both regions.

4.5: Conclusions

An abundance of research has been conducted on dune fields in both the Great Plains and eastern Lake Michigan coastal zone for over a century. More recently, quantitative methods and data collection have been utilized at a large scale in an attempt to construct dune chronologies throughout the late Pleistocene and Holocene through the use of radiocarbon and luminescence dating. Substantial effort has been applied to determining the forcing variables that cause dune activation and stabilization in both regions, as well as determining the most effective way to display luminescence and radiocarbon data obtained as part of recent dune studies in both regions.

As part of this research, three different methods of data interpretation were utilized. Construction of PDDs, PCA, and time-slice maps displayed dune chronologies for both regions in very different ways, both graphically and quantitatively. For time-constrained and regional data where a geographic component is implied, PDDs provided a suitable method for construction of dune chronologies. For interregional dune chronology research over a broad period of time (>1000 years), PCA and time-slice maps were the best methods to both statistically and spatially display luminescence and radiocarbon data. For example, given the abundance of younger luminescence dates in the Great Plains, the PDDs did not have the capacity to pick up ~25% of the luminescence data set, thereby falsely implying that dunes were not active in the Great Plains region prior to 1000 years ago. Based upon the interpretation of PCA output (Table 4.3, 4.5; Figures 4.11-4.14) and time-slice maps (Figures 4.15-4.32), dune activation events have likely been taking place in both regions from ~4400 years ago to the present. Given the apparent synchroneity of dune systems in both regions, the potential capacity of climate factors such as El Niño frequency and SST fluctuations to have major impacts on the activity of dune systems is a strong possibility.

4.5.1: Contributions of this Research

There are four major contributions as a result of this research. The first contribution is that this research provides a data set for both luminescence and radiocarbon dates obtained from sand dunes in both the Great Plains and eastern Lake Michigan coastal zone. Previous research has provided local and regional data in one of the areas, but not for both within the same study. The second contribution of this study is the construction of sand dune chronologies for both the Great Plains and eastern Lake Michigan coastal zone. Incorporating PDDs and time-slice maps into a particular study has only been done on a regional level (e.g. Halfen and Johnson, 2013), but never in an interregional study. The third contribution of this study is the use of PCA in the investigation of dune chronology research. PCA introduces a data-reduction component that allows for the identification of similarities and differences within and across regions. As a result, corresponding locations are grouped, allowing for a straightforward analysis of dune evolution. The fourth contribution is represented in a discussion about how to best utilize both PDDs and time-slice maps on different scales depending upon specific research design. Briefly discussed as part of an application in the Great Plains by Halfen and Johnson (2013), interregional analysis shows the importance of integrating the geographical component into sand dune chronology research.

4.5.2: Future Research

The methods and results of this study provide ample opportunities for future research. Through the use and subsequent analysis of time-slice maps, gaps in spatial data and locational bias of existing chronologies have been identified. Given these tools, future research should focus on filling those “spatial gaps” to provide a more robust chronological data set, thus improving our understanding of sand dune activity through the Holocene. Further, the interregional analysis conducted as part of this study could be extended to multiple other regions in North America or potentially the world in a variety of dune systems.

APPENDIX

Table A.1: Radiocarbon and Luminescence data from the Great Plains.

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Duncan dune field, NE	Hanson et al. 2009	UNL1468	490	50		
Duncan dune field, NE	Hanson et al. 2009	UNL1338	560	50		
Duncan dune field, NE	Hanson et al. 2009	UNL1342	590	50		
Duncan dune field, NE	Hanson et al. 2009	UNL1346	670	60		
Duncan dune field, NE	Hanson et al. 2009	UNL1347	670	60		
Duncan dune field, NE	Hanson et al. 2009	UNL1348	690	60		
Duncan dune field, NE	Hanson et al. 2009	UNL1349	690	70		
Duncan dune field, NE	Hanson et al. 2009	UNL1343	700	60		
Duncan dune field, NE	Hanson et al. 2009	UNL1344	720	70		
Duncan dune field, NE	Hanson et al. 2009	UNL1345	830	90		
Duncan dune field, NE	Hanson et al. 2009	UNL1631	3440	310		
Duncan dune field, NE	Hanson et al. 2009	UNL1632	3640	280		
Duncan dune field, NE	Hanson et al. 2009	UNL1634	3720	340		
Duncan dune field, NE	Hanson et al. 2009	UNL1466	3990	350		
Duncan dune field, NE	Hanson et al. 2009	UNL1467	4170	410		
Duncan dune field, NE	Hanson et al. 2009	UNL1471	4360	360		
Duncan dune field, NE	Hanson et al. 2009	UNL1469	4980	570		
Duncan dune field, NE	Hanson et al. 2009	UNL1470	5070	430		
Abilene dunes, KS	Hanson et al. 2009	OSL1	860	70		
Abilene dunes, KS	Hanson et al. 2009	OSL2	610	40		
Abilene dunes, KS	Hanson et al. 2009	OSL3	760	70		
Abilene dunes, KS	Hanson et al. 2009	OSL4	780	70		
Abilene dunes, KS	Hanson et al. 2009	OSL5	720	60		
Abilene dunes, KS	Hanson et al. 2009	OSL6	710	80		
Abilene dunes, KS	Hanson et al. 2009	OSL7	760	60		
Abilene dunes, KS	Hanson et al. 2009	OSL8	790	100		
Abilene dunes, KS	Hanson et al. 2009	OSL9	460	40		
Abilene dunes, KS	Hanson et al. 2009	OSL10	640	70		
Abilene dunes, KS	Hanson et al. 2009	OSL11	710	60		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Abilene dunes, KS	Hanson et al. 2009	OSL12	750	80		
Abilene dunes, KS	Hanson et al. 2009	OSL13	780	80		
Abilene dunes, KS	Hanson et al. 2009	OSL14	820	80		
Abilene dunes, KS	Hanson et al. 2009	OSL15	1060	120		
Arkansas River, KS	Forman et al. 2008	UIC1407	180	15		
Arkansas River, KS	Forman et al. 2008	UIC1449	70	7		
Arkansas River, KS	Forman et al. 2008	UIC1448	80	10		
Arkansas River, KS	Forman et al. 2008	UIC1446	430	30		
Arkansas River, KS	Forman et al. 2008	UIC1445	340	30		
Arkansas River, KS	Forman et al. 2008	UIC1411	1490	130		
Arkansas River, KS	Forman et al. 2008	UIC2088	420	40		
Arkansas River, KS	Forman et al. 2008	UIC2087	380	30		
Arkansas River, KS	Forman et al. 2008	UIC1450	370	30		
Arkansas River, KS	Forman et al. 2008	UIC2086	65	5		
Arkansas River, KS	Forman et al. 2008	UIC2085	190	20		
Arkansas River, KS	Forman et al. 2008	UIC1412	320	25		
Arkansas River, KS	Forman et al. 2008	UIC1417	6280	670		
Arkansas River, KS	Forman et al. 2008	UIC1408	220	20		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC830 (RLS)	430	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC856 (RLS)	670	90		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC857 (RLS)	450	50		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC858 (RLS)	100	10		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC859 (RLS)	690	70		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC783 (CLS)	540	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC784 (CLS)	75	15		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC785 (CLS)	520	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC786 (CLS)	70	10		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC816 (CLS)	520	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC817 (CLS)	1430	120		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC827 (CLS)	1250	100		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC829 (CLS)	480	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC919 (CLS)	40	10		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC918 (CLS)	460	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC920 (CLS)	60	10		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC1225 (CLS)	1480	160		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC1226 (CLS)	480	30		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC1227 (CLS)	450	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC968 (HVLS)	400	50		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC978 (HVLS)	80	10		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC977 (HVLS)	660	50		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC976 (HVLS)	420	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC967 (HVLS)	140	20		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC966 (HVLS)	240	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC1222 (HVLS)	1490	160		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC1223 (HVLS)	480	30		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC1224 (HVLS)	70	10		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC986 (BBP)	80	10		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC991 (BBP)	540	40		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC992 (BBP)	420	30		
Nebraska Sand Hills/E Wray, CO	Forman et al. 2005	UIC993 (BBP)	70	10		
Nebraska Sand Hills	Mason et al. 2004	00RJG1	180	10		
Nebraska Sand Hills	Mason et al. 2004	00RJG3	810	60		
Nebraska Sand Hills	Mason et al. 2004	00RJG4	860	60		
Nebraska Sand Hills	Mason et al. 2004	00RJG6	3900	270		
Nebraska Sand Hills	Mason et al. 2004	00RJG10	950	70		
Nebraska Sand Hills	Mason et al. 2004	00RJG12	3400	250		
Nebraska Sand Hills	Mason et al. 2004	00RJG17	930	70		
Nebraska Sand Hills	Mason et al. 2004	00RJG15	2360	160		
Nebraska Sand Hills	Mason et al. 2004	00RJG13	3360	230		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Nebraska Sand Hills	Mason et al. 2004	00RJG22	910	70		
Nebraska Sand Hills	Mason et al. 2004	CURL-5322			0	0
Nebraska Sand Hills	Mason et al. 2004	Beta-4497			1590	70
Nebraska Sand Hills	Mason et al. 2004	CURL-5321			4150	40
Nebraska Sand Hills	Mason et al. 2004	CURL-5323			1380	35
Nebraska Sand Hills	Mason et al. 2004	Beta-50435, ETH-9088			980	55
Nebraska Sand Hills	Mason et al. 2004	Beta-50438, ETH-9089			2910	60
Nebraska Sand Hills	Mason et al. 2004	CURL-5324			2820	35
Minot dune field, ND	Muhs 1997	CAMS-23136			570	60
Minot dune field, ND	Muhs 1997	CAMS-23137			1030	60
Minot dune field, ND	Muhs 1997	CAMS-23138			0	0
Minot dune field, ND	Muhs 1997	CAMS-23139			0	0
Minot dune field, ND	Muhs 1997	CAMS-23140			570	50
Minot dune field, ND	Muhs 1997	CAMS-23141			330	60
Minot dune field, ND	Muhs 1997	CAMS-23142			1260	60
Minot dune field, ND	Muhs 1997	CAMS-23143			540	60
Minot dune field, ND	Muhs 1997	CAMS-23144			290	60
Minot dune field, ND	Muhs 1997	CAMS-24131			170	60
Great Bend Sand Prairie, KS	Arbogast 1996	7980			0	0
Great Bend Sand Prairie, KS	Arbogast 1996	7983			270	80
Great Bend Sand Prairie, KS	Arbogast 1996	7978			380	80
Great Bend Sand Prairie, KS	Arbogast 1996	7982			480	100
Great Bend Sand Prairie, KS	Arbogast 1996	7977			490	80
Great Bend Sand Prairie, KS	Arbogast 1996	7981			550	80
Great Bend Sand Prairie, KS	Arbogast 1996	8119			700	80
Great Bend Sand Prairie, KS	Arbogast 1996	8012			710	80
Great Bend Sand Prairie, KS	Arbogast 1996	9743			810	120
Great Bend Sand Prairie, KS	Arbogast 1996	8214			880	80
Great Bend Sand Prairie, KS	Arbogast 1996	9313			1030	80

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Great Bend Sand Prairie, KS	Arbogast 1996	7777			1090	120
Great Bend Sand Prairie, KS	Arbogast 1996	8218			1500	80
Great Bend Sand Prairie, KS	Arbogast 1996	7979			1500	100
Great Bend Sand Prairie, KS	Arbogast 1996	7998			2310	100
Great Bend Sand Prairie, KS	Arbogast 1996	8216			2400	130
Great Bend Sand Prairie, KS	Arbogast 1996	8314			2730	180
Great Bend Sand Prairie, KS	Arbogast 1996	6745			2940	160
Great Bend Sand Prairie, KS	Arbogast 1996	8003			3220	80
Great Bend Sand Prairie, KS	Arbogast 1996	8215			3280	100
Great Bend Sand Prairie, KS	Arbogast 1996	8221			3820	100
Great Bend Sand Prairie, KS	Arbogast 1996	8011			5370	120
Fort Morgan dune field, CO	Muhs et al. 1997	1			1560	70
Fort Morgan dune field, CO	Muhs et al. 1997	2			2190	70
Fort Morgan dune field, CO	Muhs et al. 1997	3			2160	80
Fort Morgan dune field, CO	Muhs et al. 1997	4			2580	70
Fort Morgan dune field, CO	Muhs et al. 1997	5			3600	70
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/09	595	100		
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/10	1065	125		
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/11	2370	210		
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/12	805	105		
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/14	535	115		
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/15	4850	325		
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/16	1060	95		
Fort Morgan/Wray/Sterling, CO	Clarke & Rendell 2003	NT02/17	370	50		
Keenesburg, CO	Forman et al. 1995	GX-15785			5520	410
Keenesburg, CO	Forman et al. 1995	AA-7017			5010	100
Keenesburg, CO	Forman et al. 1995	GX-15840			4760	305
Keenesburg, CO	Forman et al. 1995	GX-15841			920	260
Northeastern CO	Madole 1995	B70542			810	90

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Northeastern CO	Madole 1995	B61143			860	90
Northeastern CO	Madole 1995	B52719			910	50
Northeastern CO	Madole 1995	B61144			940	110
Northeastern CO	Madole 1995	B62192			1000	100
Northeastern CO	Madole 1995	B59164			1150	70
Northeastern CO	Madole 1995	B70543			1370	80
Northeastern CO	Madole 1995	B52846			1380	90
Northeastern CO	Madole 1995	B53002			2860	60
Northeastern CO	Madole 1995	B72203			5640	90
Southern KS/Northern OK	Werner et al. 2011	1379	460	40		
Southern KS/Northern OK	Werner et al. 2011	1381	500	70		
Southern KS/Northern OK	Werner et al. 2011	1378	630	70		
Southern KS/Northern OK	Werner et al. 2011	1372	670	130		
Southern KS/Northern OK	Werner et al. 2011	1452	720	120		
Southern KS/Northern OK	Werner et al. 2011	1453	810	90		
Southern KS/Northern OK	Werner et al. 2011	1455	520	50		
Southern KS/Northern OK	Werner et al. 2011	1456	630	50		
Southern KS/Northern OK	Werner et al. 2011	1380	700	70		
Southern KS/Northern OK	Werner et al. 2011	1373	2530	300		
Southern KS/Northern OK	Werner et al. 2011	1374	6440	760		
Southern KS/Northern OK	Werner et al. 2011	1463	3570	400		
Southern KS/Northern OK	Werner et al. 2011	1460	3590	360		
Southern KS/Northern OK	Werner et al. 2011	1461	3620	300		
Northwestern TX/Eastern NM	Feathers 2003	UW569	2410	130		
Northwestern TX/Eastern NM	Feathers 2003	UW570	5640	250		
Northwestern TX/Eastern NM	Feathers 2003	UW582	4040	310		
Northwestern TX/Eastern NM	Feathers 2003	UW583	6500	570		
Northwestern TX/Eastern NM	Feathers 2003	UW588	950	110		
TX dunes (multiple locations)	Holliday 2001	A7432.1			2340	40

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
TX dunes (multiple locations)	Holliday 2001	A7435.1			3215	348
TX dunes (multiple locations)	Holliday 2001	A7436			3475	100
TX dunes (multiple locations)	Holliday 2001	A7437			4720	320
TX dunes (multiple locations)	Holliday 2001	A6905			6130	165
TX dunes (multiple locations)	Holliday 2001	A6913			450	30
TX dunes (multiple locations)	Holliday 2001	A6912			755	35
TX dunes (multiple locations)	Holliday 2001	CAMS16006			850	60
TX dunes (multiple locations)	Holliday 2001	A7861			1480	160
TX dunes (multiple locations)	Holliday 2001	A7861.1			1480	60
TX dunes (multiple locations)	Holliday 2001	A7862.1			3890	60
TX dunes (multiple locations)	Holliday 2001	SI4585			4855	90
TX dunes (multiple locations)	Holliday 2001	AA7094			2500	60
TX dunes (multiple locations)	Holliday 2001	AA7095			3800	60
TX dunes (multiple locations)	Holliday 2001	A7445			720	193
TX dunes (multiple locations)	Holliday 2001	A7446			4120	208
TX dunes (multiple locations)	Holliday 2001	A7448.1			5110	388
TX dunes (multiple locations)	Holliday 2001	A7450.1			645	148
TX dunes (multiple locations)	Holliday 2001	A7872			0	0
Lauder Sand Hills, Manitoba	Havholm & Running 2005	2			5240	60
Lauder Sand Hills, Manitoba	Havholm & Running 2005	3			5250	50
Lauder Sand Hills, Manitoba	Havholm & Running 2005	4			5800	50
Lauder Sand Hills, Manitoba	Havholm & Running 2005	5			5790	50
Southwestern Manitoba	Running et al. 2002	111143			2500	40
Southwestern Manitoba	Running et al. 2002	165740			5780	50
Southwestern Manitoba	Running et al. 2002	165741			5760	50
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1048			490	40
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1049			0	0
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1050			0	0
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1044			0	0

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1045			0	0
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1046			140	40
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1047			0	0
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1051			0	0
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1913			670	45
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1914			1600	45
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1915			2205	55
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1941			920	150
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1944			4180	75
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1945			2180	55
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1961			1430	60
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	WW1962			2150	60
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU1378			2690	170
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU1377			2950	160
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU1429			1090	90
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU1287			1310	330
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU1286			1370	100
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU155			1510	100
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU316			2780	170
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU315			4540	250
Brandon Sand Hills, Manitoba	Wolfe et al. 2000	QU314			4560	370
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O168	0	0		
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O170	0	0		
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O172	0	0		
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O173	5600	270		
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O174	4040	150		
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O175	2050	120		
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O176	3440	150		
Brandon Sand Hills, Manitoba	Wolfe et al. 2002	O177	3040	150		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Hutchinson dune field, KS	Halfen et al. 2012	1874	270	30		
Hutchinson dune field, KS	Halfen et al. 2012	1875	320	50		
Hutchinson dune field, KS	Halfen et al. 2012	1876	330	40		
Hutchinson dune field, KS	Halfen et al. 2012	1877	450	50		
Hutchinson dune field, KS	Halfen et al. 2012	1878	320	30		
Hutchinson dune field, KS	Halfen et al. 2012	1879	320	30		
Hutchinson dune field, KS	Halfen et al. 2012	1880	1150	140		
Hutchinson dune field, KS	Halfen et al. 2012	2091	120	10		
Hutchinson dune field, KS	Halfen et al. 2012	2092	390	50		
Hutchinson dune field, KS	Halfen et al. 2012	1881	290	20		
Hutchinson dune field, KS	Halfen et al. 2012	1882	920	80		
Hutchinson dune field, KS	Halfen et al. 2012	1883	300	30		
Hutchinson dune field, KS	Halfen et al. 2012	2090	350	30		
Hutchinson dune field, KS	Halfen et al. 2012	2553	180	10		
Hutchinson dune field, KS	Halfen et al. 2012	2554	200	20		
Hutchinson dune field, KS	Halfen et al. 2012	2555	170	20		
Hutchinson dune field, KS	Halfen et al. 2012	2562	100	10		
Hutchinson dune field, KS	Halfen et al. 2012	2563	520	50		
Hutchinson dune field, KS	Halfen et al. 2012	2560	80	10		
Hutchinson dune field, KS	Halfen et al. 2012	2561	140	30		
Hutchinson dune field, KS	Halfen et al. 2012	2558	110	10		
Hutchinson dune field, KS	Halfen et al. 2012	2559	220	20		
Hutchinson dune field, KS	Halfen et al. 2012	2556	80	80		
Hutchinson dune field, KS	Halfen et al. 2012	2557	160	20		
Hutchinson dune field, KS	Halfen et al. 2012	2551	180	20		
Hutchinson dune field, KS	Halfen et al. 2012	2552	190	20		
Hutchinson dune field, KS	Halfen et al. 2012	2686	200	20		
Hutchinson dune field, KS	Halfen et al. 2012	2687	240	20		
Hutchinson dune field, KS	Halfen et al. 2012	2688	260	30		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Hutchinson dune field, KS	Halfen et al. 2012	2689	200	20		
Hutchinson dune field, KS	Halfen et al. 2012	2692	220	20		
Hutchinson dune field, KS	Halfen et al. 2012	2693	240	30		
Hutchinson dune field, KS	Halfen et al. 2012	2694	960	80		
Hutchinson dune field, KS	Halfen et al. 2012	2695	960	80		
Hutchinson dune field, KS	Halfen et al. 2012	2696	100	10		
Hutchinson dune field, KS	Halfen et al. 2012	2697	600	50		
Hutchinson dune field, KS	Halfen et al. 2012	2700	240	20		
Hutchinson dune field, KS	Halfen et al. 2012	2701	920	90		
Hutchinson dune field, KS	Halfen et al. 2012	2702	190	20		
Hutchinson dune field, KS	Halfen et al. 2012	2703	420	50		
Hutchinson dune field, KS	Halfen et al. 2012	2690	220	20		
Hutchinson dune field, KS	Halfen et al. 2012	2691	200	20		
Hutchinson dune field, KS	Halfen et al. 2012	2698	80	10		
Hutchinson dune field, KS	Halfen et al. 2012	2699	190	20		
Hutchinson dune field, KS	Halfen et al. 2012	2984	140	10		
Hutchinson dune field, KS	Halfen et al. 2012	2985	140	20		
Hutchinson dune field, KS	Halfen et al. 2012	2986	220	30		
Hutchinson dune field, KS	Halfen et al. 2012	2971	2050	190		
Hutchinson dune field, KS	Halfen et al. 2012	2972	2080	200		
Hutchinson dune field, KS	Halfen et al. 2012	2974	1880	190		
Hutchinson dune field, KS	Halfen et al. 2012	2975	2070	200		
Hutchinson dune field, KS	Halfen et al. 2012	2976	210	20		
Hutchinson dune field, KS	Halfen et al. 2012	2977	270	50		
Hutchinson dune field, KS	Halfen et al. 2012	2981	80	10		
Hutchinson dune field, KS	Halfen et al. 2012	2982	160	20		
Hutchinson dune field, KS	Halfen et al. 2012	2983	90	10		
Hutchinson dune field, KS	Halfen et al. 2012	2987	100	10		
Hutchinson dune field, KS	Halfen et al. 2012	2988	200	20		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Hutchinson dune field, KS	Halfen et al. 2012	2969	110	10		
Hutchinson dune field, KS	Halfen et al. 2012	2970	810	70		
Southwestern KS	Olson & Porter 2002	92120			5870	60
Southwestern KS	Olson & Porter 2002	73448			3730	90
Southwestern KS	Olson & Porter 2002	75029			1600	80
Nebraska Sand Hills	Mason et al. 2011	1111	1480	120		
Nebraska Sand Hills	Mason et al. 2011	980	490	50		
Nebraska Sand Hills	Mason et al. 2011	1122	710	90		
Nebraska Sand Hills	Mason et al. 2011	1124	2800	200		
Nebraska Sand Hills	Mason et al. 2011	1097	540	50		
Nebraska Sand Hills	Mason et al. 2011	1099	3000	200		
Nebraska Sand Hills	Mason et al. 2011	1103	700	60		
Nebraska Sand Hills	Mason et al. 2011	1105	2500	200		
Nebraska Sand Hills	Mason et al. 2011	1107	2100	200		
Nebraska Sand Hills	Mason et al. 2011	1604	680	50		
Nebraska Sand Hills	Mason et al. 2011	1605	740	60		
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	1			3000	400
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	2			3560	70
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	3			3810	80
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	4			4900	500
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	5			5150	400
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	6			3600	400
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	7			3110	80
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	8			5040	80
Nebraska Sand Hills	Ahlbrandt & Fryberger 1983	9			860	55
Muleshoe dunes, NM/TX	Rich & Stokes 2011	98/2/1	90	20		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/13/3	1300	200		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/13/4	890	90		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/13/5	80	10		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/13/4	890	90		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/13/5	80	10		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/14/3	4000	700		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/15/2	830	70		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/15/3	70	10		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/16/1	1100	100		
Muleshoe dunes, NM/TX	Rich & Stokes 2011	99/17/1	1200	100		
Lea-Yoakum dunes, NM/TX	Rich & Stokes 2011	99/18/2	3600	400		
Lea-Yoakum dunes, NM/TX	Rich & Stokes 2011	99/18/3	110	10		
Mescalero dunes, NM/TX	Rich & Stokes 2011	99/19/2A	3900	400		
Mescalero dunes, NM/TX	Rich & Stokes 2011	99/19/2B	3700	300		
Mescalero dunes, NM/TX	Rich & Stokes 2011	99/19/3	2300	300		
Mescalero dunes, NM/TX	Rich & Stokes 2011	99/19/4	70	20		
Monahans/Andrews dunes, TX	Rich & Stokes 2011	99/21/2	2000	300		
Monahans/Andrews dunes, TX	Rich & Stokes 2011	99/22/1	5100	500		
Monahans/Andrews dunes, TX	Rich & Stokes 2011	99/22/2	70	10		
Monahans/Andrews dunes, TX	Rich & Stokes 2011	803/2	4300	400		
Alfalfa County, OK	Brady 1989	GX-14706			1200	70
Alfalfa County, OK	Brady 1989	GX-14709			6385	285
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	Beta-131206			1250	40
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	Beta-131207			1730	40
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL98-06	810	40		
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL98-06-1	800	50		
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL99-01	870	50		
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL99-01-1	880	50		
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL99-02C	830	50		
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL99-02B	870	50		

Table A.1: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL99-02A	3330	180		
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL99-03B	770	40		
SE Major Co/NW Kingfisher Co, OK	Lepper & Scott 2005	KL99-03A	830	50		

Table A.2: Radiocarbon and Luminescence data from the Eastern Lake Michigan Coastal zone.

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Northeastern Lake Michigan	Loope & Arbogast 2000	B83880			30	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B87102			40	60
Northeastern Lake Michigan	Loope & Arbogast 2000	WW2058			60	40
Northeastern Lake Michigan	Loope & Arbogast 2000	B87195			60	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B85491			70	60
Northeastern Lake Michigan	Loope & Arbogast 2000	WW905			80	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B85490			80	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B83235			110	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B106926			120	30
Northeastern Lake Michigan	Loope & Arbogast 2000	B82537			120	70
Northeastern Lake Michigan	Loope & Arbogast 2000	WW1161			120	50
Northeastern Lake Michigan	Loope & Arbogast 2000	WW980			120	50
Northeastern Lake Michigan	Loope & Arbogast 2000	B87104			130	40
Northeastern Lake Michigan	Loope & Arbogast 2000	B83974			150	50
Southern Lake Michigan	Loope & Arbogast 2000	WW985			150	50
Southern Lake Michigan	Loope & Arbogast 2000	WW972			150	50
Southern Lake Michigan	Loope & Arbogast 2000	WW974			160	50
Northeastern Lake Michigan	Loope & Arbogast 2000	WW2057			170	50
Southern Lake Michigan	Loope & Arbogast 2000	WW909			190	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B87103			190	60
Southern Lake Michigan	Loope & Arbogast 2000	WW975			200	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B56525			220	50
Northeastern Lake Michigan	Loope & Arbogast 2000	B83877			240	70
Northeastern Lake Michigan	Loope & Arbogast 2000	WW971			240	60
Southern Lake Michigan	Loope & Arbogast 2000	WW982			260	60
Southern Lake Michigan	Loope & Arbogast 2000	WW977			270	50
Northeastern Lake Michigan	Loope & Arbogast 2000	WW1163			270	50
Southern Lake Michigan	Loope & Arbogast 2000	WW897			280	50
Southern Lake Michigan	Loope & Arbogast 2000	WW900			280	60

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Northeastern Lake Michigan	Loope & Arbogast 2000	B56520			300	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B83534			310	60
Southern Lake Michigan	Loope & Arbogast 2000	WW981			310	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B87196			330	60
Southern Lake Michigan	Loope & Arbogast 2000	WW908			330	60
Southern Lake Michigan	Loope & Arbogast 2000	WW984			340	50
Southern Lake Michigan	Loope & Arbogast 2000	WW983			360	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B56521			390	50
Southern Lake Michigan	Loope & Arbogast 2000	WW898			390	50
Northeastern Lake Michigan	Loope & Arbogast 2000	B85488			420	50
Southern Lake Michigan	Loope & Arbogast 2000	WW902			430	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B83881			480	70
Northeastern Lake Michigan	Loope & Arbogast 2000	B56524			600	60
Southern Lake Michigan	Loope & Arbogast 2000	WW901			670	60
Northeastern Lake Michigan	Loope & Arbogast 2000	WW906			670	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B56522			900	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B83977			920	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B83976			1040	80
Northeastern Lake Michigan	Loope & Arbogast 2000	B85487			1130	90
Southern Lake Michigan	Loope & Arbogast 2000	WW976			1230	60
Southern Lake Michigan	Loope & Arbogast 2000	WW899			1280	60
Northeastern Lake Michigan	Loope & Arbogast 2000	WW2059			1380	40
Northeastern Lake Michigan	Loope & Arbogast 2000	B83236			1480	70
Southern Lake Michigan	Loope & Arbogast 2000	WW907			1660	50
Northeastern Lake Michigan	Loope & Arbogast 2000	WW1065			1890	50
Northeastern Lake Michigan	Loope & Arbogast 2000	WW1066			2029	70
Northeastern Lake Michigan	Loope & Arbogast 2000	B83975			2280	70
Northeastern Lake Michigan	Loope & Arbogast 2000	B85489			2340	70
Northeastern Lake Michigan	Loope & Arbogast 2000	B56523			2460	100

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Northeastern Lake Michigan	Loope & Arbogast 2000	B83879			2600	70
Northeastern Lake Michigan	Loope & Arbogast 2000	B85955			2690	50
Southern Lake Michigan	Loope & Arbogast 2000	WW903			2800	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B83234			2840	60
Southern Lake Michigan	Loope & Arbogast 2000	TX2890			2890	60
Southern Lake Michigan	Loope & Arbogast 2000	CAMS36652			2920	60
Northeastern Lake Michigan	Loope & Arbogast 2000	B92229			2920	90
Northeastern Lake Michigan	Loope & Arbogast 2000	B83878			3070	80
Northeastern Lake Michigan	Loope & Arbogast 2000	WW2060			3250	50
Southern Lake Michigan	Loope & Arbogast 2000	CAMS39354			3720	50
Southern Lake Michigan	Loope & Arbogast 2000	CAMS39355			3730	50
Northeastern Lake Michigan	Loope & Arbogast 2000	B83233			3820	90
Southern Lake Michigan	Loope & Arbogast 2000	B106929			4030	50
Northeastern Lake Michigan	Loope & Arbogast 2000	WW1068			4250	50
Northeastern Lake Michigan	Loope & Arbogast 2000	WW1064			4380	60
Northeastern Lake Michigan	Loope & Arbogast 2000	WW1067			4500	50
Northeastern Lake Michigan	Loope & Arbogast 2000	B83876			5330	150
Arcadia Dunes	Blumer et al. 2012	UIC2128	410	40		
Arcadia Dunes	Blumer et al. 2012	UIC2124	970	10		
Arcadia Dunes	Blumer et al. 2012	UIC2121	1765	190		
Arcadia Dunes	Blumer et al. 2012	UIC2119	3495	335		
Arcadia Dunes	Blumer et al. 2012	UIC2118	3530	300		
Arcadia Dunes	Blumer et al. 2012	UIC2122	320	50		
Arcadia Dunes	Blumer et al. 2012	UIC2123	630	85		
Arcadia Dunes	Blumer et al. 2012	UIC2129	710	80		
Arcadia Dunes	Blumer et al. 2012	UIC2125	910	95		
Arcadia Dunes	Blumer et al. 2012	UIC2127	4340	380		
Arcadia Dunes	Blumer et al. 2012	UIC2120	4500	445		
Arcadia Dunes	Blumer et al. 2012	UIC2126	4070	380		

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Holland	Arbogast et al. 2004	B179044			390	40
Holland	Arbogast et al. 2004	B175383			3090	40
Indiana Dunes Natl Lakeshore	Arbogast et al. 2004	B159504			50	50
Indiana Dunes Natl Lakeshore	Arbogast et al. 2004	B159508			160	40
Indiana Dunes Natl Lakeshore	Arbogast et al. 2004	B159509			240	40
Indiana Dunes Natl Lakeshore	Arbogast et al. 2004	B159506			2070	40
Montague	Arbogast et al. 2004	B172560			420	60
Holland	Hansen et al. 2002	LLAW1	3720	650		
Holland	Hansen et al. 2002	LLAW2	4340	570		
Holland	Hansen et al. 2002	LLAW3	4990	830		
Holland	Hansen et al. 2002	LLAW4	3870	470		
Holland	Arbogast et al. 2002	NSRL-10488			1050	65
Holland	Arbogast et al. 2002	NSRL-10489			2980	55
Holland	Arbogast et al. 2002	NSRL-10490			3560	55
Holland	Arbogast et al. 2002	NSRL-10491			3750	55
Holland	Arbogast et al. 2002	NSRL-10347			430	55
Holland	Arbogast et al. 2002	NSRL-10346			4090	55
Holland	Arbogast et al. 2002	NSRL-10345			4840	65
Holland	Arbogast et al. 2002	NSRL-10492			35	45
Holland	Arbogast et al. 2002	NSRL-10493			200	45
Holland	Arbogast et al. 2002	NSRL-10494			310	50
Holland	Arbogast et al. 2002	NSRL-10495			2390	65
Holland	Arbogast et al. 2002	NSRL-10496			3730	55
Holland	Arbogast et al. 2002	B-132389			130	50
Holland	Arbogast et al. 2002	B-132390			320	50
Holland	Arbogast et al. 2002	B-132391			390	40
Holland	Arbogast et al. 2002	B-132392			930	40
Rosy Mound Natural Area	Arbogast & Loope 1999	TX-8608			2890	60
Rosy Mound Natural Area	Arbogast & Loope 1999	NSRL-3518			2920	60

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Nugent Quarry	Arbogast & Loope 1999	NSRL-3676			3720	50
Jackson Quarry	Arbogast & Loope 1999	NSRL-3677			3730	50
Nordhouse Dunes Wilderness Area	Arbogast & Loope 1999	B-106928			4030	50
Northeastern Lake Michigan	Lovis et al. 2012	B-237014			860	40
Northeastern Lake Michigan	Lovis et al. 2012	B-237015			870	40
Northeastern Lake Michigan	Lovis et al. 2012	B-237016			1240	40
Southern Lake Michigan	Lovis et al. 2012	B-238129			820	40
Northeastern Lake Michigan	Lovis et al. 2012	B-40288			2630	70
Northeastern Lake Michigan	Lovis et al. 2012	B-40289			6550	80
Northeastern Lake Michigan	Lovis et al. 2012	B-40290			6430	70
Northeastern Lake Michigan	Lovis et al. 2012	B-40291			5440	70
Northeastern Lake Michigan	Lovis et al. 2012	B-40292			6450	80
Northeastern Lake Michigan	Lovis et al. 2012	B-40304			850	60
Northeastern Lake Michigan	Lovis et al. 2012	B-40305			5380	70
Northeastern Lake Michigan	Lovis et al. 2012	B-251817			190	40
Northeastern Lake Michigan	Lovis et al. 2012	DIC-651			2050	80
Northeastern Lake Michigan	Lovis et al. 2012	DIC-652			1830	120
Northeastern Lake Michigan	Lovis et al. 2012	DIC-653			1620	150
Northeastern Lake Michigan	Lovis et al. 2012	M-2311			870	120
Northeastern Lake Michigan	Lovis et al. 2012	M-2312			1290	130
Northeastern Lake Michigan	Lovis et al. 2012	M-2398			430	100
Northeastern Lake Michigan	Lovis et al. 2012	M-2401			1000	140
Northeastern Lake Michigan	Lovis et al. 2012	M-2405			670	100
Northeastern Lake Michigan	Lovis et al. 2012	M-2406			740	100
Northeastern Lake Michigan	Lovis et al. 2012	N-1268			905	115
Northeastern Lake Michigan	Lovis et al. 2012	M-2059			730	110
Northeastern Lake Michigan	Lovis et al. 2012	M-2060			240	100
Northeastern Lake Michigan	Lovis et al. 2012	M-2065			1320	120
Southern Lake Michigan	Lovis et al. 2012	NSRL-3969			3000	50

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Southern Lake Michigan	Lovis et al. 2012	NSRL-3970			500	50
Southern Lake Michigan	Lovis et al. 2012	NSRL-3965			150	50
Southern Lake Michigan	Lovis et al. 2012	NSRL-3966			2080	40
Southern Lake Michigan	Lovis et al. 2012	NSRL-3967			2830	50
Northeastern Lake Michigan	Lovis et al. 2012	Shfd-06138	920	90		
Northeastern Lake Michigan	Lovis et al. 2012	Shfd-06139	740	70		
Northeastern Lake Michigan	Lovis et al. 2012	Shfd-06140	5150	390		
Northeastern Lake Michigan	Lovis et al. 2012	Shfd-06141	1300	110		
Northeastern Lake Michigan	Lovis et al. 2012	Shfd-06142	1950	180		
Northeastern Lake Michigan	Lovis et al. 2012	Shfd-07001	2150	170		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2134	1950	205		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2135	575	70		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2136	930	90		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2137	1930	225		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2138	3280	265		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2139	3380	300		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2143	3240	260		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2144	2315	220		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2145	2420	240		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2146	3260	305		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2147	3160	280		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2148	2490	230		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2149	2765	225		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2150	540	65		
Northeastern Lake Michigan	Lovis et al. 2012	UIC-2151	910	90		
Southern Lake Michigan	Lovis et al. 2012	UIC-2178	920	80		
Southern Lake Michigan	Lovis et al. 2012	UIC-2179	870	80		
Southern Lake Michigan	Lovis et al. 2012	UIC-2207	2360	260		
Southern Lake Michigan	Lovis et al. 2012	UIC-2208	2820	210		

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Southern Lake Michigan	Lovis et al. 2012	UIC-2209	2500	220		
Southern Lake Michigan	Lovis et al. 2012	UIC-2227	2480	200		
Southern Lake Michigan	Lovis et al. 2012	UIC-2228	1510	130		
Hoffmaster State Park	Hansen et al. 2010	Shfd03078	2250	250		
Hoffmaster State Park	Hansen et al. 2010	Shfd03079	2830	190		
Hoffmaster State Park	Hansen et al. 2010	Shfd03080	2790	260		
Hoffmaster State Park	Hansen et al. 2010	Shfd03082	4320	280		
Hoffmaster State Park	Hansen et al. 2010	Shfd03083	2200	130		
Hoffmaster State Park	Hansen et al. 2010	Shfd03084	1900	130		
Hoffmaster State Park	Hansen et al. 2010	Shfd05052	1990	120		
Hoffmaster State Park	Hansen et al. 2010	Shfd05053	3710	240		
Hoffmaster State Park	Hansen et al. 2010	Shfd05054	2830	200		
Hoffmaster State Park	Hansen et al. 2010	Shfd05055	3780	240		
Hoffmaster State Park	Hansen et al. 2010	Shfd05056	2800	180		
Hoffmaster State Park	Hansen et al. 2010	Shfd05057	2660	170		
Hoffmaster State Park	Hansen et al. 2010	Shfd05105	710	80		
Hoffmaster State Park	Hansen et al. 2010	Shfd05106	960	140		
Hoffmaster State Park	Hansen et al. 2010	Shfd05107	880	120		
Hoffmaster State Park	Hansen et al. 2010	Shfd05108	4360	290		
Hoffmaster State Park	Hansen et al. 2010	Shfd05109	3290	230		
Hoffmaster State Park	Hansen et al. 2010	CAMS-108778			330	35
Hoffmaster State Park	Hansen et al. 2010	CAMS-108779			925	35
Hoffmaster State Park	Hansen et al. 2010	CAMS-108780			915	35
Hoffmaster State Park	Hansen et al. 2010	CAMS-108892			180	40
Hoffmaster State Park	Hansen et al. 2010	CAMS-108895			1580	40
Hoffmaster State Park	Hansen et al. 2010	CAMS-108777			310	40
Hoffmaster State Park	Hansen et al. 2010	CAMS-108896			420	40
Warren Dunes State Park	Hansen et al. 2010	Shfd05058	3850	290		
Warren Dunes State Park	Hansen et al. 2010	Shfd05059	2260	150		

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Warren Dunes State Park	Hansen et al. 2010	Shfd05060	4030	270		
Warren Dunes State Park	Hansen et al. 2010	CAMS-156730			290	60
Warren Dunes State Park	Hansen et al. 2010	CAMS-156731			2970	80
Warren Dunes State Park	Hansen et al. 2010	CAMS-108781			865	35
Warren Dunes State Park	Hansen et al. 2010	CAMS-108897			345	40
Warren Dunes State Park	Hansen et al. 2010	CAMS-116835			940	35
Warren Dunes State Park	Hansen et al. 2010	CAMS-116837			685	35
Warren Dunes State Park	Hansen et al. 2010	CAMS-108893			970	40
Petoskey State Park	Lepczyk & Arbogast 2005	Beta132995	4620	195		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta132996	150	150		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta132997	128	123		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta132998	150	150		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta132999	380	90		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta133000	1740	115		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta133001	415	100		
Petoskey State Park	Lepczyk & Arbogast 2005	PP11/31	2180	240		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta133003	2800	60		
Petoskey State Park	Lepczyk & Arbogast 2005	PP14/31	1770	100		
Petoskey State Park	Lepczyk & Arbogast 2005	PP16/31	1030	100		
Petoskey State Park	Lepczyk & Arbogast 2005	Beta1333992	0	0		
Van Buren State Park	Van Oort et al. 2001	INSTAAR1			16	30
Van Buren State Park	Van Oort et al. 2001	B2			4620	60
Van Buren State Park	Van Oort et al. 2001	B3			5160	60
Van Buren State Park	Van Oort et al. 2001	B4			0	0
Van Buren State Park	Van Oort et al. 2001	B5			200	50
Van Buren State Park	Van Oort et al. 2001	B6			2090	40
Van Buren State Park	Van Oort et al. 2001	B7			3220	40
Van Buren State Park	Van Oort et al. 2001	B8			3190	50
Van Buren State Park	Van Oort et al. 2001	B9			3800	40

Table A.2: (cont'd)

Site	Author(s)	Lab Number	Lum. Mean Date	Error (1σ)	RC Mean Date	Error (1σ)
Van Buren State Park	Van Oort et al. 2001	B10			4550	80
Van Buren State Park	Van Oort et al. 2001	INSTAAR11			155	30
Van Buren State Park	Van Oort et al. 2001	INSTAAR12			235	35
Van Buren State Park	Van Oort et al. 2001	INSTAAR13			3320	45
Van Buren State Park	Van Oort et al. 2001	INSTAAR14			4890	45
Van Buren State Park	Van Oort et al. 2001	INSTAAR15			300	60
Van Buren State Park	Van Oort et al. 2001	INSTAAR16			5000	40
Sleeping Bear Dunes Natl Lakeshore	Snyder 1985	S1			4559	225
Sleeping Bear Dunes Natl Lakeshore	Snyder 1985	S2			2781	160
Sleeping Bear Dunes Natl Lakeshore	Snyder 1985	S3			688	180
Northeastern Lake Michigan	Arbogast et al. 2012 (unpub)	ISGS163	4400	420		
Northeastern Lake Michigan	Arbogast et al. 2012 (unpub)	ISGS160	4040	390		
Northeastern Lake Michigan	Arbogast et al. 2012 (unpub)	ISGS158	5050	440		
Northeastern Lake Michigan	Arbogast et al. 2012 (unpub)	ISGS157	4520	370		

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