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Loess Deposits, Origins and Properties

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LOESS DEPOSITS, ORIGINS AND PROPERTIES

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Introduction

Loess is an eolian (windblown) sediment that is an important archive of Quaternary climate changes. It may provide one of the most complete terrestrial records of interglacial–glacial cycles. Loess is unusual as a record of Quaternary climate change because it is one of the few sediments that is deposited directly from the atmosphere. Thus, it is a geologic deposit that contains a record of atmospheric circulation and can be used to reconstruct synoptic-scale paleoclimatology. Loess is also unusual in that it can be dated directly using 'trapped electron' or luminescence methods that require only the sediment itself. Commonly, loess deposits are not homogenous sediments, but most contain buried soils, or paleosols. It is the combination of both unaltered loess deposits and intercalated paleosols that gives this sedimentary record much of its richness as a Quaternary paleoclimate record.

Definition of Loess

Loess can be defined as sediment that has been entrained, transported, and deposited by the wind and is dominated by silt-sized (50–2 μm-diameter) particles. Most loess deposits are not composed completely of silt, but also contain measurable amounts of sand (>50 μm) and clay (<2 μm). Nevertheless, loess typically has 60–90% silt-sized particles. To distinguish loess from fine-grained (aerosolic) dust that may have a subtle presence within soils or sediments, loess should be recognizable in the field as a distinctive sedimentary body. It commonly forms a mantle or cover on preexisting landscapes and can be anywhere from a few centimeters to several hundred meters in thickness.

Unlike eolian sands, fluvial sediments, or marine sediments, primary structures in loess are subtle. Some loess deposits have primary bedding structures, such as faint, horizontal laminations and, less commonly, cross-bedding. Many loess deposits are characterized by a massive (as opposed to 'loose' or structured) condition. Interparticle binding by clays and/or carbonates often results in considerable material strength and explains the ability of loess deposits to form vertical faces along river or stream banks and road cuts. In fact, some European researchers regard this weak cementation by carbonate as a process called 'loessification', a prerequisite for a sediment to be considered true loess. Most other researchers do not have such a restricted definition of loess, however, and regard all eolian silt that forms a distinct sedimentary body as loess (Pye, 1987; Muhs and Bettis, 2003). Secondary structures in loess are more common than primary structures, and consist of fractures, burrows, rhizoliths (root casts composed of iron oxides or carbonate), carbonate nodules or concretions, oxidation or reduction streaks or bands, and paleosols. Although mammal fossils are sometimes found in loess deposits, the most common fossils are shells of land snails, which can be powerful paleoclimatic tools (Rousseau and Kukla, 1994).

Spatial Distribution of Loess

Loess covers a significant amount of the Earth's land surface, perhaps as much as 10% (Pye, 1987). Because of its widespread distribution and favorable texture and mineralogy, it forms some of the world's most important agricultural soils. In the Eastern Hemisphere, loess is abundant over much of Eurasia (Fig. 1). 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 in western and central Europe, Russia, and Central Asia (Pye, 1987; Rozycki, 1991; Frechen *et al.*, 2003). An important exception is China, where loess covers large areas at lower latitudes that were not near continental ice sheets, mountain ice caps, or valley glaciers (Liu, 1988). Loess is largely absent from subtropical and tropical latitudes of Eurasia.

In the Western Hemisphere, loess is present in both North and South America (Figs. 2 and 3). In South America, there are two major loess belts, the Pampas loess in central Argentina and the Chaco loess in northern Argentina; less-certain loess deposits may be located in Bolivia, Paraguay, Uruguay, and Brazil (Zárate, 2003). In North America, loess is found in Alaska and adjacent Yukon Territory (Péwé, 1975), the Palouse area of eastern Washington and adjacent Oregon (Busacca *et al.*, 2004), the Snake River Plain and adjacent uplands of Idaho, the Great Plains region east of the Rocky Mountains, and the greater Mississippi River drainage basin (Bettis *et al.*, 2003). Loess bodies of the North American midcontinent appear to be continuous at small scale. At a larger scale, it is apparent that these loess bodies have very different thickness trends that

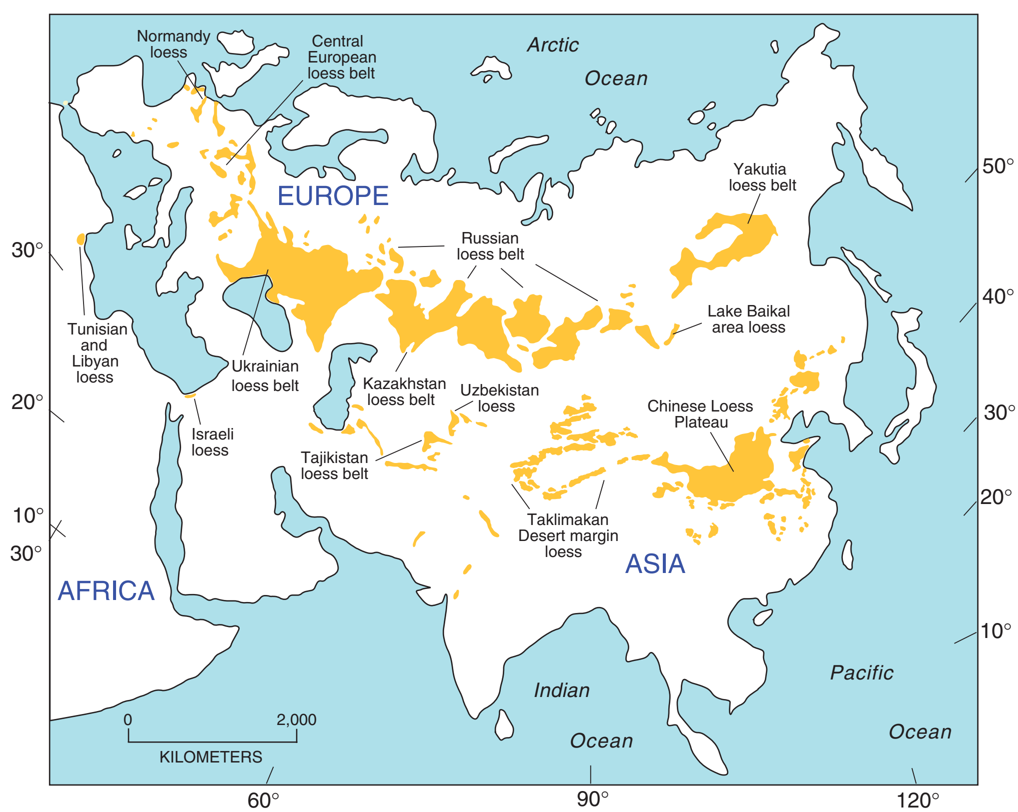

Figure 1 Map showing the distribution of loess in Eurasia and localities or regions referred to in the text. Compiled from Rozycki (1991) and Liu (1988), and redrawn from figure in Muhs and Bettis (2003).

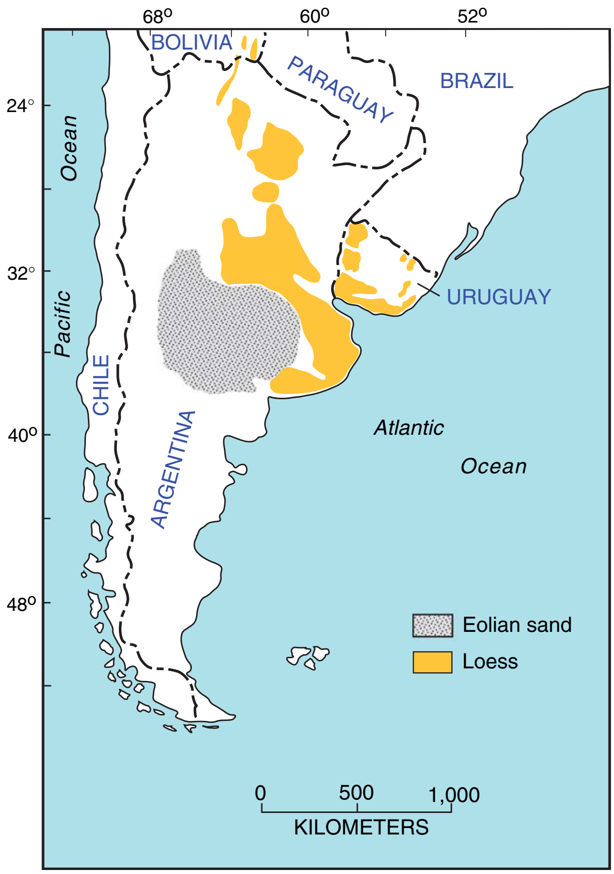

Figure 2 Map showing the distribution of loess and eolian sand in southern South America. Redrawn from Zárate (2003) and sources therein.

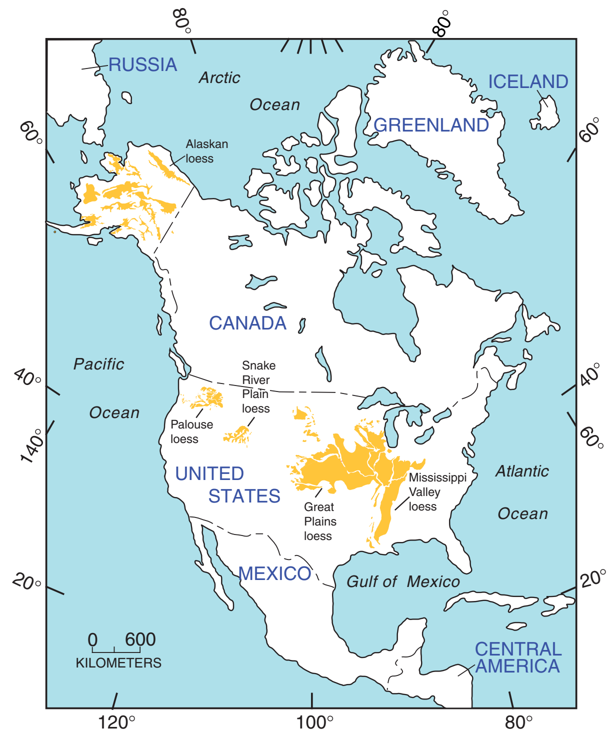

Figure 3 Map showing the distribution of loess in North America, from compilations in Péwé (1975), Bettis *et al.* (2003), and Busacca *et al.* (2004), and references therein.

are not part of a larger regional trend (Bettis *et al.*, 2003; Muhs and Bettis, 2003). The variability of loess thickness over a landscape is, however, one of the most powerful tools in using this sediment for paleoclimatic reconstructions.

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 areas of loess in Tunisia, Libya, Nigeria, Namibia, and Israel (Fig. 1). Loess is also largely absent in Australia, although there are areas of fine-grained eolian mantles and considerable evidence of exotic quartz in soils (Hesse and McTainsh, 2003). However, loess is found over much of New Zealand, where its stratigraphy (e.g., Berryman, 1993) and distribution (Eden and Hammond, 2003) have been studied in considerable detail.

Mineralogy and Geochemistry of Loess

Most loess deposits have a mineralogy that includes quartz, plagioclase, K-feldspar, mica, calcite (and sometimes dolomite), and phyllosilicate clay minerals (smectite, chlorite, mica, and kaolinite). Heavy minerals are usually present, but in small amounts. Bulk geochemical studies show that the dominant constituent in loess is SiO_2, which ranges from ~45% to 75%, but is typically 55–65%. The high SiO_2 contents of loess deposits reflect a dominance of quartz, but smaller amounts of feldspars and clay minerals also contribute to this value. Plots of SiO_2 versus Al_2O_3 show that most loess has a composition that falls between that of average shale and quartz-dominated sandstone (Muhs and Bettis, 2003). Loess with high clay mineral content has more Al_2O_3, Fe_2O_3, and TiO_2; loess with higher carbonate (calcite and dolomite) content has more CaO and MgO.

Loess Origins: Processes of Silt Particle Formation

A traditional view of loess is that silt-sized particles are produced mostly by glacial grinding of crystalline rocks, deposited in till, reworked by fluvial processes as outwash, and finally entrained, transported, and deposited by wind (Fig. 4). This classical model of loess formation has led to the view that loess deposits are primarily markers of continental-scale (global) glacial periods. The model is supported by observations of the geographic proximity of loess bodies to

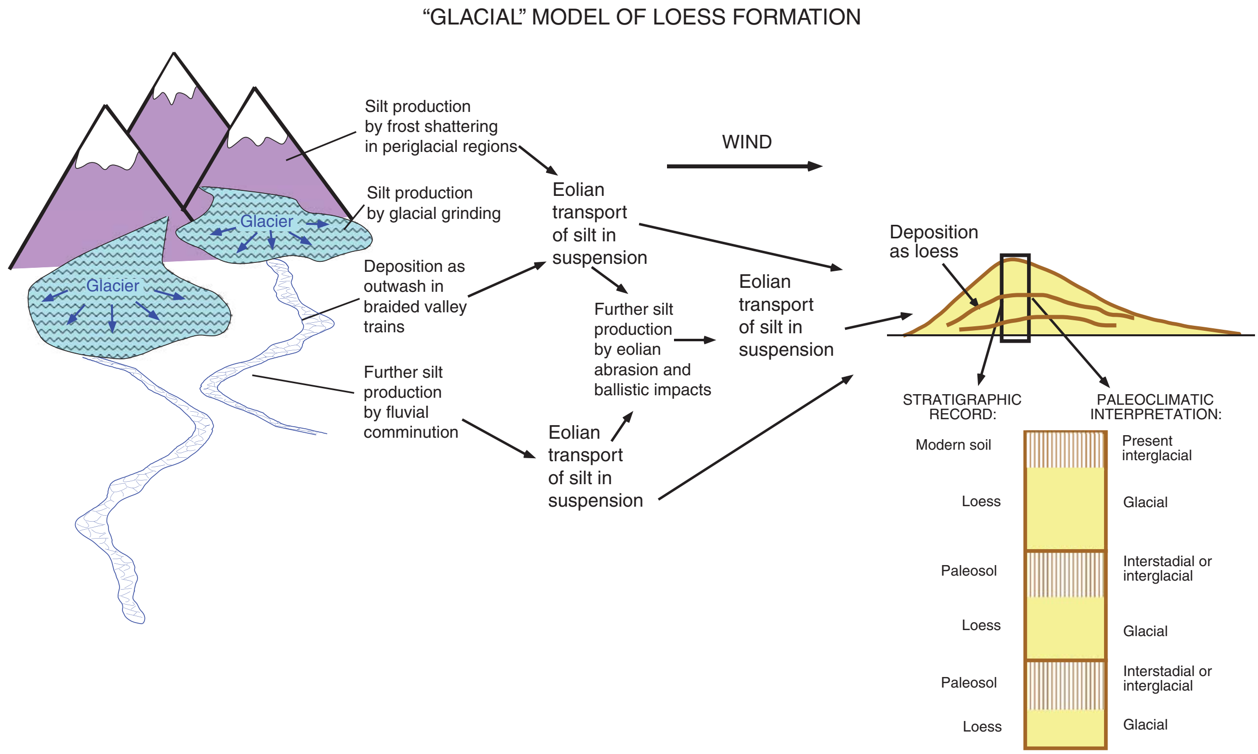

Figure 4 Classical model of 'glacial' loess formation wherein silt-sized particles are produced primarily by glacial grinding, delivered to outwash streams and finally entrained by wind. Redrawn from Muhs and Bettis (2003).

the southern limits of the Laurentide ice sheet in North America (Ruhe, 1969) and the Fennoscandian ice sheet in Europe (Frechen *et al.*, 2003), as well as smaller glaciers in Asia (Dodonov, 1991) and South America (Zárate, 2003). 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 (Ruhe, 1969). More recently, many luminescence ages show that the youngest loess dates to the last glacial period in Europe as well (Frechen *et al.*, 2003).

Despite the long-term support for the classical 'glacial' concept of loess formation, there have been challenges to this model going back at least 50 years. The debate has continued to this day and centers on the issue of 'glacial' loess versus 'desert' loess (Smalley, 1995; Wright, 2001; Muhs and Bettis, 2003). 'Desert' loess is a term used loosely to describe eolian silt generated in and derived from arid or semiarid regions that were not glaciated. The debate on desert loess versus glacial loess centers on whether silt-sized particles can be produced by mechanisms other than glacial grinding; specifically, whether or not they can be produced in deserts. A variety of mechanisms can, in principle, produce silt-sized particles in arid regions and these are summarized in a highly simplified model (**Fig. 5**). These processes include frost shattering, comminution (particle size reduction by crushing or grinding) by fluvial and mass-movement transport, chemical weathering, salt weathering, eolian abrasion, and ballistic impacts.

China is the region most often cited as the best example of a long-term and spatially extensive non-glacial (or 'desert') loess record. The observations cited for a desert origin are loess thickness and particle size trends that show decreases downwind of desert basins. In addition, modern dust storms originate in the same desert basins. However, loess in China may have, as its ultimate source, glacially derived silt. The mountains surrounding the largest desert basins in China have glaciers at present and were more extensively glaciated in the past. It is possible that much primary silt production takes place by glacial grinding (as well as other processes) in the mountains, and outwash may carry the silts into the basins (Smalley, 1995). The silts are then transported from the desert basins by wind. If this model is correct, then the arid basins are simply reservoirs for particle storage and have little to do with silt production itself, a concept supported by geochemical and isotopic data (Sun, 2002).

Despite continuing controversy over whether loess in China is of 'glacial' or 'desert' origin (or both), it does appear that the main periods of loess sedimentation in China correspond to glacial periods, whereas periods of soil formation (when loess deposition appears to cease) correspond to interglacials or

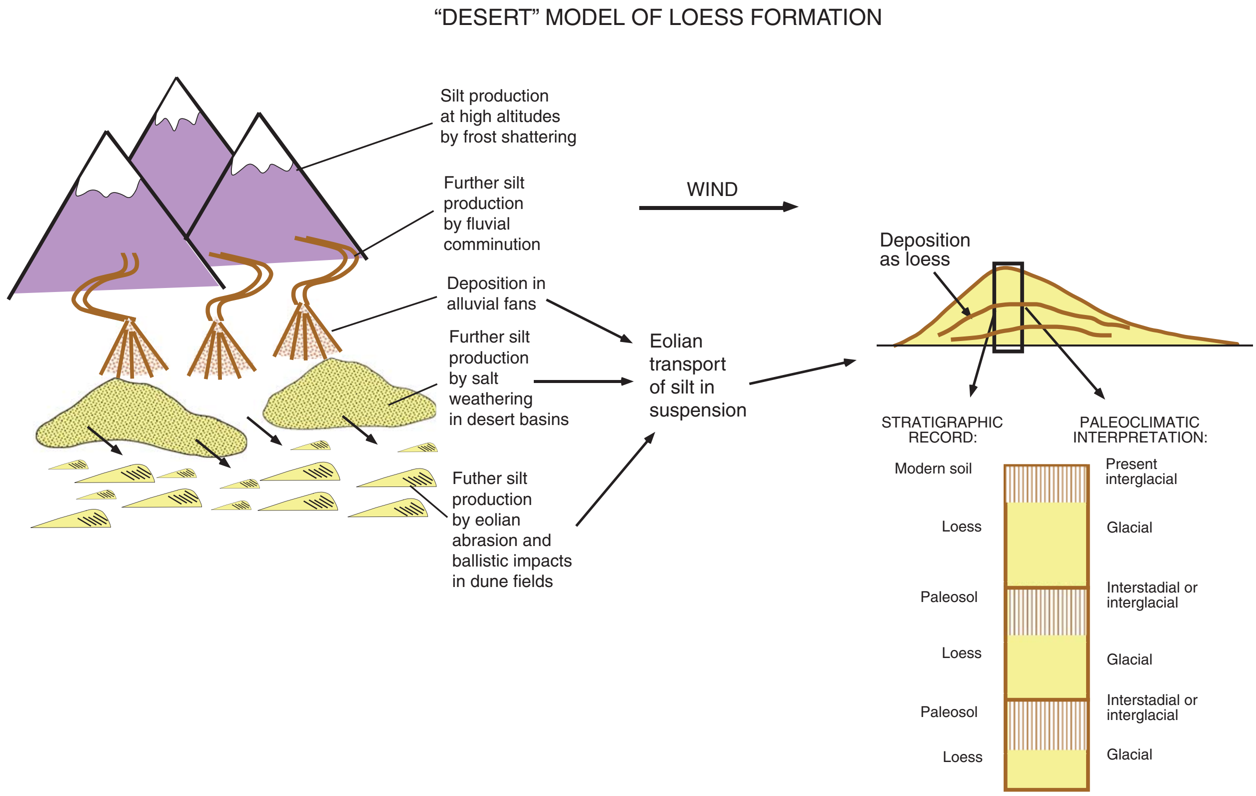

Figure 5 Model of 'desert' loess formation wherein silt-sized particles are produced by a variety of nonglaciogenic processes before eventual entrainment by wind. Redrawn from Muhs and Bettis (2003).

interstadials (Kukla and An, 1989; Shen *et al.*, 1992; Porter, 2001). Indeed, the loess-paleosol record of China can be reasonably well correlated with the deep-sea sediment oxygen-isotope record of glacials and interglacials (Fig. 6). Nonglacial loess in the Great Plains of North America is also dated to the last glacial period (Maat and Johnson, 1996; Aleinikoff *et al.*, 1999; Muhs *et al.*, 1999; Roberts *et al.*, 2003). These observations suggest that even in regions where glacial sediment may not have been abundant as a loess source, glacial periods may be favorable times for eolian silt availability, entrainment, transportation, and deposition. Glacial-period factors that may have favored loess entrainment and transportation include decreased vegetation cover, increased aridity, increased wind strength, and a decreased intensity of the hydrological cycle, such that silt can stay in suspension for longer distances (Mahowald *et al.*, 1999; Kohfeld and Harrison, 2000).

Loess Stratigraphy

Loess stratigraphy is rarely simple. Although loess is sometimes conceptualized as a thick accumulation of unaltered, massive silt, in reality it is usually sediment that has experienced varying degrees of weathering and pedogenesis (soil-forming processes). Some workers have pointed out that loess sedimentation and soil formation are essentially competing processes: when loess sedimentation rates are high, pedogenic processes cannot keep up and relatively unaltered sediment accumulates (Verosub *et al.*, 1993; Muhs *et al.*, 2004). When loess sedimentation rates are low, soil-forming processes extend deeper into previously deposited loess, but soils may also continue to accumulate small amounts of eolian sediment during pedogenesis. Thus, loess sequences should not be viewed in the same way as other Quaternary records, such as deep-sea or lacustrine sediments, where a better case can be made for more-or-less continuous sedimentation.

One distinct advantage of loess over many other Quaternary sediments is that it can be dated directly, using luminescence methods (Aitken, 1998). Because of the decay of naturally occurring ionizing radiation in surrounding sediment, electrons are trapped in defect areas in minerals such as quartz and feldspar. These electron traps are effectively emptied, or 'zeroed' when sediment is entrained by wind and exposed to sunlight. In the case of optically stimulated luminescence (OSL), the traps are emptied and therefore the signal is zeroed usually in a matter of

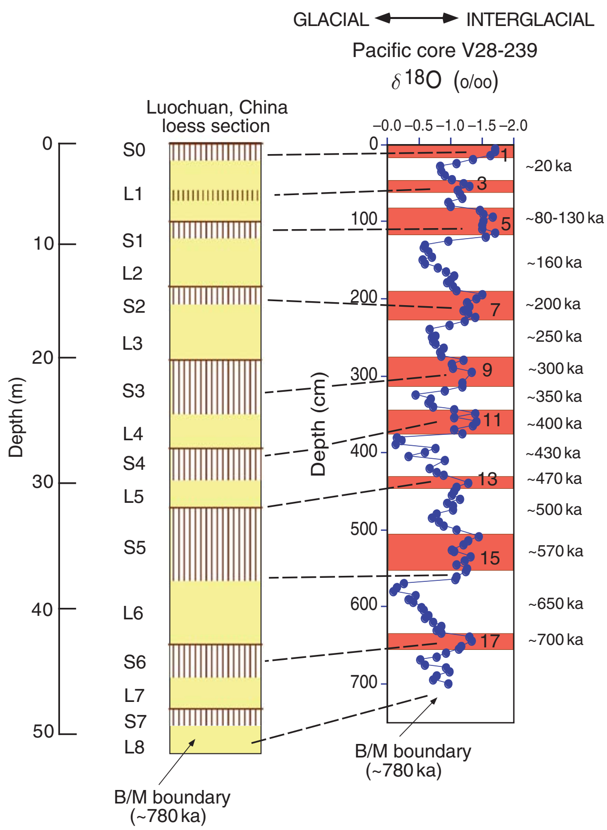

Figure 6 Loess stratigraphy at Luochuan, China (Kukla and An, 1989) and correlation with the deep-sea oxygen isotope ($\delta^{18}O$) record of equatorial Pacific core V28-239 (Shackleton and Opdyke, 1976). Periods dominated by loess deposition ('L' units) occur during glacials and periods dominated by soil formation ('S' units) occur during interglacials. Correlations are based on ^{10}Be accumulation in loess and paleosols at Luochuan (from Shen *et al.*, 1992) and identification of the Brunhes-Matuyama (B/M) boundary at 50.5 m at Luochuan and at 726 cm in V28-239. Approximate ages in V28-239 are based on the depth of the B/M boundary (~780 ka) and an assumed long-term average sedimentation rate of ~0.93 cm/ka.

seconds to minutes. After deposition and sediment burial, radiation, largely from naturally occurring elements (potassium (K), rubidium (Rb), urainium (U), thorium (Th)) within the sediment itself, excites electrons and causes them to be trapped again within the crystal structures and defect areas of minerals. Subsequent stimulation in the laboratory by optical or thermal sources causes luminescence as the trapped electrons are released. The amount of luminescence is a function of the total radiation dose to which the mineral has been exposed. Because the natural annual environmental dose rate can be calculated from the concentrations of K, Rb, U, and Th within the sediment, it is therefore possible to determine the time the sediment was last exposed to sunlight. Luminescence dating is ideal for loess deposits because unlike other dating methods, no fossils or organic materials are required; the minerals of choice (quartz and feldspar) are common in loess; being eolian sediment, it is effectively zeroed; and dating is possible back to 60–100 thousand years ago (ka). Errors are typically of the order of 5–10% (e.g., Roberts *et al.*, 2003), but tend to increase as the limit of the technique is approached.

Loess, as a representation of the glacial record, has been studied extensively in Europe and North America. Decades of study and dating have established a clear link between the loess record and glacial–interglacial cycles. The modern soils of much of Europe have been developing since the end (~13 ka) of the last ('Weichshelien' or 'Würm') glacial period. Hundreds of luminescence ages confirm that the uppermost loess in Europe was deposited during the Weichshelien-Würm glacial period, from ~28 ka to ~13 ka (Frechen *et al.*, 2003). Loess from this period is well displayed as relatively unaltered sediment in many exposures, such as the classical section near Kesselt, Belgium (**Fig. 7**), described in detail by Vandenberghe *et al.* (1998) and Van den Haute *et al.* (1998). This last-glacial loess has an equivalent in North America that is called Peoria Loess (**Figs. 8 and 9**). Weichshelien loess is, in turn, underlain by a minimally developed paleosol (LH, or 'Limon Humifère') that may have its equivalent in North America as the Farmdale 'Geosol' (= paleosol) and Gilman Canyon Formation (the upper part of which contains a paleosol). In Europe, a well-developed soil, the Rocourt paleosol, is found below the LH paleosol and formed during the last interglacial period. This soil has its equivalent in North America as the Sangamon Geosol. Both the Rocourt paleosol and Sangamon Geosol probably developed over tens of thousands of years during a long interglacial period with little loess sedimentation. The Rocourt paleosol, in turn, is developed in loess of the penultimate glacial period ('Saalien'), which has its equivalent in North America as the Loveland Loess. The age of penultimate glacial loess on both continents may be on the order of around 160–140 ka (Maat and Johnson, 1996; Forman and Pierson, 2002)

In nonglacial environments, loess stratigraphy is generally similar to that of glacial regions. Thus, even where glacial silt is not the primary sediment source, loess deposition occurs primarily during glacial periods and soil formation occurs primarily during interglacial periods. In Central Asia (Dodonov, 1991) and in the Great Plains region of North America (Aleinikoff et al., 1999), loess is derived from both nonglaciogenic and glaciogenic sources. Nevertheless, many of the same stratigraphic units have been identified and correlated with loess sequences near continental ice. In Central Asia, for

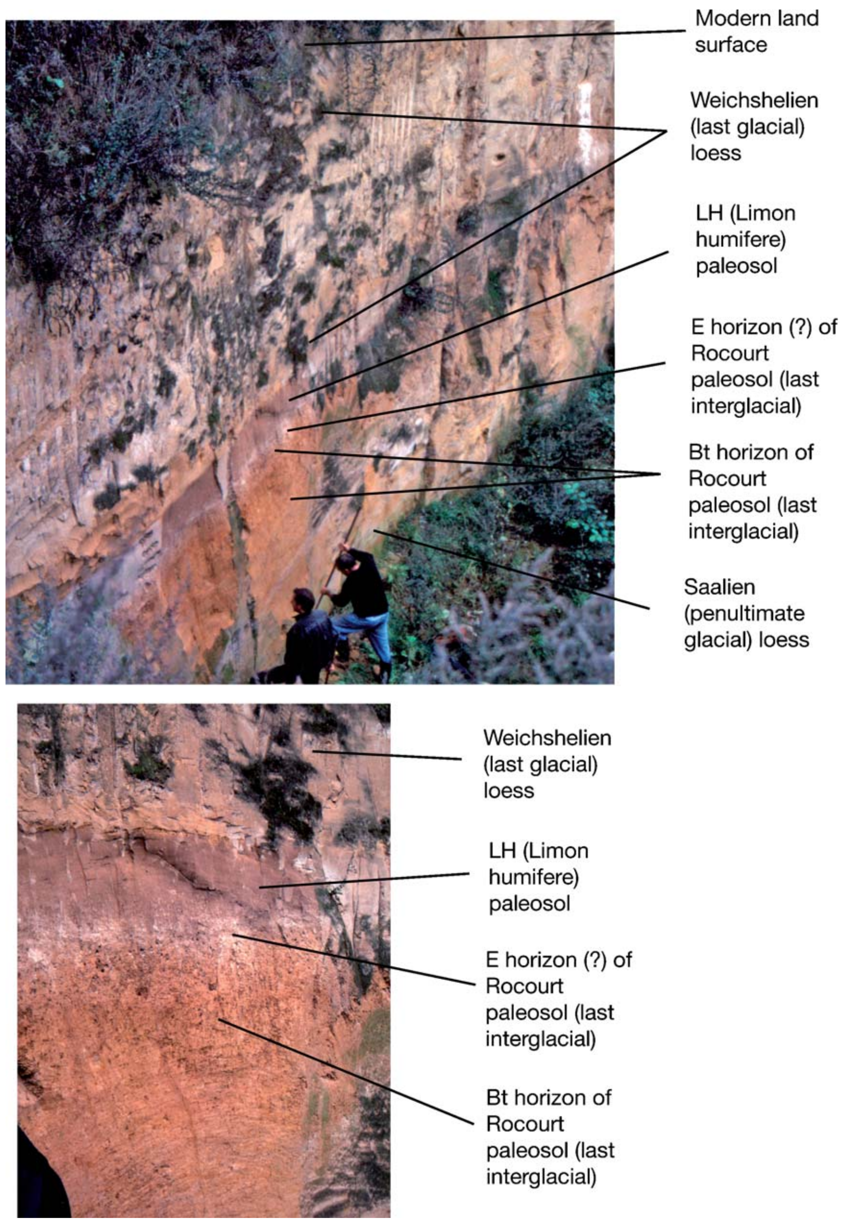

Figure 7 Photograph of loess and paleosols representing the last interglacial–glacial cycle exposed in brickyard near Kesselt, Belgium (see Vandenberghe *et al.*, 1998 and Van den Haute *et al.*, 1998). Photograph by DR Muhs.

example, the main episodes of loess deposition were during the last two glacial periods (Frechen and Dodonov, 1998). In the Great Plains of North America, Peoria Loess, a Farmdale-equivalent soil (a paleosol in the Gilman Canyon Formation), the Sangamon Geosol, and Loveland Loess have all been identified (**Fig. 9**). Last-glacial (Peoria) loess in North America also has its equivalent as the 'Malan' or 'L1' loess in China, although Malan Loess spans a longer period of time and includes what in North America would be called the Roxana Silt or the Gilman Canyon Formation. The last interglacial soil complex (the Sangamon Geosol of North America) is called the 'S1' paleosol in China; it is developed in the 'L2' loess, which is roughly equivalent to Loveland Loess in North America.

There are, however, exceptions to the generalization of loess deposition occurring only in glacial periods. For example, there is well-documented evidence of Holocene loess in China (see Roberts *et al.*, 2001, for a recent example) and in North America, both in the Great Plains (e.g., Miao *et al.*, 2005) and Alaska (e.g., Muhs *et al.*, 2004). In other regions, it is difficult to correlate loess deposition and soil formation with specific glacial and interglacial periods. For example, in Israel, desert loess and fine-grained dust

Figure 8 Photograph of loess and paleosols representing the last interglacial–glacial cycle exposed on the north end of Crowley's Ridge, Arkansas, USA (see Markewich *et al.*, 1998). Photograph by DR Muhs.

Figure 9 Photograph of loess and paleosols exposed in the Elba canal cut, eastern Nebraska, USA (see May *et al.*, 1995). Note paleochannel cut into the Gilman Canyon Formation, Sangamon Geosol, and Loveland Loess, filled by Peoria Loess. Photograph by DR Muhs.

are thought to have been deposited over much of the Quaternary (Dan and Yaalon, 1971), probably during both glacials and interglacials. Soil formation seems to take place syndepositionally, that is, concurrently with loess deposition. In this area, relatively unaltered loess is, therefore, not apparent in most stratigraphic sections; clay-rich (Bt) horizons form in the loess and calcic (Bk) horizons form below the Bt horizons. Nevertheless, stratification is apparent in these sections, and several cycles of loess deposition/soil formation can be seen in outcrops (**Fig. 10**).

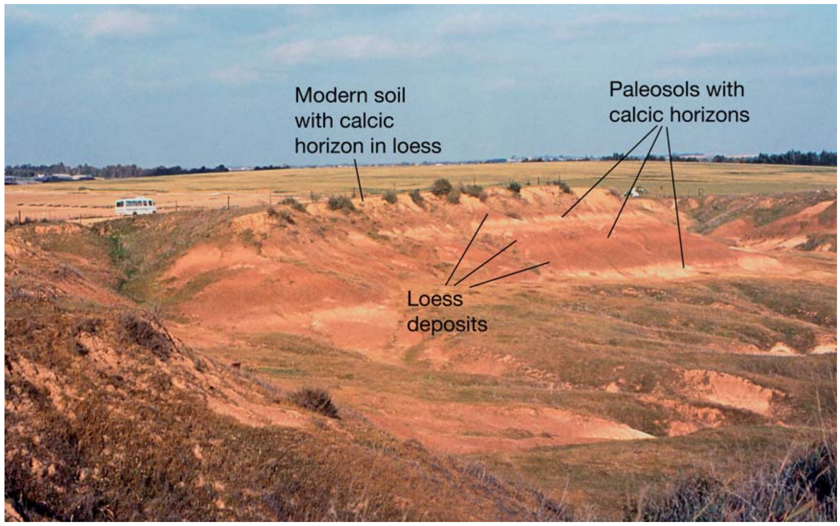

Figure 10 Loess deposits with calcic-horizon-bearing paleosols, northern Negev Desert, Israel (see Dan and Yaalon, 1971). Photograph by DR Muhs.

The stratigraphy of loess-paleosol sequences can sometimes be used as a relative dating tool. In China, the sequence of loesses (S0, L1, S1, L2, etc.) is so readily identifiable, it can be used as a relative-dating or correlation tool for stream terraces when these landforms are mantled with loess (Porter *et al.*, 1992). In New Zealand, loess deposits, tephras, and paleosols have an increasingly complex record on successively older marine terraces (Berryman, 1993). The oldest marine terraces have the most complete succession of loess deposits, tephras, and paleosols (**Fig. 11**). Younger marine terraces have only the upper part of the record, and the youngest marine terrace is not overlain by loess at all.

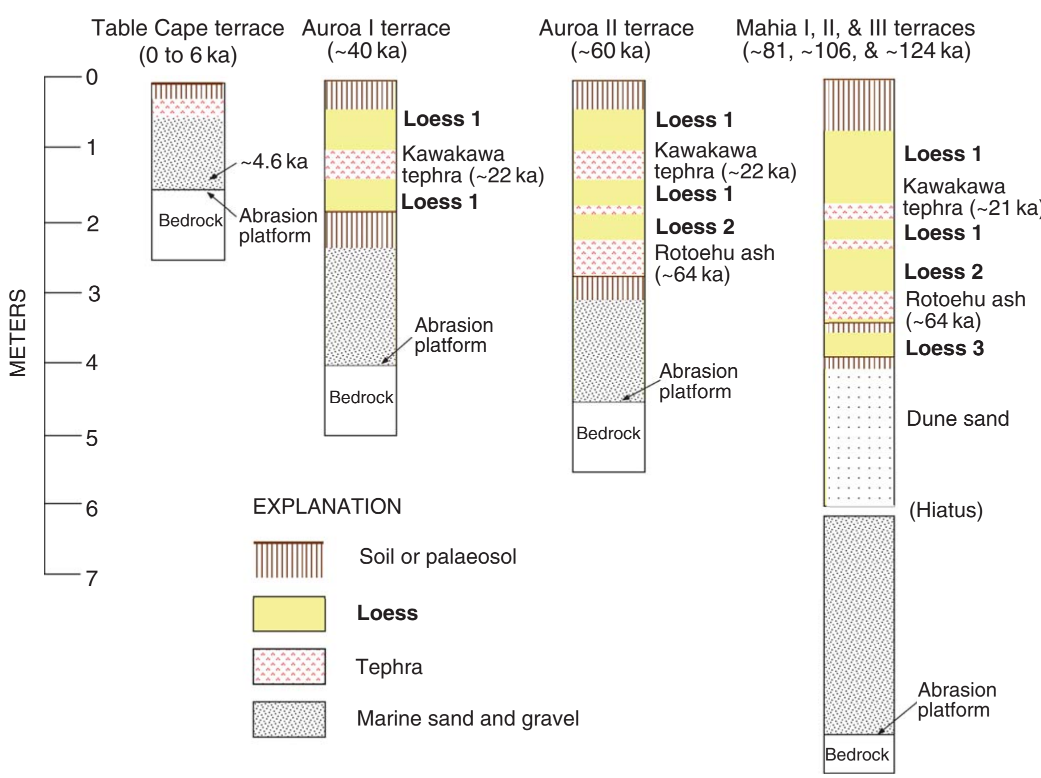

Figure 11 Loess, paleosol, and tephra stratigraphy on marine terraces on the Mahia Peninsula, New Zealand. Modified from Berrryman (1993).

Quaternary Paleoenvironmental Information from Loess Sequences

There is a wide variety of paleoenvironmental information that can be obtained from loess-paleosol sequences. Loess itself, as its properties change over a landscape, can yield important clues about the paleowind that deposited it. Loess thickness, particle size, and carbonate content generally decrease away from the source (Smith, 1942; Ruhe, 1969; Liu, 1988; Porter, 2001; Mason, 2001; Bettis *et al.*, 2003; Muhs and Bettis, 2003; Muhs *et al.*, 2004). The decrease in loess thickness reflects a reduction of sediment load downwind from the source, the decrease in mean particle size reflects winnowing of the coarse load, and the decrease in carbonate content reflects syndepositional leaching downwind, where deposition rates are lower. If a loess source were a north-to-south-trending river valley, a decrease in loess thickness and mean particle size to the east of the river would imply northwesterly, westerly, or southwesterly paleowinds (Fig. 12), at least during those periods when winds were strong enough to transport silt-sized particles.

Loess lacks many of the Quaternary paleoecological indicators that are commonly used in lacustrine or marine sediments, such as pollen, diatoms, ostracodes, radiolaria, or foraminifera. Furthermore, it is rare for mammal fossils to be preserved in loess. However, it is common for the shells of land snails to be preserved in loess, and they are abundant in China, Europe, and North America. Most or all of these snails are extant species, and their modern zoogeography is reasonably well established. Thus, it is possible to infer past climates during the times of loess deposition by identification of extralimital taxa, i.e., those species that do not presently live at a locality where they are found as fossils. In North America, the upper part of last-glacial loess of the central Great Plains contains several extralimital boreal or Cordilleran species of snails (Fig. 13). The presence of these northern-forest and mountain-forest species implies a much cooler-than-present last-glacial climate with forest vegetation, as opposed to the present, temperate grassland of the region (Rousseau and Kukla, 1994).

Whereas sedimentologic and paleontologic data in loess give information about glacial periods, paleosols within loess deposits yield information about interglacial or interstadial periods. Without question, the most common method applied to loess-derived paleosols since the 1980s has been measurement of magnetic susceptibility and other mineral magnetic properties (Kukla and An, 1989; Verosub *et al.*, 1993; Maher *et al.*, 1994; Porter, 2001; Porter *et al.*, 2001). Magnetic susceptibility is essentially a measurement of the abundance of magnetic minerals such as magnetite, a primary, rock-forming mineral, and maghemite, a secondary, pedogenic mineral. Other minerals, such as hematite, have very low but measurable magnetic susceptibility that can be differentiated from magnetite and maghemite. Measurement of these properties is rapid, inexpensive, and highly reproducible. Numerous studies have shown that Chinese loess has relatively low magnetic susceptibility and intercalated paleosols have high susceptibility. This makes the technique highly valued as a section-to-section correlation tool (Kukla and An, 1989) and many researchers have extended the method to correlation with deep-sea

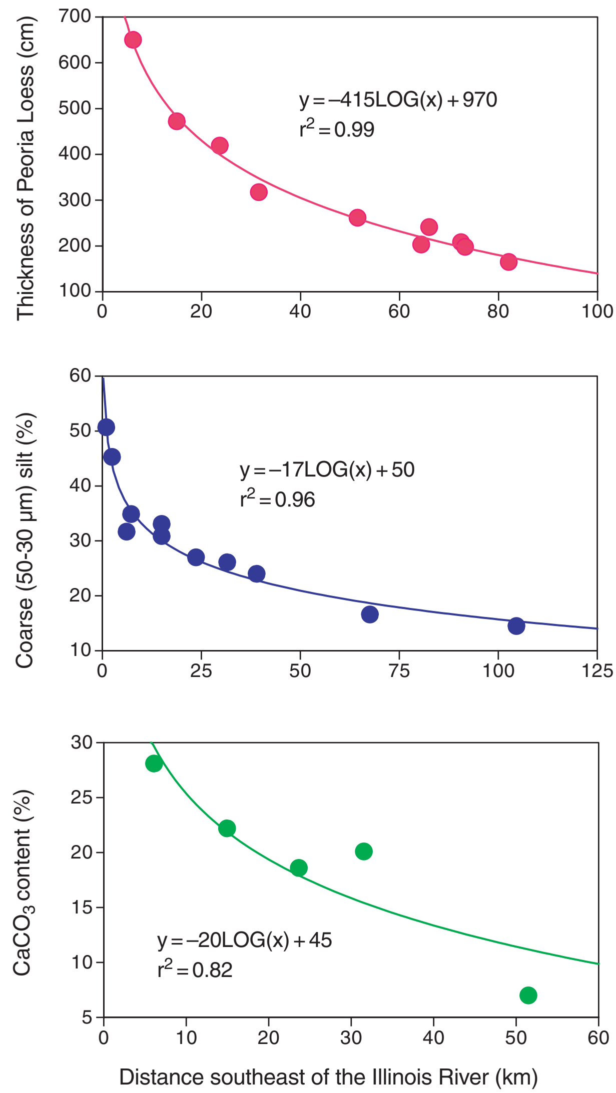

Figure 12 Thickness, coarse silt content, and carbonate content of Peoria (last glacial) Loess as a function of distance southeast of the Illinois River, IL, USA. Data from Smith (1942); regression equations computed by D.R. Muhs.

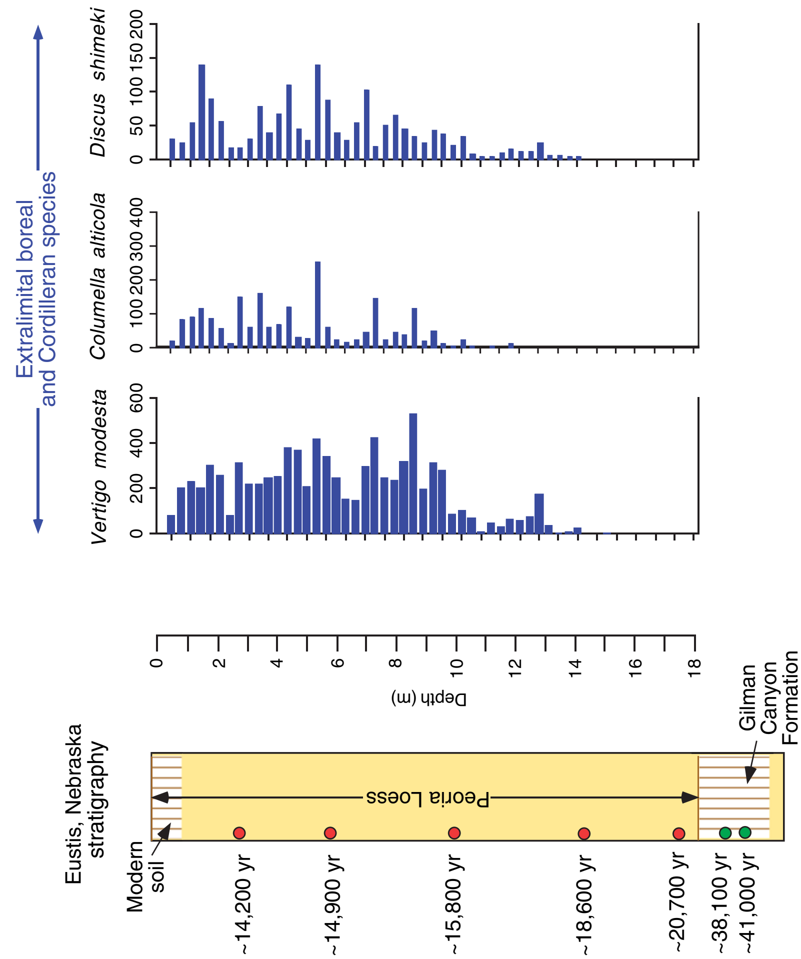

Figure 13 Stratigraphy of last-glacial (Peoria) loess at Eustis, Nebraska, USA, with optically stimulated luminescence (OSL) ages and calibrated radiocarbon ages (data from Roberts *et al.*, 2003 and Maat and Johnson, 1996). Also shown are absolute abundances of extralimital boreal and Cordilleran species of land snails (data from Rousseau and Kukla, 1994). Note that the section thickness as given by the latter authors differs slightly from that in Roberts *et al.* (2003); thus, depths of OSL ages in Peoria Loess are approximate. yr, year.

oxygen isotope records. Other researchers have attempted to develop transfer functions, correlating magnetic susceptibility in modern soils with climate parameters, such as mean annual precipitation (Maher *et al.*, 1994). If the assumptions are valid in this approach, then it would, in principle, be possible to estimate past climate from magnetic susceptibility of paleosols in loess. However, several problems arise with this approach. One is that magnetic susceptibility in modern, loess-derived soils in China is partly a function of particle size and sediment accumulation rate (as a dilution effect), as well as climate. Both of these factors are spatially variable but highly correlated with one another (and climate) across the Chinese Loess Plateau (Porter *et al.*, 2001). Another problem is that transfer functions of magnetic susceptibility and climate assume that soils quickly reach a steady state with regard to pedogenic magnetic mineral production. Soil chronosequence studies, however, show that magnetic susceptibility in soils continues to increase over time (Singer *et al.*, 1992). Finally, in some regions, magnetic susceptibility trends are the reverse of what they are in China. In Siberia and Alaska, for example, susceptibility is highest in loess and lowest in paleosols, due to high-magnetite loess sources and little or no production of secondary maghemite in soils (Begét *et al.*, 1990; Chlachula, 2003). Undoubtedly, part of the attraction of using magnetic susceptibility in studying loess and paleosols is the relative ease, rapidity, and low cost of analysis. Nevertheless, it is important to remember that in addition to the problems just summarized, magnetic minerals constitute a very small portion of the mineral suites of loess and its paleosols.

Less-controversial methods have also been utilized in studying loess-derived paleosols, although not as commonly as magnetic susceptibility. In the

Mississippi River valley of Illinois, soil morphology, particle size, and mineralogical and geochemical data show that paleosols differ in the amount of development and chemical weathering they have experienced (Grimley *et al.*, 2003). For example, the Sangamon Geosol and an older paleosol, called the Yarmouth paleosol, are redder and more clay-rich than the Farmdale Geosol or the modern soil. Proxies for plagioclase depletion (Na_2O/TiO_2), apatite depletion (P_2O_5/TiO_2), and silicate mineral depletion in general (SiO_2/Al_2O_3) show that the Yarmouth paleosol has experienced more weathering than the Sangamon Geosol, which in turn has experienced more weathering than the Farmdale Geosol or modern soil (Fig. 14). These data can be interpreted to mean that past interglacials were warmer and more humid than the present one, with enhanced chemical weathering in soils. An alternative interpretation is that past interglacials had a longer duration than what the present one has experienced, or that past interglacials were warmer, more humid, and longer than the present.

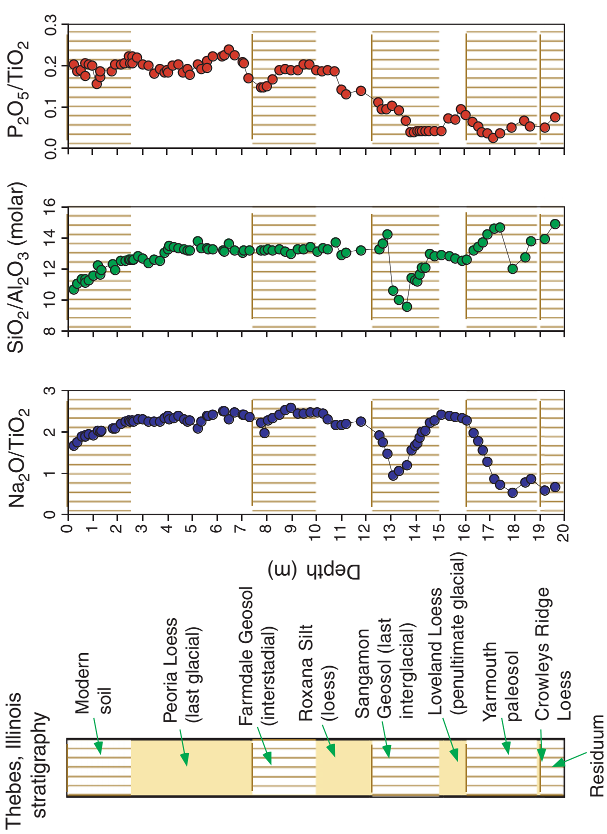

Figure 14 Stratigraphy and geochemistry of loess near Thebes, IL, Mississippi River valley, USA. Stratigraphy and Na_2O/TiO_2 data are from Grimley *et al.* (2003); other data, previously unpublished, are courtesy of DA Grimley, Illinois State Geological Survey.

Conclusion

Loess-paleosol sequences are one of the most important terrestrial records of Quaternary climate change. Loess is dominantly silt-sized, windblown sediment, typically composed of quartz, feldspars, micas, carbonates, and clay minerals. These deposits usually blanket pre-existing landscapes and can be centimeters to hundreds of meters thick. Loess is found over a large portion of the Earth's surface, in the central and northwestern US, Alaska, Argentina, Europe, Russia, Central Asia, China, and New Zealand. It has distinct advantages over other Quaternary sediments in that it is a direct record of atmospheric circulation and can be dated directly, using luminescence methods. Many loess records span much or all of the Quaternary and thus represent a terrestrial analog to the deep-sea sediment record. In most regions, loess was deposited during glacial periods, and soils formed during interglacial periods. There are exceptions to this, however, and in some areas, such as China, neither loess deposition nor soil formation ever cease completely. Loess can be used to reconstruct paleowinds using spatial trends of thickness, particle size, and carbonate content. Although many paleoecological indicators are rare or absent in loess, shells of land snails are common and can be a powerful tool in reconstructing paleoclimate. Finally, paleosols in loess sequences have many characteristics that can be used to estimate past climates.

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See also: **Loess Records**: Central Asia; China; Europe; North America; South America. **Luminescence Dating**: Thermoluminescence. **Paleoceanography, Physical and Chemical Proxies**: Oxygen Isotope Stratigraphy of the Oceans. **Paleosols and Wind-Blown Sediments**: Nature of Paleosols; Mineral Magnetic Analysis; Weathering Profiles; Soil Morphology in Quaternary Studies.

References

Aitken, M. J. (1998). *An introduction to optical dating*. Oxford University Press, Oxford.

Aleinikoff, J. N., Muhs, D. R., Sauer, R., and Fanning, C. M. (1999). Late Quaternary loess in northeastern Colorado, Part II – Pb isotopic evidence for the variability of loess sources. *Geological Society of America Bulletin* **111,** 1876–1883.

Begét, J. E., Stone, D. B., and Hawkins, D. B. (1990). Paleoclimatic forcing of magnetic susceptibility variations in Alaskan loess during the Quaternary. *Geology* **18,** 40–43.

Berryman, K. R. (1993). Distribution, age, and deformation of Late Pleistocene marine terraces at Mahia Peninsula, Hikurangi subduction margin, New Zealand. *Tectonics* **12,** 1365–1379.

Bettis, E. A., III., Muhs, D. R., Roberts, H. M., and Wintle, A. G. (2003). Last glacial loess in the conterminous USA. *Quaternary Science Reviews* **22,** 1907–1946.

Busacca, A. J., Begét, J. E., Markewich, H. W., Muhs, D. R., Lancaster, N., and Sweeney, M. R. (2004). Eolian sediments. In *The Quaternary period in the United States* (A. R. Gillespie, S. C. Porter and B. F. Atwater, Eds.), pp. 275–309. Elsevier, Amsterdam.

Chlachula, J. (2003). The Siberian loess record and its significance for reconstruction of Pleistocene climate change in north-central Asia. *Quaternary Science Reviews* **22,** 1879–1906.

Dan, J., and Yaalon, D. H. (1971). On the origin and nature of the paleopedological formations in the coastal desert fringe areas of Israel. In *Paleopedology: origin, nature and dating of paleosols* (D. H. Yaalon, Ed.), pp. 245–260. Israel Universities Press, Jerusalem.

Dodonov, A. E. (1991). Loess of Central Asia. *GeoJournal* **24.2,** 185–194.

Eden, D. N., and Hammond, A. P. (2003). Dust accumulation in the New Zealand region since the last glacial maximum. *Quaternary Science Reviews* **22,** 2037–2052.

Forman, S. L., and Pierson, J. (2002). Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi River valleys, United States. *Palaeogeography, Palaeoclimatology, Palaeoecology* **186,** 25–46.

Frechen, M., and Dodonov, A. E. (1998). Loess chronology of the Middle and Upper Pleistocene in Tadjikistan. *Geologische Rundschau* **87,** 2–20.

Frechen, M., Oches, E. A., and Kohfeld, K. E. (2003). Loess in Europe – mass accumulation rates during the Last Glacial Period. *Quaternary Science Reviews* **22,** 1835–1857.

Grimley, D. A., Follmer, L. R., Hughes, R. E., and Solheid, P. A. (2003). Modern, Sangamon and Yarmouth soil development in loess of unglaciated southwestern Illinois. *Quaternary Science Reviews* **22,** 225–244.

Hesse, P. P., and McTainsh, G. H. (2003). Australian dust deposits: modern processes and the Quaternary record. *Quaternary Science Reviews* **22,** 2007–2035.

Kohfeld, K. E., and Harrison, S. P. (2000). How well can we simulate past climates? Evaluating the models using global palaeoenvironmental datasets. *Quaternary Science Reviews* **19,** 321–347.

Kukla, G., and An, Z. (1989). Loess stratigraphy in central China. *Palaeogeography, Palaeoclimatology, Palaeoecology* **72,** 203–225.

Liu, T. (1988). *Loess in China*. 2nd edn. China Ocean Press and Berlin: Springer-Verlag, Beijing

Maat, P. B., and Johnson, W. C. (1996). Thermoluminescence and new ^{14}C age estimates for late Quaternary loesses in southwestern Nebraska. *Geomorphology* **17,** 115–128.

Maher, B. A., Thompson, R., and Zhou, L. P. (1994). Spatial and temporal reconstructions of changes in the Asian palaeomonsoon: a new mineral magnetic approach. *Earth and Planetary Science Letters* **125,** 461–471.

Mahowald, N., Kohfeld, K., Hansson, M., *et al.* (1999). Dust sources and deposition during the last glacial maximum and current climate: a comparison of model results with paleodata from ice cores and marine sediments. *Journal of Geophysical Research* **104,** 15,895–15,916.

Markewich, H. W., Wysocki, D. A., Pavich, M. J., *et al.* (1998). Paleopedology plus TL, ^{10}Be, and ^{14}C dating as tools in stratigraphic and paleoclimatic investigations, Mississippi River Valley, USA. *Quaternary International* **51/52,** 143–167.

Mason, J. A. (2001). Transport direction of Peoria Loess in Nebraska and implications for loess sources on the central Great Plains. *Quaternary Research* **56,** 79–86.

May, D. W., Swinehart, J. B., Loope, D., and Souders, V. (1995). Late Quaternary fluvial and eolian sediments: Loup River Basin and the Nebraska Sand Hills. In *Geologic field trips in Nebraska and adjacent parts of Kansas and South Dakota, Guidebook No. 10* (R. F. Diffendal, Jr and C. A. Flowerday, Eds.), pp. 13–31. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Lincoln, NE.

Miao, X., Mason, J. A., Goble, R. J., and Hanson, P. R. (2005). Loess record of dry climate and aeolian activity in the early- to mid-Holocene, central Great Plains, North America. *The Holocene* **15,** 339–346.

Muhs, D. R., and Bettis, E. A., III. (2003). Quaternary loess-paleosol sequences as examples of climate-driven sedimentary extremes. *Geological Society of America Special Paper* **370,** 53–74.

Muhs, D. R., Aleinikoff, J. N., Stafford, T. W., Jr. *et al.* (1999). Late Quaternary loess in northeastern Colorado: part I – age and paleoclimatic significance. *Geological Society of America Bulletin* **111,** 1861–1875.

Muhs, D. R., McGeehin, J. P., Beann, J., and Fisher, E. (2004). Holocene loess deposition and soil formation as competing processes, Matanuska Valley, southern Alaska. *Quaternary Research* **61,** 265–276.

Péwé, T. L. (1975). Quaternary geology of Alaska. *US Geological Survey Professional Paper* **835,** 1–145.

Porter, S. C. (2001). Chinese loess record of monsoon climate during the last glacial–interglacial cycle. *Earth-Science Reviews* **54,** 115–128.

Porter, S. C., An, Z., and Zheng, H. (1992). Cyclic Quaternary alluviation and terracing in a nonglaciated drainage basin on the north flank of the Qinling Shan, central China. *Quaternary Research* **38,** 157–169.

Porter, S. C., Hallet, B., Wu, X., and An, Z. (2001). Dependence of near-surface magnetic susceptibility on dust accumulation rate and precipitation on the Chinese Loess Plateau. *Quaternary Research* **55,** 271–283.

Pye, K. (1987). *Aeolian dust and dust deposits*. Academic Press, San Diego, CA.

Pye, K. (1995). The nature, origin and accumulation of loess. *Quaternary Science Reviews* **14,** 653–657.

Roberts, H. M., Wintle, A. G., Maher, B. A., and Hu, M. (2001). Holocene sediment-accumulation rates in the western Loess Plateau, China, and a 2500-year record of agricultural activity, revealed by OSL dating. *The Holocene* **11,** 477–483.

Roberts, H. M., Muhs, D. R., Wintle, A. G., Duller, G. A. T., and Bettis, E. A., III. (2003). Unprecedented last glacial mass accumulation rates determined by luminescence dating of loess from western Nebraska. *Quaternary Research* **59,** 411–419.

Rousseau, D. D., and Kukla, G. (1994). Late Pleistocene climate record in the Eustis loess section, Nebraska, based on land snail assemblages and magnetic susceptibility. *Quaternary Research* **42,** 176–187.

Rozycki, S. Z. (1991). *Loess and loess-like deposits*. Ossolineum Press, Polish Academy of Sciences, Warsaw.

Ruhe, R. V. (1969). *Quaternary landscapes in Iowa*. Iowa State University Press, Ames, IO.

Shackleton, N. J., and Opdyke, N. D. (1976). Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-239 late

Pliocene to latest Pleistocene. *Geological Society of America Memoir* **145,** 449–464.
Shen, C., Beer, J., Liu, T., *et al.* (1992). ^{10}Be in Chinese loess. *Earth and Planetary Science Letters* **109,** 169–177.
Singer, M. J., Fine, P., Verosub, K. L., and Chadwick, O. A. (1992). Time dependence of magnetic susceptibility of soil chronosequences on the California coast. *Quaternary Research* **37,** 323–332.
Smalley, I. J. (1995). Making the material: the formation of silt-sized primary mineral particles for loess deposits. *Quaternary Science Reviews* **14,** 645–651.
Smith, G. D. (1942). Illinois loess: variations in its properties and distribution, a pedologic interpretation. *University of Illinois Agricultural Experiment Station Bulletin* **490,** 139–184.
Sun, J. (2002). Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. *Earth and Planetary Science Letters* **203,** 845–859.
Vandenberghe, J., Huijzer, B. S., Mücher, H., and Laan, W. (1998). Short climatic oscillations in a western European loess sequence (Kesselt, Belgium). *Journal of Quaternary Science* **13,** 471–485.
Van den Haute, P., Vancraeynest, L., and de Corte, F. (1998). The Late Pleistocene loess deposits and palaeosols of eastern Belgium: new TL age determinations. *Journal of Quaternary Science* **13,** 487–497.
Verosub, K. L., Fine, P., Singer, M. J., and TenPas, J. (1993). Pedogenesis and paleoclimate: interpretation of the magnetic susceptibility record of Chinese loess-paleosol sequences. *Geology* **21,** 1011–1014.
Wright, J. S. (2001). Desert' loess versus 'glacial' loess: quartz silt formation, source areas and sediment pathways in the formation of loess deposits. *Geomorphology* **36,** 231–256.
Zárate, M. A. (2003). Loess of southern South America. *Quaternary Science Reviews* **22,** 1987–2006.