CHAPTER

12

Late Quaternary Eolian Records of the Americas and Their Paleoclimatic Significance

DANIEL R. MUHS AND MARCELO ZÁRATE

Abstract

Eolian deposits, consisting of both dune and sheet sand as well as loess, are extensive in South and North America. Much of the loess present on both continents was derived from glacial outwash sources and deposited during the last glacial maximum (LGM). However, both continents have loess deposits that are nonglaciogenic; e.g., derived from volcaniclastic sources which are unrelated to glaciation. Nevertheless, cold, dry, windy conditions during the last glacial period may have favored loess deposition from a variety of sources. Eolian sand is also extensive on both continents, and some was deposited during the last glacial period as well, particularly in South America, the midcontinent and deserts of North America, and Alaska. Mid-Holocene eolian sand was deposited in parts of the midcontinent of North America under warmer and drier conditions. However, in both the midcontinent of North America and the southwestern deserts, the most recent and extensive eolian sand units were deposited during the late Holocene. Much of the late Holocene eolian sand in midcontinental North America may have been reworked from older sand deposited during the last glacial and mid-Holocene. Late Holocene eolian sand is also abundant in the Pampas region of South America and also may have been reworked from older deposits.

Far-traveled, fine-grained dust is transported to and from the Americas. Deep-sea sediment cores, ice cores, and soils contain long-term records of this dust flux. Deep-sea cores from off the coast of South America and ice cores from the Andes indicate that the last glacial period was characterized by much greater fluxes of dust than the Holocene. Both deep-sea cores and soil chronosequences suggest that the flux of dust from Africa to the Americas via the trade winds has been an important process for much of the Quaternary period. Isotopic data indicate that dust in Antarctic ice cores, also found in greater abundance during glacial periods, has its sources in the Pampas region of South America.

Deposition of loess and eolian sand, from multiple sources during the last glacial period, agrees with pollen records, lake records, and COHMAP; Cooperative Holocene Climate Mapping) climate simulations which suggest that the last glacial period was cold, dry, and windy (relative to now) in the mid- and high-latitude regions of both continents. In the Pampas region of South America, there is at least fair agreement between summer surface winds simulated by COHMAP and paleowinds as recorded by eolian sand and loess. In midcontinental North America, however, the presence of a

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strong glacial anticyclone centered over the Laurentide ice sheet (as derived from COHMAP models) would have generated northeasterly winds in the region immediately to the south of the ice sheet. Loess paleowind records are not in agreement with this model and suggest westerly or northwesterly winds. The reason for this disagreement is not understood and needs further study. Mid-Holocene eolian activity in parts of the mid-continent of North America agrees with pollen data and COHMAP simulations, both of which suggest that this may have been a warm and dry period. Late Holocene eolian activity on both continents cannot yet be dated precisely enough to be correlated with other records, such as those from diatoms and pollen. However, both eolian records and lacustrine records indicate that there were multiple periods of relatively dry climate during the late Holocene. Copyright © 2001 by Academic Press.

Resumen

Los depósitos eólicos que comprenden tanto dunas y mantos de arenas como loess, son extensos en Norte y Sudámerica. Ambos continentes, donde el loess ha sido depositado en gran parte durante el último máximo glacial, presentan depósitos loéssicos que no son glacigénicos, i.e, derivados de fuentes volcaniclásticas, no relacionadas con la glaciación. Sin embargo, las condiciones frías, secas y ventosas del último período glacial pueden haber favorecido la depositación de loess procedente de fuentes diversas. La arena eólica, también de amplia extensión en ambos continentes, en parte se depositó durante el último período glacial, particularmente en Sudamérica, la región continental media y los desiertos de Norteamérica, y Alaska. Arenas eólicas del Holoceno medio se depositaron en sectores de la región continental media de Norteamérica en condiciones más cálidas y más secas. Sin embargo, tanto en esta última región como en los desiertos del sudoeste, las unidades de arena eólica más recientes se depositaron durante el Holoceno tardío. Gran parte de la arena eólica del Holoceno tardío en la región continental media de Norteamérica puede haber sido retrabajada de arenas más antiguas depositadas durante los períodos del último glacial y del Holoceno medio. La arena eólica del Holoceno tardío también es frecuente en las Pampas de Sudamérica, donde puede haber sido retrabajada a partir de depósitos más antiguos como en Norteamérica.

Polvos de grano fino procedentes de fuentes lejanas, son transportados hacia y desde las Américas. Los testigos de sedimento de los fondos marinos, los testigos de hielo, y los suelos contienen registros temporalmente prolongados de este flujo de polvo. Los testigos de fondo marino costa afuera de Sudamérica y de hielo en los Andes indican que el último período glacial estuvo caracterizado por flujos de polvo mucho mayores que durante el Holoceno. Tanto los testigos de fondo marino como las cronosecuencias de suelos sugieren que el flujo de polvo desde Africa a las Américas a través de los vientos alisios ha sido un proceso importante durante la mayor parte del Cuaternario. Los datos isotópicos indican que el polvo en los testigos de hielo de Antártida, también encontrados con mayor abundancia durante los períodos glaciales, tienen sus áreas de procedencia en la región pampeana de Sudamérica.

La depositación de loess y arenas eólicas a partir de múltiples áreas de procedencia durante el último período glacial concuerda con los registros de polen, lagos y las simulaciones climáticas de COHMAP (Cooperative Holocene Mapping Project), las que sugieren que el último período glacial fue frío, seco y ventoso (en relación con la actualidad) en las regiones de latitudes medias y altas de ambos continentes. En las Pampas de Sudamérica, existe al menos un claro acuerdo entre los vientos estivales de superficie simulados por COHMAP y los paleovientos inferidos a partir de las arenas eólicas y el loess. En la región continental media de Norteamérica, sin embargo, la presencia de un fuerte anticiclón glacial centrado sobre el Manto de Hielo Laréntico (tal como se deriva de los modelos COHMAP) habría generado vientos del noreste en la región inmediatamente al sur del manto de hielo. Los paleovientos indicados por los registros de loess no están de acuerdo con este modelo y sugieren vientos del oeste o noroeste. Aún no se entiende la causa de este desacuerdo que requiere más estudios. La actividad eólica en sectores de la región continental media de Norteamérica concuerda con los datos de polen y las simulaciones COHMAP; ambos sugieren que este intervalo pudo haber sido un período cálido y seco. La actividad eólica del Holoceno tardío en ambos continentes no puede ser aún datada con precisión suficiente para ser correlacionada con otros registros tales como aquellos de diatomeas y polen. Sin embargo, tanto los registros eólicos como lacustres indican que hubo múltiples períodos de clima relativamente seco durante el Holoceno tardío.

12.1. INTRODUCTION

The Americas contain rich late Quaternary eolian records in the form of loess (Fig. 1), eolian sand sheets, and dunes. Eolian deposits are important in paleoclimatic studies because they (1) put limits on the moisture balance of a region at the time of formation, (2) can be sensitive indicators of the amount of vegetation cover, and (3) are records of wind direction. The record of

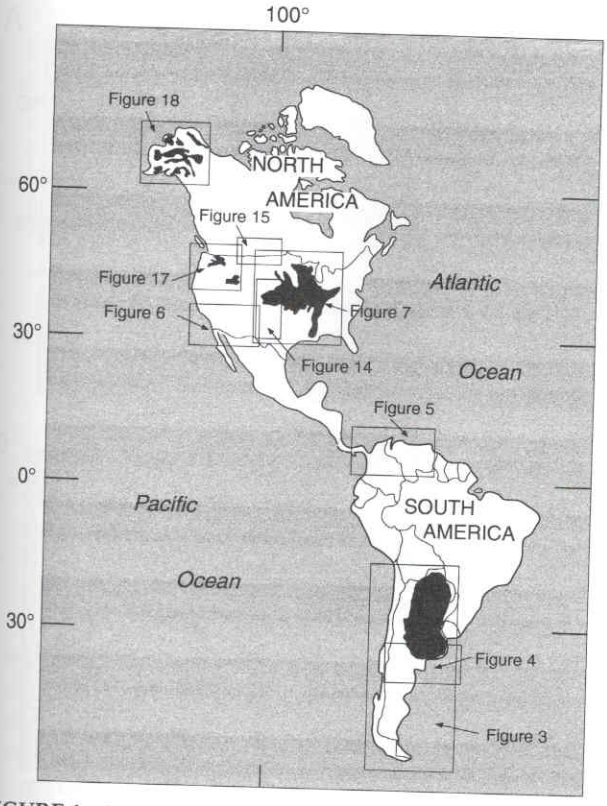

FIGURE 1 Map showing the distribution of loess (shaded areas) in North and South America and locations of detailed figures: loess distribution in North America from Thorp and Smith (1952) and Péwé (1975), and loess distribution in South America from Sayago (1995).

loess and eolian sand is summarized for South and North America with emphasis on three time periods: the last glacial maximum (LGM), the mid-Holocene, and the late Holocene. Throughout this chapter, all ages given, unless otherwise noted, are in uncalibrated radiocarbon years before present (^{14}C years B.P.).

The evolution of concepts about the genesis of loess make for a fascinating history of scientific thought (see Follmer, 1996). A now classical and generally accepted model of loess formation near glaciated terrain (Fig. 2) is that silt-sized particles are formed by glacial grinding and are delivered as outwash to valley trains (Ruhe, 1983). Wind entrains the particles from floodplains of the valley trains and deposits them in downwind-thinning blankets that also show systematic downwind decreases in particle size and carbonate content. The classical concept of loess stratigraphy, therefore, is that thick, unaltered loess deposits record glacial periods and intercalated paleosols record interglacial or interstadial periods (Fig. 2). In this chapter, certain aspects of the classical loess model are supported by loess studies in the Americas, and many aspects are not.

Although eolian sand deposits of the Americas have not received the attention that loess deposits have, there is also a traditional interpretation that such deposits are related to glacial periods. Several investigators (e.g., Sarnthein, 1978; Kutzbach and Wright, 1985) have considered large dune fields in the midlatitudes to be dominantly relict features that were last active during the LGM, when conditions are thought to have been cold, dry, and windy. In addition, eolian sand and loess were thought to be genetically related: i.e., essentially one deposit with a coarse, proximal facies (sand) and fine, distal facies (loess). In some regions of the Americas, this model seems to apply, and in other regions, it does not. New studies from both South and North America are now demonstrating that many dune fields have a rich record of Holocene activity and that dunes and loess may have distinctly different sources.

12.2. EOLIAN RECORDS OF THE SOUTH AMERICAN PAMPAS

The late Quaternary record of the Pampas (Fig. 3) is mainly composed of eolian deposits that include loess, loessial sands, eolian sand mantles, and dunes. Although several new contributions have been recently published (Iriondo, 1997, 1999; Sayago, 1995, 1997), controversial explanations emerge when specific aspects are considered, such as loess distribution, source areas, and origin of the eolian particles. First, the Pampas are a heterogeneous environment with different climatic, geomorphologic, and vegetative characteristics; key stratigraphic localities are found in different set-

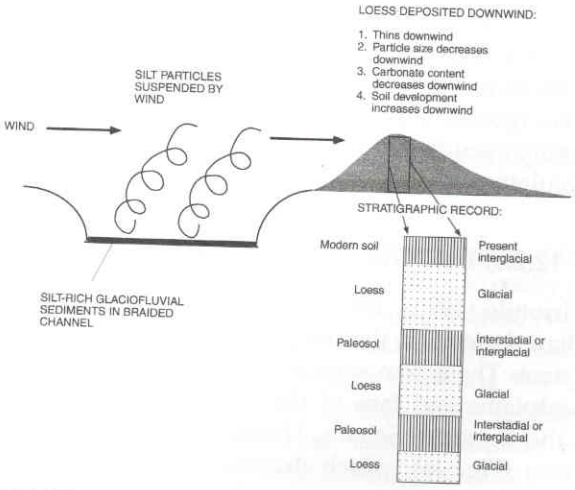

FIGURE 2 Classical model of midlatitude loess formation by eolian deflation of glaciogenic silt, downwind trends, and traditional climatic interpretation of the loess stratigraphic record.

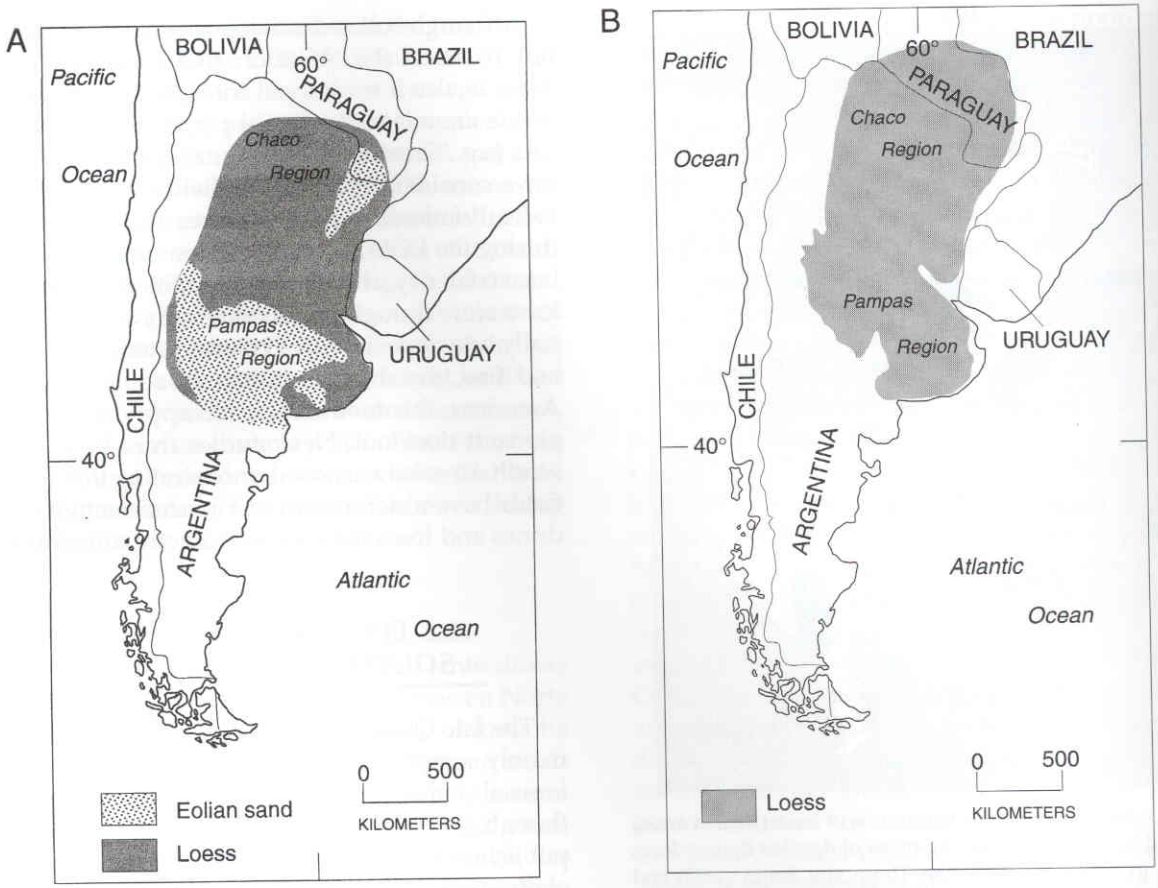

FIGURE 3 Alternative distributions of eolian sand (stippled) and loess (shaded) in Argentina, Paraguay, and Uruguay. (a) Redrawn from Iriondo (1997); (b) redrawn from Sayago (1995).

tings. Pioneering contributions on Pampean loess composition and distribution came from one key locality (Mar del Plata; see Figs. 4a and 4b) on the coast of the southern Pampas, from which results were extrapolated to the rest of Argentina (Teruggi et al., 1957; Teruggi, 1957). Second, inadequate chronological control, based on few ages, hinders stratigraphic correlation of eolian records between different areas of the Pampas, making even the present interpretations tentative and speculative.

12.2.1. Full Glacial and Late Glacial Times

Iriondo (1990a, 1997) proposed a regional model of eolian deposition that he named the Pampean Eolian System. The eolian source areas are thought to be the floodplains and fans of the combined fluvial system of the Bermejo, Salado, Desaguadero, and Colorado Rivers (Fig. 4a), which drained the glaciated Andes Mountains from approximately 28°–38°S latitude. A minor amount of material was supplied locally from the mountain ranges in central Argentina (Córdoba and San Luis). Volcanic ashfalls were a secondary source of eolian particles transported in high suspension, which came from volcanoes south of 38°S (southern Mendoza and Neuquén; Fig. 4a) and from volcanoes from the Puna region (Bloom, 1990), and were deposited in the extensive Chaco-Pampean plains.

The initiation of late Quaternary eolian deposition has not been extensively dated. Traditionally, the latest episodes of major deposition of the loess and sandy eolian facies have been related to the LGM (Groeber, 1936; Iriondo, 1997; Zárate and Blasi, 1991), and this is supported broadly by magnetostratigraphic data from the classic Mar del Plata section (see Zárate and Fasano, 1989). Recently, Kröhling (1999) reported thermoluminescence (TL) ages of ~36,000 cal. B.P. near the base of loess assigned to the Tezanos Pinto formation and ~9000 cal. B.P. near the top of this unit, in the Carcarañá River basin. These bracketing ages, if correct, broadly support a last glacial age for major loess deposition in this area, although Kröhling (1999) also shows eolian sand deposited prior to the loess deposition, with TL ages going back to at least 52,000 cal. B.P. During the

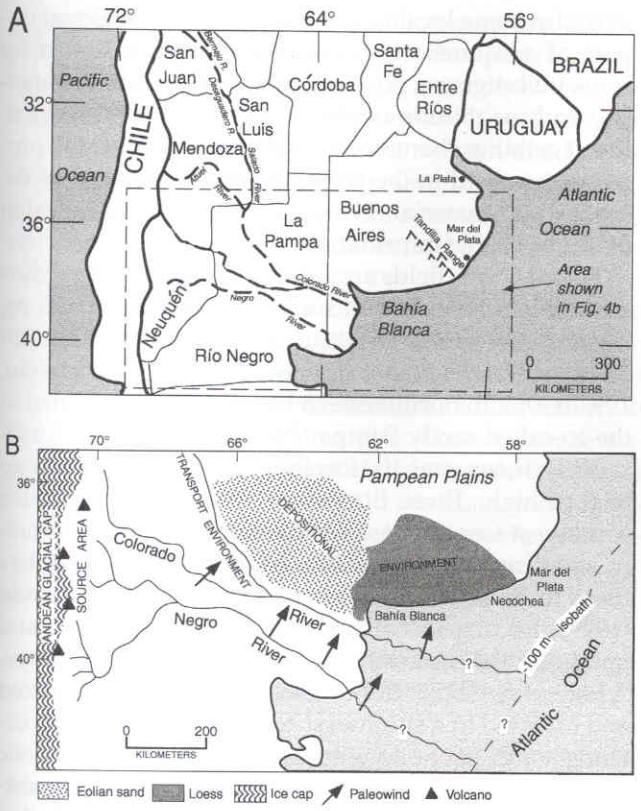

FIGURE 4 (a) Location map of provinces within central Argentina and surrounding countries. (b) Sediment sources and transport directions during the last glacial maximum (LGM) in southern Buenos Aires Province, Argentina. (Redrawn from Zárate and Blasi, 1993.)

LGM, the aggradation of fluvial valleys was mostly related to eolian deposition under dry conditions, with eolian material partially reworked and redeposited by fluvial processes.

The eolian sediments are of volcano-pyroclastic composition, characterized by an abundance of volcanic glass shards and plagioclase, with quartz as a minor component. A relatively coarse grain size is characteristic of these eolian deposits, which are classified as loessial sands, sandy loess, and loess (Zárate and Blasi, 1991, 1993; Bidart, 1996). Mobilization of the eolian grains and particles is attributed to short-term suspension and modified saltation. These mechanisms are related to the occurrence of low-level dust storms, which account for the bulk of the eolian deposits. The source areas of the loessial sands and sandy loess are thought to be the distal segments of the Colorado and Negro Rivers, located ca. 200 km south of the southern Pampas, when sea level was about 120 m below present levels at the LGM (Fig. 4b). Consequently, the eolian deposits of the southern Buenos Aires Province can be regarded as proximal facies and ascribed to a medium-distance transport of dust. Only a minor amount of sediment (estimated to be less than 10%) was transported in high suspension during volcanic ashfalls (Zárate and Blasi, 1991).

In the southern Pampas, no evidence has been found to support the physical weathering suggested by Iriondo (1990a) as the main mechanism for particle formation. The dominant explosive vulcanism of the Andes seems to have played an important role in particle formation, generating extensive pyroclastic deposits along the Andean piedmont and northern Patagonia, which were easily reworked by glacial, fluvial, and eolian processes (Zárate and Blasi, 1993). This interpretation is supported by recent geochemical and isotopic studies, which confirm the importance of volcanic-source sediments for loess in this region (Gallet et al., 1998).

The southern Pampas facies of fine sand sheets grade into dune fields toward La Pampa (Gardenal, 1986; Salazar Lea Plaza, 1980), southern San Luis (Ramonell et al., 1992), northwest of Buenos Aires, and southern Córdoba (Giménez, 1990; Iriondo, 1990a). According to Iriondo (1997, 1999), this central region of Argentina is characterized by a sand sea that covers an area of 180,000 km^2. Hence, the loess distribution is much more restricted than what was mapped by Teruggi (1957) and slightly modified by Sayago (1997) (compare Figs. 3a and 3b).

The eolian facies of the southern Pampas have been deposited by westerly and southwesterly winds. Geomorphological analysis revealed the occurrence of southwest-to-northeast- and west-to-east-oriented eolian landforms, partially superposed in the western Buenos Aires Province (Gardenal, 1986). The inferred south-southwesterly and westerly paleowinds have been related to high-pressure cells situated on the ice fields of the Patagonian Andes (Groeber, 1936; Tricart, 1973; Iriondo, 1997). The subhumid-semiarid climate of the late glacial inferred from pollen analysis in this region could have been due to a more northerly location of the subtropical circulation or a stronger Atlantic anticyclone. An asymmetry with the Pacific anticyclone would imply a meridional circulation predominantly from the southwest (Prieto, 1996).

In the northern Pampas (northern Buenos Aires, Santa Fe, and northern Córdoba; see Fig. 4a), silty eolian facies are dominant. In these areas, Iriondo (1997) located a loess belt that rims the sandy facies of central Argentina (Fig. 3b), with TL ages spanning the late glacial period (Kröhling and Iriondo, 1998; Kröhling, 1999), as was discussed earlier. This distribution also suggests a general trend of decreasing grain size northward and northeastward.

The rate of eolian deposition decreased remarkably between 11,000 and 10,000 B.P. and was followed by an

interval of pedogenesis under more humid conditions. Instead, Iriondo (1999) and Tonni et al. (1999) suggested that cold and dry conditions extended until ca. 8500 B.P. This humid period gave rise to most of the present cultivated soils in the southern Pampas (Zárate and Flegenheimer, 1991). The change to more humid conditions could be related to a poleward shift of the Atlantic Convergence Zone, with a predominant circulation from the northeast, or alternatively to a weakening of the southern Atlantic anticyclone (Prieto, 1996).

12.2.2. Mid- and Late Holocene

The lack of chronological control does not permit a detailed reconstruction for the mid- and late Holocene, but a broad approximation of the environmental conditions can be made. The eolian activity, which was very much reduced or negligible during the early and mid-Holocene, increased sometime between 5000 and 4000 ^{14}C B.P. and continued during the late Holocene period. In the southern Pampas, after 5000 B.P., soils were partially truncated at some locations, whereas small ponds and swampy areas of floodplains dessicated and were somewhat modified by soil formation (Zárate et al., in press). Sandy loess accumulation started at ca. 5200 B.P. in Bahía Blanca (González and Weiler, 1987/1988) and at ca. 4600 B.P. in the Tandilia Range (Fig. 4a), where localized eolian activity mostly reworked and redeposited late Pleistocene sandy loess (Zárate and Flegenheimer, 1991); this eolian activity continued for an unknown span of time. In a fluvial setting, loessial sand up to 2.5 m thick with an A/C soil horizonation gave a TL age of ~4300 cal. years B.P. in its lower section (Prieto, 1996). At another locality (also in a fluvial setting), 1-m thick sandy loess with a cumulic A horizon is bracketed between alluvial deposits (which have been modified by pedogenesis) dated at ca. 2500 B.P. and modern alluvium (Zárate et al., in press). A more recent and localized episode of eolian redeposition in the Tandilia Range occurred after the Spanish arrival in the sixteenth century (Zárate and Flegenheimer, 1991).

In the northeastern Pampas of Buenos Aires, several indicators of much drier conditions during the late Holocene also have been reported. Deflation basins were reexcavated and lunettes formed, whereas soils were truncated and then covered by a thin blanket of loess, which in turn was modified by pedogenesis (Tricart, 1973). According to Iriondo and García (1993), further northwest, in Santa Fe (Fig. 4a), a thin eolian layer was deposited regionally during a dry interval between 3500 and 1000 B.P. Recently, a basal TL age of 2050 ± 100 years B.P. was reported by Kröhling and Iriondo (1998). Although soil truncation certainly occurred at some localities, the ubiquity and regional impact of soil erosion processes currently assumed by some investigators pose critical questions on the intensity and magnitude of the hypothesized dry interval, the vegetation changes associated with it, and the processes involved in the transport and deposition of the eroded soil material. These assumptions are untested by the available information.

Several dune fields are assumed to have formed during the late Holocene in southern San Luis, Córdoba, Buenos Aires (Fig. 4a), and along the distal eastern piedmont of the Andes (Ramonell et al., 1992; Iriondo, 1997, 1999). In northwestern Buenos Aires, included in the so-called sandy Pampa (Pampa arenosa) are longitudinal dunes over 100 km long, 2–5 km wide, and up to 6 m high. These dunes are arranged as extensive southwest-to-northeast archlike forms and are presently stabilized by vegetation; Iriondo (1999) considers them to be of late Pleistocene age. However, Iriondo (1999) also maps smaller dunes, both longitudinal and parabolic, that he considers to be of late Holocene age. A field of parabolic dunes, most of them also stabilized and oriented in a southwest-to-northeast direction, extends south of the longitudinal dunes. The parabolic dunes have developed from the reworking of preexisting sandy deposits. Their dimensions are variable, between 0.2 and 6 km long and from 0.2–3 km wide (Cabral et al., 1988; Giménez, 1990). Soils in both the longitudinal and the parabolic dunes show weak development (Entisols) with A/C horizon sequences, including buried A horizons that indicate previous intervals of stability (Hurtado and Giménez, 1988).

The late Holocene eolian reactivation was apparently triggered by a climatic shift to drier conditions at about 5000 B.P. that may have lasted until ca. 1000 B.P. (Tonni 1992) when subhumid-semiarid conditions returned (Prieto, 1996). This climatic change is interpreted as a northward shift of the anticyclonic centers (Prieto 1996). The shift may have been seasonal, equatorward during the winter and poleward during the summer (Markgraf, 1993a). A seasonal anticyclonic anomaly that covered most of the region and generated a warm and semiarid climate is proposed by Iriondo (1990b, 1997). His estimated paleowind trajectories are based on an assumption that eolian deposits in the region are synchronous. In the area of southern Córdoba, geomorphological studies do not support the inferred paleowind trajectories from this anticyclonic anomaly, suggesting northeasterly winds for supposedly late Holocene eolian deposits (Cantú and Degiovanni, 1984). Little evidence is currently available to support the notion of synchronous, regionwide dune formation. It is likely, as the few available ages suggest, that several pulses of eolian reactivation may have oc-

curred during the mid- and late Holocene that did not necessarily affect the heterogeneous Pampean region in the same manner. Factors such as geomorphic setting, vegetation, and soils may have exerted local controls, resulting in responses of different magnitudes. For the most recent dry interval after the fifteenth century, Markgraf (1993a) proposed a transitional or intermediate stage of the circulation patterns that remained between the extreme positions.

The distribution, age, and thickness of the mid- and late Holocene eolian deposits show that the Pampean region may have presented a diverse sensitivity to climate change, with much more intense eolian activity at the southern and western margins. These areas are currently characterized by transitional climatic conditions toward the semiarid/subhumid environments of central Argentina, where sandy eolian deposits were remobilized and dunes formed or were reactivated.

12.3 EOLIAN RECORDS OF THE CHACO REGION

For the Chaco region (Fig. 3), Iriondo (1997) has also proposed a model of eolian deposition. In his conception, glacial and periglacial processes occurred during the LGM in the upper basins of the Parapetí, Pilcomayo, and Bermejo Rivers, which drain the Bolivian Andes. Northern winds were the transport agents of these materials, giving rise to the formation of parabolic dunes in the Bolivia–Paraguay low plain and loess deposits along the sub-Andean ranges and the Argentine Chaco plain. The mineral composition of these sediments is markedly different from that of eolian deposits of the Pampas; quartz is dominant (60–80%) with lesser amounts of hornblende and altered plagioclase. The heavy mineral assemblage is composed of more than 50% magnetite, zircon, tourmaline, and apatite; volcanic glass is completely absent. Only one ^{14}C age of 16,900 ± 270 years B.P. is available from the whole section of the type locality. According to Iriondo (1997), the large dune fields in southeastern Bolivia and northwestern Paraguay, consisting of well-preserved parabolic dunes, were formed by northern winds during the later Holocene. Clapperton (1993) also suggested that the southern Altiplano of Bolivia could have been a potential source area for the eolian sediments of the Chaco region. The subtropical jet stream may have entrained the fine particles, which were then carried eastward where they were eventually reworked by the strong seasonal northerly winds.

A different mode of origin for sediments of the Chaco region was postulated by Sayago (1995). He suggested that the *neotropical loess* of northwestern Argentina was transported by southerly winds during cool and dry periods due to a northward shift of the Polar Front and a weakening of the midlatitude South Pacific anticyclone. The significant differences in mineral composition between the Pampean loess and eolian deposits of the Chaco region might be attributed to transport processes, local lithological influences, or postdepositional processes driven by the regional climate (Sayago, 1995, p. 758).

12.4. LATE PLEISTOCENE EOLIAN RECORDS OF NORTHERN SOUTH AMERICA

Although fewer studies of the late Quaternary eolian record have been conducted in northern South America, one spectacular example of a large, stabilized dune field is discussed here. In the Llanos del Orinoco of Venezuela and extending into Colombia, Roa (1980) mapped a large dune field of geomorphically well-expressed linear and parabolic dunes (Fig. 5). A minimum limiting radiocarbon age of ~11,000 years B.P. was obtained by Roa (1979) from a paleosol capping one of these dunes, which in turn is overlain by younger eolian sand. Iriondo (1997) also described a finer grained loess that occurs downwind of the dune field. Roa (1979), Iriondo (1997), and Clapperton (1993) interpreted this sand to represent deposition during a time when there was a migration of the Intertropical Convergence Zone (ITCZ) to the south during the last (?) glacial period, with the result that the Llanos del Orinoco region became drier and favored dune formation. If this interpretation is correct, it is consistent with the paleontological, geochemical, and mineralogical record of relatively dry conditions in this part of Venezuela during the late glacial period (~13,000–

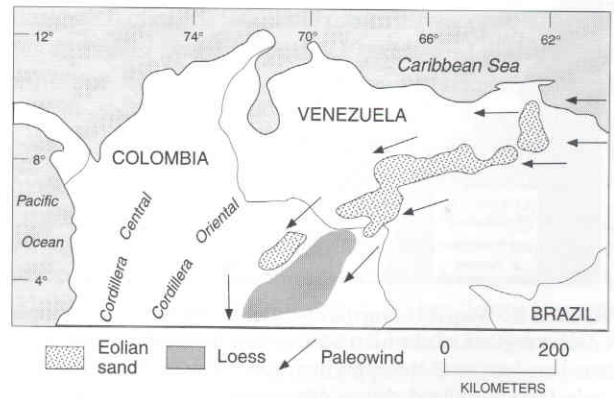

FIGURE 5 Map showing the distribution of eolian sand and loess (silt) and paleowind directions in Venezuela and Colombia. (Redrawn from Iriondo, 1997.)

10,000 B.P.) as is seen in the sediments of Lake Valencia (Bradbury et al. 1981).

12.5. EOLIAN RECORDS IN THE DESERTS OF THE SOUTHWESTERN UNITED STATES AND NORTHERN MÉXICO

Dune fields are widespread over the desert regions of the southwestern United States and northern México, although these features are generally smaller than those found in the Great Plains to the east (Fig. 6). The largest dune fields, mostly stabilized, are found on the Colorado Plateau in northeastern Arizona and northwestern New Mexico (Hack, 1941; Wells, et al. 1990). Elsewhere in this mostly arid region, some dune fields are active, such as the Gran Desierto in México, most of the Algodones and parts of the Kelso dunes in California, and White Sands in New Mexico.

Detailed studies on the Colorado Plateau show that these dune fields have a long and complex history. Wells et al. (1990) conducted stratigraphic and soil geomorphic studies in the Chaco dune field of northwestern New Mexico and identified three main periods of eolian sand activity. Radiocarbon ages indicate that while the oldest eolian sand unit in the area is of late Pleistocene age (~16,000–12,000 ^{14}C years B.P.), the other two units are both of late Holocene age, ca. 5600–2800 ^{14}C years B.P. and less than ~1900 ^{14}C years B.P. These ages agree with late Holocene luminescence ages of dunes elsewhere on the Colorado Plateau in northeastern Arizona (Stokes and Breed, 1993). Results of both studies indicate that, in contrast to earlier concepts, the mid-Holocene *Altithermal* warm period was not a particularly important period for eolian sand activity. Wells et al. (1990) point out that late Holocene eolian sand is volumetrically far more important than mid-Holocene eolian sand.

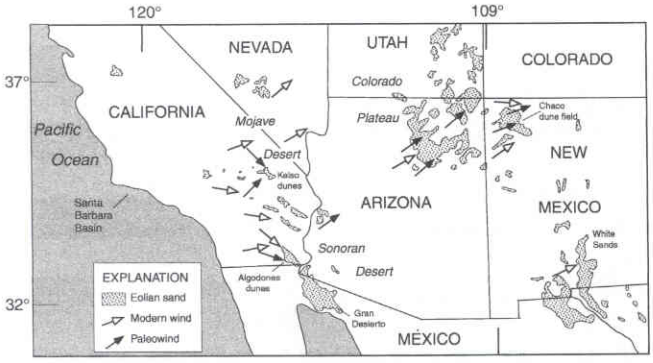

FIGURE 6 Map showing the distribution of eolian sand (stippled) in desert regions of northern México and the southwestern United States, modern sand transport directions, and late Holocene paleowinds from stabilized dunes. Data compiled mainly from Hack (1941), Jennings (1967), Hunt (1977), Lancaster et al. (1987), Wells et al. (1990), Lancaster (1994), Muhs and Holliday (1995), and Muhs et al. (1995); modern wind data are compiled by the authors.

Although they are of smaller extent than elsewhere in North America, the dunes of the Mojave and Sonoran Desert regions of southeastern California, Arizona, and northern México have received the most attention for studies of geomorphology, sediment transport, and origins (Lancaster et al., 1987; Tchakerian, 1991; Lancaster, 1994; Zimbelman et al., 1995; Muhs et al., 1995; Lancaster and Tchakerian, 1996), as well as geochronology (Clarke, 1994; Wintle et al., 1994; Rendell et al., 1994; Clarke et al., 1996; Rendell and Sheffer, 1996; Clarke and Rendell, 1998). Despite the evidence that Great Plains dunes seem to record relatively arid periods (see discussion later), a general concept that is emerging from studies in the Mojave and Sonoran Deserts is that the degree of activity of many dunes is only indirectly a function of climate. Many of the dune fields in southeastern California seem to be supply-limited systems, and therefore, the degree of dune activity may not be related to overall moisture balance per se, but rather to the effect climate has on supplying new sediment from fluvial or lacustrine sources (Lancaster, 1994; Lancaster and Tchakerian, 1996; Muhs et al., 1995; Clarke and Rendell, 1998). In an overall summary of luminescence dating of Mojave Desert dunes and sand sheets, Clarke and Rendell (1998) showed that ages range from as old as ~23,000 cal. years B.P. to the late Holocene, and are similar to ages of nearby pluvial lake high stands, whether of late Pleistocene or Holocene age. They suggested that the main effect of climate change on dune activity is to bring about conditions whereby new supplies of sediment become available to dune fields, such as from pluvial lake beaches or alluvial sources. An arid climatic regime with a minimal vegetation cover almost certainly plays some role in degree of dune activity, however. For example, Muhs et al. (1995) showed that while sediments of the Algodones dunes had a pluvial lake source in the past, the region is sufficiently arid now that the dunes are active, despite no new supplies of pluvial lake beach sand.

12.6. EOLIAN RECORDS IN THE NORTH AMERICAN MIDCONTINENT

12.6.1. Full Glacial and Late Glacial Times: Loess

During the LGM, loess was deposited over much of the North American midcontinent, particularly in the central United States (Fig. 7). Little loess was deposited in Canada during the last glacial period because the

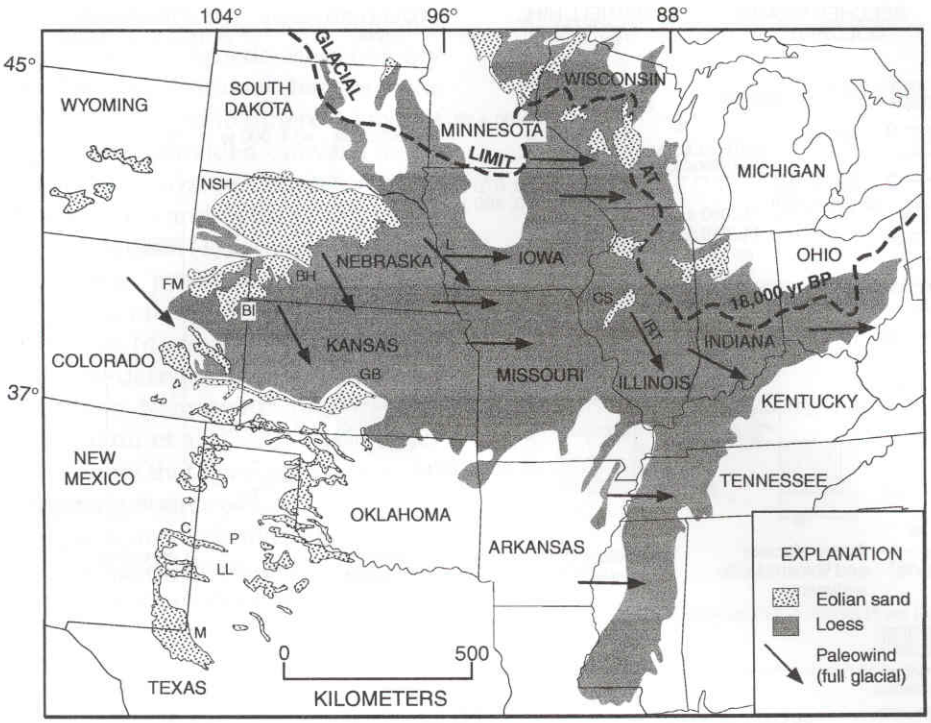

FIGURE 7 Map showing the distribution of mostly late Pleistocene loess and mostly Holocene eolian sand in the midcontinent region of North America and inferred paleowinds during the last glacial maximum (LGM). Loess distribution data from Thorp and Smith (1952), eolian sand distribution data from Muhs and Holliday (1995), and inferred LGM paleowinds data from Muhs and Bettis (2000). NSH, Nebraska Sand Hills localities (Gudmundsen Ranch and Swan Lake, see Fig. 10; Whitman and Snake River, see Fig. 13); FM, Fort Morgan dune field localities (Logan County, see Fig. 10; Hudson and Coors Quarry, see Fig. 11; Friehaufs Hill and Hillrose, see Fig. 13); GB, Great Bend Sand Prairie localities (Cullison Quarry and Reno County, see Fig. 13); C, Clovis, NM (see Fig. 10); M, Midland, TX (see Fig. 10); BI, Beecher Island, CO (see Fig. 8); BH, Bignell Hill, NE (see Fig. 8); L, Loveland, IA (see Fig. 8); CS, Cottonwood School, IL (see Fig. 8); IRT, Illinois River transect (see Fig. 9).

Laurentide ice sheet covered most of the region during the glacial maximum and extensive proglacial lakes covered the region and served as sediment sinks as ice receded. Eolian silt dating to the LGM in the United States is referred to as Peoria Loess. Peoria Loess is as thick as ~50 m in western Nebraska (Maat and Johnson, 1996) and as thick as ~40 m in western Iowa (Muhs and Bettis, 2000). From western Iowa to the east, loess is thickest adjacent to major valleys, such as those of the Missouri, Mississippi, Illinois, and Wabash Rivers.

Numerous studies show that while the bulk of late Quaternary loess in midcontinental North America dates broadly to the LGM, there are important differences in the timing of deposition within the region. Maximum limiting radiocarbon ages of Peoria Loess range from ~30,000 to ~20,000 years, and minimum limiting ages range from ~14,000 to ~10,000 years (Fig. 8). Localities near major loess sources record deposition earlier than those farther away. For example, in western Tennessee, immediately east of the Mississippi River, maximum limiting ages for Peoria Loess are as old as ~29,000 ^{14}C years B.P., and an age of 21,800 ^{14}C years B.P. has been reported in the lower part of the loess (Markwich et al., 1998). Thermoluminescence and ^{10}Be ages of Peoria Loess from this locality and elsewhere in Tennessee agree with these ages (Markewich et al., 1998; Rodbell et al., 1997). In much of Illinois, Peoria Loess deposition probably began sometime after ca. 25,000 ^{14}C B.P. (Curry and Follmer, 1992) and was still in progress at ca. 12,000 ^{14}C B.P. (Grimley et al., 1998). In central Illinois, however, maximum limiting radiocarbon ages for Peoria Loess decrease from ~25,000 to ~21,000 ^{14}C years B.P. along a 20-km long traverse away from the source (Kleiss and Fehrenbacher, 1973). Similarly, in Iowa, the maximum period of Peoria Loess deposition was from ca. 24,000 to 14,000 ^{14}C B.P. (Ruhe, 1983). Ruhe (1983) points out, however, that initiation of Peoria Loess deposition in Iowa, like Illinois, was

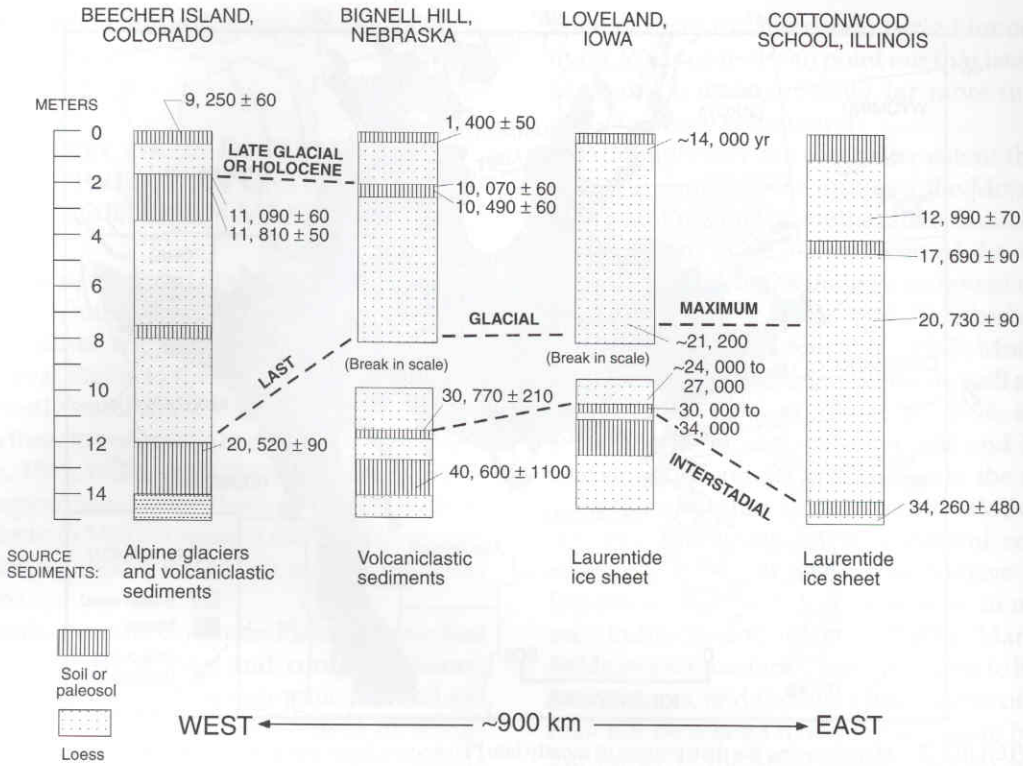

FIGURE 8 Stratigraphy, radiocarbon ages, and source sediments of selected loess sections from Colorado to Illinois in the North American midcontinent (locations of sections given in Fig. 7). Data from Colorado and Nebraska from Muhs et al. (1999), Iowa data from Ruhe (1983) and Forman et al. (1992a), and Illinois data from Grimley et al. (1998).

time transgressive; maximum limiting radiocarbon ages are ~24,500 ^{14}C years B.P. near the Missouri River source, whereas they are ~19,000 ^{14}C years B.P. ~280 km to the east of the river.

Loess deposition in Tennessee, Illinois, Iowa, and other areas east of the Missouri River was a function of source sediment availability from the Laurentide ice sheet via the Ohio, Wabash, Illinois, Mississippi, and Missouri Rivers, and the timing of loess deposition probably followed the history of movement of the ice sheet. However, in the Great Plains region of Nebraska, Kansas, and Colorado, west of the area that drained outwash from the Laurentide ice sheet, extensive loess sheets were derived from Rocky Mountain glaciers and, more importantly, Tertiary volcaniclastic sediments (Aleinkoff et al., 1998, 1999). Interestingly, in some places, the timing of loess deposition seems to differ little from that of Laurentide outwash-derived loess found farther to the east (May and Holen, 1993; Martin, 1993; Pye et al., 1995; Maat and Johnson, 1996; Muhs et al., 1999). For example, in eastern Colorado, loess deposition began after ca. 20,000 ^{14}C B.P., but ended by ca. 11,800 ^{14}C B.P. (Fig. 8). Elsewhere, however, loess deposition differs significantly from that found farther east. In western Nebraska, Peoria Loess was deposited sometime after ca. 30,000 ^{14}C B.P., but continued until sometime just before ca. 10,500 ^{14}C B.P. (Maat and Johnson, 1996; Muhs et al., 1999), indicating a much longer period of eolian sedimentation.

Loess deposition was not continuous in midcontinental North America during the LGM. In western Illinois, multiple, poorly developed buried soils are found within Peoria Loess, indicating brief periods of landscape stability with little or no loess deposition (Wang et al., 1998). Radiocarbon ages indicate as many as five cycles of loess sedimentation and soil formation in the period from 20,710 to 17,630 ^{14}C B.P. Ruhe et al. (1971) also report multiple buried soils in Peoria Loess in western Iowa, and at least one possible buried soil has been identified in Peoria Loess in eastern Colorado (Muhs et al., 1999).

Multiple lines of evidence indicate that loess sources changed during the LGM over midcontinental North America, even within the area draining the Laurentide ice sheet. The most detailed work has been done in Illinois, where Peoria Loess shows distinctive zonations,

based on clay mineralogy (Frye et al., 1968), dolomite content (McKay, 1979), and magnetic susceptibility (Grimley et al., 1998). The compositional changes of the loess in this area are clearly linked to different lobes of the Laurentide ice sheet that provided outwash to the Mississippi and Illinois River systems (Grimley et al., 1998). In western Iowa, Muhs and Bettis (2000) found three zones within Peoria Loess: (1) a lower zone characterized by low carbonate, probably related to syndepositonal leaching; (2) a middle zone, probably derived dominantly from the Missouri River; and (3) an upper zone that could be derived from both the Missouri River and sources in Nebraska farther west. In eastern Colorado, Aleinikoff et al. (2000) used Pb isotopes in K-feldspars to show that Peoria Loess was derived from two competing sources: outwash derived from Front Range glaciers and volcaniclastic Tertiary siltstone. At least two cycles of alternating dominance by these competing sources are evident in the period of Peoria Loess deposition.

Loess distribution, as well as thickness, particle size, carbonate, and geochemical trends, indicates that most loess in North America was deposited by northwesterly winds (Figs. 7 and 9). There were apparently some episodes of easterly winds, because areally limited tracts of loess occur to the west of some source valleys (see Muhs and Bettis, 2000, for a review of these localities). Nevertheless, such areas are of minor extent, and the picture that emerges is one of dominantly northwesterly winds.

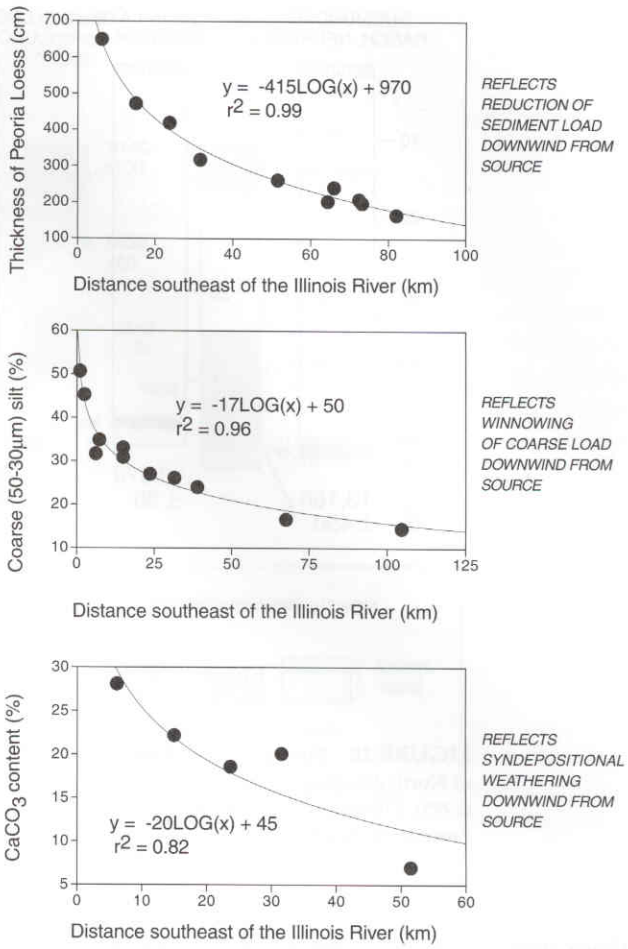

FIGURE 9 Thickness, coarse silt content, and carbonate content of Peoria (last glacial) loess as a function of distance southeast of the Illinois River (location of transect given in Fig. 7). (Data from Smith, 1942.)

12.6.2. Last Glacial Period: Eolian Sand

Eolian sand deposits are extensive in North America, but until recently were much less studied than loess deposits. The most widespread eolian sands in North America are found in the central and southern Great Plains region, from Nebraska south to Texas (Fig. 7). There are few active dunes in this region at present. However, stabilized dunes and sand sheets cover tens of thousands of square kilometers. Recent studies show that the most critical factor in the amount of eolian activity in this region—assuming that adequate winds and sand supplies are available—is the degree of vegetation cover, which in turn is a function of the balance between precipitation and evapotranspiration (Muhs and Maat 1993; Muhs and Holliday 1995; Wolfe 1997; Muhs and Wolfe, 1999).

Limited radiocarbon ages, archaeology, and degree of soil development suggest that eolian sand sheet, lunette, and dune deposition took place during the last glacial period in Nebraska, Colorado, New Mexico, and Texas (Fig. 10). Radiocarbon results from the Nebraska Sand Hills indicate that there was sufficient dune building to dam sizable rivers and create lakes during late glacial time (Loope et al., 1995; Mason et al., 1997). These data are supported by an earlier report of maximum limiting ages of ~13,000 years B.P. for some of the largest barchanoid ridges (see Swinehart, 1990) in the Nebraska Sand Hills (Swinehart and Diffendal, 1990). In Colorado, stratigraphic, radiocarbon, and soil evidence indicate that eolian sheet sands were deposited over large areas during the last glacial period (Forman and Maat, 1990; Forman et al., 1992a, b, 1995; Madole, 1995; Muhs et al., 1996). Stratigraphic studies show that eolian sheet sands in eastern Colorado have maximum limiting radiocarbon ages of ~27,000 ^{14}C years B.P. and, where exposed at the surface, have a degree of soil development similar to that in river terrace sands dated to ca. 11,000–10,000 ^{14}C B.P., suggesting that sand sheet deposition took place between ca. 27,000 and 10,000 ^{14}C B.P. (Muhs et al., 1996). In Texas,

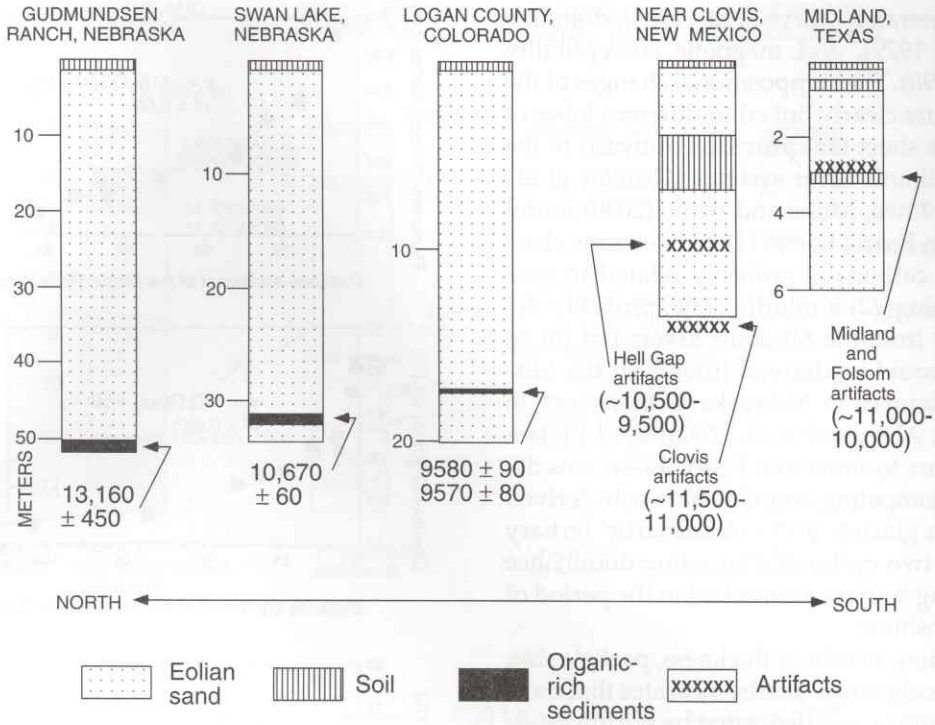

FIGURE 10 Stratigraphy and radiocarbon ages of selected eolian sand sections in the Great Plains region of North America that show evidence of possible late glacial eolian activity. Nebraska data from Loope et al. (1995), Colorado data are from Muhs et al. (1996), and New Mexico and Texas data from Holliday (1997b). Locations are shown in Fig. 7.

there was widespread lunette formation during full glacial time (Holliday, 1997a), and extensive eolian sand sheet deposition is dated to ca. 11,000–10,000 ^{14}C B.P. (Holliday 1997b, 2000). Extensive eolian sheet sands in Texas and adjacent parts of New Mexico are confidently correlated to the late glacial period because of their association with well-dated artifacts (Fig. 10). Forman et al. (1995) stated that eolian activity in the midcontinent ceased between ca. 12,000 and 9000 ^{14}C B.P., based on examination of a few sections in a limited area of northeastern Colorado. However, the studies from Nebraska (Loope et al., 1995; Mason et al., 1997), Texas, and New Mexico (Holliday, 2000) indicate that the late glacial period was an important time of eolian sand deposition in the midcontinent.

Because few dunes (as opposed to sand sheets) can be confidently linked to the last glacial period in the Great Plains, it is difficult to reconstruct paleowinds. However, distribution of last glacial eolian sands relative to probable source sediments indicates that winds were probably northwesterly on the central Great Plains and westerly on the southern Great Plains during last glacial time (Loope et al., 1995; Mason et al., 1997; Muhs et al., 1996; Holliday, 1995a, 1997a), similar to the present.

12.6.3. Mid-Holocene: Loess and Sand

Mid-Holocene eolian sediments have been reported in some parts of midcontinental North America. A thin (1–4 m) eolian silt called the Bignell Loess is found in a patchy distribution west of the Missouri River in the Great Plains region of Nebraska, Kansas, and Colorado (Johnson and Willey, 2000; Mason and Kuzila, 2000). Radiocarbon ages indicate that it was deposited between ca. 11,000 and 9000 B.P. at some localities and possibly during the mid-Holocene, between ca. 10,000 and 1500 B.P., at others (Fig. 8). Direct dating of Bignell Loess using TL methods gives ages ranging from ~9000 to ~3000 cal. years B.P. (Pye et al., 1995; Maat and Johnson, 1996). A recent study by Olson et al. (1997) indicates that a post-mid-Holocene loess covers extensive parts of southwestern Kansas and may be younger than the Bignell Loess found farther north. Holocene loess has also been described in Saskatchewan (David, 1970; Vreeken, 1996) and, as with Holocene loess farther south, has a patchy distribution.

Although there is little direct geomorphic evidence for it, some stratigraphic evidence suggests mid-Holocene eolian sand activity in midcontinental North

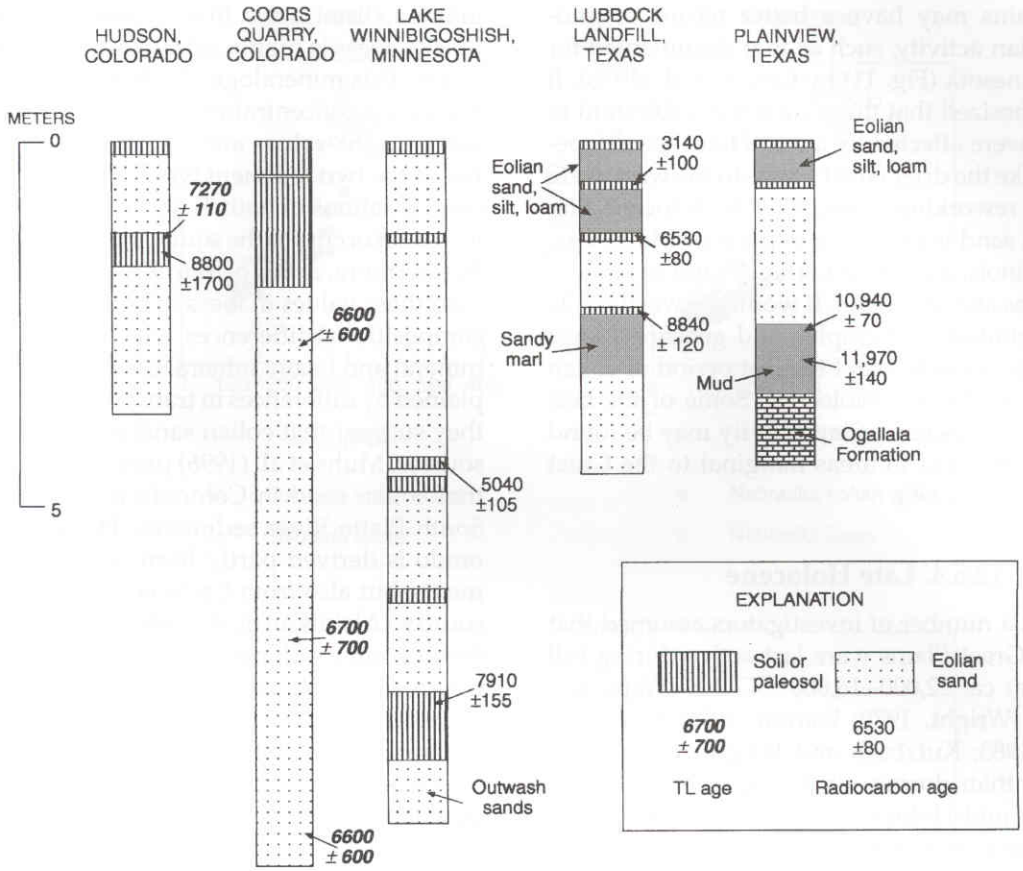

FIGURE 11 Stratigraphy and ages of selected eolian sand sections in Colorado, Minnesota, and Texas that show evidence of mid-Holocene eolian activity. Colorado data are from Forman and Maat (1990) and Forman et al. (1995), Minnesota data are from Grigal et al. (1976), Texas data are from Holliday (1995b). Locations are shown in Fig. 7.

America (Fig. 11). Radiocarbon ages and stratigraphic data from the western Nebraska Sand Hills indicate that mid-Holocene eolian activity probably created a large dune dam that blocked a major drainage in the area, as was the case during the late glacial period (Loope et al., 1995; Mason et al., 1997; Muhs et al., 2000). In eastern Colorado, there are a few closely spaced localities where evidence of mid-Holocene eolian sand movement has been documented (Forman and Maat, 1990; Forman et al., 1995). Mid-Holocene dune activity took place in parts of the intermountain basins of Wyoming to the west of the Great Plains (Gaylord, 1990). Holliday (1995b, 1997a,b) reported radiocarbon and stratigraphic evidence of mid-Holocene lunette formation in the southern Great Plains, and dry valleys or *draws* in this region contain thick eolian sands that are of mid-Holocene age. However, the upland dunes in this region, mostly parabolic forms, do not date from the mid-Holocene and are largely of late Holocene age (Holliday, 1995c). Preservation of mid-Holocene eolian sand in draws and not on uplands may be a function of the more protected sedimentary setting in the draws, where late Holocene reworking of sediment would be less likely. Elsewhere, the record for mid-Holocene eolian sand deposition is scanty and is based on indirect lines of evidence such as dunes with a degree of soil development that is greater than that on late Holocene eolian sand, but less than that on late Pleistocene sand (Madole, 1995; Muhs et al., 1996). In some parts of the Great Plains, dunes are depleted in carbonate minerals, thought to be the result of physical reduction of sand-sized grains from extended periods of eolian activity in the mid-Holocene period (Muhs et al., 1997b; Arbogast and Muhs, 2000). Although it seems likely, from other proxy paleoclimate evidence (discussed later), that conditions were optimal for eolian sand activity over the semiarid Great Plains during the mid-Holocene extensive late Holocene, eolian activity may have removed much of the record.

Interestingly, subhumid areas around the margins of

the Great Plains may have a better record of mid-Holocene eolian activity, such as that documented for northern Minnesota (Fig. 11) by Grigal et al. (1976). It can be hypothesized that these currently subhumid to humid areas were affected by a mid-Holocene dry period, but, unlike the drier Great Plains to the west, were unaffected by reworking during the late Holocene. Stabilized eolian sand is extensive in parts of Minnesota, Wisconsin, Illinois, and Indiana (Fig. 7) and in smaller areas in Kansas and Michigan. It would be worthwhile to conduct detailed stratigraphic and geochronologic studies of these areas to see if the last period of eolian activity dates to the mid-Holocene. Some of the best records of mid-Holocene eolian activity may be found in lake sediments and in areas marginal to the Great Plains (Dean et al., 1996).

12.6.4. Late Holocene

In the past, a number of investigators assumed that dunes in the Great Plains were last active during full glacial time, at ca. 22,000–16,000 ^{14}C B.P. (Watts and Wright, 1966; Wright, 1970; Warren, 1976; Sarnthein, 1978; Wells, 1983; Kutzbach and Wright, 1985), or at least no later than during what is perceived to be a warm and dry mid-Holocene, at ca. 8000–5000 B.P. Recent studies have confirmed (as discussed earlier) that the last glacial period was indeed a time of eolian sand activity over much of the region. However, a number of recent studies also show that much eolian sand in the Great Plains region is of late Holocene age. Indeed, in the Great Plains of both Canada and the United States, the areal extent of late Holocene eolian sand is much greater than that of last glacial sand and is a more important part of the record than previously thought. For example, dunes of the Nebraska Sand Hills cover ~50,000 km^2, yet all have only simple A/AC/C soil profiles (Entisols), similar to the young dune fields of the Pampas in Argentina discussed earlier. This observation, along with late Holocene radiocarbon ages at numerous localities, suggests that most or all of the Nebraska Sand Hills region has been active at some time in the late Holocene, though not all parts of the dune field necessarily were active simultaneously (Muhs et al., 1997a).

An indirect piece of evidence supporting late Holocene ages for eolian sand comprises new data that show that sand and loess in the Great Plains are geochemically and mineralogically distinct, indicating different source sediments. This is a departure from the long-held concept, articulated by Lugn (1935, 1939, 1962, 1968), that eolian sand and loess in the Great Plains are essentially the same deposit, with eolian sand a coarse-grained, proximal facies and loess a fine-grained, distal facies. In both eastern Colorado and Nebraska, loess is highly calcareous, whereas eolian sand is not. This mineralogical difference is reflected in the higher Ca concentrations in loess compared to eolian sand; Ca/Sr values are also significantly different between the two sediment types (Fig. 12). Eolian sand has concentrations of both Ti and Zr that are lower than in loess that occurs to the south and east of the dune fields. Furthermore, ratios of Ti to Zr in eolian sand are lower than these values in loess in both areas (Fig. 12). These compositional differences, which reflect both carbonate mineral and heavy mineral assemblages, cannot be explained by differences in transport processes alone, and they suggest that eolian sand and loess have different sources. Muhs et al. (1996) presented evidence to show that eolian sand in Colorado is derived mainly from South Platte River sediments. However, loess in Colorado is derived partly from South Platte River sediments, but also from Cretaceous and Tertiary bedrock sources (Aleinikoff et al., 1998, 1999). Thus, because different source sediments supply dune fields and loess, eolian sand and loess entrainment need not be synchronous in time.

Stratigraphic, soil geomorphic, radiocarbon, and luminescence methods demonstrate that eolian sand over a wide range of midcontinental North America has been active in the past 3000 years (Ahlbrandt et al., 1983; Muhs, 1985; Swinehart and Diffendal, 1990; Madole, 1994, 1995; Holliday, 1995a,c, 1997a,b; Forman et al., 1995; Loope et al., 1995; Arbogast, 1996; Muhs and Holliday, 1995; Muhs et al., 1996, 1997a,b; Wolfe et al., 1995, 2000; Stokes and Swinehart, 1997). In addition, most of these studies have stratigraphic data indicating multiple periods of eolian activity in the late Holocene (Fig. 13). The number of radiocarbon ages and their analytical uncertainties do not yet make it possible to test the hypothesis of regional synchroneity of activity. However, these observations indicate that, contrary to earlier beliefs, eolian sand in this region can be active under an essentially modern climatic regime. In fact, observations by explorers in the nineteenth century indicate that many parts of the Great Plains had active dune sand where it is now stable (Muhs and Holliday, 1995; Muhs and Wolfe, 1999). The evidence for multiple periods of activity and stability in the past few thousand years indicates that Great Plains eolian sand is quite sensitive to small changes in the overall moisture balance and degree of vegetation cover. Most of the late Holocene dunes in the midcontinent of North America are parabolic forms, which are excellent paleowind indicators. Orientations of late Holocene dunes indicate northwesterly winds in the central Great Plains and southwesterly winds in the southern Great Plains, similar to modern wind regimes (Fig. 14).

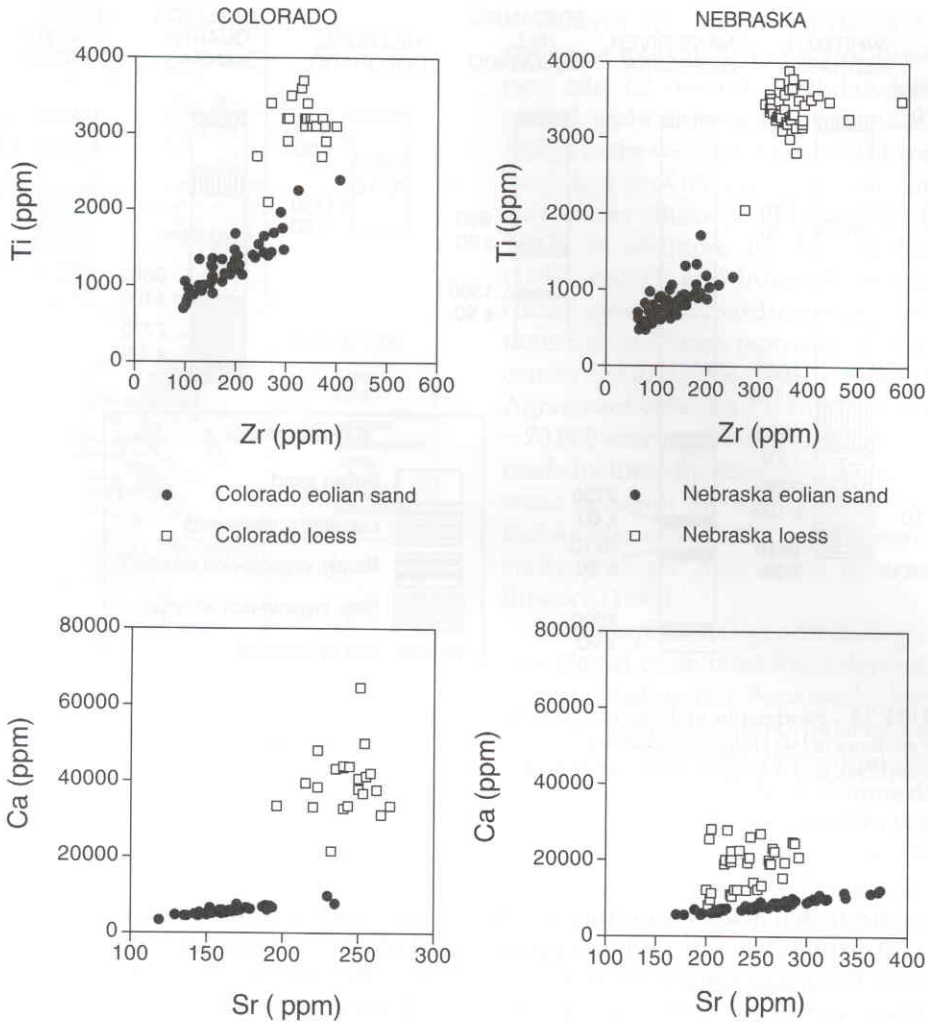

FIGURE 12 Plots of Ca, Sr, Ti, and Zr concentrations in eolian sand and loess in Colorado and Nebraska. Data are from Muhs et al. (1996, 1999) and previously unpublished Nebraska eolian sand data of the authors.

Stable and partially active dune fields, dominated by parabolic dunes, are widespread over the subhumid to semiarid northern Great Plains of southern Canada and the northern United States (Fig. 15). Although winds in the northern Great Plains are among the strongest in the world (compared to other areas where eolian sand is found), most dunes are presently inactive because of relatively high ratios of precipitation to potential evapotranspiration, which has the dual effects of increasing moisture content within dunes and maintaining a vegetation cover (Wolfe, 1997). Dune fields in the region are smaller than those in the central and southern Great Plains, as most are derived from finite supplies of glaciofluvial or glaciolacustrine sediments deposited during the last deglaciation (David, 1971; Wolfe et al., 1995, 2000; Wolfe, 1997; Muhs et al., 1997b; Muhs and Wolfe, 1999). Although some dune fields in Canada appear to have been generated from glaciofluvial and glaciolacustrine sediments by northeasterly glacial anticyclonic winds as the ice receded (David, 1981, 1988), stratigraphic and geochronologic studies indicate that many northern Great Plains dunes are not relict features from the last deglaciation. The last episodes of eolian activity were during the late Holocene, and several localities show evidence of having been active in the past millennium (Fig. 16), as is the case with the central and southern Great Plains. Although several dune fields in the northern Great Plains of Canada and the northern United States show evidence of multiple episodes of activity in the past few thousand years, as yet, there is too little evidence to ascertain whether there is regional synchroneity of dune sand movement.

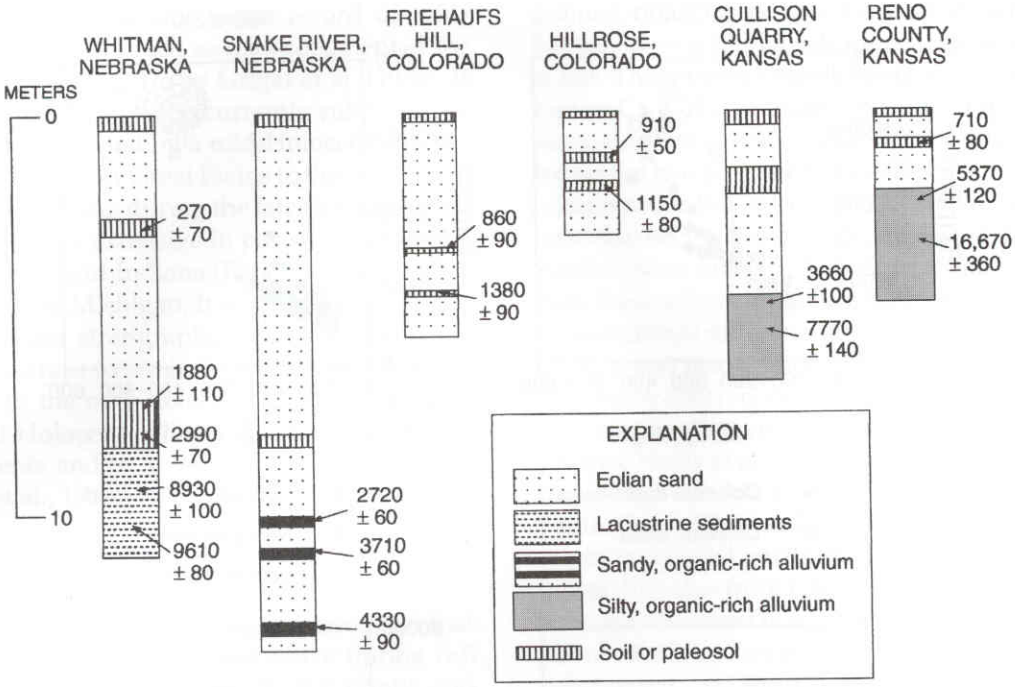

FIGURE 13 Stratigraphy and ages of selected eolian sand sections in Nebraska, Colorado, and Kansas that show evidence of late Holocene eolian activity. Data are from Stokes and Swinehart (1997), Muhs et al. (1997b), Madole (1994), and Arbogast (1996). Locations are shown in Fig. 7.

Historic accounts indicate that at least four dune fields had some degree of activity in the mid-nineteenth century before major European settlement of the region took place (Muhs and Wolfe, 1999). Orientations of stabilized parabolic dunes indicate late Holocene paleowinds from the west or northwest, similar to dune-forming winds of the present (Fig. 15).

12.7. EOLIAN RECORDS IN THE NORTHWESTERN UNITED STATES

Loess is extensive over parts of the northwestern United States, including a small part of western Wyoming, a large part of eastern Idaho, a small part of northern Oregon, and much of eastern Washington (Fig. 17). Loess in this region has not been studied for as long as loess in the midcontinent of North America. However, recent work indicates that a long stratigraphic record is present and that loess origins in parts of the region differ from those found elsewhere.

In Idaho and adjacent parts of westernmost Wyoming, loess covers large areas to the north and south of the Snake River Plain, which is probably one of its major sources (Lewis et al., 1975; Scott, 1982; Pierce et al., 1982; Glenn et al., 1983). Loess in this region has a thickness of up to 12 m in places, but most is 2 m or less (Lewis et al., 1975). Thickness and particle size data (Lewis et al., 1975; Lewis and Fosberg, 1982; Pierce et al., 1982; Glenn et al., 1983) suggest that loess deposition took place under northwesterly or westerly winds (Fig. 17).

Stratigraphic studies of loess in Idaho have been conducted by Scott (1982), Pierce et al. (1982), and Forman et al. (1993). Pierce et al. (1982) studied the loess stratigraphy at numerous localities over an ~400-km long transect from western Wyoming to central Idaho and found two major units, informally designated loess *A* and loess *B*. The two loesses are separated by a well-developed paleosol. Based on the degree of soil development and stratigraphic relations with K/Ar-dated lava flows and well-dated Lake Bonneville flood deposits, they suggested that loess A was deposited during the last glacial period and loess B was deposited during the penultimate glacial period. Forman et al. (1993) studied loess at two closely spaced sites in eastern Idaho and reported TL data that support correlation of loess A with the last glacial period (late Wisconsin time). However, they suggested, on the basis of TL data, that loess B was also deposited during the last glacial period (early Wisconsin time). At present, probably too few data exist to determine which age estimate is correct.

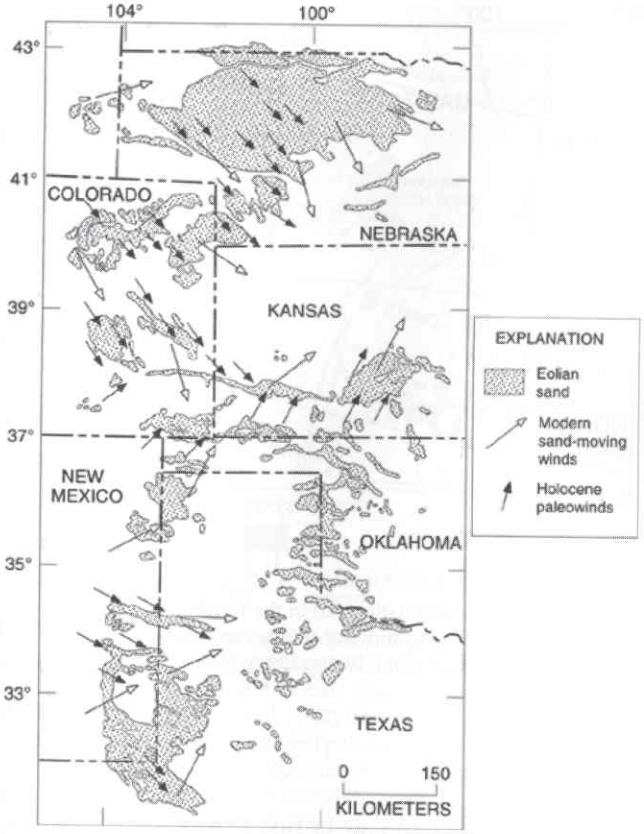

FIGURE 14 Map showing the distribution of eolian sand (stippled) in the central and southern Great Plains of the United States, modern potential drift directions, and inferred late Holocene paleowinds based on dune orientations. Sand distribution data from Muhs and Holliday (1995); drift directions and paleowinds data from Madole (1995), Muhs et al. (1996, 1997a), Arbogast (1996), and unpublished data of D.R. Muhs and V.T. Holliday.

In eastern Washington, detailed studies by A.J. Busacca and colleagues (Busacca, 1991; Busacca et al., 1992; McDonald and Busacca, 1992; Busacca and McDonald, 1994; Berger and Busacca, 1995; Richardson et al., 1997) have added tremendously to our knowledge of loess history in this region. Loess in eastern Washington and adjacent parts of Idaho and Oregon may cover as much as 60,000 km^2 (McDonald and Busacca, 1992). It is as thick as 75 m (Ringe, 1970), and Busacca (1991) estimates that loess deposition may have begun as early as 2 Ma (million years ago). There are dozens of paleosols within eastern Washington loess, indicating many periods of nondeposition and surface stability between times of loess deposition. The loess itself is thought to be derived primarily from fine-grained slackwater sediments, which in turn are derived from cataclysmic floods of proglacial Lake Missoula (McDonald and Busacca, 1992).

Busacca and McDonald (1994) designated the two youngest loess units in eastern Washington as *L1* (upper) and *L2* (lower). Well-dated Holocene and late glacial tephras from the volcanically active Cascade Range to the west are found within eastern Washington loess and provide valuable time lines for dating and correlation (Busacca et al., 1992; Richardson et al., 1997). In addition, TL ages by Berger and Busacca (1995) and TL and infrared stimulated luminescence (IRSL) ages by Richardson et al. (1997) confirm correlations inferred from tephra data that L1 is of late Wisconsin age and L2 is of early to middle Wisconsin age. Agreement between TL and IRSL ages is good back to ~70,000 years ago, which strengthens the age estimates made by these investigators. However, there are differences between the two studies; TL ages reported by Richardson et al. (1997) for the same sections are generally younger than those reported by Berger and Busacca (1995).

Stratigraphic and geochronologic data show when in a glacial cycle most loess deposition takes place in eastern Washington. Because the loess is thought to be derived primarily from proglacial Lake Missoula flood sediments, most loess deposition probably takes place late in each glacial cycle, and some deposition has continued into the Holocene. Eastern Washington loess becomes thinner and finer grained from southwest to northeast, indicating that late glacial winds were from the southwest (Busacca, 1991; Busacca and McDonald, 1994).

12.8. EOLIAN RECORDS IN ALASKA AND NORTHWESTERN CANADA

Loess is areally the most extensive surficial deposit in Alaska and adjacent parts of the Yukon Territory in Canada and is found over most parts of this region where rugged mountains, such as the Alaska Range and the Brooks Range, are absent (Fig. 18). As with South America and the North American midcontinent, the classical concept has been that most loess deposition in Alaska took place during glacial periods. However, extensive Holocene loess is found in Alaska (Péwé, 1975; Begét, 1990, 1996; Muhs et al., 1997c), and, at localities near Fairbanks (Eva Creek and Fox), Holocene deposits are almost as thick or thicker than the best candidates for deposits of last-glacial age (Fig. 19). Because glaciers still exist in Alaska and northwestern Canada, it is not surprising that abundant glaciogenic silt is available in many of the region's major river systems, and contemporary loess deposition is well documented (Péwé, 1951, 1975; Nickling, 1978).

Eolian sand is also extensive in Alaska (Fig. 18), but

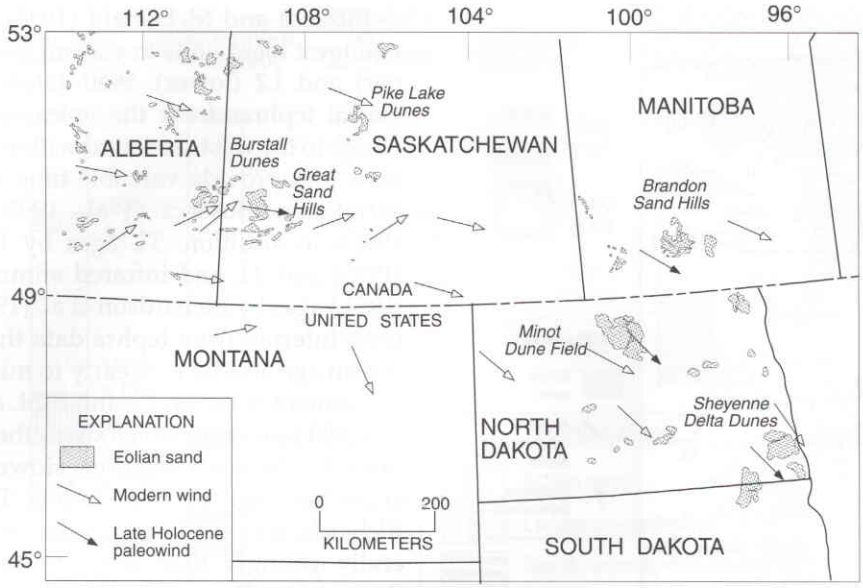

FIGURE 15 Map showing the distribution of mostly late Holocene eolian sand (stippled) in the northern Great Plains of southern Canada and the northern United States, modern sand-moving winds, and late Holocene paleowinds based on dune orientations. Data compiled from Running (1996), Wolfe (1997), Muhs et al. (1997b), and Muhs and Wolfe (1999).

with few exceptions is largely stabilized by boreal forest or tundra vegetation. Geomorphic and stratigraphic evidence suggests that most eolian sand was derived from glaciofluvial sediments and was deposited originally in sand sheets rather than dunes, at least in part because of limited sand supply (Lea and Waythomas, 1990; Lea, 1996). Later dune building is thought to have occurred mainly as a result of reworking of previously deposited sheet sand. It is not clear at all localities, however, whether most of this dune building took place during latest Pleistocene, early Holocene, or mid-Holocene time (Lea and Waythomas, 1990). Available radiocarbon ages suggest that much eolian sand deposition, whether of sand sheets or dunes, took place in the interval from ca. 18,000 to ca. 10,000 ^{14}C B.P. However, Holocene eolian sand deposition is also docu-

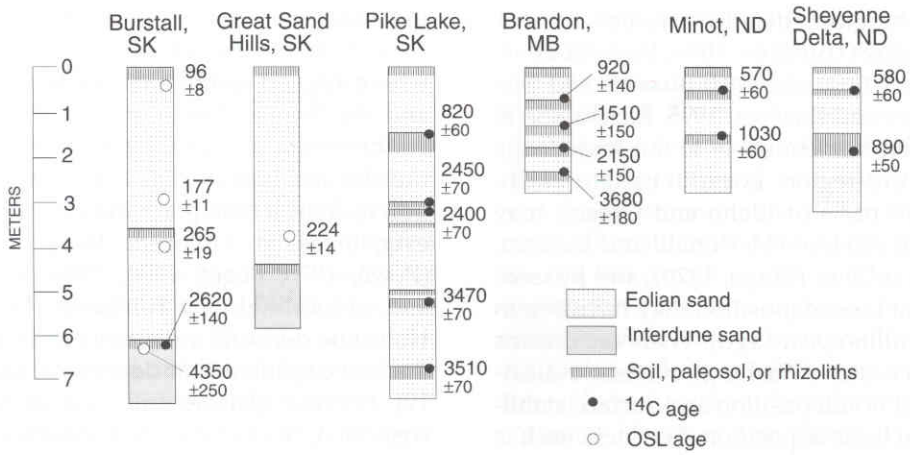

FIGURE 16 Stratigraphy, radiocarbon, and optically stimulated luminesence (OSL) ages of eolian sand in the northern Great Plains of the United States and Canada, showing evidence of multiple episodes of late Holocene eolian activity. Localities are shown in Fig. 15. Data from David (1971), Wolfe et al. (1995), Running (1996), Muhs et al. (1997b), and sources in Muhs and Wolfe (1999).

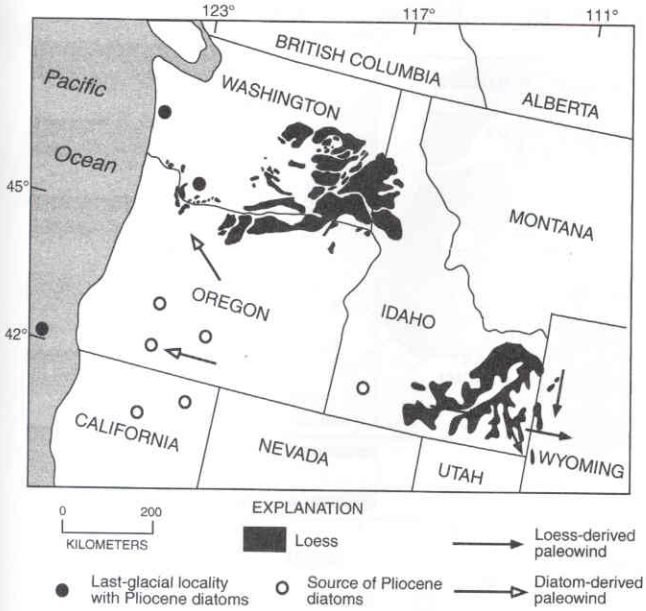

FIGURE 17 Map showing the distribution of loess in the northwestern United States (from Thorp and Smith, 1952), inferred paleowinds from loess and wind flute data (from Lewis et al., 1975; Lewis and Fosberg, 1982; Pierce et al., 1983; Glenn et al., 1983; and Busacca and McDonald, 1994), and inferred paleowinds from offshore and lacustrine diatom data (from Sancetta et al., 1992). Locations of last glacial maximum (LGM) localities where exotic Pliocene diatoms are found are from Sancetta et al. (1992); locations of Pliocene diatom-bearing beds are from Bradbury (1982, 1992).

mented in both the interior of Alaska and on the Arctic Coastal Plain (Fig. 20). Distribution of eolian sand relative to probable source sediments and, in some places, orientations of dunes indicate northeasterly paleowinds in most parts of Alaska (Fig. 18).

12.9. LONG-DISTANCE TRANSPORT OF FINE-GRAINED AIRBORNE DUST

A third category of eolian sediment (in addition to sand and loess) is fine-grained aerosolic dust that is capable of traveling long (intercontinental) distances (Prospero, 1981; Pye, 1987; Rea, 1994). The particle size range of this dust overlaps the finest particle size range of loess, but has mean values less than ca. 5 μm. Fine-grained dust is of considerable interest to climate modelers because studies have demonstrated that it can play a role in climate change, both through changes in the Earth's radiative balance and as a nutrient for primary productivity in the oceans (Harvey, 1988; Joussaume, 1993; Li et al., 1996; Tegan et al., 1996; Overpeck et al., 1996; Andersen et al., 1998; Mahowald et al., 1999). Where they can be found, geologic records of far-traveled dust are also important paleoclimate indicators because they yield information about synoptic-scale circulation. Records in deep-sea sediment cores, ice cores, and soils indicate that the Americas have been both a source and a sink for far-traveled, fine-grained dust.

Darwin (1846) was one of the first investigators to observe airborne dust over the Atlantic Ocean enroute to the Americas. A century later, numerous researchers have confirmed that African dust travels to the Americas via the northeasterly trade winds (Fig. 21). Delany et al. (1967), Prospero et al. (1970, 1981), and Prospero and Nees (1977, 1986) demonstrated, through analysis of satellite imagery and dust trap collections, that African dust falls on Florida, Barbados, and northern South America. By the time it reaches the western Atlantic Ocean, airborne dust from Africa is composed mostly of particles less than 20 μm in diameter, and about half of this is clay-sized material less than 2 μm in diameter (Prospero et al., 1970). The most important mineral in the silt-sized fraction is quartz, and mica dominates the clay-sized fraction (Delany et al., 1967; Glaccum and Prospero, 1980). The modern flux of dust from Africa is, to a great extent, a function of the degree of aridity in the southern Sahara and Sahel (Prospero

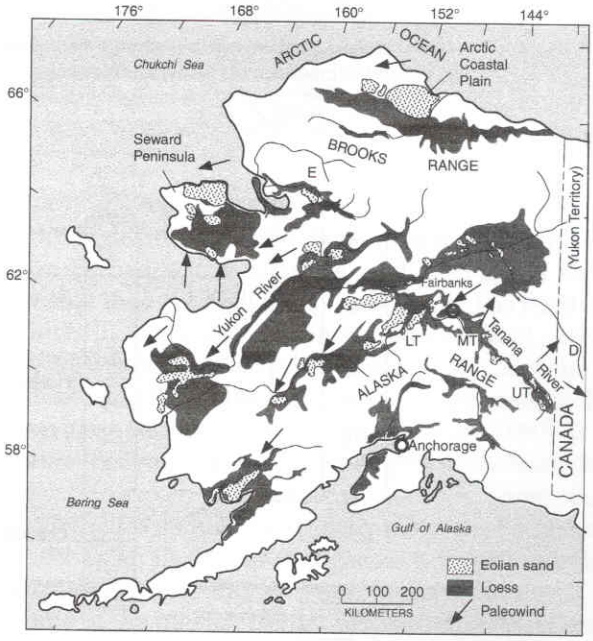

FIGURE 18 Map showing the distribution of eolian sand and loess and paleowinds inferred from eolian sand data in Alaska and northwestern Canada. E, Epiguruk (see Fig. 20); UT, upper Tanana River (see Fig. 20); MT, middle Tanana River (see Fig. 20); LT, lower Tanana River (see Fig. 20); D, Dawson, Yukon Territory, Canada (see Fig. 19). Eolian sand and paleowinds data are from Lea and Waythomas (1990); loess distribution is redrawn from Péwé (1975).

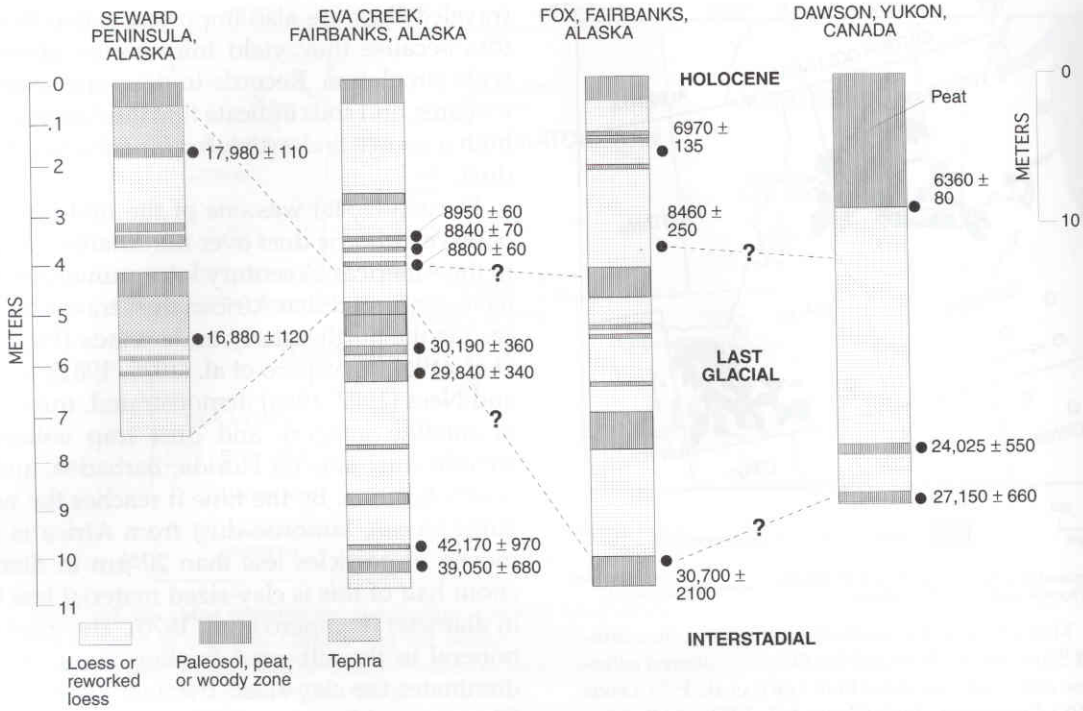

FIGURE 19 Stratigraphy and radiocarbon ages of selected loess sections in Alaska and northwestern Canada. Localities are shown in Fig. 18. Generalized from Hamilton et al. (1988), Höfle and Ping (1996), Muhs et al. (1997c), and Fraser and Burn (1997).

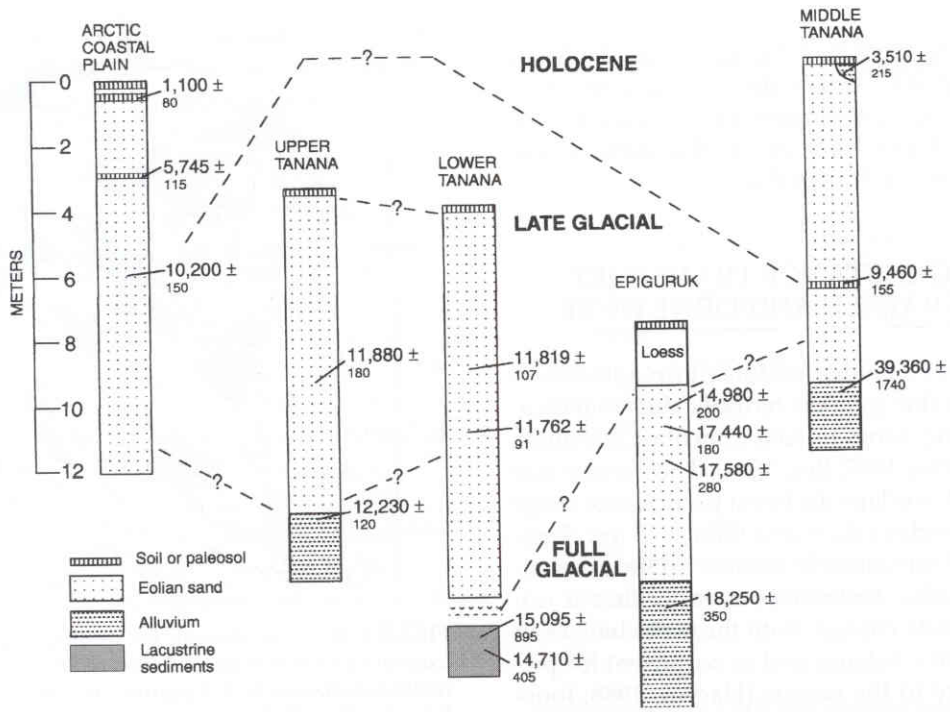

FIGURE 20 Stratigraphy and radiocarbon ages of selected eolian sand sections in Alaska. Localities are given in Fig. 18. Generalized from Weber et al. (1981), Carter and Galloway (1984), Galloway and Carter (1993), Hamilton and Ashley (1993), and Lea (1996).

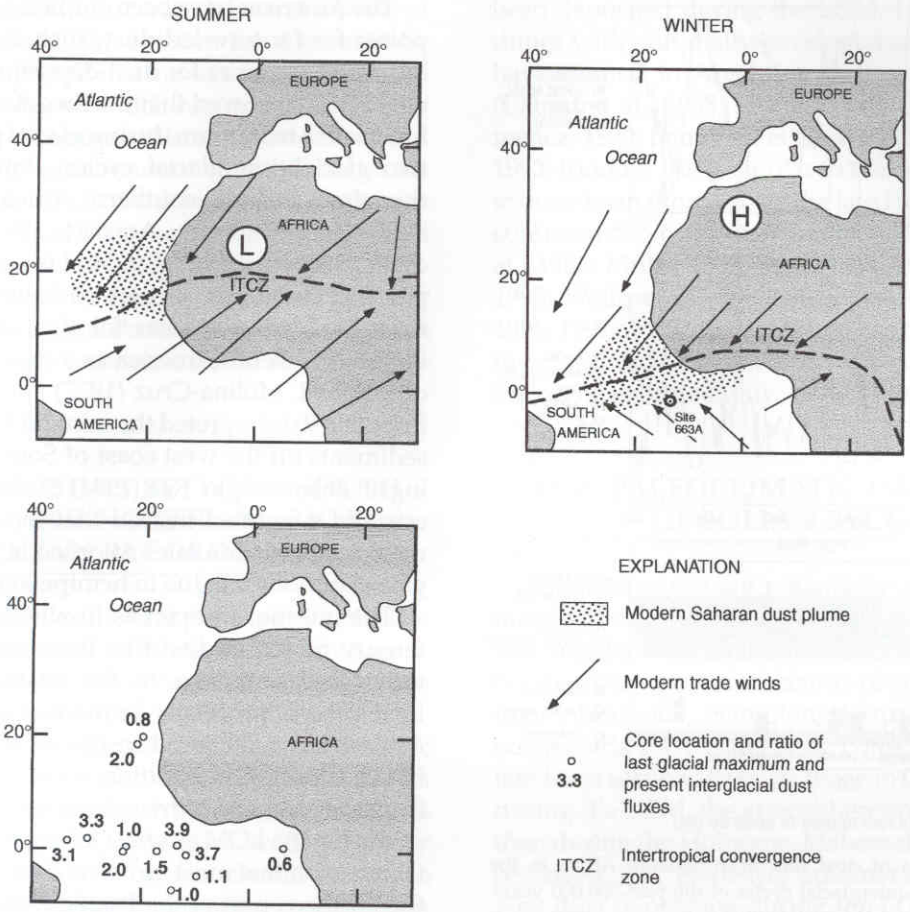

FIGURE 21 Modern summer and winter circulation patterns over a portion of the Atlantic Ocean, the location of modern Saharan dust plumes, and the ratio of last glacial maximum (LGM) to modern dust fluxes as recorded in deep-sea cores between Africa and South America. (Redrawn from Ruddiman 1997.)

and Nees, 1977), but measurable dust has been collected in Florida and Barbados most years since collections began in the 1960s (Prospero, 1981).

It has been known for some time that deep-sea sediments in the Atlantic Ocean that date to the LGM are enriched in quartz relative to Holocene sediments (Bowles, 1975; Kolla et al., 1979). Quartz enrichment in the North Atlantic is due to ice rafting, but in the equatorial Atlantic it is interpreted to be the result of westward eolian transport of quartz-rich particles from Africa via the trade winds. Deep-sea sediment records and soils indicate that African dust transport to the Atlantic Ocean and the Americas have been an important process for hundreds of thousands of years, and show distinctive maxima (Fig. 22). At site 663A in the Atlantic Ocean, maximum fluxes of African dust to the Atlantic Ocean generally occur during glacial or stadial periods, whereas peak interglacial periods have low dust fluxes (deMenocal et al., 1993; Ruddiman, 1997). Studies of soils on high-purity carbonate reef terraces and eolianites on Barbados, the Bahamas, and the Florida Keys show that they are unlikely to have formed as residual products by carbonate dissolution (Muhs et al., 1987, 1990). Lesser Antilles island arc volcanic ash deposition on these islands has been an important process in the Quaternary period (Carey and Sigurdsson, 1980). It is possible that soils have developed primarily from this source. However, geochemical analyses show that African dust is a much more likely parent material and has been so for the last several glacial–interglacial cyles (Fig. 22).

Some of the highest resolution paleoclimate records of the Americas are ice cores from glaciers in the high Andes of South America. Dust flux is one of the records available from these cores, and there are differences over both time and space. The Huascarán, Peru, ice core shows a dust flux during the LGM that is about 200 times greater than most Holocene values (Thompson et

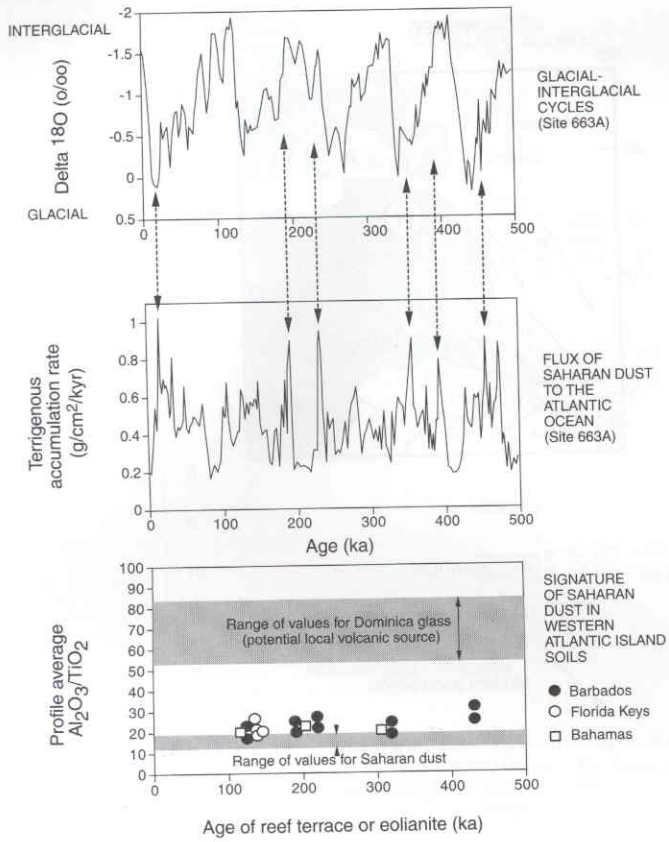

FIGURE 22 Records of dust flux from Saharan Africa to the Americas over glacial–interglacial cycles of the past 500,000 years. Top: Oxygen isotope record of foraminifera in deep-sea sediments at site 663A in the Atlantic Ocean showing glacial–interglacial cycles. Middle: Accumulation rates of terrigenous sediments at site 663A, interpreted to be a measure of Saharan dust flux to the Atlantic Ocean. Arrows show correspondence between generally cold (glacial or stadial) periods with periods of maximum dust flux. Bottom: Soil profile average values of Al_2O_3/TiO_2 on Barbados, the Bahamas, and the Florida Keys compared to average values (plus or minus one sigma) for soil parent material sources. Site 663A data from deMenocal et al. (1993); soil data from Muhs et al. (1990).

al., 1995). The timing of this high dust flux is remarkably similar to that found in Greenland and Antarctic ice cores. Thompson et al. (1995) interpreted the high dust flux during the LGM to reflect an overall decrease in humidity, precipitation, and vegetation cover in South America at this time, as well as enhanced eolian transport processes (i.e., stronger winds). In contrast, an ice core taken from the summit of Sajama mountain in Bolivia shows much higher values in the Holocene than during the LGM, which is inconsistent with both the Peruvian record and that of polar ice cores (Thompson et al., 1998). Thompson et al. (1998) interpreted the enhanced Holocene dust flux in Bolivia to represent increased volcanic activity, elevated snow lines, and decreased net accumulation since the LGM.

The Americas have been studied not only as the endpoints for far-traveled dust, such as that from Africa, but also as sources for dust deposited elsewhere. Petit et al., (1990) showed that the flux of dust into Antarctic ice was at a maximum during glacial periods of the past two glacial–interglacial cycles. Potential sources for this dust include southern Africa, Australia, New Zealand, and South America. Basile et al. (1997) demonstrated, using Sr and Nd isotopes, that the Pampas and Patagonia regions of South America are the most likely source areas for this dust. Other studies identifying South America as a dust source have been questioned. Molina-Cruz (1977) and Molina-Cruz and Price (1977) interpreted the mineral fraction of deep-sea sediments off the west coast of South America as having an eolian origin. Rea (1994) challenged this hypothesis and suggested instead that the increased mineral mass accumulation rates recorded in these cores during glacial periods are due to hemipelagic processes.

The question is open as to whether there is a Quaternary record of dust flux from arid regions of western North America to the eastern Pacific Ocean. Hemipelagic processes dominate much of the mineral accumulation recorded in cores off the west coast of North America. In addition, winds are predominantly from the west or northwest and are likely to have been so during the LGM as well (Johnson, 1977). There is little question that most airborne dust that is delivered to the northern part of the Pacific Ocean comes from the loess regions of Asia (Rea, 1994), and eolian quartz has been found in soils as far east of Asia as the Hawaiian Islands (Jackson et al., 1971). Nevertheless, some data suggest eolian inputs from North America to the eastern Pacific Ocean, at least locally. A high-resolution core from the Santa Barbara basin (for location, see Fig. 6) is dominated by silt- and clay-sized particles, with a few thin sandy layers present, over the past two interglacial–glacial cycles (Stein, 1995). Quartz abundances in these sediments show distinct maxima during three glacial periods: oxygen isotope stages 2, 4, and 6. Stein (1995) speculated that the quartz enrichments at these times may have been due to greater eolian flux from North American desert regions. Other data also suggest that the Mojave Desert of California periodically supplies dust to the eastern Pacific. Although prevailing winds are from the northwest on the California coast, easterly winds known as "Santa Anas" occur several times per year. After the passage of a frontal system, high pressure settles in the Great Basin and winds from this high move to the south and southwest over the Mojave Desert. In areas where there are loose, dry, silt- and clay-sized particles, Santa Ana winds are strong enough to carry the sediments at least as far west as the California Channel Islands, based on examina-

tion of satellite imagery, dust trap data, and reports of aircraft pilots (Muhs, 1983). Soils on San Clemente Island, CA, rest on uplifted marine terraces cut primarily into Miocene andesite, which has no mica and only scarce quartz. Nevertheless, soils on alluvial fans and marine terraces contain abundant silt- and clay-sized quartz and mica at all depths in all soils of deposits ranging in age from the Holocene to greater than 1.0 Ma (Muhs, 1982). These observations support the hypothesis of Stein (1995) that the Mojave Desert may deliver eolian dust to the eastern Pacific Ocean and that the process may have been important for much of the Quaternary period.

12.10. COMPARISONS BETWEEN SOUTH AMERICAN AND NORTH AMERICAN EOLIAN RECORDS

There are both similarities and differences in the late Quaternary eolian records of South and North America. Both continents have extensive loess and eolian sand deposits. Loess is widespread over much of Argentina and Paraguay (Zárate and Blasi, 1991, 1993; Sayago, 1995; Iriondo, 1997, 1999). Similar to North American loess deposits, much of this sediment was deposited during the LGM under cold, arid, and windy conditions. In contrast, however, South American loesses have a much higher contribution from volcaniclastic sources delivered by fluvial transport and even directly from explosive eruptions (Zárate and Blasi, 1993). In North America, only Great Plains loesses have a significant volcaniclastic component, and this is mostly reworked from Tertiary rocks (Aleinikoff et al., 1998, 1999). On both continents, however, fluvial transport is an important step in the sediment cascade before eolian entrainment (Zárate and Blasi, 1993). One difference is that there was significant Holocene loess deposition in South America (Zárate and Blasi, 1993), but it was rare in North America outside of Alaska and isolated parts of the Great Plains.

In South America, eolian sand is found on the Llanos del Orinoco in Venezuela and Colombia, in the Pantanal and Beni basins of Paraguay and southwestern Amazonia, and on the Pampas and Patagonian plains of Argentina (Zárate and Blasi, 1993; Roa, 1979, 1980; Clapperton, 1993; Iriondo, 1997, 1999). As is the case with its North American counterparts, almost all of this eolian sand is stabilized by vegetation. As in North America, active dunes in South America are rare, an important exception being the field of active barchan dunes along the coast of Peru (Finkel, 1959). Most South American eolian sand is undated (see Kröhling, 1999 for an exception to this), but much is thought to have been deposited during the LGM. However, parabolic dunes with minimally developed soils are reported to have formed in Argentina during the late Holocene (Cabral et al., 1988; Hurtado and Giménez, 1988; Giménez, 1990; Ramonell et al., 1992; Iriondo and García, 1993; Iriondo, 1999), similar to the episodes of parabolic dune formation during the late Holocene in the mid-continent of North America (David, 1971; Ahlbrandt et al., 1983; Muhs, 1985; Swinehart, 1990; Madole, 1994, 1995; Wolfe et al., 1995; Arbogast, 1996; Muhs et al., 1996, 1997a,b). Buried soils in these dunes, on both continents, indicate that there were multiple periods of Holocene eolian activity.

12.11. PALEOCLIMATIC IMPLICATIONS OF EOLIAN RECORDS

Eolian deposits are potentially important paleoclimate proxies because of their sensitivity to overall moisture balance and degree of vegetation cover and because they are direct records of atmospheric circulation. Worldwide, many long-term and quasi-continuous records such as deep-sea cores, ice cores, and certain loess sections (such as those in China) suggest that during the LGM, the atmosphere contained more dust than during the Holocene. Mahowald et al. (1999), who reviewed this evidence, summarized three reasons why dust deposition during the LGM may have been greater than it is now: (1) increased glacial age wind intensities could entrain more dust and carry it farther from sources, (2) reduced intensity of the hydrological cycle could allow dust to remain suspended in the atmosphere longer (i.e., fewer *rain-out* periods), and (3) increased source areas for dust existed, due to reduced vegetation cover and decreased soil moisture. In this section, we compare paleoclimatic inferences made from eolian records with paleoclimate models and independent records of paleoclimate such as pollen, faunas, and lake levels. Climate models and synoptic-scale paleoclimatic reconstructions for the past 18,000 years provided by the COHMAP effort (COHMAP Members, 1988; Kutzbach et al., 1993; Markgraf et al., 1993b; Thompson et al., 1993; Webb et al., 1993a,b), as well as later modeling efforts (Kutzbach et al., 1998; Bartlein et al., 1998; Mahowald et al., 1999), are particularly well suited to comparisons with eolian records of South and North America.

12.11.1. Low Latitudes

The greater dust flux at low latitudes during the LGM is well recorded in Atlantic deep-sea sediments from Africa to South America (Ruddiman, 1997) and in

Huascarán ice cores from Peru (Thompson et al., 1995). Ruddiman (1997) concluded that glacial age aridity in the source areas of Africa cannot explain the greater flux of dust to the Atlantic (and the Americas) during the LGM because there was no increase in dust flux following the early Holocene monsoon maximum. Instead, he argued that stronger winter trade winds were the most likely cause for the greater dust flux during the LGM and that there was also a southward shift in these winds by several degrees of latitude. An atmospheric general circulation model simulation by Rind (1987) demonstrated that a cooler North Atlantic Ocean sea surface would have intensified the winter subtropical high over the Atlantic, which in turn would have increased the strength of the winter trade winds. Countering Ruddiman's (1997) viewpoint, however, is the notion that the amount of dust transport is not a simple function of average wind speed. Rea (1994) pointed out that, at the present time, virtually all dust transport from Africa to Barbados or from Asia to the Pacific Ocean takes place in spring, when both the northeasterly trade winds (Africa to Barbados) and the westerlies (Asia to the North Pacific Ocean) are weaker than during winter. In addition, he noted that there is a good correlation between wind speed and size of particles transported, but little correlation between accumulation rates and size of particles. The simulations of Mahowald et al. (1999), based on both source area conditions *and* transport processes, show the Sahara and Sahel of Africa as important dust sources during the LGM; so perhaps it is a combination of source sediment conditions and wind strength that is critical to explaining the Atlantic Ocean dust flux record.

The record of formerly active dunes on the Llanos del Orinoco in Venezuela has been inferred to represent a drier climate in this region during the LGM (Roa, 1979; Iriondo, 1997; Clapperton, 1993). These latter workers suggested that the drier conditions could have resulted from a southward migration of the ITCZ during the LGM, which agrees with the reconstruction made by Ruddiman (1997) from data on dust flux to the east of South America. Although most lake and pollen records in this region go back only to ca. 13,000 ^{14}C B.P., they support the notion that this region was drier during the late glacial period (Bradbury et al., 1981; Markgraf, 1993b).

12.11.2. Midlatitudes: Last Glacial Period

Many of the paleoclimate records derived from pollen and lake-level data (Markgraf, 1993b; Thompson et al., 1993; Webb et al., 1993a,b) suggest that during the LGM, midlatitude regions such as the North American midcontinent south of the Laurentide ice sheet and the Pampas region of Argentina (east of the Andes glacial cap) were very cold, dry, and windy. Virtually all investigators who have studied last glacial eolian deposits in Argentina agree that paleoclimatic conditions at the time of deposition were cold, dry, and probably windy (Zárate and Blasi, 1991, 1993; Iriondo, 1999; Kröhling and Iriondo, 1999; Kröhling, 1999; Carignano, 1999). These interpretations are in agreement with pollen and faunal data for the last glacial period (Markgraf, 1993b; Prieto, 1996; Prado and Alberdi, 1999; Tonni et al., 1999). They are also in agreement with COHMAP model results, which indicate that midlatitudes in the Southern Hemisphere were colder and drier during the LGM and the late glacial period (Kutzbach et al., 1993; Markgraf et al., 1993b; Webb et al., 1993b). Because South American glaciers were of much smaller extent than those in the Northern Hemisphere (Clapperton, 1993), it can be inferred that an important reason for greater eolian activity was a drier climate and diminished vegetation cover, rather than solely an increased sediment supply from glaciogenic silt. The studies of Zárate and Blasi (1993) and Gallet et al. (1998), which demonstrate the importance of volcaniclastic sediments as sources, suggest that loess in the Pampas region is not primarily dependent on glaciogenic silt. Identification of the Pampas as the most important source area for dust found in Antarctic ice cores (Basile et al., 1997) is also consistent with COHMAP simulations of this region as drier during the LGM (Markgraf et al., 1993b; Webb et al., 1993b). Transport of fine-grained loess from the Pampas to Antarctica also agrees with the simulation of Mahowald et al. (1999) showing that this part of South America was an important dust source region.

In contrast, the causes of abundant loess deposition during the LGM and the late glacial period in North America vary from region to region. East of the Missouri River, where the headwaters of major drainages were glaciated, the Laurentide ice sheet generated abundant silt-sized material that was carried in major outwash valleys. Timing of loess deposition shows that shortly after the ice left the headwaters of major drainages to the south, loess deposition ceased (Ruhe, 1983). This concept is supported by the studies of Frye et al. (1968), McKay (1979), and Grimley et al. (1998), which show the linkages between loess composition and various ice lobes, as discussed earlier. These observations indicate that the reason for much loess deposition during the LGM is that the region was a supply-dominated system. The dust model of Mahowald et al. (1999) does not show the area south of the Laurentide ice sheet as a significant dust source during the LGM, although their model does not account for extraordinary sediment supplies due to glacial meltwaters.

Similarly, the northwestern United States is not simulated as a major loess source during the LGM (Mahowald et al., 1999), despite the abundance of loess deposits found in Idaho and Washington (Busacca, 1991). However, as described earlier, eolian entrainment of silt in this region is a function of a particular sediment supply, namely, slackwater deposits of proglacial Lake Missoula outbreak floods. Therefore, loess deposition is a function of a short-lived, supply-dominated system and not primarily a function of strong winds or lack of vegetation cover (although these factors may enhance silt entrainment). Furthermore, loess deposition in this region occurs during both late glacial and Holocene times, rather than primarily during the LGM.

On the other hand, areas of North America not immediately adjacent to glaciated terrain, in the Great Plains, have some of the thickest LGM loess deposits on the continent. As was described earlier, the isotopic studies of Aleinikoff et al. (1998, 1999) demonstrate that loess sources in this region are mostly nonglaciogenic. Thus, the COHMAP and later climate models (COHMAP Members, 1988; Thompson et al., 1993; Kutzbach et al., 1993, 1998; Bartlein et al., 1998) that simulate cold, dry, windy conditions in this region agree well with the loess record. Vegetation cover on the Great Plains is not abundant at present and likely was even more sparse under the cold, dry conditions of the LGM. Lack of vegetation cover may have been one of the most important factors in allowing sediment entrainment in this region during full glacial times. However, the Mahowald et al. (1999) simulation does not suggest that there were significant dust sources in the Great Plains region during the LGM.

There is a major disagreement between LGM circulation modeled by COHMAP studies and the loess record of North America. COHMAP and later simulations (COHMAP Members, 1988; Kutzbach et al., 1993, 1998; Bartlein et al., 1998) indicate that the Laurentide ice sheet generated a glacial anticyclone that would have produced northeasterly winds in the region to the south of the ice sheet. In contrast, the well-dated LGM loess paleowind record of midcontinental North America (Fig. 7) indicates a westerly or northwesterly wind during full glacial times (Muhs and Bettis, 2000). If a zone of northeasterly winds existed, then the loess distribution pattern described earlier indicates that it was extremely limited in geographic extent and may have affected only a narrow zone near the ice sheet. An alternative explanation is that loess deposition occurred during short, exceptionally strong northwesterly winds that occurred infrequently, but transported much sediment (Muhs and Bettis, 2000).

In the northwestern United States, there is also an apparent disagreement between LGM paleowinds derived from the loess record and the COHMAP simulations. As with the midcontinent, LGM paleowinds in unglaciated portions of the northwestern United States are simulated by COHMAP to have been easterly or northeasterly, in this case due to glacial anticyclonic circulation over both the Laurentide and Cordilleran ice sheets (COHMAP Members, 1988; Kutzbach et al., 1993, 1998; Bartlein et al., 1998). Based on eastern Idaho loess thickness and particle size trends, westerly or northwesterly paleowinds can be inferred (Fig. 17) and are in conflict with model simulations.

In contrast, marine and terrestrial records of exotic diatoms provide an independent and novel method to infer LGM paleowinds in the northwestern United States. Sancetta et al. (1992) studied sediments, pollen, and diatoms in a core taken 120 km off the coast of southern Oregon (Fig. 17), with a record that goes back to ca. 30,000 ^{14}C B.P. In the interval from ca. 25,000–11,000 B.P. (but not in the Holocene), they reported abundant extinct diatoms that occur only in Pliocene lacustrine sediments found in interior Oregon and California and also in southwestern Idaho (Bradbury, 1982, 1992). Although a fluvial mode of transport cannot be completely ruled out, an eolian origin is far more likely, based on the lack of certain Quaternary taxa that would also be expected if streams were the primary means by which the Pliocene diatoms were delivered to the ocean. This finding implies at least occasional easterly paleowinds in the northwestern United States over the period from ca. 25,000–11,000 B.P. Sancetta et al. (1992) suggested that winter was the most likely time that easterly transport might have occurred and that easterly winds need not have been constant. Nevertheless, they pointed out that their findings support the concept of a glacial anticyclone, as modeled then by Kutzbach and Guetter (1986). Perhaps easterly, diatom-bearing winds reflect winter conditions during the LGM, and westerly, loess-bearing winds reflect summer conditions. This intriguing possibility needs to be investigated more thoroughly with additional loess and exotic diatom studies.

There is less disagreement between modeled circulation and the loess and eolian sand record for the Pampas region of Argentina. COHMAP results (Kutzbach et al., 1993) suggest that during full glacial southern summers (January), surface winds would have been westerly, which agrees reasonably well with southwesterly paleowind data derived from loess and eolian sand studies as described by Zárate and Blasi (1993).

During the late glacial period and transition into the Holocene (ca. 12,000–9000 ^{14}C B.P.), Forman et al. (1995) suggested that the midcontinent of North America experienced little eolian activity. They presented a model wherein the Gulf of México (cooled by glacial

meltwaters) and the continental interior (warmed by higher summer insolation) generated a stronger monsoonal flow of air from the Gulf of México to the interior. Because the Gulf of México is the major moisture source for midcontinental North America, they hypothesized that this should have been a time of relatively high precipitation and little eolian activity and cited supportive evidence from some sections studied in eastern Colorado. This model has appeal, but there are numerous examples from the region that do not support it. Eolian activity in the Nebraska Sand Hills is inferred to have been important at this time, sufficient to build dunes that dammed drainages (Loope et al., 1995; Mason et al., 1997; Muhs et al., 2000). Furthermore, maximum limiting radiocarbon ages suggest that some of the largest barchanoid ridge dunes in the Nebraska Sand Hills (see Swinehart, 1990) may have been built at this time (Swinehart and Diffendal, 1990). For the Southern High Plains, Holliday (2000) has compiled numerous well-characterized and well-dated sections that indicate that the Folsom period, which occurred in this late glacial interval, was a time of significant eolian sand movement.

12.11.3. Midlatitudes: Holocene

For South America, some workers who have studied eolian deposits in the Pampas region note that the early to mid-Holocene period appears to have been a period of soil formation rather than eolian activity (Zárate and Flegenheimer, 1991; Kröhling and Iriondo, 1999; Kröhling, 1999). Therefore, these workers infer a warm, but humid, period at this time. Pollen data for the region also seem to suggest a warm, humid period (Prieto, 1996). Faunal data suggest that the early to mid-Holocene from ca. 9000–7000 B.P. was relatively dry (Prado and Alberdi, 1999; Tonni et al., 1999). However, these latter workers also infer a more humid period between ca. 7500 and 5000 B.P. COHMAP model results suggest that this part of South America may have been warmer, but drier, during the mid-Holocene, with a suppressed monsoon (Markgraf, 1993b). More pollen, faunal, and eolian studies with good age control are probably necessary before a clear picture emerges for the mid-Holocene of the Pampas region.

Several workers (Zárate and Blasi, 1993; Iriondo, 1997, 1999; Kröhling and Iriondo, 1999) infer a drier period in the late Holocene for the Pampas region, although not as dry as during the LGM. Loess deposition and dune formation are both recorded for parts of the Pampas region, and there may have been numerous, short-lived episodes of relatively dry conditions. This interpretation is in agreement with pollen (Prieto, 1996) and faunal data, which suggest a predominantly humid late Holocene period punctuated by arid phases (Prado and Alberdi, 1999).

In North America, there is limited evidence of mid-Holocene eolian activity. The Bignell Loess of the Great Plains may have been deposited at this time (Pye et al., 1995; Maat and Johnson 1996; Johnson and Willey, 2000; Mason and Kuzila, 2000), and there are localities within the Great Plains where eolian sand was active, such as in Nebraska (Loope et al., 1995), Colorado (Forman and Maat, 1990; Forman et al., 1995), and Texas (Holliday, 1995a,b). These periods of eolian sand movement are consistent with pollen data, suggesting that at least parts of the midcontinent were relatively warm and dry during the mid-Holocene (Webb et al., 1993a; Fredlund, 1995; Baker et al., 1998). Mid-Holocene eolian activity is also consistent with COHMAP reconstructions of a relatively warm and dry midcontinental North America (Kutzbach et al., 1993, 1998; Thompson et al., 1993; Webb et al., 1993b; Bartlein et al., 1998). However, there is some disagreement with COHMAP models of overall moisture balance and the eolian record in the Southern High Plains of Texas and New Mexico. The COHMAP simulations suggest positive moisture balances for both summer and on an annual basis ca. 6000 B.P. (Thompson et al., 1993), perhaps due to an enhanced monsoon that affected the southern Great Plains but not the central and northern Great Plains. Packrat midden data from southern New Mexico, just to the west of the southern Great Plains, also suggest wetter conditions at both 9000 and 6000 B.P. (Thompson et al., 1993). In contrast, the eolian record of the southern Great Plains suggests that there was a negative moisture balance at this time (Holliday, 1995a,b).

There is excellent agreement, however, between the eolian record, the vegetation record (primarily from packrat midden data), and model simulations for the Colorado Plateau region during the mid-Holocene. The geomorphic, stratigraphic, and soil data of Wells et al. (1990) suggest there was little eolian activity during the mid-Holocene, and this conclusion agrees well with vegetation records that imply a more positive moisture balance than at present (Thompson et al., 1993). The latest climate model experiments for the southwestern United States for this period (Bartlein et al., 1998) also suggest a much stronger monsoonal flow and a more positive moisture balance.

There is abundant evidence of late Holocene eolian activity in all parts of the Great Plains, from southern Texas to the Canadian prairie provinces. Holocene eolian activity was so widespread that it is likely that much eolian sand active during the mid-Holocene was reworked, and this may explain why the mid-Holocene

record of sand movement is sparse. In addition, many localities show stratigraphic evidence of multiple episodes of late Holocene eolian activity, suggesting alternating periods of relatively dry and wet conditions. Independent paleoclimate data for the late Holocene are mostly limited to the northern Great Plains, where there are abundant lacustrine records of diatoms, ostracodes, and pollen (e.g., Fritz et al., 1991, 1994; Laird et al., 1996). Although limits on dating of eolian sediments preclude precise timing of short dry periods, the lacustrine records indicate that there were many alternations of relatively dry and moist periods in the late Holocene. Eolian sand was active during the late Holocene over much of the Colorado Plateau as well (Wells et al., 1990; Stokes and Breed, 1993). Orientations of late Holocene dunes in both the Great Plains and the Colorado Plateau regions indicate that dune-forming winds were very similar to modern winds (Figs. 6, 14, and 15). This observation suggests that dune activation in these regions can take place under climatic regimes that have circulation patterns similar to those of modern climates.

12.11.4. High Latitudes

The loess record of Alaska and adjacent parts of Canada has been used to interpret paleoclimate in a number of ways. The traditional interpretation is that thick loess deposits represent glacial periods, as in the North American midcontinent (Péwé, 1975). However, near Fairbanks, some Holocene loess deposits with good radiocarbon control are as thick or thicker than what could be LGM loess deposits. There is no question that glaciers were more extensive in Alaska and northwestern Canada during the LGM (Péwé, 1975), and it is very likely that more glaciogenic silt was produced at that time compared to the present. However, the relatively thick Holocene loess compared to last glacial loess may be a consequence of the vegetation cover at the time of loess deposition. Since the early Holocene, there has been a boreal forest cover in interior Alaska, whereas during full glacial time, herb tundra was the dominant vegetation (Ager and Brubaker, 1985). The Boreal forest may have served as a more efficient trap of airborne sediment compared to tundra vegetation, even if overall glaciogenic silt production during full glacial time was greater (Begét, 1988, 1991). If this hypothesis is correct, then extreme care must be taken in interpreting Alaskan loess stratigraphy for paleoclimatic records.

Béget (1990, 1991), Béget and Hawkins (1989), and Béget et al. (1990) used magnetic susceptibility variations in Alaskan loess–paleosol sequences to infer glacial to interglacial changes in late Quaternary wind strengths. Loess–paleosol sequences in Alaska are analogous to those in China in that loess deposition and pedogenesis occur during both glacial and interglacial periods and are competing processes. In this model, loess deposition rates exceed rates of pedogenesis in glacial periods and the reverse occurs in interglacial periods. Thus, although a paleosol may represent a slowing of loess sedimentation, particles are still added to what becomes a cumulic soil surface. Béget and co-workers further assumed that with lower deposition rates, wind strengths should be lower; therefore, mean particle size should be finer, and heavy mineral content should be lower. Using magnetic susceptibility as a proxy for heavy mineral content (and therefore wind strength), they demonstrated that values are higher in loesses (assumed to represent glacial or stadial periods) and lower in paleosols (assumed to represent interglacials or interstadials). These observations suggest that winds were stronger during the last glacial period compared to the Holocene.

Much still remains to be learned about the paleoclimatic significance of Alaskan loess. Loess source areas in Alaska are not well established, nor is the amount of loess deposition that took place during the LGM. Paleowinds during the LGM could be reconstructed from loess data if well-dated loess sequences were convincingly linked to source areas by using mineralogy, geochemistry, and isotopic composition. However, even apart from the larger glaciers that were present during the LGM, the dust-source model of Mahowald et al. (1999) suggests that interior Alaska was an important source at this time, consistent with the pollen record of cold, dry conditions and a sparsely vegetated landscape (Ager and Brubaker, 1985).

In interior Alaska, eolian sand sheets, rather than dunes, were deposited during the LGM (Lea and Waythomas, 1990). Although mechanisms for the formation of sand sheets are still not entirely understood, it is known that sheet sand tends to be deposited in favor of dune sand in settings where there are sediment supply limitations. Although there was abundant glacial outwash source material at the LGM, Lea and Waythomas (1990) infer that sediment supplies were effectively limited because of ice cementation, snow cover, high groundwater tables, and vegetation cover. Partial vegetation cover during sand sheet formation is inferred from vertebrate tracks that are common in many eolian deposits in Alaska (Lea, 1996). Thus, sheet sand formation during the LGM may imply a sparsely vegetated, permafrost-dominated landscape, which agrees well with full glacial climate reconstructions based on pollen (Ager and Brubaker, 1985). Dunes seem to have formed mainly during the late glacial or

Holocene period, at least in interior and southern Alaska. Lea and Waythomas (1990) hypothesize that the shift from sheet sand deposition to dune formation resulted, at least in part, from deeper seasonal thaws that occurred at the close of the last glacial period, which would have resulted in greater sediment availability. Countering this view are pollen data, which indicate that vegetation in late glacial time would have been more abundant than during the LGM, including an increase in the amount of dwarf birch (Ager and Brubaker, 1985). However, Lea and Waythomas (1990) infer that the deeper thaws and increased sediment supply of the late glacial and early Holocene periods may have outweighed the effect of greater precipitation and more abundant vegetation, with the result that dune formation could take place.

On the Arctic Coastal Plain of Alaska, a different style of eolian deposition took place compared with that of interior Alaska. Longitudinal dunes formed during the LGM, whereas sand sheets formed on top of these after the last glacial period (Carter, 1981). However, some Holocene sands were also worked into dunes, both longitudinal and parabolic types, during at least four late Holocene periods of activity (Galloway and Carter, 1993, 1994). These workers correlated the periods of dune activity with neoglacial expansions of cirque glaciers in the Brooks Range and inferred that dune activity resulted from cooler and drier conditions.

As is the case with the North American midcontinent and the northwestern United States, there is a conflict with paleowinds inferred from eolian sands and model-derived paleowinds in Alaska (Kutzbach et al., 1993, 1998; Bartlein et al., 1998). The model results suggest that paleowinds during the LGM and the late glacial period were dominantly from the southwest. In contrast, both dune orientations and locations of most sand bodies relative to probable sources (note association of dune fields with major drainages on Fig. 18) suggest paleowinds from the northeast. Although Lea and Waythomas (1990) point out that the dunes probably date to the late glacial or early Holocene periods, as was discussed earlier, the locations of the sand bodies from which the dunes were derived probably have not changed since the LGM and still imply mostly northeasterly paleowinds.

12.12. CONCLUSIONS

The Americas contain a rich record of late Quaternary eolian sand, loess, and aerosolic dust. Full glacial time in the midlatitudes of both continents was likely cold, dry, and windy, based both on the eolian record of sand and loess and on other paleoclimate proxies such as pollen. This inference is supported, in part, by the observation that much loess on both continents is nonglaciogenic, implying dry, windy conditions with minimal vegetation cover, prerequisites for eolian entrainment. During full glacial time, midlatitude regions of South America were probably the source for dust in Antarctica, and low-latitude regions of South America received dust from Africa. Paleoclimatic reconstructions of cold, dry conditions from eolian sediments are in agreement with climate model results for the LGM.

There are both agreements and disagreements between last glacial circulation patterns derived from eolian sediments and patterns derived from climate models. In South America, inferred westerly and southwesterly directions of last glacial eolian sand and loess movement are in agreement with westerly paleowind simulations by climate models. However, in North America, including the midcontinent, the northwestern United States, and Alaska, paleowinds derived from eolian sediments do not agree with climate model simulations. The reason for this difference is not understood and needs additional study by both modelers and field scientists.

The mid-Holocene is a time for which eolian records are not as well understood on both continents. In South America, little eolian sediment movement seems to have taken place and warm, humid conditions are inferred; this agrees with pollen and some faunal data, but is not entirely in agreement with climate model simulations. In midcontinental North America, mid-Holocene eolian records are sparse, but may be partly the result of late Holocene reworking. Pollen data and climate model simulations suggest that, at least in the central and northern Great Plains, this should have been an important period of eolian activity, and limited data support that interpretation. On the Colorado Plateau, pollen and climate model data suggest that the mid-Holocene was more moist than at present, and the eolian record agrees with this interpretation.

The late Holocene records eolian sand movement in the midlatitudes of both continents. Too few data currently exist to assume that eolian sand movement was regionally synchronous within dune fields in both South and North America. However, both continents show evidence of widespread late Holocene eolian sand activity and multiple episodes of eolian sand movement during the late Holocene, based on the presence of paleosols within sections. These observations indicate that eolian sediments are highly sensitive to slight shifts in climate and vegetation cover and that widespread eolian sand movement can take place in the midlatitudes of both continents under essentially modern climatic conditions.

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