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Dune Fields: Mid-Latitudes

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Mid-Latitudes

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Introduction

Large dune fields, or sand seas, are landscapes often thought to be found only in deserts beneath the great, subtropical high-pressure zones, where subsiding air suppresses rainfall. Dune fields are also quite common in mid-latitude regions, to the north and south of subtropical deserts (Fig. 1). Two major characteristics distinguish many mid-latitude dune fields from the sand seas of lower latitudes. One difference is that many of those in mid-latitudes are in semiarid, rather than arid climates, and therefore are not

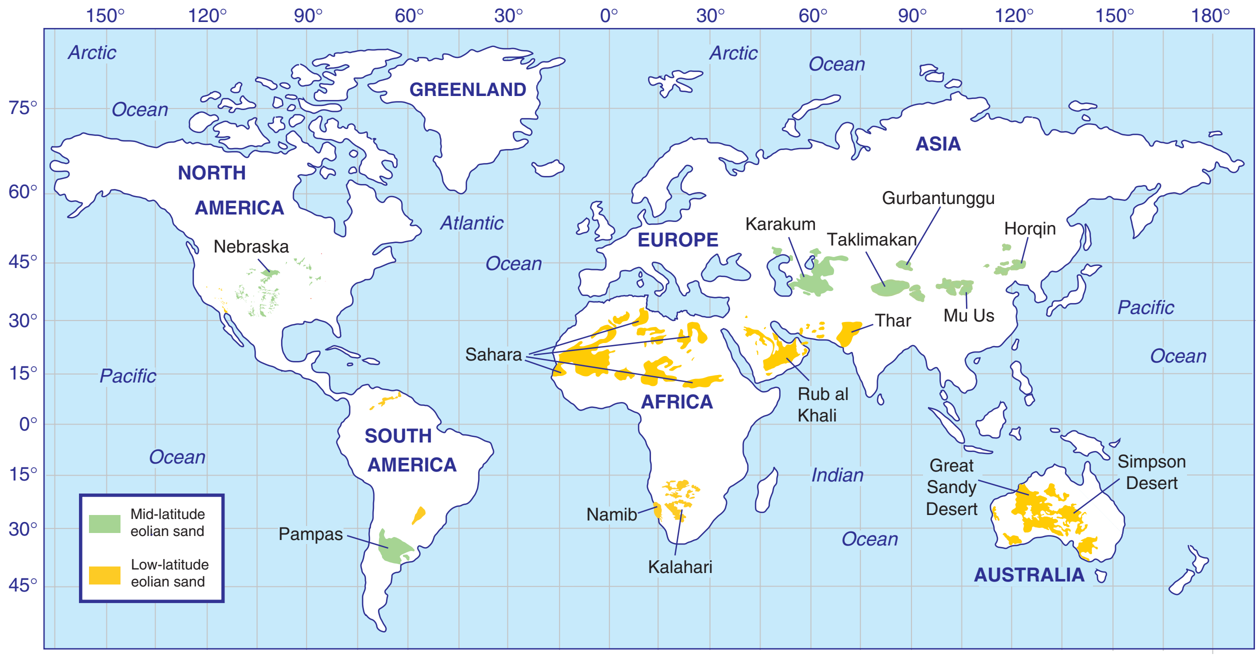

Figure 1 Map showing the global distribution of eolian sand, whether active or stabilized. Sources: North America: Muhs and Zárate (2001), Muhs and Holliday (1995), and Thorp and Smith (1952); South America: Muhs and Zárate (2001) and sources therein; Africa: Wilson (1973), Lancaster (1988), and Thomas and Shaw (1991); Central Asia and India: Wilson (1973); China: Sun and Muhs (this article) and sources herein; Australia: Bowler *et al.* (2001). Mid-latitude dune fields reviewed in this chapter are shown in green; low-latitude dune fields reviewed by N. Lancaster (this volume) are shown in yellow.

presently active. In this article, 'active' refers to eolian sand bodies that are not covered with vegetation, and where particles are currently being transported by the wind. Evidence of active sand transport often takes the form of well-expressed sand ripples on a dune's surface. Where sand is vegetated and particles are not being transported by the wind, a sand body is 'stable.'

A second characteristic of mid-latitude dune fields is that many are situated near mountain ranges or at least areas of relatively high relief. Glaciation in high mountains reduces local bedrock to sand-sized particles, and additional reduction of rock to sand sizes takes place through colluvial and fluvial processes quickly in terrains of steep relief. Through these processes, new sediment becomes available to feed growing dune fields much more rapidly than in areas of low relief, which characterize lower-latitude regions.

Because of their occurrence in semiarid climates, mid-latitude dune fields are particularly sensitive indicators of shifts in the regional moisture balance. Sand dunes move only where there is wind, sand-sized sediment, and a lack of vegetation cover. A shift to drier conditions may result in loss of vegetation cover and activation of sand by wind. A shift back to wetter conditions may stabilize dunes because of enhanced vegetation cover. The geologic record of this alternation of dry and moist climates tends to be preserved in many mid-latitude dune fields as eolian sand–paleosol sequences. In areas downslope of high sediment production, such as mountains, fresh sediment may accumulate in a dune field during periods of eolian activity, bury the pre-existing landscape, and preserve former surface soils as buried soils (or paleosols). In arid, low-latitude environments of low relief, previously stabilized eolian sand may be continually reworked without addition of much new sand, and formerly stable surfaces, which would be marked by paleosols in semiarid climates, may not be preserved.

Throughout this article, we correlate eolian dune-building events, where they can be dated or where the age can be inferred, to the marine oxygen-isotope stratigraphic framework of Martinson *et al.* (1987). Where the abbreviation 'MIS' occurs, this refers to 'marine isotope stage,' using the numbering system and approximate ages in Martinson *et al.* (1987).

Dune Fields in China

Introduction

Dune fields in China form an east–west trending belt in the mid-latitude interior (latitude 35–50° N, longitude 75–125°E) (Fig. 2). The total desert area is 1,308,000 km^2, or 13.6% of China's land area

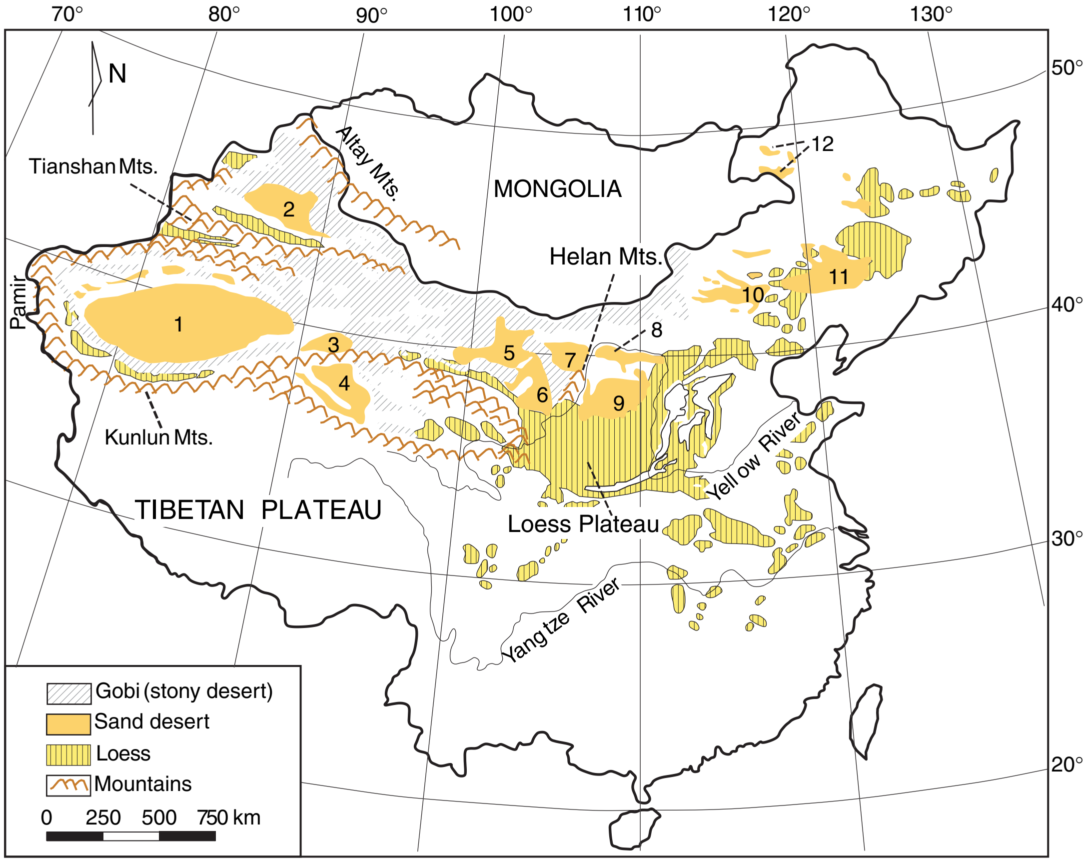

Figure 2 Map showing gobi (stony desert), dune fields, and loess distribution in China.

(Zhu *et al.*, 1980). These dune fields can be divided into two parts by the north–south trending Helan Mountains (Fig. 2). Dune fields, west of the Helan Mountains, include the Taklimakan, Gurbantunggut, Kumtag, Qaidam, Badain Jaran, Tengger, and Ulan Buh deserts, which are situated in inland basins or adjacent to high mountains. The formation of these dune fields is a function of their inland geographic location, far from moisture sources. Climate in these deserts is controlled by the westerlies. Dune fields east of the Helan Mountains, situated in the East Asian monsoonal zone, are mainly stabilized and semistabilized at present.

Dune Types in China

The Taklimakan Desert, which is surrounded by the Tianshan and Kunlunshan mountains, is in the Tarim Basin and dominated (85%) by active sand dunes (Fig. 2). The climate is extremely arid, with a mean annual precipitation of only 15–40 mm. Local residents call the Taklimakan Desert the 'dead sand sea.' Dune types are quite diverse in this desert (Fig. 3), consisting mainly of complex dune chains and transverse dunes. Dunes with heights exceeding 50 m occupy 80% of the area in its interior.

The Gurbantunggut Desert is the second largest dune field in China (48,800 km^2), situated in the Junggar Basin (Fig. 2). The mean annual precipitation in the Gurbantunggut Desert is 70–150 mm, which is the highest among the deserts in northwestern China. Stabilized and semistabilized sand dunes occupy 97% of this desert, and linear (or longitudinal) dunes are the dominant type (Fig. 4). There are also erosional landforms in the northwestern part of the desert, called 'yardangs' (Fig. 5).

The Badain Jaran Desert is the third largest dune field in China (44,300 km^2). The climate is extremely arid, with a mean annual precipitation of less than 50 mm. There are two remarkable properties of the landscape in this desert. First, the desert consists mainly of complex sand hills, dune chains, and pyramidal landforms called 'star' dunes, with an average height of 200–300 m. Second, as many as 144 small lakes are found in the interdune lowlands of the desert (Zhu *et al*., 1980). The source of these lakes is melting water of the Qilian Mountains, ~500 km to the southwest, which reaches the desert through a subsurface fault system (Chen *et al*., 2004). The Kumtag Desert also has complex dune chains and star-shaped pyramidal dunes. In this sand sea, heights of the dunes vary between 100 and 200 m (Fig. 6).

The Tengger Desert is the fourth largest desert in China (42,700 km^2). Sand dunes occupy 71% of the desert, and 93% of the dunes are active. The dominant dune type is transverse dune, with heights usually between 10 and 20 m.

The Qaidam Desert is located in the Qaidam Basin (Fig. 2). Yardangs in its interior make up 67% of the desert's area (Fig. 7). Sand dunes are mainly distributed in the marginal areas, dominated by transverse dunes.

Transverse dunes dominate other dune fields in China, especially those east of the Helan Mountains. Most dunes are stabilized or semistabilized (Fig. 8), and vary in height between 5 and 15 m.

Figure 3 Sand sea of the Taklimakan Desert. About 80% of this dune field is active at present and precipitation-to-potential-evapotranspiration (P/PE) values are generally less than 0.2 (Wang *et al*., 2005).

Figure 4 Semistabilized linear dunes in the Gurbantunggut Desert.

Figure 6 Star-shaped pyramidal sand dunes in the Kumtag Desert.

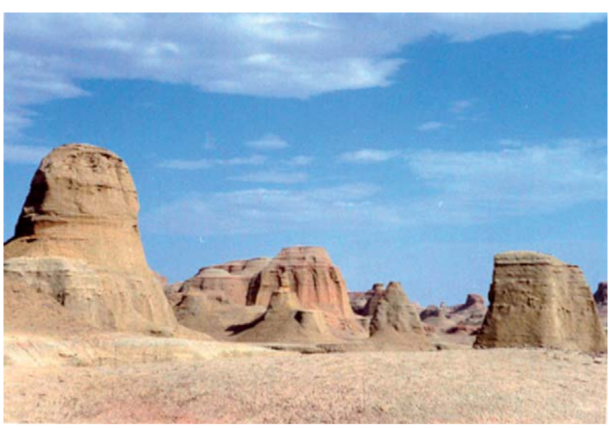

Figure 5 Deflation landforms (yardangs) in the northwestern Gurbantunggut Desert.

Figure 7 Deflation landforms (yardangs) in the interior of the Qaidam Desert.

Figure 8 Stabilized or semistabilized sand dunes are the dominant dune types in the deserts, distributed to the east of the Helan Mountains.

Figure 9 Landsat thematic mapper (TM) image of alluvial fans in the piedmont of the Qilian Mounatins, China. Sediments in these large alluvial fans are important sources of the dune sand and loess in China.

Origin of Chinese Dune Fields

Origins of the dune fields in China can be divided into two categories. Dune fields to the west of the Helan Mountains are situated in the inland basins near the Tianshan, Kunlunshan, and Qilianshan mountains. The mean annual precipitation varies from 20 to 150 mm. Geomorphic processes in the adjacent mountains (especially glacial grinding) have played an important role in producing the vast amounts of sand-sized materials for the formation of these dune fields. Elevations of the Tianshan, Kunlunshan, and Qilianshan mountains range mostly from ~3,000 m to ~5,500 m above sea level. The high elevation gives rise to extremely cold climatic conditions, thus favoring glacial grinding and frost weathering. This leads to the physical weathering of rocks in the surrounding regions, and thus the production of clastic materials (Sun, 2002a, b). The high relief and steep gradients of these mountains give rise to high potential energy of melting water. Thus, the clastic materials can be transported to the piedmont areas, forming large alluvial fans. Examination of multispectral Landsat thematic mapper (TM) imagery indicates that a series of huge alluvial fans have formed in the piedmont of the Qilian Mountains (**Fig. 9**). The zonal distributions of the gobi (stony desert), dune fields, and loess bodies are the result of wind sorting of the piedmont fluvial materials (Sun, 2002a).

Deserts to the east of the Helan Mountains are situated in the high plains of northeastern China. Because this region lies in the East Asian monsoonal zone, the mean annual precipitation ranges from 200 to 450 mm. Most of the dunes are stabilized and semistabilized. However, due to poor land-use practices in historic time, active sand dunes also occur in these deserts, largely due to reworking of last glacial age (MIS 2) sand dunes (Sun, 2000). The provenance of the sediments in these dunes is dominantly from fluvial sediments of several large rivers.

Age of Desert Dunes

One approach for studying long-term dune field history is to examine the chronology of loess deposition, as there are few age estimates of the oldest dunes in China. In the northern piedmont of the Kunlun Mountains, dust derived from the Taklimakan Desert accumulates as loess sediment. Because the Taklimakan Desert lies within the rainshadow of the Tibetan Plateau, which began rising in the late Cenozoic (Gansser, 1964; Molnar and Tapponnier, 1975; Harrison *et al*., 1992), it is possible that dunes have existed in this basin since the latest Cenozoic.

Recent studies of eolian silt on the Chinese Loess Plateau indicate that the source areas are the gobi (stony) desert in southern Mongolia and the adjoining gobi and sandy deserts (including the Badain Jaran Desert, Tengger Desert, Ulan Buh Desert, Hobq Desert, and Mu Us Desert) in China (**Fig. 10**). These gobi and sand deserts only serve as 'holding areas' of dust and silt, rather than the original source of loess particles. Mountain processes (especially glacial grinding) in the high elevations of Asia have played an important role in producing the vast amounts of loess-sized material for forming the Loess Plateau (Sun, 2002a). Because the basal age of the loess in the Loess Plateau is 2.58 Ma (Liu, 1985; Liu and Ding, 1993), and the loess materials are transported by the near-surface winds from the deserts listed above, these basins have been arid environments for at least 2.58 Ma.

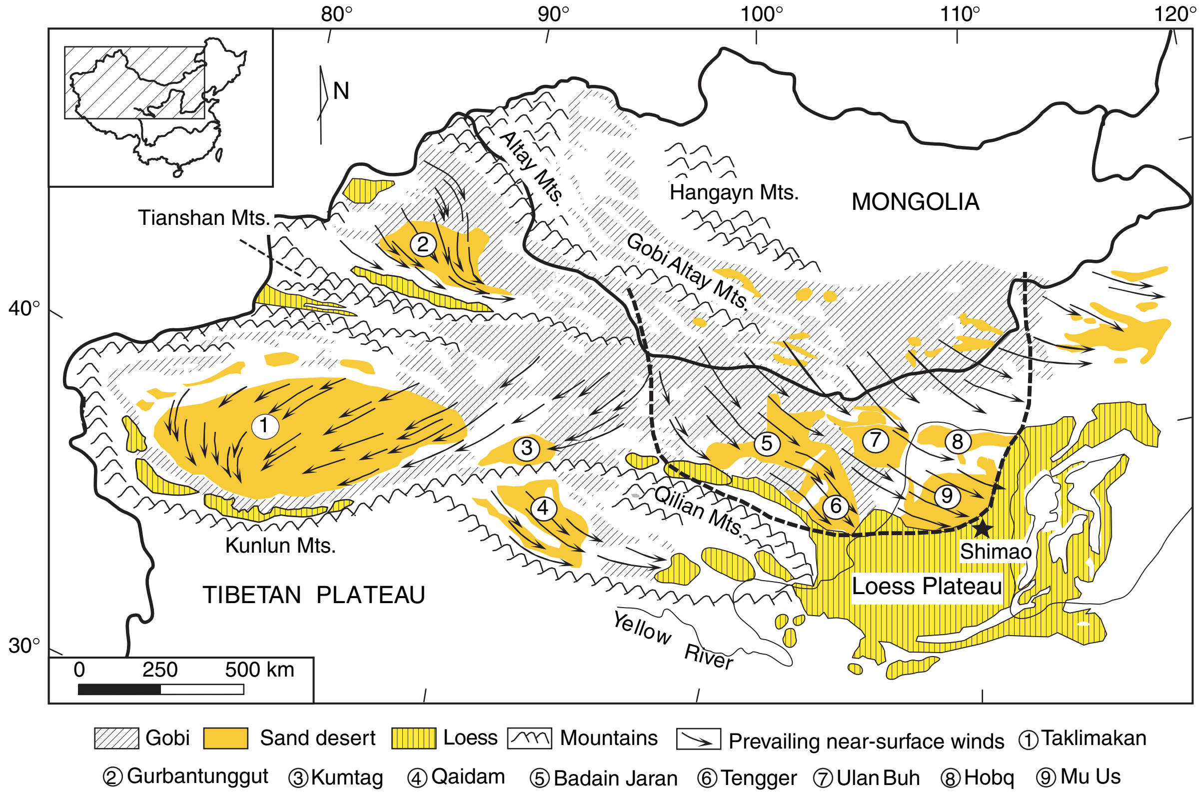

Figure 10 Map showing the near-surface wind directions (arrows) based on dune orientation in the studied regions. Area circled by dashed line indicates the source region of the Loess Plateau (Sun, 2002a).

Relations of Desert Dunes to Loess Deposits

Because Chinese loess is derived from the deserts, desert expansions and contractions, in response to Quaternary glacial–interglacial cycles, may be recorded by eolian deposits at the margins of deserts. Among the 12 deserts in China, only the Mu Us Desert is geographically proximal to the Chinese Loess Plateau. Eolian deposits on the southern margin of the Mu Us Desert are ideal for studying the response of the desert to climatic changes of the Quaternary.

The eolian deposits in the southern marginal Mu Us Desert are characterized by alternations of eolian sand, loess, and paleosols, making it a potential region for recording the ecosystem changes during the Quaternary. Eolian sand accumulated when the Mu Us Desert expanded southeasterly to the Loess Plateau during glacial maxima (Sun *et al.*, 1999).

Paleosols developed under warm and humid conditions of interglacial periods, as a response to the enhanced summer East Asian monsoon winds. The existence of the paleosols in the desert marginal regions indicates that the dunes in the Mu Us Desert were stabilized by vegetation during interglacial maxima.

The loess beds imply intermediate climate conditions, between full glacial and full interglacial climates. The nearly unweathered character of these loess layers suggests that they were deposited under the dominant winter monsoon winds but with greatly reduced wind energy than what is necessary for sand transportation.

The most representative section of these complex eolian deposits is located at Shimao, in the southern marginal Mu Us Desert (Sun *et al.* (1999); see **Fig. 10** for location). The eolian sequences of this section consist of 40 eolian stratigraphic units, of which 13 are sands, 13 are loess, and 14 are paleosols. Based on paleomagnetic polarity studies and a comparison with the composite marine oxygen isotope records (Shackleton and Pisias, 1985; Shackleton *et al.*, 1990), the basal age of this section is about 0.63 Ma (**Fig. 11**). The eolian deposits at Shimao and their correlation with the marine records yield two important implications.

First, during the past 0.63 Ma, there have been at least 13 times of desert expansion in the Mu Us Desert, and the desert expansion occurred not only during glacial maxima, but also during the cold substages of interglacial periods, such as those of MIS 7,

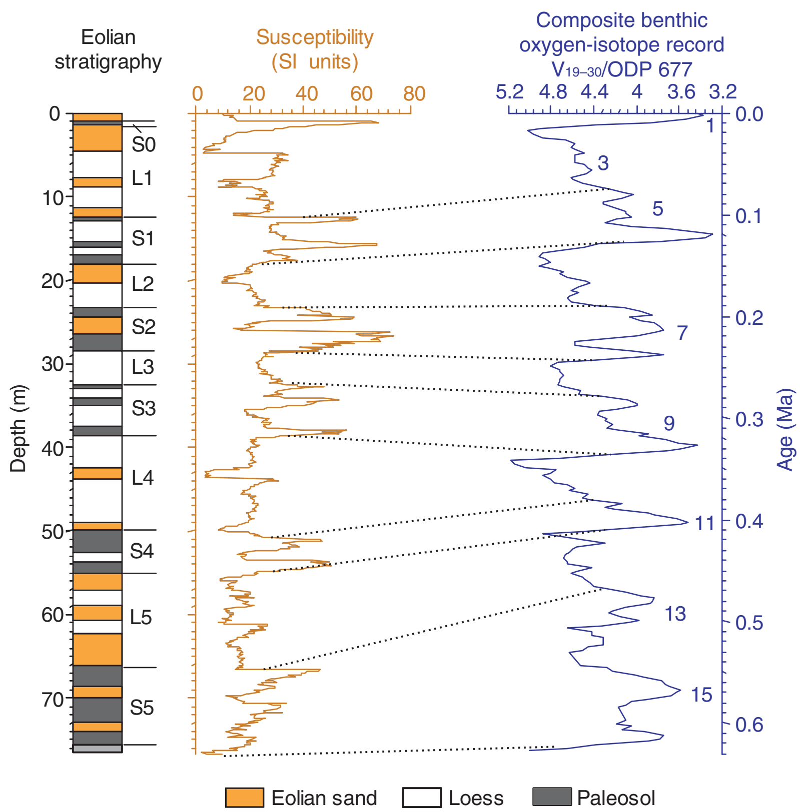

Figure 11 Pedostratigraphy and the magnetic susceptibility curve of the Shimao section and its correlation with the $\delta^{18}O$ records from the Pacific Ocean. The isotope curve is a composite record of V_{19-30} (0–0.34 Myr, Shackleton and Pisias, 1985) and ODP 677 (0.34–0.63 Myr, Shackleton *et al.* (1990)). Modified from Sun, J.M., Ding Z.L., Rokosh, D., and Rutter, N., (1999) 580,000 year environmental reconstruction from eolian deposits at the Mu Us Desert margin, China. *Quaternary Science Reviews* 18: 1351–1364.

13, and 15. Intercalated eolian sand in the interglacial paleosols S2 and S5 support this conclusion (Fig. 11).

A second major implication is that the stratigraphy of the section at Shimao shows that except for the Holocene paleosol (S0), all the other paleosols (S1, S2, S3, S4, and S5) are pedocomplexes, with eolian sand or loess beds intercalated within the soil complexes. The sand or loess intercalations indicate that the warm climate during each interglacial time was interrupted by cold–dry episodes.

Desert Distributions during the Holocene Optimum and the Last Glacial Maximum in China

Recent studies indicate that dust from Asia dominates the entire Pacific Ocean north of the intertropical convergence zone (Merrill *et al.*, 1989; Duce *et al.*, 1991). China is considered as one of the two dominant source regions for atmospheric mineral aerosols originating from Asia (Rea, 1994). The waxing and waning of the summer monsoon during the Quaternary must have had a great effect on the expansion and contraction of the deserts in northeastern China, which in turn modulated the flux of dust from Asia to the Pacific Ocean.

Former extent of deserts during the Last Glacial Maximum Variation in global ice volume may have played a key role in modulating and pacing the strength of the East Asian monsoon (Ding *et al.*, 1994). During the Last Glacial Maximum (LGM), the enlarged high-latitude ice sheets of the Northern Hemisphere greatly strengthened the Siberian High, giving rise to an enhanced cold–dry northwest winter monsoon. Under winter monsoonal winds, strong eolian erosion, transportation, and dune building characterized the arid and semiarid regions of northern China.

Since the 1980s, 44 profiles with LGM dune sands and overlying Holocene sandy loam soils have been found in northeastern China, in the monsoonal climatic zone. Thus, during the LGM, active sand dunes occurred not only in the arid inland areas of western

China, but also in the semiarid to subhumid areas, east of the Helan Mountains. The existence of the buried LGM sands implies that the southern limit of the LGM desert extended south to nearly latitude 36°N, and east to longitude 125°E (Sun *et al.* (1998); Fig. 12A).

Former extent of deserts during the Holocene optimum During the mid-Holocene climatic optimum, from ~9 ka to ~3 ka, the East Asian summer monsoon was strong. Sandy loam soils on stabilized dunes are widely distributed in desert regions, especially east of the Helan Mountains. Radiocarbon ages and optically stimulated luminescence (OSL) dating indicate that these loamy soils developed mainly between 3.0 and 9.0 ka BP, coincident with the Holocene optimum (Zhou *et al.*, 2001; Li *et al.*, 2002). Pollen analysis of these soils indicates that the vegetation was dominated by steppe taxa, implying that sand dunes in northeastern China were stabilized during the Holocene optimum (Sun *et al.*, 1998).

In contrast to the deserts in northeastern China, the distinctive Holocene sandy loam soil has not been found in the Taklimakan, Qaidam, and Badain Jaran

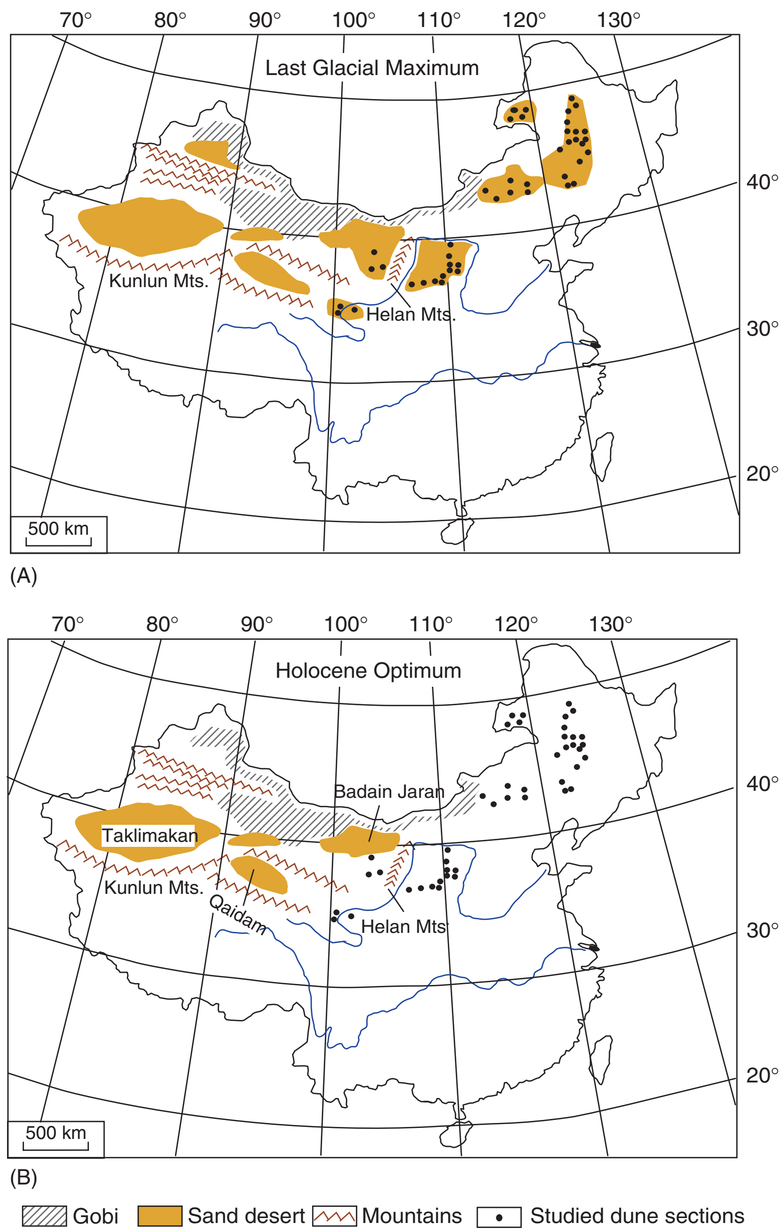

Figure 12 Desert distributions in China during the Last Glacial Maximum (A) and the Holocene Optimum (B), the filled black dots indicating the sites where Holocene loam soils and the underlying sand dunes of the LGM are found (Sun *et al.*, 1998).

deserts. Its absence implies that during the Holocene optimum, the much-enhanced summer monsoon did not penetrate into the interior of the western desert regions, and thus active dune fields existed then (and still exist today). Compared with the desert of the LGM, the extent of desert in the Holocene was greatly reduced, with the eastern limit of desert retreating from longitude 125°E (LGM time, MIS 2) to about 105°E, a distance of well over 1,600 km (**Fig. 12B**).

Dune Fields in Central Asia and South America

Central Asia

To the west of China, dune fields occupy large areas of Central Asia, in the desert basins of Kazakhastan, Uzbekistan, and Turkmenistan. The largest dune fields are situated mostly southeast of the Caspian Sea, Aral Sea, and Lake Balkhash (**Fig. 13**). Wilson (1973) estimates these dune fields to encompass

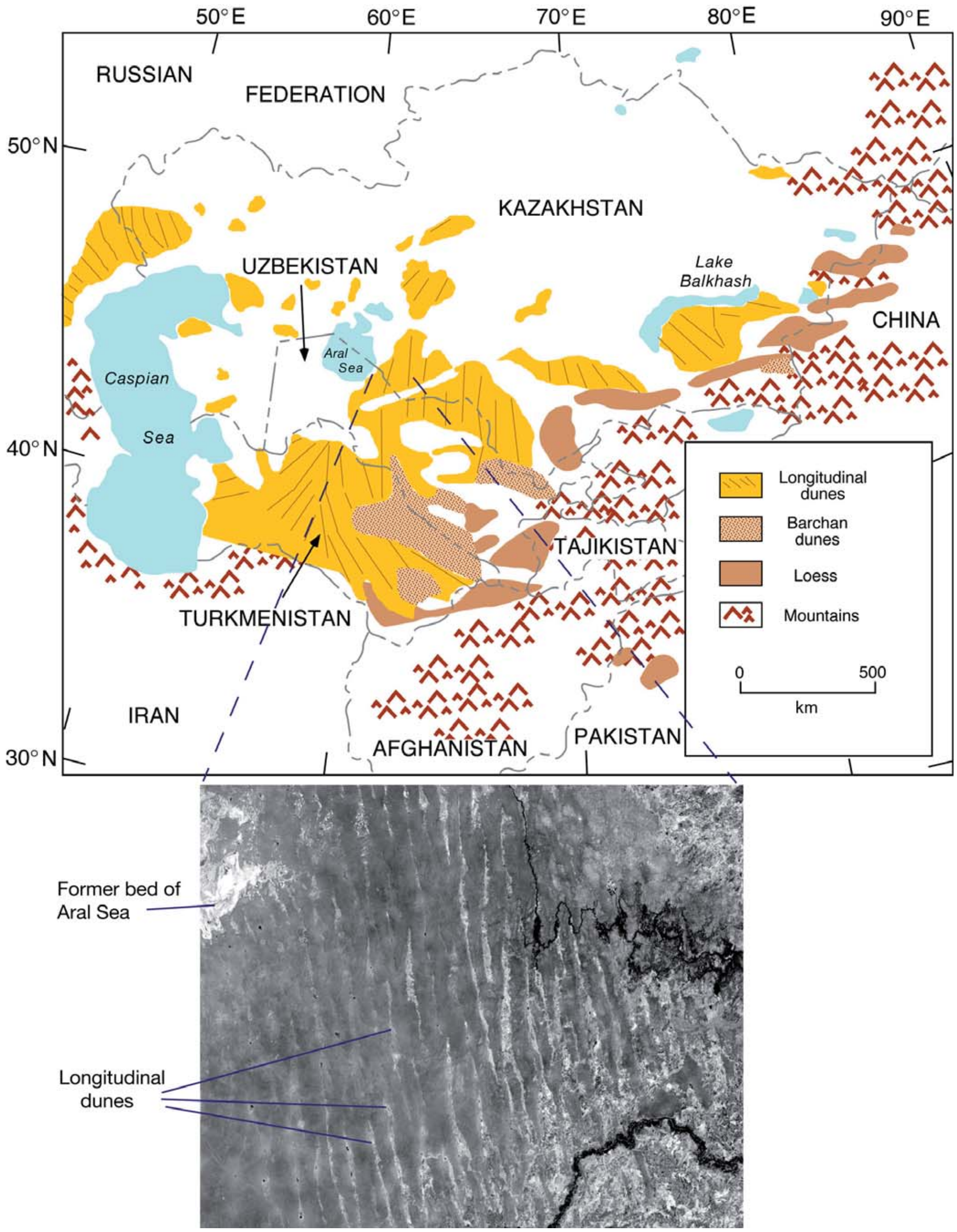

Figure 13 Upper: map showing the distribution of eolian sand and loess in Central Asia (redrawn from data in Lioubimtseva (2002) and sources therein for sand; from Dodonov (1991) for loess). Lower: Landsat TM image (path 159, row 029; band 1, visible blue; image taken 5 August 1987) of longitudinal dunes southeast of the Aral Sea, Kazakhstan and Uzbekistan.

~380,000 km^2 (Karakum sand sea, southeast of the Caspian Sea), ~276,000 km^2 (Kyzylkum sand sea, southeast of the Aral Sea), and ~38,000 km^2 (Myunkum sand sea, southeast of Lake Balkhash). The region is semiarid to arid, and precipitation ranges from ~100 to 400 mm yr^{-1} (Goudie, 2002; Lioubimtseva, 2002).

The main dune forms in the region are longitudinal (linear) dunes, which are easily visible on Landsat imagery (**Fig. 13**). Goudie (2002) reports that the linear dunes are as much as 30 m high and are separated by interdune areas floored with clay-rich sediments. Wilson (1973) indicates that most or all of these dunes are active at present. At the broadest scale, orientations of the dunes (**Fig. 13**) agree fairly closely with modern, dominant wind directions (Letollé and Mainguet, 1993), but in detail, there are some differences, as pointed out by Lioubimtseva (2002). Southeast of the areas of linear dunes, barchans are the dominant landforms, and many of these are also active at present (Goudie, 2002; Lioubimtseva, 2002).

High mountain ranges in Afghanistan, Tajikistan, and China are drained by rivers that flow westward to the basins occupied by the Caspian and Aral Seas. The Volga River, the largest river in Europe, carried sediment from the Fennoscandian ice sheet that covered northern Europe during the LGM (MIS 2). Thus, abundant sediment is delivered to the desert basins of Central Asia at present and it is likely that even more sediment was transported there during glacial periods of the Pleistocene. Because sources of specific dune fields in the region are little studied, it is not known which rivers are most important as dune sand sources.

The paleoclimatic significance of dunes in Central Asia is difficult to assess, as there has been little study of dune stratigraphy, and numerical ages are lacking. However, as with China, some comparisons can be made with chronologies developed for loess deposits that are downwind of the dune fields. Loess deposits are extensive in the southern margins of the desert regions in Central Asia (**Fig. 13**). Dodonov (1991) suggests that this loess is derived from a combination of glaciogenic sources in the neighboring mountains and dust sources in the desert basins. Long-distance transport from desert basin sources is supported by the relatively fine grain size of loess particles in sections exposed in Tadjikistan (Frechen and Dodonov, 1998). Luminescence dating indicates that there was considerable loess deposition during both the early (MIS 4) and later (MIS 2) parts of the last glacial period (Frechen and Dodonov, 1998). These data suggest that winds were strong and desert basin source areas were relatively dry and minimally vegetated during the last glacial period. Nevertheless, during the early part of the last glacial period (MIS 4), the Caspian Sea was connected to the Aral Sea, whereas during the last interglacial period (MIS 5), it was of lesser extent than during the Holocene (Chepalyga, 1984). If the level of the Caspian Sea is at least a partial indicator of the overall moisture balance of the arid basins of the region, these observations suggest that the dune fields may be active primarily during interglacial, rather than glacial periods.

South America

There is a large area of stabilized dunes in the mid-latitudes of South America, primarily in the Pampas region of Argentina. The precipitation gradient in this region is steep, with present mean annual precipitation ranging from less than 500 mm (southwest) to more than 1,000 mm (northeast). In parts of Argentina (particularly in La Pampa and Buenos Aires provinces), there are longitudinal (linear) dunes over 100 km long and 2–5 km wide (**Fig. 14**). Iriondo (1999) refers to this large dune field as the Pampean Sand Sea. The largest dunes in this sand sea are arranged as extensive southwest-to-northeast arch-like forms and are presently stabilized by vegetation. Although the longitudinal dune forms are easily recognizable on Landsat TM imagery (**Fig. 14**), the low relief of these features makes them difficult to identify in the field (Martinez *et al*., 2001). A large field of parabolic dunes, most of them also stabilized and oriented in a southwest-to-northeast direction, is situated south of the longitudinal dunes (**Fig. 14**). The parabolic dunes may have developed from reworking of pre-existing sands.

Zárate and Blasi (1993) present a model for eolian deposition in Argentina that explains the origin of both dunes and loess. They report sedimentological and mineralogical data that lead them to infer that the main dune sand sources, as well as loess sources, are the Colorado and Negro River floodplains, which are situated to the southwest of the Pampean Sand Sea. The Colorado and Negro rivers drain the Andes, and thus volcaniclastic sediments from these mountains are the ultimate source of much or all of the sediment in the sand sea and loess bodies. Zárate and Blasi (1993) point out that the fluvial regime supplying the particles was dependant, to a large degree, on the extent of glacial cover in the Andes. The Colorado and Negro rivers are presently underfit and have a meandering pattern. In the last glacial period, they apparently had a broad, braided pattern, and during seasonal melting periods, both rivers carried large volumes of meltwater and sediment.

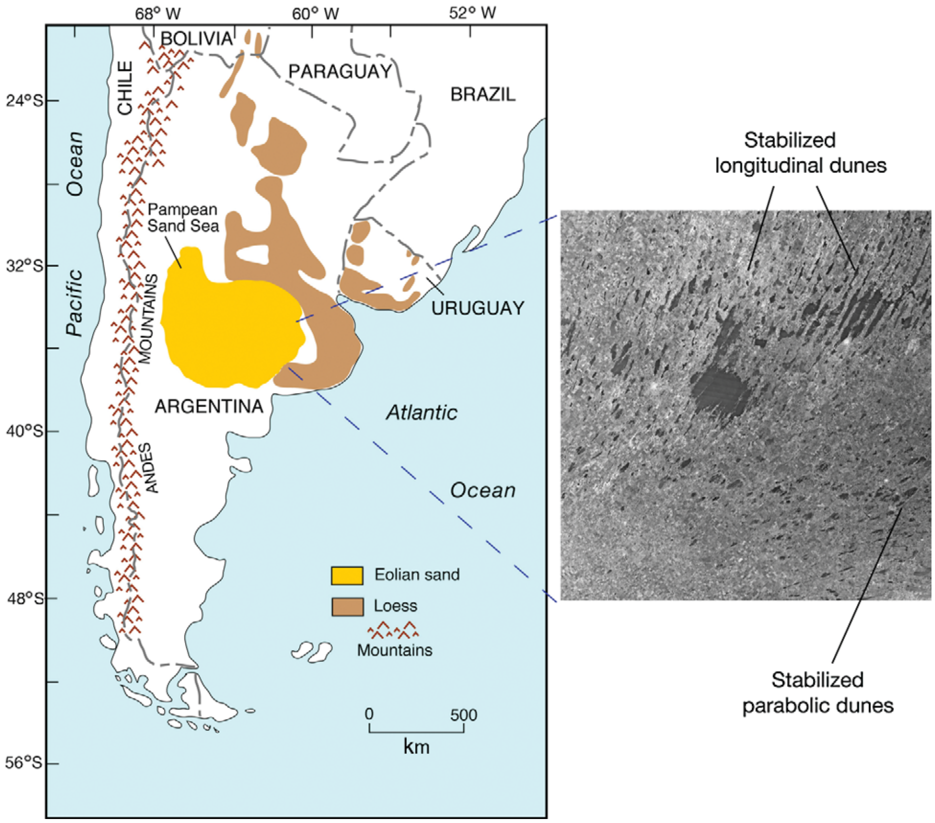

Figure 14 Left: map showing the distribution of eolian sand and loess in southern South America (taken from Zárate (2003), and sources therein). Right: Landsat TM image (path 227, row 085; band 1, visible blue; image taken 17 February 1988) of linear and parabolic dunes in Buenos Aires province, Argentina.

During periods of low flow, sediment availability was large, and provided the source of both sand to build dunes and silt for loess.

There are few data on the ages of eolian sand in Argentina. Iriondo (1999) considers the longitudinal dunes that occur in northwestern Buenos Aires province and surrounding areas to be of late Pleistocene (early last glacial, or MIS 4) age. Thermoluminescence (TL) ages reported by Kröhling (1999) indicate that the earliest part of the Pampean Sand Sea may have formed during the early part of the last glacial period (MIS 4), with reworking of this sand occurring between ~52 and ~36 cal kyr BP. Kröhling (1999) also recognizes an eolian sand facies in a loess-dominated unit called the Tezanos Pinto Formation. Bracketing TL ages of ~32 and ~9 cal kyr BP are reported for the loess facies of the Tezanos Pinto Formation. If these ages are correct, they imply a major period of eolian sand movement during the latter part of the last glacial period (MIS 2). The inference of eolian sand movement occurring during major glacial periods (MIS 4 and 2) is consistent with the sediment origin model of Zárate and Blasi (1993). However, eolian sand movement may also have occurred during the Holocene. For example, Iriondo (1999) considers the parabolic dunes that are found to the southeast of the longitudinal dunes (**Fig. 14**) to be of late Holocene age. Several workers (Zárate and Blasi, 1993; Iriondo, 1999; Kröhling, 1999) use loess and dune formation to infer a relatively dry period for the Pampas region in the late Holocene, although not as dry as during the last glacial period.

Dune Fields in North America

Introduction

Dunes occupy a considerable portion of the mid-latitude regions of North America, particularly in the Great Plains region of the central United States and the Colorado Plateau region of the southwestern United States (**Fig. 15**). The dune fields of the Great Plains have been intensively studied since the 1980s and much is now known about their geographic extent, geomorphic expression, source sediments, chronology, and paleoclimatic significance. The dunes of the Colorado Plateau have been studied less extensively, but work in progress (e.g., Redsteer and Block (2004)) promises important new information about these smaller sand seas.

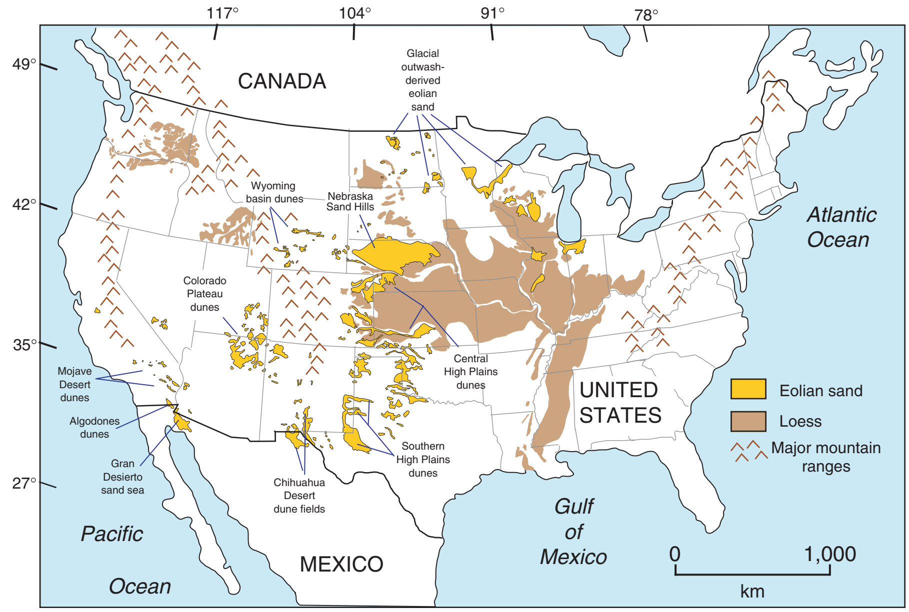

Figure 15 Map showing the distribution of eolian sand and loess in the United States and adjacent parts of Mexico. Redrawn from Thorp and Smith (1952), Muhs and Holliday (1995), Muhs and Zárate (2001), Bettis *et al.* (2003) and sources therein.

Dune Forms in Mid-Latitude Regions of North America

There is a wide range of dune forms in the Great Plains region of North America. The greatest variety of dune forms is found in the Nebraska Sand Hills. In this large (~50,000 km^2) dune field, barchanoid ridges, many 10–20 km long, are present over extensive areas (Fig. 16). Most of these barchanoid ridges have smaller, superimposed parabolic dunes, indicating multiple episodes of eolian deposition. In other areas of the Nebraska Sand Hills, barchans are the main dune form (Fig. 16), but again superimposed parabolic dunes indicate that the barchan forms were generated during earlier phases of dune formation. Linear (longitudinal) dunes are present over extensive areas of the Nebraska Sand Hills, many of which appear to be superimposed on older dune forms (Fig. 16). The Nebraska Sand Hills subregion is semiarid and mean annual precipitation ranges from about 400 mm in the western part to about 600 mm in the eastern part. With the exception of small blowouts on dune crests, all of these dunes are presently stabilized by vegetation (Fig. 17).

Dune fields farther south, in Colorado, Kansas, New Mexico, and Texas, are numerous, but are much smaller than the Nebraska Sand Hills. In eastern Colorado, for example, the total area occupied by dunes is ~25,000 km^2 (Madole *et al.*, 2005). As with Nebraska, the region is semiarid and mean annual precipitation ranges from about 300 mm (west) to about 770 mm (east). The most common landforms in these dune fields are stabilized parabolic dunes, often separated by stabilized eolian sand sheets (Fig. 18). In many places, compound dunes are common, with small parabolic dunes superimposed on larger, older parabolic dunes.

Still farther south, however, in the Chihuahuan Desert of southern New Mexico, western Texas, and northern Mexico, active barchanoid ridges, barchans, and parabolic dunes are found (Fig. 18). Mean annual precipitation in this region is lower than on the Great Plains, and ranges from about 220 to 320 mm. Farther west, on the Colorado Plateau, many different dune forms exist in close proximity to one another. For example, in the Moenkopi Plateau of northeastern Arizona, barchan, linear, and parabolic dunes can all be found within a relatively small area (Fig. 19). Mean annual precipitation on this high plateau region is lower still, and ranges from about 150 to 300 mm. As a result, while some dunes are stable, many are active. In places, for example, stabilized eolian sand sheets separate active linear dunes (Fig. 19).

Dune Origins in North America

In the past, it was commonly assumed that dunes in most parts of central North America, particularly the Great Plains, were derived from local sandstone bedrock, notably the Tertiary Ogallala Formation. This formation occurs over much of the region, crops out close to the land surface, and is rich in clean sand.

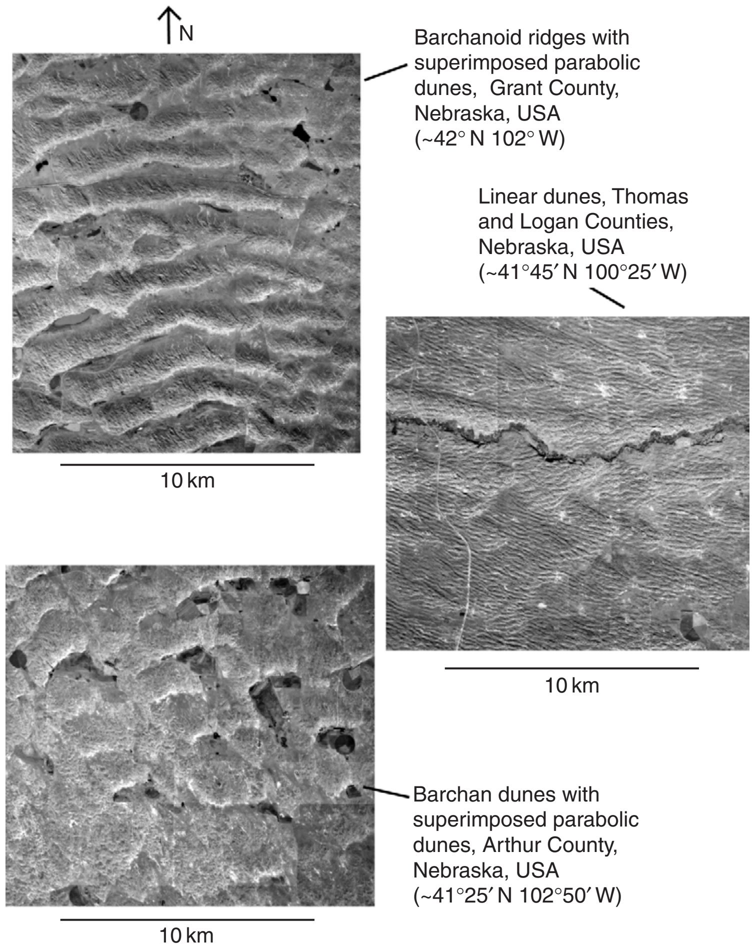

Figure 16 Dune landforms in the Nebraska Sand Hills, USA. All aerial photographs are from the U.S. Geological Survey National High Altitude Aerial Photography (NHAP) program. Frames: Grant County (HAP 182-77, 25 October 1984); Thomas and Logan Counties (HAP 152-52, 31 October 1981); Arthur County (HAP 242-184, 26 September 1985).

It is likely that many early investigators were struck by the close geographic match between the distribution of dune fields and the Ogallala Formation and inferred a genetic link. Nevertheless, much or all of the Ogallala Formation is anchored by a thick, well-cemented calcrete caprock and is not easily eroded.

Later investigators questioned the importance of bedrock as a source sediment for Great Plains dunes. Mineralogical and geochemical studies suggest that in much of the Central High Plains of Colorado and Kansas, dune sediments are derived from major rivers that head in the Rocky Mountains and flow eastward onto the Great Plains. In the Central High Plains, these fluvial sources include the South Platte River, which supplies sediment to dune fields in northeastern Colorado and southwestern Nebraska (not the Nebraska Sand Hills, however), and the Arkansas River, which supplies sediment to dunes in southeastern Colorado and western Kansas (Muhs *et al*., 1996; Arbogast, 1996). In the Southern High Plains of Texas and New Mexico, dune fields appear to be derived mainly from an older Pleistocene eolian sheet sand called the Blackwater Draw Formation (Muhs and Holliday, 2001), which is, in turn, probably derived from the Pecos River.

One of the greatest unanswered questions about dune fields in North America is the origin of the Nebraska Sand Hills, the largest dune field on the continent. No major rivers are situated upwind (to the northwest) of this dune field. The best available evidence, based on isotopic studies, is that it has multiple sources, most of which are sand-rich Tertiary rocks that underlie, or occur upwind of the dune field (Aleinikoff *et al*., 1994). Whatever their ultimate sources, dunes of the Nebraska Sand Hills are more mineralogically mature (i.e., quartz rich and depleted in feldspars) than any of their possible source sediments (Muhs *et al*., 1997; Muhs, 2004). One explanation for this maturity is that most

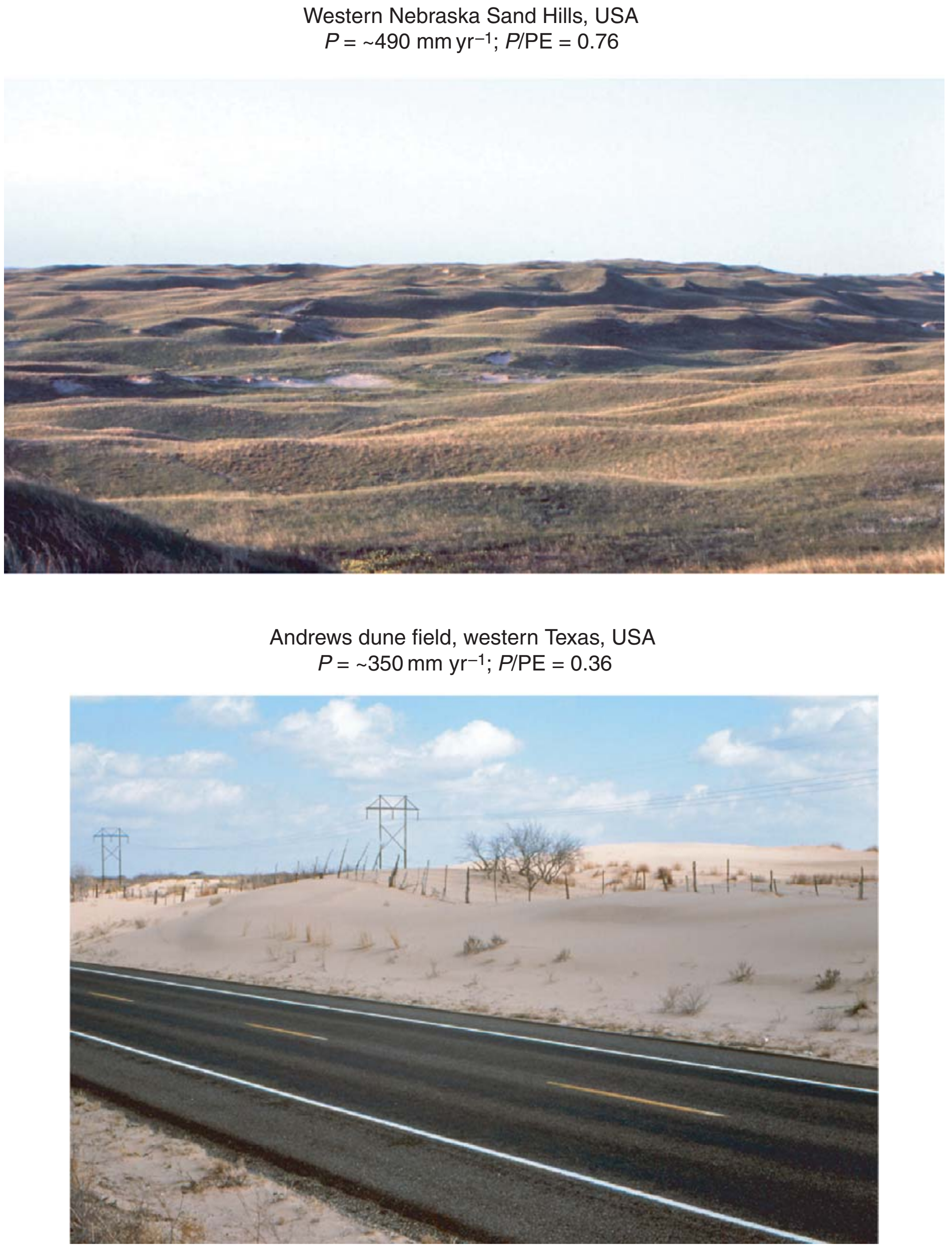

Figure 17 Contrasting degrees of dune activity in the Great Plains of the USA as a function of moisture balance (P/PE) in the western Nebraska Sand Hills (upper) and Andrews dune field, Texas (lower). Photographs by D. R. Muhs.

feldspars have been reduced to silt-sized sediments through ballistic impacts, an idea that has support in both theory and laboratory evidence (Dutta *et al.*, 1993). If this explanation is correct, it suggests that the Nebraska Sand Hills dune field has a long history of repeated dune activity, with little input from fresh sand sources.

Dune Ages in North America

For decades, many investigators assumed, with no numerical age control, that dunes in the Great Plains of the United States were last active during full glacial time (MIS 2). More recent studies confirm that the last glacial period was indeed a time of eolian sand activity over much of the region (Swinehart and Diffendal, 1990; Loope *et al.*, 1995; Muhs *et al.*, 1996; Goble *et al.*, 2004; Madole *et al.*, 2005). However, many studies also show that much eolian sand in the Great Plains region is of late Holocene age. In the Great Plains, the areal extent of late Holocene eolian sand is much greater than that of last glacial sand. For example, dunes of the Nebraska Sand Hills cover ~50,000 km^2, yet all have only

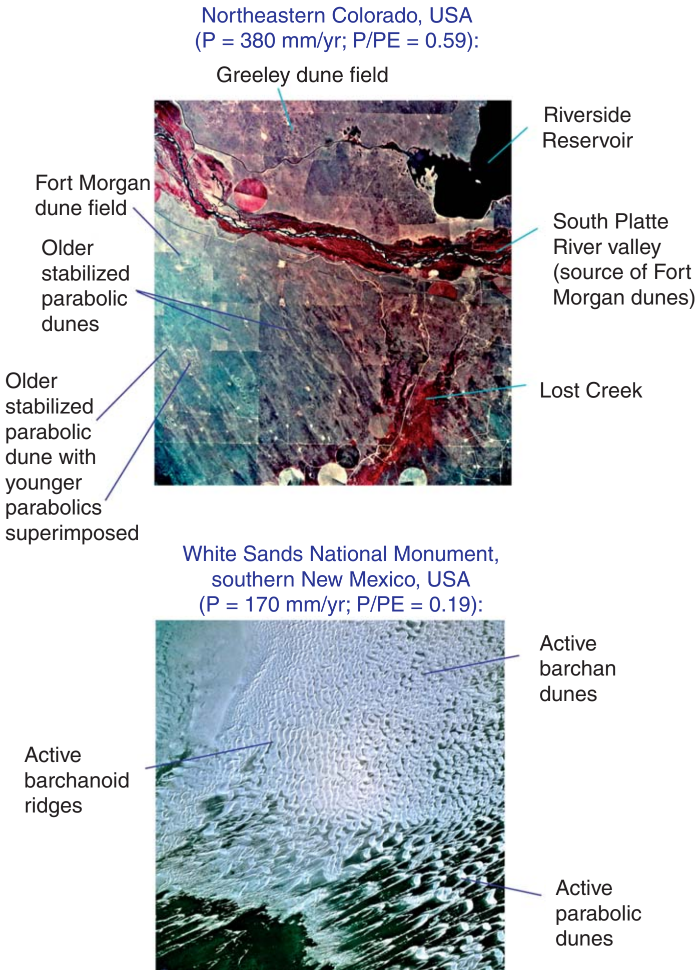

Figure 18 Dune forms in the Central High Plains of Colorado (upper) and northernmost Chihuahuan Desert of New Mexico (lower). Upper photograph is false-colored IR aerial photograph (USGS NHAP 61-107, 22 June 1985); lower photograph is natural-color aerial photograph (USGS NAPP 9524-114, 6 October 1996).

simple A/AC/C soil profiles (Entisols) that develop in a few hundred or few thousand years. This observation, along with late Holocene radiocarbon and optically stimulated luminescence (OSL) 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. However, all parts of the dune field were not necessarily active simultaneously.

Late Holocene eolian sand deposition has now been well documented in Nebraska, Colorado, Kansas, Texas, and New Mexico (Swinehart and Diffendal, 1990; Arbogast, 1996; Muhs *et al.*, 1997; Holliday, 2001; Goble *et al.*, 2004; Forman *et al.*, 2005; Madole *et al.*, 2005). Most of these studies have stratigraphic data indicating multiple periods of eolian activity in the late Holocene (Fig. 20). The small number of radiocarbon and OSL ages and their large analytical uncertainties preclude testing hypotheses of regionally synchronous activity. However, these observations show that eolian sand in this region has been active under modern climatic regimes. Explorers in the nineteenth century observed active dune sand in many parts of the Great Plains where it is now stable (Muhs and Holliday, 1995).

Paleoclimatic Significance of Dunes in North America

One of the most important paleoclimatic inferences made from stabilized, mid-latitude dune fields is that periods of dune activity indicate drier-than-present climate. Many factors influence the degree of dune activity, including wind strength, sediment availability, and degree of surface disturbance by animals or human activity. Nevertheless, several studies show that in many regions, including southern Africa (Lancaster, 1988; Thomas *et al.*, 2005), China (Wang *et al.*, 2005), and North America (Muhs and Holliday, 1995; Wolfe, 1997), the degree of dune activity is influenced to a great extent by the amount

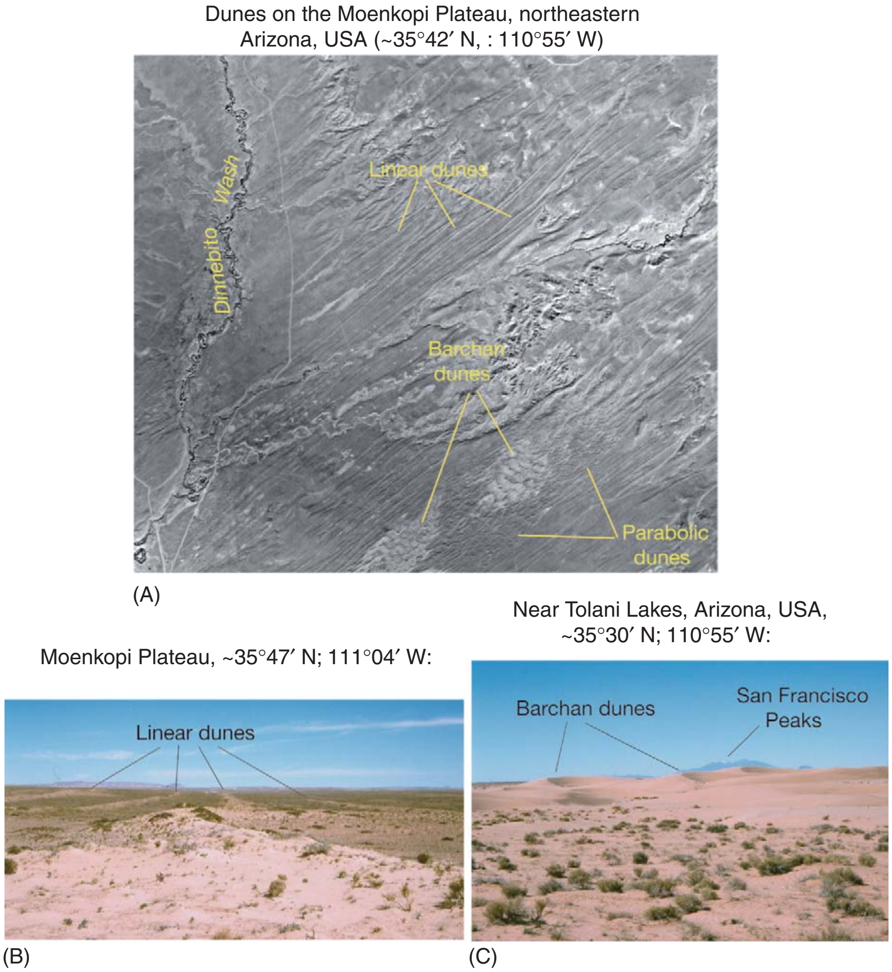

Figure 19 Dune forms on the Colorado Plateau, USA. Upper: aerial photograph showing dune types (USGS NAPP 5240-178, 22 September 1992). Lower: active linear dunes separated by stable eolian sand sheets (left) and active barchan dunes (right). Lower photographs by D.R. Muhs.

of plant cover, which in turn is influenced significantly by moisture balance. Moisture balance can conveniently be calculated, at least to a first approximation, by the ratio of precipitation (*P*) to potential evapotranspiration (PE). Values less than 1.0 indicate a net moisture deficit and are typical of regions with semiarid, arid, or hyperarid climates. In areas where *P*/*PE* is greater than about 0.35–0.40, dunes are stabilized by vegetation. When *P*/*PE* is less than about 0.35–0.40, dunes are at least partially active, and as this ratio diminishes, dune activity increases (**Fig. 17**). In desert regions of the southwestern United States and northwestern Mexico, *P*/*PE* is less than about 0.25. Thus, dunes in the Chihuahuan Desert, Algodones, and Gran Desierto dune fields (**Fig. 15**) are quite active (**Fig. 18**). In the Taklimakan Desert of China, eolian sand is active over most of the dune field (**Fig. 3**) and *P*/*PE* values for stations in and around this sand sea are less than 0.2 (Wang *et al*., 2005). With these observations in mind, it can be inferred that in areas now characterized by stable dunes, past periods, represented by eolian sand, were more arid than present. In contrast, periods represented by paleosols were times that may have had a moisture balance similar to the present.

One of the remarkable observations of many North American Great Plains dune field records is the presence of multiple paleosols, all dating to the Holocene, intercalated within eolian sand (**Fig. 20**). The evidence for multiple periods of dune 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. As in the Mu Us Desert in China, the Great Plains region of North America is highly sensitive to fluctuations in the strength of a monsoonal moisture source. In central North America, the main monsoonal flow of moist air is from the Gulf of Mexico in summer. When this flow is diminished, summer precipitation is lower and

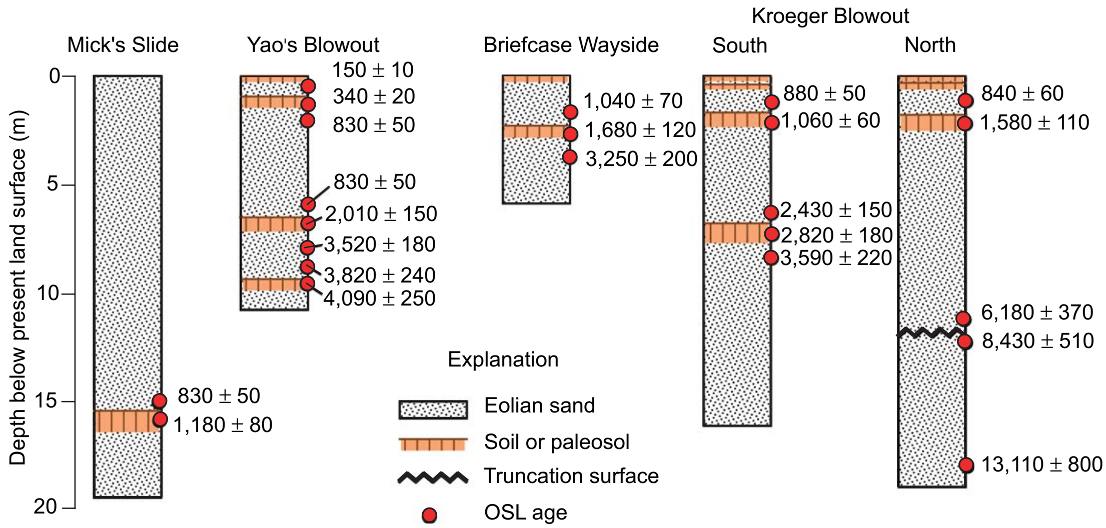

Figure 20 Stratigraphic sections showing optically stimulated luminescence (OSL) ages, in calendar years, of eolian sand in the Nebraska Sand Hills. Redrawn from Goble *et al.* (2004).

vegetation cover is reduced. Dry periods in the Great Plains are characterized not only by decreased summer monsoonal flow from the Gulf of Mexico, but also by an increase in zonal, or westerly flow of Pacific air (typically a winter pattern). Pacific air is usually dry by the time it reaches the Great Plains. Moisture in Pacific air masses is lost on north–south trending mountain ranges between the Pacific Ocean and the Great Plains (Fig. 15). Reactivation of stabilized dune sand or mobilization of new sand by wind is enhanced under conditions of reduced vegetation cover during periods of decreased monsoonal flow and increased zonal flow.

Another important application of dunes to paleoclimate studies in mid-latitude North America is wind direction inferred from dune orientation. Most of the late Holocene dunes in the midcontinent of North America are parabolic forms, which are excellent paleowind indicators. Parabolic dunes have arms that point upwind, with noses that face downwind, as seen when they are active in areas such as White Sands, New Mexico (Fig. 18). On the Great Plains of North America, orientations of many late Holocene dunes indicate northwesterly winds in Nebraska, and northern and central Colorado (Fig. 18), similar to modern, sand-moving wind regimes of fall, winter, and spring (Fig. 21). Such orientations are consistent with the scenario of increased zonal or westerly flow discussed above. Late Holocene dunes in southeastern Colorado and Kansas have orientations that indicate southwesterly paleowinds, again similar to present. However, in eastern New Mexico and western Texas, dunes have orientations that indicate northwesterly winds, whereas modern dune-forming winds are dominantly from the southwest. One explanation is that during the periods of late Holocene dune formation, there was less of an influence from southwestern (Gulf of California), monsoonal airflow, and a greater influence from zonal (westerly) circulation.

Summary

Large dune fields, or sand seas, are widespread in the interiors of continental mid-latitudes. Most of them are found in China, Central Asia, Argentina, and the United States. Mid-latitude dune fields in the United States are generally smaller than those of low latitudes, but those in China, Central Asia, and Argentina are quite large. Where climates are arid, such as in western China and Central Asia, active dunes dominate these sand seas. Other dune fields, in the semiarid climates of eastern China, Argentina, and the United States, have mostly stabilized dunes. Mid-latitude dune fields are often near mountains, which supply much of the sediment to the sand seas on a regular basis, particularly during glacial periods. Many different kinds of eolian landforms are found in mid-latitude sand seas, including transverse dunes, longitudinal (linear) dunes, star dunes, parabolic dunes, and eolian sand sheets. Where dune fields of mid-latitudes occur in semiarid climates, they are particularly sensitive indicators of shifts in climate. In China, records of dune field expansion and contraction extend back hundreds of thousands of years.

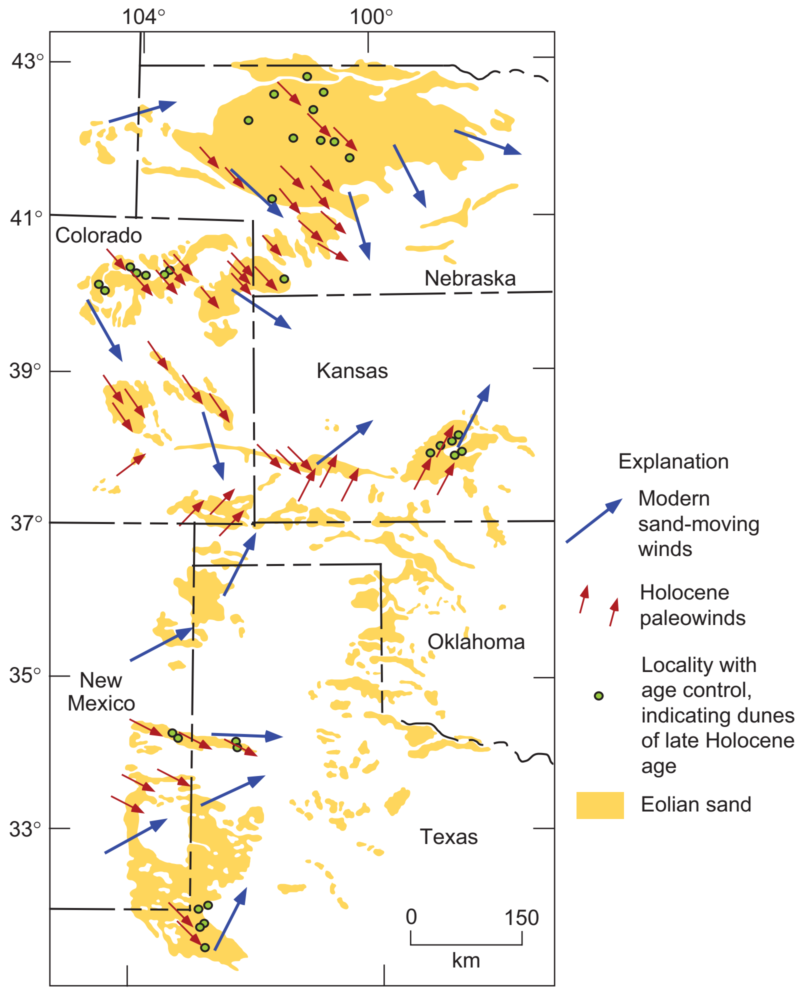

Figure 21 Map showing the distribution of eolian sand in the Great Plains, USA, direction of modern, sand-moving winds, and late Holocene paleowinds based on dune orientations (modified from Muhs and Zárate (2001)). Also shown (green circles) are localities where there are late Holocene radiocarbon or OSL ages for eolian sand. From Swinehart and Diffendal (1990), Arbogast (1996), Muhs *et al*. (1997), Holliday (2001), Goble *et al*. (2004), Forman *et al*. (2005), Madole *et al*. (2005). Modern sand-moving winds constructed using methods of Fryberger and Dean (1979).

See also: **Dune Fields**: High Latitudes; Low Latitudes. **Eolian Records, Deep-Sea Sediments**; **Loess Deposits, Origins and Properties**. **Loess Records**: Central Asia; China; North America; South America. **Luminescence Dating**: Optically-Stimulated Luminescence. **Paleosols and Wind-Blown Sediments**: Nature of Paleosols.

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Low Latitudes

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Low-latitude sand seas (also called ergs) are extensive areas of sand dunes located in the tropical and sub-tropical deserts of the world (**Fig. 1**), where they occupy as much as one-third of the area classified as arid. Major low-latitude sand seas occur in the Sahara and Arabian deserts, the Thar Desert of India, the interior of Australia, and in southern Africa (Namib and Kalahari deserts). Large sand seas are absent in the Americas, where areas of dunes cover less than 1% of the area classified as arid. Important studies and surveys of low-latitude sand seas include those by Wilson (1973) and McKee (1979). Lancaster (1999) provided a review of modern paradigms of sand sea geomorphology. Important summaries of chronologic data include Munyikwa (2005) for Southern Hemisphere sand seas, Glennie and Singhvi (2002) for Arabia, and Swezey (2001) for the Sahara.

Sand seas contain large volumes of sand (tens to hundreds of cubic kilometers) and have accumulated episodically during the Quaternary. Their construction has therefore been determined by climatic, tectonic, and sea-level changes that have affected sand supply, availability, and mobility, as well as the preservation of deposits and landforms from prior episodes of eolian construction. As significant sedimentary deposits in low-latitude desert regions, sand seas also provide an archive of the effects of climate change on these areas.

Sand seas and dune fields typically form part of well-defined regional- and local-scale sediment transport systems in which sand is moved by wind from

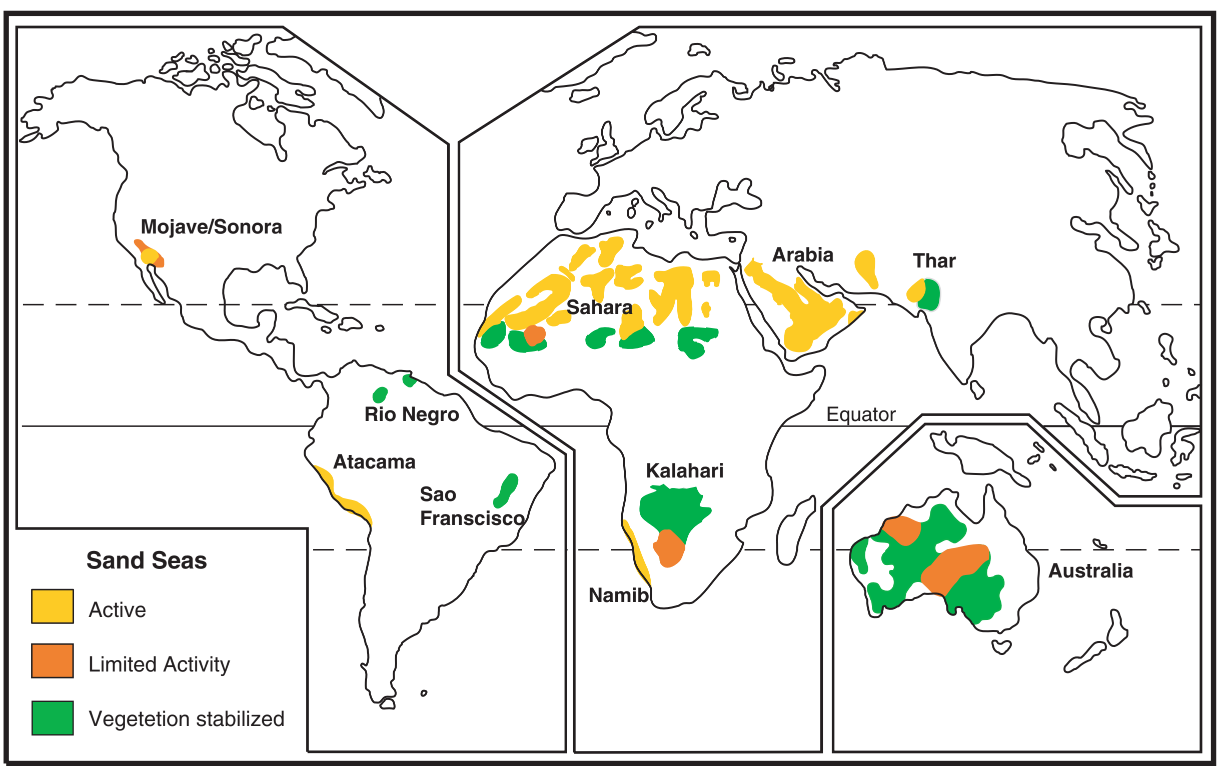

Figure 1 Distribution of major low-latitude sand seas, showing areas of active, partly active, and vegetation-stabilized dunes. For names and details of sand seas, see regional maps.

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