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Quaternary loess-paleosol sequences as examples of climate-driven sedimentary extremes

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ABSTRACT

Loess is a widespread, wind-transported, silt-dominated deposit that contains geologic archives of atmospheric circulation and paleoclimate on continents. Loess may cover as much as 10% of the Earth's land surface. It is composed mainly of quartz, feldspars, and clay minerals, with varying amounts of carbonate minerals. The geochemistry of loess differs from region to region, depending on source materials, but all loess is very high in SiO_2 with lesser amounts of other major elements. Trends in loess downwind from source areas include systematic decreases in thickness and amounts of sand and coarse silt, and increases in amounts of fine silt and clay. Loess particle size also varies at a given locality over time within individual depositional packages. This variability may be a function of changing wind strengths, different source sediments, or some combination of the two.

The classical concept of loess is that it is a product of glacial grinding, with subsequent entrainment by wind from outwash deposits. However, it is now known that other processes contribute to silt particle formation, including frost shattering, salt weathering, fluvial and colluvial comminution, eolian abrasion, and ballistic impact. Much debate has taken place over the concept of "desert" (nonglaciogenic) loess, which is widespread in some regions but of limited distribution elsewhere. Nevertheless, glacial silt production probably exceeds the amount of silt generated by all other processes. Much of the loess in or adjacent to deserts may be inherited silt-sized particles from siltstone, mudstone, shale, and volcanic ash.

In many regions, loess is near dune fields or eolian sand sheets. A question that arises from this geographic assocation is whether or not eolian sand and loess should be considered facies of the same depositional unit. There are regions such as China where these deposits are interbedded, which supports the facies concept. In other regions, such as North America, detailed geochemical and isotopic analyses show that the majority of loess particles were derived from a different, and more distant source than eolian sand.

Key to understanding loess stratigraphy and interpreting environments of the past is the recognition of buried soils (paleosols). Ancient soils can be recognized by their distinctive morphological features and by vertical changes in particle size, chemistry, and mineralogy. Paleosols represent past periods when loess sedimentation rates decreased to zero or slowed significantly. Thus, loess and their interstratified soils represent end members of a continuum of sedimentary extremes: high rates of sedimentation yield relatively unaltered loess in the stratigraphic record, whereas low or

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episodic rates of sedimentation commonly leave a record of buried soils. The shift between these sedimentary extremes is preserved in the long-term glacial-interglacial record of the Quaternary.

Although it is now known that not all eolian silt is glaciogenic, in almost all loess regions, eolian sedimentation rates were much higher during glacial periods than during interglacial periods. Drier, colder climates, a decreased intensity of the hydrologic cycle, stronger or more-persistent winds, increased sediment supply, decreased vegetation cover, and increased sediment availability all probably contributed to the sedimentary "extreme" of rapid loess accumulation during the last glacial period. The present interglacial period represents an opposite sedimentary "extreme" of minimal loess sedimentation and is characterized primarily by soil formation within loess deposits of last glacial age.

Keywords: loess, eolian, Quaternary, paleosols, paleoclimate, climate extremes, glacial-interglacial cycles.

INTRODUCTION

Loess is an important archive of Quaternary climate changes, and may have one of the most complete terrestrial records of interglacial-glacial cycles (e.g., Kukla et al.,1988; Hovan et al., 1989; Porter and An, 1995; Porter, 2001; Palmer and Pillans, 1996; Muhs et al., 1999a). Because loess is deposited from the atmosphere, it is also one of the few geologic deposits that directly records atmospheric circulation and can be used to test atmospheric general circulation models (e.g., Muhs and Bettis, 2000). Furthermore, airborne dust itself may be significant in bringing about climate change through its radiative transfer properties or through its role in the fertilization of primary producers in the world's oceans. Loess records hold promise for evaluating the role of dust in climate change (Tegan et al., 1996; Mahowald et al., 1999; Kohfeld and Harrison, 2000, 2001; Harrison et al., 2001). Finally, there has been an increasing recognition that loess, in the form of loessite, may be a more common part of the sedimentary rock record than previously supposed (Johnson, 1989; Soreghan, 1992; Chan, 1999).

In this paper, we review recent studies that report the composition of loess, its origins, and its paleoclimatic significance. Because loess covers a significant portion of the Earth's surface, it is an important part of Quaternary geologic and climatic records. Loess is also the surficial deposit on which millions of humans live, and it forms the parent material for some of the world's most productive agricultural soils. The history of loess studies was recently reviewed by Smalley et al. (2001). In this paper, we concentrate on issues regarding loess origins and its paleoclimatic importance. We present data to show that loess-paleosol sequences in the Quaternary geologic record represent good examples of sedimentary extremes. By sedimentary "extremes" we mean periods of unusually high or low rates of eolian silt sedimentation. We attempt to show that in the Quaternary geologic record, the stratigraphic sequences of loesses and paleosols represent sedimentary extremes that are largely climate-controlled, either directly or indirectly.

DEFINITION OF LOESS

Loess is often perceived as a rather homogenous deposit that has considerable similarity from continent to continent. It is surprising, therefore, how much variation there is in various workers' definitions of loess. Smalley and Smalley (1983) defined loess in terms of process and considered four mechanisms to be a part of its formation: (1) loess-sized material (20–60 μm) forms, (2) the material is transported by the wind, (3) the sediment is deposited, and (4) the sediment experiences post-depositional changes. Pésci (1990) listed 10 characteristics that, in his view, define loess. These include the following: loess is wind-deposited, homogenous, porous, permeable, pale-yellow, predominantly coarse silt (10–50 μm) with small amounts of fine silt and clay, dominantly quartz with some feldspars and carbonate, usually unstratified (but contains paleosols), slightly cemented, stable when dry, easily eroded when wet, and contains fossil flora and fauna. Pésci (1990) and other investigators have referred to post-depositional compaction and minor diagenetic cementation of loess particles by carbonate as an important process of "loessification." Many European workers feel that this is a key process that defines loess as a sedimentary body. We think that the concept of "loessification" is unnecessarily restrictive. Although minor cementation does occur in many calcareous loess bodies, other loesses (such as those in Alaska and New Zealand) do not contain carbonates and are not cemented. However, few workers would disagree that the eolian silts in these two regions should be called loess. Pye (1987) defines loess simply as a terrestrial, windblown silt consisting chiefly of quartz, feldspar, mica, clay minerals, and carbonate grains in varying proportions.

Despite the differences apparent in these workers' views, common to all definitions are two factors: loess is wind-deposited and is dominated by silt-sized particles. Pye's (1987) definition is the one we adopt here, with the modification that many loesses, such as most of those in Alaska and New Zealand, do not contain carbonates. We consider loess to be any terrestrial, wind-deposited sediment dominated by silt-sized particles, whether calcareous or not. Thus, eolian sediments in the deep-sea record are excluded in this definition, although they may have an origin common with some loess deposits (e.g., Hovan et al., 1989). A corollary definition we present here is that loess is an eolian silt of sufficient thickness that it is recognizable as a sedimentary body in the field.

GEOGRAPHY OF LOESS

Compilation of loess maps worldwide shows that wind-blown silt covers a significant amount of the Earth's land surface, perhaps as much as 10% (Figs. 1–4). In the western hemisphere, loess is present in both North and South America (Fig. 1). In South America, there are two major loess belts, the Pampas loess in central Argentina and the Chaco loess in northern Argentina and Paraguay. Although the distribution of loess in South America appears at small scale to be continuous, the compositions of these two named loess bodies are distinct. The different origins for South American loesses were reviewed recently by Muhs and Zárate (2001). In North America, there are five distinct areas of loess: (1) extensive but discontinuous bodies of loess in Alaska and adjacent Yukon Territory, (2) the Palouse loess of eastern Washington and adjacent Oregon, (3) the Snake River Plain and adjacent uplands of Idaho, (4) the Great Plains region of the midcontinent, and (5) the central lowlands region of the midcontinent. As with the Pampas and Chaco region loess bodies of South America, the Great Plains (Nebraska, Kansas, and Colorado) and central lowlands (Missouri, Iowa, Illinois, Indiana, and areas to the north and south) loesses of the North American midcontinent appear to be continuous at small scale (Fig. 1). At a larger scale (Fig. 2), it is apparent that these loess bodies have very different thickness trends that are not part of a larger regional trend, and as will be shown, Great Plains and central lowlands loesses have different origins. Loess is not present in Canada except in small, isolated patches because most areas were covered by the Laurentide ice sheet at the most recent times of eolian silt deposition in North America. As the Laurentide ice sheet receded, glaciogenic silt became available, but in much of eastern and central Canada, this silt was deposited in proglacial lakes rather than entrained by the wind and deposited as loess (Flint, 1971). In fact, the termination of loess deposition farther south in the midcontinent may be, in part, the result of this silt deposition in proglacial lakes. Thick (>1 m) loess has not been reported in Mexico or most parts of the southwestern United States, and its absence in those regions has significance for the origin of loess.

In the eastern hemisphere, loess is abundant over much of Eurasia (Fig. 3). Most loess in Eurasia is distributed in a latitudinal belt between about 40° and 60°N, covering areas south of the limits of continental or mountain glaciers of Quaternary age. An important exception is China (Fig. 4), where loess covers large areas at lower latitudes that were not close to either continental or mountain glaciers. Loess is largely absent from the subtropical and tropical latitudes of Eurasia.

Loess is not extensive over Africa, nor is it widespread in adjacent subtropical parts of the Middle East. There are, however, well-documented but geographically limited loess deposits in Tunisia, Libya, Nigeria, Namibia, and Israel (e.g., Bruins and Yaalon, 1979; McTainsh, 1987). Loess is also largely absent in Australia, although there are limited occurrences of clay-rich eolian deposits termed *parna* that some workers interpret as essentially a clay-rich loess (Butler, 1974). However, loess is widespread over much of New Zealand, where it has been studied in considerable detail (Palmer and Pillans, 1996; Graham et al., 2001).

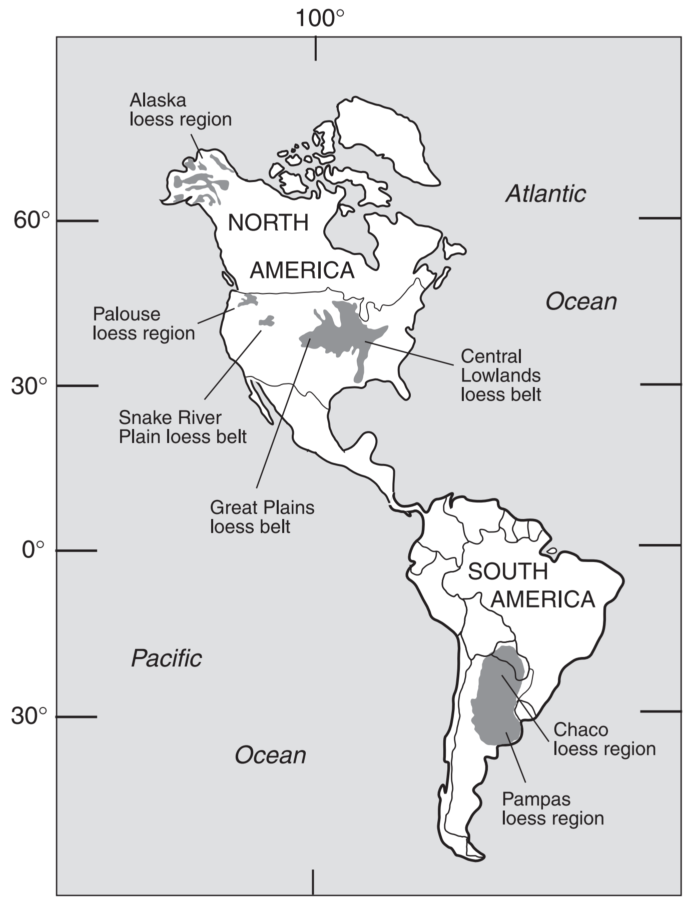

Figure 1. Map showing the distribution of loess in North America and South America and names of loess belts used in this paper. Loess distribution from compilation in Muhs and Zárate (2001) and sources therein.

SEDIMENTOLOGY OF LOESS

Although loess is silt-dominated by all definitions, there is a surprising range of particle size distributions reported, even within the same sedimentary body. Mean particle sizes for loess vary from coarse silt to fine silt, and individual loess bodies span this entire range (Fig. 5). Variation in loess particle size can occur either spatially or temporally. In China, for example, loess in the northwesternmost part of the Loess Plateau is described as "sandy" and has a mean particle size between about 4.75–5.0 phi (37–31 microns). At the southeastern por-

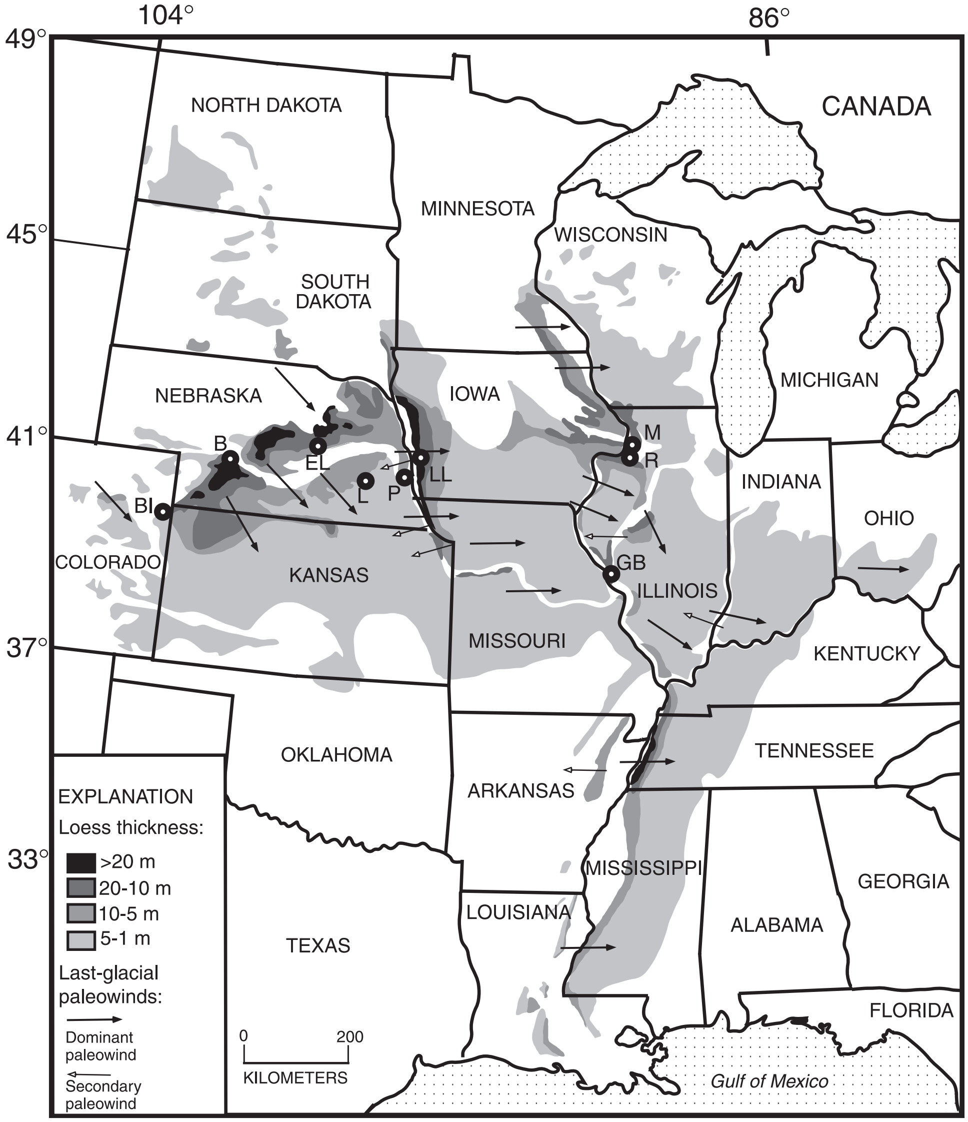

Figure 2. Map showing distribution and thickness of loess in central North America and stratigraphic sections referred to in text. Loess distribution from compilation by Bettis et al. (2003). Arrows indicate inferred paleowinds based on loess thickness, particle size trends, and other data (see compilation by Muhs and Bettis, 2000). Stratigraphic sections referred to in text: BI—Beecher Island; B—Bignell Hill; EL—Elba; L—Lincoln; P—Plattsmouth; LL—Loveland; M—Morrison; R—Rapid City; GB—Greenbay Hollow.

tion of this loess body, what is referred to as "clayey" loess has a mean particle size of about 6 phi (15–16 microns). Standard deviations of loess can have a range of several phi units within a loess body, as illustrated by the range for loess in the Yakutia region of Russia and to a lesser degree by the loess of eastern Colorado in central North America. The wide range of mean particle size and relatively poor sorting in a loess body compared to eolian sand can be the result of (1) multiple sources, (2) clay-sized particles being transported as silt-sized aggregates, (3) loess bodies extending considerable distances from their sources, or (4) varying wind strengths over time. It is apparent from the data in Figure 5 that eolian sands and loesses are distinctively different in terms of their sedimentological properties, as there is neither overlap in mean particle size nor much in degree of sorting. This distinction is important for understanding the origin of loess, which we discuss later.

Numerous workers have shown that a wide variety of loess sedimentological parameters show strong distance-decay functions away from probable sources. Smith (1942) and Ruhe (1983) summarize many of the trends for North American loess bodies, and Porter (2001) shows similar trends for Chinese loess. Loess thickness, mean particle size, sand content, and coarse silt content all decrease away from a source while fine silt and clay contents increase away from a source (Figs. 2 and 6). The decrease in overall loess thickness reflects a net decrease in the sediment load away from the source, at least when vegetation cover is sufficient to trap particles (Tsoar and Pye, 1987). The decrease in sand and coarse silt contents and increase in fine silt and clay contents reflect a winnowing of the coarse load away from the source.

Loess also shows particle size variations at individual localities, even within the same depositional package. In China, Porter and An (1995) showed that mean diameters of the quartz fraction

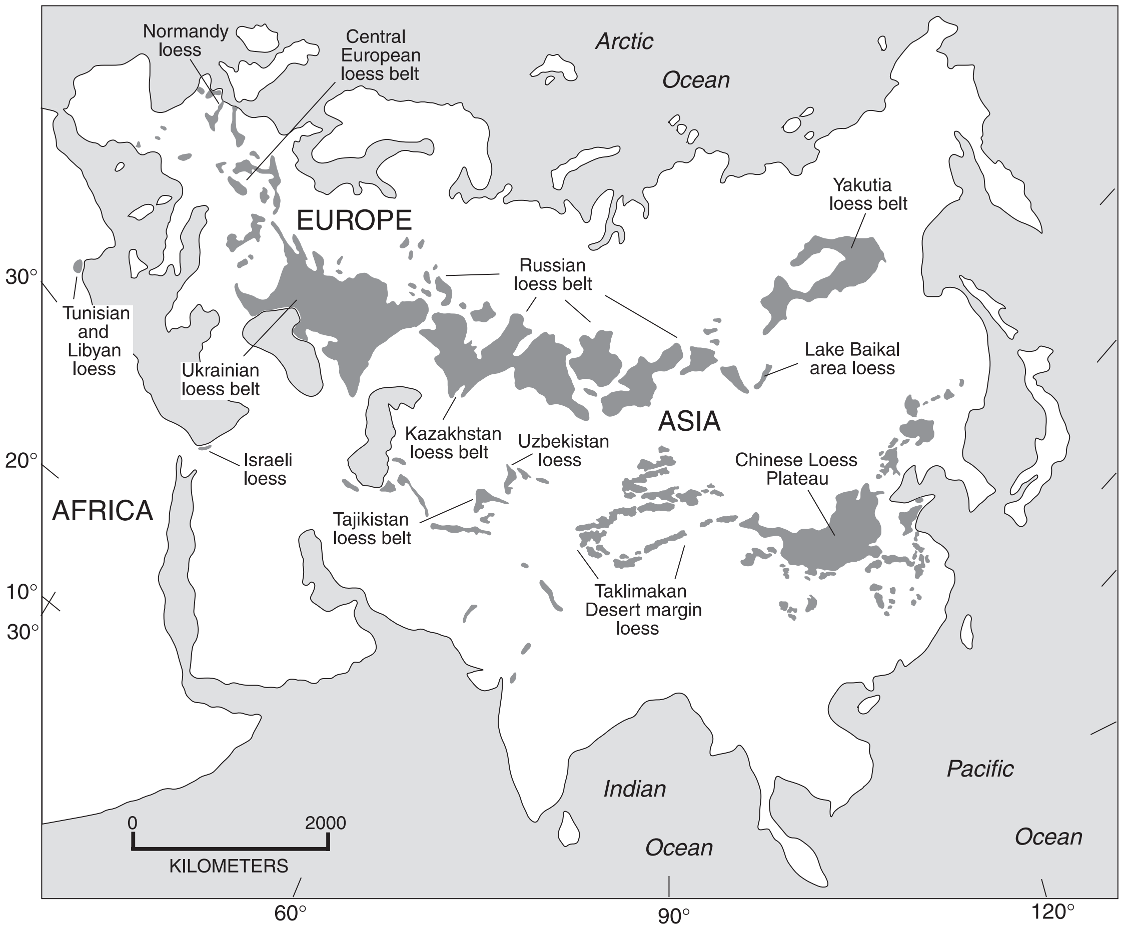

Figure 3. Map showing distribution of loess in Eurasia and localities or regions referred to in text. Compiled by the authors from Rozycki (1991) and Liu (1985).

in loess varied significantly over the last glacial period (Fig. 7). They interpret these data to indicate varying wind strengths over the period of loess deposition. In other regions, loess particle size variability has been interpreted to indicate changing loess sources over time. For example, at a locality in North America (Loveland, Iowa; see Fig. 2), Muhs and Bettis (2000) demonstrated that last-glacial-age (Peoria) loess, which is ~40 m thick, has three distinct zones based on particle size distribution. The differentiation of the upper two zones at Loveland, Iowa, is interpreted to be a function of changing dominance by two sources, the nearby Missouri River and distant Great Plains.

GEOCHEMISTRY OF LOESS

There are now many data available on loess geochemistry that yield important information about loess mineralogy and origins. In all loesses, the dominant constituent is SiO_2, which ranges from ~45% to 75%, but is typically 55–65%. Plots of SiO_2 versus Al_2O_3 (Fig. 8) show that most loess has a composition that falls close to the range of average upper crustal rock (Taylor and McLennan, 1985). Mineralogical studies show that the high SiO_2 contents of loess reflect a dominance of quartz, but smaller amounts of feldspars and clay minerals also contribute to this value. Most loesses also fall between fields spanning the average composition of shales and quartz-dominated sandstones. Sandstones, particularly quartz arenites, are very high in SiO_2 whereas shales are clay-dominated and are therefore high in Al_2O_3. An exception to these generalizations is shown by the highly variable composition of loesses from the North Island of New Zealand, near Wanganui (Graham et al., 2001). Amounts of SiO_2 in these loesses range from 40% to 50% to greater than 70%, a range that spans compositions from basalt to granite and shows little relation to a continuum from shale to sandstone. It seems likely that the loesses in this region had sources that ranged in composition from highly mafic to highly felsic and that the relative amount of sediment from these sources changed over time.

Although most loesses have a composition between that of shale and sandstone, loesses from different localities nevertheless show considerable variation in composition. Plots of complimentary element pairs that represent the non-quartz mineral fractions

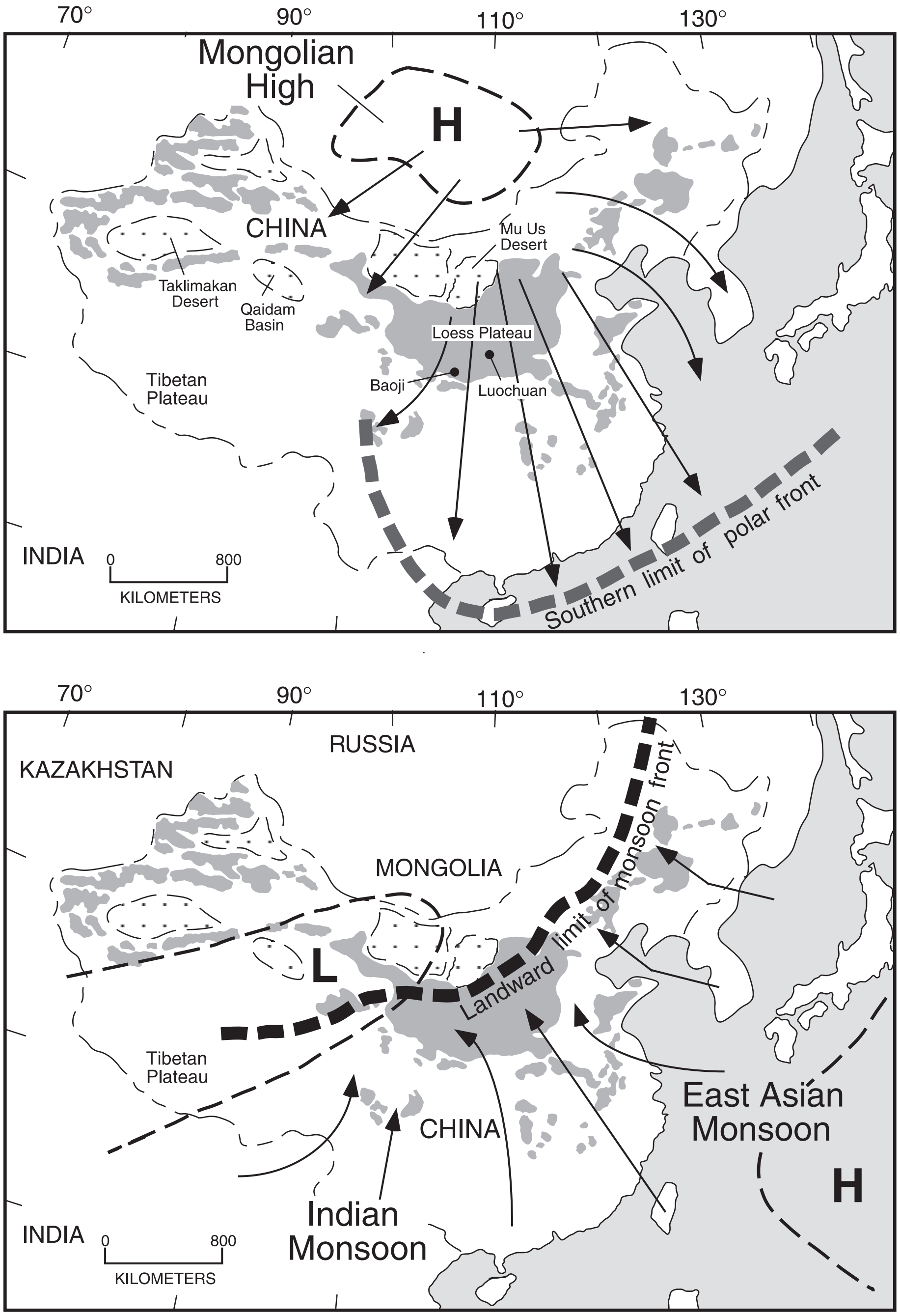

Figure 4. Distribution of loess (shaded areas), sandy deserts (dotted areas), localities referred to in text, and synoptic climatology of China during winter (upper diagram) and summer (lower diagram) showing pressure systems and dominant surface winds (arrows). Climatic data from Porter and An (1995); loess distribution from Liu (1985).

are particularly revealing in this regard because they define geochemical fields that are distinctive for each loess body (Fig. 9). North American (Illinois) loess derived from outwash of the Laurentide ice sheet has abundant carbonate minerals, particularly dolomite (McKay, 1979; Grimley et al., 1998). Thus, compared to Russian or Chinese loesses, MgO contents in Illinois loesses are high. In contrast, Russian and Chinese loesses have greater amounts of silt-sized feldspars and micas, represented by Na_2O and K_2O, and clay minerals, represented by Al_2O_3 and Fe_2O_3, compared to loess from Illinois.

LOESS ORIGINS: PROCESSES OF SILT PARTICLE PRODUCTION

"Glacial" versus "Desert" Loess

A common and probably oversimplified view is that silt-sized particles in loess are produced almost exclusively by glacial grinding, deposited in till, reworked by fluvial processes as outwash, and finally entrained and deposited by wind (Fig. 10). This classical model of loess formation has led to the view that

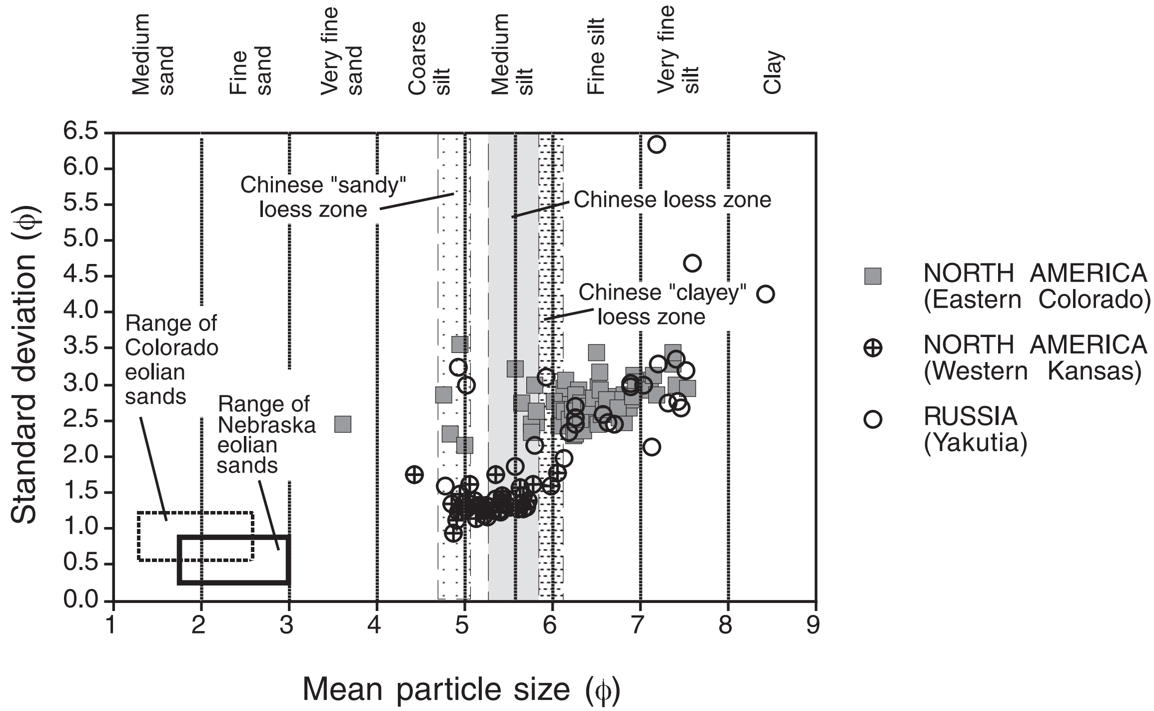

Figure 5. Mean particle size and standard deviation (sorting) of North American, Chinese, and Russian loesses. Shown for comparison are ranges of these parameters for eolian sands in North America (Nebraska and Colorado). Chinese loess data from Liu (1985); Russian loess data from Péwé and Journaux (1983); Kansas loess data from Swineford and Frye (1951); Colorado loess data from Muhs et al. (1999b). Ranges of Nebraska eolian sand data from Ahlbrandt and Fryberger (1980); Colorado eolian sand data from Muhs et al. (1999a).

loess deposits are primarily markers of glacial periods, because no significant mechanism of silt particle formation existed during interglacial periods. The model is reinforced by observations of the geographic proximity of loess bodies to the southern limits of the Laurentide Ice Sheet in North America and the Fennoscandian Ice Sheet in Europe, as well as smaller glaciers in Asia and South America. In the 1950s and 1960s, widespread application of radiocarbon dating showed that the youngest loess deposits in North America coincided with the ages of the last major expansion of the Laurentide Ice Sheet (see summaries in Willman and Frye, 1970, and Ruhe, 1983).

There is little question that silt is produced by glacial grinding. In North America, tills in Canada and the United States that were deposited by the Laurentide and Cordilleran Ice Sheets have abundant silt, based on hundreds of careful and detailed particle size analyses. In North America, for example, tills of last-glacial age have, on average, silt contents of ~40% (Willman and Frye, 1970; Kemmis et al., 1981; Clague, 1989). Outwash deposits derived from modern glaciers also contain much silt. In areas of active glaciers, rivers draining glacierized valleys have abundant silt-sized particles in suspension that give the waters a distinctive milky appearance; we have observed this in the Alaska Range and Chugach Mountains; Canadian Rockies; French and Swiss Alps; and Vatnajökull and Myrdalsjökull, Iceland. Detailed studies in Alaska by Hallet et al. (1996) show that sediment yields in rivers are up to an order of magnitude higher in glacierized basins than in those that are not. In glacierized areas of Alaska and Iceland, we have observed spectacular dust storms derived from silt-rich outwash plains and valleys.

Despite the abundance of geological, geographical, and geochronological support for the classical "glacial" concept of loess formation, there have been challenges to this model for at least 50 years (see Thorp, 1945, *in* Bryan, 1945) and perhaps longer (Smalley et al., 2001). The debate has continued to this day and centers on the issue of "glacial" loess versus "desert" loess. "Desert" loess is a term used loosely to describe eolian silt generated in and derived from arid or semiarid regions that were not glaciated. We feel that "glacial loess" and "desert loess" are terms that are inappropriate for what is probably a complex of processes, some of which are common to both environments. Nevertheless, we have retained their usage in this review simply because the terms have been used in loess origin debates for more than half a century and it is convenient for reference to the abundant literature on the issue (Bryan, 1945; Smalley and Krinsley, 1978; Whalley et al., 1982; Tsoar and Pye, 1987; Wright, 2001a, 2001b).

The debate on desert loess versus glacial loess centers on whether silt-sized particles can be produced by mechanisms other than glacial grinding and whether they can be produced in hot

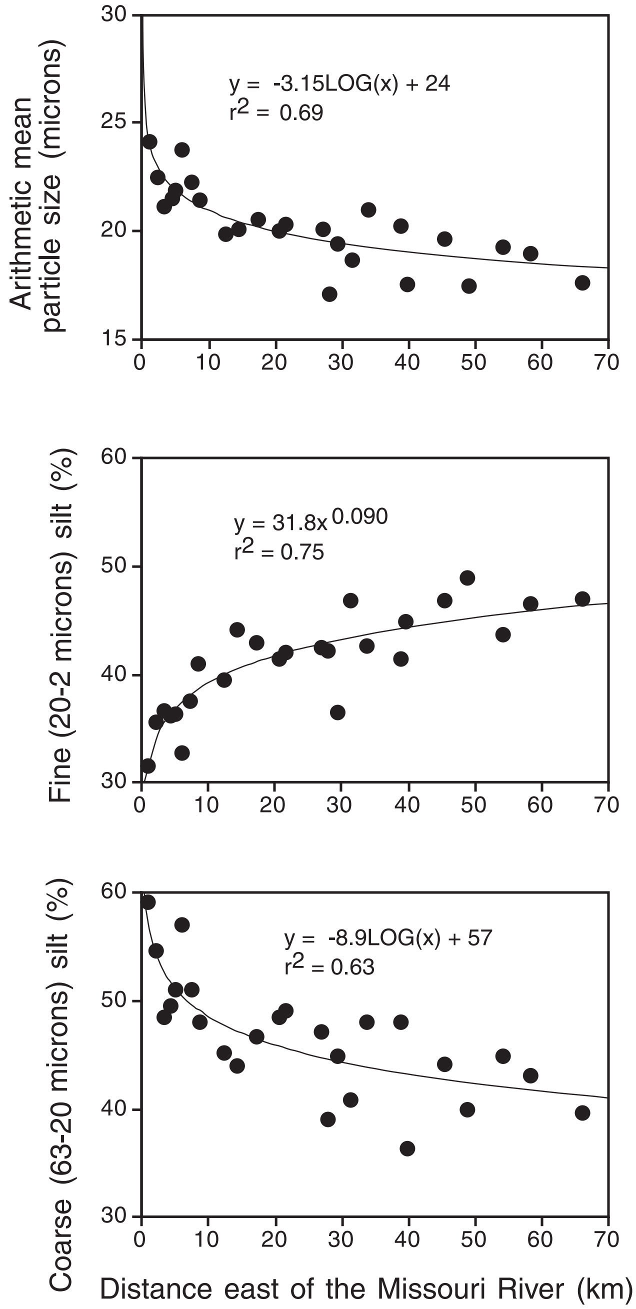

Figure 6. Mean particle diameter, coarse-silt (63–20 μm) content, and fine silt (20–2 μm) content in last-glacial-age loess as a function of distance east of Missouri River bluffline in western Iowa. Particle size data are derived from previously unpublished sedigraph analyses of the authors; sample localities are identical to those in Muhs and Bettis (2000).

deserts. A variety of mechanisms can, in principle, produce silt-sized particles in arid regions; we have summarized these in a highly simplified model (Fig. 11). Processes of silt production that have been proposed for arid regions (or the mountainous areas adjacent to them) include frost shattering (Wright et al., 1998), colluvial and fluvial comminution (Wright and Smith, 1993; Wright, 1995; Derbyshire et al., 1998), salt weathering (Goudie et al., 1979; Wright et al., 1998), eolian abrasion (Whalley et al., 1982; Wright et al., 1998), and ballistic impacts (Dutta et al., 1993). Experimental studies, many of them conducted in laboratory settings by J.S. Wright and summarized by her (Wright, 2001b), show that frost weathering, salt weathering, fluvial comminution, and eolian abrasion can all produce silt-sized particles. An important follow-up question, then, is: if silt *can* be produced in deserts, *has* sufficient silt been generated in deserts to produce loess deposits? A first step toward answering the question of desert loess formation is to determine simply whether there are loess deposits adjacent to deserts.

Desert Loess in China

The region that has been cited most often with regard to desert loess is China. Thorp (1945, in Bryan, 1945) was one of the first North American scientists to point out that nearby deserts could be the sources of thick loess deposits in China. Studies of loess in China have accelerated in the past couple of decades, particularly since the publication of Liu's (1985) excellent synthesis of loess studies in this region. On the basis of modern dust storm observations, geochemical and isotopic provenance studies, and loess thickness and particle size trends, most workers now agree that the desert basins of China and Mongolia (Fig. 4) are the immediate sources of loess in China (Liu, 1985; Liu et al., 1994; Derbyshire et al., 1998; Porter, 2001). Nevertheless, a question that has been debated intensively is whether the silt-sized sediments in the desert basins owe their origin to processes operating within the basin itself or whether they were formed by glacial grinding in nearby mountain ranges. Smalley and Krinsley (1978) proposed that much of the silt in Chinese loess was produced by glacial grinding in mountain ranges rimming the desert basins. Derbyshire (1983) challenged this interpretation by pointing out that glaciation in the mountains of northern and western China was of limited extent and that tills derived from these mountains are not particularly silt-rich. He suggested instead that much of the silt in Chinese loess was produced by salt weathering and frost shattering, either in the desert basins themselves or in the nearby mountains. Wright (2001a) reiterated Derbyshire's (1983) arguments against a glacial origin for Chinese loess and agreed that salt weathering and frost shattering in the desert basins are important processes of silt particle formation. Furthermore, she suggested that chemical weathering, fluvial comminution, and eolian abrasion have all been important processes in Chinese silt particle formation.

It is important to point out that Smalley and Krinsley (1978), Derbyshire (1983), and Wright (2001a) do not provide much in the way of quantitative field data to support their arguments. For example, although Derbyshire (1983) describes the tills of the Tian Shan as silt-poor, he gives no particle size data to support this statement. Smalley and Krinsley (1978), on the other hand, provide no maps of the extent of the glaciers that they propose

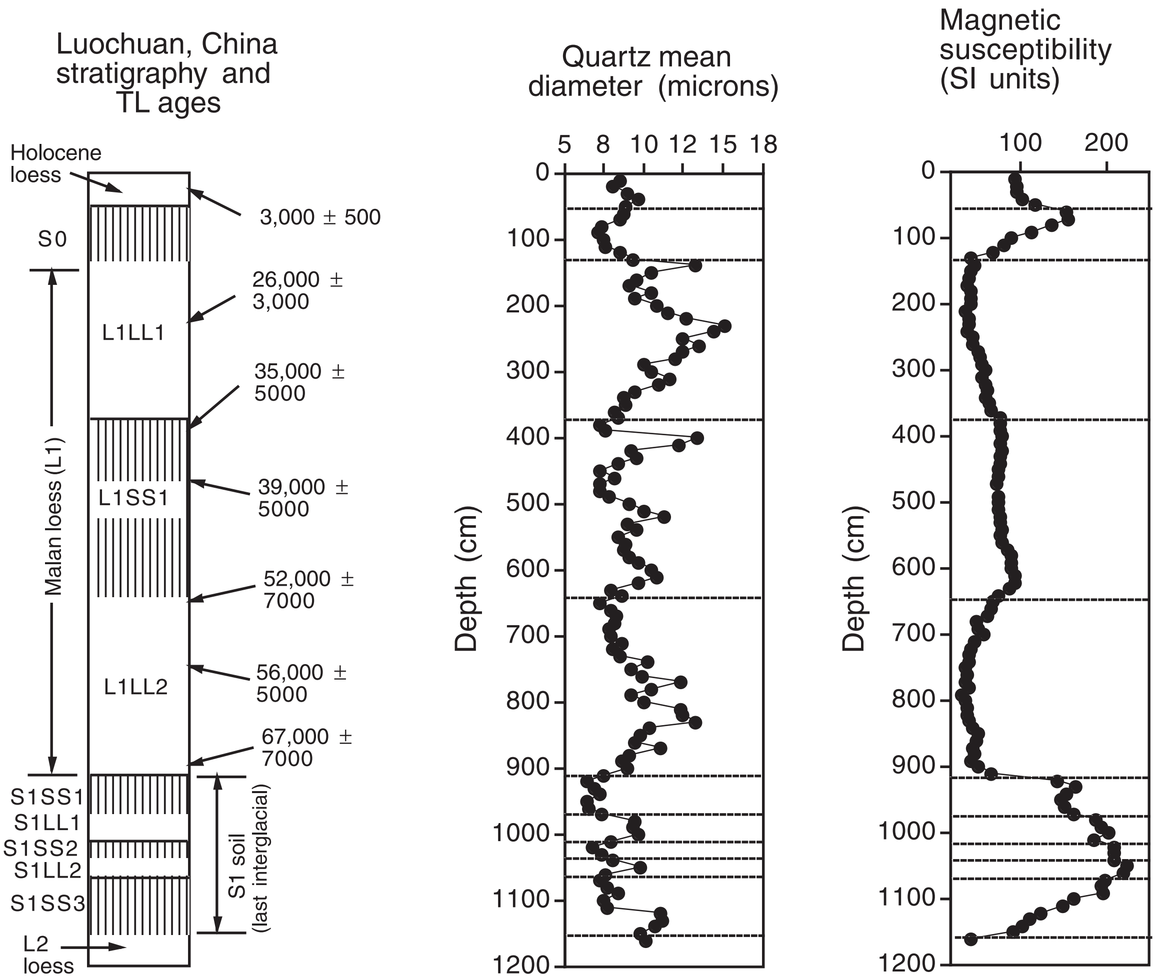

Figure 7. Stratigraphy, thermoluminescence (TL) ages, quartz mean diameter, and magnetic susceptibility of loess and paleosols over the last interglacial-glacial cycle at Luochuan, China. Loess units indicated by "L" prefix; paleosols indicated by "S" prefix. Stratigraphy, quartz mean diameter, and magnetic susceptibility data from An et al. (1991), Porter and An (1995), and Xiao et al. (1995, 1999); TL data from Forman (1991).

generated the silt. More research needs to be conducted on Chinese loess and possible source sediments that might help answer the question of silt particle formation in this important region. We feel it is premature to debate the efficacy of silt particle formation in the Chinese desert basins as a source of loess and to make paleoclimatic interpretations when the sediments in those basins and in the mountains surrounding them have not been adequately characterized.

Desert Loess in North America, Africa, and Australia

The largest area of dominantly non-glacial loess in North America is the semiarid Great Plains region of Nebraska, Kansas, and Colorado (Fig. 2). During the last glacial period, most of this region was upwind and upstream of the Laurentide Ice Sheet and the rivers that drained it. Detailed isotopic analyses indicate that loess in Colorado and Nebraska is probably derived mostly from volcaniclastic siltstones of the Tertiary White River Group, with small contributions from Rocky Mountain glaciers (Aleinikoff et al., 1998, 1999). Despite the dominantly non-glacial source sediment, loess of last-glacial age in the Great Plains is as much as 48 m thick (Maat and Johnson, 1996).

Other arid and semiarid regions in the world show evidence of only modest silt production and little evidence of loess formation along their margins. Elsewhere in North America, thick loess deposits have not been reported in desert regions of the southwestern United States and Mexico, although silt-dominated eolian mantles less than one meter thick have been described (Muhs, 1983; McFadden et al, 1986; Reheis et al., 1995). A detailed study with good stratigraphic control has shown that dust fluxes were greater during the last glacial period than during the Holocene in the Mojave Desert of the southwestern United States

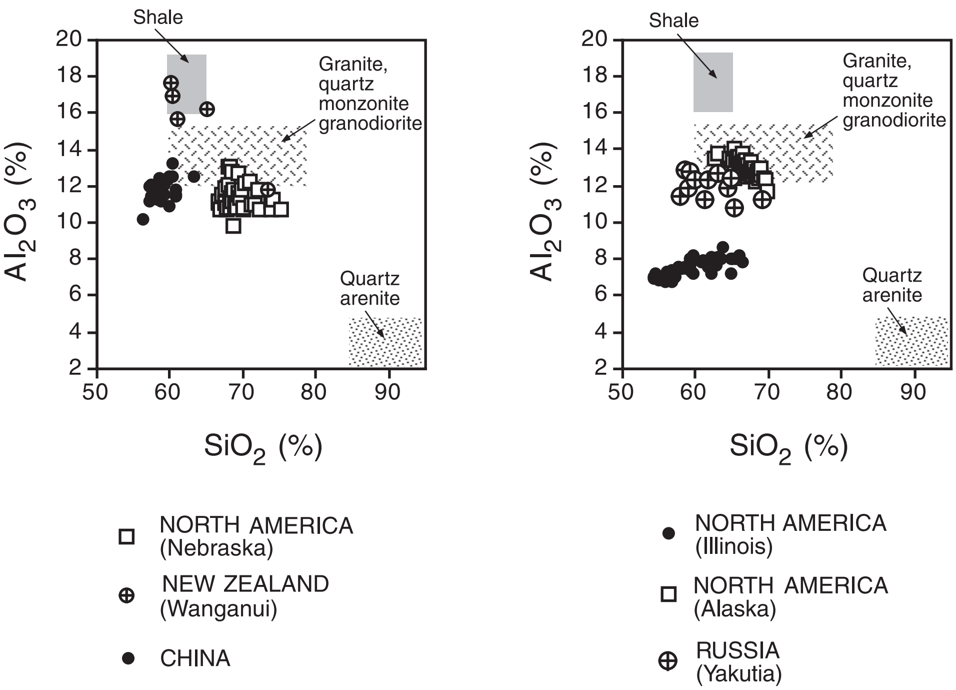

Figure 8. Plots of SiO_2 and Al_2O_3 concentrations in North American (Alaska, Illinois, and Nebraska) loess compared to similar data for loess in New Zealand (Wanganui), Russia (Yakutia), and China (Luochuan area). Illinois localities are Morrison and Rapid City; Nebraska localities are Elba, Lincoln, and Plattsmouth (Fig. 2). North American loess data from Muhs and Bettis (2000) and Muhs et al. (2001, 2003); New Zealand data from Graham et al. (2001); Russian loess data from Péwé and Journaux (1983); Chinese loess data from Gallet et al. (1996) and Jahn et al. (2001). Ranges of values in shale from Condie (1993); ranges of values in quartz arenite from Pettijohn et al. (1972).

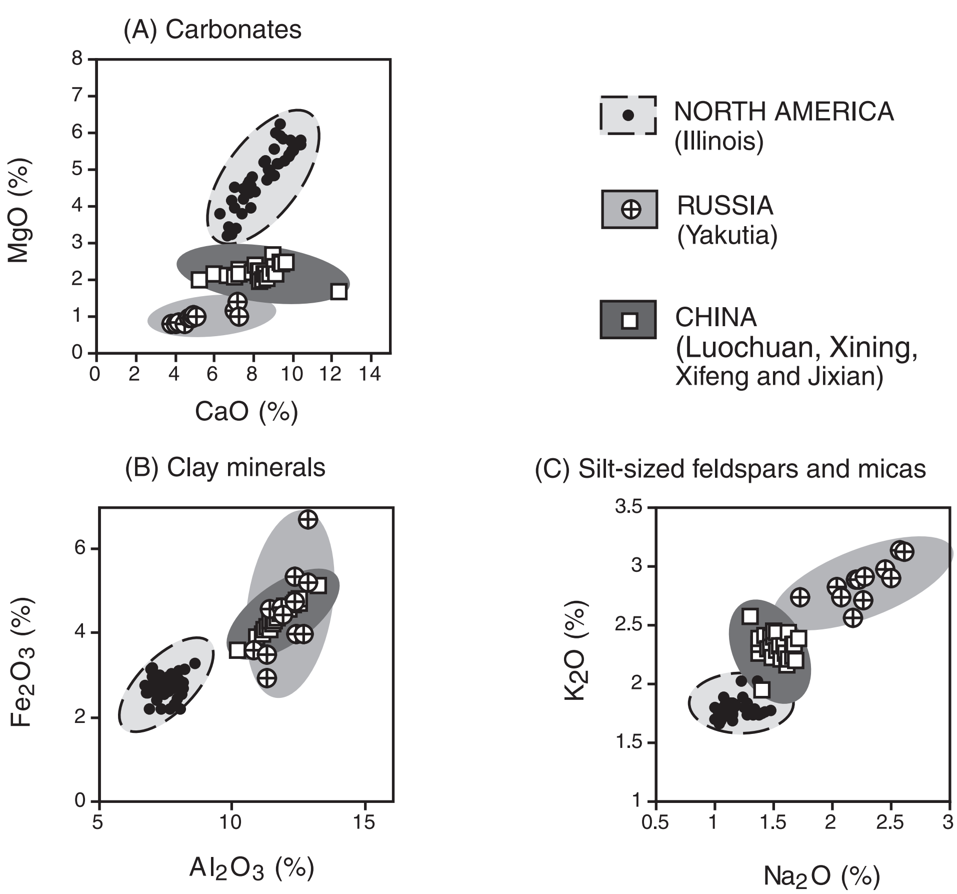

Figure 9. Plots of element pairs (A) CaO-MgO, (B) Al_2O_3-Fe_2O_3, and (C) K_2O-Na_2O that reflect the relative abundances of (A) carbonates, (B) clay minerals, and (C) silt-sized feldspars and micas in loess from various regions. Data sources as in Figure 8.

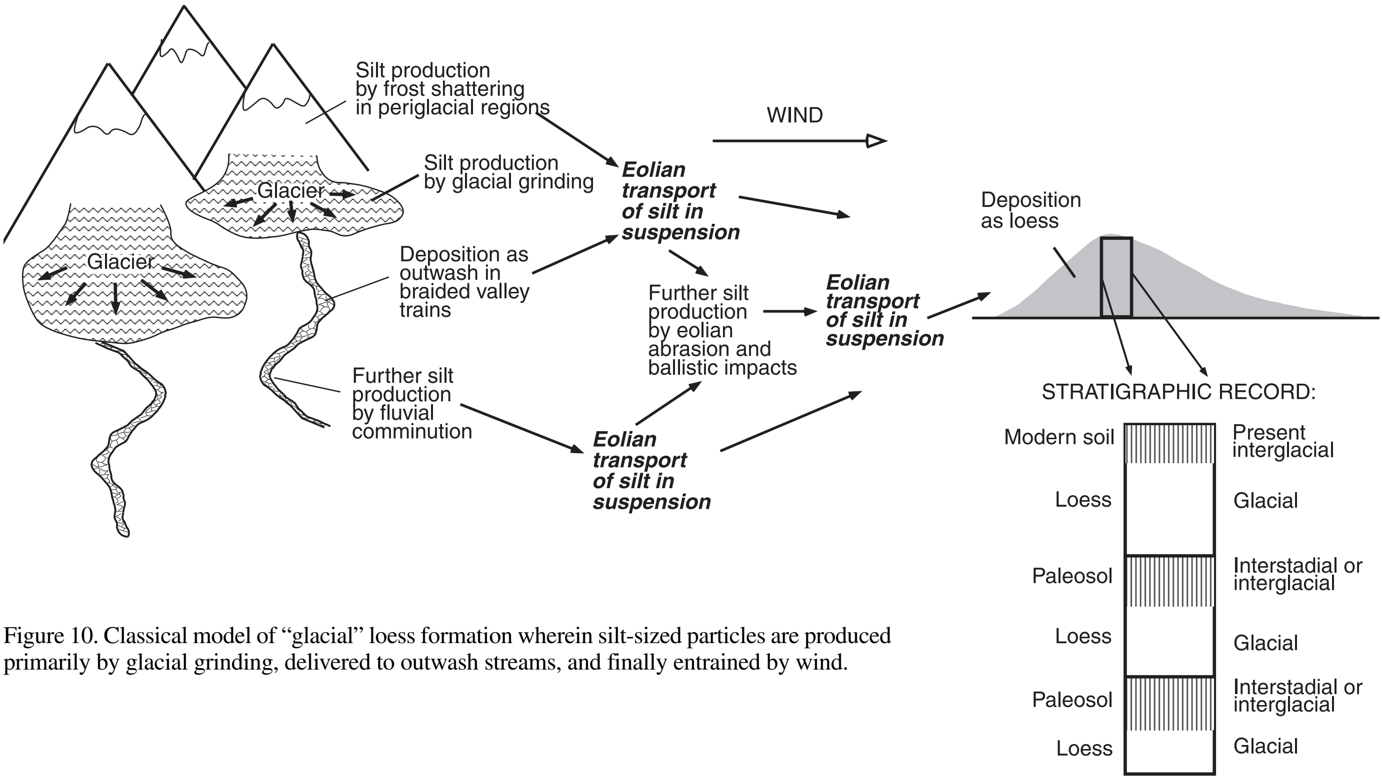

Figure 10. Classical model of "glacial" loess formation wherein silt-sized particles are produced primarily by glacial grinding, delivered to outwash streams, and finally entrained by wind.

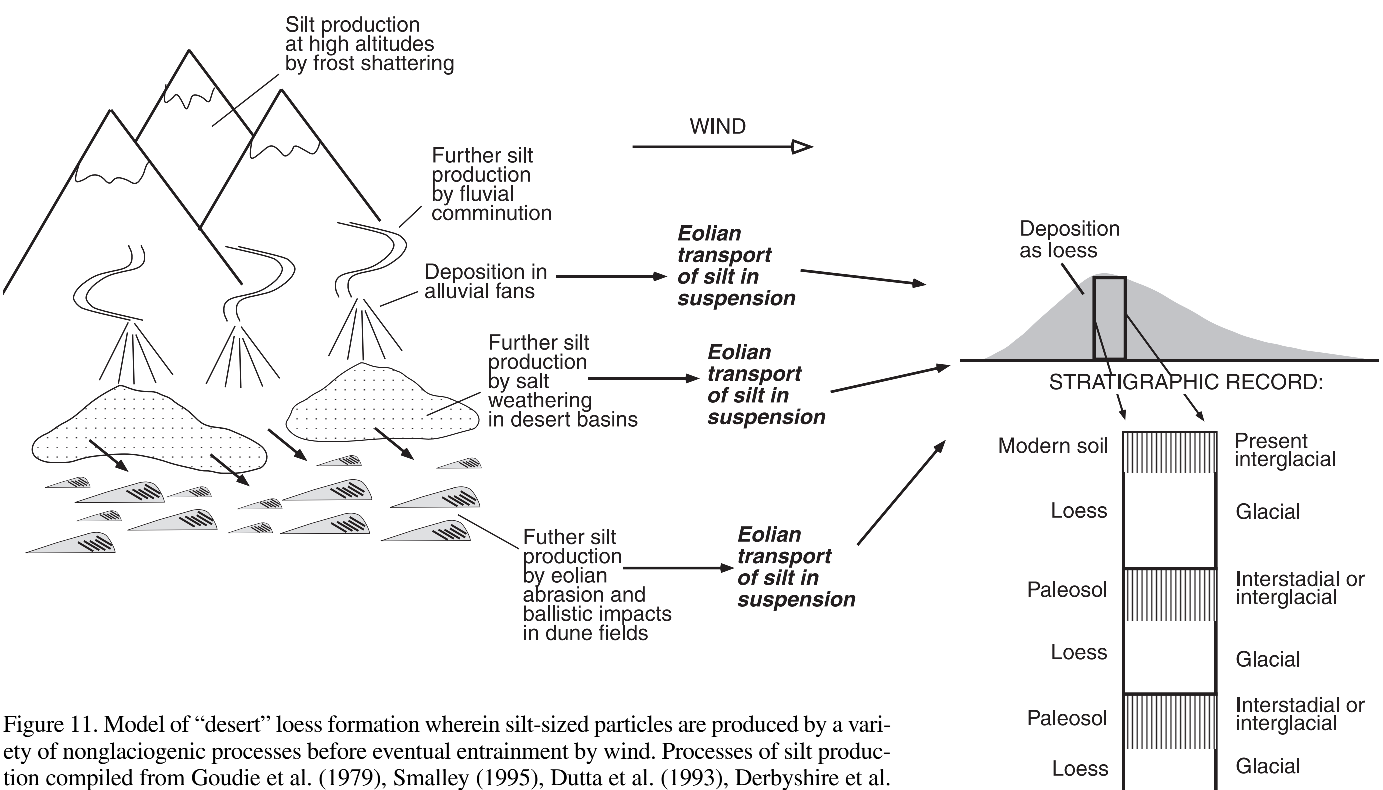

Figure 11. Model of "desert" loess formation wherein silt-sized particles are produced by a variety of nonglaciogenic processes before eventual entrainment by wind. Processes of silt production compiled from Goudie et al. (1979), Smalley (1995), Dutta et al. (1993), Derbyshire et al. (1998), and Wright (2001a, 2001b).

(Reheis et al., 1995). Nevertheless, the magnitude of last-glacial dust flux in this region is quite modest, generally less than 50 $g/m^2/yr$. These rates are much lower than those for loess in the North American midcontinent, which range from 400 to 4,000 $g/m^2/yr$ (Bettis et al., 2003).

A region that has been cited extensively as evidence for silt production in deserts is the Sahara. Dust, virtually all of it less than 20 µm in diameter, is removed by wind from the Sahara and adjacent semiarid Sahel region and carried west across the Atlantic Ocean on the Trade Winds as far as Barbados and Florida (Prospero et al., 1970). Observations of dramatic dust storms in the Sahara and distant transport westward suggest that loess occurrence along the margins of the desert should be common. Despite the impressive evidence for dust production and transport from the Sahara, there is actually evidence of only modest tracts of loess around the margins of this enormous desert. Although loess deposits on the margins of the Sahara sometimes have impressive thicknesses (e.g., Israel, see Bruins and Yaalon, 1979), they are of very limited areal extent and do not form continuous loess bodies over large areas such as those in North America, South America, Europe, or Asia. Based on records from cores across parts of the Atlantic (Ruddiman, 1997), it is apparent that Saharan mass accumulation rates are actually relatively low (2–15 $g/m^2/yr$) compared to loess fluxes in the midcontinent of North America or China.

Dust storms are common in Australia and show distinctive tracks toward offshore regions in the Indian and Pacific Oceans and the Tasman Sea (McTainsh, 1989). Some of the best records of dust derived from the deserts of Australia are from the Tasman Sea (Hesse and McTainsh, 1999), but fluxes are relatively low (McTainsh, 1989). As a result, silt-dominated loess deposits have not been reported in Australia (McTainsh, 1989). Eolian deposits that are finer-grained than sand are limited to small areas of eolian clay, or "parna" deposits (Butler, 1974).

Thus, the long-term record of particle flux from the Sahara and Australia (whether in desert margins or in the oceans) is not nearly as high as that in areas that were adjacent to large glaciers in North America, South America, Europe, and Asia. We conclude, therefore, that the magnitude of production of "desert" loess, as proposed by Wright (2001b), may be somewhat overstated. It is possible that much of the silt in Saharan dust and other deserts is derived not from silt-sized particles newly formed from sand, but from sediments eroded chiefly from siltstones. For example, geologic mapping in Libya has shown that Paleozoic and Mesozoic siltstones or silt-rich shales are extensive over much of the Sahara (Conant and Goudarzi, 1964), including siltstone facies of the Cretaceous Nubian Sandstone, which is widespread in Libya and Egypt. These rocks could be the sources of some of the loess found in Tunisia and Libya. In at least some regions of Australia, such as the Lake Eyre Basin, the sources of silt in dust storms are siltstones and mudstones of the Rolling Downs Group of Cretaceous age (McTainsh, 1989) rather than newly formed silt-sized particles produced in the desert basin. As discussed above, recent studies in eastern Colorado and Nebraska show that the same is true for much of the loess in the semiarid Great Plains of North America, where silt-sized particles are inherited from volcaniclastic siltstone (Aleinikoff et al., 1998, 1999). In South America, Zárate and Blasi (1993) interpreted many of the loess particles of the Pampas region to be inherited from a volcanic source. This conclusion is supported by recent isotopic analyses of loess from the Pampas region (Gallet et al., 1998). Inheritance of silt-sized particles is not limited to desert regions. Palmer and Pillans (1996) point out that some of the most important loess sources in New Zealand are volcanogenic silts and Pliocene-Pleistocene siltstones and mudstones. Thus, much desert silt actually appears to be inherited from silt-rich protoliths rather than particles newly produced in the desert.

LOESS AND ITS RELATION TO EOLIAN SAND

In many regions, loess belts are proximal to dune fields or eolian sand sheets. The Great Wall of China separates a region of eolian sand in the Mu Us Desert (Fig. 4) from the Loess Plateau to the southeast (Baosheng et al., 2000). At the boundary between the Mu Us Desert and the Loess Plateau, the stratigraphic record and thermoluminescence ages of sediments from the last interglacial-glacial cycle show that sediment deposition and paleosol formation took place at times similar to those on the Loess Plateau (Sun et al., 1998). However, along the desert margin (as opposed to the central part of the Loess Plateau) loess is interbedded with eolian sand. Within the Loess Plateau itself, areas immediately southeast (downwind) of the deserts are referred to as "sandy loess," whereas silt-dominated loess occurs farther to the southeast and clayey loess occurs still farther downwind (Liu, 1985; see also Fig. 5).

In periglacial regions, a facies relation between eolian sand and silt has also been recognized. For example, in Greenland, eolian sand and silt are described as facies of an eolian sediment continuum where active fine-particle production and eolian deflation are occurring at present (Dijkmans and Tornqvist, 1991). In southwestern Alaska, loess bodies occur downwind of areas of eolian sheet sand, which are, in turn, downwind of dune fields (Lea, 1990). Eolian sheet sands in this region have a greater component of silt in a downwind direction. In the Pampas loess belt of Argentina, there is a west-to-east transition from dunes to sheet sands to loess (Zárate and Blasi, 1993). In the Great Plains of North America, loess occurs immediately downwind of eolian sand in Nebraska and Colorado (Muhs et al., 1999a).

All of these observations raise the question of whether loess should be considered as a distinct sediment body or whether it is essentially a fine-grained facies of eolian sand with a common source. Pye (1995) presented several models of eolian sediment changes downwind from a source (Fig. 12). His simplest case (Fig. 12A) is typical of many loess bodies in areas adjacent to continental-scale ice sheets, such as North America, Europe, and parts of Asia; these sediments are referred to as "periglacial" loess. In two other models, loess is shown as a finer, downwind facies of eolian sand, either with an intervening zone of sediment

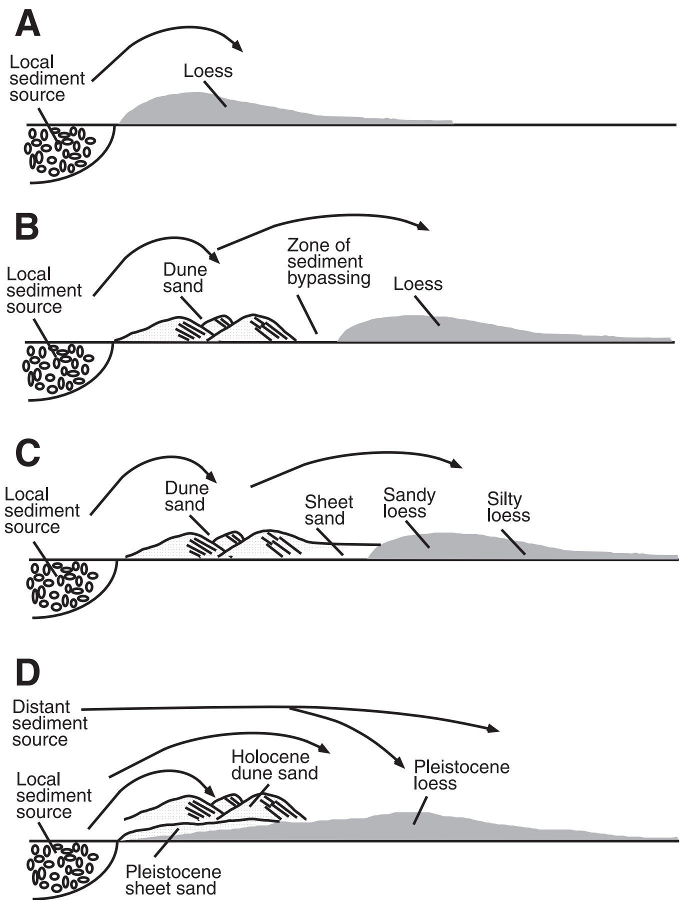

Figure 12. Models of eolian sand-loess facies changes downwind from a source. Models (A), (B), and (C) are redrawn from Pye (1995); model (D) is from the present study.

bypassing (Fig. 12B) or as part of a zone of continuous deposition with a gradual fining downwind (dune sand to sheet sand to sandy loess to silty loess). The models shown in Figure 12B and C call upon saltation-dominated transport downwind from a source to explain the origin of the dunes and sand sheets and suspension-dominated transport to explain the origin of the loess body. In the case of the model shown in Figure 12C, vegetation cover is sufficient over much of the region to trap particles continuously in a downwind direction, with a gradual downwind fining as large particles fall out. This situation contrasts strongly with that shown in the model in Figure 12B, where there is a zone of sediment bypassing. Pye's sediment-bypassing scenario is applicable to geomorphic settings where the source sediment for eolian sand and loess is in an arid basin. Because sand-sized particles are coarse, they may be deposited close to the source; however, if there is an insufficient vegetation cover farther downwind, finer-grained, silt-sized particles remain in suspension. Ultimately, much farther downwind, these finer particles are deposited when a more humid climate, with a greater degree of vegetation cover, is reached.

In places, loess occurs downwind of eolian sand, but the two sediments have different sources and possibly even different times of deposition. This variation on the models of Pye (1995), described above, is shown in Figure 12D, and an example can be found in eastern Colorado. Mineralogical, geochemical, and geochronological data show that although loess is found downwind of eolian sand, it has a different source and was deposited mainly in Pleistocene time, whereas much of the eolian sand was deposited in Holocene time (Muhs et al., 1999b; Muhs and Zárate, 2001; Aleinikoff et al., 1999).

PALEOSOLS IN QUATERNARY LOESS SEQUENCES

Soil-forming Processes

Some of the most important components of Quaternary loess sequences are buried soils or paleosols. Paleosols formed in loess have been studied at many localities and are significant for both stratigraphic interpretations and paleoclimatic reconstructions. Buried soils represent former land surfaces. Soils form in a deposit when the rate of sedimentation has slowed so that the soil-forming processes can take place and leave an imprint on the deposit. For these pedologic processes to operate, it is also essential that the land surface has enough geomorphic stability such that little or no erosion takes place.

A loess-paleosol sequence we studied at Greenbay Hollow, Illinois, a short distance from the Mississippi River Valley source (Fig. 2), illustrates some of the changes in properties that reflect humid-climate processes of soil additions, removals, translocations, and transformations (Fig. 13). Carbonate minerals, calcite and dolomite, are depleted in the modern soil, the Farmdale soil (interstadial, about 30–55 ka), the Sangamon soil (last interglacial, about 55-130 ka), and older buried soils. These depletions are apparent in the low CaO and MgO contents compared to unaltered Peoria (last glacial) Loess. Translocation of fine particles to form clay-rich, B-horizons is also apparent in the field in all soils. This is shown by the presence of clay coatings on soil structural unit ("ped") faces, but also in the higher amounts of clay in the soil B-horizons of the modern soil and the paleosols at depths of ~1200 and ~1600 cm (Fig. 13). Transformations in this loess section include the possible alteration of Na-plagioclase by hydrolysis to clay minerals within the paleosols. This is shown in the Greenbay Hollow section as relatively low Na_2O/TiO_2 values in the modern soil, the Sangamon soil, and the oldest pre-Sangamon buried soil, found at at the bottom of the section, compared to the unaltered loesses. Note that clay content is highest where Na_2O/TiO_2 values are lowest, suggesting that the clay increases, in addition to translocation, are due to the transformation of plagioclase to clay.

The Greenbay Hollow section illustrates how paleosols in loess could be used to interpret past climates. Muhs et al. (2001) showed that in a transect of modern loess-derived soils, Na_2O/TiO_2 values—as well as other indicators of chemical weathering—decrease from north to south, which parallels a

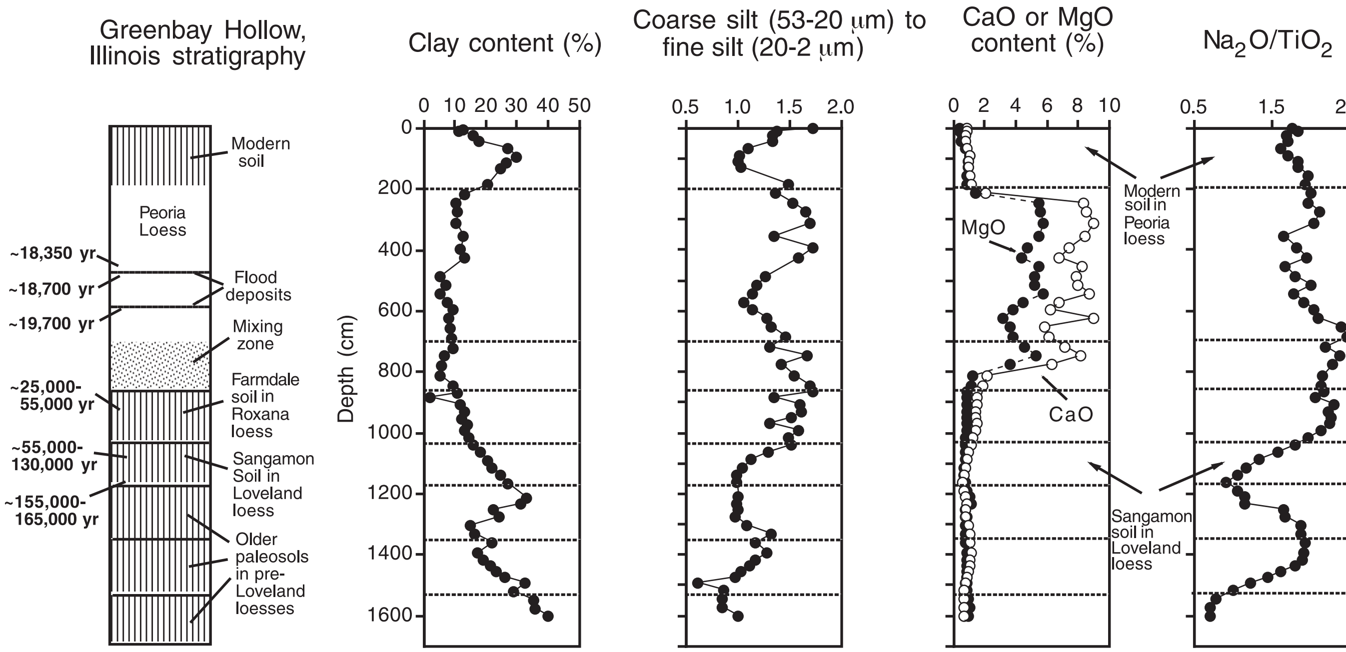

Figure 13. Stratigraphy, ages, clay content, silt ratios, CaO content and MgO content, and Na_2O/TiO_2 ratios of Greenbay Hollow loess section, western Illinois (see Fig. 2 for location; see Hajic (1990) and Grimley et al. (1998) for additional data on this section). Stratigraphy, particle size data, and chemical data from present study and Muhs et al. (2001). Peoria loess ages are correlated from a nearby section reported by Grimley et al. (1998); other ages given are approximate and based on radiocarbon, thermoluminescence (TL), and ^{10}Be age estimates for these units at other localities in the Mississippi River Valley reported by Leigh (1994), Curry and Pavich (1996), and Markewich et al. (1998).

southward-increasing mean annual temperature and precipitation gradient. Thus, the lower Na_2O/TiO_2 values in the Sangamon soil compared to the modern soil at Greenbay Hollow could be interpreted to mean that conditions during the Sangamon interglacial period were warmer and more humid than at present. However, such an interpretation is complicated by the fact that the Sangamon interglacial period could have lasted several tens of thousands of years, compared to only 10,000 years for the present interglacial. Thus, the duration of pedogenesis may also explain the lower-than-modern Na_2O/TiO_2 values.

Stratigraphic Significance of Paleosols in Glacial-Interglacial Cycles

The stratigraphic record of loess with intercalated paleosols shows sedimentary extremes in glacial-interglacial cycles. The Greenbay Hollow loess section contains examples of pedogenesis that occurred when there was little or no loess sedimentation. If glaciogenic silt is the major source of loess in this region (see earlier discussion on loess origins), then little or no eolian sediment deposition took place during periods when the Laurentide Ice Sheet had retreated from the headwaters of the Mississippi River. In essence, therefore, loess sedimentation in this region is a "turn-on, turn-off" process that is a function of glacial sediment sources. Thus, the loess record in midcontinental North America is a good example of sedimentary extremes: abundant loess deposition occurred during glacial periods, whereas very little or no loess deposition took place during interglacial or interstadial periods, which are periods of soil formation. The loess stratigraphic record in much of Europe is similar to that of regions that were near glaciers in North America. Stratigraphic and geochronologic studies in western Europe show that the last major period of loess deposition was during the last glacial period (e.g., Antoine et al., 2001; Rousseau et al., 2002).

In other regions, there is a less distinct record of loess sedimentation versus soil formation. In China, for example, the loci of modern dust storms match closely the distribution of Quaternary loess (Derbyshire et al., 1998). Modern dust storms in China are a function of dry, strong, northwesterly winds that are generated by the Mongolian high pressure cell that develops over Asia in late fall, winter, and early spring (Fig. 4). In contrast, a thermal low develops over this region in summer, and high pressure offshore generates weak, moist, southeasterly winds associated with the summer monsoon. During the summer period, rainfall is abundant and winds are not passing over dust source regions; thus, little or no eolian sediment transport takes place. In addition to observations of modern dust storms, the stratigraphic record indicates abundant loess deposition throughout the Holocene, both due to natural and anthropogenic causes (e.g., Roberts et al., 2001). Thus, many of the surface soils in China are receiving at least small increments of dust. The fact that soils mantle the surface of the landscape merely indicates that the rate of soil development exceeds the rate of dust accretion. Similar observations have been made in Alaska (Begét, 1996; Muhs et al., 2003). Alaskan paleosols contain higher amounts of fine silt than the loess units in which they are developed, indicating that sedimentation (albeit with a decreased wind competence and reduced sediment supply) is continuing simultaneously with pedogenesis. All of these observations show that loess deposition in China and Alaska is not an exclusively glacial-period process. In fact, recent stratigraphic studies in central Alaska indicate that there is only a modest record of last-glacial loess deposition, although this may be due largely to a lack of loess *preservation* rather than a lack of last-glacial loess *deposition* (Muhs et al., 2003).

In China, it appears, as proposed by Verosub et al. (1993), that loess deposition and soil formation are essentially competing processes: loess deposition is greater during glacial periods and soil formation is greater during interglacial periods, but both processes proceed simultaneously. Porter et al. (1992) formulated these concepts into a simple model that explains much of the stratigraphic record of loess in China (Fig. 14). During glacial periods, the Mongolian high-pressure cell is stronger over Asia and is dominant during a greater part of the year while the summer monsoon is weaker during such periods (Fig. 4). As a result, dust accumulation rates are high and soil development cannot keep pace with sedimentation. In contrast, during interglacial periods, although dust deposition still occurs—primarily during the late fall, winter and spring—the strength and residence time of the Mongolian high pressure cell are diminished whereas the summer monsoon is strengthened. Thus, dust deposition rates are lower and soil development can keep pace with or exceed sedimentation. The stronger summer monsoon, with its increased rainfall, enhances pedogenesis. During interglacial periods, the mean diameter of loess particles is smaller and the ratio of clay to silt increases (Fig. 7). The greater abundance of clay-sized particles is due not only to pedogenesis (i.e., greater clay production through alteration of silt-sized particles via chemical weathering under a strong summer monsoon) but also decreased wind competence that results in more clay in the primary airborne particles.

In the preceeding discussion, we emphasized that loess deposition is not limited to glacial periods. Having said this, it is also apparent from detailed stratigraphic records that span the last interglacial-glacial cycle (Fig. 7), as well as those that span several interglacial-glacial cycles (Fig. 15), that the amount of loess deposition in most areas is greater during glacial periods than during interglacial or interstadial periods. Even in those areas where loess was not derived exclusively from glacial deposits, such as South America, China, and the Great Plains of North America, the amount of loess deposited during the last glacial period was much greater than during the Holocene (Fig. 16). Because loess deposition in these areas was not dependent exclusively on glaciogenic silts, the higher rates of sedimentation during the last glacial period must have been a function of other factors. Mahowald et al. (1999) reviewed some of the possible causes of high rates of loess flux during the last glacial period. These include stronger or more persistent winds, greater aridity, decreased intensity of the hydrological cycle, decreased vegetation cover, and increased sediment availability. It is possible that all these factors combined to produce the sedimentary extreme of rapid and dramatic loess deposition during the last glacial period. In this regard, we agree with Wright (2001a) that regardless of the process of origin, much loess can be considered to be "glacial" in the sense that the optimum climatic and geomorphic conditions for loess formation in many regions occurred during glacial periods.

Variability in Loess Sedimentation within a Single Glacial Period

In the past, loess was perceived to be a relatively uniform sediment that, at least within one depositional package, showed little variability over the period of sedimentation. Studies over

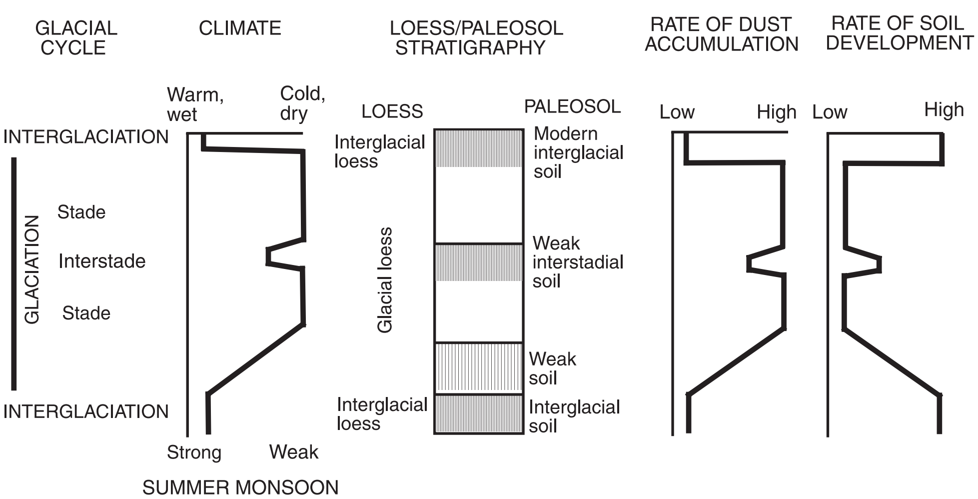

Figure 14. Model of loess deposition and soil formation cycles in China as a function of glacial-interglacial cycles and relative strengths of winter and summer monsoons. Redrawn from Porter et al. (1992).

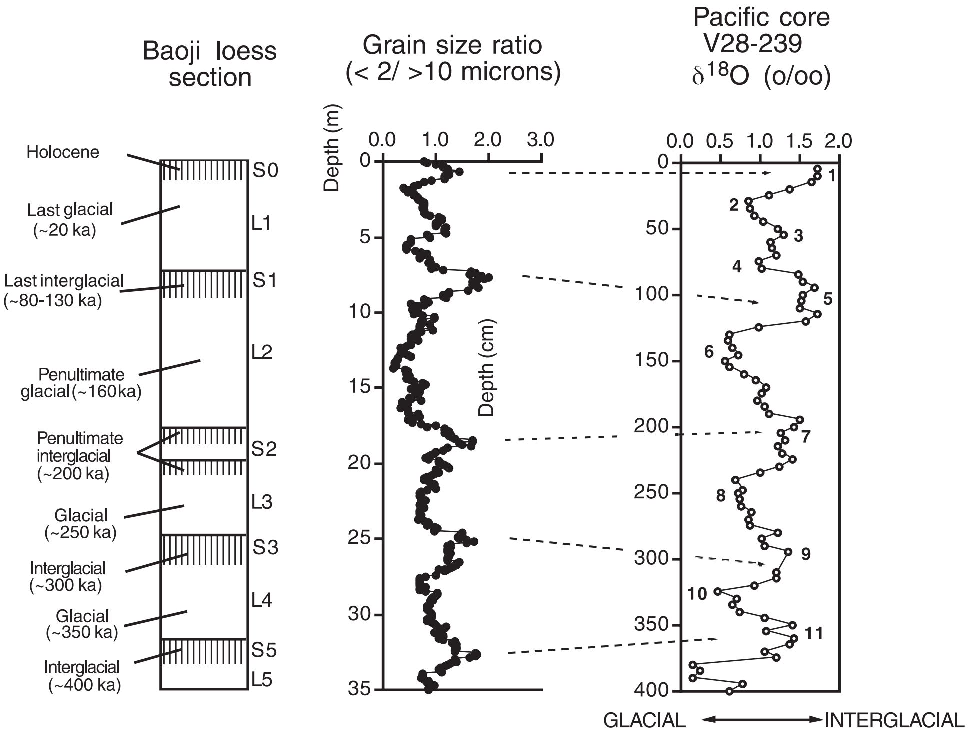

Figure 15. Illustration of relation of loess-paleosol sequences with glacial-interglacial cycles: stratigraphy, age estimates, and clay to medium and coarse silt ratios of upper part of loess section at Baoji, China, and proposed correlation with deep-sea oxygen isotope foraminiferal record of Pacific core V28-239 over the past five interglacial-glacial cycles. Loess units indicated by "L" prefix; paleosols indicated by "S" prefix. Oxygen isotope stages (bold numbers) indicate glacial periods (even numbers) or interglacial periods (odd numbers) Loess data from Ding et al. (1994); oxygen isotope data from Shackleton and Opdyke (1976). Correlations are based on age estimates in core V28-239, in turn derived from identification of the Brunhes-Matuyama boundary at 726 cm, an age for this boundary of ca. 780 ka (Spell and McDougall, 1992), and an assumed long-term average sedimentation rate of ~0.93 cm/ka.

the past 3 decades have shown that loess deposition rates can vary markedly within a single period of sedimentation, and subtle changes in loess properties can yield considerable information about changes in climate conditions and source areas within a glacial period. In several parts of North America (Iowa, Illinois, and Indiana) detailed stratigraphic studies also show that last-glacial (Peoria) loess sedimentation rates were not constant and are thought to reflect changes in source sediment supply and/or climatic conditions that influence source sediment availability (Ruhe et al., 1971; Hayward and Lowell, 1993; Wang et al., 2000).

Recent detailed studies of loess in the Rhine Valley of Germany indicate that loess in Europe, like that in North America, was not constantly deposited during the last glacial period (Antoine et al., 2001; Rousseau et al., 2002). Stratigraphic studies show that periods of loess sedimentation were separated by brief intervals of tundra soil formation (Fig. 17). The gleyed tundra soils are not well developed, indicating that periods of pedogenesis were brief and that loess sedimentation probably occurred contemporaneously, albeit at a greatly reduced rate. Furthermore, particle size analyses show that the periods of low sedimentation rate, which are marked by tundra soils, were characterized by much finer-grained loess than the periods of more rapid sedimentation. Rousseau et al. (2002) interpret these data to mean that wind competence was lower during periods of lower sedimentation rate. An alternative interpretation is that loess sources changed during the periods of differing sedimentation rate, as at Loveland, Iowa (Muhs and Bettis, 2000).

Magnetic Susceptibility in Loess-Paleosol Sequences

One of the primary means of verifying the presence of paleosols, correlating them from section to section and quantifying the degree of soil development in Chinese loess sequences, has been measurement of bulk magnetic susceptibility. A full discussion of this property and other magnetic mineralogical properties is beyond the scope of this paper, and Singer et al. (1996) and Maher (1998) provide useful reviews. Nevertheless, some discussion of this method is critical, because it has become the most commonly measured property in loess-paleosol sequences in China and in many other regions. Kukla et al. (1988) showed that bulk magnetic susceptibility in Chinese loess is relatively low, whereas the intercalated paleosols have relatively high values (Fig. 7). Heller and Liu (1984) interpreted the higher magnetic susceptibility in paleosols to be the result of concentration of magnetic minerals by sediment compaction and carbonate leaching in the soils. Kukla et al. (1988) interpreted these trends to be the result of quartz-dominated-dilution of a small component of detrital magnetic minerals in loess. Later workers (Zheng et al., 1991; Verosub et al., 1993; Maher and Thompson, 1995) proposed that much of the magnetic mineral enhancement in Chinese loess-derived paleosols is due to production of ferrimagnetic minerals, such as maghemite and fine-grained magnetite, during pedogenesis. This finding has led to the use of magnetic susceptibility not only to identify paleosols and correlate them between sections, but also to quantify paleoclimate at the time of soil formation (e.g., Maher and Thompson,1995; Maher, 1998).

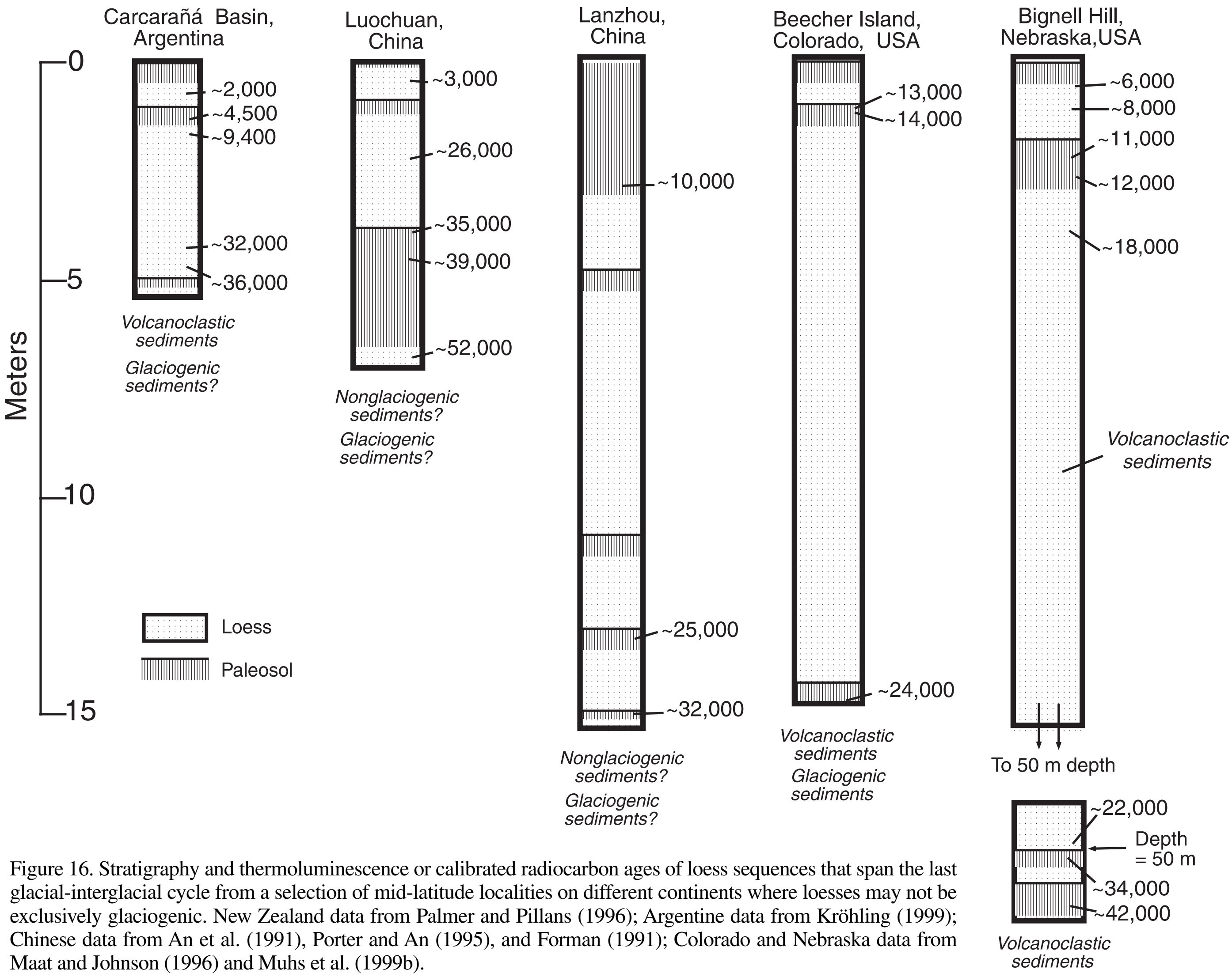

Figure 16. Stratigraphy and thermoluminescence or calibrated radiocarbon ages of loess sequences that span the last glacial-interglacial cycle from a selection of mid-latitude localities on different continents where loesses may not be exclusively glaciogenic. New Zealand data from Palmer and Pillans (1996); Argentine data from Kröhling (1999); Chinese data from An et al. (1991), Porter and An (1995), and Forman (1991); Colorado and Nebraska data from Maat and Johnson (1996) and Muhs et al. (1999b).

The widespread use of magnetic susceptibility in loess studies is likely due, at least in part, to the ease, rapidity, and inexpensive nature of the analysis. Magnetic susceptibility can be measured in the field rapidly with relatively high precision and accuracy. Nevertheless, interpreting magnetic susceptibility data is not simple, and not all loess sequences show the same trends as in China. For example, in Alaska and Siberia, magnetic susceptibility is not highest in soils and lowest in loess, but highest in loess and lowest in soils (Begét, 1990; Chlachula et al., 1997). Begét (2001) has summarized the current hypotheses for magnetic susceptibility variations in Alaskan loess. The trend of high susceptibility in loess and low susceptibility in paleosols has been interpreted to be a function of wind competence, with magnetic susceptibility as a proxy for amount of detrital magnetite, which is in turn a proxy for abundance of heavy minerals. Detailed particle size analyses of loess-paleosol sequences in Alaska support this interpretation, as loess has higher amounts of sand and coarse silt than intercalated paleosols, indicating stronger winds during periods of relatively high sedimentation rate (Fig. 18).

IMPLICATIONS FOR INTERPRETING LOESSITE IN THE ROCK RECORD

Loess deposits are not limited to the Quaternary. Ding et al. (1999) have shown that the Chinese loess record extends well back into the Tertiary period. As we alluded to at the beginning of this review, there has been an increasing recognition that loess, in the form of loessites, may be a more important part of the sedimentary rock record than previously thought (Johnson, 1989; Soreghan, 1992; Chan, 1999). A number of the concepts and observations discussed for the Quaternary loess-paleosol record are important for recognizing and interpreting loessites in the

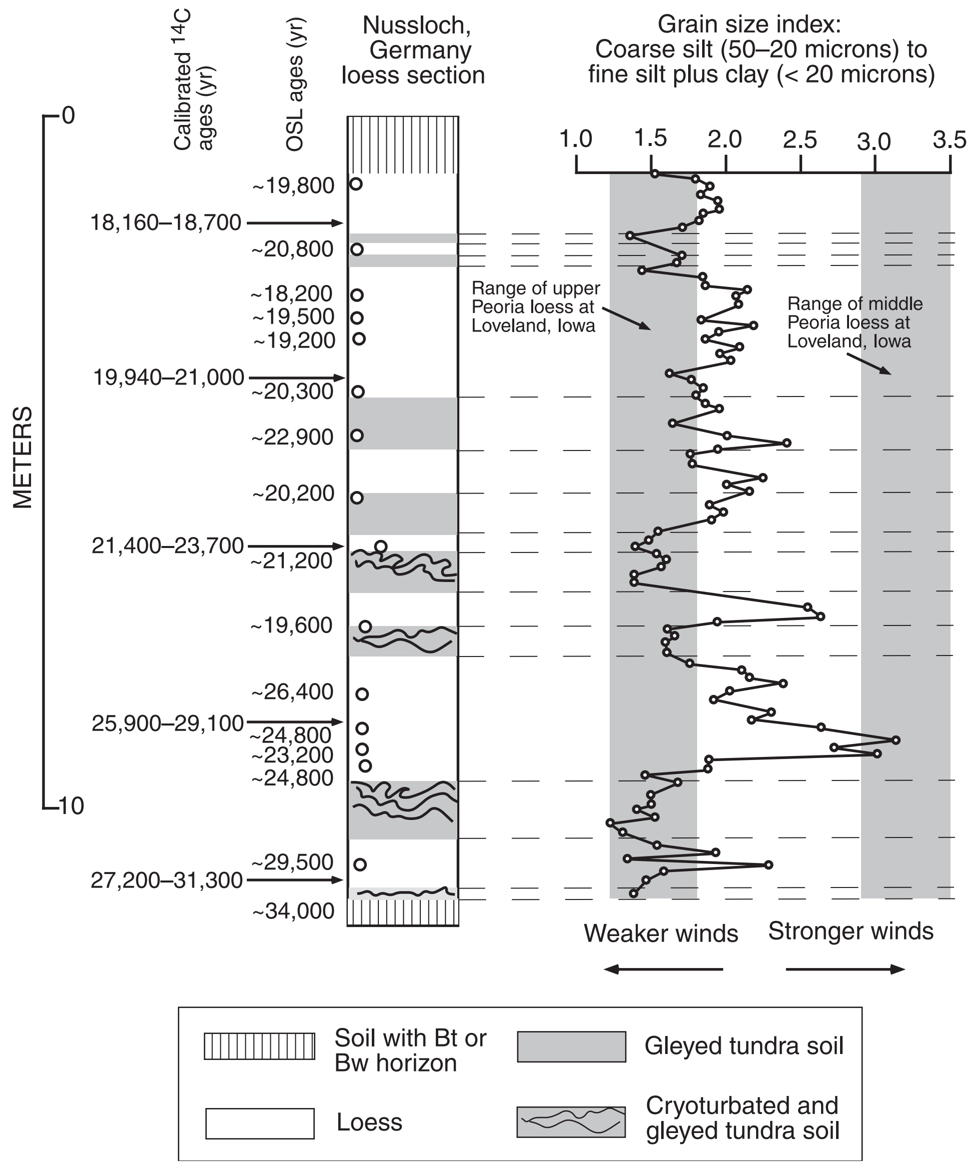

Figure 17. Stratigraphy, radiocarbon, and optically stimulated luminescence (OSL) ages and variations in loess particle size at Nussloch, Germany, loess section as an illustration of loess sedimentation variability within a single glacial period. Shown for comparison are similar particle size data for Loveland, Iowa, loess section. Nussloch data from Antoine et al. (2001) and Rousseau et al. (2002); Loveland data from Muhs and Bettis (2000).

rock record. The silts comprising the bulk of most widely distributed and thick loess deposits appear to be derived from glacial grinding, silt-rich protoliths, volcanic ash, or some combination of these sources. There is little evidence for *abundant* primary production of silt from sand in desert regions. Regional thickness, grain-size, geochemical, and isotopic trends of loess sediments permit identification of source areas, and by inference, the directions of transporting winds. Secondary alterations of loess, including soil development, can potentially provide key information for interpreting sedimentation history, as well as past climatic and vegetation conditions. However, as shown with the example from Greenbay Hollow, separating the effects of climate and time on pedogenesis is not easy, and care must be taken in paleoclimatic interpretations of loess-derived paleosols.

SUMMARY

Loess is a terrestrial eolian deposit that records climatically driven sedimentary extremes and may cover as much as 10% of the Earth's surface. It is dominated by silt-sized particles with a

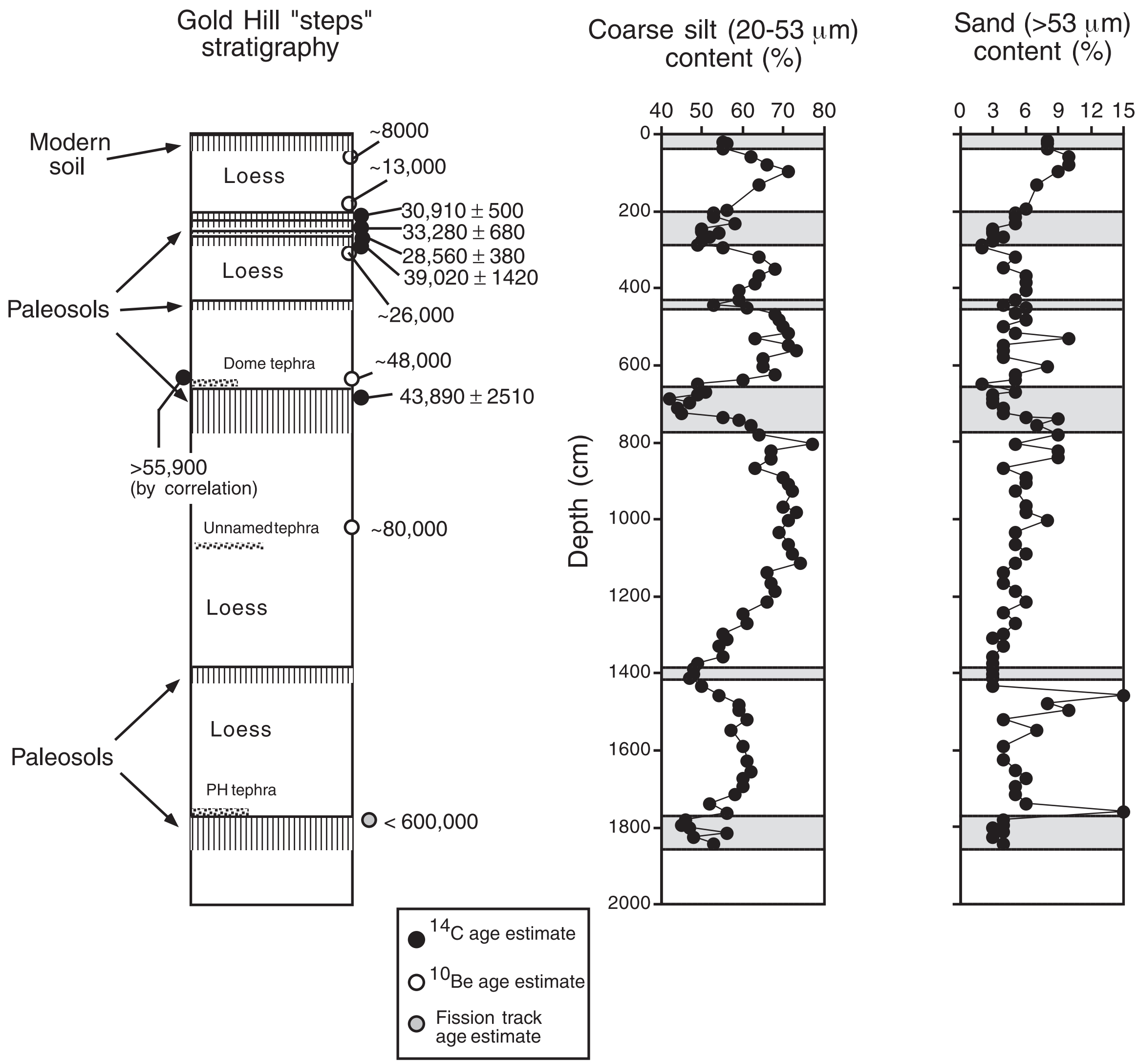

Figure 18. Stratigraphy, age estimates, and coarse silt and sand contents of loess and intercalated paleosols at the Gold Hill "steps" section near Fairbanks, Alaska. Stratigraphy and ages are from Muhs et al. (2003); coarse silt and sand contents are previously unpublished data obtained by the authors through conventional sieve and pipette methods.

majority of grains comprised of quartz, feldspars, and clay minerals. In many regions, loess also has varying amounts of carbonate minerals (calcite and dolomite). The geochemistry of loess varies from region to region, depending on source area, but it generally has a composition that resembles the bulk composition of upper crustal rocks. Trends in loess away from source areas include decreasing thickness, decreasing amounts of sand and coarse silt, and increasing amounts of fine silt and clay. Loess particle size also varies at a given locality over time and may be a function of varying wind strengths, changing source sediments or a combination of these two factors.

Traditionally, loess has been viewed primarily as a product of glacial grinding, with subsequent entrainment by wind from the surfaces of outwash deposits. Numerous studies have shown that this is an oversimplified concept and that other processes contribute to silt particle formation and loess accumulation. Recognition of these processes has led to the concept of "desert," nonglaciogenic loess, which is widespread in some regions, including China and the semiarid Great Plains of North America, and has limited occurrences elsewhere, such as Africa, Australia, and arid North America. Despite challenges to the importance of the role of glacial grinding, a review of the evidence suggests that glacial processes may still be much more important in the *new* formation of silt-sized particles. However, the importance of inheritance of silt-sized particles in loess from siltstones, mudstones, shales, and volcanic ash, whether in glaciated regions or elsewhere, probably has not been appreciated.

Loess is often geographically associated with eolian sand. Transects in loess bodies typically show decreasing amounts of sand downwind. At some localities, sand and loess are interbedded, which indicates that they are facies of the same deposit. However, in other regions, geochemical and isotopic analyses show that while sand may contribute to the sediment population of a loess body, the majority of loess particles are derived from a different and more distant source.

Buried soils, or paleosols, are important components of loess stratigraphy. They can be recognized by their distinctive morphological features and by systematic changes in particle size, chemistry and mineralogy. Buried soils formed during past periods when loess sedimentation rates either dropped to zero or at least slowed significantly enough that soil formation could keep ahead of loess deposition. Thus, loess and soils represent opposite members of a continuum of sedimentary extremes: high rates of sedimentation yield relatively unaltered loess in a stratigraphic record, whereas low rates of sedimentation leave a record of buried soils. This swing between sedimentary extremes can be recognized in the long-term glacial-interglacial record of the Quaternary. In some regions such as China and Alaska, loess deposition continues today. However, in most regions, including China, loess sedimentation rates were much higher during glacial periods than during interglacial periods. The sedimentary extreme of high loess sedimentation rates during the last glacial period on many continents was probably due to a cold, dry climate with strong winds, a decreased intensity of the hydrologic cycle, decreased vegetation cover, and increased sediment supplies, whether from glacial or nonglacial sources.

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